Study of Astrophysical Collisionless Shocks and Particle Acceleration with Lasers

Plasma Science Frontiers
June 30- July 1, 2015
Bethesda, MD, USA

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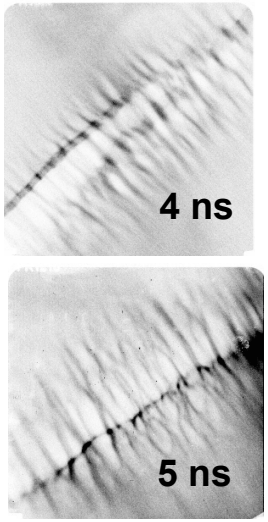
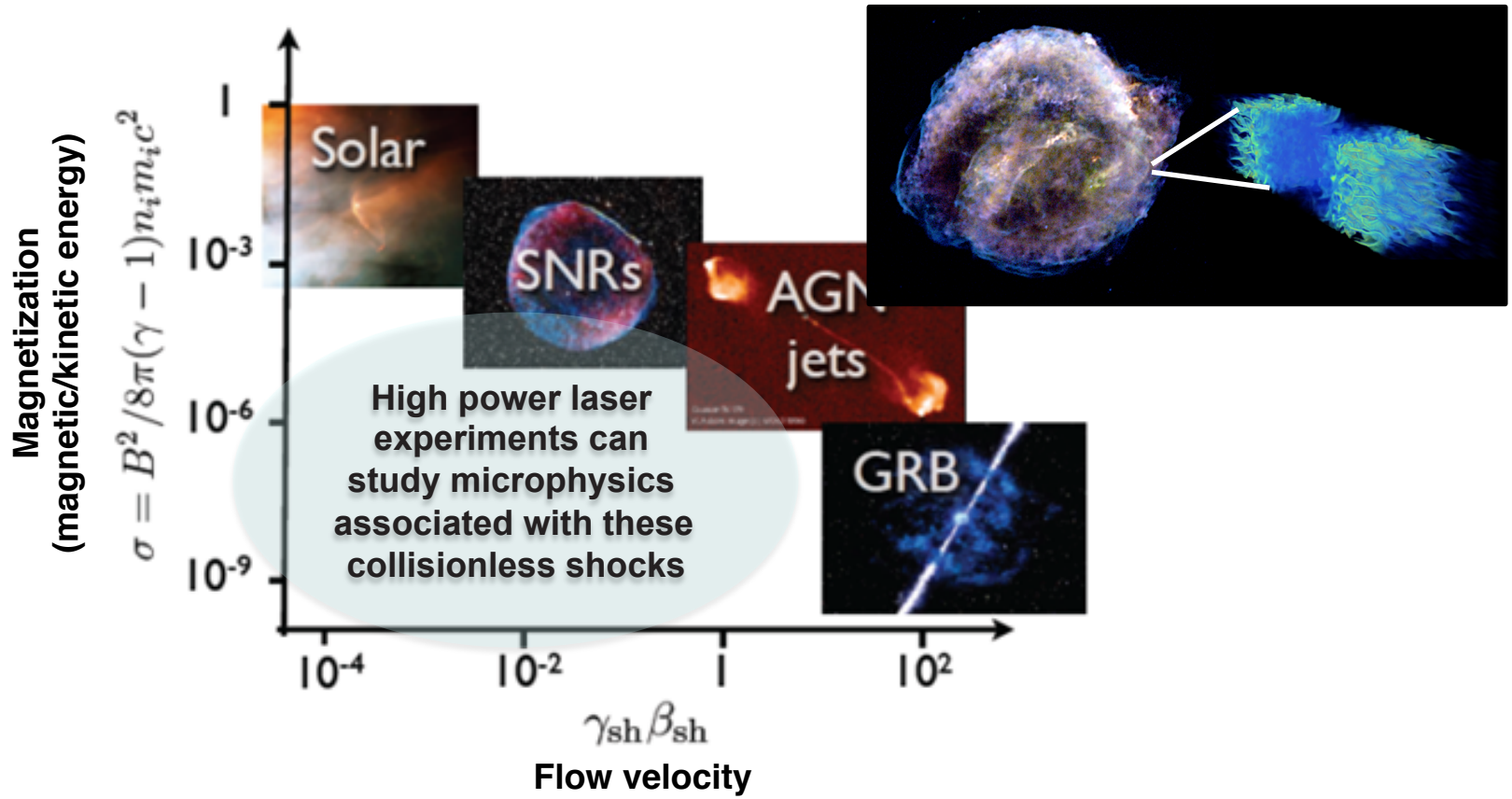
Weibel filaments



Astrophysical collisionless shocks are ubiquitous



Shocks span a range of parameters:

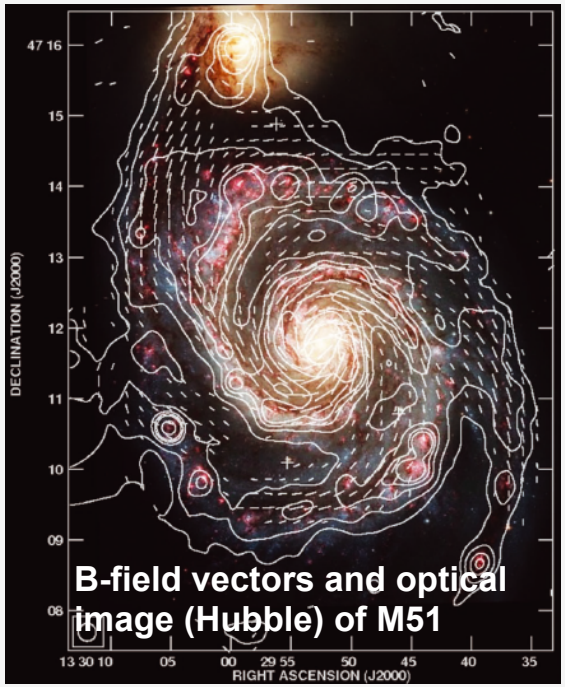
- **Non-relativistic to relativistic flows**
- **magnetization (ratio of magnetic/kinetic energy density)**

Collisionless shocks create self-generated magnetic fields via Weibel instabilities and are responsible for particle acceleration

Generate and amplify magnetic fields

- The universe is ubiquitously magnetized
- The origin and nature of the weak seed fields is unknown
- Collisionless shock may be a possible mechanism

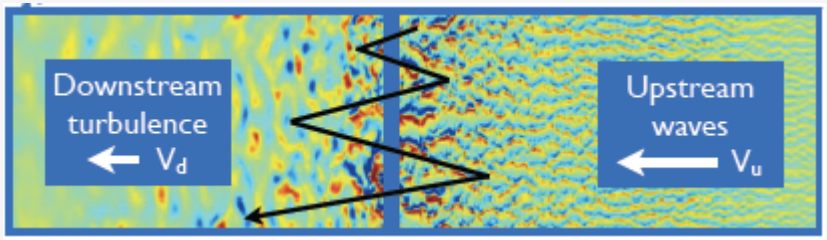
Neronov, Science, 2010

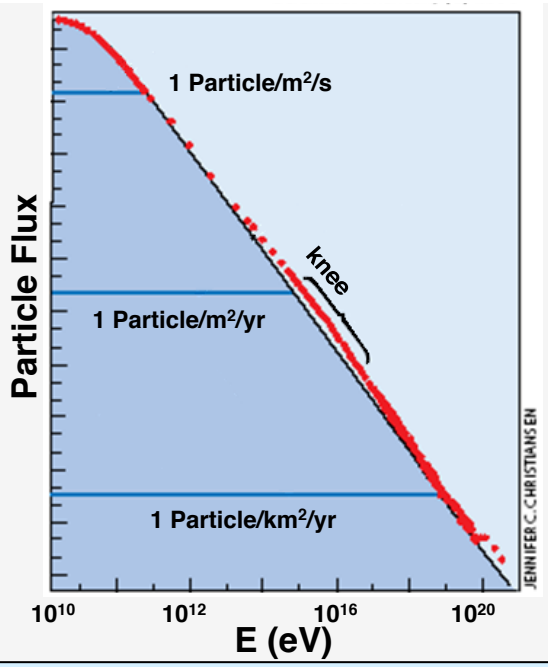


B-field vectors and optical image (Hubble) of M51

Fletcher, MNRAS, 2011

Accelerate particles





Diffusive shock acceleration is one of the proposed mechanism for cosmic ray acceleration [R. Blandford, Physics Reports,1987]

