Importance of and related laser experiments on reconnection physics in collisionless shock formation in Supernova Remnants (SNRs)

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Informal Meeting on Magnetic Reconnection in HED

April, 4-5, 2013

PPPL, Princeton University

Laboratory Astrophysics

Collisionless shock group : Collaborators

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Hiroshima U; Chiba U (Japan) :	T. N. Kato; Y. Matsumoto
U. Tokyo (Japan); JAMSTEC (Japan) :	M. Hoshino, Y. Ono; T. Sugiyama
Tohoku U; KEK; U Elect. Comn (Japan) :	N. Ohnishi ; A. Mizuta; H. Yoneda, K. Nagamine
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York University (UK):	N. Woolsey, C. Gregory, J. Waug, R. Crowston
Oxford University (UK):	G. Gregori, C. Murphy, A. Bell, H. Doyle, J. Meinecke
LULI (France); CEA (France) :	M. Koenig, A. Ravasio, A. Pelka, A. Diziere; B. Loupias
LUTH (France):	C. Michaut, P. Barroso
IOP (China) ; NAO (China) :	D. Yuan, Q. Dong, Y. Li; J. Zhong, K. Zhang, F. Wang
Shanghai Jiao Tong University (China) :	J. Zhang
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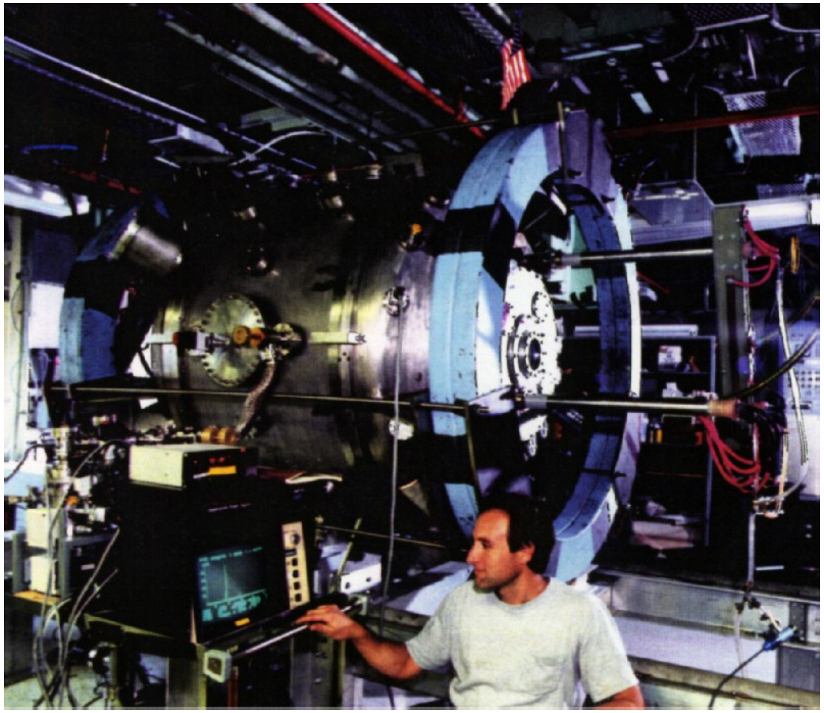
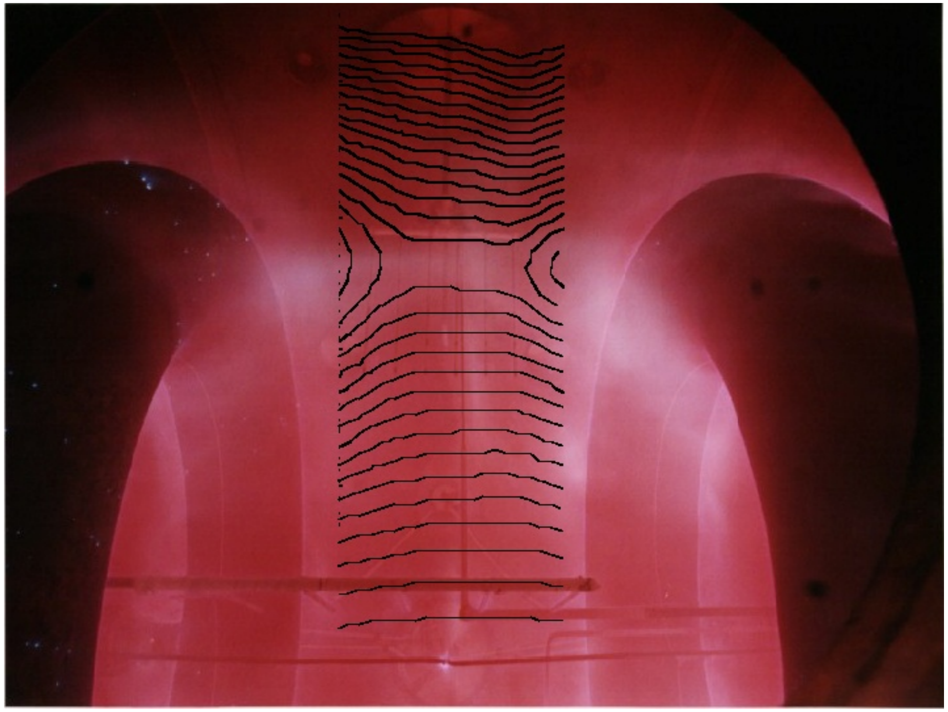
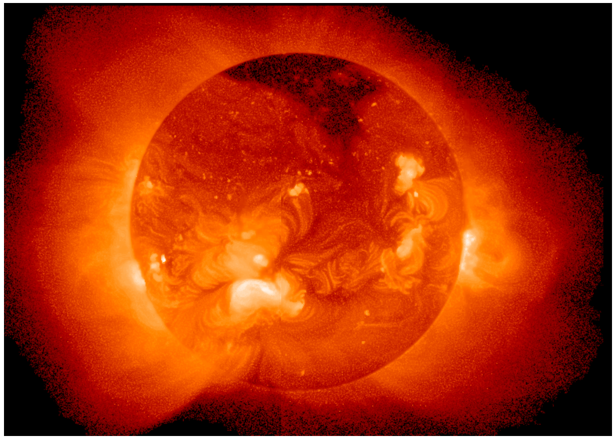
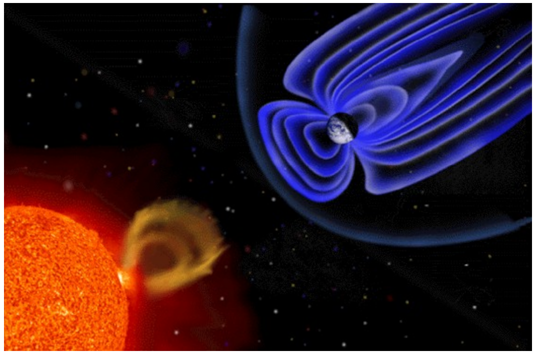
LLE, Univ. of Rochester (USA):	D. Froula, J. Knauer, G. Fiskel
ETH Zurich (Switzerland):	F. Miniati
Rice University (USA):	E. Liang
University of Michigan (USA):	E. Rutter, M. Grosskopf, C. Kuranz, P. Drake
University of Nevada, Reno (USA):	R. Presura

Magnetic Reconnection Experiment







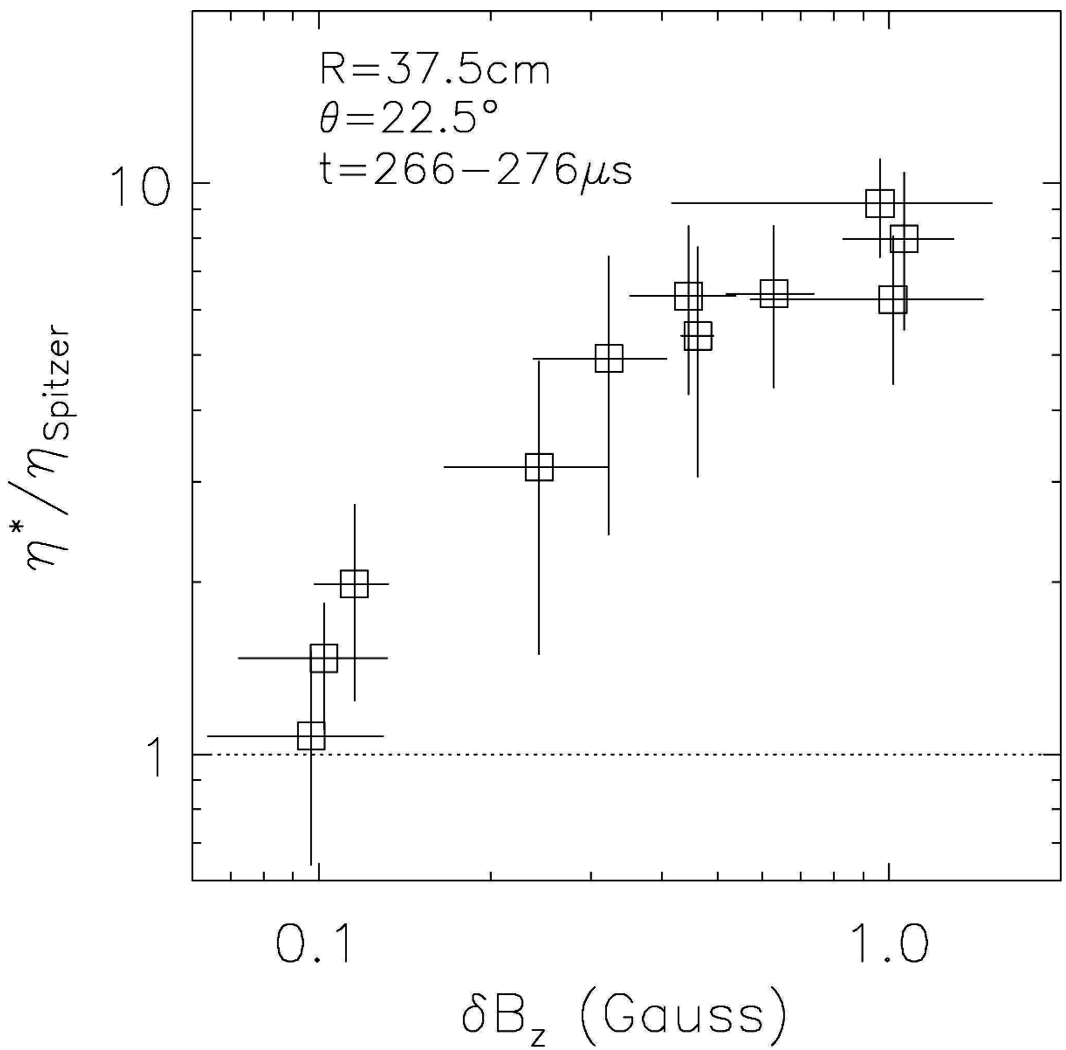


PPPL
PRINCETON PLASMA PHYSICS LABORATORY

By Dr. Hantao Ji (PPPL, USA)

Cf：小野（東大）

Turbulence Amplitudes Correlate with Resistivity Enhancement



By Hantao Ji

Faraday-Rotation Measurements of Megagauss Magnetic Fields in Laser-Produced Plasmas*

J. A. Stamper and B. H. Ripin
Naval Research Laboratory, Washington, D. C. 20375
(Received 24 October 1974)

Magnetic fields in the megagauss range have been observed in the laser-produced plasma near the focus of a high-power laser pulse. Faraday-rotation measurements utilizing the lig ser light both show the presence o

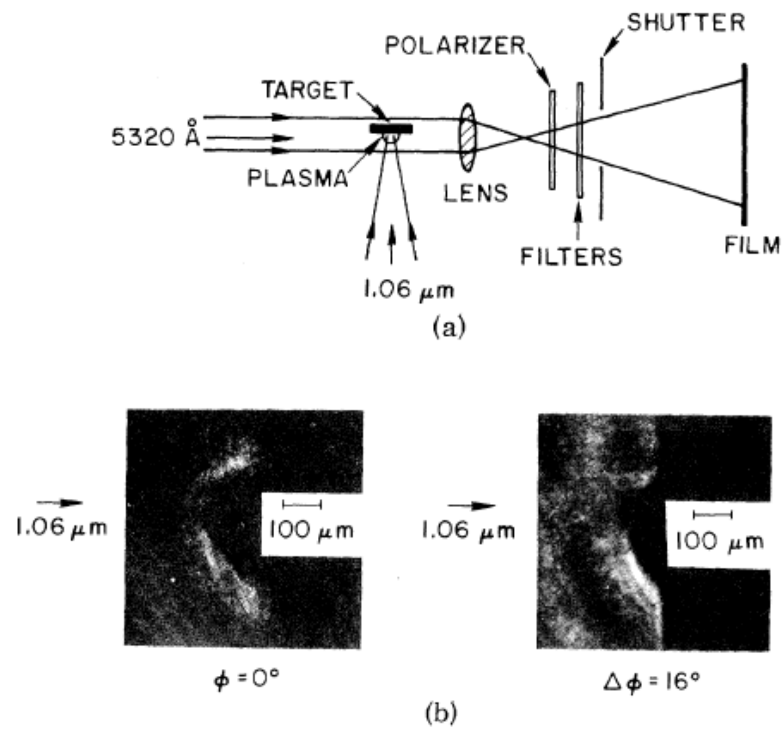


FIG. 1. Measurements of Faraday rotation of a probing beam. (a) Arrangement for detecting the rotation of polarization. (b) Sample photographs as a function of polarizing-sheet orientation.

Farady Rotation Diagnostics for Magnetic Field

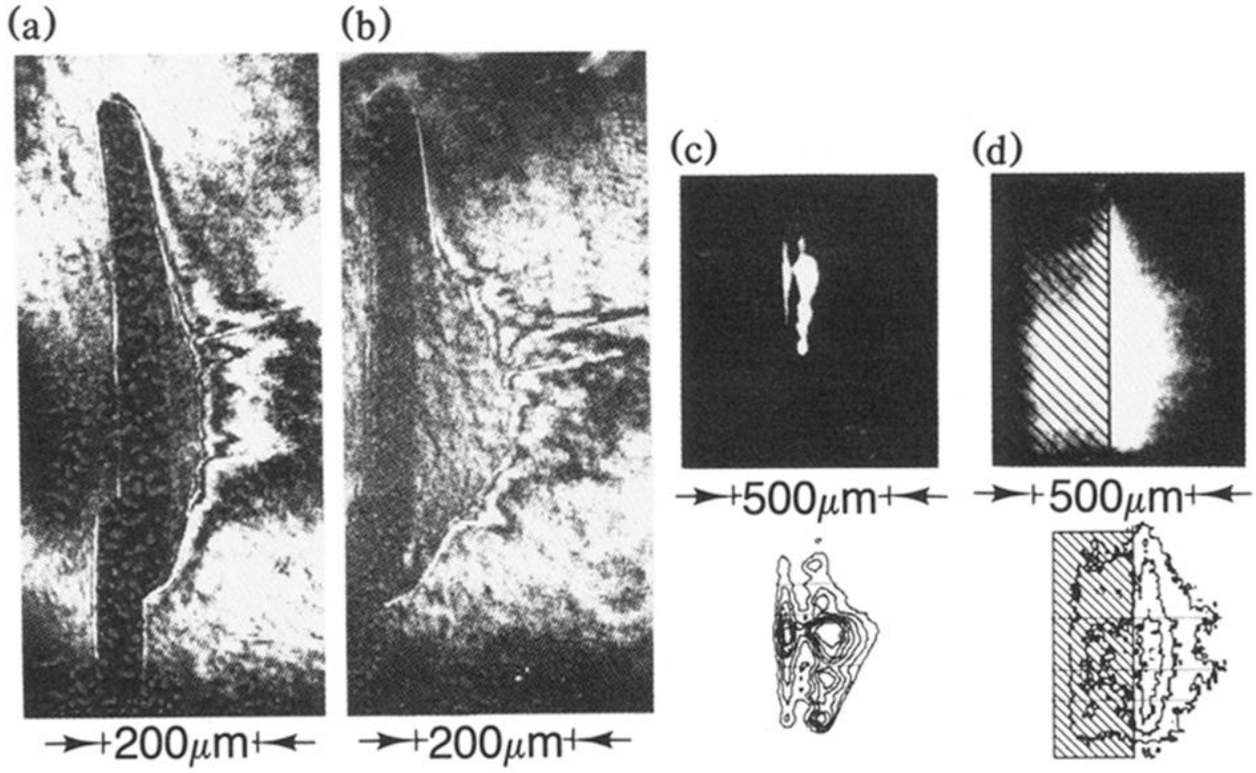


FIG. 3. Jetting is observed with a 3000-μm offset on the divergent side of best focus for a picket laser pulse. Interferograms taken at (a) 320 and (b) 720 ps show a number of small jets. (c) The *M*-band and (d) soft-x-ray emission indicates that the jets are cool.

J. A. Stamper, Magnetic Field Generation by Lasers, Laser & Particle Beams 9, 841 (1991).

MHD Equations

$$\mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B}$$

$$\mathbf{j} = \sigma\left(\mathbf{E} + \mathbf{u} \times \mathbf{B}\right)$$

$$\mathbf{E} = \frac{1}{\sigma\mu_0} \nabla \times \mathbf{B} - \mathbf{u} \times \mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\sigma\mu_0} \nabla^2 \mathbf{B} + \nabla \times \left(\mathbf{u} \times \mathbf{B}\right)$$

Biemann's Battery mechanism

$$\mathbf{j} = \nabla \times \mathbf{H}$$

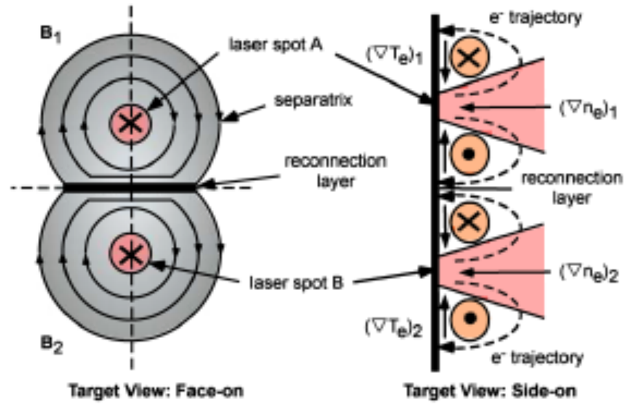
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

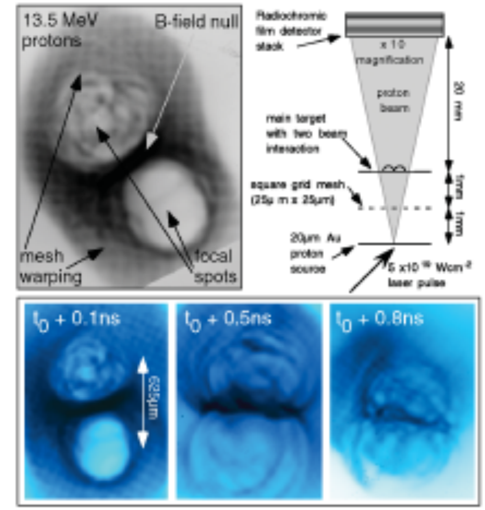
$$0 = -e\mathbf{E} - \frac{1}{n_e} \nabla P_e$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\frac{1}{e n_e} \nabla P_e \right) = -\frac{1}{e {n_e}^2} \nabla n_e \times \nabla P_e$$

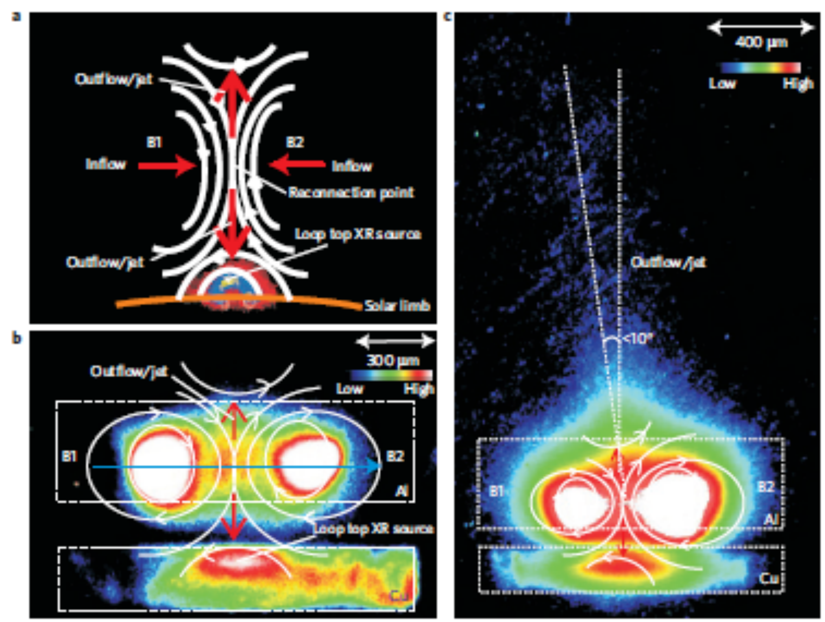
Magnetic reconnection in laser produced plasmas

- Experiment
  - Nilson+ 2006 PRL
  - Li+ 2007 PRL
  - Nilson+ 2008 PoP
  - Willingale+ 2010 PoP
  - Zhong+ 2010 Nature Physics
  - Dong+ 2012 PRL
  - Kuramitsu+ submitted
- Theory/Simulation
  - Fox+ 2011 PRL
  - Fox+ 2012 PoP





