Collisionless Shock and Particle Acceleration Computation and Experiment

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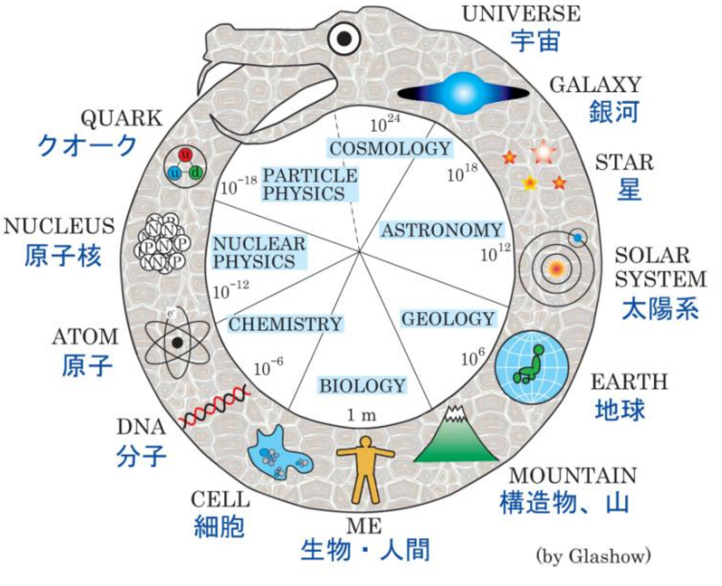
December 3, 2011

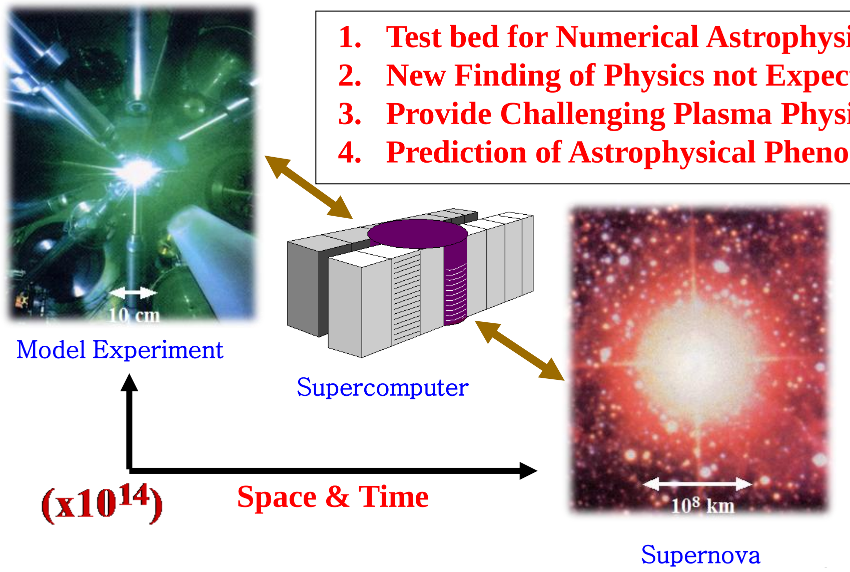
自然の階層性（ウロボロスの蛇）
Layer Structure of Nature (Snake of Uroboros)



(by Glashow)

Challenging Basic Science in Laboratory Astrophysics

1. Test bed for Numerical Astrophysics
2. New Finding of Physics not Expected
3. Provide Challenging Plasma Physics
4. Prediction of Astrophysical Phenomena



Scaling Parameters Controlling Physics

1. Hydrodynamics

$$M = \frac{U}{Cs}$$

$$\mathrm{Re} = \frac{UL}{\nu} = M\frac{L}{\ell}$$

$$\propto M \times L \times n$$

2. Atomic Process

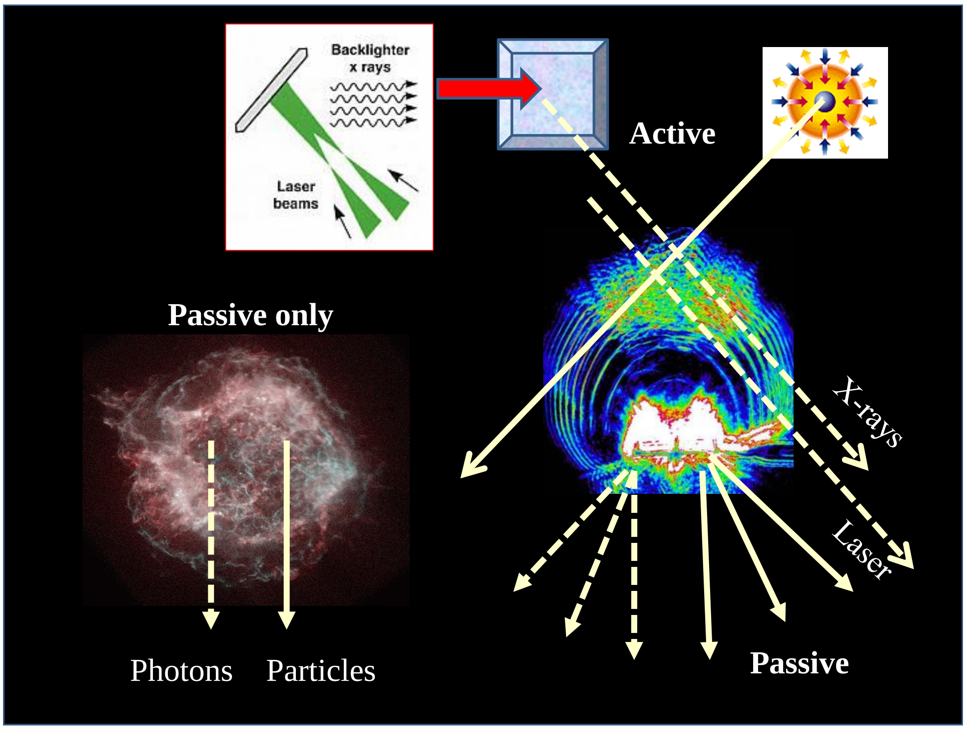
$$\mathrm{I_c} = nt \qquad \xi = \frac{L}{nR^2}$$

3. Plasma Shocks

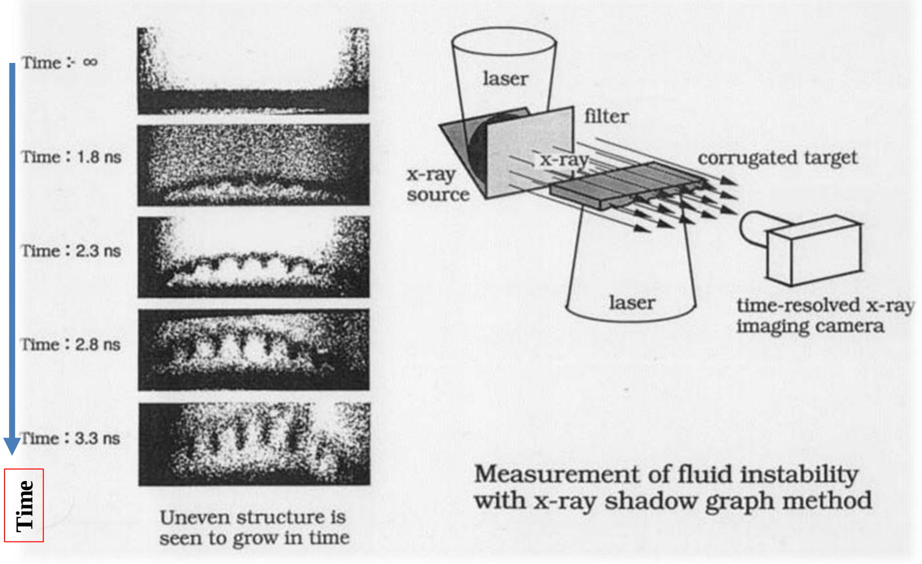
$$\sigma = \frac{B^2/\mu_0}{mnU^2} = \left(\frac{1}{M_A}\right)^2$$

4. Rel. Pair Plasmas

$$\Gamma = 10 - 100$$



Active, Multi-angle and Time-evolution Diagnostics are Possible



1. Hydrodynamic Instability and Turbulent Mixing

1. Test bed for Numerical Astrophysics
2. New Finding of Physics not Expected
3. Provide Challenging Plasma Physics
4. Prediction of Astrophysical Phenomena

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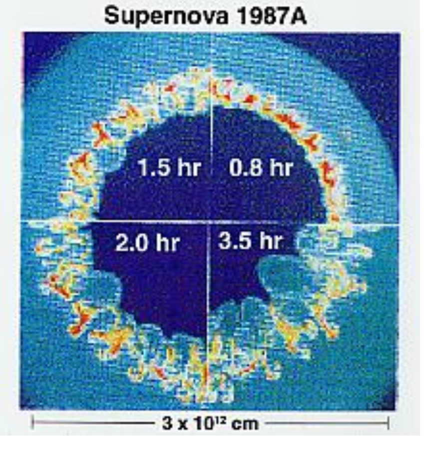
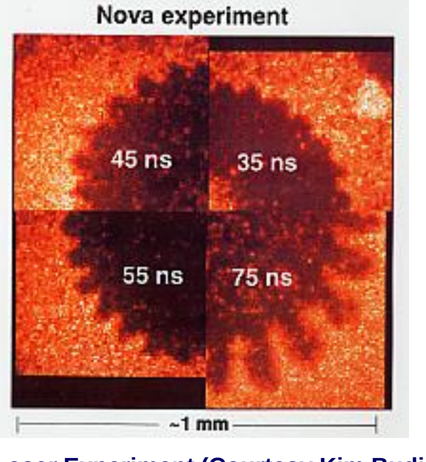
1. To Validate and Verify Physics Models and Codes through Comparison with Model Experiments in Laboratory.

