Collisionality studies in HEDP: Pulsed-Power plasma jets

M. P. Valdivia
Center for Energy Research, University of California San Diego

Team: F. N. Beg (PI), F. Conti, A. Williams (PhD student), K. Inzunza (Undergraduate student)

Collisionality studies: Motivation

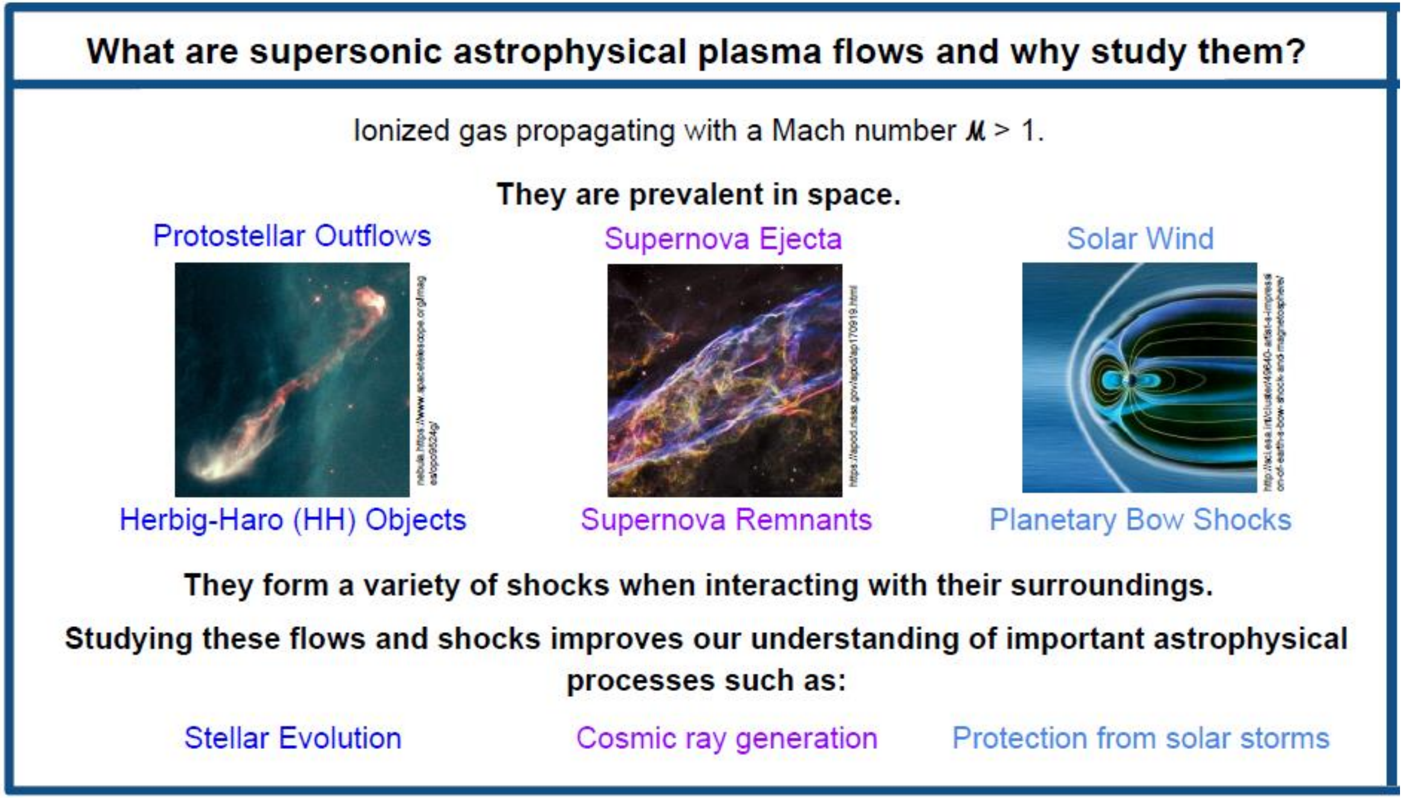
- Planetary nebulae, active galactic nuclei, supernovae, and young stellar objects
  - Supersonic plasma outflows. Wide range of physical parameters and features, e.g., shocks produced by weakly-collisional and strongly-radiating Herbig-Haro (HH) objects [Schwartz et al, Astrophys. J. 223, 884 (1978)].
- Pulsed-power: astrophysically-scalable laboratory experiments
  - Dimensionless analysis. Valuable information to complement the scarcer observational data

Southern Ring Nebula: James Webb Telescope

Supersonic jets: ablation of conical wire arrays:

Variation of wire array geometry and/or atomic number produce different jet parameters and transport properties: **collisionality**, **radiative cooling**, and **thermal conduction** [Lebedev et al, PPCF 47 B465 (2005)].

“Cosmic Cliffs” in the Carina Nebula (vast stellar nursery): James Webb Telescope



What are supersonic astrophysical plasma flows and why study them?

Ionized gas propagating with a Mach number $\mathcal{M} > 1$.

They are prevalent in space.

Protostellar Outflows

nebula https://www.spacetelescope.org/images/opo9524g/

Herbig-Haro (HH) Objects

Supernova Ejecta

https://apod.nasa.gov/apod/ap170919.html

Supernova Remnants

Solar Wind

http://sci.esa.int/cluster/49640-artist-s-impression-of-earth-s-bow-shock-and-magnetosphere/

Planetary Bow Shocks

They form a variety of shocks when interacting with their surroundings.

