University of Nebraska Lincoln

Ultrashort Duration Radiation from Ultra-Intense Laser-Matter Interactions

Donald Umstadter

Motivation and Perspective

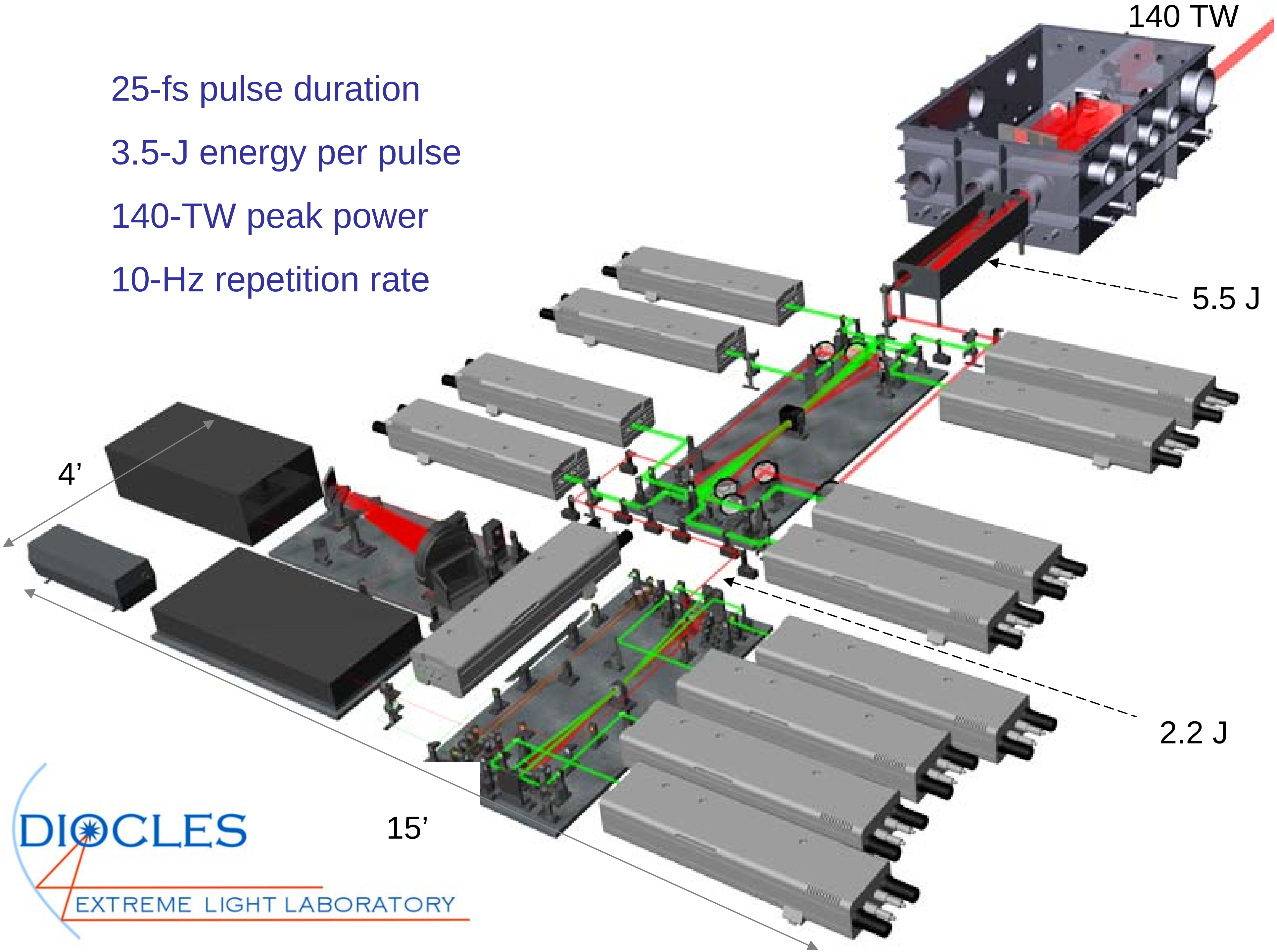
- Some ultrafast applications would benefit from a greater number of photons (e.g., 2γ processes) or higher photon energy (e.g., diffraction).
- Plasma is not limited by breakdown in high fields.
  - Relativistic nonlinear optics
  - Acceleration of electrons to 100-MeV/mm
- Compact 100-TW laser operating at 10-Hz

25-fs pulse duration

3.5-J energy per pulse

140-TW peak power

10-Hz repetition rate



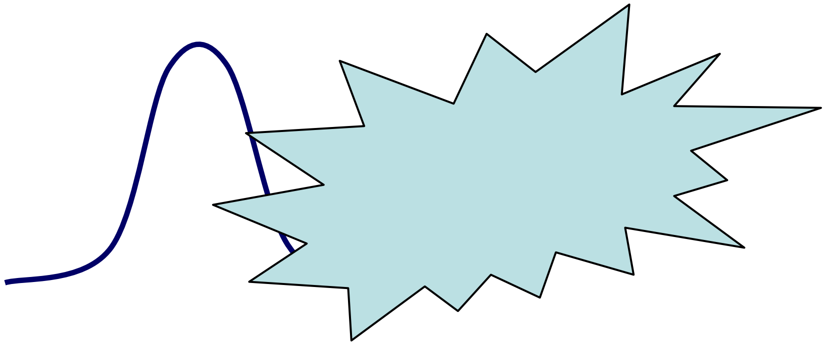
DIOCLES

EXTREME LIGHT LABORATORY

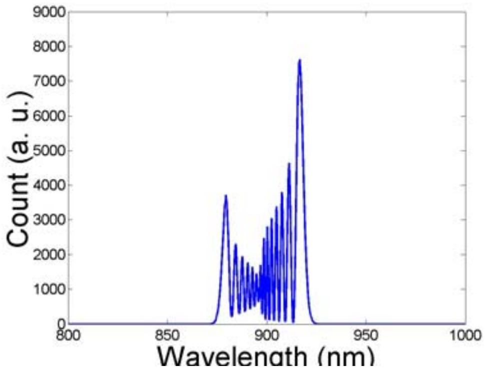
Outline

- Ultrashort light pulses from relativistic cross-phase modulation in plasma
- Slicing electron beams with light to produce ultrashort electron pulses.
- The role of longitudinal fields of focused light >>> a novel laser field model.
- Methods for generating ultra-short x-ray pulses by means of laser light and plasma.

