High Intensity Laser-Solid Interaction: Collisionless Absorption and Instabilities

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- "Fast" electron transport and instabilities
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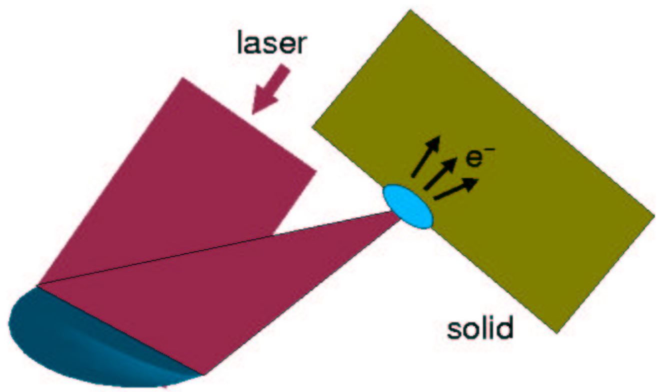

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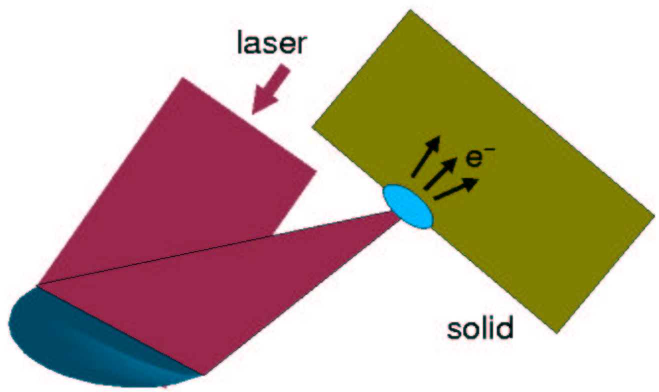

Laser–Solid Interaction is a route for laser energy conversion into thermal or suprathermal electrons and ions and into coherent and incoherent XUV radiation.

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4. electron energy transport and conversion (radiation, ions, fields . . .)

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Field ionization by the laser pulse is "instantaneous" (faster than an optical cycle) when the laser field exceeds the atomic field ("barrier suppression" ionization):

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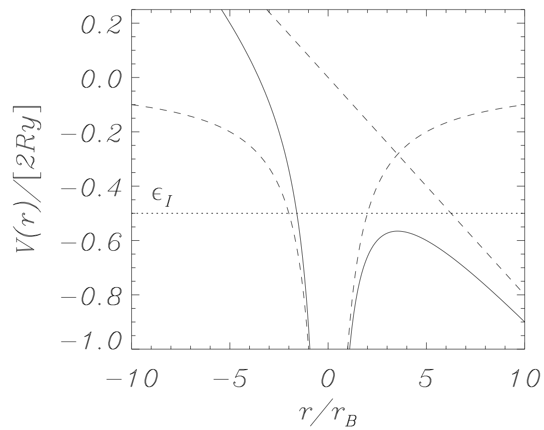

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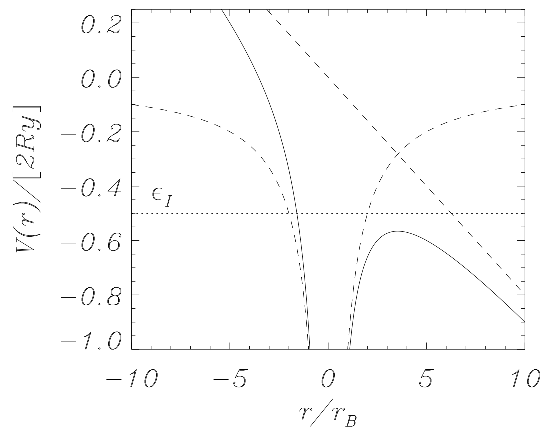

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Oscillating free electrons contribute to collisional ionization (quiver energy $\mathcal{E}_{osc} \simeq 6$ keV at $I_L\lambda_L^2 = 3.5 \times 10^{16}$ W cm$^{-2}\mu$m^2).

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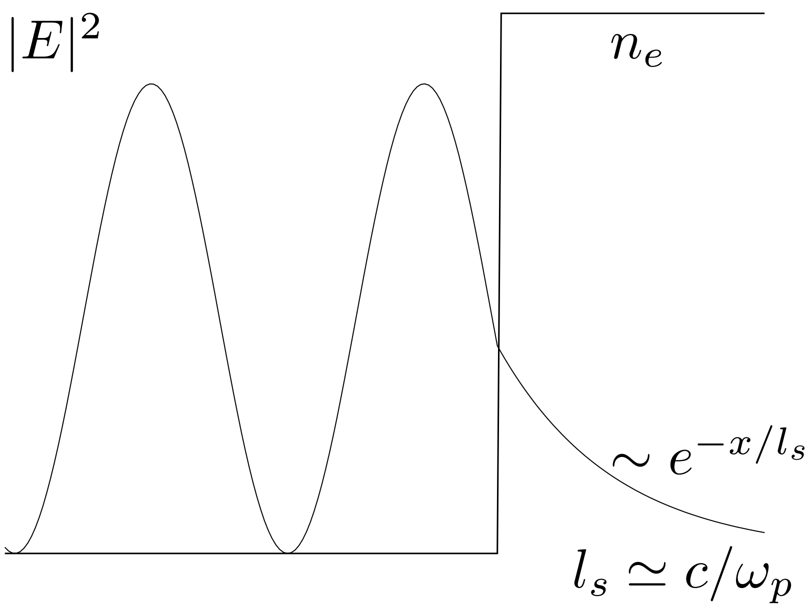

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$$\mathsf{n} = 1 - \omega_p^2/\omega^2 < 0 \qquad (\omega_p = \sqrt{4\pi n_i e^2/m_e})$$

$$B_z(x,t) = B_z(0^+) e^{iky\sin\theta - x/l_p - i\omega t} + \text{ c. c.},$$

$$E_y(x,t) = -\frac{i\omega l_p}{c} B_z(0^+) e^{iky\sin\theta - x/l_p - i\omega t} + \text{ c. c.},$$

$$E_x(x,t) = \left(\frac{\omega l_p}{c}\right)^2 \sin\theta B_z(0^+) e^{iky\sin\theta - x/l_p - i\omega t} + \text{ c. c.},$$

$$l_p = \frac{c}{\omega_p} \left(\cos\theta(1 - \omega^2\cos^2\theta/\omega_p^2)\right)^{-1/2},$$

$$\frac{B_z(0^+)}{B_{z,i}} = \frac{2\mathsf{n}^2\cos\theta}{\sqrt{\mathsf{n}^2 - \sin^2\theta} + \mathsf{n}^2\cos\theta}$$

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In addition to the electric force at frequency ω, the force at the plasma surface has a magnetic component at frequencies 0 and 2ω:

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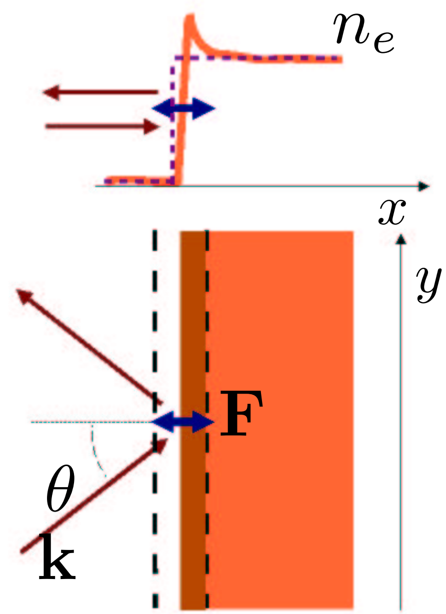

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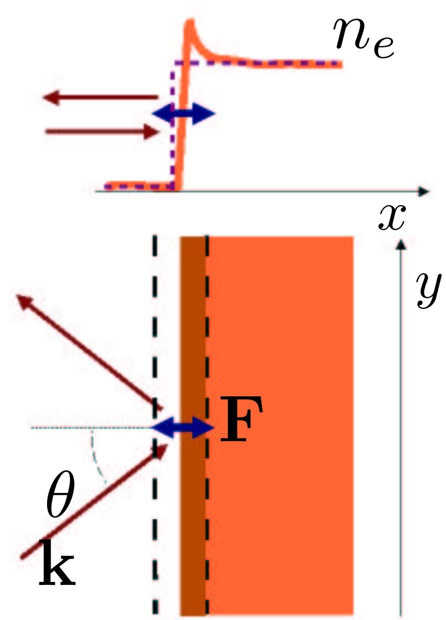

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It turns out that the dynamics at the plasma surface is dominated by *the force component normal to the surface*. The latter strongly depends on polarization and incidence angle.

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This technique is very convenient for analytical and numerical modelling.

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Effective dielectric function becomes (Drude's model)

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Assuming isochoric heating, complete thermalization and diffusive transport, scaling laws for T_e and L_{th} (ablation depth) are found:

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$\Rightarrow$ at high irradiances absorption is dominated by collisionless processes.

Stage 3: collisionless absorption

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$$\nu_{eI} \sim v_e^{-3} \quad ; \quad v_e \approx \max(v_{th}, v_{osc}) \quad ; \quad v_{th} \sim T_e^{1/2} \quad ; \quad v_{osc} \sim (I_L \lambda_L^2)^{1/2}$$

$\Rightarrow$ at high irradiances absorption is dominated by collisionless processes.

Weak absorption dependence on target material
[Price et al, PRL **75**, 252 (1995)].

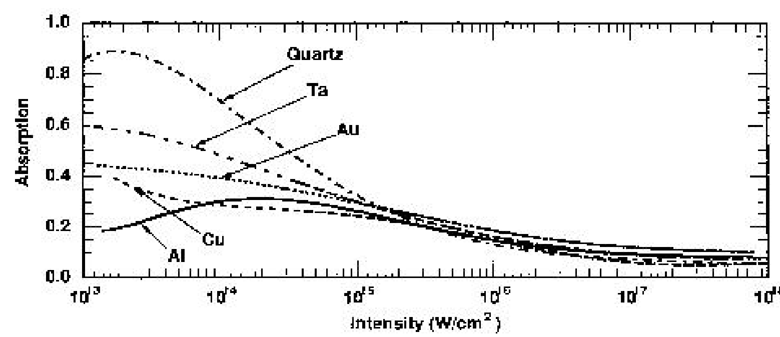

FIG. 1. Absorption fraction vs peak laser intensity for aluminum, copper, gold, tantalum, and quartz targets. In Figs. 1, 3, 4, and 5 laser intensity is the temporal and spatial peak value of the laser intensity.

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This constraint may be however violated: non–steady state effects, aperiodic motion, 2D effects,. . .

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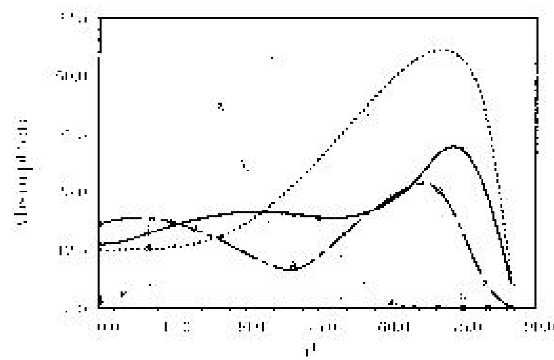

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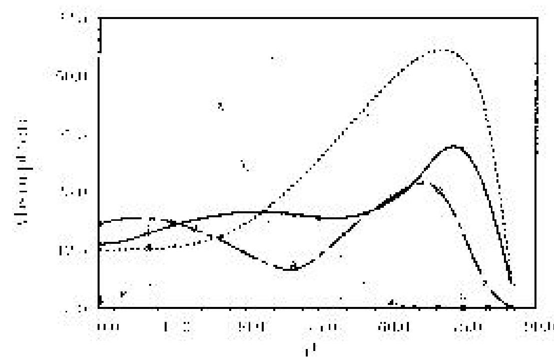

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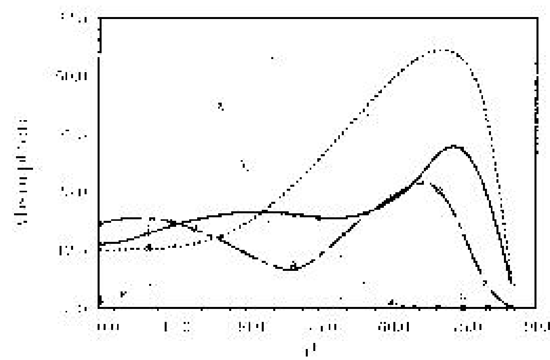

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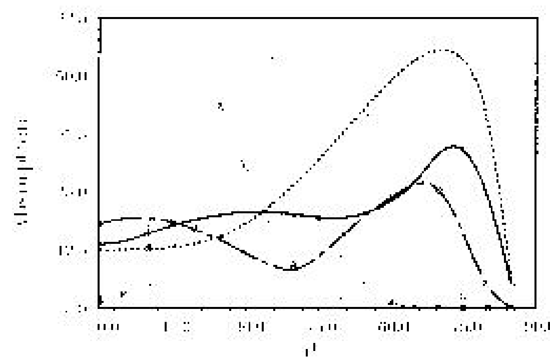

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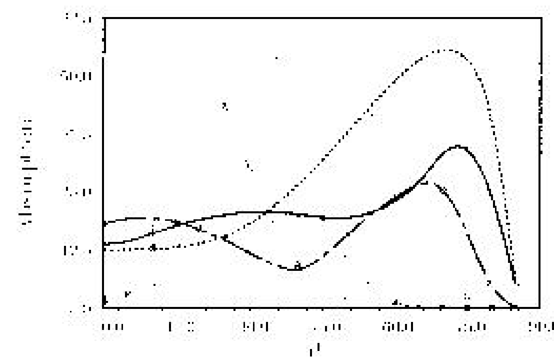

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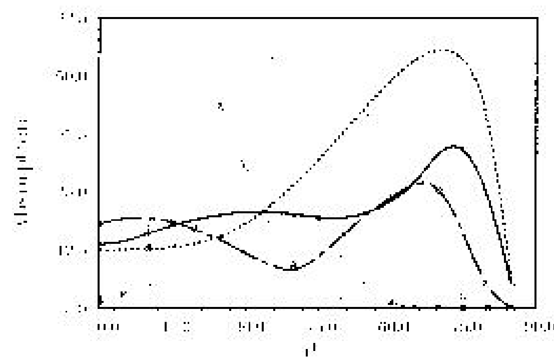

