Laser Plasma Physics and Simulation
-Self-Generated Magnetic Field& Fast Ignition-

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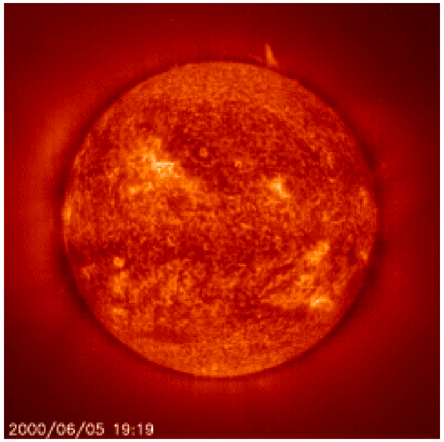
Outline
Introduction to laser plasma physics
B-fields in laser plasmas
Generation mechanisms of B-fields: EMHD
Fast ignition target design
Hybrid simulation and Weibel instability(EMHD turbulence)
Summary

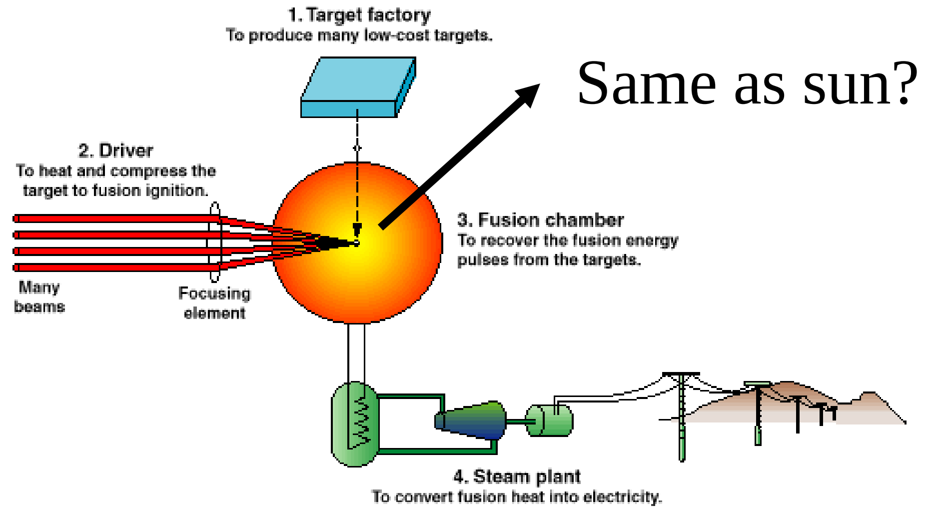
UK Winter School & UK-J. Seminar, January 5, 2011
at the Royal Observatory, Edinburgh.

Sun and Laser Fusion

The Sun: a natural fusion reactor



Solar Flare , Sun Spot,Corona Mass Ejection, and so on are connected to magnetic phenomena.



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3D simulation by K.Shibata.
Blue lines are open field line.
Yellow lines are closed lines.
Colors on the surface are polarity.

Simulations for high energy density plasmas produced by H.P. laser

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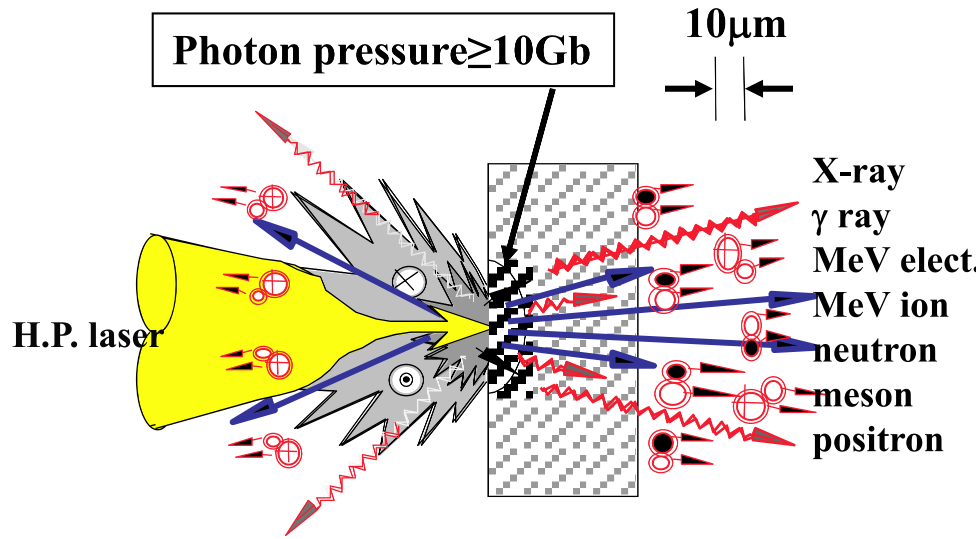
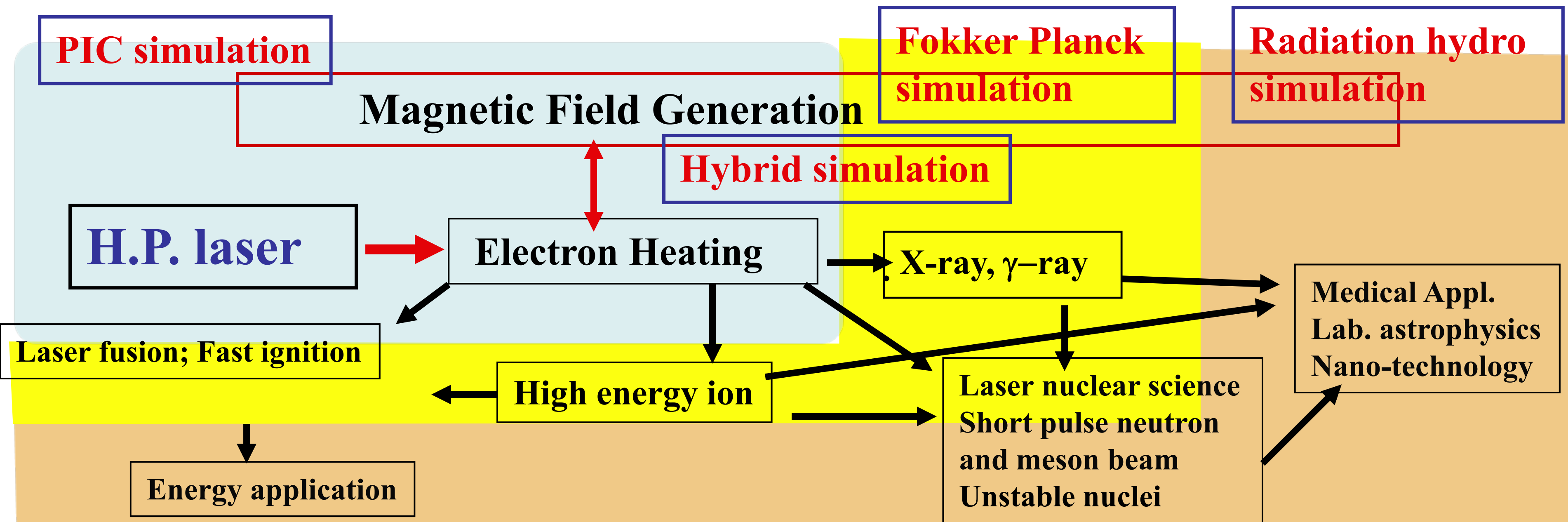
Laser: 10^{13} V/m, 10^{9} G
B field: Giga Gauss





Modeling on magnetic field generation in laser plasmas

- **Many pioneers: J.Stamper, B.Ripin, M.Hains, C.Max, T.Yabe, Mike Key, J.Evans, T.Bell, R.Petrasso, P.Norreys, K.Li, and so on**

Magnetic fields produced by laser heat deposition and momentum transfer have been investigated for many years.

