Laboratory astrophysics and basic plasma physics with high-energy-density, laser-produced plasmas

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Experiments are being conducted on laser facilities to study fundamental problems in plasma astrophysics

Example topics cited in the Workshop on Opportunities in Plasma Astrophysics (e.g. WOPA, H. Ji et al 2010):

MAJOR QUESTIONS include

- How are cosmic rays accelerated?
- How do magnetic explosions (e.g. solar flares) work?
- How are cosmic magnetic fields generated?

PLASMA PHYSICS PROCESSES include:

- Magnetic Reconnection
- Collisionless shocks
- Radiation hydrodynamics
- hydrodynamic instabilities, turbulence
- self-generated magnetic fields, dynamos
- electron-positron plasmas

HED Astrophysics also a major theme of HEDP ReNeW (Hammer et al, 2009), and NRC “X-games” report (Davidson 2003)

Laser produced plasmas on HED facilities produce highly interesting plasmas for laboratory astrophysics

TOPICS

- hydrodynamic instabilities, turbulence
- self-generated magnetic fields, dynamos
- high-Mach number flows, strong shocks
- collisionless shocks
- magnetized flows, magnetized shocks, reconnection
- electron-positron plasmas

DESIRED PROPERTIES

- L / d_i ($\sim L\, n^{1/2}$) large, to allow e.g. fully formed shocks and "plasmoid" regime for reconnection
- $R_M \sim L\, T^2$ large, for low dissipation
- $L_{mfp} \sim T^2/n$ large (collisionless plasma behavior),
- $V \sim C_s$: supersonic flows and shocks.
- Radiation can be important

Some comments on landscape of the field

- Many exciting results obtained on OMEGA, OMEGA EP, other laser facilities (100's J - 10 kJ) (I will show a sampling of these shortly)
- New opportunities exist on the NIF at high Energy ~ n T L^3 (~ 100's kJ). Gets to:
  - larger mean-free-path vs. system size
  - larger number of ion-skin depths
  - = astrophysically-relevant self-organized regimes
- Opportunities at MEC to go to probe at high (~solid) density or on very fast (~fs) timescales based on LCLS free-electron laser

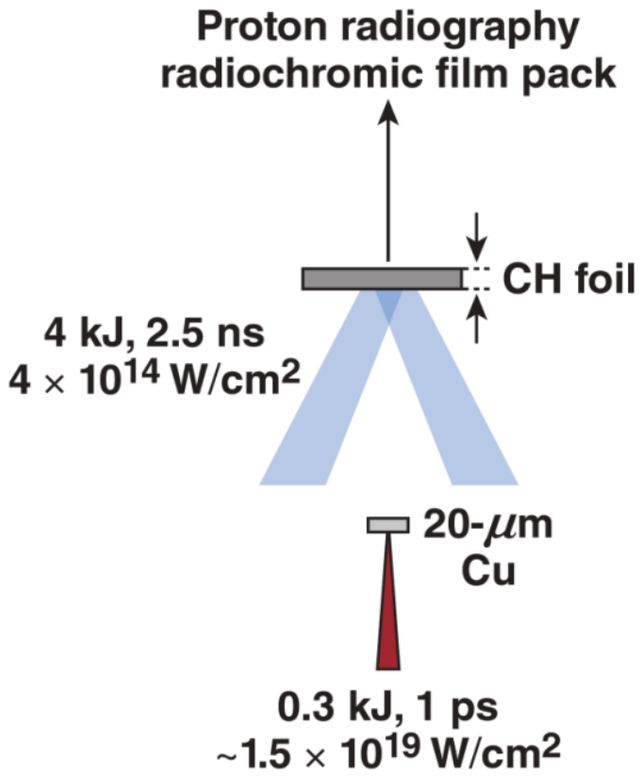
- Challenges:
  - sufficient simultaneous diagnostics to make deep tests of theory (e.g. vs. a qualitative observation, "we found it"). This is always improving but remains a challenge.

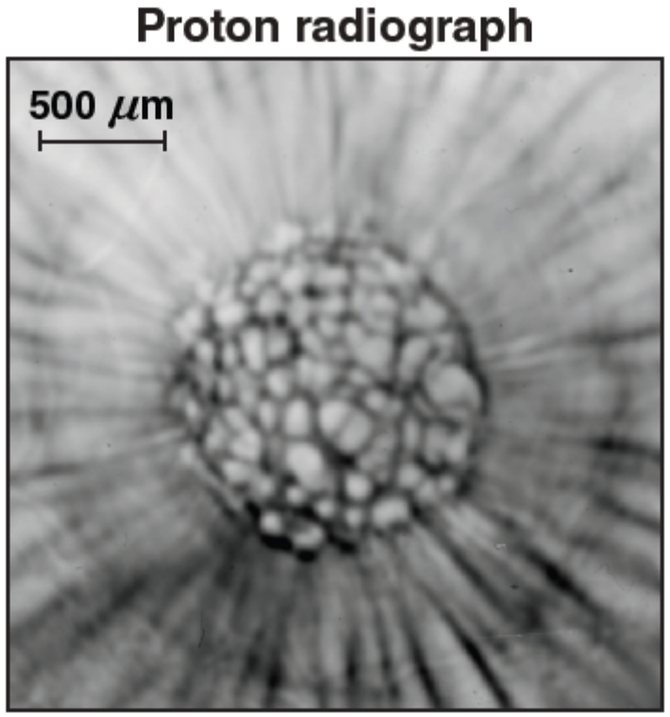
- Connections:
  - Many of these "basic" experiments have analogues in ICF. Understanding them can help this effort, e.g. colliding plasmas and magnetic field generation in ICF hohlraums
  - Most efforts have strong connections to advanced computing: advanced radiation-hydro or fluid simulations and particle-in-cell.

