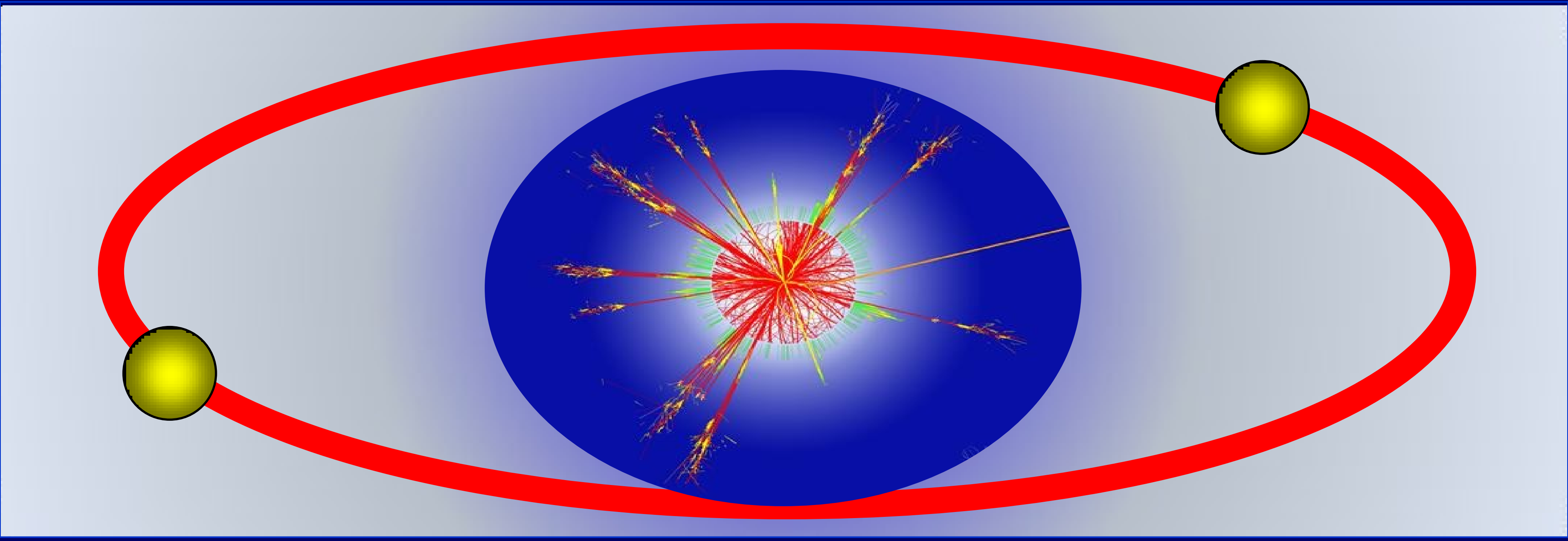
Particle Accelerators



Prof. Glenn Patrick

University of Portsmouth

Quantum, Atomic and Nuclear Physics, Year 2
University of Portsmouth, 2012 - 2013

Last Week - Recap

Nuclear Reactions, Conservation Laws
Reaction Energy, Q Value
Cross-section
Nuclear Fission: Induced and Spontaneous
Neutron Reactions, Fission Energy Release
Chain Reaction
Uranium Fuel Cycle
Fission Reactor Designs
Thorium
ADSR
Nuclear Fusion
Magnetic Confinement and Inertial Confinement

Today's Plan

06 November Accelerators

Voltage Multiplier
Van de Graaff Generator
Tandem Accelerators
Linear Accelerator (LINAC)
Cyclotron
Relativistic Effects
Syncro-Cyclotron Iso-Cyclotron
Synchrotron
Synchrotron Radiation
Large Hadron Collider (LHC)
Beyond the LHC
Super LHC
International Linear Collider and CLIC

BOOKS

Edmund Wilson, *An Introduction to Particle Accelerators*, OUP

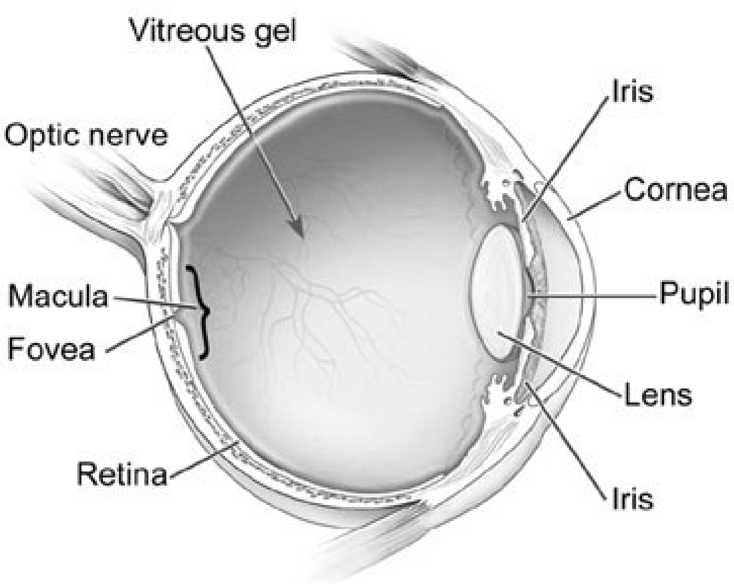
Klaus Wille, *The Physics of Particle Accelerators*, OUP

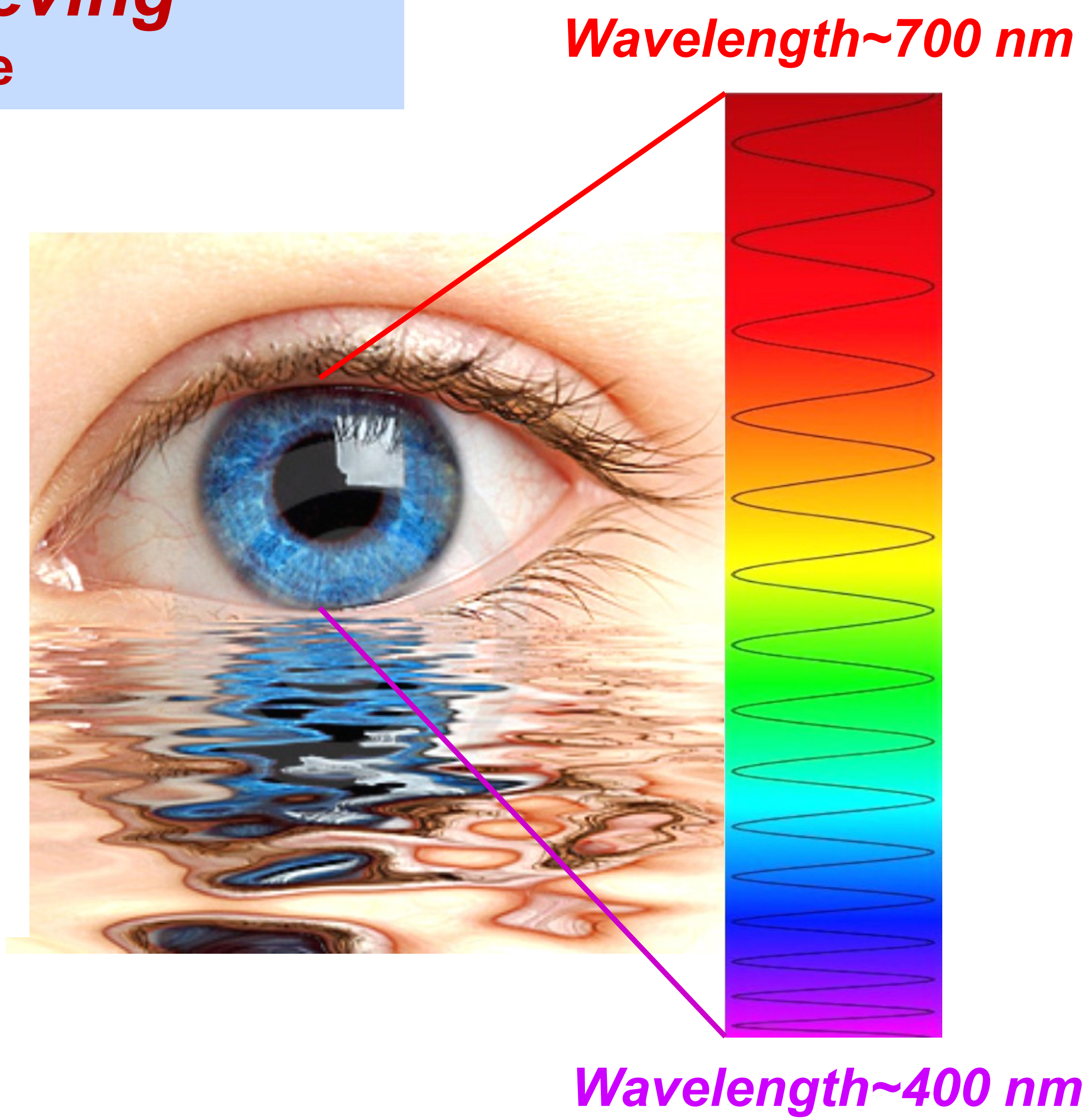
Copies of Lectures:

http://hepwww.rl.ac.uk/gpatrick/portsmouth/courses.htm

Visible/Optical Spectrum

"Seeing is beleeving"
1639, J. Clarke



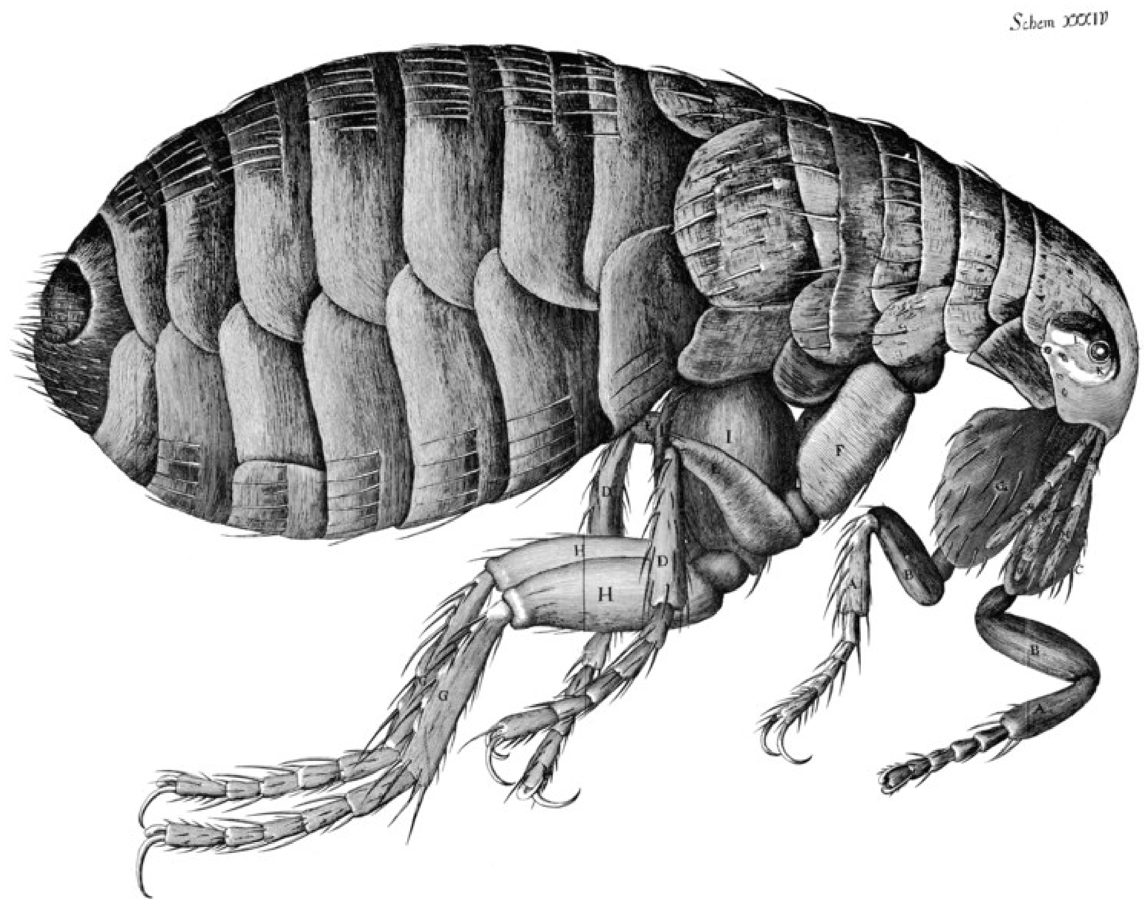


The eye is the **detector**

The Very Small ~ 400 years Ago

Compound Microscope, ~1670, Glasgow

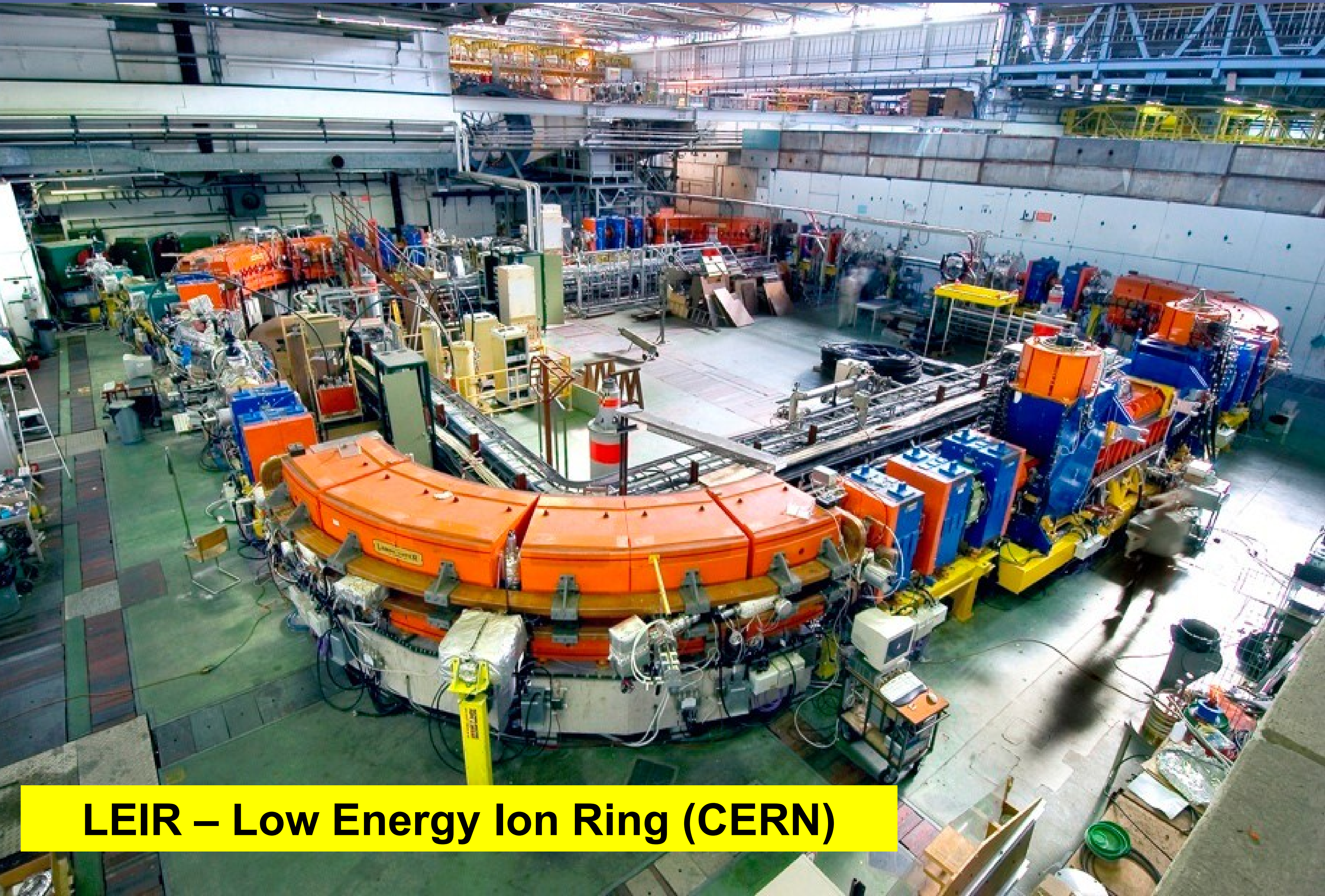
Magnification ~30



Micrographia, Robert Hooke, 1665

"Cell" appears for the first time.

Modern Microscope?



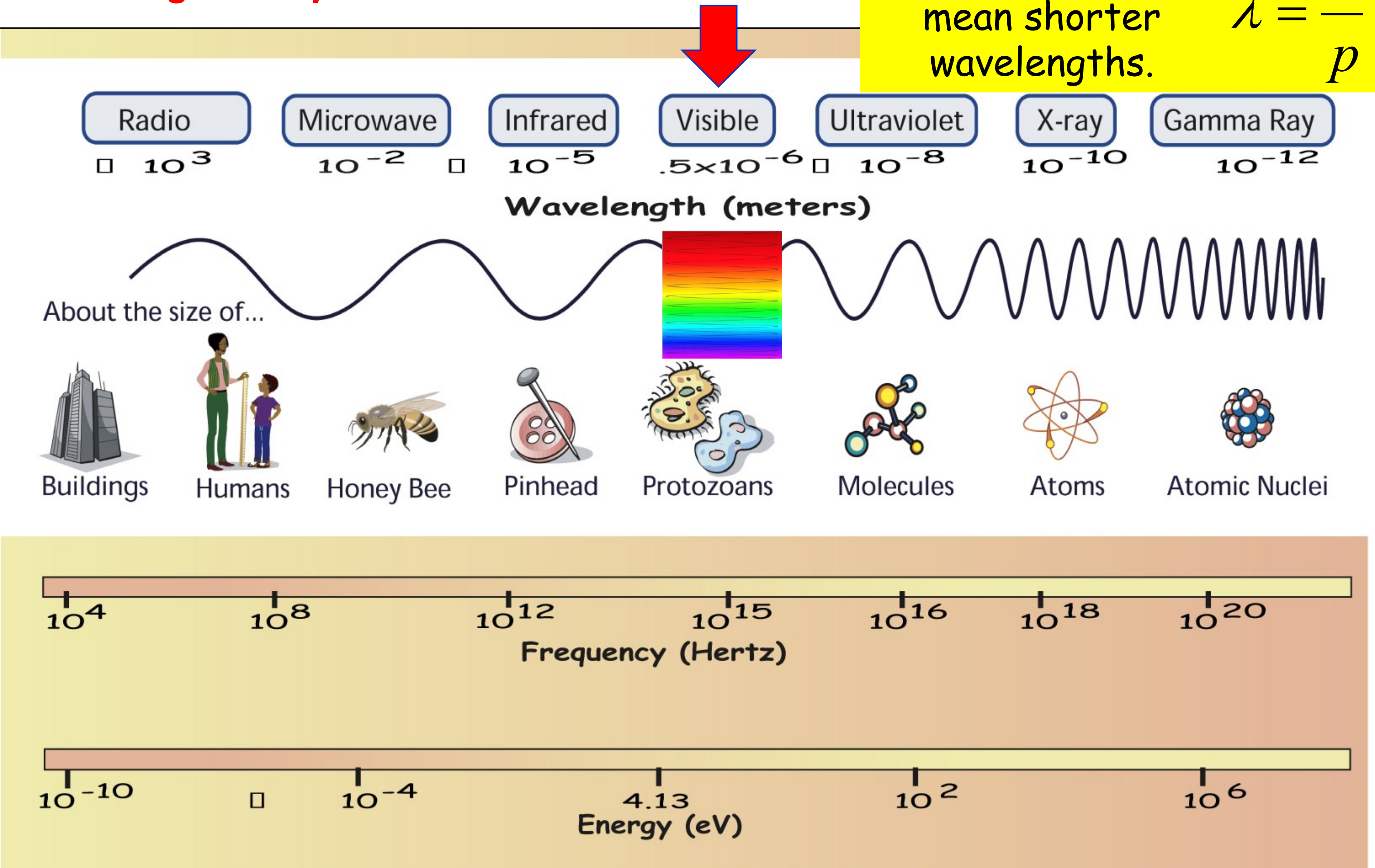
LEIR – Low Energy Ion Ring (CERN)

Wave Particle Duality

Visible light can probe down to ~1 micron

Higher energies mean shorter wavelengths.

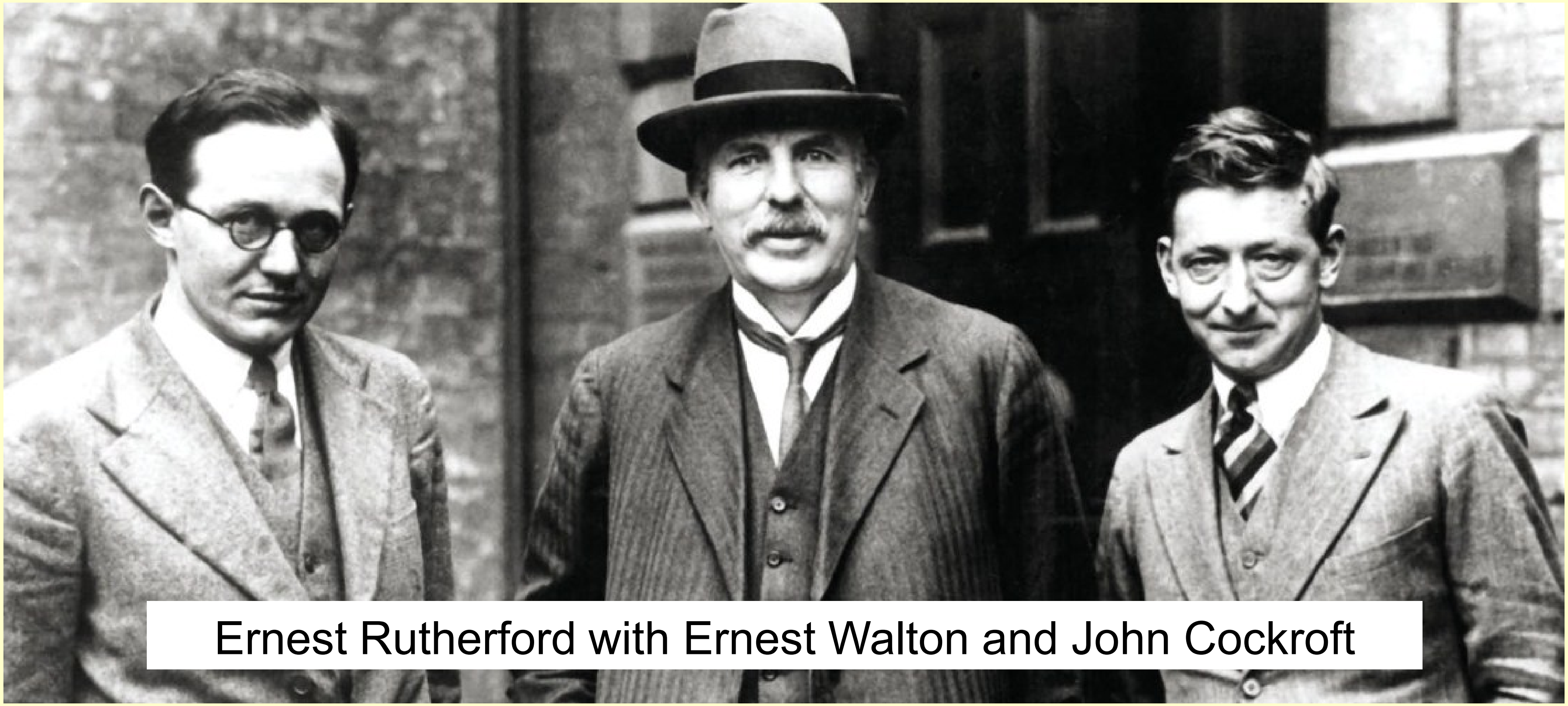
$$\lambda = \frac{h}{p}$$



The Quest for Higher Energies

In the early 20th century, the only known sources of particles that could induce nuclear reactions were the natural alpha particle emitters (usually radium).

The only type of nuclear reaction was an α particle interacting with a nucleus.

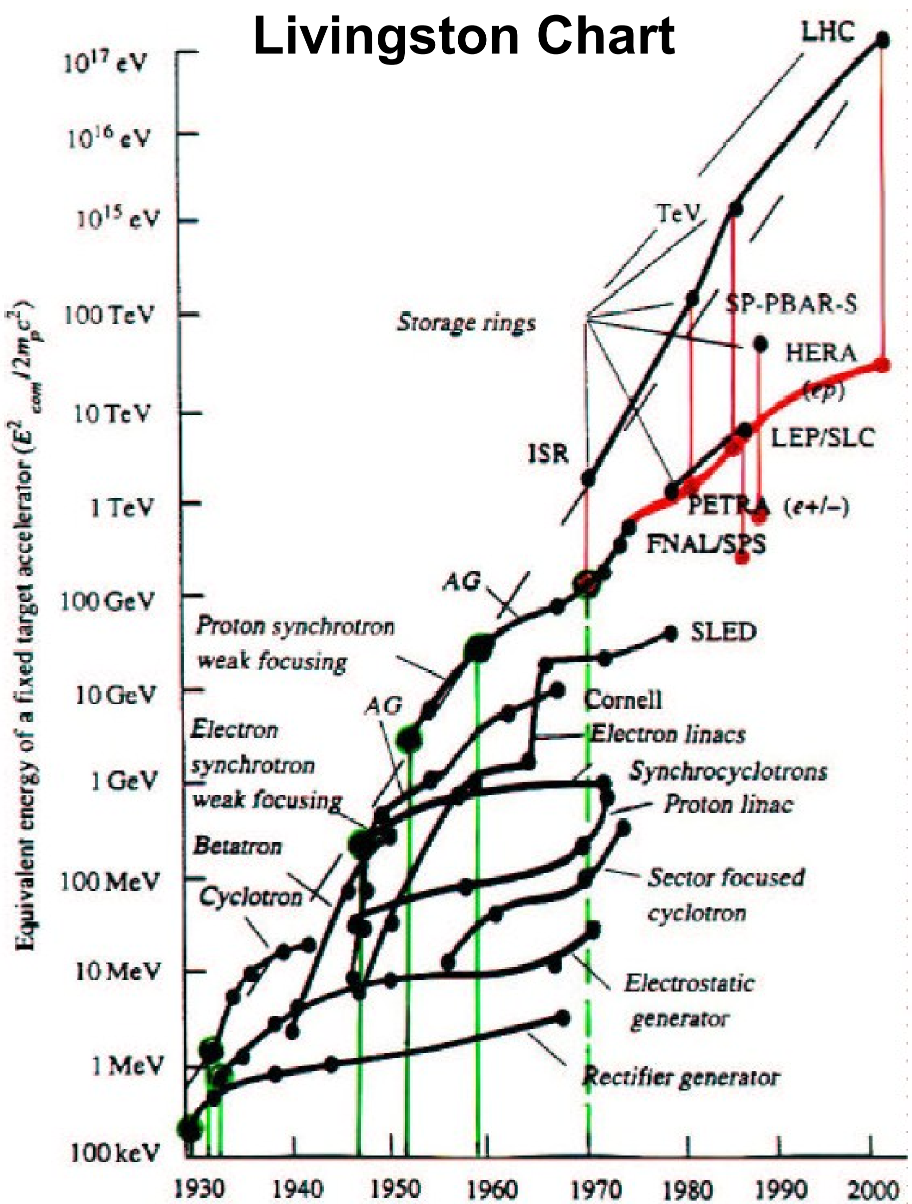


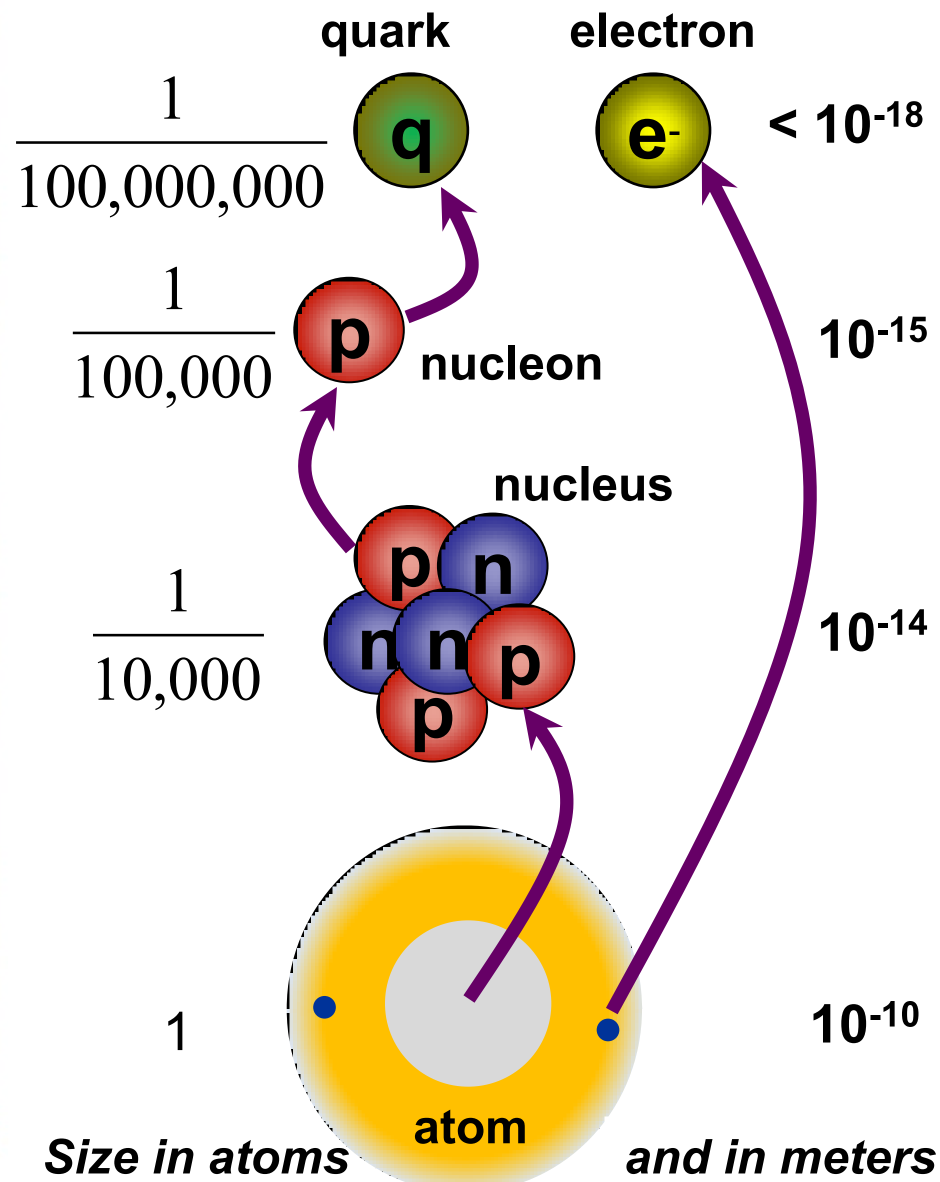
Ernest Rutherford with Ernest Walton and John Cockroft

Need for a device – an **accelerator** – to accelerate charged particles to higher energies.