Example (1): Mixing in Supernova Explosion (B. Remington et al)



PROMETIUS Code for Astrophysics



Laser Experiment (Courtesy Kim Budil)

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2. Photo-ionized Plasma

1. Test bed for Numerical Astrophysics
2. New Finding of Physics not Expected
3. Provide Challenging Plasma Physics
4. Prediction of Astrophysical Phenomena

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X-ray from Companion Star of Cyg X-3

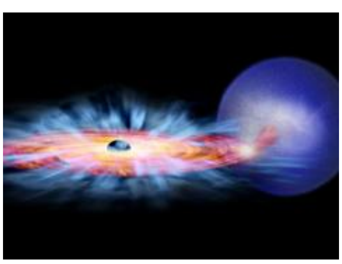
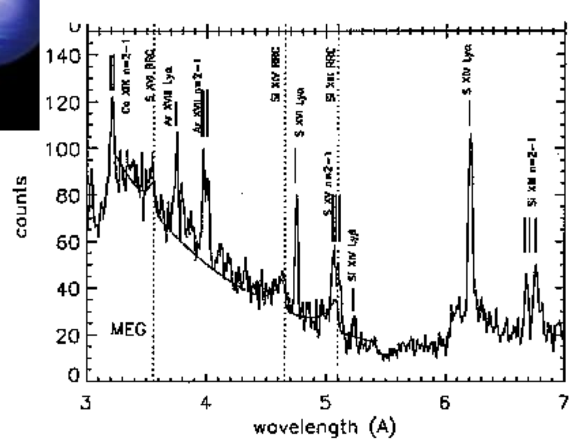


Photo-ionization by
X-rays from BH

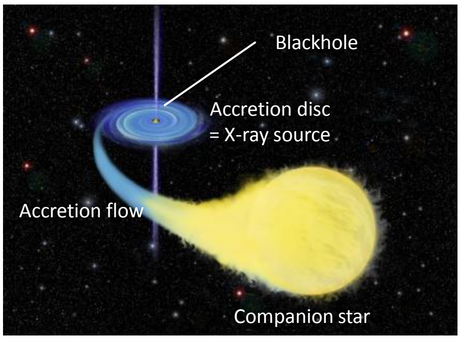


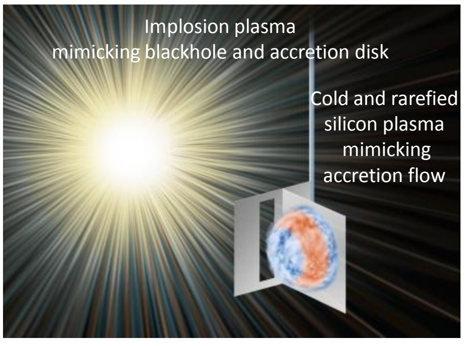
Chandra
Observation

The origin of x-ray emission near blackhole can be studied by using the implosion x-ray source.

Binary system

Laboratory expriment





S. Fujioka, **H. Takabe** et al.,
Nature-Physics, **5**, 11, pp 821-825 (2009)

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High-Mach Number Collisionless Shock Formation and Origin of Cosmic-Rays

1. Test bed for Numerical Astrophysics
2. New Finding of Physics not Expected
3. Provide Challenging Plasma Physics
4. Predict Astrophysical Phenomena

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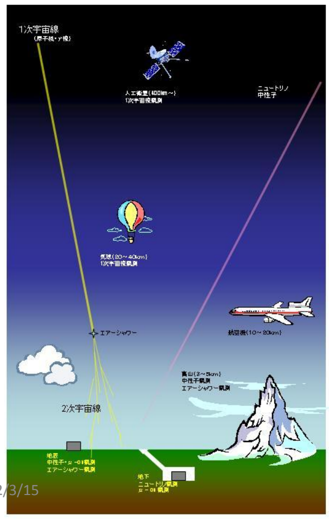
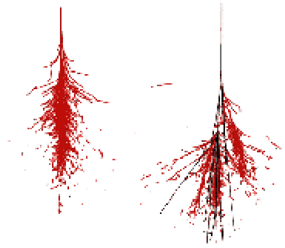
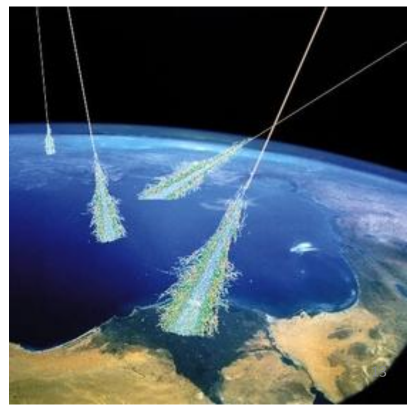
What is Cosmic-Ray?

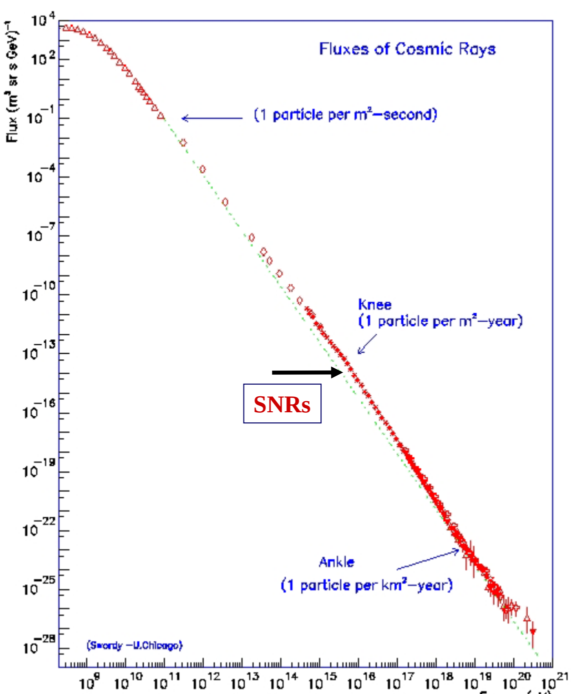




ガンマ線　　陽子



2012/3/15



Cosmic Rays

1. **Bow Shock of Earth**
2. **Bow Shock by CME**
3. **Pulsar Driven BS**
4. **Supernova Remnants**
5. **Cosmological Jets**
6. **Gamma-ray Bursts**
7. **…..**
8. **…..**

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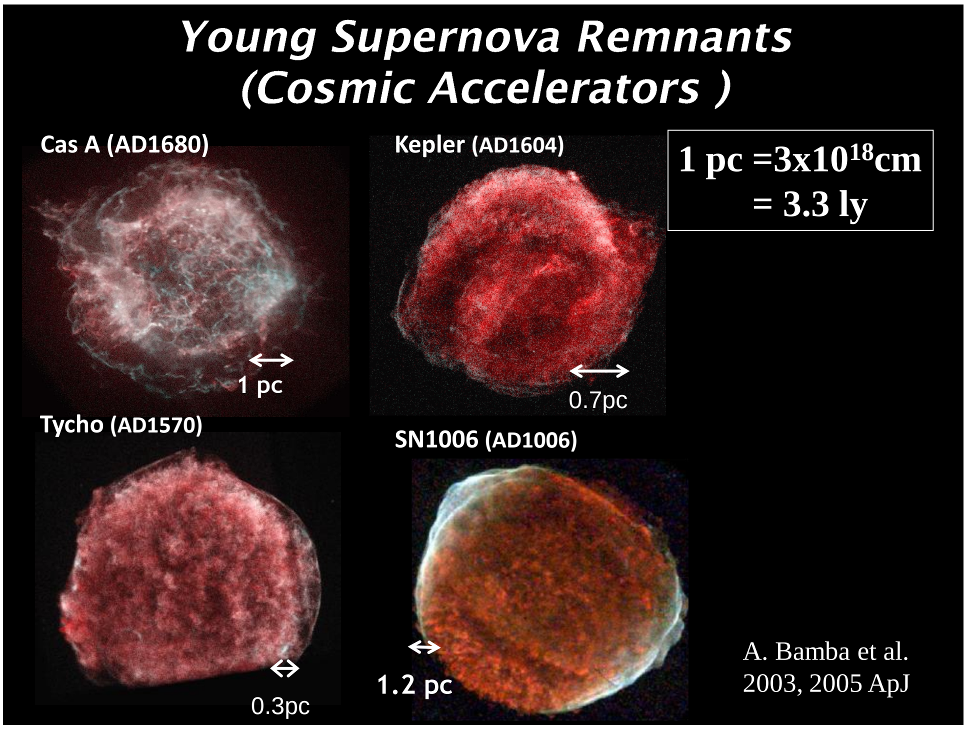
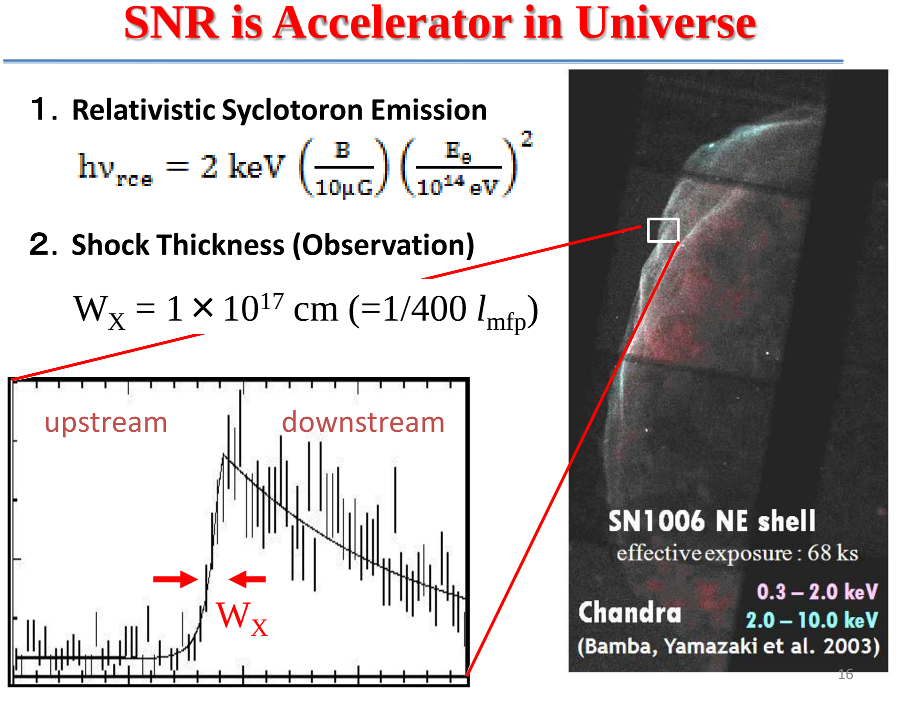

Young Supernova Remnants
(Cosmic Accelerators)
Cas A (AD1680)
1 pc
Kepler (AD1604)
0.7pc
1 pc =3x10^18cm
= 3.3 ly
Tycho (AD1570)
0.3pc
SN1006 (AD1006)
1.2 pc
A. Bamba et al.
2003, 2005 ApJ


SNR is Accelerator in Universe
1. Relativistic Syclotoron Emission
$h\nu_{rce} = 2\ \mathrm{keV} \left(\frac{B}{10\mu G}\right)\left(\frac{E_e}{10^{14}\ \mathrm{eV}}\right)^2$
2. Shock Thickness (Observation)
$W_X = 1 \times 10^{17}$ cm (=1/400 l_{mfp})
upstream
downstream
W_X
SN1006 NE shell
effective exposure : 68 ks
Chandra
0.3 – 2.0 keV
2.0 – 10.0 keV
(Bamba, Yamazaki et al. 2003)
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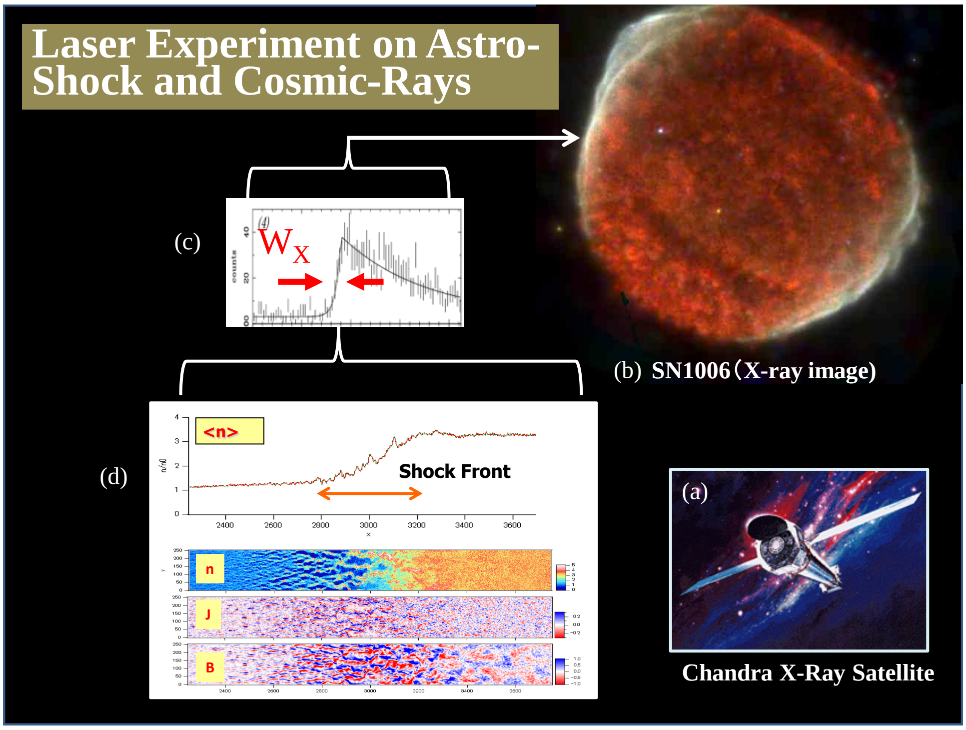


