THz generation by ultra-short laser pulses propagating in nonuniform plasma channels

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Why High-Field THz Pulses?

- Study non-linear effects in materials ($E \geq 100$kV/cm).
- Displace atoms in polar solids (especially in systems near to a structural phase transition, e.g. ferroelectrics) ($E \geq 1$MV/cm).
- Induce large transient currents e.g., exceed critical current in thin film superconductors ($E \geq 100$kV/cm).
- Modify magnetic moments / spins to follow their dynamics
  ($H \geq 0.1$ T or $E = H \times c = 300$ kV/cm)
- **And others**

DOE-NSF-NIH Workshop on Opportunities in THz Science
February 12–14, 2004

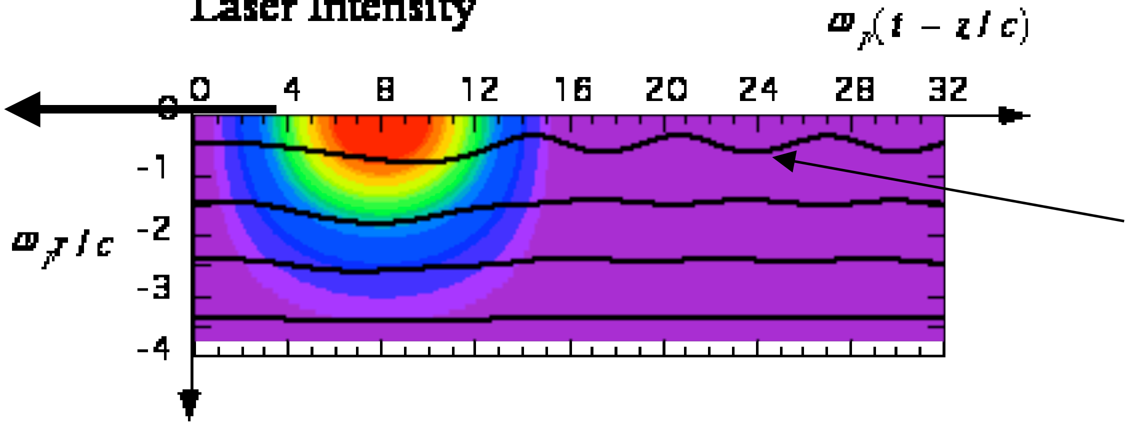
Pulsed THz Sources

- Conventional sources using short pulse lasers rely on pulse generation in a solid and are generally limited to μJ/pulse.
- Higher energies per pulse can be generated at accelerator facilities with intense bunched electron beams via synchrotron or transition radiation.
- Recently, intense THz pulses with energies in excess of 100 μJ/pulse have been generated as transition radiation by a laser generated and accelerated electron beam passing from plasma to vacuum.
- Our scheme for THz generation involves the creation of miniature corrugated plasma channels (period ~ 40 μm) that act as slow wave structures.
- Offer possibility of high efficiency of conversion of laser pulse energy to THz.

Excitation of Plasma Waves by Laser Pulse
Ponderomotive Force

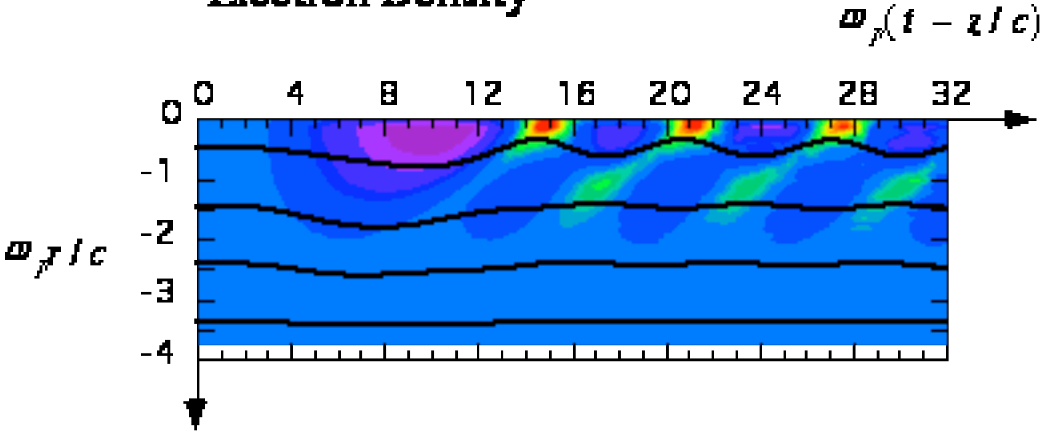
Viewed in laser frame

Laser Intensity



Particle trajectories

Electron Density



Plasma Currents $\sim \tau_{laser}$

But no radiation $f \sim 1/\tau_{laser}$

Why ?

