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International Workshop on Fast Ignition of Fusion Plasmas

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Powerful terahertz emission from laser
wakefields in inhomogeneous underdense
plasma

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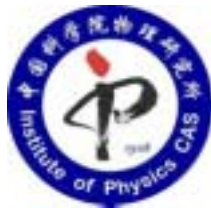
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Collaborators

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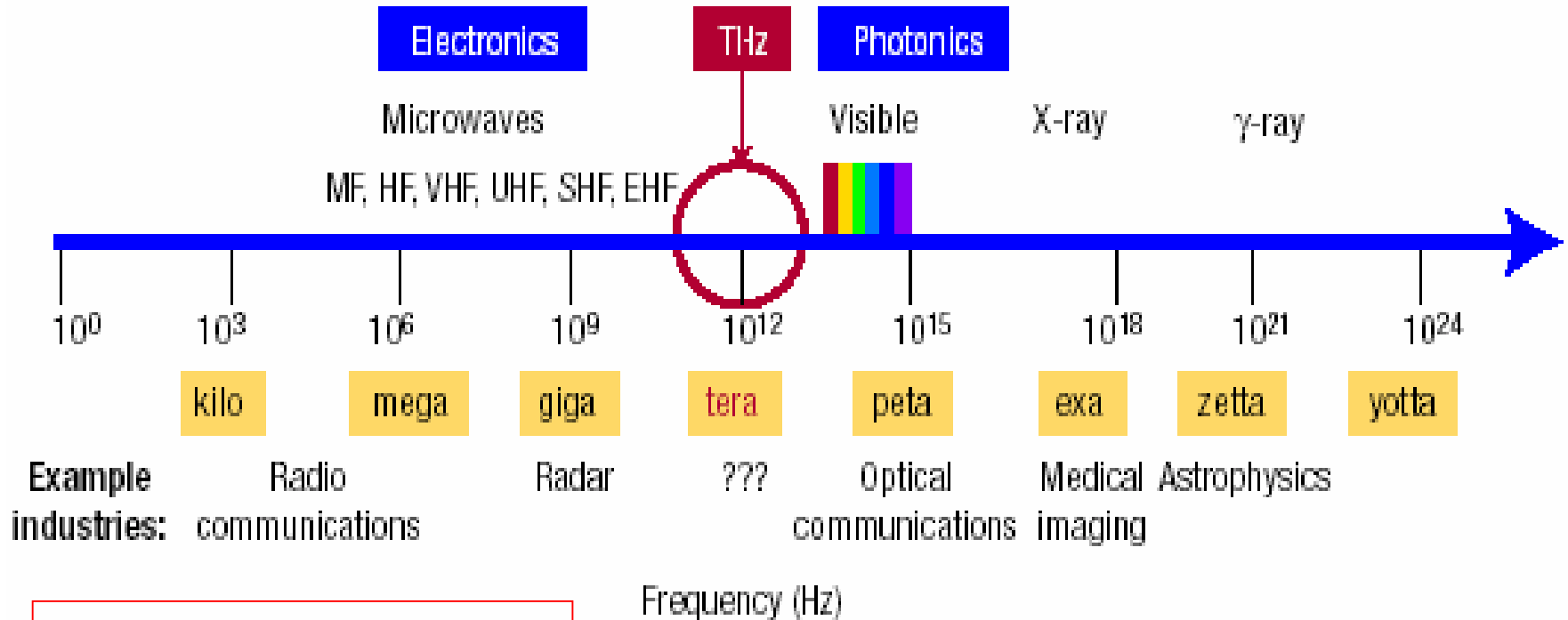
H. Sanuki, National Institute for Fusion Science, Toki, Gifu



Outline

- *THz wave and its generation*
- *Simulation of THz wave generation from laser wakefields*
- *Theory of mode conversion*
- *Comparison of the theory with simulations*
- *Effect of laser beam diameters*
- *Emission from plasma channels*
- *Conclusions*

Terahertz wave



Applications:

Material characterization by THz spectroscopy;
Tomographic imaging;
Biomaterial applications.

B. Ferguson and X.-C. Zhang,
Nature Materials 1, 26 (2002)

THz Wave Emitters

- Photoconductive dipole antenna
- Optical rectification in Electro-optic crystals with femtosecond laser
- Upconversion of radio frequency sources or downconversion of optical (Gunn, Bloch oscillator, gas lasers, optical parametric generators and oscillators)
- Semiconductor THz laser

“The lack of a high-power, low-cost, portable room-temperature THz source is the most significant limitation of modern THz system.”

--- B. Ferguson and X.-C. Zhang, *Nature Materials* 1, 26 (2002).

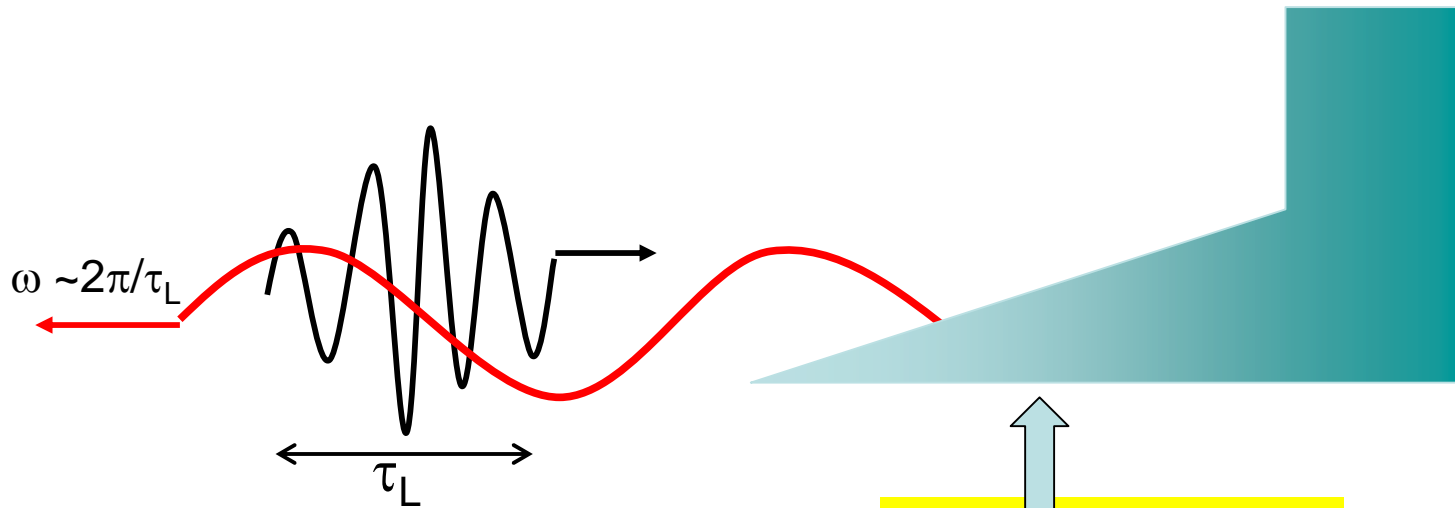
Some THz Emitters associated with plasma and electron beams

- THz emission from plasma was observed as earlier as in 1993 by H. Hamster et al., Phys. Rev. Lett. 71, 2725 (1993);
- Radiation from Cerenkov Wakes in a Magnetized Plasma:
N. Yugami et al., Phys. Rev. Lett. 89, 065003 (2002), J. Yoshii, C. H. Lai, T. Katsouleas, C. Joshi and W. B. Mori, Phys. Rev. Lett. 79, 4194 (1997).
- Coherent synchrotron radiation by short bunches of electrons circulating in the storage ring:
M. Abo-Bakr et al., Phys. Rev. Lett. 90, 094801 (2003).
- Terahertz emission from a laser-plasma accelerated electron bunch crossing a plasma-vacuum boundary through transition radiation:
W. P. Leemans et al., Phys. Rev. Lett. 91, 074802 (2003).
- Coherent subterahertz radiation from femtosecond infrared filaments in air:
S. Tzortzakis et al., Opt. Lett. 27, 1944 (2002); G. Mechain et al., Appl. Phys. B 77, 707 (2003).
- Free electron laser:
Highest T-ray power (Nature, Nov. 14, 2002)

An electron plasma wave is potentially a high-power THz source

- Plasma waves that can be driven by ultrashort laser pulses oscillate typically at the THz range (e.g., $n_e=10^{18}\text{cm}^{-3}$, $\omega_p/2\pi=9\text{THz}$).
- The field strength before wave-breaking is as high as 100 GV/m for $n_e=10^{18}\text{cm}^{-3}$.
- How can an electrostatic wave be converted to an electromagnetic wave?

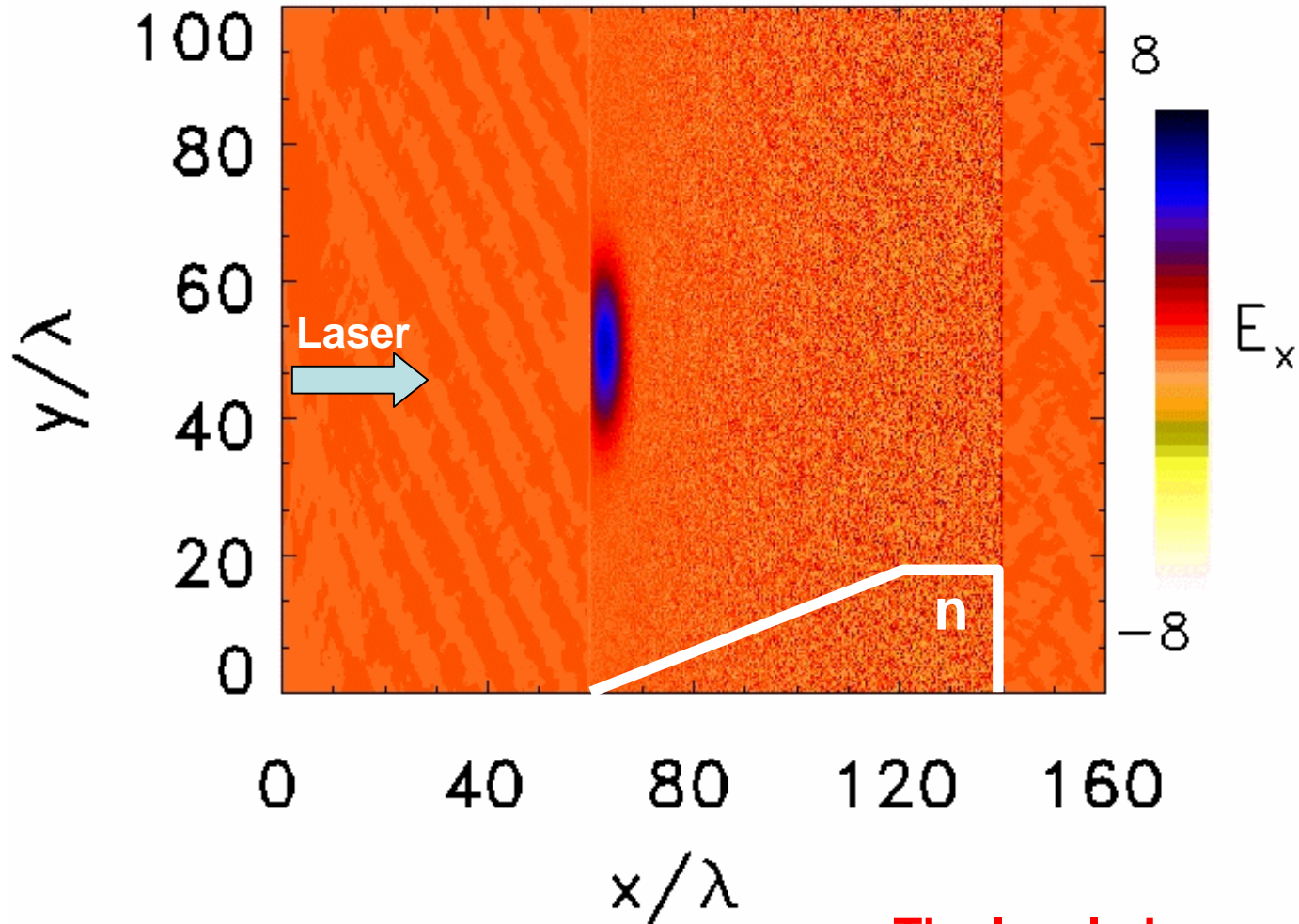
THz radiations from a vacuum-plasma interface by introducing an inhomogeneous plasma region



