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Megawatt THz emission from tenuous plasma and gas targets irradiated by ultrashort intense laser pulses

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Outline

- Motivation
- THz waves emitted from laser wakefields in inhomogeneous plasma
- THz waves emitted from laser wakefields in thin plasma layers
- Phase-sensitive terahertz emission from gas targets irradiated by few-cycle laser pulses
- THz waves driven by chirped laser pulses
- Summary

High THz electric field physics

- The quiver energy of a free electron in EM fields:

$$E_p = m_e v_{quiver}^2 / 2 \propto 1/\nu^2$$

- For one regime of **high field** physics: $\mathbf{E_p > h\nu}$ for high-order multiphoton processes dominated.

- At optical frequencies, the electric field amplitude where this occurs may exceed the threshold for laser damage in materials, and has therefore largely confined such studies to atoms.

- At THz frequencies, however, this regime is accessed in the range of few 100 kV/cm to MV/cm – well below dielectric breakdown in materials. Thus, a new regime of high-field studies in materials is enabled by THz techniques. Nonperturbative THz electro-optics, nonperturbative phenomena in condensed matters and semiconductors, non-equilibrium and nonlinear states of matter, etc.

From “Opportunities in THz Science”, Report of a DOE-NSF-NIH Workshop held February 12 – 14, 2004, Arlington, VA, Ed. by M. S. Sherwin et al.

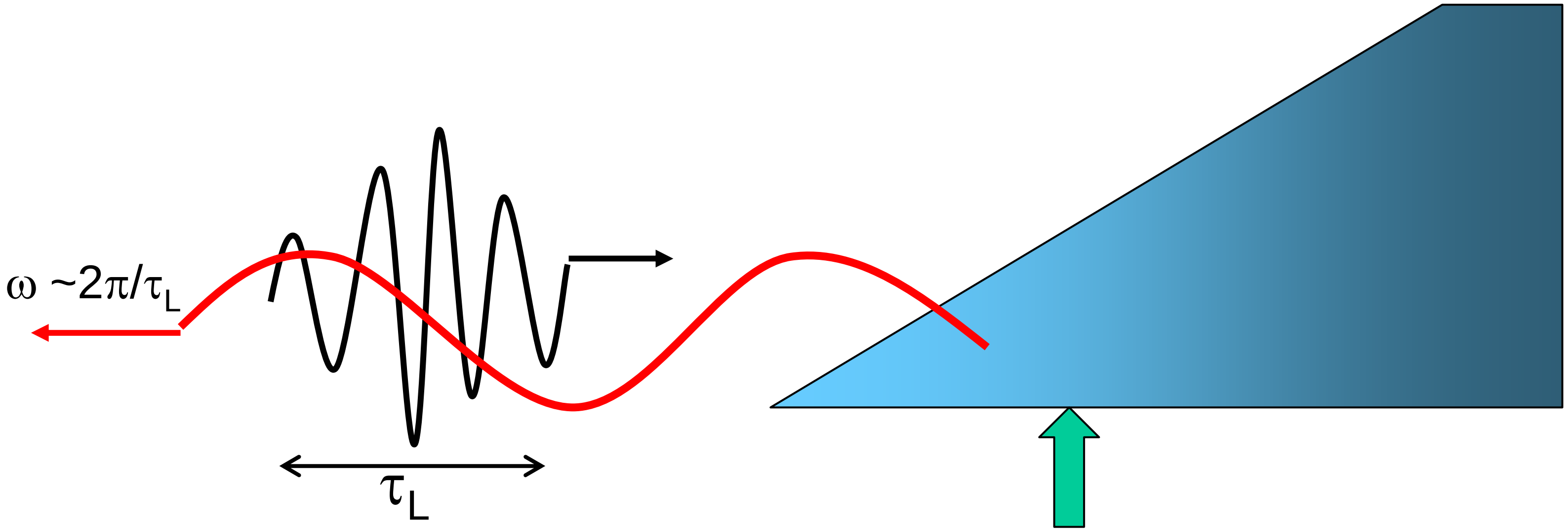
An electron plasma wave is potentially a high-power THz source

- Plasma waves that can be driven by ultrashort laser pulses oscillate typically at the THz range (e.g., $n_e=10^{18}\mathrm{cm}^{-3}$, $\omega_p/2\pi=9\mathrm{THz}$).

- The field strength before wave-breaking is as high as 100 GV/m for $n_e=10^{18}\mathrm{cm}^{-3}$.

- How can an electrostatic wave (E//k) be converted to an electromagnetic wave?

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



$$\frac{2\pi}{\omega_{pe}} = 1THz, \Rightarrow n_e = 1.11\times10^{16}\,cm^{-3}$$

$$\omega_p = \omega = 2\pi / \tau_L$$

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

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

ZM Sheng, K Mima, J Zhang, H Sanuki, Phys. Rev. Lett. 94, 095003 (2005).

ZM Sheng, K. Mima, and J. Zhang, Phys. Plasmas.12, 123103 (2005).

