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IAEA International Atomic Energy Agency

2155-30

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Outline of Lecture on Laser Plasma Physics/2

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Outline of Lecture on Laser Plasmas Physics

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- Introduction for laser plasma physics
  - laser science, fusion & laser plasma accelerator-
- Physics of Fast Ignition:
  1. Relativistic laser plasma interactions

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  2. Generation of intense relativistic electron and ion beams in dense plasmas
  3. Self generated magnetic fields and electron transport

ICTP, Trieste, Italy, 12, July, 2010

Relativistic laser plasma physics in Fast ignition

Laser intensity; I_L ~ 2x 10^{20} W/cm^2

Electron fluid equation:

$$\partial \mathbf{p}/\partial t + \mathbf{v}\cdot\nabla \mathbf{p} = \partial \mathbf{a}/\partial t + \mathbf{v}\times\nabla\times\mathbf{a} + \nabla\phi \quad \text{--->}$$

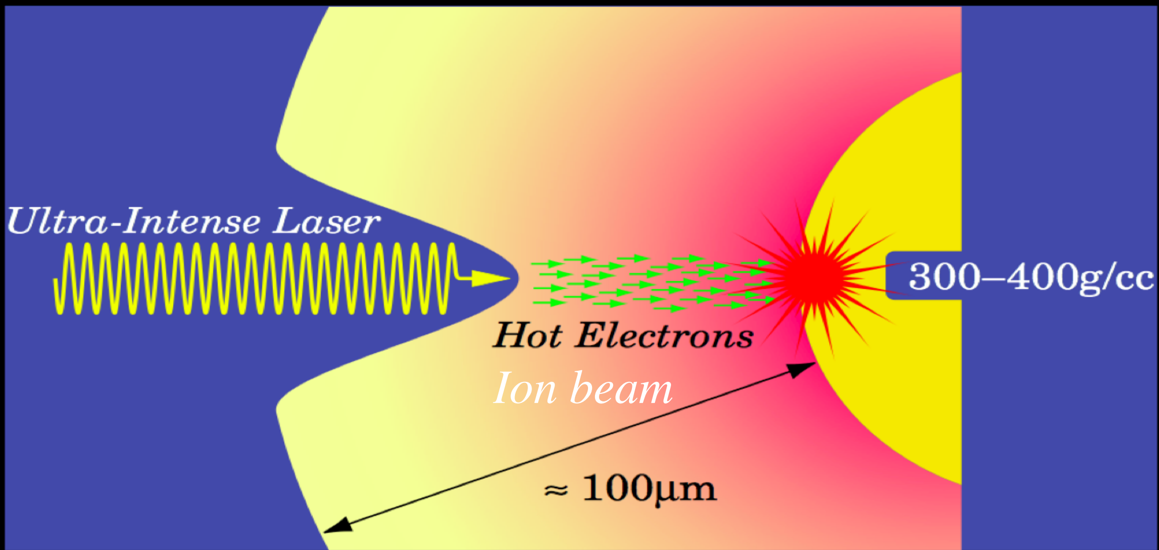
$$\partial/\partial t\,(\mathbf{p}-\mathbf{a}) + \mathbf{v}\times\nabla\times(\mathbf{p}-\mathbf{a}) = -\nabla\gamma + \nabla\phi$$

transverse motion: $\partial/\partial t[\nabla\times(\mathbf{p}-\mathbf{a})] + \nabla\times \mathbf{v}\times[\nabla\times(\mathbf{p}-\mathbf{a})] = 0$

longiyudinal moion: $\partial p_l/\partial t = -\nabla\gamma + \nabla\phi$, $\gamma = (1+a^2+p_l^2)^{1/2}$

Back ground electron energy in the laser field; $\varepsilon_r = (\gamma-1)mc^2$,

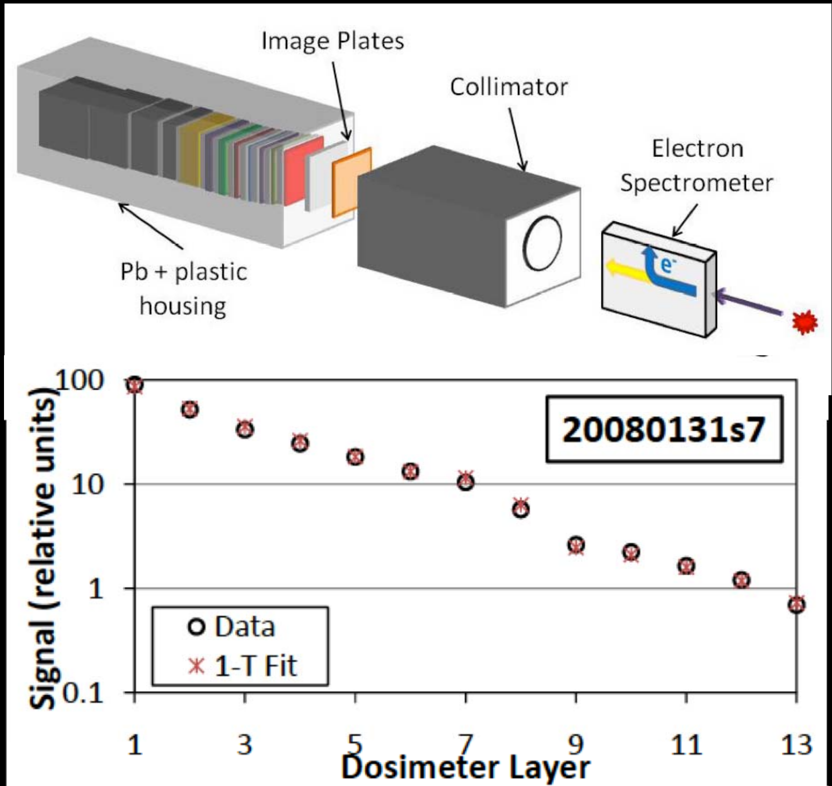
$\gamma = [1+ (eA/mc)^2]^{1/2} = [1+ I_L/(2.4\text{x}10^{18}\text{W/cm}^2)]^{1/2}$, So, $\varepsilon_r \sim$ 3~5 MeV



Laser produced relativistic electron beam and/or ion beam are discussed.

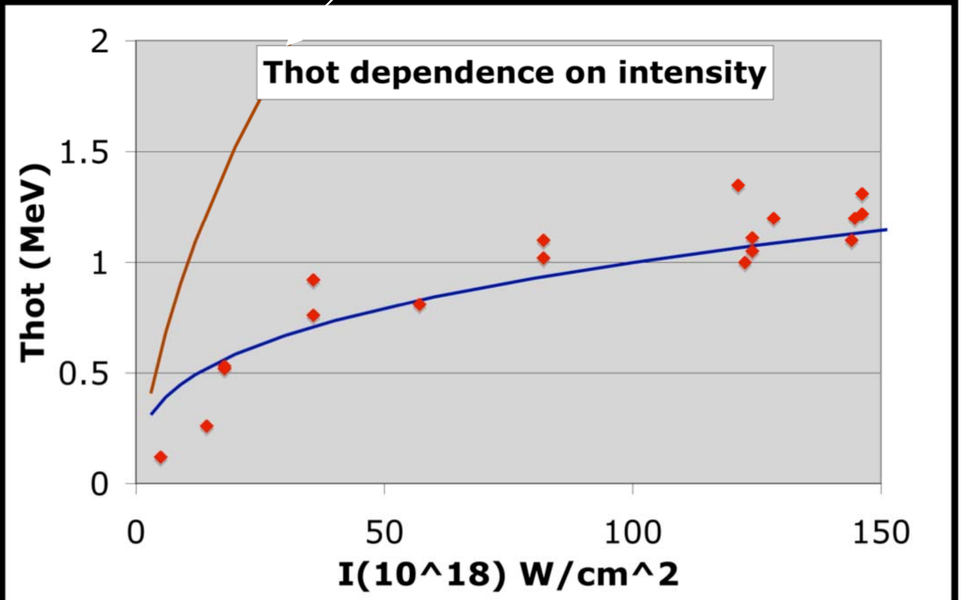
Bremsstrahlung diagnostic* confirms low hot electron temperature

- Fast electrons produce bremsstrahlung in target
- Detected with image plates interleaved with filters
- Detector response modeled with T_h and n_e as variables



Wilks scaling

T_{hot} **(MeV)= 0.5(1+** $I_L/(2.4\times10^{18} W/cm^2))^{1/2}-1$



Single temperature fit shows hot electron temperature follows Beg's scaling†: $T(\mathrm{MeV}) = 0.215(I_{18})^{1/3}$

*C. Chen et al., HTPD conference 2008
†F.N. Beg *et al.*, Phys. Plasmas **4**, 447 (1997)

Collision-less absorption in highly relativistic regime is relevant to Fast Ignition

- There are very many experiments and simulations, but not well understood yet!
- In this regime, density profile steepening is essential --> polarization dependent
- Steep plasma-vacuum surface oscillates by $2\omega_0$ oscillating ponderomotive force.--> Oscillating piston
- The oscillating mirror producing many higher harmonics together with high energy electron

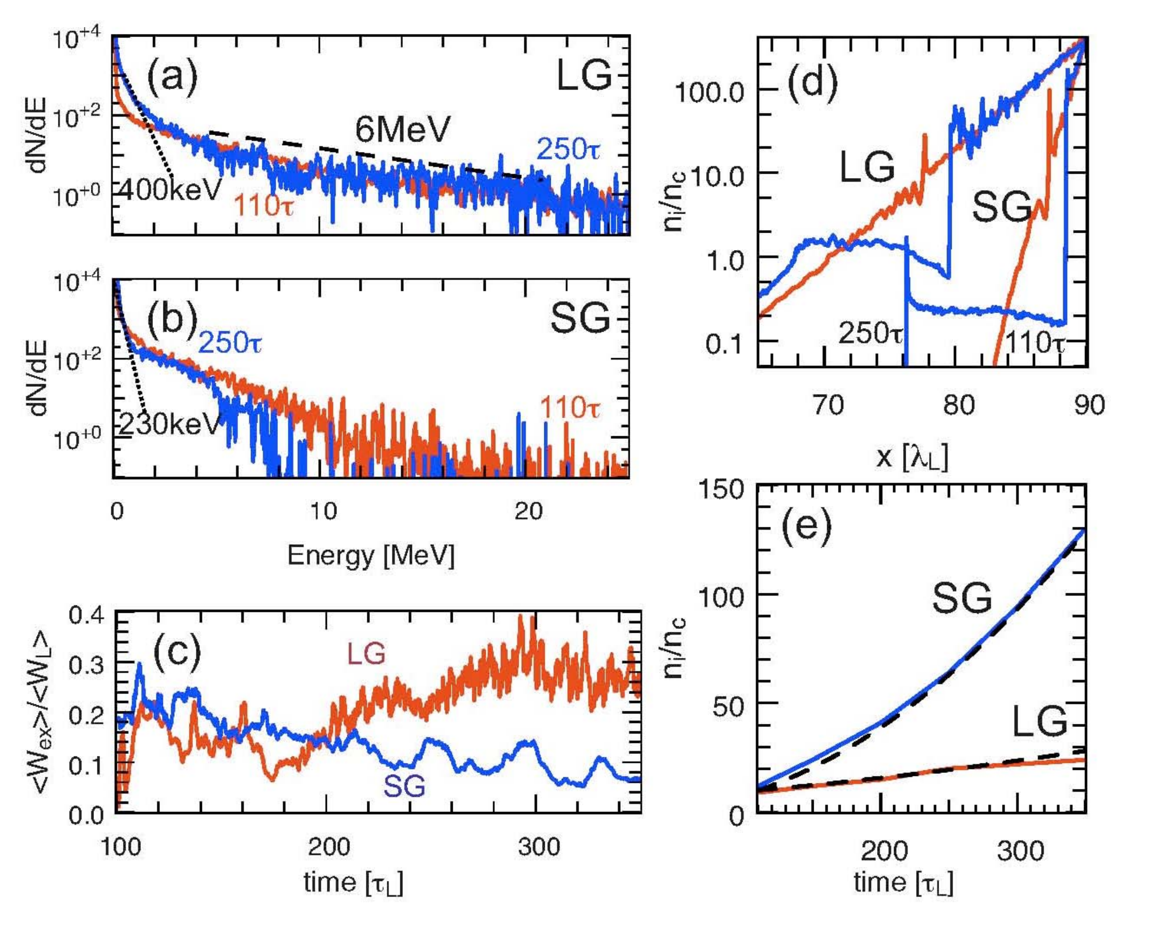
  ---> many observation (Gibon etal, Gibbon, 1992)

Electron energy spectrum

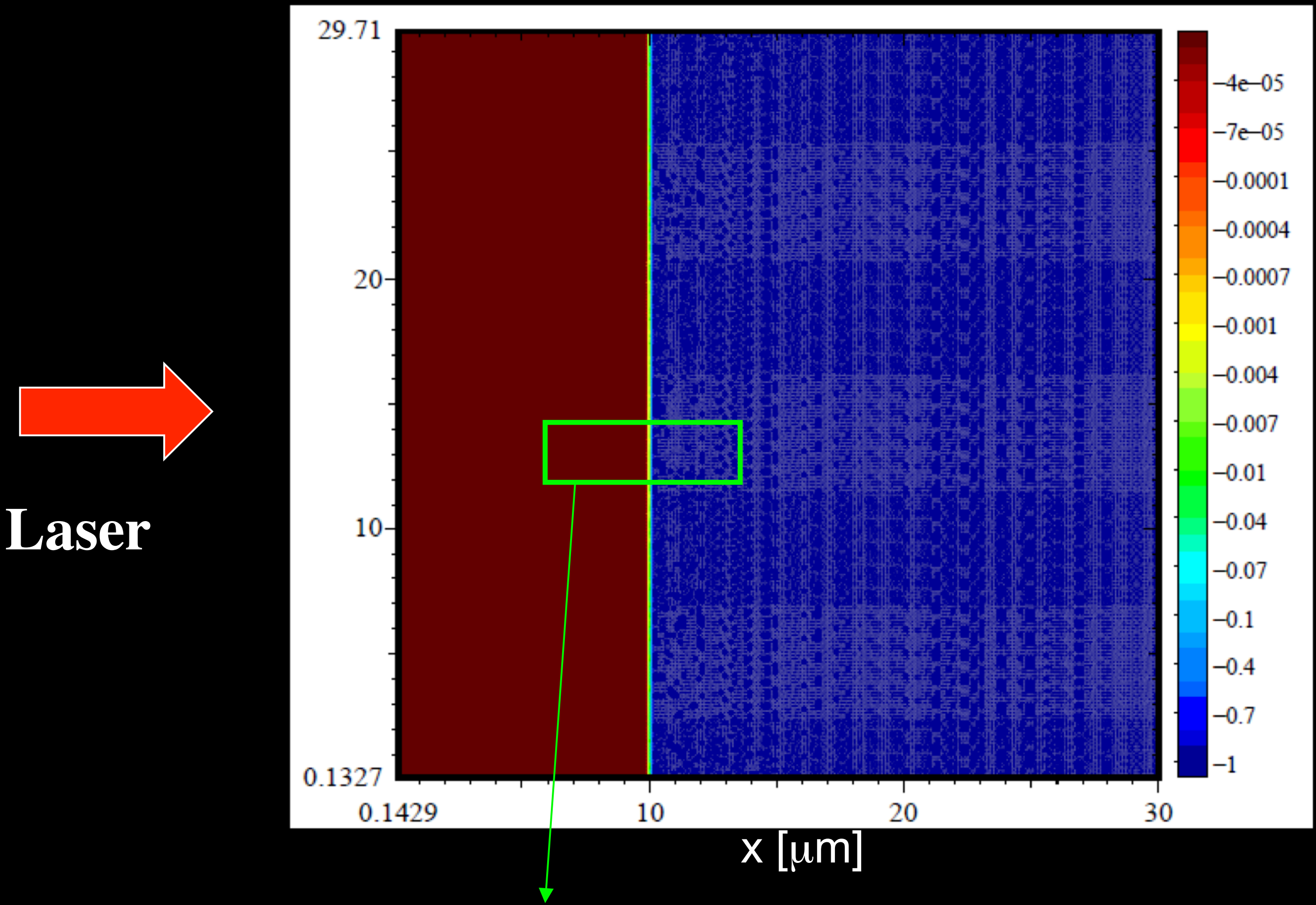
M.Hains (PRL 102, 045008 (2009)),

$T_h = mc^2 \{[1+2(I/mn_c c^3)^{1/2}]^{1/2} - 1\}$

A.Kemp & Y.Sentoku (PHYSICAL REVIEW E 79, 066406 (2009))