There are many areas to be explored on astrophysical collisionless shocks

Astrophysical collisionless shocks
- Electrostatic
- Electromagnetic
- Non-relativistic
- Relativistic

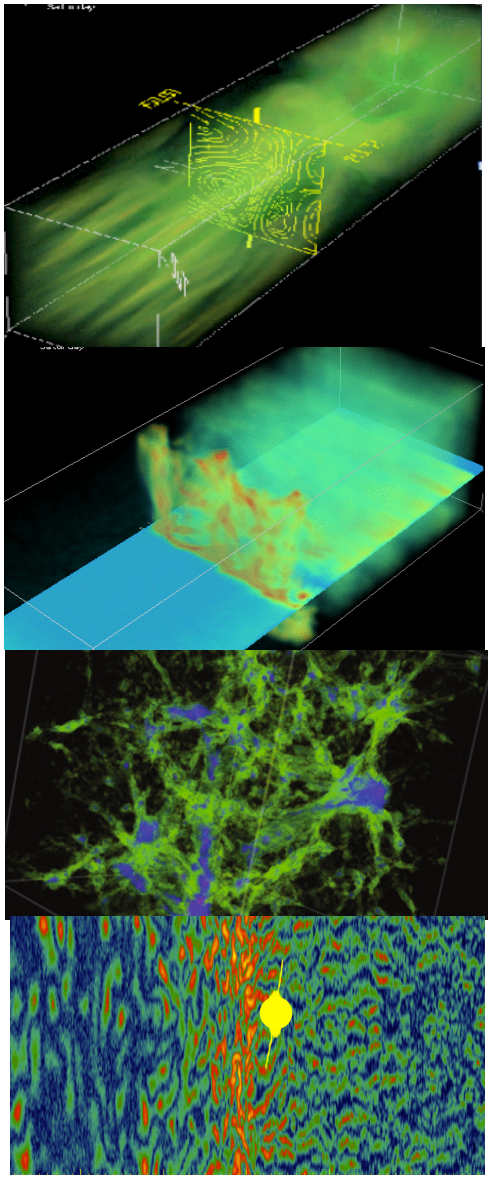
Unmagnetized: Self-generated magnetic fields — Weibel instability

Magnetized: Magnetic reflection — Coherent Larmor loop and particle bunching

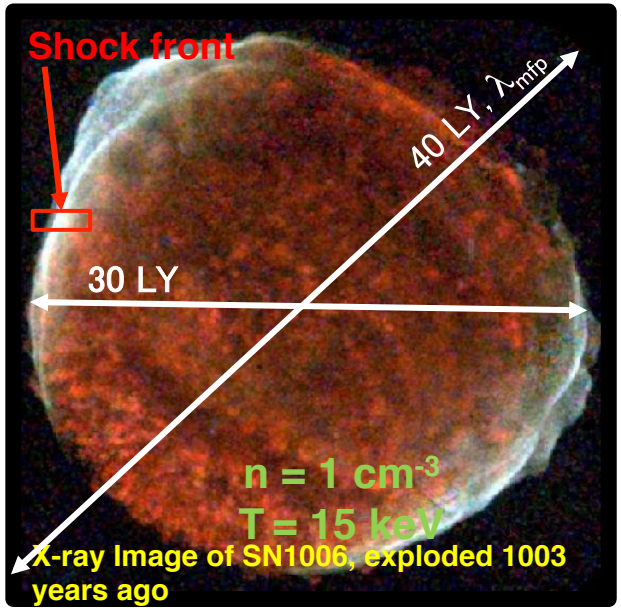
Magnetic field amplification — Turbulent dynamos

Particle acceleration — First order Fermi (DSA)

Relativistic collisionless shocks



Basic scaling for laboratory collisionless shock experiments require high velocity and high temperature plasma flows

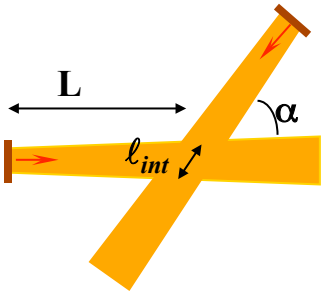


Mean-free-path: λ_{mfp} ~ 40 LY
Diameter of SNR: 30 LY
(Cassam et al., ApJ 680, 1180, 2008)

Shock width : 1x10^{15}m (i.e. ~1/400 λ_{mfp})
(Bamba et al., ApJ, 589, 827, 2003)

The conditions for generating a collisionless shock require:

$$\ell^* << \ell_{int} << \lambda_{mfp}$$



ℓ^*, characteristic (electrostatic or electromagnetic) instability length scale
ℓ_{int} intersection zone length scale
λ_{mfp}, Coulomb mean free path length

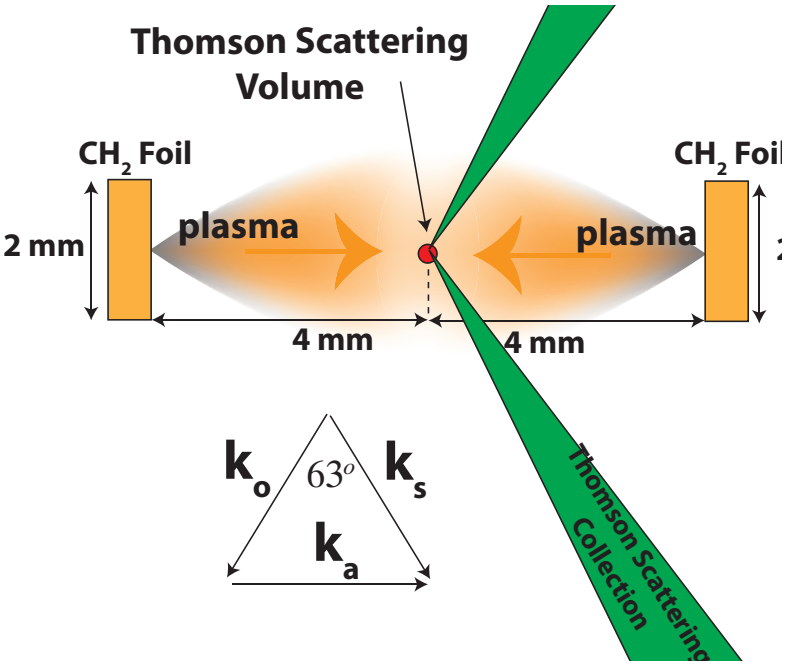
$$\lambda_{mfp} \sim 5x10^{-13} \frac{A_Z^2}{Z^4} \frac{[v(cm/s)]^4}{n_z(cm^{-3})}$$

$$\ell^*_{ES} \sim K' \frac{v}{\omega_{pi}} \frac{W}{T_e} \qquad \ell^*_{EM} \sim K \frac{c}{\omega_{pi}}$$

