International symposium
Topical problems Nonlinear Wave Physics

Confinement of high energy density plasma produced by the interaction between high intensity laser and structured medium

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Acknowledgements : A. Ishizawa (Kyoto Univ.), N. Iwata(Osaka Univ.)

Contents

- Motivation
  - High energy density plasma, a high pressure hot matter state, which is confined during inertia time and not usually in equilibrium state
  - Effort in extending the “confined” state of high energy density plasma, which will widen the class of application
- Structured medium consisting of plural different materials and/or mediums contacting each other across boundary layer

  cf J. Fuck, Lab1, July 23, 2017,
  A boundary layer between expanding plasma and background gas
  - An assembly with sub-μm size using 3D cluster and/or rod incorporated with ambient gas or magnetic field

    cf Y. Fukuda et al., Lab1, July 23, 2017
  - Self-organization and structure formation leading to a confinement exceeding inertia time
- Summary

Self-organization in in high beta fusion device

General fusion

β = 30–40 %

$\beta \sim$ 100 %

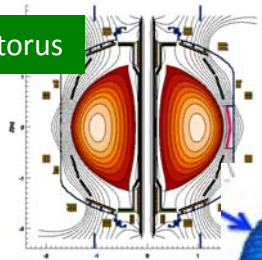
Tokamak

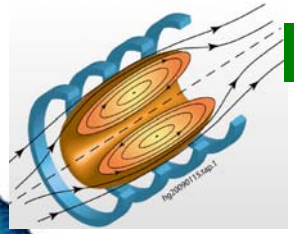
Spherical torus

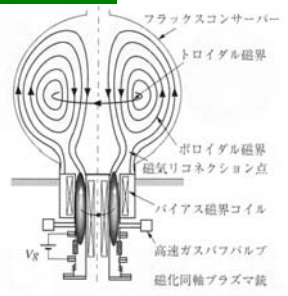
FRC

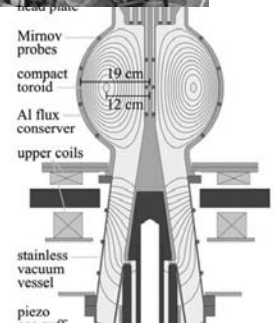
Sheromc

RFP





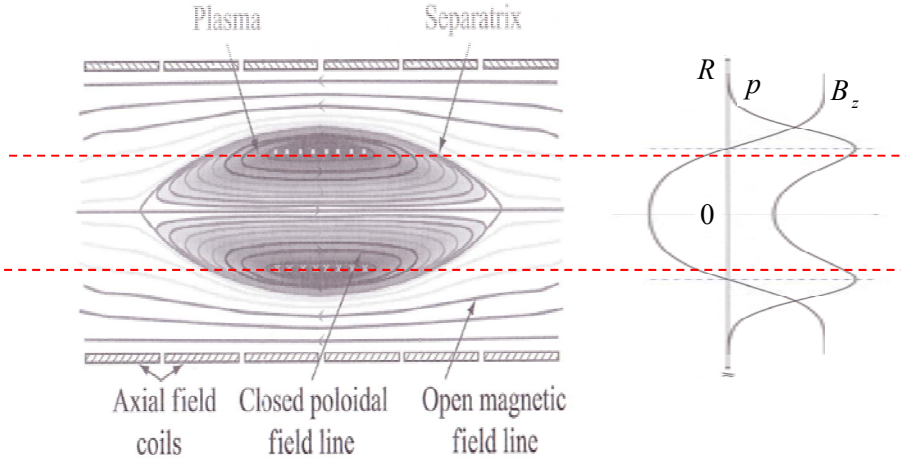


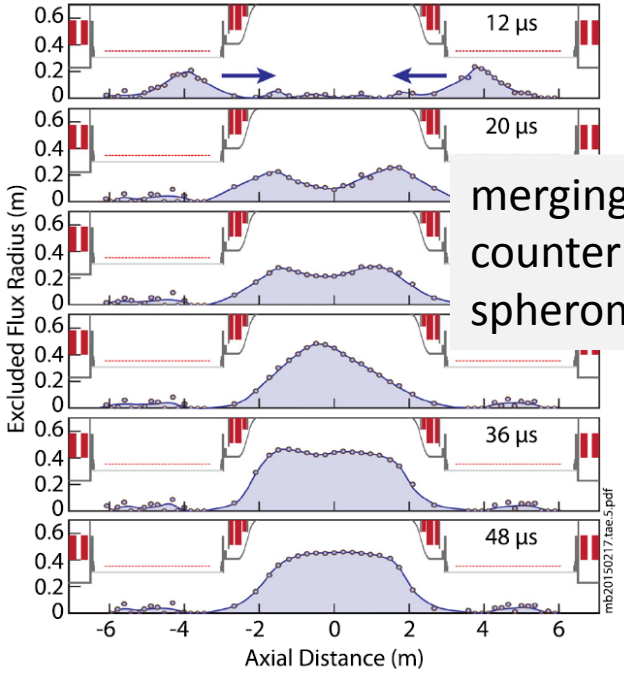


A. High performance field Reversed configuration

Binderbauer, Tajima et al., PoP 22, 056110 (2015)

