Magnetic Reconnection Experiments with MIFEDS

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- NIF Discovery Science
- DOE / NNSA Joint Program
- DOE / INCITE for simulation

Princeton RS
Princeton GS

Summary

Magnetized High-energy-density plasmas provide very interesting opportunities for basic plasma physics and plasma astrophysics.

B fields important in astrophysical plasmas to mediate violent energy conversion and acceleration processes

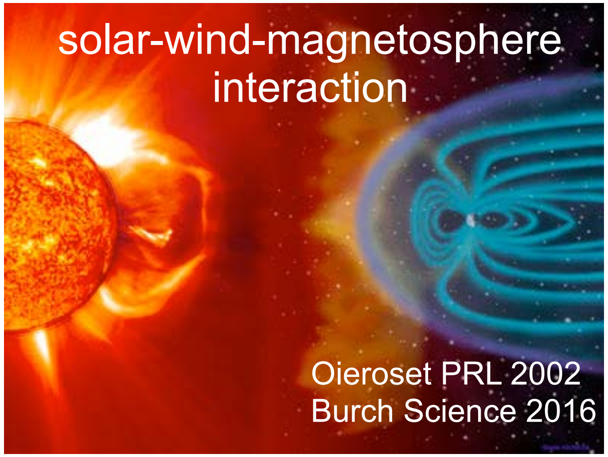
Tour through recent results on magnetized plasmas in HEDP -

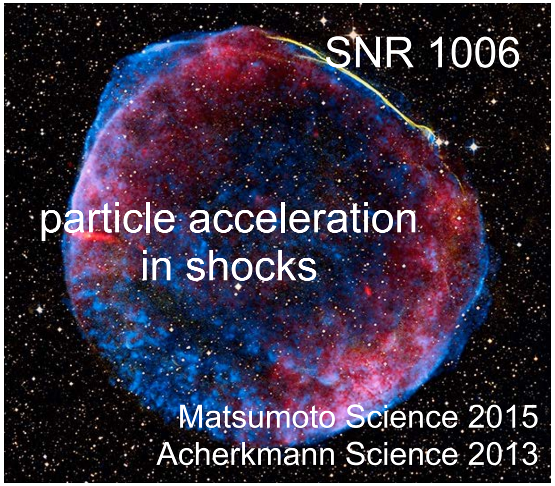
- Weibel instability, magnetized shocks, magnetic reconnection, particle acceleration

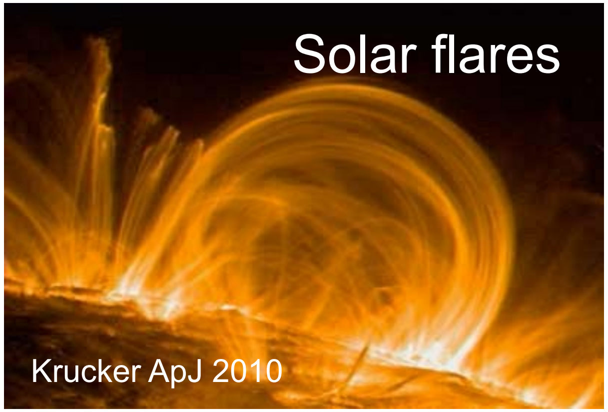
Key tool is combination of fully kinetic simulation and experiments