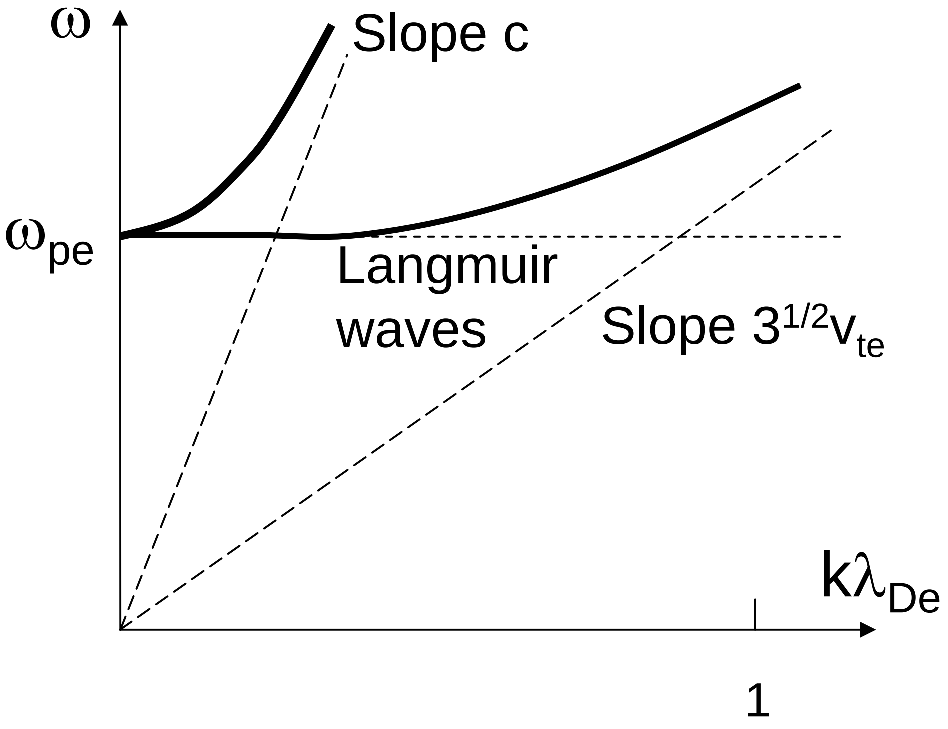
Dispersion of electromagnetic waves and electron plasma waves

EM wave

$$\boxed{\omega^2 = k^2c^2 + \omega_{pe}^2}$$

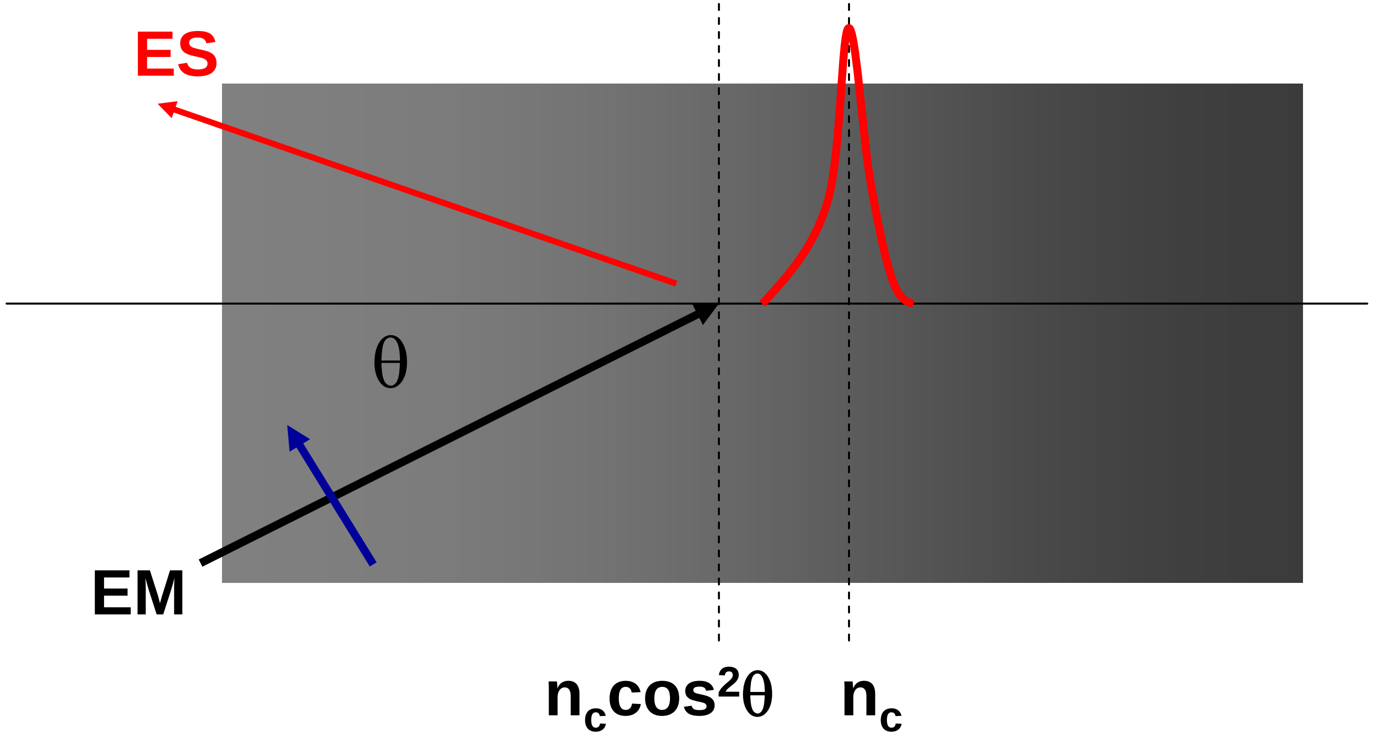
ES wave

$$\boxed{\omega^2 = 3k^2v_e^2 + \omega_{pe}^2}$$



They meet each other only at **k=0**.