C2U（Tri-Alpha Energy）





merging of counterhelicity spheromaks

Confinement time in fusion device

MTF: Magnetized Target Fusion
General fusion

β = 30–40 %

$\beta \sim$ 100 %

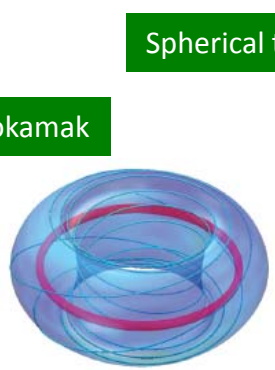
Tokamak

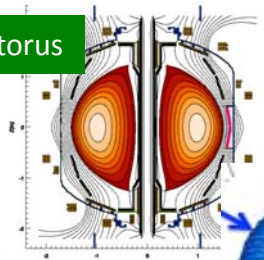
Spherical torus

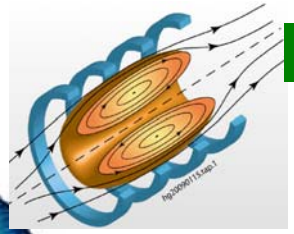
FRC

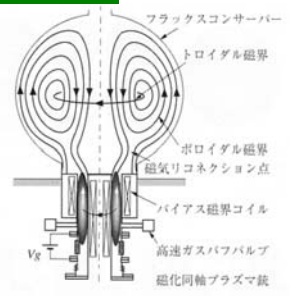
Sheromc

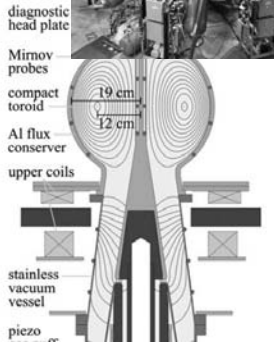
RFP



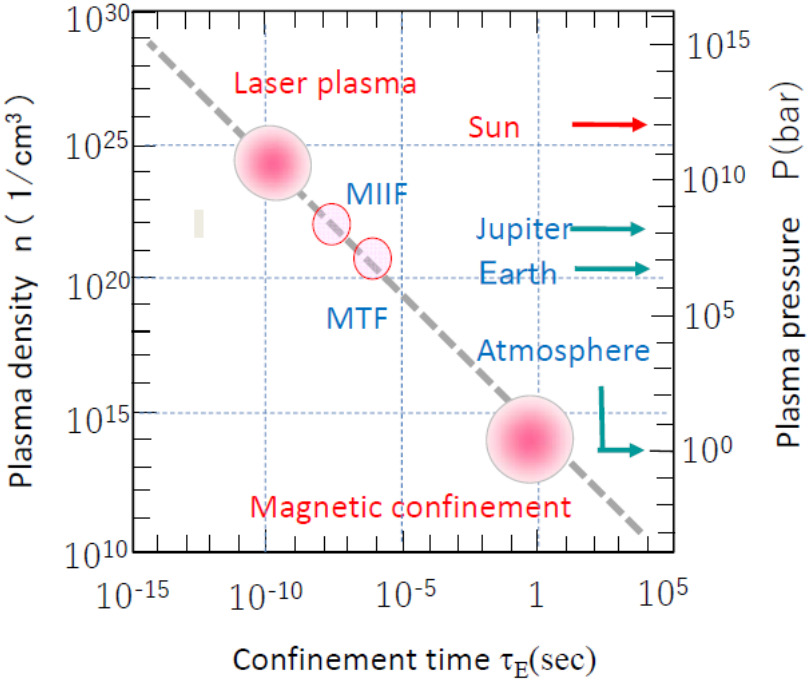








Acoustic Magnetized Fusion target
General fusion Inc.



1986 VOLUME 56, PHYSICAL REVIEW LETTERS

Magnetically Insulated Inertial Fusion: A New Approach to Controlled Thermonuclear Fusion

Akira Hasegawa
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

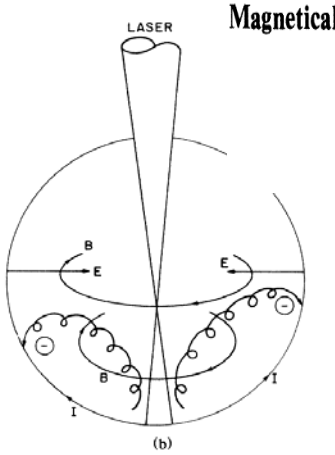


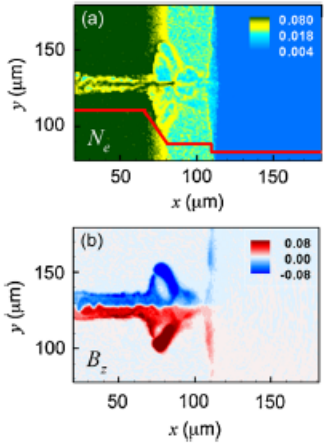
FIG. 1. Schematic diagram of (a) the reactor chamber and (b) process of magnetic field generation.

$\sim 10^{21}\mathrm{cm}^{-3}$ ~100 T

Pressure confined by metallic container while insulating heat by magnetic field

$$C_s = \sqrt{ZT_e/M}$$

New function in cluster and rod assembly, a structured medium, irradiated by high power laser



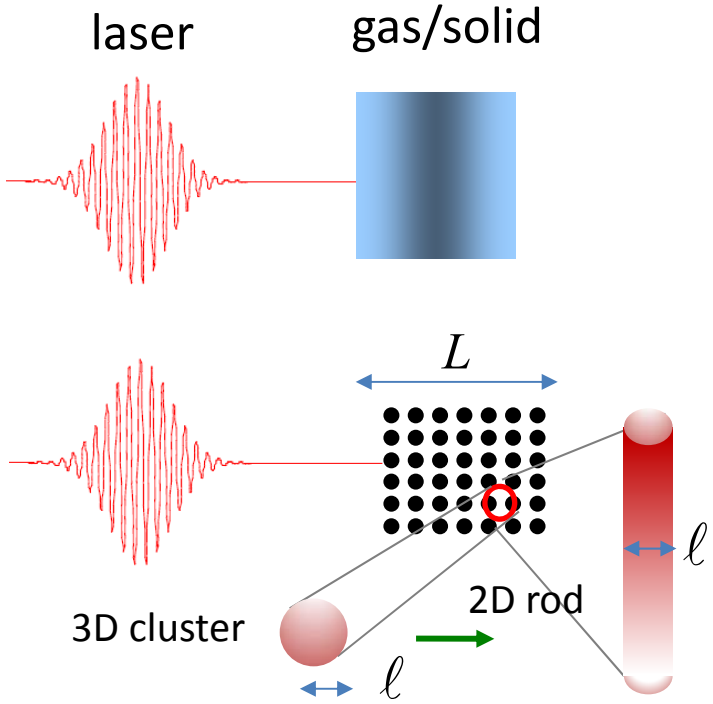
Fukuda et al, PRL 2009
Nakamura et al., PRL 2010