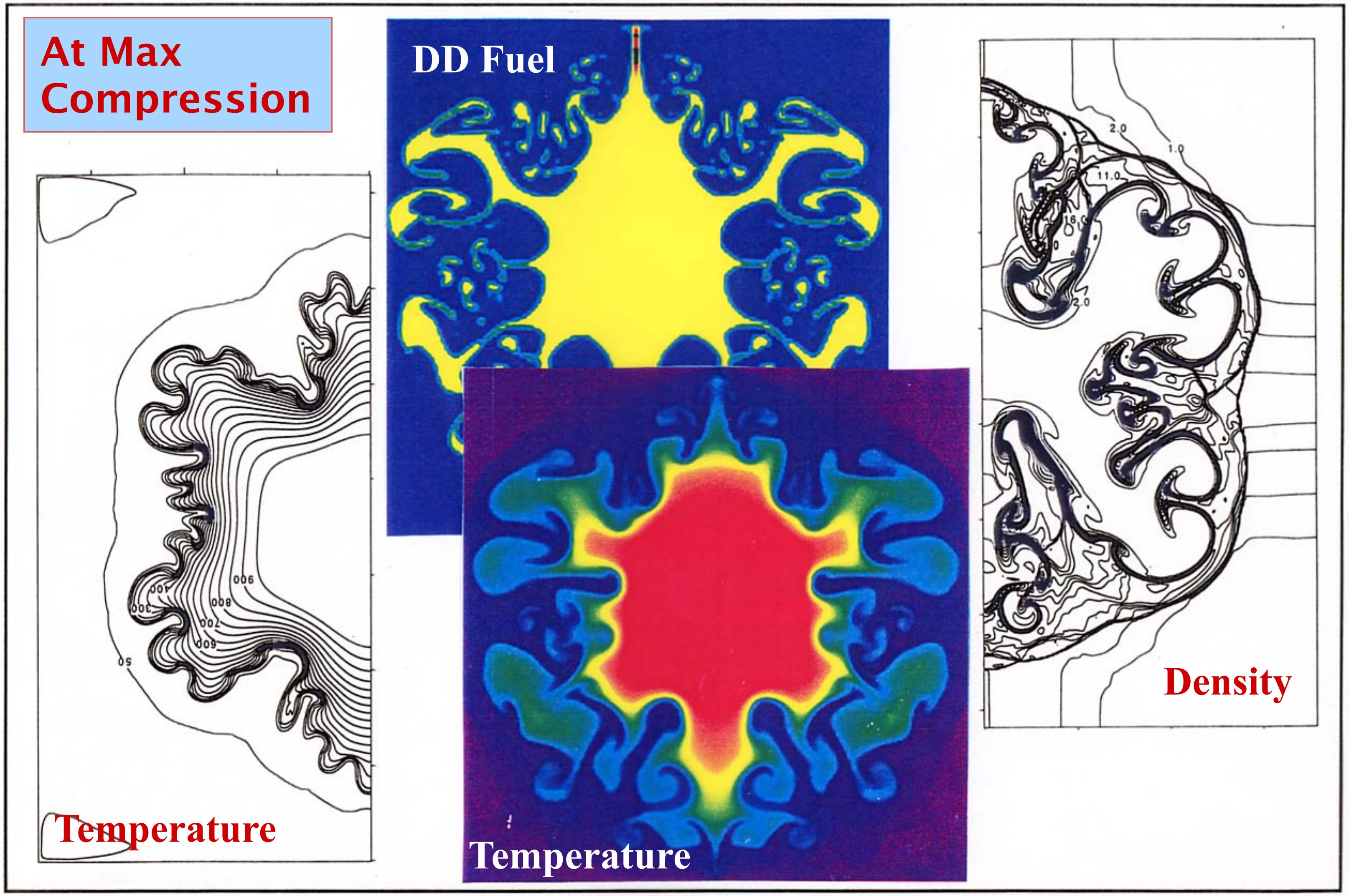
Nilson+ 2006 PRL



Zhong+ 2010 Nature Physics

Vortex Formation and Hydrodynamic Instability
= Vortex in Fluid is Magnetic Field in Plasma =

Large Scale Computing for Laser Fusion Energy Research



By H. Takabe (see NF Paper)

Equation for Complete Fluids

$$\frac{d\mathbf{u}}{dt} = -\frac{1}{\rho}\nabla P + \nabla\Phi$$

$$\rightarrow \frac{\partial \mathbf{u}}{\partial t} = -\nabla\left(\Pi + \frac{1}{2}u^2\right) + \mathbf{u}\times\boldsymbol{\omega} \qquad \Pi = \int\frac{dP}{\rho}$$

- **Belnoulli Theorem** $\left(\frac{\partial}{\partial t}\rightarrow 0, \boldsymbol{\omega} = 0\right)$

$$\Pi + \frac{1}{2}u^2 = \text{const} \qquad \rightarrow \qquad \frac{P}{\rho} + \frac{1}{2}u^2 = \text{const}$$

(incompressible)

- **Equation for Vorticity ω** $(\nabla\times\ \ )$

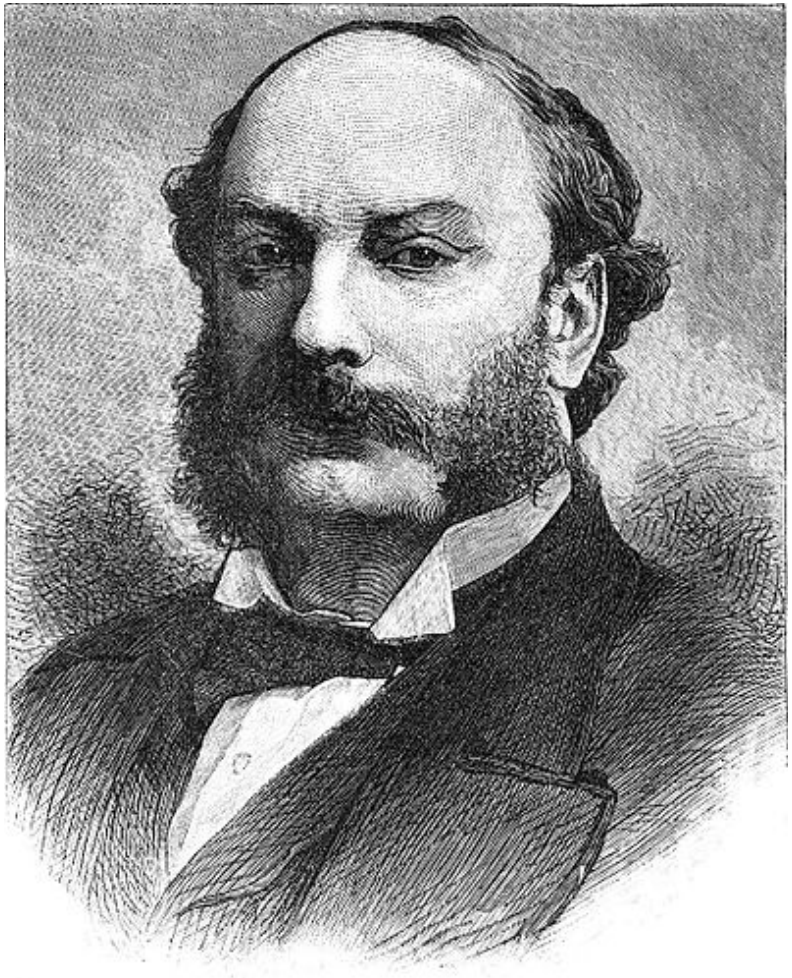
$$\boxed{\frac{d}{dt}\boldsymbol{\omega} = (\boldsymbol{\omega}\cdot\nabla)\mathbf{u} - \boldsymbol{\omega}(\nabla\cdot\mathbf{u}) + \frac{1}{\rho^2}\nabla\rho\times\nabla P}$$

① ② ③

① Vorticity stretching along streamline

② Vorticity dilatation due to compressibity

③ Vorticity creation by baroclinic effect



Lord Rayleigh (1842 –1919)

Geoffrey Ingram Taylor (1886 –1975)

Meshkov with me, January 1992 at Cheriyabinsk-70, Russia (just after the collapse of USSR)

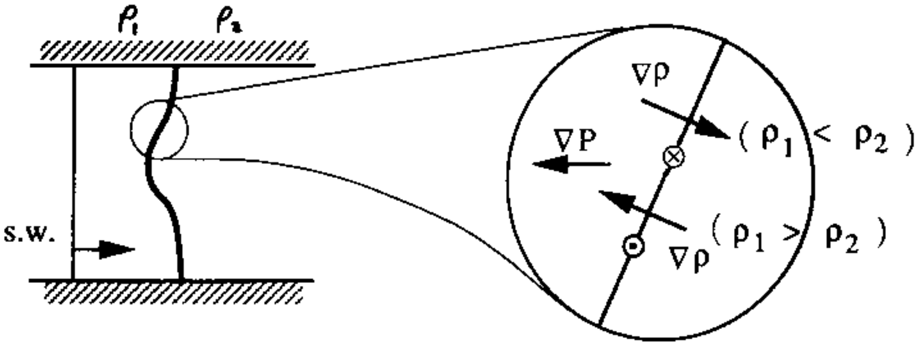
Vortex in fluids

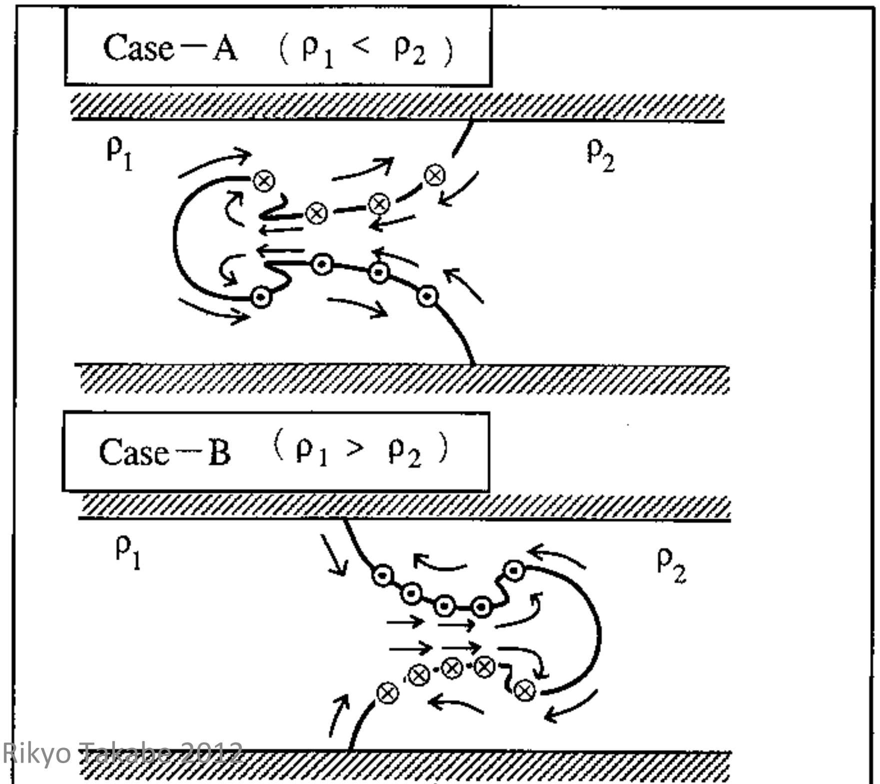
$$\frac{d\mathbf{u}}{dt} = -\frac{1}{\rho}\nabla P$$

$$\boldsymbol{\omega} = \nabla \times \mathbf{u}$$

$$\frac{d\boldsymbol{\omega}}{dt} = (\boldsymbol{\omega} \cdot \nabla)\mathbf{u} - \boldsymbol{\omega}(\nabla \mathbf{u}) + \frac{1}{\rho^2}\nabla\rho \times \nabla P$$

Physical Mechanism, Physics Analogy





- 流体の運動方程式

$$\frac{d\mathbf{u}}{dt} = -\frac{1}{\rho}\nabla P$$

- 渦の運動　$(\omega = \nabla \times \mathbf{u})$

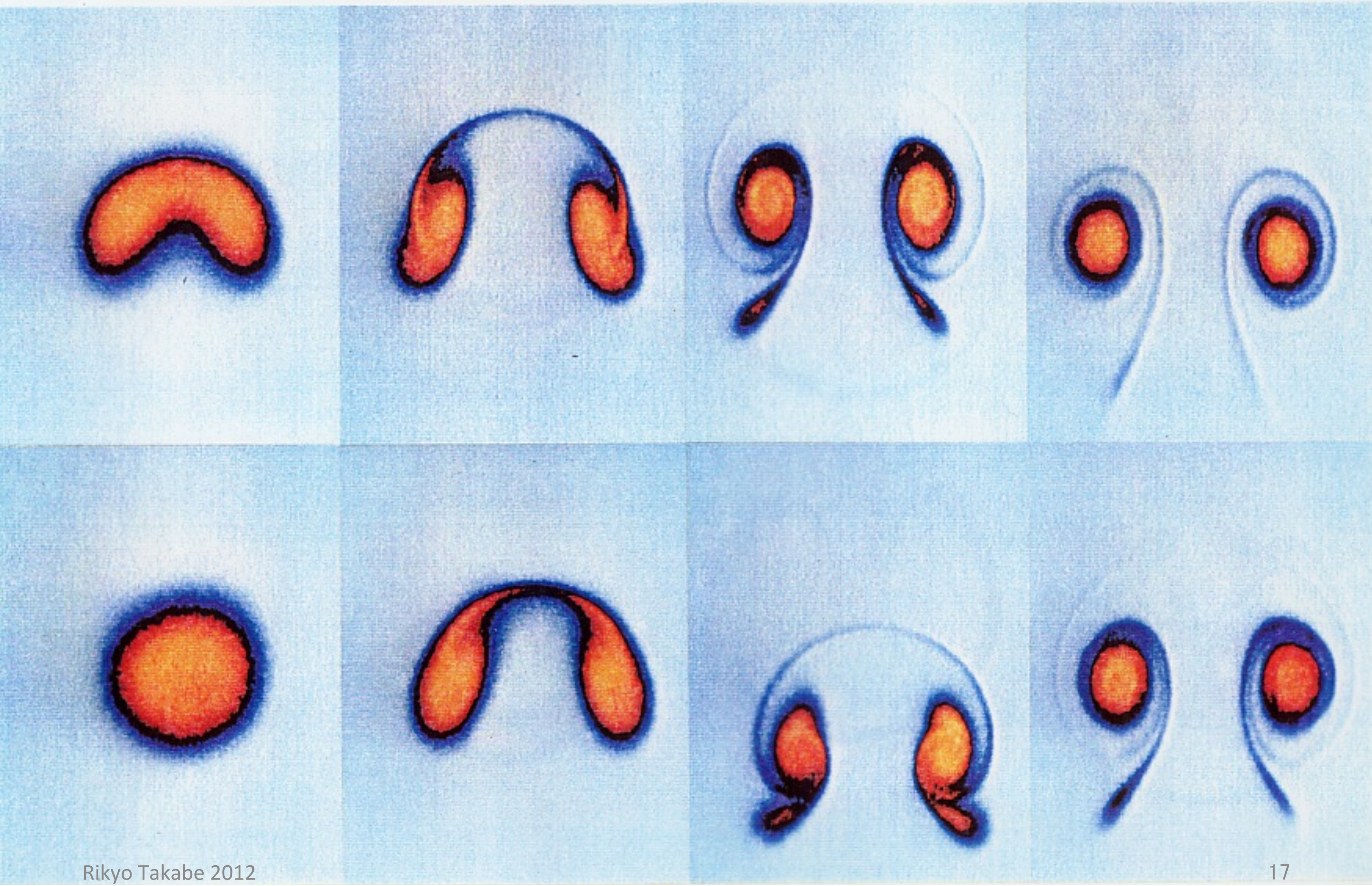
$$\frac{d\omega}{dt} = (\omega \cdot \nabla)\mathbf{u} - \omega(\nabla \cdot \mathbf{u}) + \frac{1}{\rho^2}\nabla\rho \times \nabla P$$

（右辺第 3 項）＝Baroclinic 項

- ∇ρ と∇ Pが並行でないためBaroclinic 項により境界面に流れの渦が作られる。
- 渦が境界面に作られると回りに速度場が形成される。これが境界面の変形を引き起こす。
- 渦と速度の関係は電流と磁場の関係と同じ。

$$\left.\begin{array}{l}\nabla \times \mathbf{u} = \omega \\ \nabla \times H = j\end{array}\right]\ \text{つまり}\ \begin{pmatrix}\omega \\ u\end{pmatrix} \Leftrightarrow \begin{pmatrix}j \\ H\end{pmatrix}$$

Helium cylinder in Air hit by Shock (exp.)



Biemann's Battery mechanism

$$\mathbf{j} = \nabla \times \mathbf{H}$$

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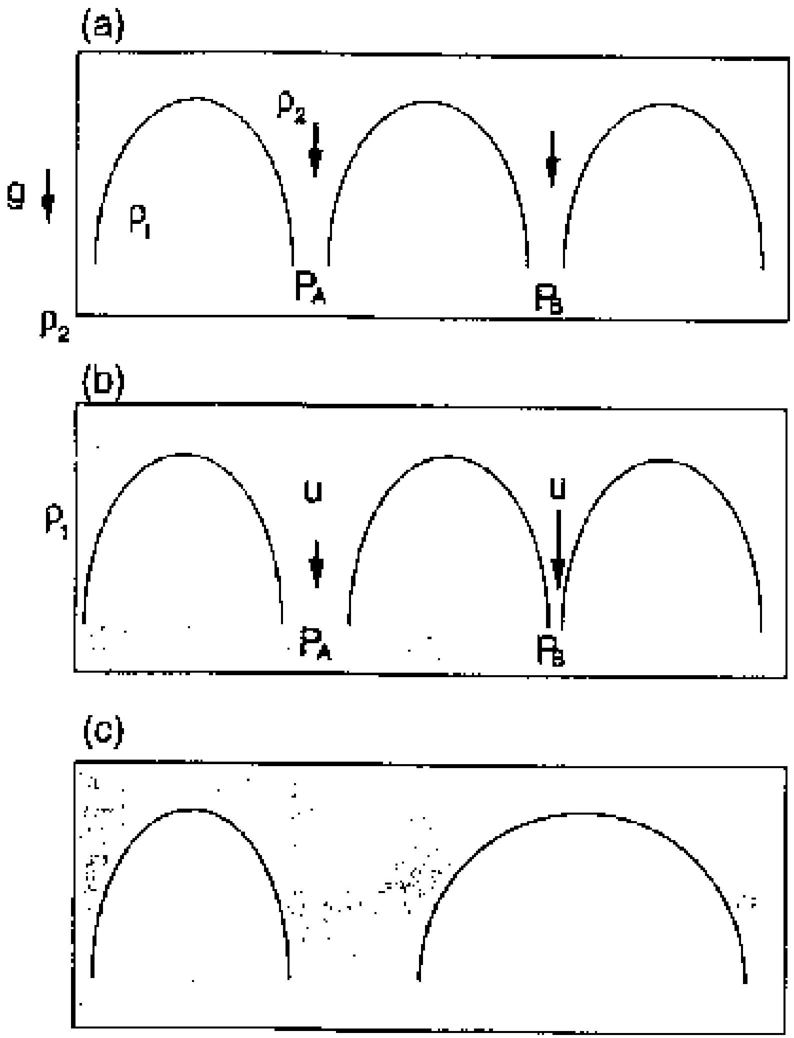
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\frac{1}{e n_e} \nabla P_e \right) = -\frac{1}{e {n_e}^2} \nabla n_e \times \nabla P_e$$

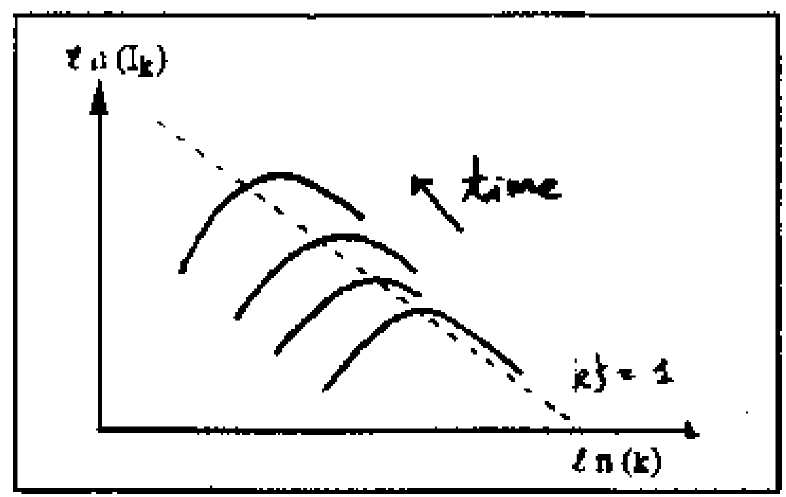
Bubble Coalescence (Inverse-Cascade)



