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Instrumentation Frontier

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8.1 Introduction

Detector instrumentation is at the heart of scientific discoveries. Cutting edge technologies enable US particle physics to play a leading role worldwide. This report summarizes the current status of instrumentation for high energy physics, the challenges and needs of future experiments and indicates high priority research areas. We also lay out five high-level key messages that are geared towards ensuring the health and competitiveness of the US detector instrumentation community, and thus the entire particle physics landscape.

The Instrumentation Frontier studies detector technologies and R&D needed for future experiments in collider physics, neutrino physics, rare and precision physics and at the cosmic frontier. It is divided into more or less diagonal areas with some overlap among a few of them. The areas are different detector types, including Solid State Detectors and Tracking (IF03), Noble Elements (IF08), and Micro Pattern Gas Detectors (IF05), along with different sensing aspects specific to Calorimetry (IF06), Photon Detectors (IF02), and Radio Detection (IF10). Sophisticated electronics and read-out technologies are essential to all detector types, including Electronics/ASICs (IF07) and Trigger and DAQ (IF04). Quantum sensors are already offering radically new opportunities to particle physics (IF01). Synergies between the different areas, as well as with other Frontier groups and research areas outside of HEP are organized by Cross Cutting and Systems Integration (IF09).

8.2 Executive Summary

For the field of high energy physics to continue to have a bright future, priority within the field must be given to investments in both evolutionary and transformational detector development that is coordinated across the national laboratories and with the university community, international partners, other disciplines and industry. While the fundamental science questions addressed by high energy physics have never been more compelling, there is acute awareness of the challenging budgetary and technical constraints when scaling current technologies. Furthermore, many technologies are reaching their sensitivity limit and new approaches need to be developed to overcome the currently irreducible technological challenges. This situation is unfolding against a backdrop of declining funding for instrumentation, both at the national laboratories and in particular at the universities. This trend has to be reversed for the country to continue to play a leadership role in particle physics. In this challenging environment it is essential that the community invest anew in instrumentation and optimize the use of the available resources to develop new innovative, cost-effective instrumentation. We need to invest in modernized facilities with enhanced capabilities, address intermediate planned project needs, and carry out blue-sky R&D that enable new physics opportunities to successfully accomplish the mission of high energy physics.

Much of the HEP portfolio is dominated by mid-sized to large scale experiments, which take decades to design, build and operate, and often span the entire lifetime of individuals' careers. In this environment it is becoming increasingly difficult for students and young researchers to have the opportunity to learn hands-on about detector instrumentation. For example on the collider physics side, there will be potentially a large gap in time between the current HL-LHC upgrades finishing and concrete designs and construction for the next generation collider experiments starting. The key challenge here will be to maintain the technical skills and experience within the community, and to train a new generation of instrumentation experts. This gap will have to be bridged partially by an increased effort in generic detector R&D, as well by encouraging and supporting PIs to get involved in other short-term, smaller scale experiments in other areas, such as astro-particle physics or accelerator-based dark matter and rare processes experiments. An expansion into newly enabled QIS experiments, exploiting recent transformative technological advances should also be encouraged. In general, careers in detector instrumentation in HEP need better support. A valuable addition would be increased opportunities for interdisciplinary PhDs, leveraging the SCGSR program. Furthermore, the field needs more mid-career positions for instrumentation experts, especially at Universities, where an additional advantage lies in the potential for cross-cutting positions with other departments, such as material science, quantum information, or engineering disciplines.

In addition to the maintenance of the technical workforce and expertise, it is also crucial that the community invests in modern facilities, which enable breakthrough advances in detector technologies for future experiments. A coherent set of supporting facilities needs to be maintained and enhanced over the coming years. Furthermore, the US HEP community needs to consider the creation of a detector R&D collaborative framework similar to the current RD collaboration model at CERN. These could be in specific technological areas and under the guidance and oversight of CPAD.

In order to stimulate transformational breakthroughs, we need to pursue synergies with other disciplines outside of HEP, as well as close collaborations with industry. Recent successful examples of this are QIS and Microelectronics, where communication and exchange between the HEP and other communities led to enhanced funding for technology development, which together with a new suite of available or achievable detector technologies and methods opened up a new suite of small-scale experiments that enhance the HEP portfolio, and can in turn contribute new solutions to traditional experiments.

To conclude, the science frontiers, CF, EF, NF and RPF, are pursuing a breadth of different future experiments, which have aggressive schedules and are technically challenging. They urgently require significant developments within the instrumentation frontier, which in turn requires significant investment now. The key challenges can be summarized as follows:

IF-1 Advance performance limits of existing technologies and push new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.

IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.

IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D Consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.

IF-4 Expand and sustain support for blue-sky, table-top RD, and seed funding. Establish a separate review process for such pathfinder R&D.

IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.

8.3 Key Technology Needs and R&D

8.3.1 Quantum sensors

The use of quantum sensors in high energy physics has seen explosive growth since the previous Snowmass Community Study. This growth extends far beyond high energy physics (HEP) impacting many areas of science from communications to cryptography to computing. Quantum sensors have been used in searches for dark matter - particle and wave, fifth forces, dark photons, the EDM, variations in fundamental constants, and gravitational waves, among others. These sensors come in a wide range of technologies: atom interferometers and atomic clocks, magnetometers, quantum calorimeters and superconducting sensors to name a few. Early work with quantum sensors was often focused in the cosmic and rare and precision frontiers, but recent concepts seek to expand the use of quantum sensors to the energy and neutrino frontiers solidifying them as fundamental technologies for the future of experimental HEP. Much of the early work in quantum sensors came from outside of 'traditional' HEP - for example development of atomic clocks for precision timing - but is now poised to make significant contributions to the most fundamental questions in physics.

Technology advances in quantum information science (QIS) provide exceptional theoretical and experimental resources to advance quantum sensing, with promising ideas and arising research projects that could provide mutual benefits in several areas such as materials, detectors, and devices. There are numerous 'table-top' scale experiments underway or ready to start that will explore parameter spaces not previously achievable. These experiments provide the community large 'bang-for-buck' while exploring a wide range of sensing techniques. As these experiments mature, concepts for larger experiments - in terms of the scale of the sensors and number of sensors networked together - are being developed. Future advanced of quantum sensors will require supporting small and larger scale experiments along with an in-demand workforce that stretches beyond field of HEP.

8.3.2 Photon Detectors

The Photon Detectors Topical Group has identified two areas where focused R&D over the next decade could have a large impact in High Energy Physics Experiments. These areas described here are characterized by the convergence of a compelling scientific need and recent technological advances.

The development of detectors with the capability of counting single photons from IR to UV has been a very active area in the last decade. Demonstration for sensors based on novel semiconductor (CMOS, skipper-CCD, SiPM) and superconducting technologies (MKID, SNSPD and TES) have been performed. These sensors open a new window for HEP experiments in the low photon number regime. Several ongoing and future projects in HEP benefit from these developments (Cosmology, Dark Matter, Neutrinos) which will also have a large impact outside HEP (BES, QIS, Astronomy). The combined scientific needs and technological opportunities make photon counting an ideal area for focused R&D investment in the coming decade. Such investment will secure leadership in photon counting technologies in the US, producing a large impact in HEP, with applications outside HEP. This opportunity is summarized in Ref [248].

A technological solution for the photon detection system in the first two modules of the DUNE detector exist, based on the by now well-known Arapuca light traps, with wavelength shifters and SiPMs as the photon detector [1], [2]. However, new photon detector developments are being considered for modules 3 and 4. Some of the proposed ideas consist on novel light collectors, the so-called dichroicons which are Winston-style light concentrators made from dichroic mirrors, allowing photons to be sorted by wavelength, directing the long-wavelength end of broad-band Cherenkov light to photon sensors that have good sensitivity to those wavelengths, while directing narrow-band shortwavelength scintillation light to other sensors [6]. This technology could be used in water-based liquid scintillators thus realizing a hybrid Cerenkov/scintillator detector.

Also notable are research and development efforts in new materials that could be directly sensitive to the VUV light, such as amorphous selenium (a-Se) [7] and organic semiconductors [8] Future investment in the above technologies over the next decade will enhance the science of the DUNE project.

8.3.3 Solid State Detectors and Tracking

Tracking detectors are of vital importance for collider-based high energy physics (HEP) experiments. The primary purpose of tracking detectors is the precise reconstruction of charged particle trajectories and the reconstruction of secondary vertices. The performance requirements from the community posed by the future collider experiments require an evolution of tracking systems, necessitating the development of new techniques, materials and technologies in order to fully exploit their physics potential.

Relative to the currently operating systems and their upgrades, the technical requirements for tracking detectors (trackers) in the next 20-40 years are significantly more stringent:

- Tolerance to fluences 1-2 orders of magnitude higher
- Larger areas at lower costs
- Segmentation and position resolution 2-4 times finer
- Precision timing resolution in a tracking environment
- Radiation length per layer from 0.1-1% X_0
- Cooling below the triple-point of CO_2
- Integration of novel radiation-hard materials

Successful completion of these programs requires focused efforts from the community on the development of the next generation technologies, steady development and refinement of existing technologies, and the pursuit of novel technologies to enable transformative progress. Collaborative efforts should be encouraged when possible to reduce the financial burden on individual groups, and to enlarge the pool of expertise in the field. Especially critical is to encourage and support young researchers to engage and pursue intensive research programs to develop these new technologies, to ensure a healthy workforce is sustained for the long term.

Eight white papers on solid state trackers were submitted during the 2022 Snowmass [**?**], focusing on a broad set of R&D topics that the US community is actively pursuing. While these papers don't completely capture the full breadth and depth of the R&D carried out in the US, they highlight the key challenges that future trackers will face and summarize the main research thrusts actively pursued by the community.

Advanced 4-dimensional trackers with ultra fast timing (10-30 ps) and extreme spatial resolution (O(few μm)) represent a new avenue in the development of silicon trackers, enabling a variety of physics studies which would remain out of experimental reach with the existing technologies. Several technology solutions are being currently pursued by the community to address the challenges posed by various experiments, both for the sensors and the associated electronics. Bringing in technological innovation and fully exploiting the potential of future detectors through the usage of ultra fast timing is a unique and exciting opportunity for the particle physics community. In order to reach this goal, it is of paramount importance in the coming years to undertake thoroughly the R&D studies to investigate how to best combine timing with spatial information.

The packaging and integration of the sensors and readout electronics will become more critical for future experiments, as device segmentation decreases to mitigate the increased track density. Bump bonding technologies have nearly reached their limits; more advanced 3D packing technologies including wafer-to-wafer and die-to-wafer hybrid bonding and through silicon vias (TSV) have the potential to meet the goals of future particle physics experiments. Collaboration between research groups and industrial partners with this expertise is crucial to introduce this technology to the HEP community. This research will take consider time and efforts to have confidence to use these technique in future large-scale tracking systems, and as such need to being urgently.

Detector mechanics will also play a significant role in future detector's performance. Material necessary for cooling and structural stability will be the lower bound on the radiation length for future tracking systems. Increased segmentation will lead naturally to larger power densities; in order to minimize material, solutions with integrated services and cooling are necessary. A holistic approach to design, simulation and manufacturing will be required. Novel materials, new cooling and composite manufacturing technique will need to be developed in order to reach the targeted performance.

To develop these new technologies, simulations of the properties of silicon and novel sensor materials throughout the lifetime of the experiments will be critical. These studies can drive device design included implant locations, size and strength to the most promising directions of development. To reach their full potential, further developments are needed to improve accuracy, precision and new devices. With this research, the performance of future experiments can be better predicted for its full life cycle prior to construction.

8.3.4 Trigger and DAQ

A trend for future high energy physics experiments is an increase in the data bandwidth produced from the detectors. Datasets of the Petabyte scale have already become the norm, and the requirements of future experiments—greater in size, exposure, and complexity—will further push the limits of data acquisition technologies to data rates of exabytes per seconds. The challenge for these future data-intensive physics facilities lies in the reduction of the flow of data through a combination of sophisticated event selection in the form of high-performance triggers and improved data representation through compression and calculation of high-level quantities. These tasks must be performed with low-latency (*i.e.* in real-time) and often in extreme environments including high radiation, high magnetic fields, and cryogenic temperatures.

Developing the trigger and data acquisition (TDAQ) systems needed by future experiments will rely on innovations in key areas:

- pursue innovations in the application of Machine Learning (ML) to TDAQ systems, particularly in the co-design of hardware and software to apply ML algorithms to real-time hardware and in other novel uses to improve the operational efficiency and sensitivity to new physics of future experiments;
- invest in the design of TDAQ system architectures that leverage new technologies, techniques, and partnerships to enable more intelligent aggregation, reduction, and streaming of data from detectors to higher-level trigger systems and offline data processing; and,
- develop improved readout technologies that increase data bandwidth and are capable of operating in extreme environments, while fitting the material and power constraints of future experiments.

Critically, innovations in TDAQ rely on the people and processes behind them, and require investments in those people and infrastructure for R&D. To that end, we call for:

- increased effort to build and retain domain knowledge for complex TDAQ systems by reliably supporting facilities and people – particularly engineers and technical staff, and early-career scientists through recruitment and training – in order to bring new ideas from early design and prototyping all the way through integration, commissioning, and operation in future detectors; and,
- the creation of a dedicated (distributed) R&D facility that can be used to emulate detectors and TDAQ systems, offer opportunities for integration testing (including low- and high-level triggering, data readout, data aggregation and reduction, networking, and storage), and develop and maintain an accessible knowledge-base that crosses experiment/project boundaries.

8.3.5 Micro Pattern Gas Detectors

Gaseous Detectors are the primary choice for cost effective instrumentation of large areas and for continuous tracking of charged particles with minimal detector material. Traditional gaseous detectors such as the wire chamber, Resistive Plate Chamber (RPC), and time projection chamber (TPC) with multiwire proportional chamber (MWPC) readout remain critically important for muon detection, track-finding, and triggering in ongoing and planned major particle physics experiment, including all major LHC experiments (ALICE, ATLAS, CMS, LHCb) and DUNE.

Micro Pattern Gaseous Detectors (MPGDs) are gas avalanche devices with order $\mathcal{O}(100\ \mu\text{m})$ feature size, enabled by the advent of modern photolithographic techniques. Current MPGD technologies include the Gas Electron Multiplier (GEM), the Micro-Mesh Gaseous Structure (MicroMegas), THick GEMs (THGEMs), also referred to as Large Electron Multipliers (LEMs), the Resistive Plate WELL (RPWELL), the GEM-derived architecture (micro-RWELL), the Micro-Pixel Gas Chamber (µ-PIC), and the integrated pixel readout (InGrid).

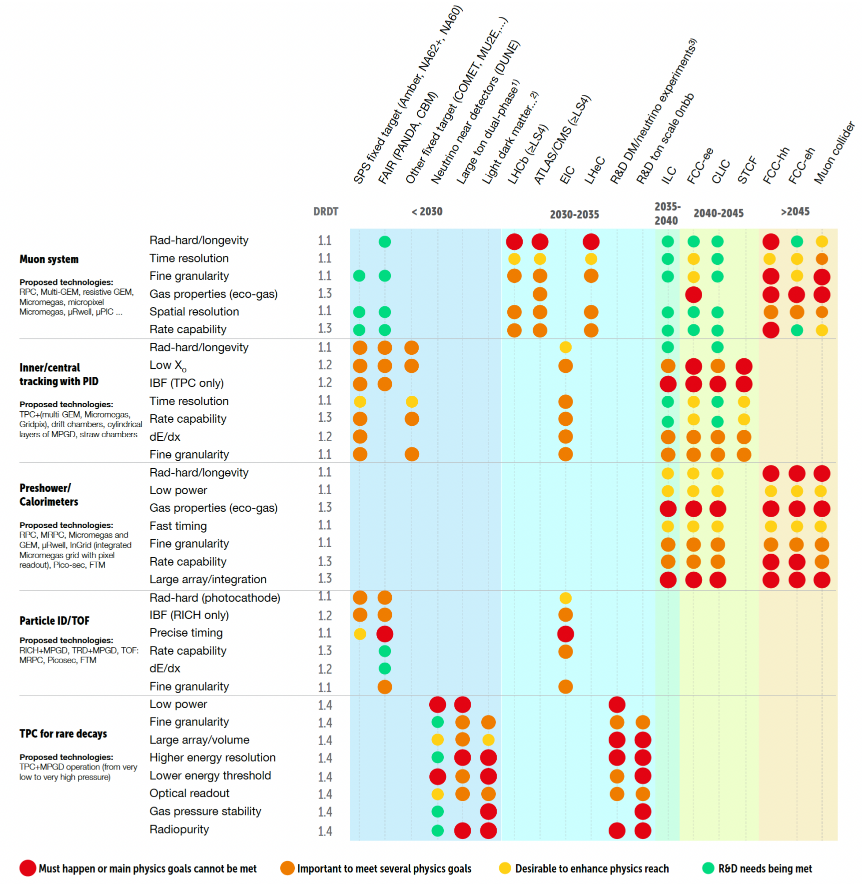
MPGDs have already significantly improved the segmentation and rate capability of gaseous detectors, extending stable operation to significantly harsher radiation environments, improving spatial and timing performance, and even enabling entirely new detector configurations and use cases.

In recent years, there has therefore been a surge in the use of MPGDs in nuclear and particle physics. MPGDs are already use for upgrades of the LHC experiments and are in development for future facilities (e.g., EIC, ILC, FCC, and FAIR). More generally, MPGDs are exceptionally broadly applicable in particle/hadron/heavy-ion/nuclear physics, charged particle tracking, photon detectors and calorimetry, neutron detection and beam diagnostics, neutrino physics, and dark matter detection, including operation at cryogenic temperatures. Beyond fundamental research, MPGDs are in use and considered for scientific, social, and industrial purposes; this includes the fields of material sciences, medical imaging, hadron therapy systems, and homeland security.

Five commissioned white papers on MPGDs were developed during the 2021 Snowmass decadal survey. These summarize R&D on MPGDs [?], the future needs for MPGDs in nuclear physics [?] and in three broad areas of particle physics: low-energy recoil imaging [?], TPC readout for tracking at lepton colliders [?], and tracking and muon detection at hadron colliders [?]. A white paper with further details on a proposed TPC tracker for Belle II was also submitted [?].

Key Points

- Research directions: The field of MPGDs is relatively young and continues to evolve. The main R&D directions where advances are needed and expected are:
  - pico-second timing
  - particle-identification
  - stable operation in ultra-high rate applications
  - extended triggering capabilities, including topological and machine-learning based
  - dedicated electronics, DAQ, readout technoligies
  - reduced ion backflow
  - improved radiopurity
  - single-electron counting
  - negative ion drift
  - mass production
  - large-area systems
  - algorithm-development
  - gas purification, recovery, environmentally friendly gas mixtures
- Blue-sky R&D: Exploring the fundamental performance limits of MPGDs, such as pico-second time resolution or single-electron-counting, will further advance the field, likely lead to new experimental techniques, and may enable new classes of experiments.



			< 2030						2030-2035						2035-2040	2040-2045			>2045		
		DRDT	SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E...)	Neutrino near detectors (DUNE)	Large ton dual-phase$^{1)}$	Light dark matter...$^{2)}$	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments$^{3)}$	R&D ton scale 0nbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_o	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟡	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	1.4				🟢	🔴	🔴					🔴	🔴							

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

Figure 8-1. *From ECFA report. To be replaced with simplified Snowmass figure.*

- Experimental needs: Significant production of MPGDs will be required for planned HEP and NP experiment with US leadership or participation (Fig. 5-1) to meet the physics performance requirements.
- Dedicated MPGD development facilities: Currently, the majority of MPGD developers and users in the U.S. rely on production facilities and expertise, diagnostic facilities, and standardized readout electronics associated with the RD51 collaboration and CERN. This significantly slows down the R&D cycle and limits the speed of innovation in the US. It also means all production for US-led experiments has to be outsourced.

  A U.S.-based MPGD Center of Excellence is needed and would address this issue. We envision a facility similar in nature to the Gaseous Detector Development (GDD) lab at CERN or the SiDet facility at FNAL. Such a facility would benefit both the nuclear physics and particle physics communities in the US. There are also ample opportunities for commercialization and collaboration with industry. We envision such a facility hosted by one of DOE's National Laboratories, such as Jefferson Lab or Brookhaven National Laboratory.

8.3.6 Calorimetry

The IF06 Calorimetry group has considered major issues in present and future calorimetry. Input has been taken from a series of talks, group discussions, LOIs, and White Papers. Here we report on two major approaches to calorimeter systems - Particle Flow and Dual Readout, the critical extra dimension of precision timing, and the development of new materials for calorimeters.

The potential for precision timing at the 10ps level or better opens new possibilities for precise event reconstruction and the reduction of the negative effects of challenging experimental environments. Precise timing can directly benefit calorimetry in several ways ranging from detailed object reconstruction to the mitigation of confusion from pile-up. It can also lead to improved performance for both particle flow and duel readout-based calorimeters. Given these possible performance enhancements, the focus is now on the study of timing implementation both at the device level and the calorimeter system level. Successful implementation can lead to highly performant calorimeter systems well matched to the demands from both future physics studies and experimental environments.

The construction of future calorimeters matched to the demands of high radiation tolerance, the need for fast timing, and constrained cost puts strong requirements on the properties of active calorimeter materials. Suitable materials should therefore combine high density, fast decay time, and good radiation hardness with good optical quality and high light yield. A range of inorganic scintillators has been developed possessing many of these desired properties. However, use of these materials in future large-scale calorimeter systems demands attention to material costs to assure affordability. Organic based plastic scintillators have seen very wide use, having the advantages of ease of use and relatively low cost. The combination of plastic scintillators with SiPM readout has significantly expanded the flexibility of calorimeter design. Finally, liquid scintillators, with low unit cost, have been widely used where very large volumes are required. An interesting development is the potential of metal doped (water-based) liquid scintillators for use as active materials in sampling calorimeters.

Particle flow calorimetry makes use of the associations of charged tracks and calorimeter energy deposits to achieve precise reconstruction of hadronic jets and measurement of their energy. Such associations can aslo be effectively used to reduce the effects of pileup. Implementation of a PFA-based calorimeter requires a small cell size and high granularity leading to very high channel counts. Challenges remain in realizing calorimeter systems with up to 100 million cells. Developent is onging for such systems in the areas of power (heat) management, integration of on-board ASICs, and components of signal extraction. A variety of approaches to PFA calorimeters are under developent ranging from scintillator-SiPM systems to a range of gas-based systems using GEMs, Micromegas and RPCs. Also being explored are the potential benefits of precise timing (see above) and moving some elements of a PFA into the front-end electronics.

The dual readout approach to the precise measurement of jet energies makes use of the scintillation light and Cerenkov light from showers. The relative amounts of scintillation and Cerenkov light is used to correct the shower energy. The original approach to implementing dual readout calorimetry used a matrix of scintillating fibers and clear optical fibers (for the Cerenkov component) in a block of absorber material. However, with the reduced need for spatial associations (as in particle flow), dual readout can make beneficial use of an electromagnetic front section using homogeneous scintillating crystals which have excellent electromagnetic energy resolution. Development of dual readout systems has followed both of these approaches. In the second case, the separation of the scintillation and Cerenkov signals can be achieved by the use of optical filters and SiPM readout and/or exploitation of the different time structure of the two signals. Development and testing of large-scale systems is needed to demonstrate the feasibility of both the all-fiber and homogeneous electromagnetic section plus fibers approaches to dual readout.

The field of calorimeter research and development remains very active. The precision energy measurement requirements of future physics programs is stimulating innovation in the particle flow and dual readout systems. The increasing availability of precise timing is adding an important new dimension to system implementation, while the development of a range of fast, radiation-hard active materials is leading to increased flexibility and exciting possibilities for calorimeter system designs.

8.3.7 Readout Electronics and ASICs

In pursuit of its physics goals, the high energy physics community develops increasingly complex detectors, with each subsequent generation pushing to ever finer granularity. For example, the emergence and growing dominance of particle-flow reconstruction methods has stressed the increasing importance of very fine detector granularity, not only for tracking detectors but also for calorimetry, and has also initiated the push to ”4D” detectors that combine precision measurements of both spatial and time coordinates to their measurements of energy and momentum. While these development have led to enormous growth in detector channel counts, the analog performance requirements for energy and momentum measurements, as well as spatial and timing precision, are being maintained or (more typically) even tightened.

These challenging detector requirements push the corresponding development of readout electronics. A variety of factors, including the growing specialization of the functionality required, and the explosive growth in channel counts and typically modest (if any) increases in the material budget and the power and cooling budgets, lead to the increasing reliance on custom-developed Application Specific Integrated Circuits (ASICs). This trend is further exacerbated by challenges in the various experimental environments, including radiation hardness requirements, cryogenic and deep-cryogenic operations, and space-based detector systems. The development of custom ASICs in advanced technology nodes allows HEP detector subsystems to achieve higher channel density, enhanced performance, lower power consumption, lower mass, much greater radiation tolerance, and improved cryogenic temperature performance than is possible with commercial integrated circuits (ICs) or discrete components. The higher level of integration also leads to fewer components and fewer connections, leading to higher reliability, as required by experiments that can run for decades and that provide access to the on-detector electronics at most annually, and sometimes never.

This writeup summarizes the work of “IF07”, namely Topical Working Group 7 of the Instrumentation Frontier group of the Snowmass 2021 process. Group IF07 dealt with issues pertaining to ASICs and Readout Electronics. The community efforts as part of IF07 were organized across 7 white papers submitted to the Snowmass process. The first [1] discusses issues related to the need to maintain the talented workforce required to successfully develop future HEP electronics systems, and to provide the appropriate training and recruitment. The remaining papers focused on electronics for particular detector subsystems or technologies, including calorimetry [2], detectors for fast timing [3], optical links [4], smart sensors using AI [5], cryogenic readout [6], and RF readout systems [7]. In the following section, a brief overview is provided of each of the white papers in turn. A white paper on silicon and photo-detectors was originally considered. This content is now captured by other frontiers with contributions form ASICs and readout electronics.

The interested reader is referred to the white papers themselves, and to the references each contains, for a more detailed discussion of each of the various topics.

There are some overarching goals for advancing the field of readout and ASICs. Among those three activities with broad impact are: 1) Provide baseline support and specialized training opportunities for the instrumentation work force to keep the US electronics instrumentation ASIC workforce; 2) improve mechanisms for access to advanced technology; 3) continue to develop methodologies to adapt the technology for operation in extreme environments; 4) expand framework and platform for easy access to design tools.

8.3.8 Noble Elements

Particle detectors making use of noble elements in gaseous, liquid, or solid phases are prevalent in neutrino and dark matter experiments and are also used to a lesser extent in collider-based particle physics experiments. These experiments take advantage of both the very large, ultra-pure volumes achievable and the variety of signal pathways available in noble targets. As these experiments seek to increase their sensitivity, novel and improved technologies will be needed to enhance the precision of their measurements and to broaden the reach of their physics programs. The priority research directions (PRDs) and thrusts identified in the 2019 Report of the Office of Science Workshop on Basic Research Needs for HEP Detector Research and Development (BRN report) [?] are still relevant in the context of this Snowmass 2021 topical group. The areas of R&D in noble element instrumentation that have been identified by the HEP community in the Snowmass whitepapers align well with the following BRN report PRDs:

- Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity
- Develop new modalities for signal detection
- Improve the understanding of detector microphysics and characterization to increase signal-to-noise and reconstruction fidelity
- Advance material purification and assay methods to increase sensitivity
- Address challenges in scaling technologies

This topical group identifies and documents recent developments and future needs for noble element detector technologies.

8.3.9 Radio Detection

The radio detection of cosmic rays and neutrinos has emerged as the technology of choice at highest energies. Detectors use large volumes of a naturally occurring suitable dielectric: the Earth's atmosphere and large volumes of cold ice as available in polar regions. The detection technology has matured in the past decade and as ready to move beyond prototyping or midscale applications. Instrumentation for radio detection has reached a maturity for science scale detectors. The optical technique has already been successfully implemented in large scale detectors in ice (IceCube), and efforts are projects underway to apply them in large scale in water (km3NeT, Baikal GVD). The option to detect earth-skimming neutrinos with optical Cherenkove telescopes is being explored.

- IF10-1 IceCube-Gen2 has developed a conceptual design that will be released as a Technical Design Report later this year. Further investment in RD can potentially reduce cost and optimize design.

- IF10-2 Opportunities exist in optimizing for power and simplifications: eg ASIC based digitizer/readout (PMT) or RFSoC (Radio Frequency System on Chip). Investigate if synergies with experimental needs in other areas exist.

- IF10-3 Remote power and communications approaches of very large extended arrays can still benefit from dedicated RD. Explore synergies with other experiments, like DUNE, SKA, CTA, which also need large distance communication and synchronization.

8.4 Facilities

8.4.1 Calibration and test beam facilities

Progress in particle physics depends on a multitude of unique facilities and capabilities that enable the advancement of detector technologies. Among these are test beams and irradiation facilities, which allow users to test the performance and lifetime of their detectors under realistic conditions. Test beam facilities are particularly important for collider and neutrino detector applications, while irradiation facilities are crucial for collider as well as some space-based astro particle detectors. It is important that the energy, intensity, particle composition and time structure of the beams are adequate for the detector needs for the next generation. In the area of irradiation facilities overlapping needs between detector and accelerator instrumentation as well as targetry development can be addressed.

8.4.2 Low noise and environmentally stable facilities

The particle physics community relies on a variety of specialized environmental conditions for operation of the most sensitive instrumentation. These include low vibration/geologically quite environments, low electromagnetic interference environments, low radioactive background environments, and cryogenic environments to suppress thermal noise. Low radioactivity environments are discussed in the Underground Facilities section of this report [**?**]. Environmentally stable facilities, i.e. low vibration and/or low electromagnetic interference, tend to be very specialized for specific equipment (e.g. isolating a laser system or NMR) or to suppress specific frequency bands (seismic or electromagnetic) making it difficult to define the requirements for a general purpose user facility. In addition,these facilities are generally within the reach of individual research groups to establish locally as needed.

8.4.3 Cryogenic Test Facilities

Cryogenic test facilities are critical infrastructure for physics experiments in a variety of fields. Some notable examples include studying noble liquid properties for particle detection, low-temperature device development, and research in quantum information. The required technical knowledge and infrastructure capacity, including the cost of setting up and operating the test facilities, can place them out of reach of many individual group research groups. As such, these research areas would greatly benefit from centralized user facilities. Cryogenic test facilities can require significant investments in infrastructure and ongoing operations costs, and warrant consideration of the development of national user facilities.

Several international institutions have established LAr test stands typically for specific purposes or experiments with limited measurement capabilities and access to the community. Some relatively large-sized facilities (more than 100 liters of LAr) include the ICARUS $\sim$ 50 liter LArTPC at CERN [3] with $\sim$ 250 liter LAr capacity, which is mainly used for ICARUS and DUNE detector electronics readout studies; the ArgonCube detector [5] at University of Bern with $\sim$ 1100 liter LAr capacity, which is dedicated for pixel readout in LAr and DUNE's modular detector study; and the Integrated Cryostat and Electronics Built for Experimental Research Goals (ICEBERG) at Fermilab with $\sim$ 3000 liter LAr capability, which is dedicated to DUNE cold electronics studies. As can be seen, these facilities are typically tied to the specific tasks that are not easily accessible as a user facility with the general purpose of R&D, such as testing new devices and detector designs, studying noble liquid property, calibrating detector signal response, or studying light detector performance, etc. The necessary initial components for a community LAr test facility include a large cryostat with sufficient volume and drift distance, adequate cryogenic infrastructure for condensing and gas circulation, a purification system to remove impurities with high electron attachment, a purity monitoring system with gas analyzers, basic high voltage system and readout electronics for TPC measurements, a photon detection system to study scintillation light, and the accompanying DAQ system.

The operation of sensors and systems at ultra-low temperature is a major growth field, but one which necessarily has a high barrier for entry due to the relatively high cost of equipment, not just for the cooling platform itself but also associated measurement equipment and electronics and a knowledge gap in the operation and engineering of devices and systems at cryogenic temperatures. In addition, the typical fabrication, measurement and analysis cycle associated with the development of cryogenic devices will often mean that test stands can be idle for considerable periods of time, making the economics of every PI or research group having dedicated research facilities economically unattractive. The establishment of a centralized facility would democratize the process of device development by allowing users access to test stands and measurement equipment for a variety of different tests, including but not limited to thermal, RF and low frequency tests. This is particularly valuable at the pre-proposal and proof-of-concept stages to validate new ideas before committing to full proposals or the expense of purchasing dedicated test equipment. In addition, such a facility would serve as a repository of knowledge of low temperature materials and other specialized information and offer a medium to connect researchers with specialized cryogenic engineering resources. Finally, such a facility is a vital tool for training a future workforce by providing hands-on experience in the operation of cryogenic systems and measurement equipment, typically outside the ability of a University level teaching laboratory to provide. Such a facility would necessarily consist of more than a single refrigerator test stand, since this is something that a well-equipped PI laboratory would be able to provide. Instead, it is envisaged that the proposed User Facility would provide a suite of test stands available for different experiment types, including a number of test stands providing environments for the testing of specialized devices such underground and low-background environments, test stands with optical access, and stands incorporating magnetic fields.

8.5 Synergies

8.5.1 Collaborative research models

The U.S. HEP model for these has been to base facilities/core capabilities at national labs as user facilities funded by KA-25. Alternative approaches might be considered based on models such as the the CERN RD research programs or the NNSA NA-20 research consortia. The CERN RD programs provide an organizational framework within which collaborative research is conducted, but provide no direct funding support. However, engagement in these RD programs often provides a strong argument for grant funding to support participation. In contract, the NA-20 research consortia are multi-year multi-institutional research proposals with funding provided to the university groups and an expectation of support from national laboratories already funded by the office. In both cases, the intent is to build 5+ year programs of research to address larger programmatic ambitions than individual institutions could tackle.The HEP investment in LAPPDs was to a large extent such a program.

8.5.2 Multidisciplinary research

The topic of multidisciplinary R&D was explored in the MultiHEP 2020 workshop, held virtually on Nov. 9-12, 2020 [6]. This consisted of a series of invited presentations and panel discussions to collect experience on successes, challenges, and lessons about multi-disciplinary collaborations to further High Energy Physics RD. The focus is on HEP developments that make use of expertise from outside HEP through collaborative efforts. R&D disciplines explored included chemistry, materials science, nuclear science, micro and nano fabrication. Examples included small efforts at universities, projects at labs, work with industry through SBIR and otherwise, long-term multi-institute development such as LAPPD [7], and agency experience. The workshop panel discussions identified relevant points in the categories working with other fields, working with industry, and multidisciplinary personnel and funding.

Working with other fields Development of new instrumentation is often only possible through expertise and capabilities from outside HEP. Examples at the workshop were LAPPD, barium tagging for $0\nu\beta\beta$ decay, use of carbon nanotubes for photon detection, etc. The following observations were collected:

- Informal discussions are required to establish work scope for reasons summarized as “because you don’t know what you don’t know”.
- Some interest in the HEP goals is more important than expert standing in another field.
- Research philosophy is different in other fields. in HEP negative results are a success (most HEP results are negative!) Other fields have narrowly defined goals and positive results are the measure of success.
- Publication approach is different in other fields. No preprints: scoops common so results remain secret till published. Publications are geared to the next funding proposal. Author lists are small. It’s a good idea to have agreements formalizing collaboration, funding, author lists etc. after initial informal discussions.

Working with industry There were numerous reports about successful SBIR efforts. The SBIR program offers a good path to fund multidisciplinary development by partnering with an appropriate firm. True partnerships between HEP scientists and firms are essential for success. An issue with SBIR is that many technologies critical for HEP do not have a lucrative commercialization path, but SBIR requires commercialization as the end product of Phase 2. Even when commercialization is in principle possible, there is a large gap between phase 2 and volume production for profit. It is difficult for small companies to bridge that gap.

Connecting with the right company is a challenge. Networking efforts can help. NP holds an annual exchange meeting for this purpose. Some national labs have industry days, but not regularly or at the same level. BNL has a discovery park incubator.

For multidisciplinary work there may be co-founding opportunities. Each office has to allocate and spend the required SBIR levels and this leads to roundoff errors becasue each office has to spend down an exact amount. This would allows NP to co-fund something with HEP, for example.