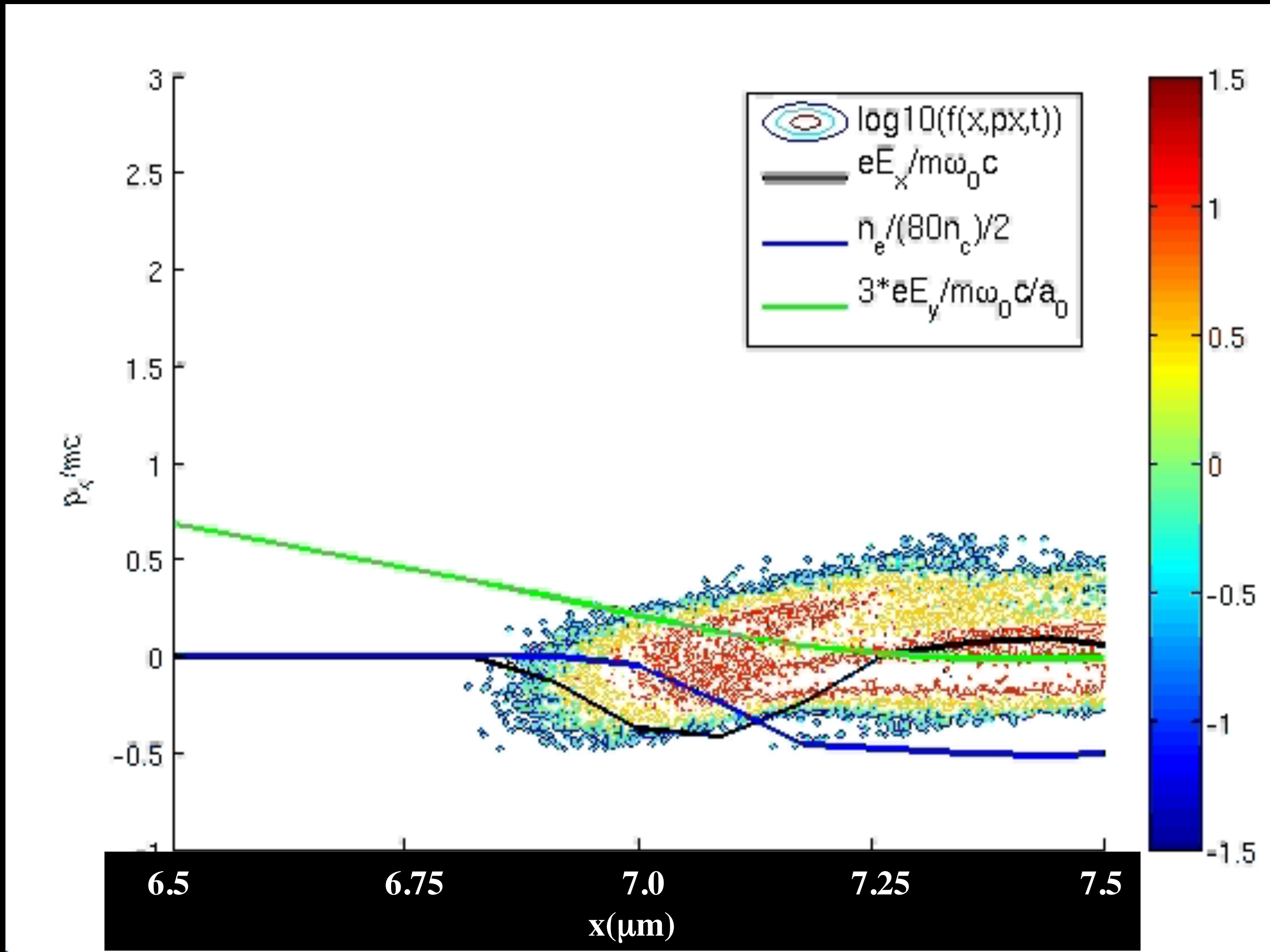


Simulation on solid surface plasma interactions



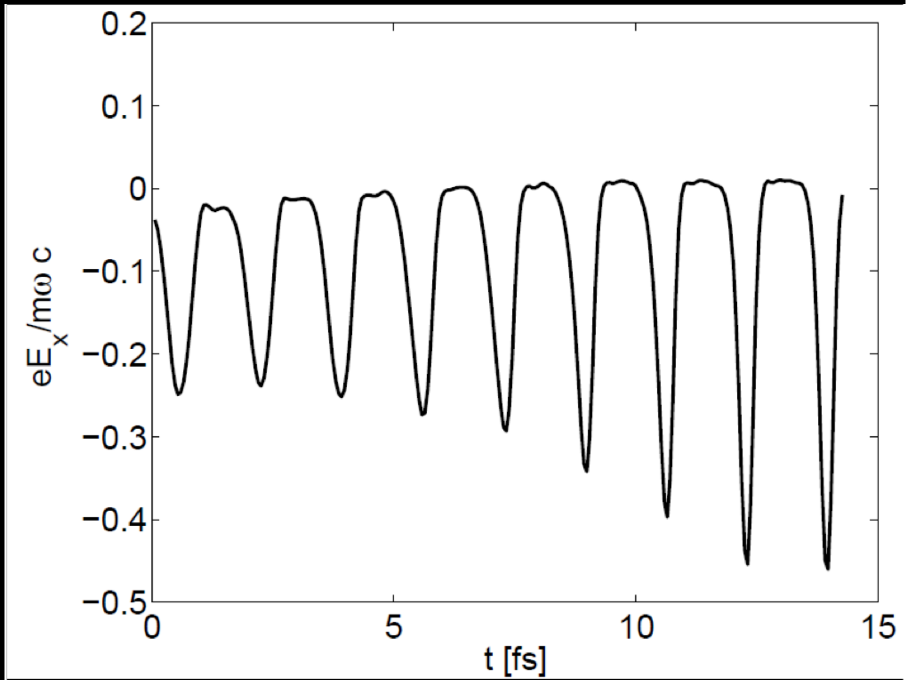
I have done a transversal mean over 2 μm of the electron density n_e, the longitudinal electric field E_x, and the transverse electric field E_y to have only the 1D behaviour without fluctuations. Note that electrostatic field is quasi longitudinal has I used a Super-gaussian laser field plane wave. In the same region I extract $f(x,p_x,t)$

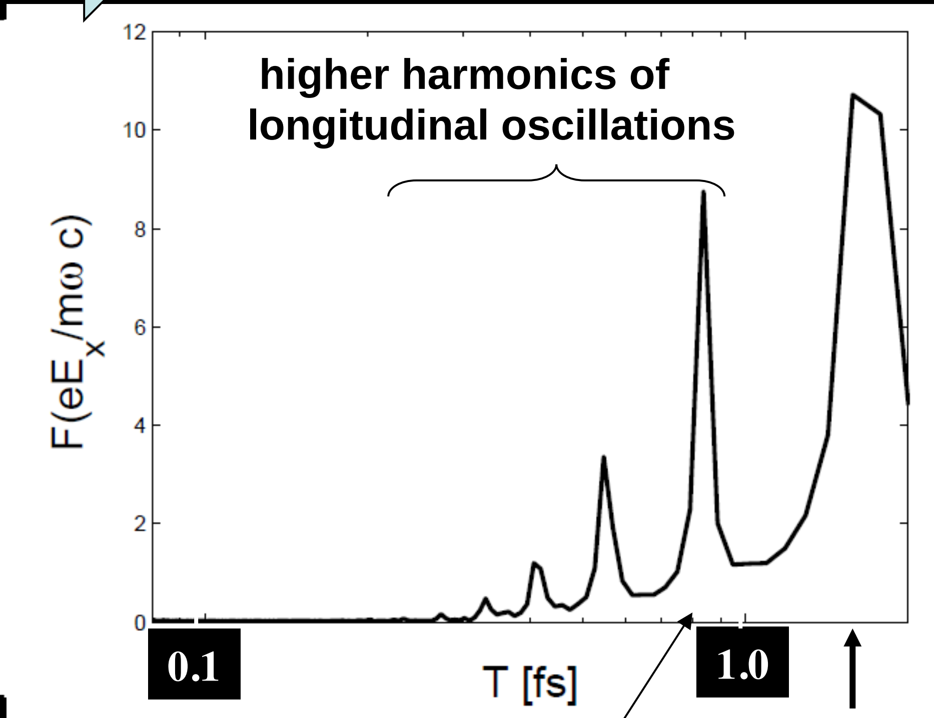
Video of all observables over ~2 laser cycles
-Oscillating piston-



Let’s have a look at the time evolution of the phase space dynamics.

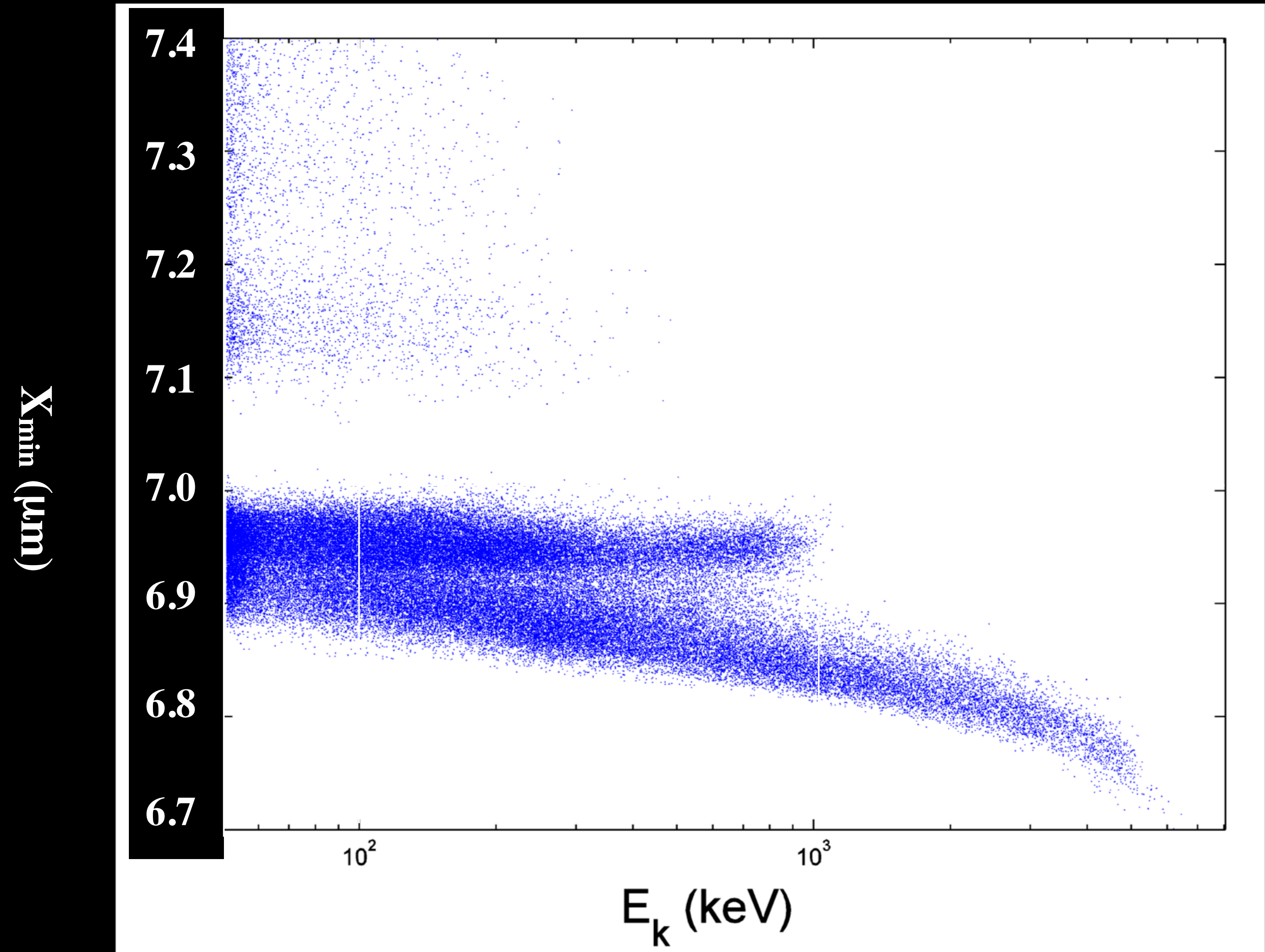
Frequency specrum of $E_x(x\sim10.01\ \mu m)$





Higher Harmonics are small in
comparing to $2\omega_0$ oscillation

Generation of Relativistic Electrons on Solid Surface



Oscillating piston model-1

$$t \to \omega_0 t, \quad x \to \omega_0 x / c, \quad A \to eA / mc, \quad \phi \to e\phi / mc^2,$$
$$n_c = m\varepsilon_0 \omega_0^2 / e^2, \quad n_e / n_c \to n, \quad n_i / n_c \to n_0,$$

Laser amplitude *A*: normal incidence

$$A = a e_y, \quad \left(\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} \right) a + na/\gamma = 0$$

Electron fluid dynamics (uniform in y direction):