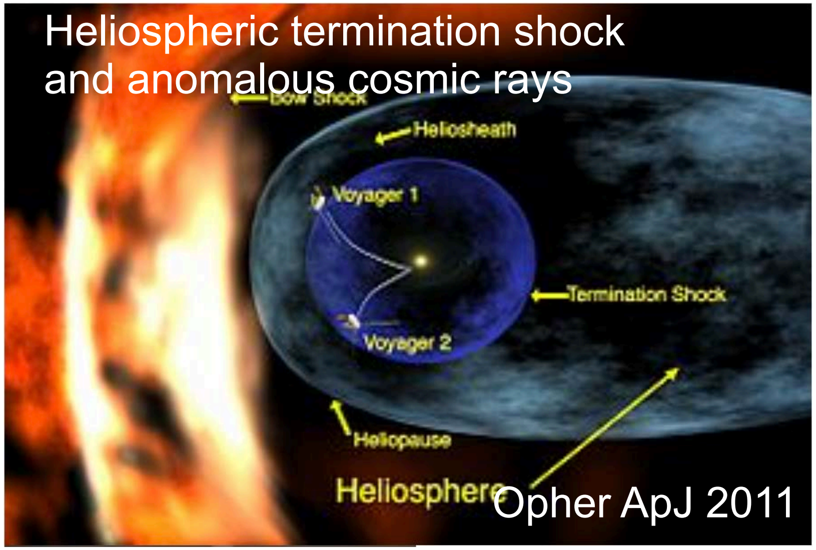
A huge thank-you to facilities and collaborators for contributions!

Laser facilities produce useful and interesting plasmas for laboratory plasma astrophysics









Laser facilities produce highly useful and interesting plasmas for laboratory astrophysics

TOPICS

- magnetic reconnection
- collisionless shocks
- collisionless plasmas, kinetic instabilities
- magnetized flows, magnetized shocks
- self-generated magnetic fields, dynamos
- ….

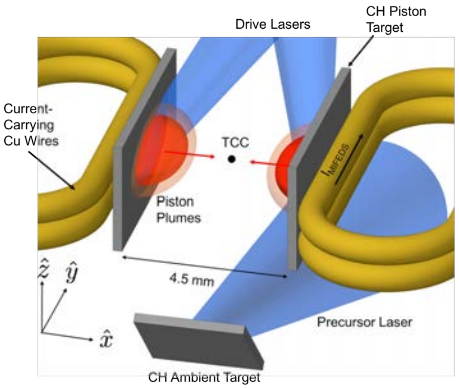
DESIRED PROPERTIES

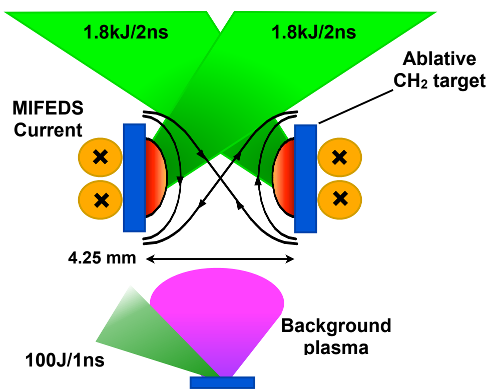
- large Energy translates to large density n, temperature T, and size L^3
- high magnetic Reynold's number $R_M \sim L\,T^2$ = low dissipation
- scale separation L / d_i large, e.g. fully formed shocks; turbulent "plasmoid" regime for reconnection; kinetic plasma turbulence
- long mean-free path: $L_{mfp} \sim T^2/n$ for collisionless plasma behavior,
- $V \sim C_s$: supersonic flows and shocks

Complementarity to other approaches:

- discharge lab experiments (e.g. MRX, TREX): Very detailed measurements, but limited system size ($L/d_i \sim$ few), so far
- solar observation: global evolution observed, but limited by remote-sensing nature
- spacecraft: fully kinetic data, but limited by single-spacecraft nature of data

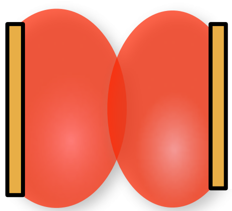
New techniques for externally magnetizing plasmas for experiments on shocks and strongly-driven reconnection at OMEGA and OMEGA EP





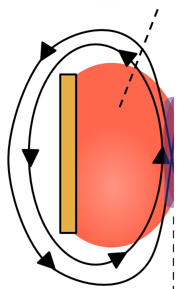
Choreography of externally-applied B fields, and plasma ablation to produce magnetized background plasmas

What can be done?