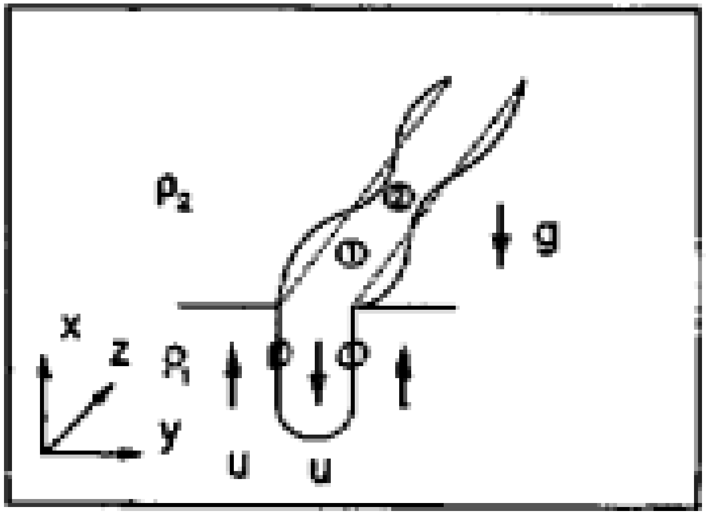
Bubble Coalescence（泡の融合）

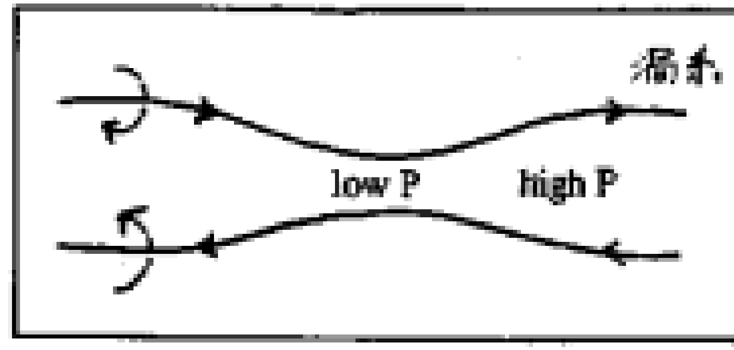
Belnoulli Theorem

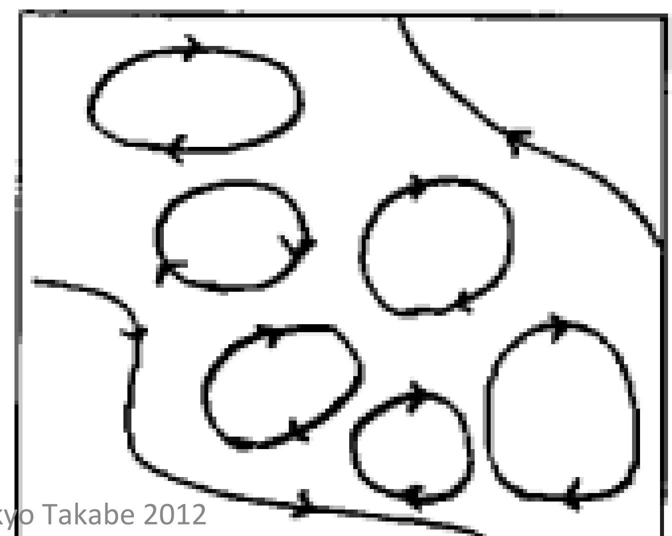
$$\frac{P}{\rho} + \frac{1}{2}u^2 = \mathrm{const}$$

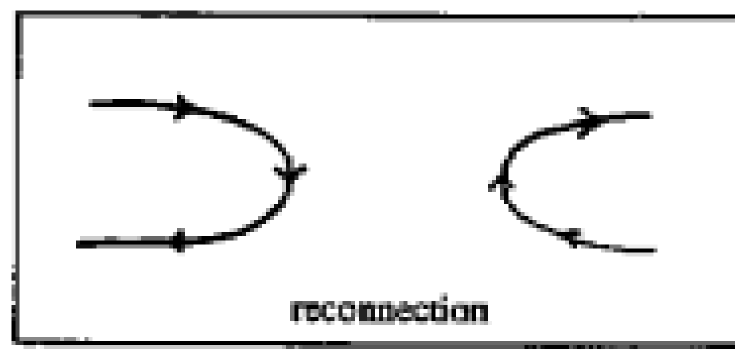


Reconnection of Vortex Lines









- ３次元バブルの方が上昇速度早い

$$U = AR^{1/2}$$

Mode-mode Coupling and I.C.

1. Haan's Saturation Model [Phys. Rev. A 39, 5812(1989)]

$$S(k) = \eta[2\pi^3/(\epsilon L k^3)]^{1/2}, \qquad \epsilon = 0.25, \quad \eta = 0.063$$

$$Z_k(t) = S(k)\{1 + \log[Z_k^{\rm lin}/S(k)]\},$$

2. Mode-Mode Coupling [S.Haan, Phys. Fluids B 3,2349(1991)]

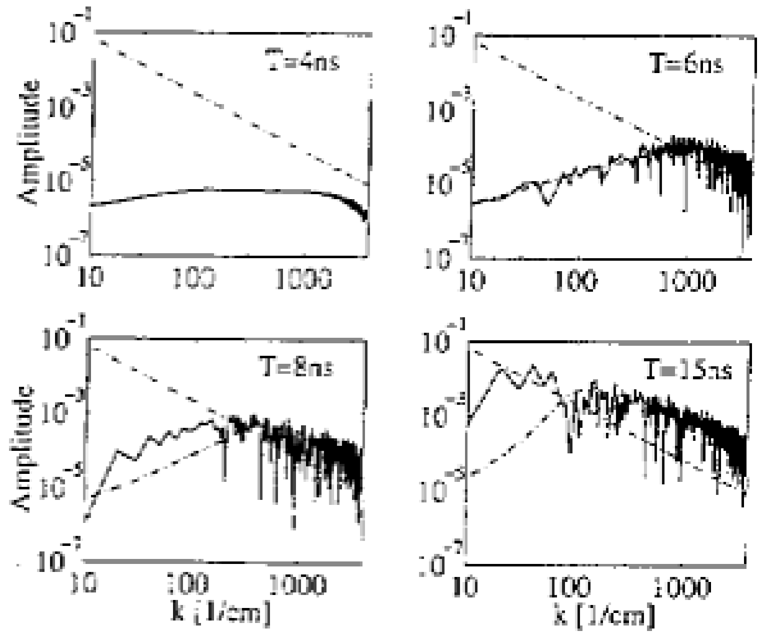
$$\ddot{Z}_k = \gamma^2(k) Z_k + A k \sum_{k_2} \left[\ddot{Z}_{k_2} Z_{k_2'} (1 - \hat{k}_2 \cdot \hat{k}) + \dot{Z}_{k_2} \dot{Z}_{k_2'} \left(\frac{1}{2} - \hat{k}_2 \cdot \hat{k} - \frac{1}{2} \hat{k}_2 \cdot \hat{k}_2' \right) \right],$$

$$Z(x) = Z_1 \cdot \cos(kx) - \tfrac{1}{2} \cdot (kZ_1) \cdot Z_1 \cdot \cos(2kx) + \tfrac{3}{8} \cdot (kZ_1)^2 \cdot Z_1 \cdot \cos(3kx) - \tfrac{1}{8} \cdot (kZ_1)^2 \cdot Z_1 \cdot \cos(kx) + O(Z_1^4),$$

$$Z_1 = Z_0 \exp(\gamma \cdot t)$$

3. Mixing Width

$$h(t) = (<\Sigma_k Z_k^2>)^{1/2}$$



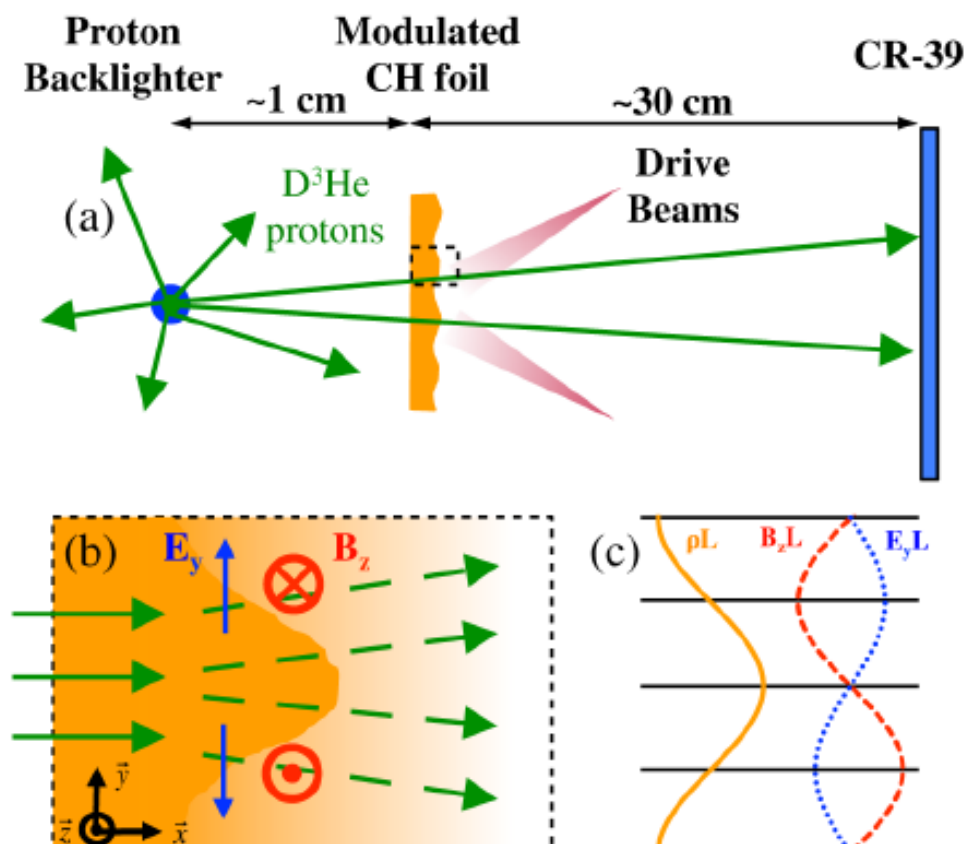
D. Ofer et. al. Phys. Plasmas 3, 3073 (1996)

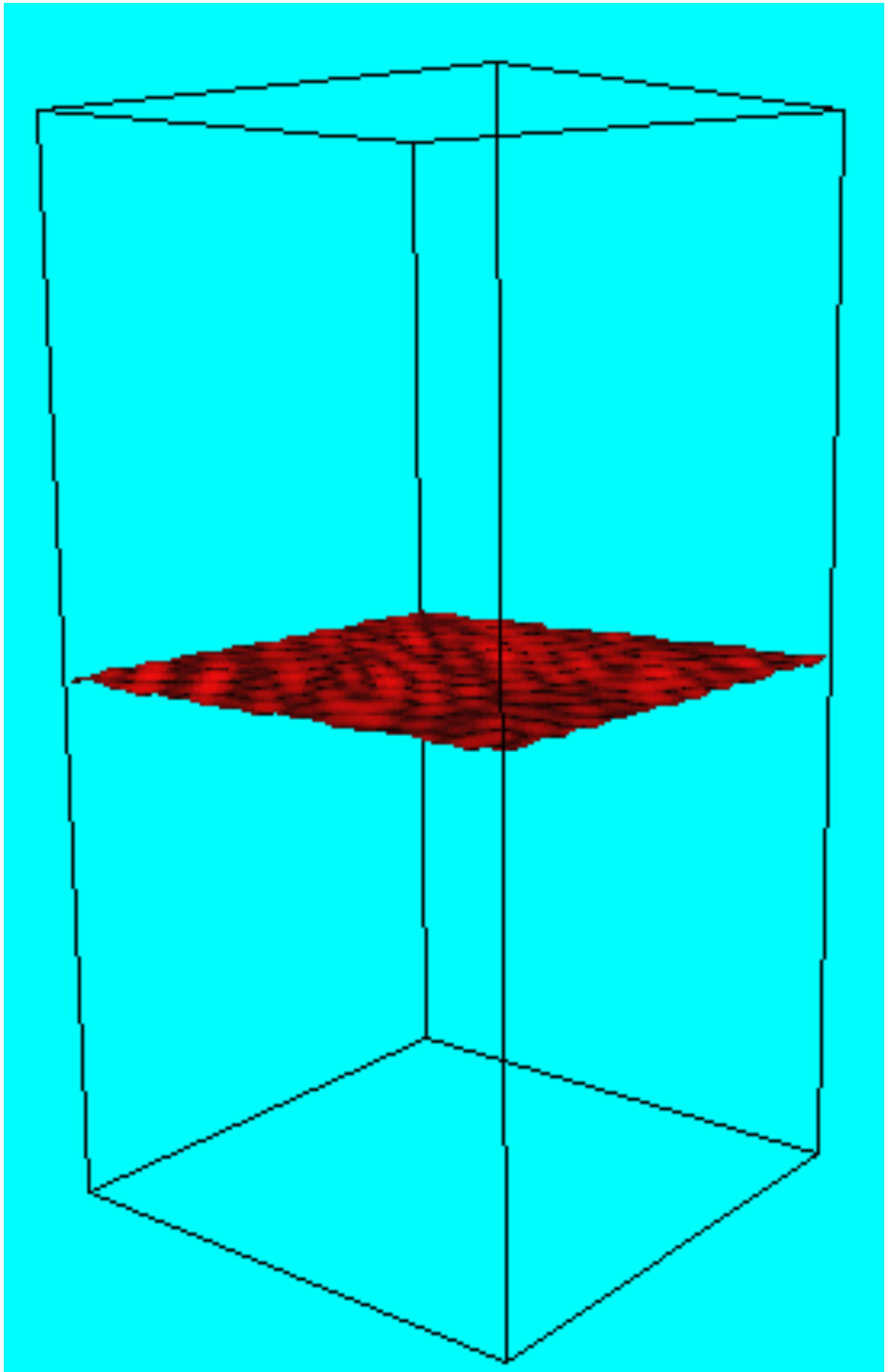
First Measurements of Rayleigh-Taylor-Induced Magnetic Fields in Laser-Produced Plasmas

M. J.-E. Manuel, C. K. Li, F. H. Séguin, J. Frenje, D. T. Casey, and R. D. Petrasso
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

S. X. Hu, R. Betti,* J. D. Hager,† D. D. Meyerhofer,* and V. A. Smalyuk‡
Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
(Received 9 February 2012; published 19 June 2012)

The first experimental demonstration (
battery effect has been made. Experimen
these illusive fields using a monoenerge
measurements were inferred from radio
linear growth phase for 120 μm perturb
scattering using measured areal density



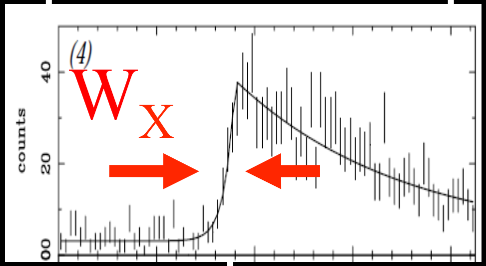


Collisionless-Shock Mediated by Magnetic (Weible) Instability

Importance of Nonlinear Growth of B field

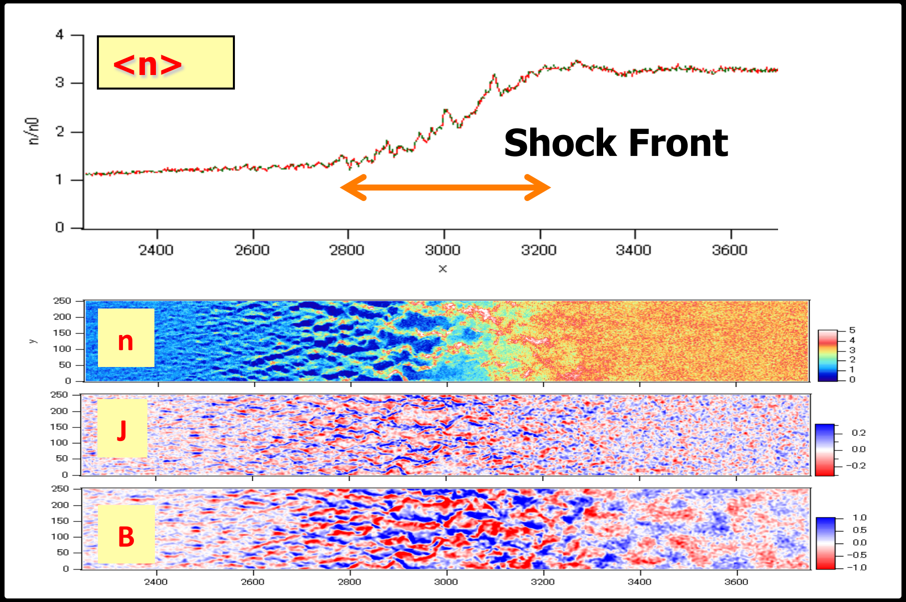
Laser Experiment on Astro-Shock and Cosmic-Rays

(c)



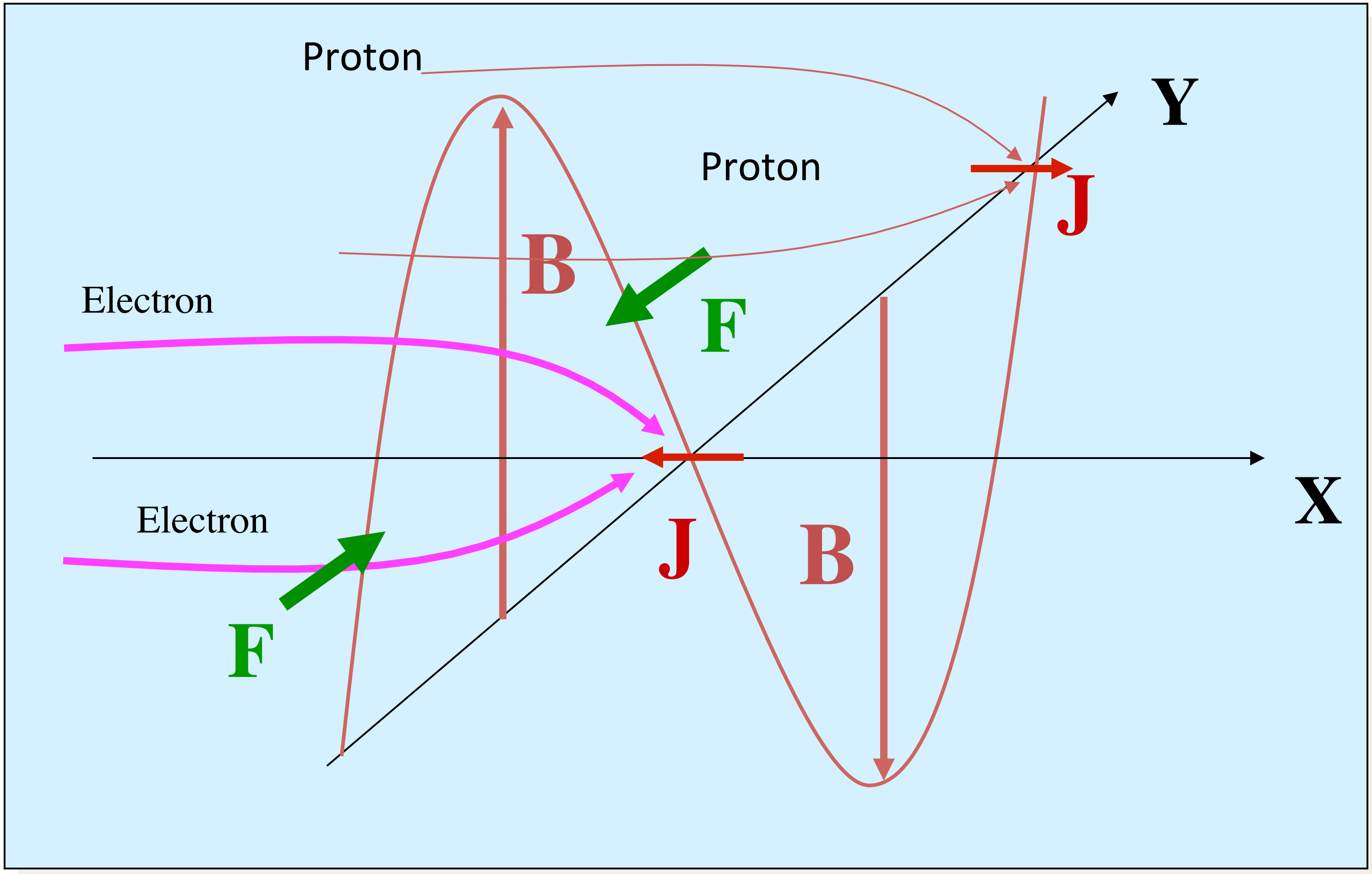
(b) SN1006（X-ray image)

(d)