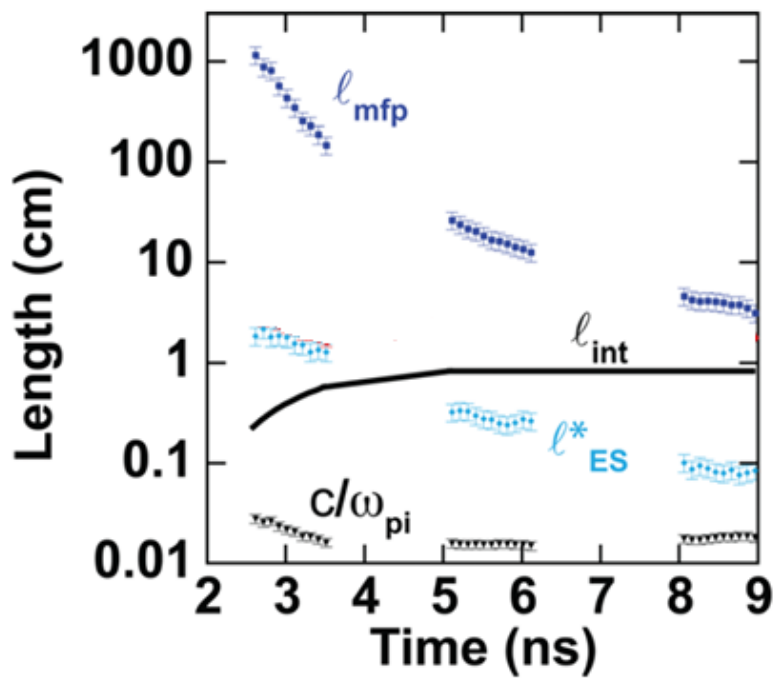
[D. Ryutov, PPCF, 2012]
[H. –S. Park, HEDP, 2012]

We use Omega laser facility to study the microphysics of collisionless shock generation and Weibel induced magnetic fields

OMEGA (4.5 kJ/target in 1 ns)



Optical Thomson scattering data provides measurements of plasma state: V, n_e, T_e, T_i



In order to demonstrate that the flows are in the collisionless regime we measure the plasma conditions using Thomson scattering diagnostics

The Coulomb mean free path length is much larger than the system size

- J. S. Ross et al., Phys. Plasmas 2012
- J. S. Ross et al., PRL 2013

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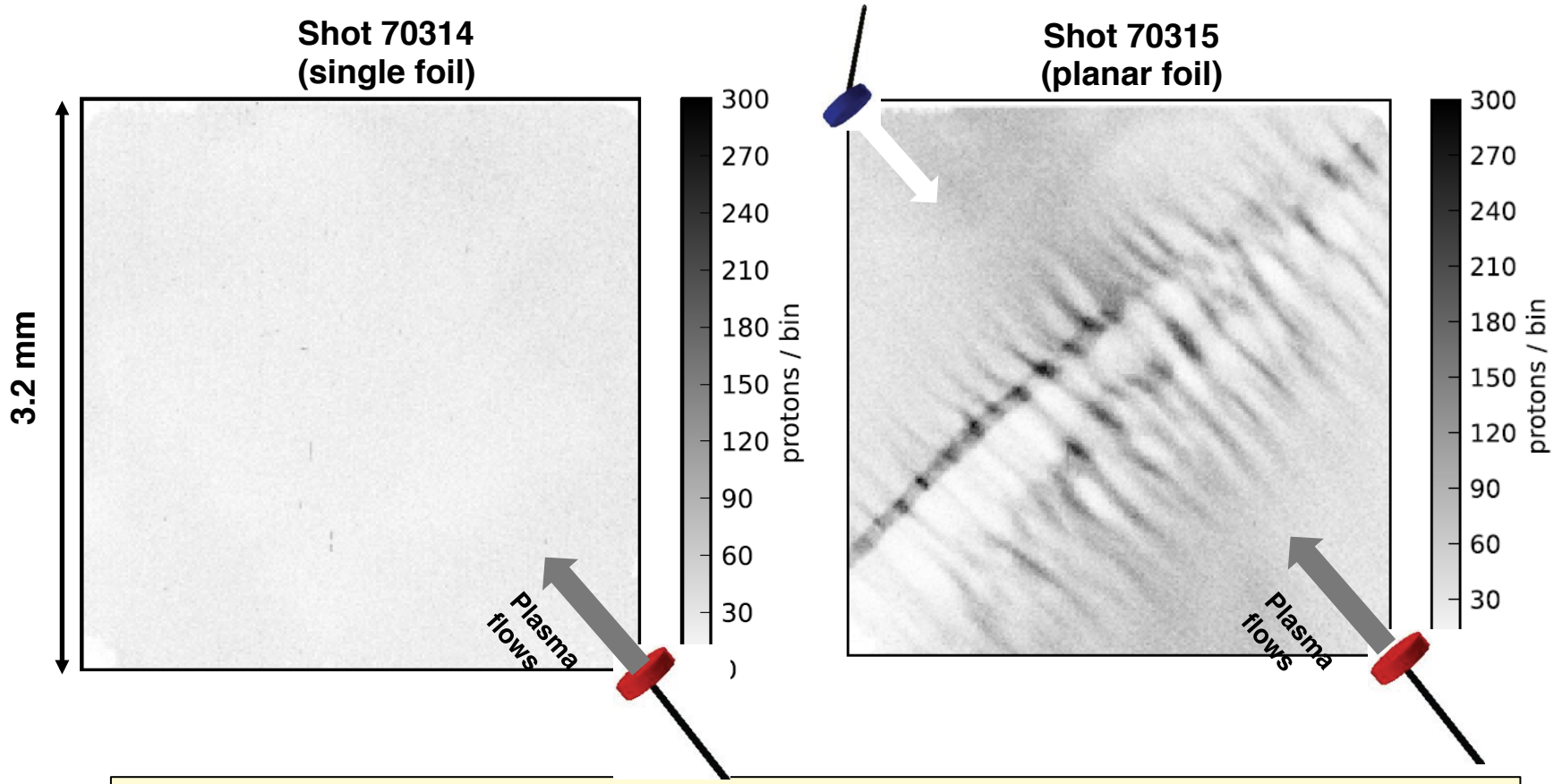
Collisionless shock experiments on Omega show clear filamentation features using the DHe3 mono-energetic proton backlighter



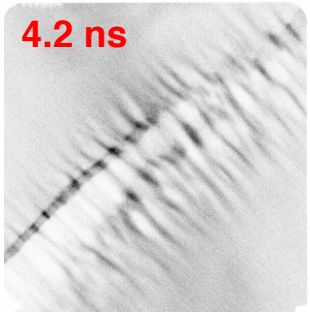
- DHe3 proton backlighter (14.7 MeV) radiographed the electromagnetic field structures in the middle of the counter streaming plasma flows
- Strong striation features are observed

C. M. Huntington et al, Nature Physics, 11, 215 (2015)

Filament temporal evolution shows we are in non-linear regime of Weibel instability growth

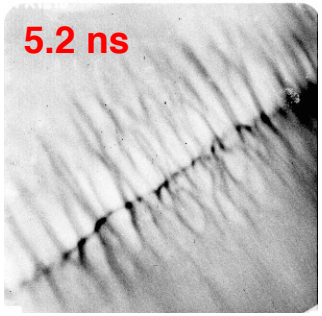
D^3He
(14.7 MeV)

Very early time; only very fast and low n_e intercepts



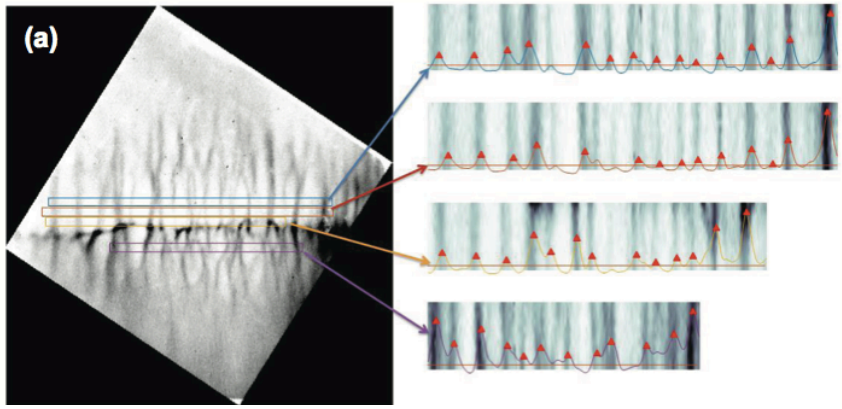
Bulk of flow intercept ;