Work Done by Ponderomotive Force

$$P_F = \int d^3x\, \mathbf{F} \cdot \mathbf{J} / q \qquad \left\{ \begin{array}{l} \mathbf{F} = -\nabla V_p \\ \mathbf{J} = \left[c\nabla \times \mathbf{B} - \partial \mathbf{E} / \partial t \right] / (4\pi) \end{array} \right.$$

Combining:

$$P_F = -\frac{1}{4\pi q} \int d^3x\, V_p \frac{\partial}{\partial t} \nabla \cdot \mathbf{E}$$

- For radiation fields in a homogeneous plasma

$$\nabla \cdot E = 4\pi q \tilde{n} = 0$$

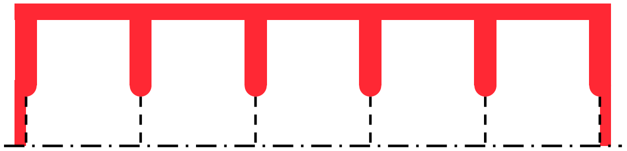
- Radiation requires inhomogeneous plasma
- Phase matching would be nice too:

$c > u_p = \omega/k_z$ for radiation, u_p pulse speed

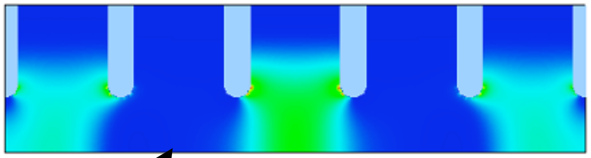
Conditions Can be Met in a Periodic Structure

Disc-loaded Structure

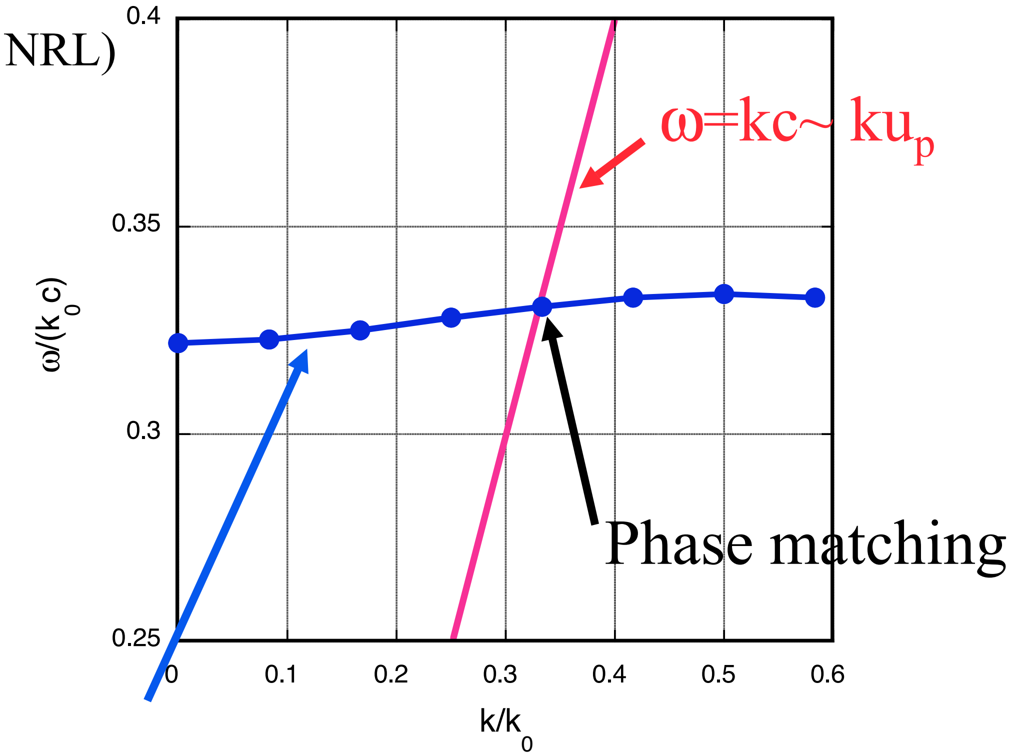
(Courtesy E. Nelson, LANL, S. Cooke, NRL)