Multidiscpiplinary personnel and funding

- Few institutes train people in multiple disciplines at once. It is therefore hard to recruit people to carry out multidisciplinary work.
- The other side of the coin is that a student or postdoc developing in two disciplines at once may have a hard time finding the next job, because they will not be competitive in either one of these disciplines with peers who devoted themselves fully to it. They need to find a job where both disciplines are required.
- Funding agency offices tend to not like paying for personnel normally under other offices, which makes it hard to find multidisciplinary work with a single grant. Recent QIS and Micrelectronics FOAs have aimed at multidisciplinary work. Microelectronics has been more successful because (unusually) multiple offices co-funded the same FOA, while this was not the case for QIS, where each office had separate FOAs. More funding like Microelectronics is needed if fostering multidisciplinary work is desired.

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TOPICAL GROUP REPORTS

Instrumentation Frontier

1

Quantum Sensors

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(contributors from the community)

1.1 Executive Summary

The use of quantum sensors in high energy physics has seen explosive growth since the previous Snowmass Community Study. This growth extends far beyond high energy physics (HEP) impacting many areas of science from communications to cryptography to computing. Quantum sensors have been used in searches for dark matter - particle and wave, fifth forces, dark photons, the EDM, variations in fundamental constants, and gravitational waves, among others. These sensors come in a wide range of technologies: atom interferometers and atomic clocks, magnetometers, quantum calorimeters and superconducting sensors to name a few. Early work with quantum sensors was often focused in the cosmic and rare and precision frontiers, but recent concepts seek to expand the use of quantum sensors to the energy and neutrino frontiers solidifying them as fundamental technologies for the future of experimental HEP. Much of the early work in quantum sensors came from outside of 'traditional' HEP - for example development of atomic clocks for precision timing - but is now poised to make significant contributions to the most fundamental questions in physics.

Technology advances in quantum information science (QIS) provide exceptional theoretical and experimental resources to advance quantum sensing, with promising ideas and arising research projects that could provide mutual benefits in several areas such as materials, detectors, and devices. There are numerous 'table-top' scale experiments underway or ready to start that will explore parameter spaces not previously achievable. These experiments provide the community large 'bang-for-buck' while exploring a wide range of sensing techniques. As these experiments mature, concepts for larger experiments - in terms of the scale of the sensors and number of sensors networked together - are being developed. Future advanced of quantum sensors will require supporting small and larger scale experiments along with an in-demand workforce that stretches beyond field of HEP.

1.2 Overview

1.2.1 Introduction

In this report we provide an overview of recent development in quantum sensors and their scientific impact to the high energy physics community as presented in the many LOIs and white papers submitted during the Snowmass 2021 process. We focus on sensors in which the quantum state of the sensor can be measured and manipulated. Also included are quantum calorimeters, which seek to measure individual quanta of energy deposited in the sensor. As a group, quantum sensors are extremely sensitive devices used to explore new physics. The goal is to use hardware and manipulation techniques developed in quantum information science and technology to reach sensitivities better than the standard quantum limit (SQL) over as broad a bandwidth as possible. Many of the most promising quantum sensors for HEP science have been developing for the past decade or more in areas outside of the traditional HEP science and funding sphere. For example, atomic clocks developed over many decades as a source of precision timing standards are now stable enough they can be used in the search for variations of fundamental constants and gravitational waves. At the same time, the field of quantum computing is experiencing multiple breakthroughs. We point the reader to the report from the Quantum Computing topical group in the Computational Frontier for more details, but highlight that many of the technological developments needed to improve quantum computers are also needed to improve quantum sensors: longer coherence times, increases numbers of quantum states, isolation from environmental noise, etc. Quantum sensing and computing also both require a highly skilled workforce. With the arrival of several major tech companies in the field of quantum computing there is fierce competition for workers. The HEP community will need to invest now in order to train the next generation of quantum scientist.

Much of the growth in quantum sensors over the past decade has occurred in small, laboratory based experiments. These small experiments have allowed the broader community to try out many different varieties of sensors (see 1.3 for examples) aimed at a broad range of scientific targets. The extreme sensitivity of quantum sensors often enables these experiments to make significant gains in unexplored parameter spaces at minimal cost while also advancing the sensor technology. Continued support of these ’table top’ experiments serves as a way to rapidly develop sensor technology and help determine those areas where quantum sensors can have the greatest impact. As the fast-paced small experiments mature, those with the significant discover potential begin to emerge along with areas of commonality between the experiments (e.g. the need for advanced high field magnets for axion dark matter experiments or ultra-stable lasers for atom interferometers and clocks). They have reached the point at which plans for larger-scale, longer-term experiments are being developed. These concepts can evaluate the potential reach that can be achieved in a larger effort and the scale of require technological development.

1.2.2 Science

Note : Would like to reference as many white papers as possible that use/discuss quantum sensors.

Quantum sensors encompasses a broad spectrum of technologies (as described in 1.3 below) and has the potential to impact a wide range of core HEP science. This can seen in the white papers submitted to this community study that make use of these sensors: dark matter - ([**?**, **?**], fifth forces, dark photons, EDM, variations in fundamental constants, and gravitational waves, among others.

1.3 Technologies

1.3.1 Interferometers, Optomechanics, and Clocks

*Note : The contents of this section are in part taken and modified from: Snowmass 2021: Quantum Sensors for HEP Science – Interferometers, Mechanics, Traps, and Clocks [**?**]*

Atom Interferometers

Atom interferometry is a growing field with a variety of fundamental physics applications including gravitational wave detection, searches for ultralight (wave-like) dark matter candidates and for dark energy, tests of gravity and searches for new fundamental interactions ("fifth forces"), precise tests of the Standard Model (e.g. fine structure constant), and tests of quantum mechanics. In light-pulse atom interferometry, laser pulses are used to coherently split, redirect, and recombine matter waves. Conventional atom interferometry makes use of a pair of counter-propagating laser beams to drive two-photon Raman or Bragg transitions while a new variation takes advantage of long-lived excited states in alkaline-earth-like atoms that can be resonantly driven by a single laser beam. In a gradiometer configuration, two identical atom interferometers are run simultaneously on opposite ends of a baseline, using the same laser sources. A comparison of the individual atom interferometer signals yields a differential measurement that enables the cancellation of noise common to both interferometers. This in principle enables superior common-mode rejection of noise, allowing for the possibility of, for example, gravitational wave detection using a single baseline. A passing gravitational wave would modulate the baseline length, while coupling to an ultralight dark matter field can cause a modulation in the energy levels. This combines the prospects for both gravitational wave detection and dark matter searches into a single detector design, and both science signals are measured concurrently.

The MAGIS concept takes advantage of features of both clocks and atom interferometers to allow for a single-baseline gravitational wave detector. MAGIS-100 is the first detector facility in a family of proposed experiments based on the MAGIS concept. The instrument features a 100-meter vertical baseline and is now under construction at the Fermi National Accelerator Laboratory (Fermilab). State-of-the-art atom interferometers are currently operating at the 10-meter scale, while a kilometer-scale detector is likely required to detect gravitational waves from known sources. The Atom Interferometric Observatory and Network (AION) project envisages a staged Atom Interferometry program, starting with a 10 m device and progressing via a 100 m experiment to a 1 km instrument. AION will enable exploration of the properties of ultra-light dark matter (DM) and gravitational waves (GWs) from the very early Universe and astrophysical sources in the mid-frequency band ranging from several mHz to a few Hz, intermediate between the sensitive ranges of LIGO/Virgo/KAGRA and LISA. The ultimate sensitivity of the AION program will be reached by interoperating and networking with other instruments around the world, similar to the existing LIGO-Virgo network, which will provide science opportunities not accessible to single detectors.

Optomechanical Sensors

Mechanical sensors that can be read read out optically (frequencies range from microwave to visible) have advanced rapidly and are now commonly operated in a regime where their sensitivity becomes dominated by quantum noise in the mechanics or readout system. A wide variety of sensors is available, ranging from single ions to kilograms-scale elements. The sensors are uniquely suited to coherent signals with a scale comparable to the size of the mechanical sensor since the signal is coherently integrated into a small number of degrees of freedom (e.g. center of mass motion). A key example of the capabilities of optomechanical sensors is LIGO. Other examples include mechanically suspended reflective pendula; optically levitated dielectrics, cold atoms, and ions; clamped nanomechanical membranes; magnetically levitated systems: and can also include collectively quantized degrees of freedom like phonons.

In addition to their use in gravitational wave detection and precision measurements in metrology, optomechanical devices are rapidly being incorporated into the portfolio of detector systems useful for a number of high energy and particle physics targets. Building on classical proposals for neutrino and dark matter detection with nanoscale targets, proposals now exist to use optomechanical sensors for detection of ultra-light, MeV-to-TeV scale, and ultra-heavy dark matter [**?**]); neutrinos; high-frequency gravitational waves;

fifth-force modifications to Newton's law at tabletop scales; deviations from standard quantum mechanics (including ideas about gravitational breakdown of quantum mechanics); and tests of quantum properties of the gravitational interaction.

Moving forward, a number of key opportunities exist to increase the utility of these devices in the search for new physics. A critical one is the need for new theoretical ideas about potential new signals!Ȧt the level of the detector technologies, an important frontier is in advanced quantum techniques to get sensitivities at and beyond the so-called Standard Quantum Limit (SQL). The most common, well-demonstrated method to go beyond the SQL is the use of squeezed light while a less-studied, but enticing option is the use of backaction evasion techniques. Further theoretical development and implementation of these techniques in disparate situations and physical architectures, especially in broadband sensing problems, will be of crucial importance in the next decade. Leveraging multiple sensors ("networks") and entanglement between them can similarly enable detection beyond the SQL; using these ideas in searches for new physics would be extremely interesting.

Clocks and Precision Spectroscopy

Optical clock precision has improved by more than three orders of magnitude in the past fifteen years, enabling tests of the constancy of the fundamental constants and local position invariance, dark matter searches, tests of the Lorentz invariance, and tests of general relativity. All current atomic clocks are based on (1) transitions between the hyperfine substates of the atomic ground state (microwave clocks) or (2) transitions between different electronic levels (optical clocks). The frequency ratio of two optical clock frequency is only sensitive to the variation of the fine structure constant α and optical atomic clocks can probe the standard matter - dark matter coupling. Promising searches for ultralight particles are feasible through isotope-shift atomic spectroscopy, which is sensitive to a hypothetical fifth force between the neutrons of the nucleus and the electrons of the shell. The analysis of precision isotope shift (IS) spectroscopy sets limits on spin-independent interactions that could be mediated by a new particle which could be associated with dark matter. Deployment of high-precision clocks in space could open the door to new applications, including precision tests of gravity and relativity, searches for a dark-matter halo bound to the Sun, and gravitational wave detection in wavelength ranges inaccessible on Earth. Space-based optical lattice atomic clocks could potentially include the possibility of a tunable, narrowband GW detector that could lock onto and track specific GW signals provide a compliment to other experiments (e.g. LISA and LIGO). Radioactive atoms and molecules offer extreme nuclear nuclear charge, mass, and deformations, and may be worked with efficiently with the advanced quantum control toolset of AMO. These rare systems offer an unprecedented amplification of both parity- and time-reversal violating properties.

Several potential pathways existing for improving clock performance: developing new clocks with much larger sensitivity factors; development of large and more integrated clock networks; making clocks more portable (critical for space applications); and improving local oscillator technology as it limits coherent integration times. Additionally it is possible to probe multiple clocks with the same laser to cancel out local oscillator noise (similar to using single laser with atom interferometer). This pushes to near SQL. Pushing beyond the SQL can be achieved by using entangled states, such as spin-squeezed states. Gains can also be made by moving to clocks using highly charged ions (also a promising avenue for isotope shift spectroscopy) or nuclear clocks which have much higher sensitivities to the variation of alpha, up to 4 orders of magnitude for nuclear clocks. Nuclear clocks are highly sensitive to the hadronic sector and could offer improvements in sensing of DM coupling by 5-6 orders of magnitude. Use of molecular clocks provide direct sensitivity to determining the ratio of the proton mass to electron mass and its variation.

1.3.2 Spin Dependent Sensors

Note : The contents of this section are in part taken and modified from: Quantum Sensors for High Precision Measurements of Spin-dependent Interactions. Arxiv (2022). [?]

Experimental techniques for precision measurement of spin-dependent interactions have substantially advanced over recent decades, in no small part because control and measurement of spins, spin ensembles, and quantum materials is at the heart of QIS and quantum computing and they share a common foundation with the robust program of research on spin-based quantum sensors for measurement of magnetic fields, magnetic resonance phenomena, and related phenomena. There are three main ways measurements of spins can probe for new physics: new physics can break symmetries of the Standard Model giving rise to novel responses of spins to other fields (e.g. searching for EDM); the new physics can directly affect the spin for example via an interaction with a new field and the spin (e.g. searches for axions and axion-like particles); and new physics can affect the environment of the spin which the spin can sense (e.g. damage to crystals containing defects centers following interaction new physics such as dark matter particles).

EDM

The general approach of EDM experiments is to search for the combined effect of a P- and T-odd Hamiltonian and an applied electric field E, which results in an energy shift for a given quantum state of the atom or molecule. Typically the system is spin polarized via optical pumping or some other hyperpolarization technique such that the system is an a superposition of quantum states with opposite EDM-induced energy shifts. Thus a nonzero EDM will cause the polarized spins to precess in the presence of E. There are several general areas of technology development that can advance the fundamental sensitivity of EDM searches: increase the energy shift by finding system with maximum enhancement factors; improve control techniques to increase the total number of polarized atoms/molecules, and achieving longer spin-coherence times.

Magnetometers

Many theories predict the existence of new force-mediating bosons that couple to the spins of Standard Model particles. One of the primary experimental strategies is to employ a sensitive detector of torques on spins and then bring that spin-based torque sensor within a Compton wavelength of an object that acts as a local source of an exotic field (e.g., a large mass or highly polarized spin sample). Since the observable in these experiments is a spin-dependent energy shift a sensor employing N independent spins with coherence time τ has a shot-noise-limited sensitivity. Common sensors include NV centers, optical atomic magnetometers and Bose-Einstein condensates (BEC). One promising technology is the development of levitated ferromagnetic torque sensors (LeFTS). The active sensing element consists of a hard ferromagnet, well isolated from the environment by, for example, levitation over a superconductor via the Meissner effect. The mechanical response of the levitated ferromagnet to an exotic spin-dependent interaction can be precisely measured using a superconducting quantum interference device (SQUID). Similar to the LeFTS concept, ultracold twobody interactions in the BEC create a fully coherent, single-domain state of the atomic spins that enables the system to evade the sensitivity limits of traditional spin-based sensors.

Beyond the intrinsic sensitivity, the principal challenge in experiments searching for exotic spin-dependent interactions is understanding and eliminating systematic errors: clearly distinguishing exotic spin-dependent interactions from mundane effects due to, for example, magnetic interactions. By comparing the response of two different systems, effects from magnetic fields can be distinguished from effects due to exotic spin-dependent interactions. This is the essence of comagnetometry, where the same field is simultaneously measured using two different ensembles of atomic or nuclear spins. This effort can be extend to searching for transient interactions through the use of networks of geographically distributed spin-dependent sensors. For example the GNOME network will search for transient and stochiastic effects that could arise from ALP fields of astronomical origin passing through the Earth.

Magnetic Resonance

One possible manifestation of ultralight bosonic dark matter is as classical fields oscillating at the Compton frequency. The bosonic dark matter field can cause spin precession via couplings to nuclear and electron spins which can be detected using the broad and versatile tools of magnetic resonance. In a dark matter haloscope experiments, the oscillating field is assumed to always be present, corresponding to case of continuous-wave NMR. The magnetic field is scanned, and if the Larmor frequency matches the Compton frequency, a resonance occurs generating a time-dependent magnetization that can be measured, for example, by induction through a pick-up loop or with a SQUID. This is the method used in the CASPEr experiment. A key to CASPEr's sensitivity is the coherent "amplification" of the effects of the axion dark matter field through a large number of polarized nuclear spins. Therefore an important technological development is the ability to carry out NMR on the largest possible number of spins.

The QUAX (QUaerere AXion) experiment searches for axion dark matter in a manner similar to CASPEr but by exploiting the interaction of axions with electron spins. Ten spherical yttrium iron garnet (YIG) samples are coupled to a cylindrical copper cavity by means of an applied static magnetic field, and the resulting photon-magnon hybrid system acts as an axion-to-electromagnetic field transducer. The QUAX experiment is one of the most sensitive rf spin magnetometers ever realized, able to measure fields as small as 5.5E-19 T with nine hours of integration time.

The ARIADNE experiment employs an unpolarized source mass and a spin-polarized 3 He low-temperature gas to search for a QCD-axion-mediated spin-dependent interaction: the monopole-dipole coupling. In contrast to dark matter haloscopes like CASPEr and QUAX, whose signals depend on the local dark matter density at the Earth, the signal in the ARIADNE experiment does not require axions to constitute dark matter and can be modulated in a controlled way.

Defects

Searches for dark matter via scattering in crystals will soon run into the neutrino floor - the background of neutrinos from the sun. One path for getting beyond the neutrino floor is to develop directional detectors. Since the direction of the sun is known, the detectors can veto signals coming from the direction of the sun; dark matter interactions by contrast will results in isotropic scattering signals. One proposal for achieving this directional detection is to monitor damage tracks in crystals that occur as the scattering dark matter displaces atoms from their lattice location. These damage tracks can be measured using techniques from quantum sensing such as NV center spin spectroscopy in noncrystalline diamond. The NV center spin state is highly sensitive to the local strain in the crystal. These detectors will require a combination of imaging methods to locate and determine the direction of the damage tracks as described in [?] but provide a pathway towards WIMP sensitivity below the neutrino limit.

1.3.3 Quantum Calorimeters

Note : Work in progress. Contact Matt Pyle for details: mpyle1[at]berkeley.edu

1.3.4 Superconducting Sensors

*Note : Contents of this section are in part taken and modified from Snowmass 2021 White Papers: Axion Dark Matter [**?**], and Searches for New Particles, Dark Matter, and Gravitational Waves with SRF cavities [**?**].*

SRF Cavities

Superconducting radio-frequency (SRF) cavities are critical components in particle accelerators. Advances in cavity performance are the results of an improved understanding of RF superconductivity and materials. In the past 50 years, new cavity processing techniques were developed to overcome limiting phenomena, such as field emission, and enhance the superconductivity.

SRF cavities are, in their essence, extremely high quality electromagnetic resonators, devices that are now of strong active interest for quantum information science (QIS), with demonstrated record-high photon lifetime $\tau \sim 2s$ ($Q > 10^{11}$) also in the quantum regime.For quantum computing, quantum states can be stored and manipulated in electromagnetic resonators, and superconductors at milli-Kelvin temperatures are employed to sustain the coherence of the quantum states for long enough to perform complex computations. For quantum sensing, SRF cavities can furnish a large volume where very weak signals of radio-frequency photons can be collected, with only a small fraction of photons being lost to heat at the cavity walls.

The main focus on the Superconducting Quantum Materials and Systems (SQMS) National QIS Research Center is to advance QIS through the understanding and mitigation of coherence mechanisms in 2D and 3D quantum systems, i.e. planar and cavity based, tackling the decoherence time as a primary limiting mechanisms. This SRF cavity effort is utilized also to pursue fundamental physics questions and pushing the detection sensitivity with SRF cavities. The Snowmass whitepaper [**?**] summarizes opportunities to search for new particles with SRF cavities at SQMS. The focus is on dark photons and axion (or axion-like particles), either as new particles or dark matter, as well as on gravitational waves. The search for gravity waves across the full spectrum of frequencies, particularly since their discovery by LIGO [**?**], is very well motivated, potentially opening a new window onto the early Universe or new physics. In this context SRF cavities can be used to search for GW's [**?**].

It is possible to explore dark photon scenarios using SRF cavities light-shining-through-wall setup. The conversion of some of the photons to dark photons before the wall and conversion back to regular photons past the wall makes such a detection possible, if dark photons exist at a hypothesized mass and coupling. Resonant cavities can be used on both sides of the wall to increase the number of photons on the emitting side and to enhance the probability of conversion of dark photons to visible ones on the receiver side. In particular, in an RF cavity the system can be designed to search for the parametrically enhanced longitudinal coupling of the dark photon. The Dark SRF experiment at Fermilab plans to conduct such a search with ultra-high quality cavities [**?**, **?**, **?**, **?**].

The following materials science and R&D efforts are highlighted to expand current physics searches: enhance the efficiency; mitigate nonlinearitites in superconducting cavities due to TLS; reaching high-Q with the cavity in a multi-Tesla field; improving methods for frequency stability and tuning in SRF cavities. New schemes include searches with multiple cavity modes for axions or gravitational waves, nonlinear effects within the cavity walls that can mimic such a signal in particularly if the signal mode is near a harmonic; networks of SRF cavities; quantum nondemolition (QND) measurements with superconducting qubits coupled to SRF cavities.

Proposals for axion searches using SRF cavities

The Axions and axion-like particles (ALPs) is a generalization of the QCD axion which does not couple to QCD, but does couple to photons or SM fermions. ALPs are well motivated in their own right in top-down constructions [?, ?]. Like the dark photon case, Light-shining-through-wall (LSW) -type axion searches can benefit from high quality factors, which warrants the harnessing of advances in SRF technology. The necessity for a background magnetic field, however presents a challenge, as high-quality superconductivity does not survive large fields. Novel approaches to allow large magnetic fields with no degradation of Q-factor in SRF cavities are posed.

Two cavities with Static Field: One technique to utilize both high-Q SRF cavities and large magnetic fields for a LSW axion search is to sequester the required magnetic fields away from the production and detection cavities [?]. With this approach neither SRF cavity is subject to large magnetic fields and neither suffers a degradation of Q-factor. However, losses in the walls of the conversion region can result in a decrease of the effective Q of the entire system.

Two Cavities with a pump mode: An alternative approach is to replace the static B-field with an oscillatory B-field, which can then be directly run inside the receiver cavity. Sources of noise due to the multi-mode setup can be mitigated by using a pump with high-Q and with the pump frequency well separated from the signal mode frequency. In addition, such noise sources can be further suppressed by optimizing the cavity geometry and material science techniques to reduce nonlinearities [?, ?].

Single-Cavity Axion Search and Euler-Heisenberg: The EH Lagrangian makes a prediction for light-by-light scattering within the SM, which has never been observed at photon frequencies below the electron mass $m_e = 511$ keV because the effect is highly suppressed at low energies. The operating system of a proposed experiment to search for both the axion-induced and EH nonlinearities using high-Q SRF cavities is described in [?, ?, ?, ?]. This two-cavity scheme is less sensitive to noise sources which generate nonlinearities in the pump region.

Qubit-based single photon counting

The integration of a qubit into an ultra high cavity may enable new schemes for quantum computing and synergetically allow for employing a photon counting non-demolition measurement for DM searches. For certain DM search schemes, it would also be beneficial to have qubits that can operate successfully even in high magnetic fields [?].

Cavity haloscopes have traditionally extracted the DM signal via an antenna connected to a linear amplifier, such as a Josephson Parametric Amplifier (JPA). Unfortunately, linear amplifiers contribute to their own noise power, and their minimum contribution is the standard quantum limit (SQL). SQL noise increases linearly with frequency, and thus it is necessary to subvert the SQL to make higher-mass searches feasible.

Several ongoing or proposed experiments utilizes SRF resonators coupled to superconducting qubits to detect bosonic dark matter candidates below the SQL. Two experiments have demonstrated sub-SQL detection:

HAYSTAC by implementing vacuum squeezing [?] and SQuAD by implementing qubit-based photon counting [?]. SQMS also plans to combine SRF cavity technology and qubit based photon counting to increase the DM search rate by several order of magnitudes. The Superconducting Qubit Advantage for Dark Matter (SQuAD) experiment plans to perform resonant searches for dark matter axions with DFSZ sensitivity in a broad range from 10-30 GHz using high quality factor dielectric cavities combined with qubit-based single photon detectors which evade the quantum zero-point noise. R&D is ongoing on developing an analogous photon counting readout based on Rydberg atoms which can be operated at the higher frequencies where qubit devices become more difficult to design and fabricate.

Networks and transduction

Recently, it was shown that the performance of a quantum network could be utilized further to improve axion DM searches [?]. However, the noise in the network will be incoherent among the network nodes. One can make use of distributed squeezed states to exploit the coherent nature of the DM signal. Combining quantum resources (squeezing) in a distributed-network setting can allow for a scan that is faster by a factor of the square number of network nodes in the ideal case. The improvement is enabled by adding the signal at the amplitude level rather than adding powers in the classical network case.

A quantum transduction project at Fermilab is exploring hybrid coherent resonance systems and bi-directional quantum transduction schemes to up/down- convert the microwave information to/from the optical regime and enhance the conversion efficiency at the quantum threshold, and below the SQL. Up/down photon conversion may also enable highly sensitive axion and dark photon haloscope searches in the THz regime, or microwave single photon counting in optical systems, taking advantage of optical sensing techniques, e.g. high precision counting in interferometry and reduced noise floor [?], also in the Snowmass LOI *Opportunities for Optical Quantum Noise Reduction* [?].

Transduction in the mm-wave regime is also proposed in the LOI *Transduction for new Regimes in quantum sensing* [?] as an effective way for linking the classical and quantum world, and for transporting quantum information on macroscopic scales. Low-loss mm-wave photonics could allow preservation of quantum information at room temperature for a simpler network at laboratory scales, as well as reaching out the frequency range for axions above 10 GHz (40 µeV) is beyond the reach of current experiments (ADMX).

Cryogenic Platform for Scaled-up Sensing Experiments

The SQMS center at Fermilab is developing a cryogenic platform capable of reaching millikelvin temperatures in an experimental volume of 2 meters diameter by 1.5 meters in height [?]. The platform is designed to host a three-dimensional qubit architecture based on SRF technology, as well as sensing experiments.

SNSPD

Superconducting-nanowire single-photon detectors (SNSPD) are ideally suited for sensing lowcount- rate signals due to their high internal efficiency and low dark-count rates. Recent proposals for axion search either require SNSPDs that can operate in the presence of large magnetic fields, or require some means of carrying the light generated by the haloscope from the high-field region to a low-field region where the detectors can operate. The recently established robustness of SNSPDs to operation in high fields and their ability to operate at elevated temperatures (relative to alternative superconducting detector technologies) make them well-suited for photon detection in the mid-infrared (meV) to visible (eV) energy range. The suitability of SNSPDs to applications requiring low dark-count rates is illustrated by recent progress in the LAMPOST prototype search for dark photon dark-matter using these devices [**?**].

Other superconducting and cryogenic sensors

Cryogenic sensors have found a large range of applications for astroparticle detection. Due to integration complexity and thermal loading from cryogenic wiring, the ability to read out multiple detectors on a single wire with cryogenic multiplexing technologies with minimal readout noise penalty is of utmost importance as experiments are scaled to ever larger detector counts. The microwave SQUID multiplexer (µmux) couples an incoming detector signal to a unique GHz-frequency resonance, thus combining the multiplexability of MKIDs with the clean separation of detection and readout interfaces. This enables multiplexing factors up to two orders of magnitude larger than conventional cryogenic multiplexing schemes.

The wide frequency operation span enables large detector counts for low-bandwidth bolometric applications such as CMB cosmology while maintaining clean interfaces between the detection and readout schemes. Additionally, the large frequency bandwidth and fast resonator response allow for cryogenic particle detection, such as low-mass threshold dark matter searches, beta decay end point measurements to determine the lightest neutrino mass, and coherent elastic neutrino-nucleon scattering.

The CUPID collaboration in the snowmass whitepaper *Toward CUPID-1T* [**?**] presents a series of projects underway that will provide advancements in background reduction, cryogenic readout, and physics searches, all moving toward the next-to-next generation CUPID-1T detector. Neutron-transmutation doped thermistors (NTDs) are expected as part of the baseline design for CUPID. Multiple modes of superconducting sensors are under development as we look toward CUPID-1T: Microwave Kinetic Inductance Detectors (MKIDs), Metallic Magnetic Calorimeters (MMCs), and high- and low-impedance Transition Edge Sensors (TESes).

1.4 Common Areas for Development

- back action evasion: Back evasion evading schemes and squeezing techniques can enhance the sensitivity measurement of quantum sensors down to the SQL. Many experiments (for example NMR experiments to axion dark matter) will have their sensitivity limited by quantum back action and techniques will need to be developed for experiments approaching fundamental projection noise sensitivity limits. One of the purposes of new transduction projects is to leverage both microwave and optical sensing techniques as a way means to implement back action evasion.
- supporting technologies (laser, cavities, magnets, etc.): Several sensing experiments are enabled by SRF cavities with high-Q. Material studies, effort to mitigate limiting TLS losses, enhancing operation under multi-Tesla magnetic field can provide new resources for quantum sensors. Similarly, many experiments rely on the use of high-field magnets. Efforts to increase the magnitude, uniformity and scale (larger magnet bores) can result in direct improvements to the experimentally reachable parameter space.
- Infrastructures: The same characteristics that allow quantum sensors to probe new parameter space allows them to be sensitive to a wide range of noise sources. In some case, experiments may need to be placed in underground labs to avoid noise sources such as cosmic rays or maintain radio purity of sensor materials. Development of shared infrastructure, e.g. underground facilities with cryogenic and or magnetic capabilities could enable the advancment of multiple experimental techniques in a single facility.

- SBIR program, interaction with companies: DOE programs for commercialization and technology transfer programs, such as SBIR/STTR, provides platforms and resources to develop technology for quantum sensors and HEP. With the rapid rise of commercial sector quantum computing and associated technologies, new opportunities are emerging for interactions between government sponsored researchers and the commercial sector.

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2

Photon Detectors

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(contributors from the community)

Executive Summary

The Photon Detectors Topical Group has identified two areas where focused R&D over the next decade could have a large impact in High Energy Physics Experiments. These areas described here are characterized by the convergence of a compelling scientific need and recent technological advances.

The development of detectors with the capability of counting single photons from IR to UV has been a very active area in the last decade. Demonstration for sensors based on novel semiconductor (CMOS, skipper-CCD, SiPM) and superconducting technologies (MKID, SNSPD and TES) have been performed. These sensors open a new window for HEP experiments in the low photon number regime. Several ongoing and future projects in HEP benefit from these developments (Cosmology, Dark Matter, Neutrinos) which will also have a large impact outside HEP (BES, QIS, Astronomy). The combined scientific needs and technological opportunities make photon counting an ideal area for focused R&D investment in the coming decade. R &D in needed for enabling large arrays of the new sensors, improving their energy resolution and extending their wavelength coverage. Such investment will secure leadership in photon counting technologies in the US, producing a large impact in HEP, with applications outside HEP. This opportunity is summarized in Ref [248].

A technological solution for the photon detection system in the first two modules of the DUNE detector exist, based on the by now well-known Arapuca light traps, with wavelength shifters and SiPMs as the photon detector [1], [2]. However, new photon detector developments are being considered for modules 3 and 4. Some of the proposed ideas consist on novel light collectors, the so-called dichroicons which are Winston-style light concentrators made from dichroic mirrors, allowing photons to be sorted by wavelength, directing the long-wavelength end of broad-band Cherenkov light to photon sensors that have good sensitivity to those wavelengths, while directing narrow-band shortwavelength scintillation light to other sensors [6]. This technology could be used in water-based liquid scintillators thus realizing a hybrid Cerenkov/scintillator detector. Also notable are research and development efforts in new materials that could be directly sensitive to the VUV light, such as amorphous selenium (a-Se) [7] and organic semiconductors [8]. R&D is needed to move from concept demonstrations to full scale implementations in an HEP experiment. Future investment in the above technologies over the next decade will enhance the science of the DUNE project.

The science for generation, detection and manipulation of light is extremely fast moving and driven mainly from outside our field. The HEP community would benefit from resources dedicated to the implementation of these advanced photonic technologies in particle physics experiments [3], [4], [5].

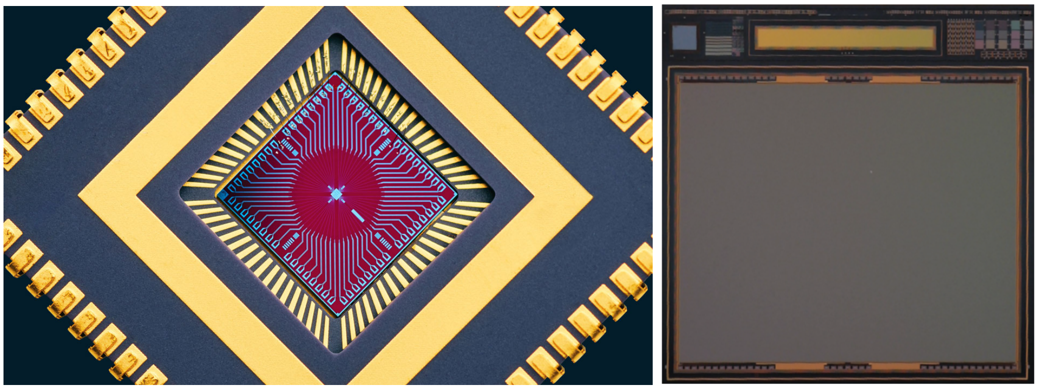

Figure 2-1. *Example recently develop of superconducting and semiconducting photon counting sensors. Left) 64-pixel SNSPD array capable of counting over 1 billion photons per second with time resolution below 100 ps for Astronomy (JPL Microdevices Laboratory). Righ) 1.3 Mpix skipper-CCD capable of deep sub-electron noise (LBNL Micro Systems Laboratory) developed for Astronomy and direct Dark Matter Search.*

2.1 Photon Counting Sensors Enabling HEP

2.1.1 Science Needs

Several novel cosmological facilities for wide-field multi-object spectroscopy were proposed for the Astro2020 decadal review, and are being considered as part of the Snowmass process [203]. Ground-based spectroscopic observations of faint astronomical sources in the low-signal, low-background regime are currently limited by detector readout noise. Significant gains in survey efficiency can be achieved through reductions by using sensors with readout noise below 1e-. Pushing the current photon counters in the direction of mega pixel arrays with fast frame rate (10 fps) would make this possible.

Dark matter searches based on photon counting technologies currently hold the world record sensitivity for low mass electron-recoil dark matter [24] semiconductors are among the most promising detector technologies for the construction of a large multi-kg experiment for probing electron recoils from sub-GeV DM (skipper-CCDs) [19]. Significant R&D is needed to scale to scale the experiments from the relatively small pathfinders to the multi-kg experiments in the future.

Single photon counting sensors have also gained importance for their potential as CEvNS detectors. (Coherent Elastic neutrino Nucleus Scattering) [27]. The deposited energy from CEvNS is less than a few keV. Only part of this energy is converted into detectable signal in the sensor (ionization, phonons, etc.) and therefore low threshold technologies are needed. Semiconductor and superconducting technologies with eV and sub-eV energy resolution for photon counting capability in the visible and near-IR are natural candidates to reach the necessary resolution for this application.

Photon counting also enables a wide range of science outside HEP [248] including QIS, BES and applications in radiation detection.

2.1.2 Technological Opportunities

Recent advances in photon counting technology addressing the needs in Section 2.1.1 are discussed here. The advances can be grouped in three areas.

2.1.2.1 Superconducting Sensors

MKIDs (microwave kinetic inductance detector) work on the principle that incident photons change the surface impedance of a superconductor through the kinetic inductance effect [159]. The magnitude of the change in surface impedance is proportional to the amount of energy deposited in the superconductor, allowing for single photon spectroscopy on chip. Frequency multiplexed arrays 20,440 pixels with energy resolution R=E/ΔE∼9.5 at 980 nm, and a quantum efficiency of ∼35% have been achieved. R&D focused on larger arrays with higher QE and better energy resolution would address the need discussed in Sec. 2.1.1.

SNSPDs (Superconducting Nanowire Single Photon Detector) is a superconducting film patterned into a wire with nanometer scale dimensions (although recently devices with micrometer-scale widths have been shown to be single-photon sensitive [133]). SNSPDs have been reported with single photon sensitivity for wavelengths out to several microns, timing jitter as low as a few ps [134], dark count rates (DCR) down to 6×10^{-6} Hz [69], and detection efficiency (DE) of 0.98 [188]. They have also been have been shown to function in magnetic fields of up to 6T [138]. Current R&D consist on scaling to large arrays and extending the spectral range for these sensors to address the needs of HEP and Astrophysics.