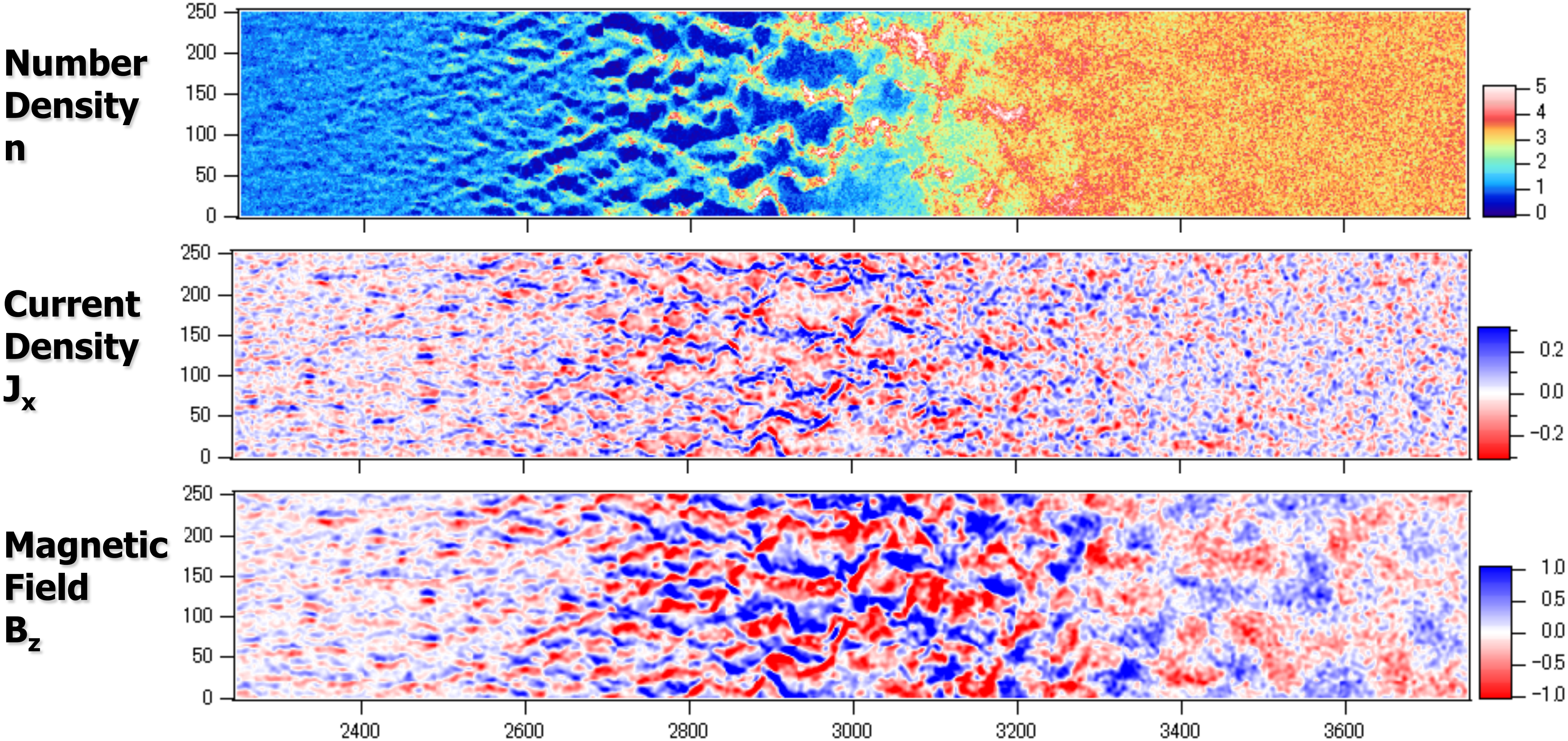
Chandra X-Ray Satellite

Weibel Instability



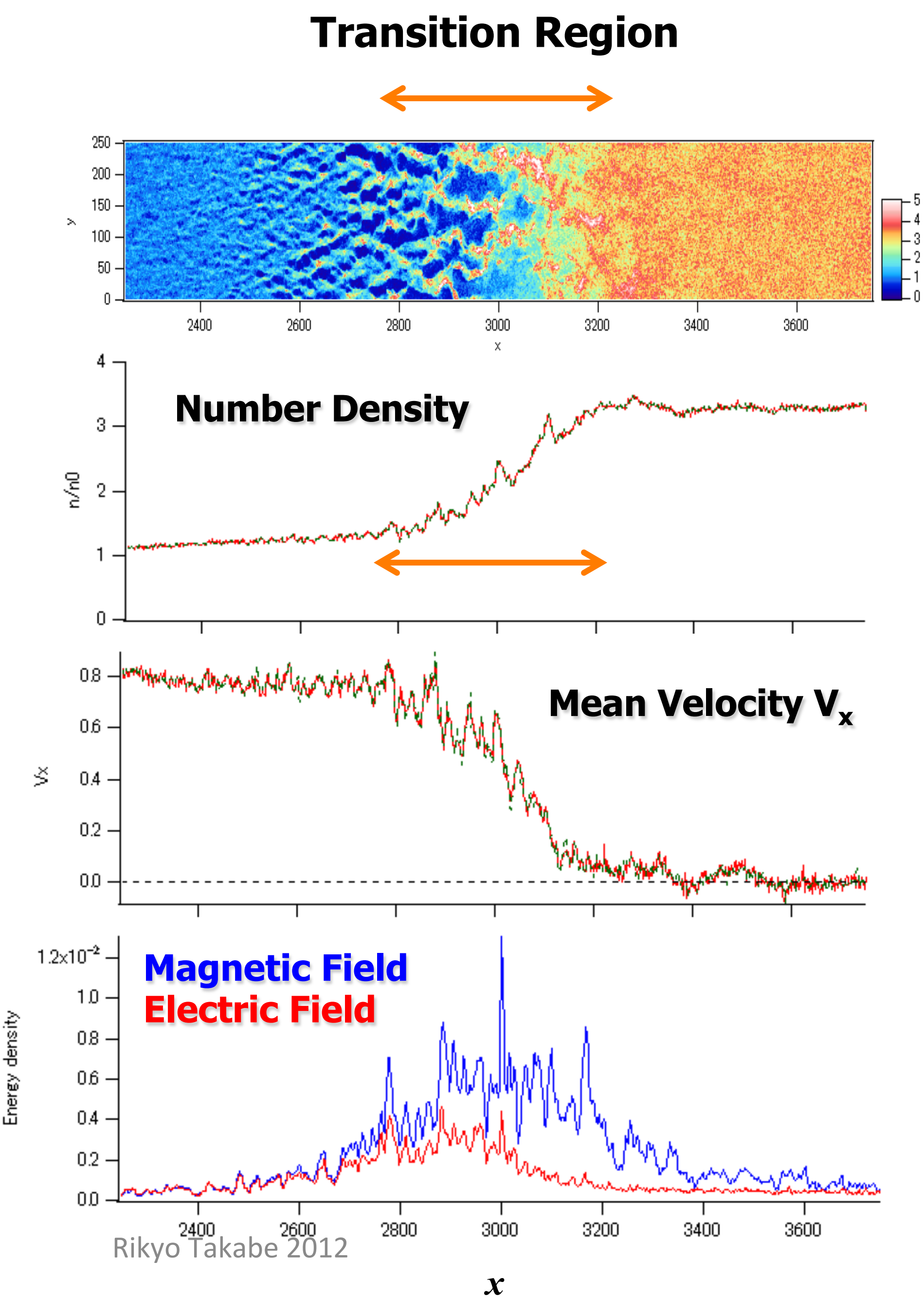
Lorentz Force: $\mathbf{F} = q\mathbf{v}\times\mathbf{B}$