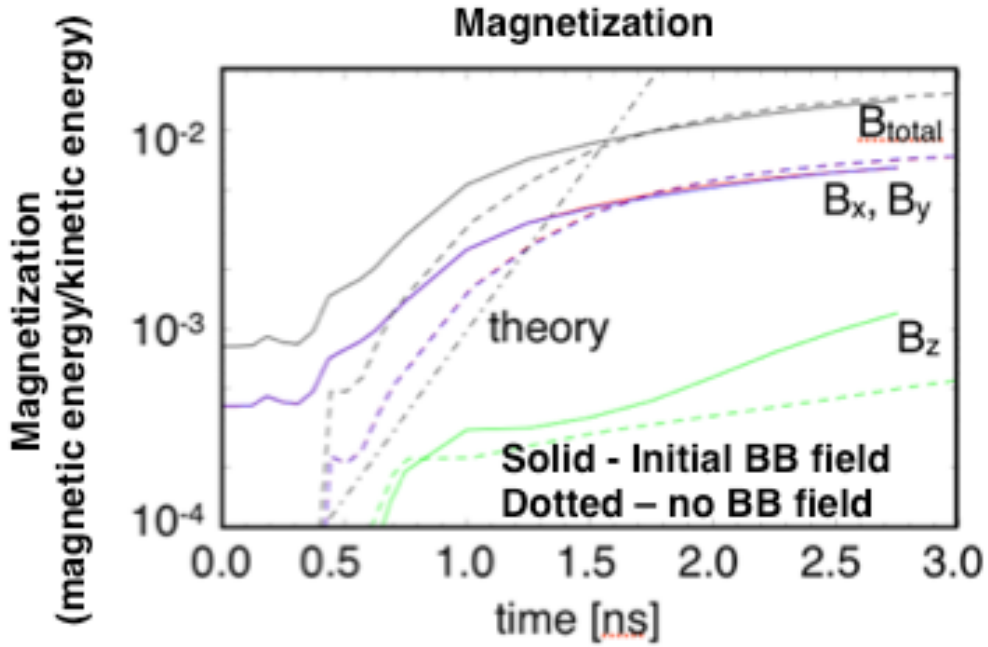
Developing Weibel instability



Weibel growth matures

Horizontal line is from Biermann recompression



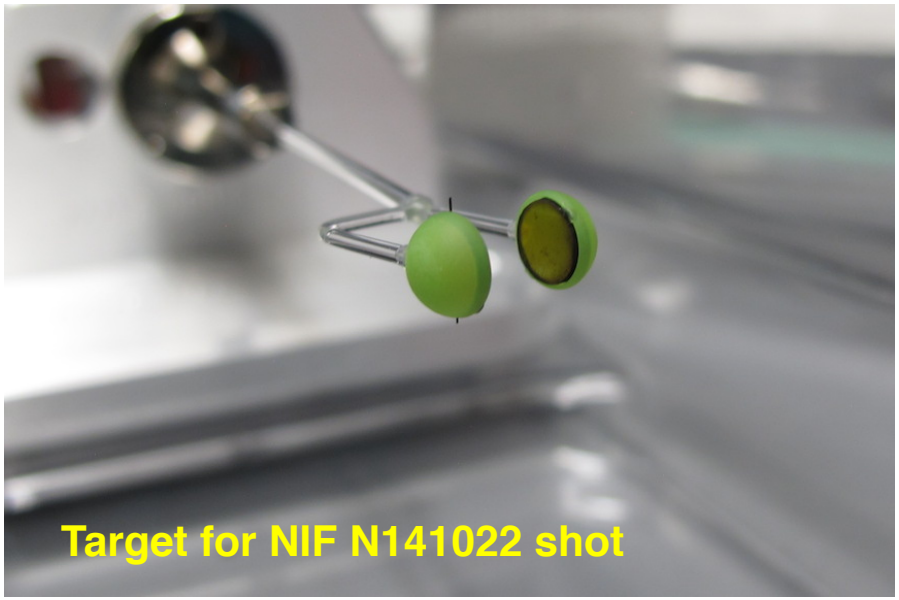


C. M. Huntington et al, Nature Physics, 11, 215 (2015)
H. –S. Park et al., Phys. Plasmas, 22, 056311 (2015)

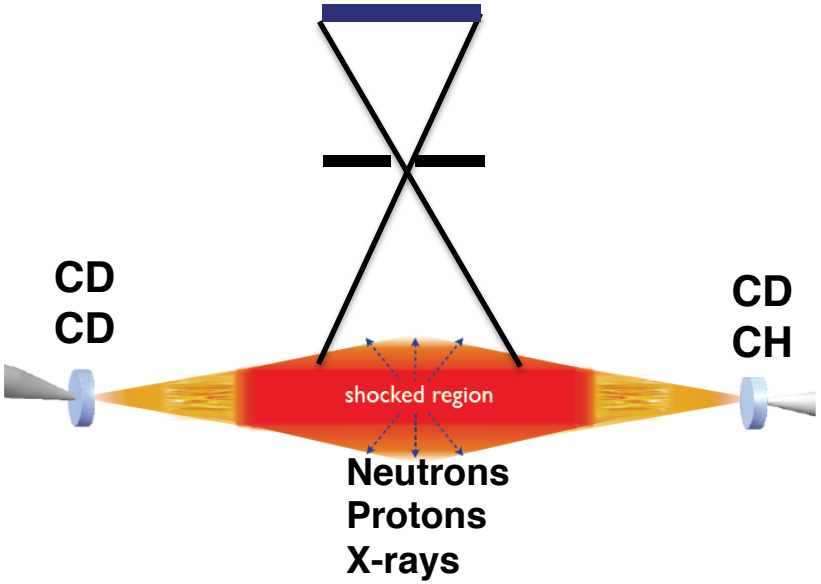
NIF Laser System
192 beams
1.8 MJ (1.2 MJ, 12/05/09)
500 TW (300 TW, 12/05/09)

NIF experiments use neutron and x-ray diagnostics; 7 shots are completed including shots on 6/16/15

Three different types of target were used: 1) CD/CD; 2) CD/CH; 3) CD single



Self-generated protons measure the location of neutron production area



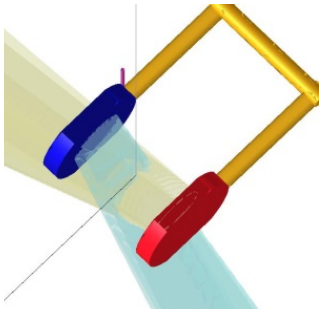
- $D+D \rightarrow T + p$
- $D+D \rightarrow {}^{3}He + n$

Shock formation can be diagnosed by:

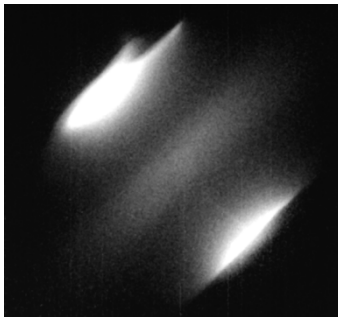
- X-ray brightening from hot plasmas
- Neutron yields comparison between CD/CD, CD/CH, CD single foil
- Proton yields and their birth location
- X-ray/neutron production time