Field profile of “π” mode



Add nonuniform plasma



ω=kc~ ku_p

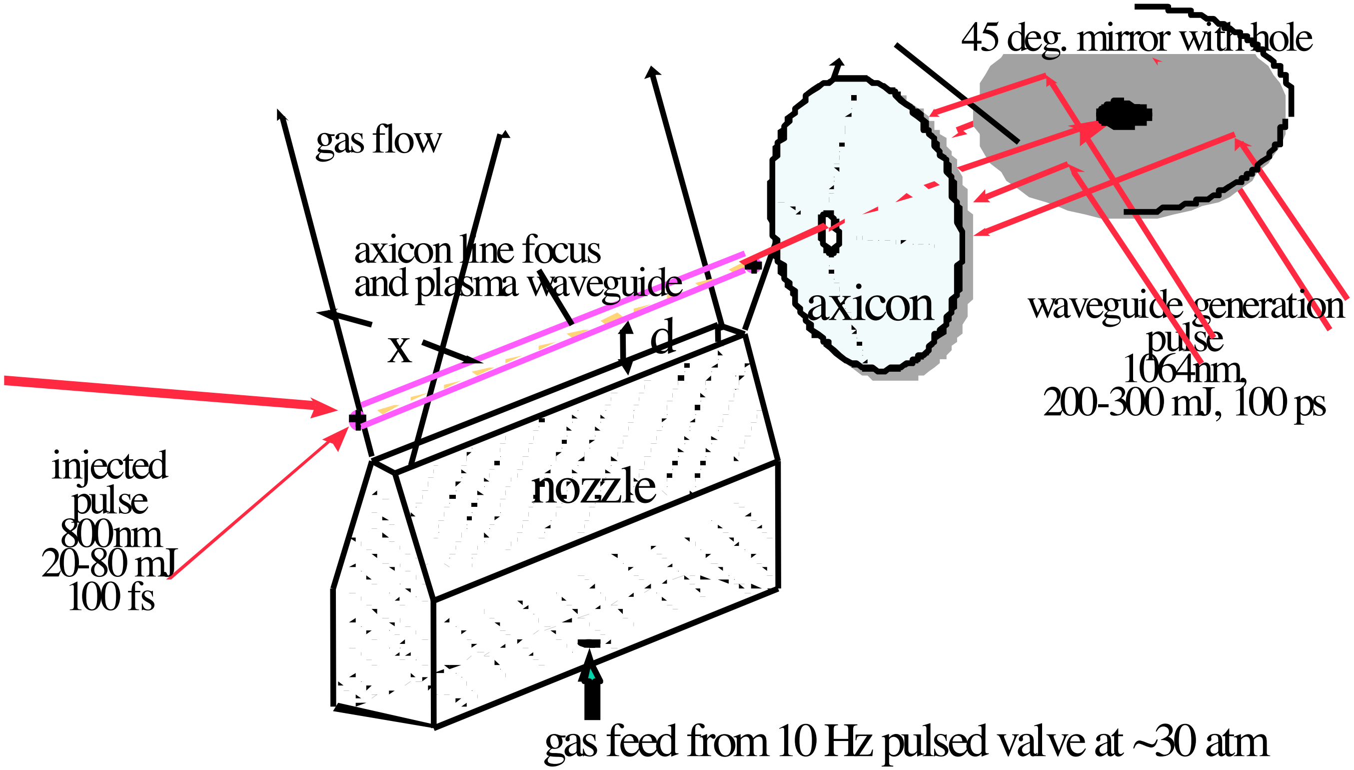
Phase matching

Structure dispersion relation

$k_0 = 2\pi/d$

University of Maryland Channel Formation Scheme

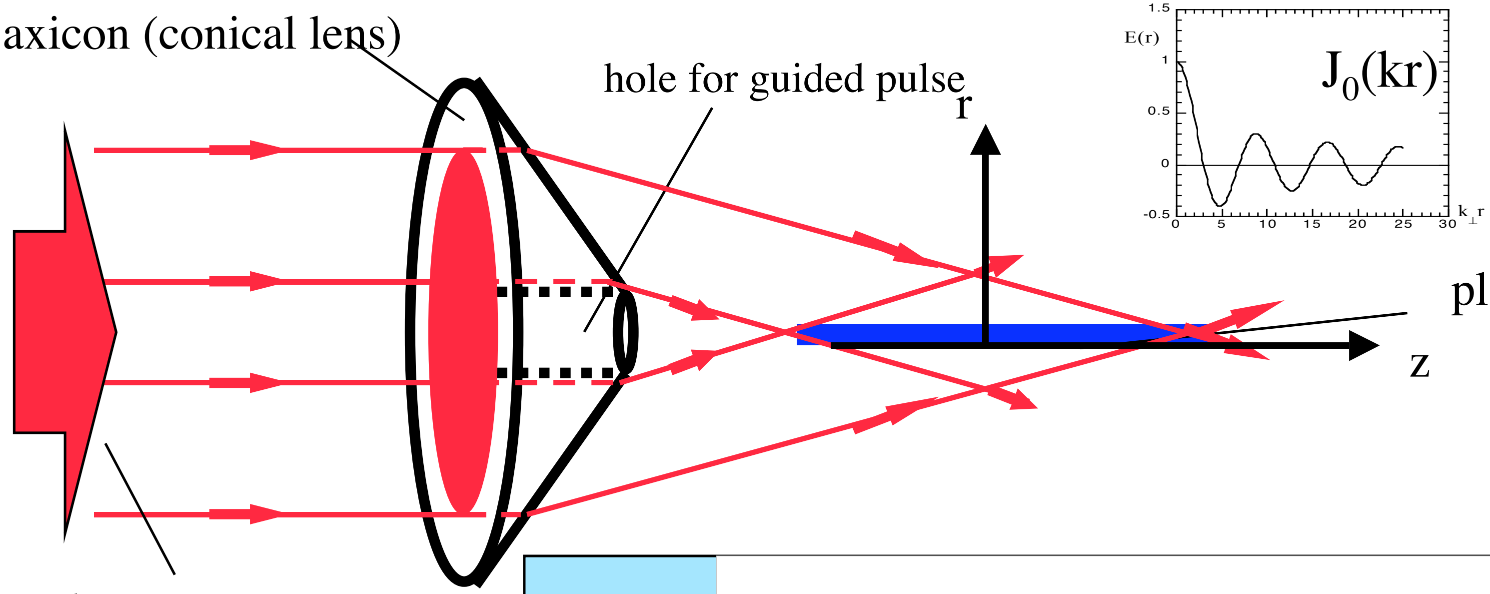
C. G. Durfee, III and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993)