TES (Transition-Edge Sensor) photon detector, which utilizes a patterned superconducting film with a sharp superconducting-to-resistive transition profile as a thermometer, is a thermal detector with a well developed theoretical understanding. When a visible or infrared photon is absorbed by a TES, the tiny electromagnetic energy of the photon increases the temperature of the TES and therefore changes its resistance. TES have been developed to measure single photons in quantum communication [194, 145, 105, 104], for axion-like particle searches [45, 88], direct detection of dark matter particles and astrophysical observations in the wavelengths between ultraviolet and infrared [56]. TES detectors can be multiplexed enabling arrays of large channel counts [47, 87, 85]. Multiplexers for detector arrays using 16,000 TESs have already been successfully implemented [47]. R&D exploiting microwave resonance techniques [85] have the potential to increase the multiplexing capacity by another factor of 10.

2.1.2.2 Semiconducting Sensors

skipper-CCDs Skipper-CCDs have an output readout stage that allows multiple non-destructive sampling of the charge packet in each pixel of the array thanks to its floating gate output sense node. This non-destructive readout has been used to achieve deep sub-electron noise in mega-pixel arrays Skipper CCDs fabricated on high resistivity silicon [119] has also demonstrated an extremely low production of dark counts. This technology as motivated to build a new generation of Dark Matter [19, 23] and neutrino experiments [172]). The R&D effort here is currently is currently focused on faster readout (10 fps) and large gigapixel arrays.

CMOS The down scaling of CMOS technology has allowed the implementation of pixels with a very low capacity, and therefore, high sensitivity and low noise (1-2 e^-) at room temperature and high frame rates (50-100 fps) [152][101]. Commercial cameras with sub-electron noise at 5 fps are now available. These sensors have not yet played a big role in HEP mainly because of the small pixel size. Active R&D taking advantage of CMOS fabrication process to address the needs of HEP is ongoing to produce, including the development of new CMOS sensors with non-destructive readout (skipper-CMOS). These sensors could address the readout speed limitations of other semiconductor photon counters. The single photon avalanche diode (SPADs) have also been implemented in standard CMOS technology and integrated with on-chip quenching and recharge circuitry addressing fast timing and radiation tolerance requirements from HEP [249].

Photon-to-Digital converter In a PDC, each SPAD is coupled to its own electronic quenching circuit. This one-to-one coupling provides control on individual SPADs and signals each detected avalanche as a digital signal to a signal processing unit within the PDC. Hence, PDCs provide a direct photon to digital conversion considering that intrinsically a SPAD is a Boolean detector by design. Digital SiPMs were first reported in 1998 [38] by the MIT Lincoln Lab and many contributions followed [38, 39]. A major step came with microelectronics integration to fabricate both the SPAD and readout quenching circuit in a single commercial process [245, 130, 132, 131, 192, 190]. These innovations led to the first multi-pixel digitally read SPAD arrays [191, 175]. A recent review can be found in Ref. [186].

2.1.2.3 Extending wave length coverage

Ge semiconductor Silicon CCDs are commonly utilized for scientific imaging applications in the visible and near infrared. These devices offer numerous advantages described previously, while the skipper CCD [224] adds to these capabilities by enabling multiple samples during readout to reduce read noise to negligible levels [26, 75]. CCDs built on bulk germanium offer all of the advantages of silicon CCDs while covering an even broader spectral range. The R&D in this area will extend the photon counting capabilities of semiconductor into the IR.

UV Jet Propulsion Laboratory showed that CCD sensitivity can be increased closed to the reflection-limited quantum efficiency of silicon down [118]. This was done by blocking the surface fields and traps through the epitaxial growth of a strongly doped very thin silicon layer (delta-doping). Quantum efficiency exceeding 50% were demonstrated in CCDs down to 125 nm wavelength [176]. The method was demonstrated efficient on backside illuminated SPAD based detectors by Schuette in 2011[205]. Other methods to address the surface fields and traps issues were also demonstrated [171]. Work is being done at Caltech (D. Hitlin) to enhance SiPMs for the detection of the fast scintillation component of BaF_2 [116]. An extensive study of the delta-doping approach to enhance VUV sensitivity in frontside illuminated SPAD based detectors was done by Vachon [229].

2.2 Photon Detectors For Neutrino Experiments

A large number of outstanding questions remain to the fundamental nature of the neutrino, which can be probed through the use of higher energy ($\mathcal{O}(\mathrm{MeV}) < E < \mathcal{O}(\mathrm{GeV})$) neutrino sources (*e.g.*, accelerator and atmospheric neutrinos). The nature of these remaining puzzles break into the distance over which the neutrinos are allowed to propogate before being detected. Thus the future class of experiements are classified as "short-baseline" and "long-baseline" experiments.

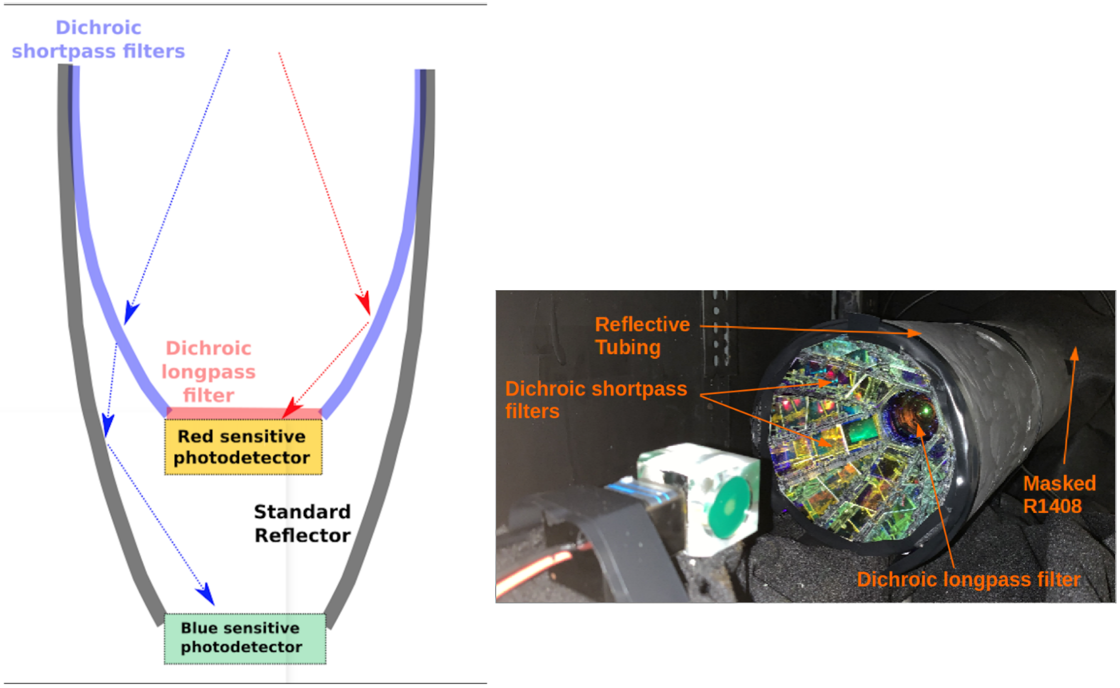

Figure 2-2. *Example of photon detector development for neutrinos: the dichroicon, from arXiv:2203.07479*

The next generation long-baseline neutrino experiments aim to answer the questions of the exact ordering of the neutrino mass states, known as the mass hierarchy, as well as the size of the CP-violating phase δ. These, as yet unknown quantities, remain one of the last major pieces of the Standard Model of particle physics and offer the opportunity to answer such fundamental questions as "what is the origin of the matter/antimatter asymmetry in the universe?" and "do we understand the fundamental symmetries of the universe?". By measuring the asymmetry between appearance of electron neutrinos from a beam of muon neutrinos ($P(\nu_\mu \rightarrow \nu_e)$) compared to the appearance of electron antineutrinos from a beam of muon antineutrinos and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$) as well as the precise measurement of the ν_e energy spectrum measured at the far detector, both the CP violating phase (δ_{CP}) and the mass hierarchy can be measured in the same experiment.

The Short-Baseline Neutrino (SBN) program aims to address the anomalous neutrino results seen by the LSND and MiniBooNE which suggest the possible existence of a eV mass-scale sterile neutrino. However, the experimental landscape is perplexing since a number of other experiments utilizing a range of different neutrino sources which should have been sensitive to such a sterile neutrino have observed only the standard three neutrino oscillations. In this landscape, the conclusive assessment of the experimental hints of sterile neutrinos becomes a very high priority for the field of neutrino physics.

To address both of these areas of neutrino research, large scale noble element time projection chambers (TPC's) [239, 196] play a central role and offer an opportunity to perform discovery level measurements through the enhancement of their capabilities. In a noble element TPC, particles interact with the medium and deposit their energy into three main channels: heat, ionization, and scintillation light. Depending on the physics of interest, noble element detectors attempt to exploit one or more of these signal components. Liquid Noble TPC's produce ionization electrons and scintillation photons as charged particles traverse the bulk material. An external electric field allows the ionization electrons to drift towards the anode of the detector and be collected on charge sensitive readout or transform energy carried by the charge into a secondary pulse of scintillation light.

A technological solution for the photon detection system in the first two modules of the DUNE detector exist, based on the by now well-known Arapuca light traps, with wavelength shifters and SiPMs as the photon detector [1], [2]. This approach is also being used in other short baseline neutrino oscillation experiments[15], but not exclusively [14]. Beyond this,new photon detector developments are being considered for modules 3 and 4 as well as for other approved or proposed experiments[6].

Going beyond DUNE's first two modules Quoting from the executive summary of the Snowmass IF2 White Paper*Future Advances in Photon-Based Neutrino Detectors*[6], "large-scale, monolithic detectors that use either Cherenkov or scintillation light have played major roles in nearly every discovery of neutrino oscillation phenomena or observation of astrophysical neutrinos. New detectors at even larger scales are being built right now, including JUNO [**?**], Hyper-Kamiokande [9], and DUNE [11].

These new technologies will lead to neutrino physics and astrophysics programs of great breadth: from high-precision accelerator neutrino oscillation measurements, to detection of reactor and solar neutrinos, and even to neutrinoless double beta decay measurements that will probe the normal hierarchy regime. They will also be valuable for neutrino applications, such as non-proliferation via reactor monitoring".

"Of particular community interest is the development of hybrid Cherenkov/scintillation detectors, which can simultaneously exploit the advantages of Cherenkov light—reconstruction of direction and related high-energy particle identification (PID) and the advantages of scintillation light, high light-yield, low-threshold detection with low-energy PID. Hybrid Cherenkov/scintillation detectors could have an exceptionally broad dynamic range in a single experiment, allowing them to have both high-energy, accelerator-based sensitivity while also achieving a broad low-energy neutrino physics and astrophysics program. Recently the Borexino Collaboration [12] has published results showing that even in a detector with standard scintillator and no special photon sensing or collecting, Cherenkov and scintillation light can be discriminated well enough on a statistical basis that a sub-MeV solar neutrino direction peak can be seen. Thus the era of hybrid detectors has begun, and many of the enabling technologies described here will make full event-by-event direction reconstruction in such detectors possible".

Among the new technologies of relevance for this topical group, it should be mentioned

New Photon Sensors : New advances in the science of photomultiplier tubes, including long-wavelength sensitivity, and significant improvements in timing even with devices as large as 8 inches, make hybrid Cherenkov/scintillation detectors even better, with high light yields for both Cherenkov and scintillation light with good separation between the two types of light. Large Area Picosecond Photon Detectors (LAPPDs) [7] have pushed photon timing into the picosecond regime, allowing Cherenkov/scintillation separation to be done even with standard scintillation time pro

les. The fast timing of LAPPDs also makes reconstruction of event detailed enough to track particles with the produced photons.

New Photon Collectors : Dichroicons, which are Winston-style light concentrators made from dichroic mirrors, allow photons to be sorted by wavelength thus directing the long-wavelength end of broad-band Cherenkov light to photon sensors that have good sensitivity to those wavelengths, while directing narrow-band shortwavelength scintillation light to other sensors. Dichroicons are particularly useful in high-coverage hybrid Cherenkov/scintillation detectors.

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3

Solid State Detectors and Tracking

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3.1 Executive Summary

Tracking detectors are of vital importance for collider-based high energy physics (HEP) experiments. The primary purpose of tracking detectors is the precise reconstruction of charged particle trajectories and the reconstruction of secondary vertices. The performance requirements from the community posed by the future collider experiments require an evolution of tracking systems, necessitating the development of new techniques, materials and technologies in order to fully exploit their physics potential.

Relative to the currently operating systems and their upgrades, the technical requirements for tracking detectors (trackers) in the next 20-40 years are significantly more stringent:

- Tolerance to fluences 1-2 orders of magnitude higher
- Larger areas at lower costs
- Segmentation and position resolution 2-4 times finer
- Precision timing resolution in a tracking environment
- Radiation length per layer from 0.1-1% X_0
- Cooling below the triple-point of CO_2
- Integration of novel radiation-hard materials

Technological developments currently underway aim to address these issues, and the successful completion of the programs outlined below requires focused efforts from the community on the steady development and refinement of existing technologies, and the pursuit of novel “blue sky” technologies to enable transformative progress. Collaborative efforts should be encouraged when possible to make efficient use of resources and reduce the financial burden on individual groups, and to enlarge the pool of expertise in the field. Especially critical is to encourage and support young researchers to engage and pursue intensive research programs to develop these new technologies, which will help to ensure an expert workforce is sustained for the long term.

Eight white papers on solid state trackers were submitted during the 2022 Snowmass [**?**], focusing on a broad set of R&D topics that the US community is actively pursuing. While these papers don’t completely capture the full breadth and depth of the R&D carried out in the US, they highlight the key challenges that future trackers will face and summarize the main research thrusts actively pursued by the community.

Throughout the tracker community, many new, novel tracking technologies are being investigated. Silicon pixel detectors based on Monolithic Active Pixels (MAPS) are, for example, being developed for a wide range of applications. Recent devices show significant improvements in pixel granularity, readout speed and radiation tolerance. Also addressing detector speed and radiation performance are so-called 3D sensors, where the collection electrodes are orthogonal to the plane of the detector. Developed in both silicon and diamond subtrates, 3D sensors serve as a first step into wide-bandgap semiconductor materials. Next, thin film detectors offer a radical new way to manufacture large-area and low-cost tracking detectors. Finally quantum-enabled detection is being investigated for trackers in novel architectures and materials, with the promise of achieving extremely fast response and high granularity with only a minimal detector thickness.

Advanced 4-dimensional trackers with ultra fast timing (10-30 ps) and extreme spatial resolution (O(few μm)) represent a new avenue in the development of silicon trackers, enabling a variety of physics studies which would remain out of experimental reach with the existing technologies. Several technology solutions are being currently pursued by the community to address the challenges posed by various experiments, both for the sensors and the associated electronics. Bringing in technological innovation and fully exploiting the potential of future detectors through the usage of ultra fast timing is a unique and exciting opportunity for the particle physics community. In order to reach this goal, it is of paramount importance in the coming years to undertake thoroughly the R&D studies to investigate how to best combine timing with spatial information.

The packaging and integration of the sensors and readout electronics will become more critical for future experiments, as device segmentation decreases to mitigate the increased track density. Bump bonding technologies have nearly reached their limits; more advanced 3D packing technologies including wafer-to-wafer and die-to-wafer hybrid bonding and through silicon vias (TSV) have the potential to meet the goals of future particle physics experiments. Collaboration between research groups and industrial partners with this expertise is crucial to introduce this technology to the HEP community. This research will take consider time and efforts to have confidence to use these technique in future large-scale tracking systems, and as such need to being urgently.

Detector mechanics will also play a significant role in future detector's performance. Material necessary for cooling and structural stability will be the lower bound on the radiation length for future tracking systems. Increased segmentation will lead naturally to larger power densities; in order to minimize material, solutions with integrated services and cooling are necessary. A holistic approach to design, simulation and manufacturing will be required. Novel materials, new cooling and composite manufacturing technique will need to be developed in order to reach the targeted performance.

To develop these new technologies, simulations of the properties of silicon and novel sensor materials throughout the lifetime of the experiments will be critical. These studies can drive device design included implant locations, size and strength to the most promising directions of development. To reach their full potential, further developments are needed to improve accuracy, precision and new devices. With this research, the performance of future experiments can be better predicted for its full life cycle prior to construction.

3.2 Requirements

Promised inputs from IF liaisons to EF and RF

3.3 Simulations of Silicon Radiation Detectors for High Energy Physics Experiments

There are currently a variety of tools available for simulating the properties of silicon sensors before and after irradiation. These tools include finite element methods for device properties, dedicated annealing models, and testbeam/full detector system models. No one model can describe all of the necessary physics. Most of these models are either fully or partially developed by HEP scientists and while there are many open-source tools, the most precise device property simulations rely on expensive, proprietary software.

The development of these simulations happens inside existing experimental collaborations and within the RD50 Collaboration at CERN. RD50 is essential for model research and development and provides an important forum for inter-collaboration exchange.

While existing approaches are able to describe many aspects of signal formation in silicon devices, even after irradiation and annealing, there is significant research and development (R&D) required to improve the accuracy and precision of these models and to be able to handle new devices (e.g. for timing) and the extreme fluences of future colliders. The US particle physics community can play a key role in this R&D program, but it will require resources for training, software, testbeam, and personnel.

For example, there is a great need for (1) a unified microscopic model of sensor charge collection, radiation damage, and annealing (no model can currently do all three), (2) radiation damage models (for leakage current, depletion voltage, charge collection) with uncertainties (and a database of such models), and (3) a measurement program to determine damage factors and uncertainties for particle types and energies relevant for current and future colliders.

This program of work is critical for the future success of collider physics. With these tools, the performance of future experiments would be better predicted throughout their lifetimes. The simulations will also be critical in directing the R& D for the next generation of complex sensors into the most promising avenues to realize the necessary performance to reach our ultimate physics goals.

3.4 Novel Sensors for Particle Tracking

The proposed future collider experiments pose unprecedented challenges for event reconstruction, which require development of new approaches in detector designs. Research in particle tracking detectors for high energy physics application is underway with a goal of improving radiation hardness, achieving improved position vertex and timing resolution, simplifying integration, and optimizing power, cost, and material. Several technologies are currently being investigated to develop technologies for the future, which approach these goals in complementary ways.

Silicon sensors with “3D technology” have electrodes oriented perpendicular to the plane of the sensor. These show promise for compensation of lost signal in high radiation environments and for separation of pileup events by precision timing. New 3D geometries involving p-type trench electrodes spanning the entire thickness of the detector, separated by lines of segmented n-type electrodes for readout, promise improved uniformity, timing resolution, and radiation resistance relative to established devices operating effectively at the LHC. The 3D technology is also being realized in diamond substrates, where column-like electrodes may be placed inside the detector material by use of a 130 fs laser with wavelength 800 nm. Present research aims for operation with adequate signal-to-noise ratio at fluences approaching 10^{18} $n_{\mathrm{eq}}/\mathrm{cm}^2$, with timing resolution on the order of 10 ps.

Monolithic Active Pixel Sensors (MAPS), in which charge collection and readout circuitry are combined in the same pixel, have been shown to be a promising technology for high-granularity and low material budget detector systems. MAPS have several advantages over traditional hybrid pixel detector technologies, as they can be inexpensively fabricated in standard CMOS imaging processes, back-thinned or back-illuminated, have demonstrated high radiation hardness, and can be stitched or tiled for large, low-mass arrays. MAPS offer the possibility of individual pixel readout at MHz speeds, with low power consumption and powered from a low voltage supply.

Many MAPS pixel geometries have been explored, but the close connection of a sensor and front-end amplifier, without the need for external interconnections, holds the promise of reducing the input capacitance significantly, and hence extremely low-noise designs are possible. The reduction of the noise floor means that even small signals, for example from thinned low-power sensors, can yield satisfactorily high S/N. The next generation of MAPS will target improved performance in speed, resolution, and radiation tolerance, and also incorporate developments in the systems integration that are needed for large scale use at a reasonable cost. Prototype detectors are currently being designed to addresses the integration issues associated with making large arrays, by first developing an intermediate scale array of tens of m^2 which include full powering and readout of large numbers of MAPS. Many different MAPS detector architectures are in development, and are being adapted to a diverse set of applications and environments; from hadron colliders to the EIC and ILC, to space-based tracker applications in γ-ray satellites.

Thin film detectors have the potential to be fully integrated, while achieving large area coverage and low power consumption with low dead material and low cost. Thin flim transistor technology uses crystalline growth techniques to layer materials, such that monolithic detectors may be fabricated by combining layers of thin film detection material with layers of amplification electronics using vertical integration.

The DoTPiX pixel architecture has been proposed on the principle of a single n-channel MOS transistor, in which a buried quantum well gate performs two functions: as a hole-collecting electrode and as a channel current modulation gate. The quantum well gate is made with a germanium silicon substrate. The active layers are of the order of 5 μm below the surface, permitting detection of minimum ionizing particles. This technology is intended to achieve extremely small pitch size to enable trigger-free operation without multiple hits in a future linear collider, as well as simplified reconstruction of tracks with low transverse momentum near the interaction point.

Lastly, a technology is under development in which a novel ultra-fast scintillating material employs a semiconductor stopping medium with embedded quantum dots. The candidate material, demonstrating very high light yield and fast emission, is a GaAs matrix with InAs quantum dots. The first prototype detectors have been produced, and pending research goals include demonstration of detection performance with minimum ionizing particles, corresponding to signals of about 4000 electron-hole pairs in a detector of 20 μm thickness. A compatible electronics solution must also be developed. While the radiation tolerance of the device is not yet known, generally quantum dot media are among the most radiation hard semiconductor materials.

3.5 4-Dimensional trackers

Future collider experiments call for development of tracking detectops with 10-30 ps timing resolution, in addition to excellent position resolution, i.e. 4-Dimensional trackers. Time resolution of the future 4D tracker detector can be factorized into contributions from the sensor itself, and those from the readout electronics. The overall detector system should contain a sensor with short drift time, high signal to noise, limited thickness in the path of a MIP to reduce the Landau fluctuations, and small TDC bin size. Several technologies to address these needs are being developed and are introduced in this section.

One approach to meet these requirements utilizes Low Gain Avalanche Detectors (LGADs), and adapts them to achieve the fine segmentation necessary for tracking. The main limitation of the DC-coupled LGADs is the presence of JTE to interrupt the gain layer, which introduces inactive regions on the sensors. Several modifications to LGAD technology have been proposed and demonstrated to make LGAD sensors suitable for tracking sensors with 100% fill-factor, achieving excellent timing and position resolution. The most advanced high granularity designs realized so far are the AC-coupled LGAD (AC-LGAD). Because the gain layer is uninterrupted, the electrodes can be designed with smaller pitch and size than standard LGADs. A key feature of AC-LGADs is the signal sharing between electrodes, which can be used to obtain the spatial resolution necessary for future colliders with a reduced number of readout channels, achieving simultaneous 30 ps and 5 μm resolutions. Another design geared towards 100% fill factor are the "Deep-Junction" (DJ-LGAD), which are formed by abutting thin, highly-doped p+ and n+ layers. Trench-isolated (TI) LGADs address the fill-factor limitation of LGADs by substituting the JTE with narrow trenches filled with dielectric material. The width of the trenches is about 1 μm, allowing for a substantial reduction of the distance between gain layers of neighboring channels with respect to standard LGADs. Intense R&D is ongoing to improve the radiation tolerance of LGADs beyond 10^{16} $n_{\mathrm{eq}}/\mathrm{cm}^2$, by e.g. exploiting the observation that deep and narrow gain layers are more radiation hard. Such "Buried Layer LGADs" achieve the deep gain layer by implanting the boron layer at low energy and then to burying it under a few microns of epitaxially grown silicon.

Another thrust to develop 4D-tracking sensors is through a usage of sensors with 3D geometries, or closer integration with electronics via monolithic pixel sensors, or adoption of new materials in sensor design. Since charge carriers are collected perpendicularly to the sensor thickness in sensors with 3D-geometries, the time uncertainties due to nonuniform ionisation density, delta rays and charge carrier diffusion are minimized. Prototypes have demonstrated promising results with time resolution below 20 ps. New materials, such as SiC detectors, can operate at very high temperatures, and are known to exhibit significant radiation hardness and extremely low leakage currents. Although the adoption of this technology in HEP has been slow, recent advances in wafer size and quality are enabling compatibility with processing tools developed for silicon devices, and allowing the price per device to sharply decrease.

Going even beyond 4D-sensors are designs that aim to simultaneously measure not only the position and time, but also the angle of passing tracks. These kind of sensors would dramatically reduce the complexity of detector modules, and enable unprecedented reconstruction capabilities on the front-end. Double Sided LGADs (DS-LGADs) achieve this goals by adding a readout layer to the p-side of the LGAD structure, which allows one to also measure signals from the slower-drifting holes. The signal p-side collects two components, holes from the primary ionization followed by the larger number of holes generated at the gain layer. This provides a unique signature of the pattern of charge deposit within the device that could enable measurement of the track angle as well. Another approach to achieve the same goal is through detection of the Shockley-Ramo current induced at the readout electrode from mobile charge carriers within the sensor. This current has a very fast rising edge ($\sim$15 ps) and can be used to precisely timestamp track hits, and is a promising direction for establishing 5D-sensor designs.

The timing ASICs under development for the ATLAS and CMS timing upgrades, named ALTIROC and ETROC, represent revolutionary steps forward as the first readout chips to bring O(10 ps) timing to collider experiments. However, they are able to use significantly more space and power than high density ASICs designed for trackers with fine pitch and limited material. Compared to RD53A, the timing chips use several hundred times more power and area per channel. The primary challenges to transform them into chips for 4D tracking will be to minimize both the power consumption and the channel size. The high luminosity of future hadron colliders will require trackers capable to survive in extreme radiation environments (accumulating a dose of up to 30 GRad and 10^{18} neutrons/cm^2). Currently there are several projects with the aim to make advance in these areas. Efforts are geared towards a specific application, however the goals are common: bandwidth optimization, low noise, low area, time resolution and power dissipation. The CERN's EP R&D WP5 chip aims to reduce the total area of the circuitry by moving to 28 nm node with the design of the low-power and compact TDC, while the Silicon-Germanium based ASIC developed by Anadyne in TowerJazz 130 nm is expected to have 0.5 mW per channel (front end and discriminator) with 10 ps of timing resolution for 5 fC charge. The CFD-chip ASIC developed at FNAL in 65 nm node was demonstrated to deliver $\sim$10 ps jitter for 15 fC of injected charge, using a constant-fraction-discriminator implementation.

3.6 Integration

In the past years, HEP experiments have been mostly relying on bump bonding for high density pixel sensor to ASIC connection. The bump bonding technology was proven to be reliable; however, it is known to have several limitations: it only works down to 20-50 μm of pitch and has yield issues for finer connections. Furthermore, the solder balls used for the connection increase the input capacitance to the amplifier and hence the noise. With bump bonding,the sensor or chip need side extensions to have external connections. In terms of mechanical properties the resulting connection is subject to heat stress since it involves different materials; the minimum thickness is also limited since both chip and sensor need a thick enough support wafers in order to meet alignment and bow requirements for the bump bonding process.

The introduction of more advanced packaging may solve many of these issues, allowing for the improvement of performance, yield and processing. 3D integration is a common widespread technology in industry, it allows tight packaging of sensor and readout chip. Furthermore it allows to stacks multiple chips in a single monolithic device. There are many technologies available for 3D integration, hybrid bonding is the most widely accepted: silicon covalent oxide bonding combined with copper diffusion bonding to provide connectivity between layers. The process can be done for wafer to wafer (w2w) or die to wafer (d2w) assembly. Through Silicon Vias (TSVs) allow multiple planes to be stacked and connected with external connections without the need of extensions or silicon interposers. There are several advantages in using 3D integration in sensor to chip connection:

- Less space: 3D chips can be multi layer and do not need extension or interposers for external connections. Reduction of single layer thickness, after integration all supports can be removed
- Very fine pitch bonding: down to a few micrometers
- Better connections: faster and shorter than in circuit boards, with reduced dissipated power
- Better performance: reduced input capacitance and lower noise
- Layered design: e.g. sensor + analog electronics + digital electronics, each layer can be manufactured by different producers
- Reduced thermal stress and increased heat dissipation since material is homogeneous, also increased robustness

Advanced packaging and wafer to wafer bonding would facilitate several applications both in HEP and outside of HEP: 4D tracking with high granularity LGADs, 3D integrated SiPM with advanced signal processing, chip tile array assembled at wafer level with no edges, small pixels connection (10 μm or less) that reduces the input capacitance of thin sensors (e.g. thin LGADs) increasing both space and time precision, double sided connection for LGADs to have readout on both sides, stacked 3D integrated chip, 3D network of algorithm cells for advanced pattern recognition, zero mass trackers with very thin and highly populated layers, sensor stacks for high energy X-ray detection and decay detection. Finally it will advance the knowledge in substrate engineering, useful, for example, in the fabrication of buried p-n layers for LGADs, necessary for the production of, for example, DJ-LGAD and buried junction LGAD.

Therefore electronics and sensor advanced packaging provide a variety of technologies that can meet the needs of future particle physics experiments. Combining these capabilities with silicon technologies developed for HEP, such as LGADs and active edge sensors, will allow the design of sophisticated detector systems that can meet the increasing challenges of next generation experiments. The collaboration between research groups and industry with established expertise in advanced packaging is crucial for the successful introduction of this technology in the research community.

Current availability of such technologies is mixed. Leading edge foundries and nodes now include 3D processes (Intel Forveros, TSMC 3DFabric, Samsung x-cube) but are typically too expensive for HEP. Hybrid bonding is available from many vendors that already work with HEP. The availability of TSVs is more limited. Small pitch TSVs are available from some foundries at advanced nodes (>32 nm), in Silicon-on-Insulator (SOI) wafers, and from specialty foundries. Larger pitch TSVs inserted in a completed wafer (via-last) are available from a variety of packaging suppliers. Reliable 3D devices with these large pitch ($>20\ \mu m$) external TSV connections can be accessed now with resources available to HEP. It is important to build design and fabrication experience with moderate scale companies now gearing up to address opportunities afforded by the US semiconductor initiative.

It is urgent that this research is begun as it will take considerable effort and time in order to have the confidence required to use these techniques in future large-scale tracking systems.

3.7 Mechanics

Detector mechanics will play a significant role in future detectors' performance; the necessary improvements will require simulations, novel ways to reduce the total mass, as well as more integrated design concepts to save on material budgets and optimize performance. The increased segmentation has naturally lead to larger power densities requiring high performance material support structures with integrated services. In many use-cases, the material in these structures can be the limiting factor for the tracking performance of the system. Particle detectors at future colliders rely on ever more precise charged particle tracking devices, which are supported by structures manufactured from composite materials. Various engineering techniques able to solve challenges related to the design and manufacturing of future support structures have been developed.

Future particle colliders, such as the high luminosity Large Hadron Collider (HL-LHC), the Future Circular Collider (FCC-ee, FCC-hh), or the muon collider (MuC) will collide particles at unprecedented rates and present a harsh environment for future detectors. A holistic approach to the design and manufacturing of detector support structures will be necessary to achieve minimal weight systems and to potentially integrating electrical and cooling services into structures. Novel techniques, materials and other design and manufacturing solutions provide an avenue to solve challenges of increasingly more complex and large tracking detectors. Complex stresses in composite structures consisting of multiple parts are a consequence of different manufacturing techniques utilized (compression molding, oven-cured lamination, etc.). These stresses pose a severe challenge to current simulation tools. Research and development efforts are underway to solve these challenges by exploring multi-functional composite structures manufactured from highly thermally conductive materials using different manufacturing techniques. Machine learning based topology optimization have been employed to fulfill the low-mass high-stiffness and thermal conductivity structure requirements.

Material savings due to novel approaches have the potential of reduction on the order of 30-50% depending on more detailed R&D studies. This is an ideal opportunity to explore the conjunction of latest techniques in composite engineering involving machine learning based algorithms for heat transfer, mechanical loading and micro-to-macro scale material response predictions for the performance of the support structure mechanics. Current R&D efforts provide a headway for future detector support structures relying on transformational novel manufacturing techniques.

Different structures are current under study to achieve these goals which include: carbon fiber support structures with integrated titanium pipes for CO_2 cooling, etched silicon and peak cooling micro-channels, Kapton-based support structures and engineered air cooling.

Historically, mechanics has had limited support in the US and international community. To reach the targeted performance of future tracking detector systems, an increase of resources will be required to be successful.

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4

Trigger and Data Acquisition Systems

v2.0

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(contributors from the community)

A trend for future high energy physics experiments is an increase in the data bandwidth produced from the detectors. Datasets of the Petabyte scale have already become the norm, and the requirements of future experiments—greater in size, exposure, and complexity—will further push the limits of data acquisition technologies to data rates of exabytes per seconds. The challenge for these future data-intensive physics facilities lies in the reduction of the flow of data through a combination of sophisticated event selection in the form of high-performance triggers and improved data representation through compression and calculation of high-level quantities. These tasks must be performed with low-latency (*i.e.* in real-time) and often in extreme environments including high radiation, high magnetic fields, and cryogenic temperatures.

Developing the trigger and data acquisition (TDAQ) systems needed by future experiments will rely on innovations in key areas:

- pursue innovations in the application of Machine Learning (ML) to TDAQ systems, particularly in the co-design of hardware and software to apply ML algorithms to real-time hardware and in other novel uses to improve the operational efficiency and sensitivity to new physics of future experiments;
- invest in the design of TDAQ system architectures that leverage new technologies, techniques, and partnerships to enable more intelligent aggregation, reduction, and streaming of data from detectors to higher-level trigger systems and offline data processing; and,
- develop improved readout technologies that increase data bandwidth and are capable of operating in extreme environments, while fitting the material and power constraints of future experiments.

Critically, innovations in TDAQ rely on the people and processes behind them, and require investments in those people and infrastructure for R&D. To that end, we call for:

- increased effort to build and retain domain knowledge for complex TDAQ systems by reliably supporting facilities and people – particularly engineers and technical staff, and early-career scientists through recruitment and training – in order to bring new ideas from early design and prototyping all the way through integration, commissioning, and operation in future detectors; and,
- the creation of a dedicated (distributed) R&D facility that can be used to emulate detectors and TDAQ systems, offer opportunities for integration testing (including low- and high-level triggering, data readout, data aggregation and reduction, networking, and storage), and develop and maintain an accessible knowledge-base that crosses experiment/project boundaries.

4.1 A compelling use case: track-based triggers

Searches for novel new physics are often made possible by the development of novel new triggers that take advantage of improvements in detectors and real-time computing. Early-stage trigger systems of experiments at hadron collider experiments, for example those at the Large Hadron Collider (LHC), often select objects with high momentum, based on calorimeter information, in order to reduce the large backgrounds to events of physical interest. However, this process necessarily loses many events, and is poorly optimized to explore a variety of potential beyond Standard Model (SM) scenarios. For instance, low momentum events with displaced vertices could lead to soft-unclustered-energy-patterns, long-lived staus or the decays of long-lived dark scalars in the Higgs portal scenario [1]. Alternatively, high-momentum and short-lived particles, such as dark matter particulates, might be missed by the existing trigger systems due to their invisible decay within the detector volume [2].

For both of these cases, early-stage triggers based on tracking information could preserve interesting signal events for study. A difficulty of including tracking information in early-stage triggers is the complexity of calculating tracks and the speed at which decisions need to be made. For instance, at the LHC [3] events are produced at a rate of 40 MHz, and this must be very rapidly reduced to the kHz level at the first step of the trigger system. The development of a fast track-based trigger is therefore an area of considerable interest in the high energy physics community, and several different approaches have been taken to solve the problem for silicon-strip tracking systems. For future hadron collider experiments, a fast tracking trigger for silicon pixel tracking layers at small radii with respect to the beam pipe, and therefore with significantly more channels than strip trackers, would open the sensitivity to particles arising from beyond SM physics in an interesting lifetime regime.