Generation of ultrashort light pulses from relativistic cross-phase modulation in plasma



$dn/d\omega < 0$



Nonlinear-index coefficient *n*$_2$ in relativistic plasma

- Refractive Index of Plasma

$$n=\sqrt{1-\frac{\omega_p^2}{\omega_0^2}}\approx 1-\frac{\omega_p^2}{2\omega_0^2}$$ where $$\omega_p^2=\frac{4\pi n_e e^2}{m_e\gamma}$$

γ is relativistic factor of the electron in a laser field

- For a linear polarized laser

$$\gamma=\sqrt{1+\frac{a^2}{2}}\approx 1+\frac{a^2}{4}$$ where $$a=8.5\times10^{-10}\lambda[\mu\mathrm{m}]I^{1/2}[\mathrm{Wcm}^{-2}]$$

is the normalized vector potential

- Further simplification of *n*

$$n\approx 1-\frac{\omega_p^2}{2\omega_0^2}(1-\frac{a^2}{4})=n_1+n_2 I$$ where $$n_2=\frac{\omega_p^2}{8\omega_0^2}(8.5\times10^{-10}\lambda[\mu\mathrm{m}])^2$$

Relativistic self-phase modulation

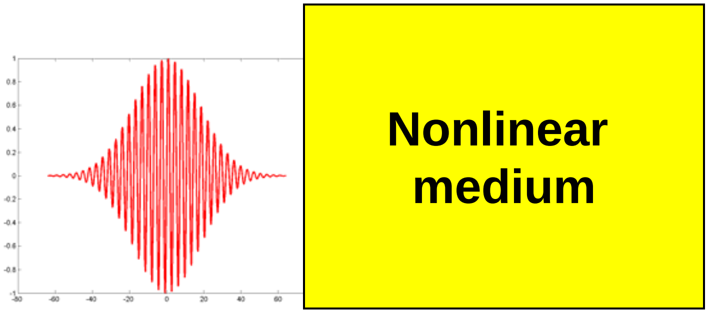
In a nonlinear medium

$$\tilde{n} = (n + n_2 I)$$

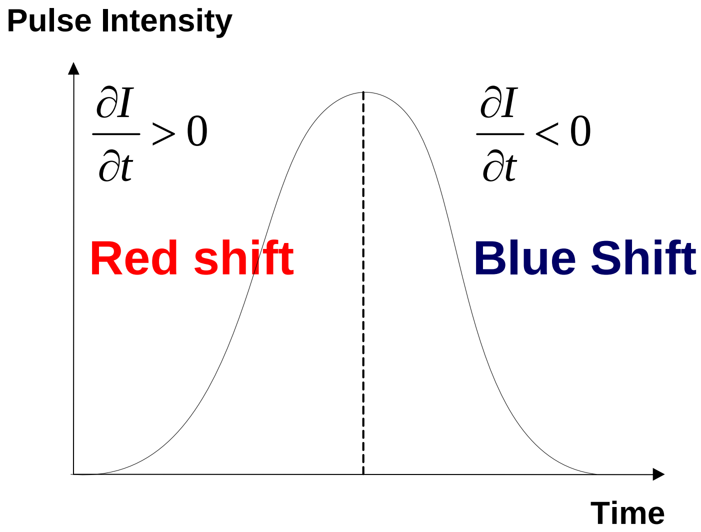
$$\phi = \tilde{n} k_0 z - \omega_0 t = (n + n_2 I) k_0 z - \omega_0 t$$

Frequency Chirp

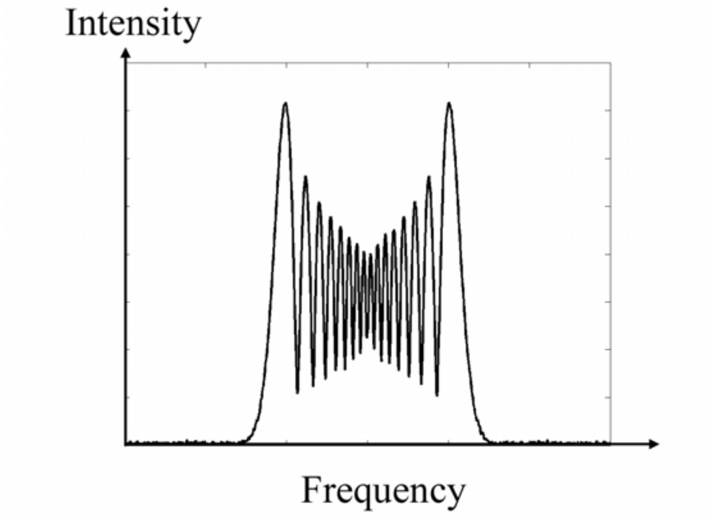
$$\omega = -\frac{\partial \phi}{\partial t} = -n_2 k_0 z \frac{\partial I}{\partial t} + \omega_0$$



Nonlinear medium



Self-phase modulation



Cross-Phase Modulation (XPM)

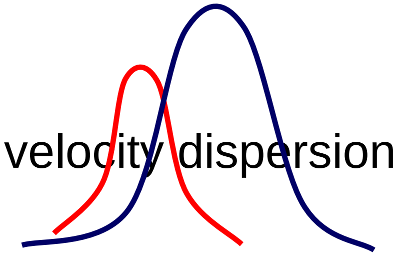
For two optical pulses with different frequencies

$$\phi_{1nl} = n_2 k_0 z\left(\underbrace{I_1{}^2}_{\text{SPM}} + 2\underbrace{I_2{}^2}_{\text{XPM}}\right)$$

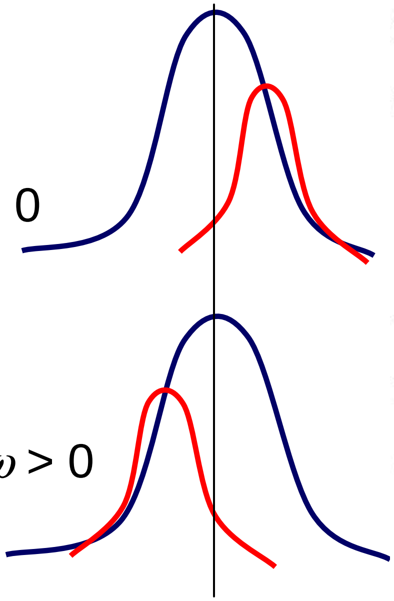
For $I_1 >> I_2$, one pulse is modulated by another pulse (XPM)

Raman generation, harmonic generation, pump probe.