$$\frac{2\pi}{\omega_{pe}} = 1\text{THz}, \Rightarrow n_e = 1.11 \times 10^{16} \text{cm}^{-3}$$

$$\omega_p = \omega = 2\pi / \tau_L$$
$$n = m\omega^2 / 4\pi e^2$$

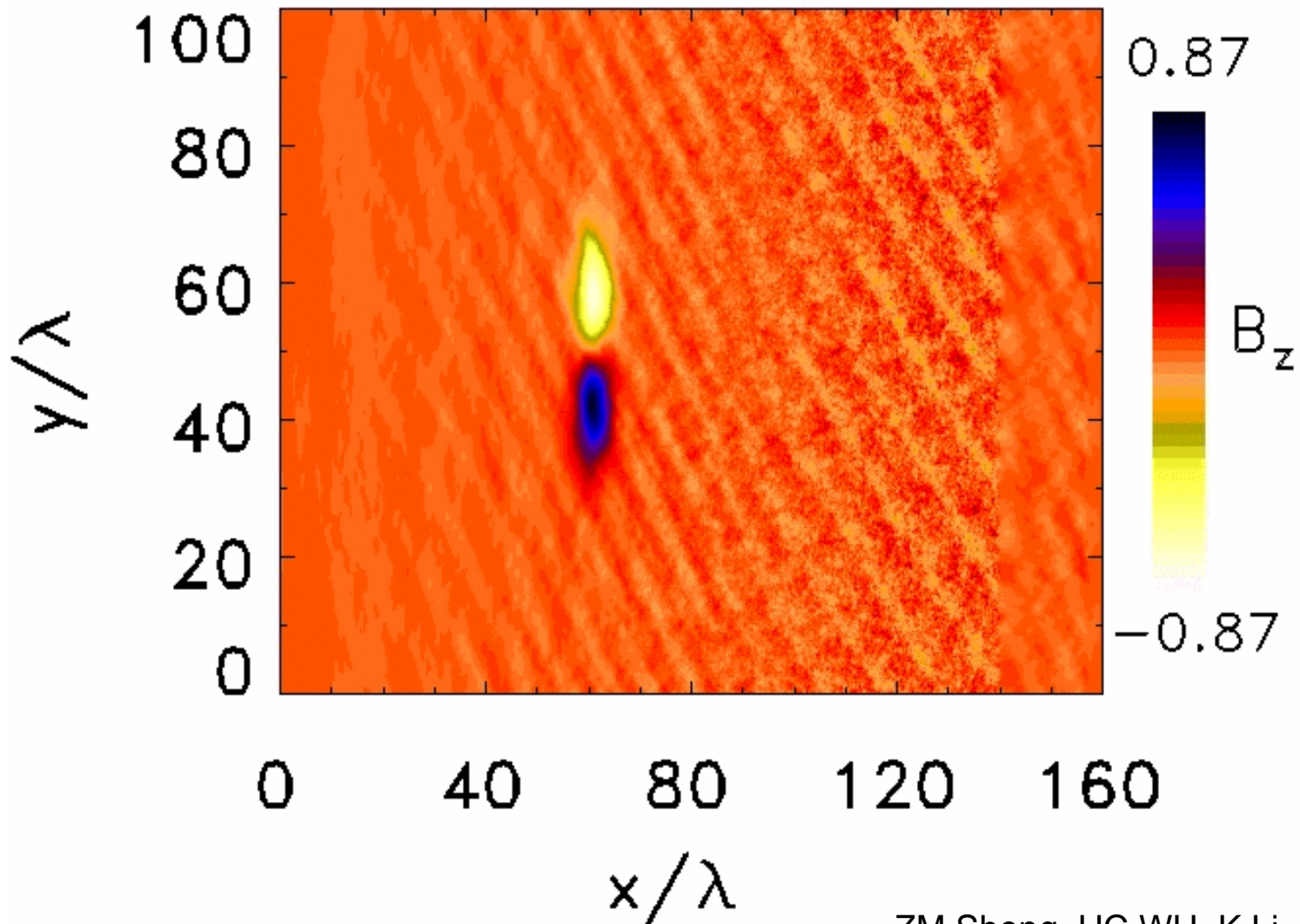
Wakefield of an ultrashort laser pulse: the longitudinal electric field (Movie)



($a=0.5$, $T=20\tau$, $n/L=0.01n_c/60\lambda$)

**The local phase velocity
is changing with time!**

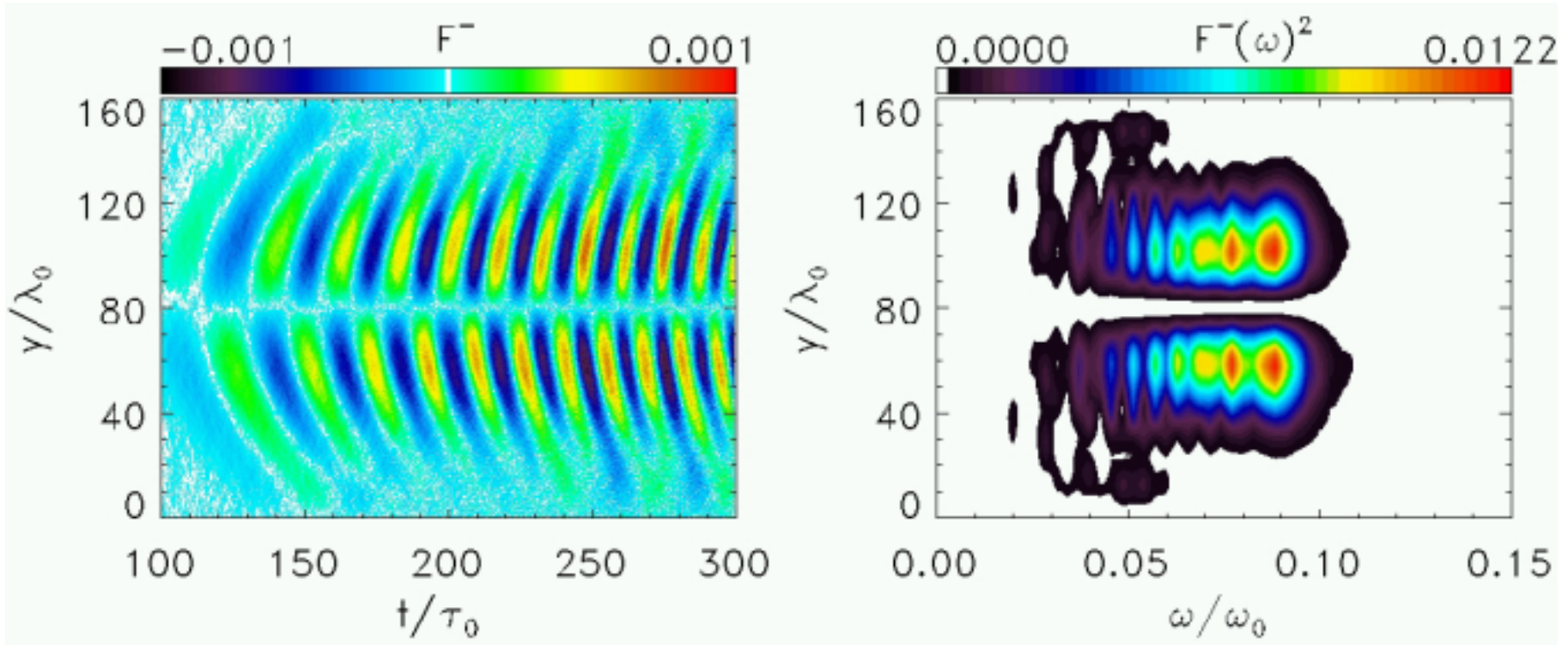
Transverse magnetic field (Movie)



($a=0.5$, $T=20\tau$, $n/L=0.01n_c/60\lambda$)

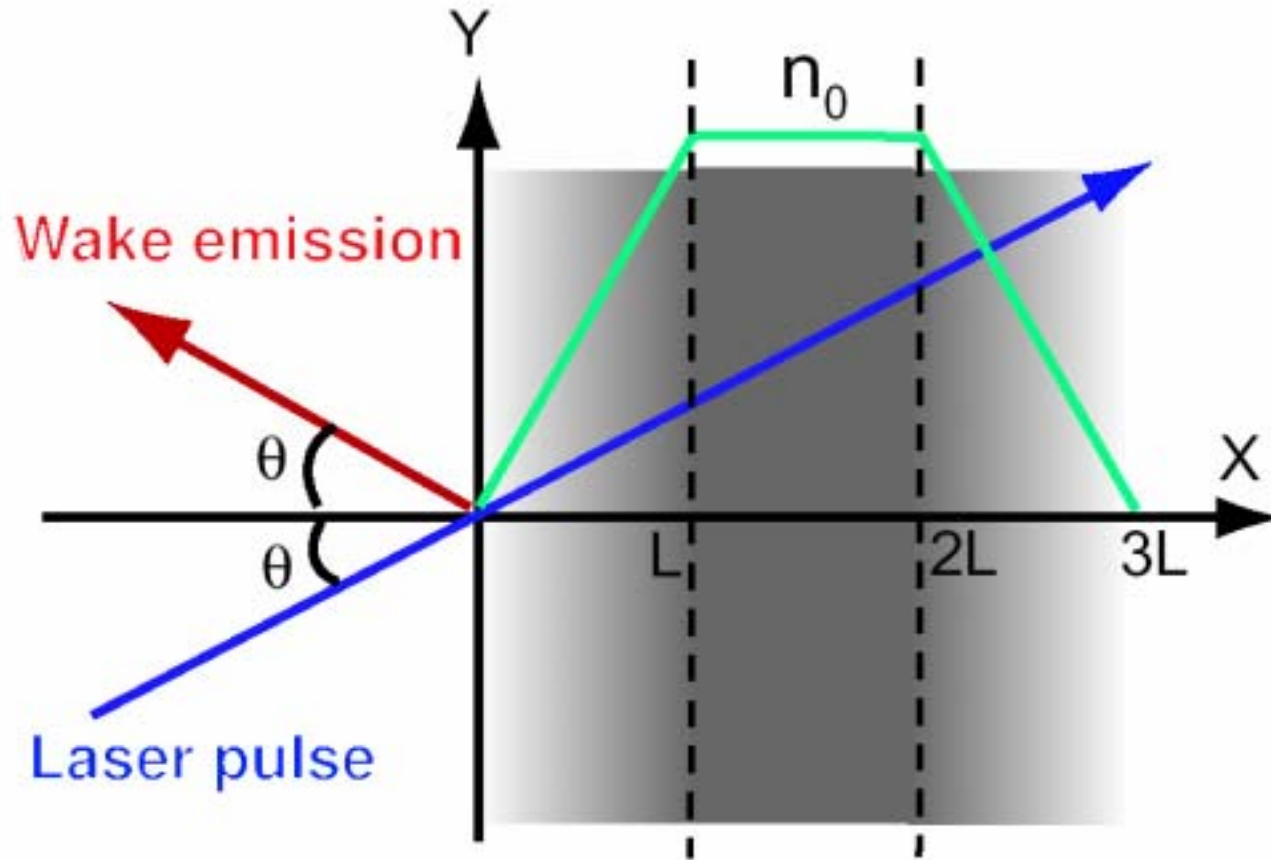
ZM Sheng, HC WU, K Li, J Zhang,
Phys. Rev. E 69, 025401(R) (2004).