As a new approach, a white paper contributed to Snowmass [2] utilizes highly-parallelized graph computing architecture using field-programmable gate arrays (FPGAs) to quickly performing tracking in small-radius silicon detectors. For LHC experiments such as ATLAS [4] and CMS [5], the silicon tracking detectors consist of multiple cylindrical layers surrounding the proton-proton interaction point. As particles pass through the detector, they interact with each layer and leave a point of information on their location. At the HL-LHC, we are expecting up to 200 proton-proton collisions per 25 ns, which is expected to result in approximately 11,000 charged tracks, which in a ten-layer detector would then result in a point-cloud of approximately 110,000 points. These points would need to be classified, such that each set corresponds to a single charged particle. CPU methods to calculate these tracks are prohibitively slow for use in the trigger, and strategies utilizing associated memories with large pattern banks for matching have met with some success but have not been adopted by LHC experiments.

Instead, this paper proposes unsupervised machine learning on a highly-parallelized graph computer constructed using modern FPGA technology. The method converts a 2-dimensional matrix of points into a graph by defining a weighted link that associates each point with all other points. Then, the tracking problem is reduced to pruning spurious links until the points are divided into groups corresponding to each charged track. The algorithm is tested on a simulated silicon detector with five layers and 100 tracks, with the assumption that each particle is successfully detected on every layer and that there are no noise hits or resolution effects. In this case, track-finding is over 99.95% efficient, and the layers and reconstructed tracks are illustrated in Fig. 4-1. This shows that the algorithm is very promising, and researchers are next going to investigate the impact of shifting to an 'imperfect' (i.e. realistic) detector model.

The algorithm was tested using a Virtex-5 FPGA, and the expected latency was on the order of 100 ns for 100 tracks, well below the 4 μs limit for trigger algorithms at LHC experiments. To fit within latency and FPGA resources, the algorithm can be modified by changing the minimum transverse track momentum or the radial granularity. Utilizing tracking information at early-stage triggers would be greatly beneficial for

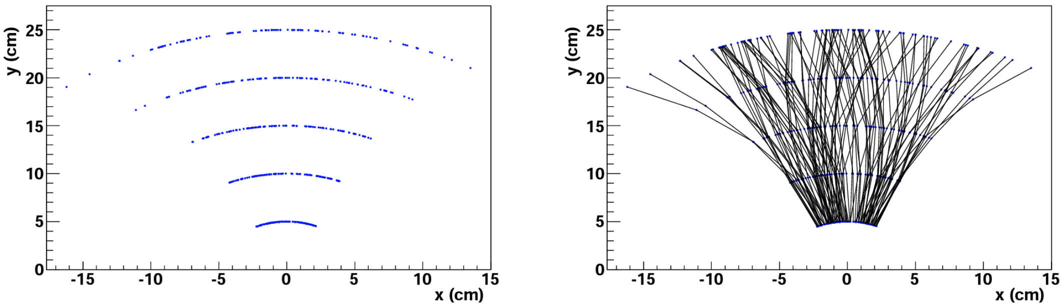

Figure 4-1. *(left) An example of the point cloud generated by 100 particles in an azimuthal sector of the silicon pixel detector of width one radian. The silicon sensors are placed in concentric circles with radial separation of 5cm.(right)The reconstruction of 100 tracks from the point cloud.* [2]

a wide variety of physics analyses at LHC experiments and future lepton and hadron collider experiments, so this is expected to remain an area of considerable interest for the future.

The development of future track-based triggers represents a specific example of many of the general thrusts of innovations in TDAQ for future high energy physics experiments. Use of machine-learning techniques to develop artificial intelligence algorithms that are sensitive to new physics, and performing real-time inference through their integration into detector front-ends or FPGAs (for low-level triggers) and/or heterogeneous computing systems using CPUs, GPUs, and other devices (at high-level) is a rapidly improving and highly promising direction for a wide variety of TDAQ applications. Demonstrating these types of triggers in current and near-future collider experiments (at the LHC and HL-LHC) may open the door for exploring new physics at more distant-future colliders, like the FCC, particularly when considered alongside further innovations in improved readout technologies that can increase data bandwidth and data locality.

Finally, we note that the design of future detector systems, especially tracking systems in dense, high occupancy environments, is best done taking into account the necessary trigger and DAQ considerations early in the process. For example, the design of the HL-LHC silicon tracker for the CMS experiment [13] utilizes the local coincidence of hits in two closely-spaced tracking layers to provide some limited momentum selection capability. This is necessary to reduce the data rate from the detector to manageable levels for the early-level trigger system.

4.2 Heterogeneous Computing Hardware and Machine Learning

As is well known, the scaling of single CPU solutions to efficiently address computational problems has reached its limits, and the need for the parallelization of tasks across many CPU cores, in Graphical Processing Units (GPUs), or in other specialized hardware like Field Programmable Gate Arrays (FPGAs) and Application Specific Integrated Circuits (ASICs) has become necessary. (The choice of technology often depends on the timescale and amount of data to handle). For high-energy physics experiments this means moving beyond the natural parallelization of processing individual data "events" (e.g. beam crossings, which are independent of each other) to the parallelization of the algorithms themselves acting upon the data of single event. This requires a new paradigm of coding algorithms to take advantage of the available heterogeneous computing hardware, and thus utilizing industry tools or developing domain specific tools to aid in this parallelization.

Machine learning algorithms lend themselves well to be distributed on such heterogeneous computing platforms using standard libraries, and thus make a natural and powerful target for trigger applications. The applications include the very specialized and local processing at the front-end of the detector electronics ("edge" computing) where low-level detector hits are converted into clusters or other higher-level data objects at high frequency and low latency, but also the more global and generalized processing needed to discriminate physics signatures from backgrounds. The latter might include discriminating low-energy signal events from backgrounds in neutrino experiments, Higgs boson decays in collider experiments, or gravitational wave signatures for multi-messenger astrophysics. Machine learning also could potentially be used to go beyond the fixed hand-curated trigger menus used to select physics data at colliders to a novel "self-driving" paradigm whereby the trigger system autonomously and continuously learns from the data to more efficiently and effectively filters and selects data from a detector system, as discussed in white paper [6]. Such systems may complement dedicated triggers, searching for specific signatures of Beyond-Standard-Model physics, by performing a general set of anomaly detection that may be sensitive to a wider variety of new physics.

4.2.1 Fast Machine Learning in early stage trigger

Development of machine learning algorithms for use in the trigger and data acquisition systems of future high energy physics experiments is particularly challenging [7]. For example, while ML-based algorithms have proven effective at performing effective data reduction, through both advanced data selection and data compression, to be used in high-luminosity environments of future particle colliders these algorithms must be capable of running in on-detector electronics with latencies on the order of nanoseconds. Future neutrino, dark matter, and astrophysics experiments require latencies on the order of microseconds to milliseconds, and often similarly extreme detector environments.

The design and development of low-latency AI algorithms requires optimization across both physics (*e.g.* selection efficiency, background rejection) and technical performance (*e.g.* latency, resource usage). It's necessary to consider a co-design of hardware and software that gives special attention to the processor element, making use of tools and expertise that can bring a variety of ML algorithms built on large datasets into FPGA and ASIC firmware. Open-source frameworks like `hls4ml` [8] and FINN [9] aim to ease the complexity of firmware programming, which have opened up development and integration of sophisticated AI into high-performance hardware. Continued development of ML frameworks that can aid hardware/software co-design, coupled with (and in many cases driving) improvements in the underlying processor technologies, can open the door to paradigm shift in how future experiments will collect, reduce, and process data.

4.2.2 Fast Machine Learning development strategies

To facilitate fast ML development, it's also very important to foster interdisciplinary collaboration between electrical engineering, computer science and physics, as people in these fields have valuable expertise in digital design, machine learning techniques and the physical problems to be addressed. The community needs to keep track of and be willing to adapt to the latest developments in industry, but also retain the expertise to continue developments addressing challenges that go beyond industry standard. An important note is the value of keeping active work, as much as possible, open source, though the main distributors of FPGAs in the current market (Xilinx and Altera) require the use of proprietary development software. As much as possible, work should be preserved in an open source manner, to be used cross-project and cross-experiment and further built upon in the future.

4.3 Innovative Architectures

4.3.1 Time Multiplexed or Asynchronous Hardware Trigger Systems

For experiments where a processing element of the trigger system must have a complete view of the data from all detectors to perform its function, scalability of the trigger system can be achieved by time multiplexing the data to individual processors. This is natural for software-based trigger levels (CPUs, GPUs) in collider experiments, where data are aggregated in an event builder and sent to a target compute node for processing asynchronously. For a hardware-based synchronous trigger level (FPGAs, ASICs), this can be achieved by sending data from all detector elements for a given time slice (or event) via links to target processors in a round-robin fashion ("time multiplexing"). This will be necessary for the CRES tritium beta decay experiment, for example, where each compute node must process the data from all receivers in a given time slice.

In collider experiments, trigger data processing in the hardware-based level is still generally synchronous to the accelerator clock, even if the processing is time multiplexed. At all stages the data are processed and registered at a multiple of this frequency in the digital pipeline, and the event number is implicit by the clock (or accelerator bunch) counter. However, it is enough to time-stamp data at the very front end of the detectors with the system clock, and transmit and process the data asynchronously as traditionally done at the software-based level [10]. Effectively the event builder infrastructure moves to the first level of the trigger system. This would alleviate the challenge of distributing and synchronizing a stable, low-jitter, high frequency clock over the entirety of a very large and distributed electronics system. It only needs to go to where the data are marked, not to all of the processing elements of a trigger system. It also has the additional benefit of blurring the lines between the first level trigger, which typically runs in fast FPGAs, with the software-based higher levels. It might be possible in the same compute node to run first the very fast algorithms on one set of attached (FPGA) resources, with subsequent processing on other attached GPU or CPU resources on the same node for more complex software-based algorithms. Another avenue of potential interest in this area is to make use of neuromorphic computing directly on analog signals.

4.3.2 Streaming DAQ

Another innovative approach to solving the data reduction problem for trigger and data acquisition systems is to move away from a pipelined and triggered readout, and instead operate in a more "streaming" design, where data is encoded with its time and origin [6]. In this model, pioneered by the LHCb experiment for its upgrade but being adopted to some degree as well by the other LHC experiments, event data can be reduced at its source, often through simple thresholding and zero suppression, and then aggregated and streamed to downstream computational and storage elements. There, full- or partial-event filtering and further processing and translation of data into higher-level quantities can be performed in order to achieve the reduction in the data throughput and offline computing. Hybrid designs that combine both traditional trigger-based DAQ for some detector subsystems and streaming-readout for others is also possible. Emphasis on such approaches for upgrades and experiments at future facilities has merit, especially due to its ability to simplify DAQ design.

4.4 Developments in novel readout technologies

The needs of future detectors continue to push readout, triggering, and data acquisition technologies to operate with growing data rates in more extreme environments. Future kton-scale neutrino and dark matter experiments like DUNE and LZ will produce many petabytes of data per year with intrinsic data rates in excess of TB/s, and require readout systems that can reliably operate in cryogenic temperatures over the long lifetimes of the experiments and minimize radiological material volumes to maintain sensitivity to low-energy interactions. In high-energy collider physics at the HL-LHC or potential future colliders like the FCC-hh, data rates in the hundreds of TB/s are possible from tracking and calorimetry systems, and must be able to withstand high radiation rates and not significantly add to the material budget of the detectors. The fundamental challenge of how to move data from readout electronics to online and offline computing resources requires a commitment to research and development in new and improved technologies.

Core to improvements in DAQ are a combination of reducing the data rate close to the detector, and increasing the data bandwidth for a given material and/or power cost, in the extreme environments required. More sophisticated data reduction techniques in detector electronics may be possible with advances in AI, particularly with improvements in translating low-latency machine-learning-developed compression and triggering algorithms to ASICs [7]. In many cases, like in fast tracking algorithms, correlations across different portions of the detector are necessary to develop effective trigger algorithms, and thus fast, localized, and low-material communication is necessary. Wireless communication technologies are an area of large promise here: microwave-based technologies already show reliable data transmission at the 5 Gb/s scale, and promising future work using free space optics may allow for wireless communication at the Tb/s scale [11]. Integration of wireless communication into HEP detector design (like, for future tracking detectors in colliders), could allow for new system designs that exploit localized readout, fast analysis, and triggering to intelligently reduce data volumes.

Technologies to allow greater bandwidth off of the detector also show significant promise [11, 12]. Silicon-photonics are an appealing alternative to the current VCSEL-based approaches: they can allow integration of fiber-optic connections directly to sensor modules or readout chips (thus reducing the need for electrical cable connections), commercial devices already show high radiation tolerance, and offer a bandwidth twice that of VCSEL devices with a power consumption that is 20% less. More promising developments exist in Wavelength Division Multiplexing (WDM), where individual serial links can be transmitted on its own wavelength, reducing the need for data aggregation to maintain high data bandwidth per link. WDM could be used in a design to bring data out of the most extreme radiation environments in colliders more efficiently, allowing for further data reduction in downstream DAQ components.

Notably, the work to develop new readout technologies is often less in design, but more in integration and testing with real detector components in real detector environments. It is important to develop and maintain tools and facilities that can allow for realistic full-system testing of readout electronics and DAQ.

4.5 Timing

Time measurements will feature prominently in the next generation of particle physics experiments and upgrades, including integration into "4D" tracking systems (see 3.5) and "5D" calorimeters (see 6.2). Timing helps disentangle the effects of particle pile-up in hadron collisions, discriminates against beam-induced backgrounds in a muon collider experiment, and can be used to separate Cerenkov and scintillation light signals in neutrino and dark matter experiments. Timing also provides particle ID information useful for a broad range of experiments, including sensitivity to any slow beyond-standard-model long-lived particles.

Thus it seems evident that timing information will work its way into the trigger processing chain to improve its selectivity and precision of measurements. A particular challenge is the need for synchronization of data at the $\mathcal{O}(10)$ ps level or better, including across large distances in the case of radio-frequency arrays.

4.6 Support for installation, commissioning, integration, and operations

Success of a detector upgrade or new experiment ultimately depends not just on the delivery of the new components, but on the successful installation, commissioning, and integration of them into the experiment as well as their efficient operation. This applies to trigger-DAQ as much as any other instrumentation area [6, 11]. These tasks need to be well thought out (preferably as part of the initial proposal to evaluate the overall cost of a new system) and supported. Lack of attention in any of these areas can lead to substantial and costly delays as well as a failure to reach the design goals, which jeopardizes the physics output. Thus the installation, commissioning, and integration tasks as well as the long-term operations (until the end of the experiment) must be a priority.

4.7 Building and retaining expertise in TDAQ instrumentation

Along with the importance in conducting the R&D to develop and ultimately construct innovative trigger and data acquisition systems for future physics facilities, equally important is to build and retain the domain knowledge and technical expertise within the high-energy physics community required to support this [6]. It can be challenging to recruit and retain highly skilled personnel to address the specialized and high-tech needs of our community. Essential technical staff can leave for higher-paying positions in industry, and younger scientists specializing in instrumentation may/will find career progression and promotion a challenge in this field. This is compounded by the timescale for large experiment facilities from construction through to the end of operations, which can be decades. Thus it is imperative for the scientific community to provide career opportunities for such highly skilled people.

Retention of highly-skilled personnel is made even more important because the needs of particle physics experiments are not always relevant to industrial partners. The particle physics community has an interest in edge cases to typical uses in industry, such as electronics that perform well under constant bombardment from radiation or in cryogenic fluids. There's also a need for a high degree of reliability, as many devices are installed in detectors in areas that are inaccessible for replacement for decades at a time. It's important for the community to continue to follow development in industry and to build strong collaborative networks, but it is as important to develop resources to pursue R&D directions that are specific to use cases in the particle physics domain.

As we explore new TDAQ architectures and hardware with increasing complexity whose performance depends on interactions on a systems level, a dedicated facility that can support TDAQ design and development while also offering opportunities for integration testing across low- and high-level triggering, data readout, data aggregation and reduction, networking, and storage should be established. While the necessary support hardware for the facility may be localized, the participating domain experts should encompass a distributed community. Given many of the common challenges across physics frontiers, such a Trigger and Data Acquisition Emulation and Integration Test Facility should cross experiment and project boundaries, offering support for emulation of detectors and TDAQ systems, and the development and maintenance of common hardware, firmware, and software, and to support TDAQ R&D for future detectors. This facility will develop and maintain an accessible knowledge-base by enabling and supporting connections and communication between engineers and scientists in many national and university labs working within different sub-fields that encounter similar problems.

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5

Micro-Pattern Gaseous Detectors

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(v1)

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5.1 MPGDs: Executive Summary

Background

Gaseous Detectors are the primary choice for cost effective instrumentation of large areas and for continuous tracking of charged particles with minimal detector material. Traditional gaseous detectors such as the wire chamber, Resistive Plate Chamber (RPC), and time projection chamber (TPC) with multiwire proportional chamber (MWPC) readout remain critically important for muon detection, track-finding, and triggering in ongoing and planned major particle physics experiment, including all major LHC experiments (ALICE, ATLAS, CMS, LHCb) and DUNE.

Micro Pattern Gaseous Detectors (MPGDs) are gas avalanche devices with order $\mathcal{O}(100\ \mu\mathrm{m})$ feature size, enabled by the advent of modern photolithographic techniques. Current MPGD technologies include the Gas Electron Multiplier (GEM), the Micro-Mesh Gaseous Structure (MicroMegas), THick GEMs (THGEMs), also referred to as Large Electron Multipliers (LEMs), the Resistive Plate WELL (RPWELL), the GEM-derived architecture (micro-RWELL), the Micro-Pixel Gas Chamber (µ-PIC), and the integrated pixel readout (InGrid).

MPGDs have already significantly improved the segmentation and rate capability of gaseous detectors, extending stable operation to significantly harsher radiation environments, improving spatial and timing performance, and even enabling entirely new detector configurations and use cases.

In recent years, there has therefore been a surge in the use of MPGDs in nuclear and particle physics. MPGDs are already use for upgrades of the LHC experiments and are in development for future facilities (e.g., EIC, ILC, FCC, and FAIR). More generally, MPGDs are exceptionally broadly applicable in particle/hadron/heavy-ion/nuclear physics, charged particle tracking, photon detectors and calorimetry, neutron detection and beam diagnostics, neutrino physics, and dark matter detection, including operation at cryogenic temperatures. Beyond fundamental research, MPGDs are in use and considered for scientific, social, and industrial purposes; this includes the fields of material sciences, medical imaging, hadron therapy systems, and homeland security.

Five commissioned white papers on MPGDs were developed during the 2021 Snowmass decadal survey. These summarize R&D on MPGDs [?], the future needs for MPGDs in nuclear physics [?] and in three broad areas of particle physics: low-energy recoil imaging [?], TPC readout for tracking at lepton colliders [?], and tracking and muon detection at hadron colliders [?]. A white paper with further details on a proposed TPC tracker for Belle II was also submitted [?].

Key Points

		DRDT	< 2030						2030-2035						2035-2040	2040-2045			>2045		
			SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E,...)	Neutrino near detectors (DUNE)	Large ton dual-phase$^{1)}$	Light dark matter...$^{2)}$	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments$^{3)}$	R&D ton scale 0nbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_o	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟡	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	1.4				🟢	🔴	🔴					🔴	🔴							

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

Figure 5-1. *From ECFA report. To be replaced with simplified Snowmass figure.*

- Research directions: The field of MPGDs is relatively young and continues to evolve. The main R&D directions where advances are needed and expected are:
  - pico-second timing
  - particle-identification
  - stable operation in ultra-high rate applications
  - extended triggering capabilities, including topological and machine-learning based
  - dedicated electronics, DAQ, readout technioligies
  - reduced ion backflow
  - improved radiopurity
  - single-electron counting

  - negative ion drift
  - mass production
  - large-area systems
  - algorithm-development
  - gas purification, recovery, environmentally friendly gas mixtures

- Blue-sky R&D: Exploring the fundamental performance limits of MPGDs, such as pico-second time resolution or single-electron-counting, will further advance the field, likely lead to new experimental techniques, and may enable new classes of experiments.
- Experimental needs: Significant production of MPGDs will be required for planned HEP and NP experiment with US leadership or participation (Fig. 5-1) to meet the physics performance requirements.
- Dedicated MPGD development facilities: Currently, the majority of MPGD developers and users in the U.S. rely on production facilities and expertise, diagnostic facilities, and standardized readout electronics associated with the RD51 collaboration and CERN. This significantly slows down the R&D cycle and limits the speed of innovation in the US. It also means all production for US-led experiments has to be outsourced.

  A U.S.-based MPGD Center of Excellence is needed and would address this issue. We envision a facility similar in nature to the Gaseous Detector Development (GDD) lab at CERN or the SiDet facility at FNAL. Such a facility would benefit both the nuclear physics and particle physics communities in the US. There are also ample opportunities for commercialization and collaboration with industry. We envision such a facility hosted by one of DOE's National Laboratories, such as Jefferson Lab or Brookhaven National Laboratory.

5.2 MPGDs: Recent advances and current R&D

Recent developments in the field of MPGDs, and the role of the RD51 collaboration, are summarized in Ref. [**?**]. MPGDs were developed to cost-effectively cover large areas while offering excellent position and timing resolution, and the ability to operate at high incident particle rates. Significant development time was invested in optimizing manufacturing techniques for MPGDs, in understanding their operation, and in mitigating undesirable effects such as discharges and ion backflow. The early MPGD developments culminated in the formation of the RD51 collaboration hosted by CERN, which has become the critical organization for promotion of MPGDs and which coordinates all aspects of their production, characterization, simulation and use in an expanding array of experimental configurations. The CERN MPGD Workshop is a source of essential expertise in production methods, mitigation and correction of manufacturing issues, and the development of MPGDs for specific experimental environments.

An impressive array of MPGDs has been developed, from the initial GEM and Micromegas, now used in a wide variety of applications and configurations, through the more recent ThickGEMs, and microR-Wells with resistive layer(s) to mitigate discharge effects. MPGDs are now also used jointly with other detector elements, for example with optical readout and in liquid Argon detectors. In parallel with MPGD detector development, there has been an important creation of a standardized, general electronics system, the Scalable Readout System (SRS). This system has seen widespread use and is of great utility in allowing integration of a variety of frontend electronics into one data acquisition system. For Snowmass 2021, a number of Letters of Interest were received that illustrate ongoing developments and expansion of use of MPGDs. Here, we highlight high-precision timing, high-rate applications, expansion of the SRS readout system triggering capabilities, and reduction of ion backflow.

Pico-second timing The RD51 PICOSEC collaboration is developing very fast timing detectors using a two-stage system with a Cerenkov radiator producing photons to impact a photocathode. The photoelectrons are then drifted to and amplified in a Micromegas layer (Fig. 5-2). Prototypes have demonstrated single-photon timing at the 45 ps level and at the 15 ps level for MIPs. Multi-pad detectors are being developed, and studies applying an artificial neural network to the waveform have shown potential for very precise timing – in agreement with simulations. Potential applications of the PICOSEC technique include precise timing in electromagnetic showers, and time of flight systems for the future Electron Ion Collider.

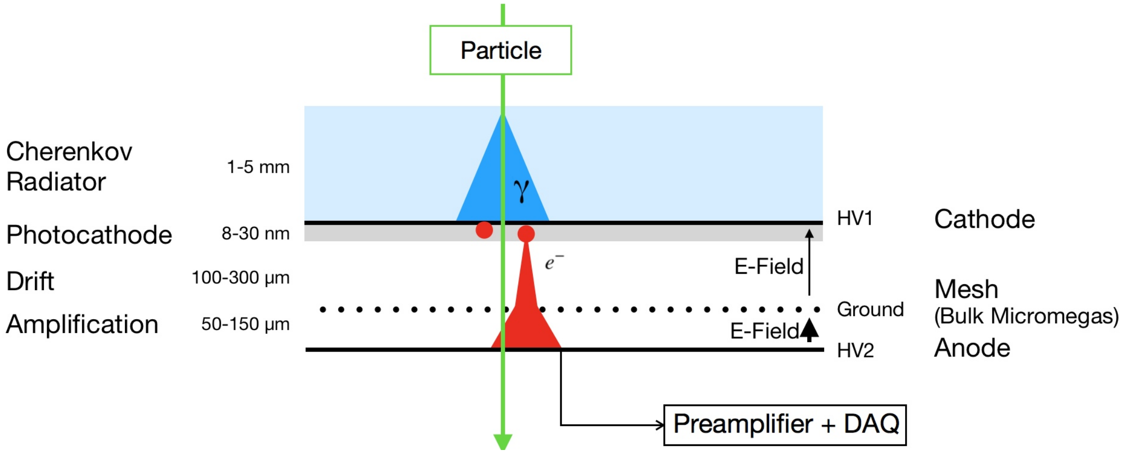

Figure 5-2. *Sketch of the PICOSEC-Micromegas detector concept. [?]*

High-rate applications Micromegas detectors with a resistive layer for spark mitigation and small readout pads are in development for high rate operation. Several schemes for implementing the resistive layer have been tested. These include resistive pads covering the readout pads, layers of Diamond-like Carbon (DLC) across the plane of the detector, and hybrid schemes using both approaches. Prototype detectors have been tested using sources and X-rays in the RD51 Gaseous Detector Developme (GDD) laboratory, as well as particle (muon,pion) beams at CERN and PSI. Comparisons have been made of the rate capability of the various prototypes. Results are reported on the gain variations and operability at high rates of $\mathcal{O}(10$ MHz/cm$^2)$ for pad and DLC prototypes. Energy resolution measured using X-rays is better for the DLC version than the pad version, attributable to the more uniform electric field in the former. Spatial resolution was measured using particle beams with the DLC configuration again performing better — at the 100 micron level. Having demonstrated the desired rate capabilities and other characteristics of the small prototypes, a larger prototype is under construction, which also may include integration of the readout electronics with the detector.

Extended triggering capabilities There has been an evolution of the Scalable Readout System (from SRS to SRSe) to include realtime trigger functionality, deep trigger pipelines and a generalized frontend link using the eFEC, extended Frontend Concentrator backend. This will allow for the expanded use of a variety of frontend ASICs, and ability to use realtime triggering with firmware in an FPGA. A range of possible triggers is possible including, for example, hit combinations and energy sums. Ongoing plans for SRSe foresee script development for FPGAs, establishing a set of initial triggers, testing of the first eFECs, and addressing the needs of specific experiments.

Reduced ion backflow New structures are being designed to restrict ion backflow, to limit performance degradation and/or detector damage. Specifically, multi-mesh MPGD structures, which preserve the desirable features of Micromegas while controlling ion backflow, have been studied. Results with double and triple mesh structures, with adjusted and optimized gaps, have shown that high gain and very low ion backflow can be achieved offering the prospect of excellent performance in future detector applications.

Many other improvements of MPGDs are being actively pursued. Several of these efforts are commented on below, in the context of their intended applications.

5.3 MPGDs for nuclear physics experiments

Many current and future nuclear physics (NP) experiments in the United States have or are implementing MPGDs for tracking and particle identification (PID) purposes. Here, we summarized the role that MPGDs play in NP experiments, and the R&D needed to meet the requirements of future NP experiments. More detail can be found in Ref. [**?**].

Advanced MPGDs for Tracking at the Electron-Ion Collider The physics program of the Electron-Ion Collider (EIC), to be built at Brookhaven National Laboratory, requires its tracking system to have low mass ($X/X_0 \lesssim 1\%$), large area $\mathcal{O}(1\ \mathrm{m}^2)$, and excellent spatial resolution $\mathcal{O}(100\ \mu\mathrm{m})$. MPGDs such as the GEM, Micromegas, and μRWELL can meet these requirements. Furthermore, the EIC is expected to have relatively low rates, below 100 kHz/cm^2, which is well within the operating range of current MPGDs. Current R&D focuses on reducing large-area detector material budgets and the number of channels needed to be read out while maintaining excellent spatial resolution. The EIC can benefit from future R&D, which aims to reduce the detector's material and service budgets further, to achieve a spatial resolution of order $\sim 20\ \mu\mathrm{m}$, and to implement particle identification capabilities into MPGD detectors.

MPGD Technologies for Particle Identification in Nuclear Physics Experiments PID plays a vital role in high energy physics (HEP) and NP physics. The next generation of high-intensity accelerators and increased demand for precision measurements will require the development of high granularity detectors, such as those based on MPGD technologies. Combining a high-precision tracker with PID-capable technology could prove valuable for future experiments. A high-precision MPGD tracker combined with a transition radiation (TR) option for particle identification could provide important information necessary for electron identification and hadron suppression. A radiator installed in front of an MPGD entrance window provides an efficient yield of TR photons. MPGD-based photon detectors offer the ability to provide PID through Cerenkov imaging techniques. Such detectors are attractive for experiments like the EIC as they can provide a cost-efficient option for large-area, low-material budget detectors that can operate in a magnetic field.

MPGD Technologies for Low Energy Nuclear Physics at FRIB The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) will become the world's most advanced facility for the production of rare isotope beams (RIBs). With the delivery of beams starting in Spring 2022, FRIB will be capable of producing a majority (around 80%) of the isotopes predicted to exist, including more than 3,000 new isotopes, opening exciting perspectives for exploring the uncharted regions of the nuclear landscape. Its scientific impact will span a better understanding of open quantum systems at the limits of stability through investigations of the structure and reactions of atomic nuclei and their roles in nuclear astrophysics, low-energy tests of fundamental symmetries, and practical applications that benefit humanity. MPGD technologies play an essential role in the science program's success at FRIB. Applications of MPGD technologies include low-pressure tracking and particle-identification (PID) at the focal planes of magnetic spectrometers, Active-Target Time-Projection-Chambers (TPCs), and TPCs for the detection of exotic decay modes with stopped RIBs. The unprecedented discovery potential of FRIB can be achieved by implementing state-of-the-art experimental equipment and overcoming the challenges of current devices by taking the following measures: improving spatial and energy resolutions, optimizing pure-gas operation for active target mode, improving reliability and radiation hardness at a lower cost, reducing ion-back flow to minimize secondary effects and increase counting rate capability, and integrating electronic readout to reach high channel density, fast data processing, and storage.

MPGD Technologies for Nuclear Physics at Jefferson Lab Future spectrometers for NP experiments at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) require large area $\mathcal{O}(\mathrm{m}^2)$, low mass ($X/X_0 \leq 1\%$), excellent spatial resolution $\mathcal{O}(100\,\mu\mathrm{m})$, excellent timing $\mathcal{O}(10$ ns$)$, high rate $\mathcal{O}(1$ MHz/cm$^2)$ tracking detectors technologies for operation in high background rate and high radiation environment. Only MPGD technologies such as GEMs, Micromegas, or μRWELL detectors can satisfy the challenges of high performances for large acceptance at reasonably low cost. Critical R&D for the next decades will focus on new ideas to develop ultra-low mass, large area, and radiation tolerant MPGD trackers with even higher rate capabilities. The performance of new materials (Chromium GEMs, Aluminum-based readout strips) and original concepts for anode readout such as capacitive, resistive, and zigzag readouts for high-performance & low channel count MPGD detectors will be explored.

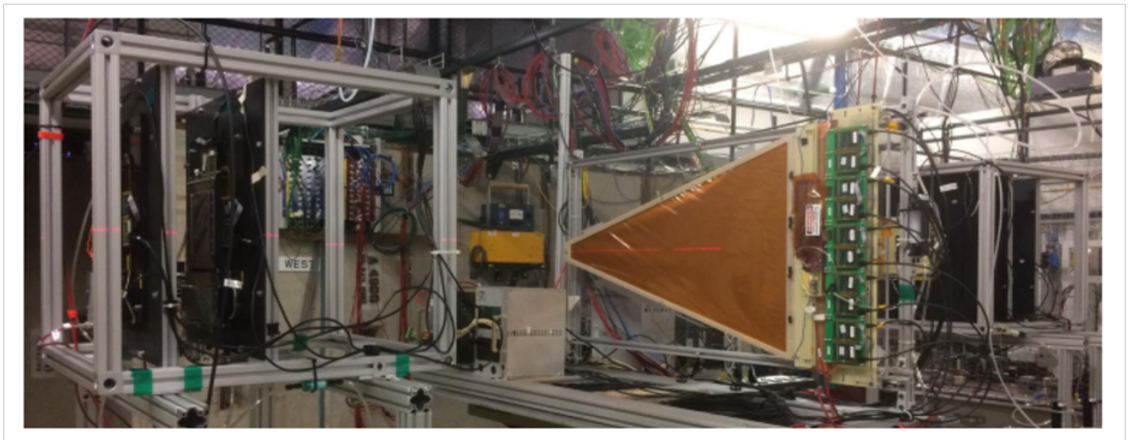

Figure 5-3. *Low mass GEM prototype in beam test at Fermilab, June – July 2018 [?]*

Electronics, DAQ, and Readout Systems for MPGD Technologies The EIC will implement a full streaming readout architecture. This trigger-less implementation will consist of front-end circuitry and processors to enable data collection, processing, and analysis: front-end ASICs will be designed to meet wide bandwidth sub-detector and system requirements; front-end processors will include FPGAs to provide data aggregation and enable flexible algorithms to reduce data volume while maintaining wide system bandwidth; system clock distribution with timing precision of the order of 1 ps; link exchange modules and servers for data processing; and data transport via extensive use of optical fibers. The development of ML/AI algorithms will play a critical role in enabling a full detector bandwidth of 100 Tbps and delivering data output rates of 100 Gbps.

The readout of MPGD detectors requires specific front-end ASICs to amplify and digitize the detector signals with performance requirements depending on their constraints and application. The ASICs should also be compatible with the high-speed streaming readout DAQ systems considered for future experiments at EIC and elsewhere. Existing chips (like SAMPA and VMM) partially satisfy these requirements and can be used for specific applications. Nevertheless, an initiative has been launched to develop a new versatile SALSA ASIC that satisfies the requirements of most MPGD applications in HEP, including both streaming and triggered readout paradigms.

A dedicated MPGD Development Facility The U.S. NP efforts listed above would benefit greatly from a U.S. based MPGD development facility, as highlighted in the executive summary.

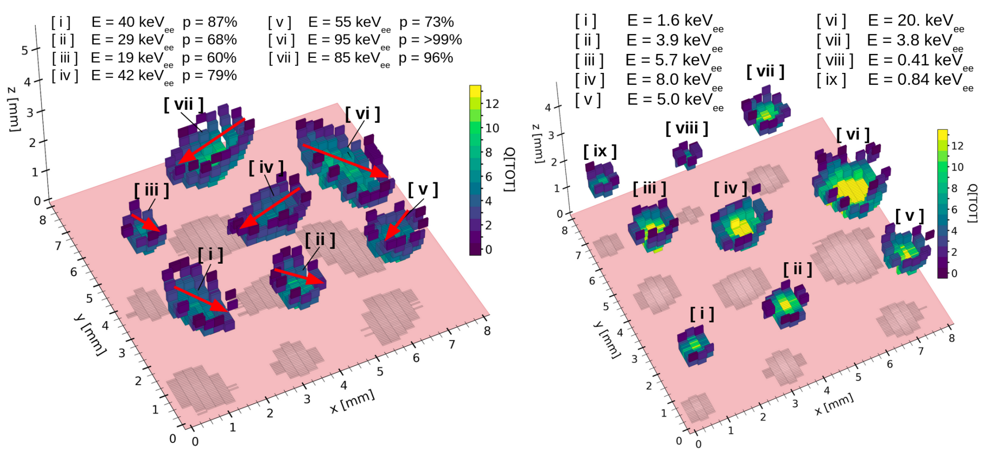

Figure 5-4. *Helium recoils measured in a gas TPC with GEM amplification and pixel ASIC charge readout, in 760 Torr He:CO$_2$ (70:30) gas. Left: 3d directional reconstruction with the detector in low-gain mode, down to 20 keV$_{\rm ee}$. The red arrows show fitted recoil directions, with the head and tail (i.e. sign of the vectors) determined by a 3D convolutional neural network. Right: Demonstration of detection down to sub-keV energies, with the detector in high-gain mode.*

5.4 MPGDs for recoil imaging in dark matter and neutrino experiments

MPGDs can be used to read out the ionization in low-density gas time projection chambers (TPCs) with exquisite sensitivity and spatial resolution. In the most advanced MPGD TPCs, even individual primary electrons—corresponding to an energy deposit on the order of $\sim$30 eV—can be detected with negligible background from noise hits, and 3D ionization density can be imaged with $\sim(100\ \mu\mathrm{m})^3$ voxel size, as shown in Fig. 5-4. This new experimental technique, enabled by MPGDs, has a large number of interesting applications in fundamental and applied physics. We briefly discuss examples below. Further detail on this emerging field can be found in Ref. [?].