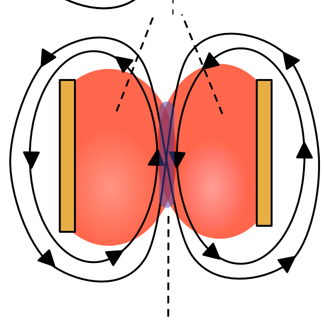
"Unmagnetized"
→ ion Weibel

WF, G. Fiksel, AB, PRL 2013



Single,magnetized
→ shocks!

D Schaeffer, WF, et al PRL 2017

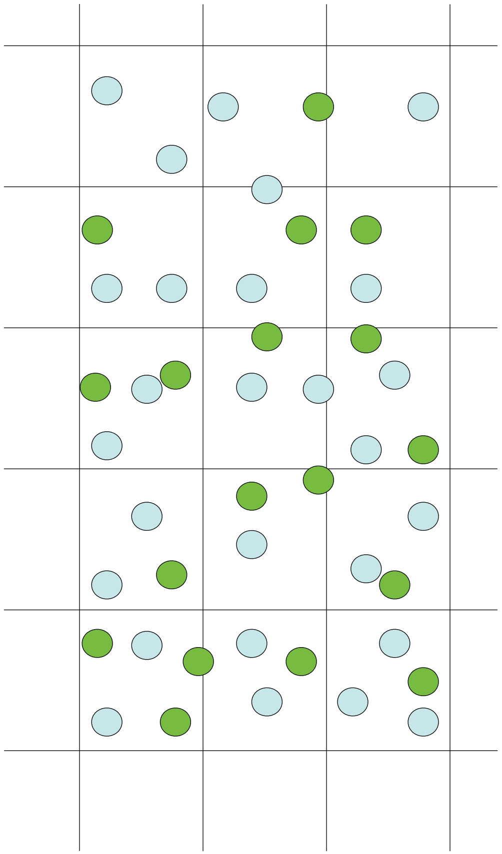


Double,magnetized
→ reconnection!

G. Fiksel, WF, AB, PRL 2014
WF, J Park PoP 2017

Magnetized plasma platform may be useful for other problems in magnetized HED plasmas

Particle-in-cell code PSC a critical tool for design and interpretation of these experiments



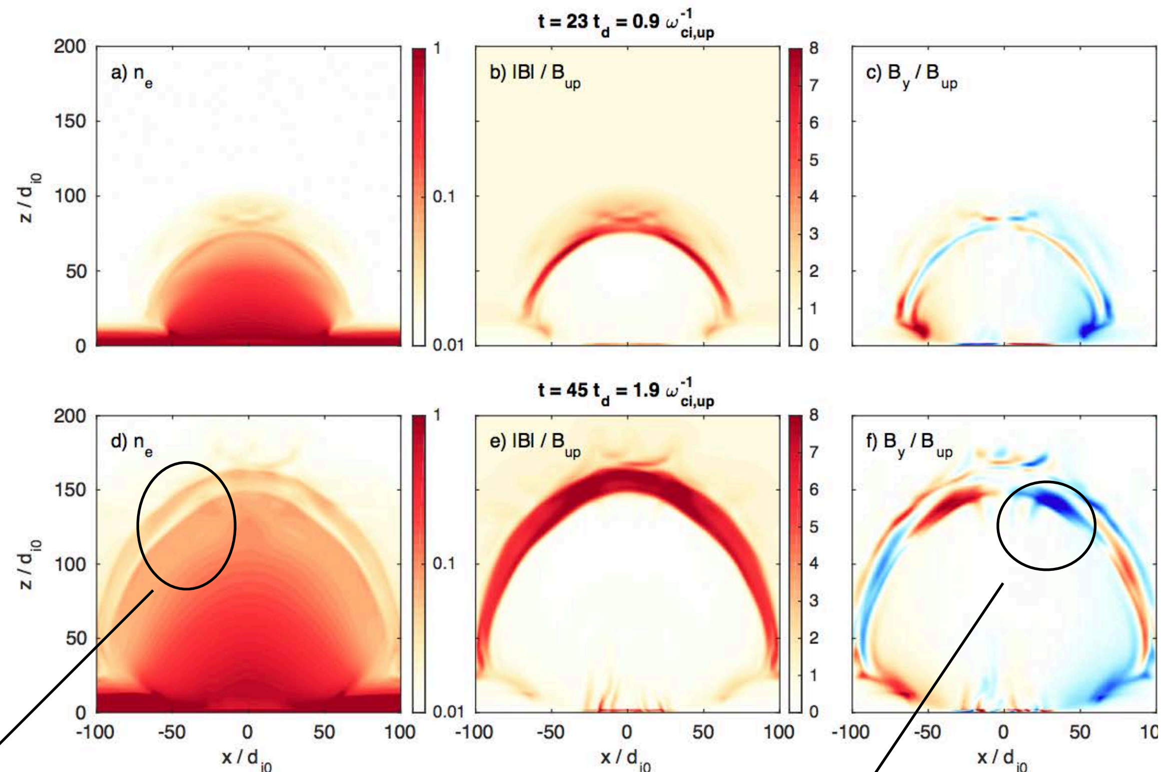
- 1-D,2-D,3-D, relativistic, explicit PIC
- 2nd-order particle shape (triangles)
- Charge conservative scheme
- No global communication, good scaling to >65000 cores
- Coulomb collision operator
- Load-balancing
- GPU support (2-D push kernel by KG, very challenging)