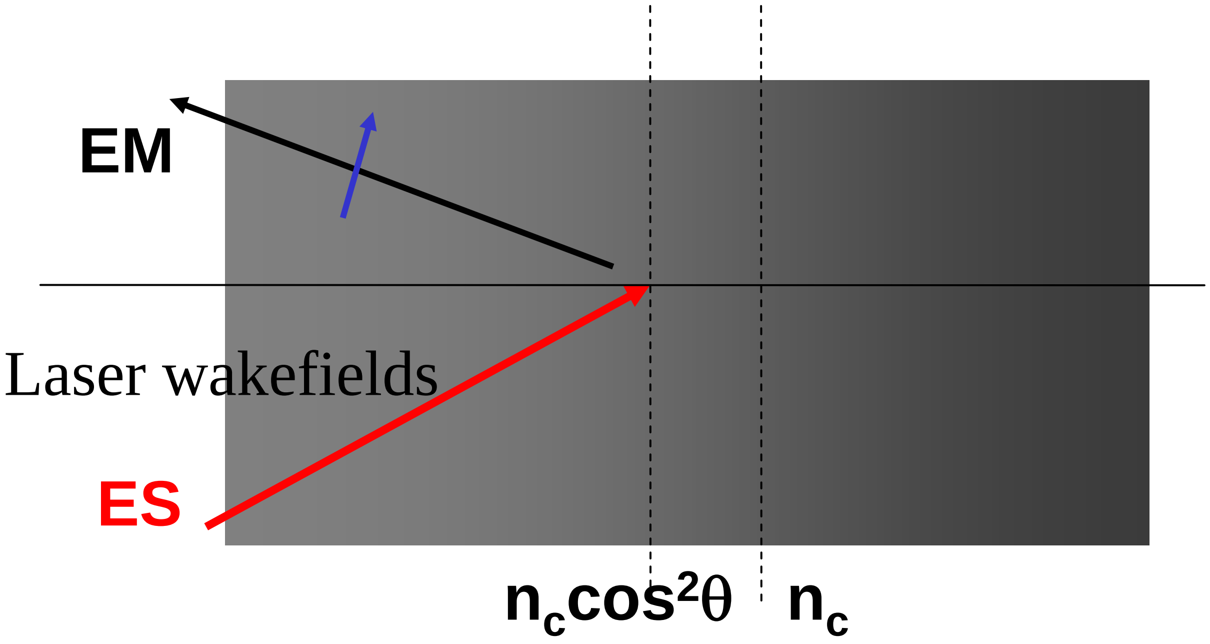
Mode conversion theory --- the direct problem: EM→ES



Conversion efficiency from electromagnetic waves into electrostatic waves η

$$\boxed{\begin{aligned}&\eta=\frac{2\alpha q}{2+\alpha q}\exp\left(-\frac{4}{3}q^{3/2}\right),\\ &q=(\omega L_\omega/c)^{2/3}\sin\theta, \qquad \alpha=2.644\end{aligned}}$$

Mode conversion theory ---
the inverse problem: ES→EM



The conversion efficiency is the same as the direct problem.
Emission spectrum from the wakefield is calculated by

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

Plasma oscillations in inhomogeneous plasmas

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

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

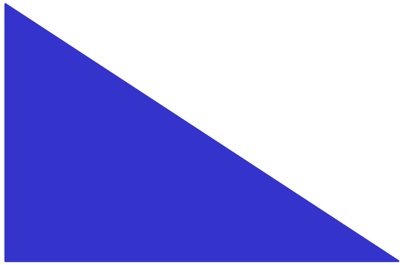
$$v_{ph}(x_0, t) = \frac{\omega}{k} = -\frac{\partial \psi / \partial t}{\partial \psi / \partial x_0}$$