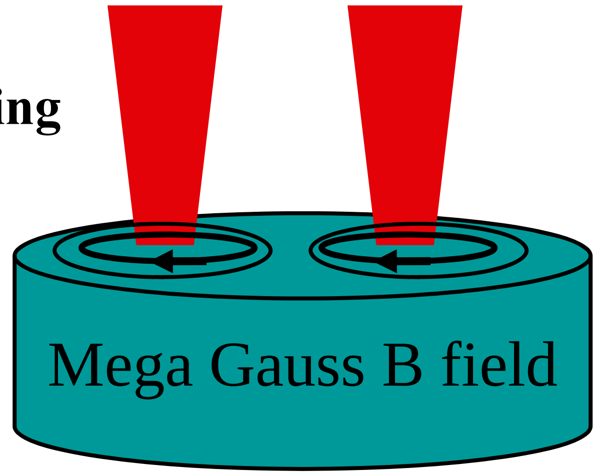
There are many mechanisms:

1) **Thermo-electric effects by laser local heating (NRL, J.Stamper, etal)**
2) **Resonance absorption (C.Max, J.Thomson)**
3) **Surface electron acceleration (T.Nakamura, etal)**
4) **Thermal instability (RAL, M.Key, T.Bell, etal)**
5) **Weibel instability (J.MyerterVehn, K.Honda, Y.Senoku)**
6) **Non-uniform density plasma -e-beam interaction (S.Kingsep, P.Norreys, H.Cai, etal)**

Magnetic fields play important rolls in laser produced Plasmas

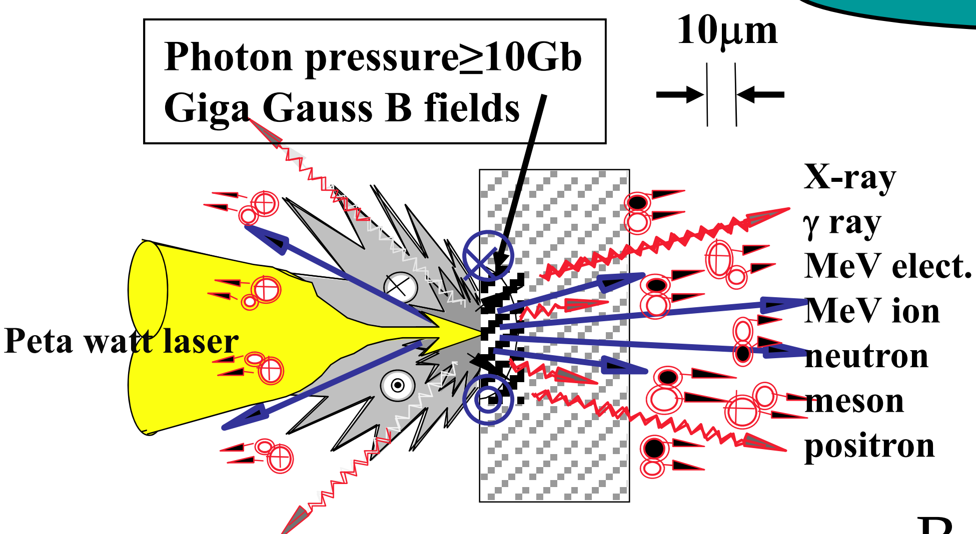
Laser field: 10^{10} V/m, 10^{2} T

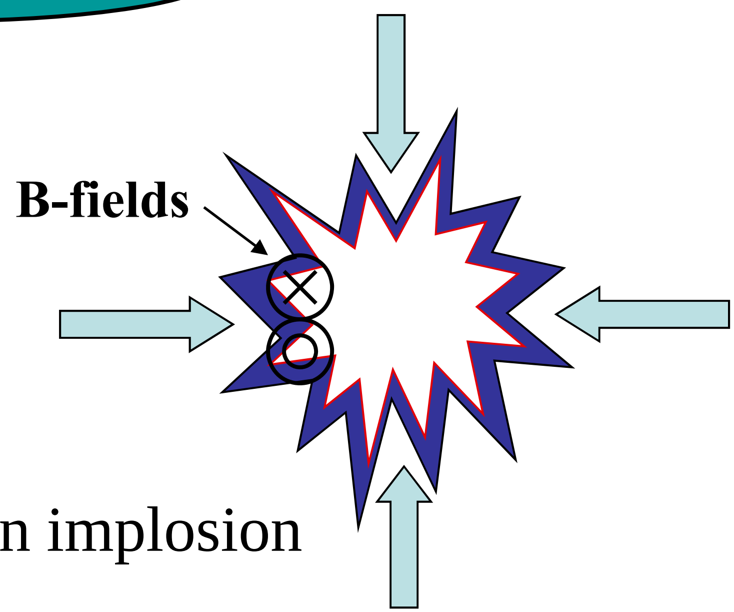
Local laser heating



r_{ec} ~ L
$\omega_c \sim 1/\tau_c$
Electron Transport is influenced by B

Laser: 10^{13} V/m, 10^{5} T





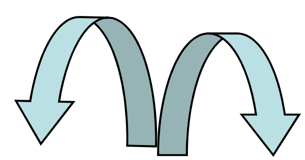
B-fields in implosion

B-field Generation in Laser Produced Plasmas

- **J.A. Stamper, etal., Phys.Rev. Lett. Vol.26,1012(1971), and Vol. 34(1975):**

Experimental observation of Maga Gauss Magnetic filed

$$\partial \mathbf{B}/\partial t - \nabla\times \mathbf{v}\times \mathbf{B} = \nabla T\times\nabla n /en \quad - \quad \nabla\times[(\nu_c \gamma \, c^2/\omega_p^2)\,(\nabla\times\mathbf{B})]$$



Modeling I of B-field generation (EMHD)

Magnetic field induction equation :

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

Electron fluid equation of motion:

$\partial \mathbf{p}/\partial t + \mathbf{v}\cdot \nabla \mathbf{p} = -e(\mathbf{E}_t + \mathbf{v}\times\mathbf{B}) + e\nabla\phi - \nabla P/n - \nu\mathbf{p}$

Magnetic field evolution is obtained by eliminating E_t:

$\partial \mathbf{B}/\partial t = \nabla\times\{\mathbf{v}\times\mathbf{B} + (1/e)(\partial \mathbf{p}/\partial t - \mathbf{v}\times\nabla\times\mathbf{p} + mc^2\nabla\gamma - e\nabla\phi$
$+\nabla P_T/n + \nu\mathbf{p})\}$

Here $\gamma^2=1+(p/mc)^2$. $\mathbf{v}\cdot\nabla\mathbf{p}$

Introducing generalized vorticity: $m\Omega = \nabla\times\mathbf{p} - m\Omega_B$

$\partial \Omega/\partial t - \nabla\times\mathbf{v}\times\Omega = -(1/m)\nabla\times(\nabla P_T/n + \nu\mathbf{p})\}$

together with $\nabla\times\mathbf{B} = \mu_0 \mathbf{j}$ **(neglecting displacement current)**

Electron Magneto Hydrodynamics (EMHD)

Non zero B_0 field, linear mode: Whistler wave: $\omega = k^2c^2\omega_c/\omega_p^2$

Validation of Modeling: Magnetic field generation mechanisms (without ion and high energy electron flow)

Ampere's equation:

$\nabla\times B=\mu_0(j+\varepsilon_0\partial E/\partial t)$ ⟶ $v=-\nabla\times B/(en\mu_0)+\varepsilon_0\partial E/\partial t/(en)$

Therefore,

$$\Omega=-\nabla\times[(\gamma\, c^2/\omega_p^2)\nabla\times\Omega_B+\gamma\,\partial^2\Omega_B/\partial^2 t/\omega_p^2]-\Omega_B$$

When scale length of B field : $L>>c/\omega_p$ **and time scale:** $\tau>>1/\omega_p$, **(Namely, no electromagnetic wave) and** $P=nT$ **:**

(LTE and ideal electron gas)

Then,

$$\partial B/\partial t-\nabla\times v\times B=(1/e)\nabla\times(\nabla P_T/n+\nu_c\, p)\}$$

$$=\nabla T\times\nabla n/en\ -\ \nabla(\nu_c\gamma\, c^2/\omega_p^2)\times(\nabla\times B)\ +\ (\nu_c\gamma\, c^2/\omega_p^2)\nabla^2 B$$

Righi-Rudac Resistivity gradient convection Mag. Diffusion

$v_e^2/c^2\sim\nu_c\,\Omega_B/\omega_p^2$: **stationary B-field. T~1keV, n~100n_c, B~MG**

Magnetic field evolution in plasma flow

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{V}_i\times\mathbf{B}) + \frac{c}{e}\left[\nabla\times\left(\frac{\nabla P_e}{n_e}\right) - \nabla\times\left\{\frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{4\pi n_e}\right\} - \nabla\times\left(\frac{\mathbf{R}_T+\mathbf{R}_U}{n_e}\right)\right]$$

①　②　③　④

$$\mathbf{R}_T = -\beta_{\parallel}^{uT}\nabla_{\parallel}T_e - \beta_{\perp}^{uT}\nabla_{\perp}T_e - \beta_{\wedge}^{uT}\mathbf{h}\times\nabla T_e$$ Thermal Force

$$\mathbf{R}_U = -\alpha_{\parallel}\mathbf{u}_{\parallel} - \alpha_{\perp}\mathbf{u}_{\perp} + \alpha_{\wedge}\mathbf{h}\times\mathbf{u}$$ Friction Force

h: The Unit Vector Parallel to Magnetic Field

u: The Unit Vector Parallel to Current Density

①:Convection and stretching of magnetic field by hydrodynamic motion

②:Thermo-Electric current

③:Hole effects : electron skin effects

④:The Term Given by Braginskii

After Baraginski

Magnetic Field Measurement

K.Li etal., PRL(2007)

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B-field measurement (2)

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Laser

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3-D PIC simulation of laser propagation and absorption in the cone target