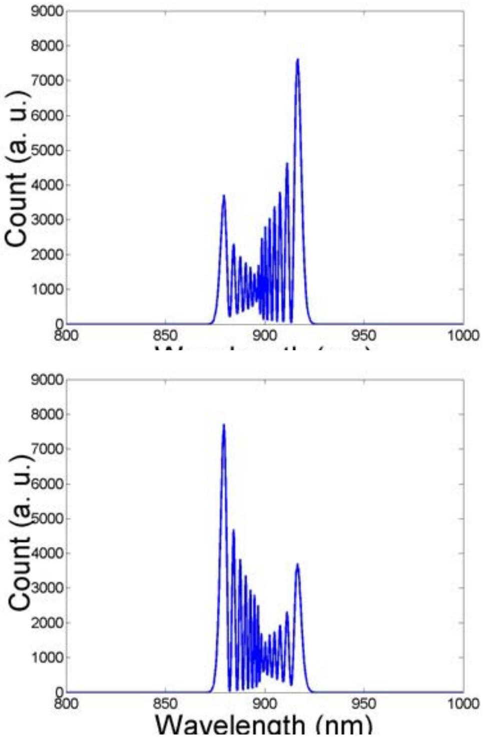
Asymmetric spectral broadening



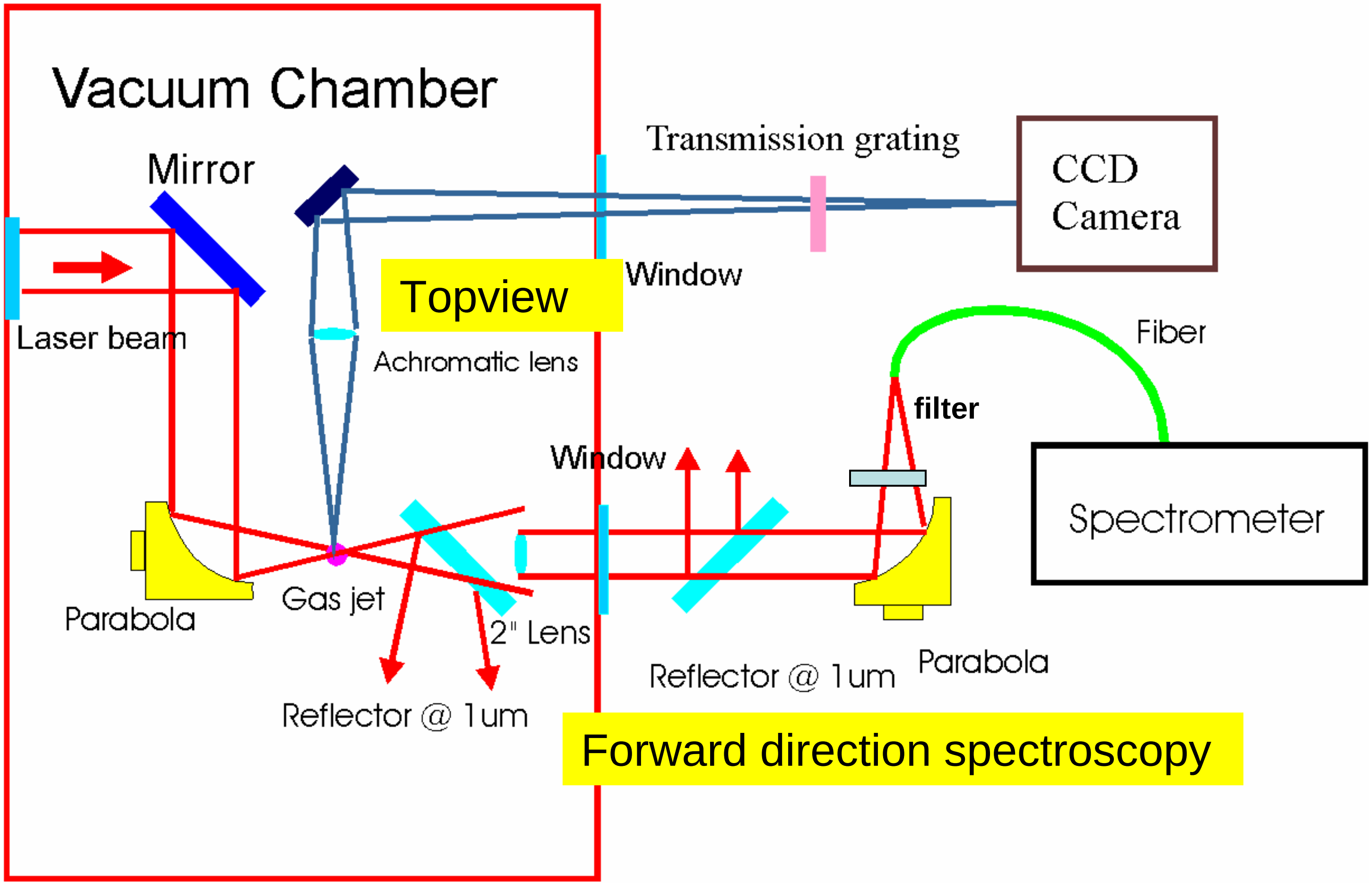
Normal Group velocity dispersion $dn/d\omega < 0$