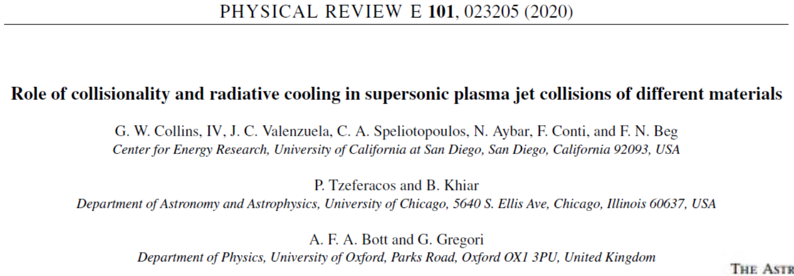
Studying these flows and shocks improves our understanding of important astrophysical processes such as:

Stellar Evolution

Cosmic ray generation

Protection from solar storms

Previous work



PHYSICAL REVIEW E **101**, 023205 (2020)

Role of collisionality and radiative cooling in supersonic plasma jet collisions of different materials

G. W. Collins, IV, J. C. Valenzuela, C. A. Speliotopoulos, N. Aybar, F. Conti, and F. N. Beg
Center for Energy Research, University of California at San Diego, San Diego, California 92093, USA

P. Tzeferacos and B. Khiar
Department of Astronomy and Astrophysics, University of Chicago, 5640 S. Ellis Ave, Chicago, Illinois 60637, USA

A. F. A. Bott and G. Gregori
Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

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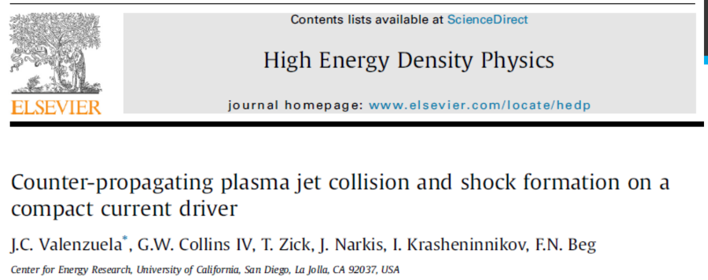

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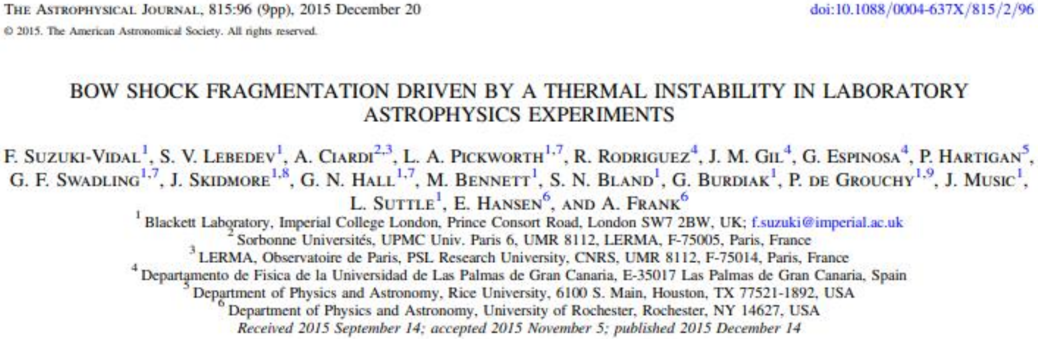
Counter-propagating plasma jet collision and shock formation on a compact current driver

J.C. Valenzuela*, G.W. Collins IV, T. Zick, J. Narkis, I. Krasheninnikov, F.N. Beg

Center for Energy Research, University of California, San Diego, La Jolla, CA 92037, USA



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BOW SHOCK FRAGMENTATION DRIVEN BY A THERMAL INSTABILITY IN LABORATORY ASTROPHYSICS EXPERIMENTS

F. SUZUKI-VIDAL[1], S. V. LEBEDEV[1], A. CIARDI[2,3], L. A. PICKWORTH[1,7], R. RODRIGUEZ[4], J. M. GIL[4], G. ESPINOSA[4], P. HARTIGAN[5], G. F. SWADLING[1,7], J. SKIDMORE[1,8], G. N. HALL[1,7], M. BENNETT[1], S. N. BLAND[1], G. BURDIAK[1], P. DE GROUCHY[1,9], J. MUSIC[1], L. SUTTLE[1], E. HANSEN[6], AND A. FRANK[6]

[1] Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2BW, UK; f.suzuki@imperial.ac.uk
[2] Sorbonne Universités, UPMC Univ. Paris 6, UMR 8112, LERMA, F-75005, Paris, France
[3] LERMA, Observatoire de Paris, PSL Research University, CNRS, UMR 8112, F-75014, Paris, France
[4] Departamento de Fisica de la Universidad de Las Palmas de Gran Canaria, E-35017 Las Palmas de Gran Canaria, Spain
[5] Department of Physics and Astronomy, Rice University, 6100 S. Main, Houston, TX 77521-1892, USA
[6] Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA

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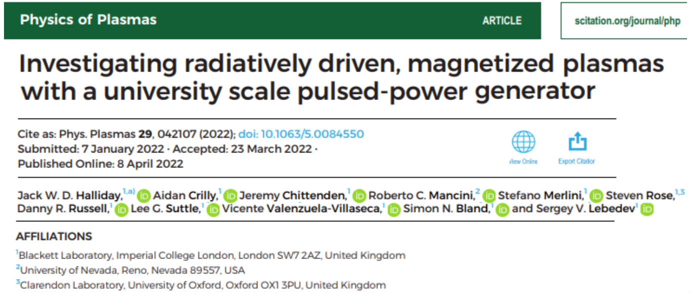

Physics of Plasmas ARTICLE scitation.org/journal/php

Investigating radiatively driven, magnetized plasmas with a university scale pulsed-power generator

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Jack W. D. Halliday,[1,a)] Aidan Crilly,[1] Jeremy Chittenden,[1] Roberto C. Mancini,[2] Stefano Merlini,[1] Steven Rose,[1,3] Danny R. Russell,[1] Lee G. Suttle,[1] Vicente Valenzuela-Villaseca,[1] Simon N. Bland,[1] and Sergey V. Lebedev[1]

AFFILIATIONS

[1] Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom
[2] University of Nevada, Reno, Nevada 89557, USA
[3] Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, United Kingdom

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PHYSICS OF PLASMAS **25**, 102101 (2018)

Emission of fast ions from conical wire array Z-pinches studied at different background pressures