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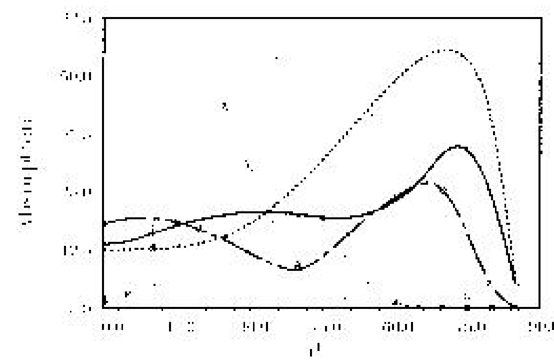

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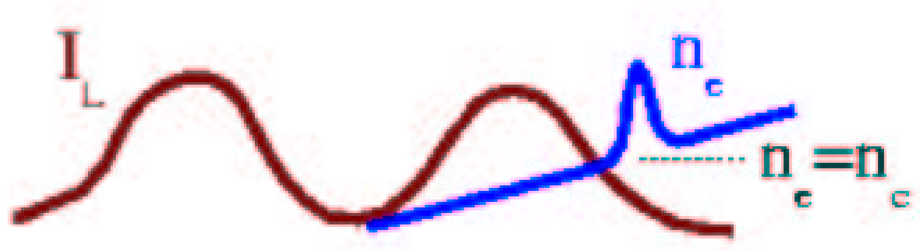

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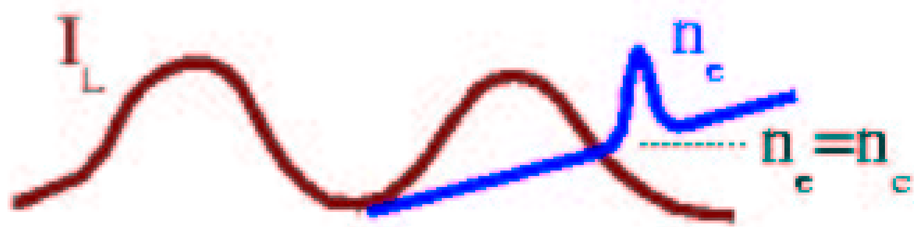

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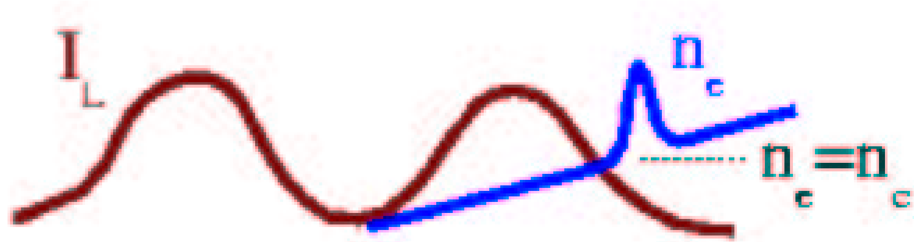

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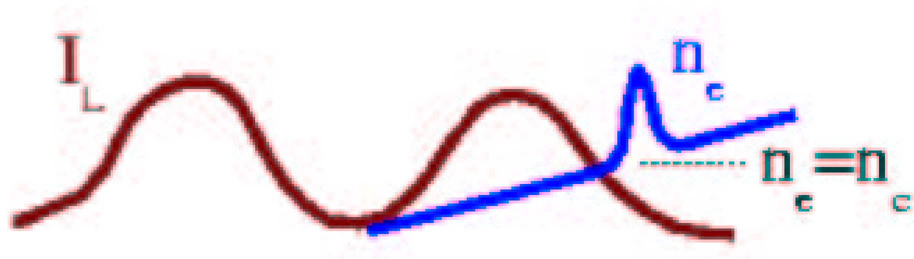

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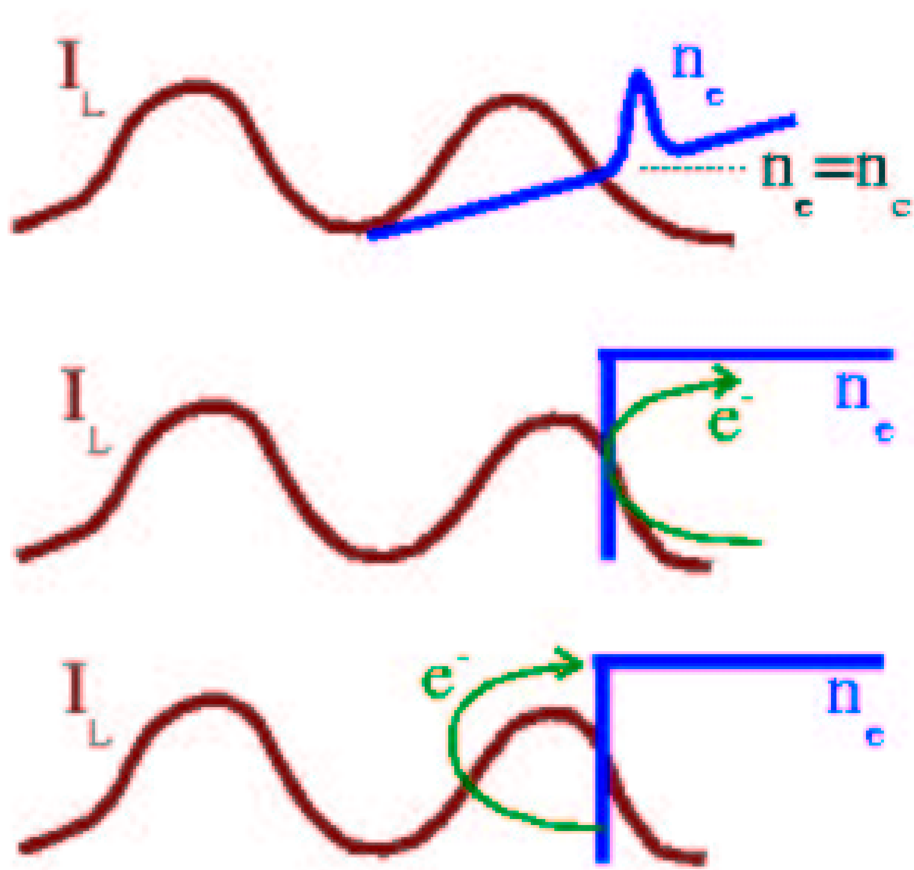

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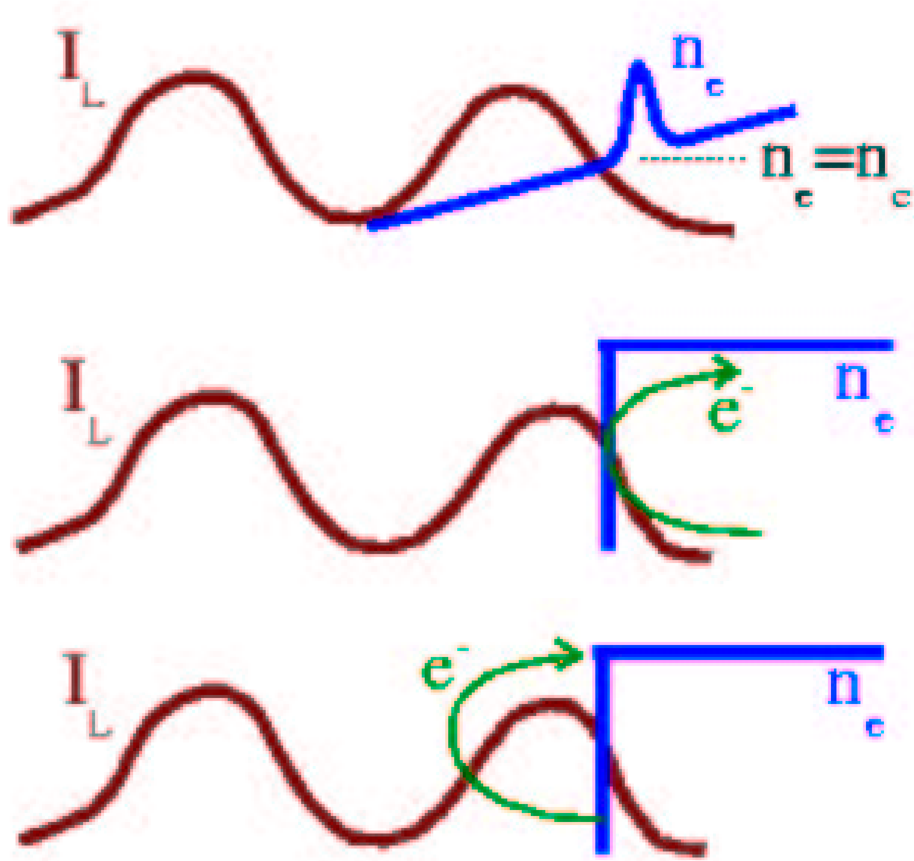

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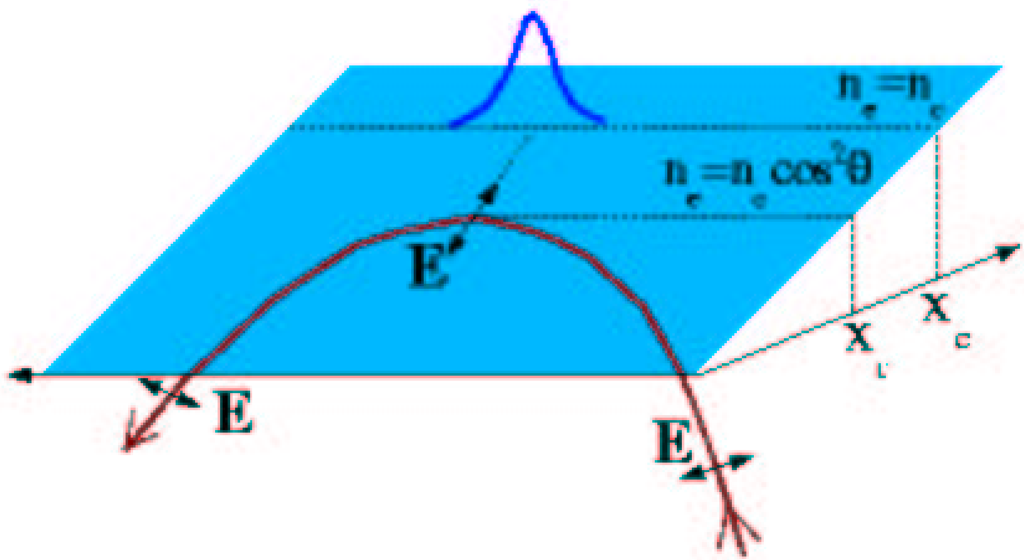

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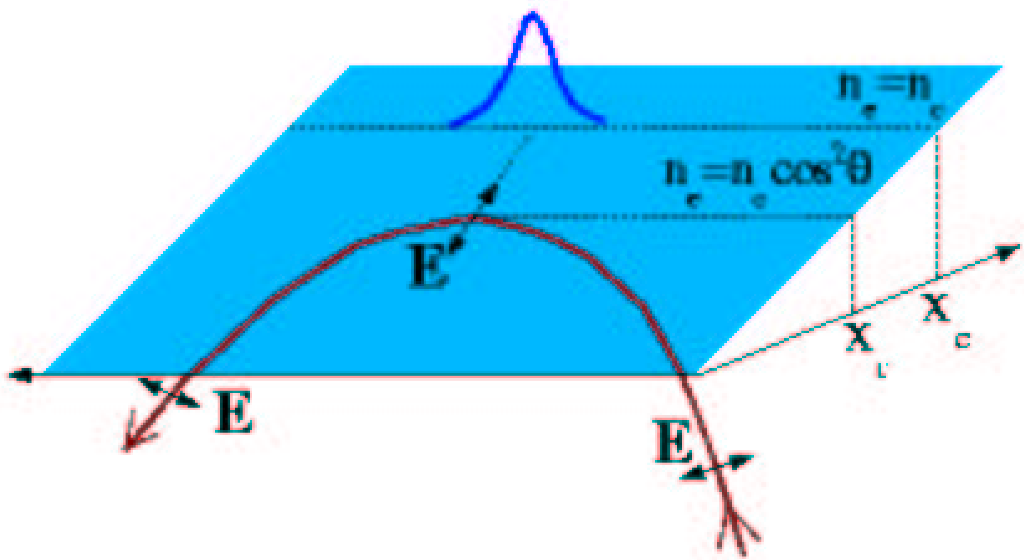

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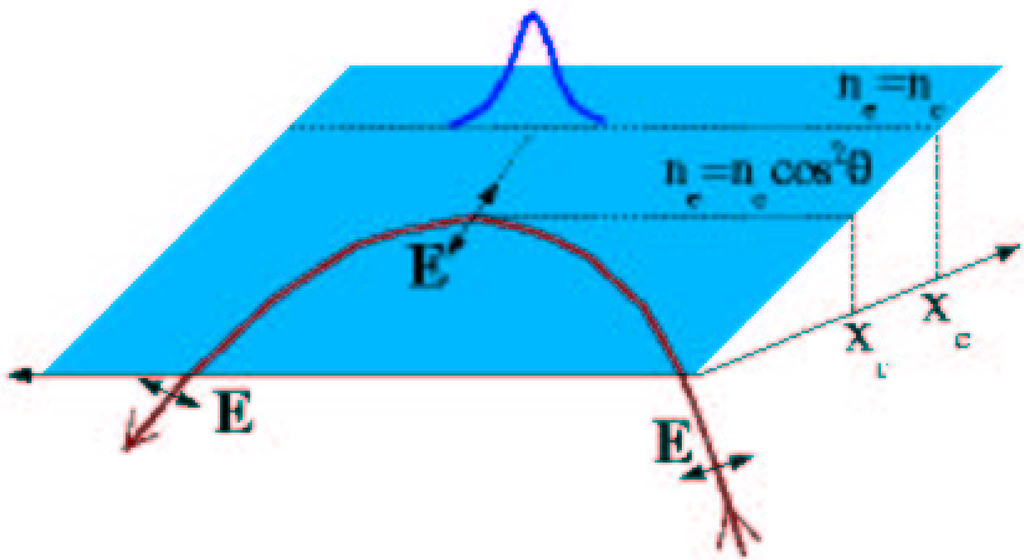