Wave vector of a plasma wave in inhomogeneous plasmas

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

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

$$k \to 0 \qquad for \qquad x_0 = v_g t / 3$$

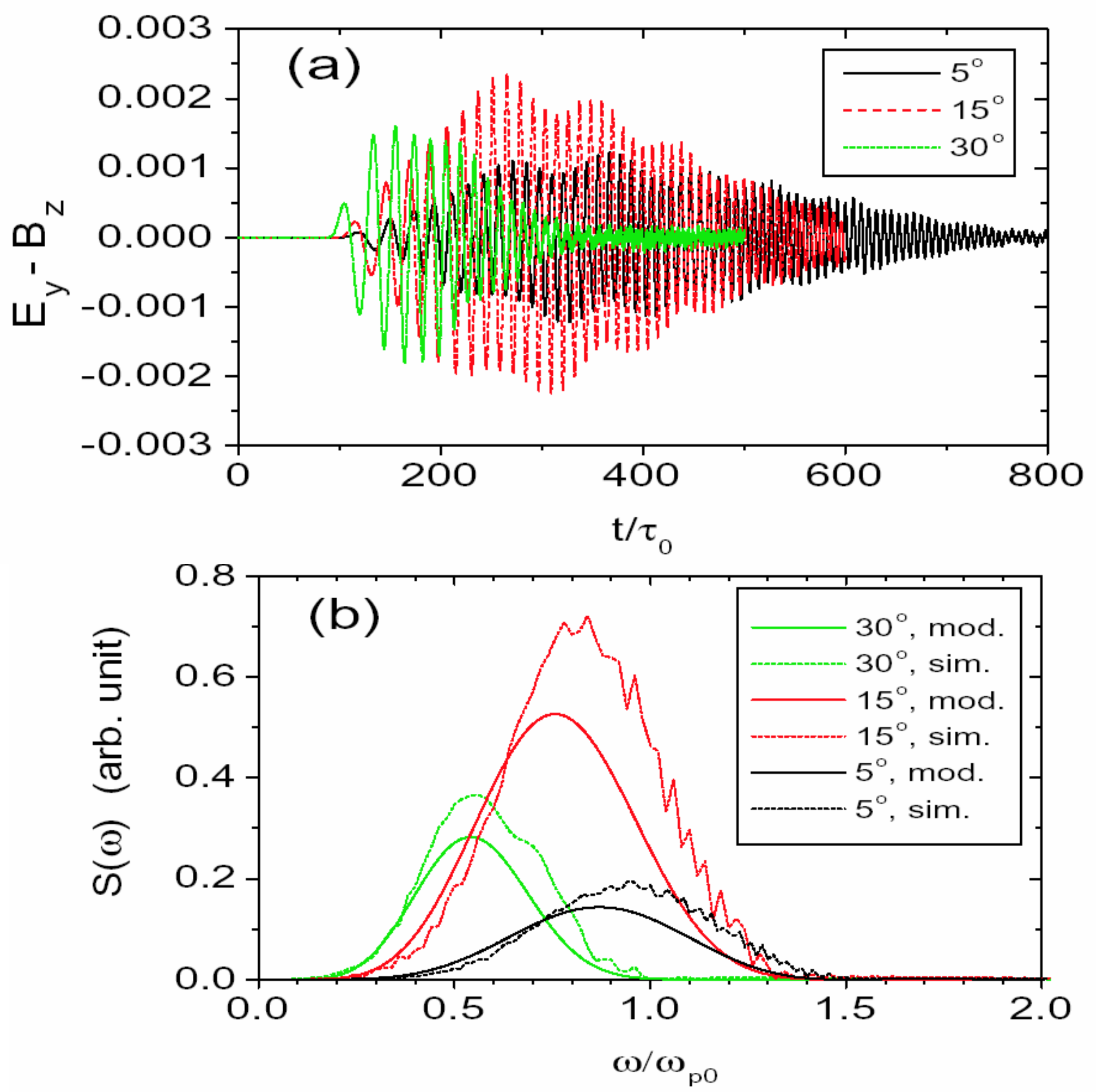


$$n = n_0 (1 - x_0 / L), \qquad \omega_p = \omega_{p0} (1 - x_0 / L)^{1/2},$$

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

$$k > 0 \qquad Since \qquad t > x_0 / v_g$$

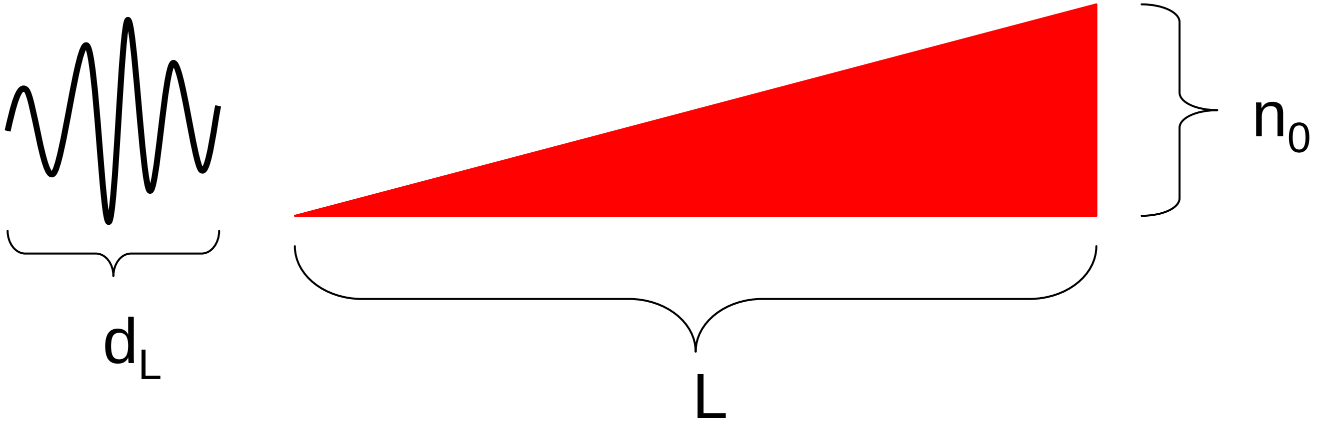