Radiation pulse and spectra



$$a_0=0.5, L=60\lambda_0, T=20\tau_0, w_0=20\lambda_0$$

Model calculation: schematic view



Plasma oscillations in inhomogeneous plasmas

$$\delta(x_0, t) = \delta_0 \cos[\psi(x_0, t)],$$

$$\psi(x_0, t) = \omega_p(x_0)(t - x_0 / v_g),$$

$$v_{ph}(x_0, t) = \frac{\omega}{k} = -\frac{\partial \psi / \partial t}{\partial \psi / \partial x_0}$$

Wave vector of a plasma wave in inhomogeneous plasmas



$$n = n_0(x_0 / L), \quad \omega_p = \omega_{p0}(x_0 / L)^{1/2},$$

$$k(x_0, t) = \frac{3x_0 - v_g t}{2x_0} \omega_p$$

$$k \rightarrow 0 \quad \text{for} \quad x_0 = v_g t / 3$$

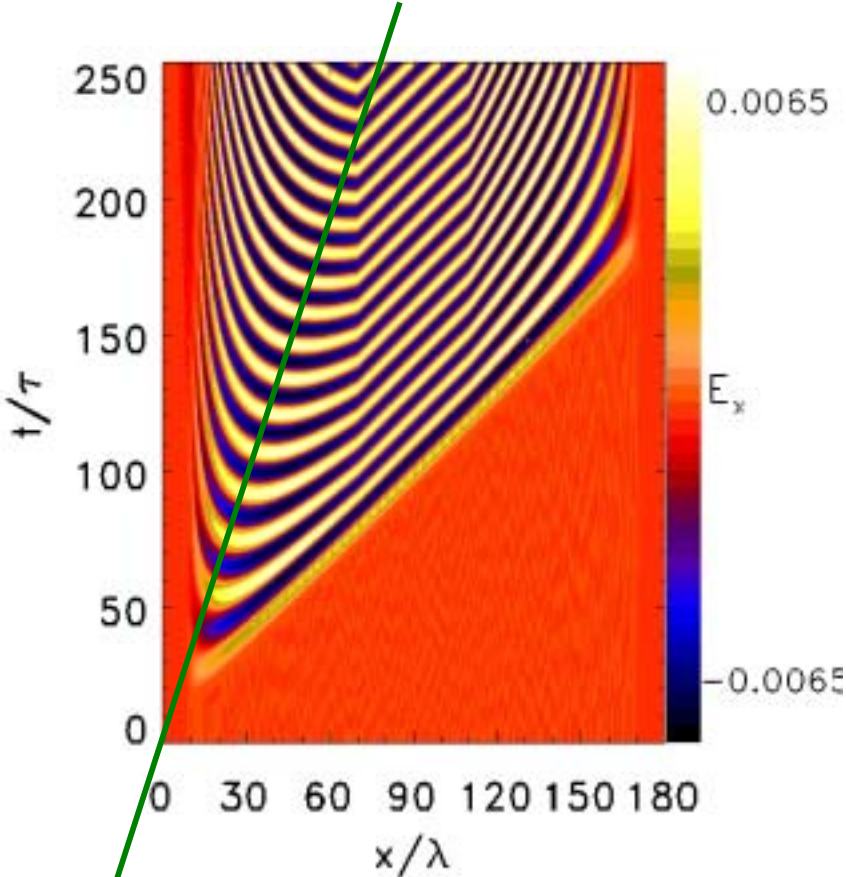
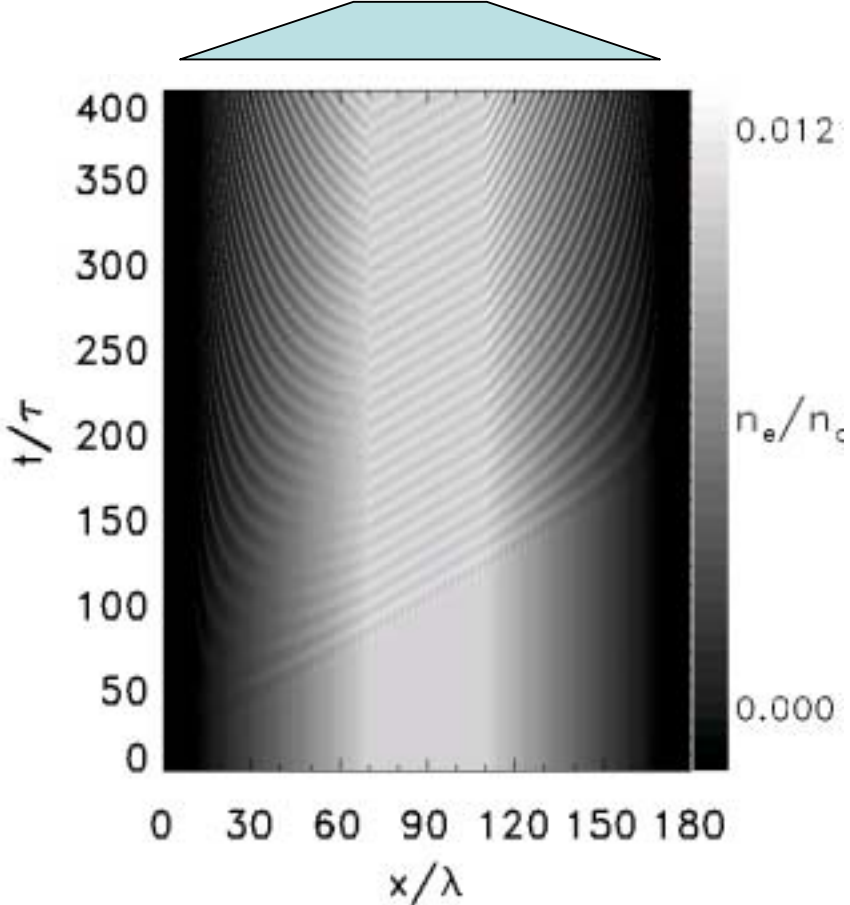


$$n = n_0(1 - x_0 / L), \quad \omega_p = \omega_{p0}(1 - x_0 / L)^{1/2},$$

$$k(x_0, t) = \frac{2(L - x_0) + (v_g t - x_0)}{2(L - x_0)} \omega_p$$

$$k > 0 \quad \text{Since} \quad t > x_0 / v_g$$

Evolution of plasma waves in inhomogeneous plasmas from simulations



$x = ct/3$

Mode conversion theory

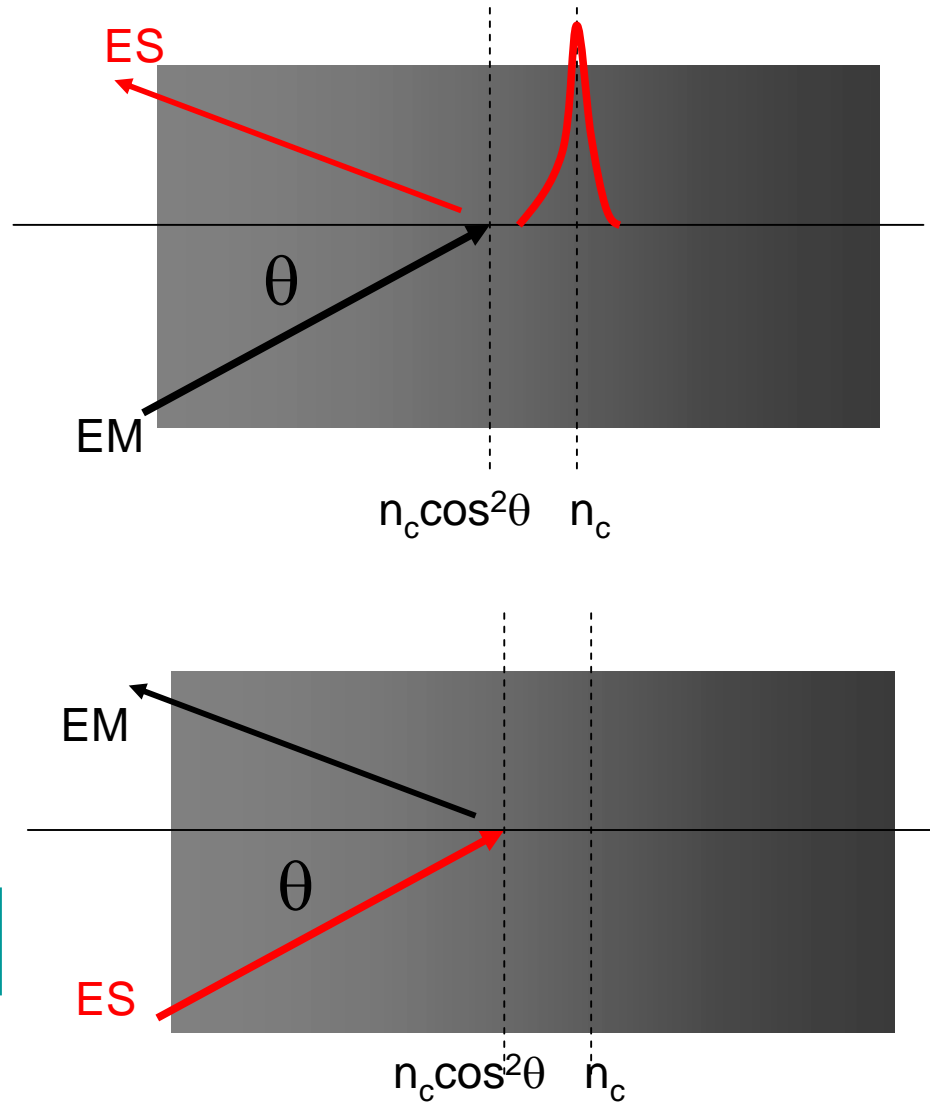
Conversion efficiency from electromagnetic waves into electrostatic waves η is the same as its inverse problem

$$\eta = \frac{2\alpha q}{2 + \alpha q} \exp\left(-\frac{4}{3}q^{3/2}\right),$$

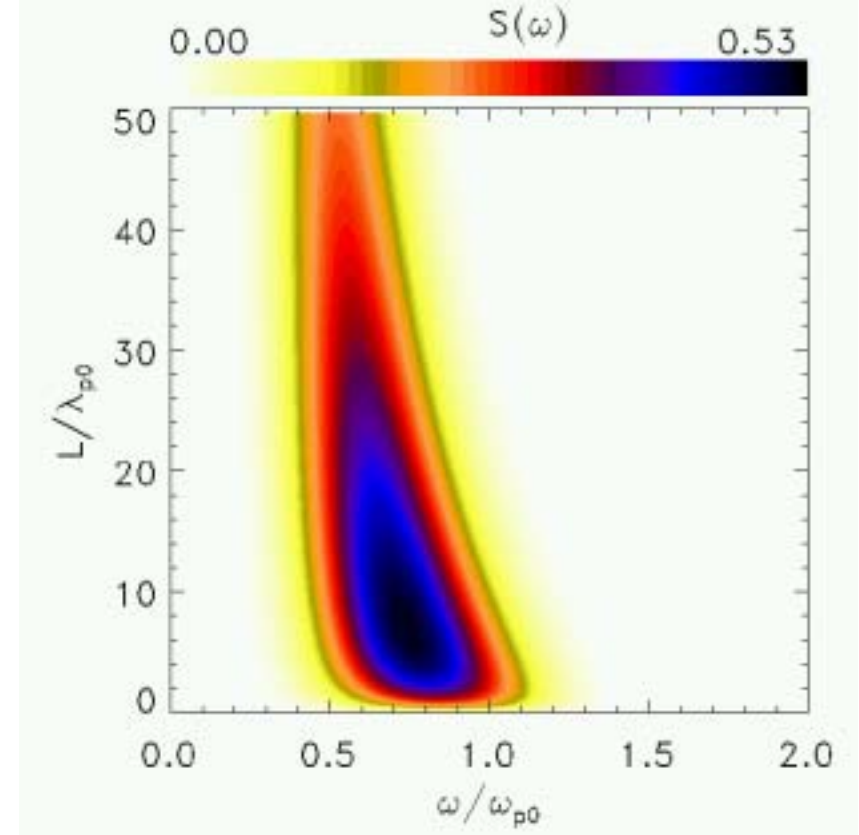
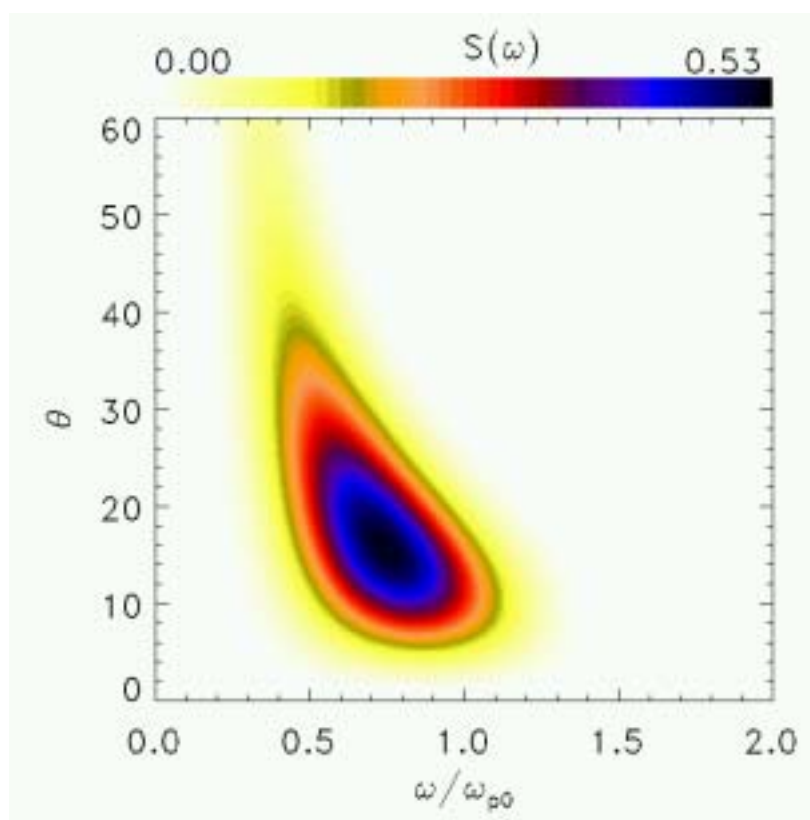
$$q = (\omega L_\omega / c)^{2/3} \sin \theta, \quad \alpha = 2.644$$