CYGNUS Early R&D has established high-definition gas TPCs (HD TPCs) with MPGD readout as the leading candidate technology for imaging the short, mm-scale tracks resulting from keV-scale nuclear recoils in gas. In this context, the detailed ionization images can distinguish electronic from nuclear recoils with high confidence, and can provide the 3D vector direction (i.e. both the recoil axis and the head/tail assignment) of both types of recoils, even at the 10-keV-scale recoil energies relevant to dark matter (DM), neutrino-nucleus scattering, and more.

One of the most intriguing applications is to scale up TPCs with MPGD readout to construct a competitive, low-background, high-definition ionization imaging experiment. By virtue of a planned ultimate sensitivity approaching a single primary electron, the proposed CYGNUS experiment would be sensitive to any process—whether known, hypothesized, or not yet thought of—that produces ionization in the target gas.

While much of RD on MPGDs occurs in the context of the RD51 collaboration at CERN, several key advances in the applications of MPGDs to low-energy physics were made in the US. There is an opportunity here for the US to take the lead and initiate a novel experimental program focused on recoil imaging, with broad scientific scope, one that we have only just started to map out. Because large areas, $\mathcal{O}(1000\ \mathrm{m}^2)$, of MPGDs are required, there are clear synergies with this proposal and the Electron Ion Collider, where MPGDs will be used broadly, and where R&D, production, and test facilities in the US are also desireable.

Required R&D To enable and optimize the sensitivity of a large-scale recoil imaging experiment like CYGNUS, several major R&D goals should be pursued in the next decade. First, HD TPCs should be advanced to their natural performance limit, where primary electrons are *counted individually* in 3D with $\mathcal{O}(100\ \mu\text{m})^3$ spatial resolution. In this regime, the energy resolution is expected to reach a fundamental limit, finite dynamic range of detectors is mitigated, and particle identification and directional capabilities required for physics measurements will be maximized.

The second step is to enable this level of performance in larger detectors, at reasonable cost. Electronic readout in the form of Micromegas detectors with 2D x/y strips are a candidate technology for this, and the main approach being pursued in the US. Key ingredients to this include self-triggering, highly-multiplexed electronics with topological programmable triggers. Another main direction is optical readout, which is the main approach pursued in Europe. In place of electron drift, *negative ion drift* (NID) will also likely be required to reduce diffusion and enable 3D fiducialization. Depending on how negative ions are used in detail, custom front-end electronics may then be required. It is desirable to achieve NID with gases that have low environmental footprint, and capabilities to clean and recirculate gas are already being developed.

The level of internal radioactivity in relevant MPGD technologies must be reduced for an experiment with large exposure. The exact level required also depends strongly on the particle identification capabilities of the detector. Early R&D has shown that modern machine learning can make a large difference in this context. For example, 3D convolutional neural networks are ideally suited to analyze the 3D ionization images created by HD TPCs. This can improve performance by up to three orders of magnitude, thereby lowering the requirement on radiopurity by the same factor. Algorithm development and machine learning both for offline analysis and for smart triggers (known as “machine learning on the edge”) are therefore a crucial part of our proposed program.

IAXO A notable application of recoil imaging in MPGDs beyond DM and neutrinos is for the International Axion Observatory (IAXO). IAXO will be an axion helioscope, an experiment that aims to detect the keV-scale photons generated when the hypothesized flux of axions coming from the Sun enters a large static magnetic field. IAXO is the proposed successor to the CAST experiment, and its intermediate stage BabyIAXO plans to begin data-taking in 2025–2026. A range of technology is planned to be tested for IAXO to further improve backgrounds levels and discrimination capabilities, including novel devices such as GridPix and Timepix3.

Other applications Recoil imaging is also a desirable strategy for background rejection and signal identification in applications totally apart from those listed already. Directional neutron detection, the measurement of the Migdal effect, X-ray polarimetry, and the detection of rare nuclear decays, are to name just a few.

High density gases and dual readout One final concept that has attracted some interest recently, is the use of high density gases such as SeF_6 or argon. Several groups are exploring TPC designs that can provide the necessary sub-mm to 10 micron resolution with such gases. One potential way this could be achieved is via the use of a ‘dual readout’ TPC which can detect both the positive ions as well as the electrons generated by a recoil event. TPCs using gaseous argon could be of interest for studies of the neutrino sector, for example τ-tracking for the study of $\nu_\tau \tau$ charged current interactions.

5.5 MPGDs at future high energy physics colliders

Advances in our knowledge of the structure of matter during the past century were enabled by the successive generations of high energy particle accelerators, as well as by continued improvement in detector technologies. In this context, MPGDs have become a preferred solution for enabling both continuous, low-mass charge-particle tracking in TPCs and large-area muon detection systems. These topics are covered in two dedicated Snowmass Whitepapers [**?**, **?**], summarized below. A dedicated Snowmass Whitepaper focused on a proposed TPC tracker for Belle II is also available [**?**].

TPCs The physics goals of a future Higgs factory and also at the flavour-precision frontier, have put stringent constraints on the need to develop novel instrumentation. Time Projection Chambers (TPCs) operating at e^+e^- machines in the 1990's reached their sensitivity limit and new approaches needed to be developed to overcome the need for improved resolution. The spatial and timing resolution goals nowadays represent an order of magnitude improvement over the conventional proportional wire/cathode pad TPC performance, which is limited by the intrinsic $\mathbf{E} \times \mathbf{B}$ effect near the wires, and approaches the fundamental limit imposed by diffusion. Other detrimental effects such as material budget, cost per readout channel and power consumption also represent serious challenges for future high-precision tracking detectors. One of the most promising areas of R&D in subatomic physics is the novel development of gaseous detectors. Micro Pattern Gas Detector (MPGD) technologies have become a well-established advancement in the deployment of gaseous detectors because those will always remain the primary choice whenever large-area coverage with low material budget is required for particle detection. MPGDs have indeed a small material budget, which is important in a high background or a high-multiplicity environment, and naturally reduce space charge build up in the drift volume by suppressing positive ion feedback from the amplification region. Of greatest importance however, is that the $\mathbf{E} \times \mathbf{B}$ effect is negligible for an MPGD because the micro holes have $\sim$100 μm spacing, which offers a rotationally symmetric distribution and thus no preferred track angle.

Many detector designs aimed at future lepton colliders utilize MPGD devices. We focus on three proposed MPGD-based TPCs: (i) the tracker of the International Large Detector (ILD) at the International Linear Collider (ILC), (ii) a potential replacement of the wire chamber of the Belle II detector at the SuperKEK B-Factory with a TPC, and (iii) a TPC for a detector at the Circular Electron Positron Collider (CEPC).

Overall, an MPGD-based TPC offers excellent tracking performance, while enabling continuous or power-cycled readouts. Historically, TPCs were the main central tracking chambers of ALEPH and DELPHI at the electron-positron collider LEP, where Americans were collaborators. The T2K Near Detector with Micromegas represents another area where TPC technology was deployed with engagement of participants from North America. The upgrade of the ALICE TPC is a more recent example of the usage of MPGDs with participation from institutions from the United States. The ALICE main central-barrel tracking used to rely on multi-wire proportional chambers, which have since been replaced by a TPC with GEM readouts designed in an optimized multilayer configuration, which stand up to the technological challenges imposed by continuous TPC operation at high rates. The requirement to keep the ion-induced space-charge distortions at a tolerable level, which leads to an upper limit of 2% for the fractional ion backflow, has been achieved. The upgraded TPC readout will allow ALICE to record the information of all tracks produced in lead-lead collisions at rates of 50 kHz, while producing data at a staggering rate of 3.5 TB/s. For both the T2K and ALICE TPCs, partnership with CERN allows the fabrication of anode boards of size of order of 50 cm x 50 cm.

The TPC concept is viewed in particle physics as the ultimate drift chamber since it provides 3D precision tracking with low material budget and enables particle identification through dE/dx measurements with cluster counting techniques. At ILC and CEPC, as well as for Belle II upgrades, MPGD TPC technologies are the preferred main tracking system for some conceptual detectors. There are synergies with other

MPGD detector activities (as summarized here) that offer clear motivation for gaseous tracking at lepton colliders. Gaseous tracking devices have been extremely successful in providing precision pattern recognition. They provide hundreds of measurements on a single track, with an extremely low material budget in the central region of the detector. This results in accurate track reconstruction and hence high tracking efficiency. The continuous measurements of charged particle tracks allow for precise particle identification capabilities, which have the possibility not only to achieve excellent continuous tracking, but also to improve jet energy resolution and flavour-tagging capability for an experiment at a future lepton collider. These are two essential advantages for experiments at a lepton collider. The main challenges for the design of a large TPC are related to the relatively high magnetic field in which planned detectors will operate. For accurate measurements of the momenta of charged particles, the electromagnetic field has to be known with high precision. Final and sufficient calibration of the field map can be achieved using corrections derived from the events themselves, or from dedicated point-like and line sources of photoelectrons produced by targets located on the end-plates when illuminated by laser systems. While the event rate at lepton collider detectors can easily be accommodated by current TPC readout technology, R&D to mitigate the effects of secondary processes from bunch-bunch interactions is ongoing. MPGD technologies offer a wide-range of applications and call for synergy in detector R&D at future lepton colliders. The availability of a highly integrated amplification system with readout electronics allows for the design of gas-detector systems with channel densities comparable to that of modern silicon detectors. This synergy with silicon detector ASIC development is very appealing for MPGD TPCs since recent wafer post-processing enables the integration of gas-amplification structures directly on top of a pixelized readout chip.

The **ILD TPC, LCTPC**, is based on mature hardware and software contributions from multiple partners and in particular from the United States (*e.g.* Cornell University and Wilson Laboratory - now the Cornell Laboratory for Accelerator-Based Sciences and Education). LCTPC is conceptually ready as it meets performance and engineering requirements. It is the outcome of decades of research and innovation in MPGDs. Single-hit transverse resolution results from testbeam at 1 T magnetic field extrapolated to the 3.5 T field of ILD clearly demonstrate that single point resolution of 100 µm after ∼2 m of drift over about 200 measurement points is achievable with several MPGD technologies (GEM, Micromegas or GridPix). LCTPC achieved unprecedented spatial resolution of 35 µm at zero drift distance for 2 mm wide readout pads, a world record, and 55 µm with 3 mm wider pads in a high field magnet [**?**]. This translates to two-hit separation of ∼2 mm and a momentum resolution of $\delta(1/p_T) \simeq 10^{-4}/$ GeV/c (at 3.5 T), which are the required performance of the TPC as a standalone tracker at ILD for ILC. Other areas of MPGD developments are ongoing on ion gating, dE/dx, power-pulsed electronics and cooling.

Similar simulations were performed by members of the **Belle II** Collaboration showing that a GridPix-based TPC could be the ultimate central tracker for an upgrade detector at a future ultra-high luminosity B-Factory. The readout choice will need to be adapted to the beam structure of an ultra-high luminosity SuperKEKB upgrade, and probably a buffer that can handle discrete readout of multiple concurrent events will be required. The baseline design of a CEPC detector is an ILD-like concept, with a superconducting solenoid of 3.0 Tesla (Higgs run) and 2.0 Tesla (Z pole run) surrounding the inner silicon detector, the TPC tracking detector and the calorimetry system. The **CEPC TPC** detector will operate in continuous mode on the circular machine. As for the ILD TPC, MPGD technologies are applicable and desirable for a detector at CEPC.

MPGDs for large-scale muon detectors at colliders Gaseous detectors are the primary choice for cost effective instrumentation of very large areas, with high detection efficiency in a high background and hostile radiation environment, needed for muon triggering and tracking at future facilities. They can provide a precise standalone momentum measurement or be combined with inner detector tracks resulting in even greater precision. Adding precise timing information ,$\mathcal{O}$(ns), allows control of uncorrelated background, mitigates pile-up and allows detection of extremely long lived particles that behave like slow muons propagating through the detector volume over a time as long as a few bunch crossings.

With the invention and evolution of MPGDs during the last twenty years, gaseous detectors improved significantly in spatial resolution and rate capability. MPGDs allow stable operation at very high background particle flux with high efficiency and excellent spatial resolution. These features determine the main applications of these detectors in particle physics experiments as precise muon tracking in high radiation environment as well as muon tagger and trigger in general purpose detectors at HEP colliders. Two of the most prominent MPGD technologies, the GEM and MicroMegas, have been successfully operated in many different experiments, such as Compass, LHCb, and TOTEM. In addition, the low material budget and the flexibility of the base material makes MPGDs suitable for the development of very light, full cylindrical fine tracking inner trackers at lepton colliders such as KLOE-2 at DAFNE (Frascati, IT) and BESIII at BEPCII (Beijing, CN).

A big step in the direction of large-size applications has been obtained both with conceptual consolidation and industrial and cost-effective manufacturing of MPGDs by developing new fabrication techniques: resistive Micromegas (to suppress destructive sparks in hadron environments) and single-mask and self-stretching GEM techniques (to enable production of large-size foils and significantly reduce detector assembly time). Scaling up of MPGDs to very large single unit detectors of $\mathcal{O}(\mathrm{m}^2)$, has facilitated their use in muon systems in the LHC upgrades. Major developments in the MPGD technology have been introduced for the ATLAS and CMS muon system upgrades, towards establishing technology goals, and addressing engineering and integration challenges. Micromegas and GEM have been recently installed in the ATLAS New Small Wheel, CMS GE1/1 station respectively, for operation from Run 3 onward, as precise tracking systems. Those radiation hard detectors, able to cope with the expected increased particle rates, exhibit good spatial resolution, $\mathcal{O}(100\ \mu\mathrm{m})$ and have a time resolution of 5–10 ns. In the CMS muon system additional stations, GE2/1 and ME0, based on GEMs with high granularity and spatial segmentation, will be installed to ensure efficient matching of muon stubs to offline pixel tracks at large pseudo-rapidities during HL-LHC operation. Several solutions (μ-RWELL, Micro Pixel Chamber (μ-PIC), and small-pad resistive Micromegas were also considered for the very forward muon tagger in the ATLAS Phase-II Upgrade Muon TDR proposal. Here, the main challenges are discharge protection and miniaturization of readout elements, which can profit from the ongoing developments on Diamond-Like Carbon (DLC) technology. The μ-RWELL is the baseline option for the Phase-II Upgrade of the innermost regions of the Muon System of the LHCb experiment (beyond LHC LS4).

The new era of Particle Physics experiments is moving towards the upgrade of present accelerators and the design of new facilities operating at extremely high intensities and particle energies such as the **Future Circular Colliders** and the **Muon Collider**. Cost effective, high efficiency particle detection in a high background and high radiation environment is fundamental to accomplish their physics program. Different critical aspects such as the high particle rates, discharge probabilities and accumulated doses expected at future colliders must be taken into account. Modifications or new detector configurations are to be investigated by relying on innovative technological solutions. Muon systems at future lepton colliders, (ILC, CLIC, CepC, FCC-ee, SCTF) or **LHeC**, do not pose significant challenges in terms of particle fluxes and the radiation environment. Therefore many existing MPGD technologies are suitable for building future large muon detection systems. For example the μRWELL technology is envisaged to be utilized for the muon detection system and the preshower detector of the IDEA detector concept that is proposed for the FCC-ee and CepC future large circular leptonic colliders. In addition μRWELL are candidates for the inner tracking system at future high luminosity tau-charm factories, STCF in Russia and SCTF in China. Generally, background rates in LHeC muon detector, which are based on the updated design of ATLAS Phase-II Muon spectrometer, are lower than in *pp* colliders. On the other hand, the expected particle rates for the muon tracking and triggering at future **hadron colliders, such as the FCC-hh**, make the existing technologies adequate in most regions of the spectrometers, but require a major R&D for the very forward endcap region. In a **multi-TeV muon collider**, the effect of the background induced by the muon beam decays is extremely important, since it can contaminate the Interaction Region (IR) from a distance that varies with the beam energy, the collider optics and the superconducting magnets. Therefore, the rate of background is particularly relevant in the forward region. Tracking and triggering can be obtained with multi-layer structures, for an efficient local muon segment reconstruction. A new generation Fast Timing MPGD (FTM, Picosec) is considered to mitigate the beam induced background, by rejecting hits uncorrelated in time.

MPGDs offer a diversity of technologies that allow them to meet the required performance challenges at future facilities and in various applications, thanks to the specific advantages that each technology provides. Ongoing R&D should focus on pushing the detector performance to the limits of each technology by overcoming the related technological challenges.

Required R&D should focus on stable operation of large area coverage, including precision timing information to ensure the correct track-event association, and on the ability to cope with large particle fluxes, while guaranteeing detector longevity using environmentally friendly gas mixtures and optimized gas consumption (gas recirculating and recuperation system). Strong constraints on response stability, discharge probability and space charge accumulation require innovative technological solutions and novel detector configurations. Considering the high rate exposure of the detectors and the radiation hazards at future colliders, very strong restrictions to access the detector for reparations and replacement are expected. In this scenario long term operation requirements have to be guarantee also in term of mechanical and electronics robustness. The main challenges include gas tightness, over-pressure operation and electronics cooling. Integration aspects have also to be optimised for easy accessibility and replaceability in complex installations. The assembly of a large scale detector components will require engineering effort to ensure mechanical precision. MPGDs require dedicated front-end electronics (FEE) development, both discrete and integrated (ASIC), focused on specific applications, while meeting a large set of challenging requirements such as: fast timing, large input capacitance, low noise, input discharge protection, cross-talk reduction, pixel size, compactness, low power consumption and detector integration.

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6

Calorimetry

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(contributors from the community)

6.1 Calorimetry: Executive Summary

The IF06 Calorimetry group has considered major issues in present and future calorimetry. Input has been taken from a series of talks, group discussions, LOIs, and White Papers. Here we report on two major approaches to calorimeter systems - Particle Flow and Dual Readout, the critical extra dimension of precision timing, and the development of new materials for calorimeters.

The potential for precision timing at the 10ps level or better opens new possibilities for precise event reconstruction and the reduction of the negative effects of challenging experimental environments. Precise timing can directly benefit calorimetry in several ways ranging from detailed object reconstruction to the mitigation of confusion from pile-up. It can also lead to improved performance for both particle flow and duel readout-based calorimeters. Given these possible performance enhancements, the focus is now on the study of timing implementation both at the device level and the calorimeter system level. Successful implementation can lead to highly performant calorimeter systems well matched to the demands from both future physics studies and experimental environments.

The construction of future calorimeters matched to the demands of high radiation tolerance, the need for fast timing, and constrained cost puts strong requirements on the properties of active calorimeter materials. Suitable materials should therefore combine high density, fast decay time, and good radiation hardness with good optical quality and high light yield. A range of inorganic scintillators has been developed possessing many of these desired properties. However, use of these materials in future large-scale calorimeter systems demands attention to material costs to assure affordability. Organic based plastic scintillators have seen very wide use, having the advantages of ease of use and relatively low cost. The combination of plastic scintillators with SiPM readout has significantly expanded the flexibility of calorimeter design. Finally, liquid scintillators, with low unit cost, have been widely used where very large volumes are required. An interesting development is the potential of metal doped (water-based) liquid scintillators for use as active materials in sampling calorimeters.

Particle flow calorimetry makes use of the associations of charged tracks and calorimeter energy deposits to achieve precise reconstruction of hadronic jets and measurement of their energy. Such associations can aslo be effectively used to reduce the effects of pileup. Implementation of a PFA-based calorimeter requires a small cell size and high granularity leading to very high channel counts. Challenges remain in realizing calorimeter systems with up to 100 million cells. Developent is onging for such systems in the areas of power (heat) management, integration of on-board ASICs, and components of signal extraction. A variety of approaches to PFA calorimeters are under developent ranging from scintillator-SiPM systems to a range of gas-based systems using GEMs, Micromegas and RPCs. Also being explored are the potential benefits of precise timing (see above) and moving some elements of a PFA into the front-end electronics.

The dual readout approach to the precise measurement of jet energies makes use of the scintillation light and Cerenkov light from showers. The relative amounts of scintillation and Cerenkov light is used to correct the shower energy. The original approach to implementing dual readout calorimetry used a matrix of scintillating fibers and clear optical fibers (for the Cerenkov component) in a block of absorber material. However, with the reduced need for spatial associations (as in particle flow), dual readout can make beneficial use of an electromagnetic front section using homogeneous scintillating crystals which have excellent electromagnetic energy resolution. Development of dual readout systems has followed both of these approaches. In the second case, the separation of the scintillation and Cerenkov signals can be achieved by the use of optical filters and SiPM readout and/or exploitation of the different time structure of the two signals. Development and testing of large-scale systems is needed to demonstrate the feasibility of both the all-fiber and homogeneous electromagnetic section plus fibers approaches to dual readout.

The field of calorimeter research and development remains very active. The precision energy measurement requirements of future physics programs is stimulating innovation in the particle flow and dual readout systems. The increasing availability of precise timing is adding an important new dimension to system implementation, while the development of a range of fast, radiation-hard active materials is leading to increased flexibility and exciting possibilities for calorimeter system designs.

6.2 Precise timing for Calorimetry

The primary purpose of electromagnetic and hadronic calorimetry is the measurement of the energy of charged and neutral particles and overall event energy. However, they are also important systems for overall event reconstruction, particle identification and triggering. The physics goals and the experimental conditions at future colliders require technical advances in calorimeter technology to fully exploit the physics potential of these facilities. For future e+e colliders, so-called Higgs Factories, the overall precision of event reconstruction is the main focus, while future hadron colliders at energies and luminosities significantly beyond the HL-LHC impose new challenges in terms of the experimental environment.

Precision timing can add an important extra dimension to calorimeter systems. The prospect of achieving timing resolution at the 10 ps level, the few ps level and even sub-ps level allows the possibility of a number of new aspects of calorimeter technology implementation and event reconstruction [1]. Event reconstruction can benefit from the calorimeter timing capacities at several hierarchical levels: timing in cells, in highly granular calorimeters, helps shower reconstruction and energy corrections, timing of individual showers improves particle identification and objects reconstruction, and object timing allows event pile-up mitigation and characterization.

Particle identification via time-of-flight systems with a resolution at the 10 ps level allows pions to be resolved up to about 3 GeV, K-mesons to about 10 GeV, and neutrons and hyperons to several tens of GeV. While this may be useful for proposed e+e- colliders detectors, future very high energy hadron colliders will require resolution at the picosecond level. Precision timing resolution can either be obtained by dedicated timing layers integrated in the electromagnetic calorimeter achieving the required resolution for minimum-ionizing particles, or by a corresponding resolution for hadronic showers provided by the overall calorimeter system. Calorimeters with tens-of-picosecond timing can also lead to significant benefits for reconstruction of heavy long-lived particles which can have distinct signatures.

Particle flow algorithms, using association of tracking and calorimetric information, can also benefit from the addition of precise timing information. Since hadronic showers show a complex time structure, with late components connected to neutron-induced processes, timing on the cell level can have benefits for the spatial reconstruction of hadronic showers. A time resolution on the order of a few 100 ps to 1 ns results in a sharper definition of the core part of the shower, and thus potentially in a better separation of different particles in the calorimeter, and improved track-cluster assignment in PFA. Full space-time evolution of showers could be achieved with 10ps or better timing resolution. Multi-dimensional information from highly granular calorimeters including timing can be used in combination with convolutional and graph neural networks.

The time information can also be used to reconstruct shower shape for longitudinally unsegmented fiber sampling calorimeters like the dual-readout calorimeter. This can be done in terms of the energy density shape obtained by deconvoluting exponentiating components from detected signals. Shower length differences can be used to distinguish between electrons and pions.

Precise timing information can also play an important role in event reconstruction with background suppression, for example in the reconstruction of jet substructure for resolving highly-boosted objects. For high energy proton collisions, precise timing at the 5-10 ps level will be essential for minimizing the effects of very large numbers of pile-up events on separation of signal events in individual analyses.

Of course, benefiting from all the desirable effects of precise timing described above is dependent on developing new timing techniques at the sub-10 ps level. An example of a possible solution is coherent microwave Cherenkov detection, which has demonstrated 2-3 ps timing of electromagnetic showers using dielectric-loaded rectangular wave-guide elements.

The actual implementation of timing in calorimeter systems can take a number of forms. Timing information can be collected by all active calorimeter cells which, when implemented in a highly granular calorimeter enables a full five-dimensional reconstruction of shower activity in the detector, with corresponding benefits for pattern recognition, spatial shower reconstruction and separation and energy measurement. However, the very large number of cells might force a compromise with only a fraction of cells instrumented for timing. A less challenging and expensive solution could be the use of timing layers, for instance before and after the electromagnetic calorimeter, and at certain depths in the hadronic calorimeter.

A variety of possible technologies are being developed for precise timing elements in calorimeters. These range from Low-Gain Avalanche Detectors and fast silicon sensors to micro-channel plates for timing layers, and from scintillator/SiPMs or multi-gap resistive plate chambers to small crystal solutions for volume timing. Given the potential benefits of including fast timing in calorimeter systems, it is critical that RD in the is area should be supported.

6.3 Materials for Future Calorimeters

Future HEP experiments present stringent challenges to calorimeter materials in radiation tolerance, time response and project cost. Here we summarize materials to be developed in the form of inorganic, liquid (oil- and water-based), and plastic scintillators and wavelength shifters to advance HEP calorimetry to face the challenges in radiation hardness, fast timing, and cost-effectiveness. Some of these materials may also find applications for future HEP time-of-flight system, and beyond HEP in nuclear physics, hard X-ray imaging and medical instruments.

Preferred materials for future calorimetry should have high density, good optical quality, high light-yield, fast decay time, good radiation hardness and low cost. High density increases stopping power and reduces calorimeter volume, thus the cost. Good optical transmission enhances signal efficacy and thus uniformity. High light-yield improves signal to noise ratio and thus energy, spatial and timing resolution, and reconstruction efficiency. Fast decay time improves timing resolution and the ability to mitigate high event rate. Good radiation hardness is essential for calorimetry survivability, so is crucial to improve the calorimetry stability. The requirement and development of calorimetric materials are driven by individual experimental goals.

Inorganic scintillators with core valence transition features with its energy gap between the valence band and the uppermost core band less than the fundamental bandgap, allowing an ultrafast decay time. As an example, BaF2 (barium fluoride) crystals have an ultrafast cross-luminescence scintillation with 0.5 ns decay time peaked at 220 nm, but also a 600 ns slow decay component peaked at 300 nm with a much higher intensity. The slow component in BaF2 crystals causes pileup in a high rate environment but can be suppressed by rare earth doping in crystals. The study of X-ray excitation and emission on BaF2 with different Y3+ doping levels showed that the light intensity of slow component decreases, while the that of the fast component is maintained, with increasing yttrium doping level.

The BaF2:Y (yttrium doped barium fluoride) crystals have the highest light yield in the 1st nanosecond and the highest ratio between the light yield in the 1st nanosecond and the total light yield, which are the figures of merit for a TOF system. Future HEP experiments at the energy and intensity frontiers require ultrafast calorimetry to mitigate high event rate and break the picosecond timing barrier, where BaF2:Y crystals and solar-blind VUV photodetectors are under development for the proposed Mu2e-II experiment. An ultrafast BaF2:Y total absorption calorimeter is also considered by the RADiCAL consortium.

High radiation doses are expected at the forward calorimeter for future collider experiments. Lu2(1x)Y2xSiO5 (Lutetium Yttrium Orthosilicate) or LYSO:Ce (Cerium-doped Lutetium Yttrium Orthosilicate) and Lu3Al5O12 (Lutetium Aluminum Garnet) or LuAG:Ce (Cerium-doped Lutetium Aluminum Garnet) show high stopping power, high light output, fast decay time and excellent radiation hardness against ionization doses and hadrons. LYSO:Ce crystals are used to construct a barrel timing layer (BTL) for the CMS upgrade for the HL-LHC, where the attenuation length of scintillation light is required to be longer than 3m after radiation doses of 5 Mrad from ionizations of 2.5×10^{13} charged hadrons per cm^2 and 3×10^{14} 1-MeV equivalent neutrons/cm^2. While LYSO:Ce crystals satisfy such requirement, LuAG:Ce ceramics shows a factor of two better radiation hardness than LYSO:Ce crystals. They both were proposed by the RADiCAL consortium for the HL-LHC and the proposed FCC-hh in development of an ultra-compact, ultra-radiation hard and longitudinally segmented shashlik calorimeter.

The cost of inorganic crystals ($1s per cc) is one of the major challenges for large calorimetry experiments. The proposed lepton Higgs factory requires good EM and jet resolutions. The dual readout CalVision crystal ECAL followed by the IDEA fiber HCAL provides an excellent option. Because of its total absorption nature, the HHCAL concept promises the best jet mass resolution, however, requires deployment of inorganic crystals at large volume. Crucial RD is to develop a cost-effective approach by either reducing manufacture material cost or enhancing stopping power of heavy inorganic scintillators to improve the project affordability.

WLS (wavelength shifter) capillaries and fiberoptic filaments form the optical “bridges” that connect the scintillation light emission from the scintillator plates to photosensors. The light collection efficiency of a colorimeter thus depends on light propagation (absorption and reemission) between the scintillator and the WLS and their energy response to the quantum efficiency of the photosensors. Ideally if sufficiently rad hard, photosensors could be mounted directly to scintillation plates positioned at shower max to avoid the use of WLS. Such a configuration could greatly improve precision timing measurement and light collection efficacy, and reduce installation cost. The performance of mixed modular configurations using different inorganic scintillators and photosensors with or without WLS is under investigation by RADiCAL.

Organic-based scintillator calorimeters, including plastics, pure liquid scintillator (LS), and water-based liquid scintillator (WbLS), have fast pulse response (1-2 ns) with adequate light-yield (10^4 photons/MeV). Plastic scintillators are widely used for ionizing radiation detection due to modest cost ($10s per kg) and scale-up availability. The most common type of plastic scintillator is composed of selected fluors and wavelength shifters in a plastic base that is an aromatic compound with delocalized -electrons. A detector configuration of plastic scintillators tiled with WLS fibers is a popular choice for sampling calorimeters. Most plastic scintillators employ polyvinyltoluene (PVT) and polystyrene (PS) as the base resins for fabrication. A new thermoplastics acrylic scintillator aiming to load scintillator materials and high-Z elements directly into acrylic monomers is under development. The mechanically advantageous property, good thermal resistance, and reduced aging effect make the acrylic a promising candidate for constructing large plastic detectors. By using modern SiPMs, a multilayer acrylic detector could further provide excellent position and energy reconstruction. The success of this improved acrylic-based scintillator material has applications in calorimetry and other particle physics fields, such as neutrino and dark matters.

Liquid scintillator and water-based liquid scintillator are most cost-effective ($1s per kg) and less sensitive to radiation damage with long optical transparency (attenuation length of $\geq$10m at 450nm) that are capable of deployment in conjunction with any detector compartments in high dose environments. The chemical safety and compatibility have been largely improved over the past decades. The modern liquid scintillators are not flammable and can be deployed in most plastic and/or steel materials. With 30% mass loading of heavy elements (i.e. tungsten) in a liquid scintillator, a radiation length of less than 10cm can be achieved. The fabrication and stability of metal-doped liquid scintillators (i.e., gadolinium, lithium, boron) at ton-scale have been demonstrated by the Daya Bay, LZ and PROSPECT experiments. The principal of loading high-Z elements at high mass percent (i.e., lead, indium, tellurium at $\geq$10%) was proved by solar (LENS) and double-beta decay (SNO+) scintillator research. The application of WbLS in nonproliferation and multi-physics detection is in progress by WACTHMAN and THEIA. Various large-scale testbeds (BNL 1- and 30-Ton Demonstrators and LBL 3-Ton EOS) are under construction to prove the WbLS deployment feasibility at kiloton scale. Significant progress towards developing extractants and techniques that will allow the loading of high-Z elements into high flashpoint and less chemical-aggressive scintillator materials has been achieved by different frontiers. Promising scintillator materials identified for calorimetry are linear alkylbenzene (LAB), cyclohexylbenzene (PCH), 1-phenyl-1-xylyl-ethane (PXE) and di-isopropylnaphthalene (DIN). The approach here is to extend the usage of metal-doped (water-based) liquid scintillators, built on the advanced techniques developed from either deployed or developing neutrino and dark matter search, as active materials for sampling calorimeters through measurements of light collection efficiency, uniformity, and radiation hardness at test beams.

6.4 Particle flow calorimetry

Particle flow (PF) calorimetry is an experimental technique to realize ultra-precise measurements of hadronic jets and thus enable discrimination between W, Z, and H bosons reconstructed in multijet final states. This is a requirement for achieving sub-percent precision on measurements of the Higgs boson mass, total width, and couplings at a future e^+e^- collider. Although these measurements were the original motivation for PF calorimeter R&D, the utility of the PF design in assigning showers to the correct event vertex in high-multiplicity environments has now also been recognized.

PF reconstruction leverages the efficient association of tracks and calorimeter deposits afforded by finely segmented detectors to make hypotheses about the exact particle content of an event (i.e. the 4-vectors of each charged hadron, neutral hadron, photon, electron, and muon). In jet reconstruction, high resolution tracking information can then be used to estimate the momentum of charged candidates over a large momentum range, leaving the momentum assignment to the relatively low resolution calorimeter information for only neutral candidates and very high momentum candidates. By clustering particle candidates, each of which has been assigned its momentum by the "best" detector, large gains in jet energy resolution can be realized over non-PF algorithms that cluster energy deposits alone, given that the charged component of a typical jet is 62% [2]. More effective association of calorimeter hits to tracks with associated primary or secondary vertices also helps to reduce pileup contamination in light and heavy flavor jets.

Benchmarks for PF calorimeter performance have been set by the requirements of precision Higgs and electroweak physics at proposed e^+e^- facilities. Broadly speaking, jet energy resolutions better than 5% are expected for energies between 50 and 250 GeV, with a stochastic term of around $30\%/\sqrt{E\,[\mathrm{GeV}]}$, where E is the jet energy. This ensures a di-jet mass resolution of approximately 2.7%, comparable to the total widths of W and Z bosons, that facilitates clean separation of W and Z hadronic decays. A measurement of the Higgs total width in ZH events using the recoil method, where the initial-state e^+e^- kinematics are used to constrain the final-state Higgs 4-vector from the measured recoiling Z, demands efficient $Z \to q\overline{q}$ identification (q is any flavor of quark) independent of the number of additional jets in the event. The engineering necessary to hit these benchmarks should, additionally, allow for efficient reconstruction of hadronic tau decays and long-lived particles decaying to SM particles within the detector volume enclosed by the calorimeter.

Although PF calorimetry has undergone extensive R&D, a number of challenges still need to be overcome to construct a realistic collider detector. Among the most important is the design of assembly, quality assurance, and quality control processes that scale to $10^7 - 10^8$ channels [3] at a reasonable cost. Ref. [4] states that "[e]ven though the overall channel counts of PF calorimeters are hundred-thousands to millions and the covered areas in the active layers are hundreds of square meters, these products are a niche for most industry areas. Usually, only the components and some of the first assembly steps can be bought from or done by companies. Examples are silicon sensors (but the requirements are unusual, so there are very few suppliers), SiPMs, Micromegas, and production and component assembly of PCBs. The production of modules (joining the active sensor with the readout electronics) and everything from there on is typically not possible in industry." Not surprisingly, efficient simulation of the enormous channel counts in a PF calorimeter is time-consuming. Simulation is critical to detector design and eventually data analysis.

A related challenge is heat management and thermal performance when trying to fit a greatly increased number of channels into roughly the same physical volume as existing energy frontier detectors. Complex front-end ASICs that perform first-level data reduction are typically embedded into the active layers in PF calorimeter designs, as there is no room to bring all of the raw data signals off detector via optical or electrical cables. Power management of these ASICs is crucial to fit within the overall cooling capacity of the experiment. In high luminosity or high radiation applications using silicon sensors or SiPMs, the thermal requirements of the active media are significant to maintain low leakage currents (noise). In addition to minimized power consumption, front-end electronics, power converters, cables, and connectors need to have a tiny vertical height to minimize the air gap between sampling layers. An increased air gap increases the effective Molière radius of the electromagnetic section of the calorimeter, which may compromise the track separation needed to fully profit from the PF approach. In low-luminosity e^+e^- scenarios, gaps as small as 1 mm are feasible, but this has not yet been demonstrated on a large scale, or for high-luminosity prototype designs where the data volume and heat load of the front-end electronics is more significant.