Canonical momentum: $P_y = p_y - a = 0$

$\partial u/\partial t = \partial\phi/\partial x - \partial\gamma/\partial x$

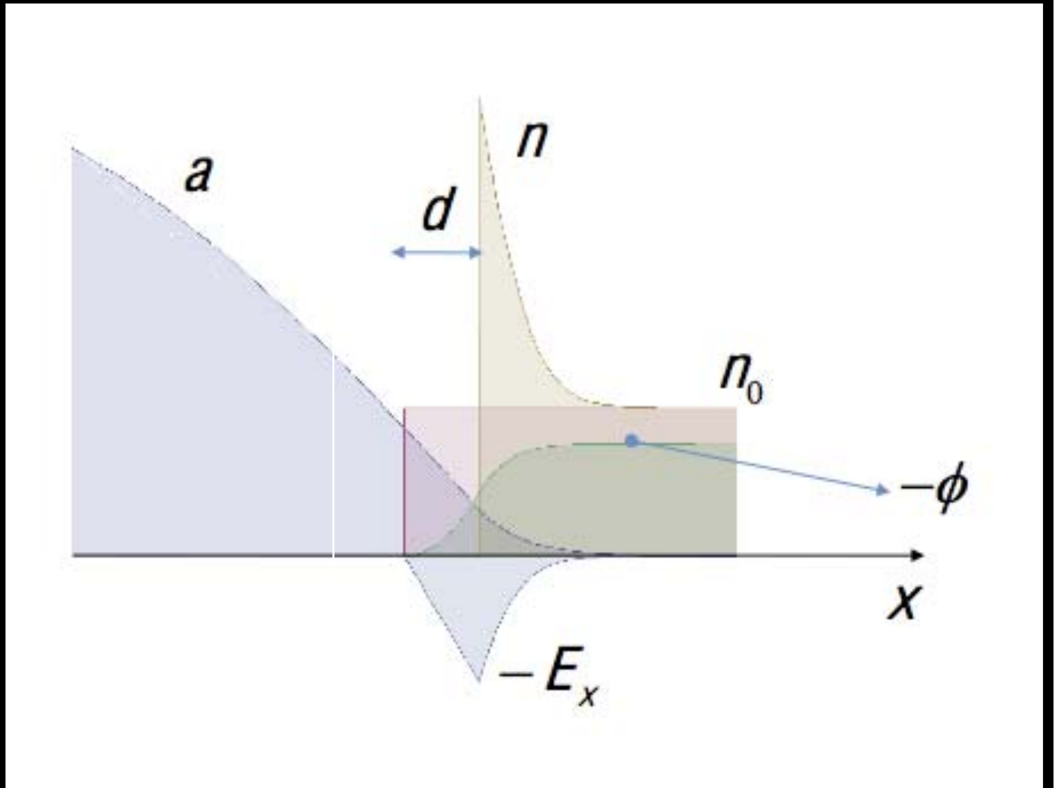
$\gamma = (1+a^2+u^2)^{1/2}$, where $u = \gamma v_x$

$\partial n/\partial t + \partial(nu/\gamma)/\partial x = 0$

$\partial^2\phi/dx^2 = n - n_0$

When $n_0 \gg 1$, $a_0^2 \gg 1$

(at $I_L \sim 10^{20}$ W/cm^2 , they are 20~100)



Then, in solid plasma, electron inertia can be neglected as the first order;
$\partial\phi/\partial x - \partial\gamma/\partial x = 0$. So, $n = n_0 + \partial^2\gamma/\partial x^2 > n_0$ in evanescent region : x>d).

Oscillating piston model-2

$$\frac{\partial^2\phi}{\partial x^2} = -n_0, \quad \Rightarrow \quad \phi = -\frac{1}{2}n_0 x^2, \quad 0 \le x \le d(t)$$

Electrons are expelled completely by the radiation pressure.

At $x = d(t)$, $\partial\phi/\partial x = \partial\gamma/\partial x$: force balance yields

$$d(t) \quad \frac{(2a_0^2/n_0^2)\sqrt{n_0-1}\left(1+\cos(2t-2d+\pi-2\varphi)\right)}{\sqrt{1+\frac{2a_0^2}{n_0}\left(1+\cos(2t-2d+\pi-2\varphi)\right)}},$$

$p_x = \gamma\, dd(t)/dt$

$\sim 2a_0^2/n_0^{3/2}$

$n_0 \sim \gamma_0 \sim a_0$ -->

$p_x \sim a_0^{1/2} \sim I_L^{1/4}$

For standing

$$a(x,t) = a_0\left(\cos(t-x) - \cos(t+x-2d-2\varphi)\right), \quad \tan\varphi = \frac{1}{\sqrt{n_0-1}}, \quad x < d$$

$$a(x,t) = \frac{2a_0}{\sqrt{n_0}} e^{-(x-d)\sqrt{n_0-1}} \cos(t-d+\pi/2-\varphi), \quad x \ge d$$

Oscillating piston model-3

Because of oscillation of ponderomotive force, electrostatic potential is modified as follows

$$\frac{\partial n}{\partial t}+\frac{\partial}{\partial x}\left(\frac{n}{\gamma}u\right)=0, \quad \Rightarrow \quad \frac{\partial}{\partial x}\left(\frac{\partial}{\partial t}\frac{\partial \gamma}{\partial x}+\frac{1}{\gamma}\left(n_0+\frac{\partial^2\gamma}{\partial x^2}\right)u\right)=0,$$

$$\Rightarrow \quad \frac{\partial}{\partial t}\frac{\partial \gamma}{\partial x}+\frac{1}{\gamma}\left(n_0+\frac{\partial^2\gamma}{\partial x^2}\right)u=0, \Rightarrow \quad u\approx-\frac{\gamma\frac{\partial}{\partial t}\frac{\partial \gamma}{\partial x}}{n_0+\frac{\partial^2\gamma}{\partial x^2}}\frac{1}{\sqrt{n_0}},$$

Then, the electrostatic potential corrected is:

$$\boxed{\frac{\partial \phi}{\partial x}=\frac{\partial \gamma}{\partial x}+\frac{\partial u}{\partial t}\equiv\gamma_x-\frac{\partial}{\partial t}\frac{\gamma\gamma_{xt}}{n_0+\gamma_{xx}}, \quad \gamma\equiv\sqrt{1+a^2}},$$

Oscillating piston model-4

The Hamiltonian for a test particle in $x > d(t)$ and its equations are:

$$H = \sqrt{1 + a^2 + p_x^2} - \phi, \quad \Rightarrow$$

$$\frac{dp_x}{dt} = -\frac{aa_x}{\sqrt{1 + a^2 + p_x^2}} + \gamma_x - \frac{\partial}{\partial t}\frac{\gamma\gamma_{xt}}{n_0 + \gamma_{xx}}, \quad \gamma \equiv \sqrt{1 + a^2},$$

$$\frac{dx}{dt} = \frac{p_x}{\sqrt{1 + a^2 + p_x^2}},$$

Equations in 0<x <d : ion sheath layer

$$\frac{dp_x}{dt} = -\frac{aa_x}{\sqrt{1 + a^2 + p_x^2}} - E_0\, x/d^2$$

$$\frac{dx}{dt} = \frac{p_x}{\sqrt{1 + a^2 + p_x^2}},$$

Equations in x<d

$$\frac{dp_x}{dt} = -\frac{aa_x}{\sqrt{1 + a^2 + p_x^2}}$$

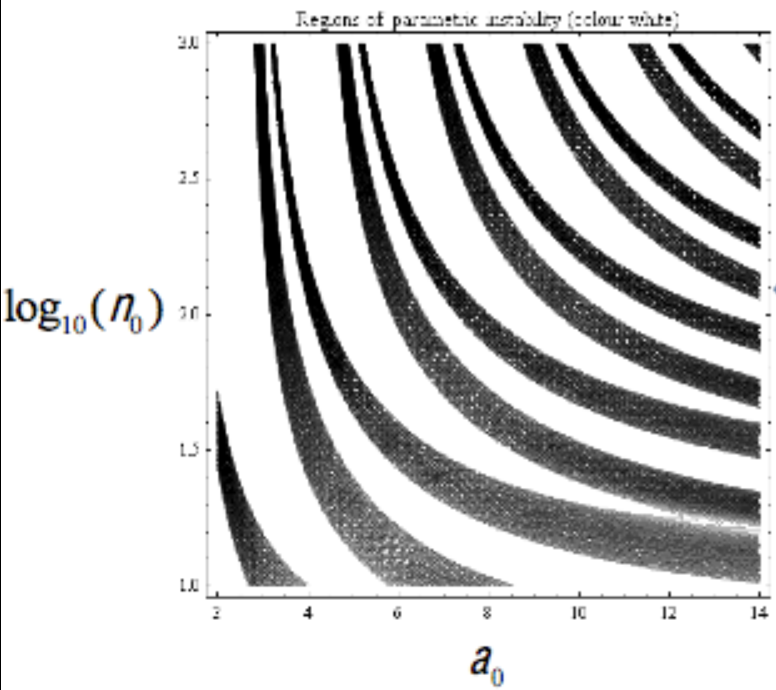
$$\frac{dx}{dt} = \frac{p_x}{\sqrt{1 + a^2 + p_x^2}},$$

Electron acceleration by piston

Electrons around x=d with very low energy are parametrically unstabilized in a region of n$_0$ and a$_0$

$$\frac{d^2x}{dt^2}+(1-\cos 2t)\,x\Theta(x)=0,\quad \Theta(x)\equiv\begin{cases} n_0, & x>0,\\ \frac{1}{2}a_0^2, & x\le 0,\end{cases}$$

➢ Period Poincaré map: $M(t+(j+1)\pi)=A^j M(t)$, $j=1,2,$



➢Let A be the matrix of the map.

➢ Boundaries of parametric instability: $|tr(A)|=2$

Particle dynamics

Electrons with not very low energy undergoing chaotic trajectories after the aparison of few internal resonances.

$$a = a_0 \sin t \sin x, \quad x \le 0,$$

$$\phi = -\frac{1}{2} n_0 x^2 (1 - \cos(2t)), \quad 0 < x \le d_0 \equiv \frac{2a_0}{n_0},$$

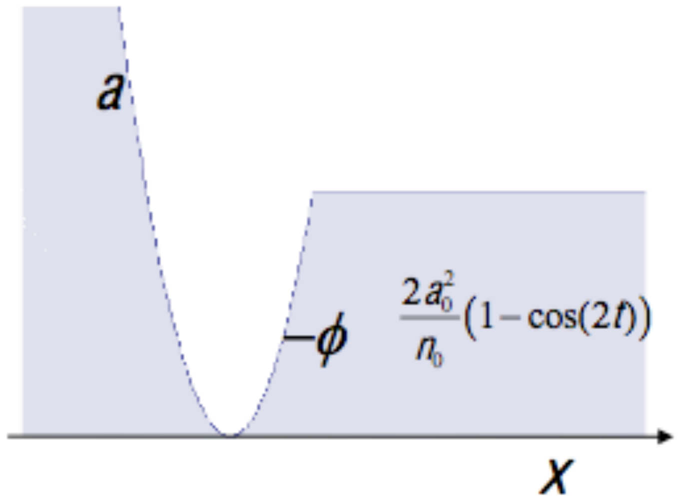
$$\phi = -\frac{1}{2} n_0 d_0^2 (1 - \cos(2t)), \quad x > d_0,$$

$$H = \sqrt{1 + p_x^2 + a^2} - \phi, \quad \Rightarrow$$

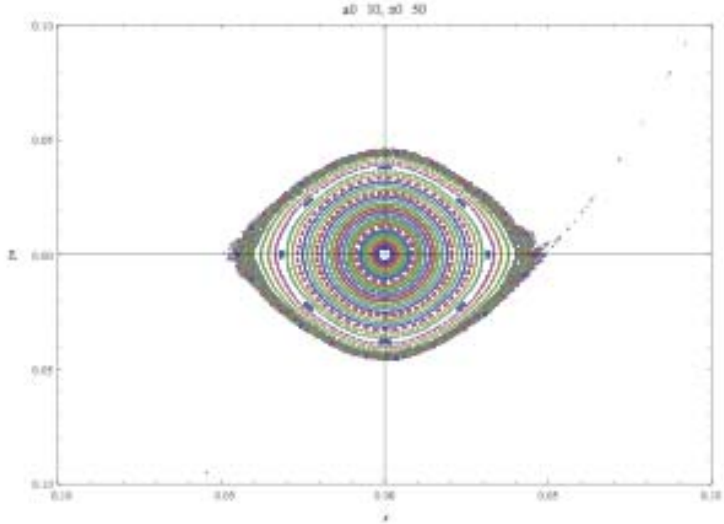
$$\frac{dp_x}{dt} = -\frac{1}{\sqrt{1 + p_x^2 + a^2}} \partial_x \left(\tfrac{1}{2} a^2\right) + \partial_x \phi, \quad \frac{dx}{dt} = \frac{p_x}{\sqrt{1 + p_x^2 + a^2}}$$

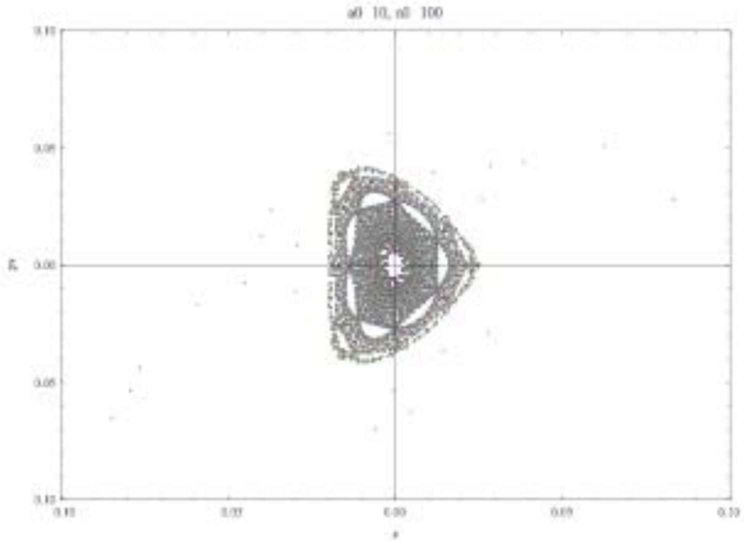
- Period Poincaré map:

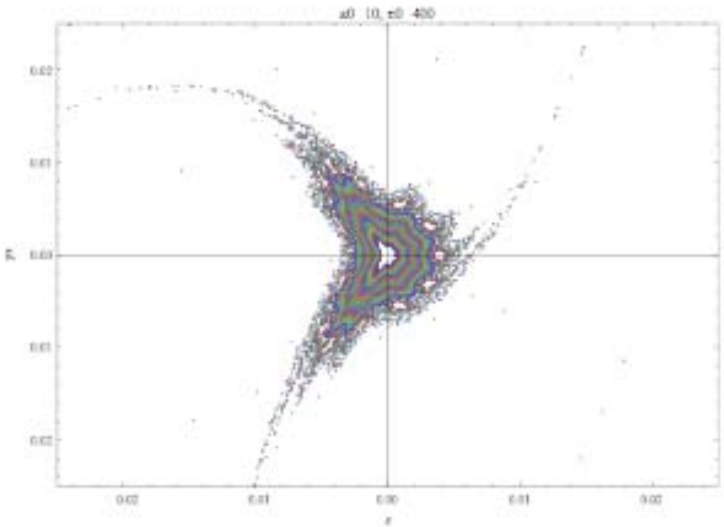
$$\boxed{\begin{aligned} p(t_0 + (n+1)\pi) &= F(p(t_0 + n\pi), x(t_0 + n\pi)), \\ x(t_0 + (n+1)\pi) &= G(p(t_0 + n\pi), x(t_0 + n\pi)), \end{aligned}}$$