- A self-organization and structure formation between magnetic vortex and electric sheath

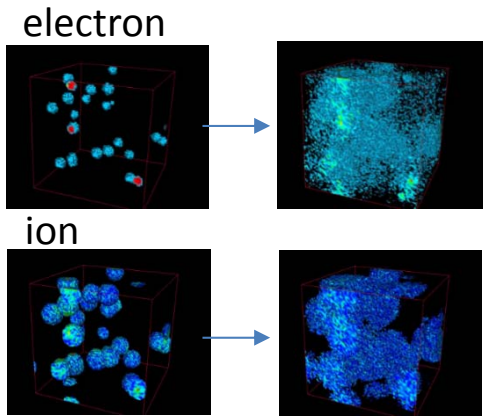
- A structure using a freedom of surface, which is a *boundary layer* between expanding plasma and vacuum

cf J. Fuck, Lab1, July 23, 2017
Boundary layer between expanding plasma and background gas

New function in cluster and rod assembly irradiated by high power laser

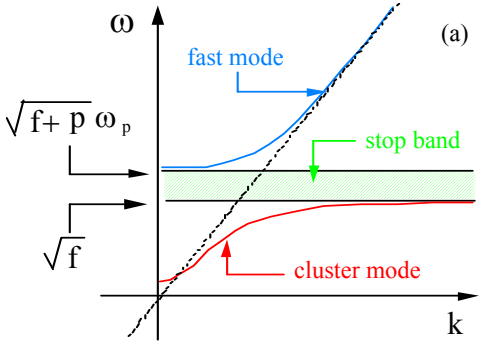


Kishmoto et al.
PoP 9, 589 (2002)

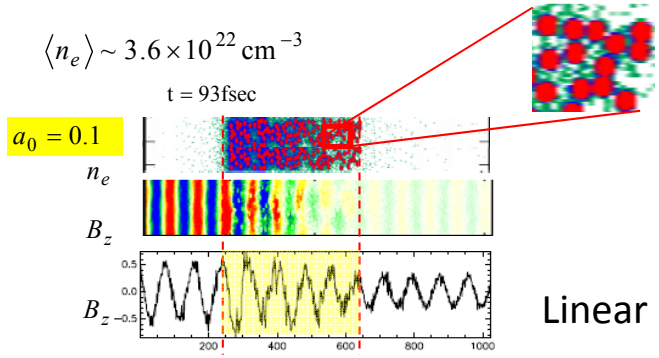


$$C_s = \sqrt{ZT_e/M}$$

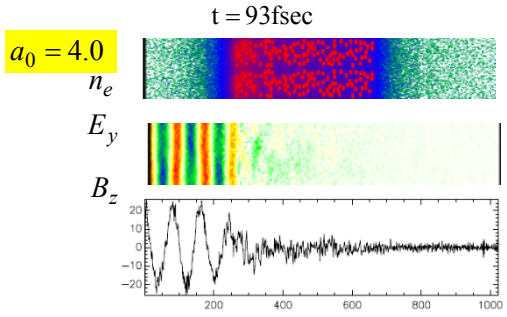
Tajima, Kishmoto, Downer,
Phys. Plasmas 6, 3759 (1999)