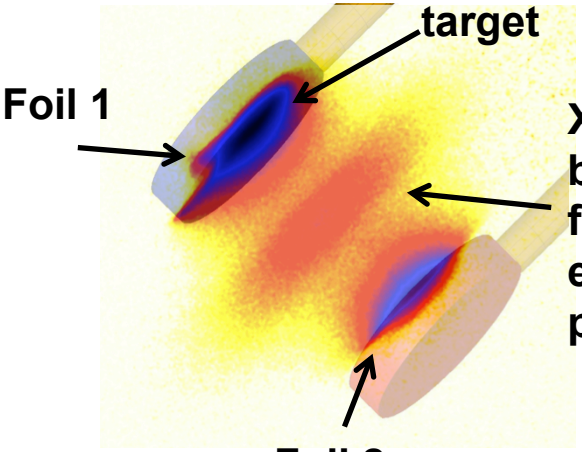
NIF data shows strong x-ray brightening and proton generations from central region indicating a shock is formed

X-ray brightening is observed from the central flow interaction region



N140729: SXI data from NIF

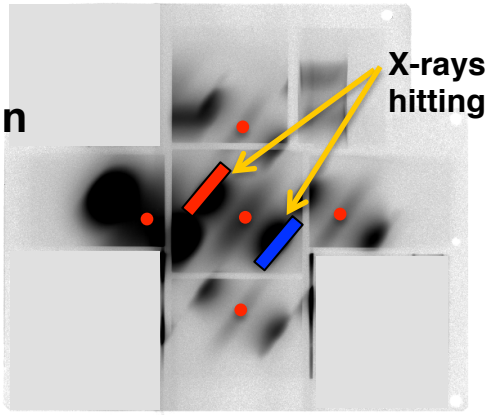


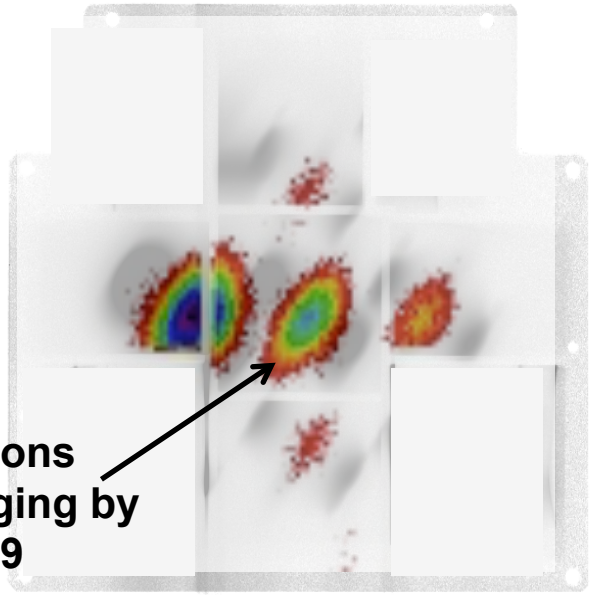


Self generated protons are from the central region

$D+D \rightarrow T + p$

$D+D \rightarrow {}^{3}He + n$





Ross et al, in preparation

There are many areas to be explored on astrophysical collisionless shocks

Astrophy
collision
shocks
- Electro
-
Electrom
- Non-rel
- Relativi

Unmagnetized:
Self-generated magnetic fields

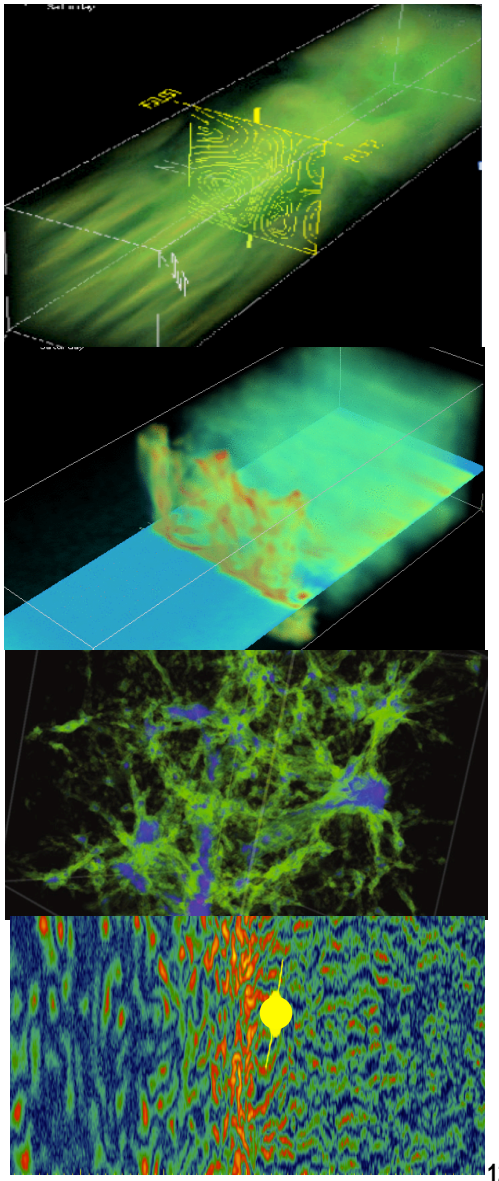
Weibel instability

- This field is new and the research is in its beginning stage. Unknowns are:
  - Nature of fully formed shocks
  - shock growth rates, saturation condition, linear to non-linear transition
  - long-term magnetic fields sustainability
  - Transition regime/mechanism from collisionless to collisional shocks
  - Effect of non-planar flows

Particle acceleration

First order Fermi (DSA)

Relativistic collisionless shocks



There are many areas to be explored on astrophysical collisionless shocks

Astrophysical collisionless shocks

- Electrostatic
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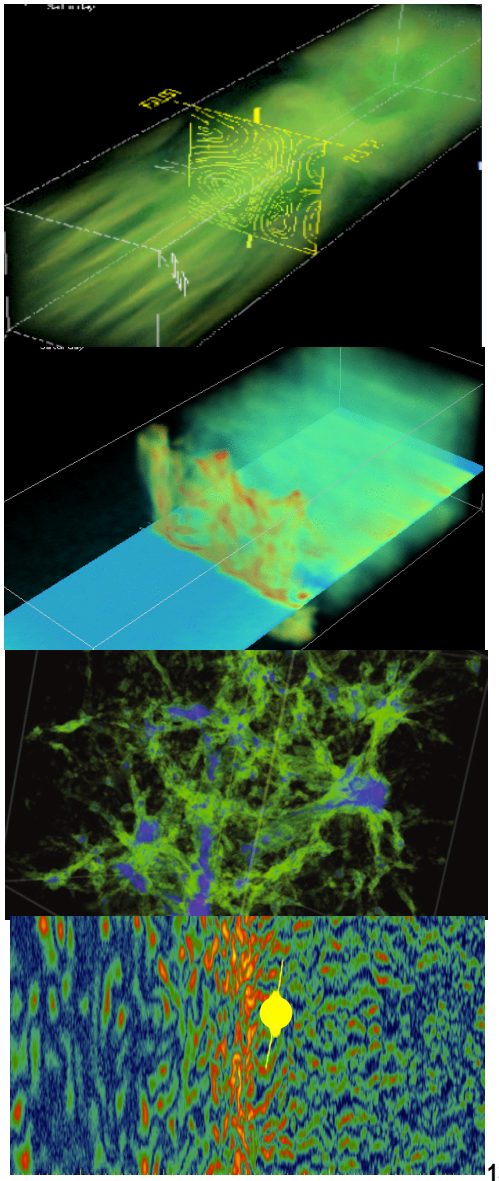
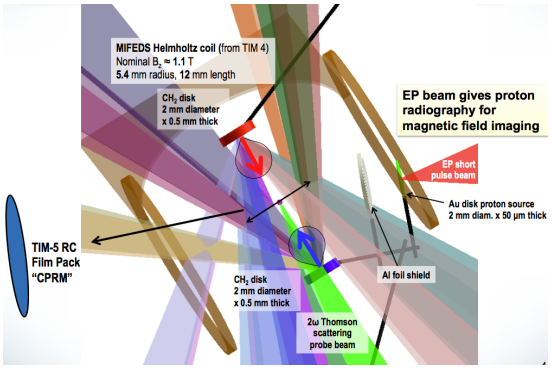
- Non-relativistic
- Relativistic