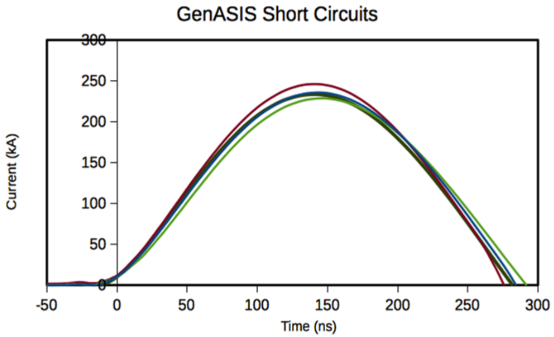
Gonzalo Muñoz-Cordovez, Felipe Veloso, Vicente Valenzuela-Villaseca,[a)] Milenko Vescovi, Wilmer Useche, Edmund Wyndham, and Mario Favre
Instituto de Física, Pontificia Universidad Católica de Chile, Santiago, Chile

GenASIS: Compact, low-inductance, mid-scale current driver[1,2]

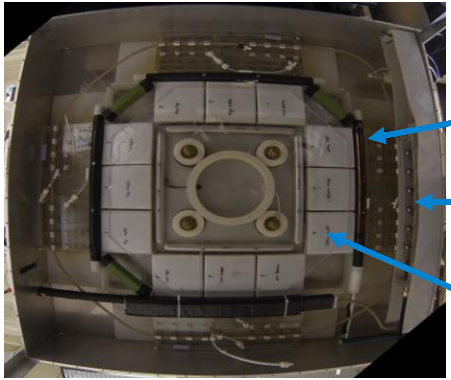
- **200 kA average current**
- **150 ns quarter-period**
- **~ 1.5 m^2 footprint**
- **4-5 shots a day with a crew of 2**

<u>Experiments:</u>

- Planar, cylindrical, and conical wire arrays
- X-ray backlighter sources (x-pinch driven by return current: <u>Laser-cut foils</u>[3])
- Gas-puffs



Many drivers in this range since 2011!



Multi-gap, low inductance switch block

Trigger Marx

3x20 nF, 100kV capacitor block

B-dot Groove

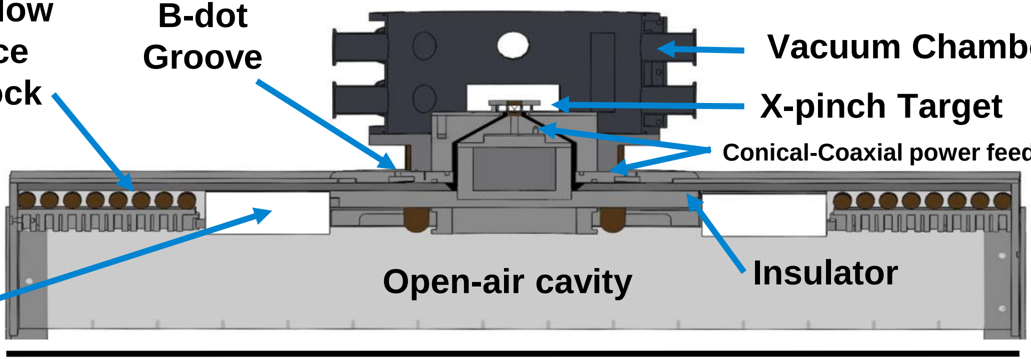
Vacuum Chamber

X-pinch Target

Conical-Coaxial power feed

Insulator

Open-air cavity



1.24 m

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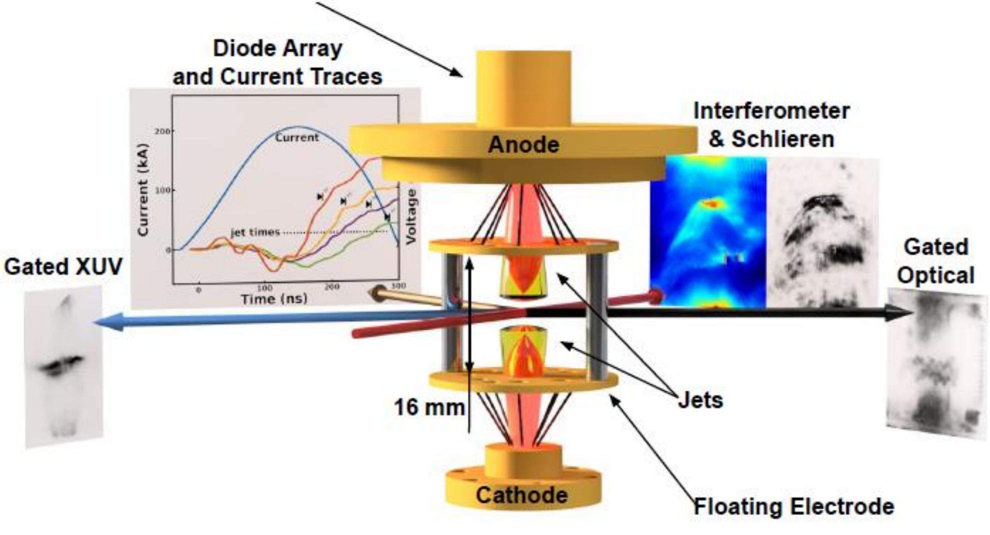
1. A. V. Kharlov *et al.*, *Rev. Sci. Instrum.*, **77**, 123501 (2006)
2. S. C. Bott *et al.*, *Phys, Rev. STAB.*, **14**, 050401 (2011)
3. **GW Collins IV, *et al.* Journal of Applied Physics 129 (7), 073301 (2021)**

Jet collisionality studies: GenASIS

Opposed conical wire arrays created shocks observed by a suite of diagnostics.



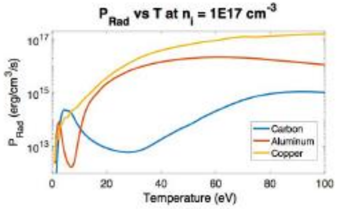
Tested 200µm C, 25µm Al, 25µm Cu, and 13µm W.