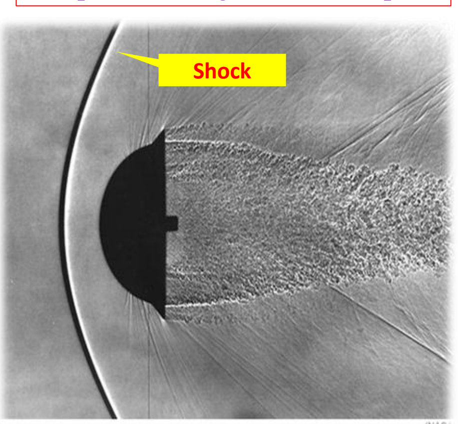
Two Different Types of Shocks

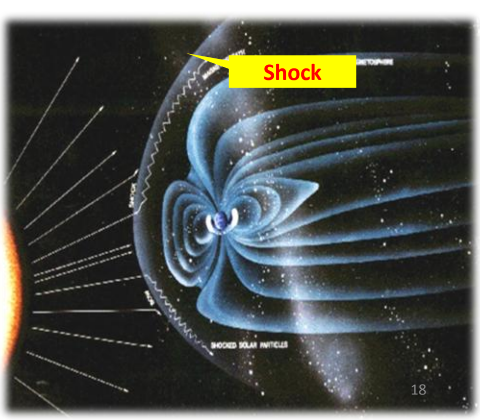
Hydrodynamic Shock
（Molecular Viscocity）

Plasma Shock
（Collisionless）

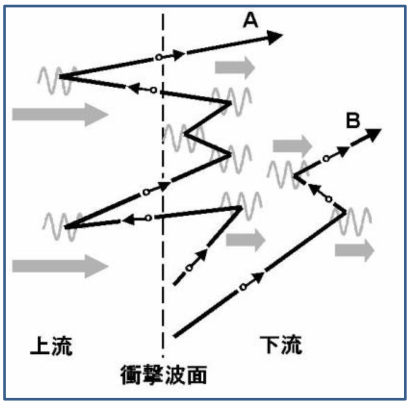
Supersonic Projectile（WT Exp.）

Solar Wind and Magnetosphere





Diffusive Shock Acceleration
(Fermi Acceleration)



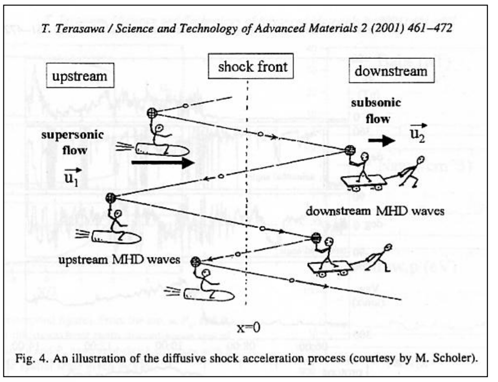


Fig. 4. An illustration of the diffusive shock acceleration process (courtesy by M. Scholer).

Widely Accepted in Astrophysics

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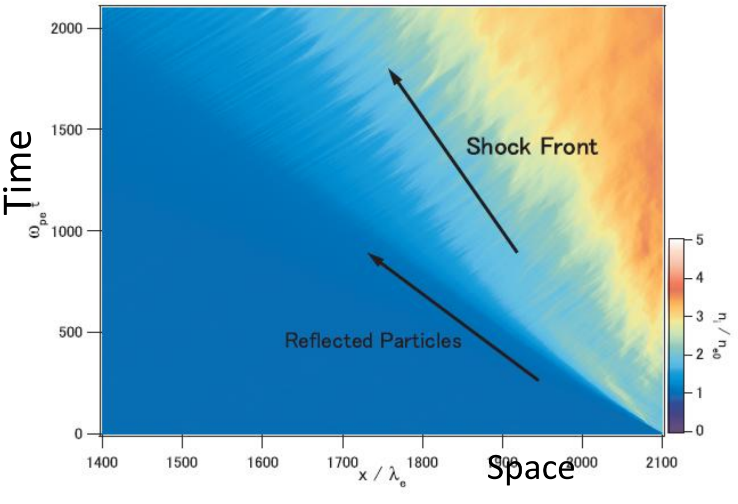
NON-RELATIVISTIC COLLISIONLESS SHOCKS IN UNMAGNETIZED ELECTRON-ION PLASMAS

Tsunehiko N. Kato and Hideaki Takabe

Astrophysical Journal **681**, L93–L96, Jul 2008



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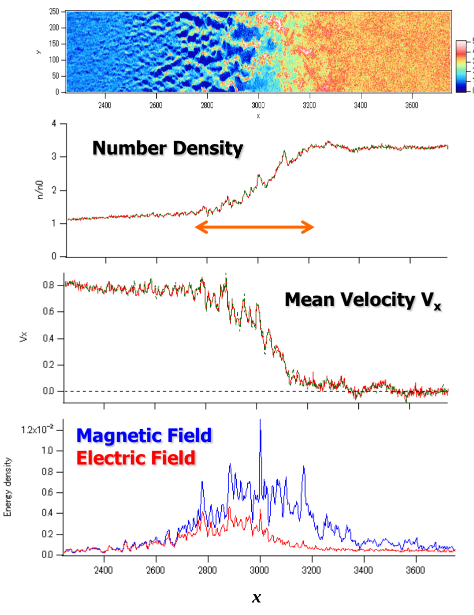
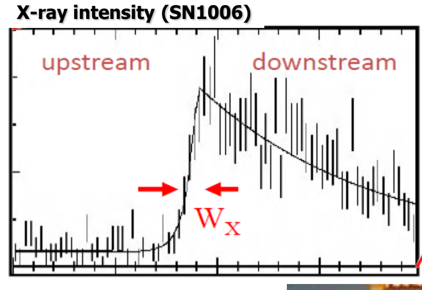
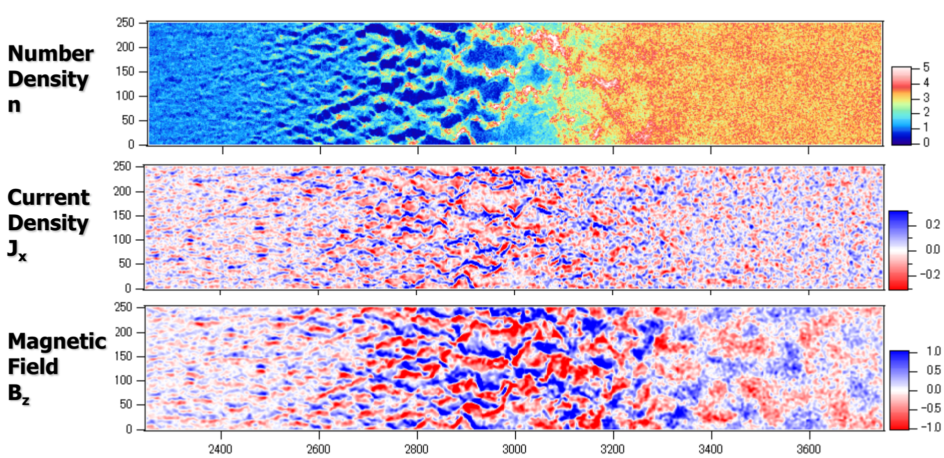
Shock Wave Formation and Profiles





T. N. Kato

Generation of Magnetic Field



Current filaments generates strong magnetic fields within the transition region

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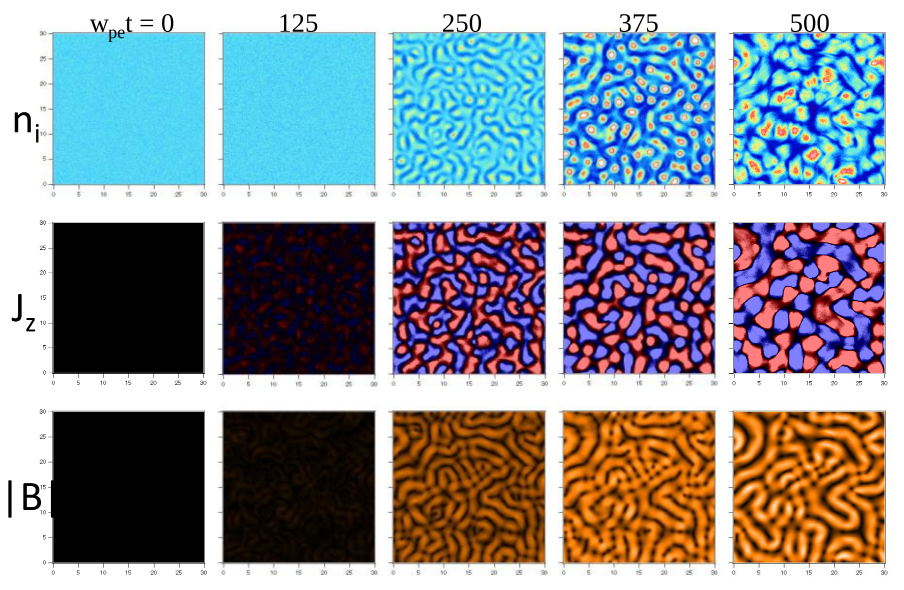
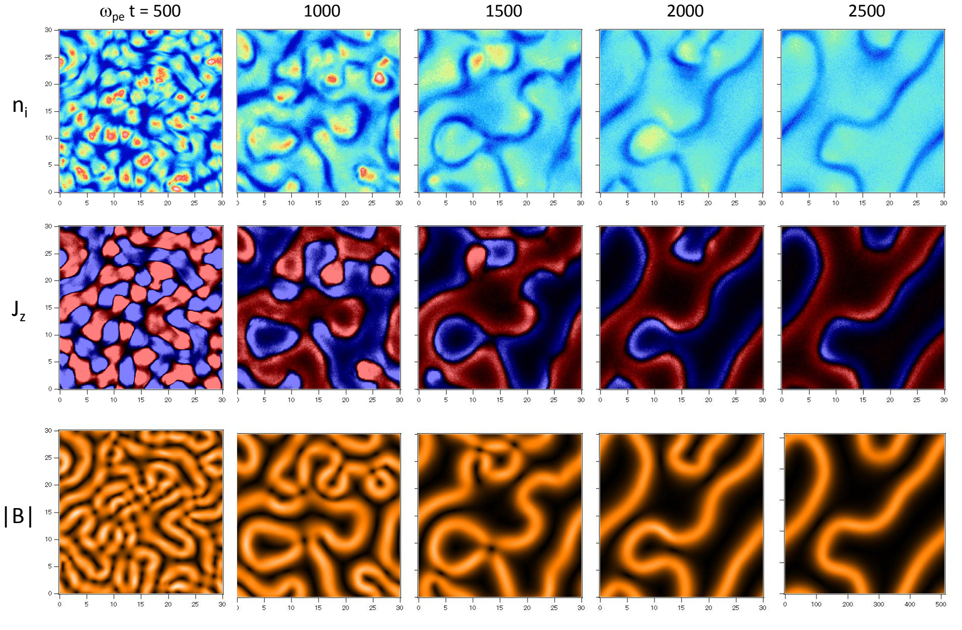
Weibel Instability in y-z Plane