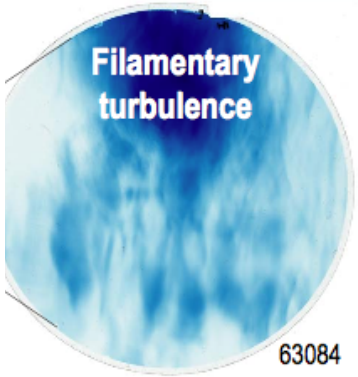
Unmagnetized: Self-generated magnetic fields	Weibel instability (1-5 yrs)
Magnetized: Magnetic reflection	Coherent Larmor loop and particle bunching (2-7 yrs)
Magnetic field amplification	Turbulent dynamos (2-7 yrs)
Particle acceleration	First order Fermi (DSA) (5-10 yrs)
Relativistic collisionless shocks (7-10 yrs)	



Magnetized collisionless shock experiments require strong external magnetic field

Omega

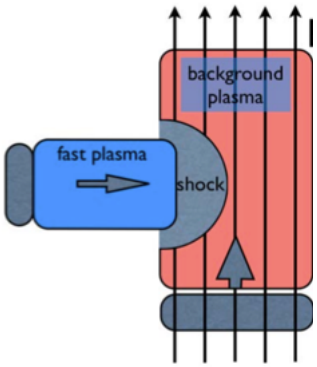


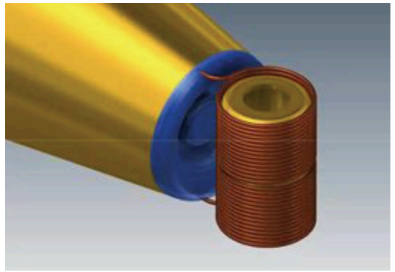


Spitkovsky

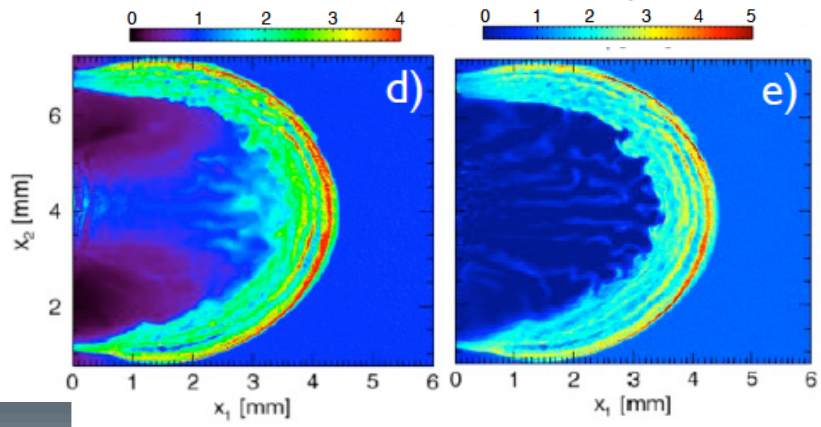
NIF

Expt. schematic





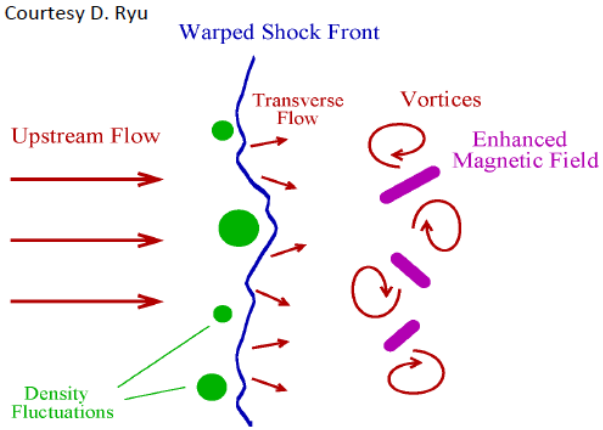
n/n_0 **B/B_0**



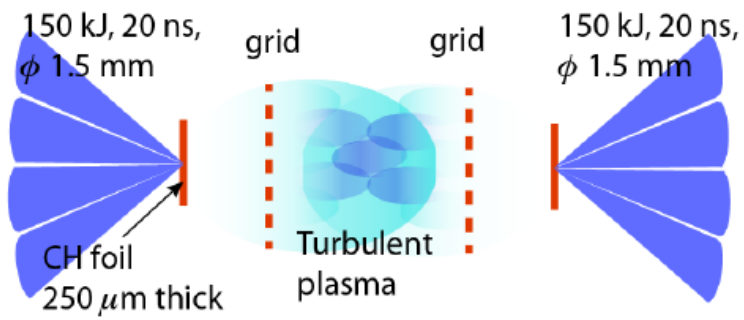
Fiuza

- **Omega experimental results begin to show the magnetic field effect**
- **External field (<4T) has weak effect on the flow**
- **We need stronger external magnetic field**

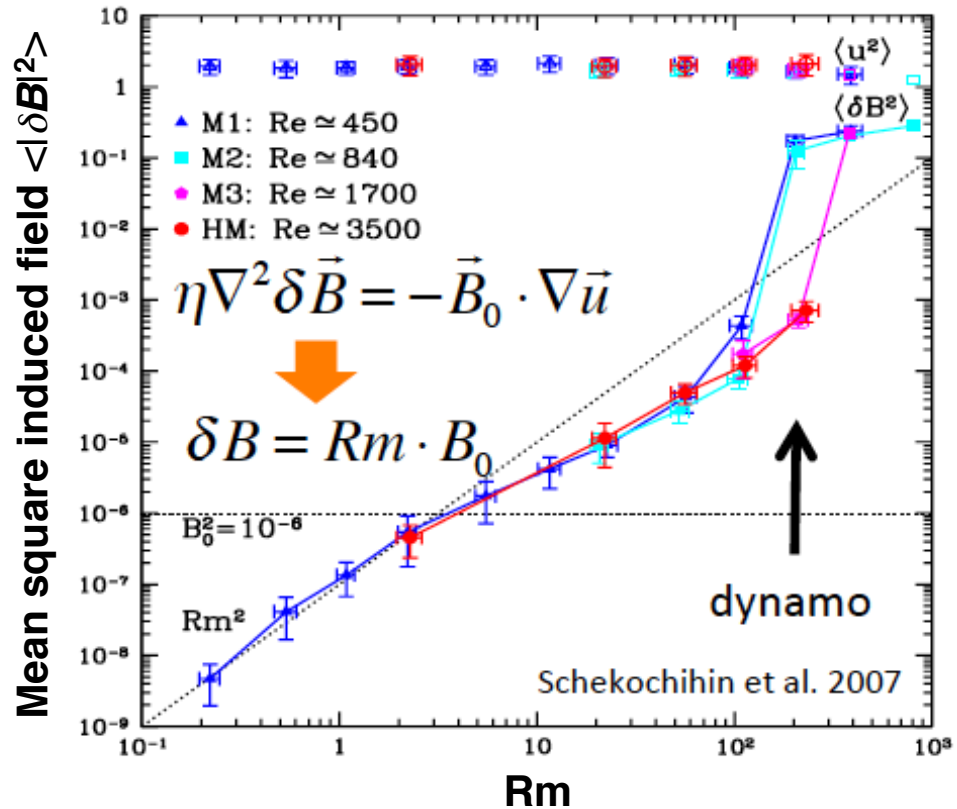
Turbulent Dynamo magnetic field amplification experiments attempts to measure density spectrum from turbulence