Generation of a plasma waveguide in an elongated, high repetition rate gas jet

J. Fan, T.R. Clark, and H.M. Milchberg, Appl. Phys. Lett. **73**, 3064 (1998)

Plasma Waveguides
University of Maryland Channel Formation Scheme

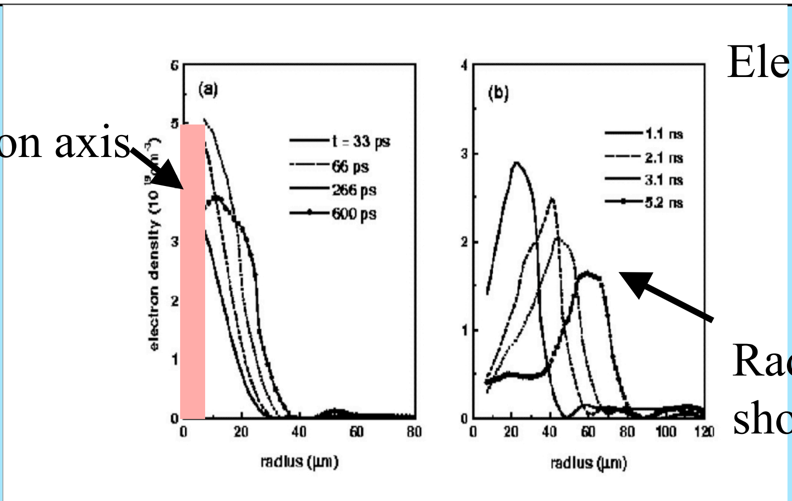


axicon (conical lens)