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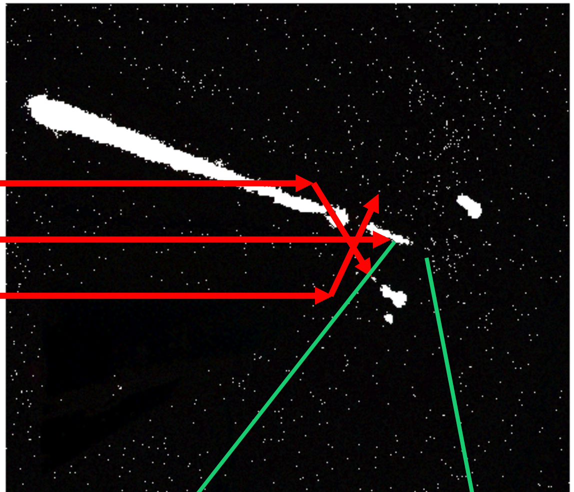
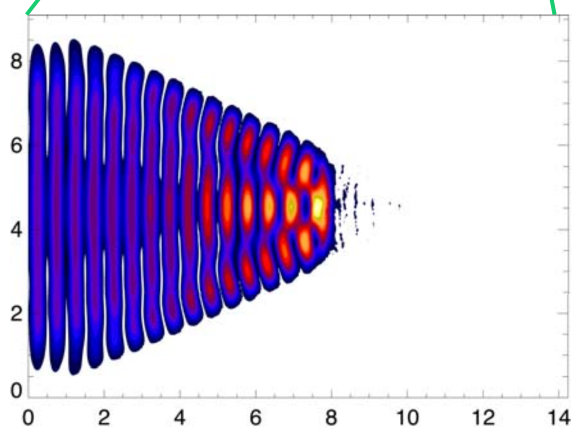


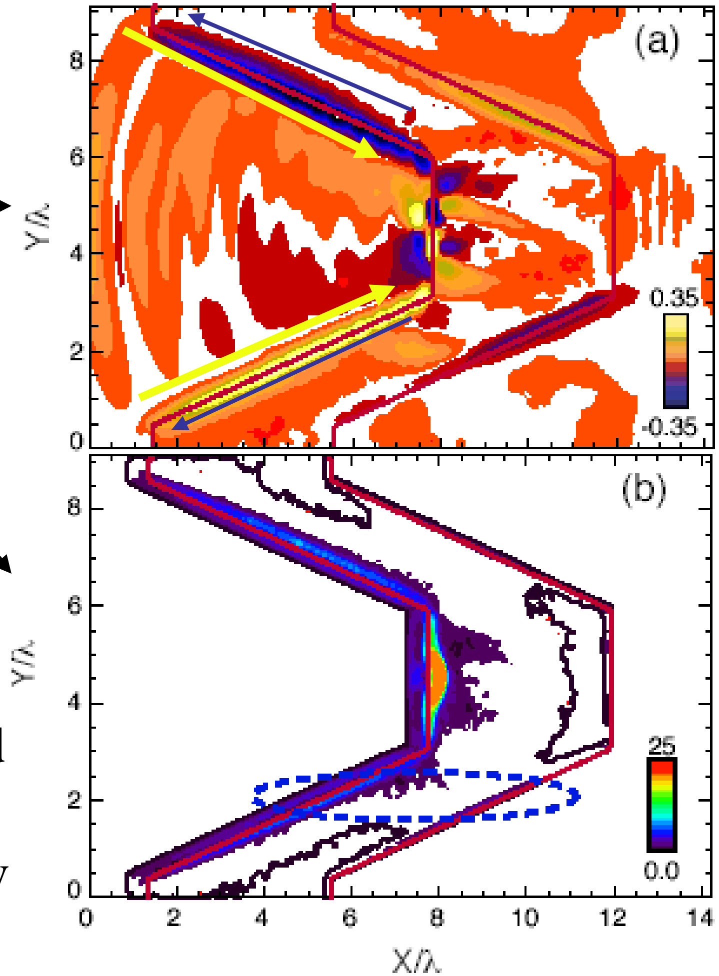
1mm



The focused intensity reaches 20 times larger than I_0.

B field profile

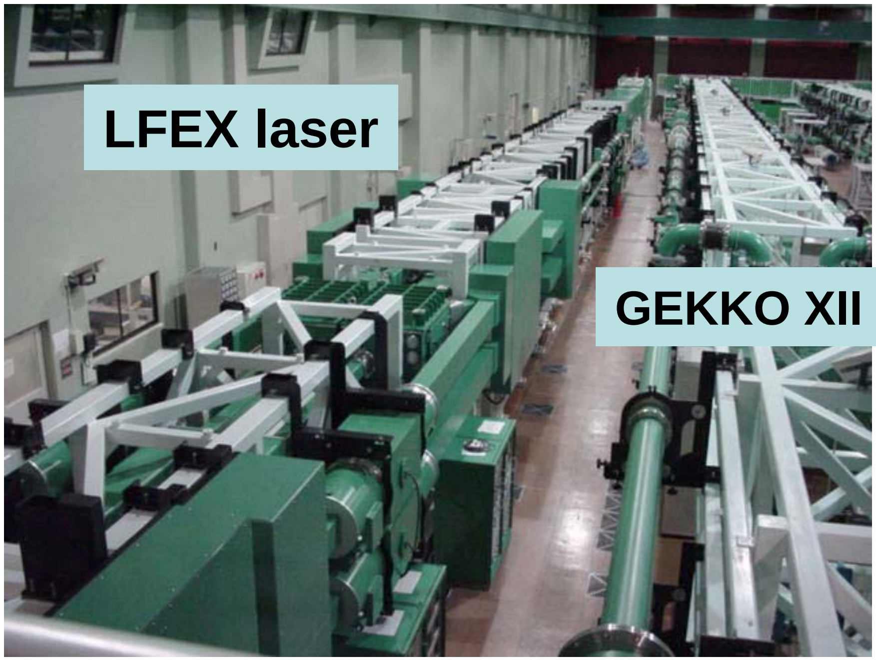
Electron energy density distribution

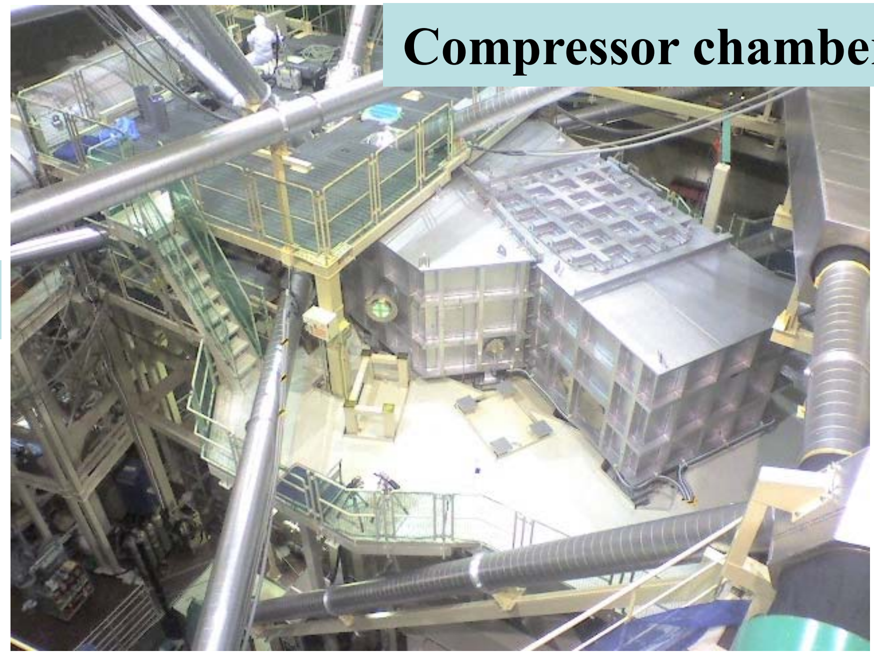


Magnetic field ;B/B_0 and energy density normalized by $n_c mc^2$

Short pulse laser is focused and generated REB is pinched in a cone target, POP'03, Sentoku, Mima etal

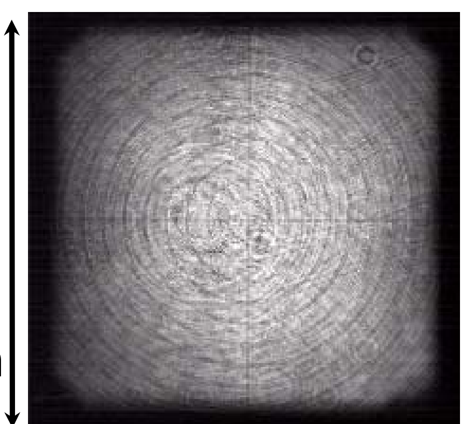
Present status of FIREX laser construction