Where can lasers shine?

(not an exhaustive or exclusive list)

Magnetic field generation by Rayleigh-Taylor instability has been studied, opening the door for possible magnetized turbulence and dynamo studies





MG-level magnetic fields generated by Biermann battery effect during the non-linear phase of Raylegh Taylor instability*. Fields follow the self-similar evolution of the RT bubbles and spikes consistent with a bubble competition and merger model**

*L. Gao *et al.,* Phys. Rev. Lett. 109, 115001 (2012).
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Opportunities: study self-organized turbulent state driven by many overlapping plumes, astrophysical magnetic field generation, and astrophysical turbulent dynamos (e.g. Kulsrud ApJ 1997)

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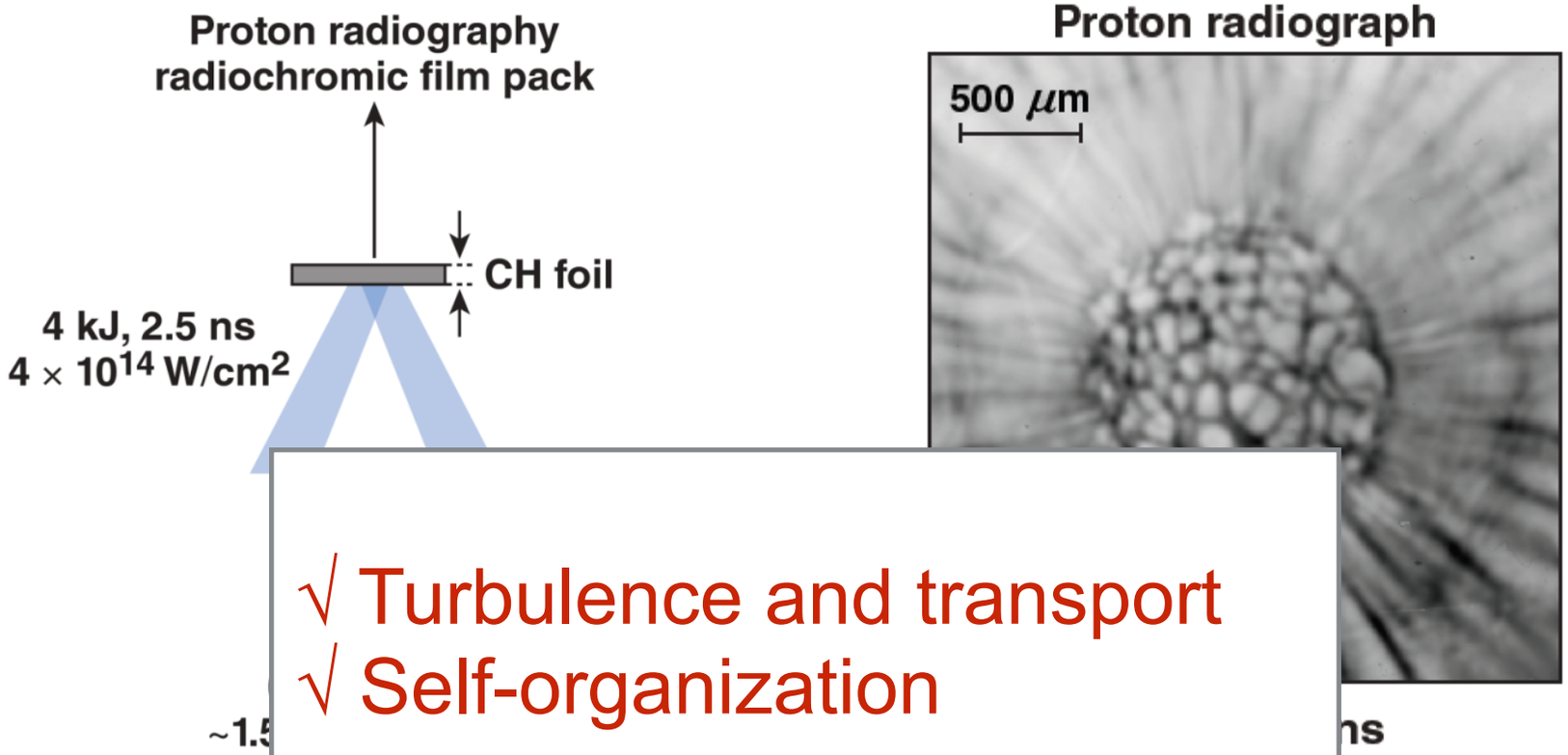