Collision and radiative cooling rates change with element:

Inter-jet ion collisionality for $\mathcal{M} \gg 1$:

$$\boxed{\lambda_{mfp-ii} \quad = 1.67\times10^{-11}\frac{\mathbf{u}_{jet}^4 A^2}{Z^{*4} ln\Lambda n_i}, \quad [\text{cm}]}$$

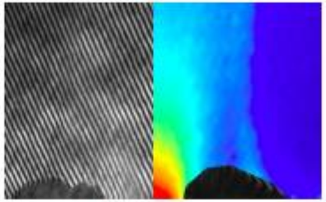
P_{Rad} - Radiative cooling rate:



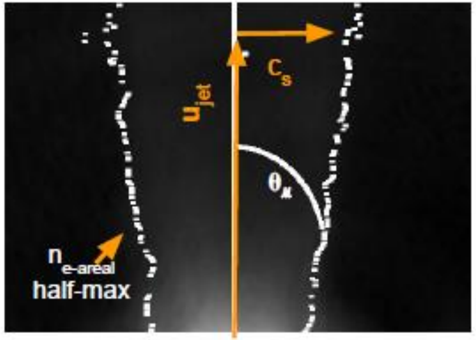
So, changing jet material enables systematic testing of the roles of λ_{mfp-ii} and P_{Rad} on shock formation and evolution (e.g. instabilities).[3,4]

Single jet experiments: parametrization

- An optical diode array measured **u**$_{jet}$.



- Interferograms unfolded into continuous areal n_e



- Jet opening angle via interferogram unfolds gave $\mathcal{M}$, c_s.
- T_e determined from c_s.
- Abel inversions of unfolded interferograms gave n_e.

- These values were used to to calculate $\lambda_{mfp\text{-}ii}$ and determine P_{Rad} from PRISM tables.

Similarity parameters

- To varying degrees, C, Al, and Cu collisions scale to Herbig-Haro (HH) objects.
- Tungsten interactions may scale to supernova remnants (SNRs).

	Similarity		Hydrodynamics		
	$\mathcal{M}$	χ_c	δ_{loc}	Re	Pe
C	3-4	weak (10^0-10^1)	10^{-3}	10^5 - 10^6	10^2
Al	4-8	moderate (10^{-2}-10^0)	10^{-2}	10^5	10^1 - 10^2
Cu	4-8	strong (10^{-2}-10^{-1})	10^{-2}	10^6	10^1 - 10^2
W	>10	strong (10^{-3}-10^{-1})	10^{-2}	10^6 - 10^7	10^2
HH Objects	5-10	strong (10^{-2}-10^{-1})	10^{-9}	10^9 - 10^{10}	10^8
SNRs	10-100	weak/strong (~10^{-1})	10^{-9}	10^{10} - 10^{11}	10^9

Establishing HYDRODYNAMIC similarity:

Localization: $\delta_{loc} = \lambda_{mfp}/\ell$ - Fluid approximation valid if $\delta_{loc} << 1$. Then:

Reynolds Number: $Re = u_{jet}\ell/\nu$ - ratio of inertial and viscous forces

Peclet Number: $Pe = u_{jet}\ell/\chi$ - ratio of thermal advection to conduction.

Establishing EVOLUTIONARY similarity:

Mach number: $\mathcal{M} = u_{jet}/c_s$ - similar propagation/expansion

Cooling Parameter: $\chi_c = \tau_c/\tau_{hydro} = \tau_c/(\ell/u_{jet})$ - ratio of radiative cooling and hydrodynamic timescales.

Two systems are dynamically comparable if they can be described by the same set of dimensionless numbers:[1,2]

[1] D. D. Ryutov *et al.*, *ApJ*, **518**, 821-832 (1999).

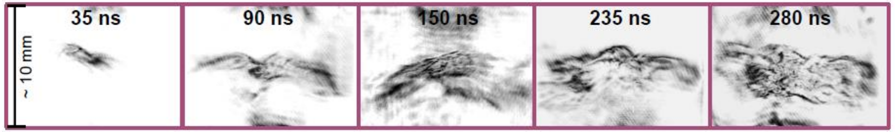
[2] D. D. Ryutov *et al.*, *ApJ Suppl.*, **127**, 465-468 (2000).

Jets collisionality: C, Al, Cu, and W

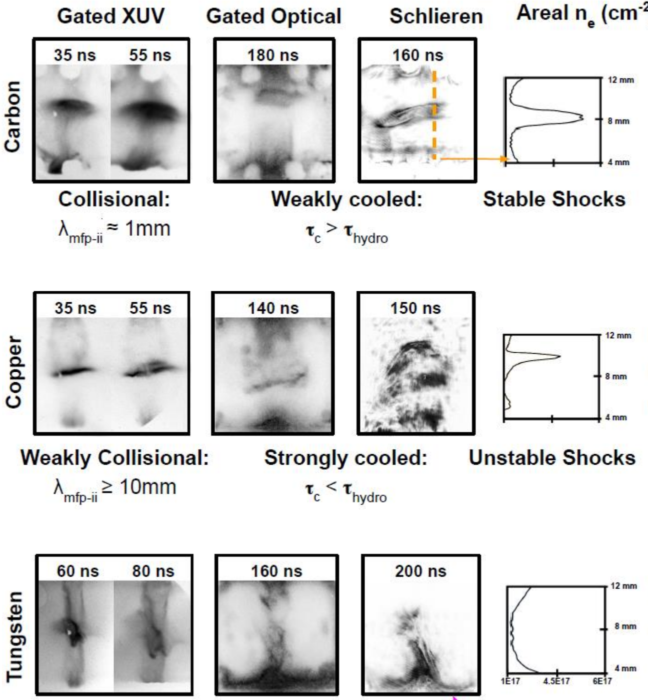
- Collisional and weakly collisional interactions form shocks.
- Collisionless interactions do not.
- Increased radiative cooling leads to increased shock instability.

Al shocks exhibit unique features.

- **Aluminum shocks form and expand similarly to C, but develop significant perturbations:**
  - Al flows were weakly collisional: $\lambda_{mfp\text{-}ii}$ 1 - 100 mm (similar to Cu).
  - Al flows were moderately cooled: $\tau_c < \tau_{hydro}$ (between C and Cu).