[K. Germaschewski, W. Fox, et al, JCP 2016]

Large-scale fully-kinetic PSC simulation shows physics of plasma expansion into a magnetized ambient plasma

Fully-kinetic PSC simulation*:

- GPU-enabled, full PIC with collisions and load-balancing
- rad-hydro coupling matches global hydro evolution while maintaining kinetic and B field physics



Double density jump
(key observable of shocks!)

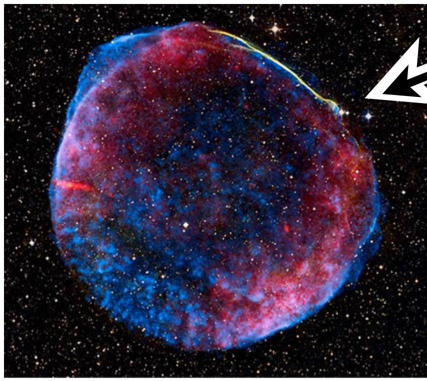
Biermann-battery generation

* Simulations: WF, J. Matteucci, C. Moissard, arxiv: (2017)

*** PSC: K. Germaschewski, W. Fox, et al, JCP 318 305–326 (2016)**

PSC may be useful for other kinetic problems in magnetized HED and ICF plasmas - let's discuss!

Observing astrophysical ion-driven Weibel instability in the laboratory



SNR1006

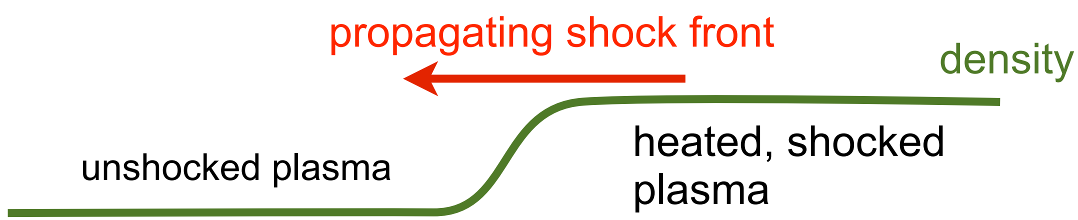
Collisionless SNR shocks shown to be the sites of cosmic ray acceleration. [Ackerman Science 2013]