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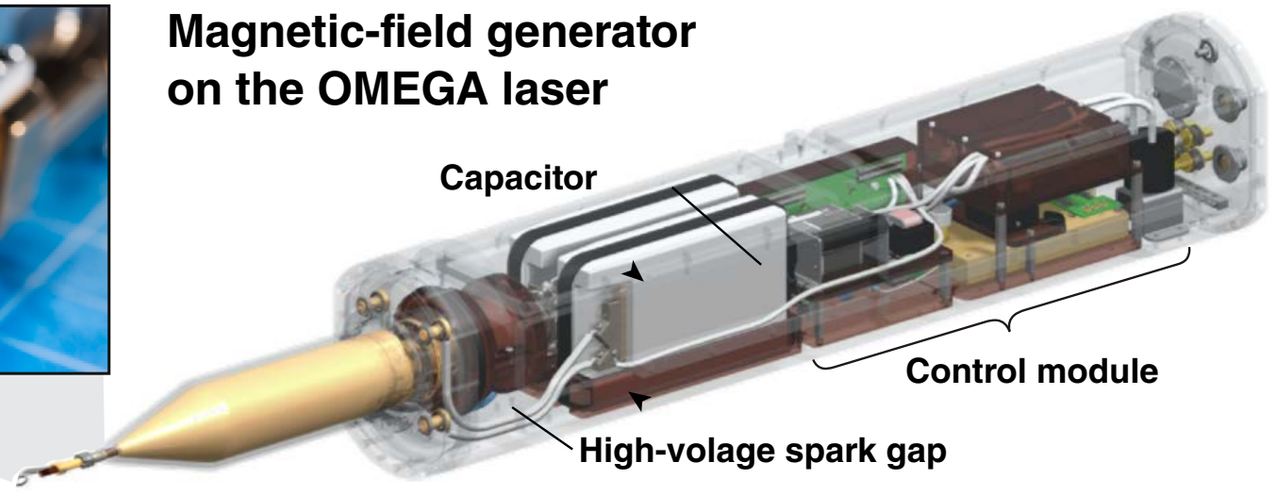
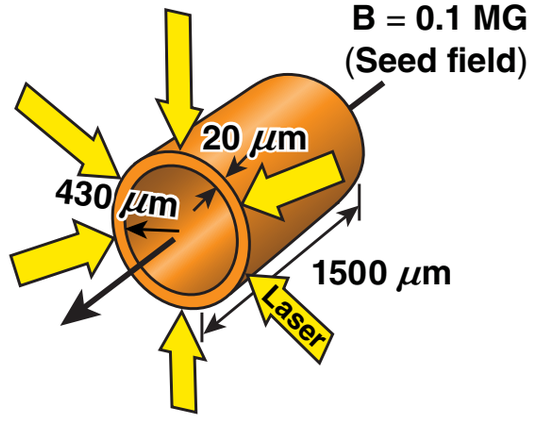
Pulsed-power devices are coupled to lasers to magnetize high-energy-density plasmas

Magnetic-field generator on the OMEGA laser



Set up for magnetic-field compression



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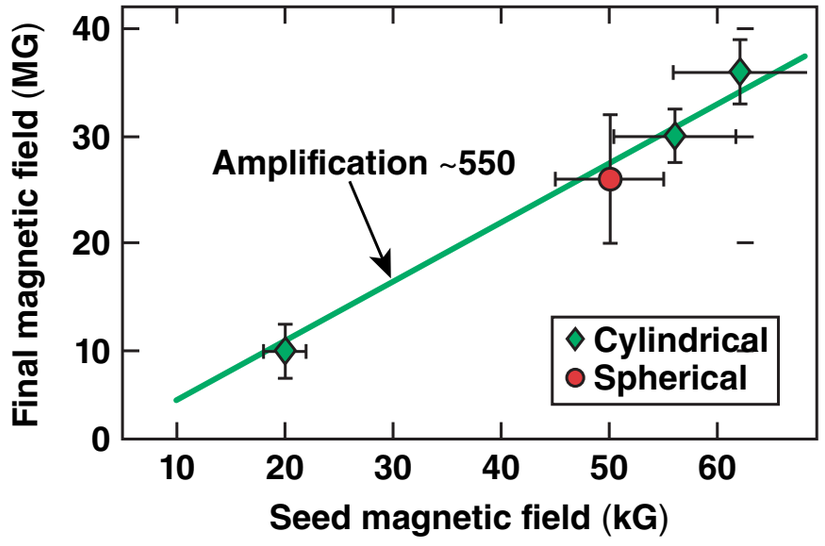
Laser-driven B-field compression



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Opportunities

- generate *magnetized collisionless shocks* relevant to astrophysical particle acceleration