hole for guided pulse

plasma channel

moderate intensity
fibre generating pulse:
100-500 mJ, 1.064 um
100 ps



Electron density

Heating on axis

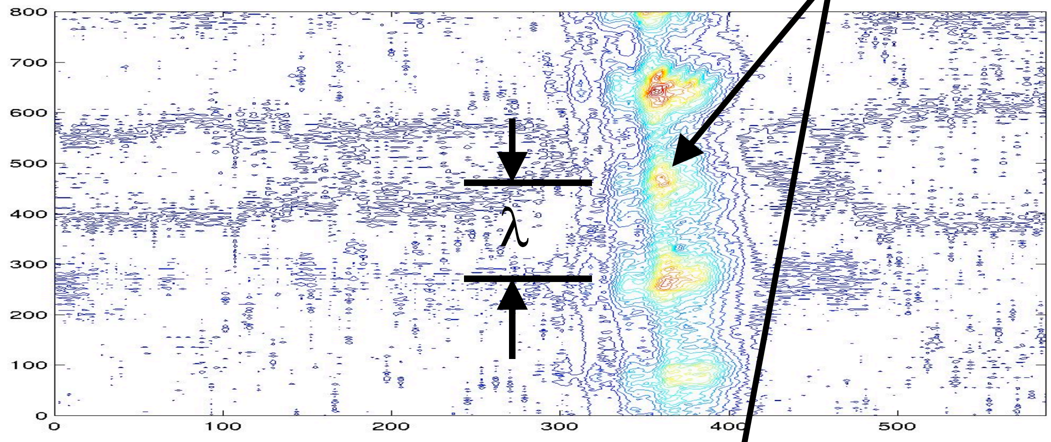
Radially expanding shock wave

Modulated Channels

J. Cooley, et al. TBP-PRE

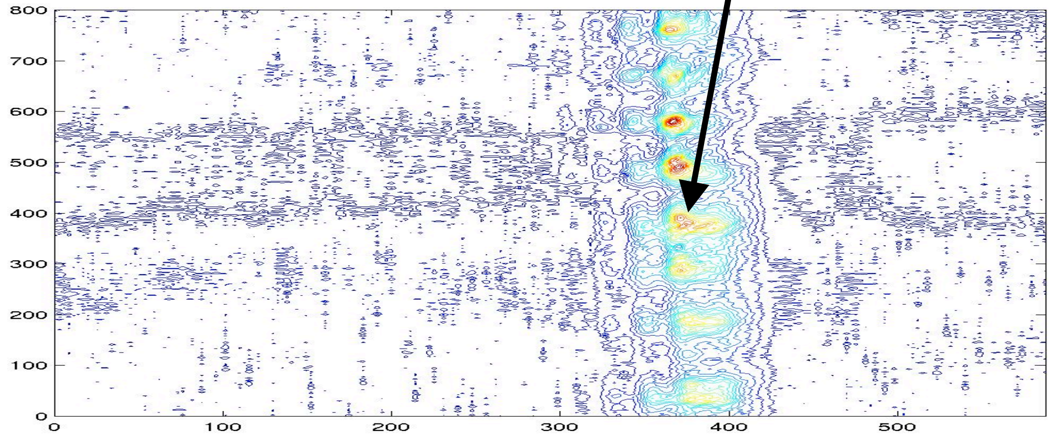
Shadowgrams

Plasma channel



Argon gas at 320 torr with 25 degree axicon and 5e13 w/cm^2