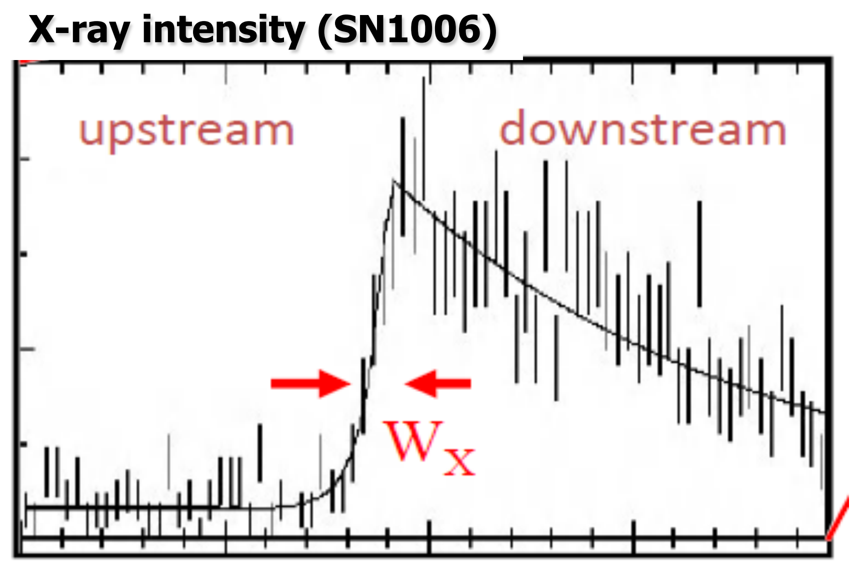
Generation of Magnetic Field



Current filaments generates strong magnetic fields within the transition region

Shock Wave Formation and Profiles

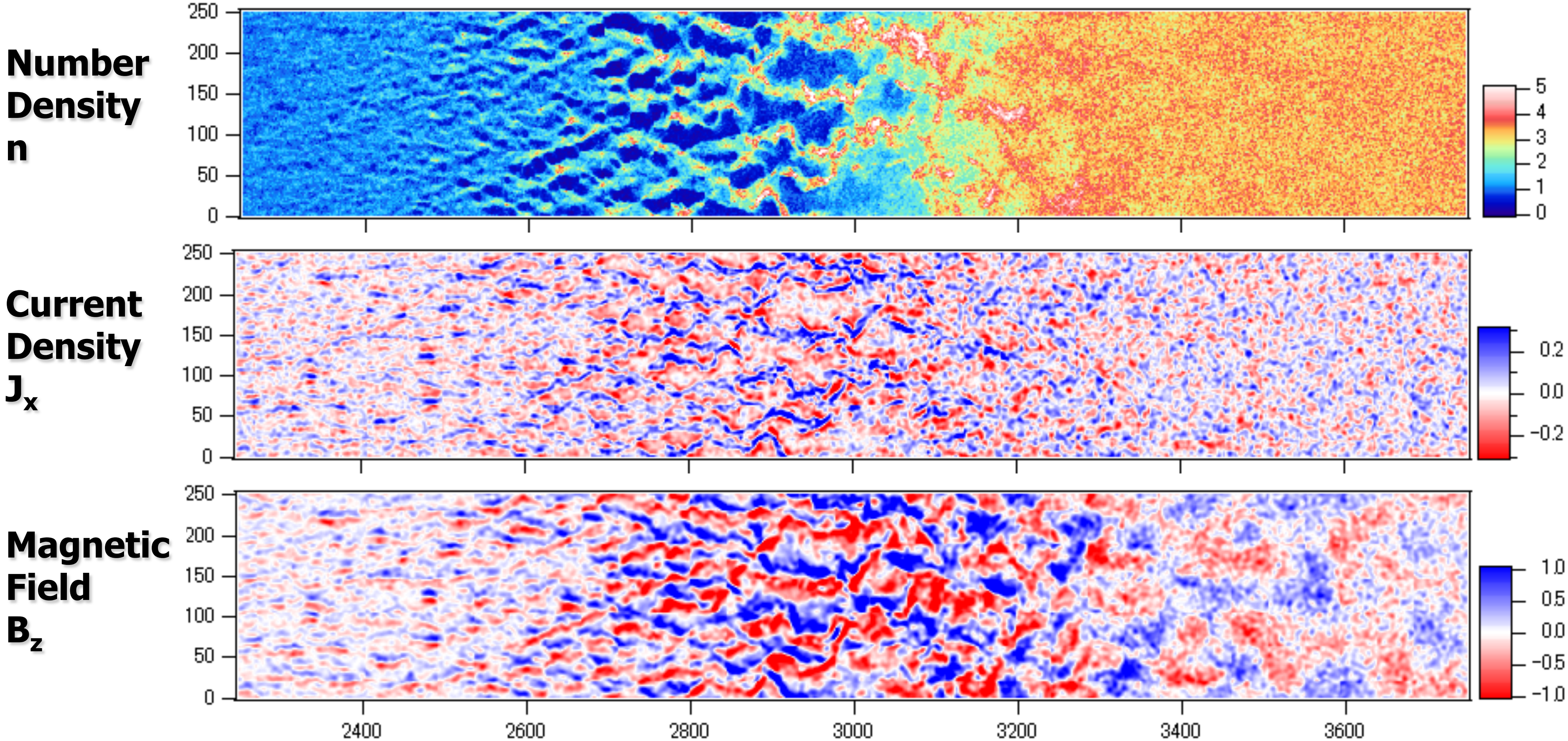




T. N. Kato

Magnetic Reconnection Plays Important Role for Shock Formation

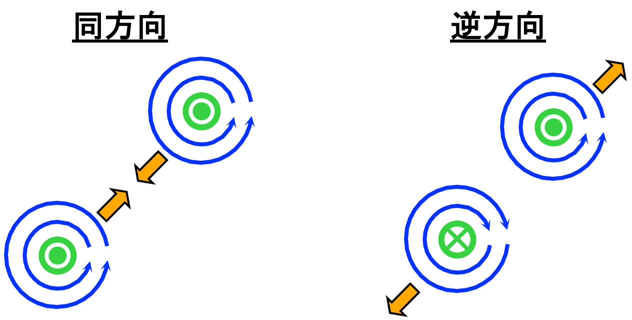
Generation of Magnetic Field



Current filaments generates strong magnetic fields within the transition region

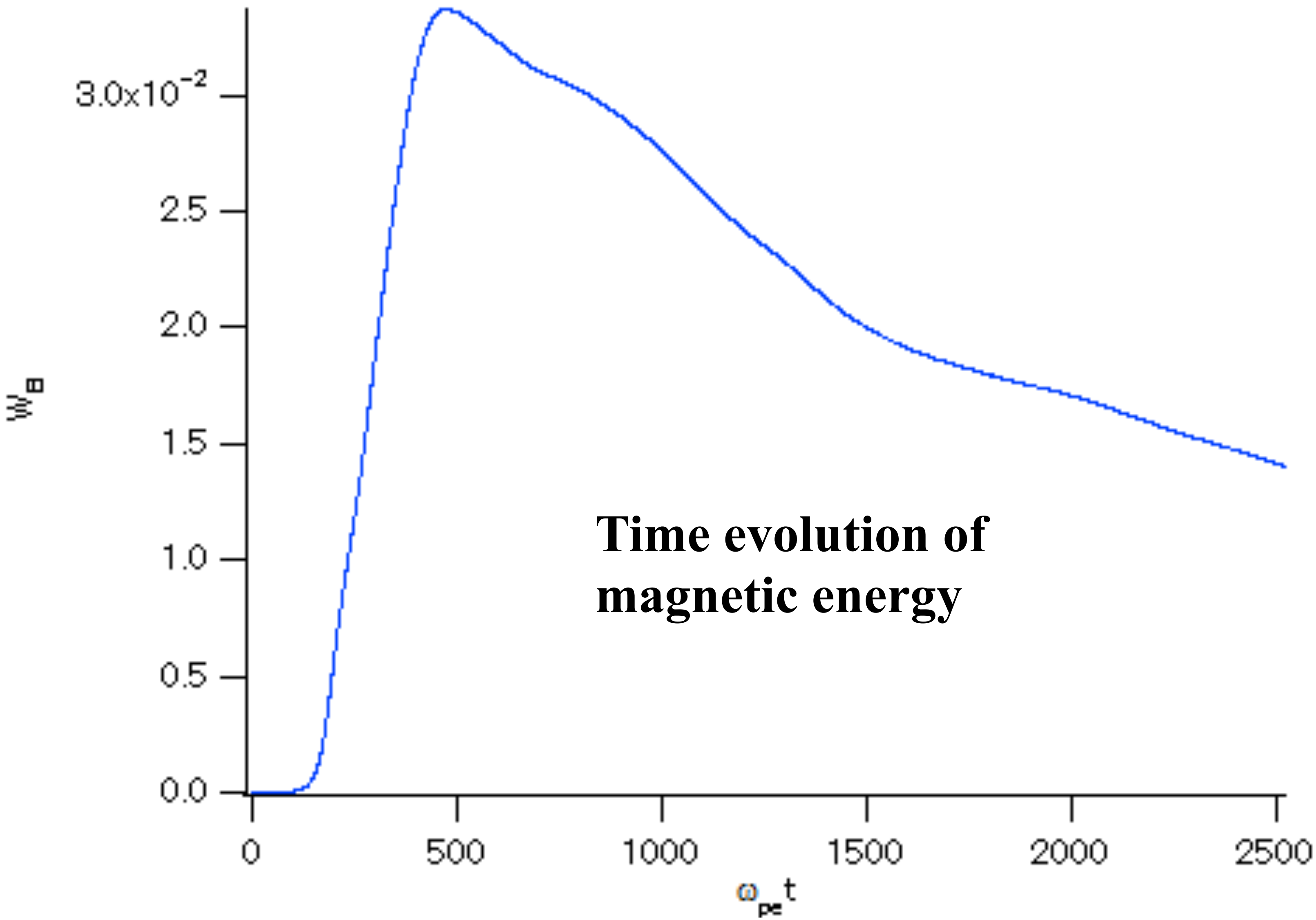
Evolution of Magnetic Structure

ビーム（電流）間に働く力



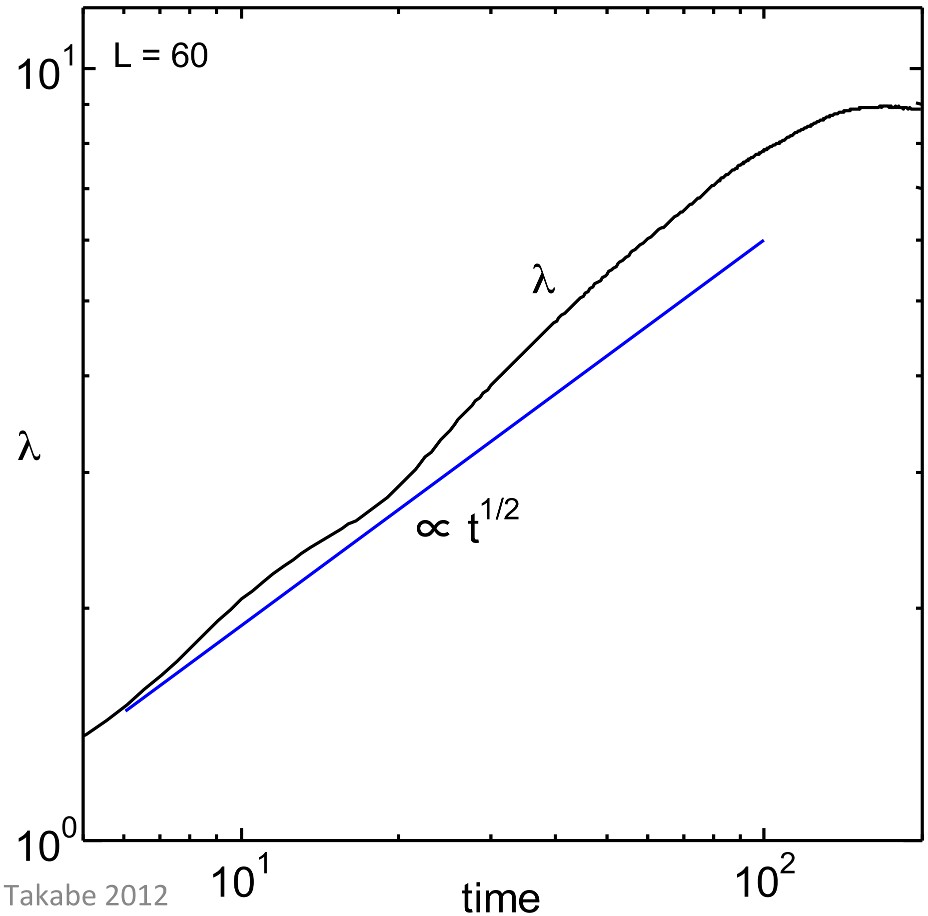
ビームの合体→より大きいスケールへ進化

平均波長のオーダー評価 → $\lambda \propto t^{1/2}$



Time evolution of magnetic energy

Time Evolution of Magnetic Scale



Averaging

$$\langle k^2 \rangle = \frac{\int k^2 P(k) dk^2}{\int P(k) dk^2}$$

として

$$\lambda = 2\pi / \sqrt{\langle k^2 \rangle}$$

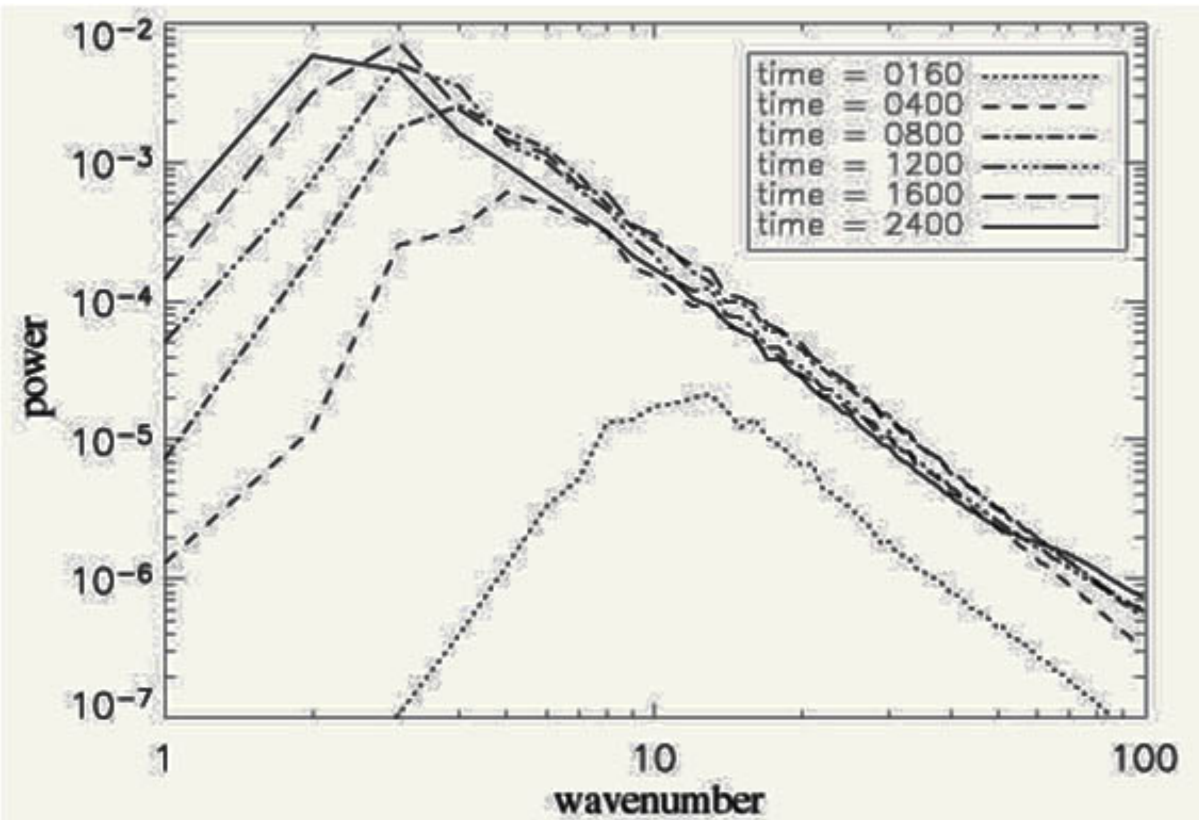
➡ t～100までは

に大体良く従う

（若干、成長率は大きい？）

$$\lambda \propto t^{1/2}$$

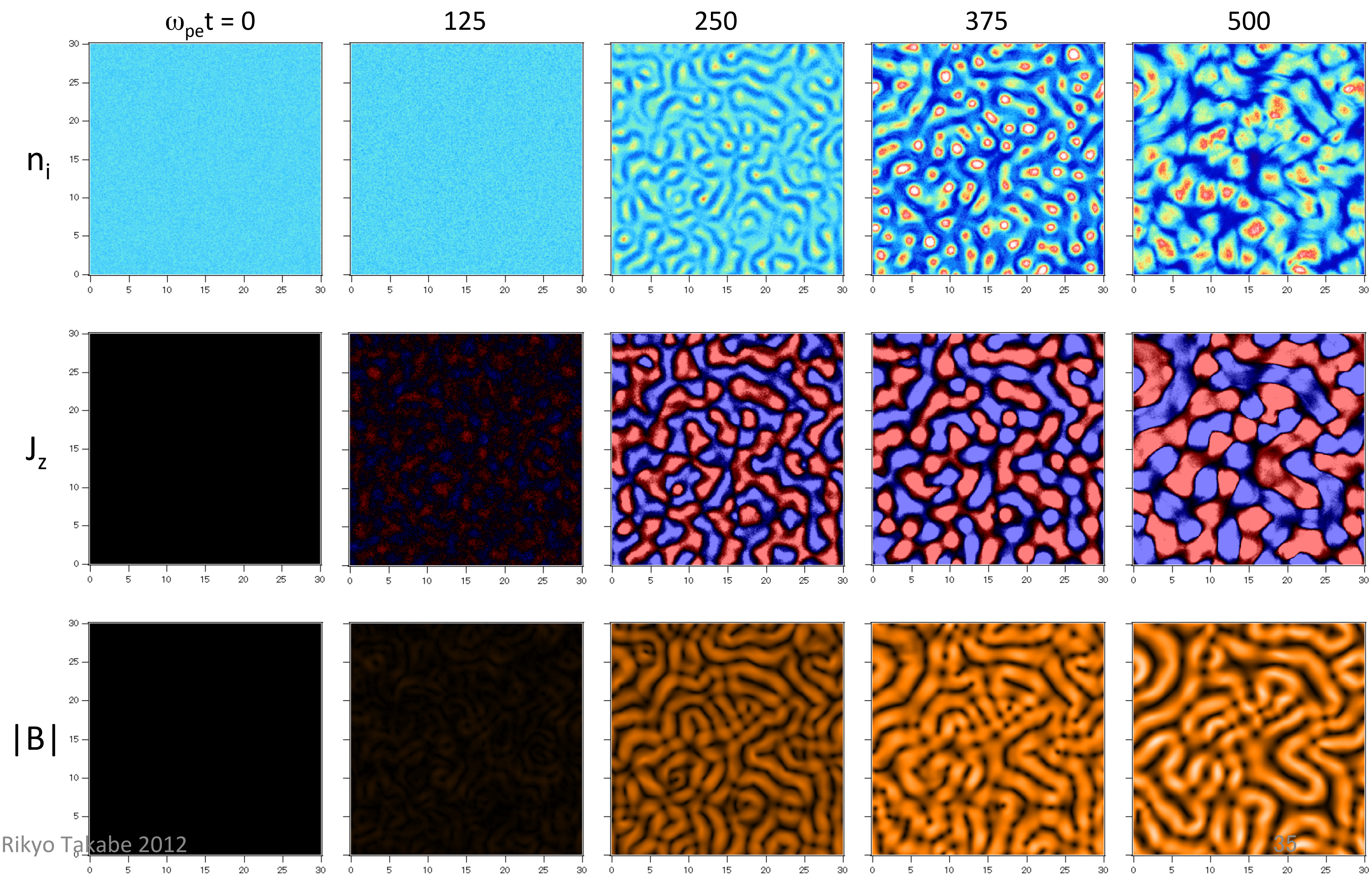
Power Spectrum of Magnetic Energy



- 特徴的な波数（ピークの位置）は、時間とともに**長波長側へ移動**する
- 特徴的波数より大きいところでは、**Power-law** 的になる
- Power-law型のエネルギースペクトルは、フェルミ加速で Power-law の高エネルギー粒子を作るために好都合

Evolution of Ion-beam-Weibel

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



Snaps of CCP2012

Memorial Photo


Super Computer : K Computer, Kobe, Japan


Banquet

3D PIC simulation of collision-less shock without ambient magnetic field

Simulation condition

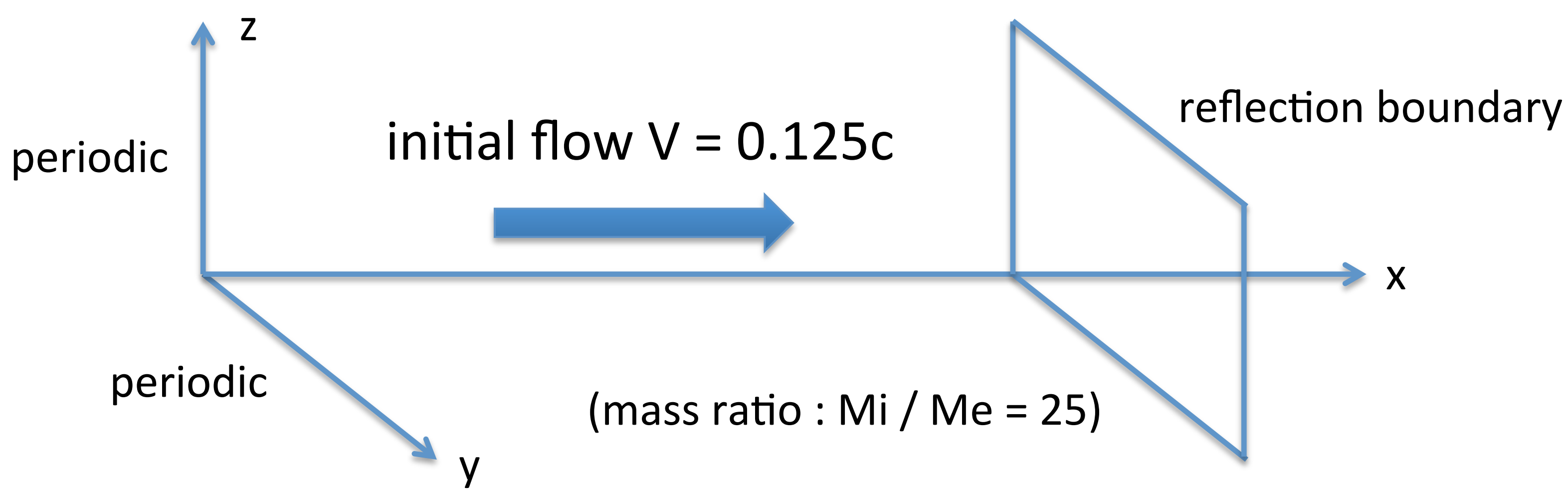
Δ : grid size, Se : electron inertia length, λ : Debye length

(x,y,z) = (4096Δ, 256Δ, 256Δ) = (692Se, 43Se, 43Se)

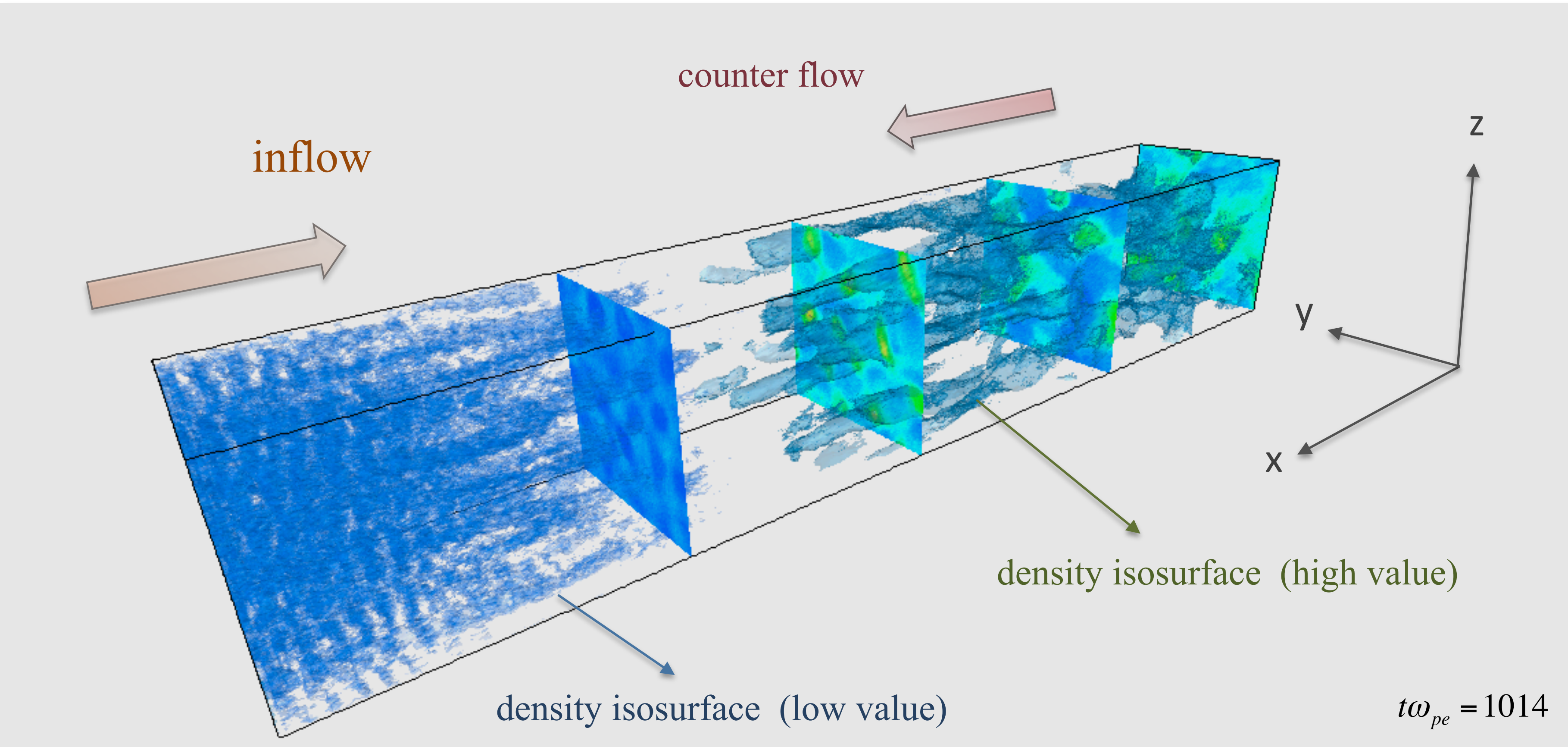
$\Delta = 2\lambda \sim Se/6$

48 × 2 particles / cell, ∼12.8×2 billion in total

1024 nodes (8192 cores), 7.5 hour in K-computer



Filament structures of plasma density



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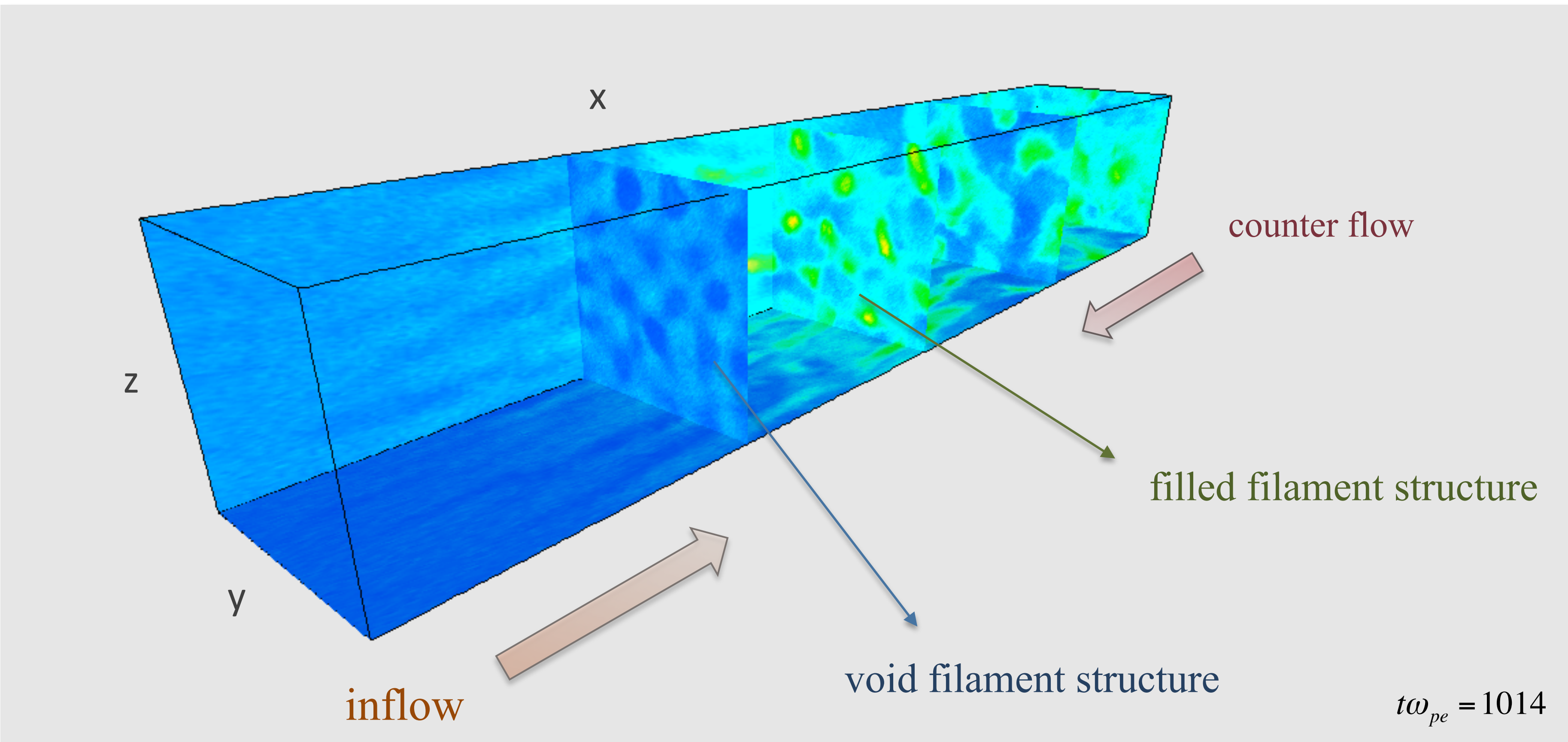
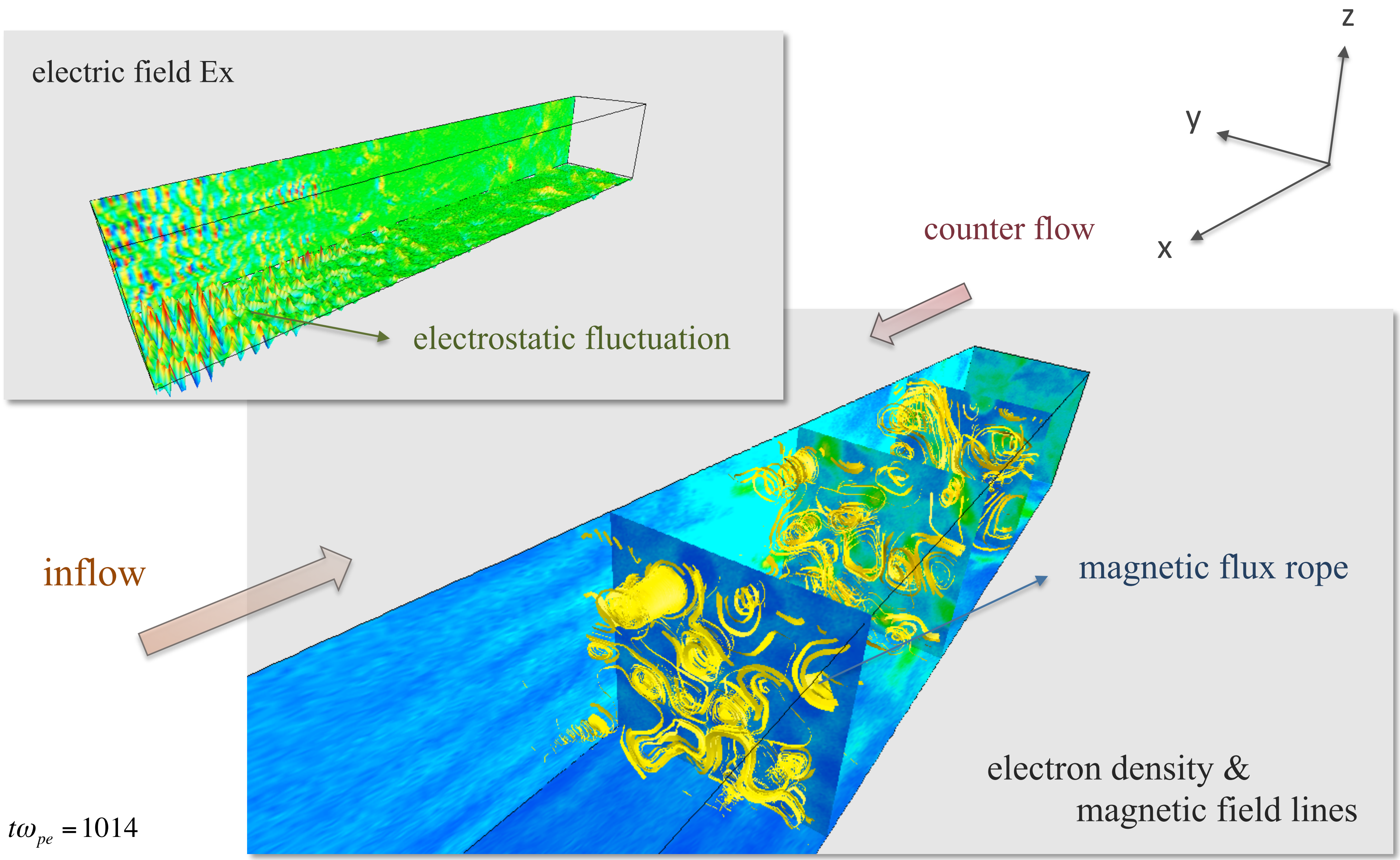
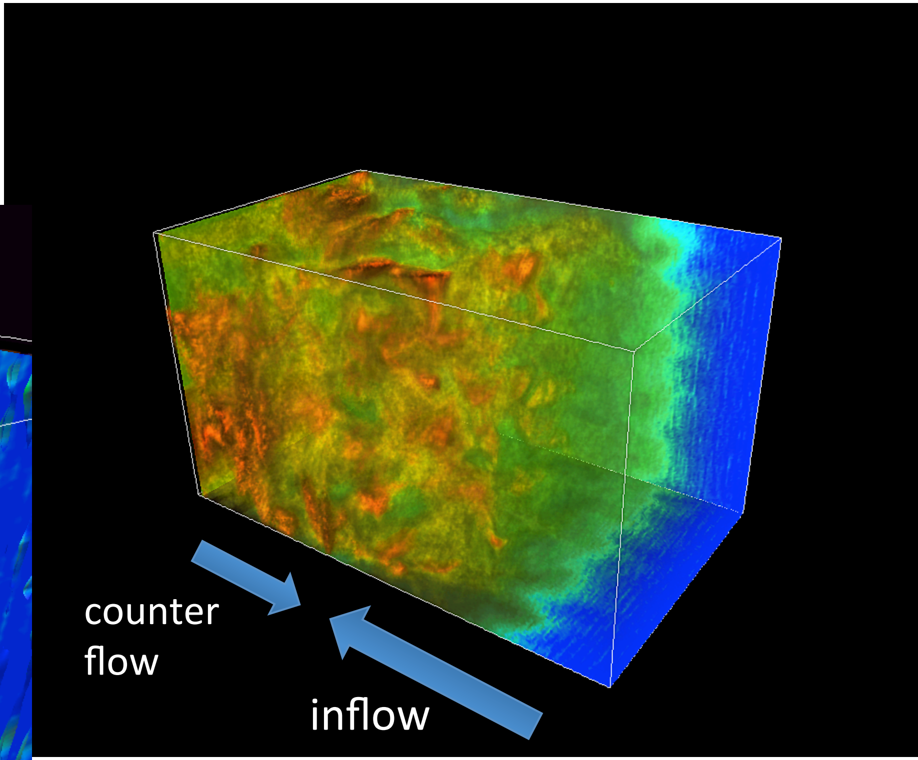