cluster (polarization) mode propagating in over dense plasma



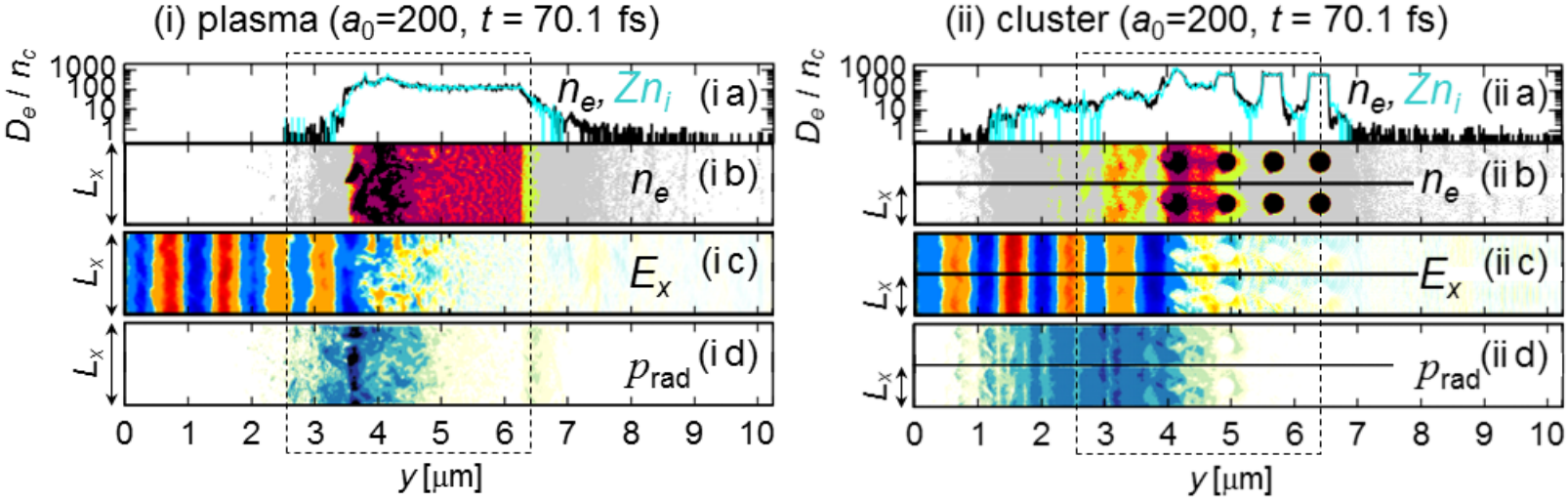
Linear regime

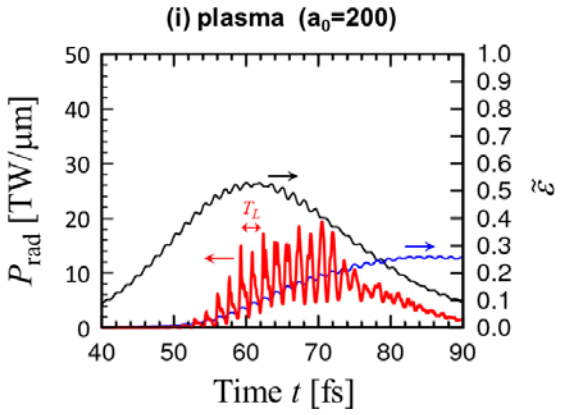


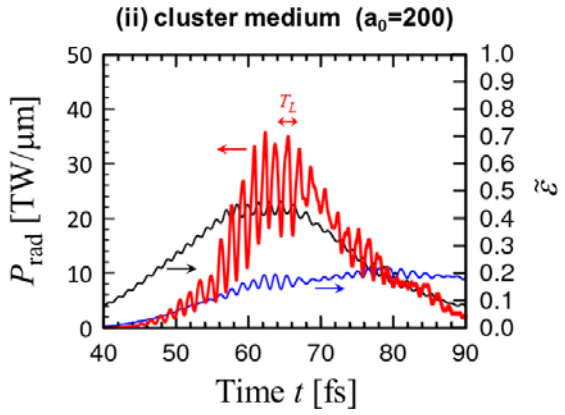
Non-linear regime

Radiation damping from clustered medium

N. Iwata, H. Nagatomo et al., PoP 23, 063115 (2016)





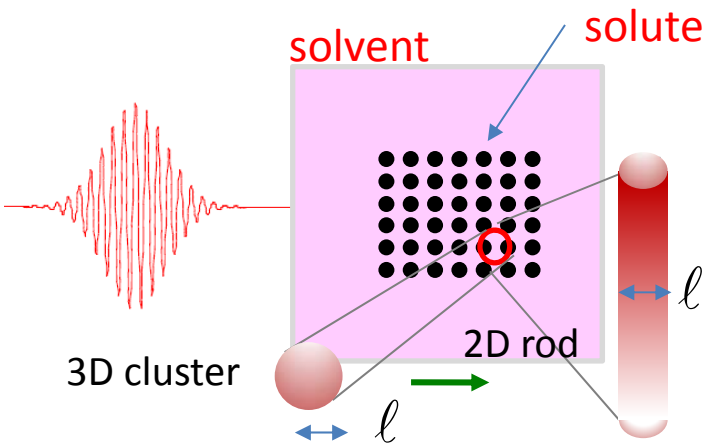


Laser	Absorption by particles	Radiation
(100 %)	→ 46 %	→ 10 %

Laser	Absorption by particles	Radiation
(100 %)	→ 77 %	→ 36 %

- Cluster (rod) medium provides large conversion rate to g-ryas vis radiation damping compared with uniform plasma.

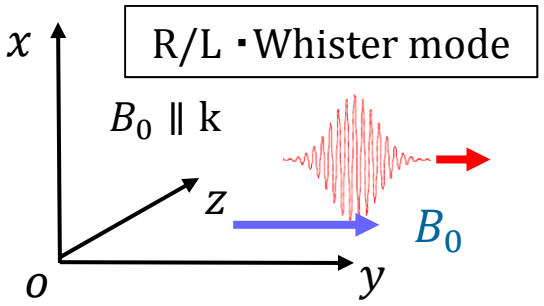
A role of ambient gas : sustain of high pressure state