m_i/m_e=20, V_z=0.05c, T=100eV



Continued

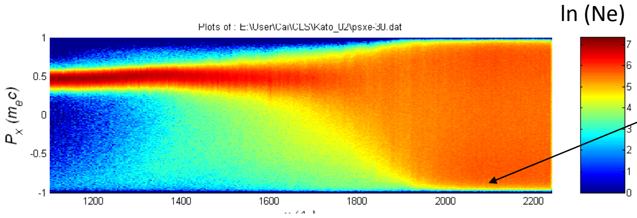


Phase space Vx and X

$\omega_{pe}t$=2100

electron

ln (Ne)



high energy electrons

ion

ln (Ni)

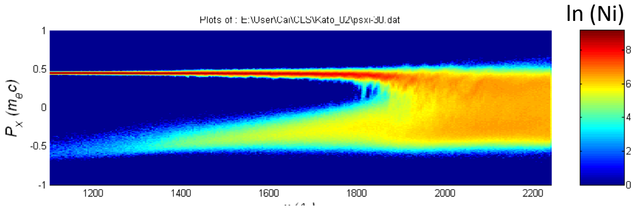
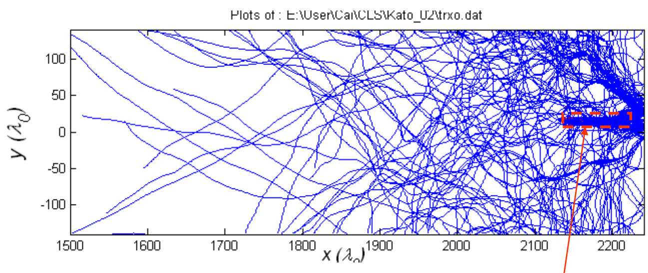
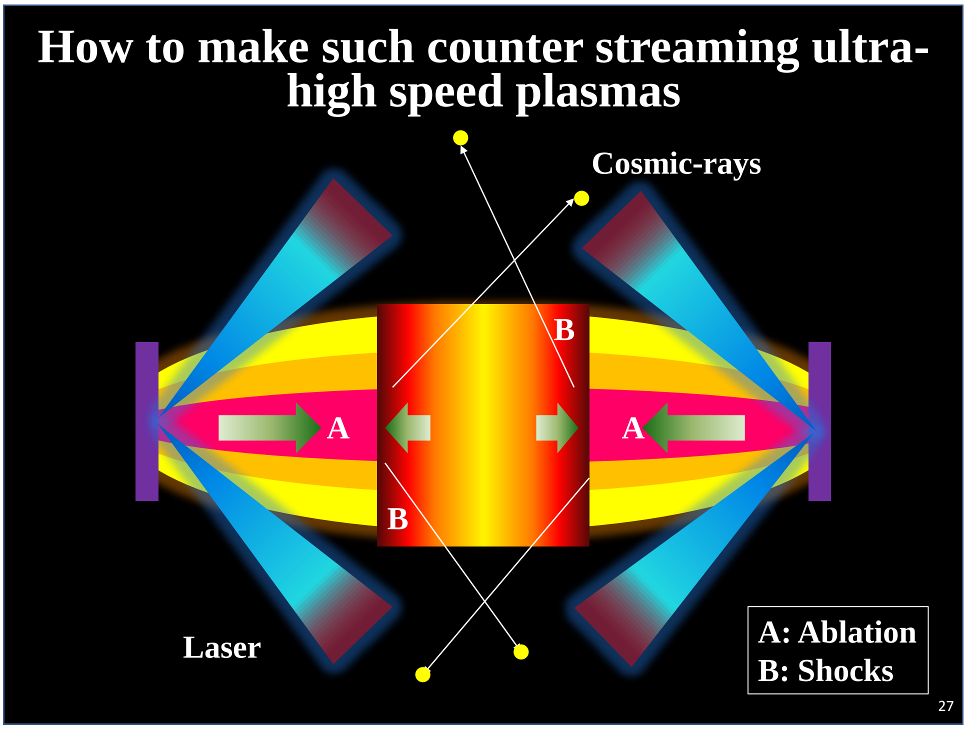


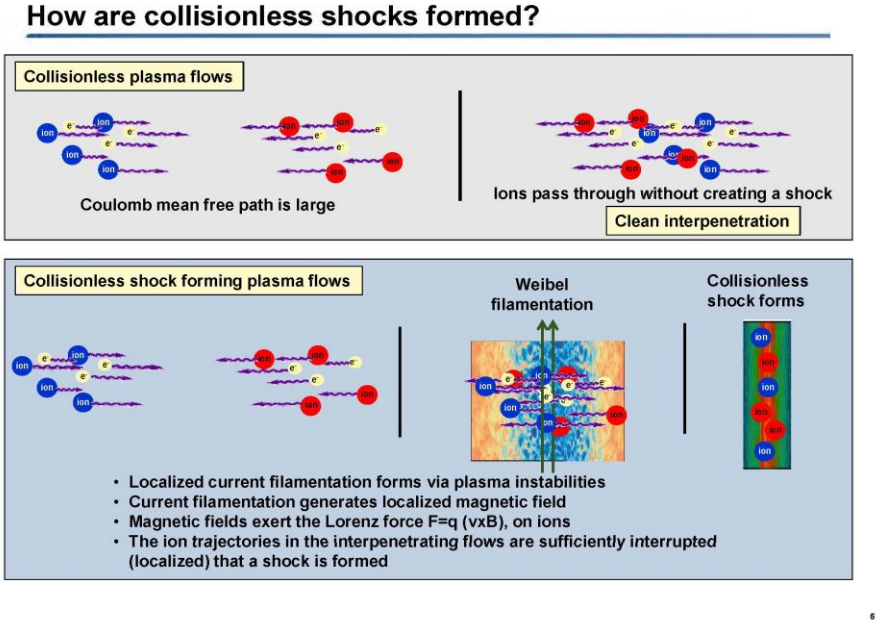
Fig. (A) shows that a large fraction of electrons have been accelerated to light velocity in the shock transition region. However, the acceleration mechanism is not very clear. It may due to the shock acceleration!

Electron Trajectory



The original positions of the tracked particles


How to make such counter streaming ultra-high speed plasmas
Cosmic-rays
B
A
A
B
Laser
A: Ablation
B: Shocks
27


How are collisionless shocks formed?
Collisionless plasma flows
Coulomb mean free path is large
Ions pass through without creating a shock
Clean interpenetration
Collisionless shock forming plasma flows
Weibel filamentation
Collisionless shock forms
• Localized current filamentation forms via plasma instabilities
• Current filamentation generates localized magnetic field
• Magnetic fields exert the Lorenz force F=q (vxB), on ions
• The ion trajectories in the interpenetrating flows are sufficiently interrupted (localized) that a shock is formed
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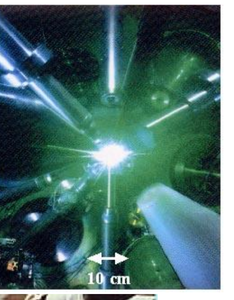
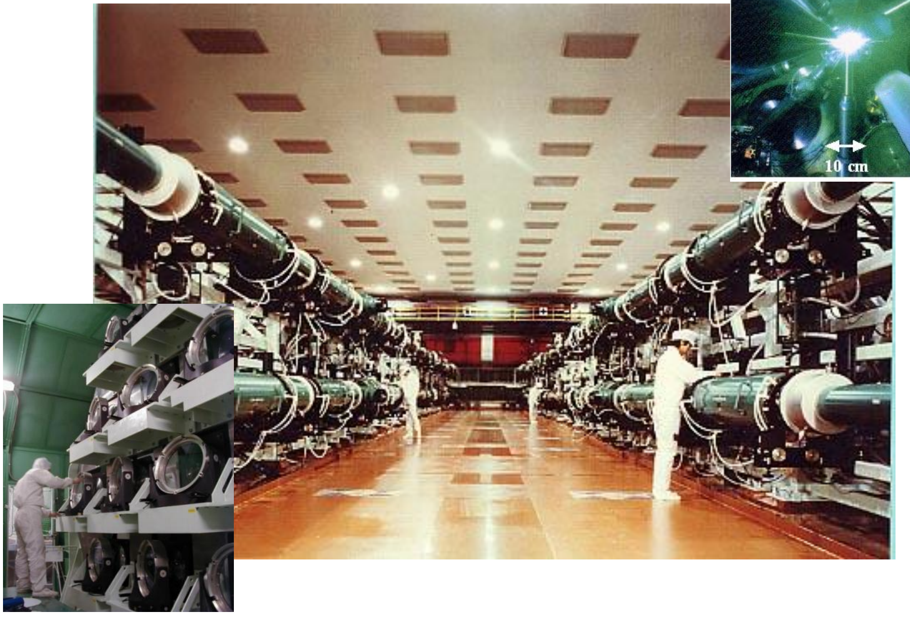
Gekko XII Laser Facility at ILE, Osaka University



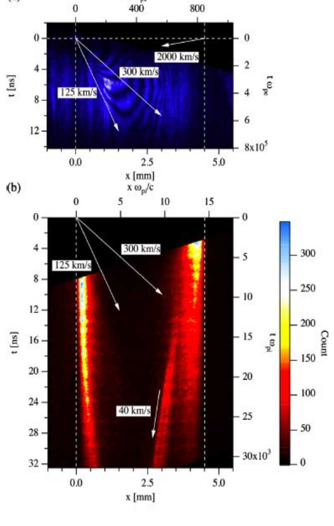


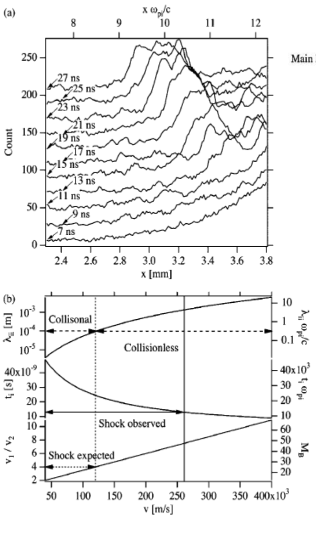
ES collisionless shock experiment using GXII laser