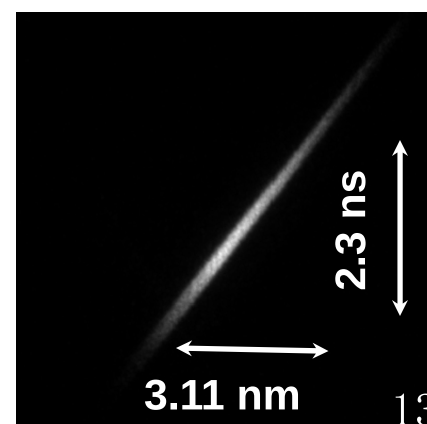




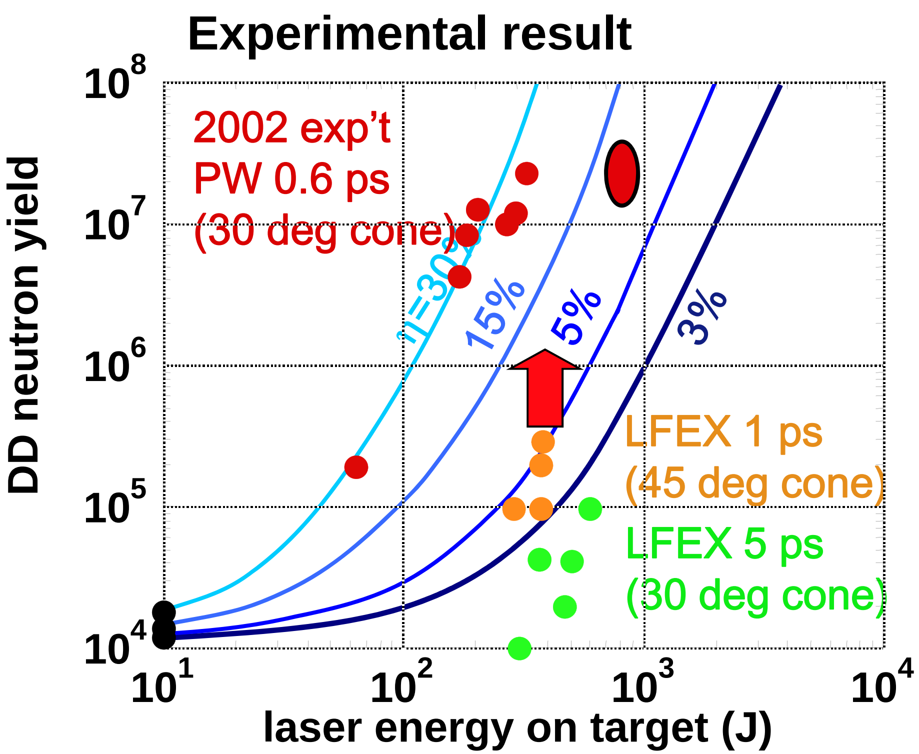
06.5. 3.6 kJ/ beam /narrow band
07.1. 2.9kJ/beam /broad band for 1ps
(4 beam total =11.6 kJ)
08.02.29 First light
08. 12 full beam heating experiment

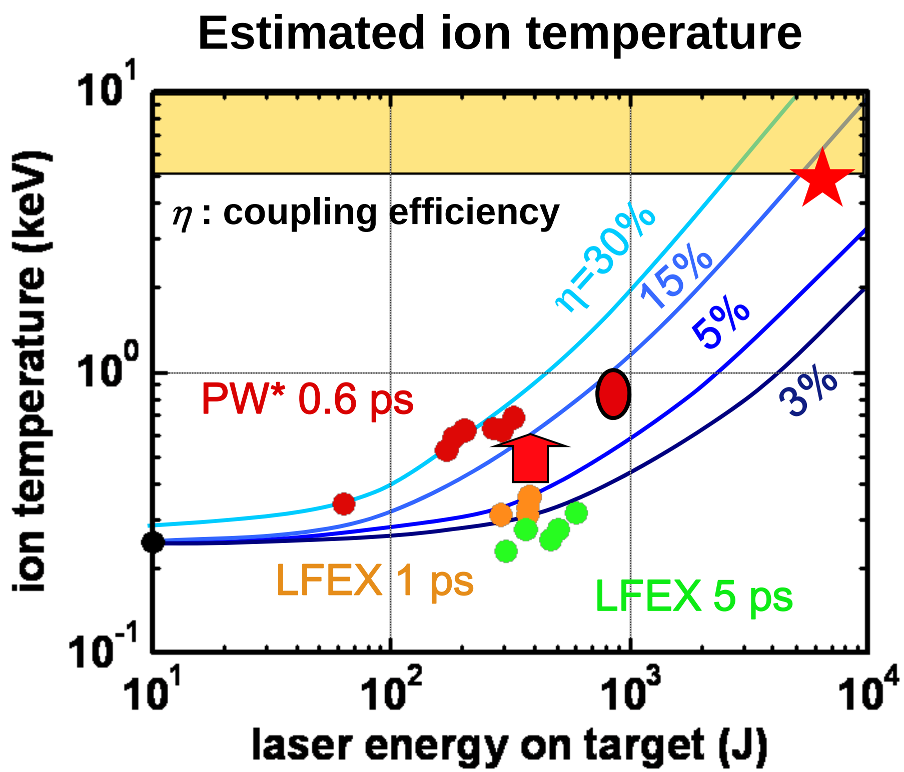
32.5 cm





Neutron yield enhanced by up to 1000-times!





Coupling efficiency from LFEX laser to the compressed fuel was estimated to be 3-5 %, in 2009.

In 2010, Dec., it increased to higher than 10%.

Critical Issues as Relativistic Plasma Ohysics

Peta watt Laser Plasma Interaction

High density relativistic electron transport in dense plasmas

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Laser Intensity; $I_L = 2 \times 10^{15}$ W/ $\pi r_h^2 \sim 1\sim2 \times 10^{20}$ W/cm^2

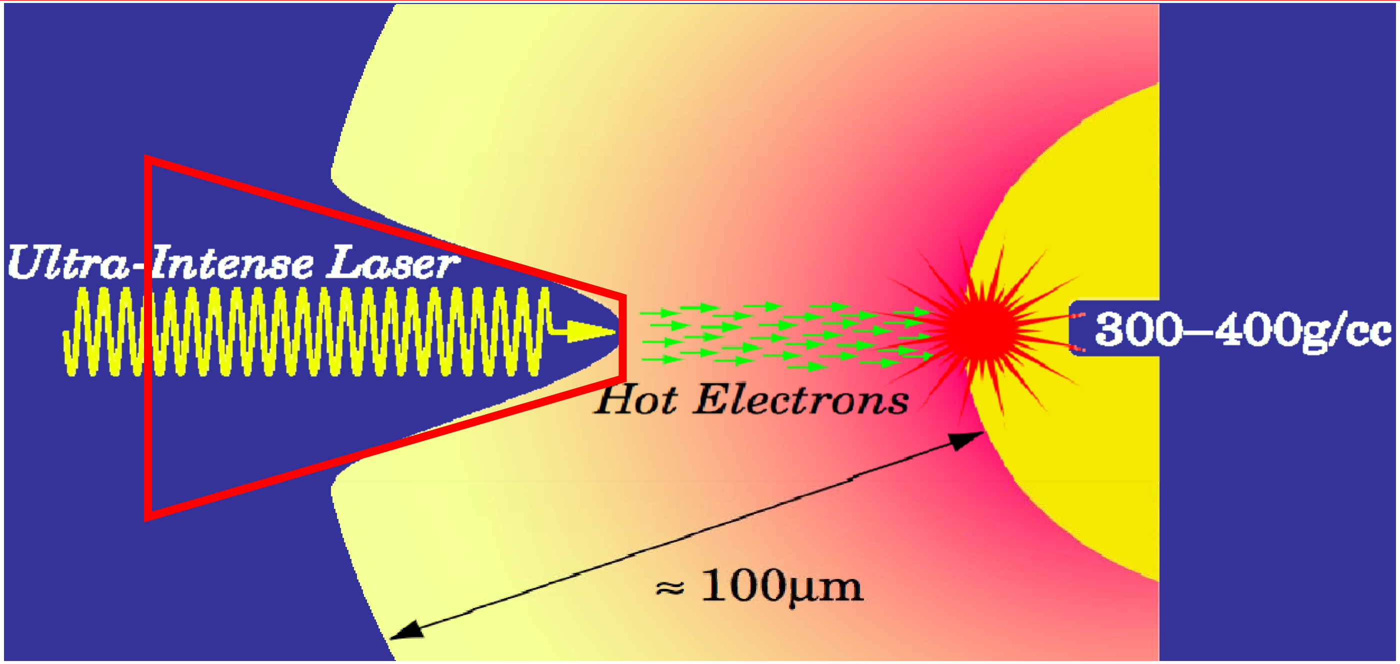
Electron energy; $\varepsilon_r = (\gamma-1)mc^2$,