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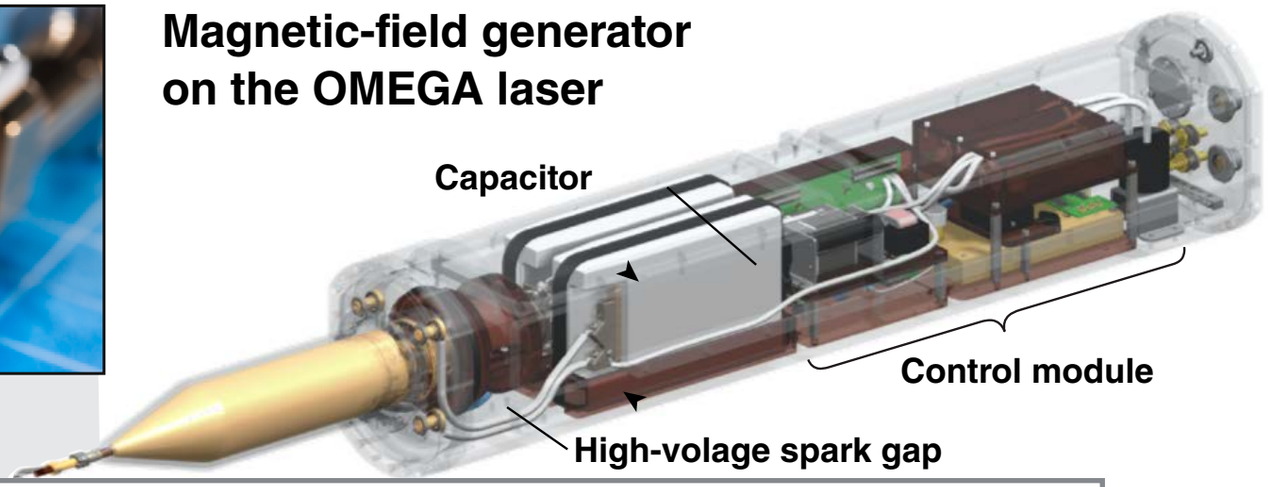
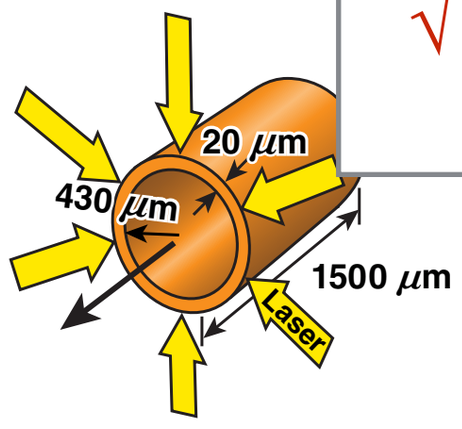


Set up for magnetic-compression



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√ Plasma and waves
√ Self-organization

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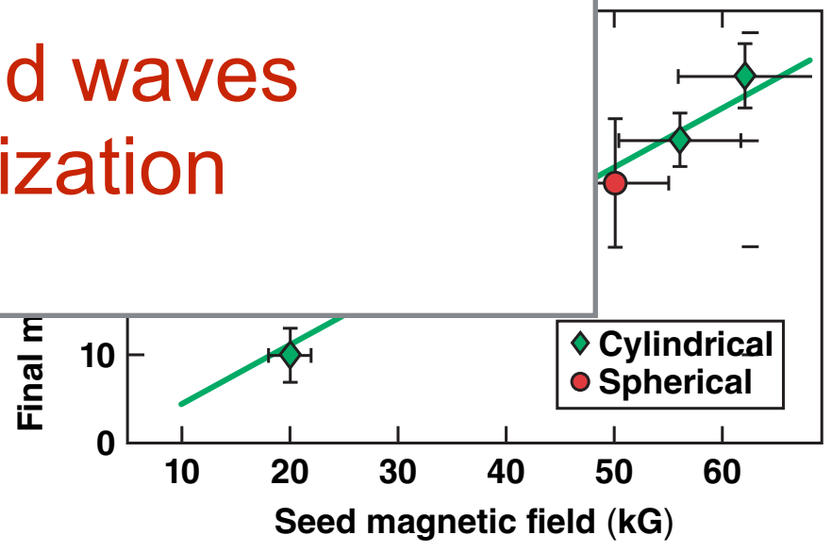

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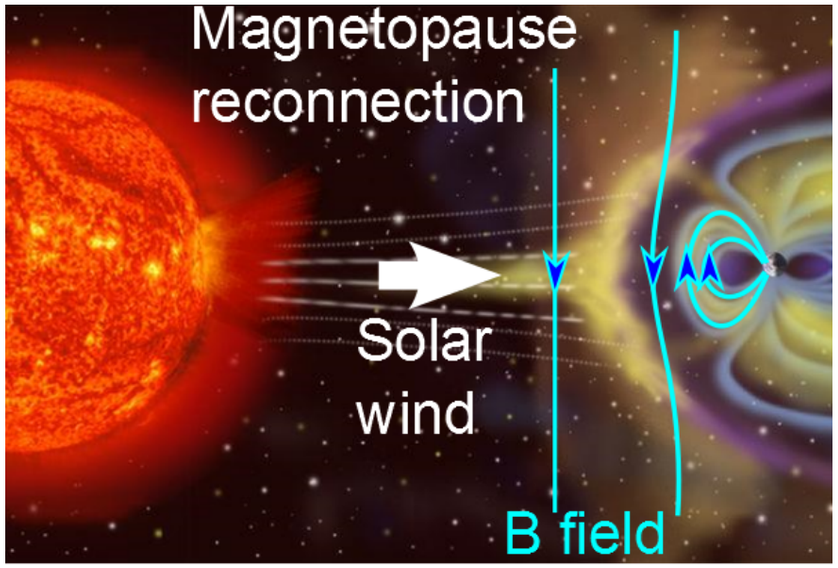
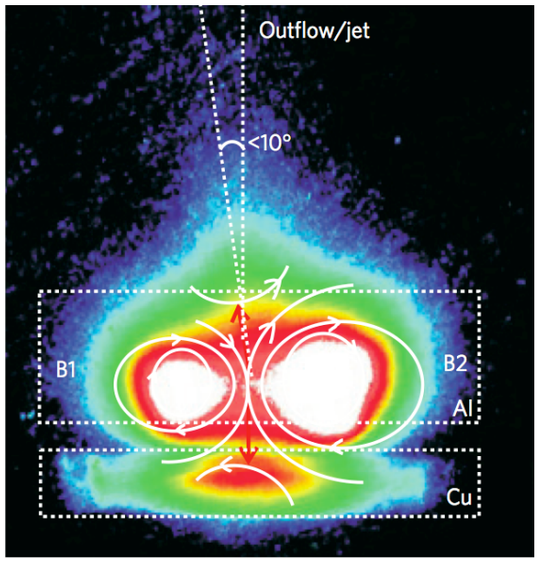
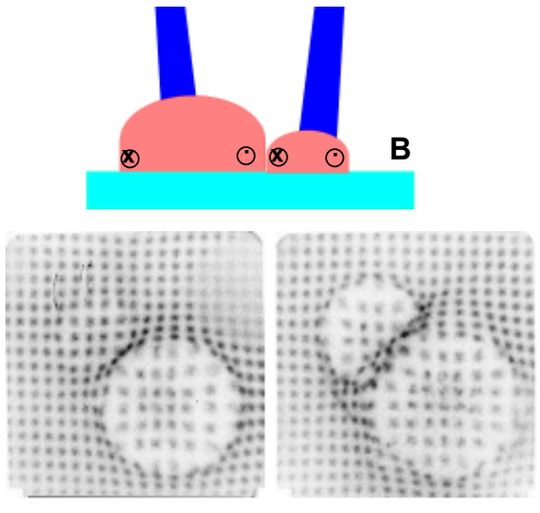
Magnetic reconnection studied in laser-plasma experiments with colliding, magnetized plumes