The way to do this was to create large electric fields.

Energy Growth of Accelerators





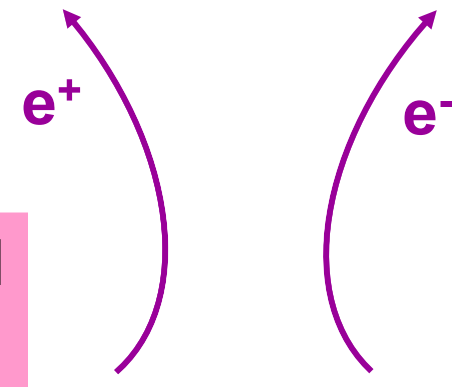
Charged Particle Beams

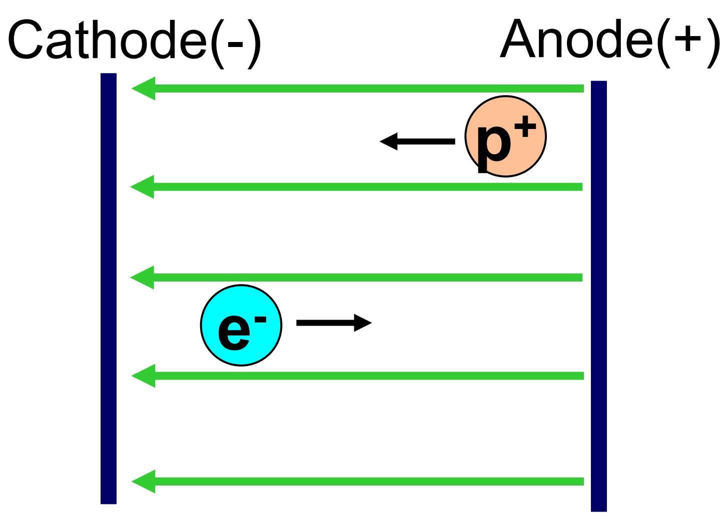
Force on charged particle is given by the Lorentz Force

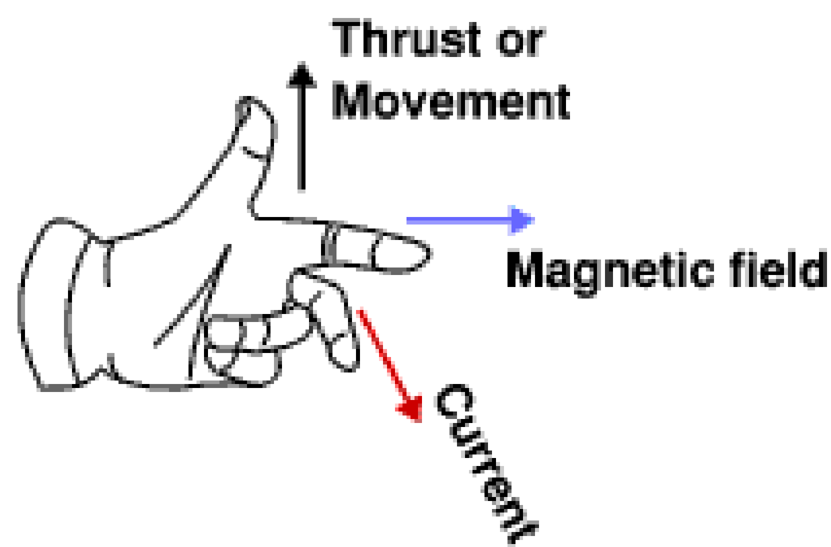
$$\overline{F} = q\overline{E} + q\overline{v} \times \overline{B}$$

Electric Field
Acceleration

Magnetic Field
Bending

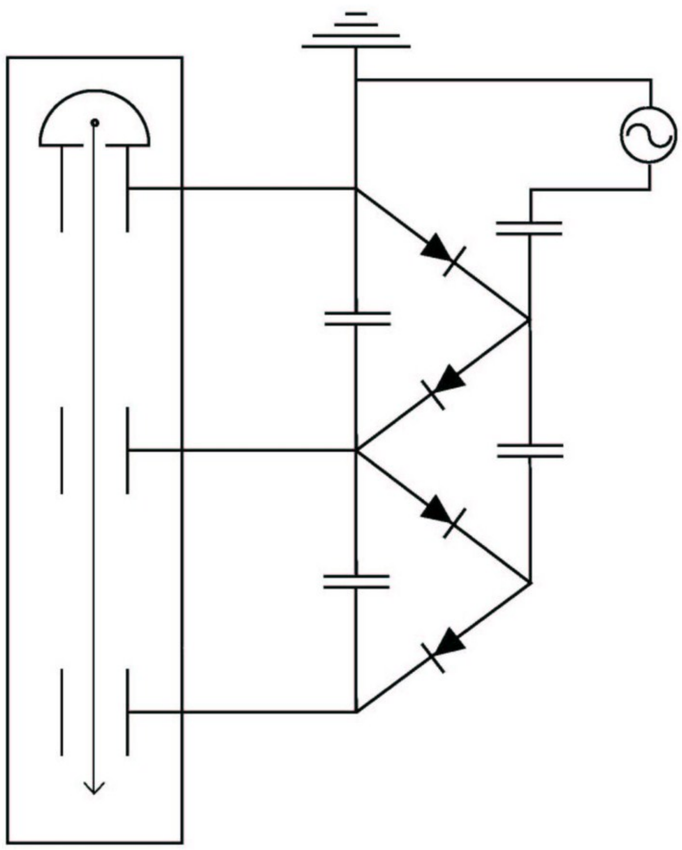




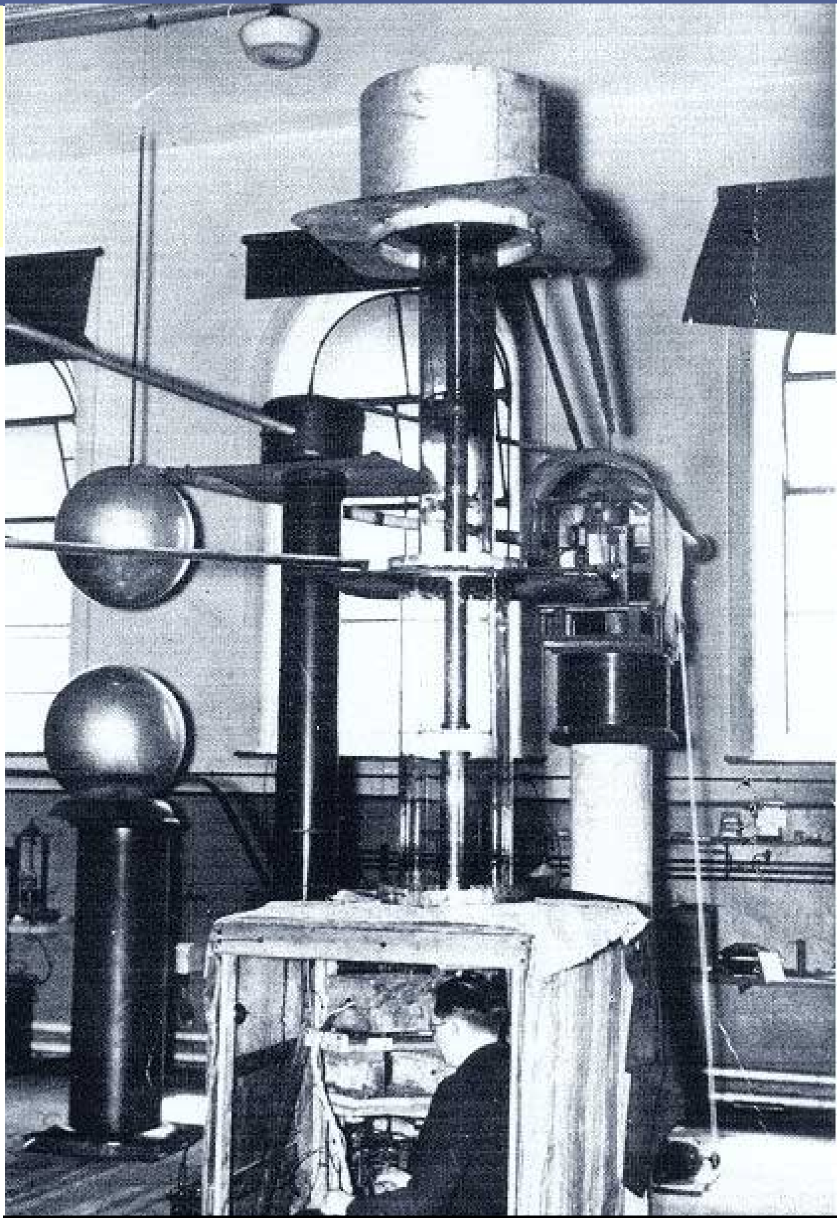


Splitting the Nucleus (1932)

John Cockroft & Ernest Walton
Voltage Multiplier (800 kV)
Cavendish Laboratory, 1932.



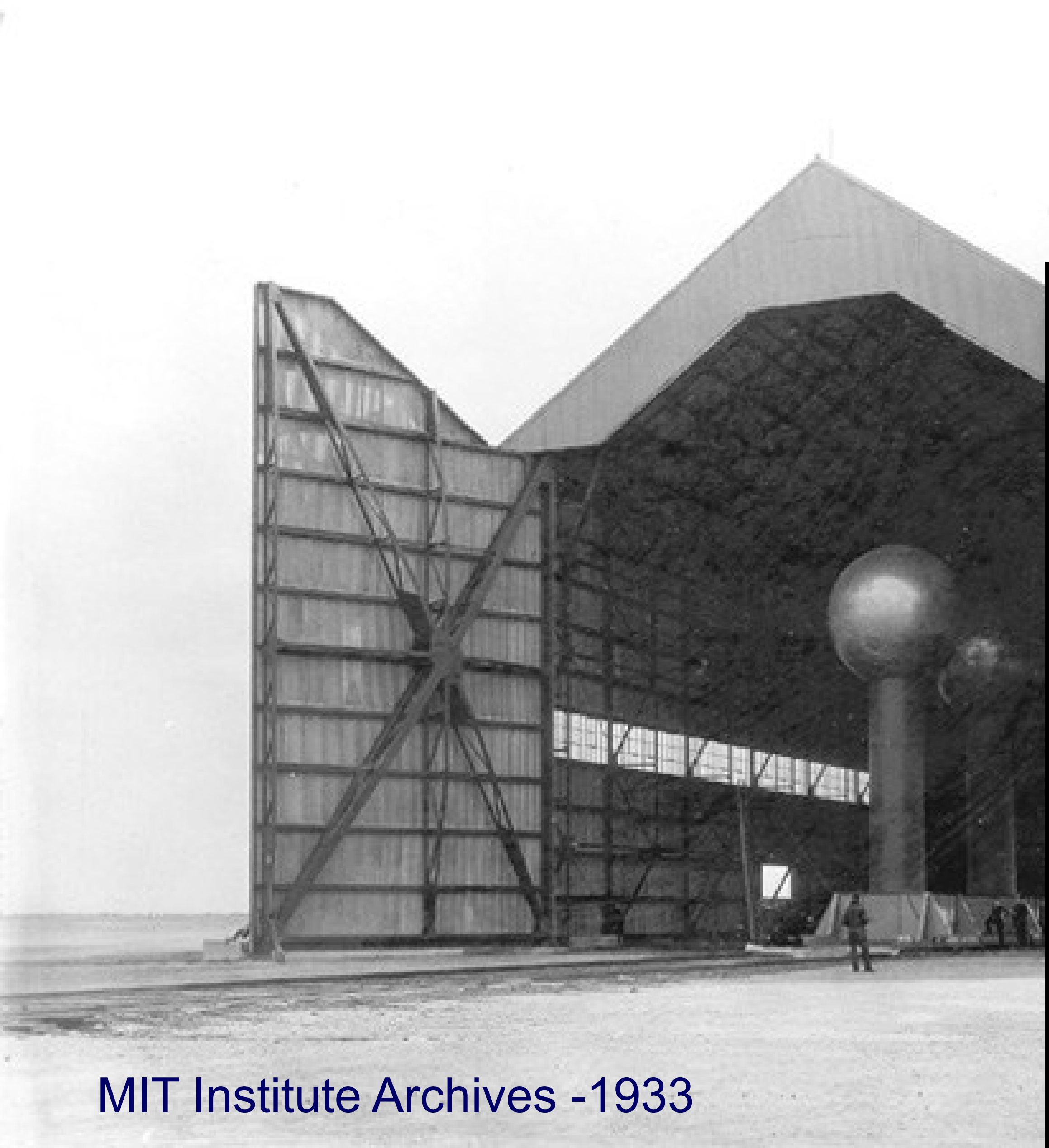
$$p + Li \rightarrow \alpha + \alpha$$



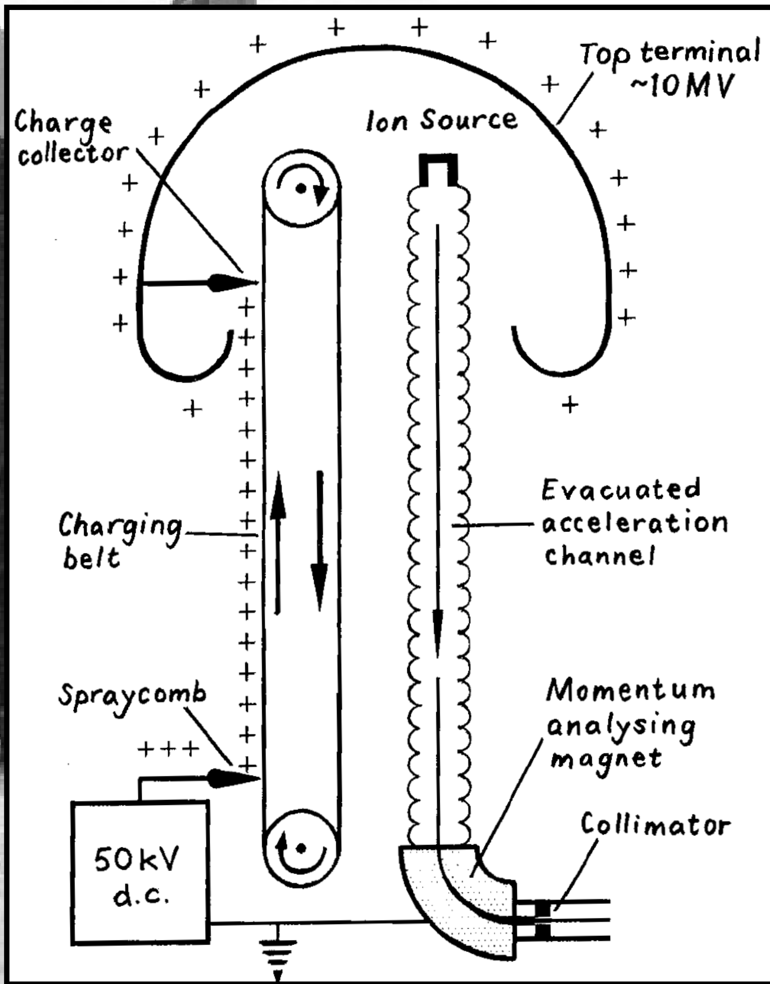
Max. accelerating voltage ~ 1MV

Cockroft/Walton Pre-Injectors

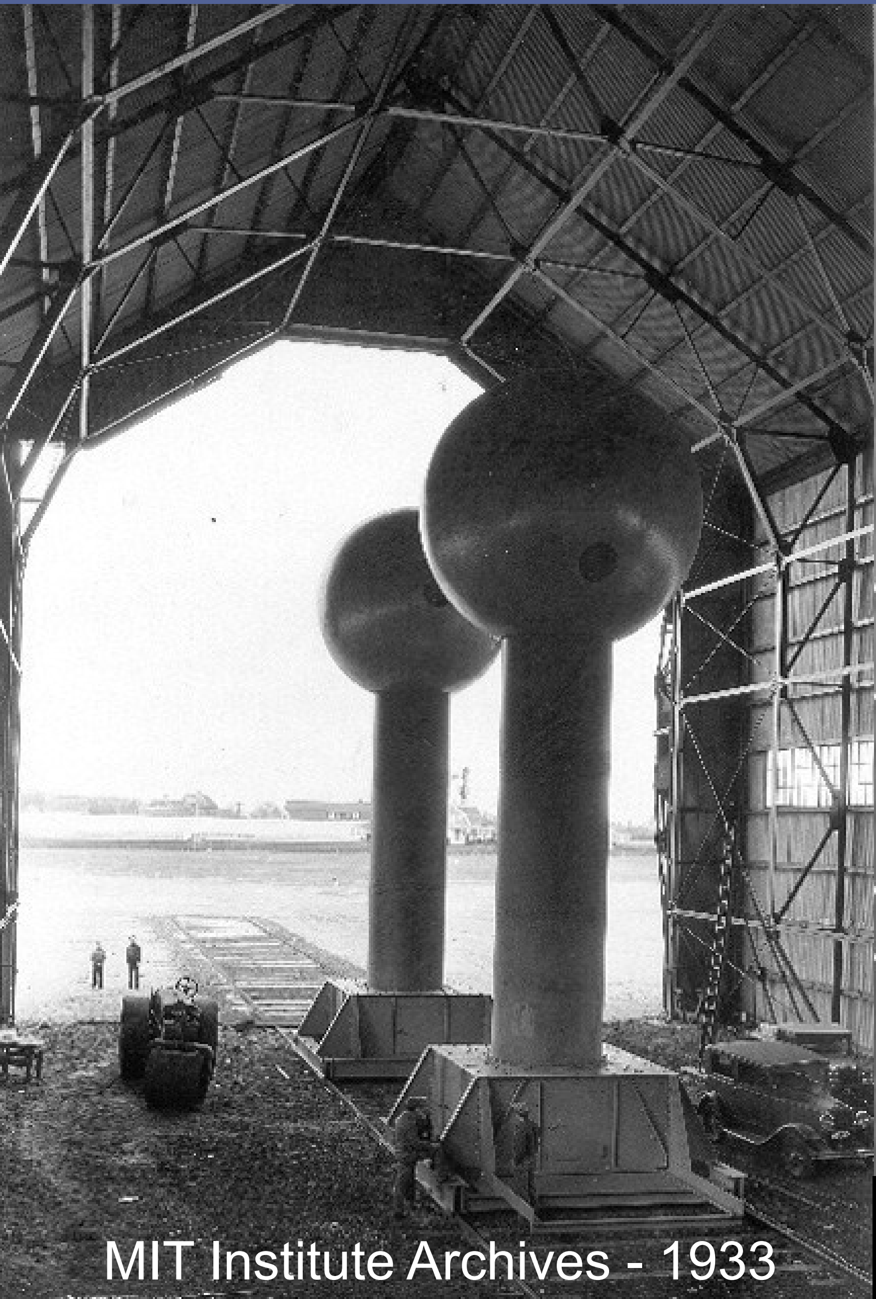
Van de Graaff High Voltage Generator



MIT Institute Archives -1933



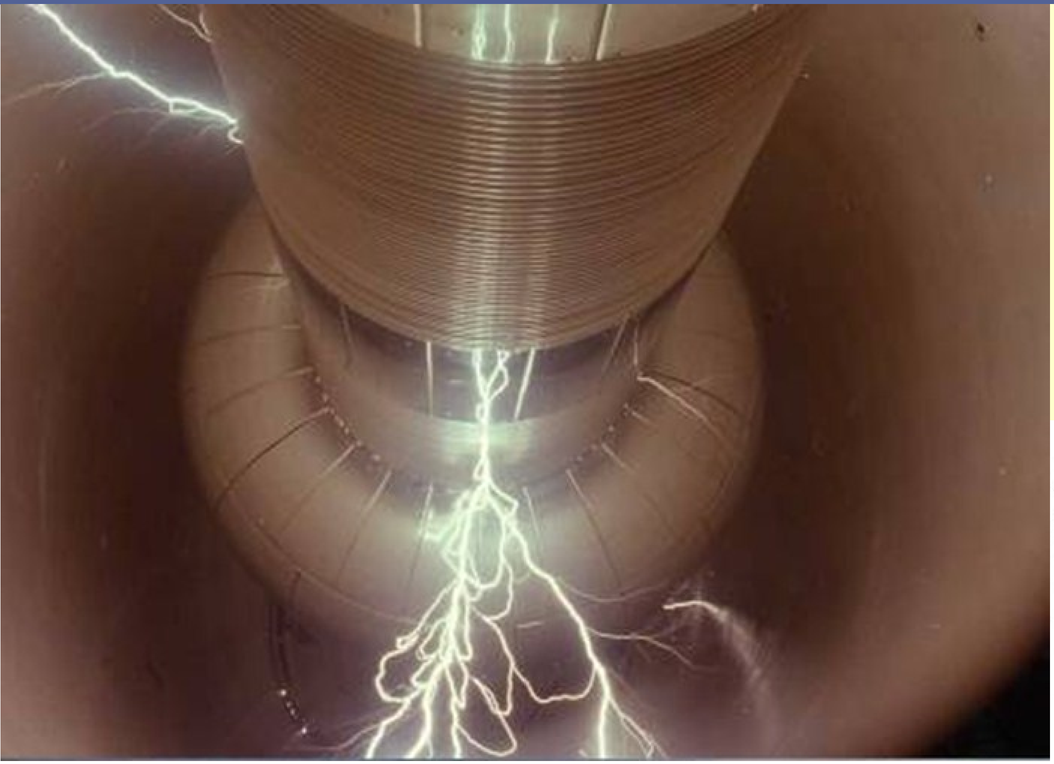
Breakdown!



MIT Institute Archives - 1933

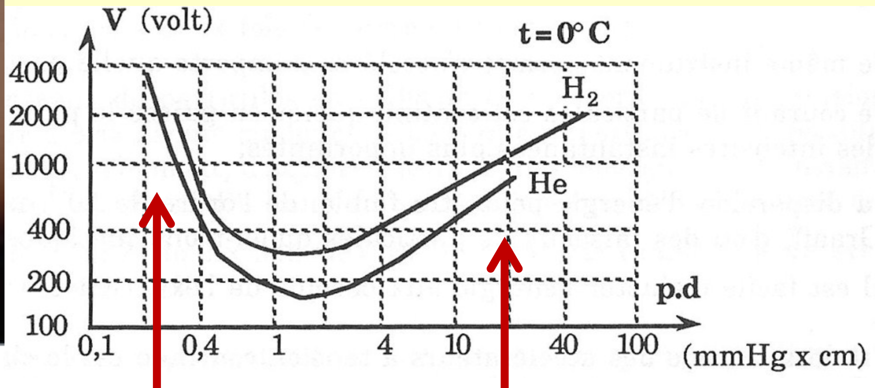
Max. accelerating voltage ~ 1 MV

High Voltage Limit!



Limit set by Paschen's Law:

The breaking voltage between two parallel electrodes depends only on the ***pressure*** *of the gas between the electrodes and their distance.*



Can reach ~10MV if high voltage parts under high pressure gas instead of air.

Low pressure: gas not too dense, long mean path of electrons between collisions.

High pressure: dense gas, more collisions reduce electron energy making it more difficult to ionise.

Sulphur Hexafluoride, SF_6 used

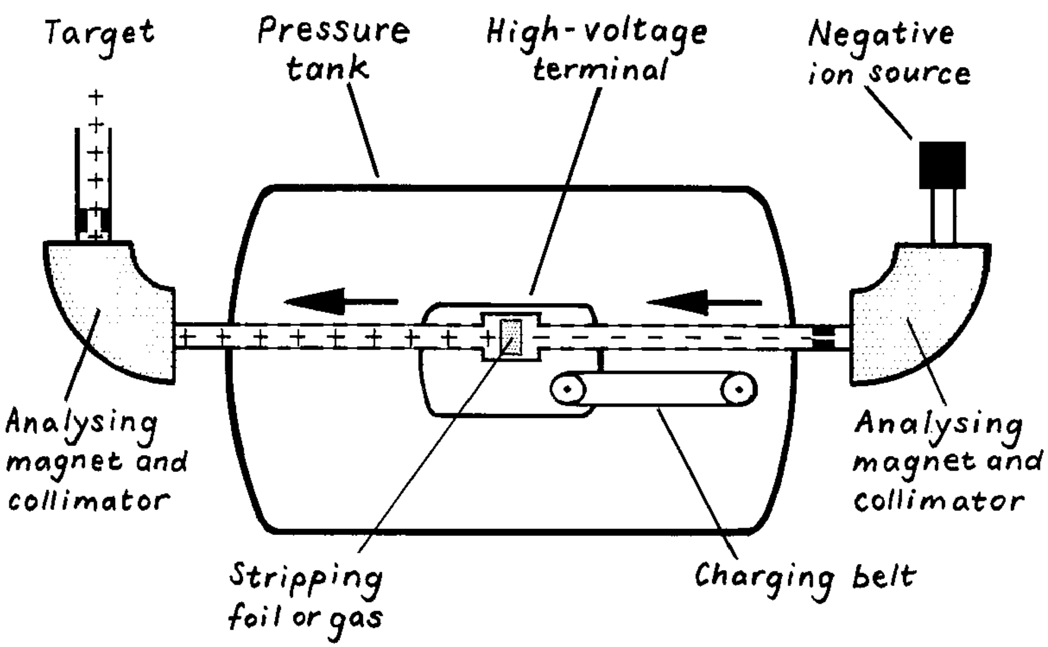
Tandem Accelerator

Problem with single Van de Graaff is that voltage only applied once per particle.