Anomalous Group velocity dispersion $dn/d\omega > 0$

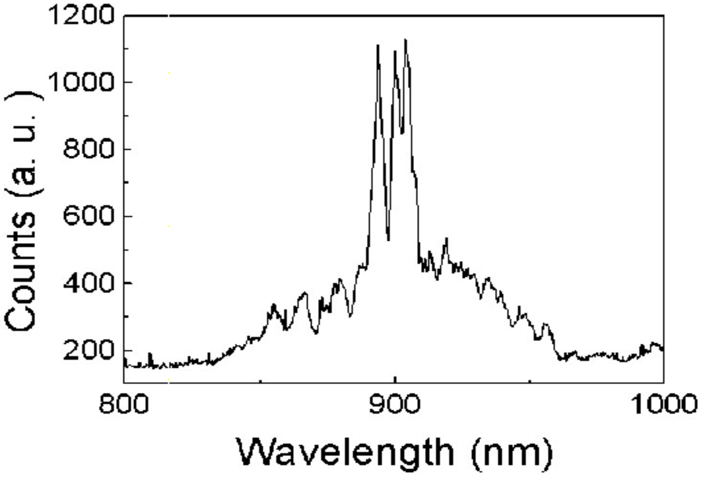
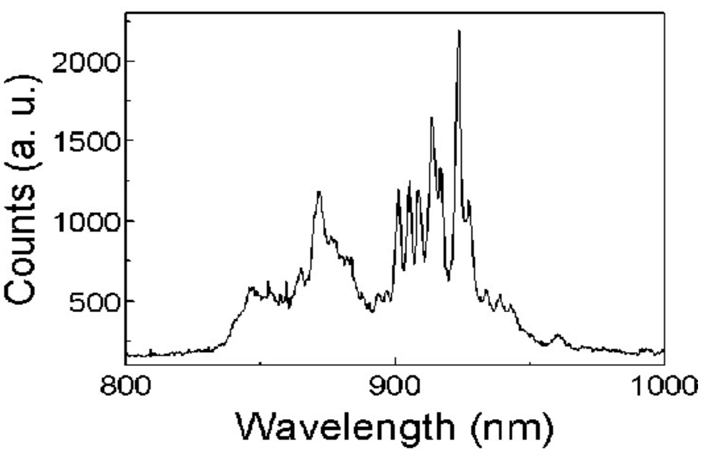
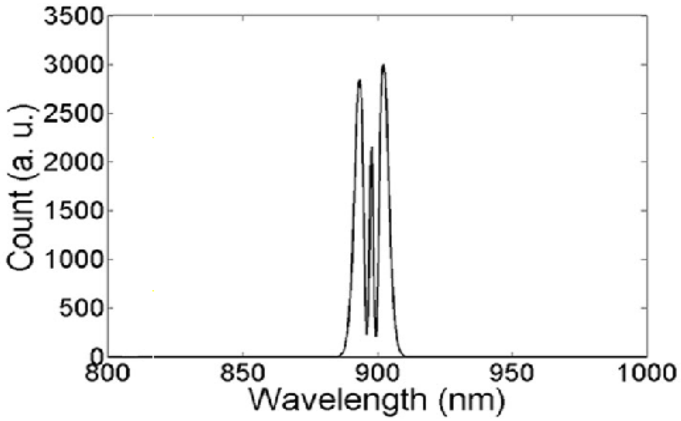
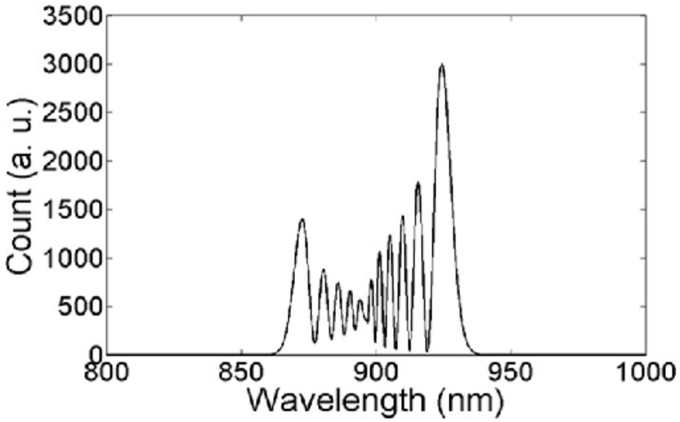


Experimental Setup



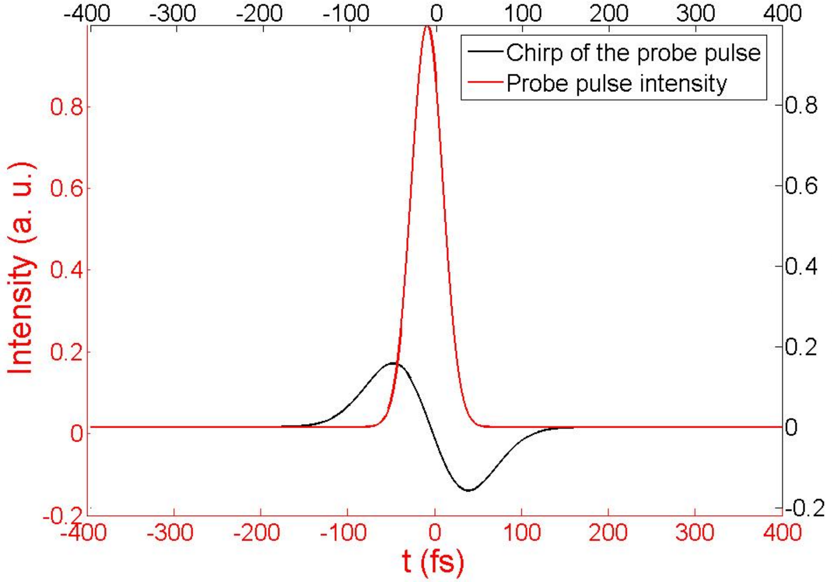
400 fs, 1 um wavelength, 0.45 TW to 3.2 TW

Comparison shows good qualitative agreement between analytical and experimental results

	A **2.0 TW**	B **2.4 TW**
Experiment		
Simulation		

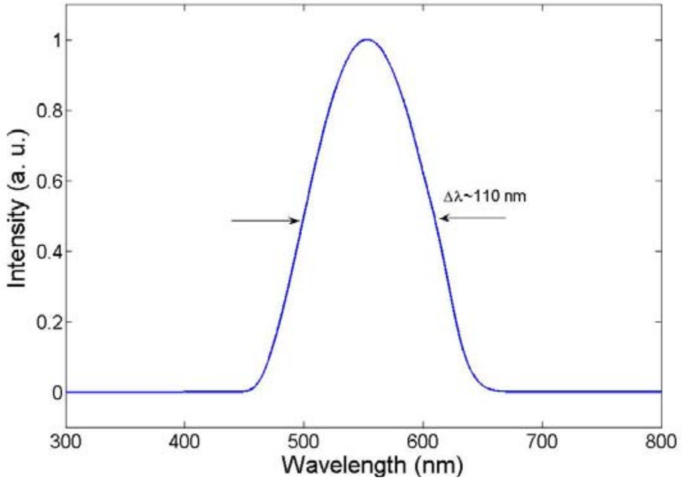
S. Chen et al., submitted for publication

Generation of ultra-short high power pulse by RXPM compression


Chirp of RXPM modulated probe pulses

Pump pulse parameters:
Power 10 TW
Pulse duration 100 fs
Propagation distance 2 mm
Wavelength 800 nm
Focus radius 6 μm

Probe pulse parameters
Power variable (up to 2 TW)
Pulse duration 30 fs
Wavelength 533 nm


Bandwidth of RXPM modulated probe pulse

For a Fourier transform limited pulse

$$\tau = \frac{2\ln(2)\lambda^2}{\pi\Delta\lambda c}$$

After compression τ=**4~5 fs**
Assuming the input pulse is 50 mJ, the final power is **10 TW**