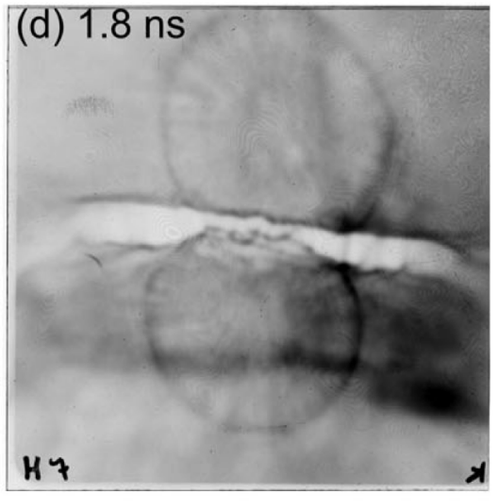




outflow jets and particle energization (Zhong *et al* Nature Phys 2010, Dong et al PRL 2012)

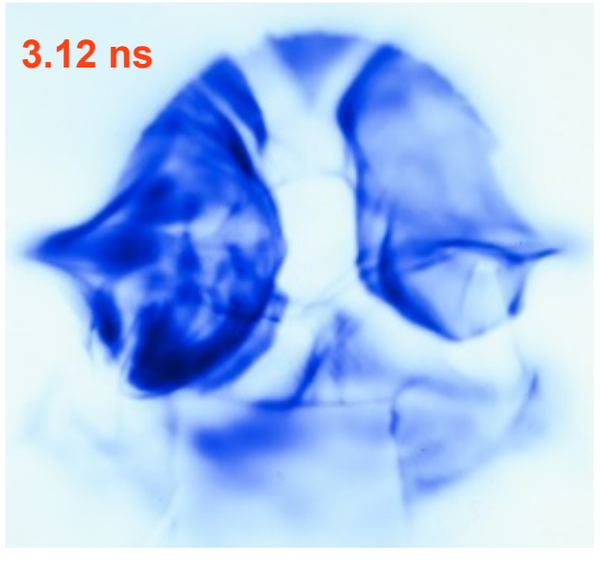
Reconnection between asymmetric plasmas (M. Rosenberg Nature Comm 2014)





Collisional slow-down of reconnection (M. Rosenberg PRL 2015)

Reconnection between externally-magnetized plasmas (G. Fiksel PRL 2014)

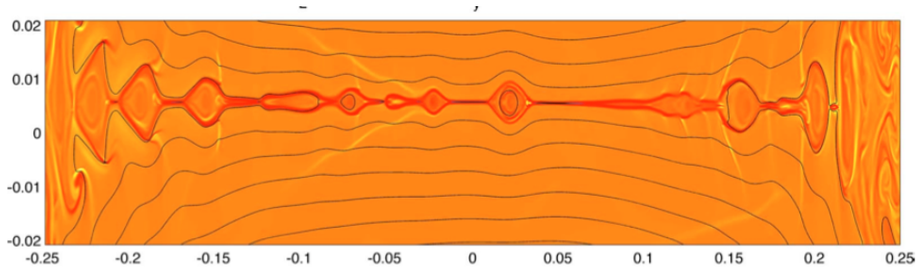


Opportunities

- astrophysical particle energization by reconnection vs. shocks
- multiple island reconnection at large system size
- *Radiative cooling* effects in reconnection (Uzdensky 2011, for review)