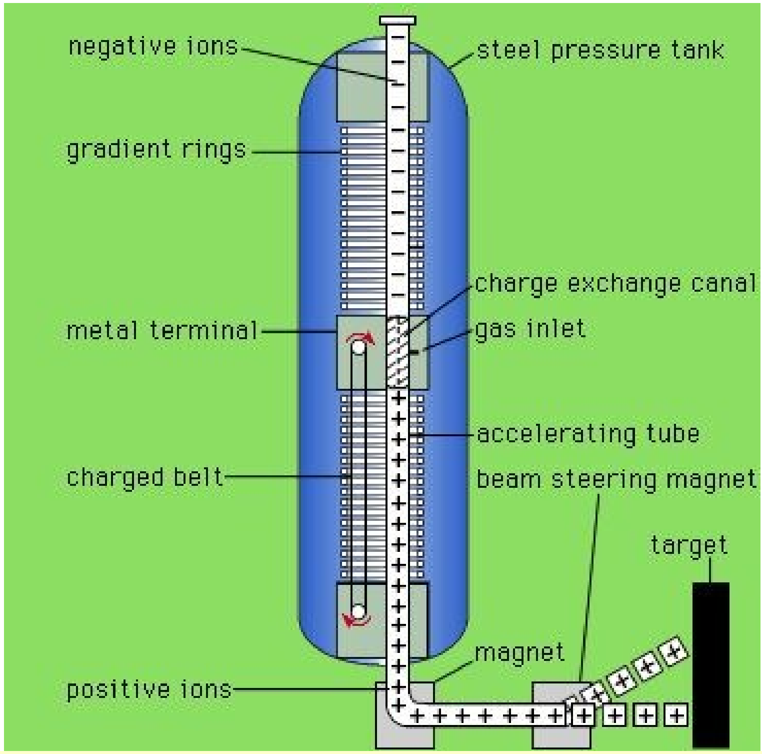
Can double the energy by using the **tandem** approach.

Start with **negative ions** (e.g. H^-) and then **strip the electrons** in the centre to get a second stage of acceleration.

Horizontal tandem



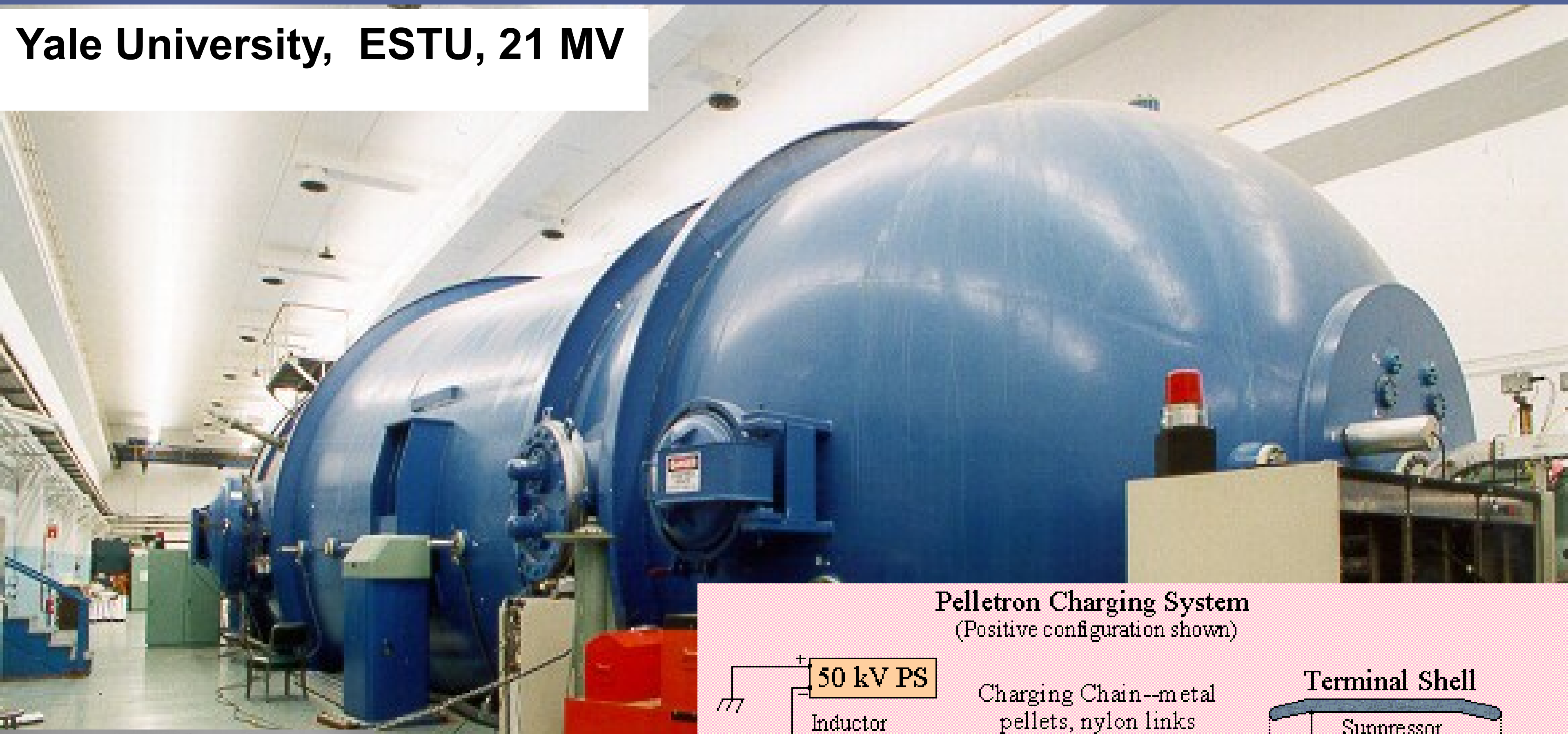
Vertical tandem

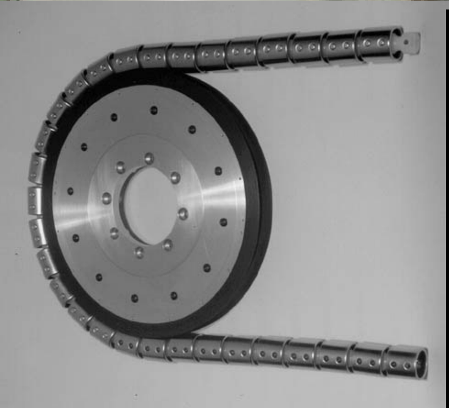


Can also have a **folded tandem** (e.g. Oxford) where two accelerator tubes are placed side-by-side and a 180° magnet deflects the beam between them.

Tandem Accelerator

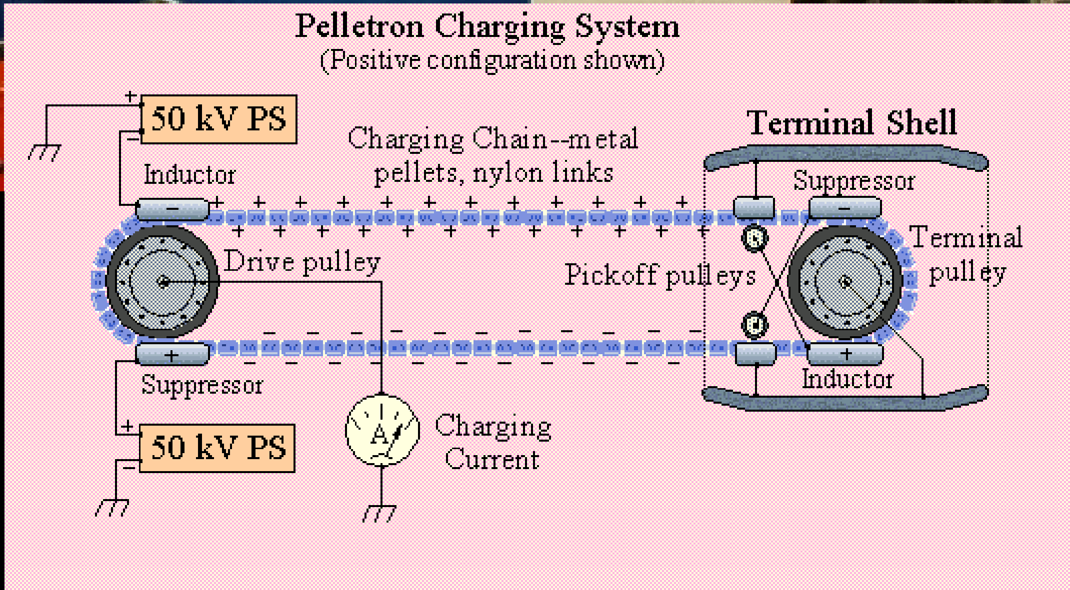
Yale University, ESTU, 21 MV





Pelletron Chain

Metal pellets with nylon links

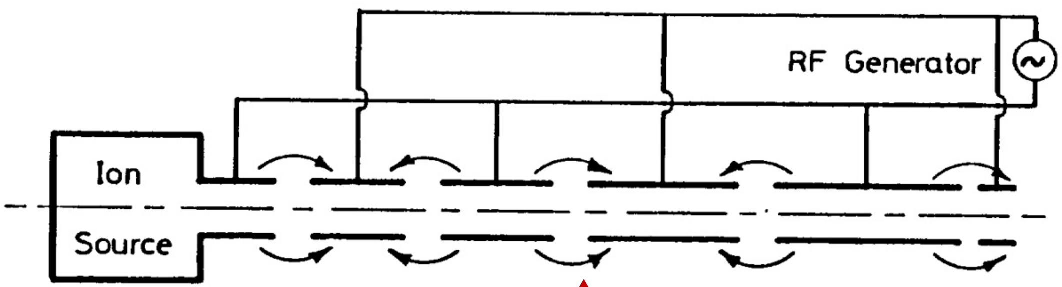


UK - Nuclear Structure Facility (NSF)

Daresbury Laboratory
Tandem Van de Graaff (1983-1992)
20-30 MV, 70m high

Linear Accelerator (LINAC)

Wideröe LINAC (1927): First successful test of using rapidly changing high frequency voltage instead of direct voltage.



25kV
1 MHz oscillator

Voltage $U(t) = U_{\max} \sin \omega t$

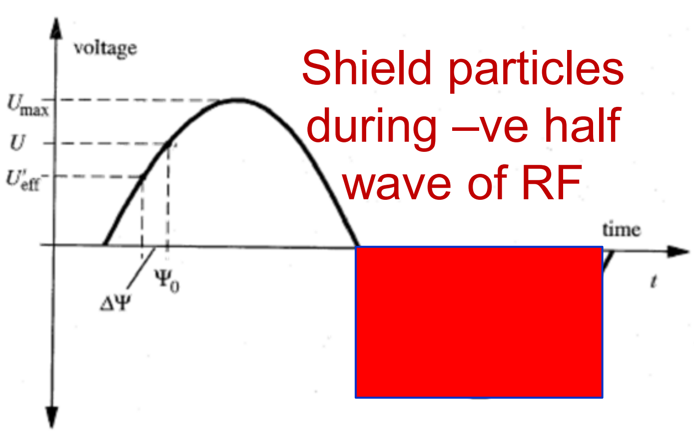
Gap F = qE

Alvarez drift tube LINAC (1946): First serious proton LINAC. High frequency RF oscillators (klystrons) become available because of radar.

After the nth tube, the particles have energy E_n, where Ψ is average phase of RF voltage that particles "see".

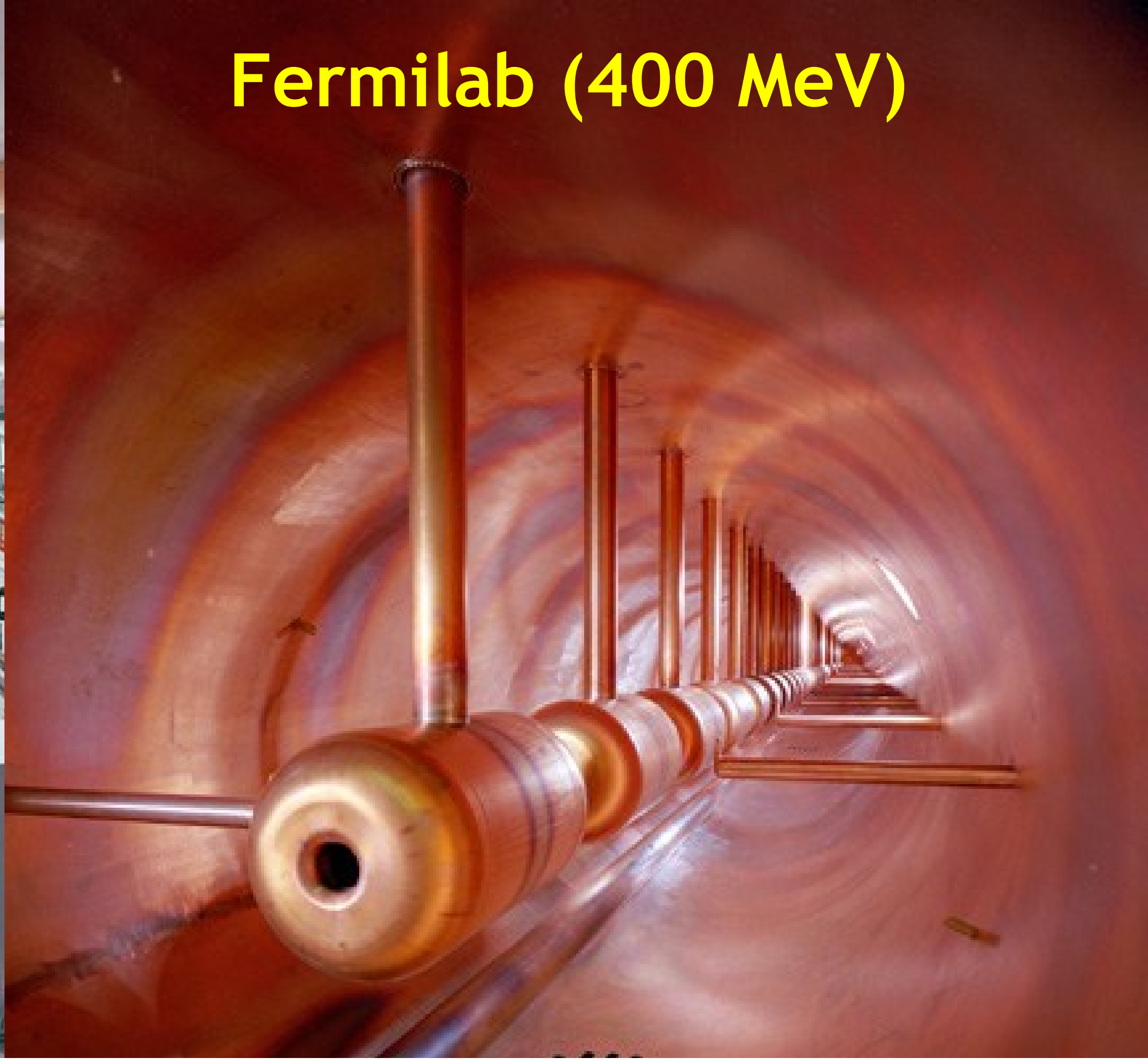
$$E_n = nqU_0 \sin \Psi_0$$

Distance between gaps has to increase to allow for increase in velocity.

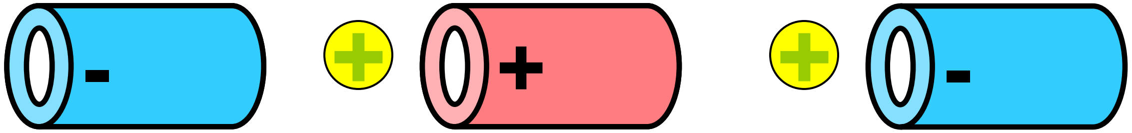


Shield particles during –ve half wave of RF

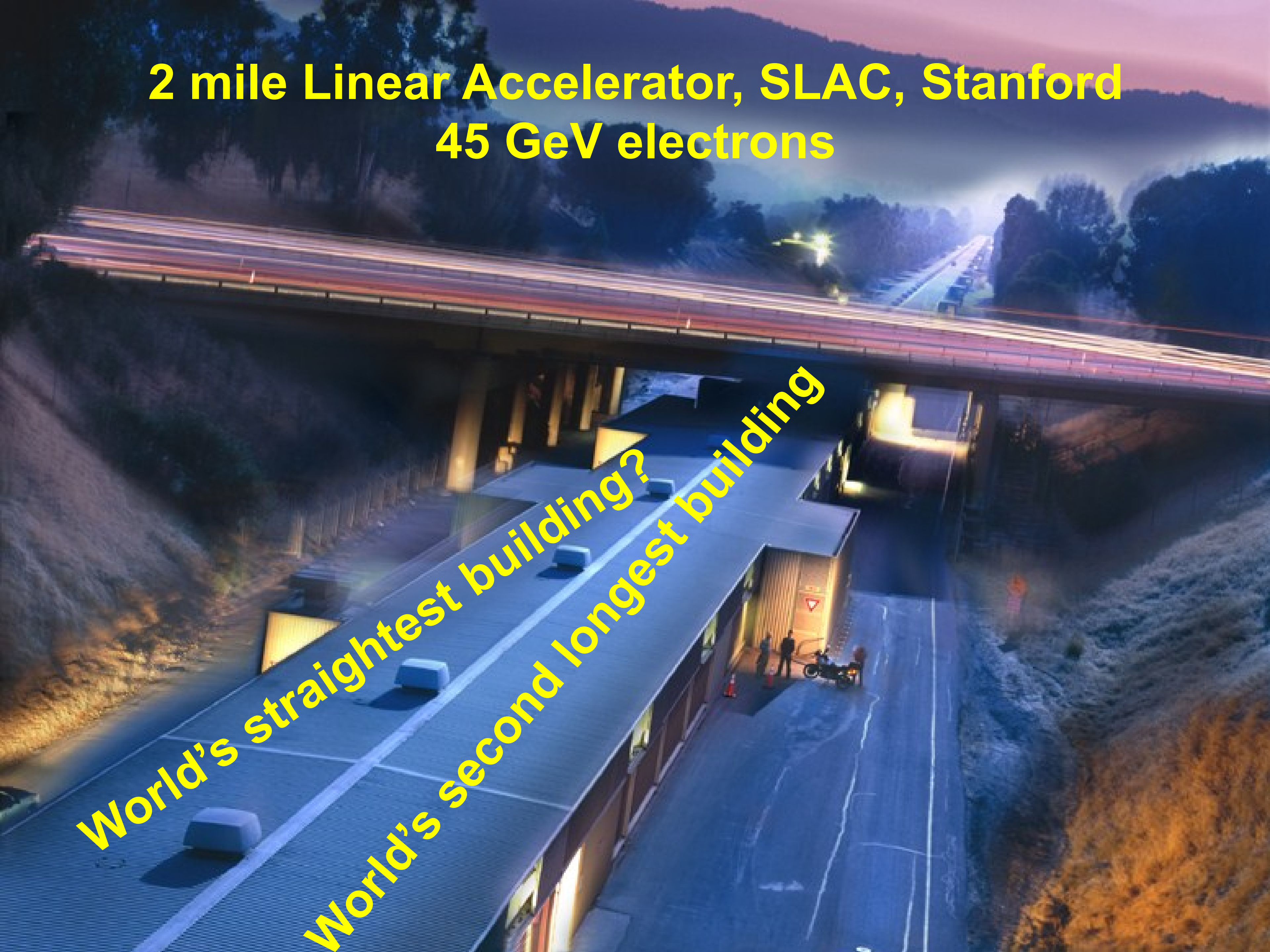
ISIS LINAC (RAL)



LINEAR ACCELERATORS



Alternating RF voltage. Each step gives a small energy increase to the particle.


2 mile Linear Accelerator, SLAC, Stanford
45 GeV electrons
World’s straightest building?
World’s second longest building

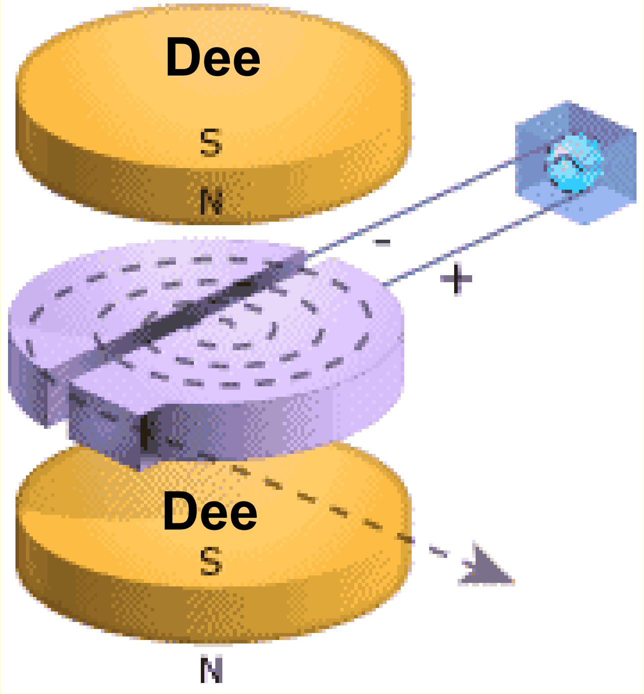
Circular Accelerators

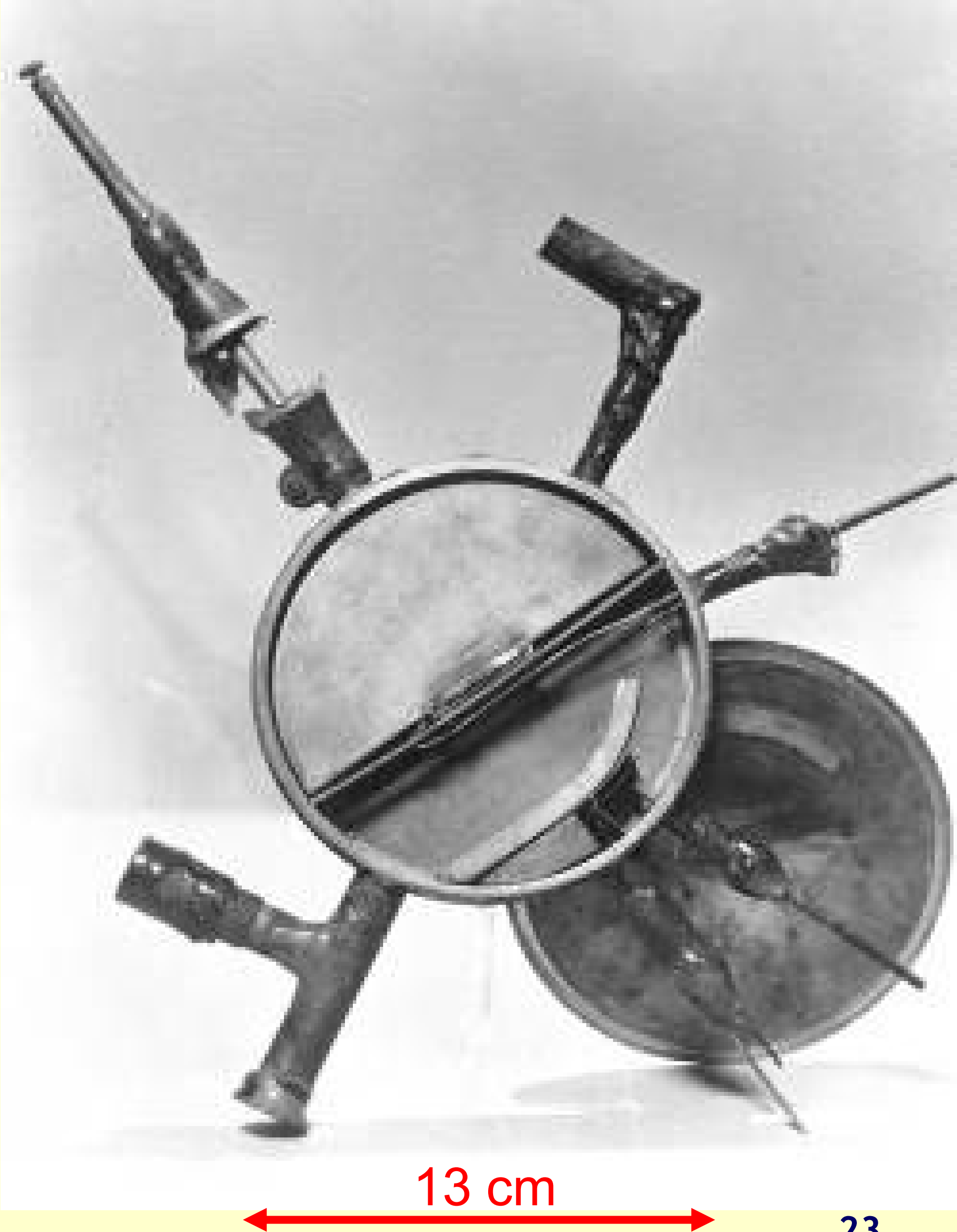
CYCLOTRON

First circular particle accelerator built by Ernest O. Lawrence & Stanley Livingston at Berkeley in 1930.

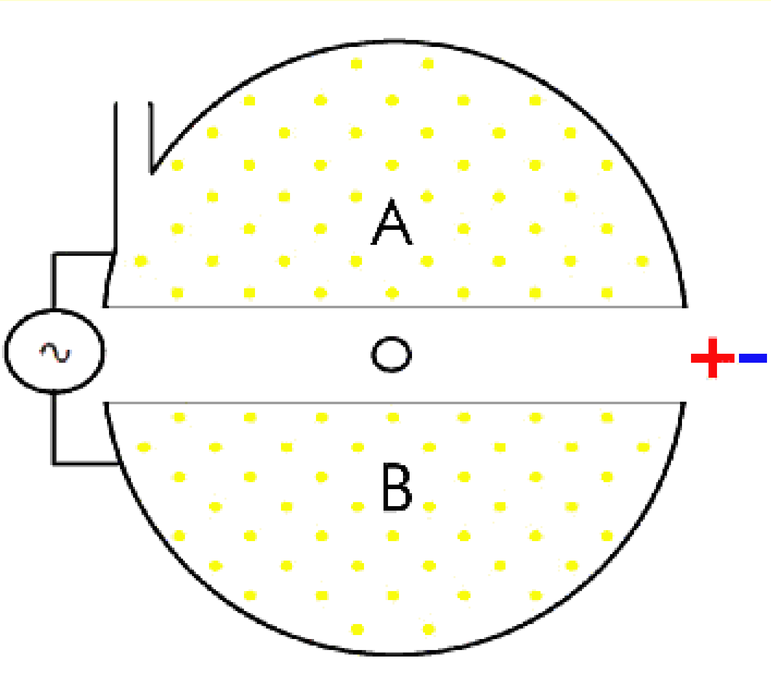
Energy = 80 keV
Diameter = 13cm

Bend beam round in a circle using **fixed** magnetic field and **constant** RF.





The Cyclotron



Lorentz Force $\bar{F} = q(\bar{v} \times \bar{B}) = qvB_z$

Classically:
Magnetic = centripetal $qvB_z = \frac{mv^2}{R}$

Magnetic rigidity
(resistance of particle to deflection)

$$\boxed{B_z R = \frac{p}{q}}$$

$$\boxed{R[m] = 3.33\, p[GeV] / B[T]}$$

Increasing radius from increasing momentum → spiral trajectory.

Frequency of revolution:

$$f = \frac{v}{2\pi R} = \frac{v}{2\pi} \cdot \frac{qB_z}{mv} = \frac{qB_z}{2\pi m}$$

Cyclotron frequency

$$\boxed{\omega = 2\pi f = \frac{qB_z}{m}}$$

independent of particle momentum

Relativistic Mass Increase

Classical cyclotrons can accelerate protons, deuterons and alpha particles up to **~22 MeV per charge**.

At these energies, the motion is still sufficiently non-relativistic (~0.15c) for the revolution frequency to remain ~constant.