Schlieren time sequence of Al shocks. Times are approximate duration since shock formation.



Carbon

$u_{jet} = 8 \times 10^6$ cm/s
$n_e = 2 \times 10^{17}$ cm^{-3}
$T_e = 10$ eV

Collisional: $\lambda_{mfp\text{-}ii} \approx 1$mm

Weakly cooled: $\tau_c > \tau_{hydro}$

Stable Shocks

Copper

$u_{jet} = 9 \times 10^6$ cm/s
$n_e = 2 \times 10^{17}$ cm^{-3}
$T_e = 15$ eV

Weakly Collisional: $\lambda_{mfp\text{-}ii} \geq 10$mm

Strongly cooled: $\tau_c < \tau_{hydro}$

Unstable Shocks

Tungsten

$u_{jet} = 15 \times 10^6$ cm/s
$n_e = 2 \times 10^{17}$ cm^{-3}
$T_e = 20$ eV

Weakly Collisional: $\lambda_{mfp\text{-}ii} \geq 100$mm

Strongly cooled: $\tau_c < \tau_{hydro}$

No Shocks

Potential filamentation instabilities?[5]

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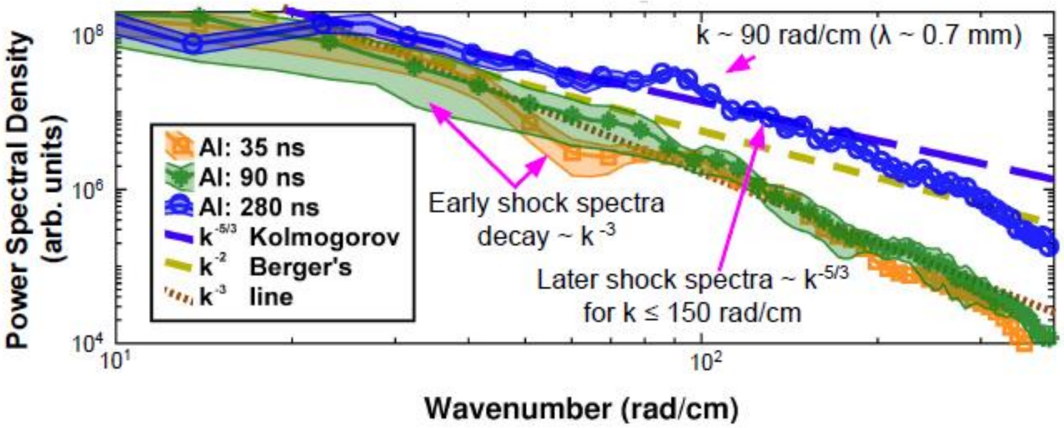
[5] E. S. Weibel, *Physical Review Letters* **2**, 83 (1959).

Al shocks exhibit unique features

- **Fourier analysis shows potential turbulence, thermal condensation instabilities in Al shocks.**[5]
  - Power spectra decaying at $k^{-5/3}$ or slower are compatible with turbulence.[6]
  - Thermal condensation instability: max growth at $\lambda = (\lambda_{Field}\lambda_{iso})^{1/2} \sim 0.5 - 1$ mm.[7]



[5] G. W. Collins IV, et al. "Role of collisionality and radiative cooling in supersonic plasma jet collisions of different materials." *Physical Review E* 101.2 (2020)

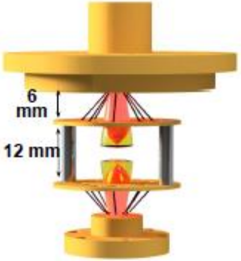
[6] A. N. Kolmogorov, *DAN SSSR*, **30**, 376 (1940)

[7] G. B. Field, *ApJ*, **142**, 531 (1965).

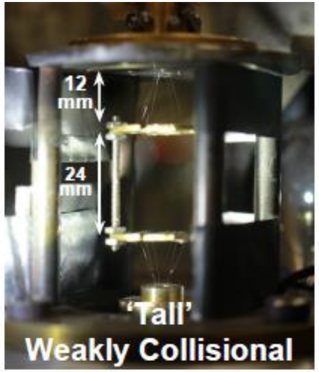
Opposed Array Geometry: Collisionality Change

By changing conical array opening angle (array height) and floating electrode length, we can change u_{jet} and n_e where the jets interact

All conical arrays made of Al wires (C or plastic)



'Short' Collisional



'Tall' Weakly Collisional

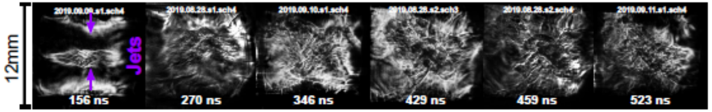
Initial results suggest:

'Tall' setup will be weakly collisional

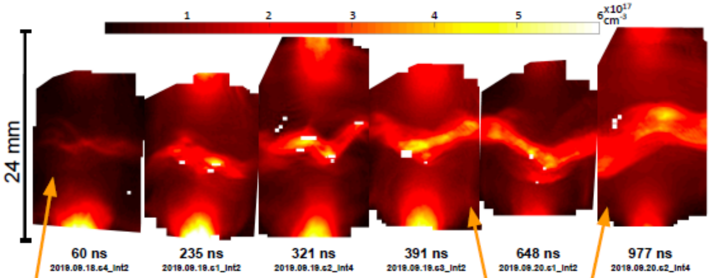
'Short' setup will be collisional

	M	u_{jet} (km/s)	Z*	T_e (eV)	$n_{e\text{-}12mm}$ (10^{17} cm^{-3})	$\lambda_{mfp\text{-}II}$ (cm)
TALL	3.6 ± 0.6	96 ± 17	5.1 ± 1.8	32 ± 16	0.61 ± 0.37 (single jet)	1.6 (0.8 - 4.6)
	M	**u_{jet} (km/s)**	**Z***	**T_e (eV)**	**$n_{e\text{-}6mm}$ (10^{17} cm^{-3})**	**$\lambda_{mfp\text{-}II}$ (cm)**
SHORT	2.5 ± 0.3	70 ± 21	5.4 ± ??	25 ± 16	1.89 ± 0.21 (single jet)	.14 (.10 - .17)

- A schlieren time sequence of 'Short' Al shocks shows increased perturbations with time.