Particle behavior

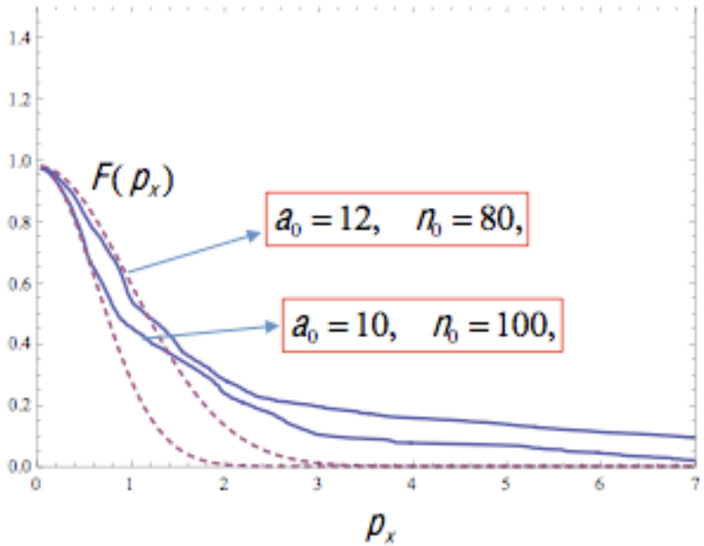


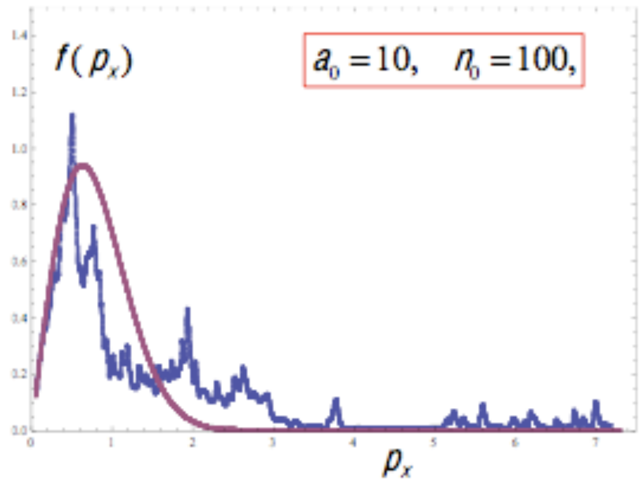


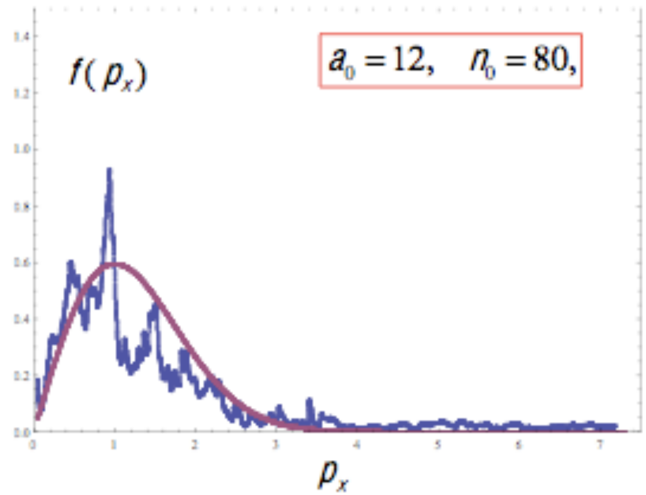


Energy distribution

Fast electrons distribution function







- F(p)=probability for p>px.
- f(px)=-dF(px)/dx.

Summary on the laser produced hot electron

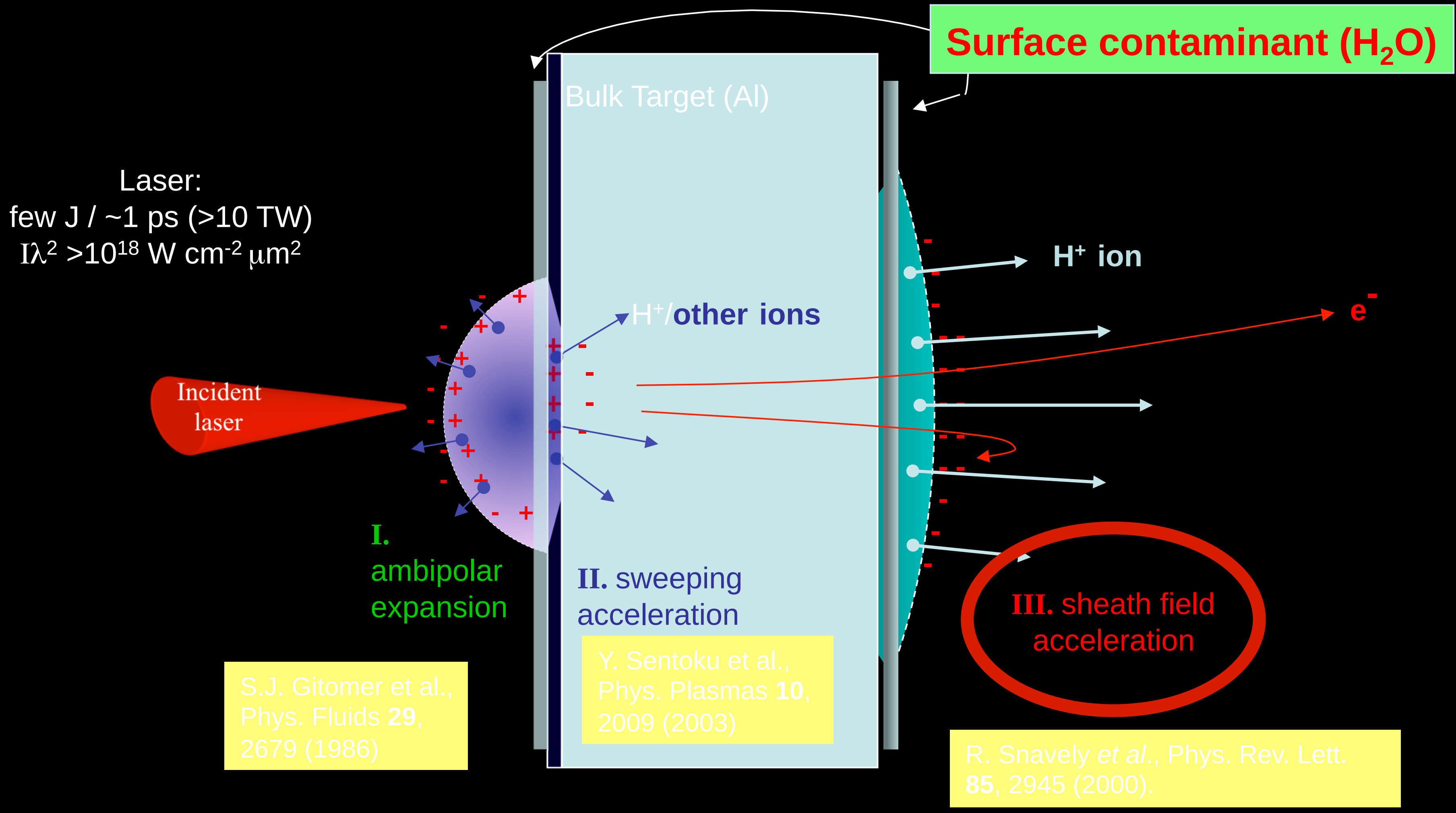
Energy and laser intensity scaling low for the relativistic electron generated on the solid surface are still open question.

$$T_h \sim \ (I_L/\lambda^2)^{1/4\sim 1/3}$$

is probable for a clean laser pulse.
Two component hot electrons from outside and inside at the laser-plasma boundary.

Further analysis for the scaling into the ignition scale plasma is necessary.
It is very important for the Fast Ignition.

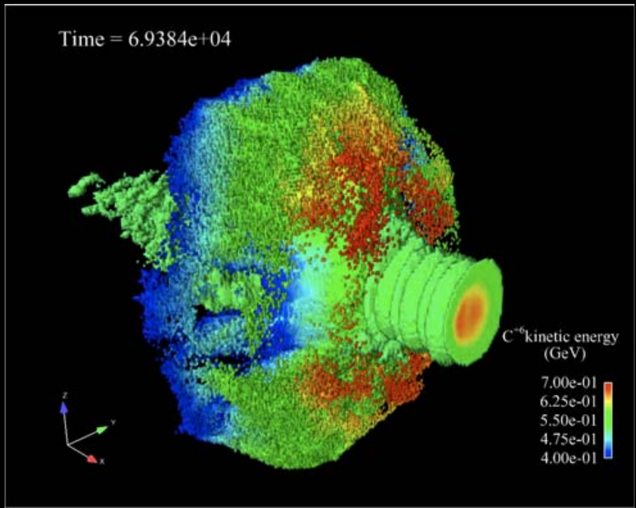
Mechanisms of laser-acceleration of *ions*



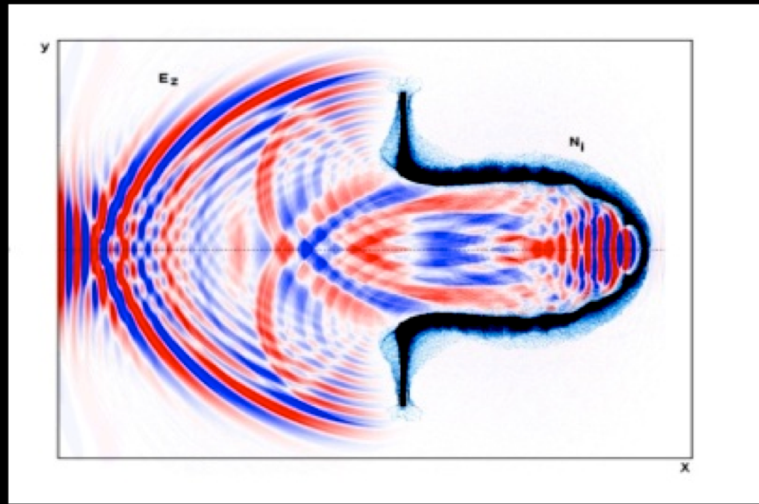
if target is heated ➔ efficient acceleration of heavy ions

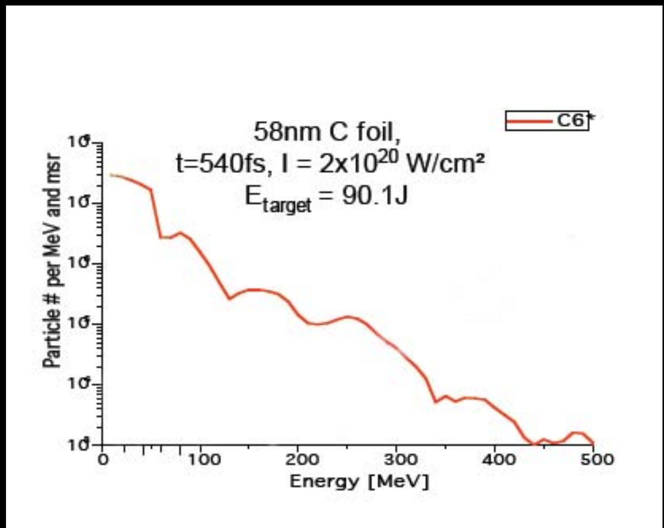
[M. Hegelich et al., Phys. Rev. Lett. **89**, 085002 (2002).]

Break-Out After-burner(BOA), Radiation Pressure Driven A.(RPDA)



T. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, and T. Tajima Physical Review Letters, 92, 175003 (2004)





Juan Fernandes, etal
LANL report, 2009

Simulation by S.Bulanov eal, Recently,very thin foil exp. with clean short pulse laserTrident, LANL

Requirements for electron fast heating

Assume hot spark area density: ρr_h: 0.6 g/cm^2

[Electron heat deposition range]

Imploded plasma density : 1000times solid density

$\rho_h \sim 200$g/cm^3

Hot spark radius: $r_h \sim$ 30μm

$\varepsilon_h < 3$MeV <---- $2\rho r_h \sim 1.2$ g/cm^2 >range

not too high energy

- Total energy of DT hot spark : $3N_hT_h \sim$ 5kJ -> 10kJ
- where $N_h \sim 2\times10^{18}$, $T_h \sim 10$keV
- Heating efficiency of 10 % then: total laser energy: 100kJ

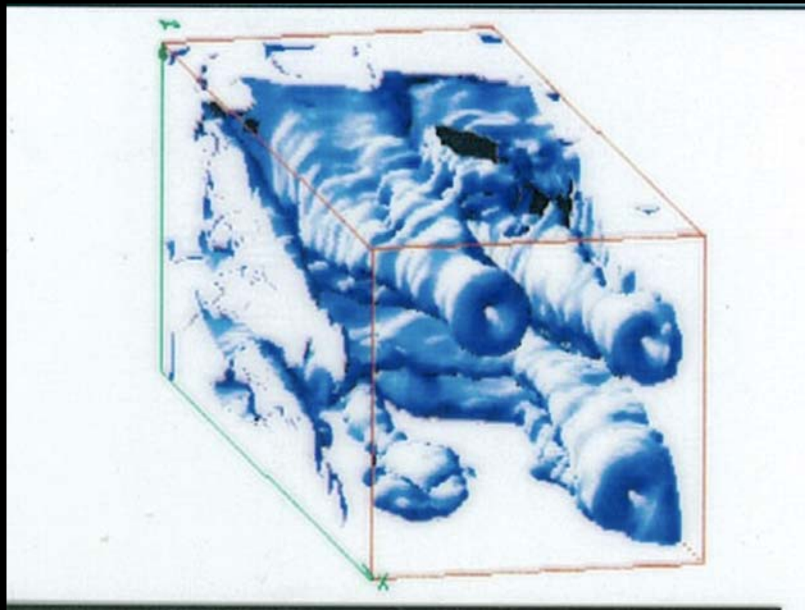
[Electron beam forcus]