$\gamma = [1+ (eA/mc)^2]^{1/2} = [1+ I_L/(2.4 \times 10^{18} W/cm^2)]^{1/2}$

$\varepsilon_r \sim$ 3~5 MeV

current> 500MA; 100 times thunder lightening ;

Nature,'04(Kodama), PRL,'04(Nakamura)



Integrated Simulation of Fast Ignition

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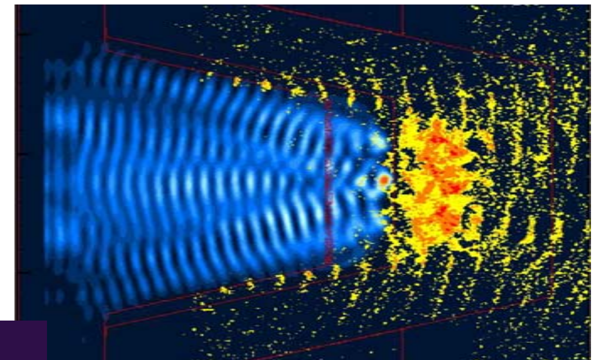
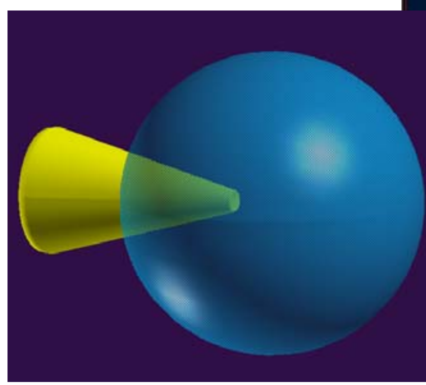
Profiles
Plasma data

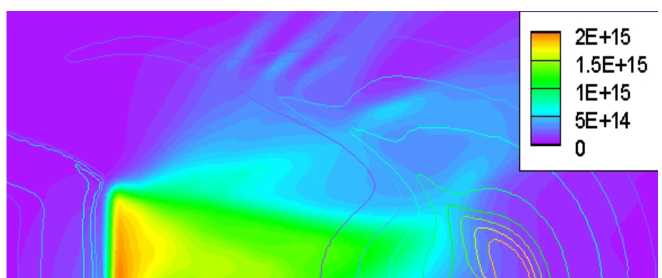
Particle in Cell



High energy electron data



T&n profiles before heating



Fokker-Planck simulation

Control of Hot Electron Angular Divergence

Divergence angle

S.Kar, , P.Norreys, etal (PRL 102, 055001 (2009))

B-filed collimation

$$E = \eta J_c = -\eta J_h$$

$$\partial B / \partial t = \nabla \eta \times j_h + \eta \nabla \times j_h$$

Experiment at RAL

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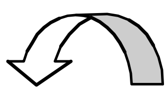
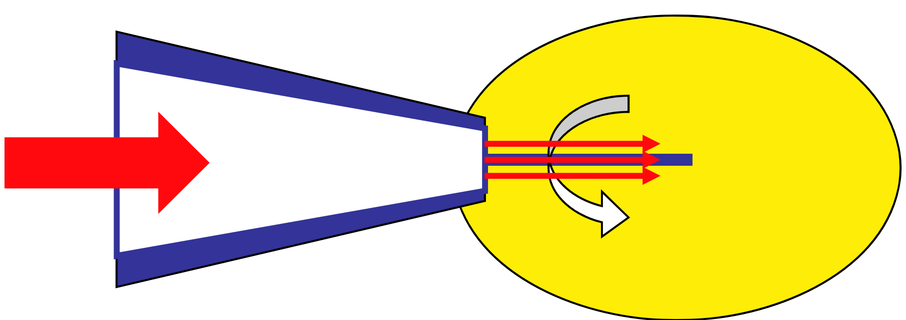
B field





Cone needle concept
Kodama,Nature, 2005
U-Rochester 2010.9.
To be experimental test

EMHD of Beam Plasmas
(two component plasmas)

Back ground electron: fluid

$\boldsymbol{v} = \boldsymbol{j}_h/en + -\nabla\times \boldsymbol{B}/(en\mu_0)$

$\boldsymbol{\Omega} = -\nabla\times [(\gamma\ c^2/\omega_p{}^2)\nabla\times\boldsymbol{\Omega}_B] - \boldsymbol{\Omega}_B + \nabla\times(\gamma \boldsymbol{j}_h/en)$

$\partial\boldsymbol{\Omega}/\partial t - \nabla\times\boldsymbol{v}\times\boldsymbol{\Omega} = -(1/m)\nabla\times(\nabla P_T/n + \nu\boldsymbol{p})\}$

$\partial \boldsymbol{n}/\partial t + \nabla \boldsymbol{n}\boldsymbol{v} = 0$

Hot (beam) electron dynamics:

$\partial n_h/\partial t + \nabla n_h v_h = 0$ ***, ---, higher order terms are important ----> kinetic description.***

Hybrid simulation (T.Taguchi, etal, PRL 2003)

Collional PIC (Y.Sentoku etal PRL(2000),
Hongbo Cai ,etalPRL(2009))

Neglect of $\nabla\times B/(en\mu_0)$ in LSP, and Fokker-Planck code

Hot electron beam and magnetic fields in a plasma channel

- **Generalized vorticity is conserved, when initially Ω is 0, then**

$$-\nabla\times[(\gamma\, c^2/\omega_p^2)\,\nabla\times\Omega_B]-\Omega_B+\nabla\times(\gamma \mathbf{j}_h/en)=0$$

When $2D$, $\mathbf{B}\,//\,z$, $\gamma=1$, n, n_h, y, v_h, *and* Ω_B **are normalized by** n_0, c/ω_{p0}, c, **and** ω_{p0}, **and** $\mathbf{j}_h$ **is uniform,**

$$[\partial/\partial y(1/n)\,\partial/\partial y]\,\Omega_B-\Omega_B=-(v_h n_h)(\partial(1/n)/\partial y)$$

$(e\mathbf{B}/m)/\omega_{p0}$

$= -\kappa S \sinh\kappa y/(\kappa\sinh\kappa d+\cosh\kappa d)$, in $-d<y<d$

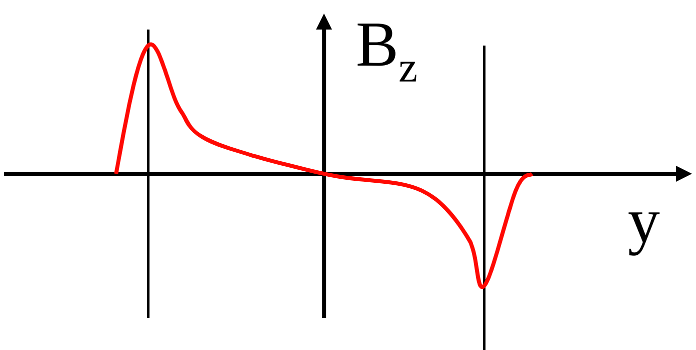
$= -\kappa S \exp(-y+d)\sinh\kappa d/(\kappa\sinh\kappa d+\cosh\kappa d)$, for $d<y$

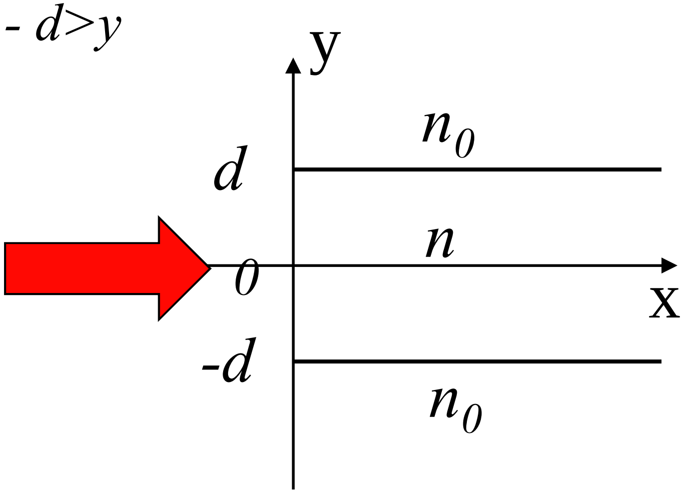
$= \kappa S \exp(y+d)\sinh\kappa d/(\kappa\sinh\kappa d+\cosh\kappa d)$, for $-d>y$