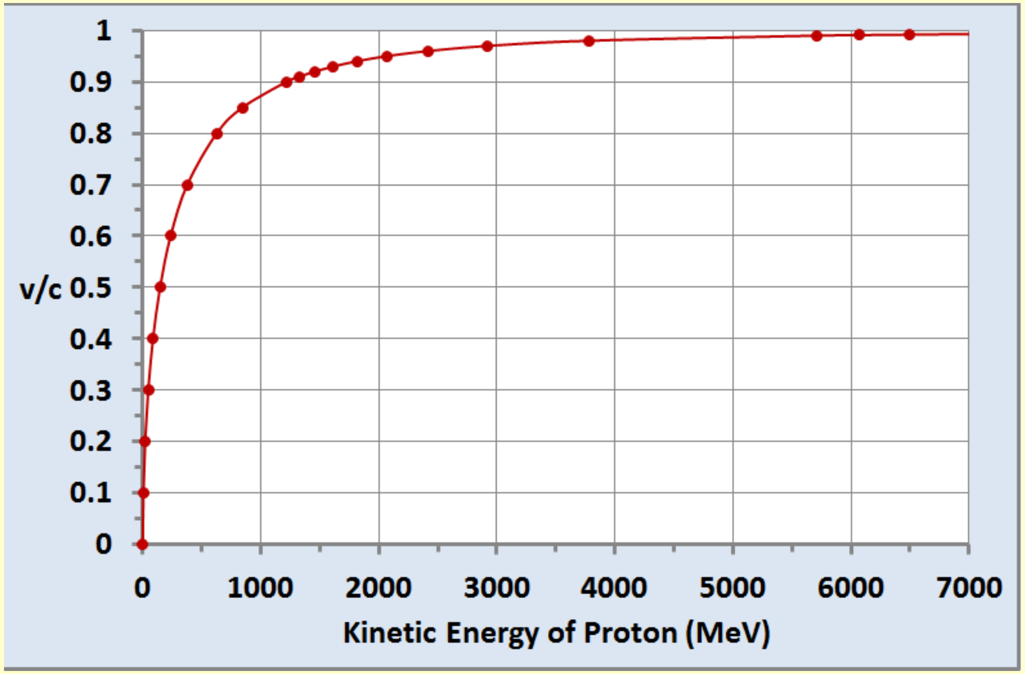
To go beyond, have to take account of relativistic Effects.

$$\omega = 2\pi f = \frac{qB_z}{m_0\gamma}$$

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

$$E_{total} = \frac{m_0 c^2}{\sqrt{1 - v^2/c^2}}$$

Machine	γ
26 MeV	26
LHC 7 TeV	7460



Cyclotron Variations

SYNCRO-CYCLOTRON (Edwin McMillan, 1945)

$$\boxed{\omega = 2\pi\, f = \frac{qB_z}{m_0\gamma}}$$

Frequency of the RF acceleration voltage decreased so that it adjusts to changes in particle orbit due to relativistic effects.

Particles have to be bunched, beam capture →low intensity.

Can reach up to ~700 MeV.

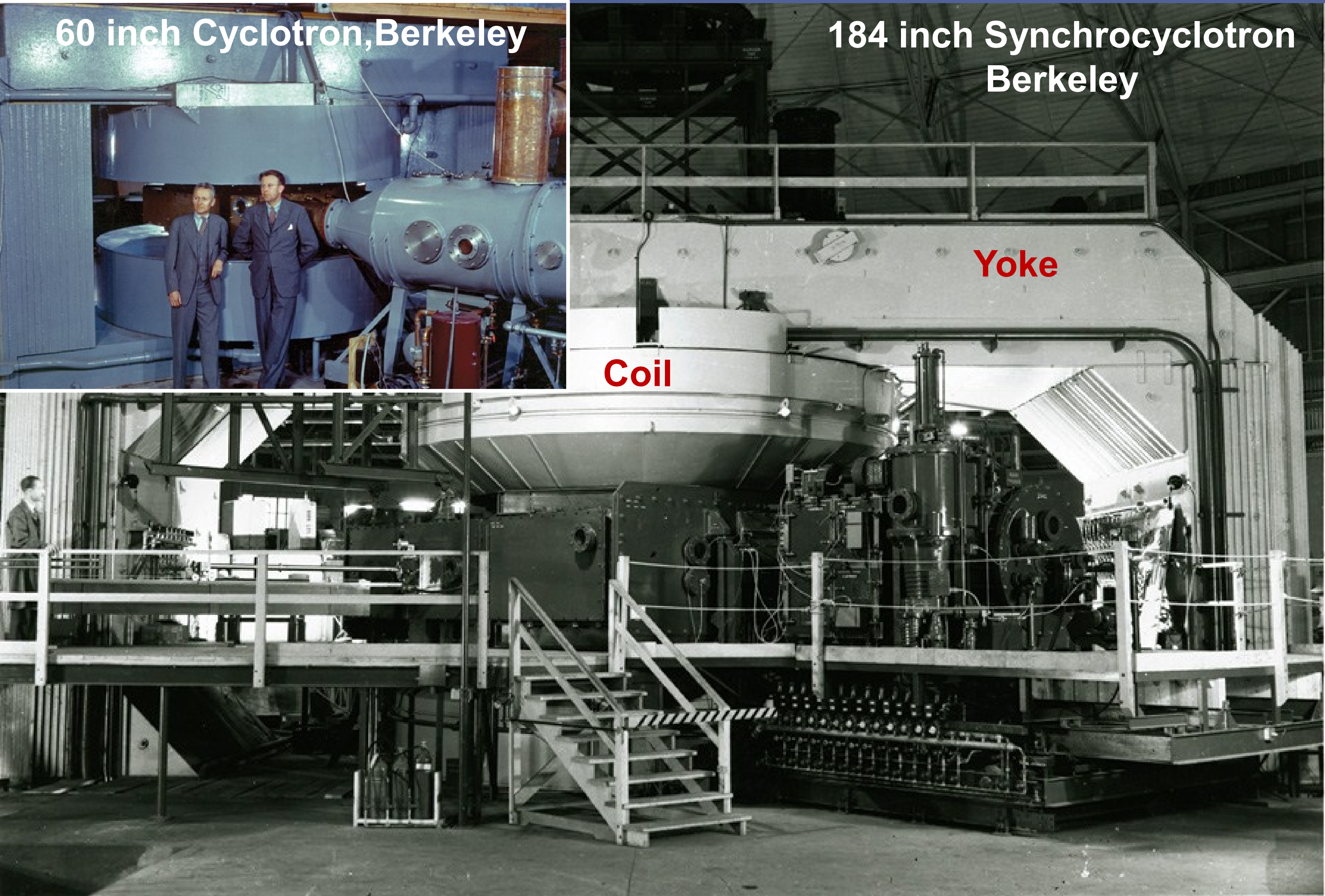
ISO-CYCLOTRON

$$\boxed{\omega = 2\pi\, f = \frac{qB_z(r(E))}{m_0\gamma} = \text{constant}}$$

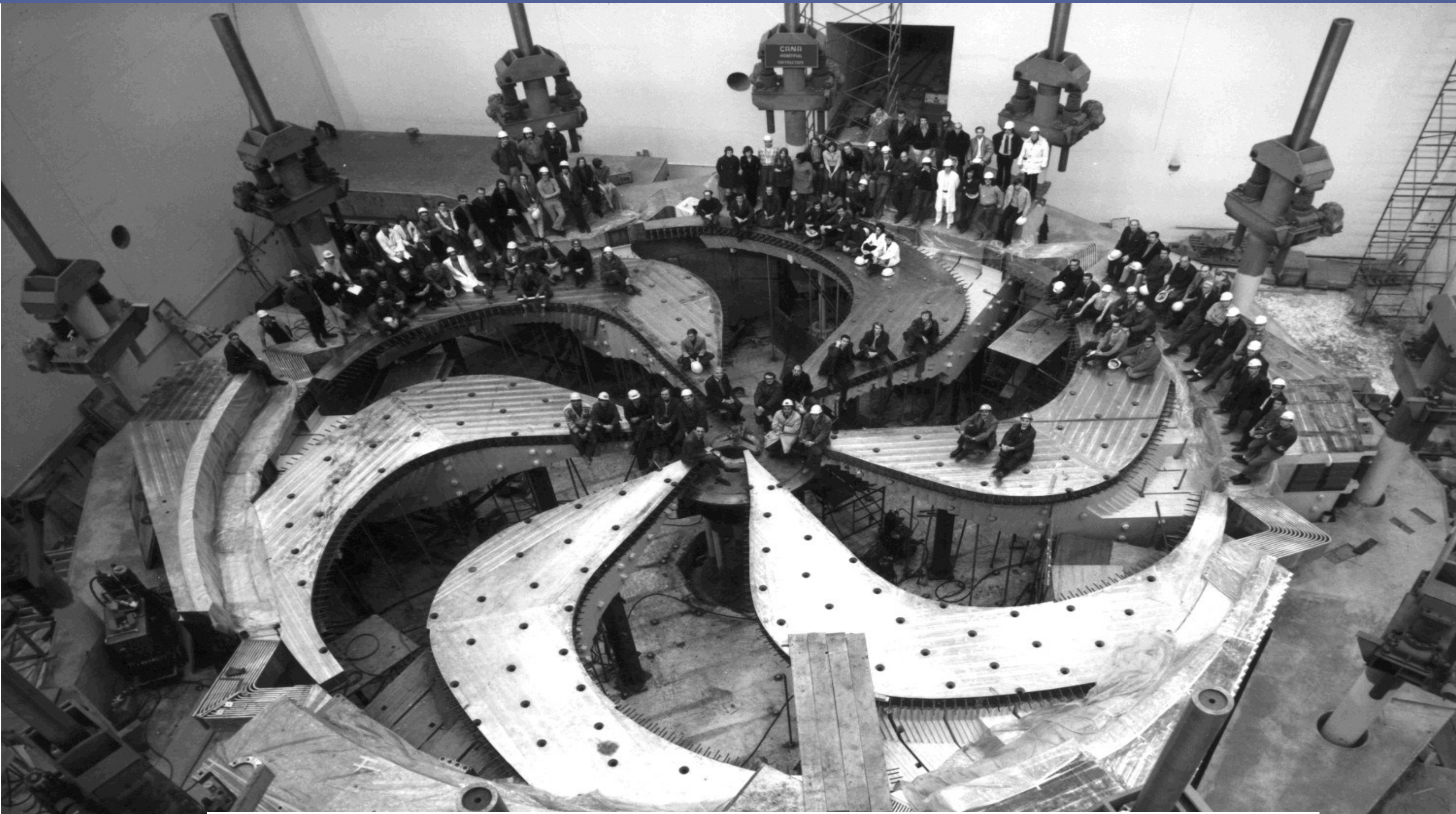
Keep RF frequency the same, but increase the radial magnetic field to compensate for mass increase.

Greater beam current than syncro-cyclotron.

Huge Magnets Needed

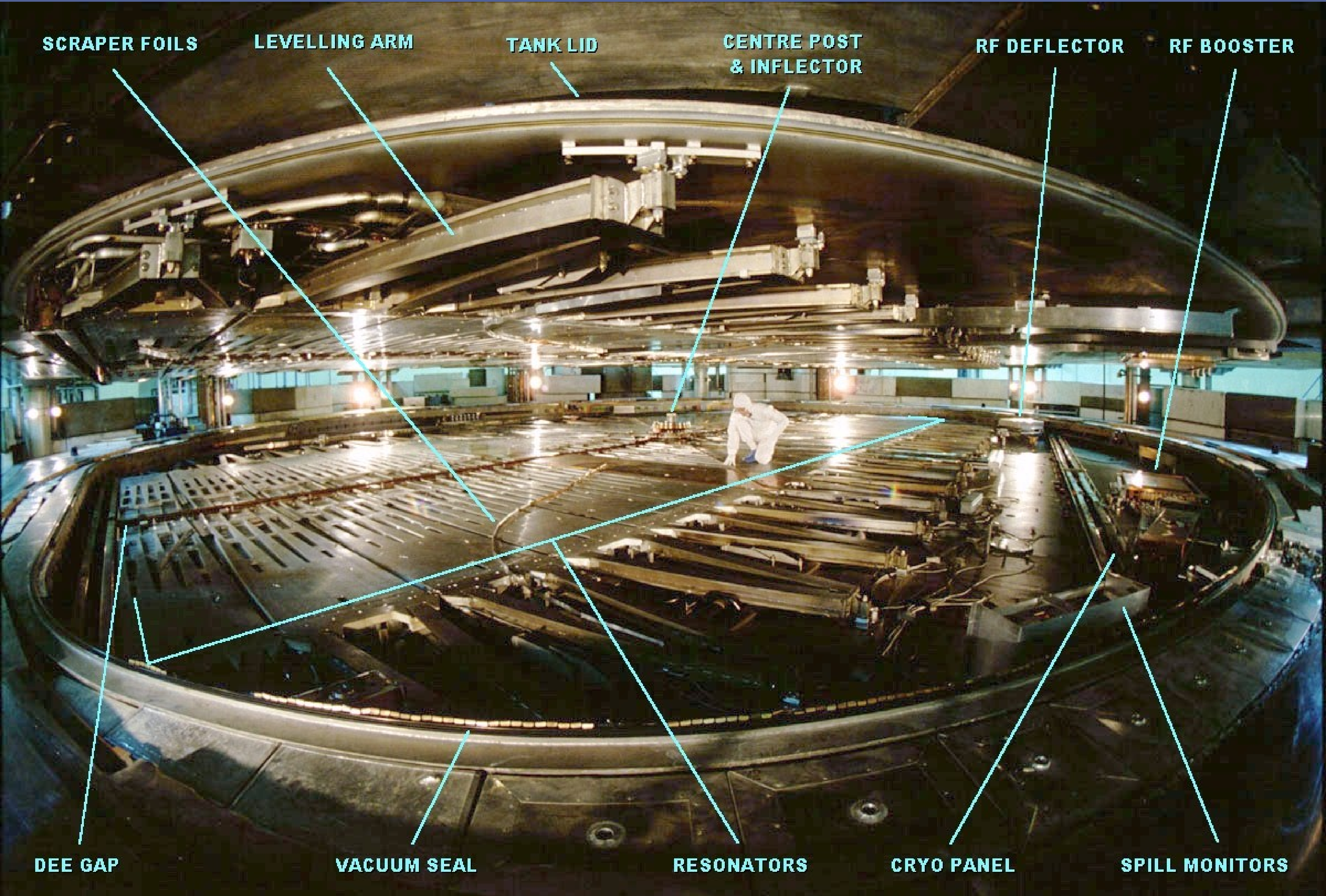


TRIUMF Cyclotron – 500 MeV



One of the world’s largest cyclotrons
Lower six sectors of electromagnet (weight 4000 tonnes).
Field = 0.56T, Current = 18,500 A

TRIUMF Cyclotron – 500 MeV



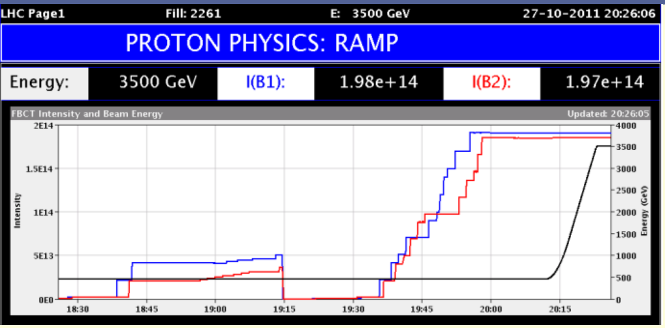
Superconducting Ring Cyclotron (SRC)

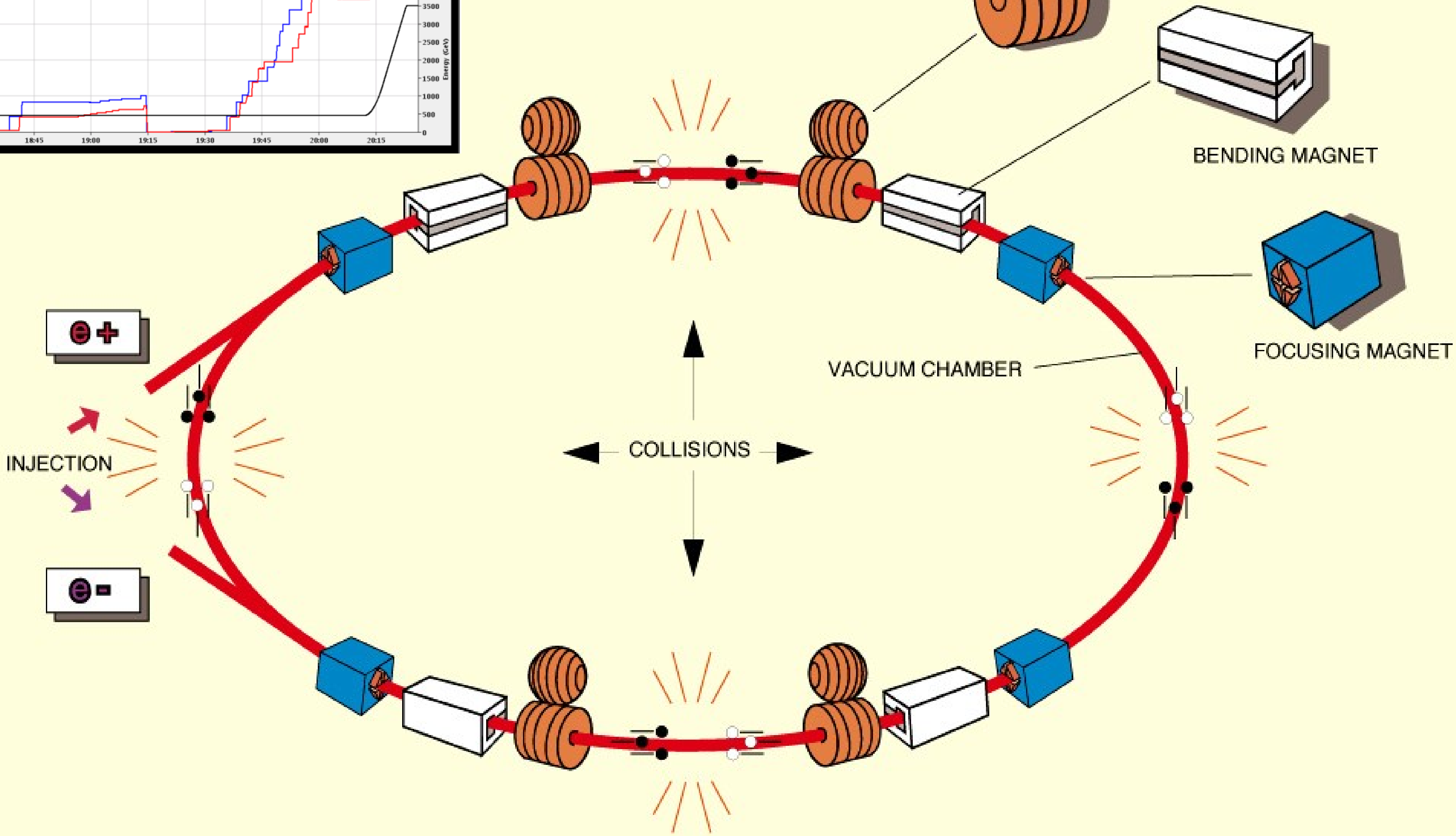
Part of Radioactive Isotope Beam Factory (RIBF) at Riken
World's highest intensity beam, 8,300 tons, 18.4m, diameter, Field=3.8 T,
Accelerate uranium up to 350 MeV/nucleon

The March of the Synchrotrons

Bevatron, LBL (1954 – 1993)
Discovered anti-proton and anti-neutron

Principal Components of a Synchrotron



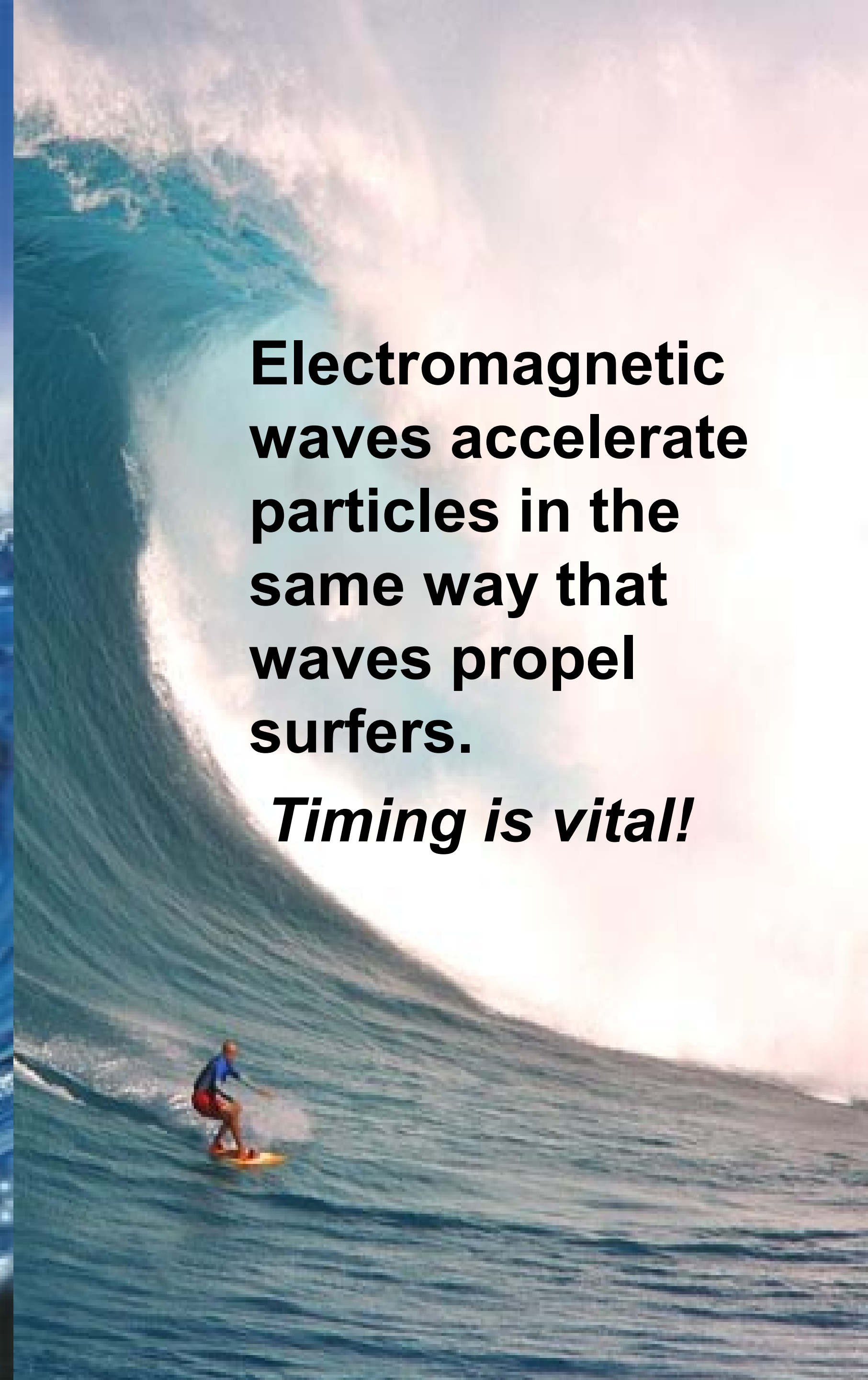


In a **Collider**, bunches of particles/antiparticles circulate in opposite directions.

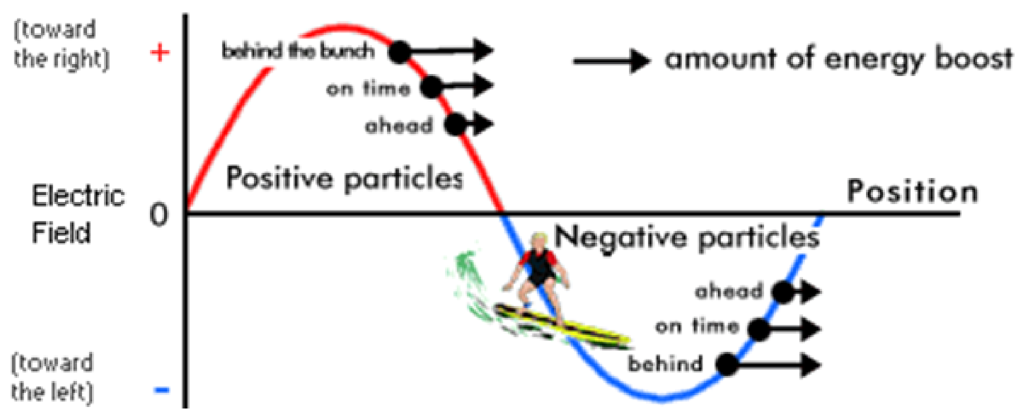
CERN AC - E509

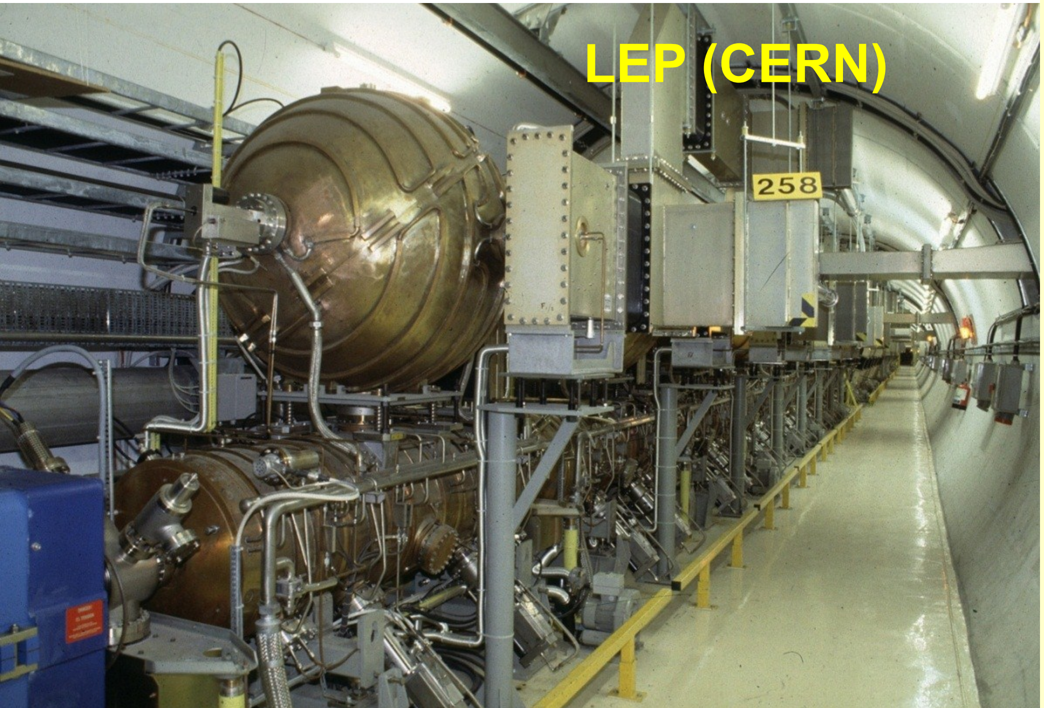
Super Proton Synchrotron (CERN)

Bending Magnets


Electromagnetic waves accelerate particles in the same way that waves propel surfers.
Timing is vital!

RF and Phase Stability





Phase stability

Cavity set up so that particle at centre of bunch acquires just the right amount of energy.