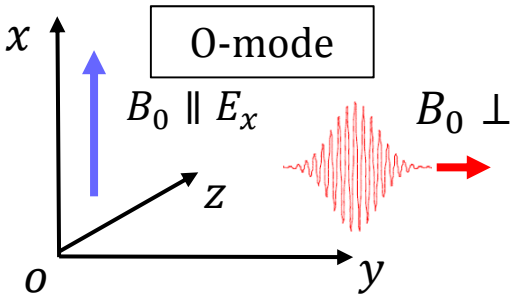


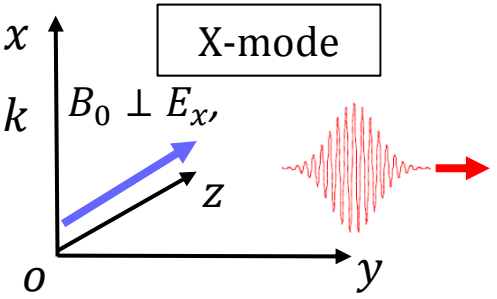
Available after publication

Available after publication

Background gas, as a solvent, replaced by magnetic field





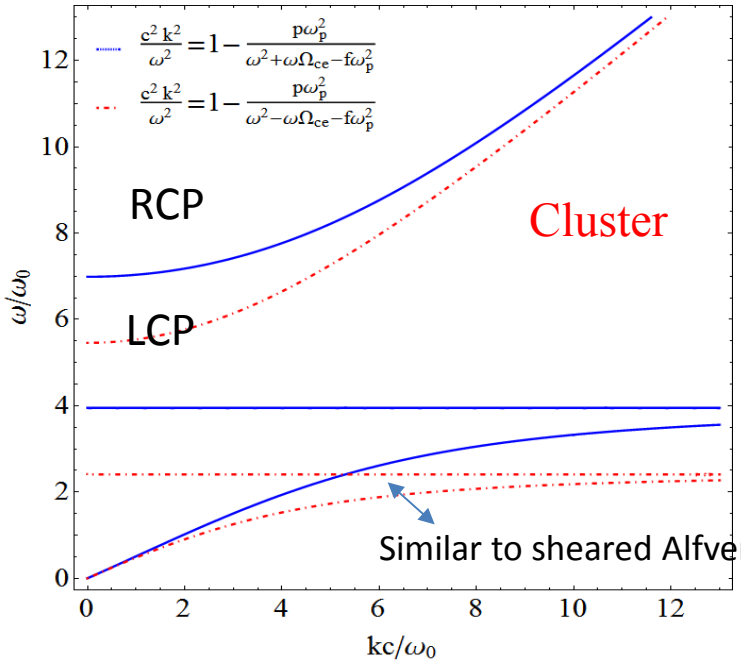


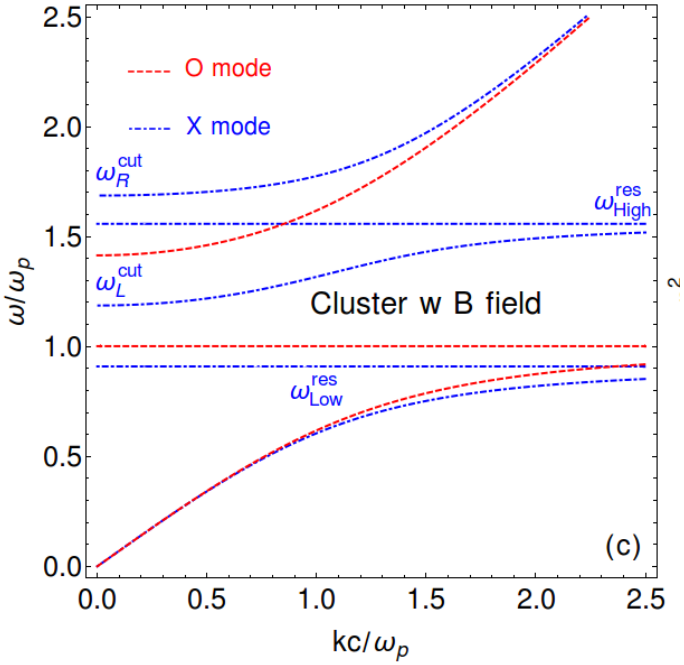
$B_0 \perp k$

Dispersion relation

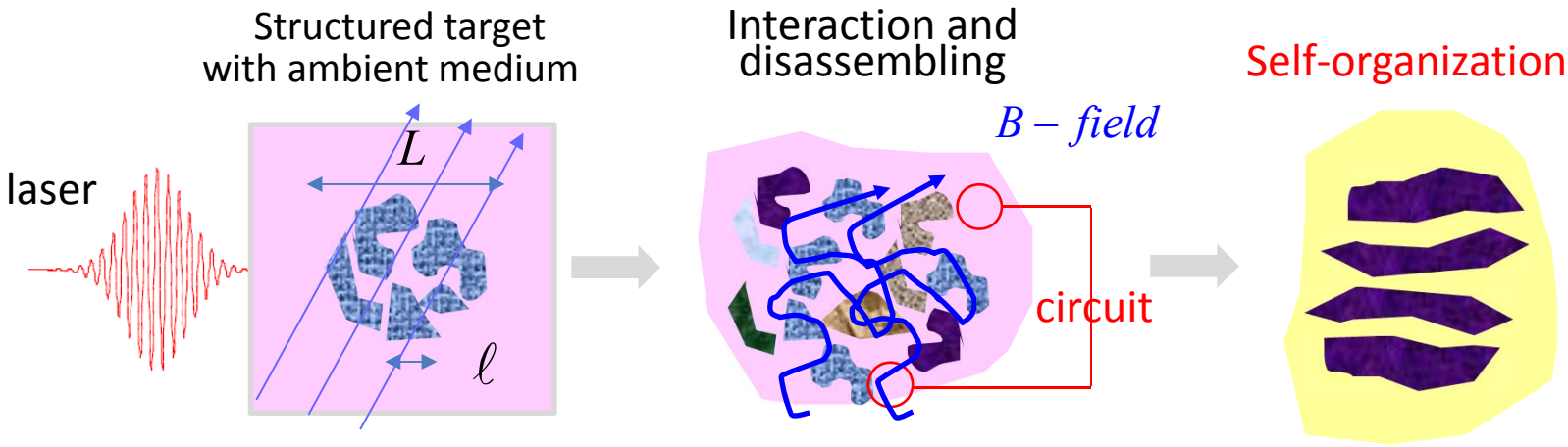
$$\frac{k^2c^2}{\omega^2} = 1 - \frac{p\omega_p^2}{\omega^2 \pm \omega\omega_c - f\omega_p^2} - \frac{q\omega_p^2}{\omega^2 \pm \omega\omega_c}$$

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{p\omega_p^2}{\omega^2}\frac{(f+p)\omega_p^2}{\left(1 - f\omega_p^2/\omega^2\right)\left[\omega^2 - (f+p)\omega_p^2\right] - \omega_c^2} - \frac{q\omega_p^2}{\omega^2}\frac{q\omega_p^2}{\omega^2 - q\omega_p^2 - \omega_c^2}.$$





How to extract self-organization characteristics in high energy density plasma produced by high power laser



- Laser period and power : τ_{laser} $\left(E_{laser} \text{ and } I_{laser}\right)$

- Specific surface area : (maximize the interaction)

$$S_m \equiv \frac{S}{\rho V}$$

- Confinement time : (~ disassembling time)

$$\tau_{macro} \sim \frac{V^{1/3}}{C_s} \sim \frac{L}{C_s} \qquad \left(\tau_{macro} \sim \frac{\ell}{C_s}\right)$$

time-scale of nonlinear process

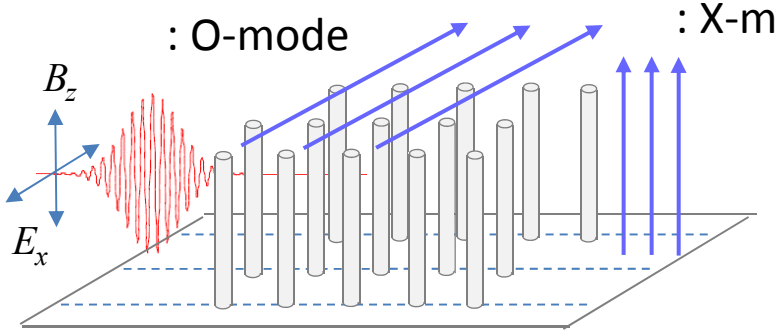
A condition for self-organization : $\tau_{macro} > \tau_N$

- Find key parameter to extract the self-organization characteristics of plasma, which is the internal degree of freedom.