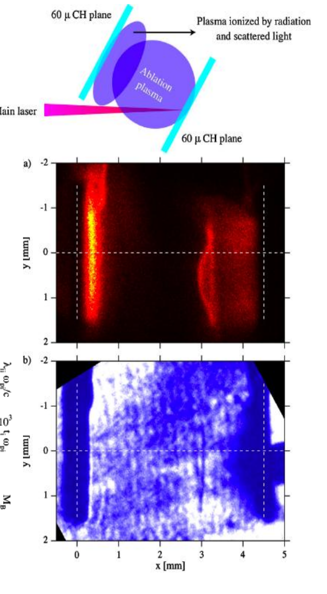
PRL 106, 175002 (2011) PHYSICAL REVIEW LETTERS week ending 29 APRIL 2011

Time Evolution of Collisionless Shock in Counterstreaming Laser-Produced Plasmas

Y. Kuramitsu,[1,*] Y. Sakawa,[1] T. Morita,[2] C.D. Gregory,[3] J.N. Waugh,[4] S. Dono,[5] H. Aoki,[2] H. Tanji,[5] M. Koenig,[3] N. Woolsey,[4] and H. Takabe[1]







PHYSICS OF PLASMAS **17**, 122702 (2010)

Collisionless shock generation in high-speed counterstreaming plasma flows by a high-power laser

T. Morita,[1,a)] Y. Sakawa,[2] Y. Kuramitsu,[2] S. Dono,[3] H. Aoki,[1] H. Tanji,[3] T. N. Kato,[2] Y. T. Li,[4] Y. Zhang,[4] X. Liu,[4] J. Y. Zhong,[5] H. Takabe,[1,2] and J. Zhang[6]
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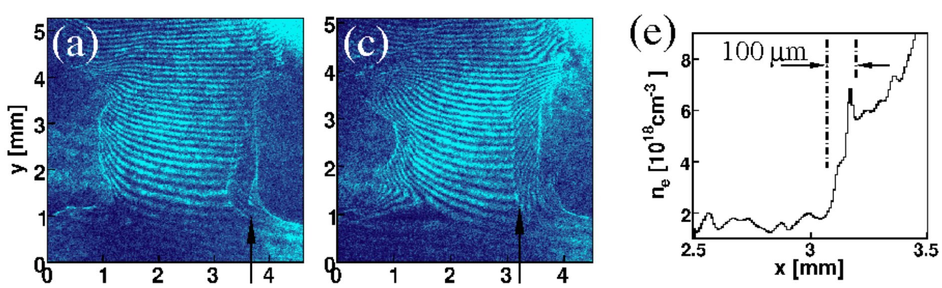
(Received 11 October 2010; accepted 15 November 2010; published online 1 December 2010)

The experimental demonstration of the formation of a strong electrostatic (ES) collisionless shock has been carried out with high-speed counterstreaming plasmas, produced by a high-power laser irradiation, without external magnetic field. The nearly four times density jump observed in the experiment shows a high Mach-number shock. This large density jump is attributed to the compression of the downstream plasma by momentum transfer by ion reflection of the upstream plasma. Particle-in-cell (PIC) simulation shows the production of a collisionless high Mach-number ES shock with counterstreaming interaction of two plasma slabs with different temperatures and densities, as pointed out by Sorasio *et al.* [Phys. Rev. Lett. **96**, 045005 (2006)]. It is speculated that the shock discontinuity is balanced with the momentum of incoming and reflected ions and the predominant pressure of the electrons in the downstream with PIC simulation. © *2010 American Institute of Physics*. [doi:10.1063/1.3524269]



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[1]*Graduate School of Science, Osaka University, 1-1 Machikane-yama, Toyonaka, Osaka 560-0043, Japan*
[2]*Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan*
[3]*Graduate School of Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan*
[4]*Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[5]*The National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*
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(Received 11 October 2010; accepted 15 November 2010; published online 1 December 2010)

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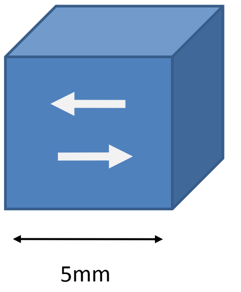
We Need NIF to Demonstrate Universality

1. Shock width

$$\Delta X = 0.2\ \mathrm{cm} \times \frac{1}{Z}\sqrt{\frac{A}{n_{20}}}$$



2. Coulomb mean-free-path

$$l = \frac{1}{n\sigma_0 \ln\Lambda} = 20\ cm \times \frac{A^2}{Z^4}\frac{V_8^4}{n_{20}}$$

3. Energy of counter-streaming plasma

$$E = Zm_p n_i V^2 L^3$$
$$= 70\ \mathrm{kJ}$$

$n_{20}=n/10^{20}cm^{-3}$
$V_8=V/10^8 cm/s$

H. Takabe et al., Plasma Physics and Controlled Fusion **50**,124057 (2008)

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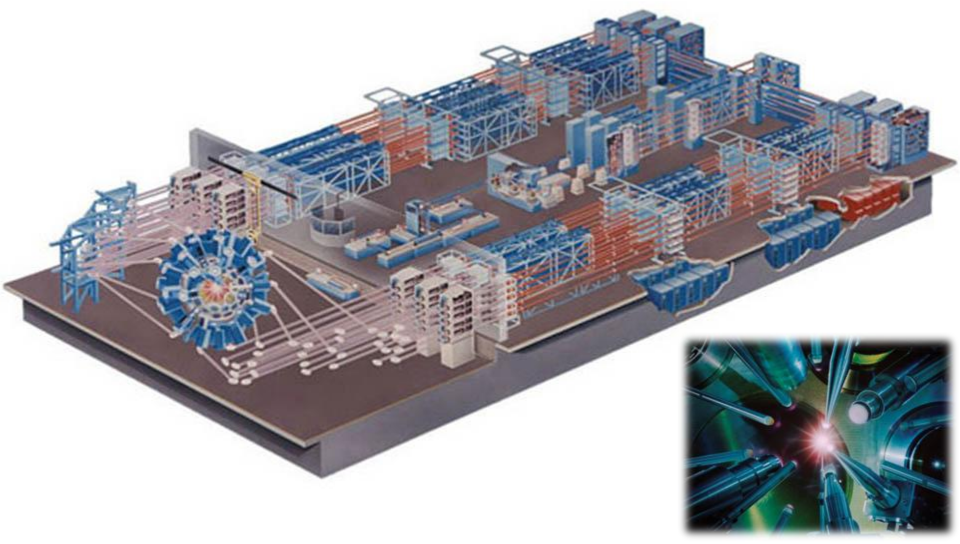
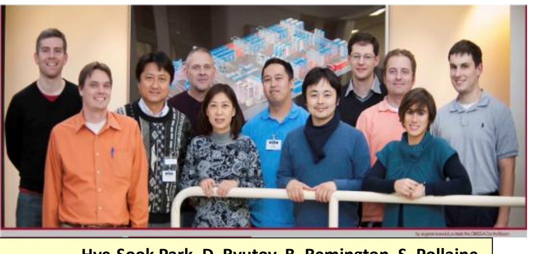
OMEGA Laser at U of Rochester, NY, USA

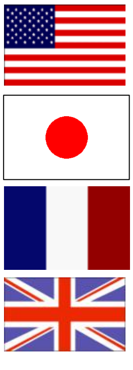


"Astrophysical Collisionless Shock Generation in Laser Driven Experiments" OMEGA Facility, Dec. 14, 2010

Participating collaborators

- Hye-Sook Park (PI), Steve Ross (LLNL)
- Youichi Sakawa, Yasuhiro Kuramitsu (Osaka University, Japan)
- Dustin Froula (LLE)
- Chris Gregory (York University, UK)
- Anatoly Spitkovsky (Princeton, USA)
- Alessandra Ravasio (LULI, France)



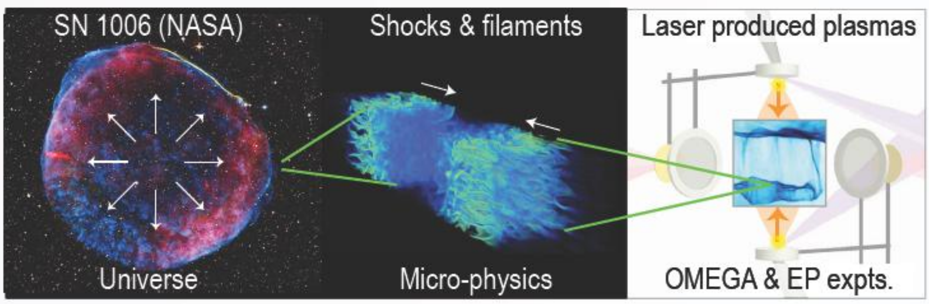


LLNL (USA):	Hye-Sook Park, D. Ryutov, B. Remington, S. Pollaine, S. Ross, S. Glenzer, N. Kugland, C. Sorce
Osaka University (Japan):	Y. Sakawa, Y, Kuramitsu, H. Takabe
Oxford University (UK):	G. Gregori, A. Bell
Princeton University (USA):	A. Spitkovsky, L. Gargate, L. Sironi
LLE, Univ. of Rochester (USA):	D. Froula, J. Knauer, G. Fiskel
Ecole Polytechnique (France):	M. Koenig, A. Ravasio
ETH Zurich (Switzerland):	F. Miniati
York University (UK):	N. Woolsey, C. Gregory
Rice University (USA):	E. Liang
University of Rochester (USA):	R. Betti
University of Michigan (USA):	E. Rutter, M. Grosskopf, C. Kuranz
University of Nevada, Reno (USA):	R. Presura

Abstract

We present progress in the use of proton imaging to study electric and magnetic fields that are relevant for collisionless shock formation in experiments at the OMEGA & OMEGA EP laser facilities. Collisionless shocks are important for understanding cosmic magnetic field generation and ultra high-energy cosmic ray acceleration.