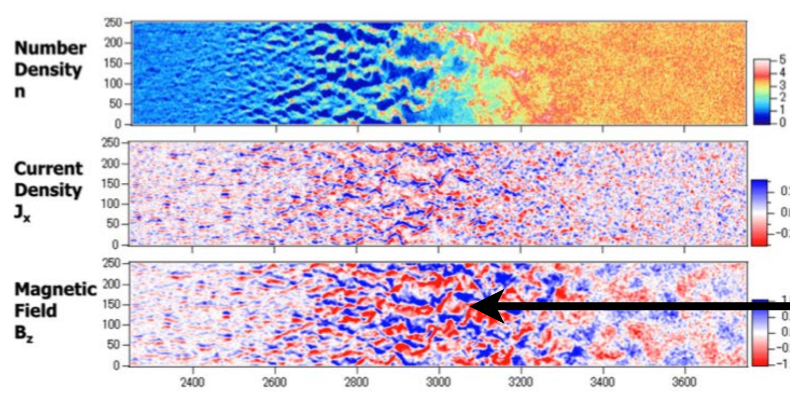
Collisionless shock front, shock width << mean-free-path.

Collective electromagnetic fields are required to mediate shock in collisionless plasmas

Proposed mechanisms:
- Pile-up of pre-existing field ("magnetized shocks" … shortly)
- Self-generation of a turbulent magnetic field near shock by Weibel instability *

Simulation of Weibel-mediated shock:





[Ref: Takabe PPCF 2008]

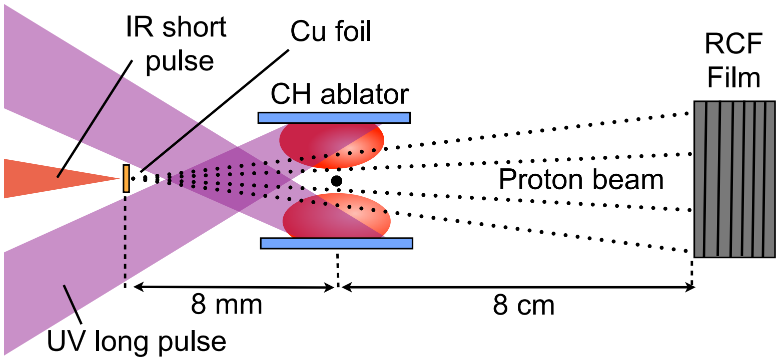
Weibel-generated B field

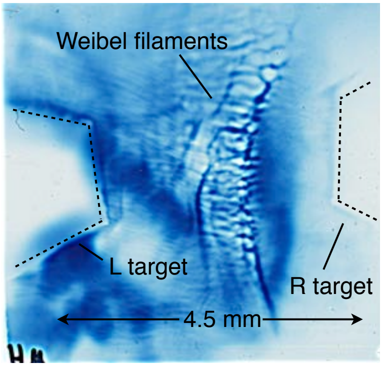
References:
[1]Weibel PRL (1959),
[2]Fried PoF (1959),
[3]R.Davidson, D. Hammer, I.Haber, C. Wagner PoF (1972)

Observing astrophysical ion-driven Weibel instability in the laboratory

Observation of ion-driven Weibel instability for the first time in the laboratory. ([1], see also [2])

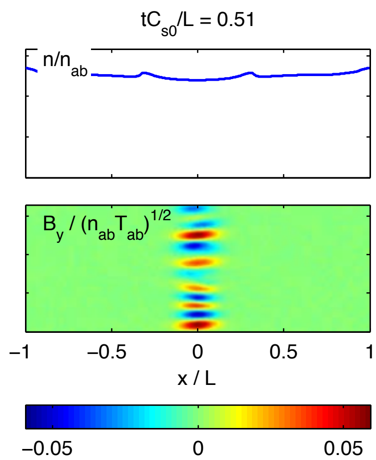
- Unmagnetized, high-Te plumes collided obtaining collisionless counter streaming ions.
- Elongated Weibel-driven magnetic field filaments observed with proton radiography
- Instability confirmed with analytic theory and PSC simulations of counterstreaming plasmas





Proton radiograph from OMEGA EP, t = 4.8 ns [1]