Particles see voltage:

$$V_0 \sin 2\pi\omega_{rf} t = V_0 \sin\varphi(t)$$

In case of no acceleration, synchronous particle has $\varphi_s = 0$

Particles arriving early see $\varphi < \varphi_s$

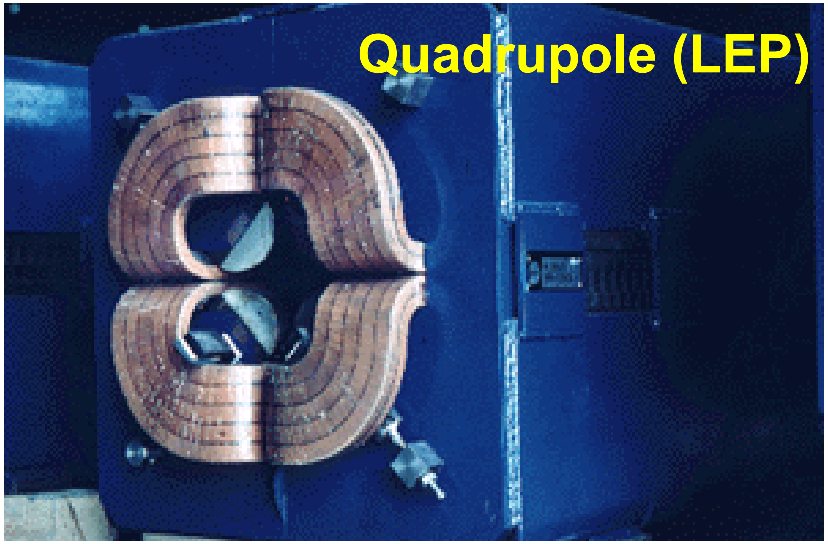
Particles arriving late see $\varphi > \varphi_s$

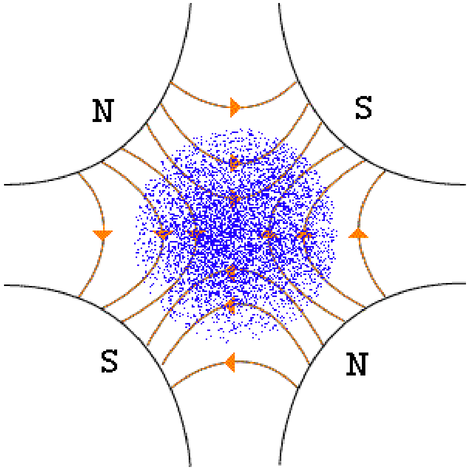
Energy of those arriving early is decreased and vice-versa.

To accelerate make $0 < \varphi_s < \pi$ so that synchronous particle gains energy.

$$\Delta E = qV_0 \sin\varphi_s$$

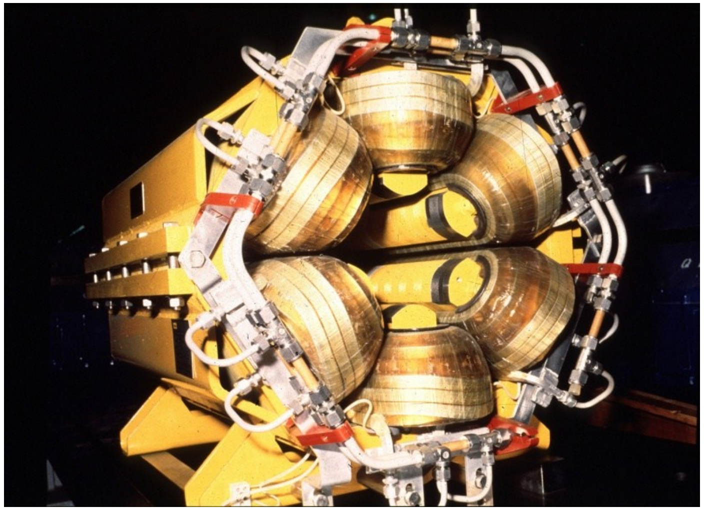
Focussing Magnets

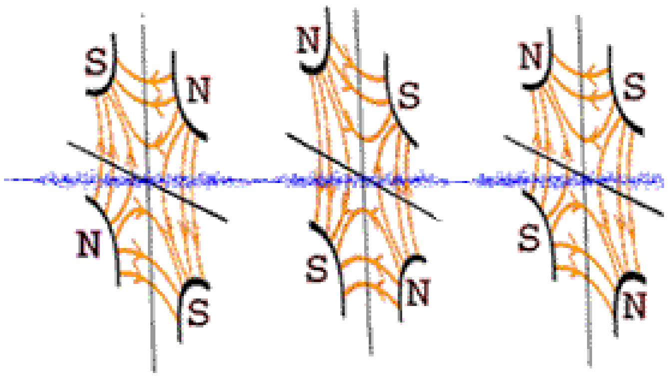


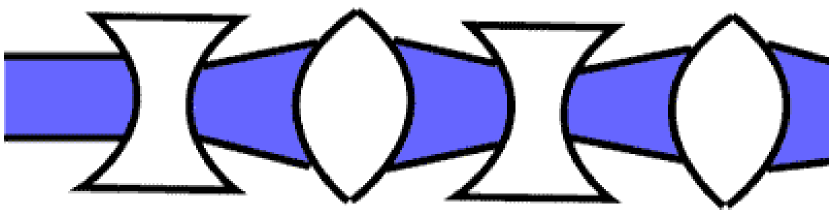


Strong Focussing
Beam alternately focussed in horiz and vert planes.

Sextupole (LEP)
Correction of chromatic spread.

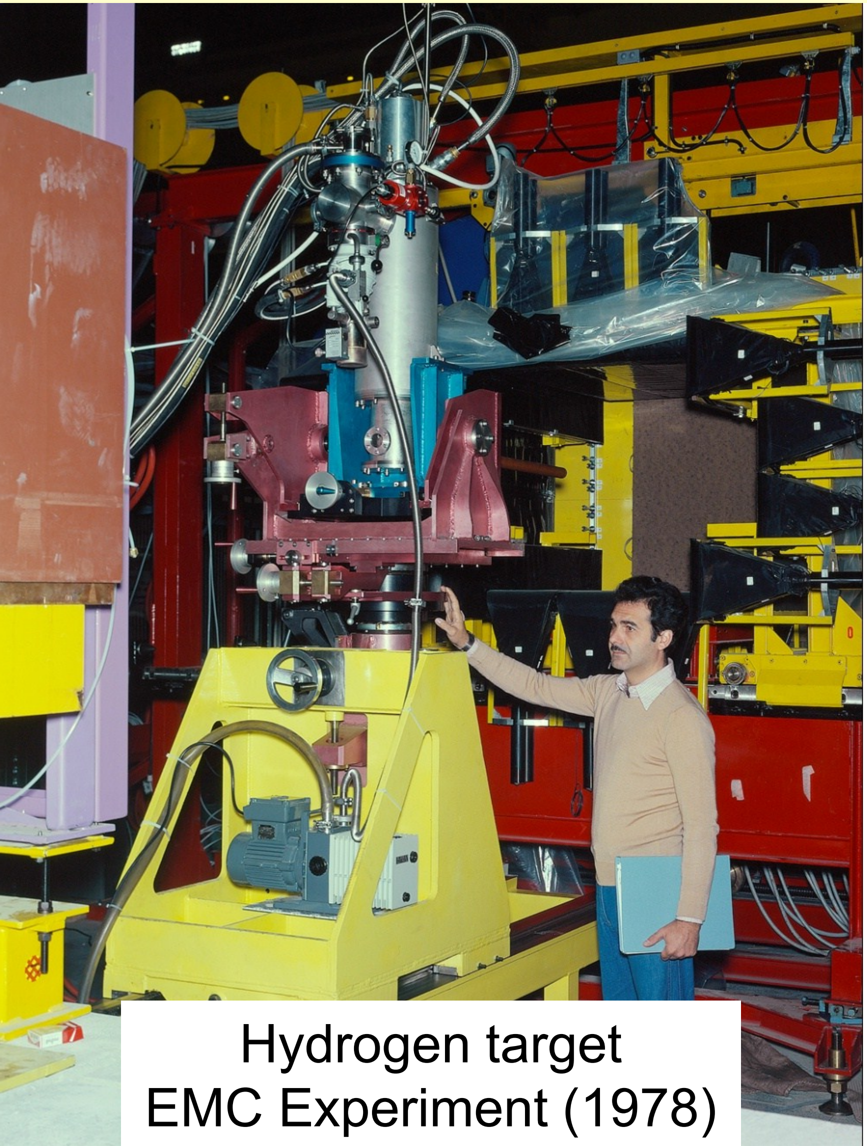




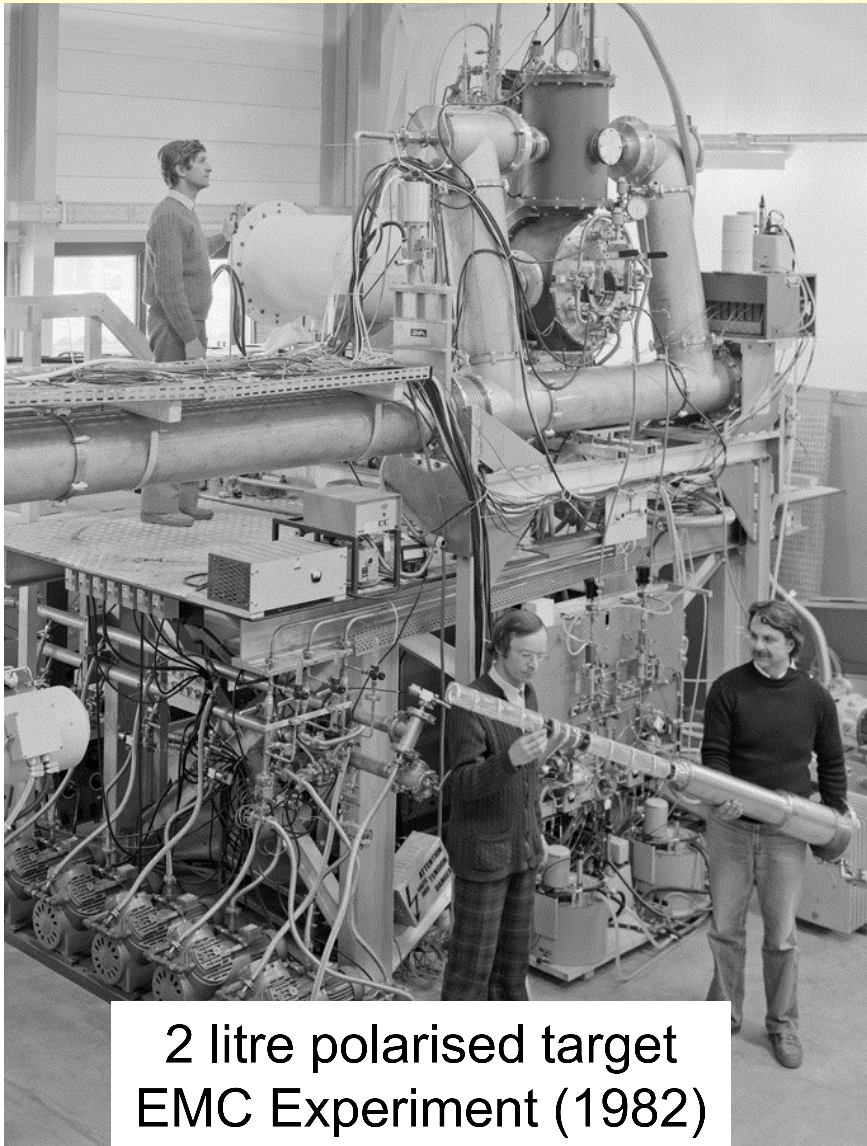


Fixed Target Experiments

Rutherford used a fixed target of gold foil. Same idea used up to the 1980s with liquid hydrogen (lots of protons) commonplace as the target.



Hydrogen target
EMC Experiment (1978)



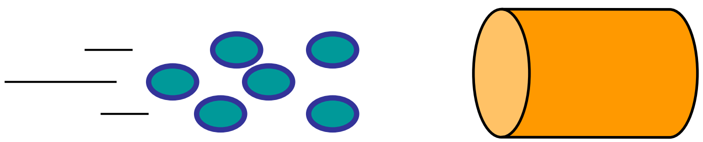
2 litre polarised target
EMC Experiment (1982)

Colliding Beam Machines

Rolf Wideroe (Norway) first had the idea of colliding two beams of particles head-on in order to maximise the energy available.

Bruno Touschek applied the idea.

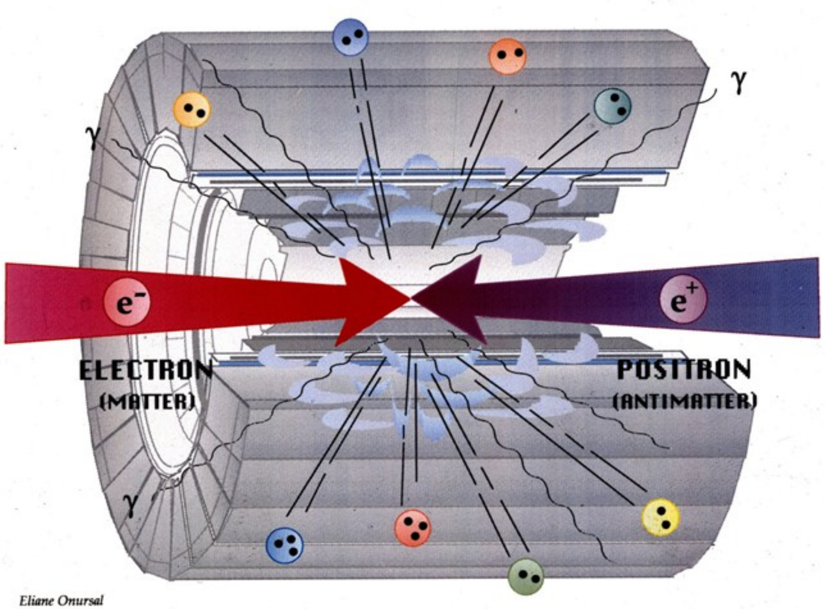
Fixed target



$$E_{CM} \approx \sqrt{(2m_T E_b)}$$

Collider

$$E_{CM} \approx 2E_b$$

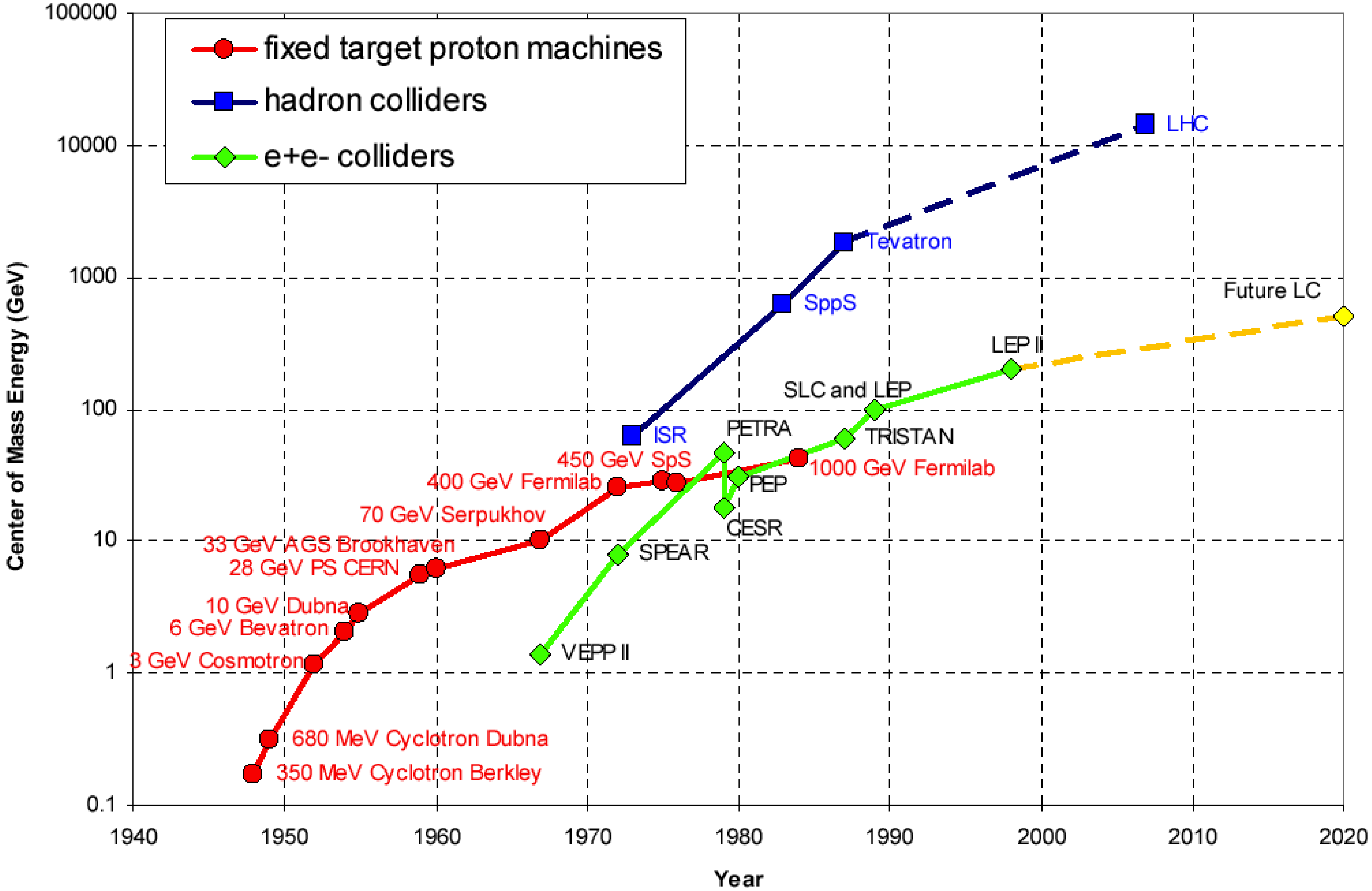


E_b = 100 GeV

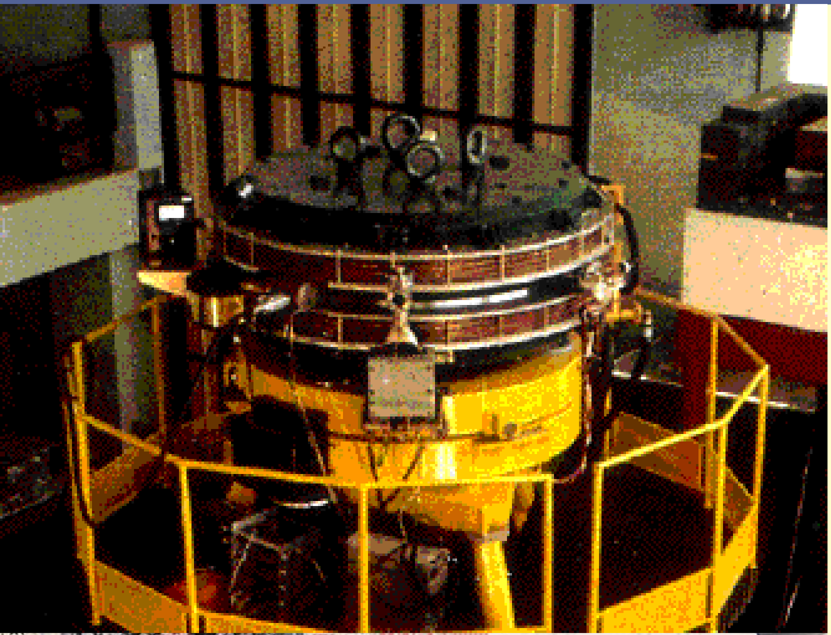
E_{CM} = 200 GeV in e^+e^- collider.

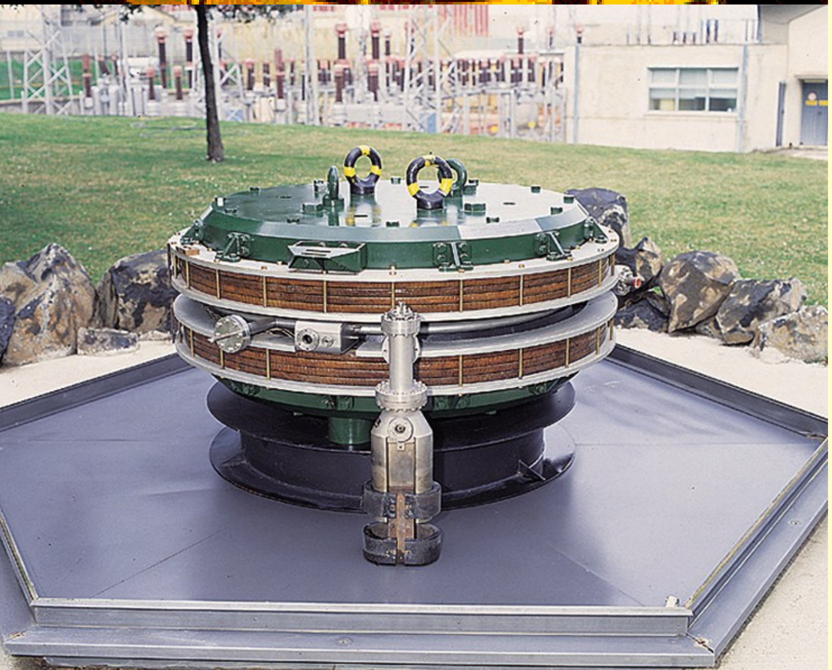
E_{CM} = 0.32 GeV for e^+ beam hitting an atomic electron.

Energy Frontier



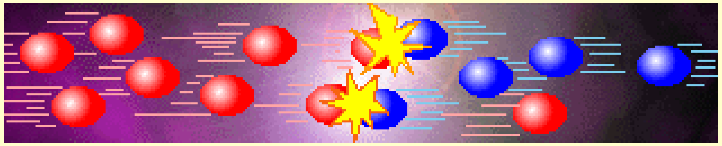
Colliding Electrons and Positrons





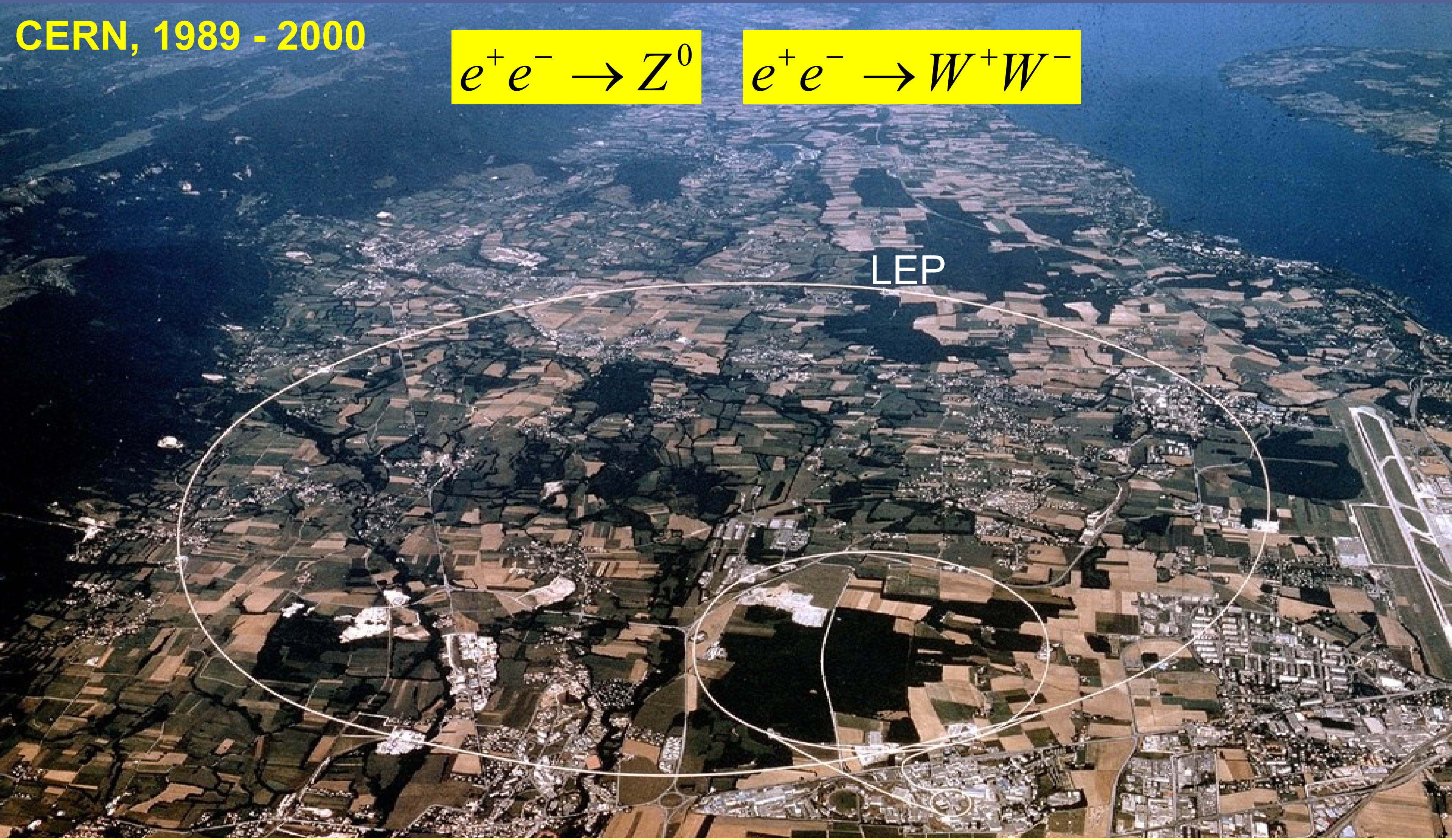
First electron-positron collider:

AdA, Frascati, Italy (1961-1964).



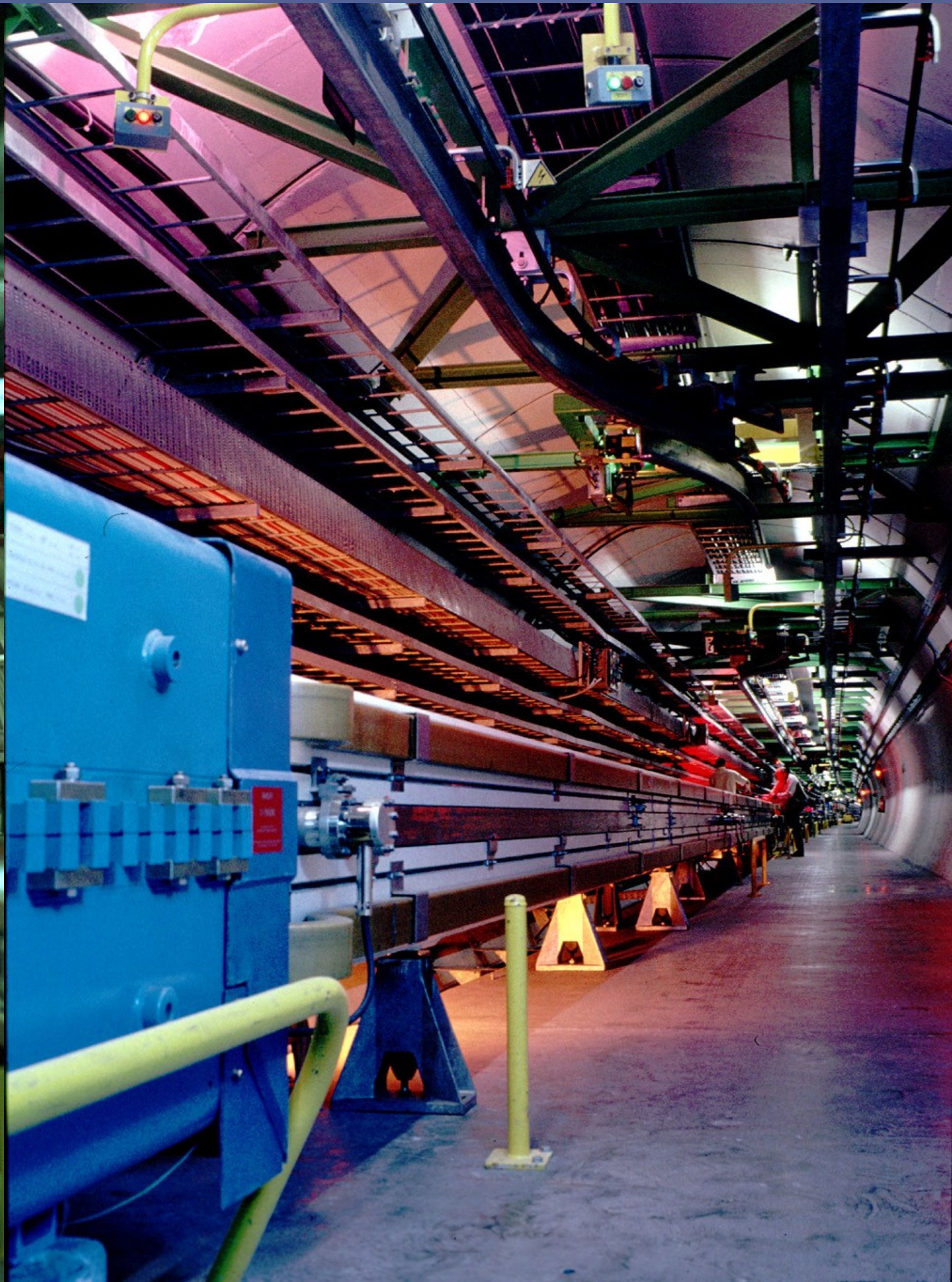
- Shipped to LAL, Orsay, France to locate alongside a better injector - a high intensity linear accelerator.
- First electron-positron interactions observed in 1964.
- Spawned a series of e^+e^- colliders: ADONE (Italy), VEPII (Russia) and most notably SPEAR (USA). Later PETRA, PEP, LEP...