We use lasers to model astrophysical plasma flows



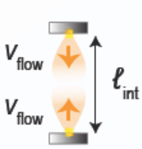
Collisionless shock formation parameters

Collisionless growth scales $\ell^* \ll \ell_{int} \ll \lambda_{mfp}$ *Collisional MFP*

$$\ell^* \propto \frac{v_{flow}}{\omega_{pi}}, \frac{c}{\omega_{pi}}$$

Interaction length

$$\lambda_{mfp} \propto \frac{A_z^2}{Z^4}\frac{v_{flow}^4}{n_z}$$

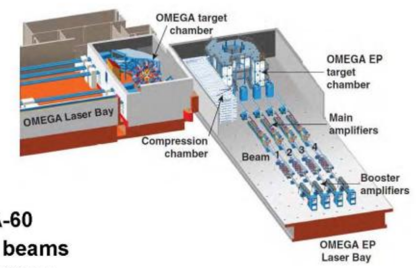
	n_i (cm^{-3})	$\frac{c}{\omega_{pi}}$	v_{flow} (cm/s)	λ_{mfp}	ℓ_{int}/λ_{mfp}
	1	2x10^7 cm	3x10^8	4x10^{19} cm *(42 light years)*	2
	10^{18}	100 µm	1x10^8	1.5 mm	5

D. Ryutov, 2010; Cassam et al, ApJ 680 1180 (2008); Bamba et al, ApJ 589, 827 (2003)

We are now conducting preparatory experiments on OMEGA through the LBS and NLUF programs

NIF

OMEGA and EP LBS and NLUF experiments are aimed at understanding the counterstreaming plasma properties and developing diagnostics



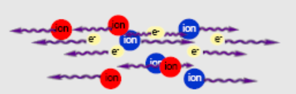
- OMEGA-60
  - 60 beams
  - 30 kJ max
  - 3 m dia target chamber
- OMEGA-EP
  - 4 beams (2 can be short pulse)
  - 1 kJ/beam short pulse (1ω)
  - ~2 kJ/beam long pulse (3ω)

8

How are collisionless shocks formed?

Collisionless plasma flows

Coulomb mean free path is large

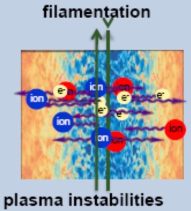


Ions pass through without creating a shock

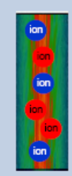
Clean interpenetration

Collisionless shock forming plasma flows

Weibel filamentation

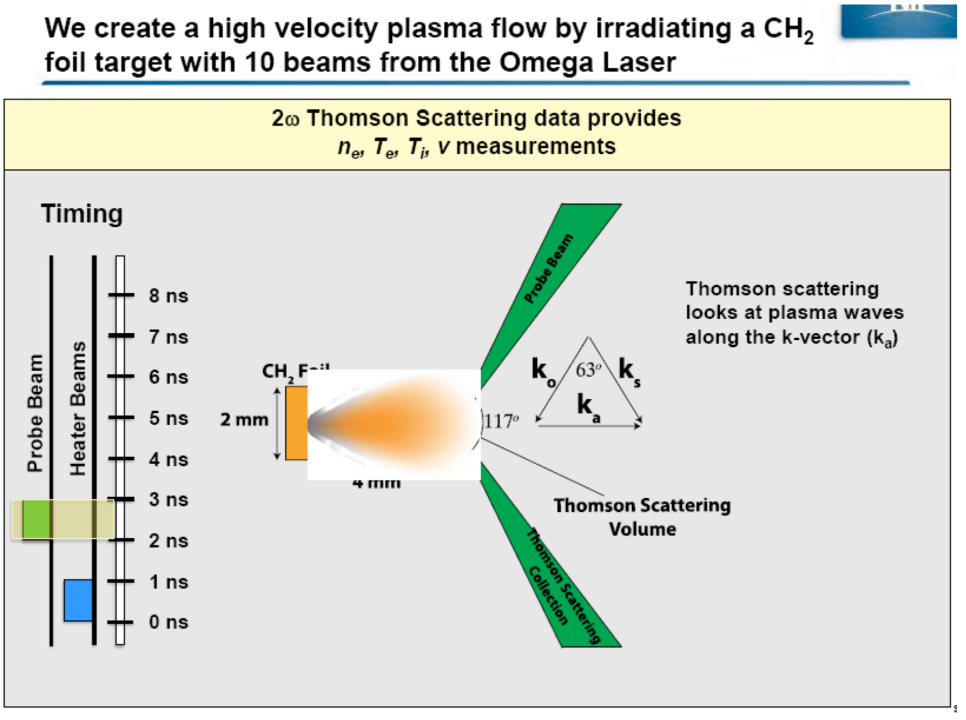


Collisionless shock forms



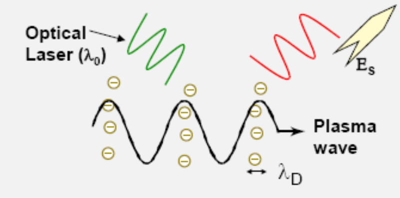
- Localized current filamentation forms via plasma instabilities
- Current filamentation generates localized magnetic field
- Magnetic fields exert the Lorentz force F=q (vxB), on ions
- The ion trajectories in the interpenetrating flows are sufficiently interrupted (localized) that a shock is formed

Thomson Scattering Diagnostics

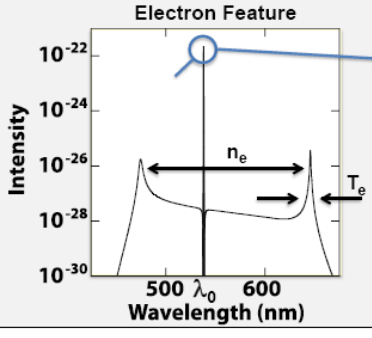


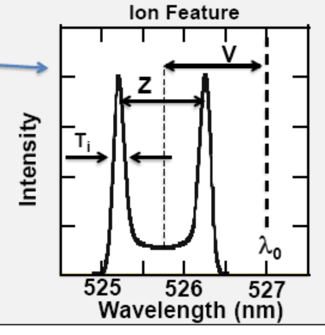
Collection Thomson scattering from ion-acoustic and electron-plasma waves is used to measure the plasma conditions

Thomson scattering is the scattering of an electromagnetic wave by free electrons.



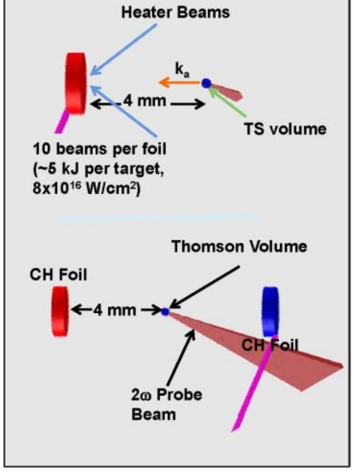
$$S(\mathrm{k},\omega) = \frac{2\pi}{k}\left|1-\frac{\chi_e}{\varepsilon}\right|^2 f_e\left(\frac{\omega}{k}\right) + \frac{2\pi Z}{k}\left|\frac{\chi_e}{\varepsilon}\right|^2 f_i\left(\frac{\omega}{k}\right)$$

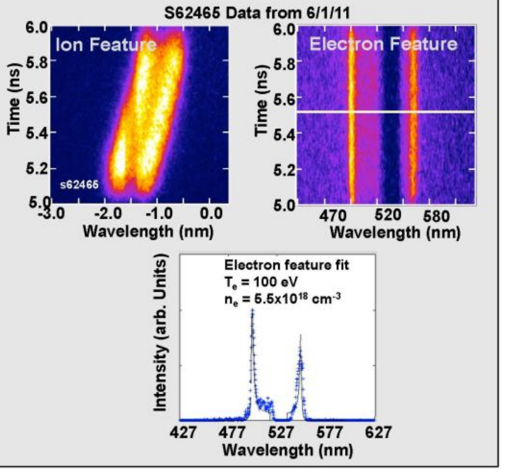




Our OMEGA experiments study the plasma conditions of single and double flows

Experimental results	2ω Thomson Scattering data provides n_e, T_e, T_i, v, v_{drift} measurements





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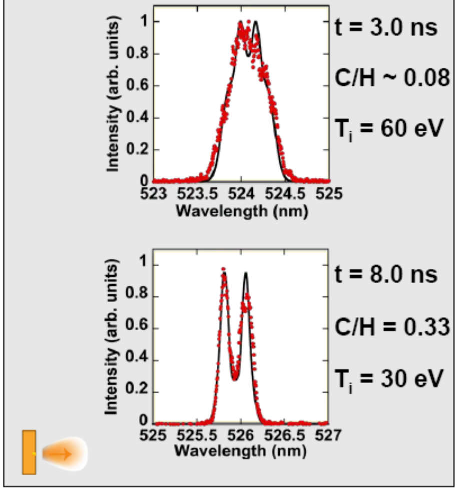
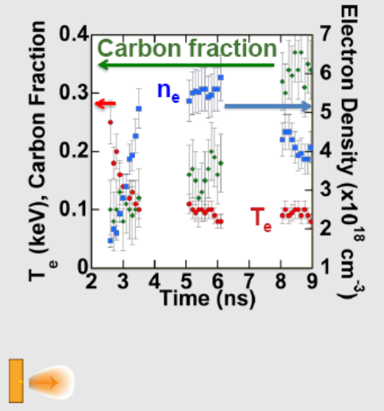
An increased Hydrogen percentage is measured in the Thomson scattering volume at early times

The ion feature can be used to measure the ion species fraction and ion temperature



The electron temperature and density are measured using the electron feature



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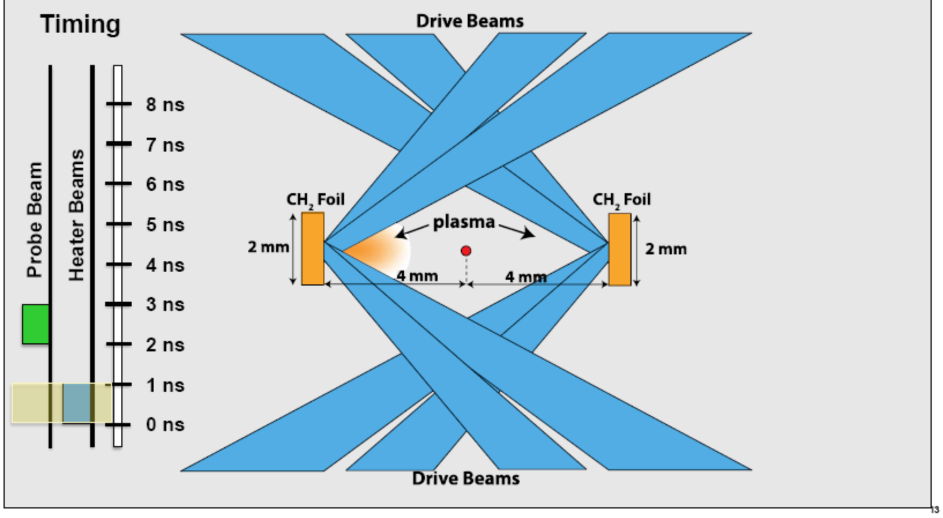
Our OMEGA experiments study the plasma conditions of double flows using a two foil configuration

Heater beams are on for 1 ns and deliver 5 kJ to each target



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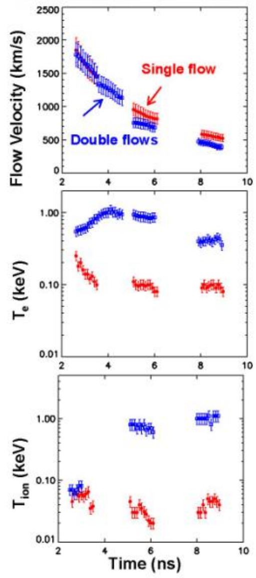
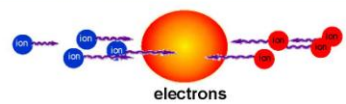
Interesting observables are measured from the double flow experiments