Comparison with model



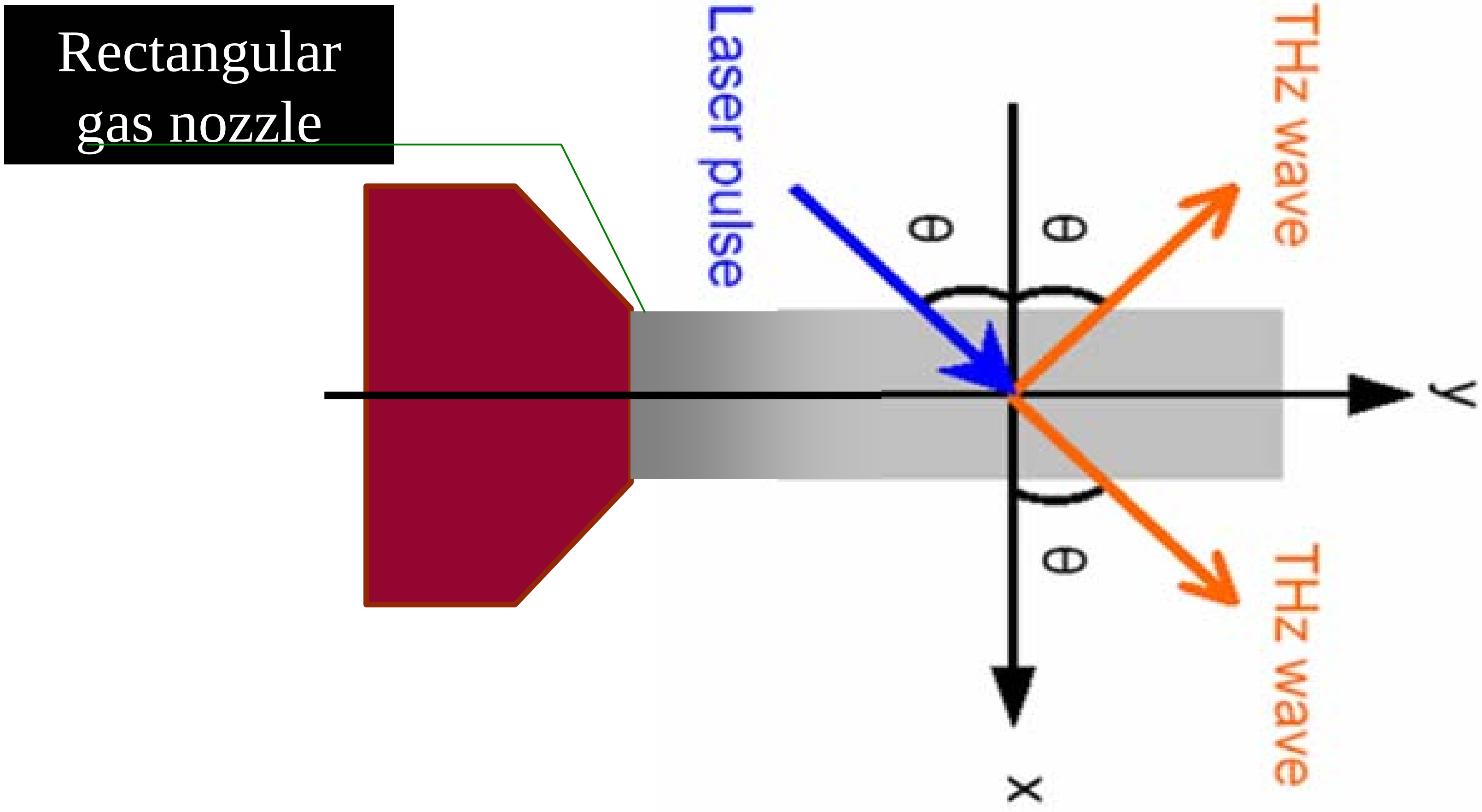
Energy conversion efficiency scaling

$$\eta_{energy} \sim C\left(\frac{\lambda_0}{d_L}\right)^5 \left(\frac{L}{n_0}\frac{n_c}{\lambda_0}\right) a_0^2 \sim a_0^2 \frac{L}{\lambda_0}\left(\frac{\omega}{\omega_0}\right)^3$$

C mainly depends upon the incident angle and the pulse profile.



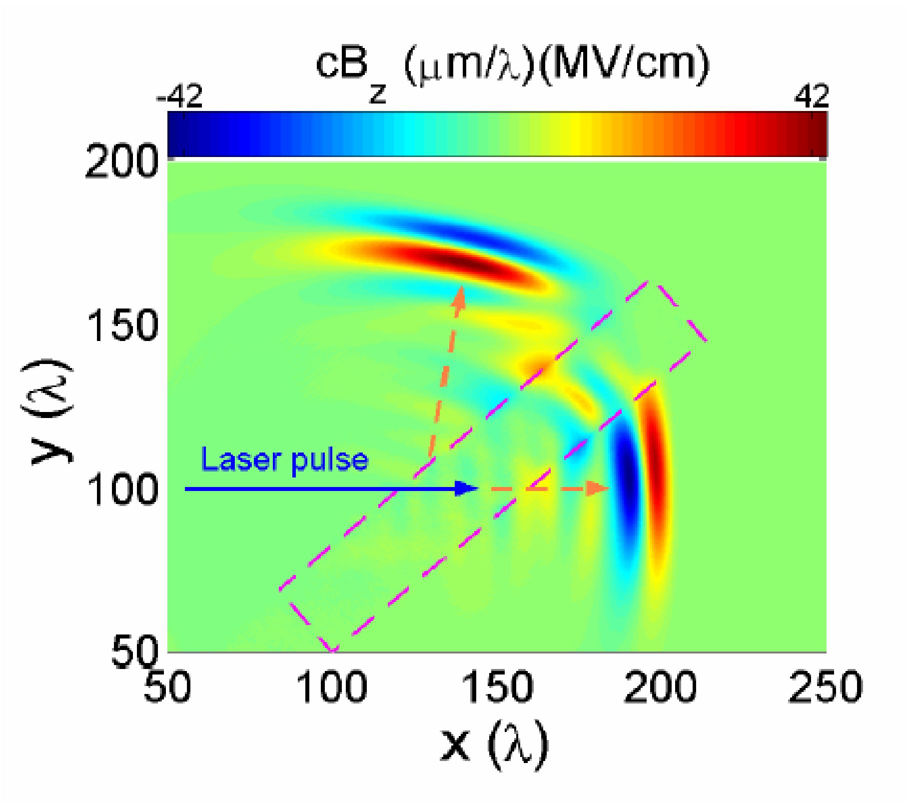
Generation of single cycle THz pulse at the MW level with few wavelength plasma oscillators