$\lambda \sim 40 - 150\ \mu m$

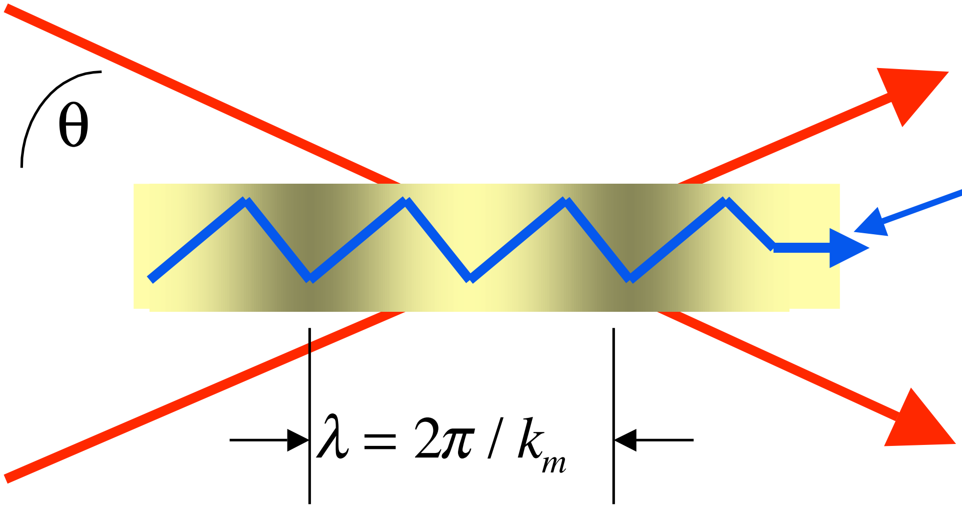


Argon gas at 370 torr with 25 degree axicon and 5e13 w/cm^2

Modulation Instability

Axicon Rays $e^{ik_a z}$

$$k_a = \frac{\omega}{c}\cos\theta$$



Guided mode

$$e^{ik_g z}$$

Modulation Wave Number

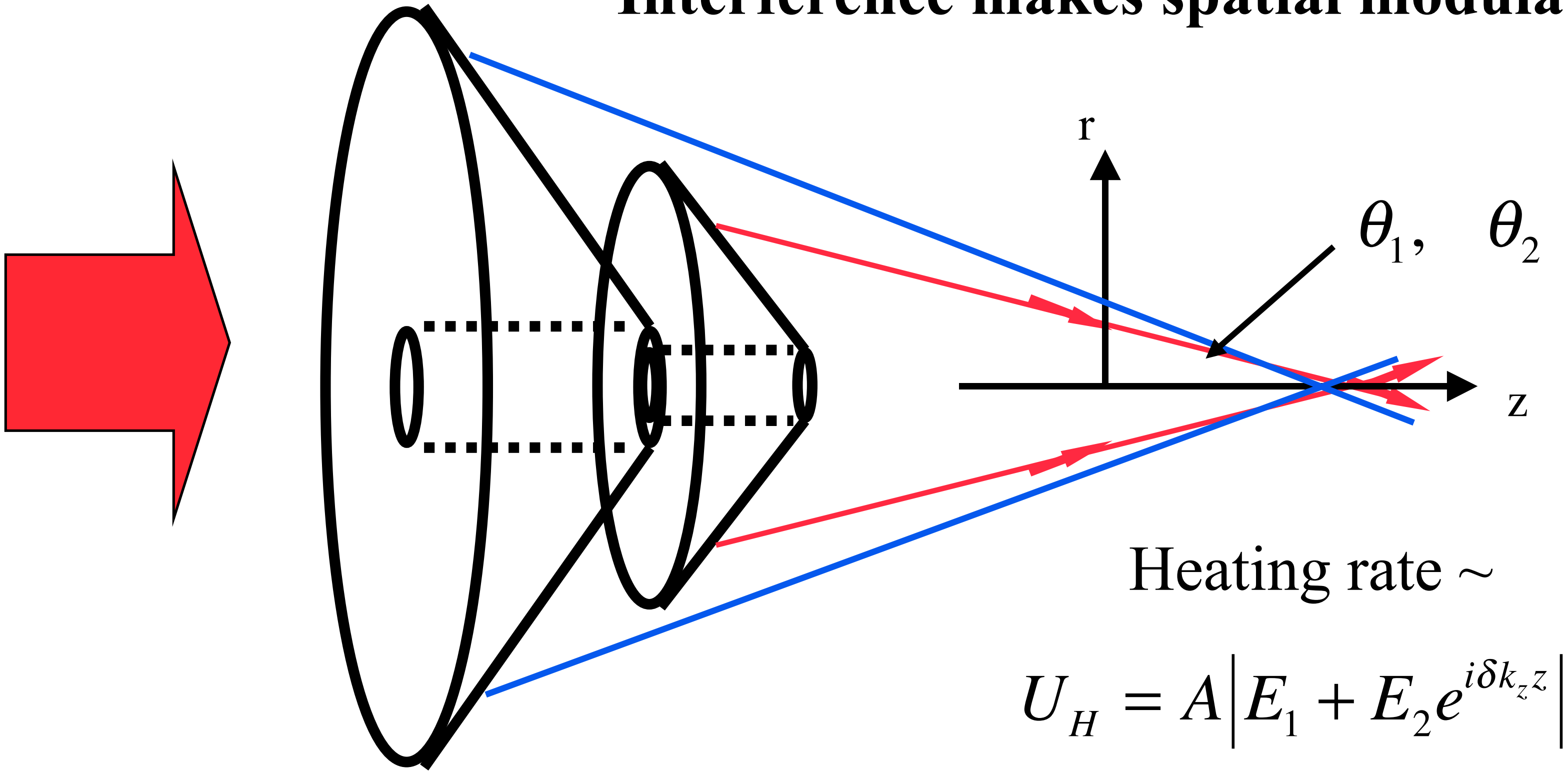
$$k_m = k_a - k_g$$