Experimental configuration



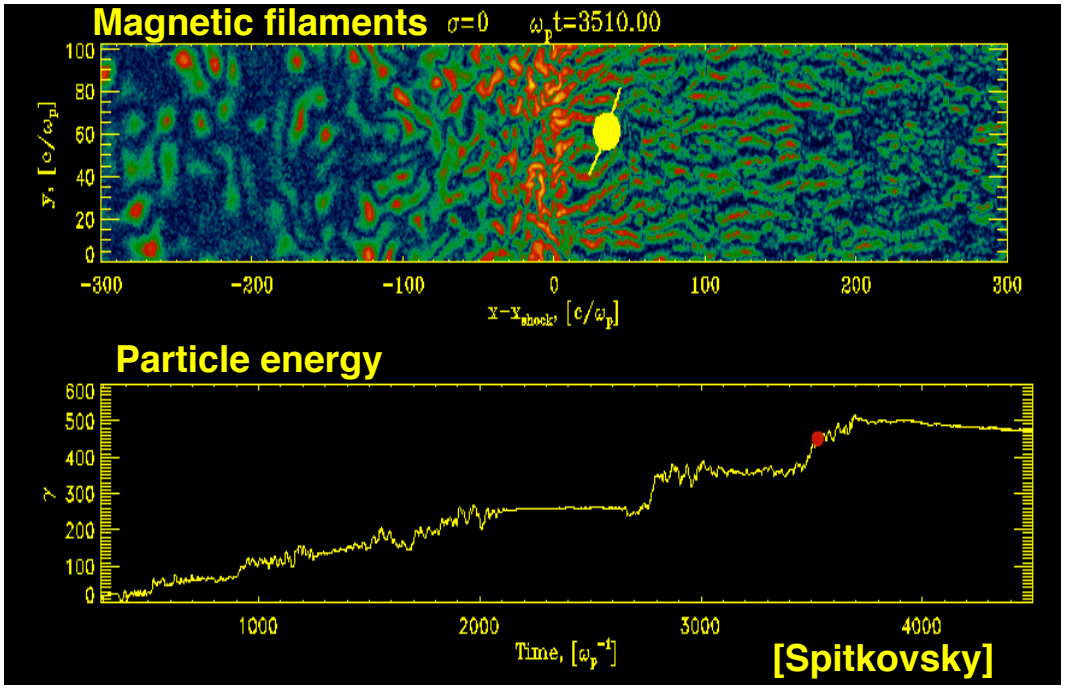
G. Gregori et al



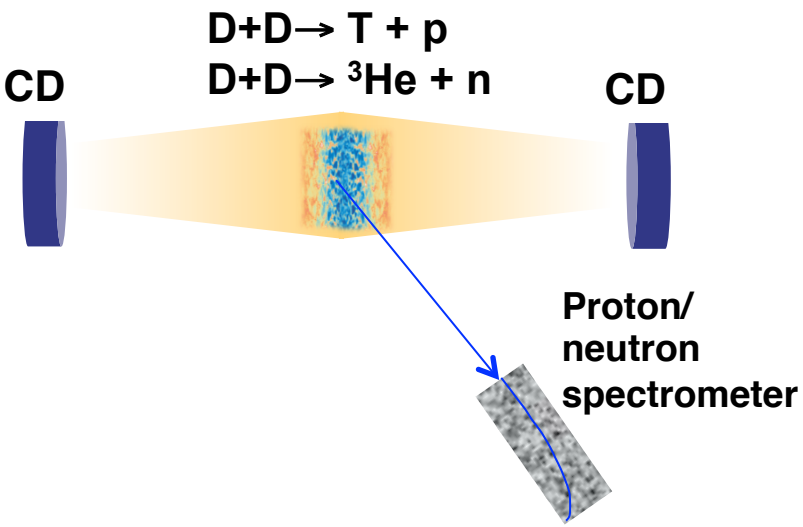
Numerical simulations shows that magnetic field is amplified by turbulence

- **Magnetic field grows linearly with Rm**
- **If Rm above a critical value, dynamo sets in**

Experiments to study particle acceleration in shocks are important; design/diagnostics in developmental stage



Possible laboratory experiment to study particle acceleration

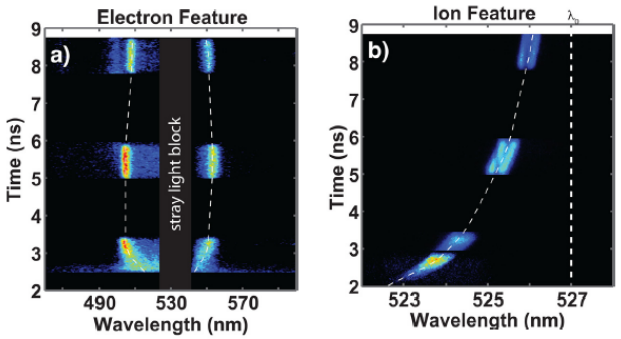


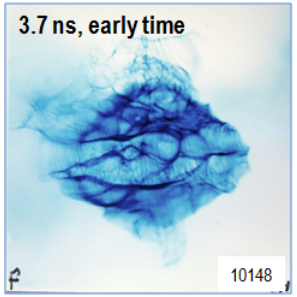
- Self-generated magnetic turbulence scatters particles across the shock; each crossing results in energy gain – Fermi Process (Blanford 1978, Bell 1978, Bhattacharjee 2000)
- In shocks, acceleration is first order in v/c
- Up to 10-20% energy gain is predicted (Caprioli & Spitkovsky, ApJ, 2014)
- Never observed in laboratory experiments

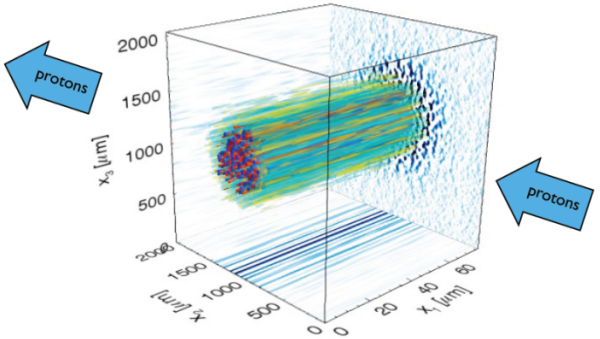
- Self-generated protons have been observed in NIF experiment
- B-field generation need to be confirmed
- Measurements in ΔE may give info on particle acceleration
- We need high-resolution proton and/or neutron spectrometers

It is very important to have proper diagnostics in order to understand the collisionless shock properties

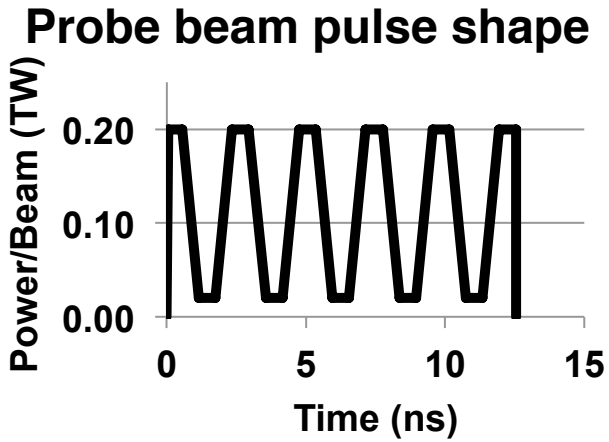
Measure	Purpose	Diagnostics
Plasma state	Measure plasma parameters of V, T_e, T_i, N_e	• Thomson scattering • X-ray spectrometer (doped target)
Shock imaging	Visualize shock formation	• Proton probe • Schlieren imaging
Magnetic fields	measure magnetic field	• Proton probe • B-dot probe • Polarimetry • Proton/neutron spectrometer
Simulation	• Rad-hydro for laser/target interaction • PIC simulation for Weibel • MHD	