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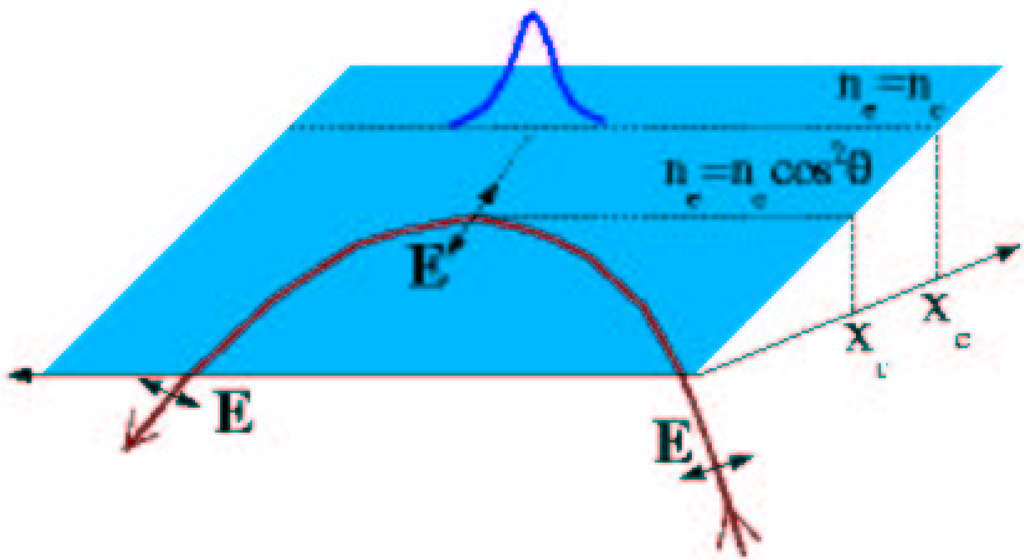

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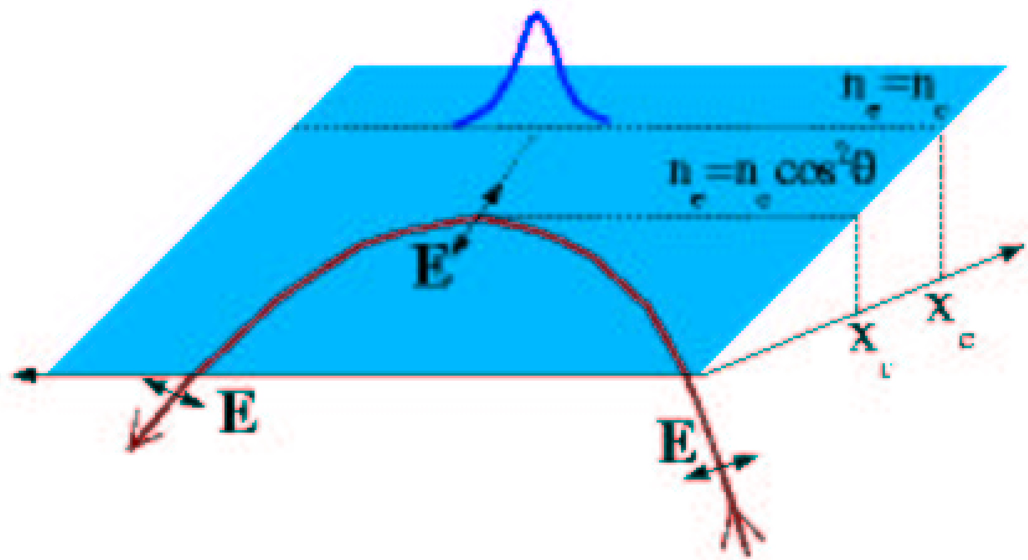

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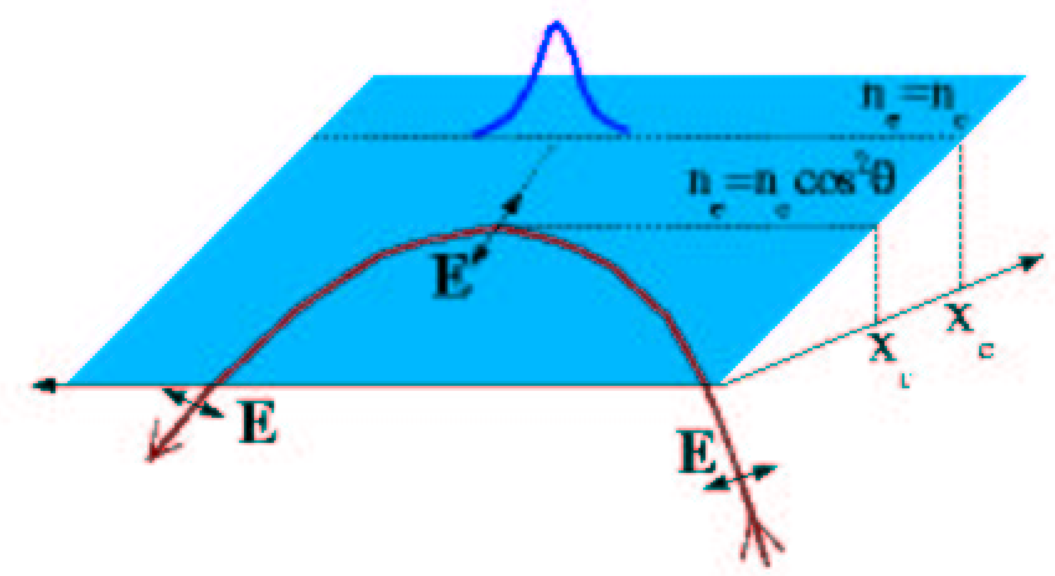

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Numerical solution of the Vlasov-Poisson system within the capacitor approximation (uniform $\mathbf{E}_d$)

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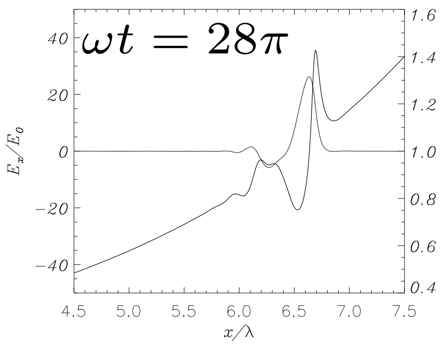

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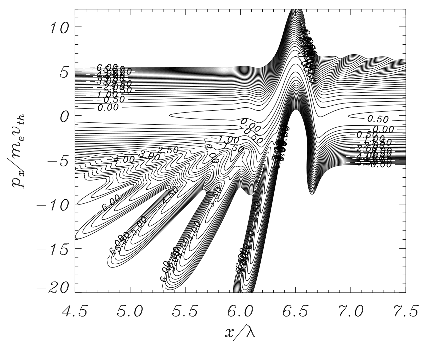

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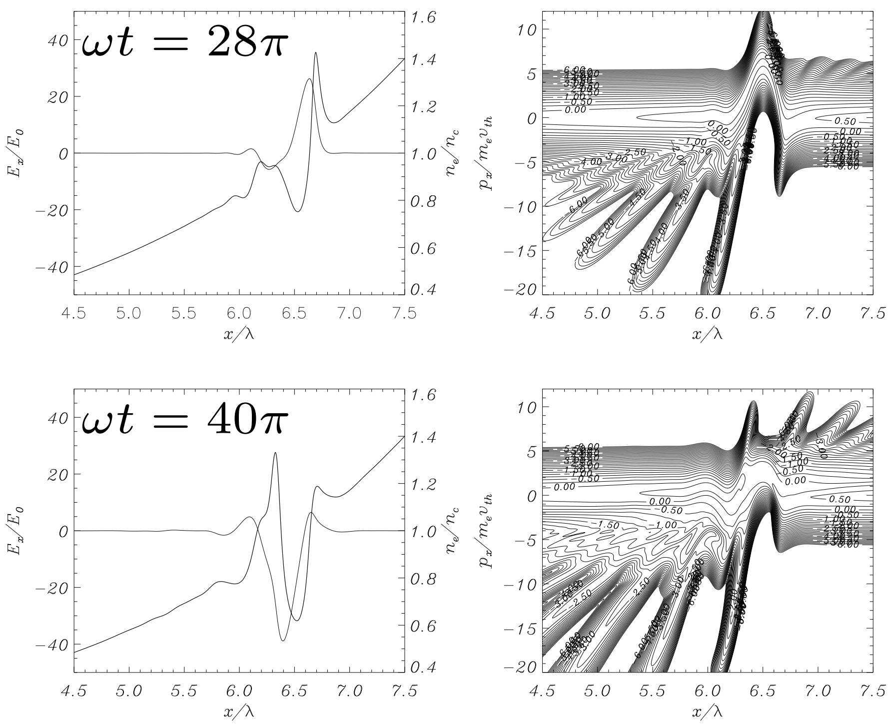

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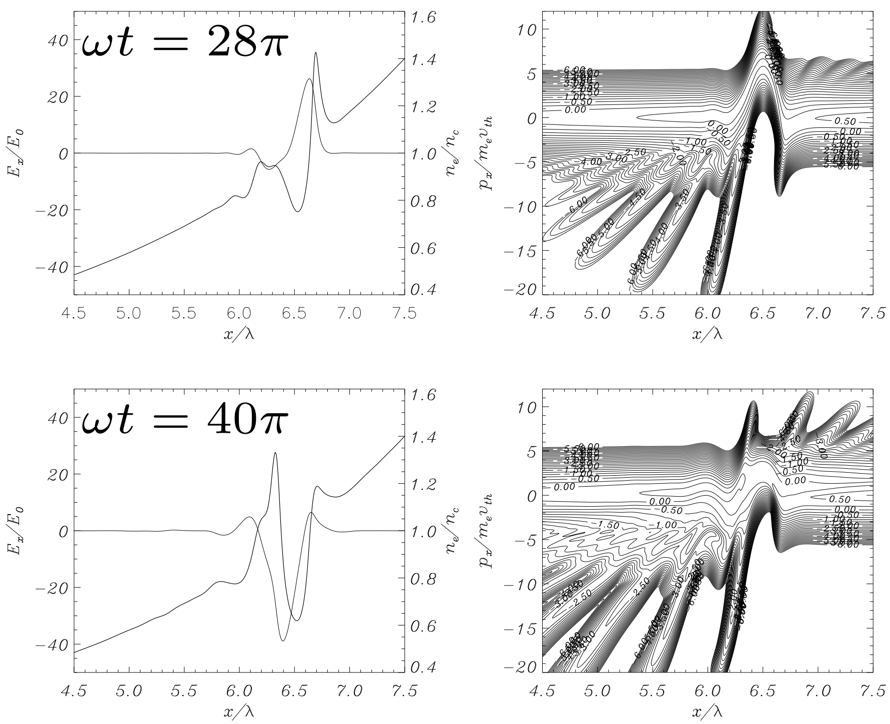

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A. Macchi and H. Ruhl, GSI Report, Darmstadt, 2000

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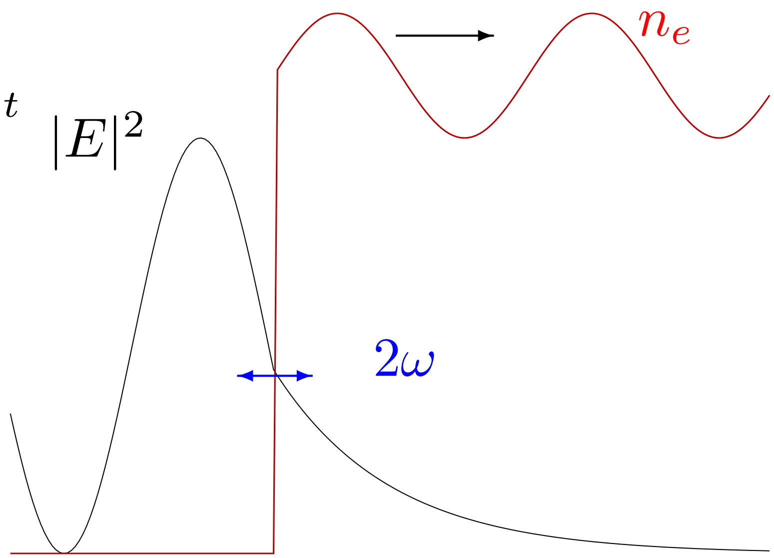

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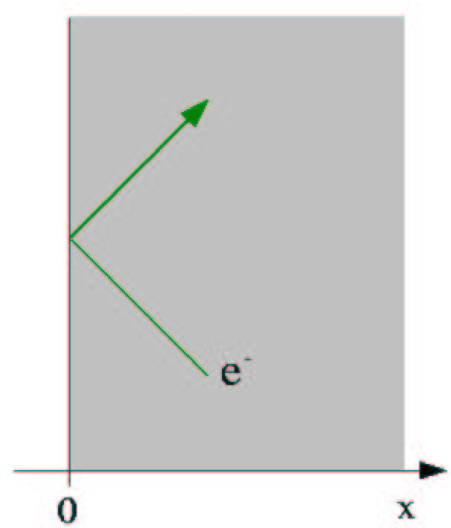

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Specular reflection at $x = 0$ is assumed:
$f(x = 0, v_x, v_y) = f(x = 0, -v_x, v_y)$

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Absorption degree A_{abs} and extinction length l_s in the limit $l_s \ll v_{th}/\omega$:

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ASE + simple diffusion model for heat losses [i.e. $T_e = T_e(t)$] explains well absorption data by Price et al. in solid target at $I \leq 10^{18}$ W cm^{-2}.
[Rozmus et al, Phys. Plasmas **3**, 360 (1996)]

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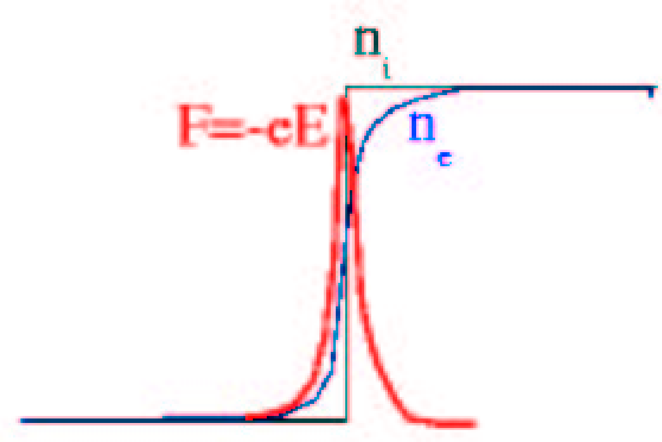

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In an external field E_d, electrons are reflected from the sheath if $v_{osc} = eE_d/m_e\omega < v_{th}$.
Since the sheath is very thin ($\approx \lambda_D$) , $E_s \sim \delta(x)$ may be assumed (reflecting boundary).