The Heating rate U_H is proportional to $|E|^2$

$$U_H = A|E|^2 e^{ik_m z}$$

Imposed Modulations

Interference makes spatial modulations

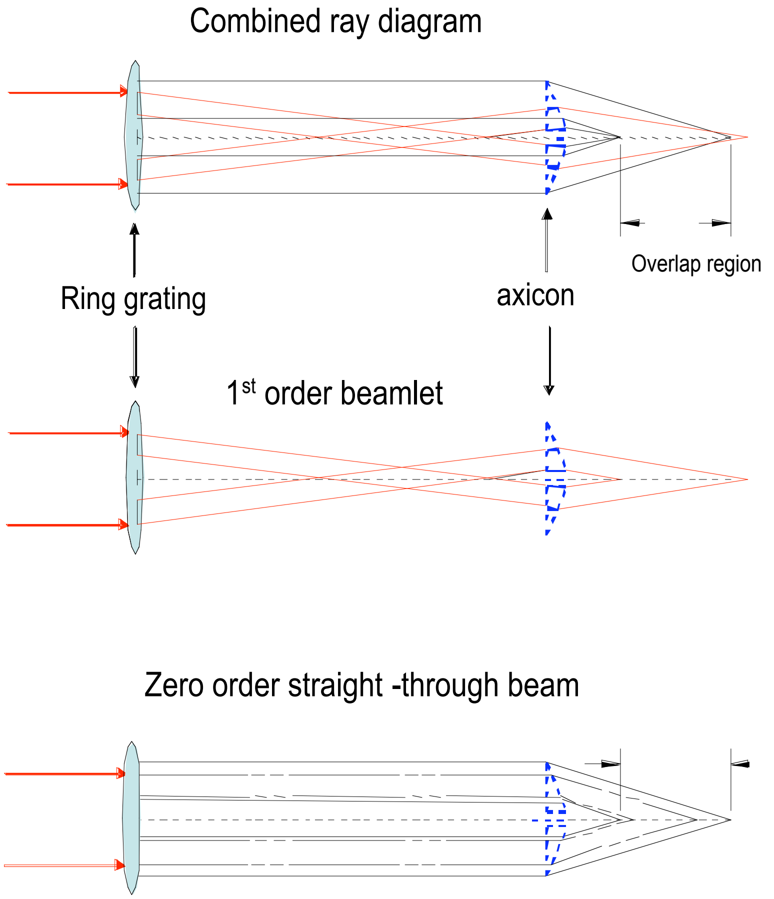


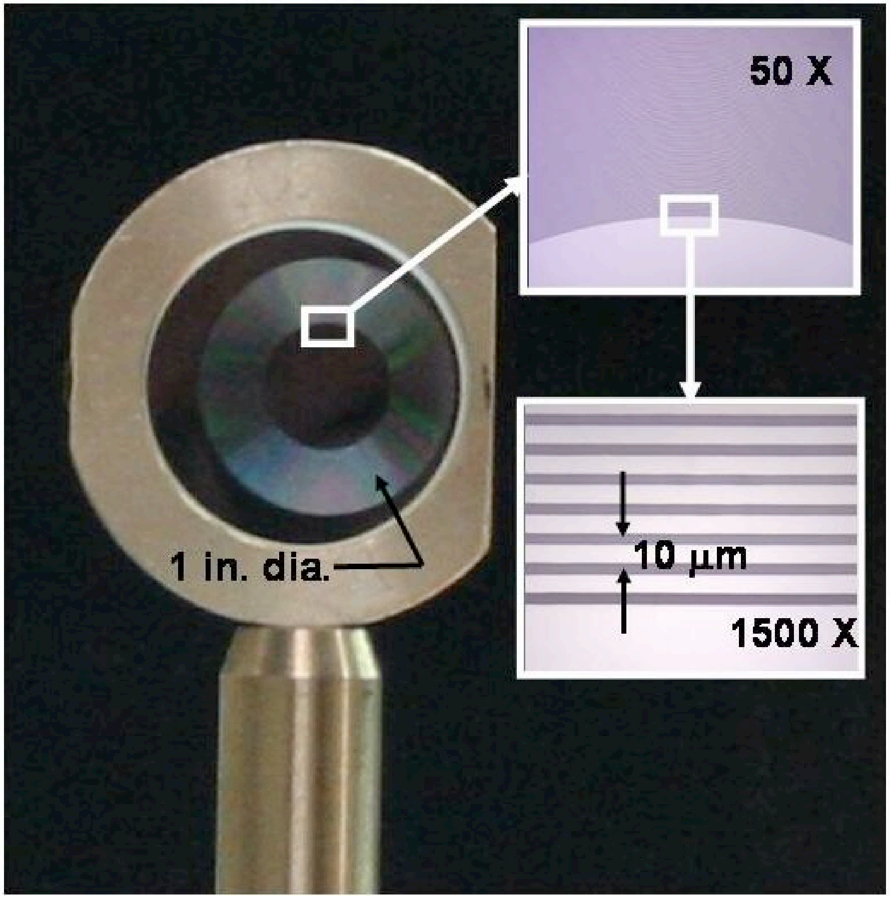
Heating rate ~

$$U_H = A\left|E_1 + E_2 e^{i\delta k_z z}\right|^2$$

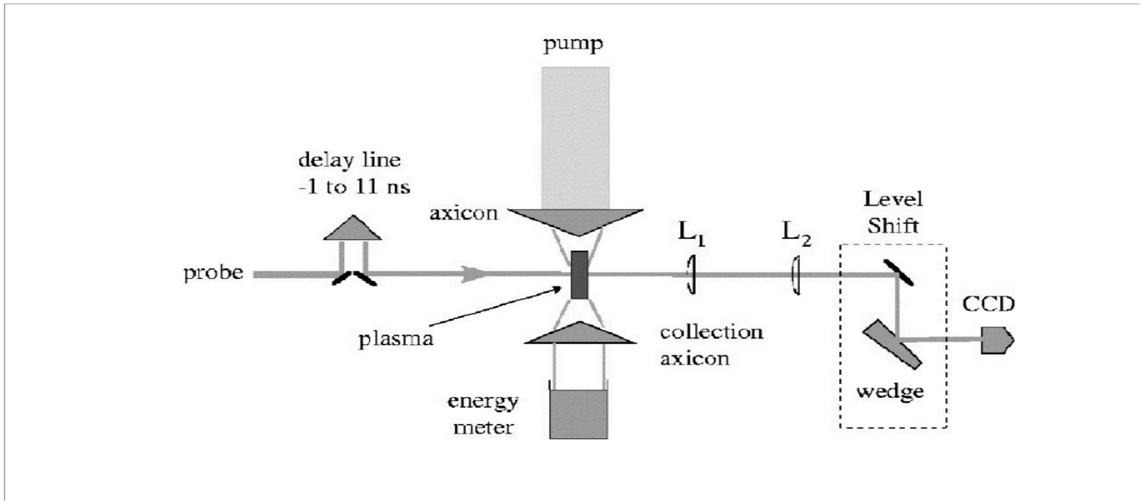
$$\delta k_z = k(\cos\theta_1 - \cos\theta_2)$$