where

$S=v_h n_h(n^{-1}-1)$, $\kappa=\omega_p/\omega_{p0}$

For $n<1$





Cone is introduced for enhancing energy coupling efficiency

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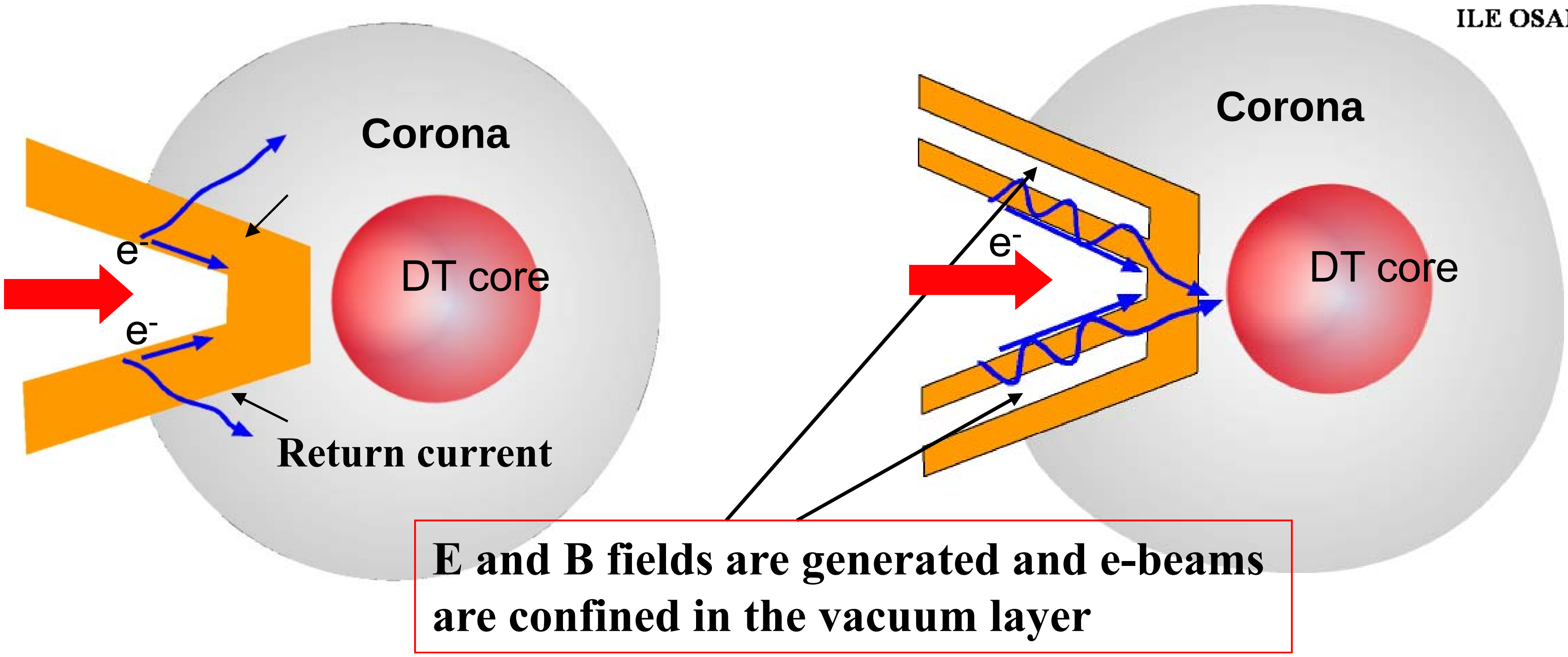


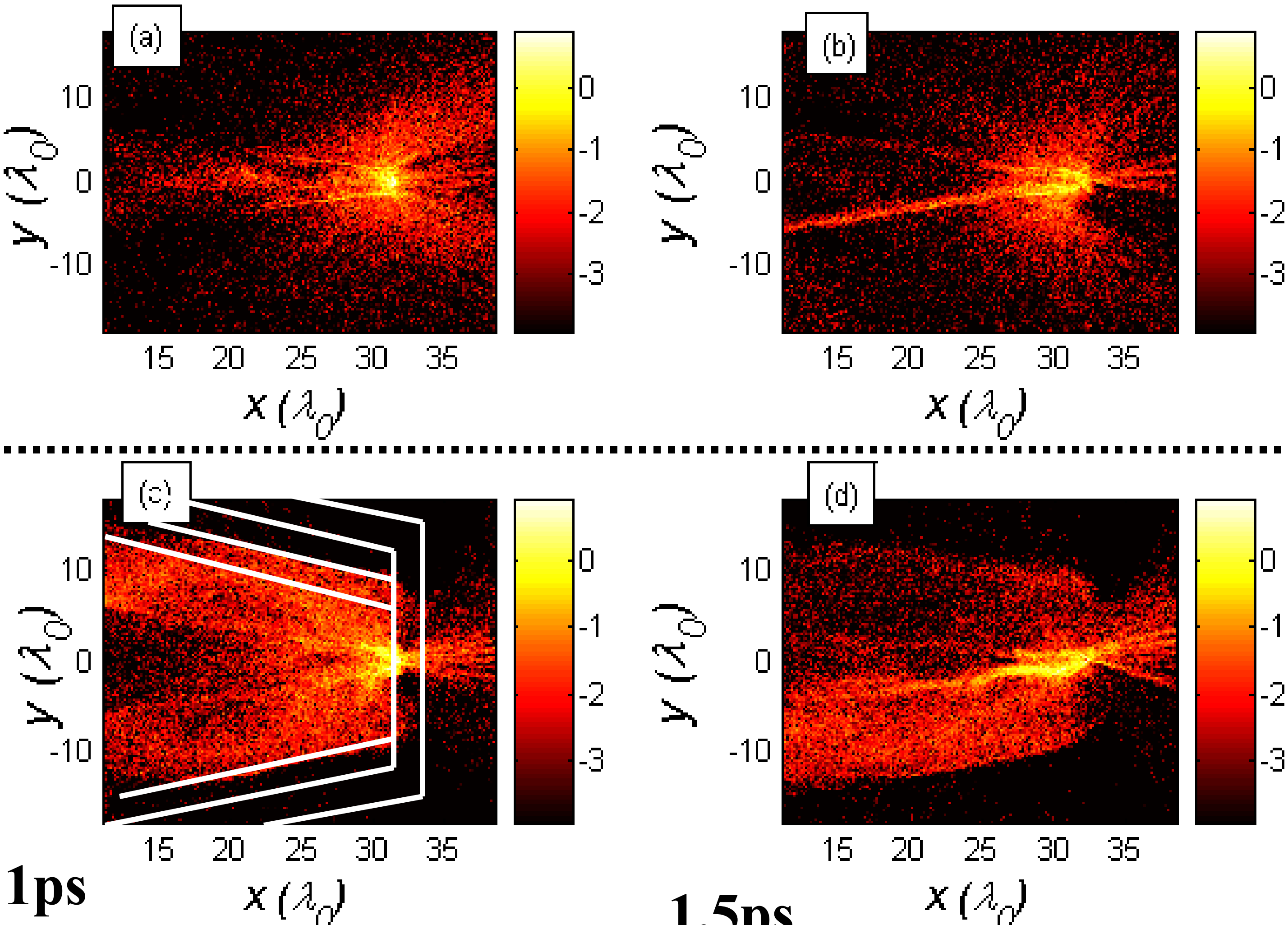
1. Single Cone target **2. Double-cone target**

H. Cai etal., PRL, 2009

Hot electron energy density for single cone and double cone

Single cone

Double cone



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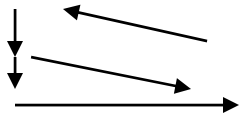
1.5ps

Hongbo Cai, etal PRL 2009

Temporal Evolution of Magnetic Fields



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Growth of B-Fields and Hot Electron into the Core

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$$\partial \mathbf{B}/\partial t = -\nabla\times\mathbf{E}$$
$$= \nabla\times\eta\mathbf{J}_h + \nabla\times[(\nabla n_h T_h)/n]$$

Laser Plasma EMHD Simulation

Hongbo Cai, IAPCM

Laser Intensity:$I\lambda^2 = 2x10^{19}$ W/cm^2

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Solution of EHD

$eB/m = \Omega$

$= - \kappa_0 \kappa S \sinh(\kappa y)/(\kappa \sinh(\kappa d)+\kappa_0 \cosh(\kappa d))$,

where

$S = v_h n_h/(n^{-1}-n_0^{-1})$, $\kappa = \omega_p/c$, $\kappa_0 = \omega_{p0}/c$