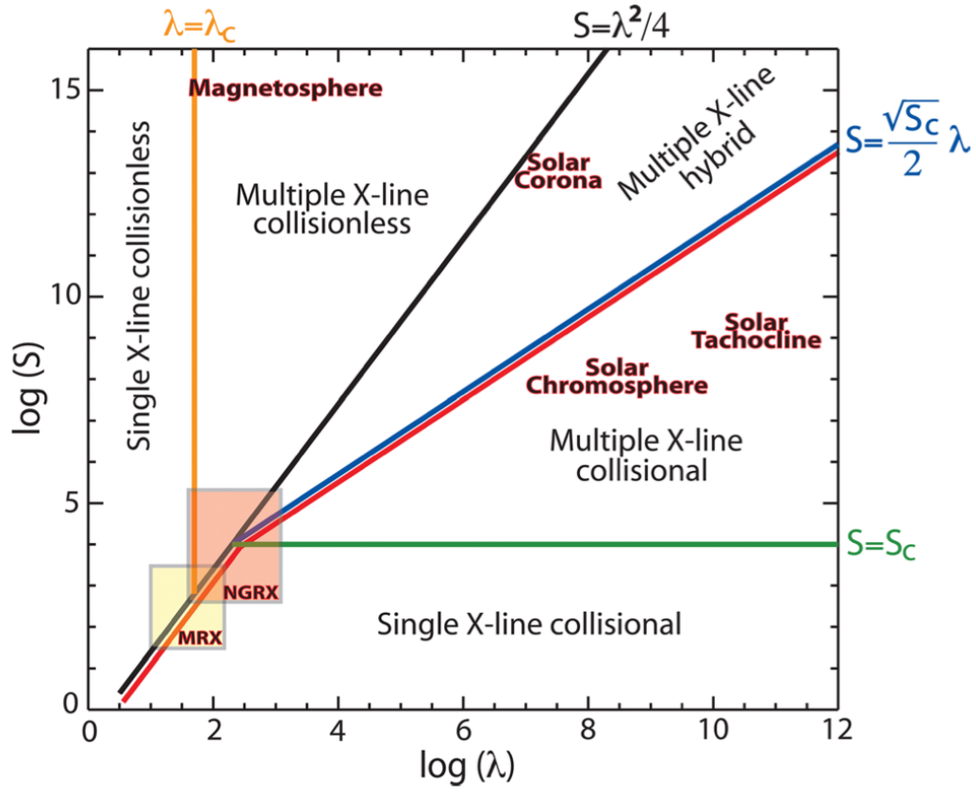
Frontier of reconnection theory and experiment: understanding reconnection physics at large system size and low dissipation

- "Scaling" a reconnection theory or experiment involves much more than just scaling "hydrodynamics" (L,V,t)
- More important (and difficult!) is to scale **plasma dissipation and microphysics**. Parameterized by:
  - Lundquist number $S = \mu_0 L V_A / \eta$
  - Ratio of system size to skin-depth $\lambda = L/d_i$



Plasmoid-unstable current sheet (e.g. Bhattacharjee and Huang, PoP 2009)

- Past experimental work has allowed detailed benchmarking of reconnection, but at moderate *S* and *L/di* regimes (see Yamada, Ji, Kulsrud RMP 2010)
- Recent theory breakthroughs demonstrate role of tearing or "plasmoid" instability in large *S* regimes
- Particles energized by Fermi acceleration process through interaction with islands (Drake 2006, Hoshino SSR 2012)



Phase diagram from H. Ji and W. Daughton, PoP (2011).

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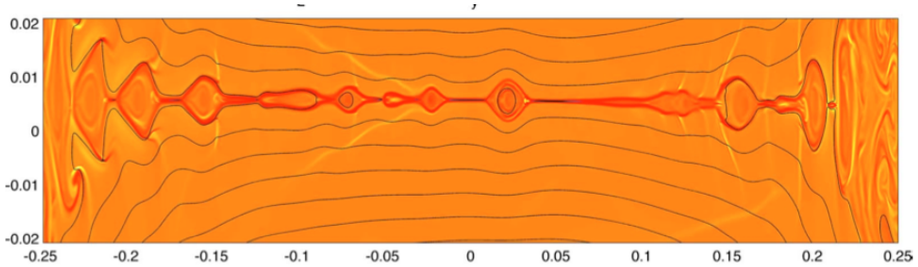

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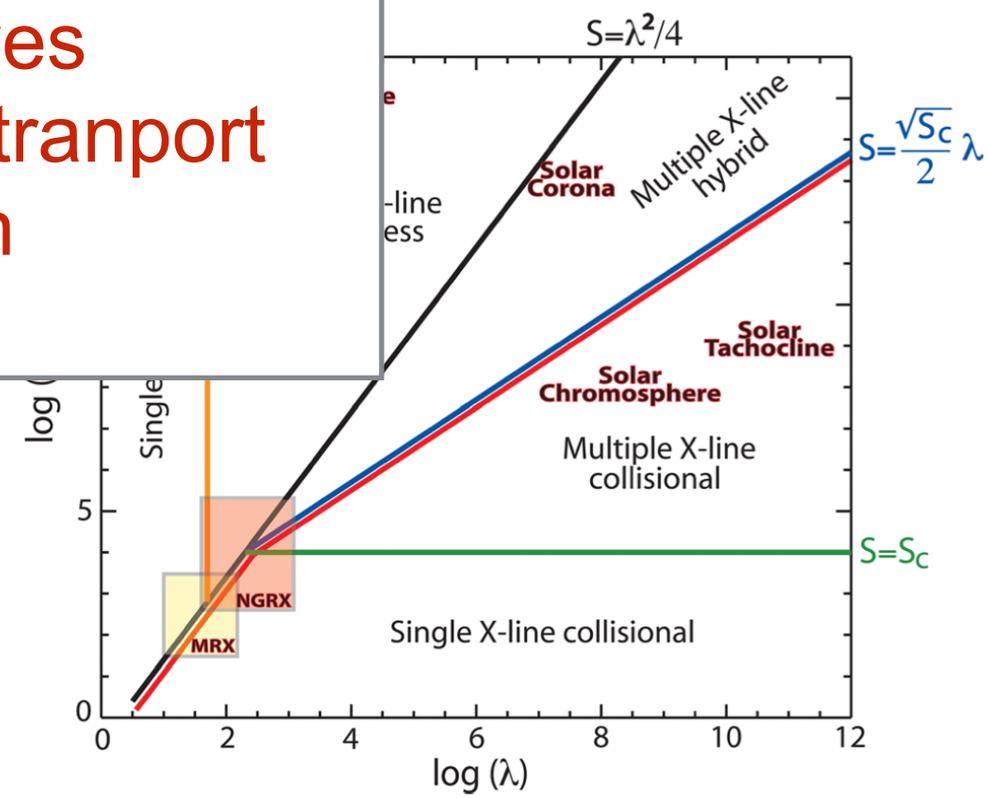