Heating e-beam diameter: 60 μm$^\phi$

Distance from heat deposition point to hot spark: 100μm

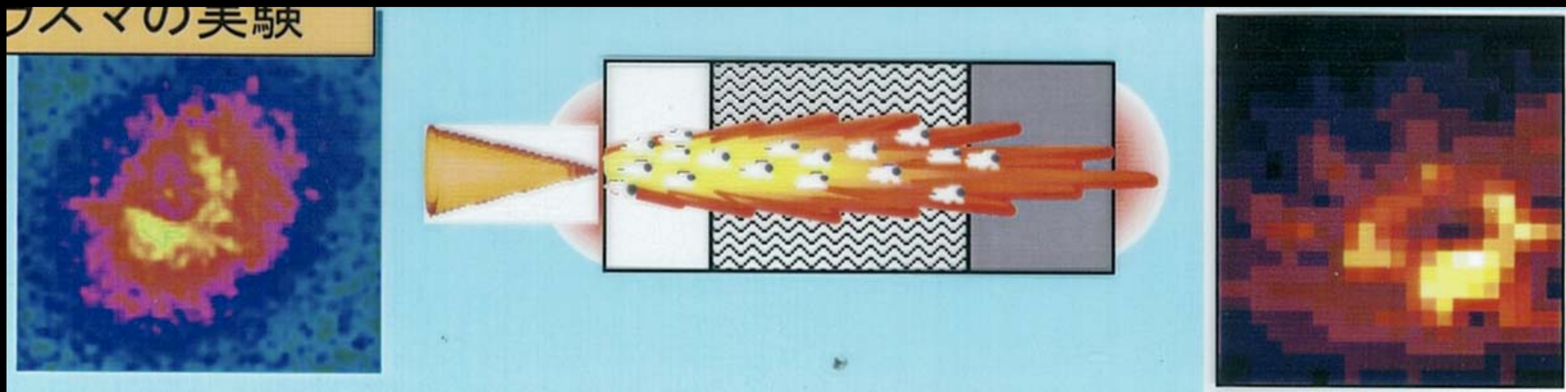
Beam divergence full angle: 0.6 radian ~ 30^o

Self generated magnetic field



Y.Sentoku, K.Mima
Phys.Rev.E(2002)

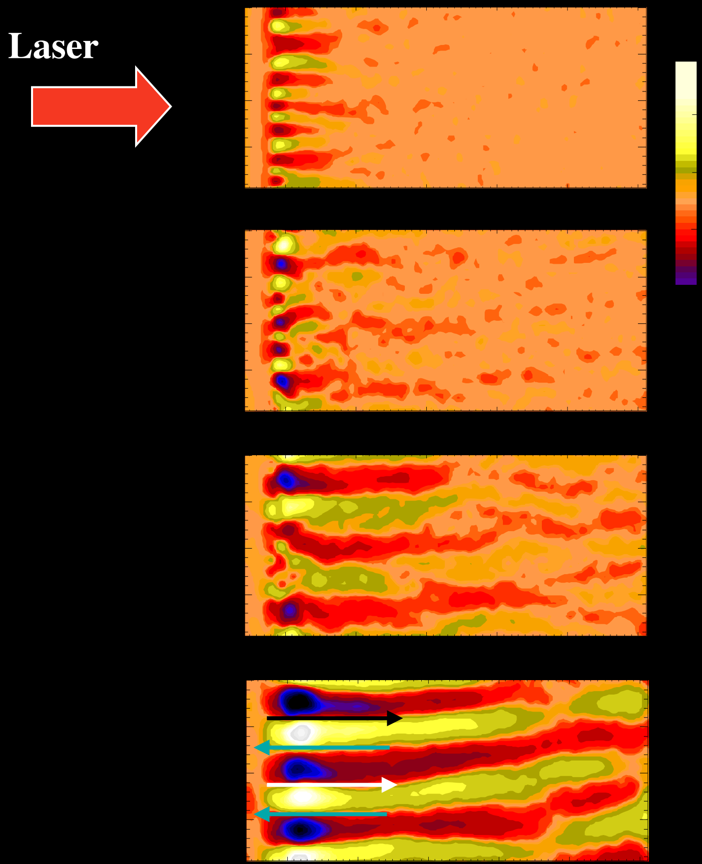
R.Kodama, etal
POP. 2002



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

Longitudinal 2D

a=3 , n/n_c =20

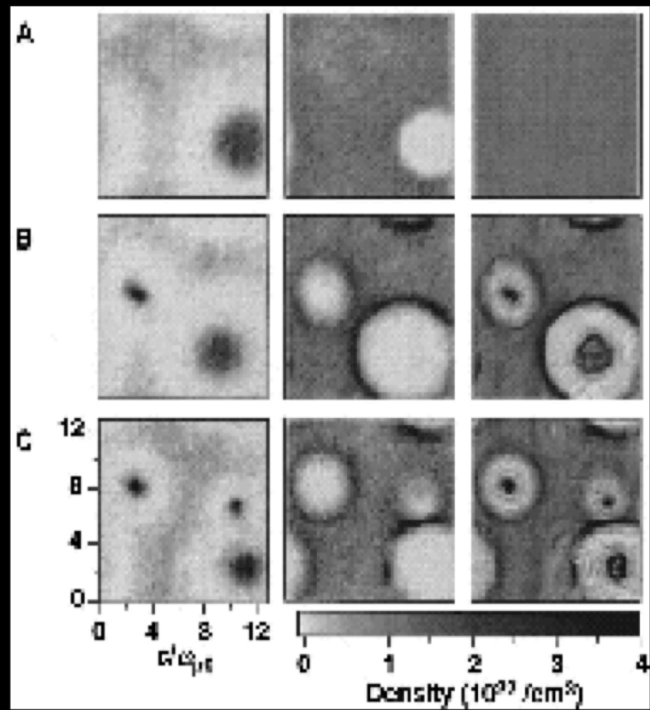


Quasi static B-fields

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

Transverse 2D

γ_b=10 , n/n_c =10



Ion immobile

Ion mobile

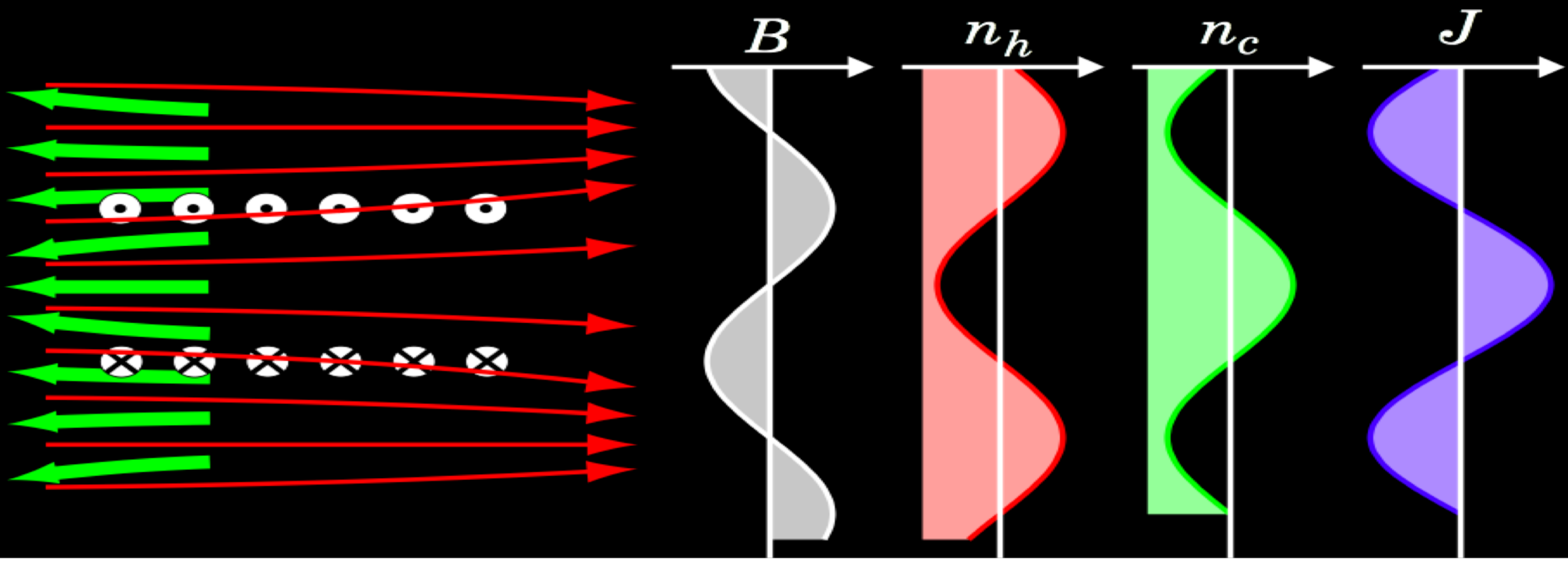
Ion mobile & Collision

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)