Large Electron Positron Collider (LEP)



27km circumference , CM energy = 209 GeV, 3,368 dipoles
revolution frequency = 11,245.5 Hz, 10^{11} particles/bunch

LEP – Z Factory



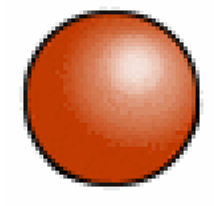
Hadron Colliders – Quark Machines

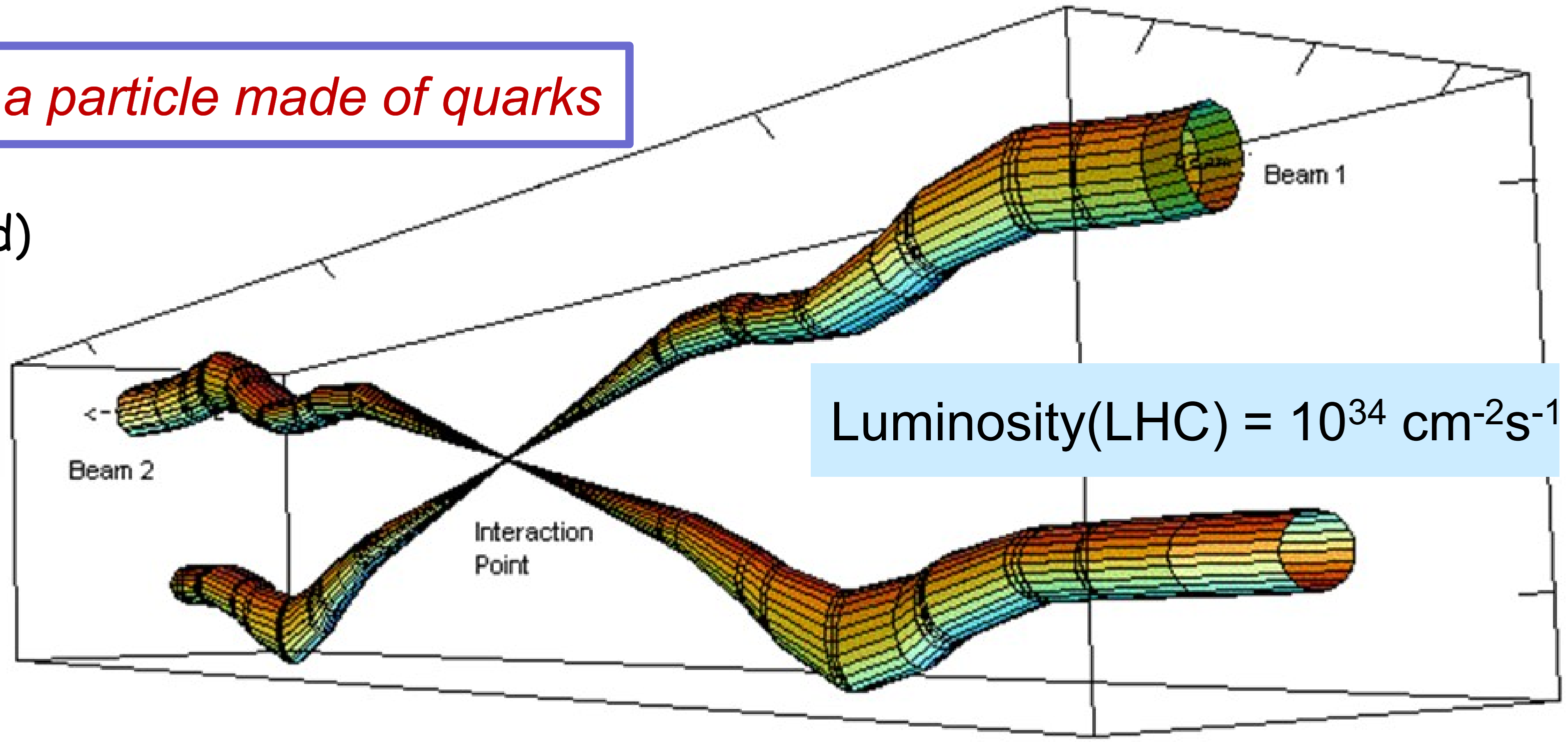
"Splitting the atom by bombardment is something like shooting sparrows in the dark in a place where there are only few birds".

Albert Einstein (1934)

Hadron *– a particle made of quarks*

proton (uud)





Luminosity(LHC) = 10^{34} $cm^{-2}s^{-1}$

The Large Hadron Collider has to collide bunches of 100 billion protons squeezed to 16 microns in diameter around a 27km ring!

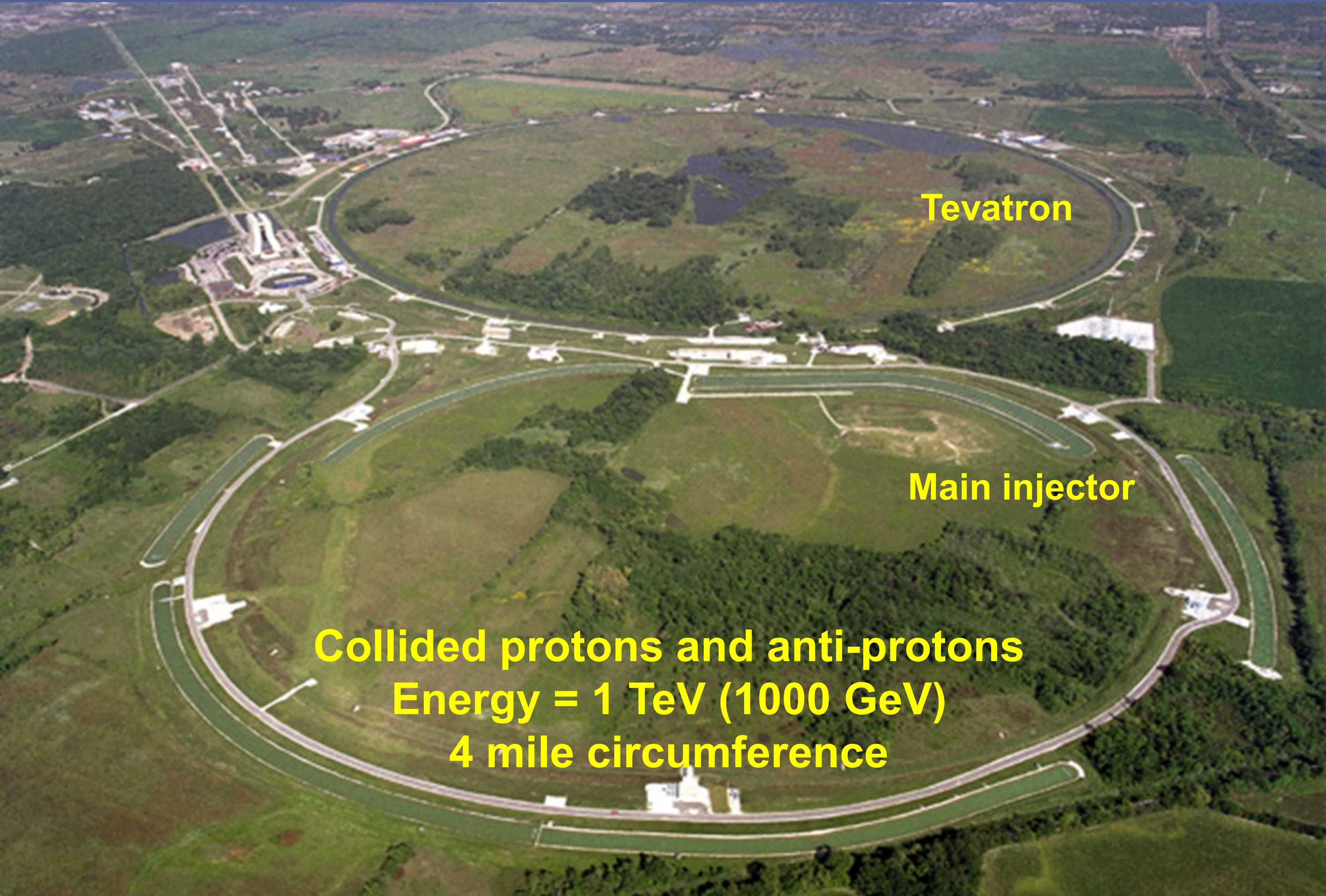
Intersecting Storage Rings (1971-1984)

27 January 1971: Two beams of protons collided in the ***Intersecting Storage Rings (ISR)*** at CERN for the first time.

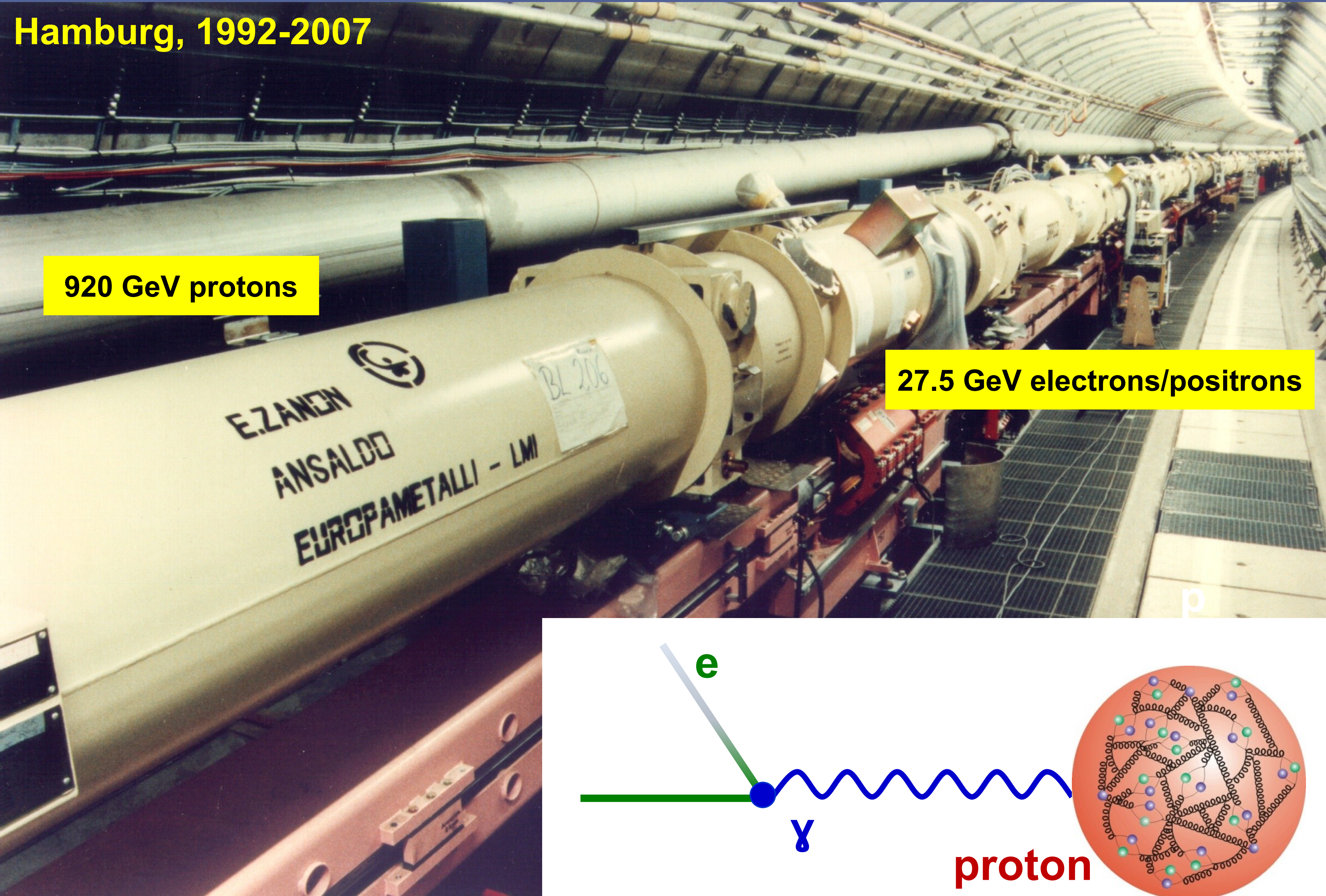
World's first hadron collider paving the way for the LHC.

- Important for research in accelerator physics.
- Necessary technical step to SPS ppbar, LEP and LHC colliders.
- Stochastic cooling invented .
- No major discovery of historical importance.
- Missed out on Nobel prizes for J/ψ and ϒ particles.

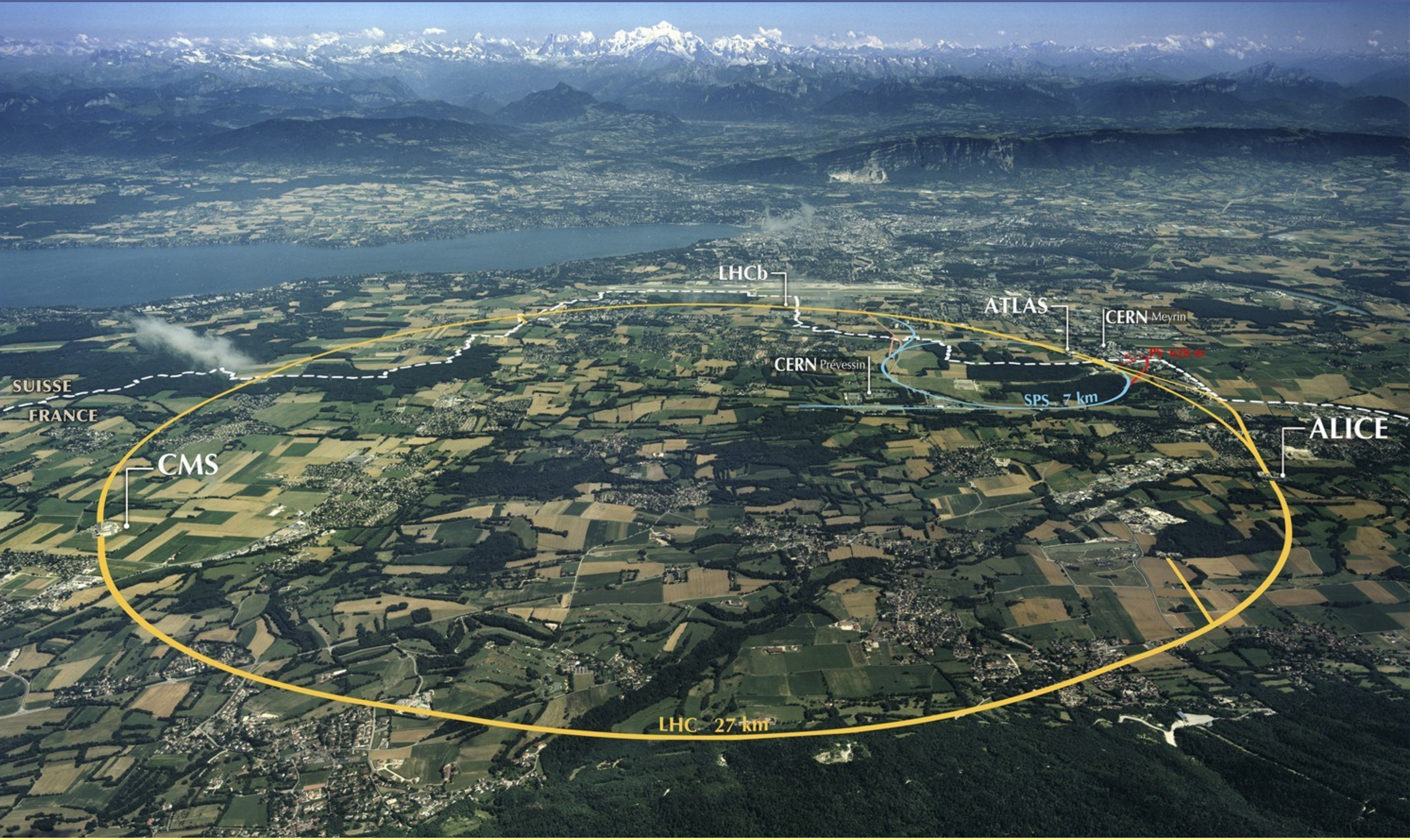
Tevatron (FermiLab, Chicago)



Electron Proton Collider - HERA(6.3 km)



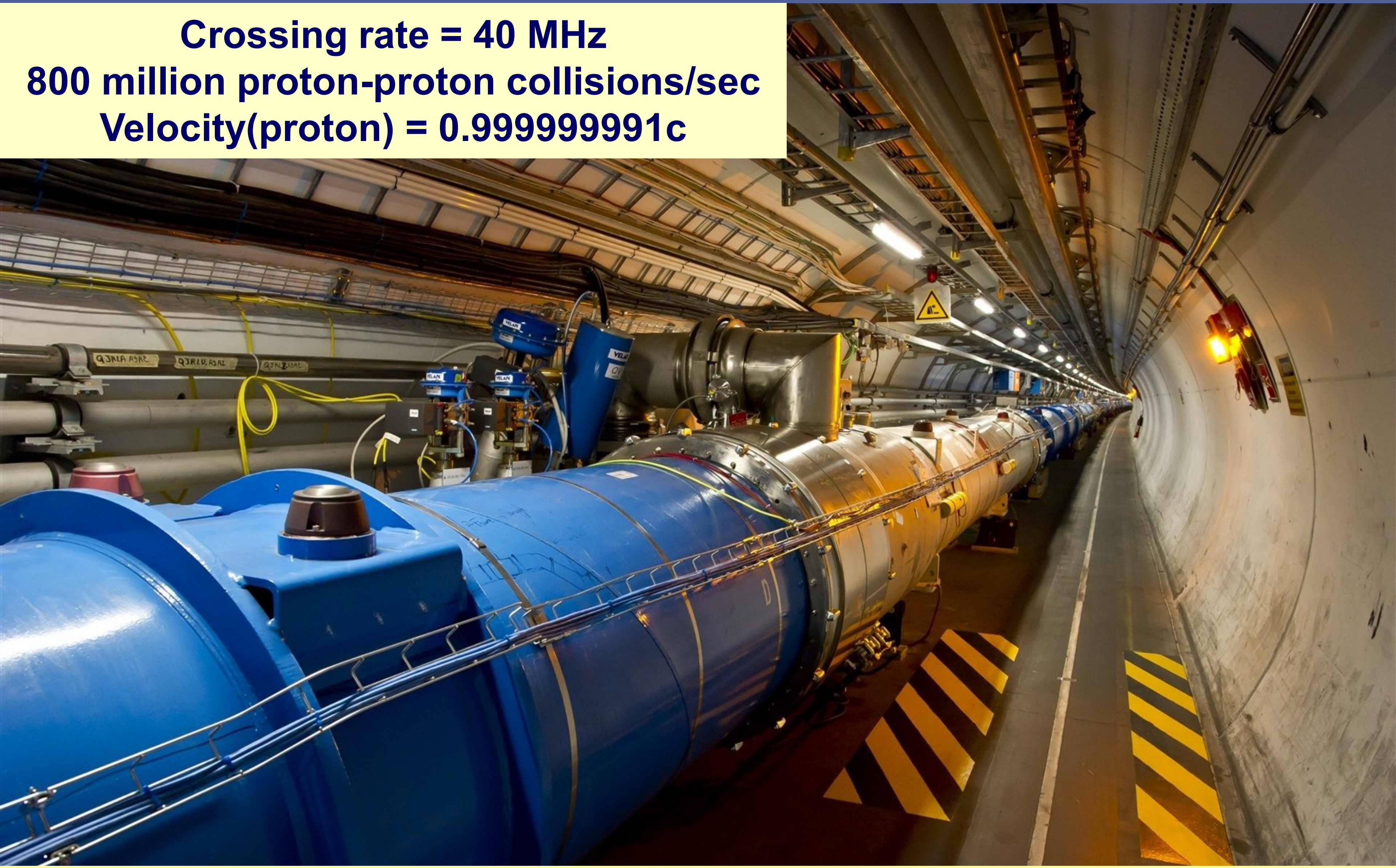
Large Hadron Collider (LHC)



27km circumference , ~100m underground

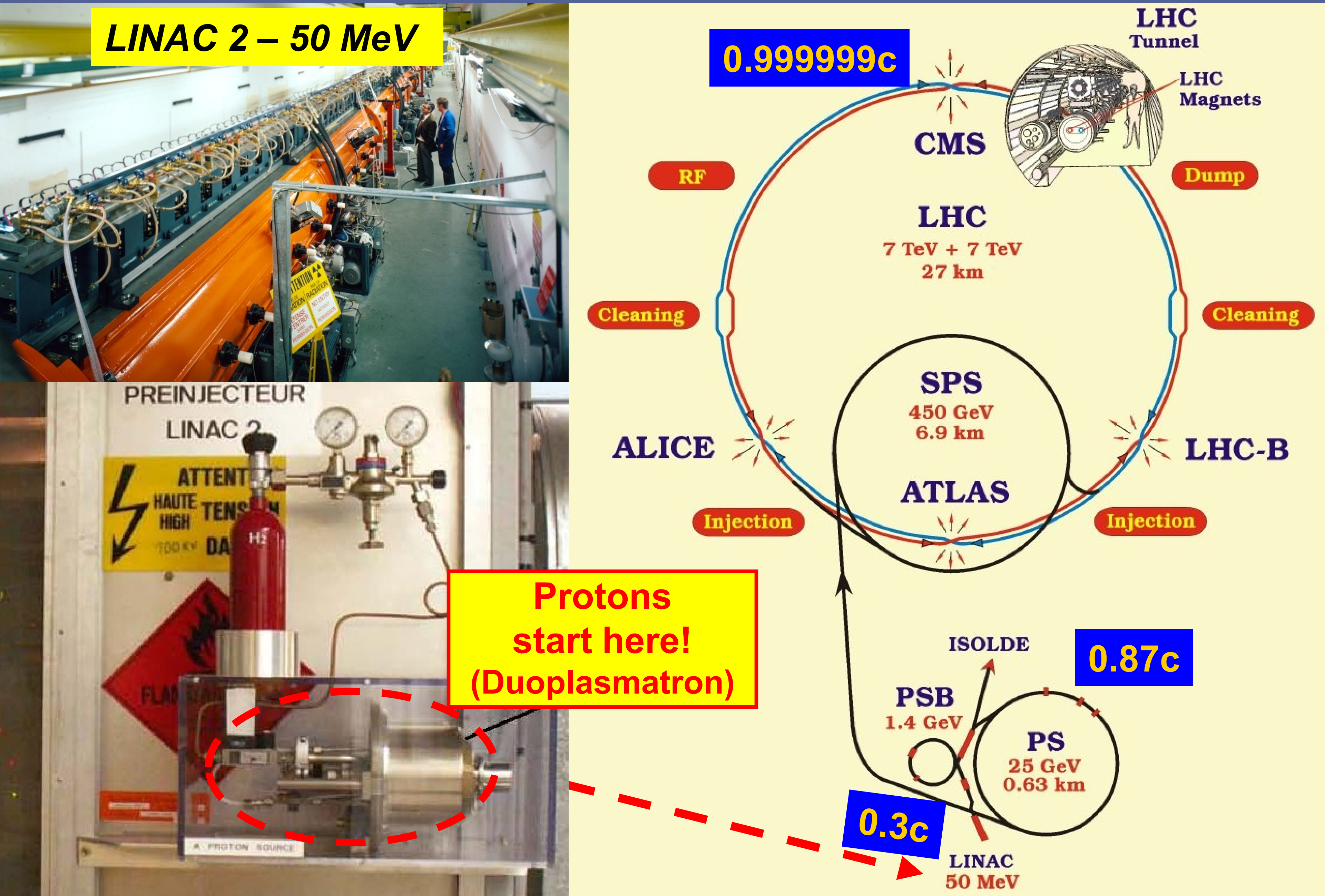
Large Hadron Collider (LHC)

Crossing rate = 40 MHz
800 million proton-proton collisions/sec
Velocity(proton) = 0.999999991c

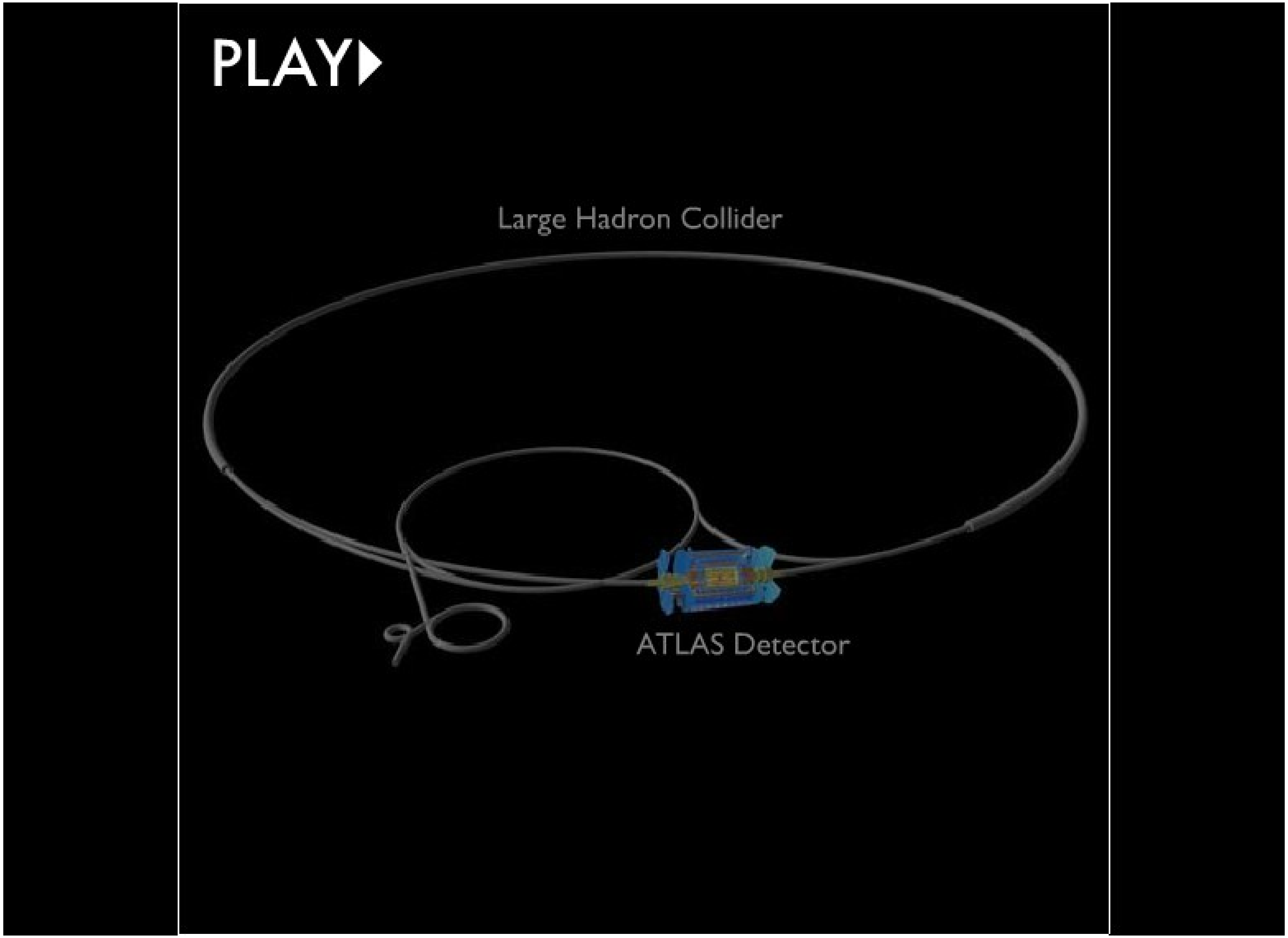


The most energetic sub-atomic particles on the planet.