Study of “magnetic turbulence” and “reconnection” using Au rod medium

$\boldsymbol{B} = B_0\hat{x}$: O-mode

$\boldsymbol{B} = B_0\hat{z}$: X-mode



ion density: 6.0×10^{22} cm^{-3} ($n_i=n_{solid}/4$)

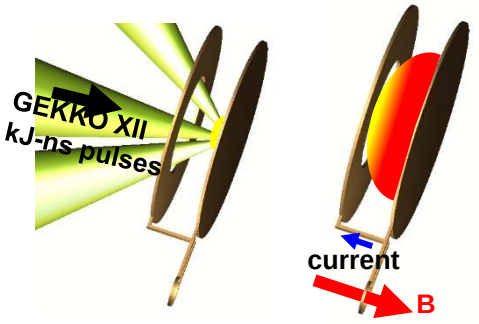
laser intensity: 1.0×10^{21} W/cm^2 (a_0=22.3)

1.0×10^{22} W/cm^2 (a_0=70.6)

pulse width : 40 fsec

External magnetic field : B_0=10kT

Magnetic field generation in the order of kT



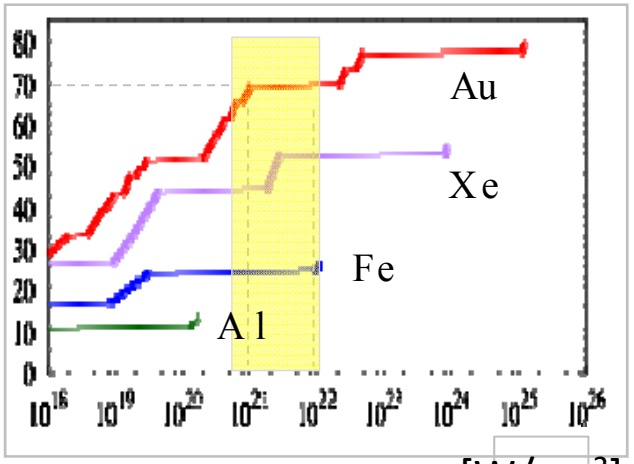
Courtesy of S. Fujioka

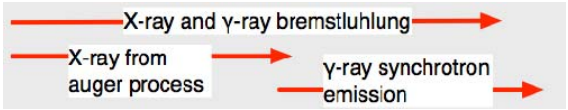
S. Fujioka et al., Sci. Rep. 3, 1170 (2013).

Laser B-field >> B_0

Laser provide large impact to the medium in short time scale while Au core will survive

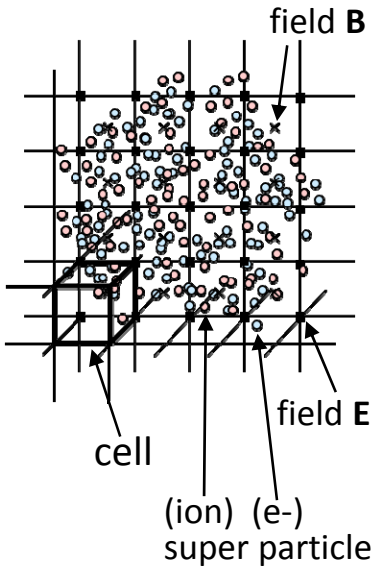
Magnetic turbulence





Extended Particle-based Integrated Code (EPIC3D)

Y. Kishimoto and T. Masaki, J. Plasma Phys.**72** (2006) 971



- 3D, Fully relativistic
- 2D parallelization (non-uniform/adaptive)
- Local field solver
- Variable mesh capability

Particle-in-cell (PIC) scheme

particle (ion, e-)

Eq. of motion

$$\frac{d\mathbf{p}_j}{dt} = q_j\left(\mathbf{E} + \boldsymbol{\beta}_j \times \mathbf{B}\right) + \mathbf{F}_{\mathrm{rad}}$$

Debye length

current density j

E, B

field

Maxwell eqs.

$\mathbf{p}_i$

n_i, n_e

$\mathbf{E}$

Radiation friction by the nonlinear Compton scattering

Important for $I > 10^{22}$ W/cm^2

N. Iwata *et al.*, to be published in Proc. 15th APR Symposium (2014)

Hard photon radiation loss

Relativistic binary collisions: e-e, e-ion, ion-ion, e-neutral

(Bremsstrahlung) γ

Hard photon radiation loss

e^+e^- pair creation in high Z material

Impact Inner-shel ionization

Radiative decay

Auger ionization

Kα emission

X-ray, γ-ray

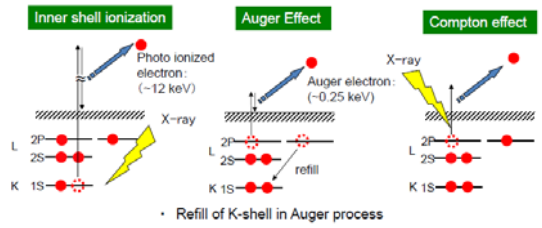
Important for high-Z material

Electron impact ionization

Field ionization

Tunneling (ADK model)

Multiphoton (Keldysh model)

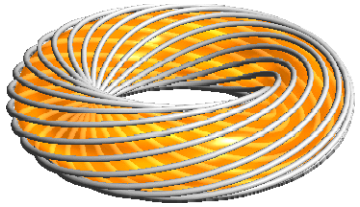


Coupled with radiation trasport (under development)