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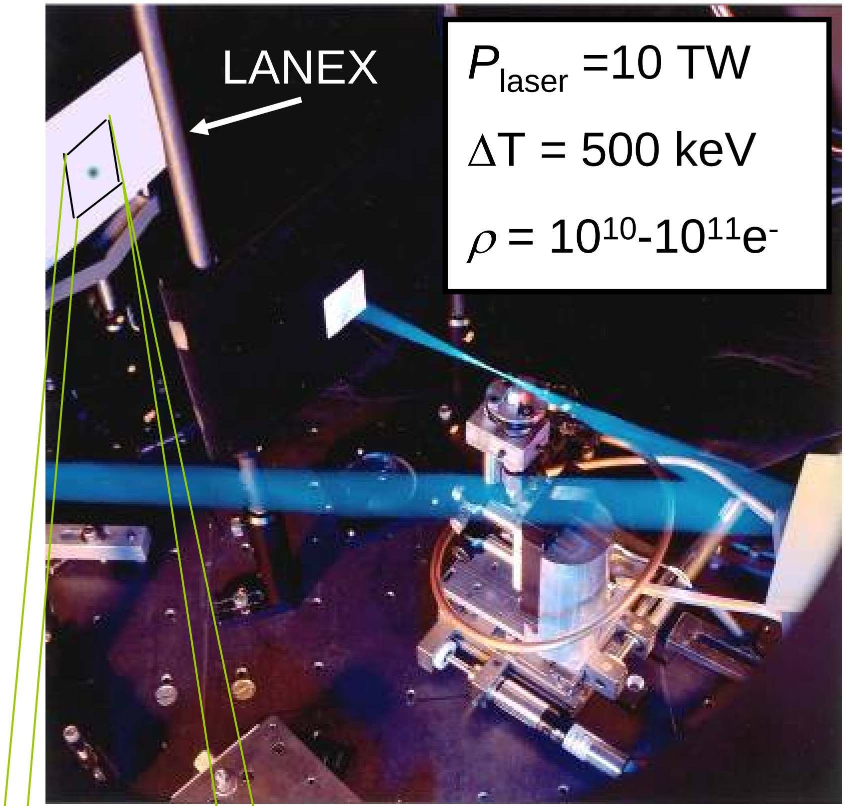
Motivation for this research

- **Problem:**
  - **Because of space-charge broadening, low-energy e-beams from laser-triggered photocathodes have limited charge and relatively long duration.**
  - **Because of nonlinearity, high-energy electrons from wakefields lack controllable energy spreads.**
- **Solution**
  - **Ultra-intense laser pulses can optically select near-monochromatic femtosecond MeV electron bunches without space-charge broadening.**

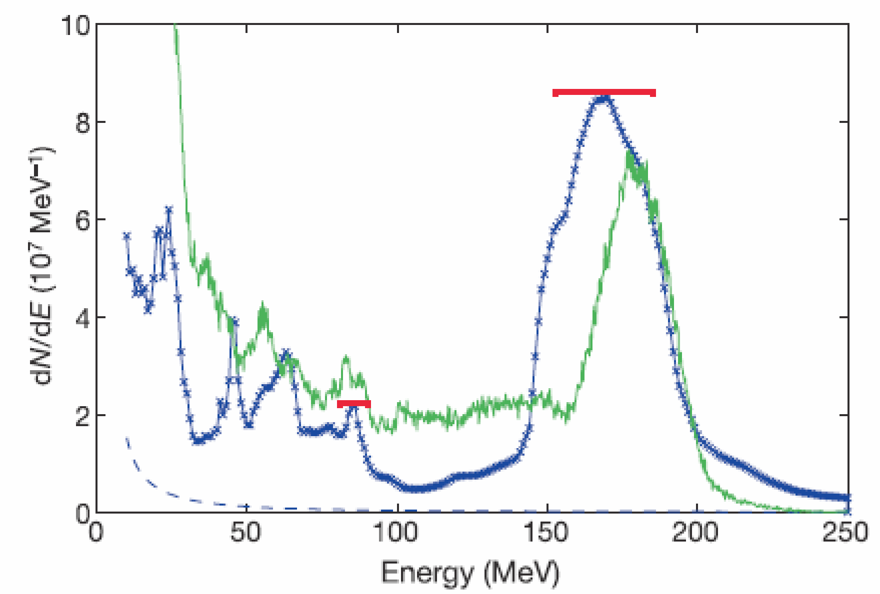
Low-angular divergence of laser-wakefield electron beam



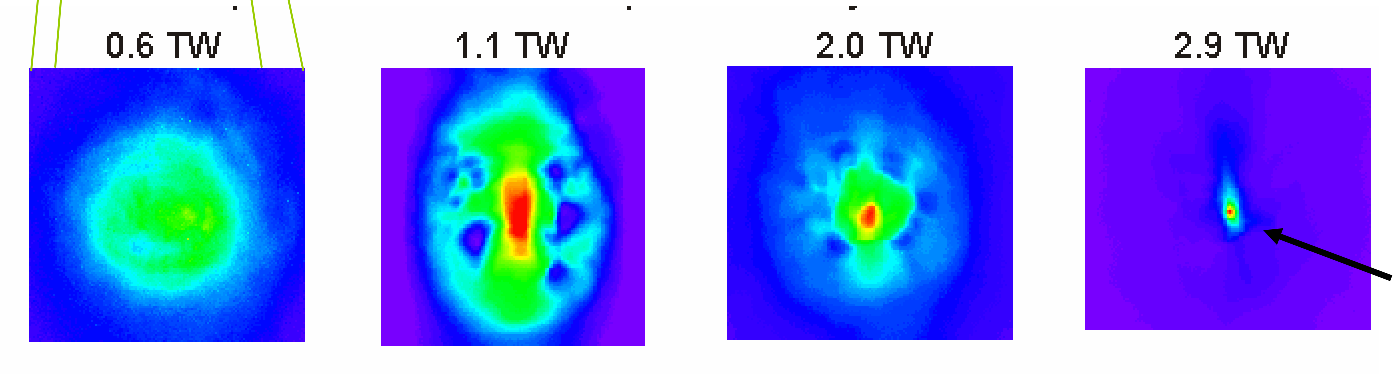
P_{laser} =10 TW

ΔT = 500 keV

ρ = 10^{10}-$10^{11}$$e^-$



- J. Faure et al., Nature **431**, 541 (2004)
- C.G. R. Geddes et al., Nature 431, 538 (2004)