B Field generation in PSC



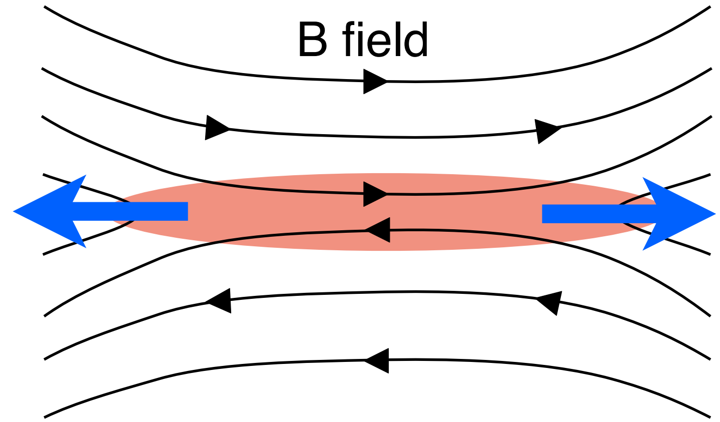
<u>Opportunities:</u>

- Detailed benchmarking of Weibel instability in linear regime
- Study non-linear evolution
- Particle acceleration by Weibel in comparison to shocks and reconnection

[1] W. Fox, G. Fiksel, A. Bhattacharjee, et al, Phys. Rev. Lett. 111, 225002 (2013)
[2] C. Huntington, et al, Nature Phys. (2015)

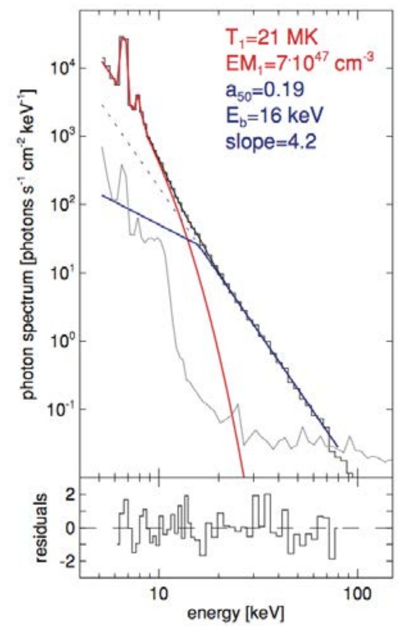
Magnetic reconnection

- Magnetic energy is stored in reversing magnetic field
- Energy released in a sling-shot, driven by magnetic forces [Yamada, et al RMP 2010]

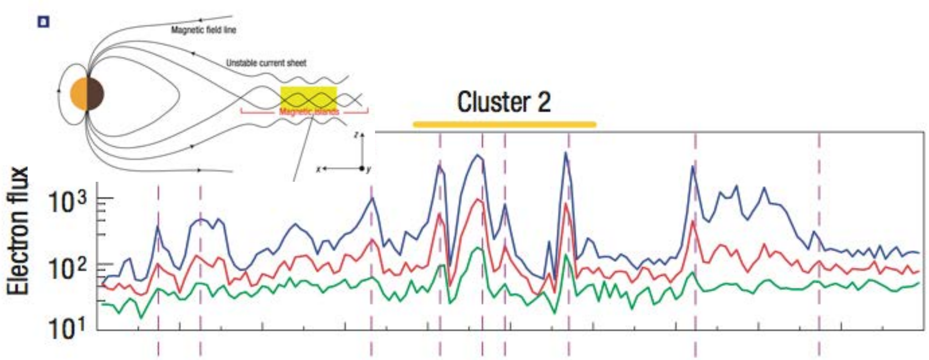


- Reconnection can energize particles in:
  - solar flares [Krucker ApJ 2010]
  - magnetosphere (L.J. Chen Nature 2007)
  - high-Mach number collisionless shocks in astrophysics (Matsumoto Science 2015)