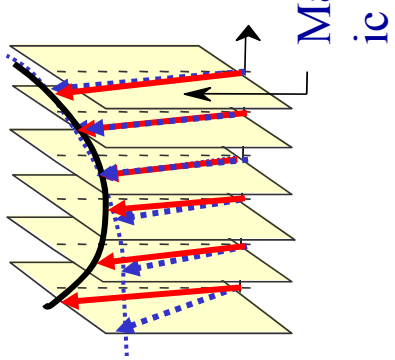
Ionization dynamics in Au rod plasma

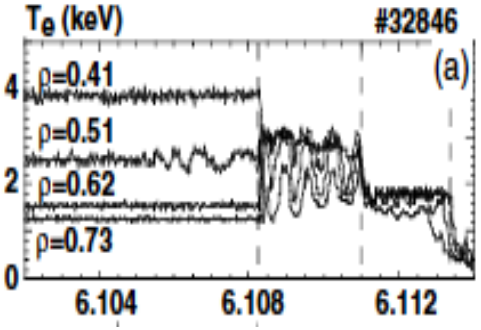
Available after publication

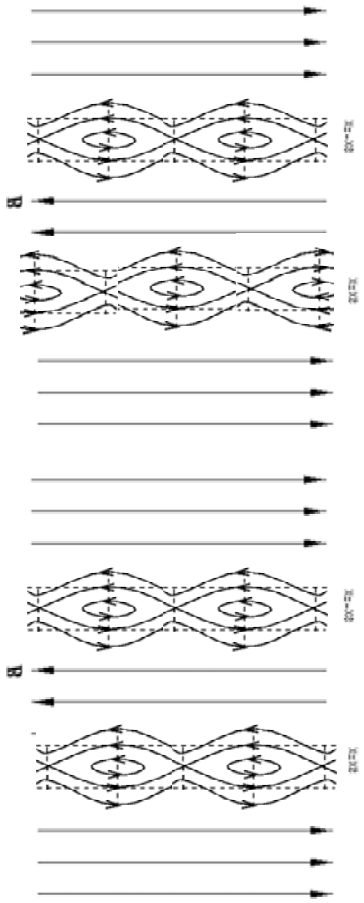
Double tearing mode and abrupt reconnection



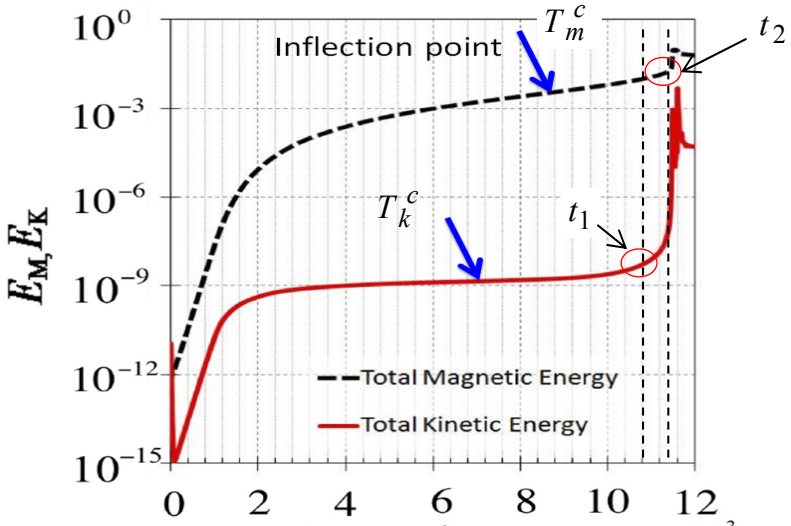
$$\boldsymbol{B} = \left(B_T\hat{\varphi} + B_P\hat{\theta}\right)$$

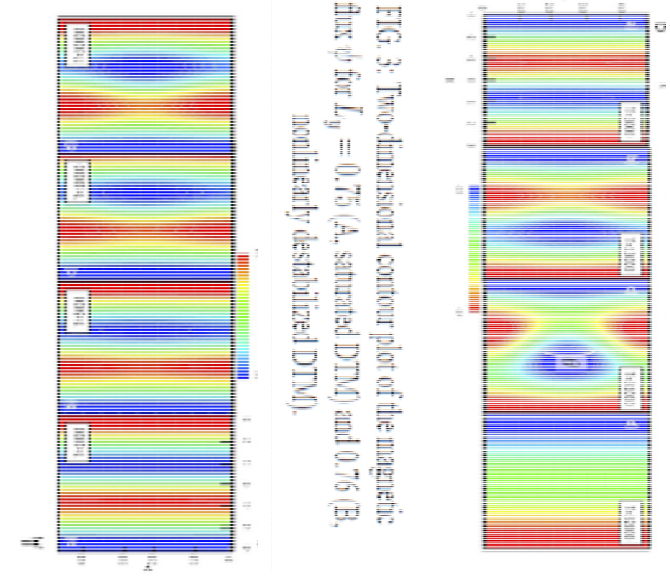






Takeji et al. NF 42, 5 (2002)





Ishii, Azumi, Kishimoto, PRL 89, 205002 (2002)
Janvier, Kishimoto, J.Q. Li, PRL (2011)

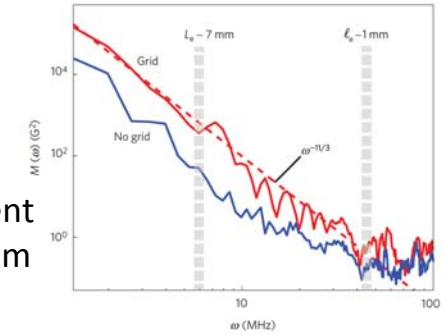
Structure driven nonlinear instability leading “Petschek type reconnection”

Dynamics of magnetic island and reconnection
Origin of magnetic field generation and particle acceleration

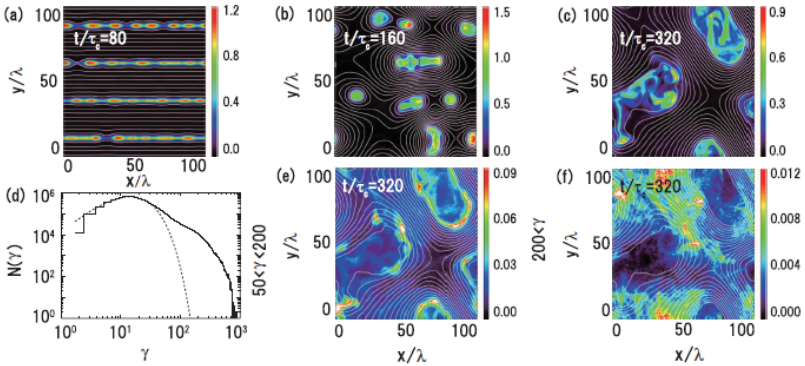
G. Gregori et al, Generation of scaled protogalactic seed magnetic fields in laser-produced shock waves, nature 481, 480 (2012)