Not Just One Accelerator



How it Works



Bending Magnets

LHC design magnet current = 11,850A, but the machine is 27km long!

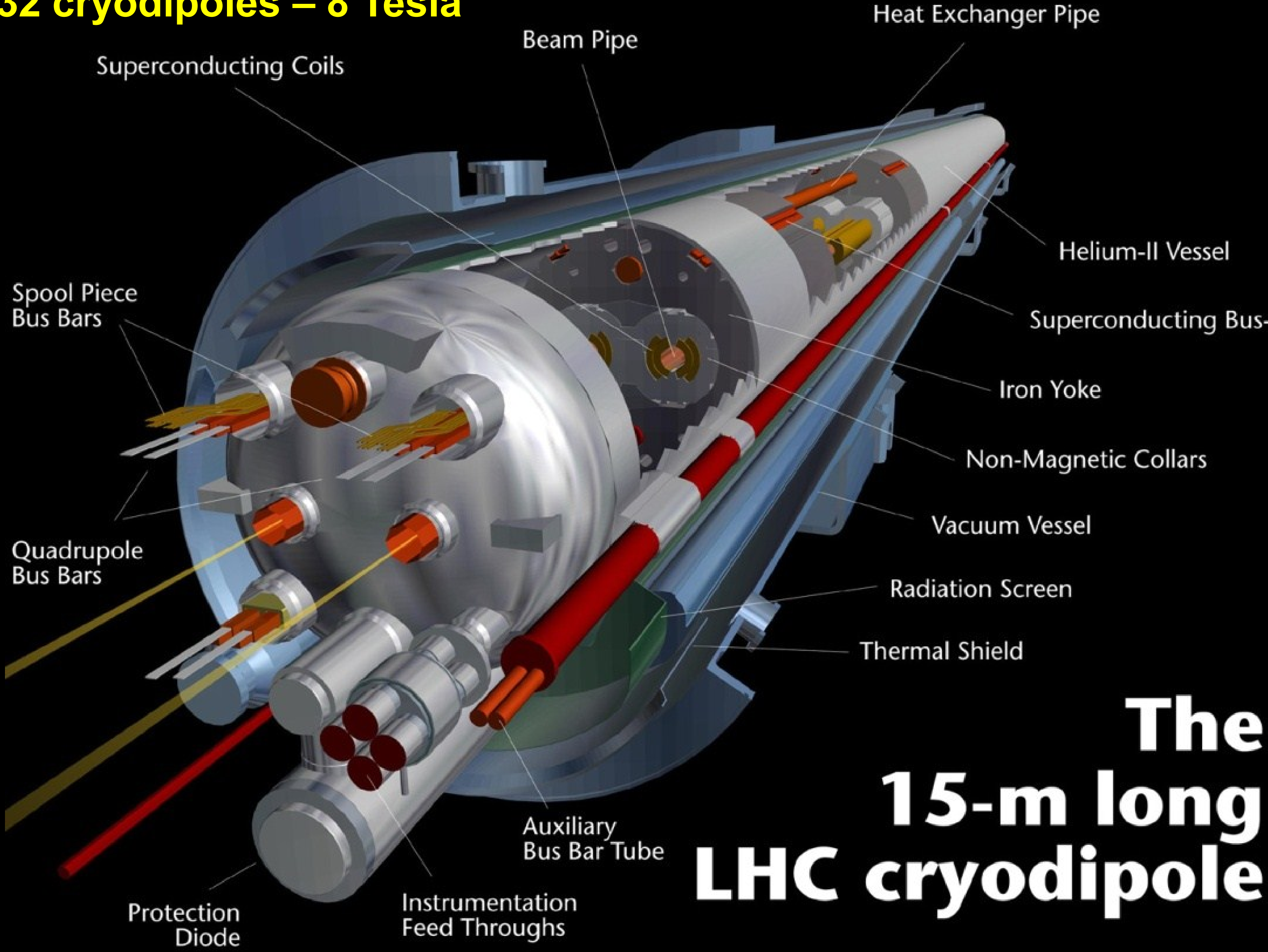
$$P = I^2 R$$

Reduce ohmic losses to a minimum.

Solution: ***Superconductivity***

Bending Magnets

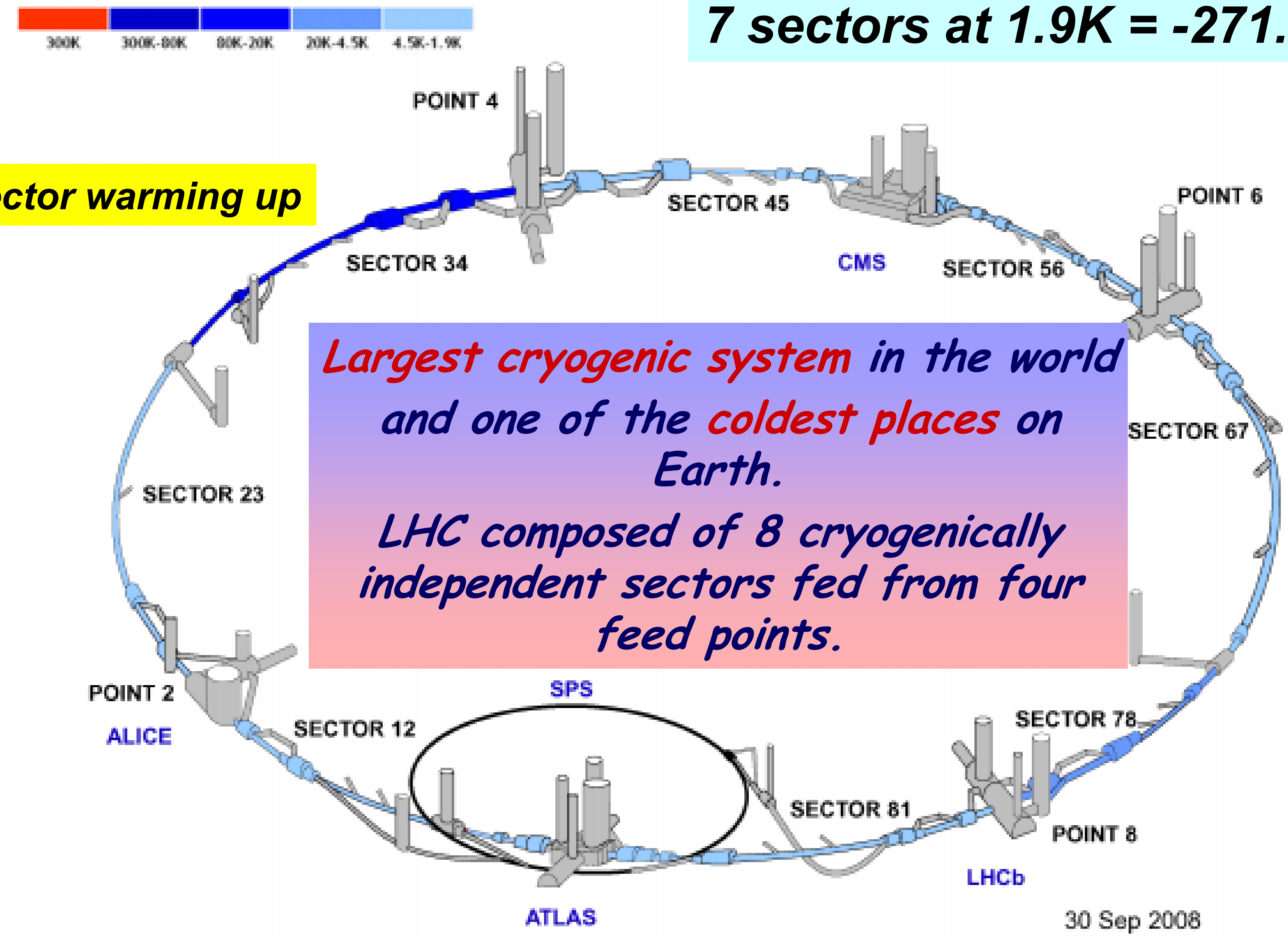
1,232 cryodipoles – 8 Tesla



Very Cold Machine

7 sectors at 1.9K = -271.1°C

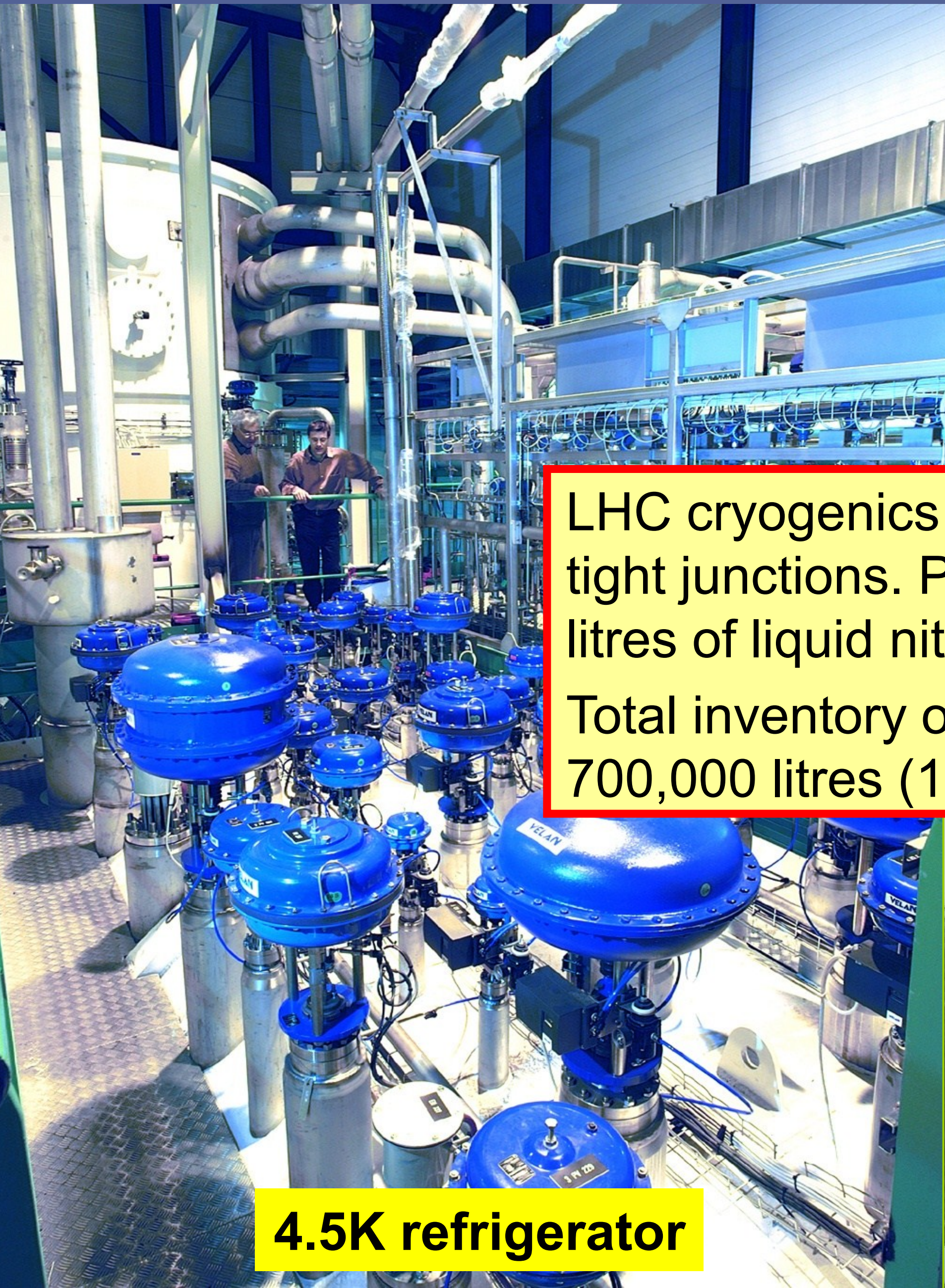
Sector warming up

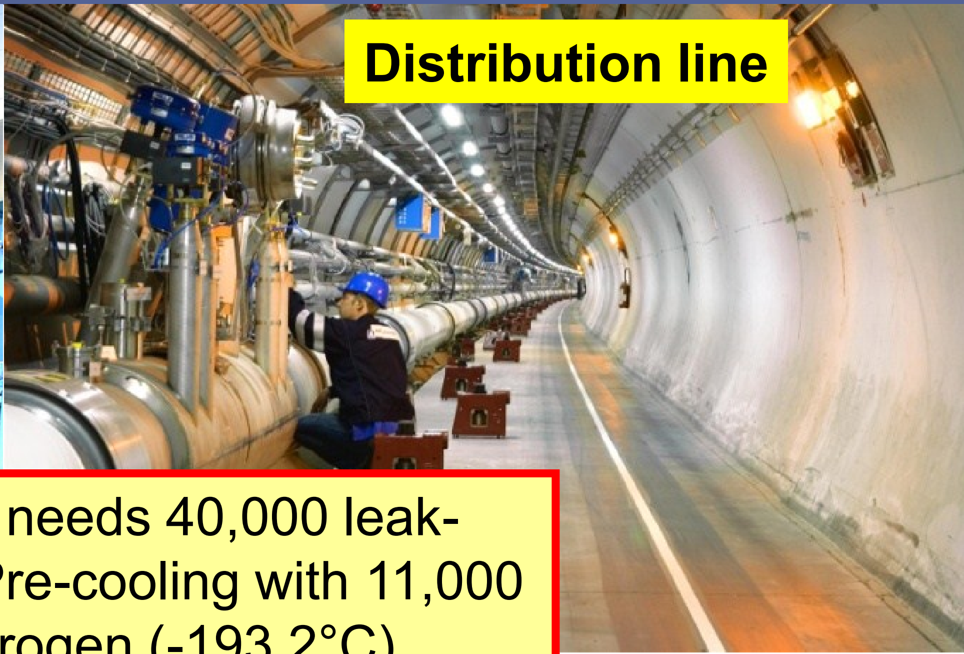


Largest cryogenic system in the world and one of the coldest places on Earth.

LHC composed of 8 cryogenically independent sectors fed from four feed points.

Superconducting Cryogenics



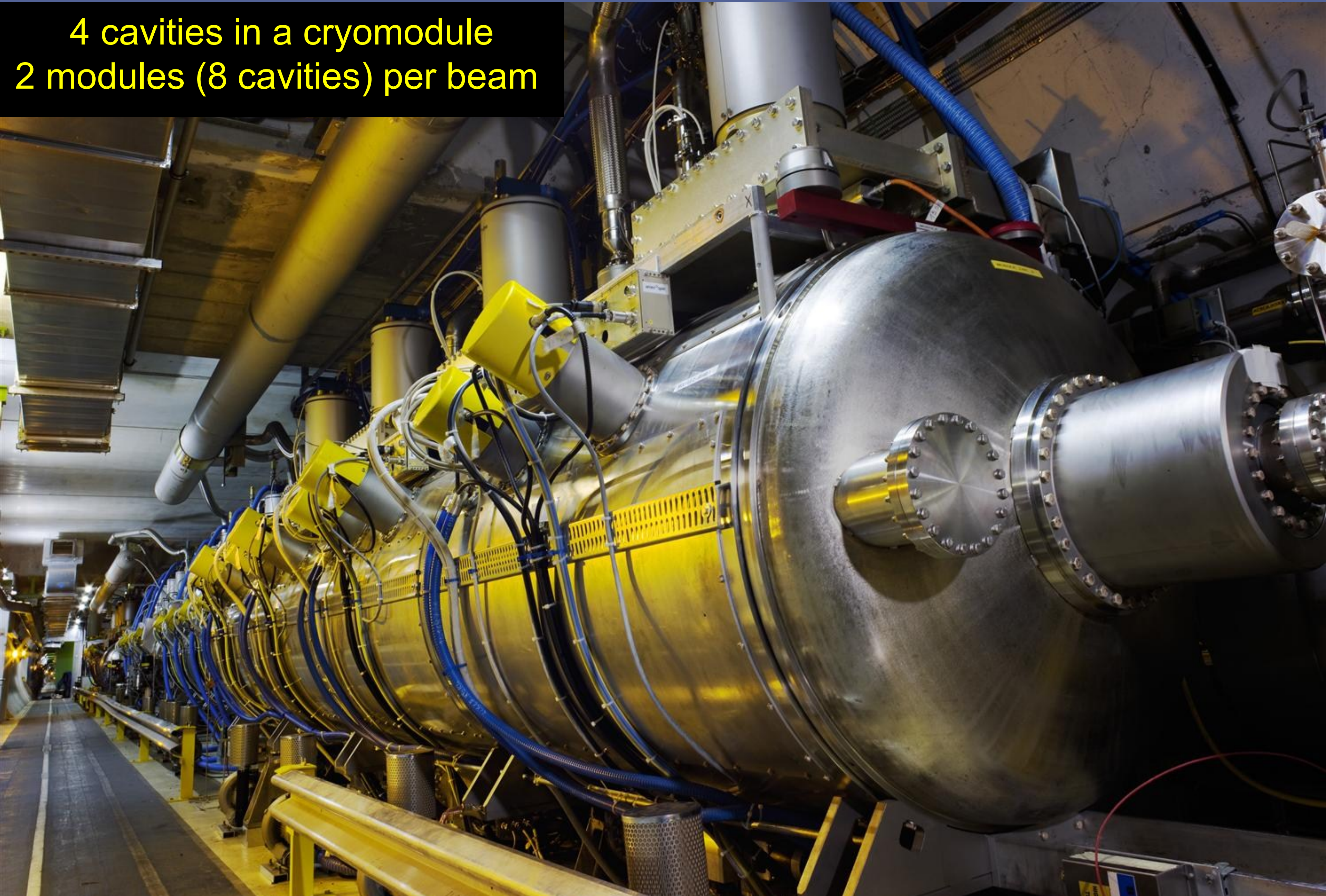


LHC cryogenics needs 40,000 leak-tight junctions. Pre-cooling with 11,000 litres of liquid nitrogen (-193.2°C).

Total inventory of liquid helium is 700,000 litres (100 tonnes).

Superconducting RF Cavity

4 cavities in a cryomodule
2 modules (8 cavities) per beam



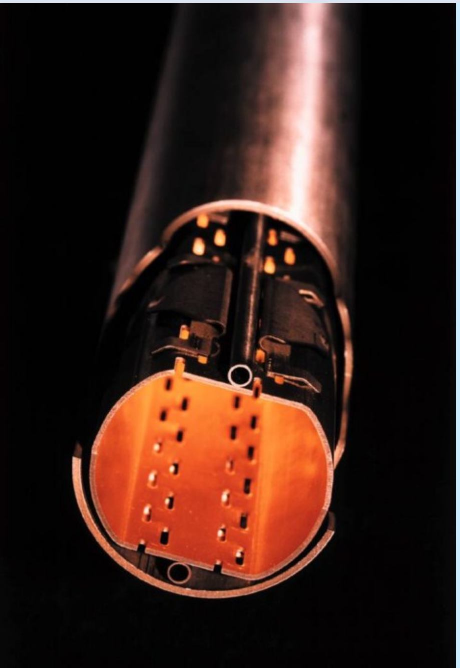
Proton Beams

Each bunch of 100 billion protons is squeezed to 16 microns in diameter as they approach the experiments.

Peak Luminosity ~10^{34} $cm^{-2}s^{-1}$

Energy stored in one beam is 360 MJoule.

- Energy of TGV train at 150 km/hour.
- 77 kg of TNT.
- Enough to melt 0.5 tonne of copper.
- Aircraft carrier travelling at 12 knots.

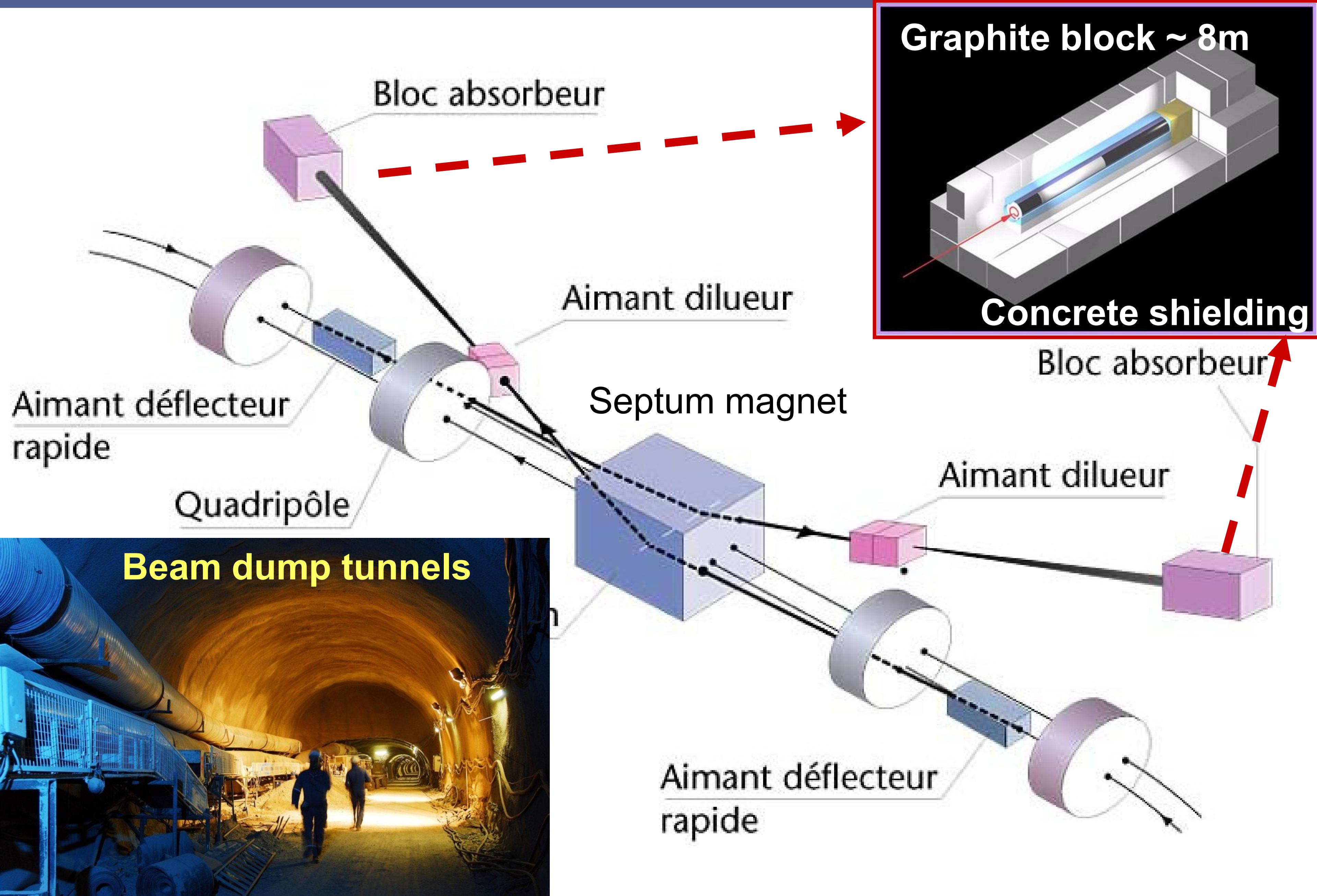


Vacuum ~ 10^{-13} Torr.

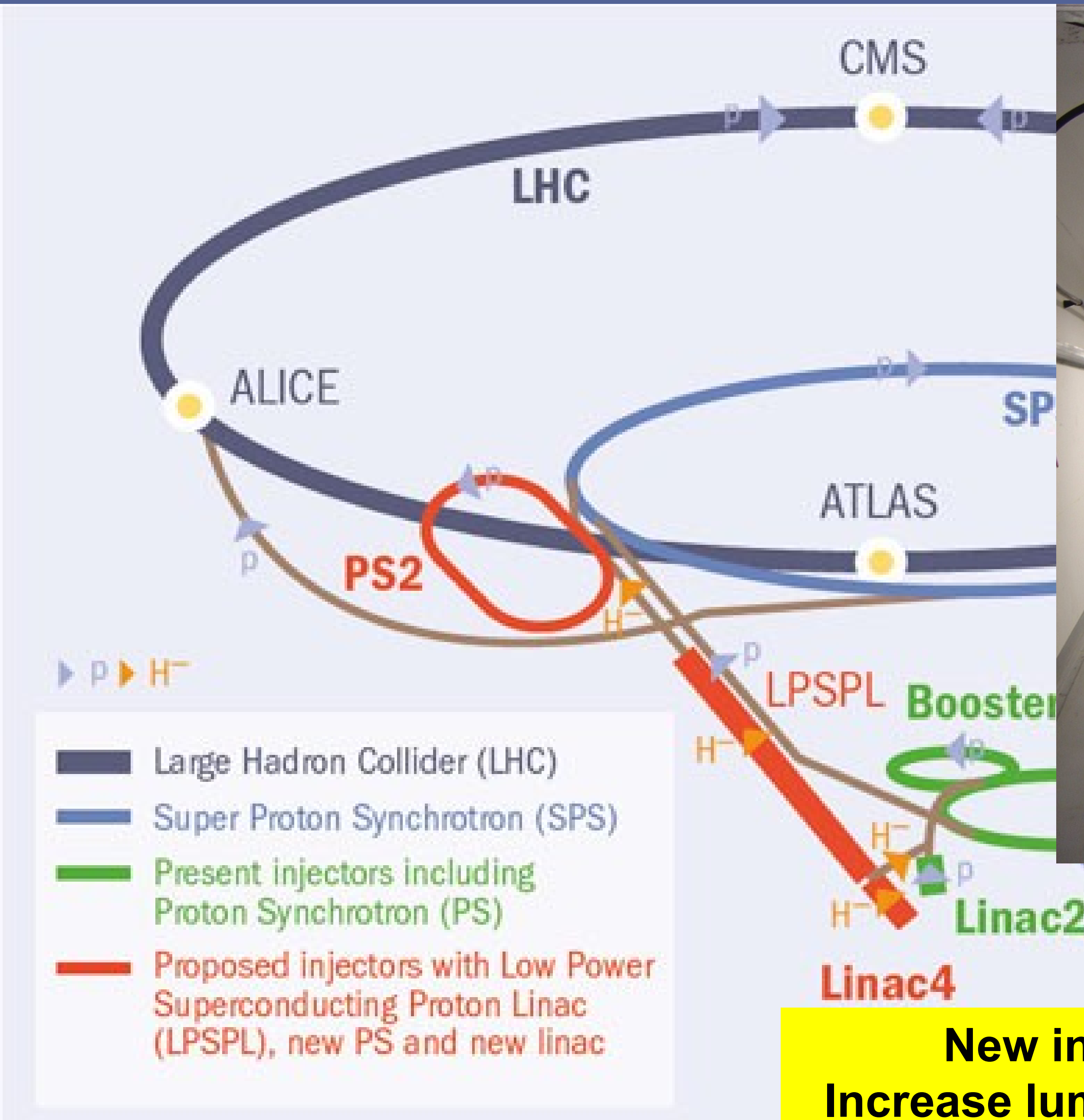
Total pumped volume ~6500 m^3

Size of a cathedral!