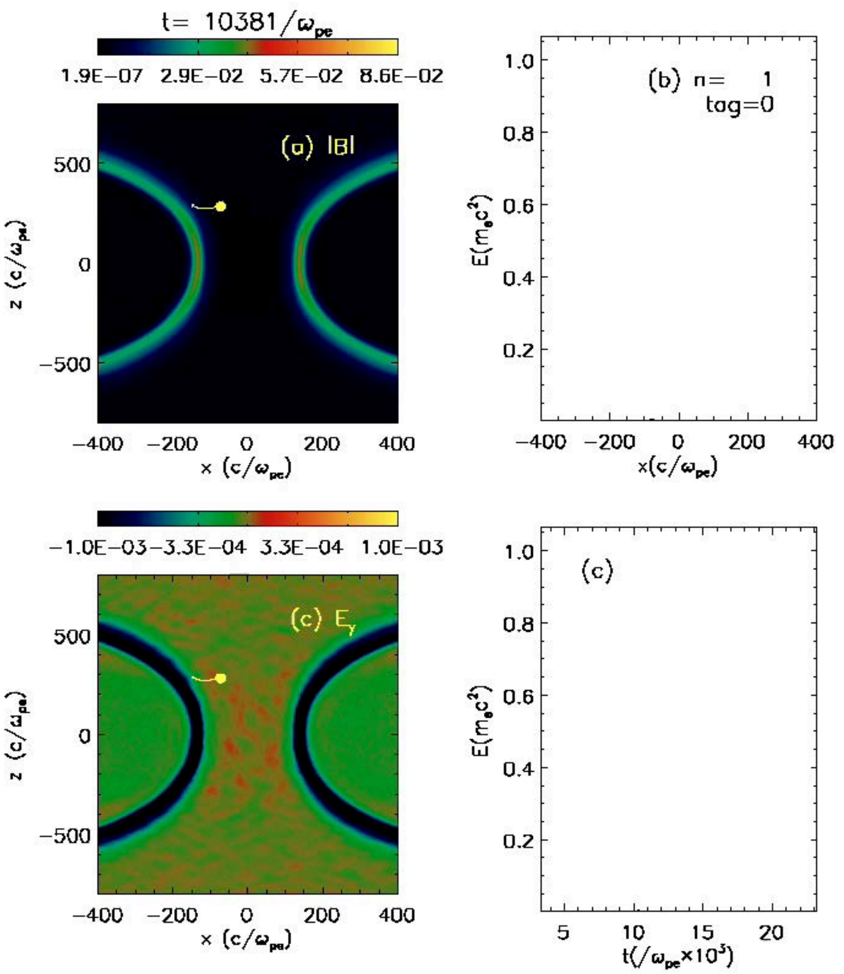
Solar flare x-ray spectrum:



[Krucker ApJ 2010]



Particle simulations show electrons may be accelerated in collision and reconnection of magnetized plasmas