τ_{laser}= 400 fs

$\Delta\Theta$ = 1°

Laser-driven electrons: large energy spread

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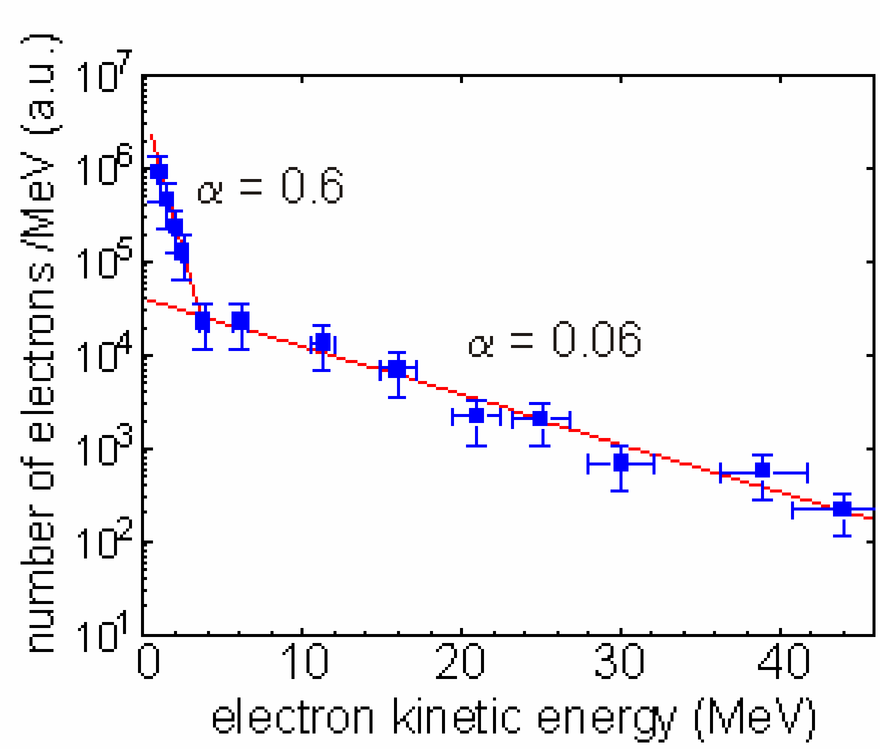
$\tau = 400$ fs
$E = 5$ J
$a_0 = 3$

10^{11} electrons total
$T \sim 0.5$ MeV

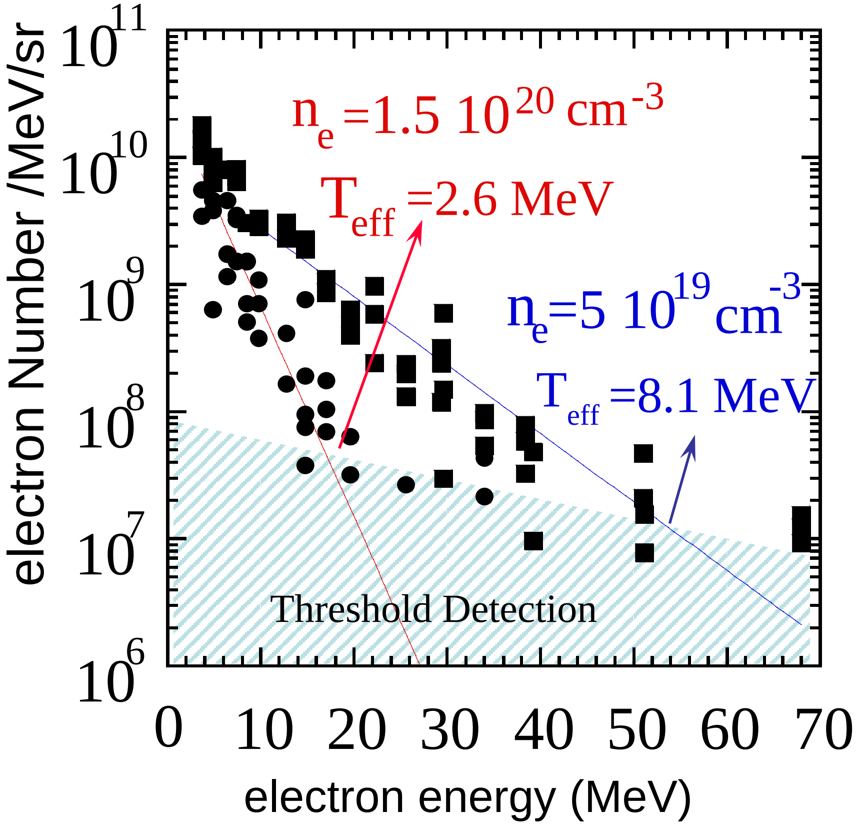


Assamagan et al., *Nucl. Instr. Meas. A* **438**, 265 (1999).