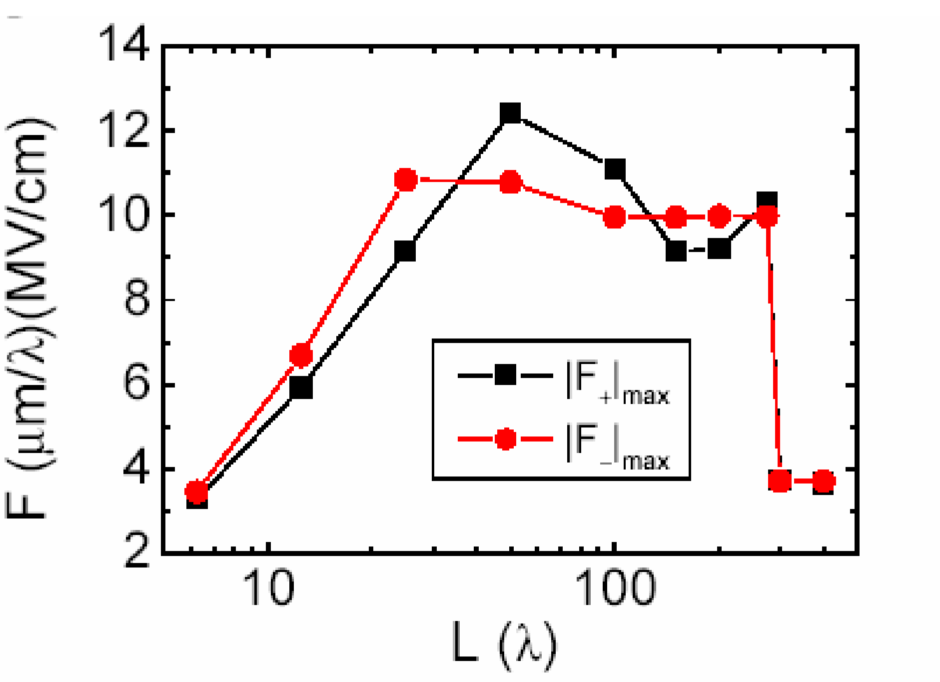


Rectangular gas nozzle

H. C. Wu, Z. M. Sheng et al., arXiv.org/physics/02/2007
Phys. Rev. E 77, 046405 (2008).

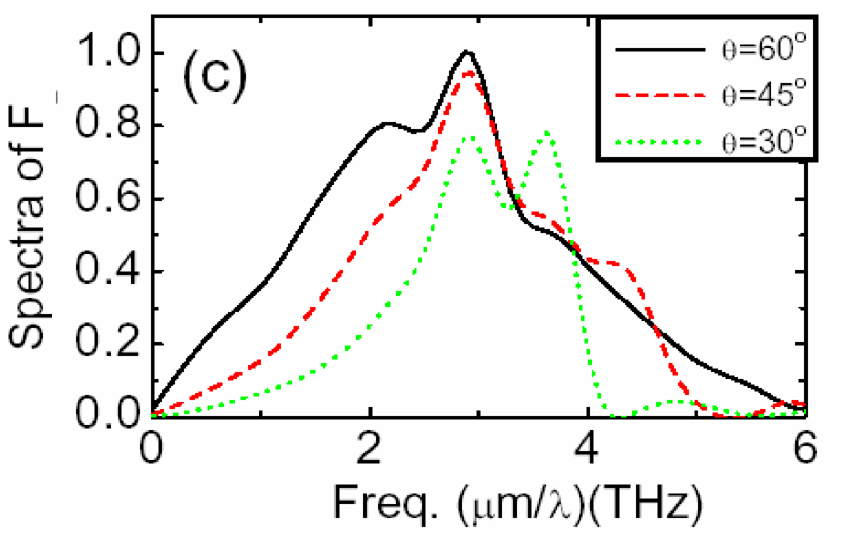
The plasma layer must be thin enough





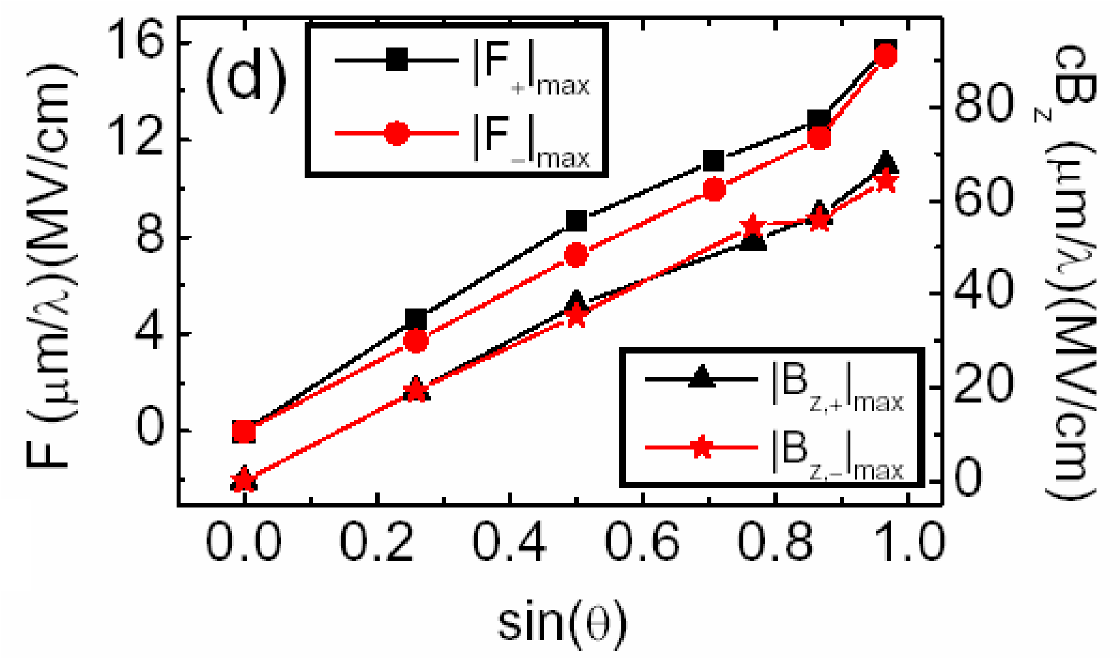
Mechanisms: net current at the vacuum-plasma boundaries.

Scaling with the laser intensity and incident angle



The THz field amplitude

$$e_T \propto n_0^{1/2} a_L^2 \sin\theta$$



Theoretical model: 3 steps of THz emission in gas targets

1. Electrons are freed from atoms by the tunneling ionization.

$$\frac{dn_e(t)}{dt} = W_i(t)n_a(t)$$

2. Free electrons get transverse momenta while the laser pulse passes by.

$$\vec{p}_\perp(t) - e\vec{A}_\perp(t) = const.,$$

$$\vec{p}_\perp(t = t_b) = 0$$

$$\vec{p}_\perp(t = \infty) = -e\vec{A}_\perp(t = t_b)$$

3. All moving electrons form an oscillating electric dipole, which emits THz waves.

$$\frac{d\vec{D}_\perp}{dt} = \frac{e^2}{m}\int dr^3 \int_0^T dt W_i n_a \vec{A}_\perp$$