At $y=-d$, $B \sim (\omega_p m/e)(v_h/c)(n_h/n) \sim 100$MG

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$B_{max} \sim 110$MG

Self-generated magnetic fields and Collimation of hot electron flow

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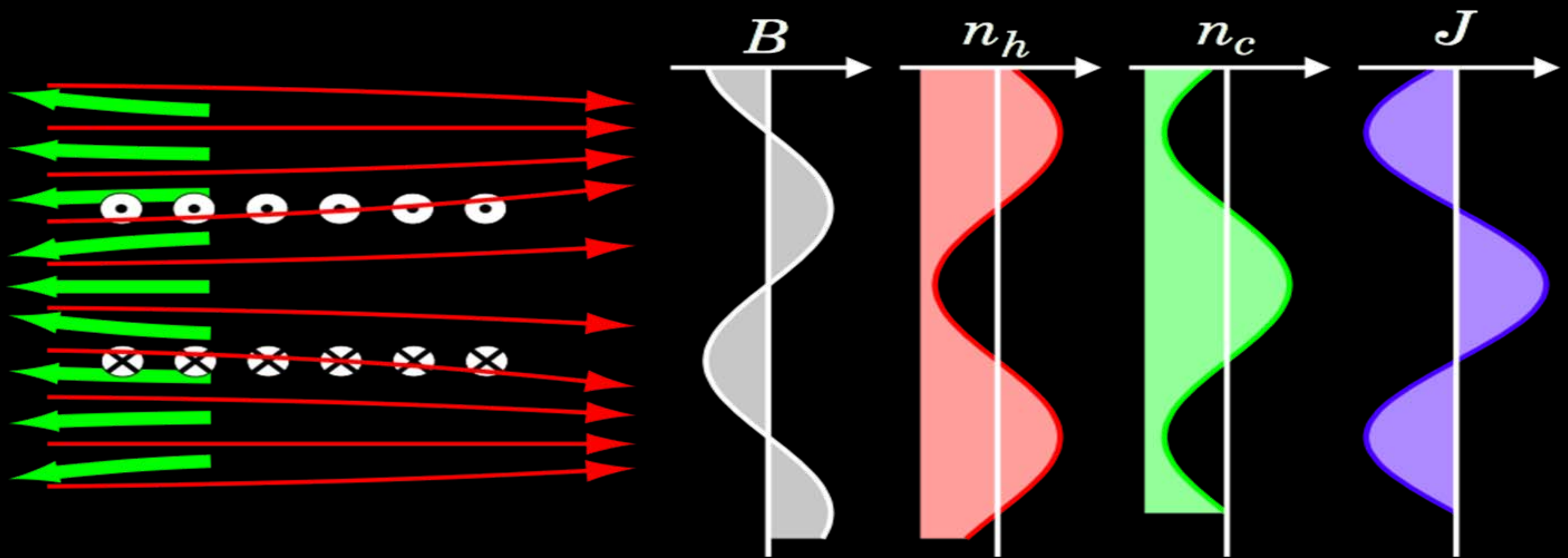
Weibel Instability

Transversely Fluctuating Magnetic Field Separate

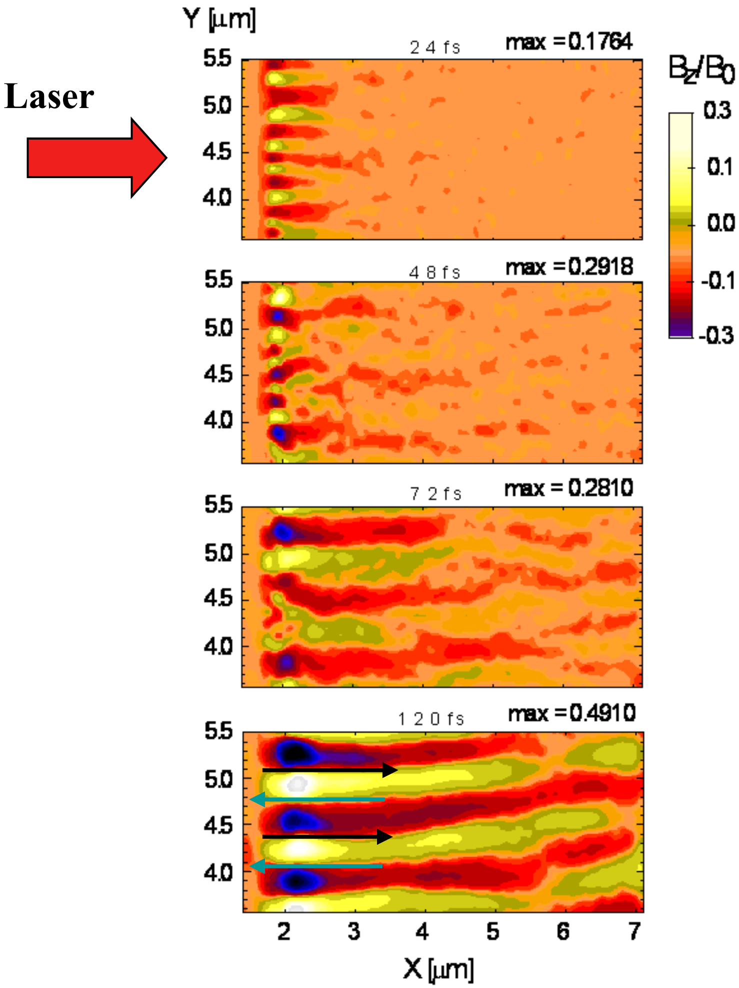
Two Electron Streams



Two-dimensional PIC simulation for relativistic electron transport in over dense plasmas

Longitudinal 2D

$a=3$, $n/n_c=20$

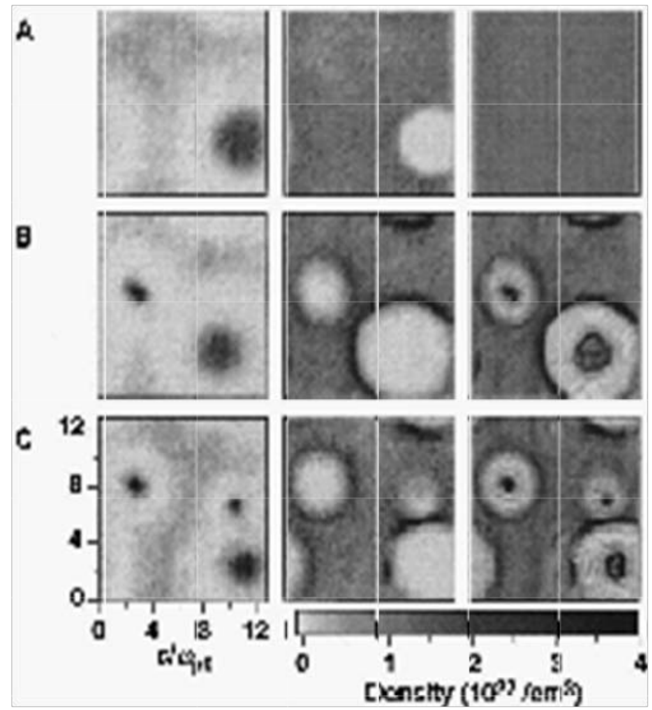


Quasi static B-fields

Y.Sentoku, K.Mima, S.Kojima, and H.Ruhl, Phys. Plasmas **7**, 689 (2000)

Transverse 2D

$\gamma b=10$, $n/n_c=10$



Ion immobile

Ion mobile

Ion mobile & Collision

Beam electron density,
Plasma electron density of return current, and
Total ion density at $\omega_p t=400$.

M.Honda, J.Meyer-ter-Vehn, and A.Pukhov, Phys. Plasmas **7**, 1302 (2000),and
Phys. Rev. Let. 85, 2128 (2000)

3MA/1MeV electron flow up-ward in the plane
Break-up into small filaments and self-organized
Excess entropy may be emmitted through electron loss.
About 40% of initial electron is confined in the channels.