- Velocity slows down when two flows intercept
  - Note: $W(eV) \sim 5x10^{-13} A_Z [v(cm/s)]^2$
  - "Missing energy"?
- Te and Ti considerably higher on double flows

Ion slowing-down by 'resting' electron gas and small angle scattering may explain our observations



Ion-ion collisional slowing-down characteristic length

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

$$\lambda_{mfp} \sim 10mm @ 5ns$$

$$\lambda_{SD} \sim 40\sqrt{A} Z \left(\frac{T_e}{W}\right)^{3/2}$$

$$\lambda_{SD} \sim 5mm$$

Heating from small-scattering

$$T_{i\perp} \sim \frac{\lambda_\theta}{\lambda_{mfp}} W \qquad T_{i\perp} = 1keV$$

$$\lambda_\theta \sim 0.9mm$$

$$W \sim 60keV(@ v \sim 10^8 cm/s)$$

(D. Ryutov, R. Berger, 2011)

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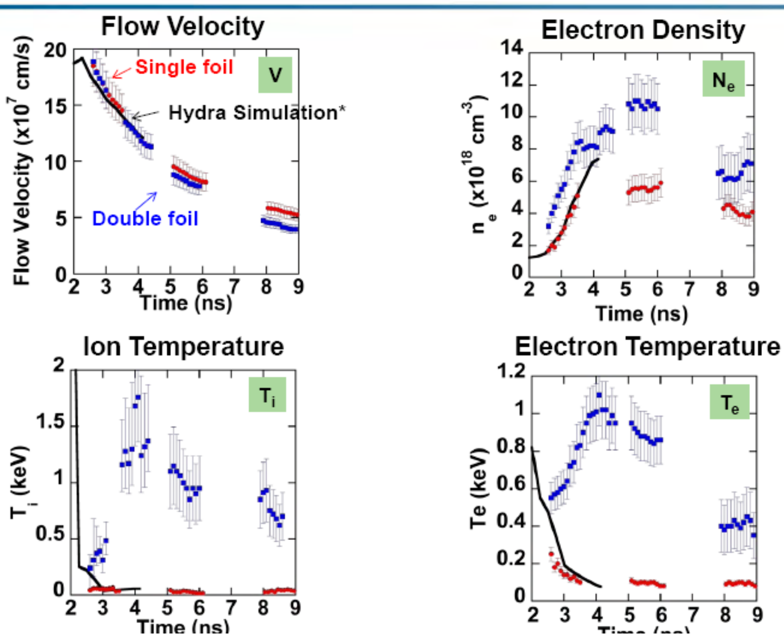
Omega experimental results show the first quantitative measurements of high-velocity interpenetrating plasma flows

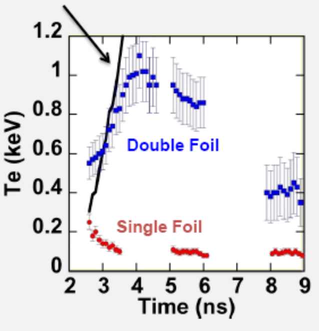


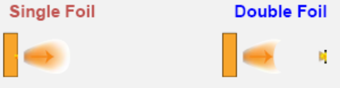
Considerably higher T_e is observed from double foils, electron heating due to electron-ion drag is considered

NIF

A drastic increase in the electron temperature is observed in the double foil geometry

Predicted electron heating due to drag





Initial electron heating is dominated by electron-ion drag

Force acting on electrons from beam 1:

$$f_1 = m_e n_e \nu_{ei}^{(1)} (u_1 - u) = m_e n_e \nu_{ei}^{(1)} n_{Z2} \frac{(u_1 - u_2)}{n_{Z1} + n_{Z2}}$$

The heating rate:

$$\frac{3}{2} n_e \dot{T}_e = f_1 \cdot u_1 + f_2 \cdot u_2 \qquad n_e = Z(n_{Z1} + n_{Z2})$$

$$\frac{3}{2} n_e \dot{T}_e = Z^2 \eta n_{Z1} n_{Z2} e^2 (u_2 - u_1)^2 \equiv Q$$

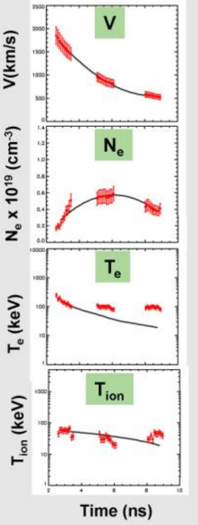
Canonical electrical resistivity:

$$\eta = \frac{m_e \left(\nu_{ei}^{(1)} + \nu_{ei}^{(2)} \right)}{e^2 n_e}$$

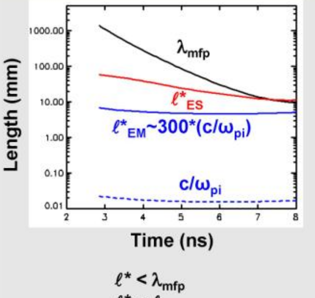
Heat conduction is not included in this simple model

Single flow Thomson scattering data is used to see if our plasma state can create collisionless shocks

NIF



We need the condition: $\ell^* \ll \ell_{int} \ll \lambda_{mfp}$ to create collisionless shock



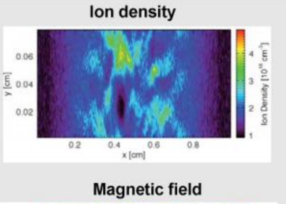
$\ell^* < \lambda_{mfp}$

$\ell^* \sim \ell_{int}$

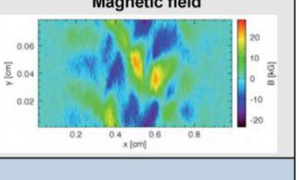
Instability length scales, ℓ^*_{ES}, ℓ^*_{EM} are from theoretical speculations. (Vedenov,, A.A. & Ryutov, D.D., Rev, Plasmas Phys1975; Spitkovsky, A., ApJ, 2005)

PIC simulation suggests that the shock was beginning to from but not fully developed

Ion density



Magnetic field



Fully formed shock require ~10x more ion density

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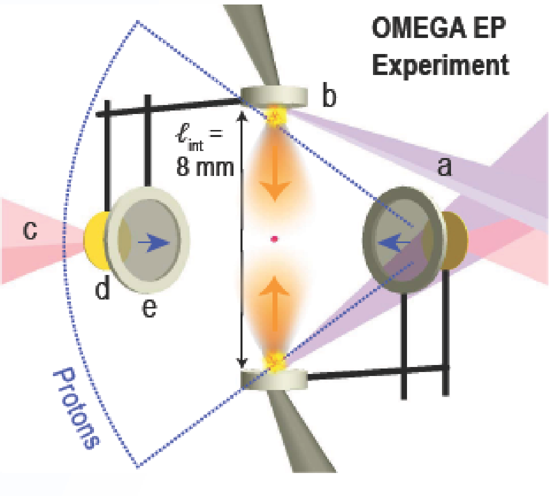
Proton Back-lighting Diagnostics

High power laser experiments can study collisionless shock relevant micro-physics in the laboratory



Two each of the following:

a) 351 nm 3 ns laser, 2200 J
100 µm spot, 9 x 10^{15} W/cm^2

b) Plasma ablation source
2 mm diameter CH_2 plastic

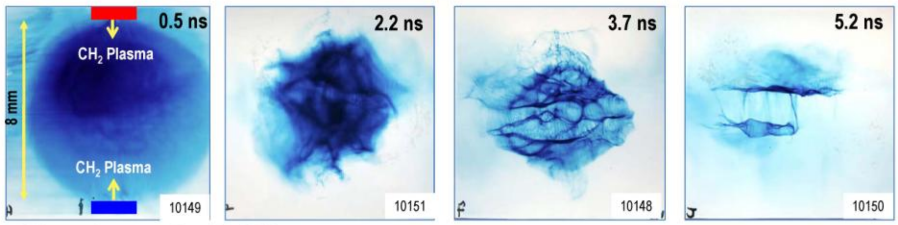
c) 1053 nm 10 ps laser, 250 J
40 µm spot, 2 x 10^{18} W/cm^2

d) Proton source
50 µm thick Au disk

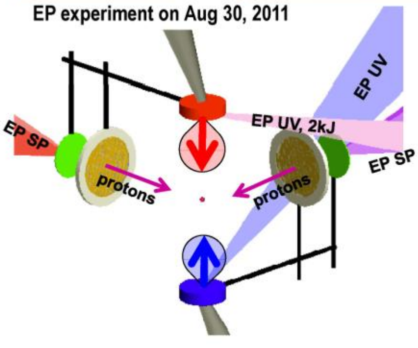
e) Proton source shields
3 µm thick Al foil on an Al washer (2.7 mm ID)

We use proton radiography / deflectometry to image shock formation and to measure magnetic fields

NIF



EP experiment on Aug 30, 2011



- Proton radiography time sequence shows eventual self-organization of the counterstreaming plasmas
- Large bubble features may be from laser ablative RT instability growth or MHD instability
- Planar features from electron temperature gradient
- Striation features may be from electrostatic field generation

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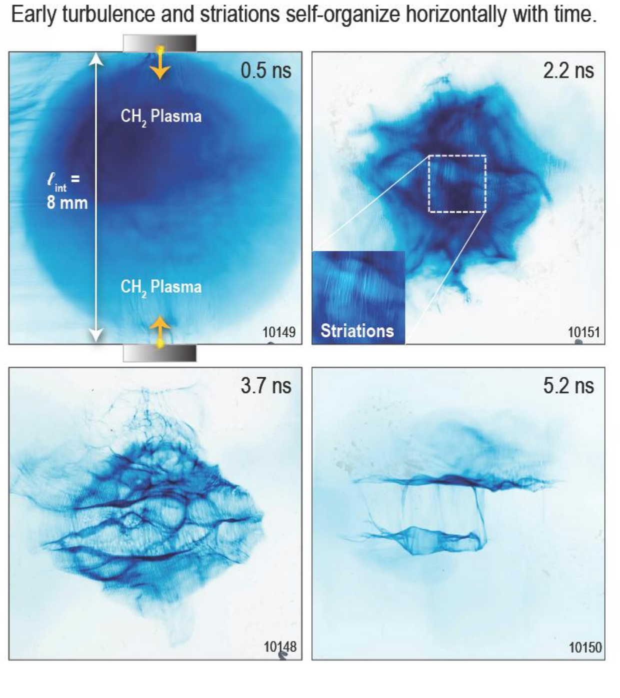
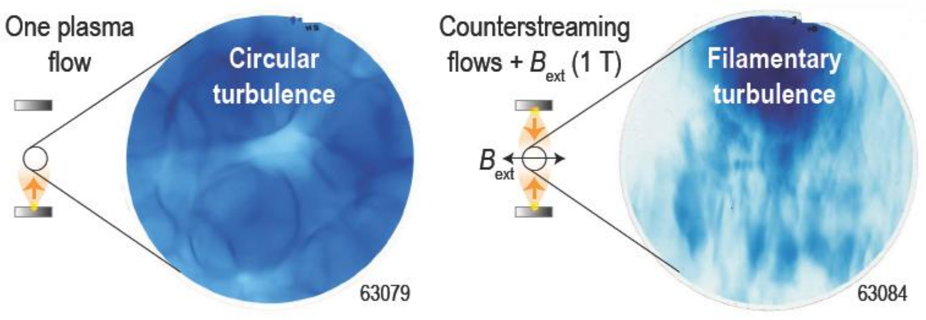
We collected very interesting proton radiography data

Early turbulence and striations self-organize horizontally with time.