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Electrons crossing the surface towards vacuum $(x_0 + \xi < 0)$ feel a discontinous force with an effective secular acceleration $\omega_p^2 x_0$.

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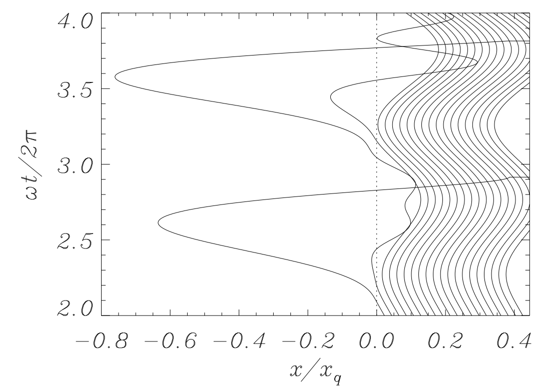

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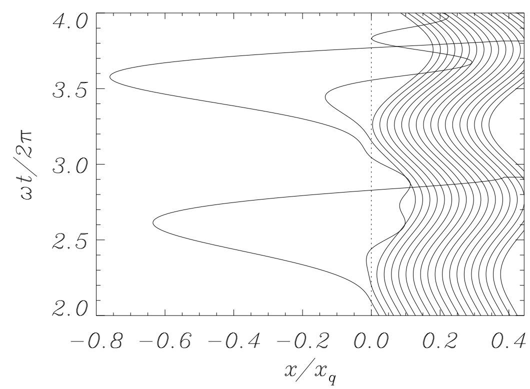

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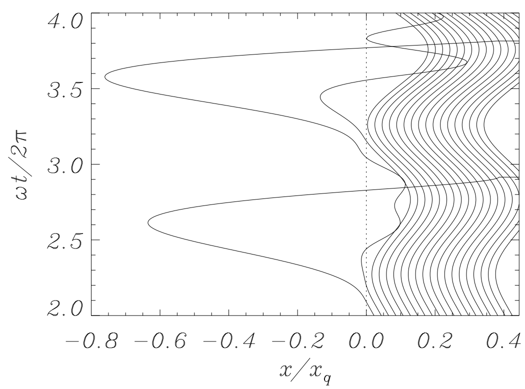

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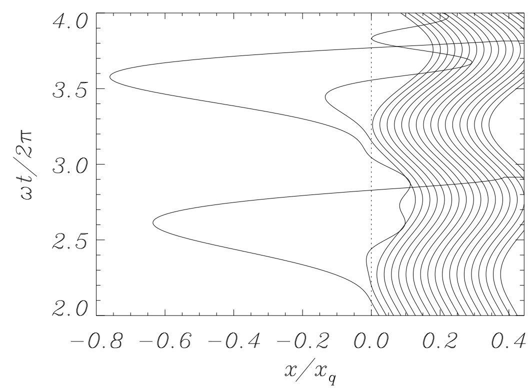

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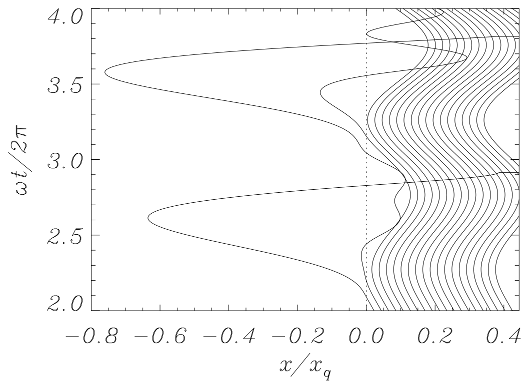

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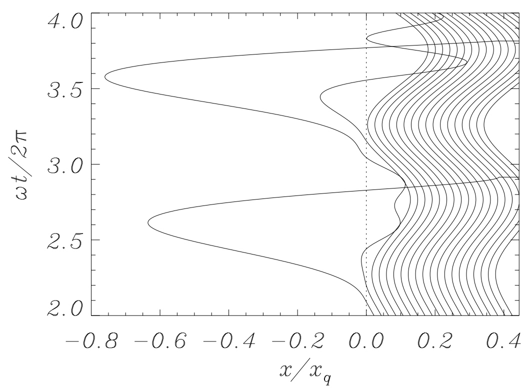

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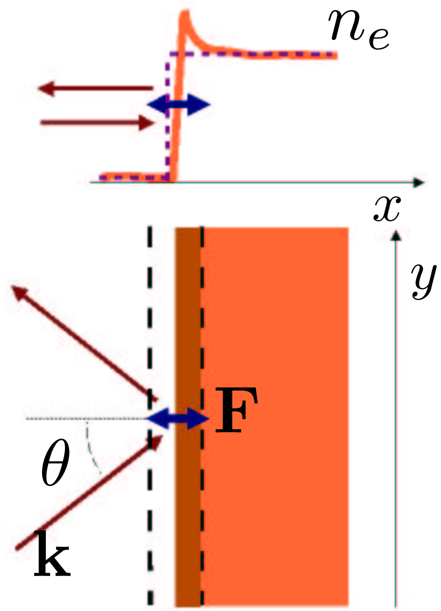

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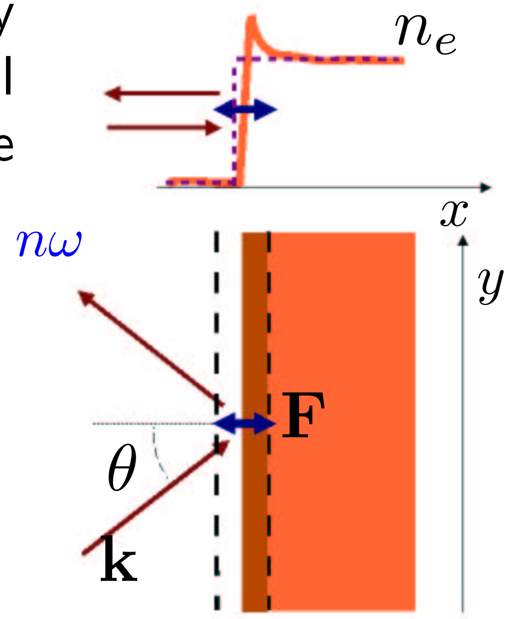
$\rightarrow$ "moving mirror" effect: generation of high harmonics 3ω, 4ω, . . . , $n\omega$ . . .



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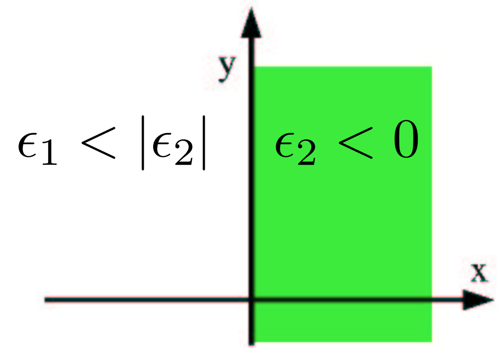

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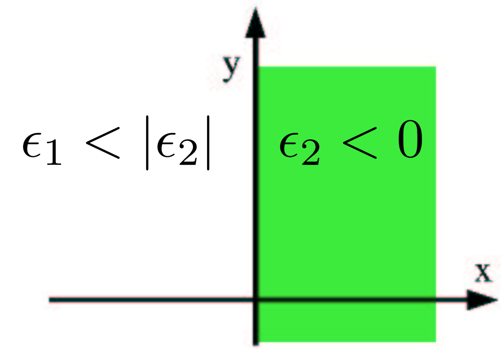

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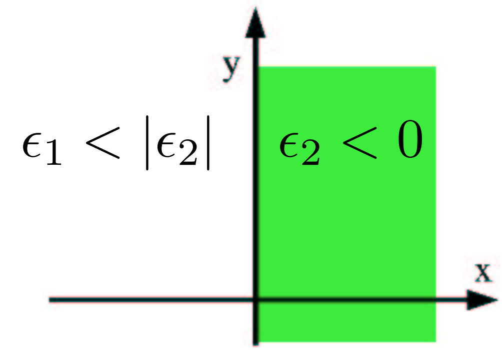
$$k^2 = \frac{\omega^2}{c^2}\frac{\epsilon_1|\epsilon_2|}{|\epsilon_2| - \epsilon_1} = \frac{\omega^2}{c^2}\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}$$



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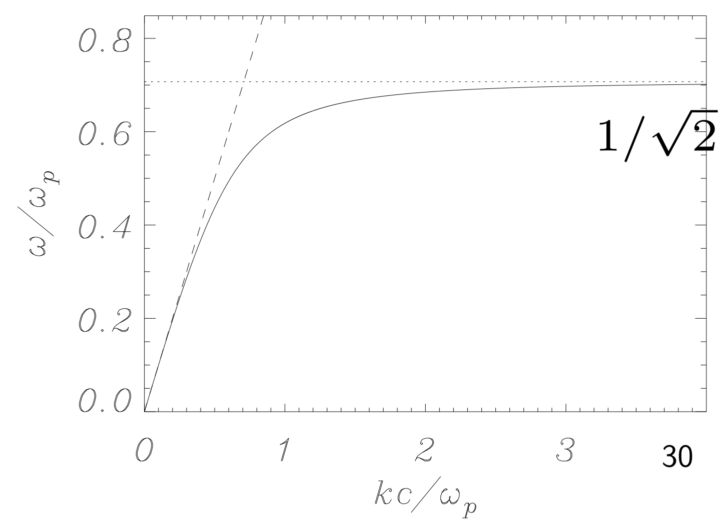

Surface wave absorption II

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Linear mode conversion of the laser pulse into a SW at a plane vacuum–plasma interface requires $\omega_L = \omega_s$, $k_L \sin\theta = k_s$ where $k_L = \omega_L / c$ $\big(L \rightarrow$laser, $s \rightarrow$SW).

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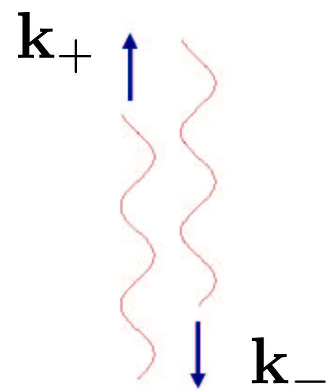

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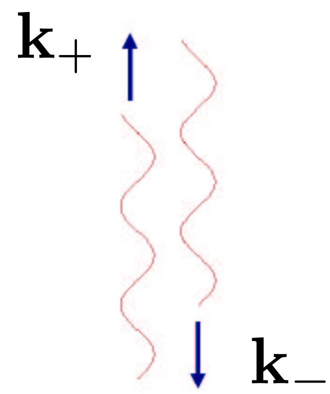

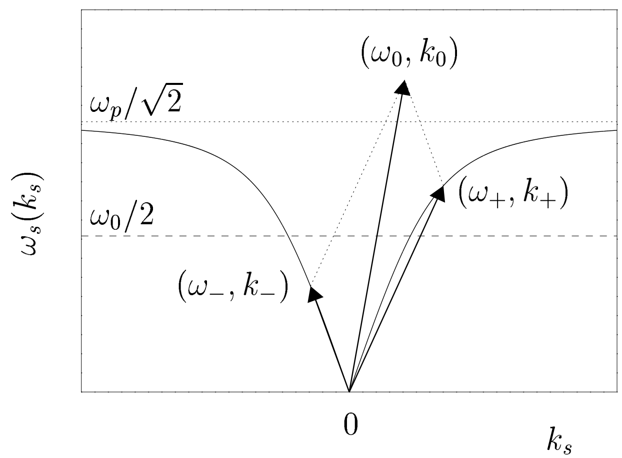

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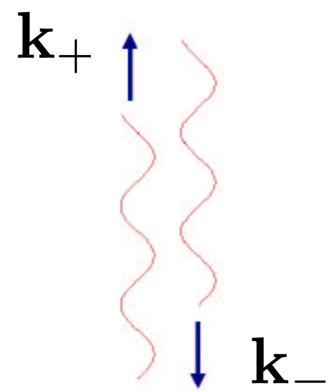

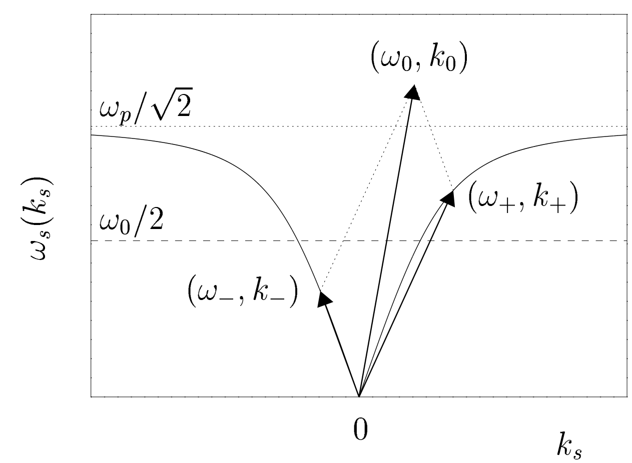

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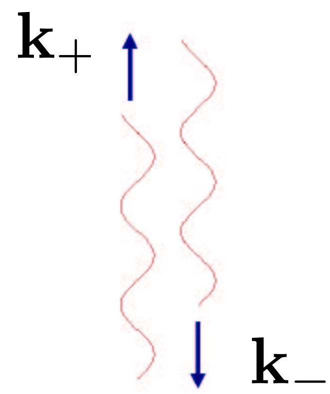

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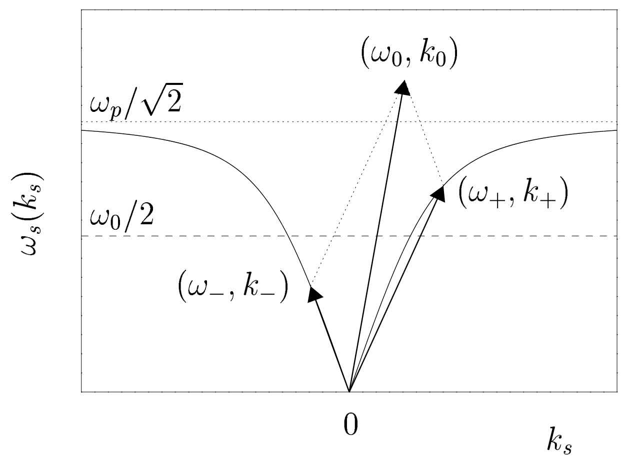

However, also the $\mathbf{v} \times \mathbf{B}$ force at $2\omega_L$ may drive TSWD at normal incidence: $k_+ = -k_-$, $\omega_\pm = \omega_L$.
[Macchi et al, PRL **87**, 205004 (2001); Phys. Plasmas **9**, 1704 (2002).]