H.C. Wu, J. Meyer-ter-Vehn, Z.M. Sheng, *New J. Phys. 10, 043001 (2008).*

PIC simulation for linearly-polarized light

$$E_{y,peak}(\varphi) \propto -\sin(\varphi + \varphi_0)$$

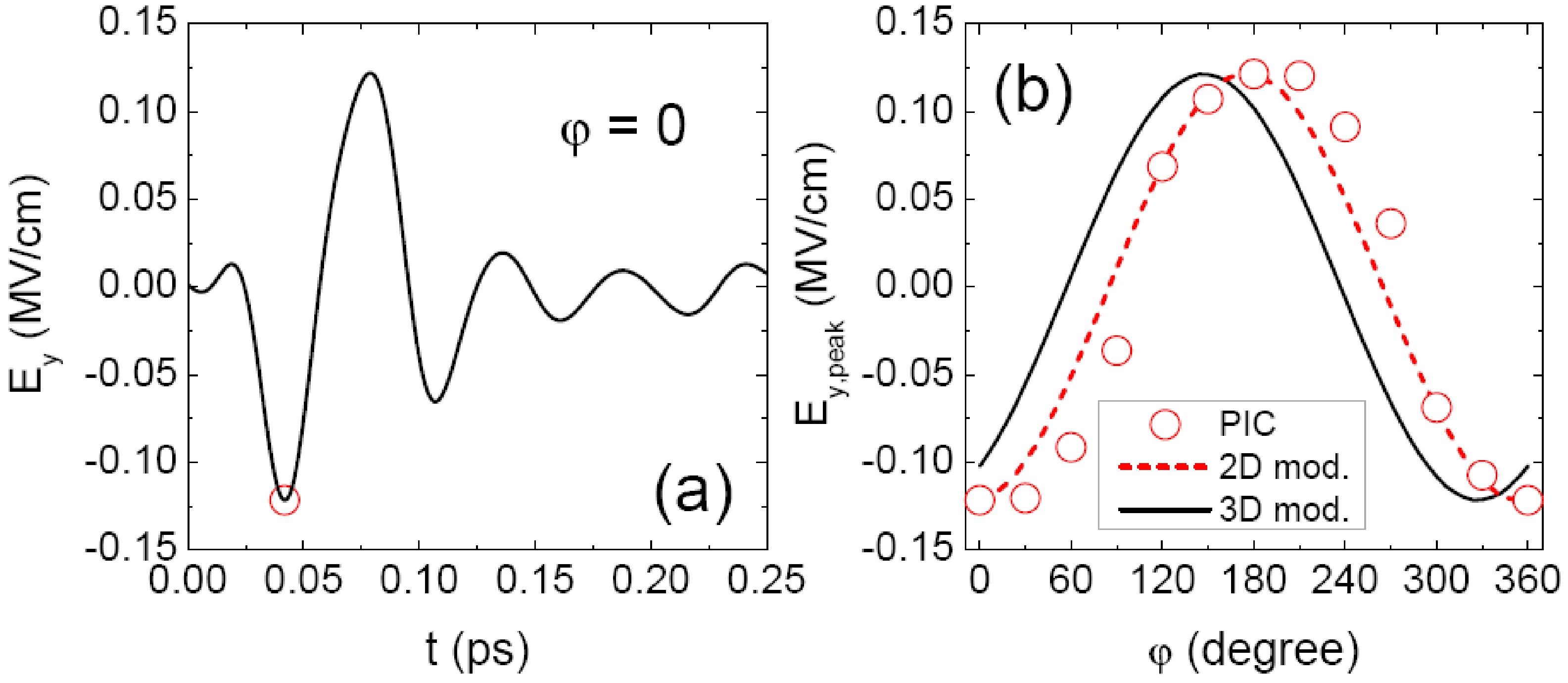


Figure 1. THz emission from H gas target for LP laser pulse with $a_0 = 0.02$. (a) The backward THz pulse for the phase $\varphi = 0°$. The circle marks the first peak $E_{y,peak}$ of this THz pulse. (b) The 1st THz peak $E_{y,peak}$ as a function of the phase φ. 2D (dotted line) and 3D (solid line) model calculations of $-dD_y/dt$ are based on Eq. (4). The circles are PIC results.

THz field scaling with chirped laser pulses

$$\varepsilon_L = a_0 \sin[k_0\xi(1+C\xi)]\sin(\pi\xi/L_t^C)$$

$$L_t^C = (\sqrt{1+4CL_t^0}-1)/2C$$

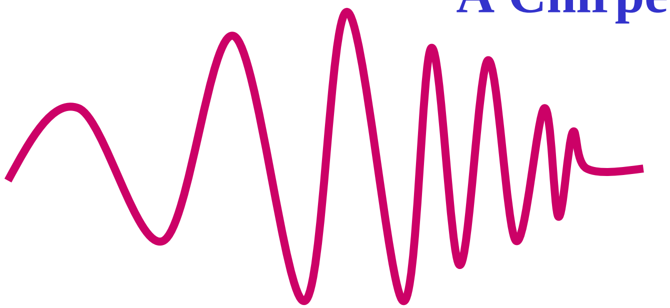
$$v_\perp \propto a_L(L_t^C) = -\int_0^{L_t^C}\varepsilon_L(\xi)d\xi$$

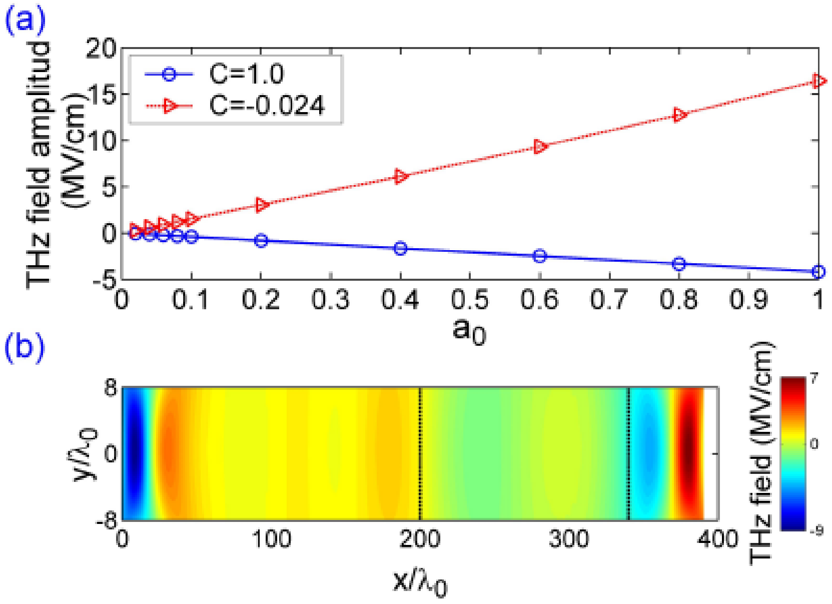
$$\sim a_0$$

when $C = 1.0$ and -0.024,

$$a_L(L_t^C) = 0.0115a_0 \text{ and } -0.0413a_0.$$

A Chirped pulse





Summary

- High power radiations at $\omega \sim 2\pi/T_L$ in the THz range can be produced by driving large-amplitude plasma waves at the plasma boundary by linear mode conversion.
- For the incident pulse at $3\text{x}10^{17}$W/cm^2, conversion efficiency can be as larger as 10^{-3}. The induced emission can as large as MW in the power and a few μJ in the energy.
- External magnetic field at the Tesla level can enhance the produced THz power significantly.
- Single cycle megawatt THz pulses can be produced with a gas jet in a diameter of the THz wavelength.
- A model is presented for THz emission with few cycle laser pulses, which is in good agreement with PIC simulation.
- Chirped laser pulses, either positive or negative chirped, can lead to THz emission with amplitudes scale linearly with the laser pulse amplitude.