Finally, in a muon collider or hadron collider detector, PF front ends need to withstand significant ionizing and non-ionizing radiation doses. For example, at the HL-LHC, the calorimeters must survive up to 1 MGy of ionizing radiation and $10^{16}\ \mathrm{n_{eq}/cm^2}$ of non-ionizing fluence. Although this constraint is not unique to PF calorimeters, it places extra pressure on the embedded front ends that are typical of these calorimeters. In silicon-based front end designs, for which radiation-induced leakage current growth can be mitigated with cooling, complicated cooling systems need to be deployed.

There is a broad landscape of PF R&D that has paved the way for wide acceptance of this technology and interest in deploying it at scale to solve future HEP calorimetry challenges. PF concepts are integral to detector designs for the HL-LHC, ILC, FCC-ee, FCC-hh, CEPC, and CLIC. Table 6-1, reprinted from Ref. [4], summarizes the current proposals. All of the concepts in Table 6-1 have been constructed as small-scale prototypes and subjected to beam tests. Large-scale technological prototypes, demonstrating the feasibility of both assembly and operation of a full-size calorimeter, have been constructed for the SiW ECAL (CALICE), FoCal (ALICE), scintillator ECAL (CALICE), analog HCAL (CALICE), and digital HCAL (CALICE). Of these, the SiW ECAL, FoCal, AHCAL, and DHCAL have undergone beam testing. One effort that has transcended R&D and is shortly entering full production is the HGCAL upgrade for the CMS detector, consisting of both silicon and scintillator active media.

Table 6-1. *Overview of the characteristics of several particle flow calorimeter concepts and technologies. Reprinted from Ref. [4].*

name	purpose	project	active material	channel size	readout	# of layers (depth)
CALICE SiW ECAL	ECAL	ILC[a]	silicon	5×5 mm^2	analog	30 ($24X_0$)
SiD ECAL	ECAL	ILC	silicon	13 mm^2	analog	30 ($26X_0$)
HGCAL Si	ECAL[b]	HL-LHC	silicon	52-118 mm^2	analog	28 ($25X_0$)
FoCal	ECAL	HL-LHC	silicon	30×30 μm^2	digital	28 ($25X_0$)
CALICE Sci-ECAL	ECAL	ILC[c]	SiPM-on-tile	5×5 mm^2[d]	analog	30 ($24X_0$)
RADiCAL	ECAL	FCC-hh	crystal + WLS[e]	4×4 mm^2[f]	analog	29 ($25X_0$)
CALICE AHCAL	HCAL	ILC[g]	SiPM-on-tile	3×3 cm^2	analog	40 ($4\lambda_I$)
HGCAL Scint	HCAL	HL-LHC	SiPM-on-tile	6-30 cm^2	analog	22 ($7.8\lambda_I$)[h]
CALICE DHCAL	HCAL	ILC	RPC	1×1 cm^2	digital	40 ($4\lambda_I$)
CALICE SDHCAL	HCAL	ILC	RPC	1×1 cm^2	semi-digital	40 ($4\lambda_I$)

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[a] also for CLIC & FCC-ee
[b] silicon also used in HCAL part
[c] also for CEPC
[d] effective size, strips have 5×45 mm^2
[e] wavelength-shifting fiber
[f] effective size at shower max; module cross-section is 14×14 mm^2
[g] also for CEPC, CLIC & FCC-ee
[h] contains also pure silicon and mixed layers

The use of silicon active layers is typically restricted to electromagnetic sections, high-η forward detectors, and environments with high pileup or non-ionizing fluence. In these cases, high lateral granularity is necessary to distinguish nearby tracks, and the advantage of silicon is the ability to pattern small cell sizes of hundreds of square microns to hundreds of square millimeters reliably in industry. Silicon readouts are usually analog, which helps to determine the shower shape and energy deposition more precisely, but in the ALICE FoCal upgrade for $3.4 < |\eta| < 5.8$, digital readout with small pixels is sufficient. The CALICE scintillator ECAL achieves an effective cell size of 5×5 mm^2 from 45-mm-long scintillator strips oriented perpendicular to each other in alternating layers, with the strips coupled to silicon photomultipliers (SiPMs). This is an example of how questions of cost control and scalability are already being addressed at the R&D level.

SiPMs are a key enabling technology for PF calorimetry. They replace bulky photomultiplier tubes, making feasible the use of scintillating media in compact, highly granular designs. Scintillators may be preferred in PF designs due to their low cost (plastics, for example, are used in the HGCAL hadronic section and CALICE AHCAL) or utility in specific challenging applications (the FCC-hh RADiCAL use case). In the latter case, SiPMs are coupled to wavelength-shifting fibers that carry light from multiple crystal scintillator layers to the rear of the detector module. In the former case, each channel (scintillator tile) is read out by an individual SiPM placed right underneath the tile in the active layer ("SiPM-on-tile").

In digital and semi-digital (2-bit) readout hadronic calorimeter designs, small cell sizes are implemented in a cost-effective way using resistive plate chambers. More advanced gaseous detectors, such as GEMs, Micromegas, and MPGDs may also be used to form the cells.

The HEP community has demonstrated its strong interest in pursuing this technology in multiple applications in various stages of development. These include the HL-LHC (CMS HGCAL), e^+e^- collider alternatives (SiD and ILD for the ILC, the CLIC detector concept, CLD for the FCC-ee, and the baseline CEPC detector concept), FCC-hh, and a possible muon collider. Among these, the CMS HGCAL upgrade for the HL-LHC is at the most advanced stage of development, with delivery of the production silicon sensors slated to begin in January 2023. The HGCAL will be a crucial demonstration of the particle flow concept. Lessons learned from the assembly, operation, and PF reconstruction of the HGCAL will influence simulation techniques, design, and costing for future PF calorimeters, and will reveal the areas in which R&D is most needed.

PF calorimetry development has synergies with developments in other areas of HEP instrumentation. Silicon detectors, SiPMs, fast scintillators, and gas ionization detectors are all good candidate active media, depending on the use case. Smart, low-power, radiation-tolerant front end electronics are needed to realize compact designs. PF reconstruction provides a benchmark for optimizing novel computational methods, like the use of machine learning in triggering or particle reconstruction, and in turn requires performance advances that can speed up detector simulation or improve jet energy resolution. Breakthroughs in any of these related technologies can drive significant progress in PF calorimetry, be it cost reduction, simplification of engineering, increased radiation hardness, or improved physics performance.

To realize the full potential of PF calorimetry, and to ensure that it is "shovel-ready" when the next large experiment is approved, R&D is needed to solve outstanding problems. Extensive beam testing, especially of large-scale technological prototypes, is needed to study integration issues and how they affect electromagnetic and hadronic energy resolution. As stated above, more research is needed in front end design, especially for high occupancy and high radiation applications like a future hadron or muon collider. Finally, the challenge of rethinking traditional assembly and QA/QC procedures to find solutions that scale to tens to hundreds of millions of channels cannot be overlooked. There is a growing need to incorporate lessons from product and process engineering into instrumentation labs, either through personnel decisions or by adapting the training of traditional physics graduate students and postdocs. Similarly, academic-industrial partnerships need to be formed with this scale in mind.

With a holistically designed PF calorimeter and tracker, unprecedented jet energy resolutions can be realized. This enables $W/Z/H$ separation in hadronic final states and a measurement of the Higgs total width at an e^+e^- machine. The detailed jet substructure imaging made possible by high granularity in PF designs can also greatly improve long-lived particle, tau lepton, and boosted object reconstruction. For these reasons, particle flow has emerged as a leading candidate design for future collider detectors. With targeted R&D, the scientific promise of particle flow calorimetry can be exploited in the medium term.

6.5 Dual readout calorimetry

Ref. [5] introduces dual-readout (DRO) calorimetry with the following:

> Dual-readout calorimetry is a proven technique for improving calorimeter resolutions and yet its full potential remains to be explored. As inelastic collisions produced in a hadronic shower are associated with a lower response due to energy lost to binding energies, neutrons migrating far from the shower, neutrinos produced in pion decays, and other sources, the method uses proxies to estimate their number. Since fluctuations in the average response due to fluctuations in the number of inelastic collisions in the shower dominates the hadronic resolution, it can be greatly improved using an energy scale correction based on this proxy. In the classic method, the total energy of all ionizing particles is estimated via scintillation light, and the energy depositions of protons produced in inelastic collisions (often via neutron interactions) are estimated via the fraction of the shower particles with a velocity too low to produce Čerenkov light. Current state-of-the-art calorimeter resolutions are the result of pioneering work by the DREAM/RD52 and IDEA collaborations.

DRO calorimetry is largely motivated by the same physics as PF calorimetry: precise measurement of jets in ZH production at an e^+e^- collider. Both methods use additional information about the hadronic shower, beyond simply its energy, to improve jet energy resolution. In the PF approach, association to tracks allows the charged component of the shower to be precisely estimated and measured by a high-resolution tracker, leaving only the neutral component to be measured by the calorimeter. In the DRO approach, the electromagnetic component of the shower is estimated from Čerenkov light, and the relative amounts of Čerenkov and scintillation light are used to correct the energy of each shower according to its measured e/h ratio. PF and DRO methods target the same benchmark of $30\%/\sqrt{E\,[\mathrm{GeV}]}$ in the stochastic term of the jet energy resolution.

PF calorimeters designed with ZH physics in mind typically have EM energy resolutions of about $15\%/\sqrt{E\,[\mathrm{GeV}]}$, which is sufficient for jet reconstruction and $H \to \gamma\gamma$ measurements but not state-of-the-art. EM resolution is limited by the effective Molière radius that can be achieved due to the finite air gap for readout electronics. However, a number of physics measurements that profit from a large-statistics "Z-pole" run of a future e^+e^- collider, including heavy flavor physics with neutral pions, searches for flavor-violating decays such as $\tau \to \mu\gamma$, or searches for non-universal couplings of the neutrino species via $e^+e^- \to \nu_e\overline{\nu}_e\gamma$, could be greatly improved by the addition of state-of-the-art EM energy resolutions. Because DRO does not rely as heavily on longitudinal granularity to perform spatial associations, it can be integrated with homogeneous scintillating crystals (with dimensions of order $1 \times 1 \times 20$ cm^3) that have excellent intrinsic EM energy resolution.

Most R&D for realizing a DRO hadronic calorimeter has focused on a "spaghetti" geometry, where scintillating and clear (for Čerenkov light production) optical fibers are installed in a prism (tower) of passive absorber material such that the fibers are parallel to the longest (projective) dimension of the prism. Towers are typically 2-2.5 m long. The sampling fraction is related to the pitch between fibers (2-4 mm) and the fiber diameter (~ 1 mm). Practically speaking, such a device is assembled by threading each fiber through a copper or brass capillary and densely packing the capillaries into an enclosing tower module.

Scintillating crystals under study for homogeneous EM calorimeters also produce Čerenkov light, although a dedicated radiator could be added to the crystal matrix to boost the yield. DRO could be added to a homogeneous EM crystal calorimeter in one of two ways: usage of two separate filter+SiPM assemblies at the rear of the crystal, each sensitive to either Čerenkov light or scintillation light; or exploitation (in additional hardware or in software) of the different time structures of promptly emitted Čerenkov light and more slowly emitted scintillation light.

Research into the design and performance of a DRO calorimeter for an e^+e^- collider has proceeded along multiple fronts. One of the detector concepts for either FCC-ee or CEPC, the Innovative Detector for an Electron-positron Accelerator (IDEA), utilizes a DRO "spaghetti" calorimeter like that described above, based on the SPACAL and RD52 calorimeters. Simulations suggest that a jet energy resolution of $38(30)\%/\sqrt{E\,[\mathrm{GeV}]}$

is achievable with 2(2.5)-m-long towers. Developments of the homogeneous crystal ECAL with DRO have been made possible recently by the availability of SiPMs with good sensitivity in the red portion of the spectrum. Even though Čerenkov light is enhanced at shorter wavelengths, most of the short-wavelength light is reabsorbed by the crystal as it travels to the SiPM, leaving mostly longer-wavelength Čerenkov light for detection. This line of R&D has led to the SCEPCAL concept of a front crystal EM section followed by a rear spaghetti hadronic section. Simulated hadronic (not jet) energy resolutions are around $27\%/\sqrt{E\,[\mathrm{GeV}]}$ for the combined ECAL+HCAL system. The EM resolution is about $3\%/\sqrt{E\,[\mathrm{GeV}]} \bigoplus 0.5\%$, typical of crystal calorimeters, and obviously much better than what is achievable in sampling PF or DRO designs.

Significant R&D is still needed to fully realize the potential of DRO. Large-scale prototypes of the IDEA and SCEPCAL calorimeters need to be constructed to understand which parts of the engineering are cost drivers, which need further R&D, and how a realistic system will perform. Such efforts have already begun for the IDEA fiber calorimeter, considering a stacked capillary arrangement as described above as well as a 3D-printed copper alveolar tower into which fibers are inserted. On the SCEPCAL front, a key open question is how to ensure that readout of the red end of the Čerenkov spectrum will yield a large enough signal with which to perform the DRO correction. Due to the large size of collider detectors, another important question is how to drive down the cost of high-performing crystal scintillators. For this, systematic surveys of many candidate materials, both known and novel, should be performed. In the long term, research into new optical materials, such as photonic crystal fibers for increased Čerenkov light collection, quantum dot and semiconductor nanoparticle wavelength shifters, and fibers that maintain polarization information, can improve the performance and/or reduce the cost of DRO fiber calorimeters.

Readout of each fiber by a SiPM opens the door to jet imaging and position reconstruction using algorithmic or deep learning techniques. This can enable gluon/jet discrimination, studies of jet substructure, or identification of tau leptons or boosted objects. Indeed, the extra front end information that DRO relies on requires advances in electronics for efficient processing and reduction. Areas of R&D in this direction include system-on-chip waveform digitizers with real-time analysis, field programmable analog arrays on the front end, and digital SiPMs. With flexibly designed readouts, it may also be possible to use the time structure of the Čerenkov and scintillation signals to estimate the shower EM fraction online and improve triggering.

A novel idea for smaller systems for forward calorimetry, high intensity experiments, and orbiting systems is the use of photomultiplier tubes (PMTs) for the direct detection of shower particles. The PMTs act as direct calorimeter sensors to detect shower particles via Čerenkov light in the PMT window, and/or by direct secondary emission from shower particles traversing the dynodes. The secondary emission proportional to dE/dx provides compensating information.

There is no reason that the advantages of PF and DRO cannot be combined in certain applications to yield even more flexibility, and in fact some proposals seek to do just that. The REDTOP [6] experiment at Fermilab would produce some 10^{13} η particles to serve as a laboratory for studying fundamental symmetry violations, carrying out searches for rare new physics scenarios, and studying SM physics at medium energies with exquisite precision. Its calorimeter, ADRIANO2 [7], consists of a sandwich of lead glass and plastic scintillator layers. Each layer is subdivided into optically isolated tiles that are each read out by an individual SiPM. The lead glass tiles are sensitive to the Čerenkov component, while the plastic tiles are sensitive to the scintillation component. This configuration, which is currently being studied as part of a multi-year R&D and test beam campaign, can provide the excellent energy resolution, position resolution, and particle ID needed to discriminate prompt photons from neutrons and π^0s in a high multiplicity event.

DRO is a promising direction in calorimetry that allows for shower-by-shower e/h compensation, ultimately yielding ultra-precise jet energy measurements. The RD52/DREAM collaboration has established the basics of DRO, but multiple R&D questions remain unanswered. This R&D has been taken up by groups pursuing the IDEA detector or the SCEPCAL calorimeter for a future e^+e^- machine. It is crucial to demonstrate the feasibility of a large-scale installation, while also pursuing “blue-sky” research into novel materials that can provide excellent EM performance and a strong Čerenkov signal. Such a program will advance DRO into a mature technology for future collider detectors.

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7

Detector Electronics and ASICs

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7.1 IF07 Executive Summary

In pursuit of its physics goals, the high energy physics community develops increasingly complex detectors, with each subsequent generation pushing to ever finer granularity. For example, the emergence and growing dominance of particle-flow reconstruction methods has stressed the increasing importance of very fine detector granularity, not only for tracking detectors but also for calorimetry, and has also initiated the push to ”4D” detectors that combine precision measurements of both spatial and time coordinates to their measurements of energy and momentum. While these developments have led to enormous growth in detector channel counts, the analog performance requirements for energy and momentum measurements, as well as spatial and timing precision, are being maintained or (more typically) even tightened.

These challenging detector requirements drive the corresponding development of readout electronics. A variety of factors, including the growing specialization of the functionality required, and the explosive growth in channel counts and typically modest (if any) increases in the material budget and the power and cooling budgets, lead to the increasing reliance on custom-developed Application Specific Integrated Circuits (ASICs). This trend is further exacerbated by challenges in the various experimental environments, including radiation hardness requirements, cryogenic and deep-cryogenic operations, and space-based detector systems. The development of custom ASICs in advanced technology nodes allows HEP detector subsystems to achieve higher channel density, enhanced performance, lower power consumption, lower mass, much greater radiation tolerance, and improved cryogenic temperature performance than is possible with commercial integrated circuits (ICs) or discrete components. The higher level of integration also leads to fewer components and fewer connections, leading to higher reliability, as required by experiments that can run for decades and that provide access to the on-detector electronics at most annually, and sometimes never.

This writeup summarizes the work of “IF07”, namely Topical Working Group 7 of the Instrumentation Frontier group of the Snowmass 2021 process. Group IF07 dealt with issues pertaining to ASICs and Readout Electronics. The community efforts as part of IF07 were organized across 7 white papers submitted to the Snowmass process. The first [1] discusses issues related to the need to maintain the talented workforce required to successfully develop future HEP electronics systems, and to provide the appropriate training and recruitment. The remaining papers focused on electronics for particular detector subsystems or technologies, including calorimetry [2], detectors for fast timing [3], optical links [4], smart sensors using AI [5], cryogenic readout [6], and RF readout systems [7]. In the following section, a brief overview is provided of each of the white papers in turn. A white paper on silicon and photo-detectors was originally considered. This content is now captured by other frontiers with contributions form ASICs and readout electronics.

The interested reader is referred to the white papers themselves, and to the references each contains, for a more detailed discussion of each of the various topics.

There are some overarching goals for advancing the field of readout and ASICs. Activities with broad impact are: 1) Provide baseline support and specialized training opportunities for the instrumentation work force to keep the US electronics instrumentation ASIC workforce; 2) improve mechanisms for access to advanced technology; 3) continue to develop methodologies to adapt the technology for operation in extreme environments; 4) expand framework and platform for easy access to design tools.

7.2 Overview of IF07 White Papers

A brief overview and high-level summary of each of the 7 IF07 white papers is provided below. For a more detailed discussion of each of the various topics, the interested reader is referred to the white papers themselves, and to the references therein.

7.2.1 Workforce and Training Needs

Two decades ago as we embarked on the design of the LHC detector systems *on detector* readout was focused on the integration of custom sensors and multiple types of Application Specific Integrated Circuits with communications rates at or below 100 Mbps. Significant effort went into the design of printed circuits on boards or flexible substrates. A new generation of ASICs were coming into use that could survive radiation tolerance levels consistent with the needs of LHC provided specialized layout techniques were employed. Designers were faced with learning new tools and rules for commercial ASICs that were attainable in a few months and system interfaces were being designed that allowed multiple institutions to design parts of a readout system nearly independently. As LHC systems were being placed into service commercial ASICs and communications systems were leap frogging forward and significant change was moving the state of the art forward faster than our communities and budgets could maintain pace. Today's HL-LHC designs have been able to take advantage of advances that are still several technology generations behind the commercial state of the art to move what previously was multi-chip functionality onto a single silicon substrate to make systems on a chip that operate at much higher clock rates and can hold and selectively readout more data and contain most or all of the readout blocks for modules of thousands of small size sensors. The price for successful submission of these far more complex, low power integrated circuits has been the requirement for a workforce with knowledge of a broad set of new tools for design and verification as well as formalized design management and integration tools that don't allow new versions or blocks to compromise the overall performance or design progress of these now highly complex systems on a chip. We also recognize the revolution in capabilities offered by new, complex FPGA's that comprise a large part of the off detector readout of detector systems designed over the past decade. Here too the required knowledge base has expanded sufficiently far that coding is no longer an easy to skill to learn for this or next generation designers. We foresee the need for continuing workforce training past the qualifying academic degrees to update commercial design skills. Many designs require HEP specialized knowledge to enable successful first time designs for extreme temperature and radiation environments. Our community needs to exploit the internet to provide an archive with searchable access to design examples from previous generations of detectors to replace the institutional knowledge passed down from previous teams. This is especially important given that the time between large detector system developments may exceed career lifetimes. In these extended interim's it is recognized that core HEP instrumentation specialists need to update their skills with practical projects to ensure their familiarity with the evolving state of the art in ASIC designs. This can be encouraged by DOE provided annual FOA's to support the design of service blocks that will be necessary in yet to be defined front end ASICs for next generation sensor arrays: High speed communication links, data storage blocks, PLL's, power converters and regulators etc. Having silicon tested designs for next generation ASICs will both speed up design cycles and help maintain workforce skill levels consistent with current (at the time of need) ASIC design tool familiarity to minimize the number of design submissions required to assure reliable ASIC performance. We encourage the HEP academic community to provide Instrumentation Based PHD degrees to formally make available expertise in the Experimental HEP community. In addition it will be beneficial to have instrumentation conferences with training available to introduce new design approaches or technologies. This training should include continuing education certification to help qualify candidates for positions in Experimental HEP. We see the recent support from DOE for Instrumentation based traineeship to be an important step towards having a better trained, better informed workforce not only for designing systems but also for the benefit of future peer reviewed systems.

7.2.2 Calorimeter Readout Electronics

Calorimeters will continue to serve as key detector subsystems at future colliders, as well as in many other applications. The traditional challenges of calorimeter readout electronics systems, including providing high precision energy measurements over a very wide dynamic range, are increasingly compounded by the demands of much finer granularity and correspondingly higher readout rates, as well as the demand of providing precision time measurements in the move toward "4D calorimetry". The on-detector location of the frontend electronics, necessitated by signal-to-noise and other requirements, imposes additional challenges, including tolerance to radiation and/or magnetic fields, reliability over periods of a year or more without maintenance, and power and cooling budgets.

Some of the key innovations in calorimetry that are driving ongoing and future readout electronics developments include particle flow algorithms, in which measurements of energies from calorimeters are combined with the momentum measurements from charged-particle tracking detectors. and dual-readout detectors, which provide a more flexible combination of the electromagnetic and hadronic components of a shower. Both of these methods aim to significantly improve the energy resolution, and both can be implemented either with or without timing information as an added component.

Particle flow algorithms are pushing calorimeter designs to ever finer granularities, and therefore greatly increasing channel counts. As an example, the High Granularity Endcap Calorimeter (HGCAL) being developed currently for the CMS HL-LHC upgrade includes over 6 million readout channels, a dramatic increase over the $\approx 200k$ channels of the ATLAS liquid argon (LAr) calorimeters that set the scale for "finely segmented" among the original LHC detectors.

Meeting the challenges for frontend calorimeter readouts has relied on custom ASICs for over 30 years, and ASICs will only become increasingly important. Fortunately, the higher level of integration available today has permitted some consolidation; for example, while the current ATLAS liquid argon (LAr) frontend required development of 11 different custom ASICs, spread over a variety of technologies, the HL-LHC development underway requires only three. The higher level of integration is most clearly seen in the digital realm, where for example the lpGBT chip in 65 nm CMOS fulfills a number of functions, including clock and control distribution, slow control monitoring, and data serialization and formatting, that were spread over a number of different ASICs for the original LHC developments. However, even in the analog realm some consolidation has been achieved, such as the 130 nm ASIC developed for LAr that combines the functions of both the preamplifiers and the shapers from the original construction.

Of key importance to maintaining the ability to develop ASICs to meet the challenges of future calorimeters will be to maintain affordable access to the specialized ASIC processes in industry, and to qualify these processes concerning their radiation tolerance and, in some applications, also their performance in cryogenic environments. A fortunate development has been the typically increasing radiation tolerance of new ASIC processes with smaller feature sizes; while the original LHC readout ASICs exploited a number of specialized processes, or used standard cells and design rules that had to be explicitly developed to improve the radiation tolerance, the HL-LHC developments can focus on commercial 130 nm and 65 nm CMOS processes and use commercial standard cell libraries. The move to ever smaller feature-size ASIC processes also greatly helps reduce the power consumption. However, the corresponding evolution to lower power rails presents a significant challenge for the very frontend analog circuits that must handle input signals over a very wide, often around 16-bit, dynamic range.

Other challenges for the development of future calorimeter readouts include powering systems, ranging from power supplies, to DC-DC convertors and low dropout regulators (LDO) or on-chip regulation, that can provide the needed power in a practical and radiation-tolerant manner, and high-speed optical links that can move off-detector the huge data volumes generated by the calorimeter frontends. Optical links will be discussed further in Section 7.2.4. Powering has long proved a thorny issue at the LHC, and carefully evaluating over many years the radiation tolerance of commercial devices has clearly demonstrated that the great majority would not survive the LHC conditions. As a result, industrial partnerships were launched for both the original LHC and for the HL-LHC to develop radiation-tolerant LDOs.

7.2.3 Electronics for Fast Timing

Picosecond-level timing will be an important component of the next generation of particle physics detectors. The ability to add a 4^{th} dimension to our measurements will help address the increasing complexity of events at hadron colliders and provide new tools for precise tracking and calorimetry for all experiments. Time is crucial for background rejection in dark matter searches and neutrino detectors. As resolution continues to increase, time will likely become an equal partner to position measurement in particle tracking and particle flow event fitting. All this has been enabled both by the rapid and continuous advance of fast electronics and the ability to generate fast signals with good signal/noise from a variety of solid state sensors, photodetectors, and micropattern gas-based detectors.

Fast silicon sensors with gain, (e.g. Low-gain Avalanche Detectors LGAD) and sensors without gain (e.g. 3D sensors), micro-pattern gaseous detectors, Cerenkov light and fast scintillators such as LYSO, microchannel plate (e.g. LAPPD), semiconductor-based photodetectors such as SPADs and SIPMs, and other sensors provide all very fast signals. There are several R&D efforts aimed at the development of fast ASIC electronics for future HEP applications with focus on using specific and advanced technology (e.g. SiGe, 28 and 22 nm CMOS) and implementing suitable concepts for the needed time resolution (e.g. full waveform digitation, TDC, monolithic solutions).

The design and optimization of the front-end amplifier is particularly important for fast electronics. The front end typically defines the signal/noise and thus the time jitter of the system. It can also consume significant power. Each design must be optimized for its environment, considering signal source, input capacitance required resolution, and subsequent processing and developed as element of a larger system design effort.

Fast timing applications put special emphasis on noise and rise time, which often requires higher front-end power. Increased pixel density to cope with required resolution and occupancy although somewhat balanced by lower load capacitance, also strains the power budget. Improved per hit time resolution may require more complex processing of the input waveform with corrections for delta rays, nonuniform ionization and varying weighting fields. This will require more complex, power hungry on-chip calculations or increased waveform information sent to downstream processing.

For ultimate time resolution non-homogenous sensor responses must be compensated, either on-detector or as part of the processing chain. This is an opportunity to employ emerging technologies such as machine learning to front or back end systems to take advantage of all possible information.

Most of the sub-75 ps systems demonstrated to date have either been in small, well constrained systems, or in beam tests. Distribution and maintenance of the clock system will be a challenge for large systems. In large systems timing must be monitored and temperature and aging effects compensated. Optical transceivers can have several ps/degree delay variation. This has been considered in detail for Xilinx Ultrascale transceivers and techniques have been developed to provide 1 ps phase resolution.

Using a combination of these instrumentation techniques and developments, including Constant Fraction Discrimination (CFD), waveform sampling combined with precise clock distribution and newly developed sensors we expect that it will be reasonable for future fast timing detector sub-systems to set a 10pS timing resolution goal that will allow for unprecedented accuracy and significantly improve the physics reach of next generation high rate, collider detectors. We anticipate that the grand challenge of measuring particles with a resolution of about 1 ps may be possible and would provide revolutionary physics opportunities.

7.2.4 Optical Links

The dramatic increase in channel count that has resulted from detectors with ever finer granularity, plus the need to deliver in real time either all or at least more of the full-granularity, full-precision detector readout data, has placed increasing demands on the optical links used to transmit the data from the on-detector frontend electronics to the off-detector digital processing and TDAQ systems. The radiation-tolerance specifications for the detector mounted links has led to reliance on custom developments, for the most part, though the original LHC detectors did use some commercial link components which were tested to be sufficiently radiation hard.

The radiation requirements plus the reliance on custom solutions have resulted in link speeds per fiber which are significantly lower than used in commercial systems. The original LHC detectors employed on-detector optical links from several 100 Mbps up to 1.6 Gbps per fiber. The per-fiber bandwidth increased to 5 Gbps for the recently completed Phase I upgrade of the LHC experiments, and currently to 10 Gbps for the ongoing HL-LHC developments. This substantial increase in per-fiber bandwidth has, however, not kept pace with the growth in data volume. For example, the original ATLAS LAr readout used a single 1.6 Gbps link per 128 channels, while the corresponding HL-LHC readout will need 22 fibers at 10 Gbps each for 128 channels. The relatively low (up to 10 Gbps) per-fiber bandwidth, compared to industry rates of up to 56 Gbps, results in large fiber plants and an inefficient use of the SerDes resources of the fast (and expensive) FPGAs that are typically used to receive and process the on-detector digital data once it arrives off-detector and away from radiation.

Realization of a functional optical link requires several building blocks, including a data fan-in and serializer, combined with a electrical-to-optical conversion coupled to an optical module that couples to the fibers.

For serializers, the custom-designed 5 Gbps GBT was developed by CERN in 128 nm CMOS, predominantly for use in the Phase I upgrades of the LHC detectors. Following this successful mode, the 10 Gbps lpGBT was then developed in 65 nm CMOS, and will be used in most HL-LHC on-detector electronic readout applications. R&D is underway that aims to increase the bandwidth by a factor of two in the short term, still within 65 nm CMOS, and then to move to 56 Gbps utilizing 28 nm CMOS.

The critical components for the optical modules themselves have been mostly satisfied by commercially available VCSELs and pin diodes, which must be painstakingly selected for radiation tolerance. However, a custom optical module that integrates these functions plus the optical connections is still required, due mostly to the tight spatial and mechanical constraints, as well as material budget, imposed, in particular, by the inner detectors at the LHC and HL-LHC.

It is apparent that future detector readouts will continue to deliver increasingly large data volumes. Meeting the corresponding readout bandwidth requirements, and in particular for on-detector environments with a significant radiation-tolerance requirement, poses a number of very significant challenges. Meeting these needs will require ongoing R&D, to facilitate the continued evolution to higher bandwidths, and in particular per-fiber bandwidths.

7.2.5 Smart Sensors Using Artificial Intelligence

Modern particle physics experiments and accelerators, exploring nature at increasingly finer spatial and temporal scales in extreme environments, create massive amounts of data which require real-time data reduction as close to the data source and sensors as possible. The demand for increasingly higher sensitivity in experiments, along with advances in the design of state-of-the-art sensing systems, has resulted in rapidly growing big data pipelines such that transmission of acquired data for offline processing via conventional methods is no longer feasible. Data transmission is commonly much less efficient than data processing. Therefore, placing data compression, extracting waveform features and processing as close as possible to data creation while maintaining physics performance is a crucial task in modern physics experiments. The implementation of Artificial intelligence (AI) and machine learning (ML) in near-detector electronics is a natural path to add capability for detector readout. It will enable more powerful data compression and filtering which better preserves the physics content of experiments, reduces downstream system complexity, and provides fast feedback and control loops. While the application of AI/ML is growing rapidly in science and industry, the needs of particle physics for speed, throughput, fidelity, interpretability, and reliability in extreme environments require advancing state-of-the-art technology in use-cases that go far beyond industrial and commercial applications.

AI, and more specifically ML, has recently been demonstrated to be a powerful tool for data compression, waveform processing, and analysis in physics and many other domains. While progress has been made towards generic real-time processing through inference including boosted decision trees and neural networks (NNs) using FPGAs (Field Programmable Gate Arrays) in off-detector electronics, ML methods are not commonly used to address the significant bottleneck in the transport of data from front-end ASICs to back-end FPGAs. Embedding ML as close as possible to the data source has a number of potential benefits

- ML algorithms can enable powerful and efficient non-linear data reduction or feature extraction techniques, beyond simple summing and thresholding, which better preserves the physics content that would otherwise be lost;

- This could in turn reduce the complexity of down stream processing systems which would then have to aggregate less overall information all the way to offline computing;

- This enables real-time data filtering and triggering like at the LHC and the EIC which would otherwise not be possible or be much less efficient; or in the case of cryogenic systems, creates less data bandwidth from cold to warm electronics and thus reduce the system complexity;
- Furthermore, intelligent processing as close as possible to the source will enable faster feedback loops. For example, in continuous learning applications, if the data is part of a control or operations loop where feedback is needed such as in quantum information systems or particle accelerators.

With rapidly growing machine learning applications comes the acute need for their efficient hardware implementations. Most of the efforts are focused on digital CMOS technology, such as implementations based on general-purpose TPUs/GPUs, FPGAs, and more specialized ML hardware accelerators. The steady improvements in such hardware platforms' performance and energy efficiency over the past decade are attributed to the use of very advanced, sub-10-nm CMOS processes and holistic optimization of circuits, architectures, and algorithms. The opportunities for building more efficient hardware may come from biological neural networks. Indeed, it is believed that the human brain, with its $>1000\times$ more synapses than the weights in the largest transformer network, is extremely energy efficient, which serves as a general motivation for developing neuromorphic hardware. There is a long history of CMOS neuromorphic circuits. However, unleashing the full potential of neuromorphic computing might require novel, beyond-CMOS device and circuit technologies that allow for more efficient implementations of various functionalities of biological neural systems.

There are several ongoing R&D efforts in our community focused on on-detector AI/ML and the key elements of both the design and implementation, and the design tools themselves. Though early in the exploration of these applications, the existing work highlights the needs for configurable and adaptable designs and open-source and accessible design tools to implement efficient hardware AI. Novel ML techniques are particularly important for resource-constrained real-time AI; advancing design, implementation, and verification tools which accelerate the development process; and emerging microelectronics technologies which could provide large gains in efficiency and speed. Different classes of future applications require dedicated investments to advance our capabilities in this field.

Many emerging devices and circuit technologies are currently being explored for neuromorphic hardware implementations. Neuromorphic inference accelerators utilizing analog in-memory computing based on floating gate memories are perhaps the closest to widespread adoption, given the maturity of such technology, the practicality of its applications, and competitive performance with almost 1000x improvement in power as compared to conventional (digital CMOS) circuit implementations. The radiation hardness of these techniques and their applicability for robust performance in extreme environments is yet to be evaluated.

7.2.6 Cryogenics Readout

A large variety of applications, including direct Dark Matter detection and neutrino oscillation experiments, require electronics which is designed to perform within cryogenic environments. Many of these applications require liquid helium temperatures, from a few Kelvin down to milli-Kelvin, while others utilize liquid noble elements, amd in particular liquid argon and liquid xenon.

Time projection chambers (TPCs) using noble liquids are finding increasing utility. Many of the current generation of experiments, such as the SBN program at FNAL or the XENON experiment at Gran Sasso, keep the active electronics in the warm, outside the cryostat. A similar approach was followed by previous and current generations of LAr calorimeters, with the exception of the ATLAS Hadronic Endcap Calorimeter, which has preamplifiers and summing circuits in the cold, realized in GaAs technology.

Dune Far Detector Wire Readout

The sheer scale of the DUNE LAr TPC makes impractical the approach of bring all the raw analog detector signals into the warm, and instead leads to the need to embed active electronics in the cold. For the case of the DUNE wire-based LAr TPC readout, the required cold functionality is achieved by a set of 3 custom ASICs, one that amplifies and provides analog filtering, one that digitizes at 2 MSPS, and one that collects and serializes the data for transmission over copper cables to the warm electronics placed on the outside of the cryostat feedthroughs.

Pixel Readout

The Dune near detector will benefit from a low power pixel readout utilizing the self triggering LarPix 64 channel pixel ASIC submerged in the Liquid Argon. Four programmable readout paths on the chip allow a board level fault tolerant readout path. Track reconstruction results from prototype boards populated with 100 ASICs have shown very promising results.