Emission spectrum from wakefield is calculated by

$$S(\tilde{\omega}, L, \theta, d_L) = \eta[q(\tilde{\omega})]E_m^2(\tilde{\omega})$$



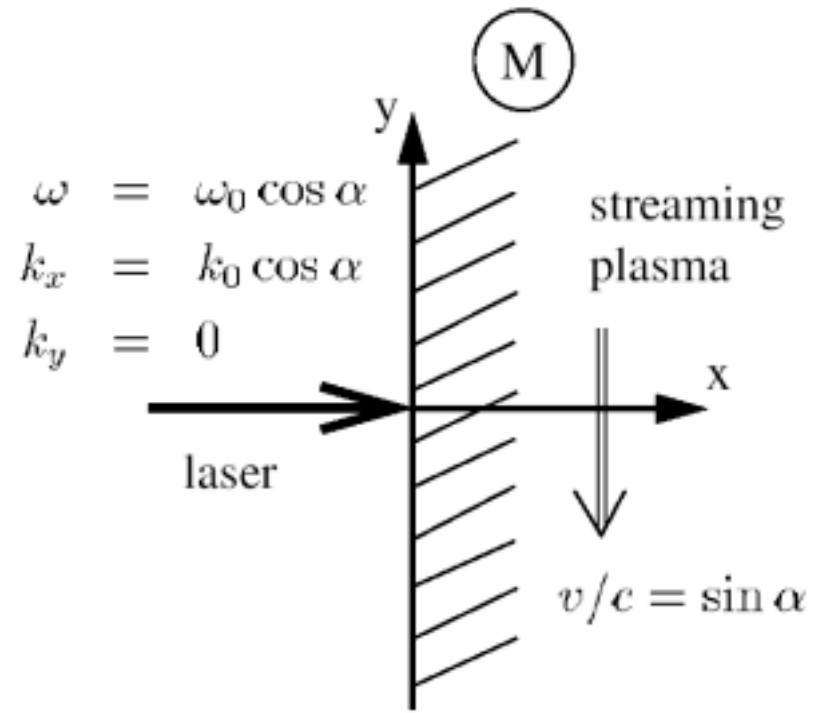
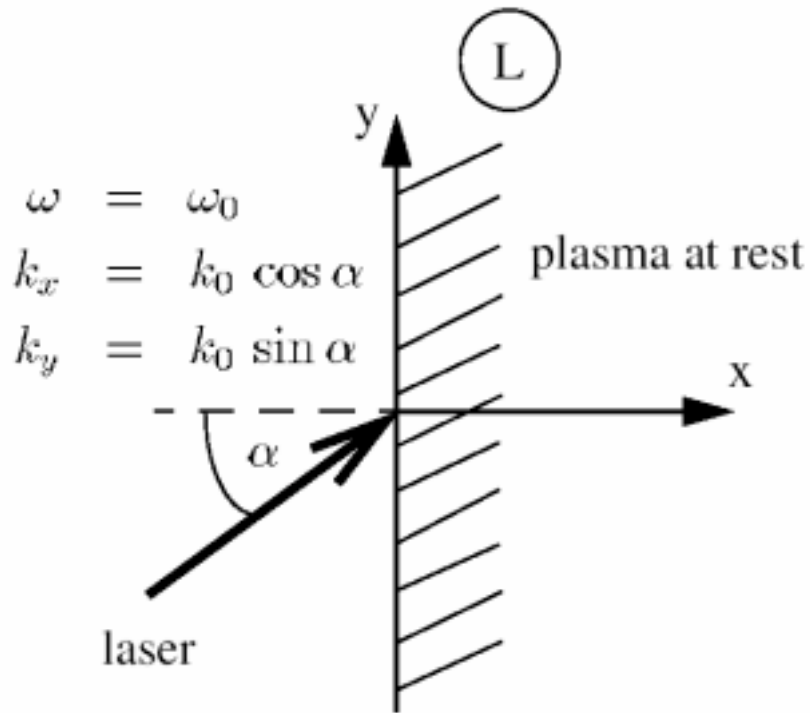
Emission spectra as a function of the incident angle and plasma scalelength



$$a_L = a_0 \sin^2 \left[\pi(x - ct) / d_L \right],$$

$$E_m(\omega_p) = \frac{m\omega_p c}{e} \frac{a_0^2}{4} \sin \left(\frac{\pi d_L}{\lambda_p} \right) \left\{ \frac{1}{1 - (d_L / \lambda_p)^2} - \frac{0.25}{1 - 0.25(d_L / \lambda_p)^2} \right\}$$

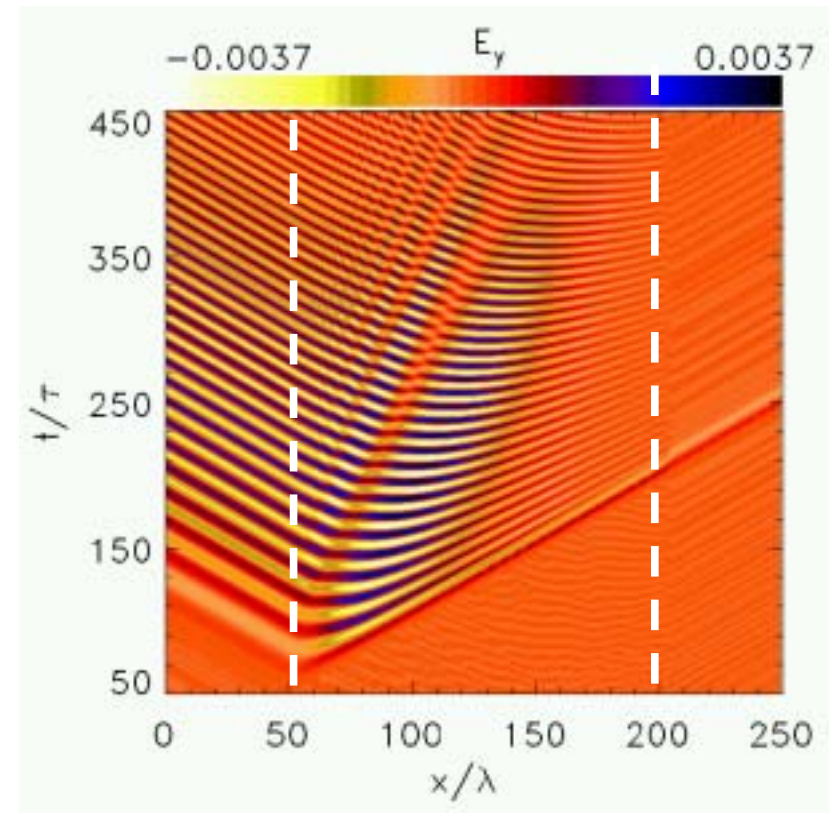
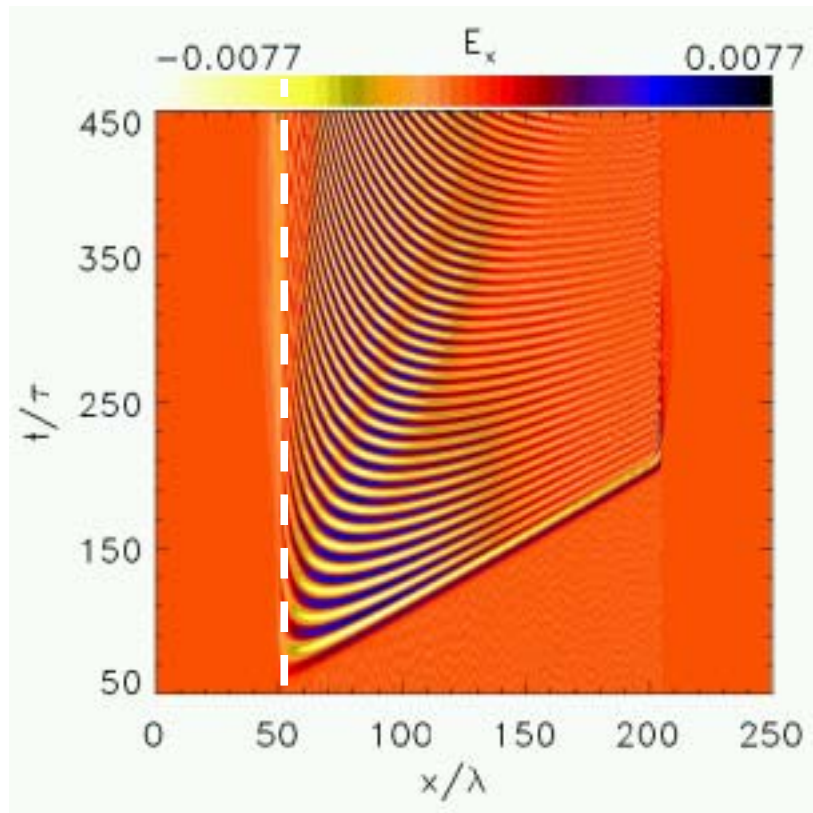
1D code for oblique incidence of laser pulses: a code in boosted frame



Bourdier et al. Phys.Fluids 26,1904 (1983);