Fluctuations of electromagnetic field

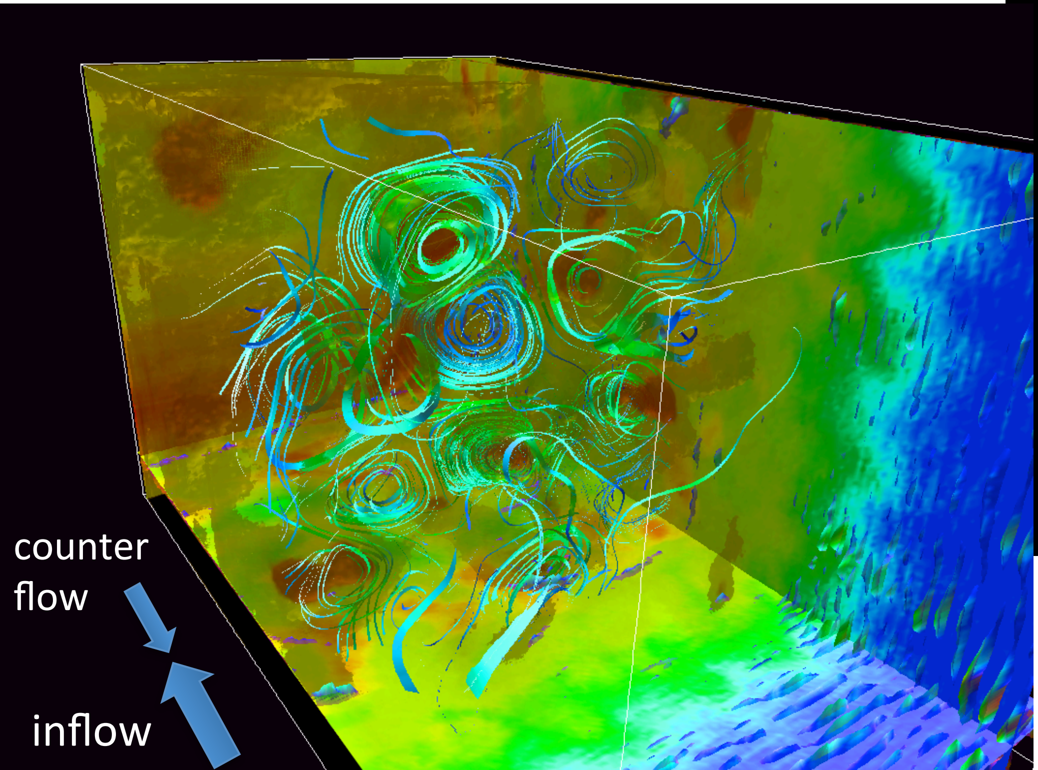


Bird's eye view in shock surface

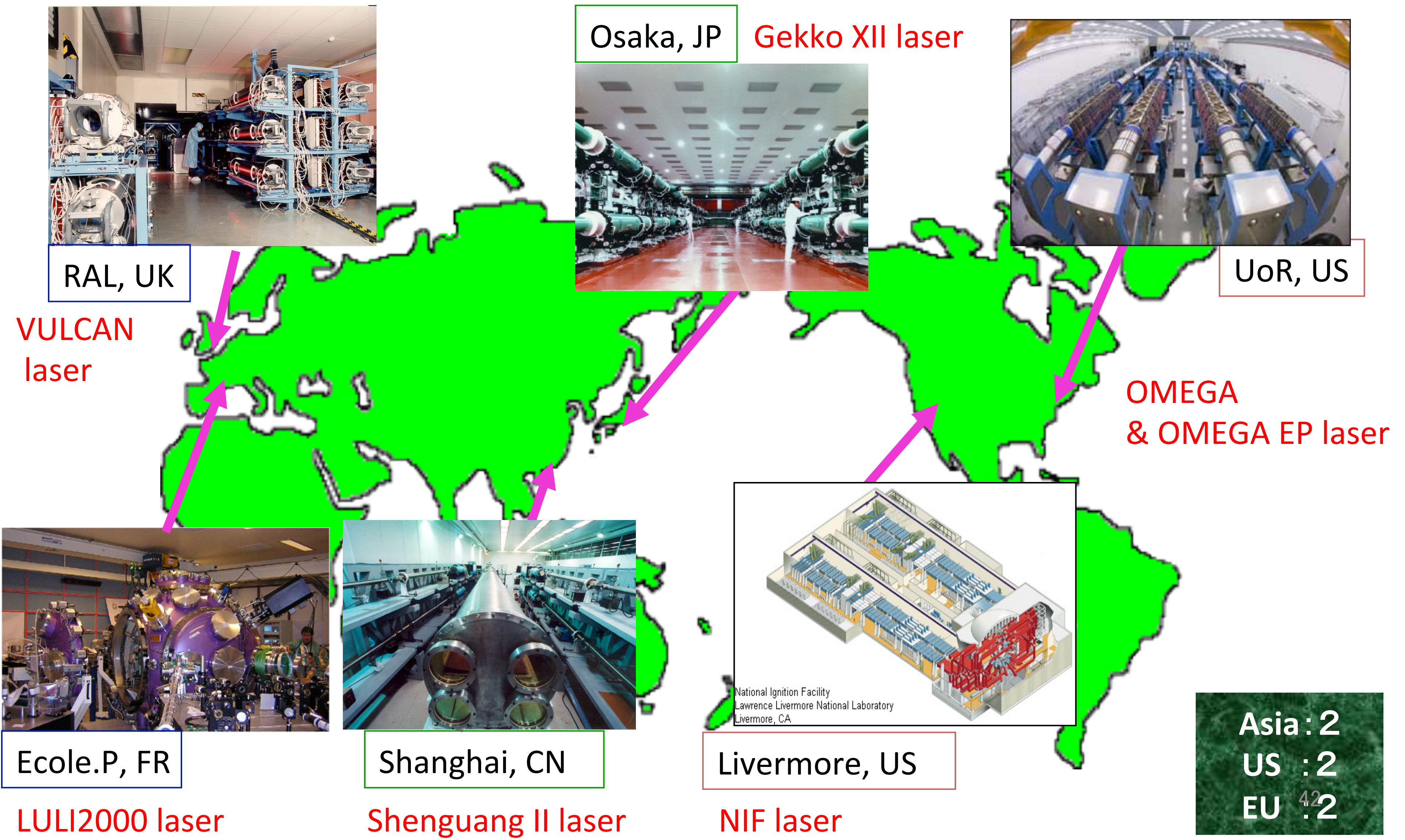
turbulence in electron density



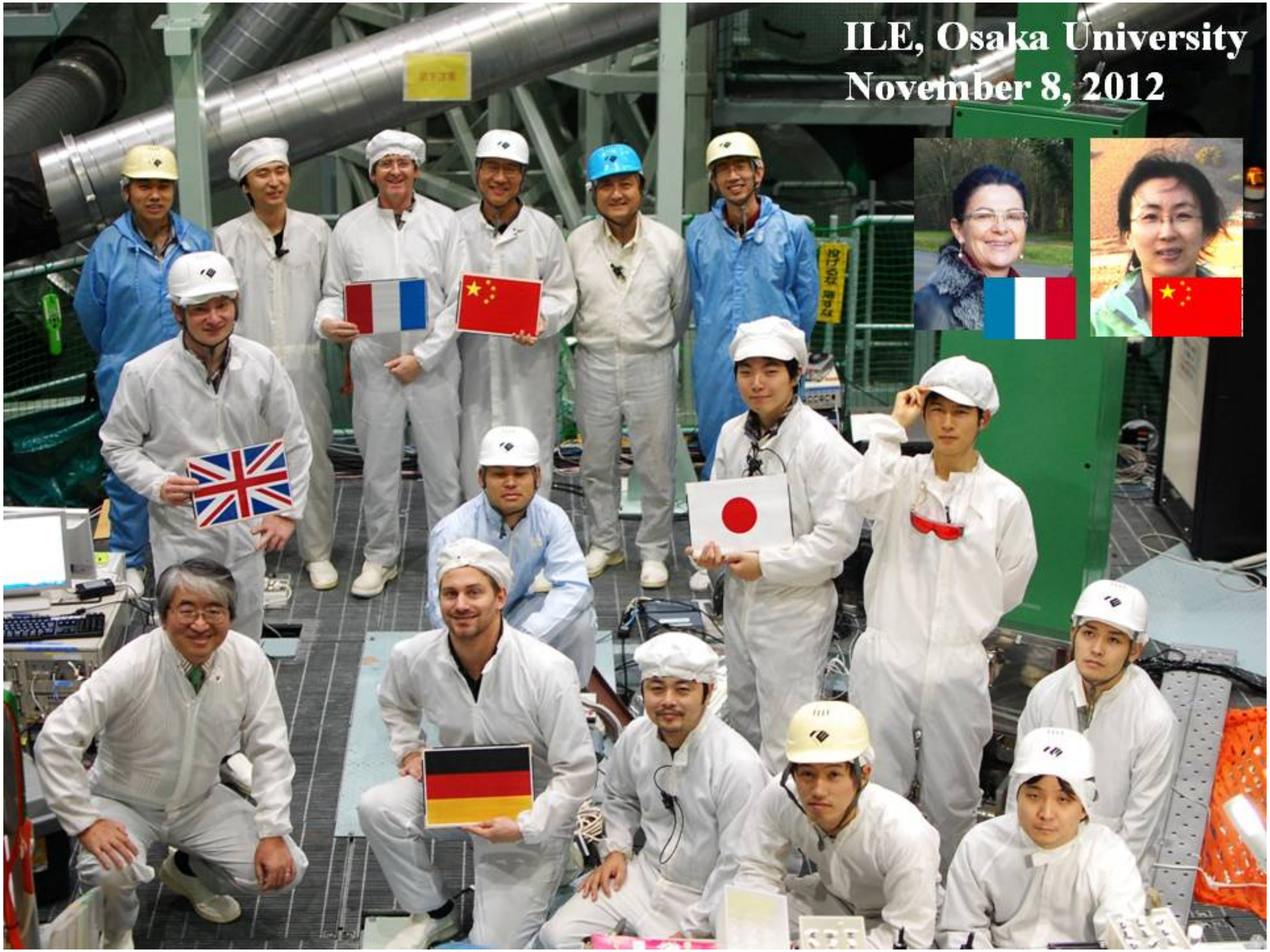
Filament-like structure of magnetic flux rope



Collaboration experiments using high-power lasers in the world



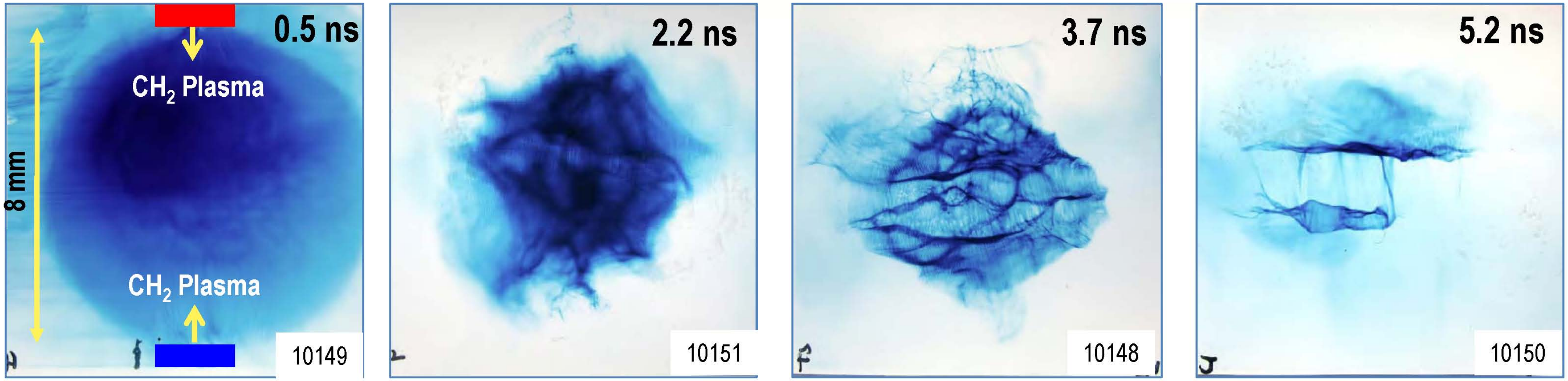
International Joint Experiment (Magnetic reconnection, Radiative shocks, Collisionless shocks)



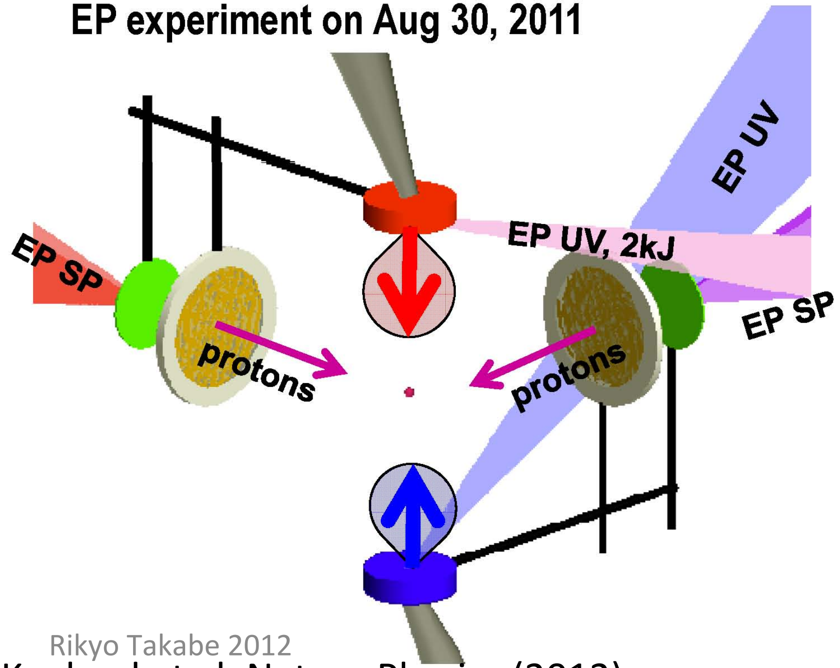
International Collisionless Experiment Group on OMEGA and NIF (ACSEL team)

Together Photo at APS-DPP at Chicago, November 19, 2010

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



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

Rikyo Takabe 2012

N. Kugland et al. Nature Physics (2012)

PHYSICS OF PLASMAS **20**, 032703 (2013)

Magnetic field advection in two interpenetrating plasma streams

D. D. Ryutov, N. L. Kugland, M. C. Levy, C. Plechaty, J. S. Ross, and H. S. Park
Lawrence Livermore National Laboratory, Livermore, California 94551, USA

(Received 20 December 2012; accepted 11 February 2013; published online 6 March 2013)

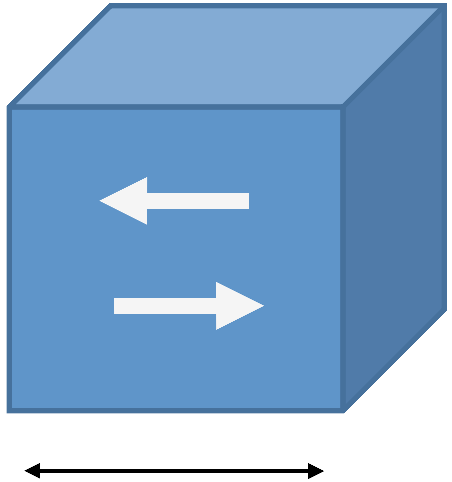
Laser-generated colliding plasma streams can serve as a test-bed for the study of various astrophysical phenomena and the general physics of self-organization. For streams of a sufficiently high kinetic energy, collisions between the ions of one stream with the ions of the other stream are negligible, and the streams can penetrate through each other. On the other hand, the intra-stream collisions for high-Mach-number flows can still be very frequent, so that each stream can be described hydrodynamically. This paper presents an analytical study of the effects that these interpenetrating streams have on large-scale magnetic fields either introduced by external coils or generated in the plasma near the laser targets. Specifically, a problem of the frozen-in constraint is assessed and paradoxical features of the field advection in this system are revealed. A possibility of using this system for studies of magnetic reconnection is mentioned. [http://dx.doi.org/10.1063/1.4794200]

We Need National Ignition Facility to Demonstrate our Physics Scenario

Scaling Laws from PIC Simulations

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

$$E = 1/2 Z m_p n_i V^2 L^3$$
$$= 35\ \mathrm{kJ}$$

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

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

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

David Arnett*, University of Arizona
Riccardo Betti, University of Rochester
Roger Blandford, Stanford University
Nathanial Fisch, Princeton University
Ramon Leeper, Sandia National Lab.
Christopher McKee, UC Berkeley

Mordecai Rosen, LNL
Robert Rosner, The Univ. of Chicago (Chair)
John Sarrao, Los Alamos National Laboratory
Hideaki Takabe, ILE, Osaka University
Justin Wark, University of Oxford
Choong-Shik Yoo, Washington State University

Collisionless Shock Experiment with NIF

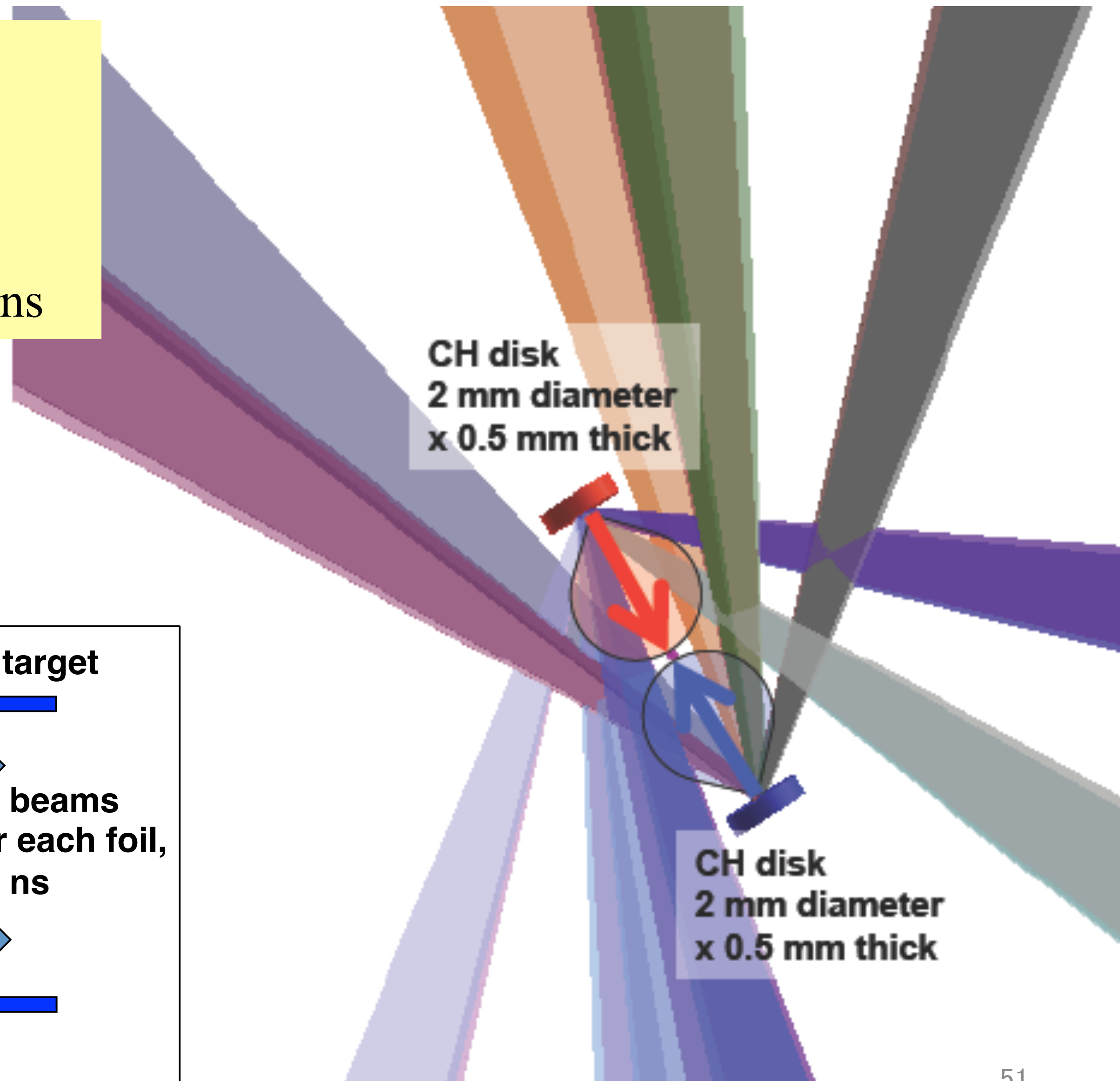
Drive beam

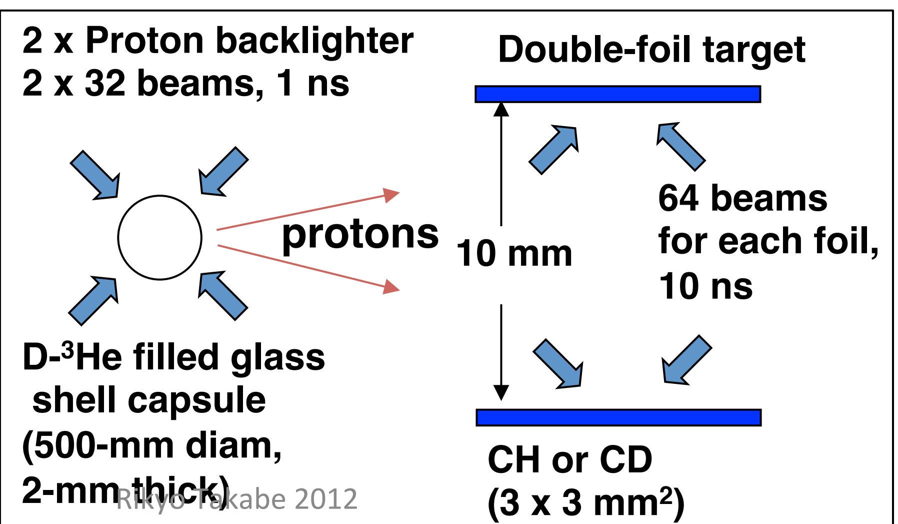
10 kJ/ beam x 64 beams

for each foil, 10 ns

D-He^3 implosion beam

1.5 kJ / beam x 64 beams, 1 ns





We have to know the Fundamental Physics of Magnetic Reconnection

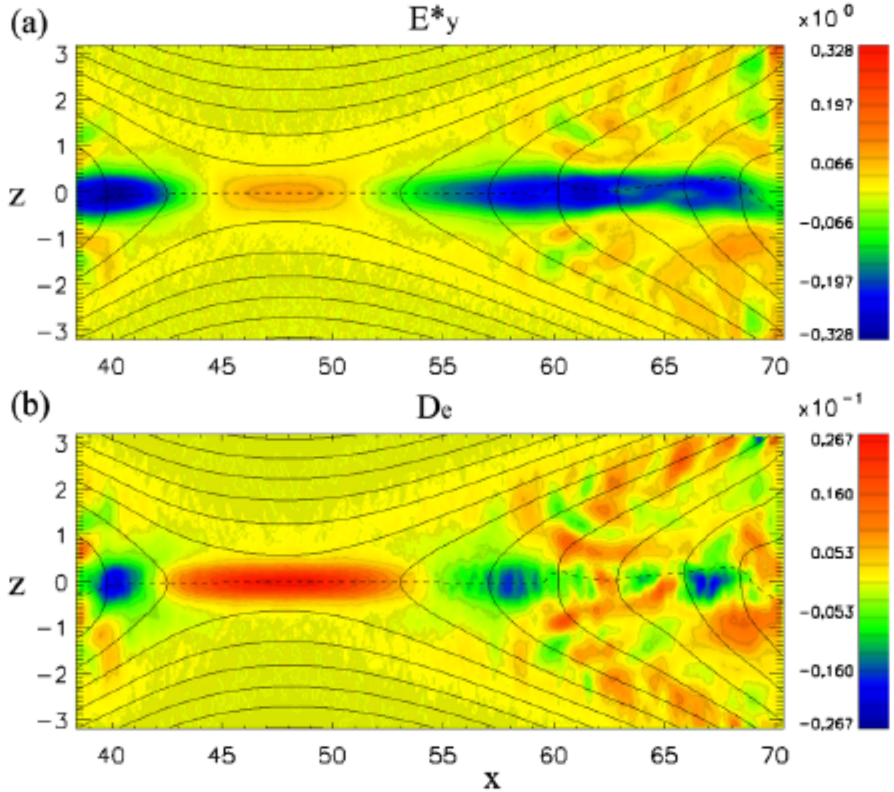
Y. Kuramitsu[1], Y. Sakawa[1], T. Morita[1], H. Tanji[2], T. Ide[2],
K. Nishio[3], C. D. Gregory[4], J. N. Waugh[5], A. Pelka[4],
A. Ravasio[4], M. Koenig[4], N. Woolsey[5],
T. Moritaka[1], K. Tomita[6], K. Uchino[6],
M. Hoshino[7] , and H. Takabe[1]