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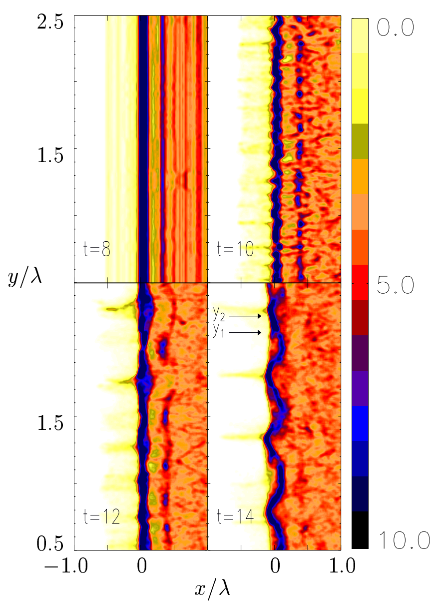

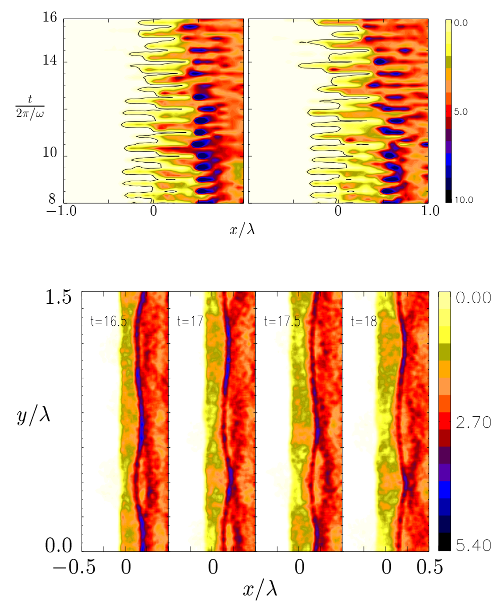

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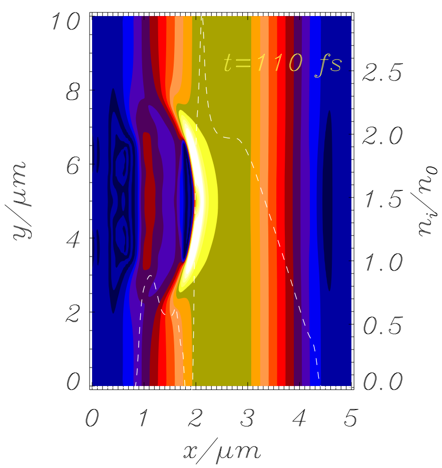

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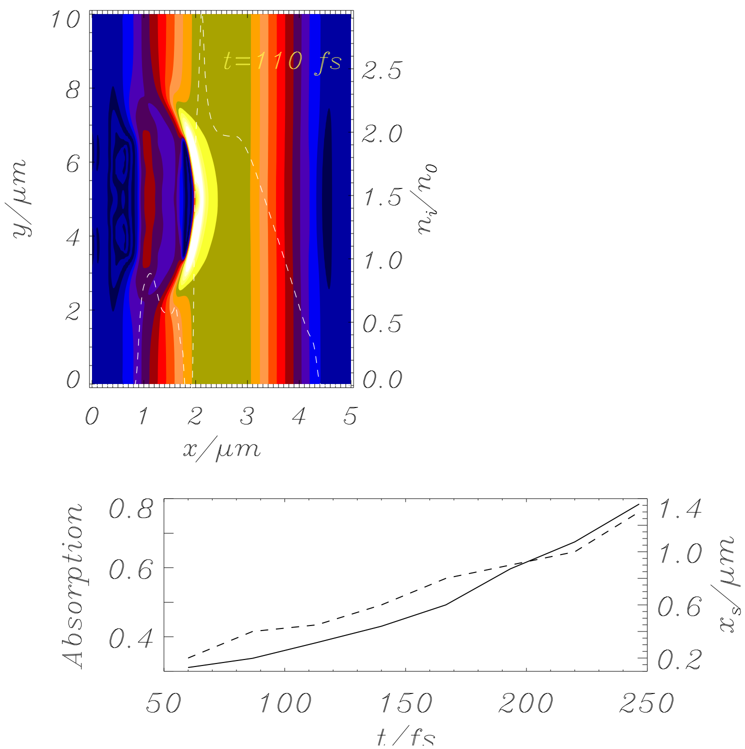

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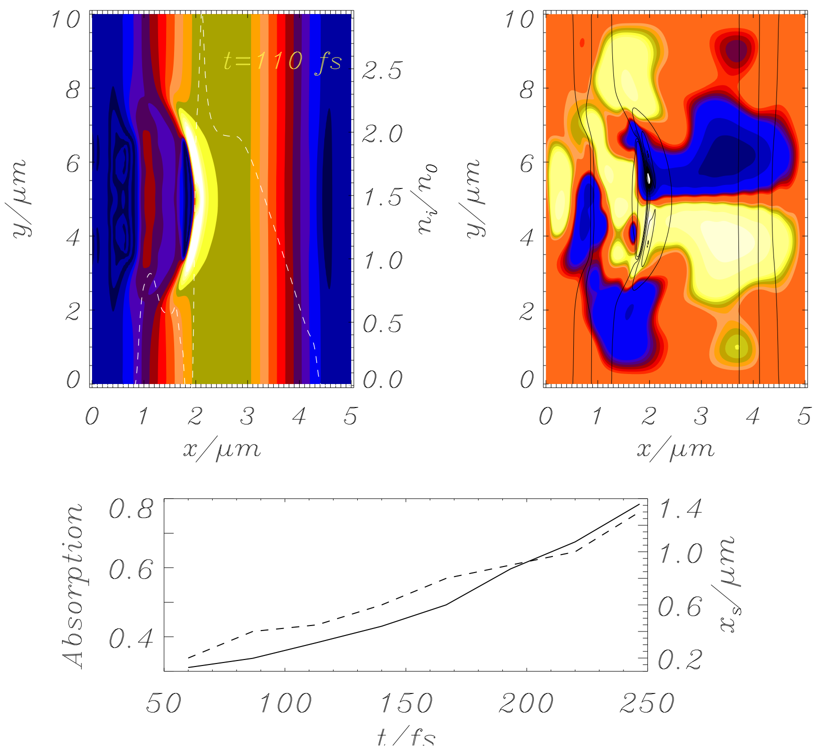

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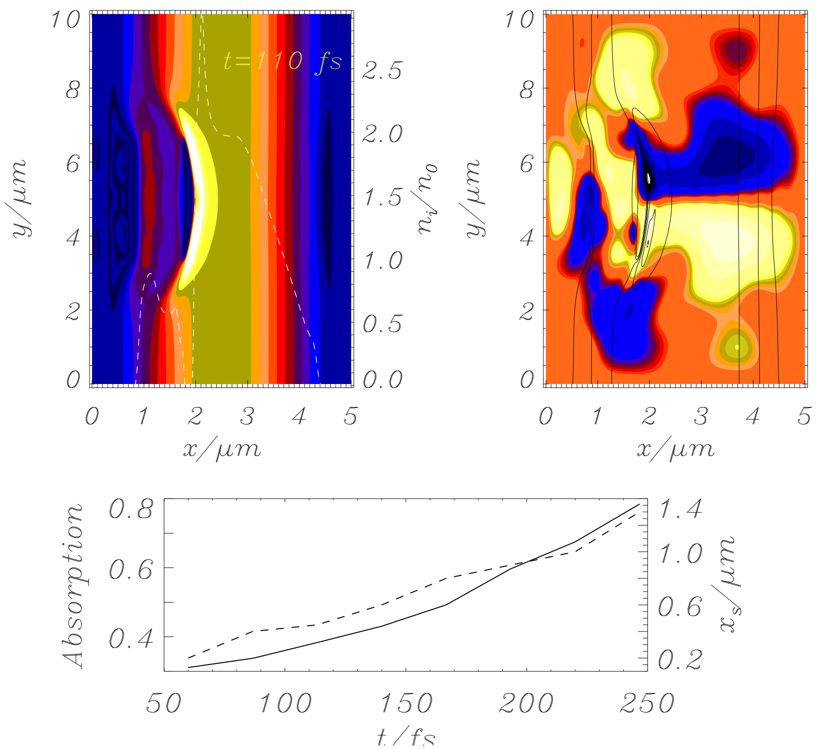

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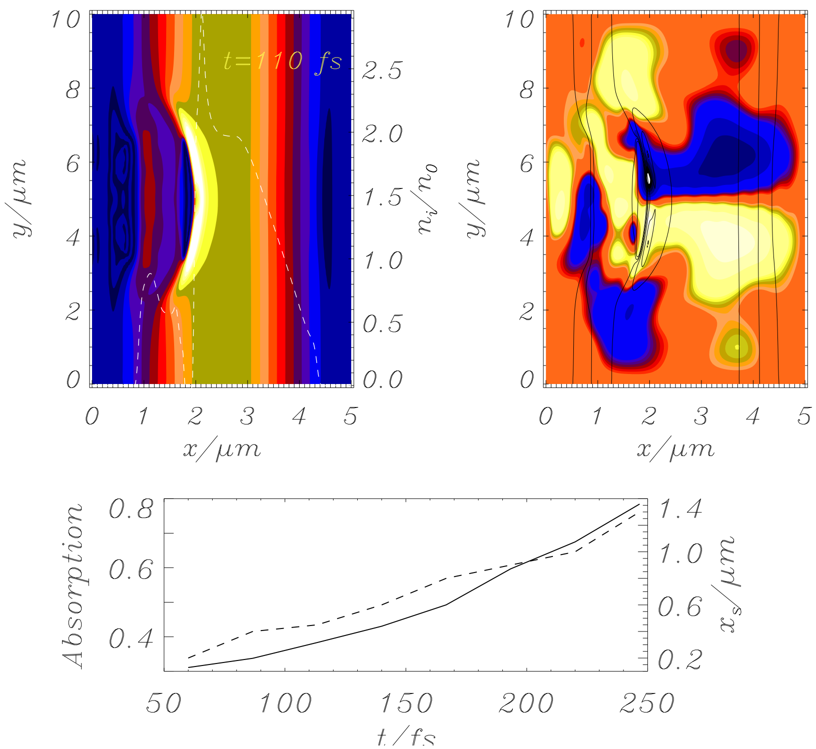

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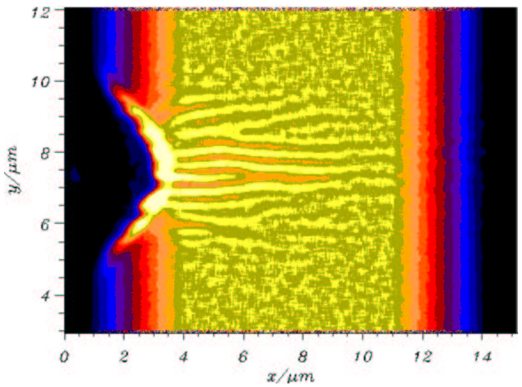

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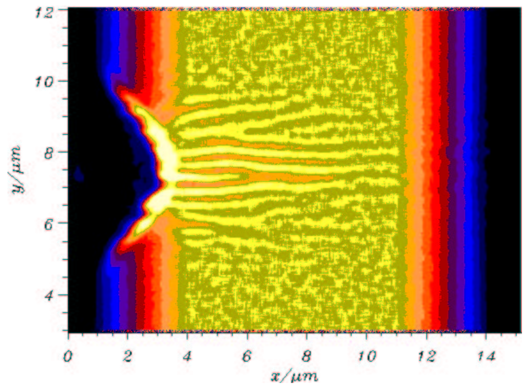

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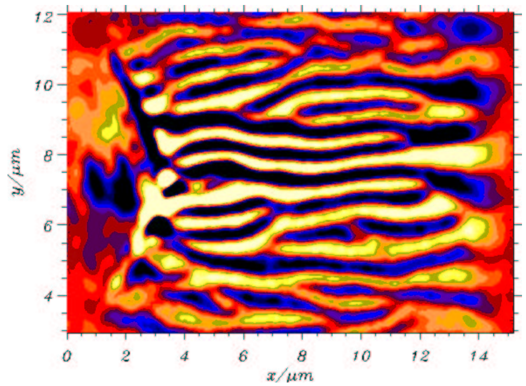

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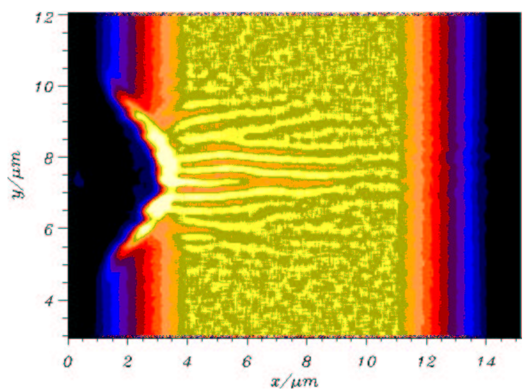

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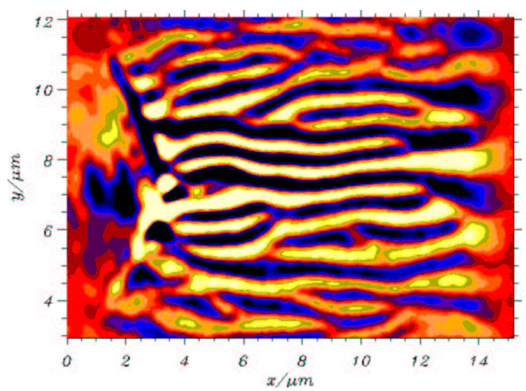

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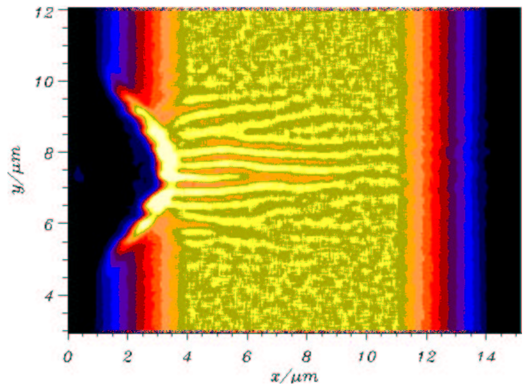