- PSD analysis suggests the shocks grow turbulent ~200 ns after forming (from plot slope at k = 25-250 rad/cm)



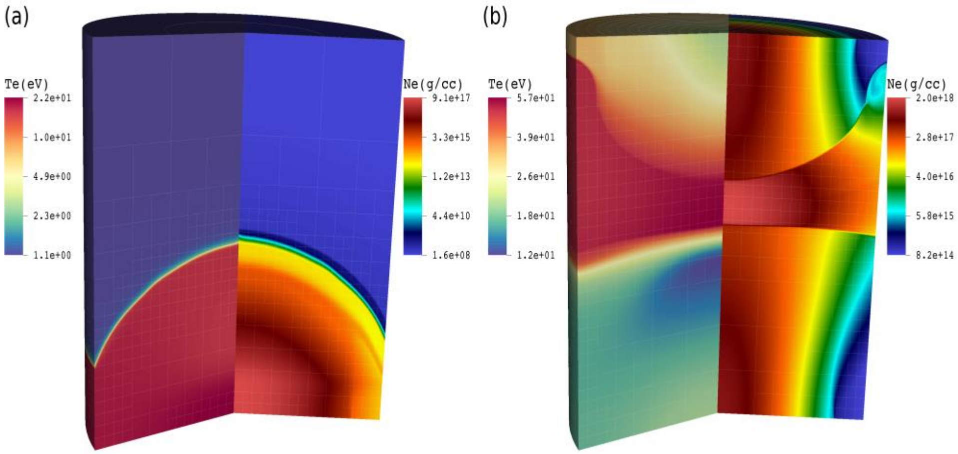
- A time sequence of areal e^- density maps of 'Tall' Al shocks show the relatively slow development time, and generally smooth, stable shock structure. (Color scale given above images)

'Tall' shocks form ~300 ns after 'Short' shocks

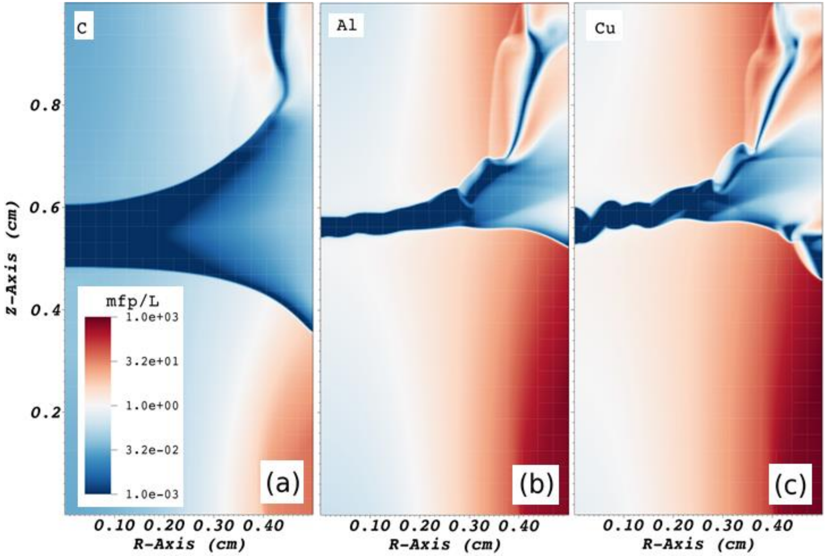
'Tall' shocks curve or bow over time in different directions from shot to shot

(Note: times are relative to estimated shock formation time)

Simulations

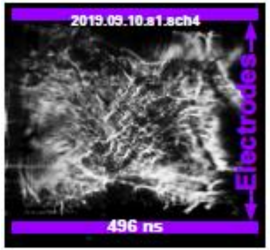


Full-physics FLASH 2D cylindrical simulation of counter-propagating C jets: (a) Bottom jet prior to collision and (b) shocked interaction region at t~300 ns.



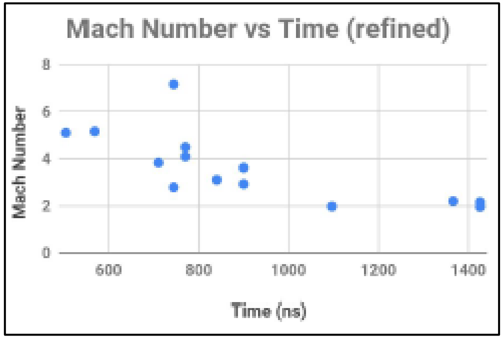
Inter-jet ion-ion normalized mpf as function of plasma composition. (a) C, (b) Al, and (c) Cu at t ~350 ns. Values below unity (blue) denote collisional conditions and values above unity (red) denote a collisionless interaction between the two flows.

Current and Future work



CESZAR LTD to access larger physical scales and expanded parameter space for T, u_{jet}, and n_e:

Array modifications on GenASIS have limits: the ‘Short’ shocks may contact the floating electrodes, and so may carry current.

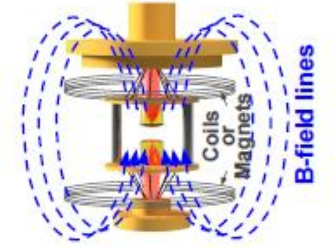


Characterizing the individual jets as a function of time using a high-resolution visible-light spectroscopy:

- $\mathcal{M}$ changes over time in the ‘Tall’ shots: meaning T increases and/or u_{jet} decreases with time
- Newly set up spectrometer and fibers allow for doppler-shift measurements of jet emission.