A second very low power readout is being investigated by the Qpix Collaboration that utilizes a novel approach to record the times of arrival of a fixed unit of charge, enabling off line reconstruction of the ionization current sensed at the pixel with a sub-fempto Coulomb unit charge sensitivity.

7.2.7 RF Electronics

RF electronics utilizes the RF domain to sense or control EM radiation well below ionization energies to make highly sensitive measurements of natural phenomena. The sophistication and sensitivity of RF related detection systems has improved dramatically with advances in wireless communications. HEP now has the opportunity to probe electromagnetic field signals measuring amplitude, phase, frequency, and polarization with unprecedented signal-to-noise and orders-of-magnitude improvement in signal processing throughput per unit of power consumption. Combining RF A/D, D/A high precision and bandwidth performance and High speed FPGA's to readout arrayed superconducting sensors such as: Transition Edge Sensors TES, Kinetic Induction Detectors KID and superconducting bolometer systems with reduced the sensor size and will give us a better view of the universe.

Measurements of the extreme red shifted 21 cm (1420 MHz) hyperfine transition of neutral atomic hydrogen are helping researchers to explore the early Universe searching in the red shifted range of 10-500 MHz inferring times before the creation of stars where a homogenous mix of materials allow robust theoretical predictions to be tested. The IF7 RF white paper describes the sophisticated very low noise techniques that are required to achieve the necessary electronics noise levels. To achieve reasonable levels of detection, undistorted signal backgrounds can only be found locally on the far side of the moon. Multiple proposals are being developed with the objective of installing sensitive antennae and electronics there with lunar orbiting satellite relay stations. The results of these explorations will benefit the ongoing development of cosmological models and may be an indicator of new physics.

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8

Noble Element Detectors

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8.1 Executive Summary

Particle detectors making use of noble elements in gaseous, liquid, or solid phases are prevalent in neutrino and dark matter experiments and are also used to a lesser extent in collider-based particle physics experiments. These experiments take advantage of both the very large, ultra-pure volumes achievable and the variety of signal pathways available in noble targets. As these experiments seek to increase their sensitivity, novel and improved technologies will be needed to enhance the precision of their measurements and to broaden the reach of their physics programs. The priority research directions (PRDs) and thrusts identified in the 2019 Report of the Office of Science Workshop on Basic Research Needs for HEP Detector Research and Development (BRN report) [?] are still relevant in the context of this Snowmass 2021 topical group. The areas of R&D in noble element instrumentation that have been identified by the HEP community in the Snowmass whitepapers align well with the following BRN report PRDs:

- Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity
- Develop new modalities for signal detection
- Improve the understanding of detector microphysics and characterization to increase signal-to-noise and reconstruction fidelity
- Advance material purification and assay methods to increase sensitivity
- Address challenges in scaling technologies

This topical group identifies and documents recent developments and future needs for noble element detector technologies.

8.2 Enhancing existing modalities

Noble element detectors developed for neutrino physics and dark matter searches record mainly the charge from the ionization electrons and the light from the scintillation produced by the passage of charged particles through the medium. The technologies to read out the charge in neutrino experiments have mostly been based on wire readouts, such as ICARUS [?, ?], ArgoNeuT [?], MicroBooNE [?, ?], LArIAT [?], SBND [?], DUNE first far detector module [?], and EXO [?], while charge measurements in dark matter searches rely on gain mechanisms such as gas electroluminescence [] and proportional gain [] (Missing refs). To read out scintillation light, both neutrino and dark matter experiments have focused on the use of PMTs and SiPMs with coverage ranging from sub-percent to up to 50% levels.

It is clear that for the future, advances in charge and light detection capabilities are highly desirable, and to this end a range of new approaches have been proposed, discussed in more detail below.

8.2.1 Pixels

Although the concept of wire-based readout has been proven and has had wide usage in neutrino detectors [?, ?, ?], it has an intrinsic limitation in resolving ambiguities, resulting in potential failures of event reconstruction. In addition, the construction and mounting of massive anode plane assemblies to host thousands of finely spaced wires poses significant and costly engineering challenges. For these reasons, a non-projective readout presents many advantages, but the large number of readout channels and the low-power consumption requirements have posed conisderable challenges for applicability in liquid noble TPCs. The number of pixels compared to the number of corresponding sense wires will be two or three orders of magnitude higher for equal spatial resolution, with an analogous increase of the number of signal channels, data rates, and power dissipation. The endeavour to build a low-power pixel-based charge readout for use in LArTPCs has independently inspired the LArPix [?] and Q-Pix [?] consortia to pursue complimentary approaches to solving this problem.

There a several benefits of a native 3D readout for noble element TPCs. An intrinsic 3D readout offers an increased event reconstruction efficiency and purity, and the ability to accurately reconstruct final state topologies with greater detail, as shown in Ref. [?]. It was also demonstrated that a pixel-based readout has enhanced capabilities to reconstruct low-energy neutrino events ($\mathcal{O}(\leq 5)$ MeV) with improvements in overall data rates and signal fidelity [?] . Additional work is ongoing to fully explore the physics potential realized by a pixel-based noble element readout, but initial studies are promising.

The technical requirements for a pixel readout are broadly classified in terms of the readout noise, power, and reliability in a cryogenic environment. While the specifics are defined by their bespoke application, the general themes of power requirements include: < 10 W/m^2 average power with mm-scale pixels, ≤ 500 e$^-$ equivalent noise charge (ENC), and sub-% failure tolerance across a system with millions to billions of channels. Along with these requirements on the pixel electronics comes some on system reliability and scalability. Robust input/output (I/O) architectures are needed to faithfully bring the data from the large number of channels created by a pixel readout to a central data logger. While this challenge is not unique to pixel readouts, there is a particular demand on the readout architecture to not introduce any noise, since a low threshold is needed to achieve the sensitivity gains that pixels aim for (see below). To scale these devices up to larger experiments, groups must leverage commercial methods for mass production. This includes targeting ASIC and printed circuit board (PCB) manufacturing processes that are well-suited for low cost and high reliability. Furthermore, in order to detect scintillation light, chambers must be equipped with a light collection system sensitive to VUV light (128-175 nm), ideally to be integrated with the pixel plane [**?**, **?**].

As the pixel technology continues to mature, there is a drive to push the detection threshold limit to lower values. Future neutrino experiments aim to have enhanced sensitivity to supernova and solar neutrino events, which will require energy thresholds around, and potentially below, 1 MeV. Such lower thresholds could also allow for the application of pixel-based noble element TPCs to explore beyond-the-standard-model (BSM) physics, as well as for probing areas of low-threshold detection (e.g., dark matter and neutrinoless double beta decay) which have thus far been focused only on the use of the secondary scintillation light for charge readout. As the thresholds are lowered, new challenges arise in increasing the “dynamic range” of circuits and in ensuring that data rates stay manageable. The need to find and share common solutions within the community of researchers pursuing pixel-based readout for noble element TPCs is a key instrumentation challenge. Often arbitrary barriers due to various intellectual property concerns of the ASIC foundries cause multi-institutional collaborations to be difficult if not impossible, which slows the progress of R&D. Platforms such as the CERN R&D collaboration have found ways to overcome this and have been essential for delivering technologies used by the current generation of large high-energy physics experiments. The creation of a similar platform within the US would allow for the best ideas to come together into a final viable design with efficient use of available resources. This structure would greatly enhance cooperative technology development across multiple experiments.

8.2.2 Light collection

The information carried by photons is critical for a wide range of physics measurements in noble element–based detectors, providing a crucial means by which to perform detector triggering as well as position and energy reconstruction and identifying interactions of interest. It is essential to fully leverage this information in next-generation measurements, including neutrino interactions from low-energy coherent scattering (CEvNS) up to the GeV energy scale, neutrino astrophysics, and Beyond the Standard Model physics searches such as for low-mass dark matter and neutrinoless double beta decay. These efforts will require substantial (even as high as 100-fold) increases in light collection, to enable percent or sub-percent level energy resolution, mm-scale position resolution, low-energy detector readout triggering, and/or highly efficient particle identification, including for events around $\mathcal{O}(\leq 1)$ MeV (keV) energies in detectors at the 10 kton (100 ton) scale. In the context of the broader program of noble element detectors, enhancements in photon collection will lead to dramatic improvements in event reconstruction precision and particle identification, in a broader range of physics signatures afforded by lower trigger thresholds, and in precision timing to unlock new handles for beam-related events.

Measurement of the light signals, however, presents a major challenge with currently available technologies. For example, in large-scale liquid argon neutrino detectors, it is typical to collect <1% of the produced photons. This limitation is driven in large detectors by geometric considerations and other active components, total heat load, data volume, and the cost of instrumented surface area. The efficiency of the photodetectors and of the wavelength shifters used to convert VUV scintillation light to optical wavelengths for detection also play a role, as do the shortcomings of currently available devices such as noise, dark rate, and after-pulsing. In consideration of the very large scales of next-generation experiments — in both run time and target mass — significant R&D is needed to move beyond these limitations and enable the future physics program. While the overall needs are common across a wide range of physics goals, specific measurements will likely require a case-specific optimization of overall photon statistics, timing, and pulse shape discrimination performance. This demands a broad effort to develop a comprehensive and robust simulation of optical photon production, transport, and detection, including characterization of the optical properties of detector materials.

Several promising approaches to improving light collection can address one or more of the limitations noted above, and taken together, provide a set of complementary tools for next-generation experiments: photon collection efficiency may be improved by imaging a large volume on a small active detector surface using novel lensing technologies [**?**], deployment of reflective and wavelength-shifting passive surfaces [](Missing ref), bulk wavelength-shifting through dissolved dopants [](Missing ref), improvement of photon detectors [] (Missing ref) and photon transport efficiency [] (Missing ref), or the conversion of photons into ionization charge for readout using a TPC [**?**]. These strategies couple to many other elements of detector design and physics performance, including photon detector technologies, low-energy/low-background physics, simulation tools, and readout and data acquisition R&D. These approaches, implemented individually or in combination as optimized using a detailed microphysical simulation, will afford radical enhancements in the capabilities of future detectors, especially in the challenging low-energy regime near and below 1 MeV.

8.2.3 Extreme low thresholds (electron counting)

The lowest energy phenomena that can be studied with existing noble-element modalities, including low-mass dark matter, reactor neutrinos, and natural (e.g. solar) neutrinos, require detectors that are sensitive to single ionization electrons. Such detectors are sensitive to $\mathcal{O}(10\text{ eV})$ electronic recoils and $\mathcal{O}(100\text{ eV})$ nuclear recoils, but lack the scintillation-dependent nuclear and electronic recoil discrimination present at higher energies. Two-phase argon or xenon detectors, which achieve this sensitivity through gas-phase electroluminescence, are well developed for heavy WIMP searches, but their signal production mechanisms and backgrounds below $\mathcal{O}(\text{keV})$ need further investigation. Liquid neon deserves further investigation, with its intrinsic radiopurity and favorable kinematics for recoil energy transfer from light dark matter and low-energy neutrinos. A new class of compact $\mathcal{O}(100\text{ kg})$ low-threshold (sub-keV) noble element detectors will offer complementary physics opportunities to large (100 tonne) noble liquid detectors in dark matter and neutrino physics, while being competitive with other low-threshold detector technologies that are more difficult to scale up in target mass.

Without nuclear and electronic recoil discrimination, systematic backgrounds and radioactivity obscure typically background-free nuclear recoil event searches, and the radiopurity of detector materials, particularly photosensors, becomes critical. Better liquid or gas purification techniques (e.g. cryogenic distillation) drastically reduce beta and gamma backgrounds stemming from ^{3}H, ^{39}Ar, ^{85}Kr, and the ^{220,222}Rn decay chains. Cosmogenic activation rates must be further studied and considered for handling detector materials above ground. Beyond background particle interactions, high rates of single- and few-electron signals are observed. Such spurious electrons have defied clear explanation and appear related to charge build-up on surfaces or in unknown chemical interactions, among other potential effects [**?**, **?**, **?**, **?**, **?**, **?**]. Dedicated R&D is needed to better understand the sources of these backgrounds and to develop mitigation techniques. Fast and efficient gas purification, liquid purification technologies, cleaner alternative detector materials, and various electric field configurations must be explored to optimize signal measurement efficiency and reduce backgrounds. Electroluminescence in a single-phase noble element detector, either high-pressure gas [] (Missing ref) or liquid [] (Missing ref) , offers a thermodynamically simpler possibility for single-electron detection, without the hypothesized electron-trapping at the liquid-gas interface in two-phase LXe detectors.

The cross-cutting challenges in Sec. 8.5, including in- and ex-situ calibrations and development of doping schemes, are particularly relevant to single-electron-sensitive experiments. Validation of sensitivity below $\mathcal{O}(\text{keV})$, including measurements of new phenomena such as the Migdal effect [**?**, **?**], will require substantial effort developing new calibration sources and techniques. Doping, with noble or non-noble dopants, can both improve operation and increase the physics reach of single-electron-sensitive detectors by boosting ionization yield.

8.2.4 Charge gain

Lower detection thresholds in track-reconstructing detectors (where the electroluminescence techniques of the previous section are less useful) may be achievable through amplification of the ionization signal in the form of charge gain, typically achieved in the gaseous phase of argon and xenon detectors. Gas-phase charge gain without scintillation is well established, and used by the NEWS-G collaboration [**?**, **?**] to search for low-mass WIMP-like particles using spherical proportional counters (SPCs) filled with gases such as neon, methane, and helium. Multiple innovative methods are being developed to either enhance the capabilities of charge amplification in gaseous detectors (e.g. to achieve stable charge gain while retaining the primary scintillation channel) or to enable amplification directly in the liquid phase. Active R&D efforts on this front are described below.

Electron multiplication in liquid argon TPC detectors: Enabling charge amplification directly in liquid argon would expand the physics reach of liquid argon detectors, reducing thresholds to < 100 keV in energy and opening up new areas of research in processes such as dark matter and CEνNS searches. Achieving charge amplification in liquid is significantly more challenging than in gas due to the denser medium and higher electric field thus required. Past work on this idea [**?**, **?**, **?**, **?**], while promising, has not yet reached a level of maturity necessary to enable the technological advances needed for physics measurements. Benefits of direct amplification in liquid are a potentially improved detector stability (due to the lack of a gas-liquid surface) and detector scalability. Active R&D through the LArCADE program is exploring this possibility through the implementation of strong local electric fields with tip-arrays instrumented at the TPC's anode readout.

Scintillating and quenched gas mixtures for high-pressure gaseous TPCs: While there is a rich history of R&D in gaseous detector readout electronics, much remains to be understood and optimized at the high pressures and large scales sought by experiments. The realization of a stable, VUV-quenched gain, scintillation-compatible, 10-15 bar TPC remains elusive. Two main approaches are pursued to enable these objectives, distinguished by their scintillation wavelength range: infra-red and near-UV or visible readout. An ongoing program of R&D aims to systematically map the space of scintillating gas mixtures of argon with admixtures of xenon, nitrogen, hydrocarbons, and fluorinated compounds. The potential of new 'ad hoc' mixtures for pure and low-quenched gases also impacts the development of new ideas, for instance in DUNE's ND-GAr detector [**?**, **?**] where Ar-CF_4 is being considered as a scintillating gas for providing the start time (T_0). In such a case, the screening of the secondary scintillation impinging on the photosensor plane might be critical, something that a GEM (conveniently optimized) can provide. Further, independent measurements and calculations also suggest that stable scintillation on very thick structures (5-10 mm thick) is likely to be possible in liquid phase [**?**, **?**, **?**, **?**].

8.3 New modalities

As a detection medium, noble elements present unique opportunities beyond the collection of scintillation photons and ionized electrons. The modalities described in this section find new ways to utilize the monolithic, ultra-pure elemental detection medium provided by noble elements, extending the reach of noble-element-based detectors to new signal regimes and enabling new methods of background discrimination in rare event searches.

8.3.1 Ion Detection and Micron-scale Track Reconstruction

The ability to reconstruct ionization tracks at micron- and sub-micron spatial resolution is the key to many currently unsolved detector challenges, including directional dark matter detection ($\mathcal{O}(10^{-6}\text{g/cm}^2)$ spatial resolution required), discrimination of single-electron backgrounds in $0\nu\beta\beta$ searches ($\mathcal{O}(10^{-1}\text{g/cm}^2)$ spatial resolution required), and potentially for detection of supernova and solar neutrino events in very large-scale neutrino detectors ($\mathcal{O}$(sub-mm) spatial resolution required). Attempts at direct (TPC-style) high-resolution reconstruction universally rely on ion drift rather than electron drift to escape the resolution-limiting effects of electron diffusion over large drift distance. The drifting ions may be either positive ions of the target itself [?], or a positively or negatively ionized dopant [?, ?, ?]. Imaging the ion arrival on the cathode (or anode for negative ions) plane can also take many forms, including CCDs in gas phase detectors [?] and long-time-scale fluorescence activation by ions in liquid phase detectors [?]. Selective readout of the imaging plane is often a necessary component of the large-scale application of these techniques, due to both pileup and data throughput limitations. Selective readout may be directed by real-time "low-resolution" electron-drift-based imaging [?].

It may also be possible to sense ion tracks indirectly via their interaction with drifting electrons, and the corresponding impact on standard TPC observables. Columnar recombination models predict variation in relative ionization and scintillation yields based on the orientation a track with respect to the applied drift field. Several efforts are investigating the magnitude of this effect and how it may be applied for directional dark matter detection [?, ?], as well as its impact in high energy neutrino experiments [?].

Ion transport and detection is also a key consideration for barium tagging, a more direct approach to $0\nu\beta\beta$ background discrimination that seeks to identify the barium ions left behind by the double-beta decay of ^{136}Xe [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. There are several key instrumentation requirements for a workable barium tagging technology. First, the system must collect and detect barium ions or atoms with high efficiency and selectivity, since a significant level of inefficiency amounts to wasted exposure time of active isotope. The sensor must be uninhibited by spurious signals from ambient background atoms or ions. A detection limit of exactly one barium ion must be reached by the senor of choice, in the environment of the sensing region. The full fiducial volume of the detector must be accessible by the barium tagging system. A spatio-temporal coincidence between the ion collected and the electrons emitted in the event must be maintained. And, the barium tagging system must be realized in such a way that it does not introduce radio-impurity or compromise other key detector functions such as energy resolution. Detection of single Ba atoms and ions has now been demonstrated using several techniques, but continued R&D is needed to achieve and quantify the high efficiency and selectivity needed for a practical barium tagging application. Development of methods to transport / extract barium from ions or atoms in either LXe or GXe is a critical step, with ongoing work focused on radiofrequency carpets and funnels, actuated cryoprobe insertions, wide-area laser scanned cathodes, and ion mobile surfaces.

8.3.2 Metastable fluids

Metastable fluid detectors amplify the energy deposited in particle interactions with the stored free energy in a superheated or supercooled liquid target. That amplification can be made selective by matching the different energy-loss mechanisms and length scales for signal and background interactions with the relevant phase-change thermodynamics, for example allowing bubble chambers to detect $\mathcal{O}(1\text{ keV})$ nuclear recoils (e.g. from dark matter or coherent neutrino scattering) while being completely blind to electron recoil backgrounds. Instrumentation efforts in this area typically focus on (1) extending phase-change based discrimination to new signal regimes, and (2) improving control of spurious phase-change nucleation to enable larger quasi-background-free exposures.

While metastable fluid detectors are not restricted to noble elements, noble-liquid bubble chambers present unique opportunities. The addition of scintillation detection to a bubble chamber is a powerful tool for discriminating against high-energy bubble-nucleating backgrounds [?], and at the same time the limited energy-loss pathways available in a noble liquid target result in orders-of-magnitude improvements in low-energy (sub-keV) electron recoil discrimination [?]. The SBC Collaboration is actively developing the liquid-noble bubble chamber technique, with focus on three bubble chamber firsts: cryogenic operation of a large "clean" bubble chamber, stable superheating at $\mathcal{O}(100\text{ eV})$ thresholds, and precision nuclear recoil calibrations with $\mathcal{O}(10\text{ eV})$ resolution. The last of these will involve both the development of new low-energy nuclear recoil calibration schemes, such as Thomson scattering by high-energy gammas and nuclear recoils from gamma emission following thermal neutron capture, and the development of the analysis techniques needed to combine diverse calibration data to constrain nucleation thresholds at the required resolution.

Freon-filled bubble chambers, such as those operated by the PICO Collaboration [?], continue to play a key role in high-mass dark matter detection, enabling quasi-background-free nuclear recoil detection in targets with high spin-dependent and low spin-independent cross-sections. This allows the exploration of orders-of-magnitude more dark matter parameter space before reaching the "neutrino fog" than can be achieved in noble liquid targets, with strong physics motivation for freon bubble chambers out to kiloton-year exposures and beyond [?]. Those exposures cannot be achieved without the development of new bubble chamber designs that are more scalable than the current fused-silica chambers, while maintaining (or improving on) current chambers' low spurious nucleation rate. This requires studies of bubble nucleation on surfaces and new bubble-imaging methods (e.g. acoustic imaging), both of which directly benefit liquid-noble bubble chambers as well. Larger exposures will also require the development of active neutron vetos compatible with the bubble chamber environment.

A third application of metastable fluids is the detection of proton recoils in water, providing a light target with nearly pure spin-dependent coupling that is kinematically matched to low-mass dark matter. Water is a notoriously difficult fluid to use as a bubble chamber target, but Snowball chambers [?] sidestep this roadblock by supercooling the target rather than superheating it. An entirely new particle detection technology, Snowball chambers face the same instrumentation challenges as SBC and PICO: surface nucleation must be mitigated, and both the threshold and discrimination power of the technique must be calibrated.

Finally, there is renewed interest in accelerator-based bubble chamber experiments to measure neutrino cross sections on light nuclei [?]. While the requirements for these devices, including high delta-ray sensitivity and fast (>10-Hz) cycling, push in a different direction than the dark matter and CEvNS-motivated chambers, practical concerns including control algorithms, photography, and image analysis remain common between these efforts.

8.3.3 New modalities in existing noble-element detectors

It is highly desirable to find novel ways to take advantage of both the field-wide expertise that has developed around noble-element-based detectors and the world-class infrastructure surrounding existing and near-future searches for new physics. In general, after an experiment has achieved its scientific goals, the experimental community ideally will continue to leverage the infrastructure for future experiments. The simplest case of this general principle is perhaps that of upgrading an existing experiment. Previous examples include KamLAND => KamLAND-Zen, and the Darkside installation in the former Borexino CTF (Counting Test Facility). There are many liquid noble installations around the world that can lend themselves to this sort of upgrade. As one example, the DEAP-3600 experiment is currently undergoing hardware upgrades for improved background rejection with future potential uses of the experimental infrastructure after the science run including a sensitive assay of ^{42}Ar in underground argon or measurements of solar neutrinos.

Currently, new ideas for upgrades of the LZ detector [?], after it completes its scientific goals in ∼2027, are under development. The specific proposals are called HydroX and CrystaLiZe, both of which would benefit from leveraging the low-background installation with water tank shielding and liquid scintillator veto detectors, as well as the associated infrastructure. However, both would also require significant upgrades or modifications to the LZ inner detector.

HydroX - The idea behind HydroX is to dissolve a hydrogen target in LZ to enable searches for very light dark matter. Hydrogen is the ideal target for low-mass dark matter because it has the lowest atomic number of any element, and because its unpaired proton (and neutron in the case of deuterium) provides sensitivity to spin dependent couplings in the low mass range. As an upgrade for LZ, HydroX would leverage both the existing TPC (using xenon ionization and scintillation to detect proton recoils in LZ) and the major investment in the low background construction and radio-clean environment. Significant R&D is still required to demonstrate the viability of this idea, primarily measuring detector properties of H_2-doped liquid xenon, including the signal yields of proton, electron, and xenon recoils, and understanding the cryogenics of H-doped LXe. A HydroX-like upgrade could also be envisioned for next generation dark matter efforts.

CrystaLiZe - this is a proposal to crystallize the liquid xenon target of the LZ instrument. R&D is underway to demonstrate the feasibility of this plan. If implemented, this upgrade could enable full tagging of radon-chain beta decay backgrounds, enabling crystaLiZe to be a neutrino-limited (rather than radon-limited) dark matter search. As with HydroX, this path forward would leverage the LZ infrastructure after LZ completes its science goals. A fundamental premise of this proposal is that crystalline xenon will have "the same" TPC-style particle detection capability as liquid xenon. Preliminary work shows the scintillation yields are identical. Next steps intend to confirm that the incident particle type discrimination is also possible.

A key point is that HydroX and CrystaLiZe appear to be fundamentally compatible with each other, that is, one could imagine doping a light element into a crystalline xenon target.

8.4 Challenges in scaling technologies

Next-generation large-scale detectors are planned to search for dark matter and $0\nu\beta\beta$ and to study neutrinos from both artificial and natural sources. Achieving these goals generally requires (i) scaled-up target procurement and purification capabilities; (ii) large area photosensor development with low noise; (iii) high voltage and electric field capabilities compatible with multi-meter drifts; and (iv) studying the effects and techniques for operating large doped noble liquid/gas detectors. The discovery capabilities of these detectors could be extended further by coupling them with a magnetic field, such to enable charge discrimination and improve momentum measurement.

Concerning target procurement, argon detectors will need new sources of underground argon (UAr) to fill large LArTPCs (e.g. a DUNE low-background module would need 7–17 kt). Reduction of ^{39}Ar is expected to reach activities 1400 times lower than atmospheric argon (AAr), at a cost ∼3× that of AAr. Xenon detectors will need ∼100 t (and potentially up to kt-scales in the future) from commercial sources, representing ∼2 years of total annual output worldwide at costs which must be coordinated with vendors. Natural Xe has sufficiently low background for future searches, and a large target mass can be sold back, substantially reducing its cost below the upfront acquisition cost of \$1M/t. Isotopic separation can benefit rare event searches by separating out ^{136}Xe from the target (for $0\nu\beta\beta$-decay) and odd-neutron isotopes (^{129,131}Xe) reduced in ^{136}Xe for a DM search. However this will significantly impact the cost of the Xe.

Backgrounds generally need to be reduced to the $\mathcal{O}(1)$ event/exposure in the <200 keVnr energy range for dark matter searches and in the $\mathcal{O}$(MeV) range for neutrino experiments. This goal requires further radiopure detector development, including the identification of radiopure pressure vessels, cryostats, and photosensor materials. Significant progress has been made in low-background SiPM development, though Xe-sensitive SiPM systems (or Xe-compatible wavelength shifters) need to be improved (especially dark rates and effective QE of large area arrays) in order for Xe detectors to transition to PMTs to SiPMs. It is also necessary to reduce radioactive impurities in the target, and enrichment is needed for Xe-based $0\nu\beta\beta$ searches. Cryogenic distillation has come a long way in this regard, and UAr has been shown to have substantially lower ^{39}Ar contamination, and ^{42}Ar may be negligible. Larger sources of UAr will be needed for applications much larger than Argo (300 t) [] (Missing ref), and upgrades may be needed to Aria [] (Missing ref) to achieve a high throughput for similarly large volumes. Cosmogenic activation of radioisotopes is also a challenge; new measurements may be needed to improve activation calculations. Improved understanding of small isolated charge and light signals, whether originating from particle interactions, chemical interactions, or electrode surfaces, is also needed in order to address accidental-coincidence backgrounds in large TPCs.

Large-area photon and charge detection techniques and their associated readouts are also needed. For light detection, this includes (i) photosensor development with expanded light collection area and large-area wavelength shifters, (ii) development and production of low-background, low-noise cryogenic SiPMs, (iii) development of power-over fiber technology and low-power, high-multiplexing cold readout electronics for photodetection empowering high timing resolution, needed to achieve 4π light detection with high surface-coverage for 4D tracking and dual calorimetry in a LArTPC, improving the PID and energy resolution. For charge detection, the development of large-area and low-noise electron multipliers is important to detect small signals in large detectors.

Combining this lower detection threshold with a magnetic field in the range of 0.5 to 1 Tesla in the fourth DUNE module would allow for an effective measurement of momentum, charge discrimination, better energy resolution for hadron showers, improved particle identification and identification of the starting point of low energy electrons. This has the potential to add significance to the physics output of the overall observatory, for instance by improving the sensitivity to CP violation with atmospheric neutrinos by 50% [] (Missing ref). Since external conventional magnets are not suited for large volume cryogenic detectors, a robust R&D program is needed to evaluate alternatives based on superconducting magnets: these could range from warm superconductors requiring dedicated cryogenic infrastructure, such as MgB_2 to be operated at 15-20 K, to hot superconductors more directly integrable in the nitrogen cooling plant or directly in the liquid argon volume, such as YBCO that can be operated at the liquid nitrogen temperature of 77 K. LArTPC performance in the presence of a magnetic field are currently being studied in an R&D effort at Fermilab to determine minimum field requirements to achieve particle charge separation and study electron diffusion in the presence of the field. (Add reference for Marco's LDRD?)

Larger noble element TPCs require higher high voltages (HV). New HV feedthrough (FT) designs are needed for these larger areas. Successful R&D implementing a conventional HV FT was developed for the 4D-LArTPC DUNE module to obtain a homogeneous, vertical electric field of 500 V/cm over a 6.5 m drift with a 3x3m^2 anode plate [](Missing ref). Examples like this can be taken as a starting point to test and develop a new technology. A FT from a co-extruded multi-layer cable made of a single plastic material with an additional semi-resistive plastic layer between the insulation and ground can robustly and compactly deliver >100kV and generate electric fields within a detector. Such a cable can be manufactured by developing a semi-resistive plastic with tunable resistivity (between 107-1013 Ohm cm for a thickness of 0.3 to 1 mm).

While current dark matter and neutrino experiments have focused on pure, noble liquid targets (e.g argon and xenon), there is a significant interest in exploring the effects of doping liquid argon with xenon and other elements [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**]. These dopants are typically chosen for ease of light detection and increasing scintillation and ionization yields. At higher concentrations, dopants can also be favorable targets in their own right. For example, hydrogen or hydrogenous compounds doped in liquid xenon provide a light nucleus with more efficient kinematic coupling to light dark matter, and nuclei with an odd number of nucleons can add spin-dependent sensitivity. Further research is needed to develop the capacity for stable, large-scale, high-purity doping and to measure the effects on signal production and propagation.

8.5 Cross-Cutting Challenges

In order to be sensitive to a wide range of physics phenomena, we must be able to make accurate and precise measurements of charge, light, and/or heat, from interactions of interest within our detectors, which requires in turn, a good understanding of the inherent noise levels, calibrations, and microphysics associated with these gaseous and liquid noble detectors. The challenges therein are cross-cutting, touching many different areas of experimental physics. But this also means that we can take a wider view to leverage facilities that will benefit many experiments across multiple frontiers. This deep understanding of the detection characteristics and calibrations will be essential components of preparing next-generation gaseous/liquid noble detectors for cutting-edge physics measurements in both the Neutrino Frontier (NF) and Cosmic Frontier (CF). Relevant searches/measurements include dark matter searches, searches for neutrinoless double beta decay, coherent elastic neutrino-nucleus scattering measurements, probing neutrino oscillations for measurements of leptonic CP violation and other PMNS matrix parameters, measurements of supernova/solar neutrinos, and searches for proton decay and other forms of baryon number violation.

8.5.1 In-situ calibrations

Looking toward the next generation of HEP experiments, there are a variety of requirements for instrumentation and calibration methodology in ensuring accurate and precise measurements of charge and light in detectors making use of noble elements, such as argon or xenon. First, it should be noted that both electron recoils and sub-keV nuclear recoils in xenon and argon are of interest, as the full range of relevant experiments collectively probe both types of recoils. Lower detector energy thresholds, both in the bulk liquid and at the liquid-gas interface for two-phase (liquid target with gas phase for signal gain) technology, are needed to pursue the physics measurements described above. Establishing measurements of noble element properties (e.g., diffusion and electron-ion recombination) to sufficient levels prior to running large, next-generation noble element detectors is necessary, given that these experiments may not be able to make these measurements in situ. This includes addressing effects related to self-organized criticality and other dynamic effects at low energies arising from the interplay of condensed matter and chemical interactions in noble liquid detectors, such as accumulations/releases of excitation energy and Wigner crystallization, which are potential backgrounds in rare event searches.

Many challenges exist in pursuing the precise calibration of charge and light measurements in next-generation noble element experiments. Greater background reduction at lower recoil energies is a significant challenge. Increasing light collection and quantum efficiencies well beyond current levels, in order to achieve lower energy thresholds and improve energy resolution, is a difficult problem. A variety of improvements are needed to increase light and charge collection efficiencies in liquid argon/xenon, including improving impurity modeling, purification methods, mitigation and accounting for material degassing, and estimating electron attachment rates for impurities. There are also currently significant uncertainties concerning how non-linear detector response becomes at the lowest recoil energies relevant to low-mass dark matter searches and coherent neutrino observations. While the development of atom-level simulations of charge and light yields (such as those being pursued by NEST [] (Missing ref)) to improve modeling for noble element detectors will help address this challenge, better particle and detector models are needed to extract more information from data. Additionally, training the next generation of physicists to become experts in noble detector characterization/microphysics requires funding agencies to support continued work on detector calibrations as a foundational part of physics research; this will further develop the workforce necessary to enable the physics measurements of interest at relevant experiments. Finally, given the connections between condensed matter and nuclear physics effects and their manifestation in HEP detectors, it is important to improve the communication between the BES, NP, and HEP communities on these cross-cutting topics, which is currently lacking.

8.5.2 Ex-situ detector characterization, facilities

Flexible user facilities (not tied to any particular group nor experiment) with both charge and light readout and fast turnaround time can promote noble element property measurements in cases where in situ measurements are insufficient. Such facilities would also allow for prototyping calibration equipment designed for large detectors in smaller test beds, and would minimize duplication of efforts by providing community-wide resources to benefit multiple research efforts. Existing successful examples include the Fermilab Test Beam Facility [] (Missing ref), and the Liquid Noble Test Facility [] at Fermilab. (check name) https://neutrinophysics.fnal.gov/facilities/liquid-argon-facilities/.

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9

Cross-cutting Themes in Support of Detector R&D

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(contributors from the community)

9.1 Major Messages from the Cross-cutting Frontier

- IF09-1: Presently US funding for advanced detector R&D is institute-based rather than collaboration-based. Yet collaborations are more essential than ever to leadership in detector RD technology. To a significant extent, funding constraints have limited the opportunity to establish significant collaborative detector R&D programs. We recommend that funding for the KA-25 Detector R&D program should be increased significantly (2X-5X) to enable establishment of collaborative R&D programs to address Grand Challenges and pursue blue-sky concepts.

- IF09-2: Both retention of key experts (institutional memory) and workforce development are critical to detector R&D. Recent "DOE traineeship in high energy physics instrumentation" is a step in the right direction and should continue. However, this focuses on the physicists while the instrumentation enterprise relies on a large set of uniquely skilled supporting players - mechanical and electrical engineers, composites designers/fabricators, device physicists, chemists, materials scientists and technicians. Development of the next generation of all of these experts is vital. We recommend that funding for key technical personnel essential to these capabilities be considered on equal footing with the physicists.

- IF09-3: Innovative instrumentation research is one of the defining characteristics of the field of particle physics. Blue-sky developments in particle physics have often been of broader application and had immense societal benefit. It is essential that adequate resources be provided to support more speculative blue-sky R&D. One difficulty in the existing funding system is comparative review of incremental and blue-sky proposals. A separate funding opportunity and review process for blue-sky proposals could lead to more innovative R&D activity.

- IF09-4: New R&D frameworks could enhance development: examples are the very successful CERN RD collaborations and NNSA NA-20 consortia. LAPPD development was a HEP example that worked like that, but that has not been the detector R&D typical model. The ECFA Detector Roadmap (2021) recommended establishing six new RD Collaborations. The U.S. should engage broadly and deeply to shape these global instrumentation RD collaborations. We recommend the U.S. HEP community establish a robust collaborative research program that includes both participation in the international RD collaborations and establishing domestic detector R&D consortia.