Beam Dumps


Graphite block ~ 8m
Concrete shielding
Bloc absorbeur
Aimant dilueur
Aimant déflecteur rapide
Quadripôle
Septum magnet
Aimant dilueur
Bloc absorbeur
Beam dump tunnels
Aimant déflecteur rapide

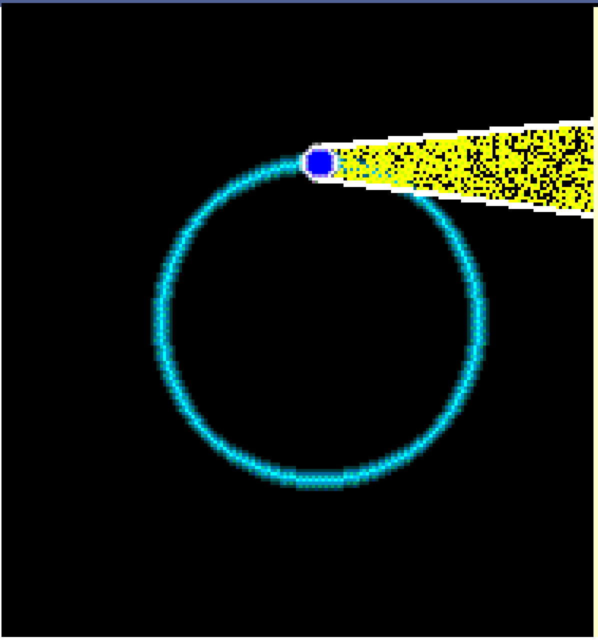
Intensity Frontier: Super LHC



LINAC4
In the beginning...

New injector accelerators
Increase luminosity by a factor of 10

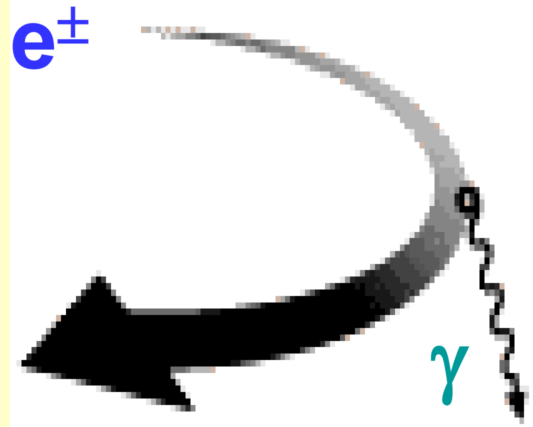
Synchrotron Radiation



A charge undergoing acceleration will radiate energy.

Radial acceleration gives rise to **synchrotron radiation.**

First observed in a circular accelerator in 1947 (General Electric)



Energy loss per turn:

$$\Delta E = \frac{q^2}{3\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{R}$$

For **electrons** only:

$$\Delta E\,[\text{keV}] = 88.5 \frac{E^4\,[\text{GeV}^4]}{R\,[\text{m}]}$$

	Particle	Energy (GeV)	R(m)	ΔE (GeV)
LEP	electrons	104	3096.175	**3.3**
LHC	protons	7000	2803.95	6.7×10^{-6}

~3% of total beam energy!

Diamond Light Source (RAL)

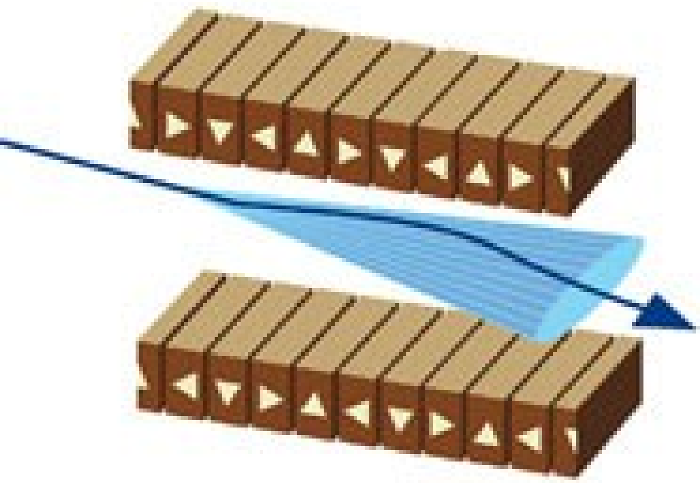
3 GeV electron storage ring. Started operation Feb 2007.

Energy loss = 3.785 MeV/turn

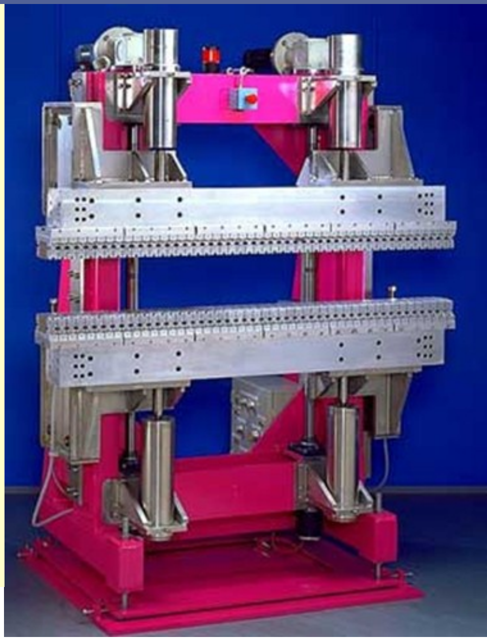
Uses synchrotron radiation for studies at molecular/atomic level.

Insertion Devices

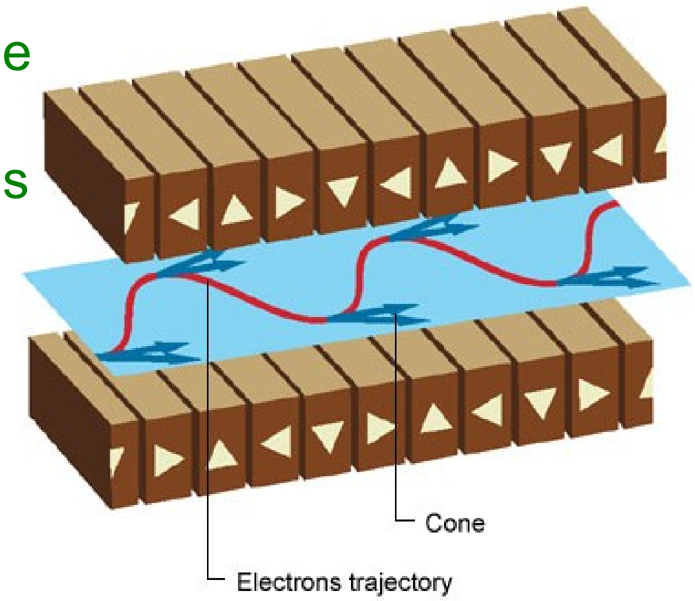
Wiggler
Wide cone, spread of wavelengths



Can increase flux & brightness of light from normal bending magnets many thousands of times by using **insertion devices**.



Undulator
Narrow cone
Specific wavelengths



Rows of small magnets which “jiggle” the electron beam causing it to emit more radiation.

Positioned on straight sections of the storage ring.

International Linear Collider

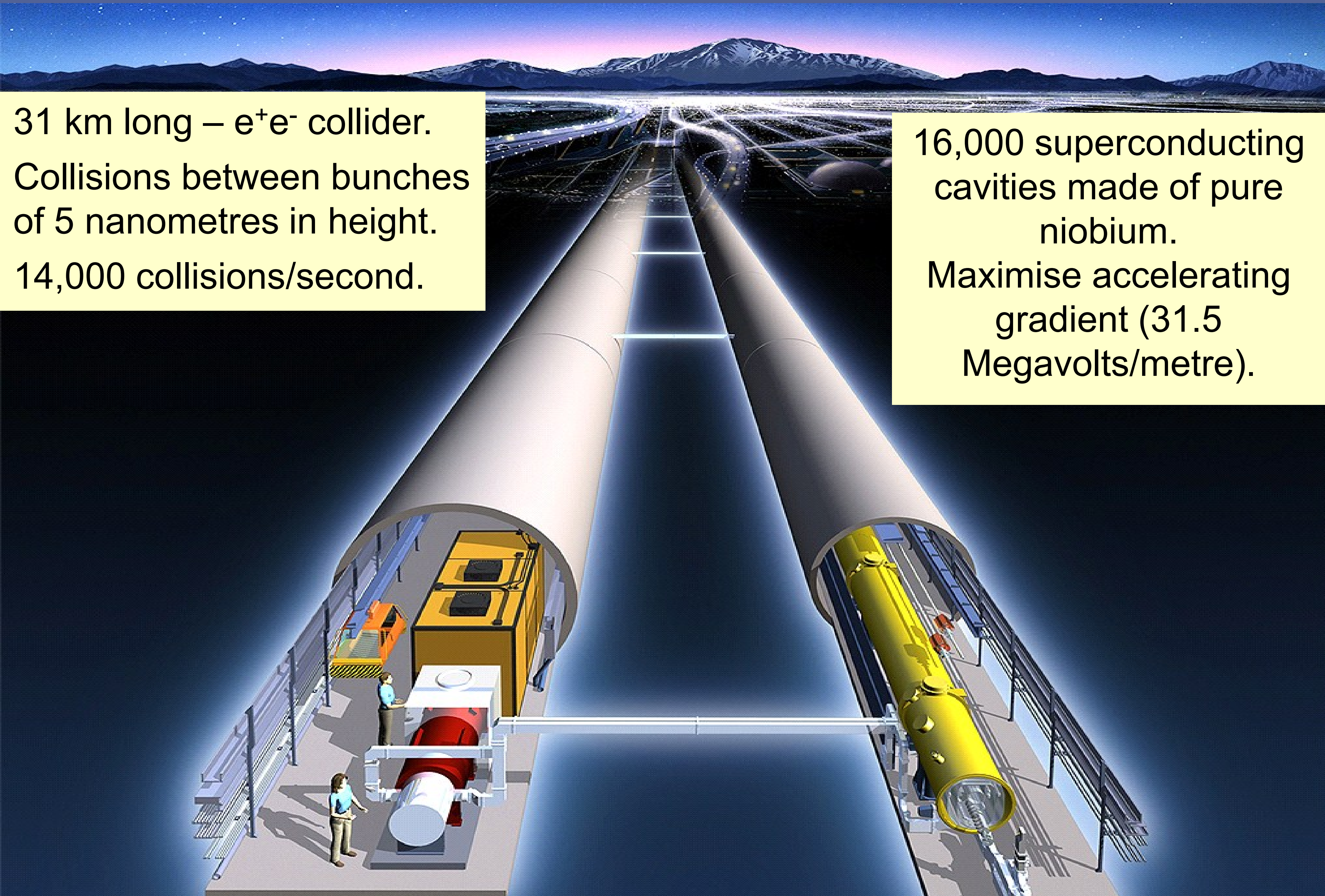
31 km long – e^+e^- collider.

Collisions between bunches of 5 nanometres in height.

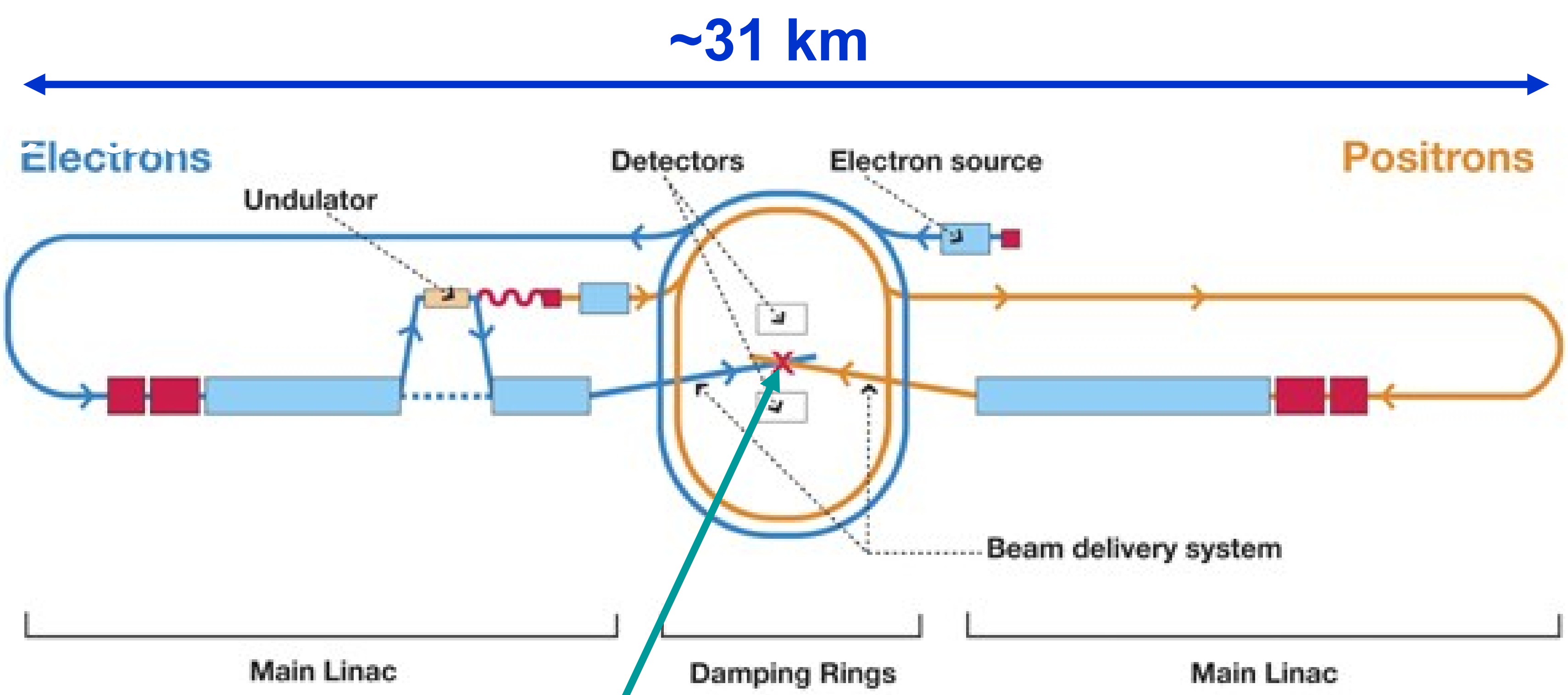
14,000 collisions/second.

16,000 superconducting cavities made of pure niobium.

Maximise accelerating gradient (31.5 Megavolts/metre).



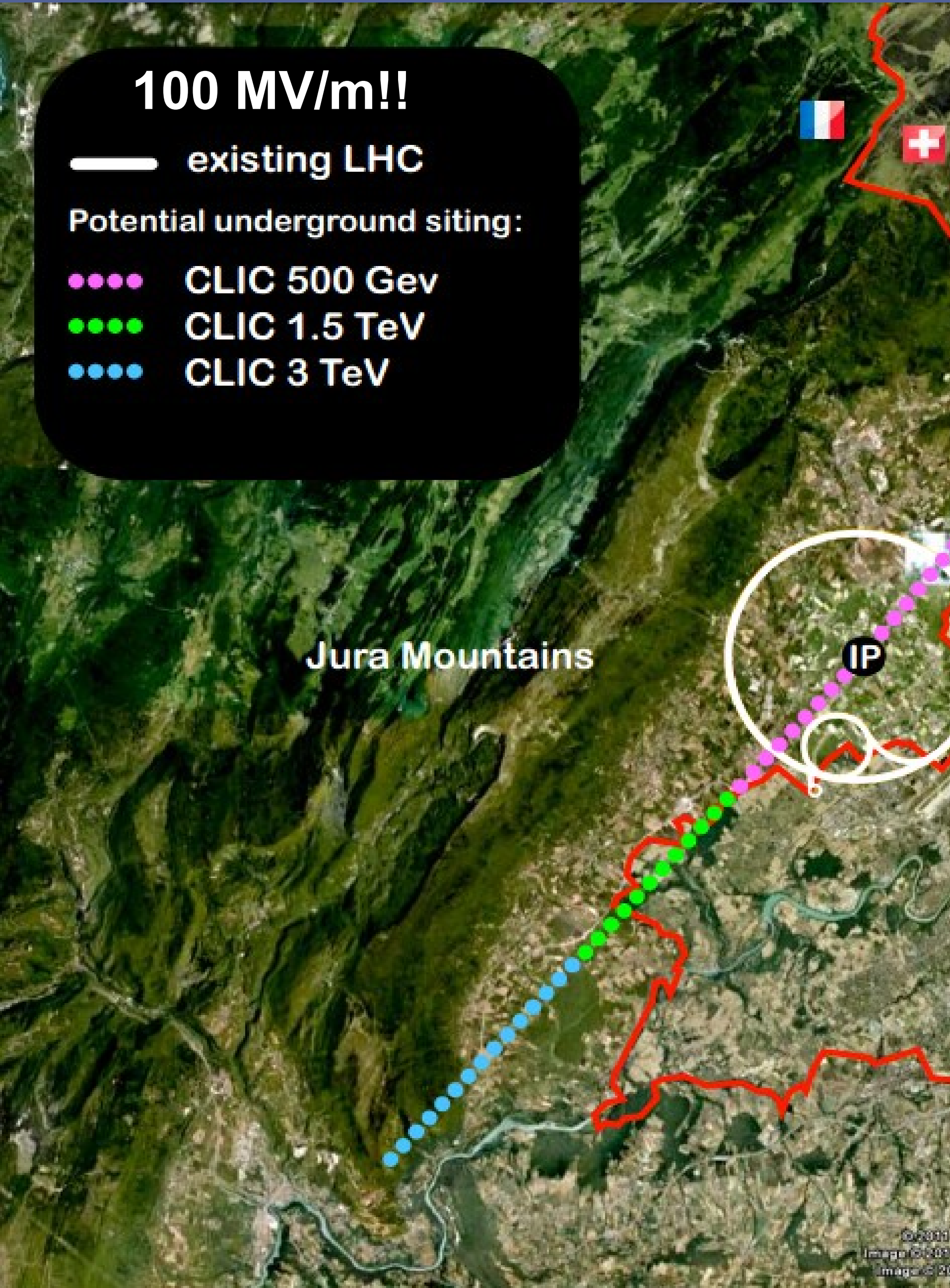
International Linear Collider

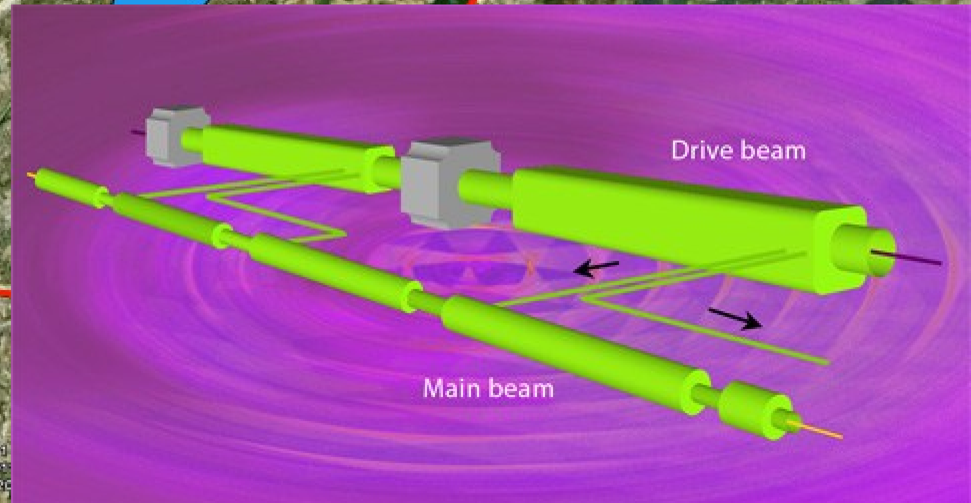


250 GeV electrons colliding with 250 GeV positrons

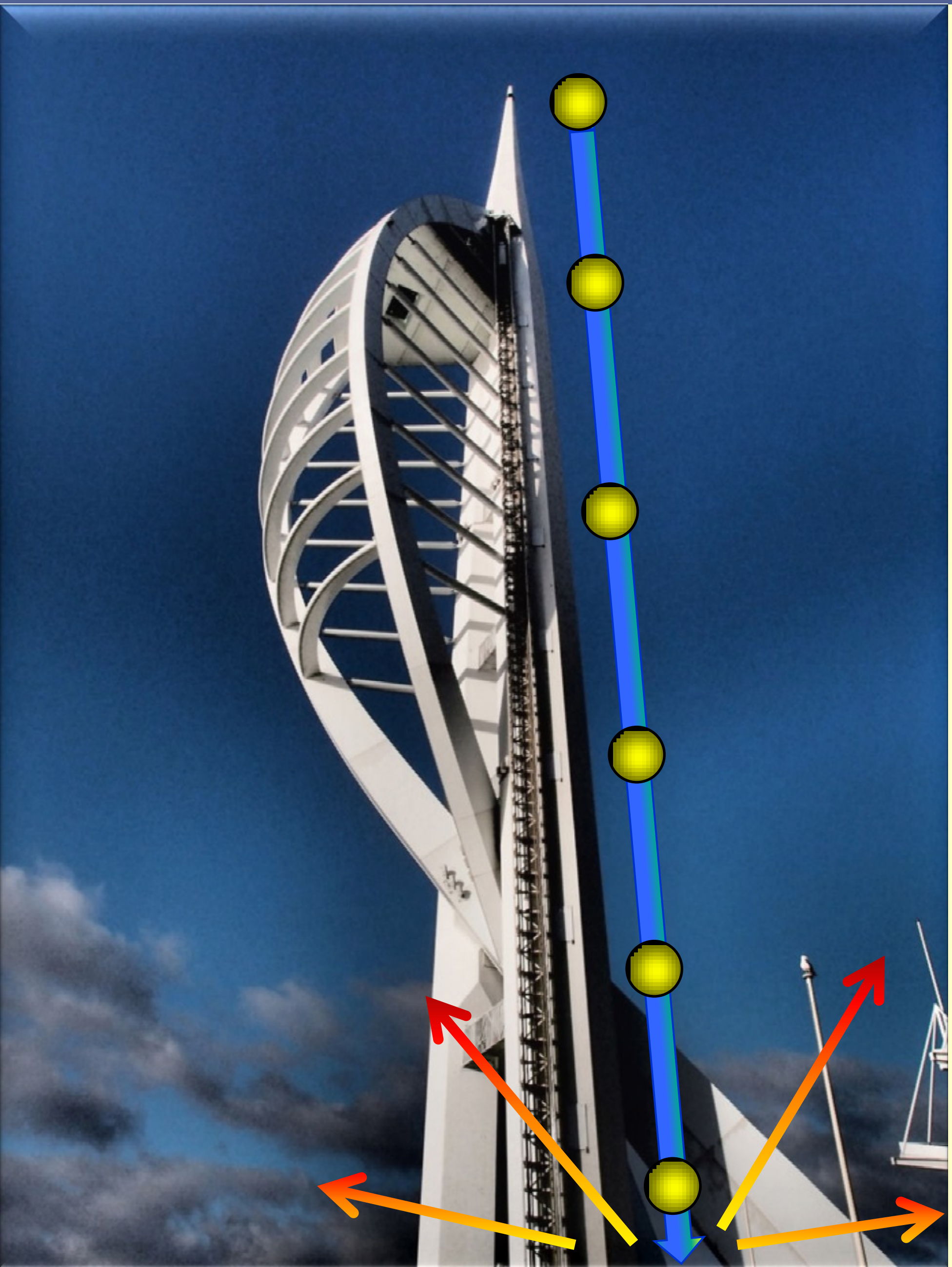
8 February 2007	Reference Design Report
2010 – 2012	Technical Design Phase
?	Construction/Operation

Compact Linear Collider (CLIC)





My Portsmouth Proposal: *Spinnakertron*



Spinnaker Tower - 170m high
Good linear structure

Good location - close to campus

Plenty of cooling water nearby.

Highest accelerating gradient ~100MV/m

Energy = 17 GeV each pass

Just need a way to recycle the beam many times or build the tower higher….

End

“IF I HAVE SEEN FURTHER
IT IS BY STANDING ON THE SHOULDERS OF GIANTS”

ISAAC NEWTON

CONTACT

Professor Glenn Patrick

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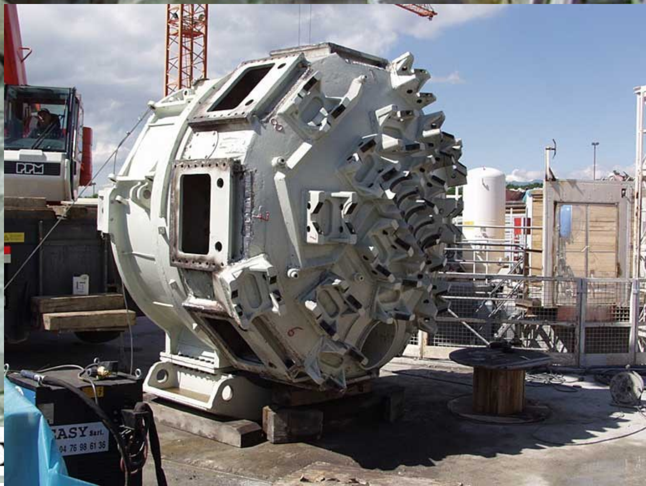
LHC Civil Engineering

Point 1 - UX15 vault demolition of central pillar - September 20, 2000 - CE



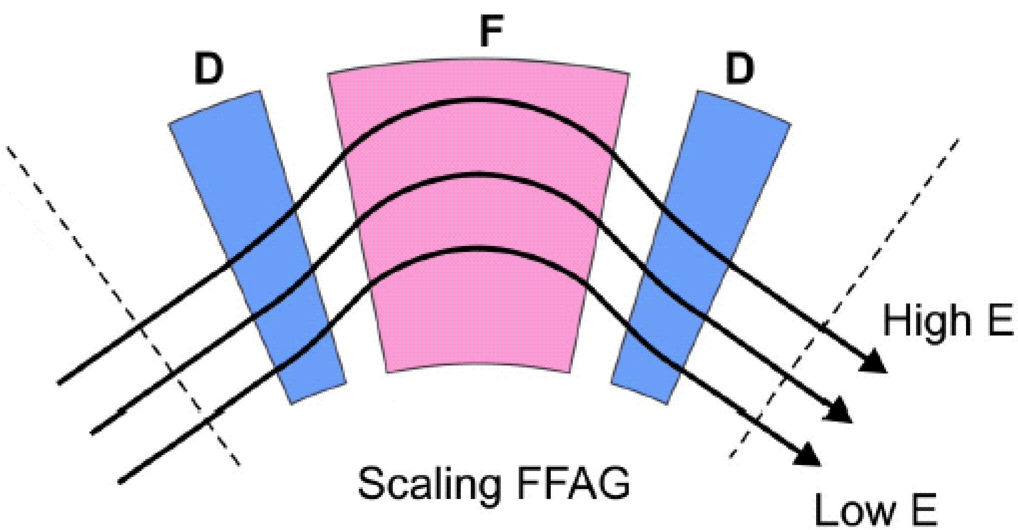
In the beginning…

SPS Proton-Antiproton Collider

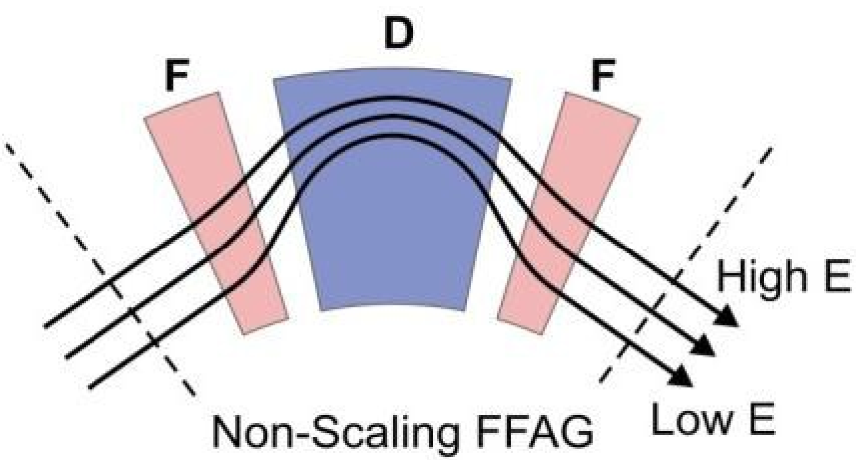
Super Proton Synchrotron
CERN, Geneva (6km circ).

Converted into proton-antiproton collider
(Rubbia & van de Meer)
Stochastic cooling technique.

FFAG



Old idea (1950s)
Use DC magnets with carefully shaped pole profiles.
Beam orbit scales with energy so apertures are large.



New idea (1990s)
Use simple DC magnets (e.g. quadrupoles).
Beam orbit changes shape with energy enabling apertures to be small.