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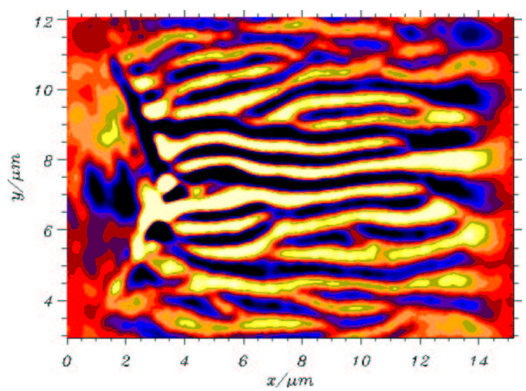

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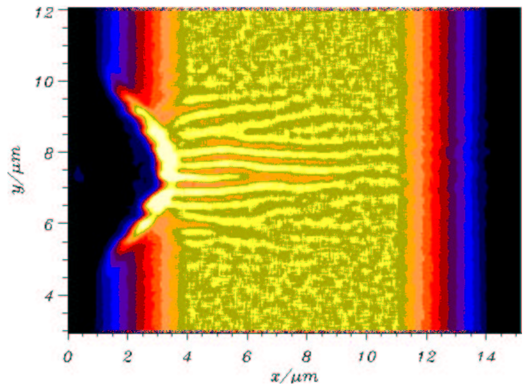

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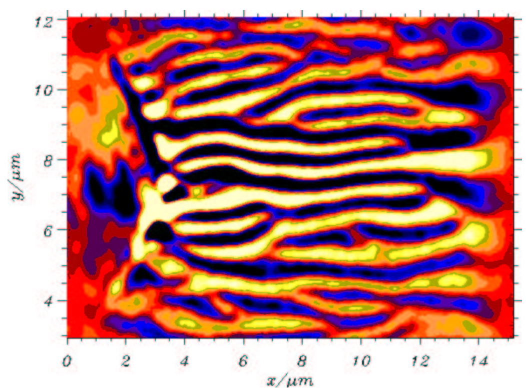

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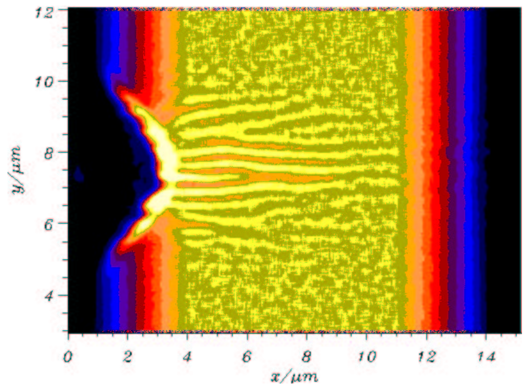

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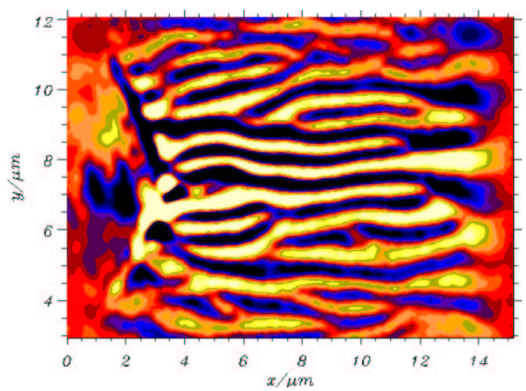

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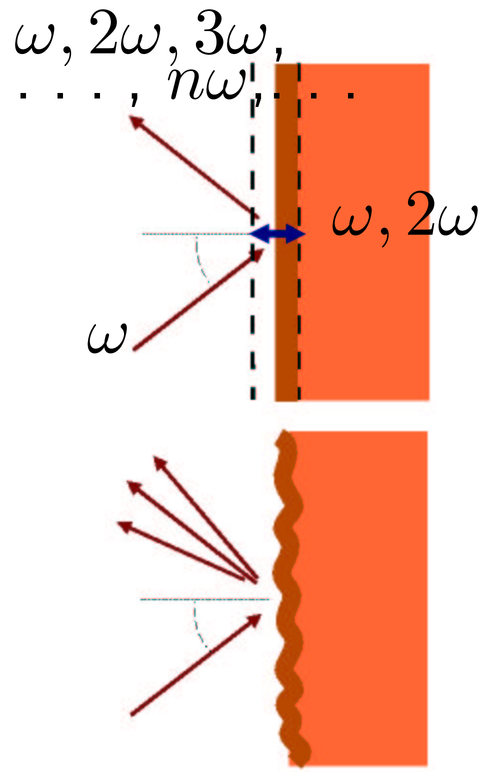

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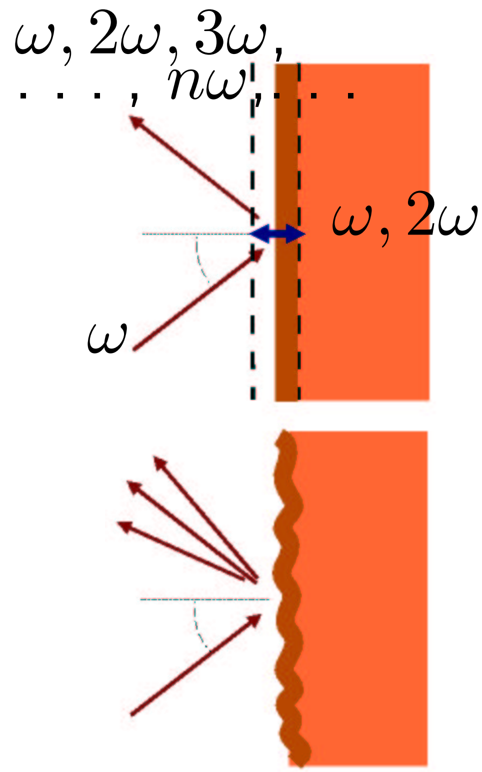

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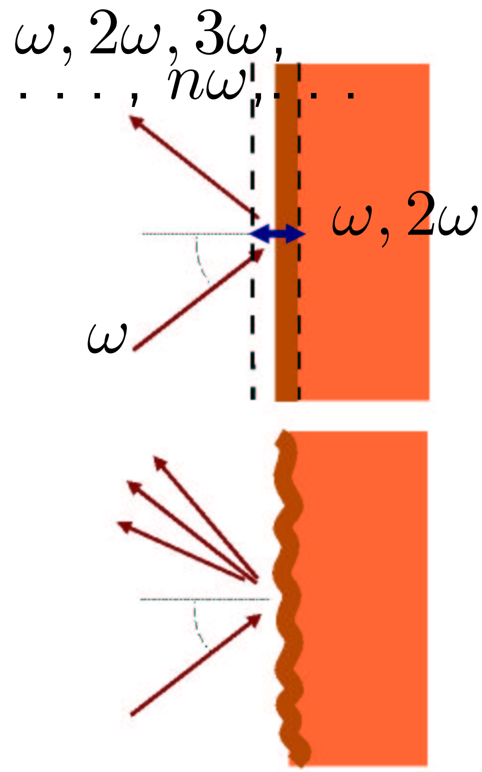

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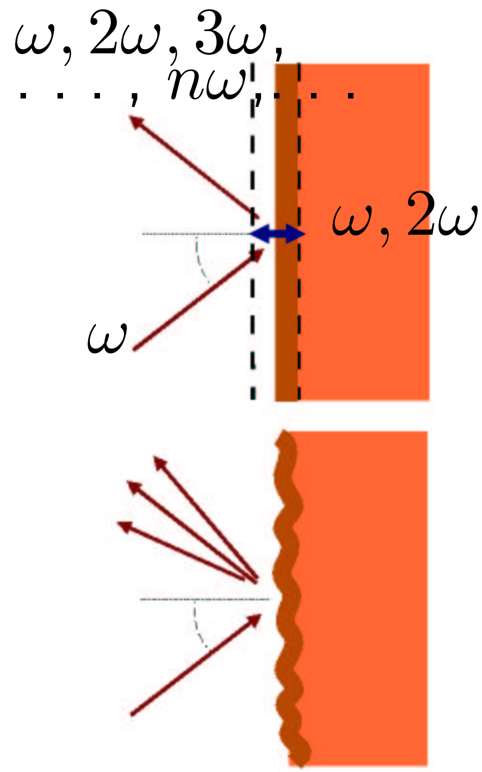

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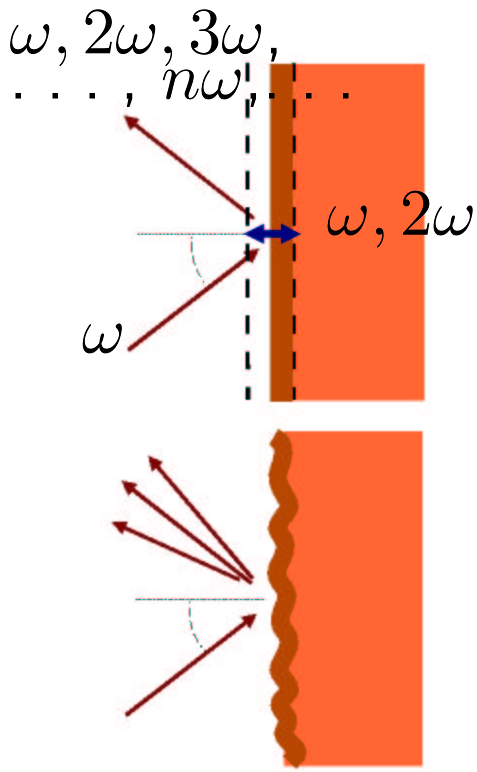
The effect is detrimental to high harmonic generation from "moving mirrors".



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$\Rightarrow$ *current neutralization* by "background" electrons is needed to avoid "self-stopping" by associated *electric* and *magnetic* fields.

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Neutralization of the "fast" electron current $\mathbf{j}_f$ by a current $\mathbf{j}_s$ of "slow" background electrons within a time:

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The equilibrium condition of opposite, neutralizing currents $\mathbf{j}_f = -\mathbf{j}_s$ is however affected by instabilities and additional effects.

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Solutions before and after the laser pulse (duration τ_L):

$$n_f(x,t) = \begin{cases} n_0 \left(\frac{t}{\tau_L}\right) \left(\frac{x_0}{x+x_0}\right)^2 & (t < \tau_L), \\ \frac{2n_0 x_0}{\pi} \frac{L(t)}{x^2+L^2(t)} & (t > \tau_L). \end{cases}$$

$$n_0 = (2I_{abs}^2 \tau_L)/(9eT_f^3 \sigma_s)\ ,$$
$$x_0 = 3T_0^3 \sigma_s / I_{abs}\ ,$$
$$L(t) = x_0 \left[(t - \tau_L)(5\pi\sigma_s T_0)/(3en_0 x_0^2) + 1 \right]^{3/5}.$$

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Much additional physics is (or *should* be) inserted: target heating, slow electron diffusion, ionization, . . .

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(Ion mass appears because Ohmic dissipation is balanced by equipartition to ions.)

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The "Weibel" instability has been invoked to explain filamentation of currents observed in PIC simulations (moderate densities, relativistic electrons, collisions not important).

Simple model of transverse “Weibel” instability – I

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Equilibrium $$f_0 = \frac{e^{-v_y^2/v_{te}^2}}{\pi(v_1 + v_2)v_{te}} \left[v_2 \delta(v_x - v_1) + v_1 \delta(v_x + v_2)\right]$$

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$$(-i\omega + ikv_y)f_1 = \frac{e}{m}\left[\left(E_x + \frac{v_y}{c}B_z\right)\partial_{v_x} - \frac{v_x}{c}B_z\partial_{v_y}\right]f_0,$$

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Dispersion relation $\omega = \omega(k)$ $(v_0^2 = v_1 v_2)$

$$\omega^2 - k^2c^2 = \omega_p^2\left(1+\frac{v_0^2}{v_{te}^2}\int dv_y\frac{1}{\sqrt{\pi}v_{te}}e^{-v_y^2/v_{te}^2}\frac{kv_y}{\omega-kv_y}\right)$$

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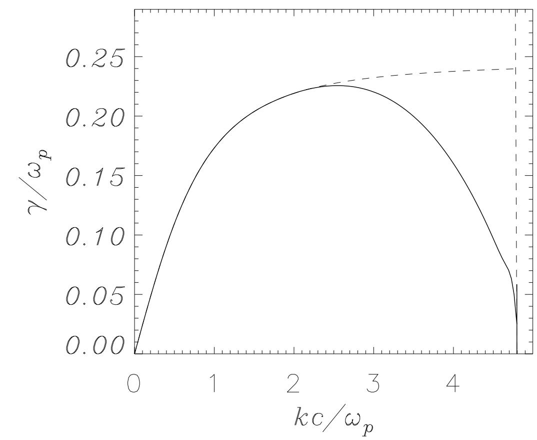

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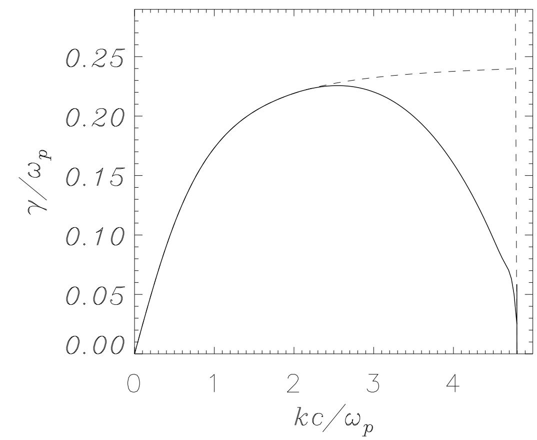

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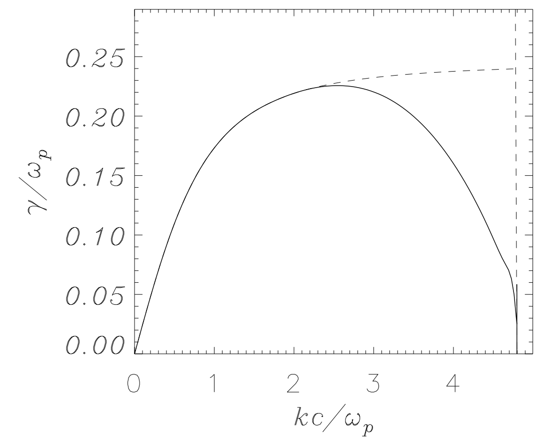