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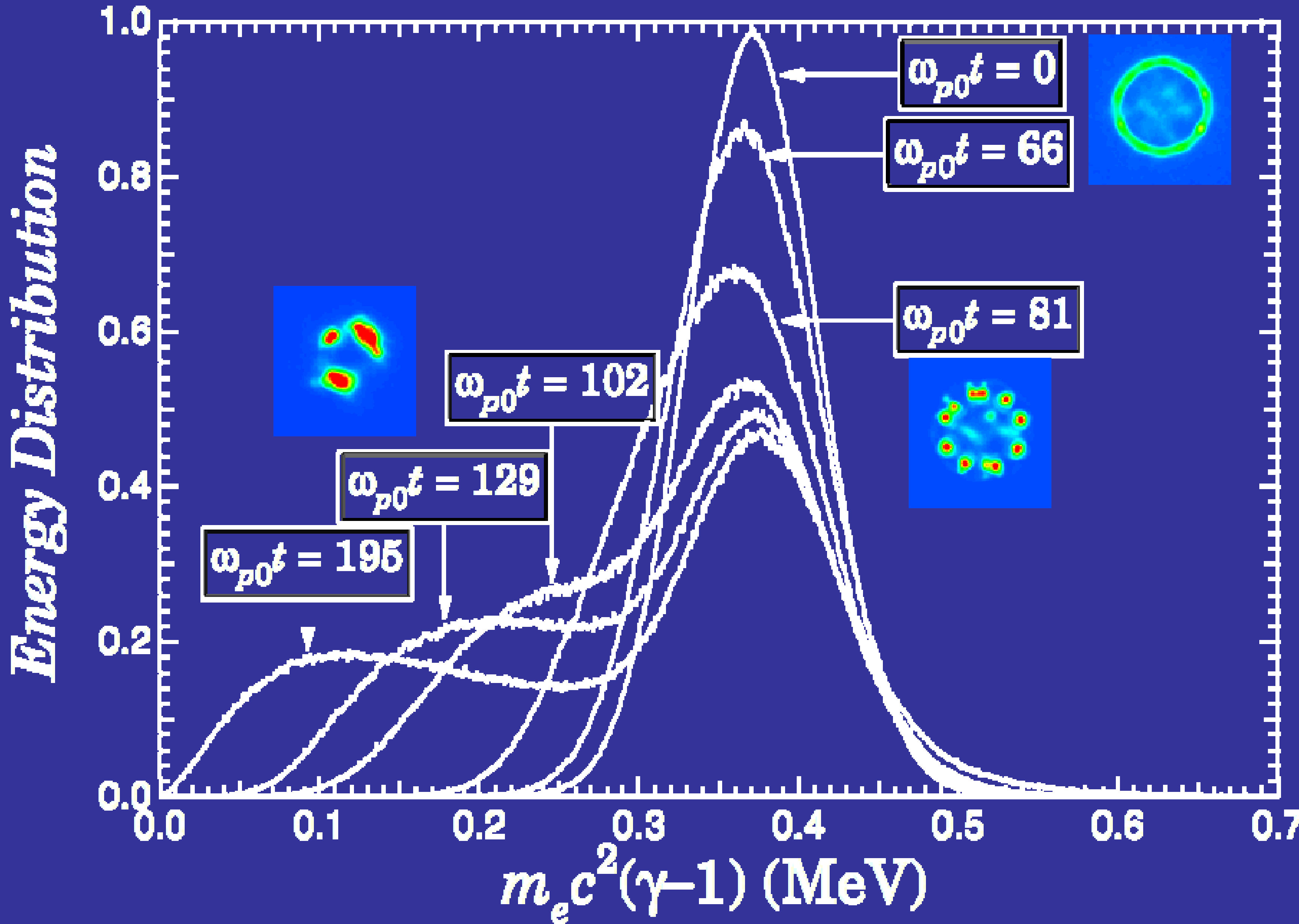
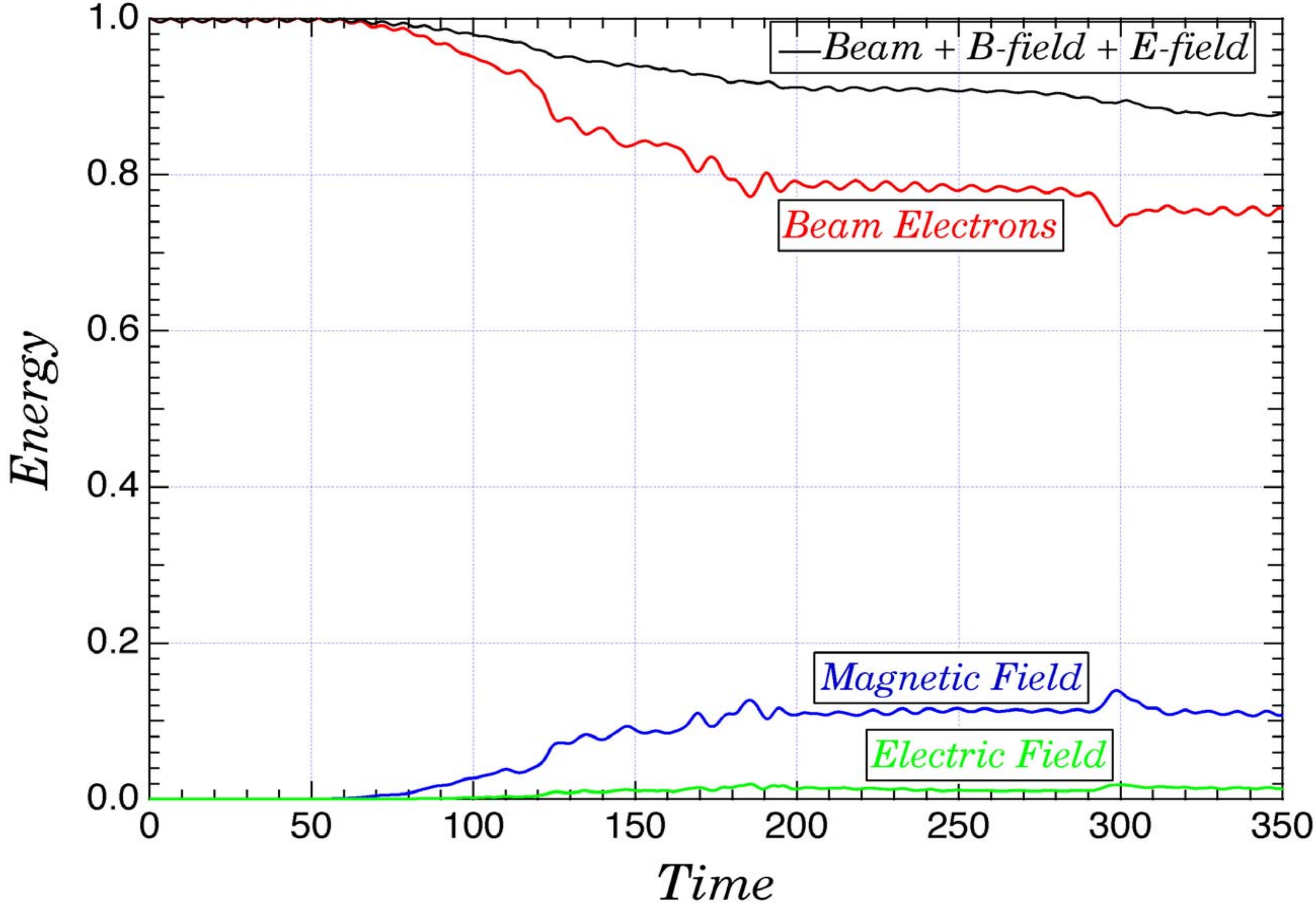
Temporal Evolution of Electron Energy Distribution



Temporal Evolution of Electron and Magnetic Field Energy

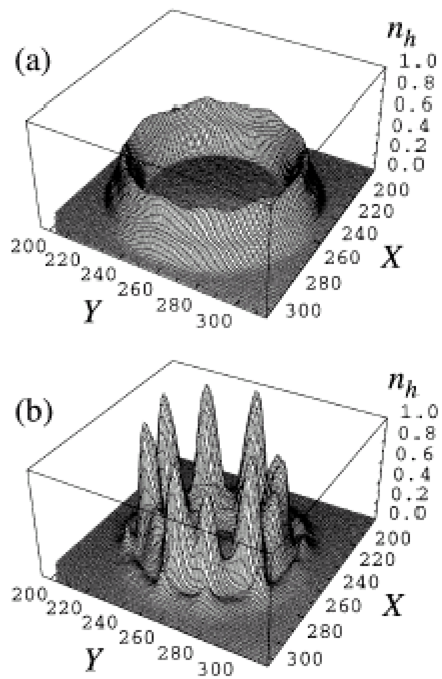


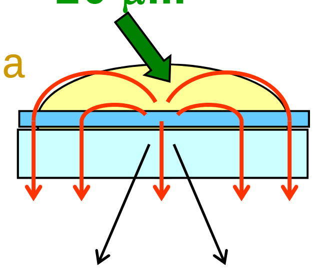
Cylindrical beam filamentation

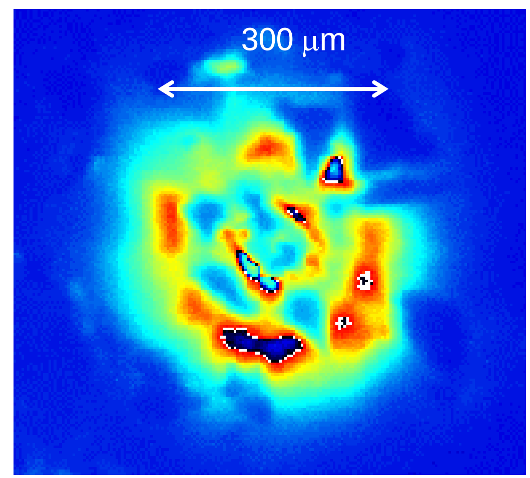
Taguchi et al.,
PRL 86, 5055 (2001)

$\omega_p t$ = 67

$\omega_p t$ = 81







After Mike Key, 2005

Weibel Instability

PRL, Honda, Meyertervehn,
PRL2001,

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Whistlerization of B fields

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EMHD turbulent magnetic field: nonlinear evolution of Weibel instability

Introducing QuickTimeý Ç² êLí£ÉvÉçÉOÉâÉÄ Ç™Ç±ÇÃÉsÉNÉ`ÉÉÇ¾å©ÇÈÇžÇ½Ç…ÇÕïKóvÇ-Ç□/ **in EMHD equation**

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A.Dus &P.Diamond
POP vol7, no1,(2000)

Inverse Cascade and Equi-partition

“Whistlerization” named by A.Dus &P.Diamond