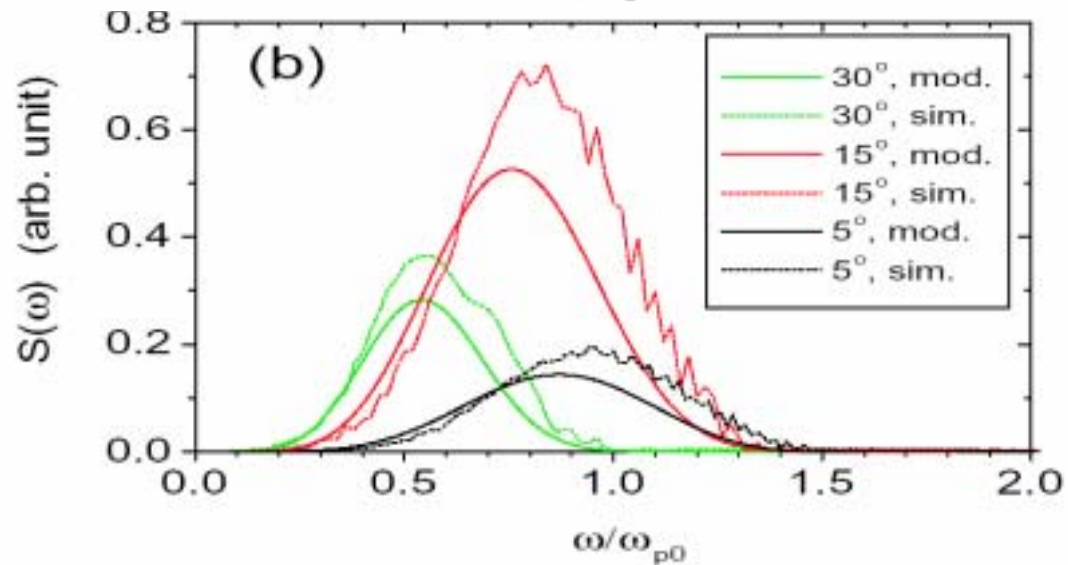
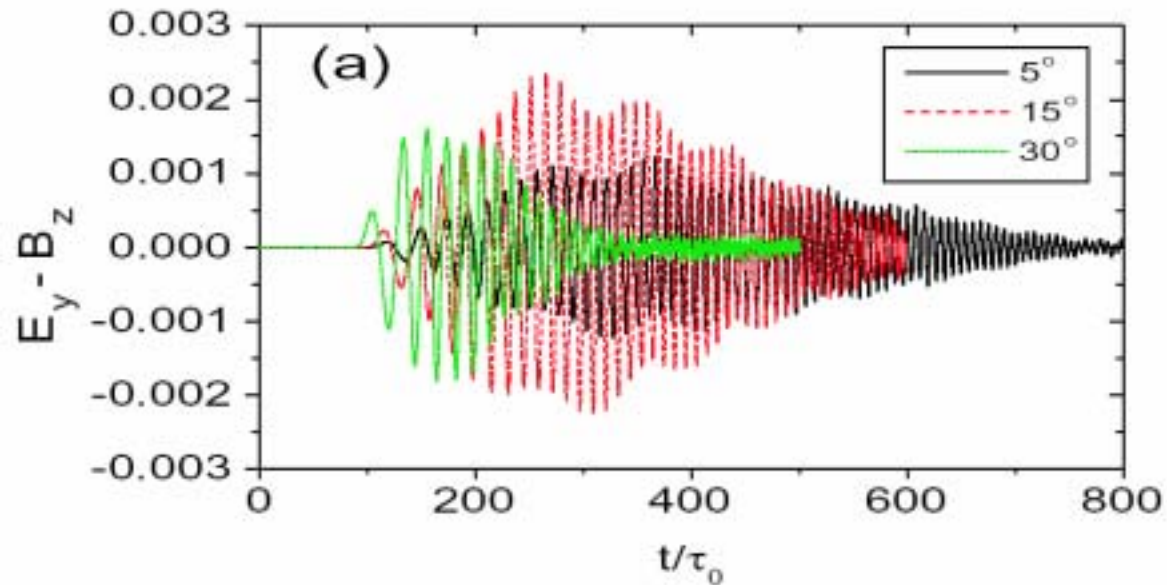
R. Lichters, J. Meyer-ter-Ven, A. Pukhov, Phys. Plasmas 3, 3425 (1996).

1D simulation at oblique incidence



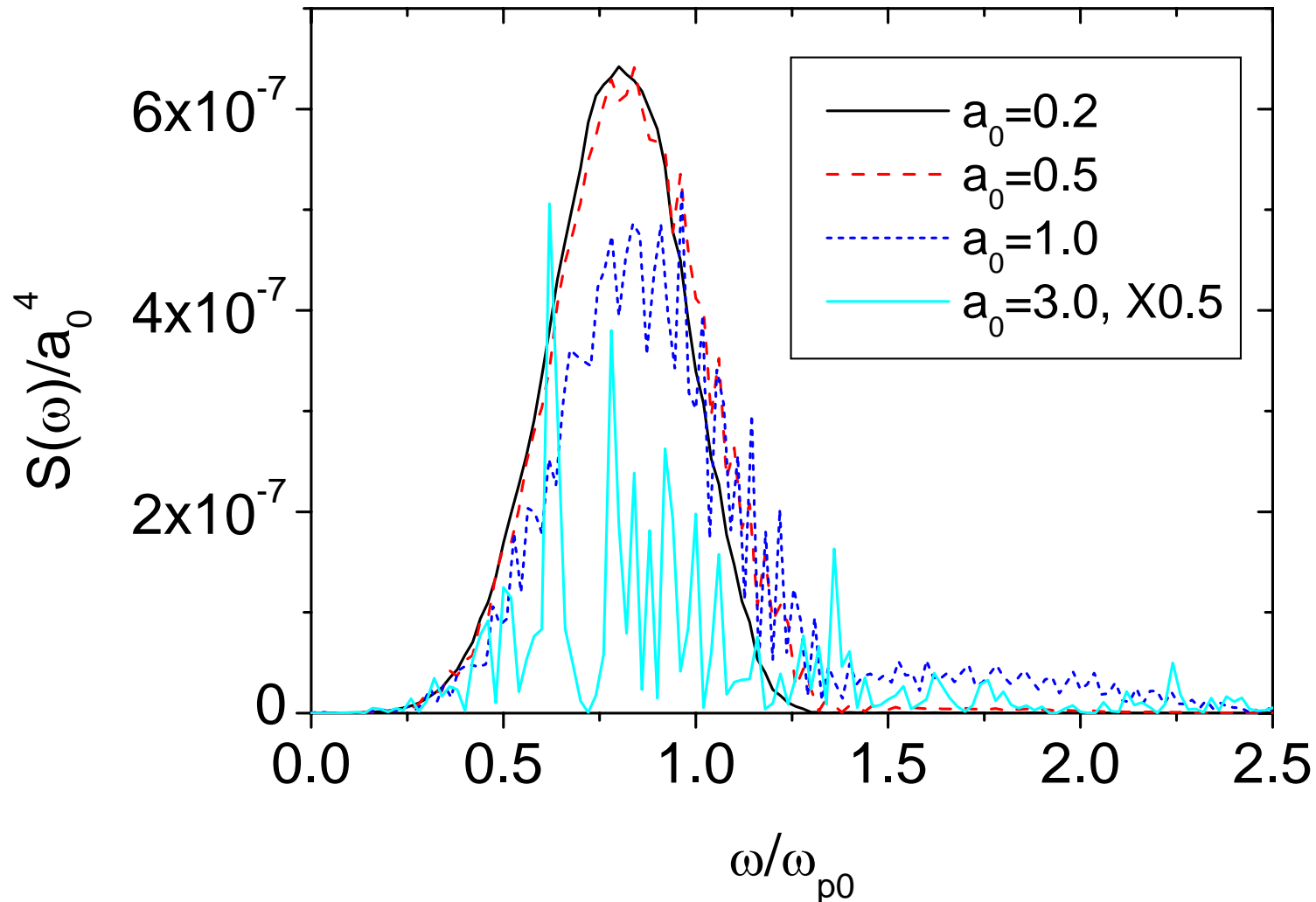
$$\theta=15, L=60\lambda, d_L=10, a_0=0.5$$

Comparison with model

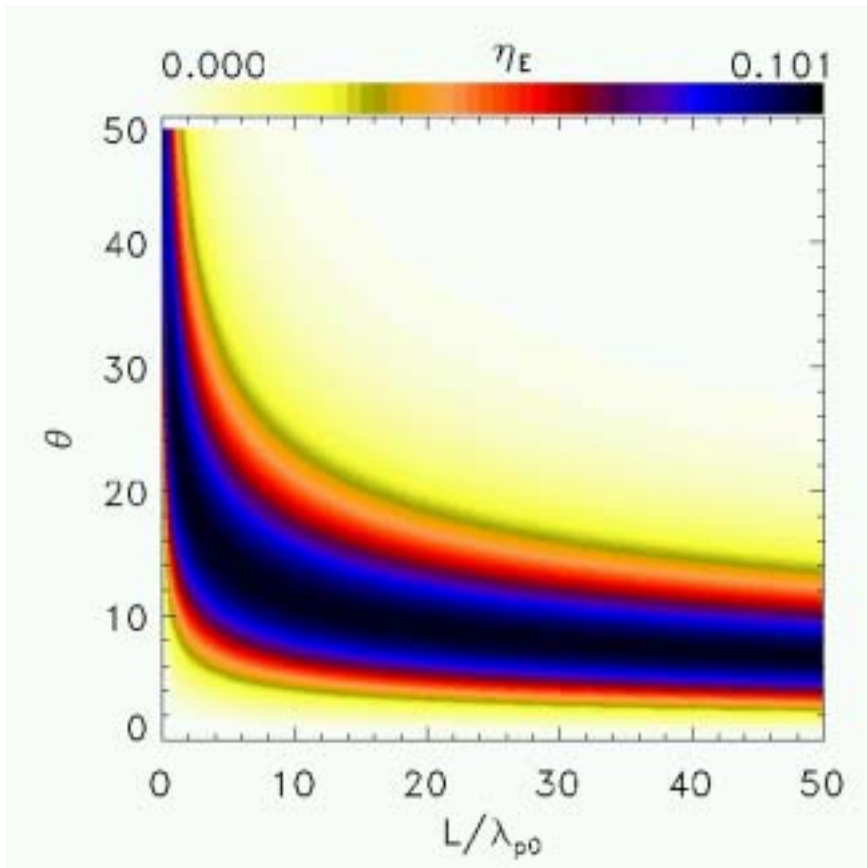


Power scaling with laser intensity

$$P \sim I_L^2 = a_L^4$$



Energy conversion efficiency in θ - L space



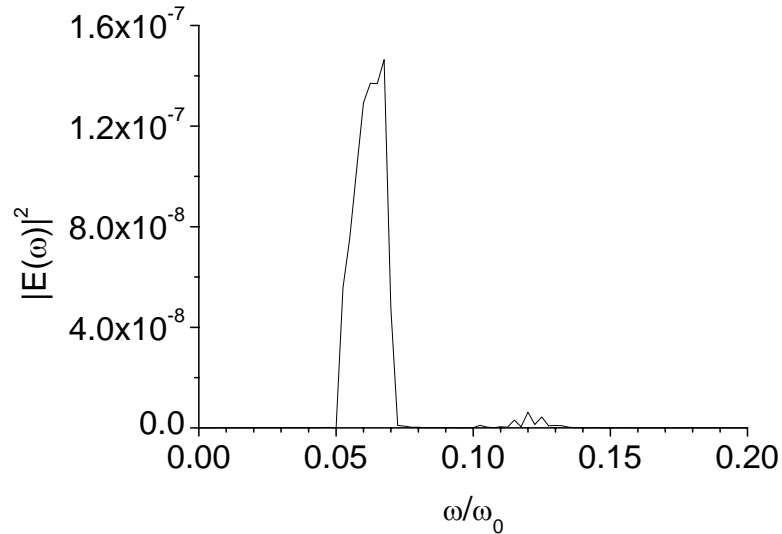
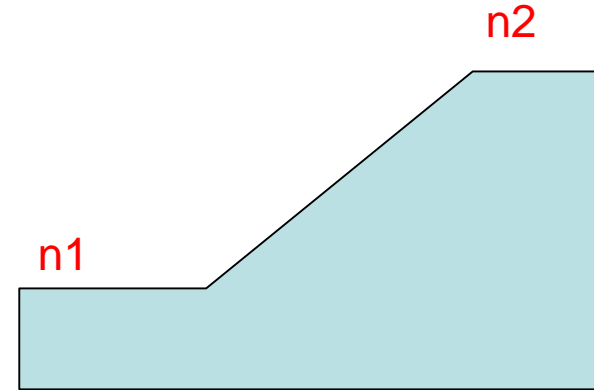
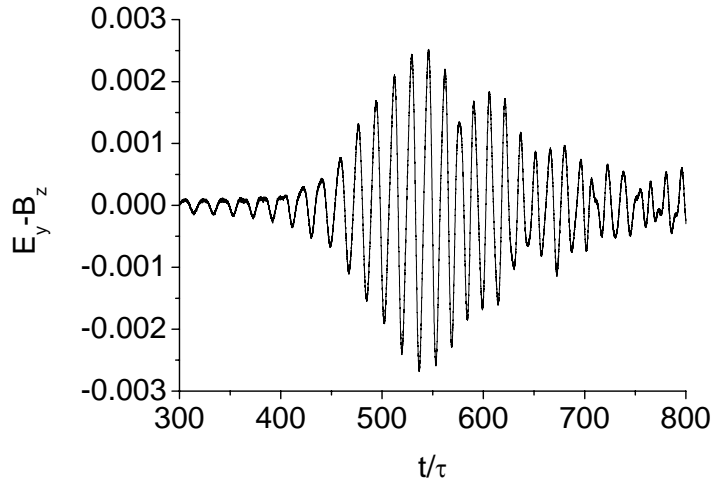
$$\eta_{eng} = \frac{a_0^2}{4} \frac{L}{g(d_L)} \frac{\omega_{p0}^2}{\omega_0^2} \eta_E(L, d_L, \lambda_{p0}),$$