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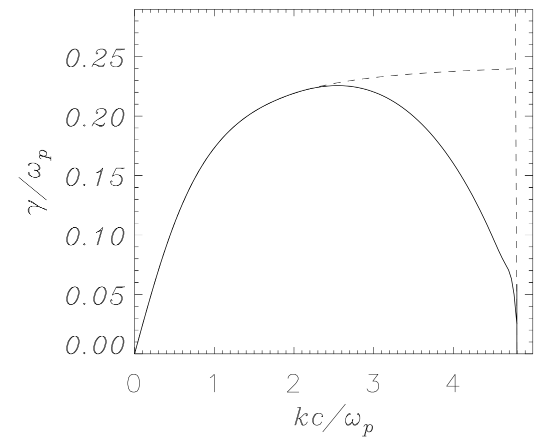

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Saturation when $B^2/8\pi \approx n_e m v_0^2/2$ ($\approx$ energy equipartition)

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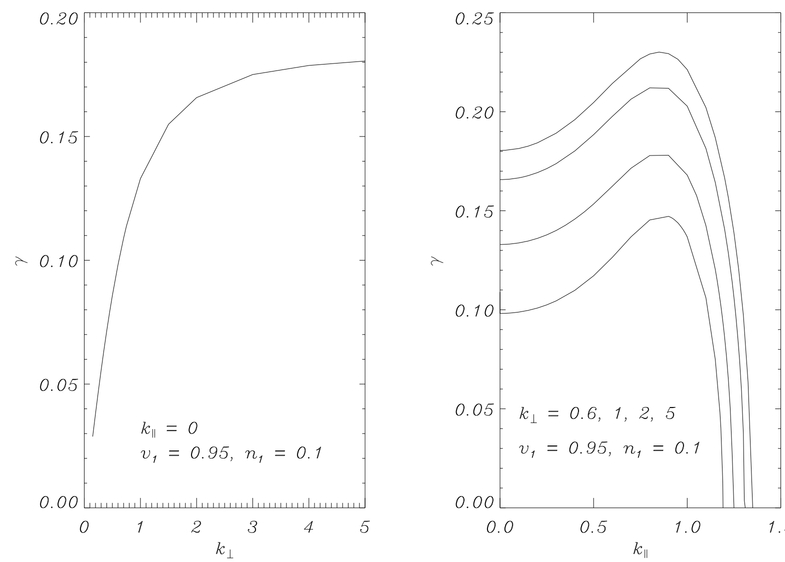

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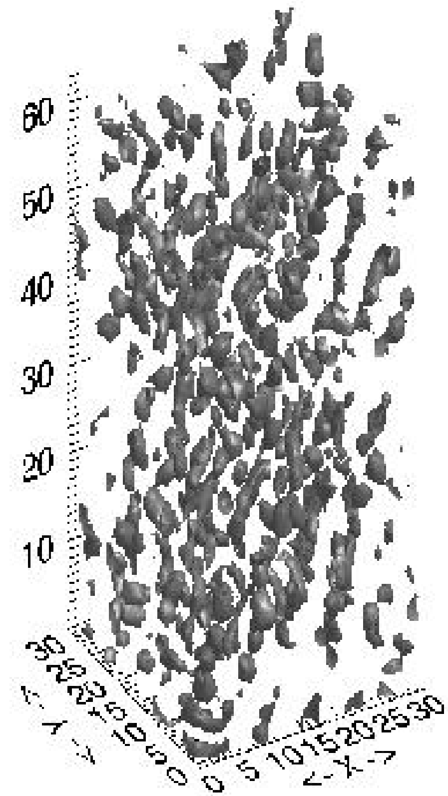

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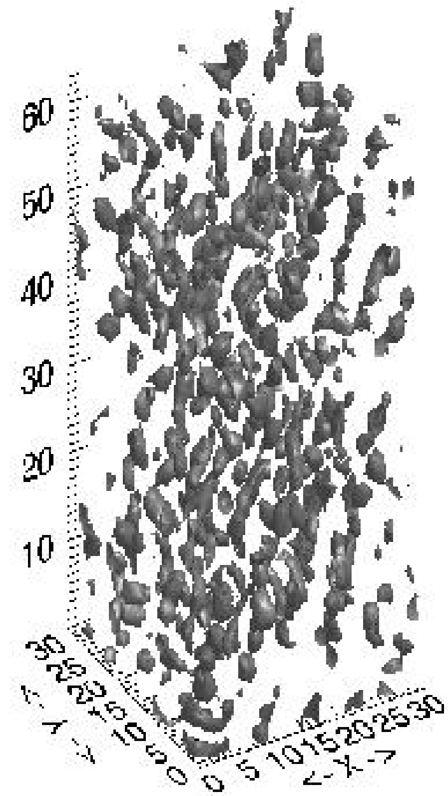

3D "bubble–like" magnetic structures are formed with typical length scales $\sim d_e = c/\omega_p$. No extended filaments in beam direction are observed.
[Simulations by F. Califano;
Macchi et al, Nucl. Fus. **43**, 362 (2003)]

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$\rightarrow$ We performed test particle simulations of electron motion in the pump+SW fields involved in TSWD.

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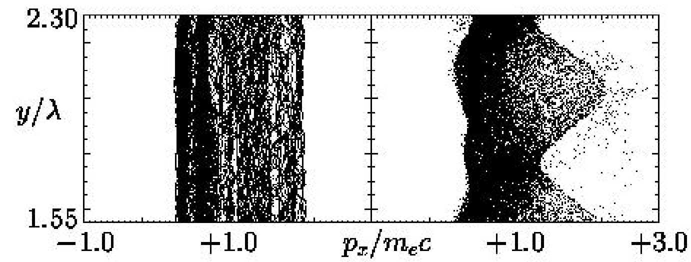
Top: (y, p_x) phase space projections from PIC simulations at two subsequent times



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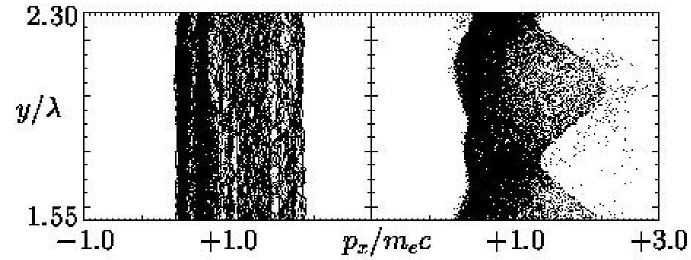

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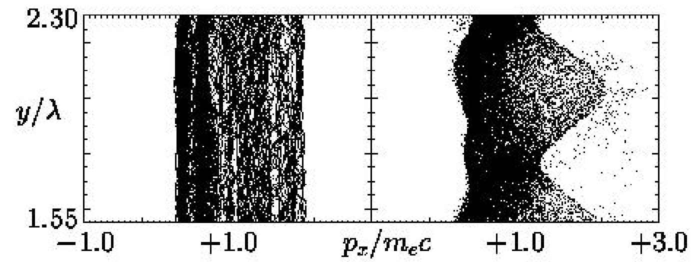

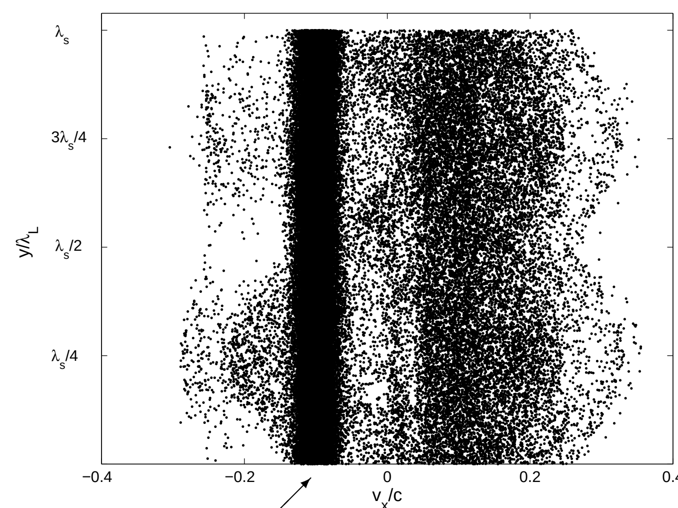

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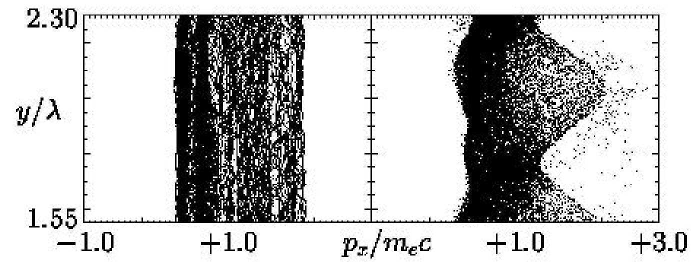

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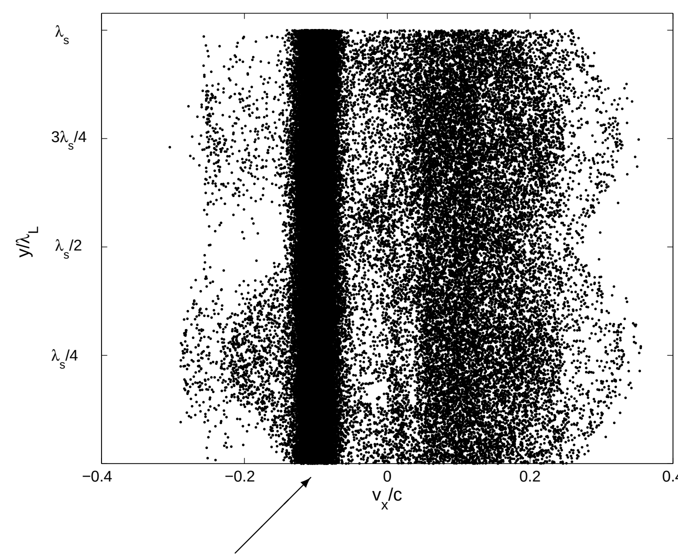
PIC and test-particle simulations both show enhanced electron heating near SW maxima



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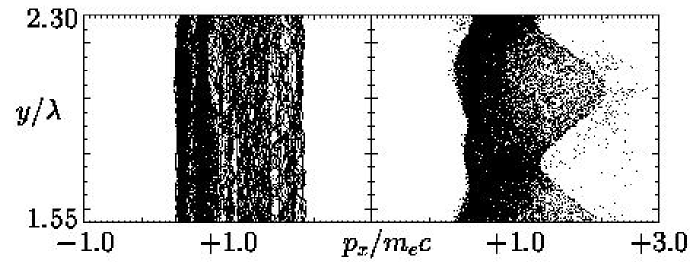
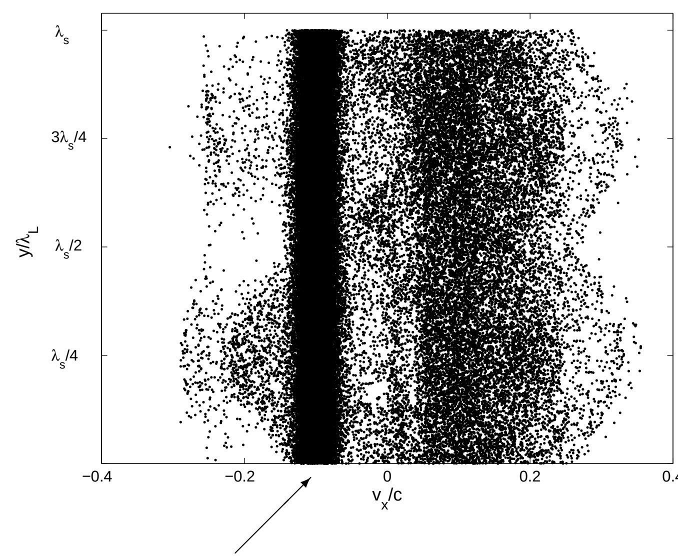
A. Macchi et al, Appl. Phys. B, in press.





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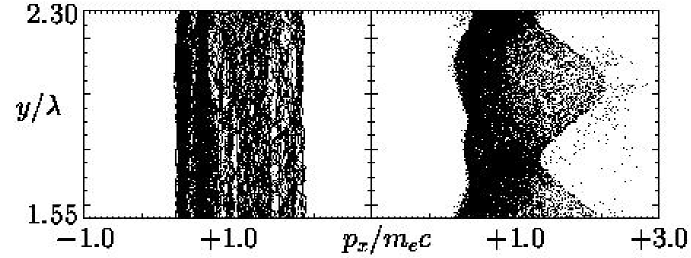
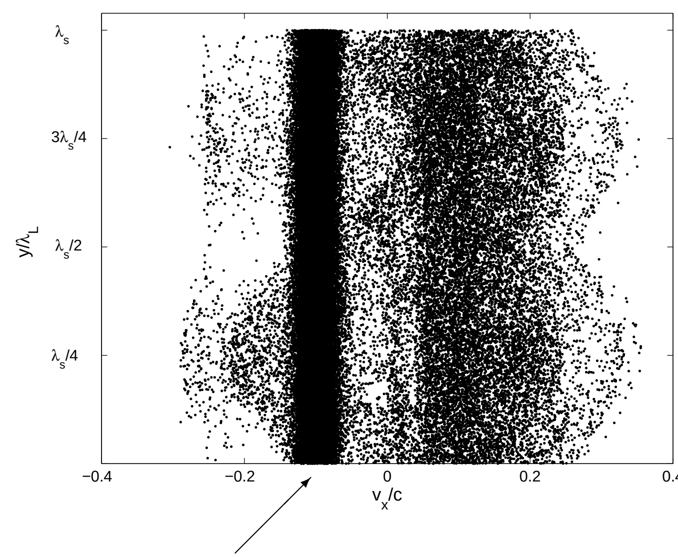


Bottom: same phase space projection from test particle simulations



"Black stripe": initial conditions

PIC and test-particle simulations both show enhanced electron heating near SW maxima

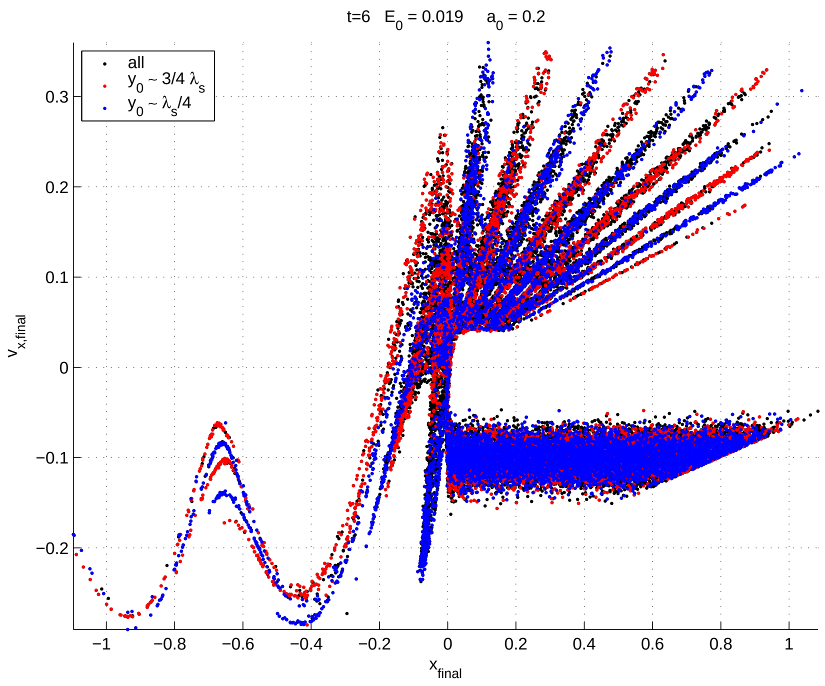
A. Macchi et al, Appl. Phys. B, in press.