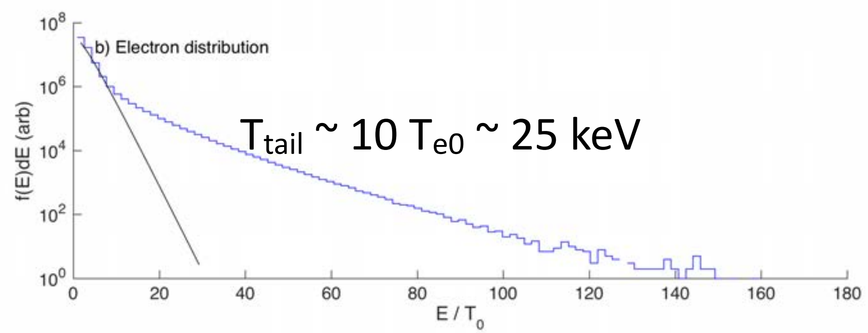


1: "Direct" Fermi acceleration between converging two flows

2. X-line acceleration during magnetic reconnection

3. Further Fermi acceleration in contracting plasmoids

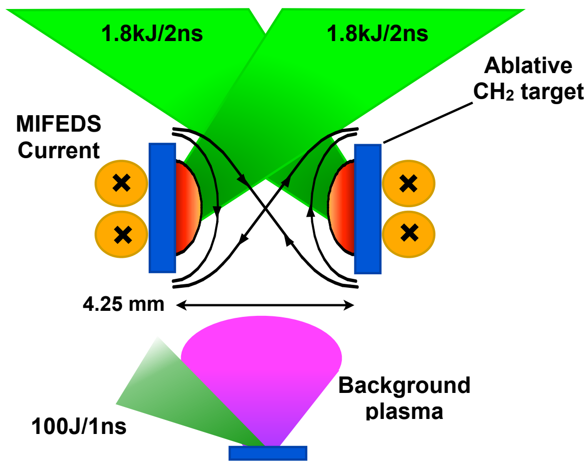
PSC Simulation Accelerated spectrum for NIF



$T_{tail} \sim 10\ T_{e0} \sim 25$ keV

WF, J. Park, et al, Phys. Plasmas (2017)
See also: S. Totorica PRL (2016); S. Lu NJP (2015)

Reconnection experiment platform based on externally-magnetized plumes developed on OMEGA EP



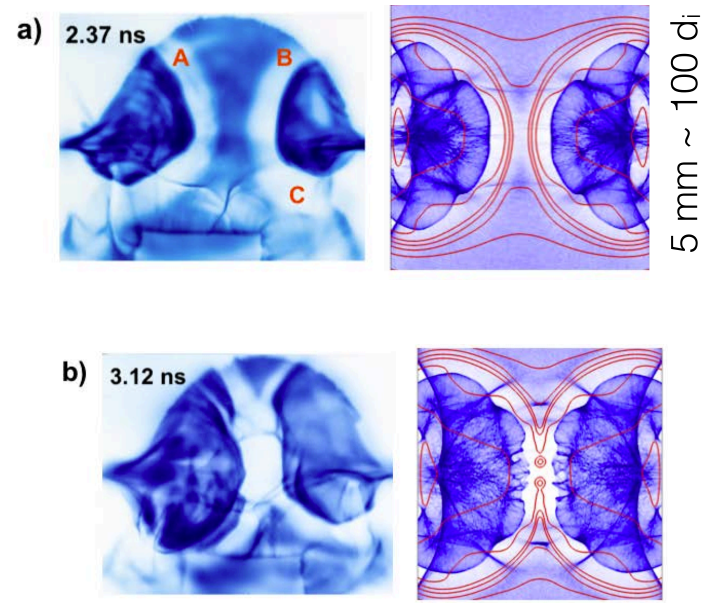
Choreography of externally-applied B fields, a “background plasma”, and two driver plumes.

Experimentally, B field can be controlled and varied (reconnecting topology, non-reconnecting parallel topology, B = 0)

Expt proton radiography | PSC Simulation synthetic radiography

white “ribbons” on radiography -> **compressed B field:**

Collision of plumes, formation of current sheet and breakup into cellular structures



<u>Opportunities and ongoing work</u>

- study regimes and stabilization of plasmoid instability
- Our Recent NLUF days unfortunately concluded negative results on particle acceleration - too much “downstream” magnetic field with MIFEDS?

[G. Fiksel, WF, AB, et al “Magnetic Reconnection between Colliding Magnetized Laser-Produced Plasma Plumes” PRL (2014)]

Summary

Magnetized High-energy-density plasmas provide very interesting opportunities for basic plasma physics and plasma astrophysics.

B fields important in astrophysical plasmas to mediate violent energy conversion and acceleration processes

Coupling of magnetic fields to HED laboratory plasmas by externally controlled fields allows Discovery Science experiments to understand dynamics of magnetized astrophysical plasmas:

- Weibel instability, shocks, magnetic reconnection, particle acceleration

Stronger MIFEDS at LLE and NIF would allow access to new regimes of stronger magnetization, lower plasma beta, and larger particle acceleration.

Key tool is combination of fully kinetic simulation and experiments

A huge thank-you to facilities and collaborators!