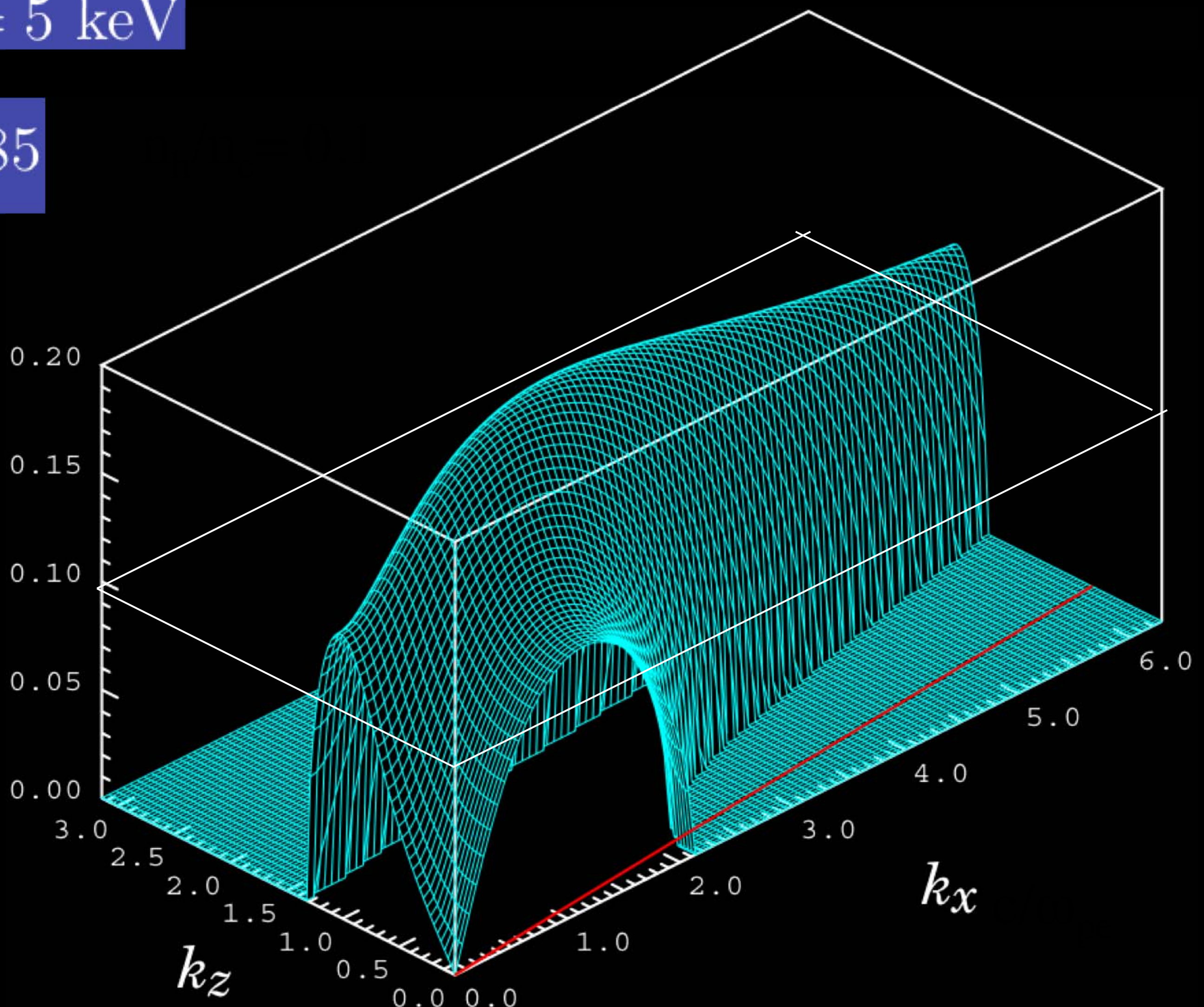
Weibel Instability

Transversely Fluctuating Magnetic Field Separate Two Electron Streams

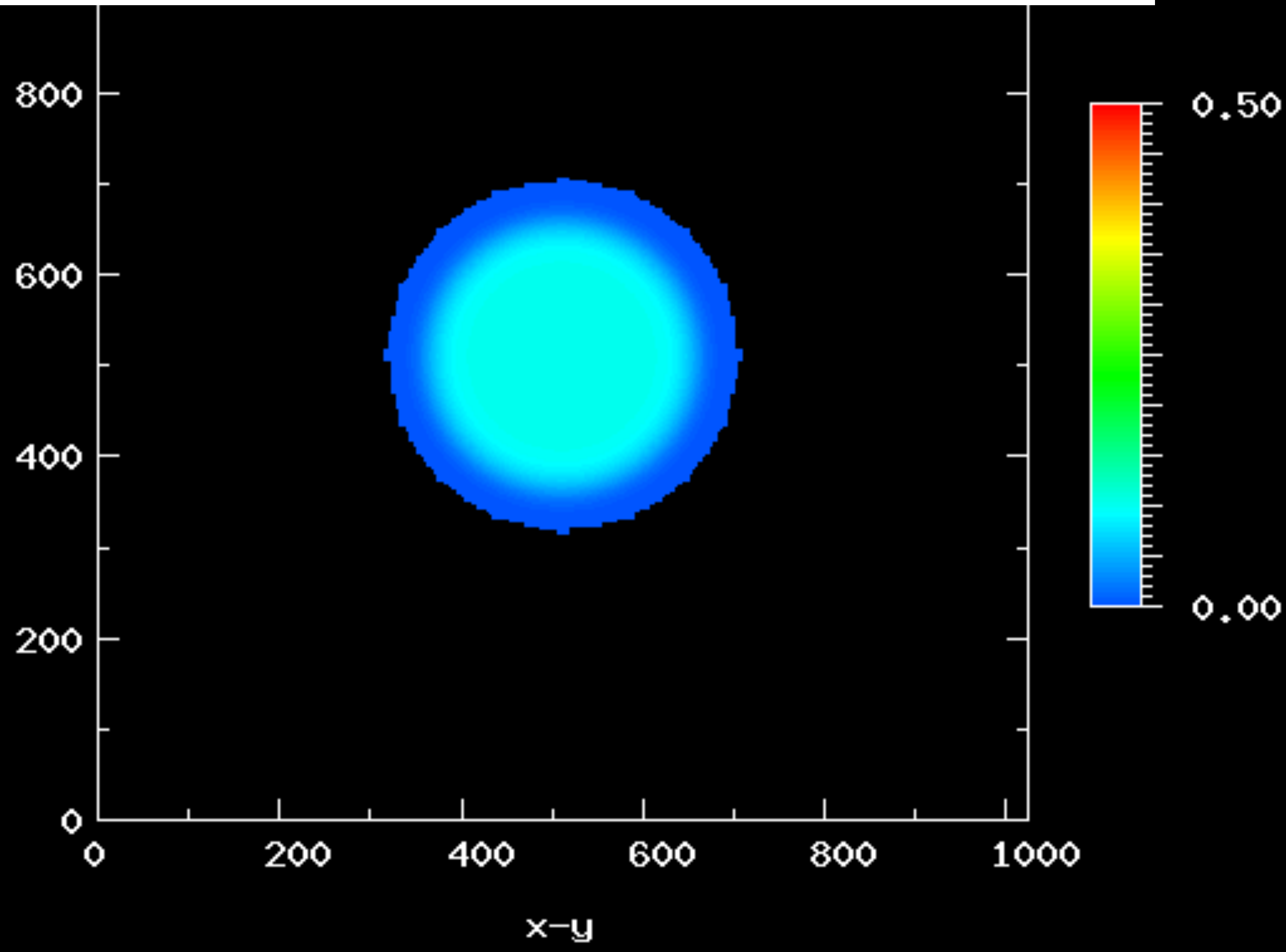


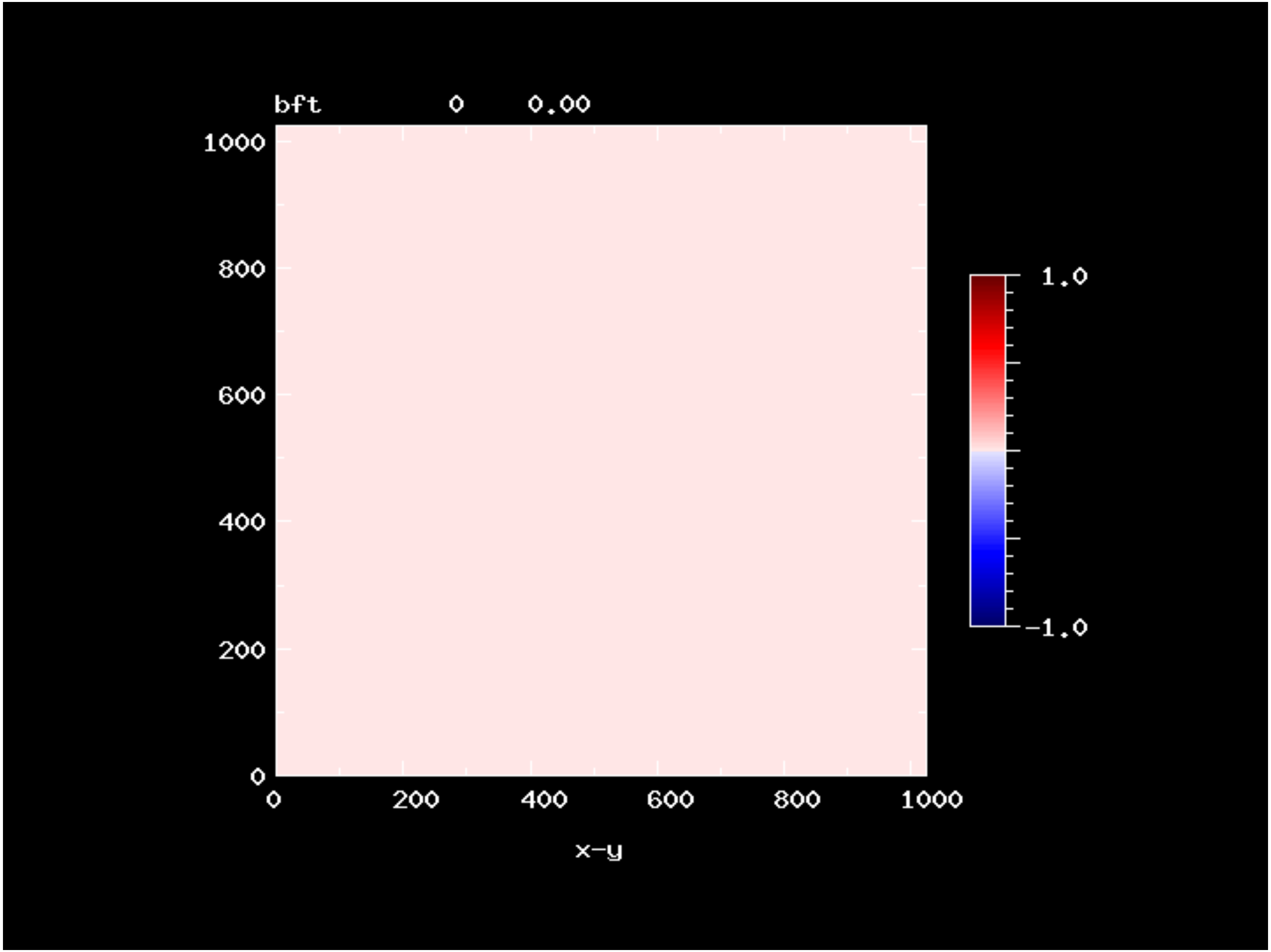
$T_h = T_c = 5 \text{ keV}$

$\frac{u_h}{c} = 0.885$



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.





bft 0 0.00
1000
800
600
400
200
0
0
200
400
600
800
1000
x-y
1.0
-1.0

From Ampere's low, $-\partial B_z/\partial y = \mu_0 j_x$, $\partial B_z/\partial x = \mu_0 j_y$,
Where $J_x = -en_e u_x$, $J_y = -en_e u_y$

Therefore , $u_\perp = \sqrt{u_x^2 + u_y^2} = 2c^2\omega_c/(\lambda\,\omega_{pe}^2)$

Average merging time: $\tau_M = \lambda/u_\perp = \lambda^2\omega_{pe}^2/(2c^2\omega_c)$

$\lambda^2 = \sigma$: one filament occupation area

When immobile ion; $\omega_c = \text{constant} = \omega_0$

$\tau_M = \lambda^2\omega_{pe}^2/(2c^2\omega_0) \propto \sigma \propto \lambda^2$

Number of filaments: N, constant magnetic field,
The magnetic energy is conserved
$N\sigma = N_0\sigma_0$ = constant

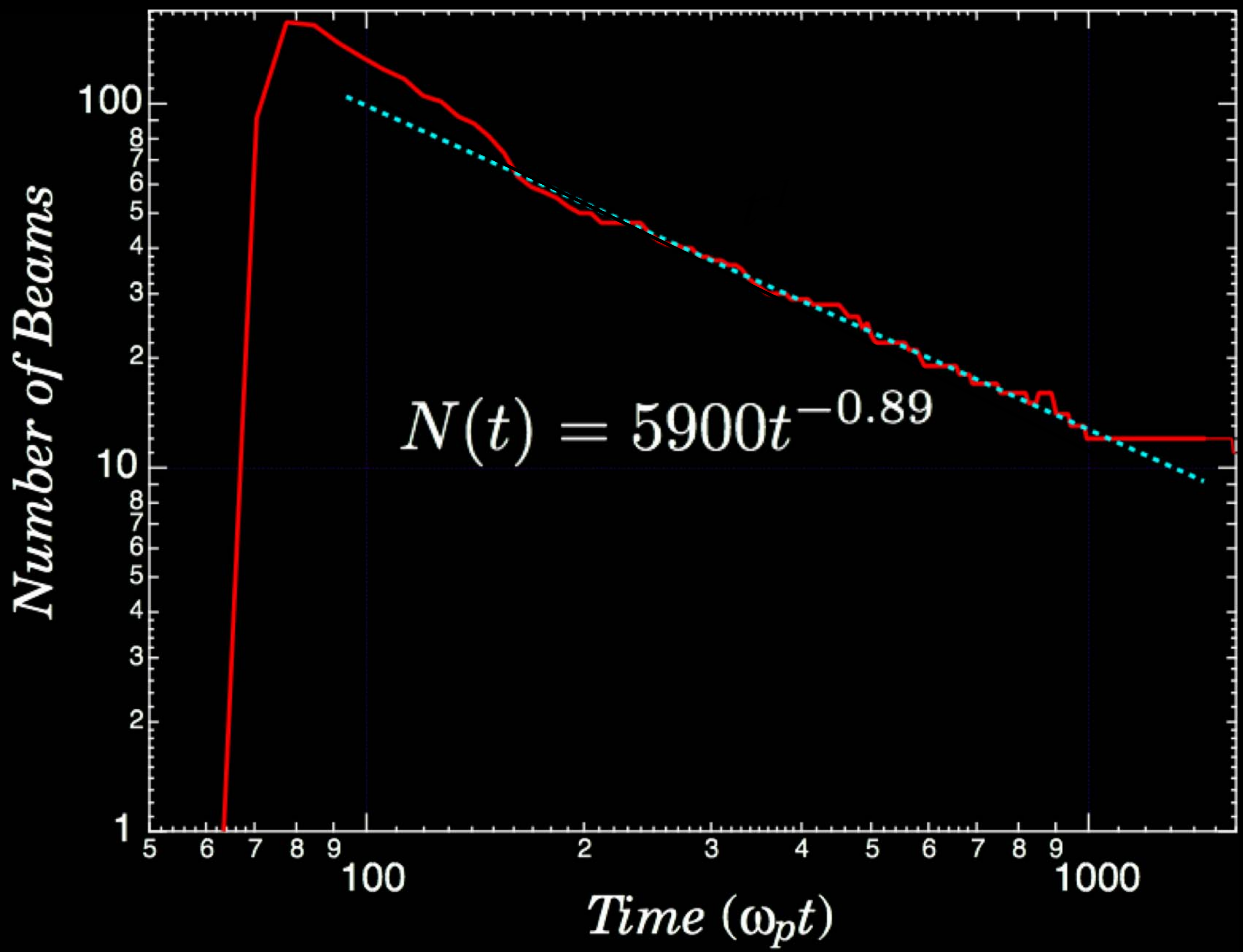
$$\frac{dN}{dt} = -\frac{\ln 2}{\tau_M} N \quad .$$

When immobile ion, $\tau_M \propto 1/N$, to obtain

$$N(t) \cong \frac{N_0}{1 + (t - t_0)/\tau_M} \quad \text{---->} \quad 1/t$$

where, $1/\tau_M = (2\ln 2\, c^2\, \omega_0)/(\sigma_0\, \omega_{pe}^2)$,
initial filament size: $\sigma_0 \sim c^2/\omega_{pe}^2$

Temporal Evolution of Total Number of Beams



Control of Hot Electron Angular Divergence

Divergence angle

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

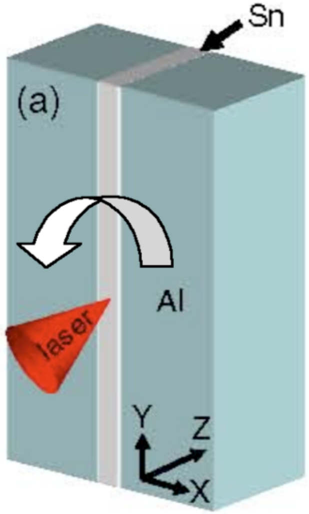
B-filed collimation

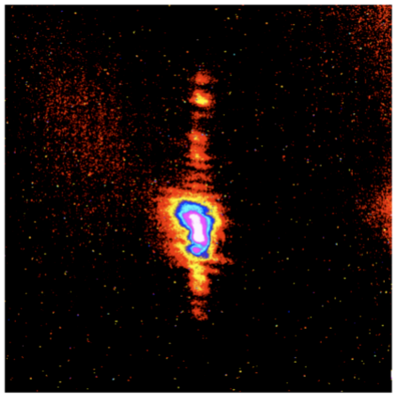
$$\partial B / \partial t = \nabla\eta \times j_h + \eta \nabla \times j_h$$

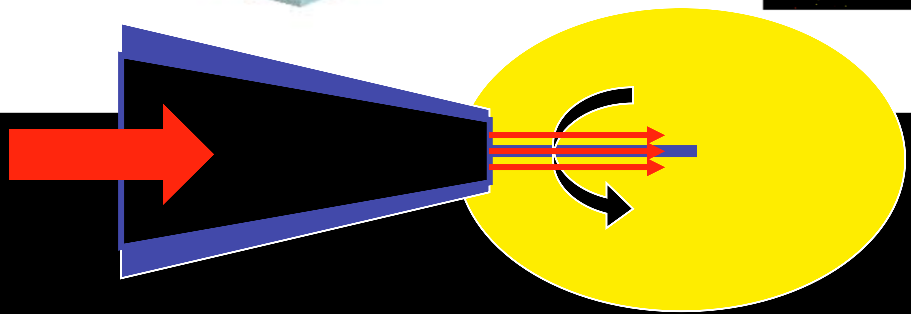
Osaka Univ. Double cone ! 2010.10. to be tested

Experiment at RAL

B field

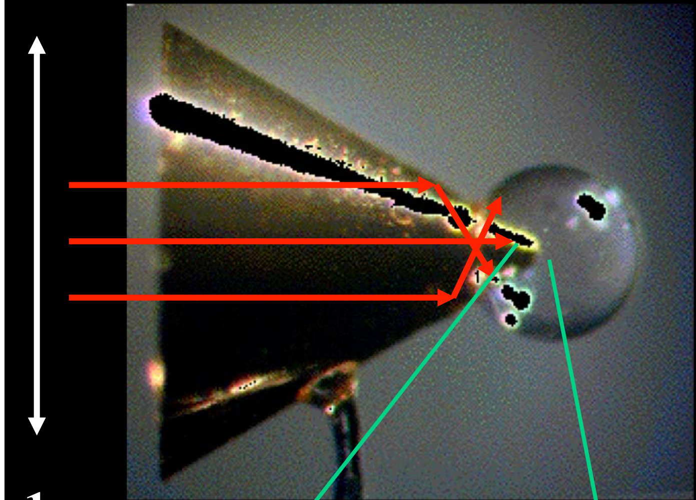






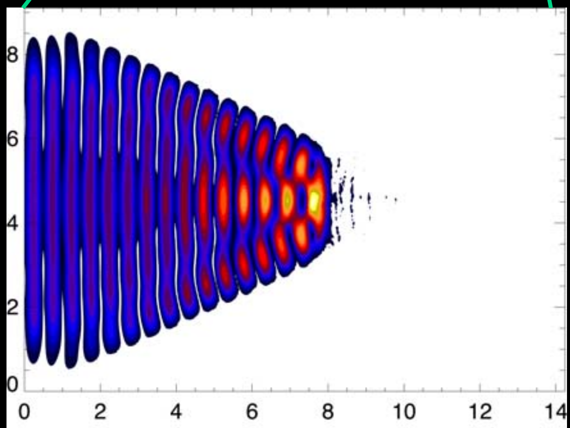
Cone needle concept
Kodama,Nature, 2005
U-Rochester 2010.9.
To be experimental test