- IF09-5: Facilities (mainly at national labs) are a vital element of detector technology development and should be supported. Present gaps that could be strengthened include: high quality electron test beams, multi-TeV test beams, user access to low temperature facilities covering liquid nobles down to mK, low noise including vibration, RF, and radioactive/cosmics, high dose irradiation, and foundry access for radiation hard microelectronics, semiconductors detectors, and superconducting devices for both development and production. What is the ask or recommendation?
- IF09-6: Multidisciplinary problems are prevalent in many areas of instrumentation development. The topic of multidisciplinary RD was explored in the MultiHEP 2020 workshop, held virtually on Nov. 9-12, 2020. Multidisciplinary work has funding, recruiting, and career development challenges that new R&D frameworks could alleviate. What is the ask or recommendation?
- IF09-7: Several themes that cut across multiple Instrumentation Frontier working groups were identified. The community should find ways to share expertise, tools, and developments in these areas: fast timing, cryogenic operation, and the need to solve challenging Materials Science/Chemistry problems. What is the ask or recommendation?

9.2 Facilities

In this section we focus on gaps or potential gaps in facilities needed for the next decade of advanced detector development. Underground and low background (radioactivity) facilities are discussed in the Underground Facilities (UF) section of this report.

There are many existing facilities (9-1) and capabilities which will not be discussed below, including carbon fiber structures (FNAL, LBNL), thin films (FNAL), superconducting device design/fab (ANL, LBNL, MITLL), CCD design/fab (LBNL, MITLL), low background materials and assay at PNNL, WbLS at BNL, silicon detector facilities (FNAL, ANL, BNL, LBNL), LAr facilities (FNAL, SLAC) etc.

we would like to be comprehensive so if we are missing your favorite facility please provide that for the list

9.2.1 Calibration and Test Beam Facilities

Progress in particle physics depends on a multitude of unique facilities and capabilities that enable the advancement of detector technologies. Among these are test beams and irradiation facilities, which allow users to test the performance and lifetime of their detectors under realistic conditions. Test beam facilities are particularly important for collider and neutrino detector applications, while irradiation facilities are crucial for collider as well as some space-based astro particle detectors. In the area of irradiation facilities overlapping needs between detector and accelerator instrumentation as well as targetry development can be addressed.

To establish the global status of calibration and test beam facilities: *The Snowmass IF09 Test and Calibration Beams and Irradiation Facilities workshop* was held virtually on Nov. 30, 2021 [1]. Following on from the workshop a group of IF members authored a Snowmass white paper [2] providing a useful summary and developed the need and proposals for future facilities.

As summarized in the recent report on Basic Research Needs for High Energy Physics Detector Research and Development [177], future particle accelerator-based experiments will experience unprecedented radiation exposures of 10 GigaGray ionizing dose, and fluences of 10^{18} 1 MeV neq/cm^2 over their lifetimes. Detectors,

Lithography Etching Film Deposition CCD Wafer

Figure 9-1. *Advanced detector development facilities within the U.S. HEP complex. Upper right: the Fermilab test beam facility; upper left the U.C. Davis reactor; middle row low bavkground facilities at PNNL including copper electroforming, materials handling and ebeam welding; lower row the Microsystems lab at LBNL.*

support structures, electronics, data transmission components, and on-board data processing units will all need to be evaluated for performance at these dose rates and integrated doses two orders of magnitude greater than systems operating today. This will require new high-dose-rate environments for accelerated testing so that the anticipated integrated dose can be delivered in days rather than months or years. Activation of the detector materials will limit facility throughput unless remote material handling techniques are implemented. Such techniques are already employed for irradiation and post irradiation evaluation of accelerator components and for targets and windows for neutrino beam lines.

A broad array of test beam capabilities are also required to develop the next generation of detectors for tracking, calorimetry, and particle identification. In particular, access to beams of different particle species at a wide range of energies is critical to test the response and performance of different detector technologies, where well-calibrated instrumentation such as trigger hodoscopes, tracking telescopes, and Cherenkov detectors is often required to analyze and understand the performance of the device under test. Meanwhile, some of the capabilities being pursued for next-generation detectors place stringent demands on test beam time structure. For example, testing detector performance at high event rate and extreme (ps-scale) time resolution require test beams with high repetition rate and extremely short pulses, respectively. The BRN report [177] calls for "a significant revitalization of U.S. [test beam] facilities...to enable the detailed tests required" and highlights very precise test beams (in multiple dimensions — spatial, energy spread, timing, and intensity) as an important area where U.S.-based facilities can play a world-leading role.

Meeting the needs of this diverse community motivates the support of a variety of test beams, with different features and capabilities, across the DOE complex as well as the use of international facilities. The whitepaper [2] surveys test-beam needs within the HEP instrumentation community and describes several opportunities for new facilities, improvements to existing test-beams, and detector test platforms that will provide essential and mutually complementary support for instrumentation development. Prospects include: plans and applications for a high-intensity proton irradiation facility at Fermilab; a new facility with improved infrastructure for test beam experiments at Fermilab (FTBF); a new multi-purpose electron beamline at SLAC capable of delivering high repetition rates and short pulses with precise, flexible timing for test beam applications; and the Water Cherenkov Test Experiment (WCTE) at CERN. Further into the future in anticipation of new accelerators at the high energy frontier multi-TeV test beams will be necessary.

9.2.2 Low Noise and Environmentally Stable Facilities

The particle physics community relies on a variety of specialized environmental conditions for operation of the most sensitive instrumentation. These include low vibration/geologically quite environments, low electromagnetic interference environments, low radioactive background environments, and cryogenic environments to suppress thermal noise. Low radioactivity environments are discussed in the Underground Facilities section of this report [**?**]. Environmentally stable facilities, i.e. low vibration and/or low electromagnetic interference, tend to be very specialized for specific equipment (e.g. isolating a a laser system or NMR) or to suppress specific frequency bands (seismic or electromagnetic) making it difficult to define the requirements for a general purpose user facility. In addition,these facilities are generally within the reach of individual research groups to establish locally as needed.

9.2.3 Cryogenic Test Facilities

Cryogenic test facilities are critical infrastructure for physics experiments in a variety of fields [4]. Some notable examples include studying noble liquid properties for particle detection, low-temperature device development, and research in quantum information. The required technical knowledge and infrastructure capacity, including the cost of setting up and operating the test facilities, can place them out of reach of many individual group research groups. As such, these research areas would greatly benefit from centralized user facilities.cryogenic test facilities can require significant investments in infrastructure and ongoing operations costs, and warrant consideration of the development of national user facilities. The remainder of this section discusses the opportunities/needs for both liquid argon and milli-Kelvin temperature test facilities.

9.2.3.1 Liquid Argon Test Facilities

Several international institutions have established LAr test stands typically for specific purposes or experiments with limited measurement capabilities and access to the community. Some relatively large-sized facilities (more than 100 liters of LAr) include the ICARUS ∼ 50 liter LArTPC at CERN [3] with ∼ 250 liter LAr capacity, which is mainly used for ICARUS and DUNE detector's electronics readout studies; the ArgonCube detector [5] at University of Bern with ∼ 1100 liter LAr capacity, which is dedicated for pixel readout in LAr and DUNE's modular detector study; and the Integrated Cryostat and Electronics Built for Experimental Research Goals (ICEBERG) at Fermilab with ∼ 3000 liter LAr capability, which is dedicated to DUNE cold electronics studies. As can be seen, these facilities are typically tied to the specific tasks that are not easily accessible as a user facility with the general purpose of R&D, such as testing new devices and detector designs, studying noble liquid property, calibrating detector signal response, or studying light detector performance, etc.

The necessary initial components for such a LAr test facility include a large cryostat with sufficient volume and drift distance, adequate cryogenic infrastructure for condensing and gas circulation, a purification system to remove impurities with high electron attachment, a purity monitoring system with gas analyzers, basic high voltage system and readout electronics for TPC measurements, a photon detection system to study scintillation light, and the accompanying DAQ system.

Two existing facilities in the complex can potential fulfil the communities needs. These are the Noble Liquid Test Facility (NLTF) at Fermilab and the Liquid Noble Test Facility (LNTF) at SLAC. Thge former is a user facility funded by KA-25 while the latter was initially built for prototyping and testing components and processes for the LUX-ZEPLIN (LZ) dark matter project. At present, the LNTF supports R&D projects for the DUNE Near Detector, LZ upgrades (HydroX and Rn reduction via chromatography), and nEXO (Rn reduction via distillation).

9.2.3.2 Milli-Kelvin Test Facilities

The operation of sensors and systems at ultra-low temperature is a major growth field, but one which necessarily has a high barrier for entry due to the relatively high cost of equipment, not just for the cooling platform itself but also associated measurement equipment and electronics and a knowledge gap in the operation and engineering of devices and systems at cryogenic temperatures. In addition, the typical fabrication, measurement and analysis cycle associated with the development of cryogenic devices will often mean that test stands can be idle for considerable periods of time, making the economics of every PI or research group having dedicated research facilities economically unattractive.

The establishment of a centralized facility would democratize the process of device development by allowing users access to test stands and measurement equipment for a variety of different tests, including but not limited to thermal, RF and low frequency tests. This is particularly valuable at the pre-proposal and proof-of-concept stages to validate new ideas before committing to full proposals or the expense of purchasing dedicated test equipment. In addition, such a facility would serve as a repository of knowledge of low temperature materials and other specialized information and offer a medium to connect researchers with specialized cryogenic engineering resources. Finally, such a facility is a vital tool for training a future workforce by providing hands-on experience in the operation of cryogenic systems and measurement equipment, typically outside the ability of a University level teaching laboratory to provide.

Such a facility would necessarily consist of more than a single refrigerator test stand, since this is something that a well-equipped PI laboratory would be able to provide. Instead, it is envisaged that the proposed User Facility would provide a suite of test stands available for different experiment types, including a number of test stands providing environments for the testing of specialized devices such underground/low background environments, test stands with optical access, and stands incorporating magnetic fields.

An initial set of capabilities for the facility would be as follows:

- DC measurements with optional optical access
- RF measurements with optional optical access
- DC and RF measurements in the presence of a magnetic field
- DC and RF measurements in a low-background (underground)environment
- Fast-turnaround with minimal DC and RF screening capabilities
- Platform for training of operators

To satisfy these capabilities, a minimum of 4 medium-frame fridges (with 300 mm diameter cold volume) and 2 small-frame fridges (with 150 mm cold volumes) would be advantageous. In addition to the test stands themselves, a set of common measurement electronics covering the DC and RF frequency ranges would be required. In particular, modern RF measurement equipment such as network analyzers and signal generators, can easily double the cost of a functional measurement setup.

It is envisaged that a user access model similar to that of existing facilities would be adopted in which potential users will apply for time using a simple proposal system defining the type of payload and measurement desired. The motivation of the facility is to promote proof-of-concept and pre-proposal projects. It is expected that Users will be required to pay nominal fees for access to the facility in order to support Operations, with rates determined by the affiliation of the User (for example, commercial Users would be required to pay a higher rate for time than an academic User).

9.2.4 Semiconductor and Superconductor Foundry Access

HEP experiments rely on semiconductor foundry access for production of custom sensors and electronics. Semiconducting sensors include silicon sensors (strips/pixels, MAPS etc.), CCD/CMOS imagers, silicon and germanium bolometers, and various microwave sensors (TES, MKID etc.). Specialized HEP electronics typically take the form of ASICs, often operating in atypical environments including high radiation dose areas and at cryogenic temperatures, but also include devices incorporating superconducting (SC) materials

(SQUIDS, Qubits), and III-V semiconductors (e.g. HEMT amplifiers). Looking further ahead, new processor technologies for on-board trigger and data acquisition for high rate experiments may require purpose-built microelectronics. Access to foundry services has been essential for progress in detector development for HEP over the past three decades and will be increasingly important as channel density and rates increase and environmental conditions become more challenging.

By semiconductor foundry standards HEP is a small volume, high mix (SVHM) customer. One of the mainstays for access to foundries by the HEP community has been the MOSIS Service, operated by USC. MOSIS, founded in 1981, provides access to state-of-the-art (SOTA) and state-of-the-practice (SOTP) foundry processes at nodes from 500nm down to 12nm using Multi-Project Wafer (MPW) runs so that multiple parties can share the cost of mask sets and wafer processing during prototyping. It should be noted that while MOSIS provides good access to SOTA CMOS processes, it does not provide access to other important processes such as III-V, SC, specialty back end of line (BEOL) processing such as back thinning and thin entrance windows, or integration (2.5D and 3D). In many cases "prototype" runs, which can produce 500-2000 die, are sufficient to support small to mid-sized HEP experiment needs. For larger experiments, a dedicated "engineering run" typically suffices.

The HEP community needs to maintain access to both SOTA and SOTP CMOS foundry processes. Access not only includes wafer processing, but access to design tools and data products - IP blocks, Process Design Kits, device performance data etc. In addition to CMOS electronics, foundry access is needed for other silicon devices such as CCDs that require somewhat different processing. For CCDs LBNL has successfully transferred the technology to a new commercial vendor, Microchip, to replace DALSA when they elected to no longer produce these detectors.

Superconducting sensors are a key enabling technology for many HEP experiments with advances in sensor capabilities leading directly to expanded science reach. The unique materials and processes required for the fabrication of these sensors makes commercial sourcing impractical in comparison with semiconducting devices. Consequently, the development and fabrication of new sensors are often performed at academic cleanrooms supported through HEP basic detector research and/or project funds. While this operational model has been successful to date, we are at a turning point in the history of superconducting electronics, as evidenced by the rapid growth in the field of quantum computing, when scale and sophistication of these sensors can lead to significant progress. In order to achieve this progress and meet the needs of the next generations of HEP experiments, it is necessary to broadly support all stages of the superconducting sensors development and to support a dedicated facility for this technology that is focused on HEP applications (with broader connections to non-HEP needs and industry).

9.2.5 TDAQ Facility

The creation of a dedicated (distributed) R&D facility that can be used to emulate detectors and TDAQ systems, offers opportunities for integration testing (including low- and high-level triggering, data readout, data aggregation and reduction, networking, and storage), and developing and maintaining an accessible knowledge-base that crosses experiment/project boundaries."

9.3 Collaboration and Workforce Development

9.3.1 Collaborative research models

The U.S. HEP model for these has been to base facilities/core capabilities at national labs as user facilities funded by KA-25. Alternative approaches might be considered based on models such as the the CERN RD research programs or the NNSA NA-20 research consortia. The CERN RD programs provide an organizational framework within which collaborative research is conducted, but provide no direct funding support. However, engagement in these RD programs often provides a strong argument for grant funding to support participation. In contrast, the NA-20 research consortia are multi-year multi-institutional research proposals with funding provided to the university groups and an expectation of support from national laboratories already funded by the office. In both cases, the intent is to build 5+ year programs of research to address larger programmatic ambitions than individual institutions could tackle.The HEP investment in LAPPDs was to a large extent such a program.

Recently both the DOE Instrumentation BRN [177] and the ECFA Detector Roadmap (2021) [8] noted the inherent value of the CERN RD collaborations to instrumentation R&D. The latter recommended the strengthening of existing RD collaborations and the creation of new ones in Calorimetry, Photo Sensors PID, Liquid Detectors and Quantum Sensing. These RD Collaborations are proposed to be global in extent and could be hosted by labs around the world. This plan has been approved by CERN Council and ECFA have been charged with its implementation over the next several year. We recommend the US HEP community engage broadly and early to help shape the global Detector RD collaborations being established by ECFA and benefit from them.

Funding constraints in the U.S. instrumentation R&D program limit the ability to establish detector RD consortia. **We recommend a significant increase in funding to enable DOE-HEP to establish a funding mechanism for collaborative/consortium funding.** It should be understood that these research consortia will be multidisciplinary in nature and must include funding for scientists and engineers outside of physics.

9.3.2 Working with industry

There were numerous reports about successful SBIR efforts. The SBIR program offers a good path to fund multidisciplinary development by partnering with an appropriate firm. True partnerships between HEP scientists and firms are essential for success. An issue with SBIR is that many technologies critical for HEP do not have a lucrative commercialization path, but SBIR requires commercialization as the end product of Phase 2. Even when commercialization is in principle possible, there is a large gap between phase 2 and volume production for profit. It is difficult for small companies to bridge that gap. In addition, some technology areas, notable semiconductor manufacturing, are not well suited to small business and there are very few mechanisms for engagement with mid-scale and large industrial partners.

9.3.3 Multidisciplinary research

The topic of multidisciplinary R&D was explored in the MultiHEP 2020 workshop, held virtually on Nov. 9-12, 2020 [6]. This consisted of a series of invited presentations and panel discussions to collect experience on successes, challenges, and lessons about multi-disciplinary collaborations to further High Energy Physics RD. The focus is on HEP developments that make use of expertise from outside HEP through collaborative efforts. R&D disciplines explored included chemistry, materials science, nuclear science, micro and nano fabrication. Examples included small efforts at universities, projects at labs, work with industry through SBIR and otherwise, long-term multi-institute development such as LAPPD [7], and agency experience. The workshop panel discussions identified relevant points in the categories working with other fields, working with industry, and multidisciplinary personnel and funding.

Working with other fields Development of new instrumentation is often only possible through expertise and capabilities from outside HEP. Examples at the workshop were LAPPD, barium tagging for $0\nu\beta\beta$ decay, use of carbon nanotubes for photon detection, etc. The following observations were collected:

- Informal discussions are required to establish work scope for reasons summarized as “because you don’t know what you don’t know’. Another element of initial discussions is developing a common understanding of terminology and language.
- Some interest in the HEP goals is more important than expert standing in another field.
- Research philosophy is different in other fields. In HEP negative results are a success (most HEP results are negative!) Other fields have narrowly defined goals and positive results are the measure of success. In addition, timelines for results are typically much shorter, often within a 3-year grant cycle.
- Publication approach is different in other fields. No preprints: scoops common so results remain secret till published. Publications are geared to the next funding proposal. Author lists are small. It’s a good idea to have agreements formalizing collaboration, funding, author lists etc. after initial informal discussions.

Connecting with the right company is a challenge. Networking efforts can help. NP holds an annual exchange meeting for this purpose. Some national labs have industry days, but not regularly or at the same level. BNL has a discovery park incubator.

For multidisciplinary work there may be co-founding opportunities. Each office has to allocate and spend the required SBIR levels and this leads to roundoff errors becasue each office has to spend down an exact amount. This would allows NP to co-fund something with HEP, for example.

Multidiscpiplinary personnel and funding

- Few institutes train people in multiple disciplines at once. It is therefore hard to recruit people to carry out multidisciplinary work.
- The other side of the coin is that a student or postdoc developing in two disciplines at once may have a hard time finding the next job, because they will not be competitive in either one of these disciplines with peers who devoted themselves fully to it. They need to find a job where both disciplines are required.

- Funding agency offices tend to not like paying for personnel normally under other offices, which makes it hard to find multidisciplinary work with a single grant. Recent QIS and Micrelectronics FOAs have aimed at multidisciplinary work. Microelectronics has been more successful because (unusually) multiple offices co-funded the same FOA, while this was not the case for QIS, where each office had separate FOAs. More funding like Microelectronics is needed if fostering multidisciplinary work is desired.

9.3.4 Workforce development for instrumentation

The instrumentation workforce includes not only the physicists making the connections to the particle physics science mission, but the world-class scientists from other disciplines and the uniquely skilled technical staff that make the enterprise a success. Engaging with world-class scientists from other disciplines requires not only funding, but rewards and recognition commensurate with their contributions to the success of the HEP program. This extends to the technical staff without whom no major detector program could be realized.

There are two cultural hurdles that need to be addressed. The first is embracing scientists from other disciplines as equals. The second is the issue that both the scientists from other disciplines and the technical staff are funded primarily from soft funding streams (e.g. projects). This makes it very difficult to sustain staff expertise through lulls between major construction projects and makes these positions less attractive than comparable positions in industry that typically also come with greater financial compensation. Establishing a set of hard funding opportunities that allow for key technical positions to be funded as career opportunities could attract more highly qualified candidates for these vital roles.

9.4 Blue Sky research and tackling Grand Challenges in instrumentation

Innovative instrumentation research is one of the defining characteristics of the field of particle physics. "Blue-sky" research is defined as highly innovative research that does not have a predefined application. In contrast, Grand Challenges have a defined goal but are transformational rather than incremental in nature. The Detector BRN defines a number of Grand Challenges for instrumentation.

In particle physics these RD activities have often been of broader application and had immense societal benefit. Examples include: the development of the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science. It is essential that adequate resources be provided to support more speculative "Blue-Sky" R&D which can be riskier in terms of immediate benefits but can bring significant and potentially transformational returns if successful both to particle physics (discovering new physics may only be possible by developing novel technologies) and to society.

9.5 Cross cutting themes

Several themes that cut across multiple Instrumentation Frontier working groups were identified. The community should find ways to share expertise, tools, and developments in these areas: fast timing, cryogenic operation, and the need to solve challenging Materials Science/ Chemistry problems.

Should we add details here?

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10

Radio Detection

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10.1 IF 10: Executive Summary

High energy astroparticle and neutrino detectors use large volumes of a naturally occurring suitable dielectric: the Earth's atmosphere and large volumes of cold ice as available in polar regions. The radio detection of cosmic rays and neutrinos has emerged as the technology of choice at highest energies. The detection technology has matured in the past decade and as ready to move beyond prototyping or midscale applications. Instrumentation for radio detection has reached a maturity for science scale detectors. The optical technique has already been successfully implemented in large scale detectors in ice (IceCube), and efforts are projects underway to apply them in large scale in water (km3NeT, Baikal-GVD). IceCube is preparing an upgrade that will increase the sensitivity by a factor of 5 to 10 driven by optical detectors and by 2 orders of magnitude driven by the radio detection technique (E $>$ 100 PeV) The option to detect earth-skimming neutrinos with optical Cherenkov telescopes is being explored.

- IF10-1 IceCube-Gen2 (IceCube-Gen2 [1] has developed a conceptual design that will be released as a Technical Design Report later this year. Further investment in RD can potentially reduce cost and optimize design.
- IF10-2 Opportunities exist in optimizing for power and simplifications: eg ASIC based digitizer/readout (PMT) or RFSoC (Radio Frequency System on Chip). Investigate if synergies with experimental needs in other areas exist.
- IF10-3 Remote power and communications approaches of very large extended arrays can still benefit from dedicated RD. Explore synergies with other experiments, like DUNE, SKA, CTA, which also need large distance communication and synchronization.

10.2 Radio detection of cosmic particles

The optical Cherenkov technique has been enormously successful in measuring neutrinos from $\mathcal{O}(\mathrm{MeV})$ to $\mathcal{O}(10\,\mathrm{PeV})$, and there is no alternative to it in this energy range. At higher energies techniques at radio frequencies are the most promising to achieve that. For the medium, like in the optical, the two options being pursued broadly are the atmosphere and solid natural ice with emphasis on neutrinos. Both can be used to pursue science with cosmic rays, energetic neutrinos, or both. Above about 100 PeV, volumes of the $\sim$100 to

$1000\,\mathrm{km}^3$ scale, which can only be naturally occurring, are necessary to detect the rare astrophysical neutrino flux in this regime. Volumes of this scale are too large to instrument with the tens-of-km spacing necessary for optical sensors. This spacing is set by the distance over which optical light is absorbed or scattered in the glacial ice that is used as the detection medium. However, clear ice is transparent to radio-frequency signals over distances of order 1 km, which sets the typical spacing for detectors using radio techniques.

Astrophysical neutrinos are excellent probes of astroparticle physics and high-energy physics [6]. High-energy and ultra- high-energy neutrinos probe fundamental physics from the TeV scale to the EeV scale and beyond.

There are many different approaches to the detection of neutrinos at radio frequencies [4]. These approaches, the instrumentation that is unique and common to each, and future developments are described in this section.

In the energy range from 10 TeV to 30 PeV a factor of 5 in increase of sensitivity is needed in order to move from the discovery of cosmic neutrinos and the first correlation with sources to identify the sources of the cosmic neutrino flux and explore fundamental physics with high energy neutrinos. An integrated facility for a wide band neutrino detector is IceCube-Gen2 that will employ both optical and radio detectors.

10.2.1 Askaryan

In dense media such as ice, particle cascades induced by neutrino interactions produce Askaryan emission, which peaks at the Cherenkov angle, about 57° in deep ice. The emission comes about from the time evolution of a charge asymmetry that develops in the neutrino-induced particle cascade. Askaryan emission was measured in test beam experiments in the early 2000's. It is coherent for frequencies up to about 1 GHz when viewed at the Cherenkov angle and is linearly polarized. Now, many experiments are searching for this signature from ultra-high energy neutrino interactions either from within the ice or by viewing ice from altitude.

10.2.1.1 In-ice

One approach to detecting neutrinos via the Askaryan signature is by embedding antennas into the ice itself, and the first experiment to take this approach was RICE. Since then, ARIANNA, ARA, and RNO-G [11] search for ultra-high energy neutrinos with antennas deployed in the ice, either at shallow depths (within $\sim$10 m of the surface) or deep (up to 200 m).

IceCube-Gen2 [7]

10.2.1.2 Balloon

Another approach to detecting the Askaryan signature from ultra-high energy neutrinos is to deploy antennas on a balloon-borne payload at stratospheric altitudes where the payload can view approximately 1.5 million km^2 of ice. The ANITA project flew four times under NASA's long-duration balloon program, and the next-generation PUEO [8] is set to launch in the 2024-2025 Austral summer season.

10.3 Geomagnetic emission

A cosmic ray incident on the atmosphere will produce a particle cascade, and charges in the cascade produce a transverse current due to the earth's magnetic field, which produces what is known as geomagnetic emission at radio frequencies (up to about 1 GHz).

10.3.1 Radio detection of cosmic rays

In addition to the traditional strategies for detecting high energy cosmic rays incident on the atmosphere, which include detection of secondary particles, optical Cherenkov emission, and fluorescence emission, geomagnetic emission is a strategy that complements the others and has seen major advancements in the past two decades [9]. Radio detection of cosmic rays has a round-the-clock duty cycle and leaves a broad ($\sim 100\,\mathrm{m}$) footprint on the ground.

10.3.2 Detection of neutrino-induced, earth-skimming air showers

The geomagnetic signature can also be used to detect air showers that can originate from energetic neutrinos that are earth skimming and tau flavor [2]. These can produce a tau lepton through a charged current interaction in dense matter, and the tau can subsequently decay to produce an electromagnetic or hadronic shower.

The pulses emitted from air showers are dominated by the geomagnetic effect, that is the transverse current that develops as the shower develops and particles deviate in the direction of the cross product of the shower direction and the Earth's magnetic field. The polarization is parallel to the transverse current and its amplitude scales with the amplitude of the component of the B-field transverse to the shower direction. The chosen frequency bands are also constrained by background noise and therefore site dependent, a common band for air shower arrays being 30-80 MHz.

The detection of pulses consistent with air showers going in the upward direction has the advantage of being flavor sensitive, and has become an objective of many detectors. BEACON [10], in prototype phase, TAROGE, and TAROGE-M are compact antenna arrays in elevated locations that aim to detect UHE ν_τ emerging upwards via the radio emission of the air showers that they trigger. ANITA and PUEO are also sensitive to upgoing ν_τ , from a higher elevation. GRAND [5] is a planned experiment that will cover large areas with a sparse antenna array to detect the radio emission from air showers triggered by UHE ν_τ, cosmic rays, and gamma rays. for PUEO, the follow-up of ANITA, and many other dedicated projects instrumenting large areas with antennas such as GRAND or putting them in mountains such as BEACON and TAROGE.

10.3.3 RADAR

An alternate strategy for detection of neutrinos at radio frequencies uses RADAR [3]. When a high-energy neutrino interacts in the ice, it produces a relativistic cascade of charged particles that traverse the medium. As they progress, they ionize the medium, leaving behind a cloud of stationary charge. This cloud of charge, which persists for a few to tens of nanoseconds, is dense enough to reflect radio waves. Therefore, to detect a neutrino, a transmitter can illuminate a volume of dense material like ice, and if a neutrino interacts within this volume, the transmitted radio will be reflected from the ionization cloud to a distant receiver, which monitors the same illuminated volume.

With this technique, a custom signal is transmitted in the ice and received after reflections from neutrino-induced cascades. With this technique, the experimenter can determine the properties of the signal (including the amplitude, up to what is permitted to be transmitted). Also, the radar method has excellent geometric acceptance relative to passive (Askaryan) methods, which require the detector to lie within a small angular window at the Cherenkov angle. Recent test beam measurements have demonstrated the feasibility of the method in the laboratory, with in-situ tests forthcoming. RET-CR will serve as a pathfinder experiment, and RET-N could make radio detections of UHE neutrinos within the decade.

For a station consisting of a single, central 40 kW transmitter and 27 receiving antennas out radially from this transmitter, RET-N is projected to probe some flux models. For 10 such stations, the sensitivity at 10 PeV is projected to be comparable to IceCube, with the potential to complement or improve upon existing technologies at higher energies, allowing RET-N to continue detection of the neutrino spectrum beyond the optical regime.

10.4 KIDs

Cosmological surveys require the detection of radiation at mm wavelengths at thresholds down to the fundamental noise noise limit. The detection of mm-wave radiation is important for: studying cosmic acceleration (Dark Energy) and testing for deviations from general relativity expectations through measurements of the kinetic Sunyaev-Zeldovich effect, precision cosmology (sub-arcminute scales) and probing new physics through ultra-deep measurements of small-scale CMB anisotropy, and mm-wave spectroscopy to map out the distribution of cosmological structure at the largest scales and highest redshifts.

Imaging and polarimetry surveys at sub-arcminute scales will require $O(10^6)$ detectors over a $O(10\ \mathrm{deg}^2)$ fields-of-view (FoV) covering 9 spectral bands from 30 GHz to 420 GHz. Spectroscopic surveys (over a smaller FoV initially, $O(1\,\mathrm{deg}^2)$, but potentially also reaching $O(10\,\mathrm{deg}^2)$) will require a further factor of 10–100 increase in detector count. The 2019 report of the DOE Basic Research Needs Study on High Energy Physics Detector Research and Development identified the need to carry out detector RD to achieve this goal. The driver for new technology is not the detector count but the increased detector *density.* Whereas in current experiments, the detector packing density is limited by the physical size of elements in existing demonstrated multiplexing schemes, KIDs eliminate the need for additional cold multiplexing components, allowing for arrays at the densities needed for the science aims of proposed cosmological surveys.

The kinetic inductance detector (KID) is a technology that has gained significant traction in a wide range of applications across experimental astronomy over the last decade. A KID is a pair-breaking detector based on a superconducting thin-film microwave resonator, where the relative population of paired (Cooper pairs) and un-paired (quasiparticles) charge carriers govern the total complex conductivity of the superconductor. Photons with energy greater than the Cooper pair binding energy (2) are able to create quasiparticle excitations and modify the conductivity. By lithographically patterning the film into a microwave resonator, this modification is sensed by monitoring the resonant frequency and quality factor of the resonator. Since each detector is formed from a microwave resonator with a unique resonant frequency, a large number of detectors can be readout without the need for additional cryogenic multiplexing components. In addition, the designs to be fabricated are relatively simple.

There are a number of KID-based architectures being developed for a variety of scientific applications. Direct Absorbing KIDs are the simplest variant, where the resonator geometry is optimized to act as an impedance-matched absorber to efficiently collect the incoming signal. To date, the only facility-grade KID-based instruments are based on this detector architecture, with the NIKA-2 experiment on the IRAM 30-meter telescope having demonstrated that the KID-based instruments are highly competitive with other approaches. Microstrip-coupled KIDs take advantage of recent advancements that allow for the ability to lithographically define circuits capable of on-chip signal processing with extremely low loss. The capability to robustly couple radiation from superconducting thin-film microstrip transmission lines into a KID with high optical efficiency is being developed. Thermal Kinetic Inductance Detectors take a similar approach as has been developed for bolometric transition edge sensor arrays. Instead of directly absorbed radiation breaking pairs, a thermally-mediated KID (TKID) uses the in- trinsic temperature response of the superconducting film to monitor the temperature, and therefore absorbed power. It combines the multiplexing advantage of KIDs with the proven performance of bolometric designs in TES detectors, at the expense of fabrication complexity.

On-chip spectroscopy is a natural extension of multi-band imaging using on-chip filters to a filter-bank architecture to realise medium-resolution spectroscopic capability. Several approaches to on-chip spectroscopy exist at a range of technological readiness.

10.5 Integrated Optical Cherenkov and Radio detection.

We briefly address here the optical Cherenkov method and the integrated approach of IceCube-Gen2. IceCube has been very successful in observing a cosmic flux of neutrinos of all flavors in the energy range from 10 GeV to 10 PeV. Currently the IceCube Collaboration is building instrumentation to deploy an upgrade of 7 densely instrumented strings optimized for low energies and precision calibration of IceCube. The completion of this upgrade planned for January 2026. This upgrade also serves as a Phase 1 exercise in designing new instrumentation for IceCube-Gen2 and prepare for a preliminary design. IceCube-Gen2 will consist of 120 additional strings, which are longer and more widely spaced to instrument a total volume of a factor of 8 times that of IceCube. At high energies, IceCube-Gen2 will be complemented by a radio detector array covering an area of about $500\,\mathrm{km}^2$ which will surpass the optical array at about 30 PeV and improve by 2 orders of magnitude over IceCube. The radio array will build on the concept of RNO-G that serves as the RD scale array (10% level) of the radio component. The design of this radio array was the result of a multi-year effort by the community, in the latest phase as an integral part of a planning effort of the IceCube-Gen2 collaboration includes the respective radio community.

The technological advancements in the optical array design:

- Optical sensors: Contain 16 or 18 PMTs (directional 4 π sensitivity, 3 x larger sensitivity of IceCube sensor)
- New PMT of 4 inch size with short stem in development by two manufacturers
- Optimized trigger and data acquisition scheme to allow factor 10 reduction in bandwidth, factor of 3 reduction in cables.
- integrated radio+scintillator air shower array on the footprint of the 5 km^2 optical array.
- more efficient drill and energy saving technology, including solar power.

The technological advancements in the radio array design:

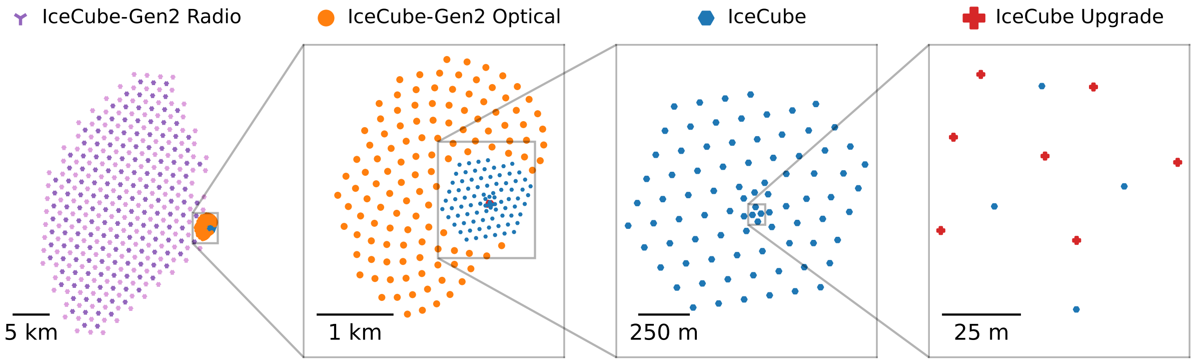

Figure 10-1. *Top view of the envisioned IceCube-Gen2 Neutrino Observatory facility at the South Pole station, Antarctica. From left to right: The radio array consisting of 525 stations (shallow and hybrid). IceCube-Gen2 strings in the optical high-energy array. 120 new strings (shown as orange points) are spaced 240 m apart and instrumented with 80 newly developed optical modules each, over a vertical length of 1.25 km. The total instrumented volume in this design is 7.9 times larger than the current IceCube detector array (blue points). On the far right, the layout for the seven IceCube Upgrade strings relative to existing IceCube strings is shown.*

- A hybrid radio array design building on developments of ARA, ARIANNA and RNO-G.
- New drill technology for fast drilling of holes for antennas down to 150 m depth.
- possible use of autonomous power and wireless communication as tested in RNO-G.

The integrated IceCube-Gen2 design is driven by the design requirement of sensitivity to a cosmic neutrino flux over a range from 10^3 to 10^{10} GeV.

The following RD opportunities have been identified for IceCube-Gen2:

- Design of a new ASIC for the PMT signal readout (100Msps, 12 bit, 2 channels). Given the large channel count of about 170,000 PMT channels, a significant cost and power saving could be realized.
- Design of an integrated readout chip could result in cost and power savings for radio DAQ systems.

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