[1] Institute of Laser Engineering, Osaka University
[2] Graduate School of Engineering, Osaka University
[3] Graduate School of Science, Osaka University
[4] Laboratoire pour l'Utilisation des Lasers Intenses, Ecole Polytechnique, France
[5] Department of Physics, University of York, UK
[6] Interdisciplinary Graduate School of Engineering Sciences, Kyushu University
[7]Department of Earth and Planetary Science, University of Tokyo

Laboratory experiment

- Controllable conditions:
  flow velocity, density, external field...
- Passive imaging
- Active imaging
- Electromagnetic field
- Energy distribution function
- Local observations

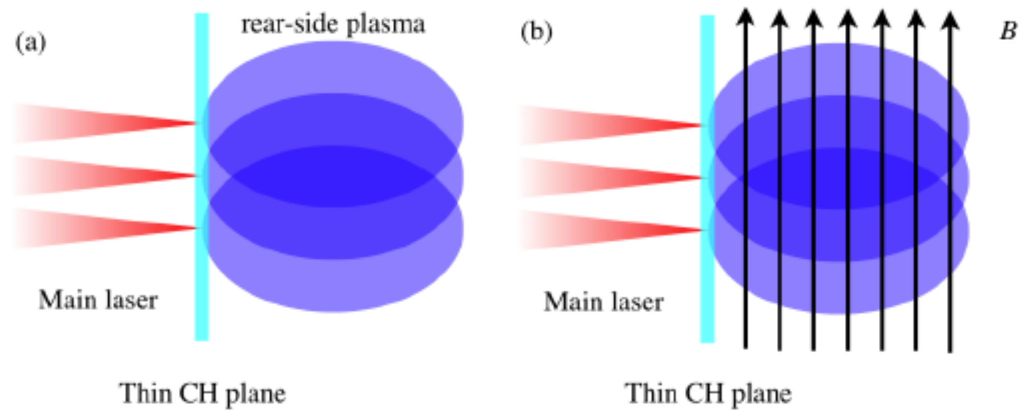
Magnetic reconnection



Electron scale dissipation region [Zenitani 2011 PRL]

Jet formation in the presence of an external magnetic field

- GXII
  - 4 beams, 500 J, 500 ps
  - offsets 200 - 300 μm for directional expansion
- Single CH plane target 10 μm
- External magnetic field
  - a permanent magnet ~ 0.7 T at the surface
  - perpendicular to the plasma axis
- Target environment: vacuum



Plasma parameters

- plasma velocity $v_i \sim 500$ km/s
- magnetic field $B \sim 0.3$ T
- electron density $n_e = Zn_i \sim 10^{19}$ cm^{-3}
- dynamic plasma beta $n_i m_i v_i^2/(B^2/\mu_0) \sim 1.1\text{x}10^5$
- ion gyroradius ~ 32 mm

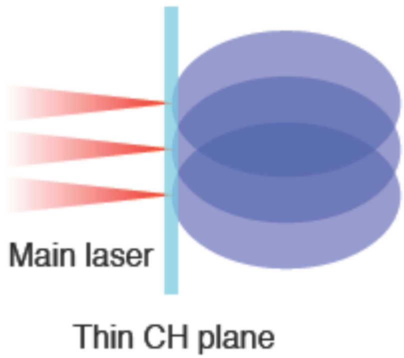
➡larger than our system size of ~ 10 mm

- electron gyroradius ~ 9.5 μm

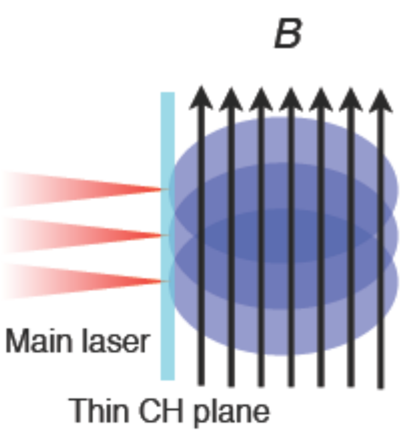
➡electron magnetized

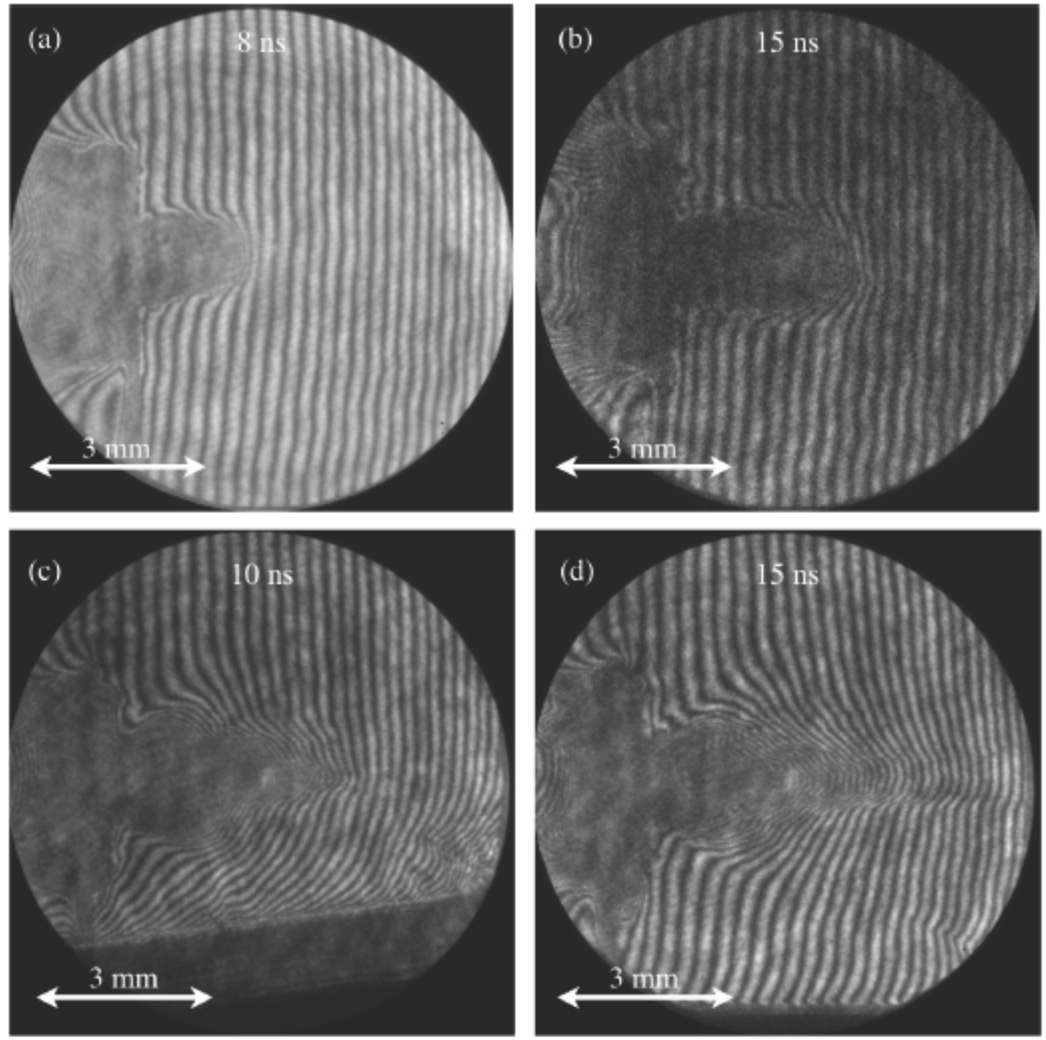
Interferograms

Without an external magnetic field



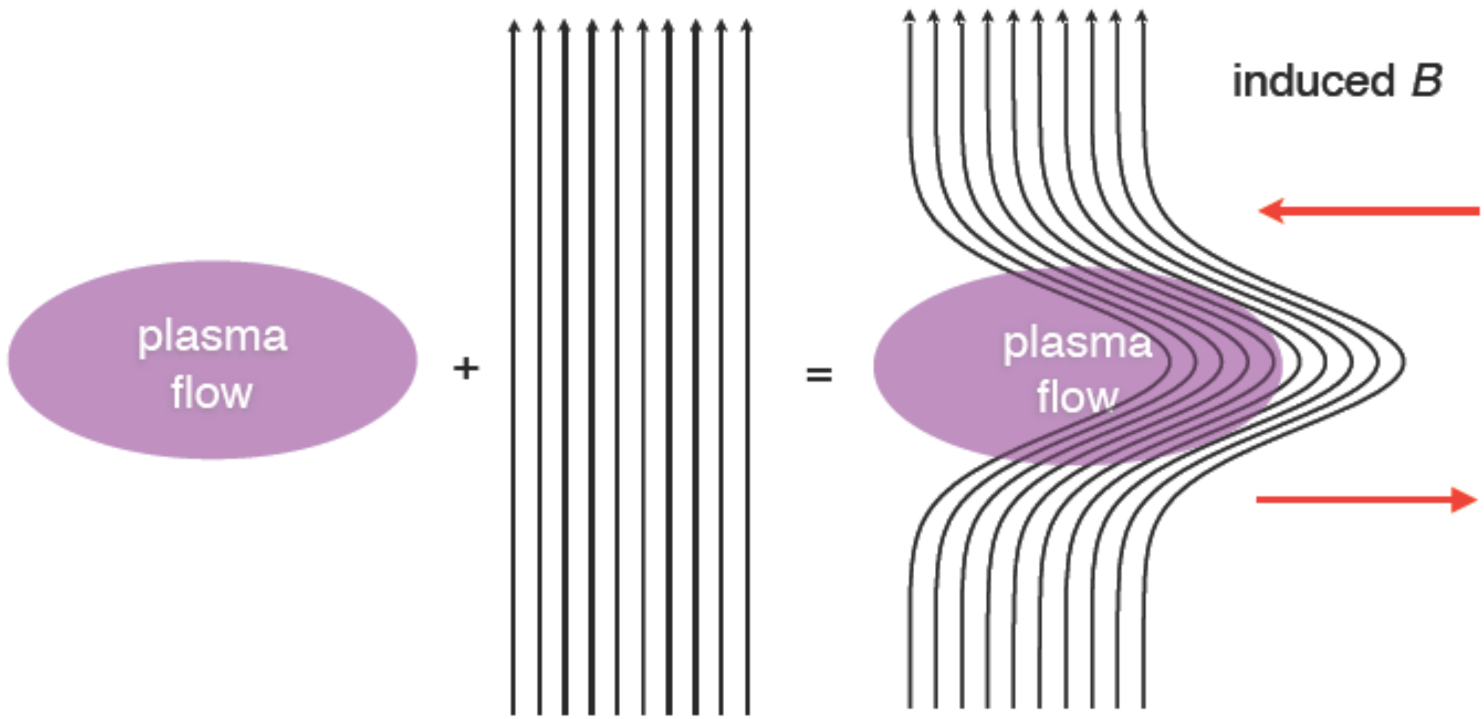
With an external magnetic field





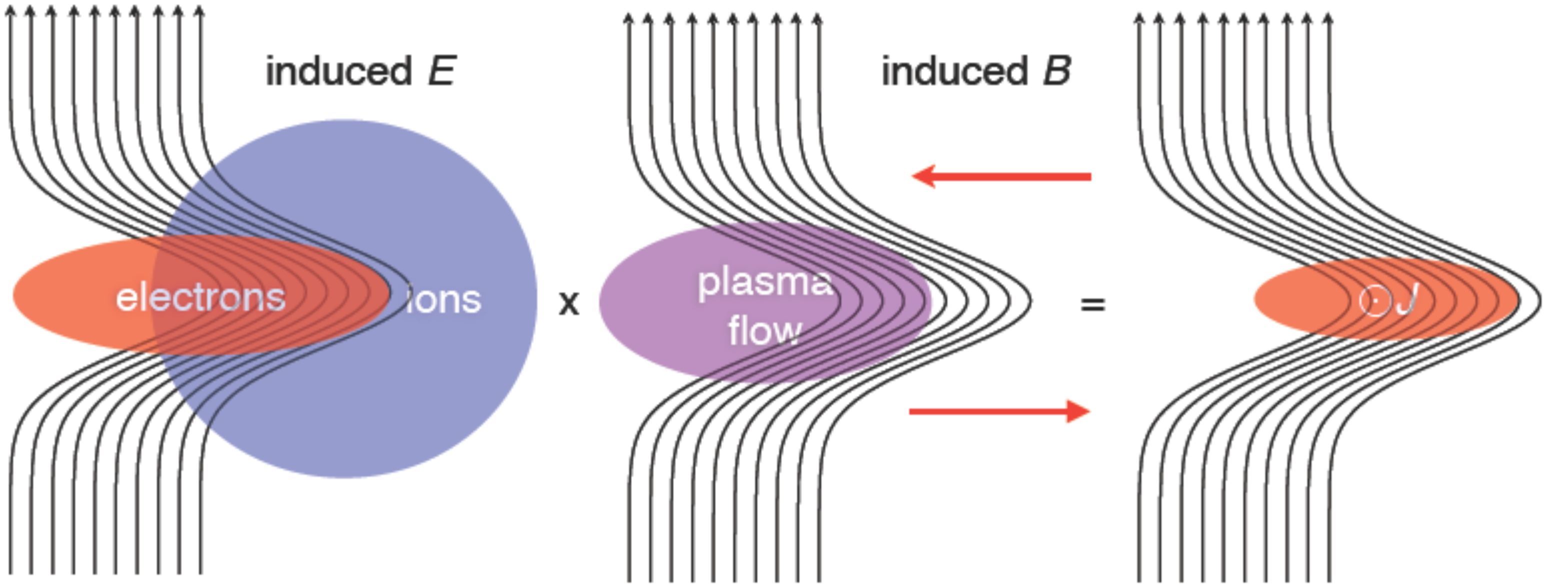
Collimation observed only when B exist.

Possible mechanism



1. Field distortion by strong dynamic pressure resulting in local parallel field.

Possible mechanism



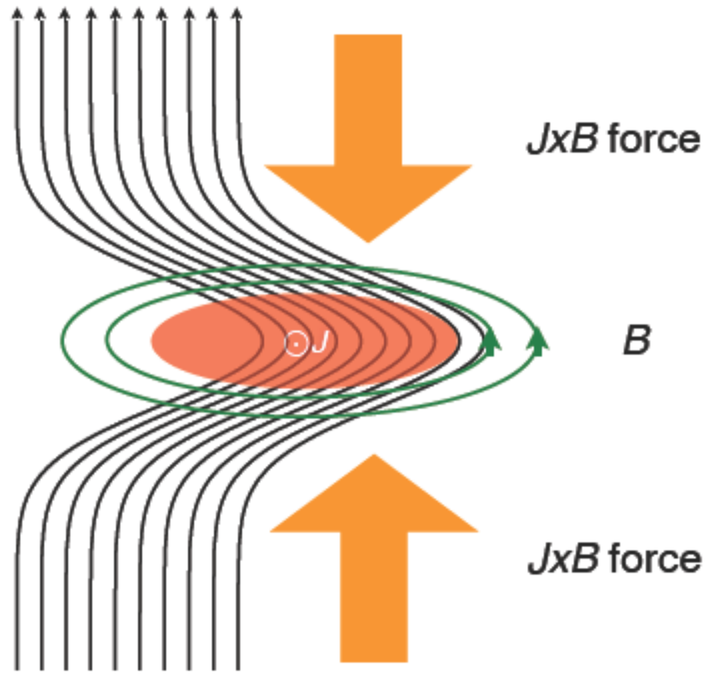
2. Charge separation due to the electron trapping by the field.