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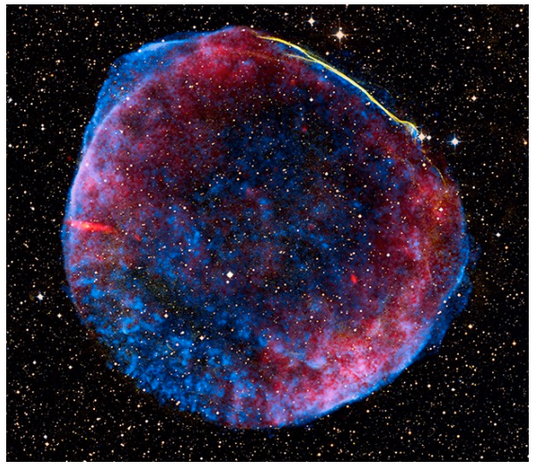
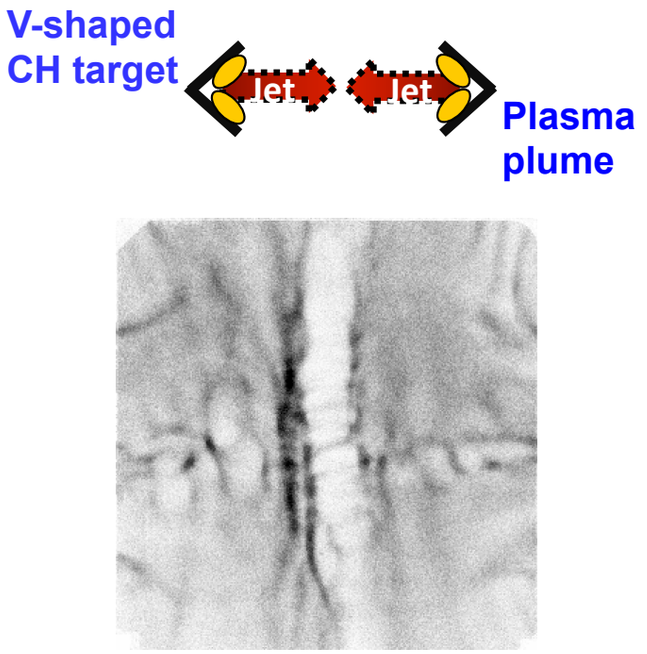
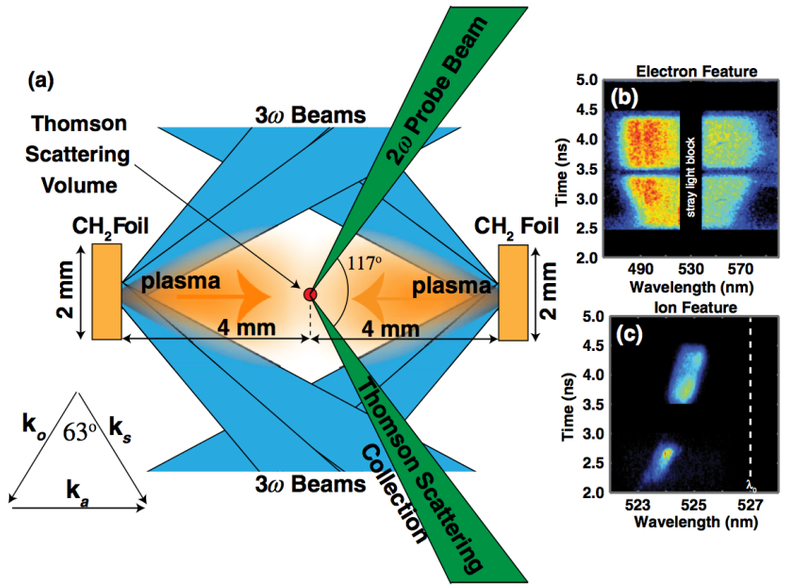
Colliding plume experiments study physics of astrophysical collisionless shocks and jets



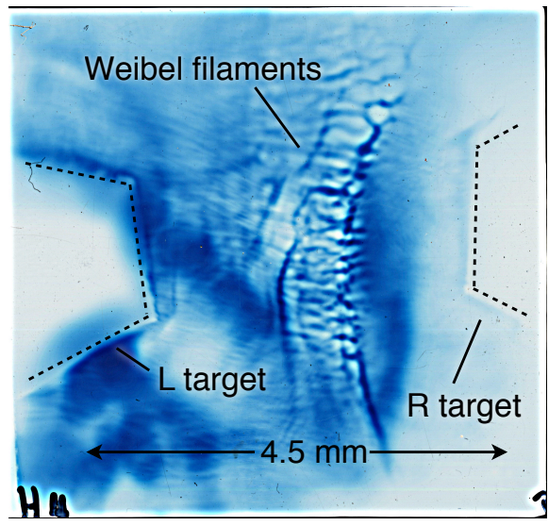
Supernova remnant and Gamma ray burst shocks, sites of cosmic ray acceleration (Ackerman Science 2013)