$$\eta_E = 2 \int \eta[q(\tilde{\omega})] \tilde{E}_m^2(\tilde{\omega}, \frac{d_L}{\lambda_{p0}}) \tilde{\omega} d\tilde{\omega},$$

$$a_0 = 0.5, \quad \frac{\omega_{p0}^2}{\omega_0^2} = \frac{n_0}{n_c} = 0.01,$$

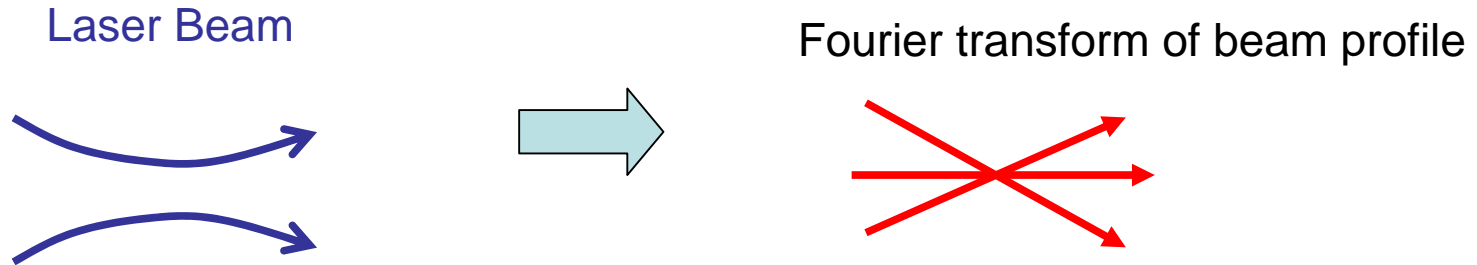
$$\eta_{eng} \approx 0.005 \eta_E \approx 0.0005$$

Controlling of the bandwidth



$$\Delta\omega < \omega_{p2} - \omega_{p1} = \frac{4\pi e^2}{m} (\sqrt{n_2} - \sqrt{n_1})$$

Effect of laser beam diameters



$$a_L^2 = a_0^2 f_1(x - ct) f_2(y), \quad f_2(y) = \exp(-2y^2 / W^2)$$

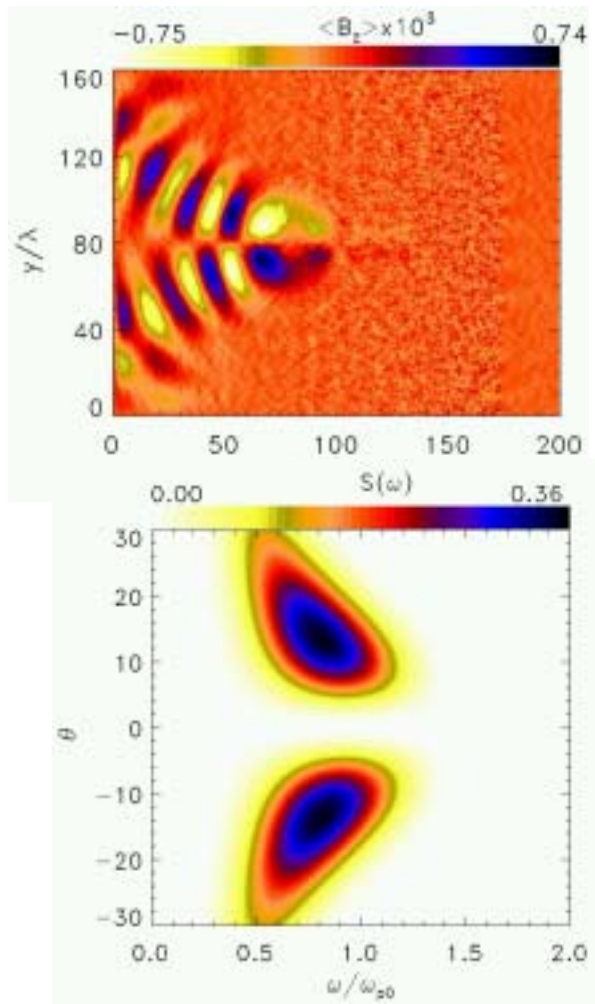
Wave vector (k_x, k_y) :

$$k_x = k_p, \quad \tilde{f}_2(k_y) = (\pi / 2)^{1/2} W \exp(-k_y^2 W^2 / 8).$$

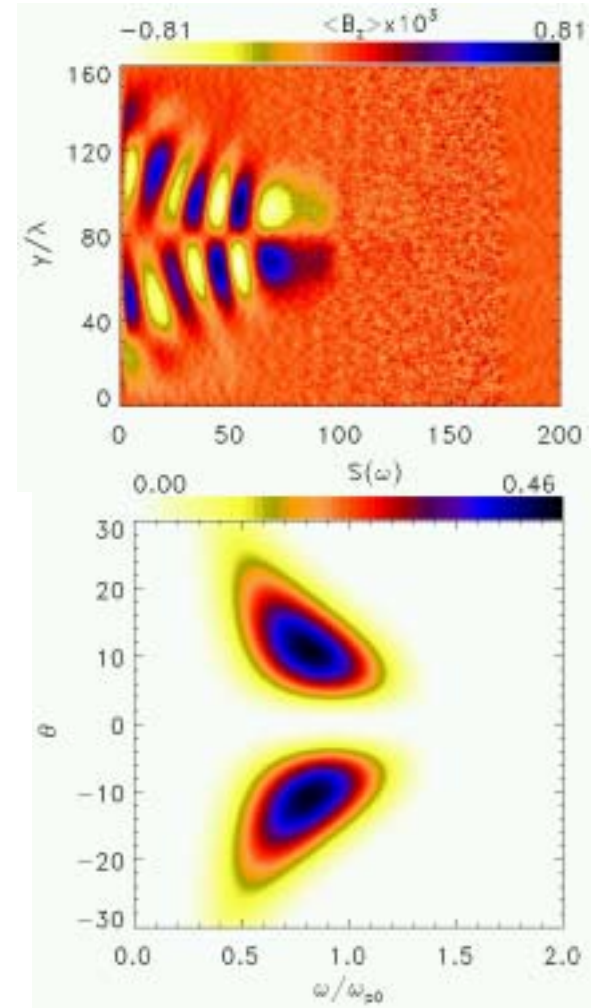
$$\text{Let } \tan \theta = k_y / k_x, \quad |\tilde{f}_2(k_y)|^2 dk_y = S_w(\theta) d\theta,$$

$$S_w(\theta, \tilde{\omega}) = \frac{1}{4} \frac{k_{p0} W^2 \tilde{\omega}}{\cos^2 \theta} \exp \left[-\frac{(k_{p0} W \tilde{\omega} \tan \theta)^2}{4} \right]$$