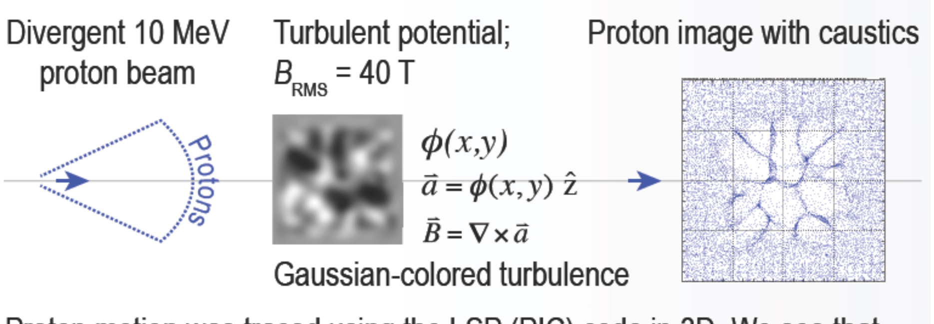


Images of single & counterstreaming plasmas flows

7 MeV proton imaging at 5 ns shows a dramatic difference (joint shot)

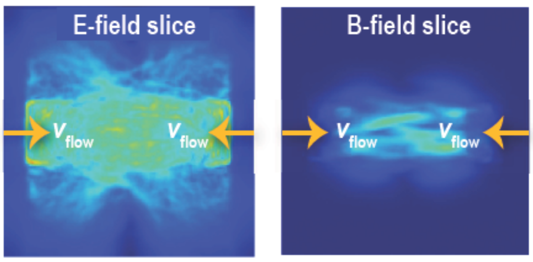


Simulated proton image (turbulent field Ansatz)



Proton motion was traced using the LSP (PIC) code in 3D. We see that soft turbulent objects generate sharp caustics in the proton image.

Turbulent field structures predicted by 3D PIC sims



Tristan-MP code, A. Spitkovsky.

Counterstreaming H plasmas:
$v_{flow} = 10^8$ cm/s
$n_i = 10^{18}$ cm^{-3}

Electric field is predicted to dominate proton imaging.

Turbulent fields are a signature of collisionless shock formation. Possibly due to electromagnetic (Weibel) or electrostatic (two-stream) instabilities.

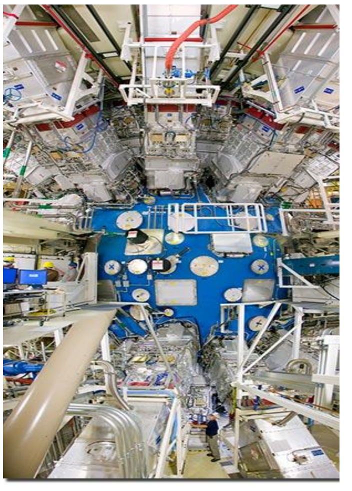
Summary of our findings

- We have seen very interesting proton images of plasma flows
- Even a single plasma flow is complicated
- We might have observed the signatures of collisionless shock formation (turbulent fields and filamentation)

Path for future investigation in 2012 & beyond

- Study late-time evolution
- Vary target composition (CH_2, pure C)
- Try two different materials for strong B-field from current drive
  D. D. Ryutov et al, Phys. Plasmas **18**, 104504 (2011)
- Create fully formed collisionless shocks with the NIF laser (contingent on diagnostic availability)

National Ignition Facility



Science on NIF Committee just after the Evaluation July 15, 2010 at LLNL

Astrophysical collisionless shock generation on NIF

PIs: Y. Sakawa (Osaka U.) / G. Gregori (Oxford U.)

Collaborators: A. Bell, A. Diziere, L. Gargate, S. Glenzer, C. Gregory, M. Hoshino, T. Ide, T. Kato, R. Kodama, M. Koenig, Y. Kuramitsu, E. Liang, M. Medvedev, F. Miniati, T. Morita, C. Niemann, H. Park, A. Ravasio, B. Remington, D. Ryutov, Y. Sentoku, A. Spitkovsky, H. Takabe, N. Woolsey, R. Yamazaki

Institutions: Osaka, Oxford, LLNL, Princeton, Ecole Polytechnique, York, ETH Zurich, UCLA, Aoyama Gakuin, Tokyo U., Kansas, Rice

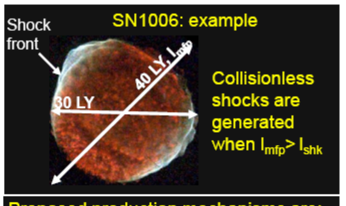
Scientific Objectives:

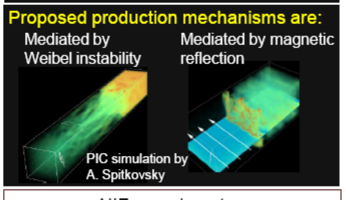
(1) To study the generation of high Mach-number non-relativistic collisionless shocks relevant to SNRs and protostellar jets

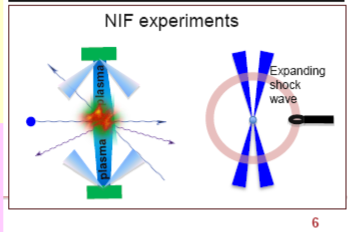
(2) To study the formation of self-generated magnetic fields from the Weibel instability and cosmic ray acceleration

Why NIF?

- Ability to reach high Mach numbers, much higher than possible in classical plasma shock tubes or at other laser facilities



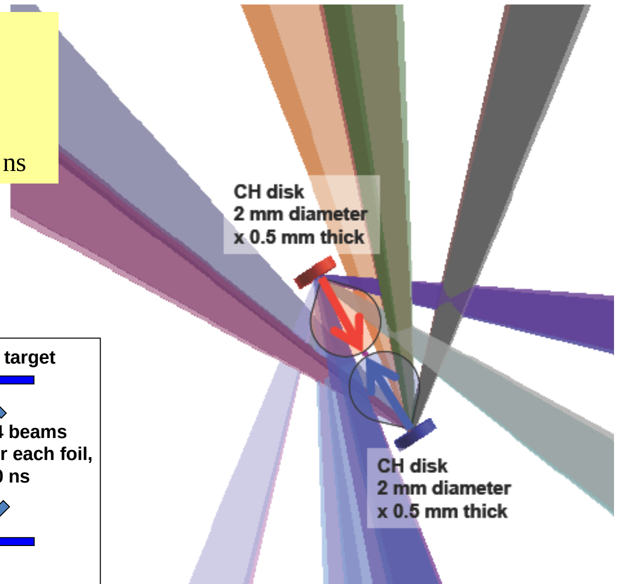


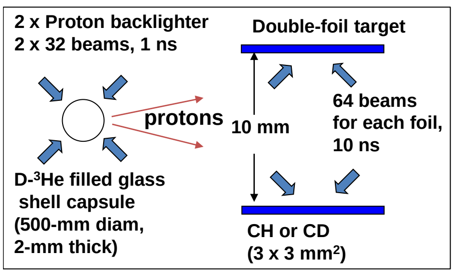


6

Collisionless Shock Experiment with NIF

Drive beam
10 kJ/ beam x 64 beams
for each foil, 10 ns
D-He[3] implosion beam
1.5 kJ / beam x 64 beams, 1 ns

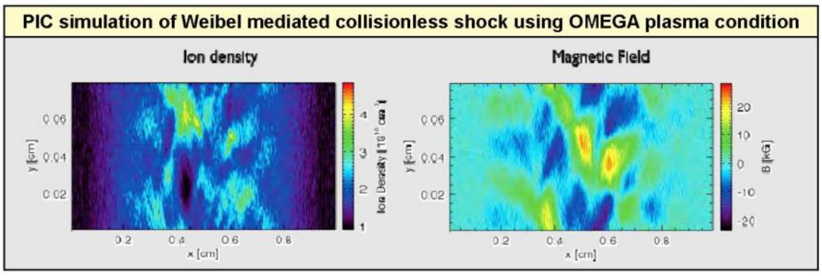




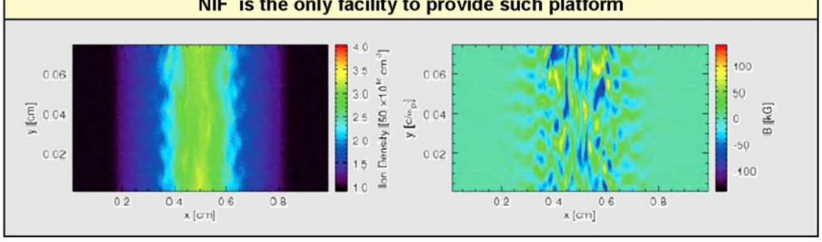
NIF is the facility where properly scaled astrophysical shock experiments in this regime are possible

NIF

PIC simulation of Weibel mediated collisionless shock using OMEGA plasma condition



We need ~50x more density to create fully formed collisionless shocks.
NIF is the only facility to provide such platform



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Summary and future work

- Detection of self-generated electromagnetic fields from plasma instabilities such as Weibel instability will be a break-through in laboratory astrophysics and may provide a generation mechanism of the seed magnetic fields in universe
- Omega experiments measure quantitative plasma conditions for optimizing collisionless shock creation
- Omega experiments suggests the existence of previously unknown mechanisms for electric and/or magnetic field generation in the counterstreaming plasma flows
- We are continuing in our Omega and EP experiments to study collisionless shock formation under pre-existing magnetic fields as well as theory and experimental optimization
- NIF experiments will begin when the required diagnostics are constructed
- NIF experiments will lead to a truly scaled collisionless shock laboratory astrophysics experiment

- See also Y. Sakawa's talk on Fri (Session N+O 13:30 pm, Room C)

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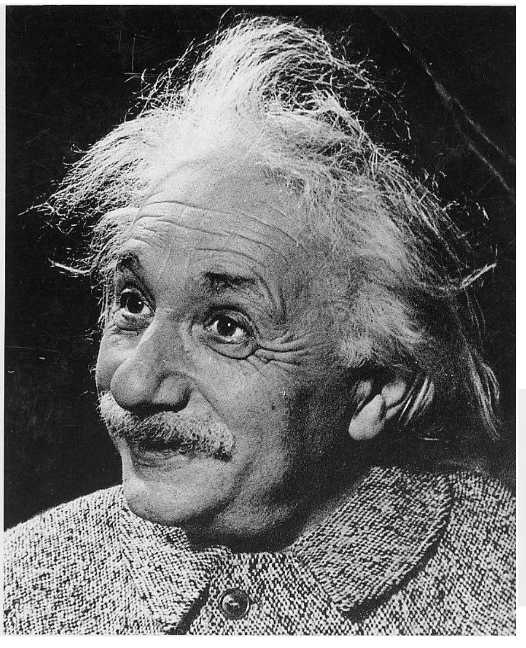

"Imagination is more important than knowledge"

Albert Einstein

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