Radiography of colliding plasma jets (C.K. Li PRL 2013)



Anomalous ion and electron heating in colliding plumes by electrostatic instabilities (J.S. Ross PRL 2013)



Observations of ion-driven Weibel instability (Fox PRL 2013, Huntington Nature Phys 2015)

Opportunities

- Detailed benchmarking of Weibel instability and associated shock physics
- Create a fully-formed collisionless shock at large system size (proposed for the NIF)

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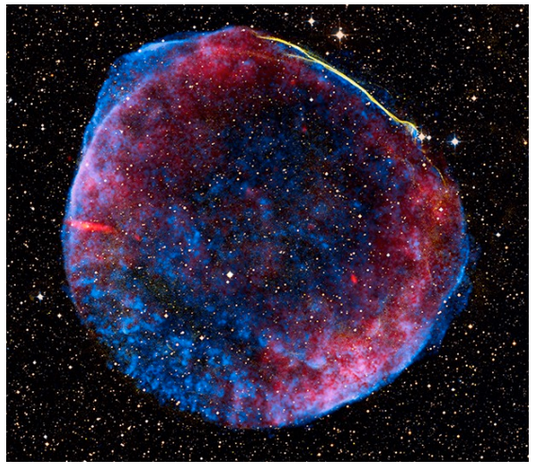

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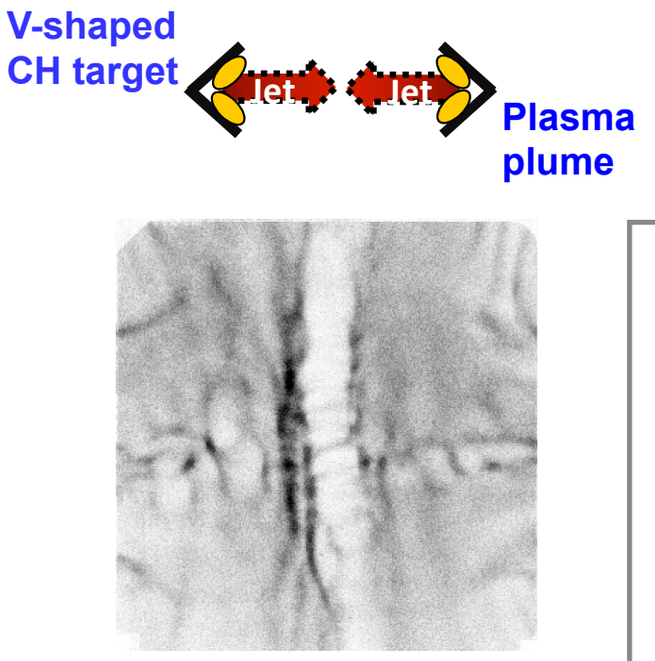

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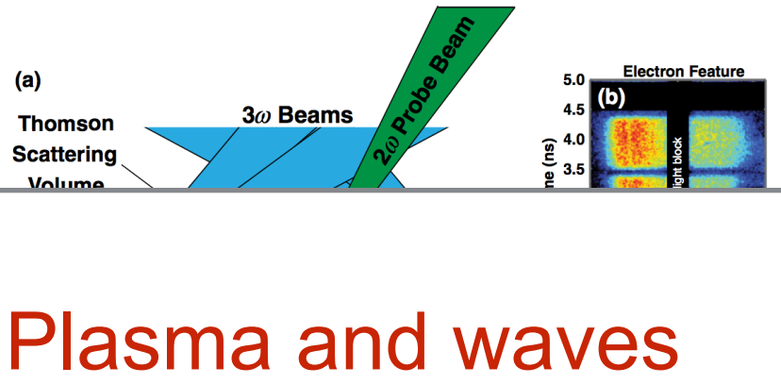

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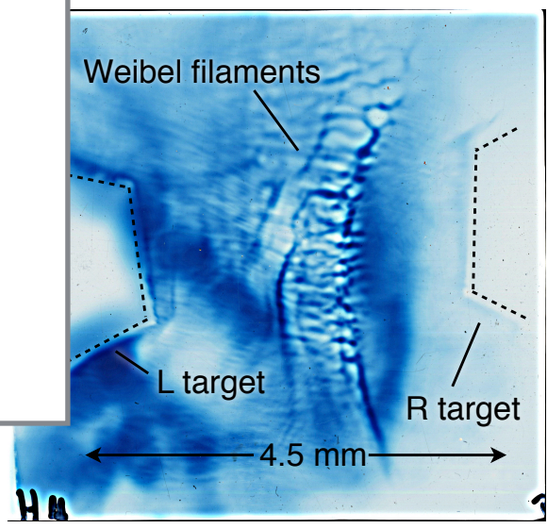

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Summary

- Laser facilities are used to study fundamental problems in plasma astrophysics. Recent results have been obtained on problems from shocks to reconnection to turbulence.

- Opportunities exist based on new machines, new and improved diagnostics, and new ideas.

- A great opportunity for discovery plasma science.