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



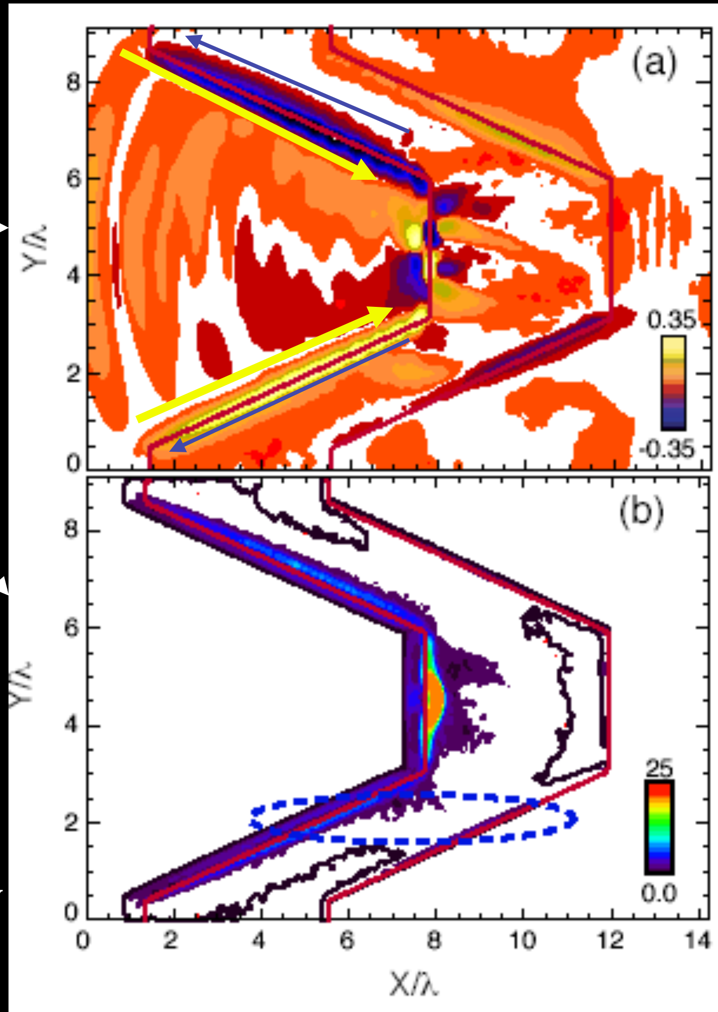
1mm

The focused intensity reaches 20 times larger than I_0.



B field profile

Electron energy density distribution

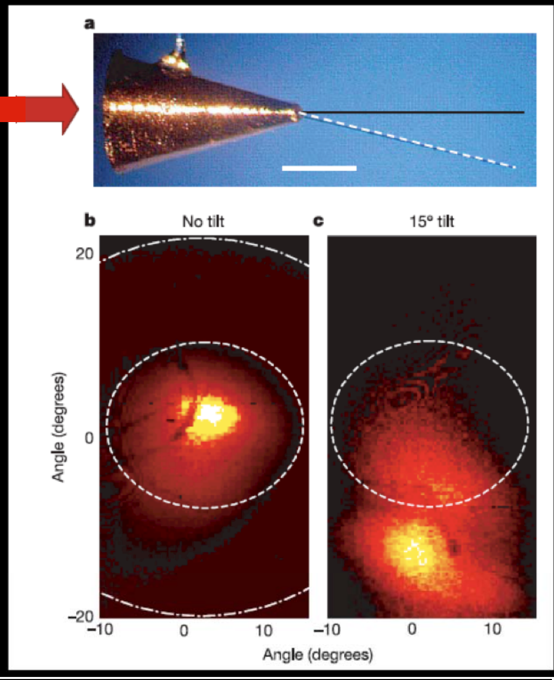


Magnetic field ;B/B_0 and energy density normalized by $n_c mc^2$

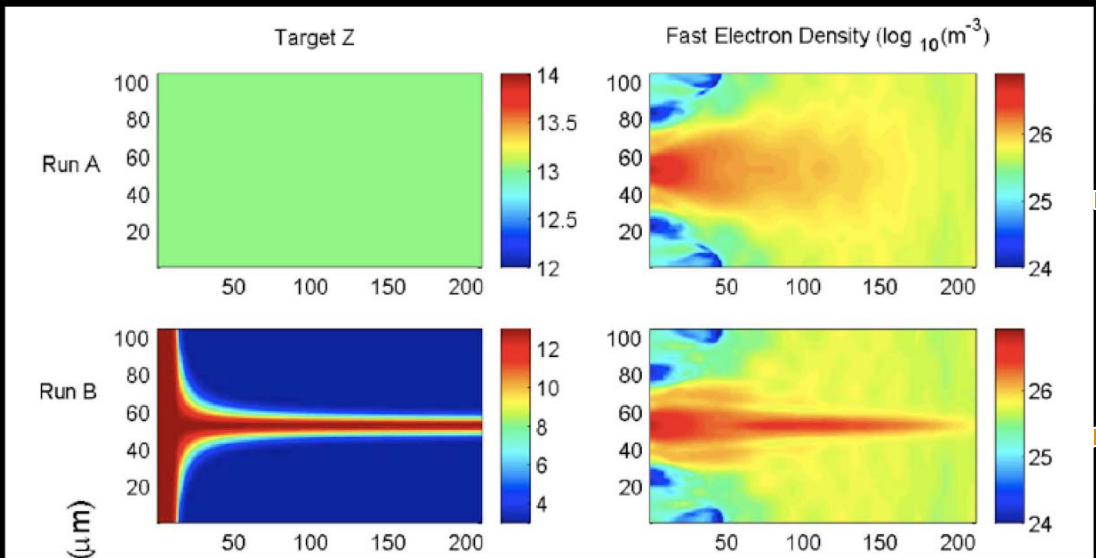
Short pulse laser is focused and generated REB is pinched in a cone target

Can electron spread be controlled?

- Experiments and models show lateral cooling in wires
  - **Electrons diverge only a few degrees leaving long wire**
  - **losing energy at surfaces by accelerating protons**
- ILE double wall cone?
- Magnetic collimation?
  - **Resistive path produces guiding field?**

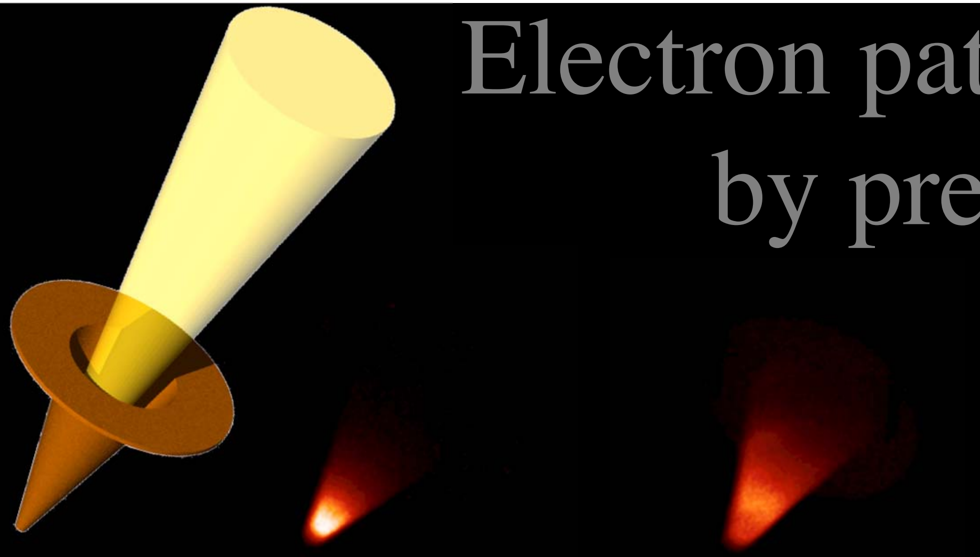


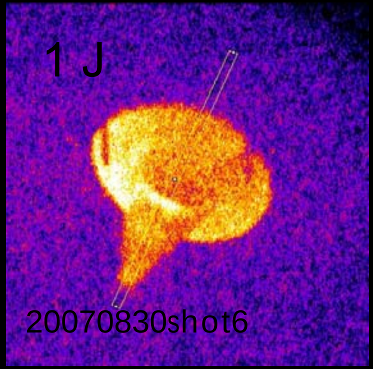
Z.L. Chen et al., PRL 96, 084802 (2006)
R. Kodama et al., Nature 432, 135 (2004)



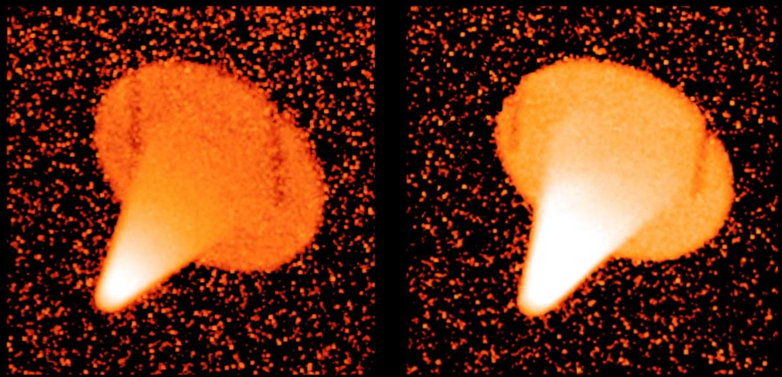
A. Robinson et al., PoP **14**, 083105 (2007))

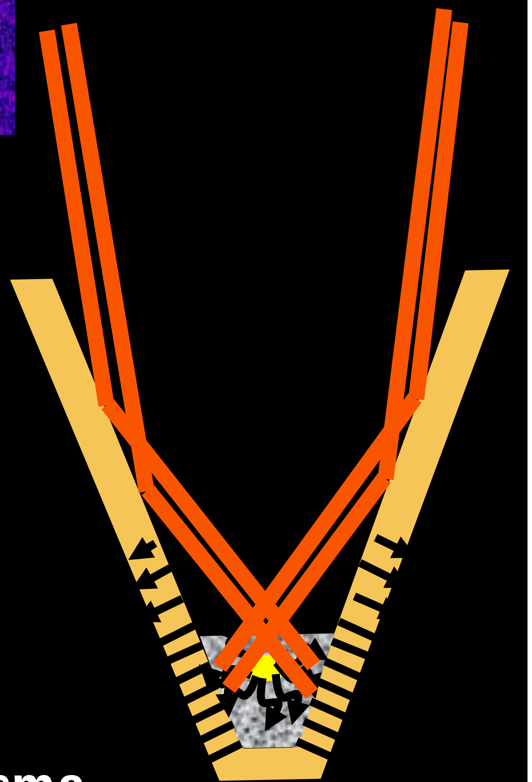
Electron paths affected by prepulse





Log intensity scale

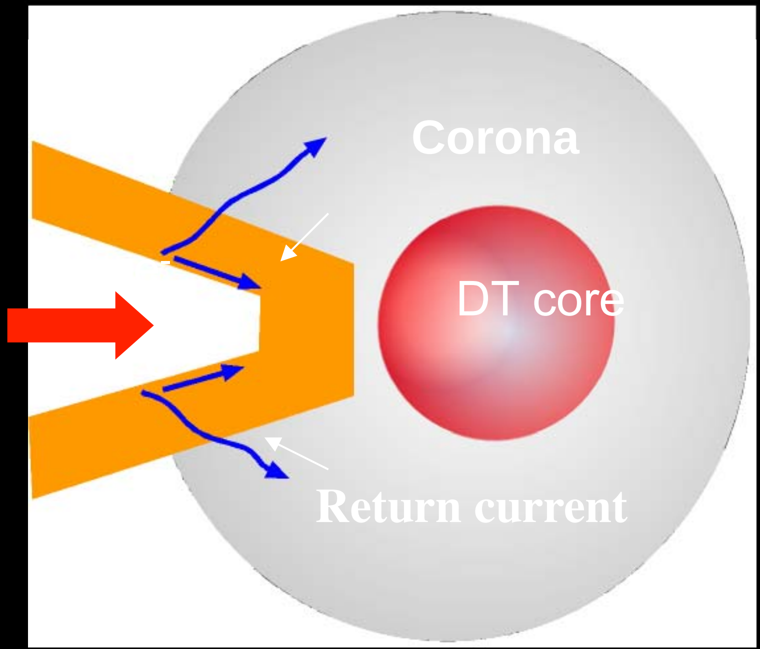


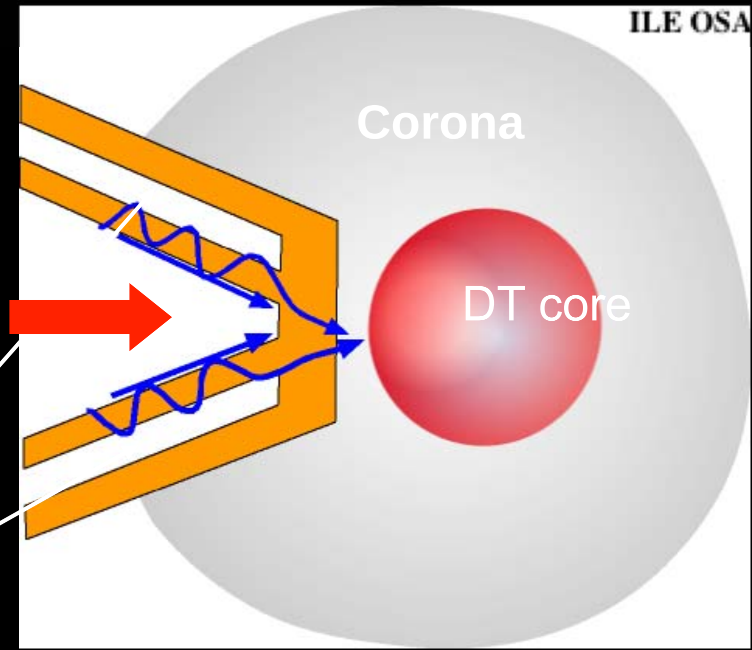


- Prepulse generated plasma fills cone tip
- Electrons move freely in that conducting volume
- And laser focus could be substantially changed by plasma

Are these electrons useful?