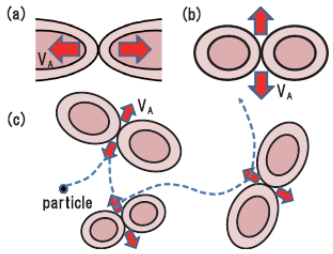
J. Meinecke et al, Turbulent amplification of magnetic fields in laboratory laser-produced shock waves, nature physics 10, 520 (2014)

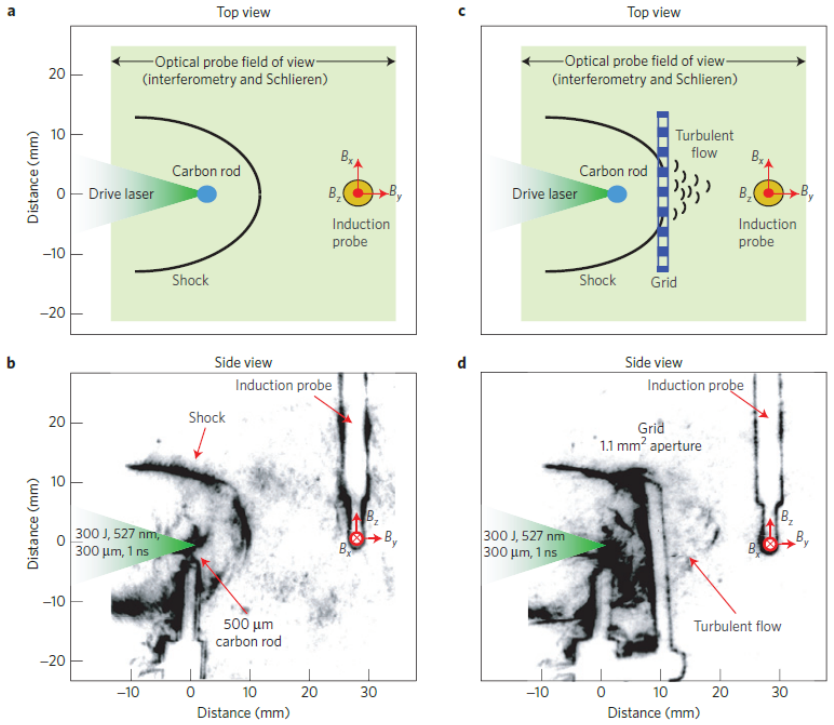
Turbulent spectrum



M. Hoshino et al, Stochastic Particle Acceleration in Multiple Magnetic Islands during Reconnection, PRL 108, 135003 (2012)



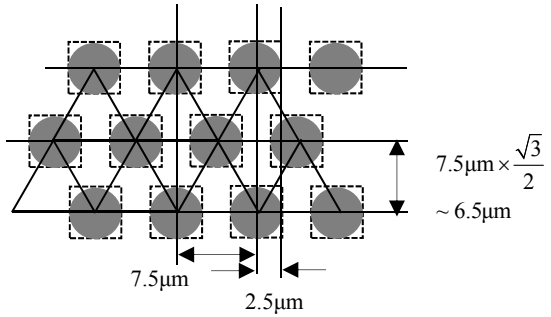




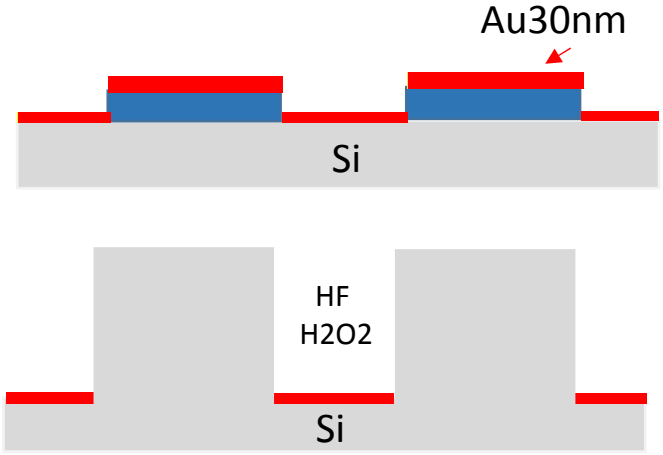
Fabrication of structured medium : silicon micro wire arrays

By Profs. Sakaguchi and Fukami (Kyoto University)

- Design of rod assembly



- Introduction of MacEtch (metal assisted chemical etching)



- Chemical reaction formula

$H_2O_2 + 2H^+ \rightarrow 2H_2O + 2h^+$

$Si + 4h^+ + 6HF \rightarrow SiF_6^{2-} + 6H^+$

Available after publication

Summary

- We have investigated the characteristics of plasma produced by the interaction between high power laser and structured medium.
  cf. rods using heavy element (Au) immersed in a strong magnetic field.
- In the system, the background coherent magnetic field is randomized leading to "magnetic turbulence" with a well defined power-law spectrum convected with plasma flows.

  Generation of plasma flows with magnetic turbulence
  → generation of "turbulence wind"
- The reconnection plays a role to accelerate (thermalize) high density heavy ions and also to emit various kinds of electromagnetic radiation including Alfven waves.
- The complex plasma state consisting of multiply charged high-Z ions, high energy relativize electrons and strong electromagnetic radiations, non-equilibrium extreme radiation plasma, can be an attractive plathome in exploring various physics of high energy density state.
- Formation of Z-pinch results from the formation of circuit 3-dimension ?