LOA

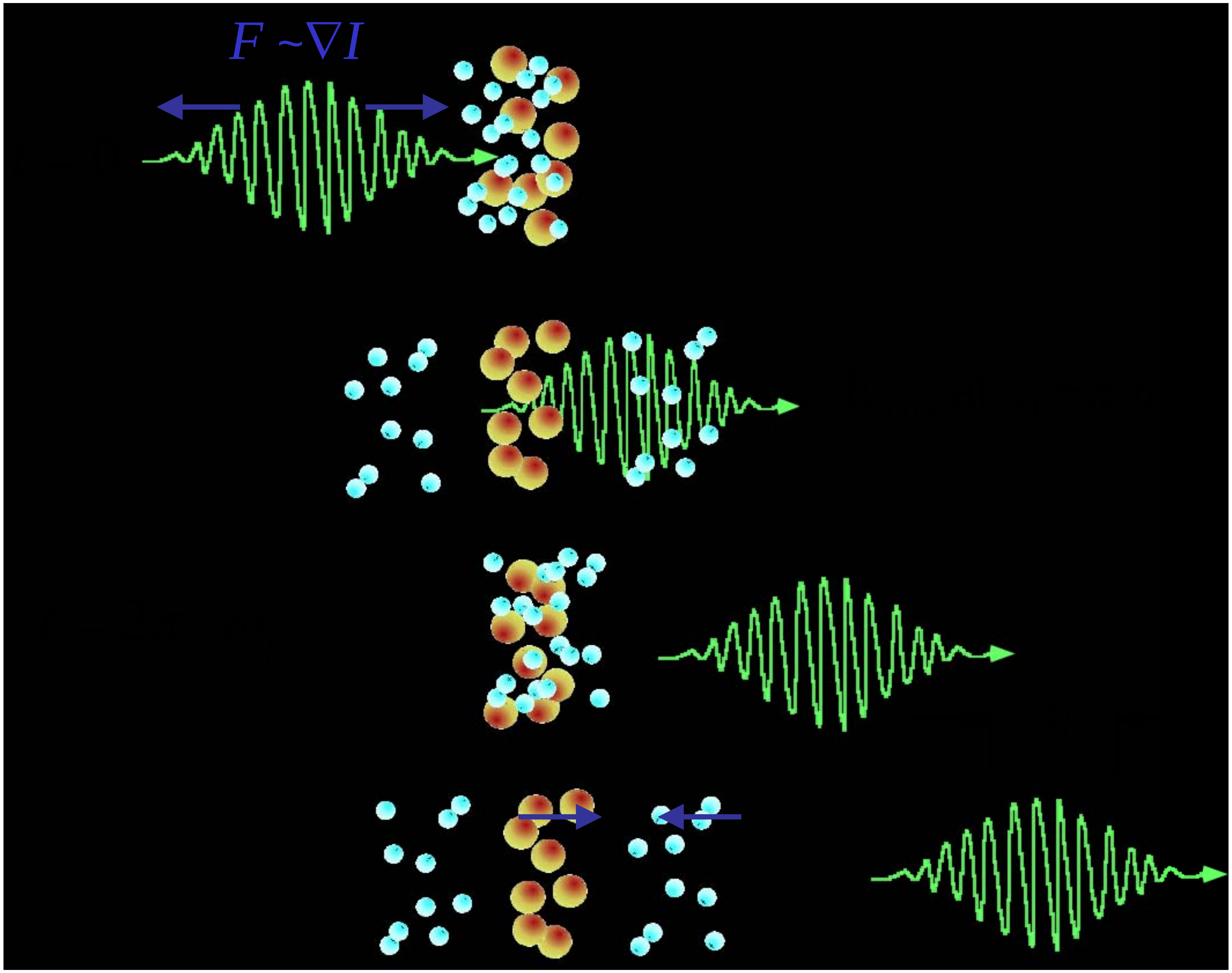
$\tau = 35$ fs
$E = 0.6$ J
$a_0 = 3$

10^{10} electrons with energy > 3.7 MeV,
$T \sim 8.1$ MeV



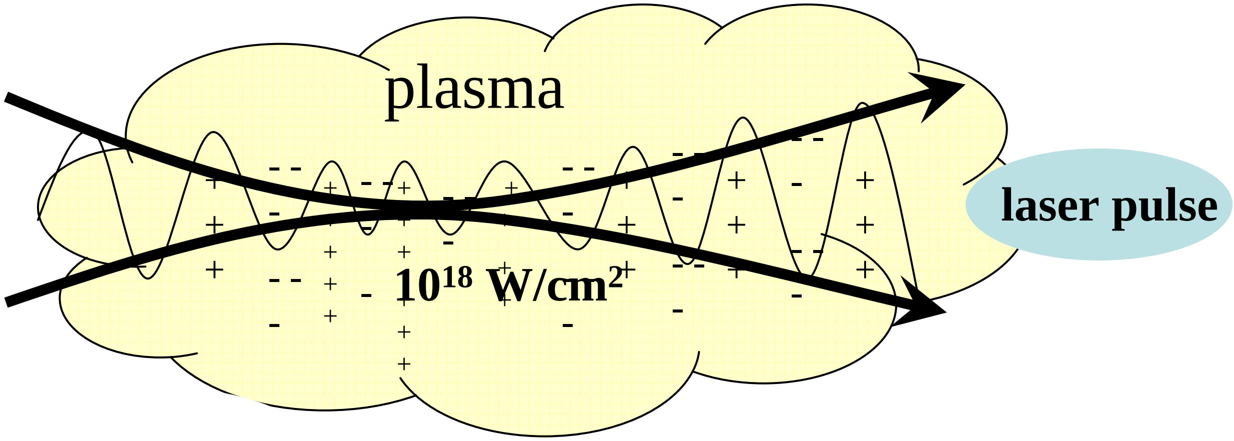
V. Malka, et al, *Phys. Plasmas* **8**, 2605 (2001).

Laser light pushes electrons longitudinally, driving wakefield plasma waves



Electrons accelerated to high energy in relativistically moving wakefield

$$E = E e^{\left(k_p z - \omega_p t\right)}$$

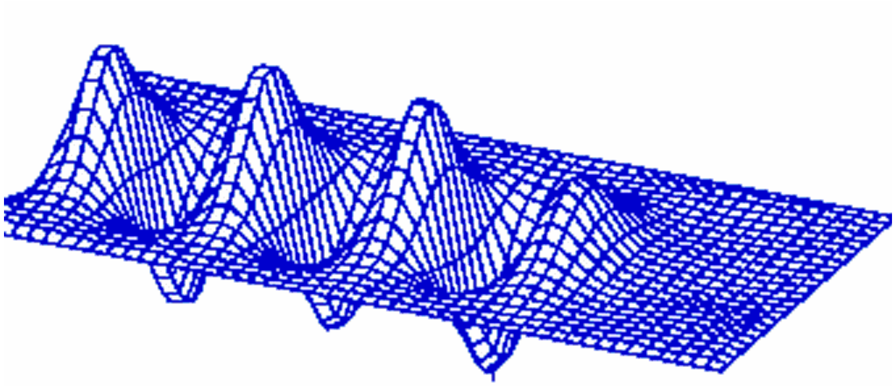


$$\nabla \cdot E \sim k_p E = \frac{\omega_p}{c} E \sim \sqrt{n_e} E \sim n_e$$

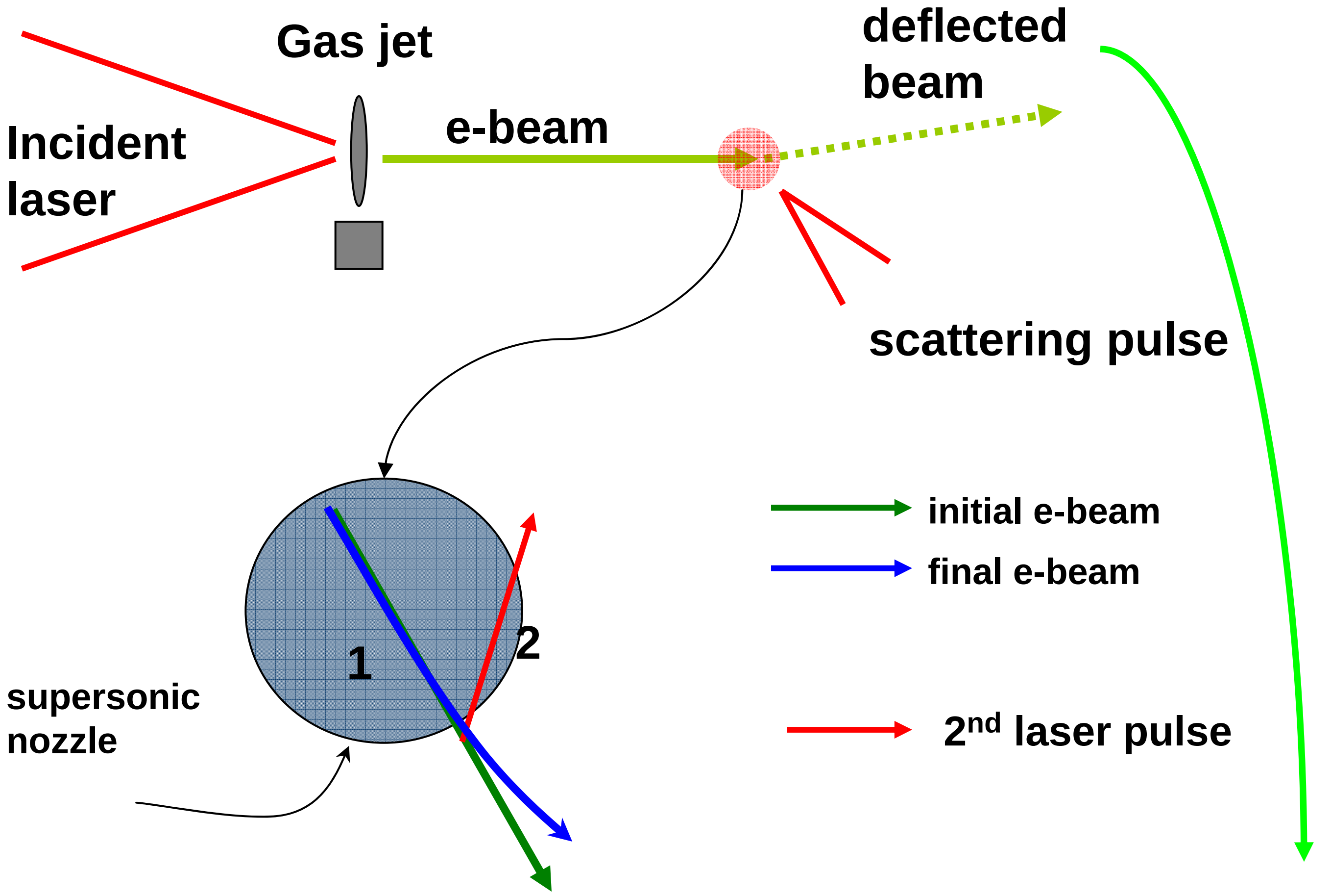
$$\Rightarrow E \sim \sqrt{n_e} \ \text{eV/cm}$$