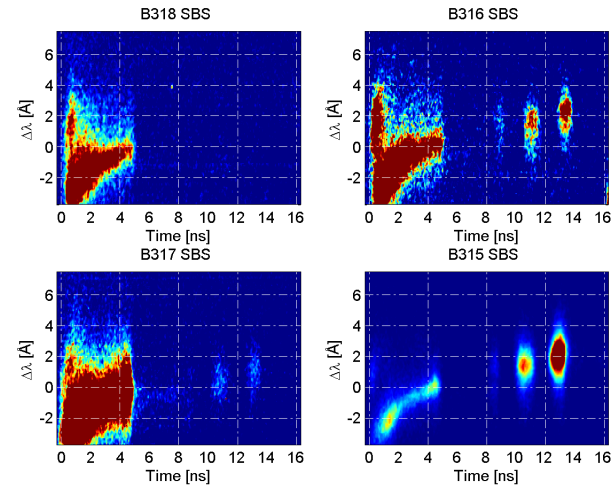


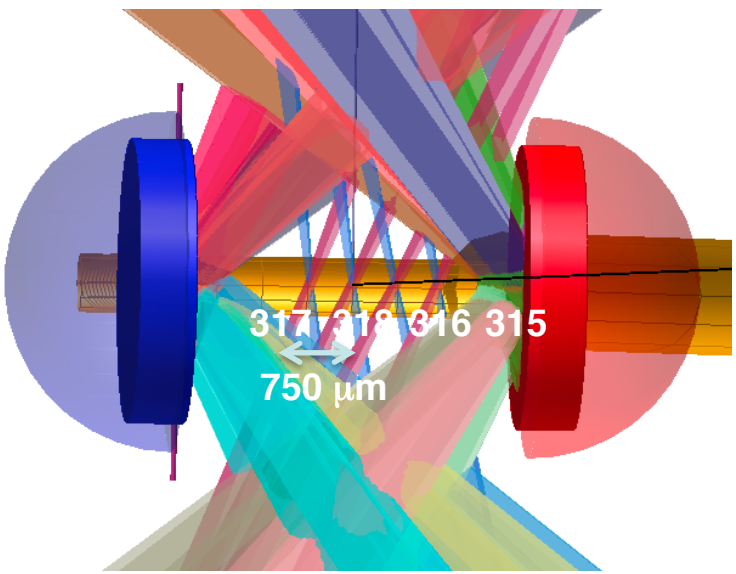




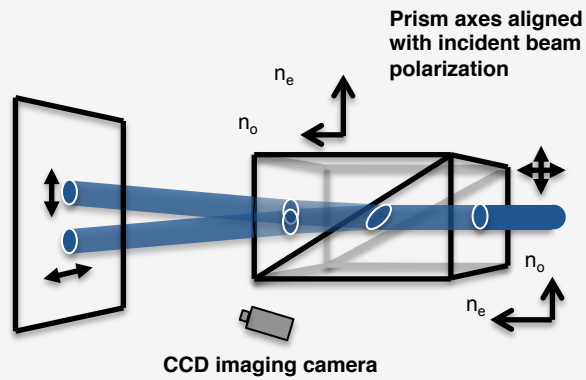
Non-perturbing magnetic field measurements are essential; Pulsed polarimetry will give Faraday rotation measurement







Polarimetry

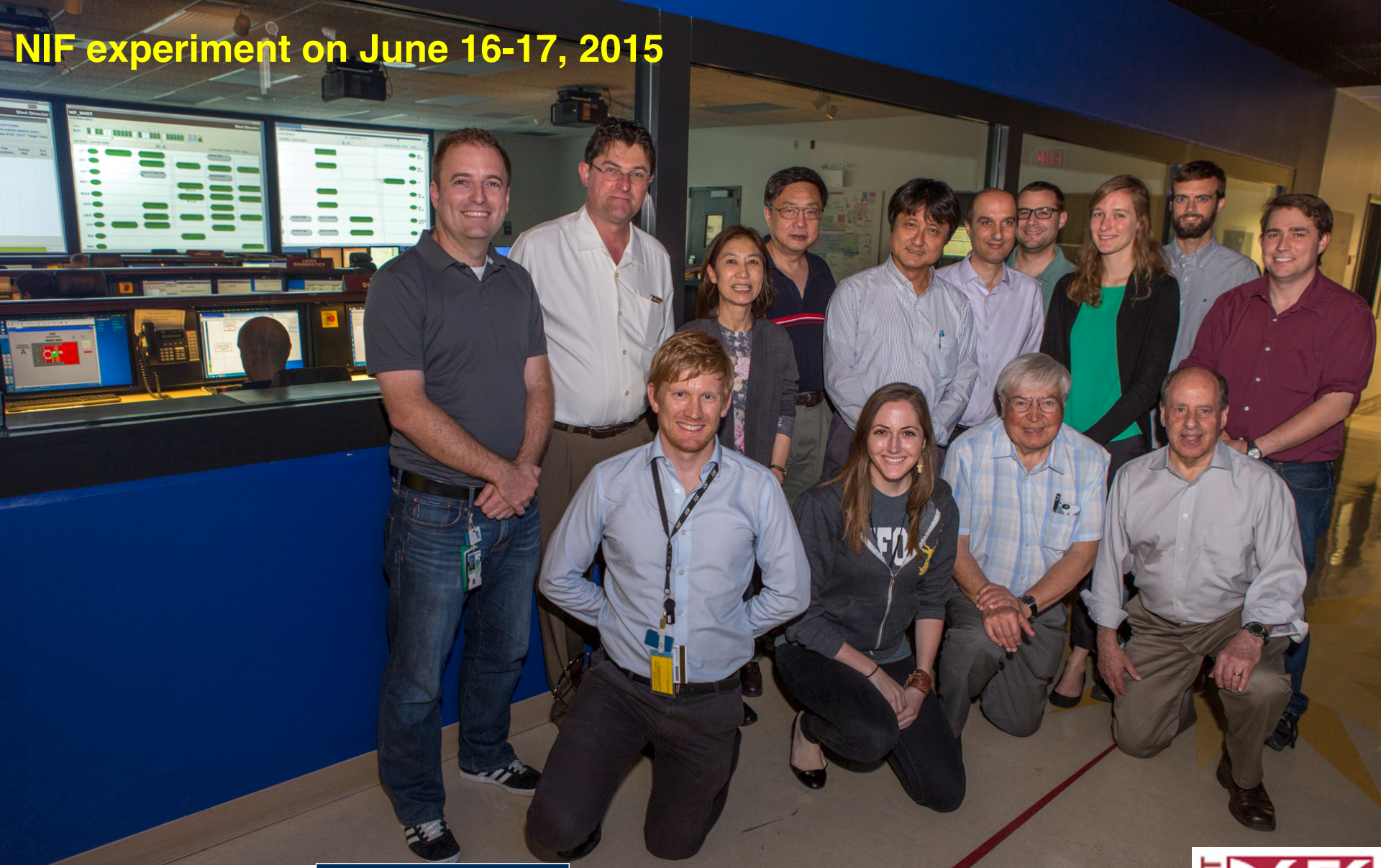


$$\Delta\theta = 20^\circ \left(\frac{\ell}{300\ \mu\text{m}}\right)\left(\frac{B}{1\ \text{MG}}\right)\left(\frac{n}{2\times10^{20}\ \text{cm}^{-3}}\right)$$

Summary and open topics

- Studying astrophysical collisionless shocks using lasers will result important scientific findings and high impact on both plasma physics and astrophysics
- This topic is interest to many generations – attracts younger researchers
- This field is new and the research is in its beginning stage. Unknowns are:
  - Shock growth rates, saturation condition, long-term magnetic fields sustainability
  - Transition regime/mechanism from collisionless to collisional shocks
  - Magnetized plasma
  - Magnetic field amplification
  - Particle acceleration
- New magnetic field diagnostics, plasma probing diagnostics, strong magnetic field coils, low-energy high-resolution proton/neutron spectrometers are essential
- Facility needs are:
  - Low-Z target: H, LiH, LiD
  - Large phase plates on Omega and NIF

NIF experiment on June 16-17, 2015



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NIF