Effect of transverse beam size

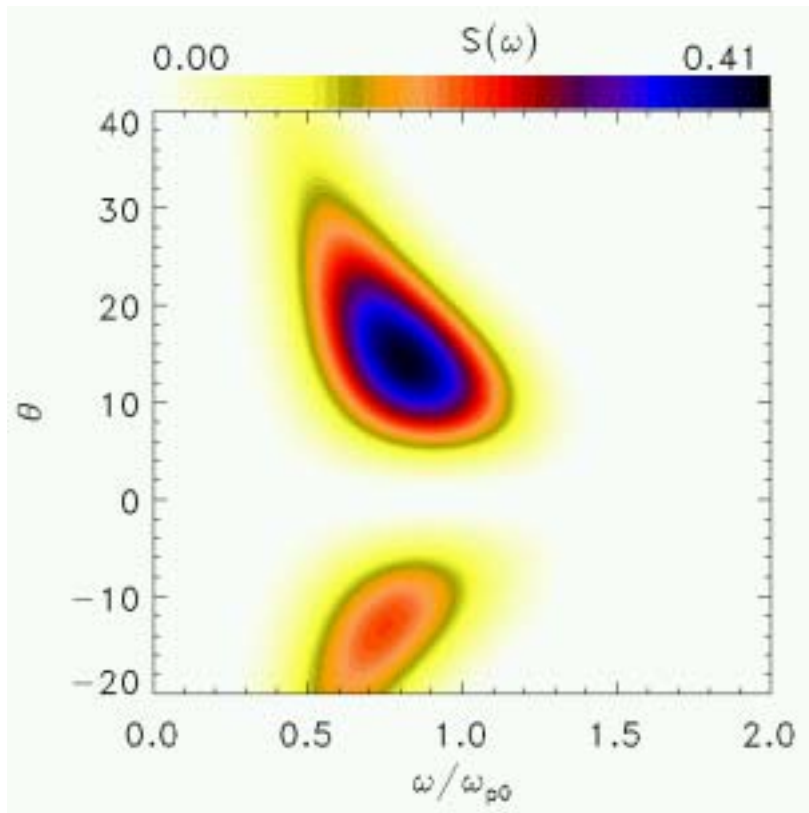


$W=10\lambda, t=150$

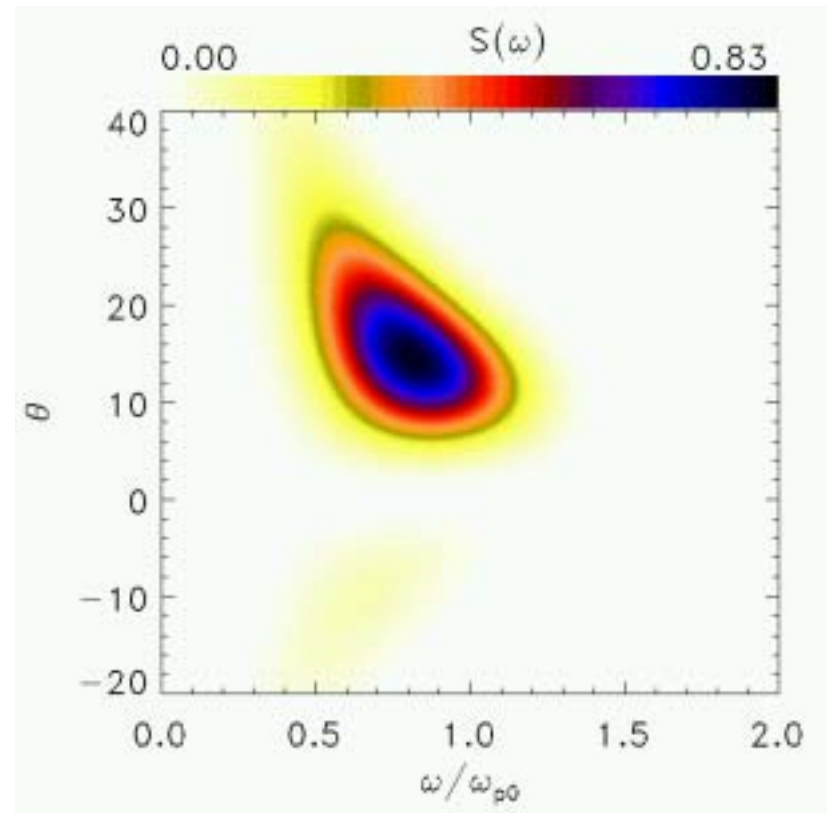


$W=20\lambda, t=150$

Oblique incidence

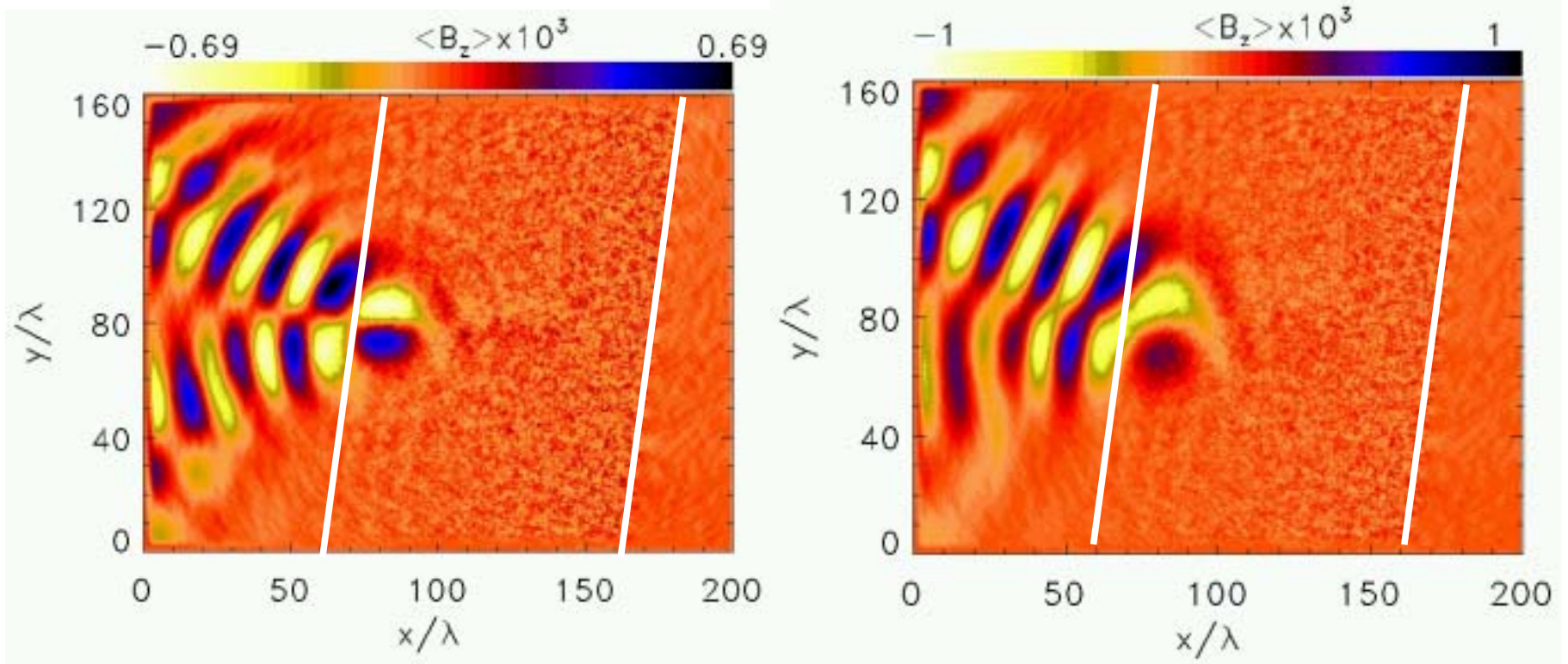


$w=1, d_L=2, \theta=15$



$w=2, d_L=2, \theta=15$

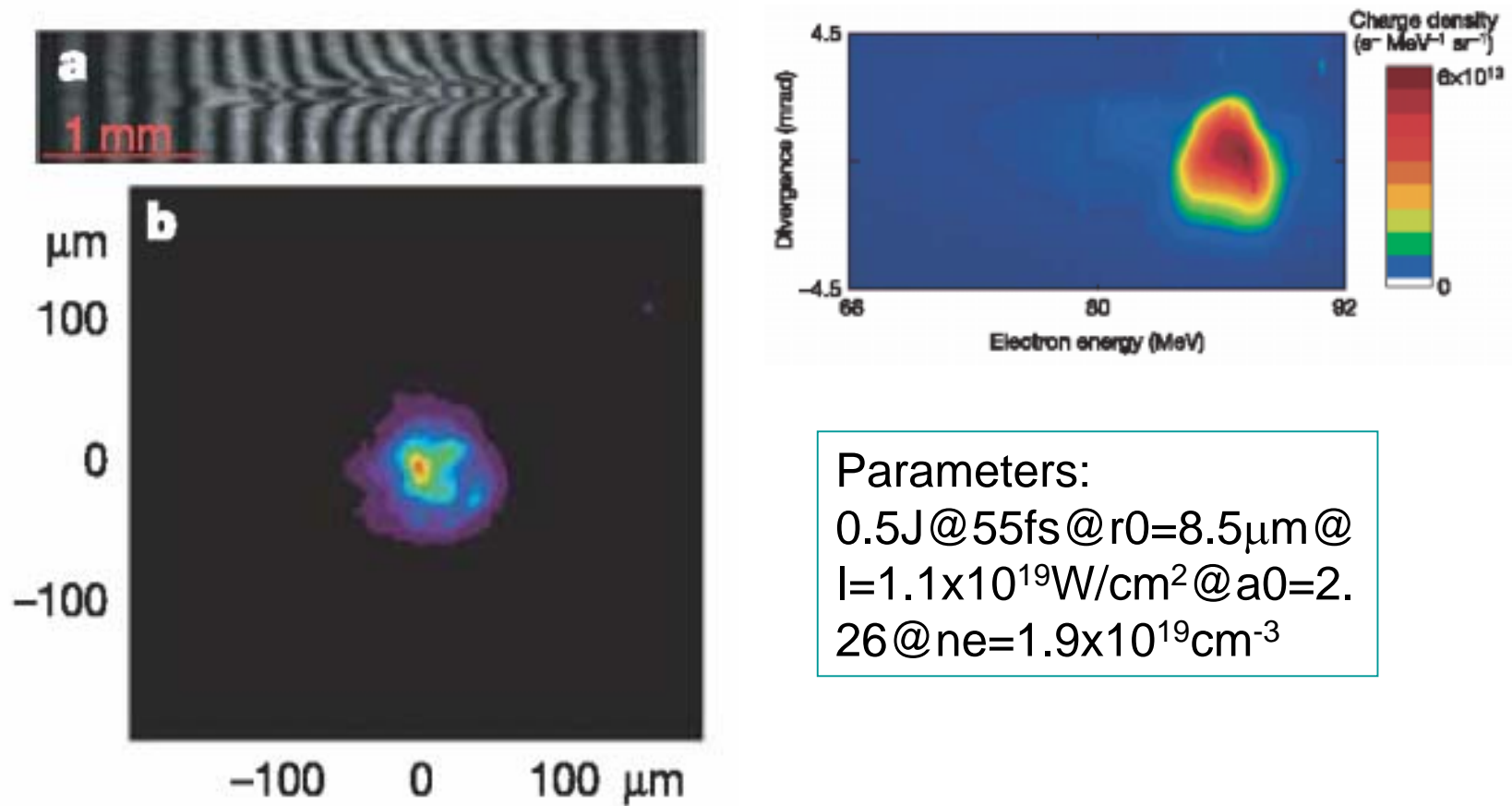
Two-dimensional simulation of oblique incidence



$W=10\lambda, \theta=15^\circ, t=160$

$W=20\lambda, \theta=15^\circ, t=160$

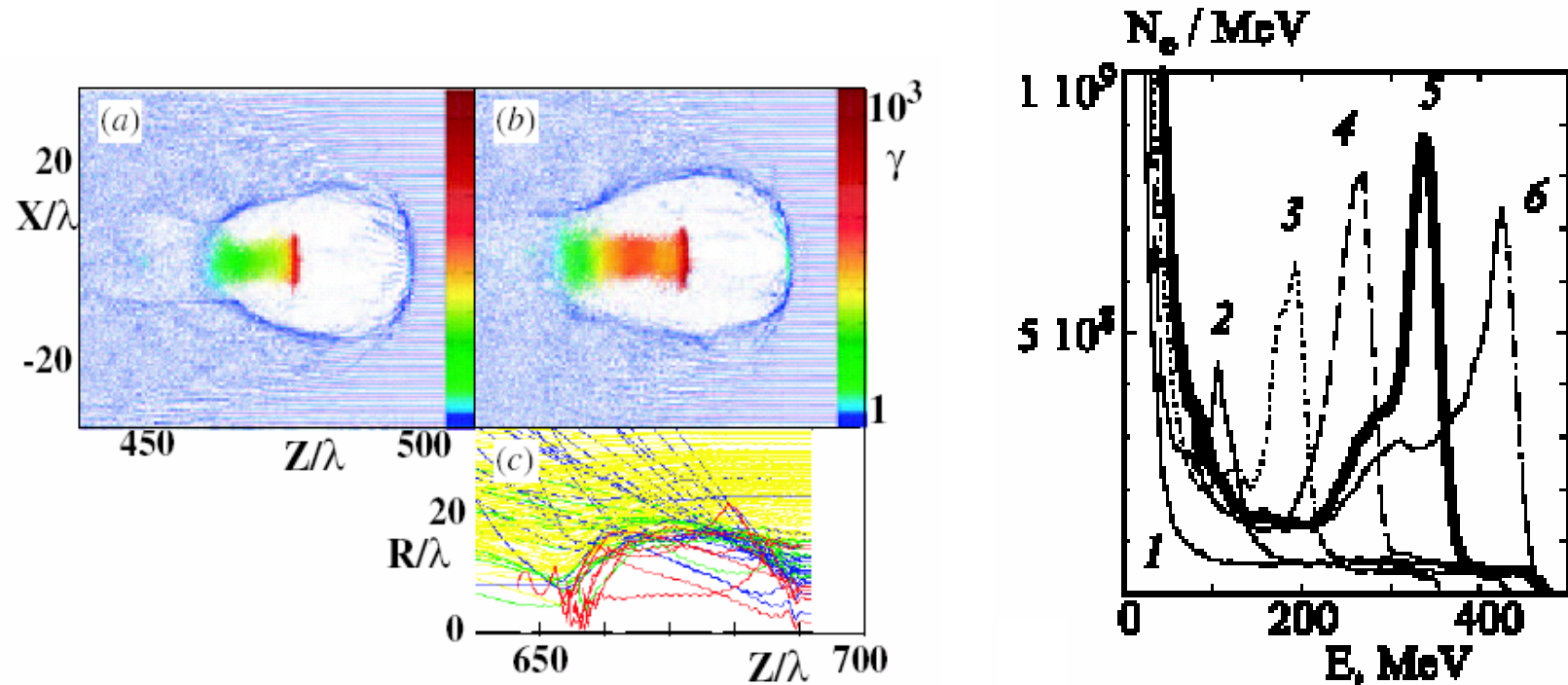
Experimental observation of mono-energetic electron beams (III) (LBNL, USA)



Parameters:

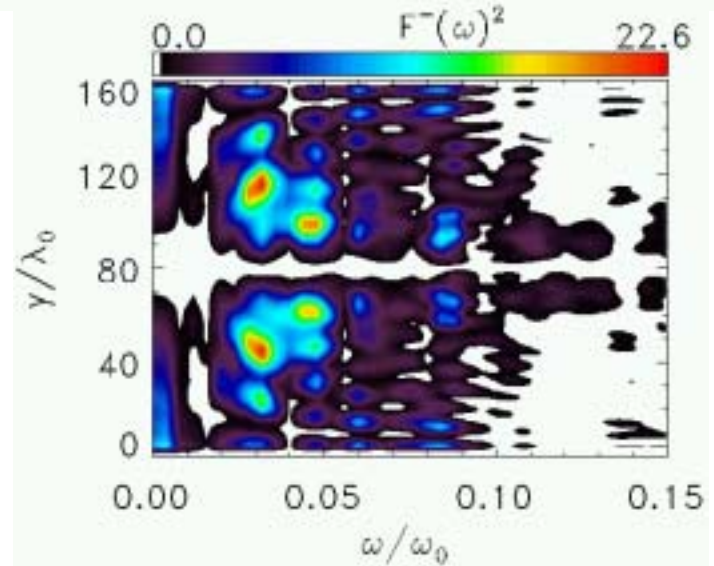
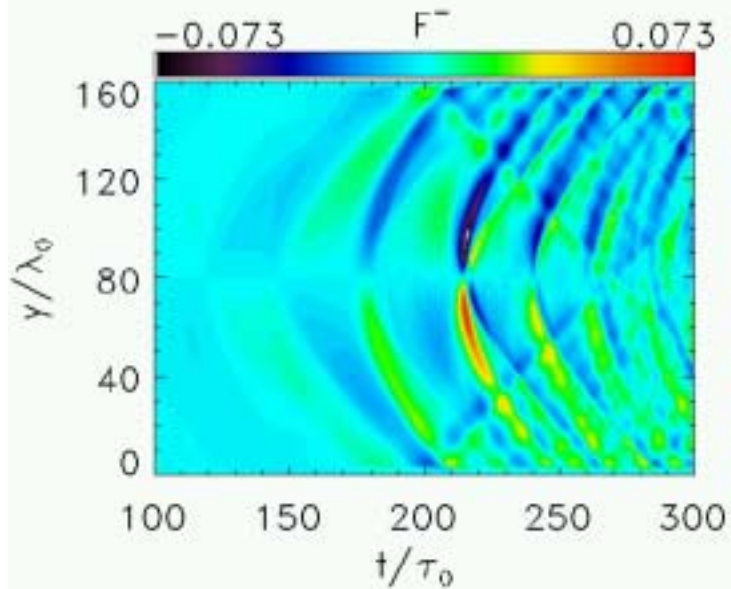
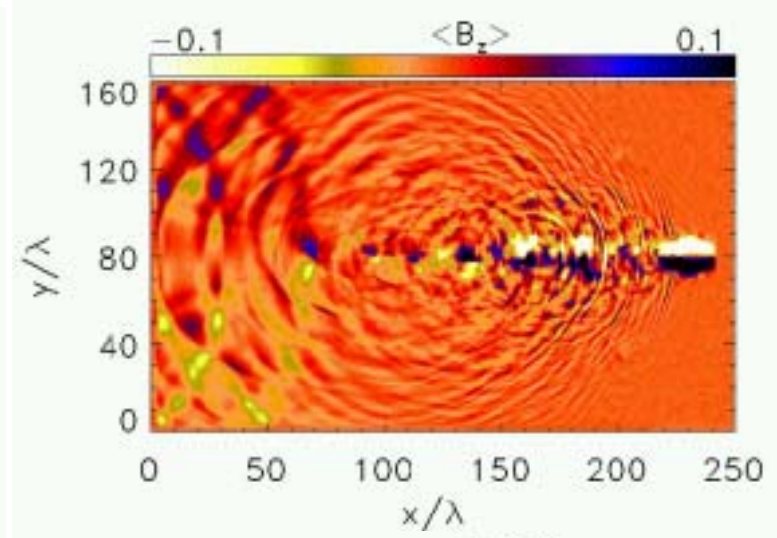
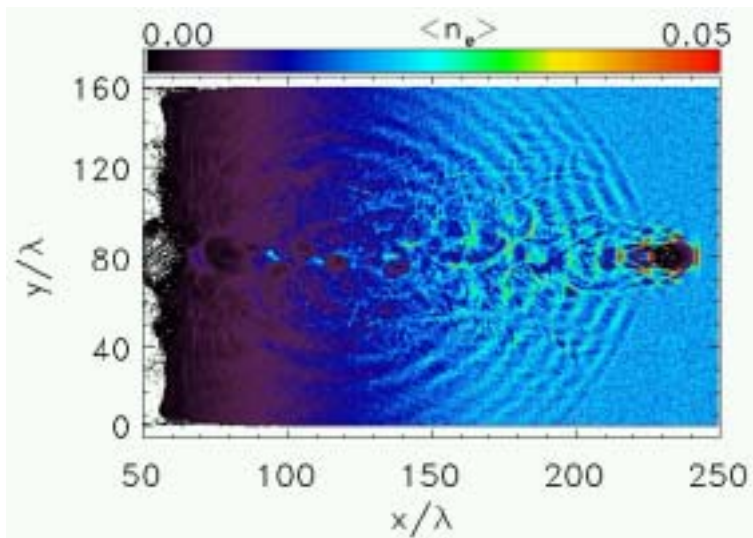
$0.5 \text{ J} @ 55 \text{ fs} @ r_0 = 8.5 \mu\text{m} @$
 $I = 1.1 \times 10^{19} \text{ W/cm}^2 @ a_0 = 2.26 @ n_e = 1.9 \times 10^{19} \text{ cm}^{-3}$

Bubble formation and generation of monoenergetic electron beams

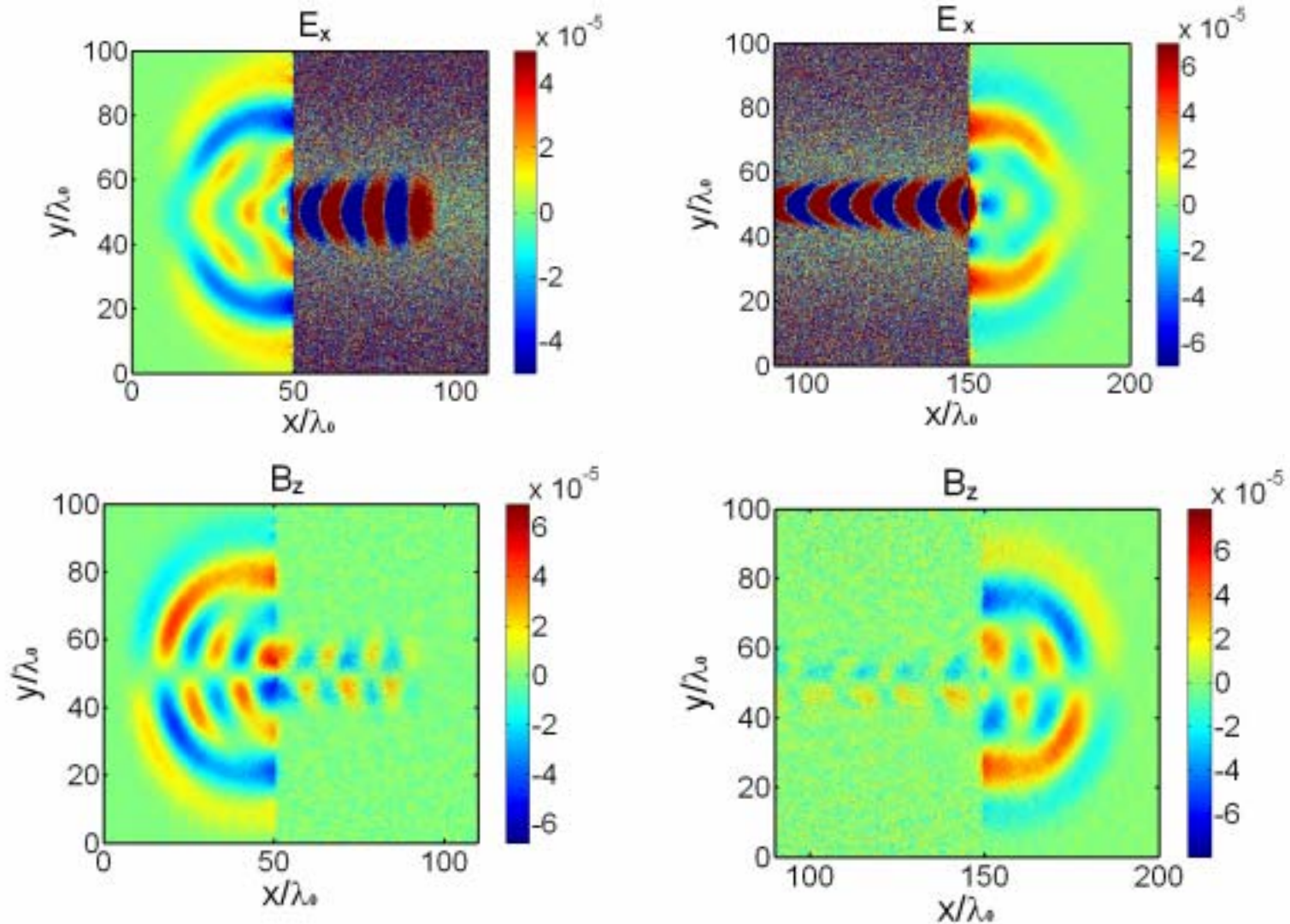


Emission from a broken plasma wave

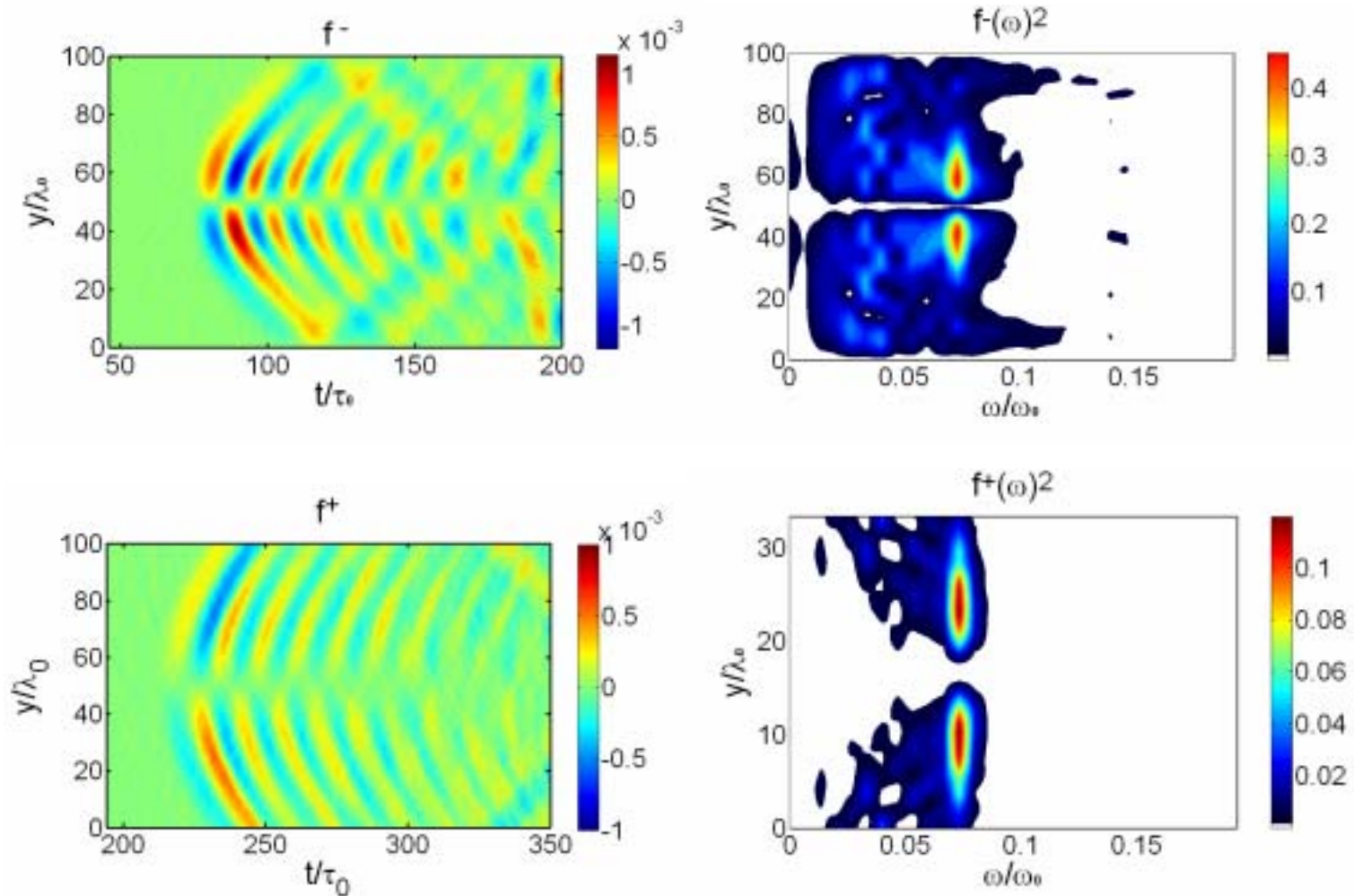
---- unipolar EM fields ($a=10$)



Emission from a plasma channel (produced for GeV energy gain)



Emitted pulses and spectra



Conclusions

- Strong low frequency radiations at $\omega \sim 2\pi/T_L$ from a vacuum-plasma interface have been observed in PIC simulations.
- The radiations result from the excited large-amplitude plasma waves at the plasma boundary and through mode conversion from electrostatic to electromagnetic waves, where the plasma inhomogeneity plays a crucial role.
- For the incident pulse at $3 \times 10^{17} \text{W/cm}^2$, conversion efficiency can be as large as 5×10^{-4} . The induced emission can be as large as MW in the power and a few μJ in the energy if the incident pulse is at tens of mJ.
- The emission can both serve as a high intensity THz source and an easy diagnostic tool for the wakefield amplitude.