Cone is introduced for enhancing energy coupling efficiency





E and B fields are generated and e-beams are confined in the vacuum layer

1. Single Cone target

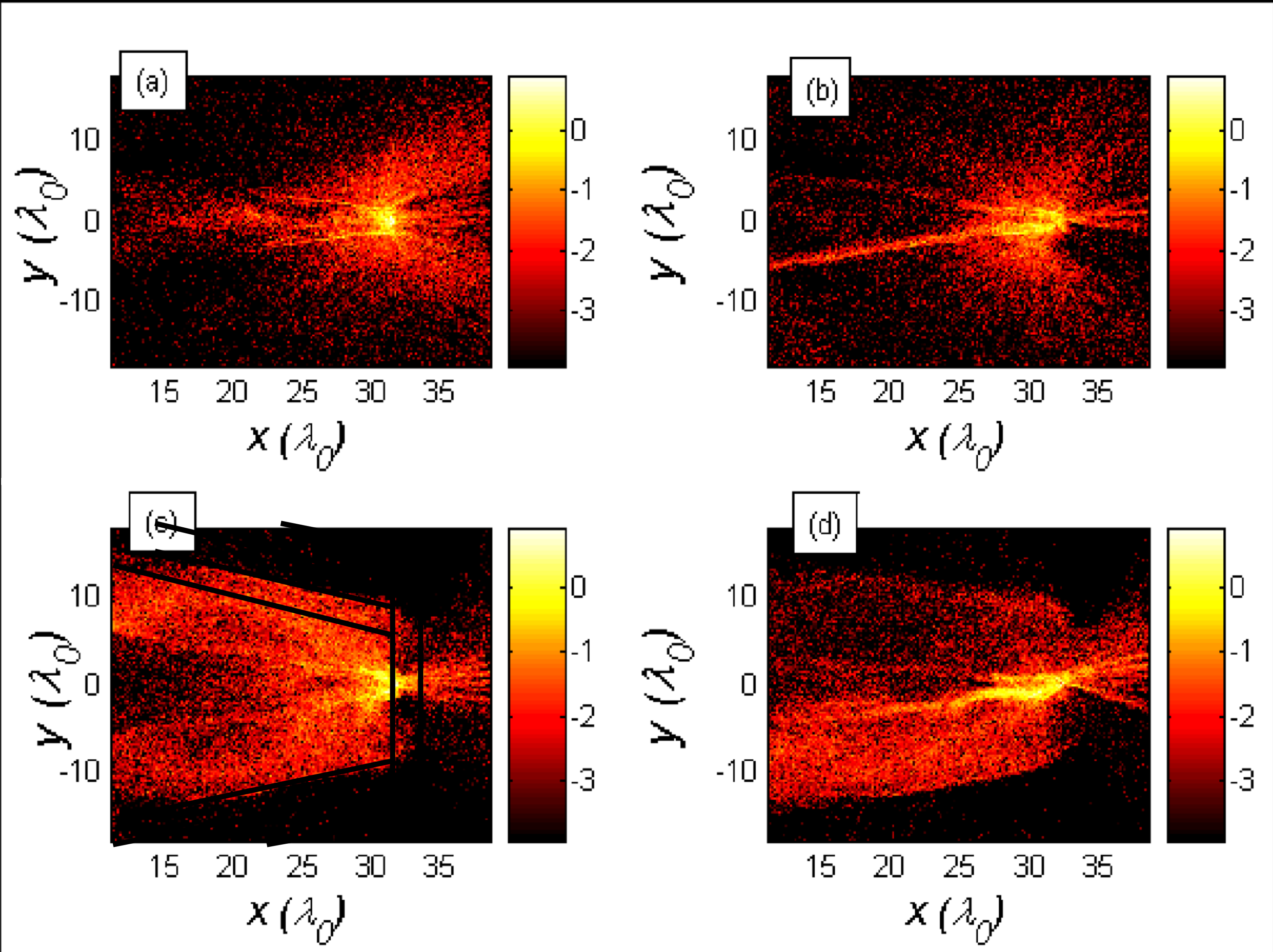
2. Double-cone target

H. Cai etal., PRL, 2009

Hot electron energy density for single cone and double cone

Single cone

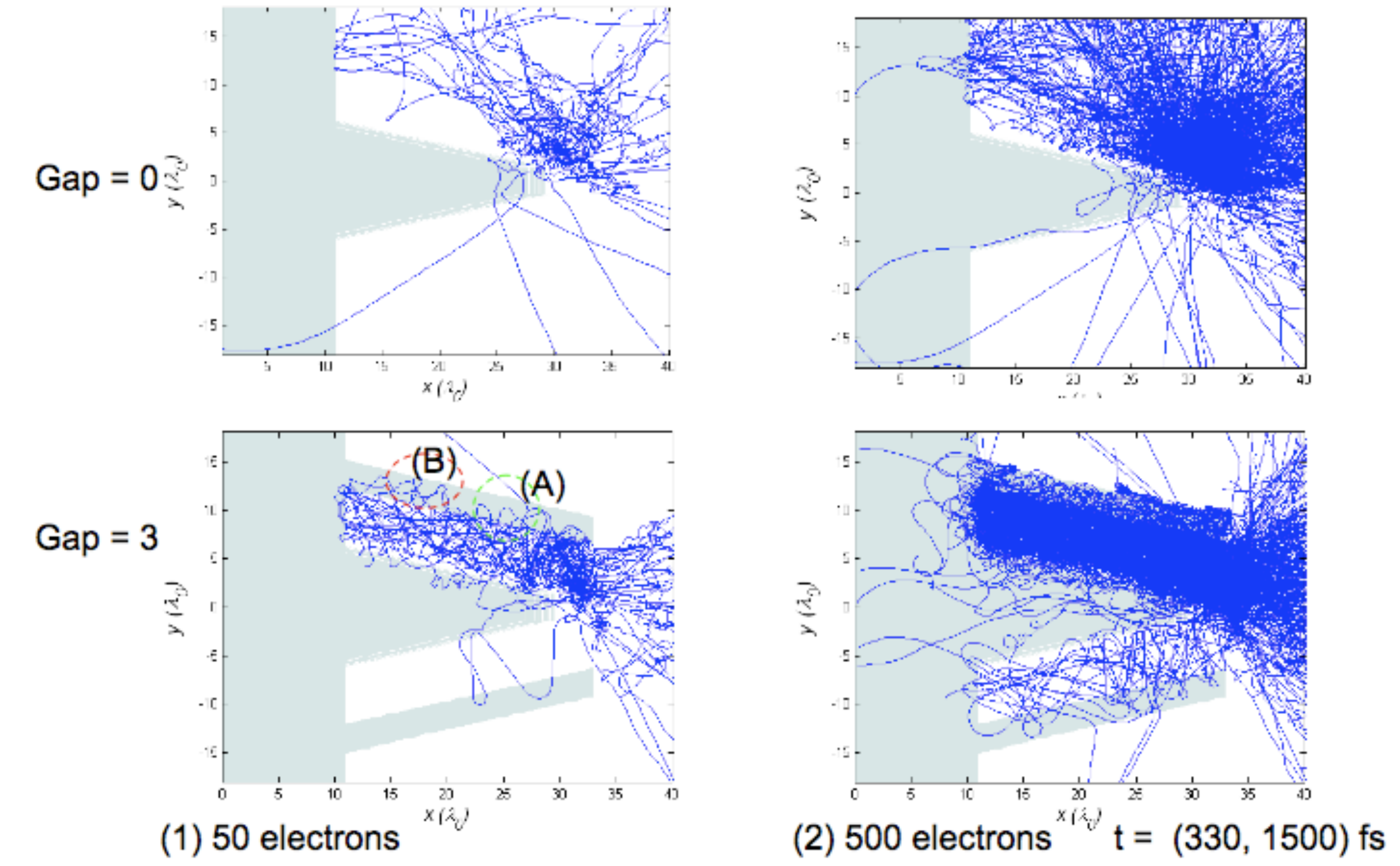
Double cone



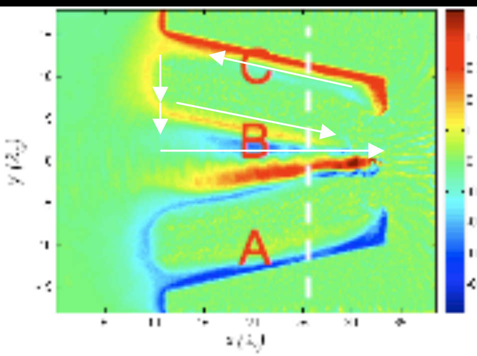
Hongbo Cai, etal PRL 2009

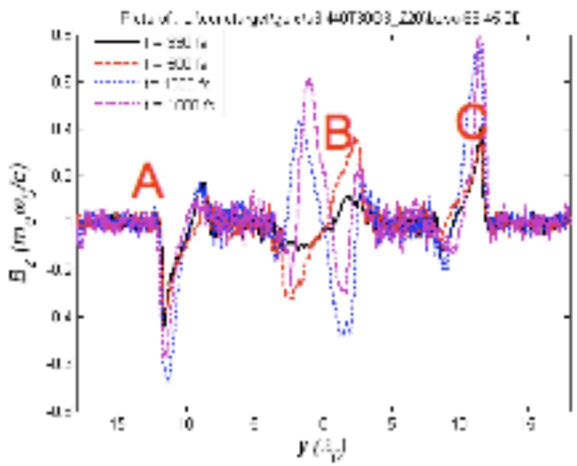
1.5ps

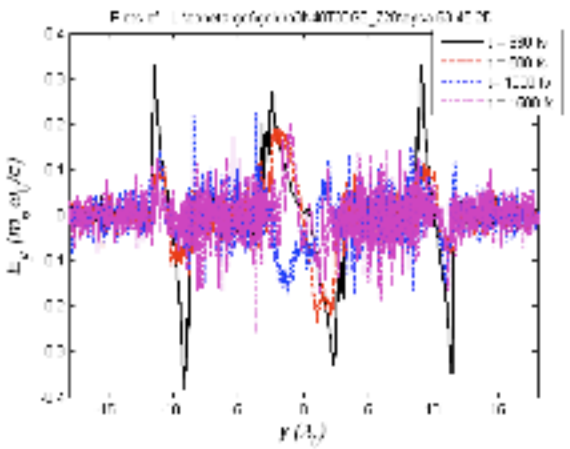
Hot Electron Orbit in the Cone



Temporal Evolution of Magnetic Fields



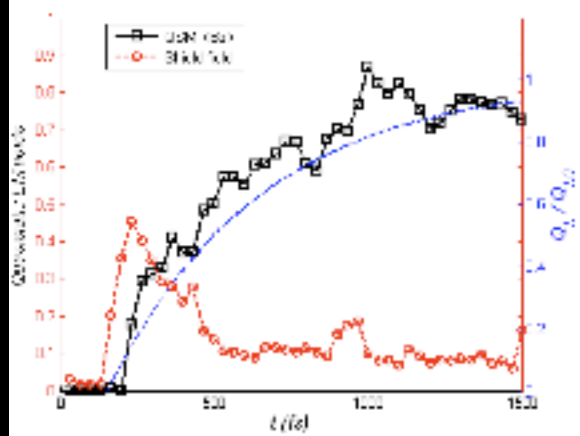




Bz

A, C: gap
B: inner cone

Ey



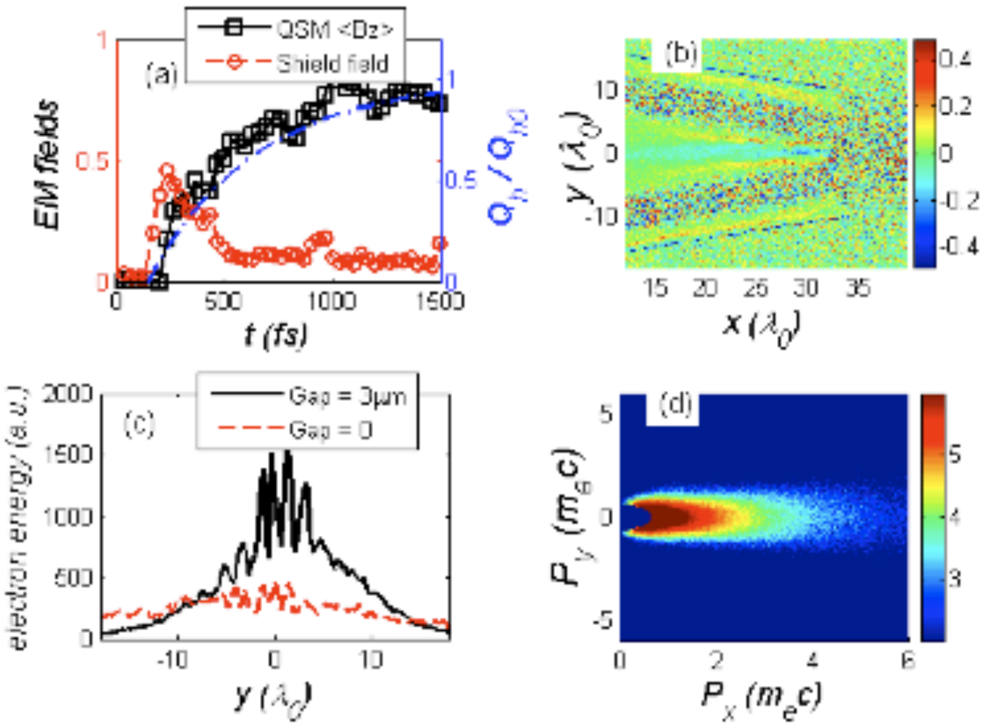
Conclusion:
(1) At the early time, sheath field inside the cone gap plays an important role in confining hot electrons.
(2) At late time, the sheath field becomes weak because of the plasma expansion, while QSM field Bz inside the cone gap can still strong enough to confine the hot electrons;

Question: what is the generation mechanism of this strong QSM field inside the cone gap?

Growth of B-Fields and Hot Electron into the Core

We evaluate Eq. (2) for the present case:
S0: 10 microns; S: 40 microns
V: 500 microns^2
Ω=cS/3V=8*10^{12}s^{-1}:
Beta: the energy escaped from the cone tip is 4 times larger than that from the cone side for the case gap=3, therefore, the ratio of third term to the second term is 4, we then obtain Beta = 15/16
T **=dln(Qh)/dt** ~ 0.5ps.
Then we can plot the Q_h/Q_{h0}, as shown in Fig. (a)

Fig. (a) The maximum values of the quasistatic magnetic field (QSM, solid line) and the sheath electric field (dashed line) inside the gap. The dash-dotted line is the plot of Qh(t) in Eq.(2). (b) The time averaged current jx at time 1500fs. (c) The transverse distribution of the energy of the escaped electrons from the right boundary. (d) The natural logarithm of the momentum distribution of the collected high-energy electrons.



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

	right $(-18,18)\lambda_0$	right 21° cone	down	up	left
Gap = 0	27.4%	4.8%	17.2%	13.0%	0.54%
Gap = 3	44.0%	14.8%	5.0%	6.4%	0.55%

Table I. Fraction of the energy flux of the emitted high-energy electrons at different boundaries with respect to the laser energy for double cone and single cone.

Summary

1. Heating efficiency defined by

$$\eta_T = W_{th}/W_L$$

2. η_T depends upon 4 processes like,

   $\eta_T = \eta_F . \eta_A . \eta_{Tr} . \eta_D$

3. η_A :Energy conversion into proper energy hot electrons ---> Wave breaking
4. η_{Tr} : Transport efficiency includes electron divergence angle, elecro-magnetic field, and scatering
6. η_D : energy deposition----> collisions,
   collective stopping