Enhanced acceleration in time domain

Enhanced acceleration in time domain

(x, p_x) phase space

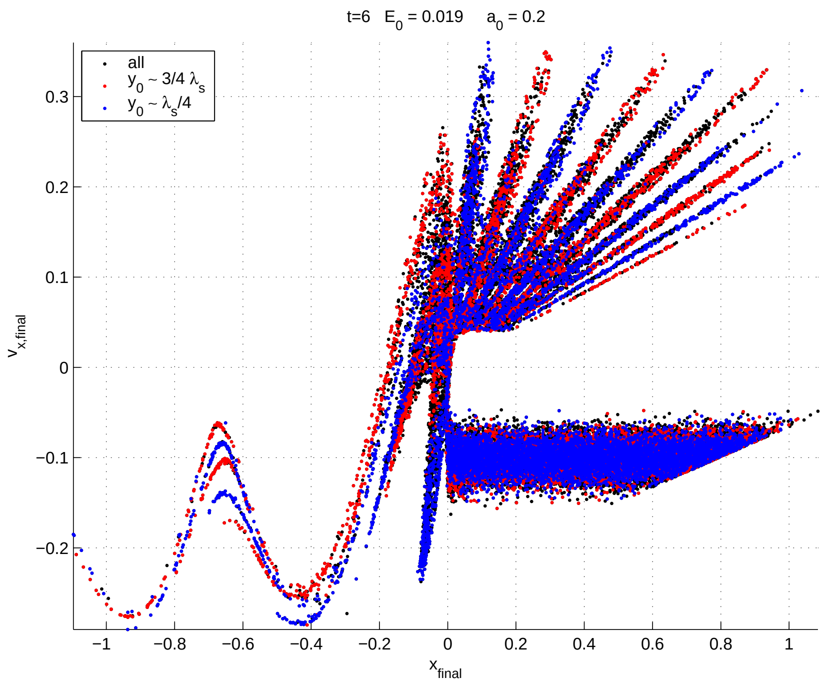
Black: all electrons in simulation



Enhanced acceleration in time domain

(x, p_x) phase space

Black: all electrons in simulation
Blue: electrons starting around $y = \lambda_s/4$



Enhanced acceleration in time domain

(x, p_x) phase space

Black: all electrons in simulation
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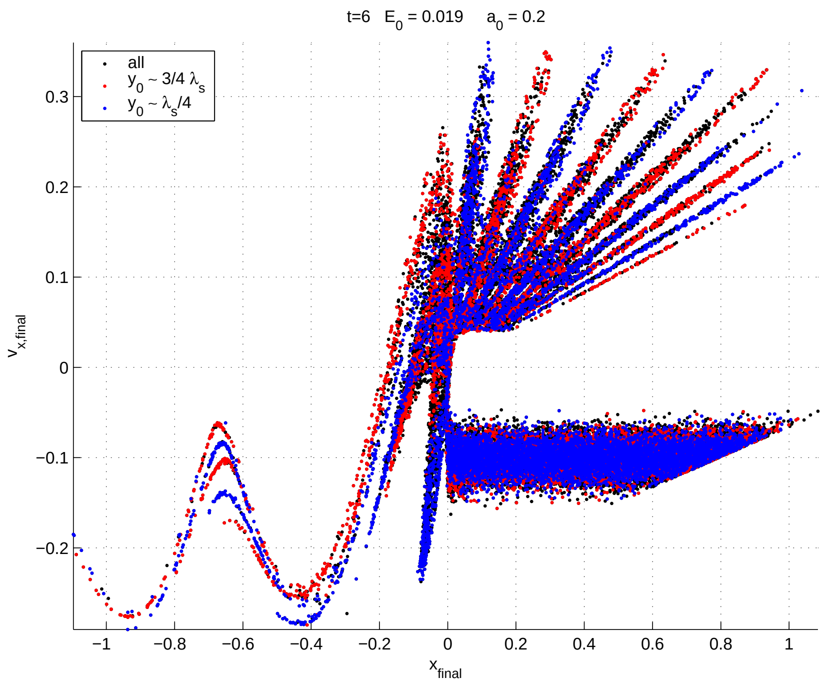
Red: electrons starting around $y = 3\lambda_s/4$



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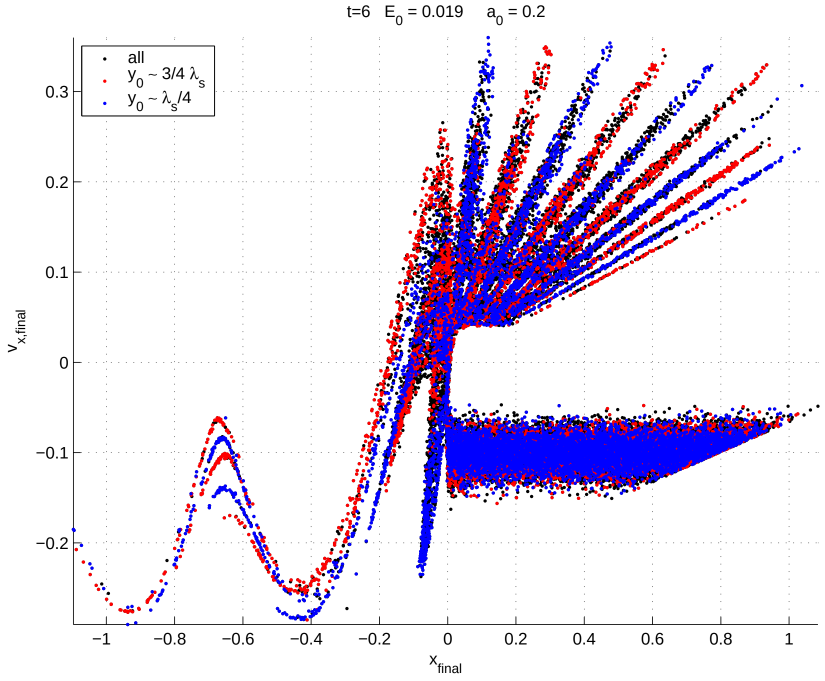

– "Jets" are produced at 2ω rate (by $\mathbf{v} \times \mathbf{B}$ force).

Enhanced acceleration in time domain

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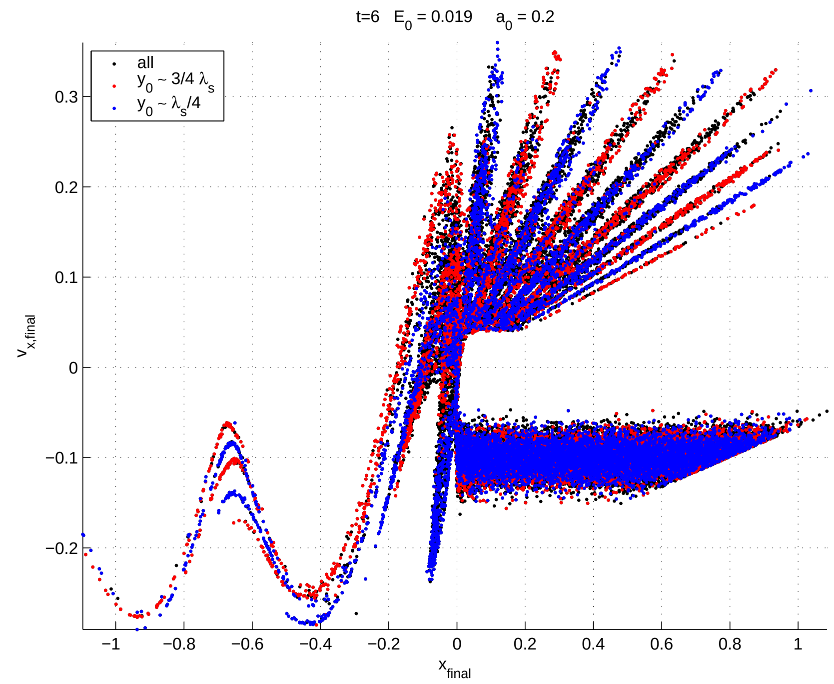

– "Jets" are produced at 2ω rate (by $\mathbf{v} \times \mathbf{B}$ force).
– Enhanced acceleration by SW occurs at ω rate.

Enhanced acceleration in time domain

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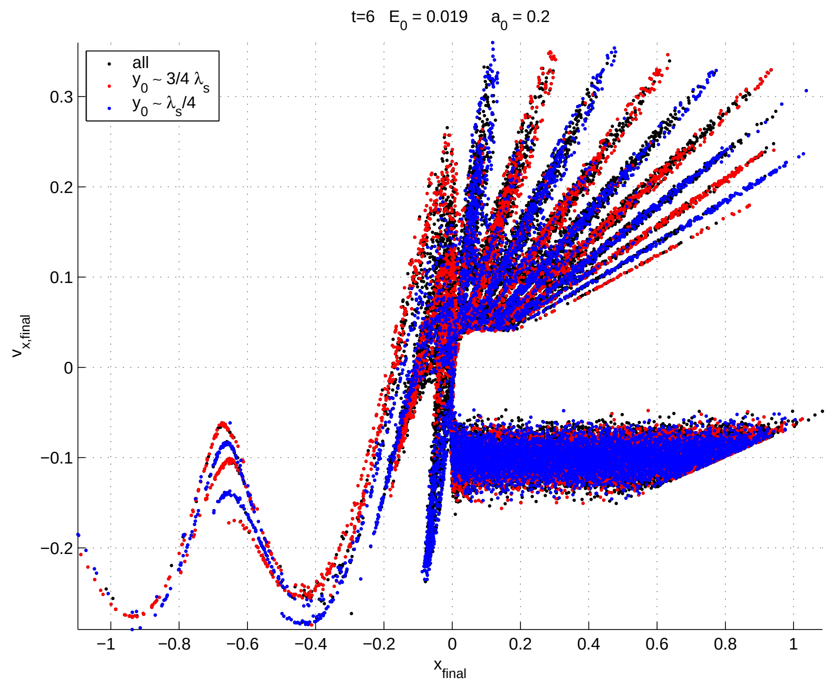

– "Jets" are produced at 2ω rate (by $\mathbf{v} \times \mathbf{B}$ force).
– Enhanced acceleration by SW occurs at ω rate.
– Near SW maxima some electrons are emitted into vacuum $(x < 0)$
(p_x modulated by $\mathbf{v} \times \mathbf{B} \sim \cos 2k_L x$ in vacuum)

Induced modulation of electron current

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The electron current density $J_{e,x}$ is reconstructed from test particle phase space.

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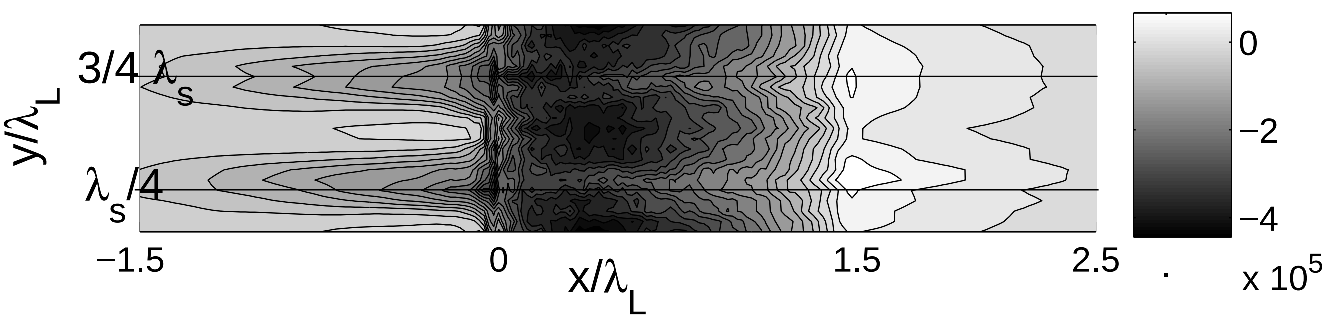

$J_{e,x}$ is spatially modulated in y with the SW periodicity.

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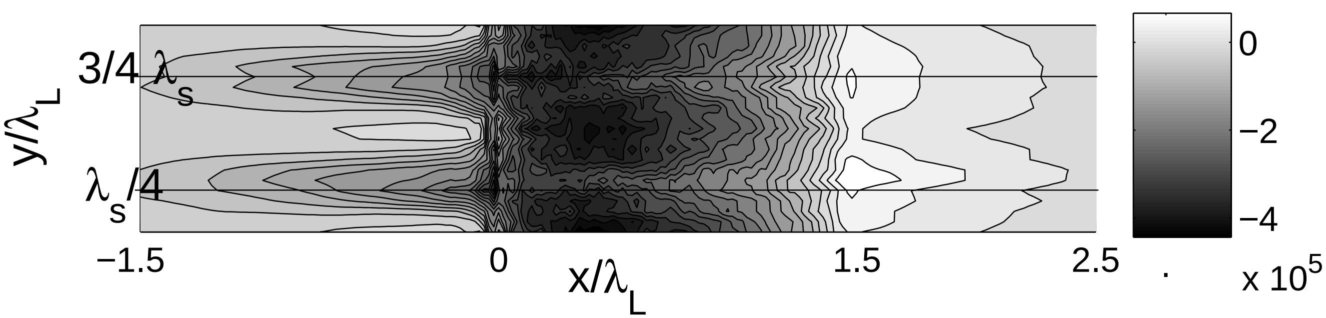

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Spatial imprint for current filamentation?

Acknowledgment

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