➡E field across the distorted B field

3. *ExB* drift **only for electrons**

➡Current formation

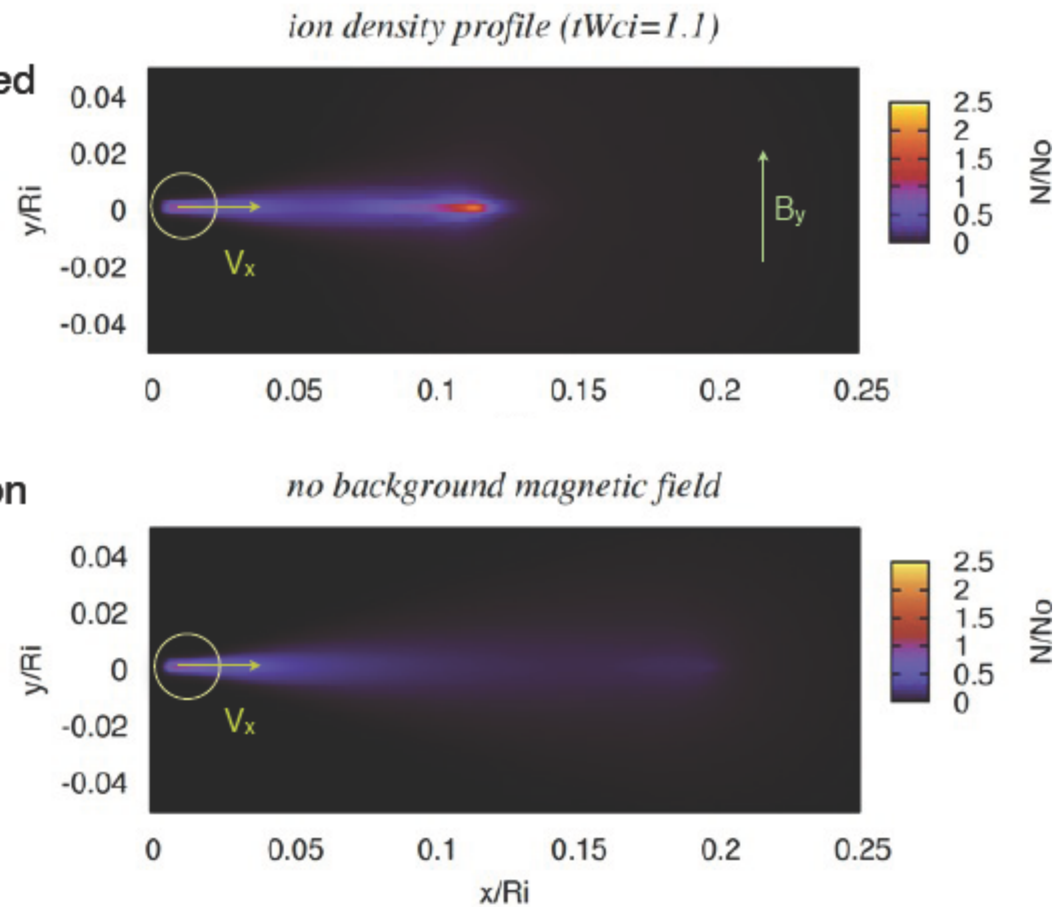
Possible mechanism



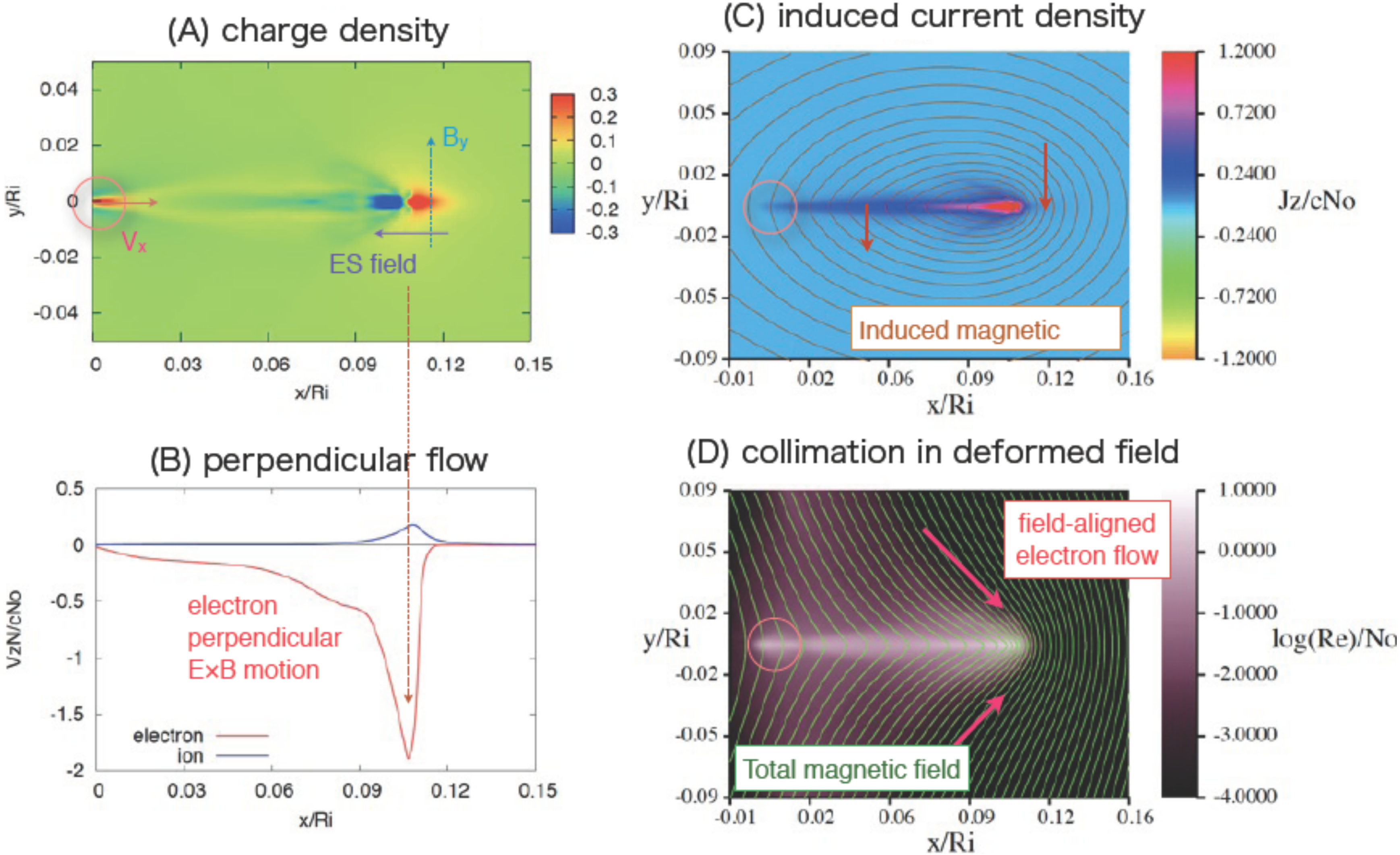
- ➡ *JxB* enhances the collimation
- ➡ *J* generates *B* field, enhancing the distortion
- ➡ Positive feedback

Particle-in-Cell simulation

- Plasma Injection $+V_x$
  - Injection velocity > thermal speed
    - $V_x/V_{te} = 2.2$, $V_x/V_{ti} = 11$
  - High beta value
    - $\beta \sim 500$ (finite B case)
- External magnetic field $+B_y$
  - perpendicular to plasma injection
  - spatially uniform
- Numerical parameters
  - $\sim 10^8$ particles
  - (1024×1024) uniform grid



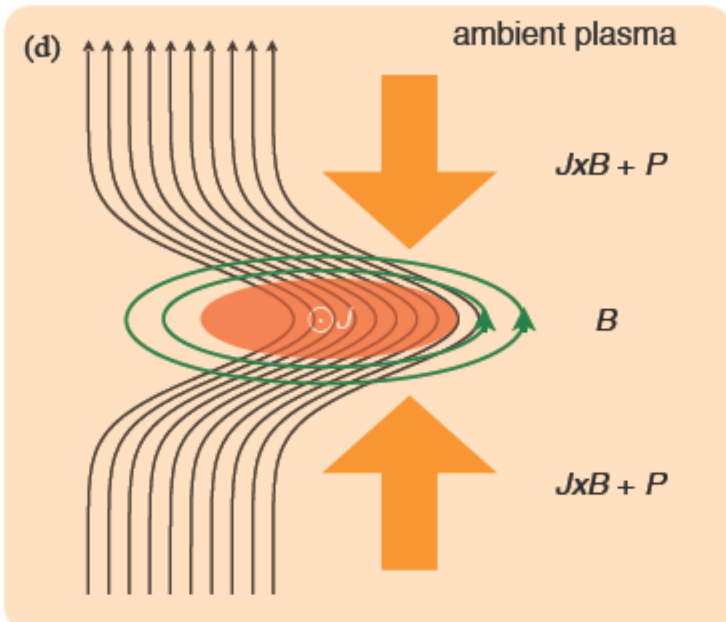
Particle-in-Cell simulation



Electron dynamics governs the global structure!

One interesting application is reconnection.

Ambient plasma



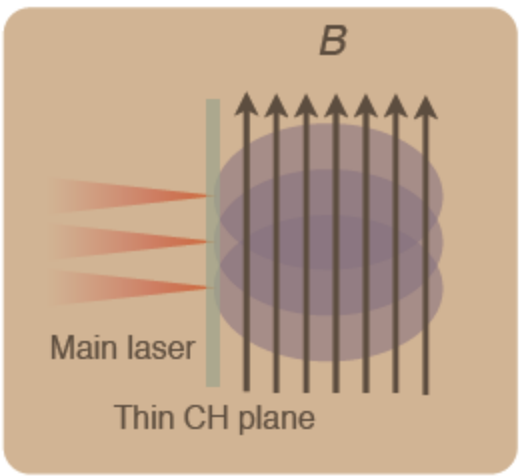
Reconnection?

4. Adding an ambient plasma enhances the field distortion and plasma collimation by the external pressure.

➡ Thinning the structure may result in reconnection.

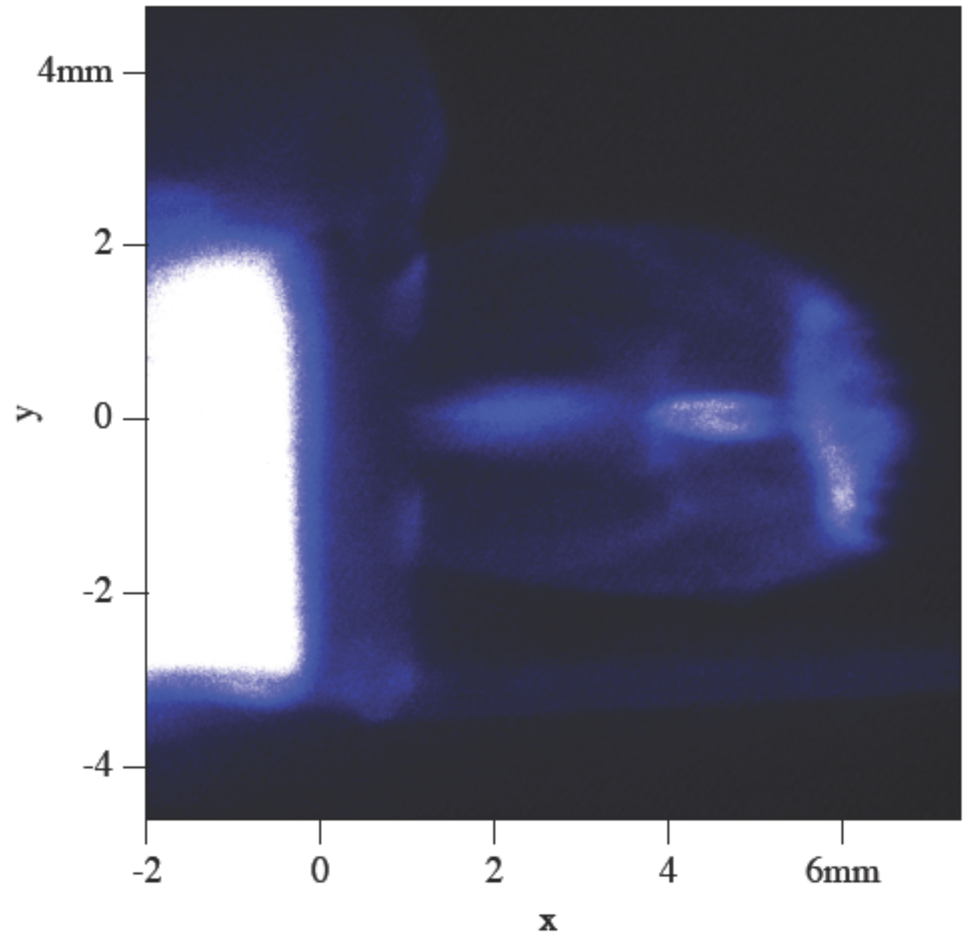
Experiment (preliminary)

External B and P



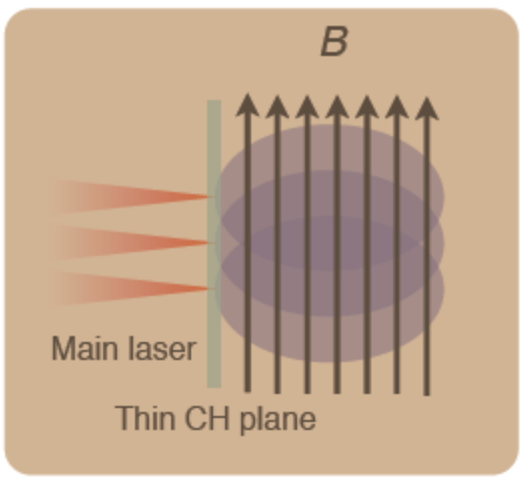
Ambient plasma

self emission 35 ns



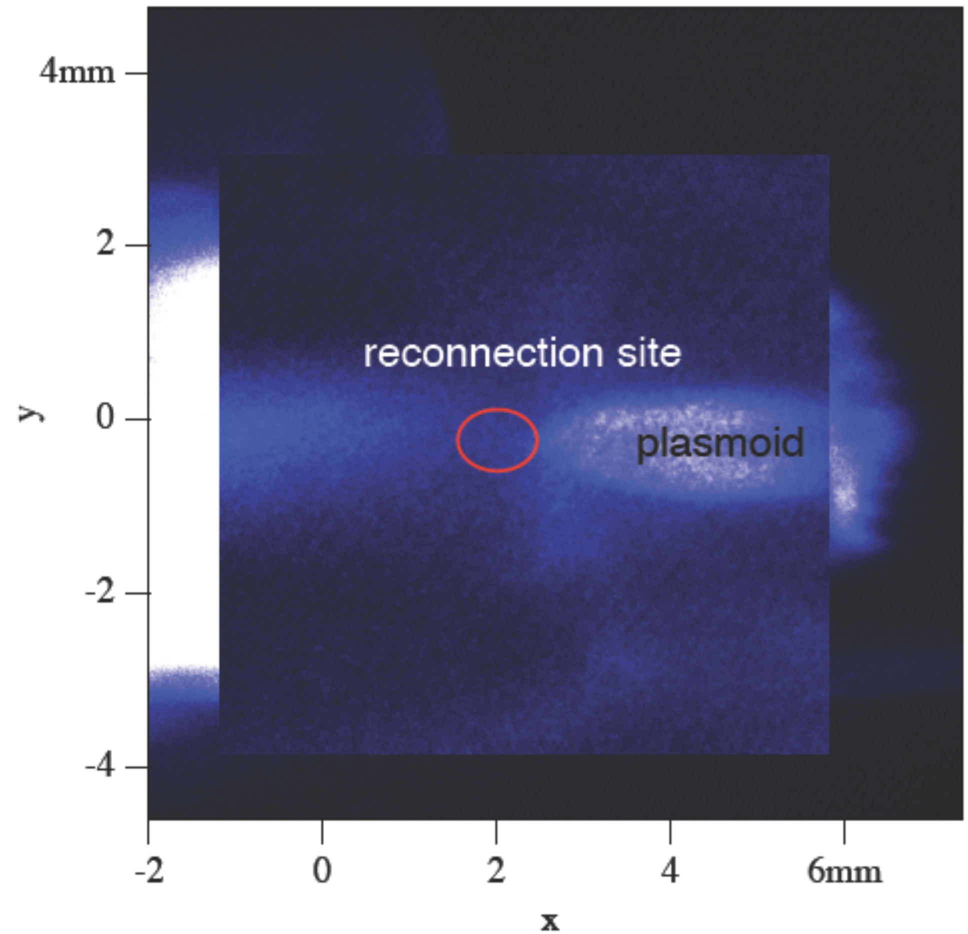
Experiment (preliminary)

External B and P



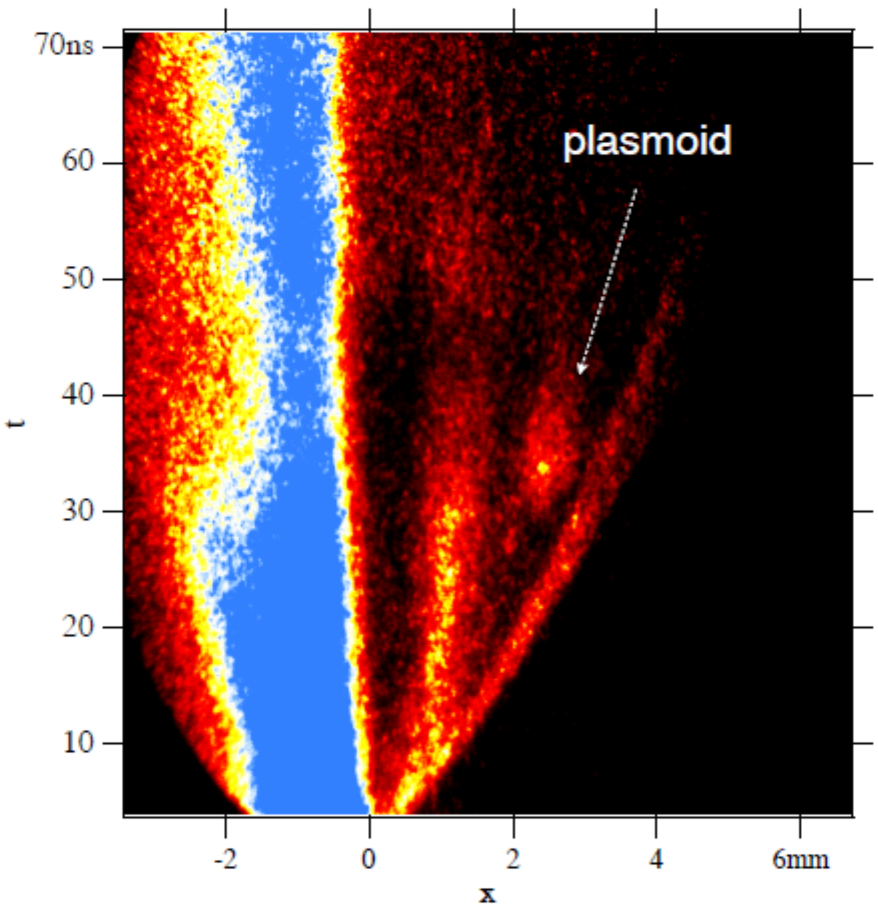
Ambient plasma

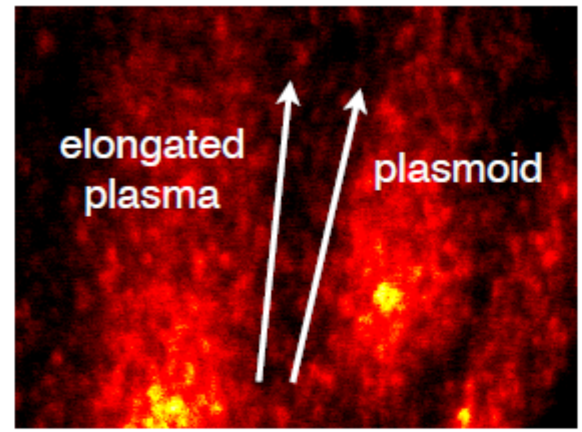
self emission 35 ns



Experiment (preliminary)

self emission optical pyrometry

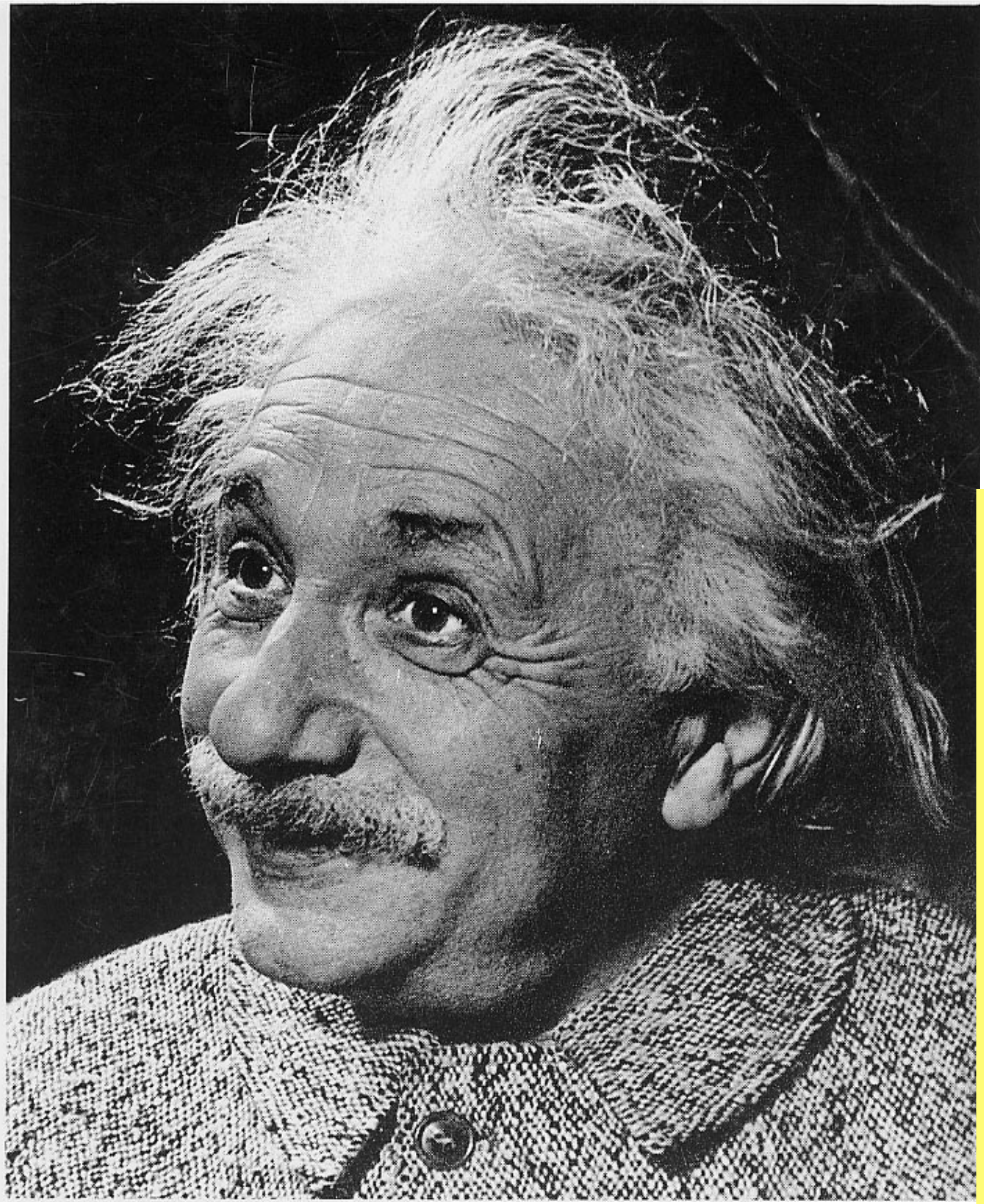




- separation velocity
  $\Delta v \sim 26$ km/s
- initial Alfvén velocity
  $c_{Ai} \sim 1.5$ km/s
  $c_{Ae} \sim 60$ km/s
- $c_{Ai} < \Delta v/2 < c_{Ae}$

Summary

- Jet formation in the presence of a weak magnetic field
- First experimental evidence of electron dynamics governing the global structure
- Electron scale reconnection



"Imagination is more important than knowledge"

Albert Einstein

International Collaboration on Simulation and Experiments give us unexpected Imagination. The Mixture of Human is essential for Imagination and Creation.

Hide-Aki Takabe