Ring Grating + Axicon

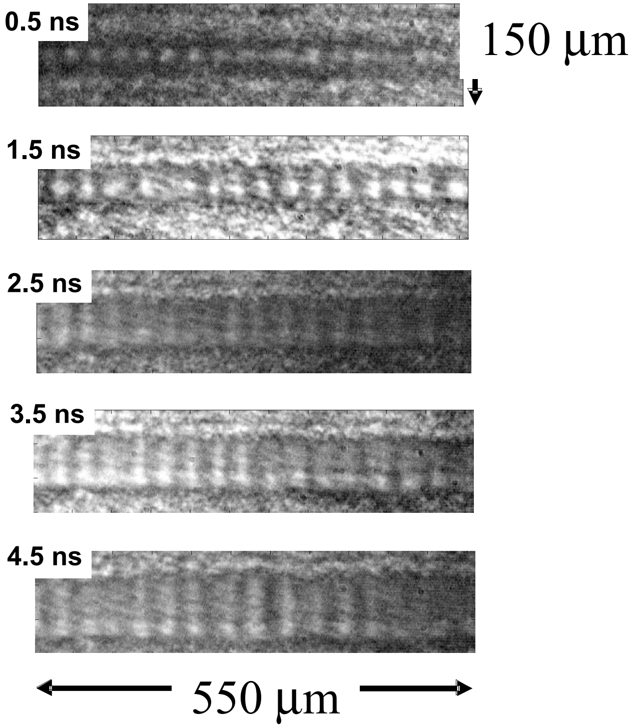




Modulated Channels



General layout of
experimental set-up



Shadowgrams

Calculation of Power Conversion Laser - THz

Assume traveling ponderomotive pulse

$$V_p(\mathbf{x},t)=\int\frac{d\omega}{2\pi}\exp\left[-i\omega\left(t-z/u_p\right)\right]\bar{V}_p(\mathbf{x}_\perp,\omega)$$

Pulse speed < c

Pulse excites waveguide mode

$$\mathbf{E}(\mathbf{x},t)=\int\frac{d\omega}{2\pi}\,\bar{E}(\omega)\,\mathbf{e}(\mathbf{x},\omega)\exp\left[-i\omega\left(t-z/u_p\right)\right]$$

waveguide mode

WG wavenumber

FT of envelope

$$\left(\frac{\omega}{u_p}-k_c(\omega)\right)\bar{E}(\omega)=\frac{2\pi i}{cA(\omega)}\int d^2x_\perp\left\langle\mathbf{e}^*\cdot\bar{\mathbf{J}}_F\right\rangle$$

Current driven by ponderomotive potential

$$\bar{\mathbf{J}}_F(\mathbf{x},\omega)=\frac{i\omega}{4\pi q}(\varepsilon-1)\left(\nabla_\perp+i\hat{\mathbf{z}}\frac{\omega}{u_p}\right)\bar{V}_p$$

Power Conversion

Power converted to radiation:

$$P_{F-EM} = \int d^3x \mathbf{J}\cdot\mathbf{F}/q \quad = \quad \frac{2\pi}{A(\omega)c\left(u_p/u_g-1\right)}\left(\frac{\omega u_p}{4\pi q}\right)^2 \left|\bar{\bar{V}}_p\right|^2$$

where $$\bar{\bar{V}}_p(\omega) = \int d^2x_\perp \bar{V}_p(\omega)\left\langle (\nabla_\perp - i\hat{\mathbf{z}}\frac{\omega}{u_p})\cdot \mathbf{e}^* \right\rangle$$

Div E

Power converted to plasma waves

$$P_{F-PW} = \frac{u_p n_0}{2m}\int d^2x_\perp \left[k_p^2 \left|\bar{V}_p(\mathbf{x}_\perp,\omega_p)\right|^2 + \left|\nabla_\perp \bar{V}_p(\mathbf{x}_\perp,\omega_p)\right|^2 \right]$$

Pump Depletion Rates (Gaussian modes)

k_d - Depletion rate ($Z_R = k_L w^2/2$ Rayleigh length)

Radiation:

$$Z_R k_{d-EM} = A \frac{\lambda_L}{z_L} \left| \omega \bar{f}(\omega) \right|^2 \frac{V_{p0}}{mc^2}$$

Structure geometry

F.T. of intensity

Plasma Waves:

$$Z_R k_{d-PW} = \frac{\lambda_L}{32 z_L} \left| \omega_p \bar{f}(\omega_p) \right|^2 \frac{V_{p0}}{mc^2}$$

Laser pulse scattering:

$$Z_R k_{d-S} = \frac{\pi}{8} \left| \frac{\delta n_e}{n_e} \right|^2 \left(k_p w \right)^4 \exp\left[-\frac{(2\pi w)^2}{\lambda_L \lambda_0} \right]$$

Conclusions

- Ponderomotive driven currents couple to THz radiation in inhomogeneous plasma channels
- Such channels can be formed hydrodynamicaly
- Pump depletion rate due to radiation generation can exceed that of scattering and plasma wave generation
- Radiation generation can be enhanced by modulational instability