Examining role of magnetic fields on shock formation:

- External **B** field at different orientations and strengths. Measured with Faraday rotation.
- Potential to employ Zeeman polarization spectroscopy

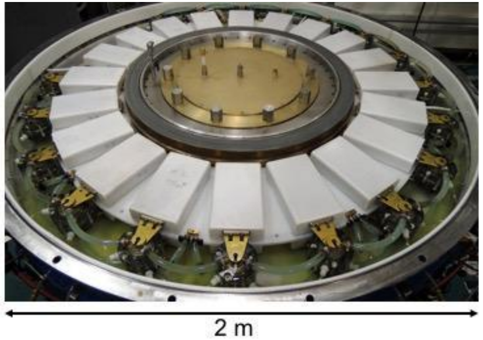


CESZAR[1]: Higher current LTD driver (>500 kA, ~ 160 ns)[3]

- Shot rate of 3-5 shots per day (limited by vacuum and diagnostics)

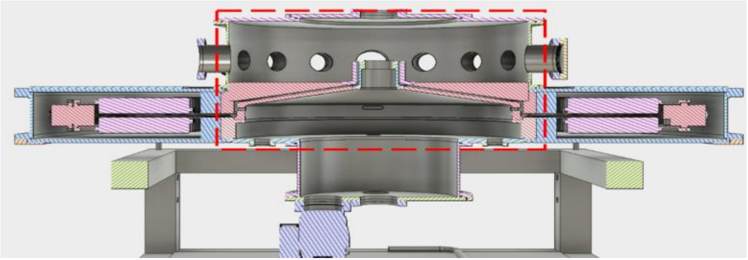
Motivation: Study radiative cooling and collision rates (and their subsequent interaction) at higher currents -> Scalability

Explore: C, Al, Cu, W, Mo, Ti, Ni, and Constantan (high resistivity alloy for different ablation rate and higher magnetic field diffusion)



Low to high atomic number -> largely collisional and moderately cooled (stable and sharp shocks) vs. weakly collisional or collisionless (rapidly cooled more structured interactions shocks)

Transition between these two regimes: insight on governing mechanisms behind the formation and evolution of these shocks



CESZAR current generator

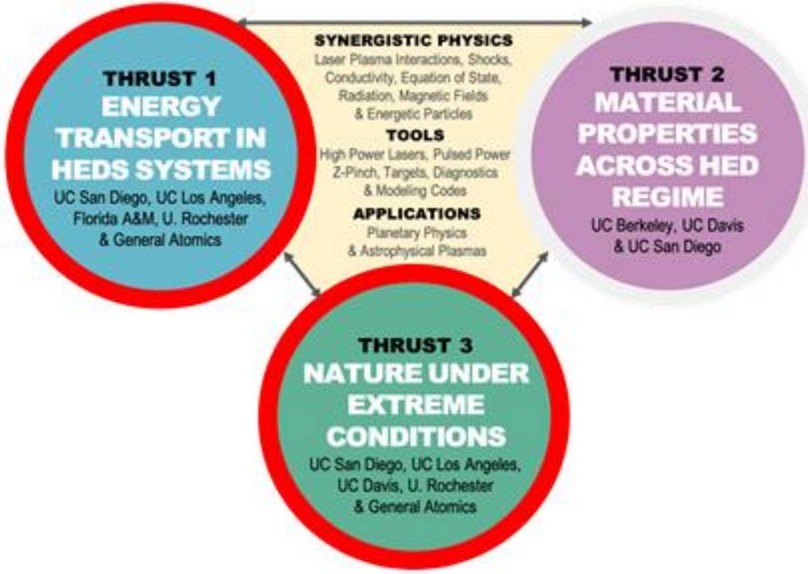
*Cooling, flow interpenetration, presence of magnetic fields, etc. relate to interactions between proto-stellar outflows and their surrounding stellar Nursery.
The resulting turbulence or shock fragments possibly play a role in the seeding of instabilities. Spontaneous B fields, either advected during the plasma flows or self-generated via the Biermann battery effect will be studied

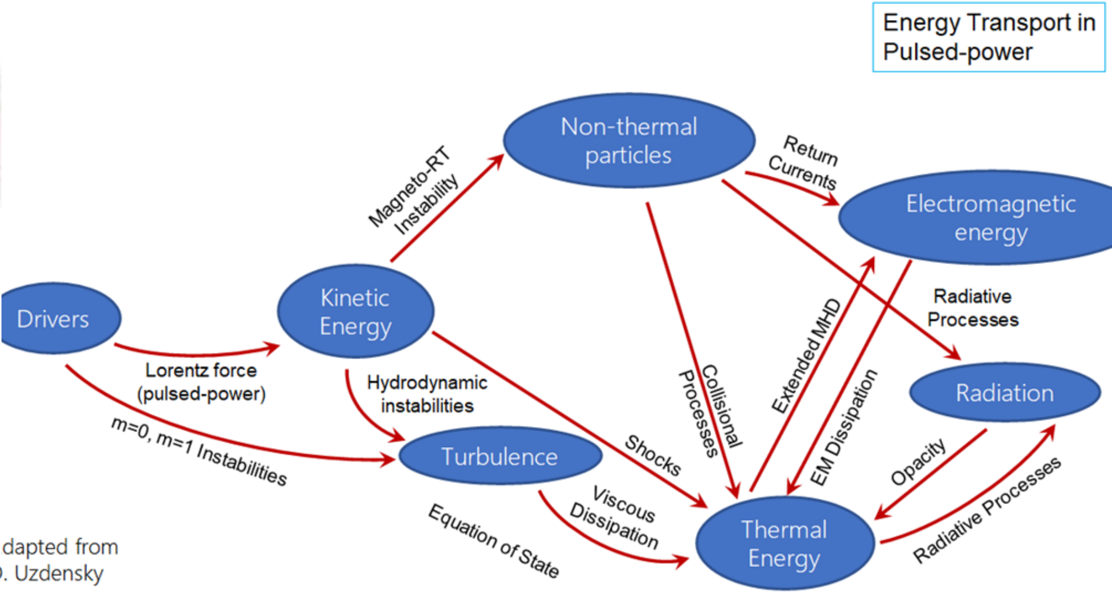
[1] F Conti, *et al.*, Physical Review Accelerators and Beams 23(9), 090401, 2020

CMEC Impact and Vision: Energy Transport in HED Plasmas and Applications

Exploring Change in Material Properties Under
EXTREME CONDITIONS

Temperature, Pressure & Magnetic Field





dapted from
D. Uzdensky

UCSD’s HEDP group: research capabilities

- Pulsed-Power experiments: Single and opposing wire arrays -> collisional to collisionless shocks

CESZAR (>500 kA, ~180 ns) will achieve flows with higher density and temperature than those previously studied on GenASIS (~200 kA, 150 ns) -> Scalability. *Charging voltage increase to 75kV -> ~800 kA

A separate pair of Helmholtz coils can deliver an external B field up to 1 Tesla with a time scale of 5 ms (effectively stationary over the <500 ns timescale of the plasma dynamics).

Diagnostics:

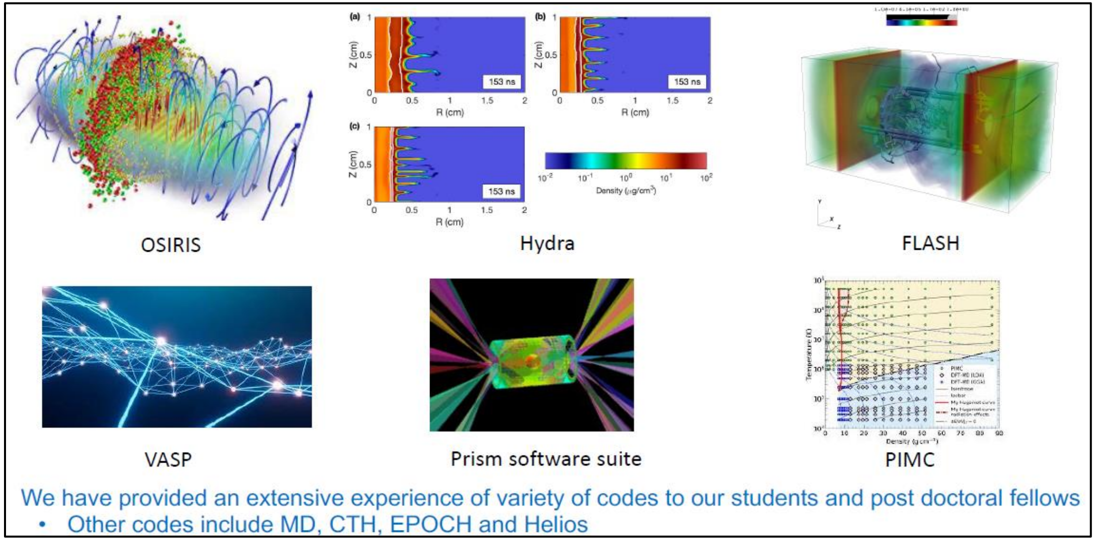
- 4ns YAG laser: 4-frame interferometry and/or schlieren system.
- 30-100ps tunable YAG laser: probing with shorter pulse duration
- 4-8ns YAG laser: Optical Thomson scattering.
- 2 4-frame gated XUV imaging cameras:
- Gated and time integrated XUV spectrometers (2-20nm) with Image plate or MCP detector
- Time integrated X-ray spectrometers quartz, mica, HOPG, PET, KAP, LiF crystals
- 0.75m focal length PI spectrometer with intensified CCD camera (OTS)
- Silicon diodes and diamond detectors: XUV and X-ray light detection.
- Time integrated pinhole cameras: X-ray imaging.
- Bdot probes
- Faraday cup (biased) probes

UCSD’s HEDP group: research capabilities

- Laser experiments:

  “Early-time Linear-saturation of the Ion-Weibel Instability in Counter-streaming Plasmas” Mario Manuel (GA)

- Simulations:



We have provided an extensive experience of variety of codes to our students and post doctoral fellows

- Other codes include MD, CTH, EPOCH and Helios

Summary

- Supersonic jets from conical wire arrays produced astrophysically scalable shocks on a small, university scale LTD current driver.

- C, Al, Cu, W were tested. The resulting interactions ranged from: **collisional** to **collisionless** and **weakly** to **strongly cooled**.

  - Collisional interactions formed shocks, while collisionless interactions did not.
  - Radiative Cooling appears to affect the stability and structure of the shock.
  - W flows clearly interpenetrate and establish long axial perturbations that could potentially be the Weibel instability.
  - Weakly collisional Al flows (with significant radiative cooling), appear to develop cooling instabilities and turbulence.

- Follow-up experiments changed the collisionality of Al shocks. Apparent turbulence develops from cooling rather than collisionality-related perturbations (this work is ongoing).

- Future experiments: explore the transition between collisional and collisionless regimes

Insight on governing mechanisms behind the formation and evolution of shocks

Tasks (1-15), Milestones (M1-M3)	
1	Single jet experiments: focus on N, T, B advection, flow velocity as function of opening angle.
2	Counter-propagating jet collision experiments and measure pre- and post-shock plasma quantities for low Z materials (C, Al, Cu).
3	2D/3D FLASH simulations of counter-propagating plasmas.
4	Studies of flow configuration and stability of colliding plasmas.
5	Experimental data analysis and publication.
M1	Thorough experimental characterization of single jet experiments and shock characterization for low Z.
6	Continue counter-propagating jet collision experiments. Measure pre- and post-shock plasma quantities for low-Z (C, Al, Cu).
7	Study magnetization effects on shock formation using external magnetic field sources for low Z materials (C, Al, Cu).
8	Ab initio 2D/3D FLASH simulations. Compare with experiments.
9	Studies of micro-instabilities and NTSI with external magnetic field.
10	Experimental data analysis and publication.
M2	Establish magnetized counter-propagating plasma jet platform, ab initio simulations. Is the shock mediated by B for low Z materials?
11	Conduct counter-propagating jet collision experiments and measure pre- and post-shock plasma quantities for high Z materials (Mo, W).
12	Study magnetization effects on shock formation using external magnetic field sources for low Z materials (Mo, W).
13	Ab initio 2D/3D MHD FLASH simulations for high Z flows
14	Analytic and numerical solutions for transition layer: high-Z regimes
15	Experimental data analysis and publication.
M3	Perform collisionless experiments using high Z materials. Can collisionless shocks be formed by adding B?