$$\therefore n_e = 10^{18} / \text{cm}^3 \Rightarrow E \sim \ 1 \ \text{GeV/cm}$$

$$v_\phi^{es} \sim v_g^{em} \sim c\left(1 - \frac{n_e}{2 n_c}\right) \sim c$$



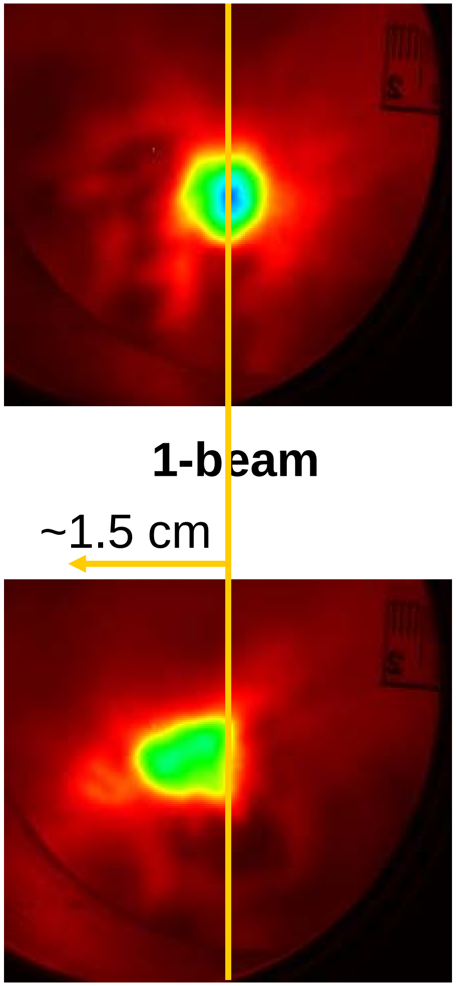
Can High Intensity Lasers Produce Robust, Controllable MeV-Energy, Femtosecond Electron Bunches?



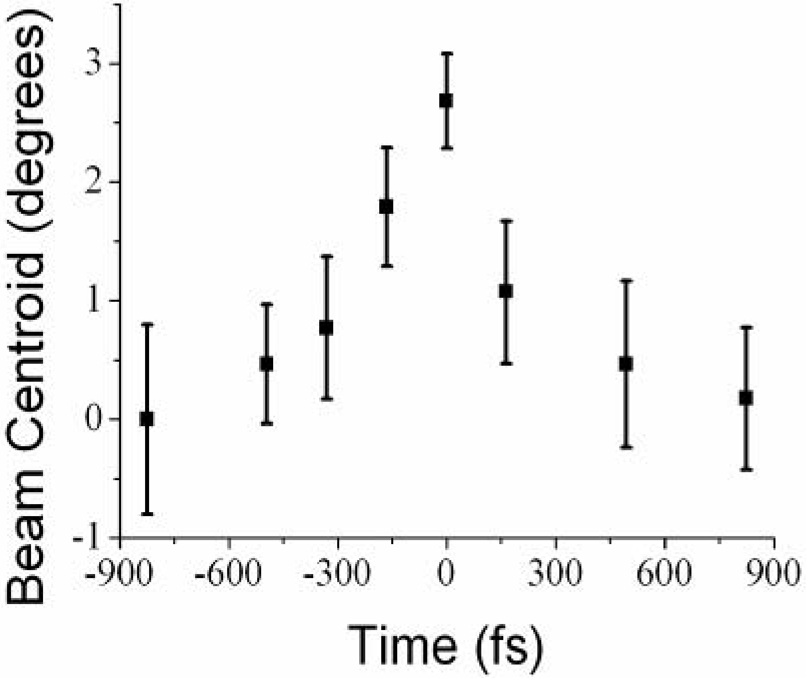
1st laser pulse – accelerates e-beam
2nd laser pulse – deflects e-beam

1. **Ultrashort electron bunches**
2. **Monochromatization of polychromatic MeV electron beams**

Observation of Ponderomotive Deflection

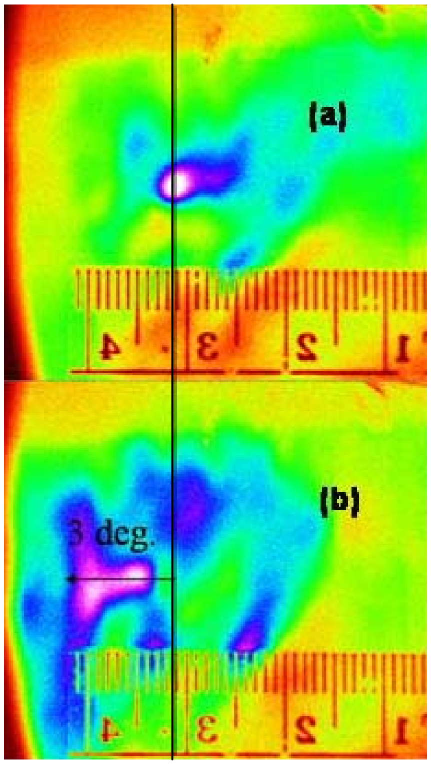


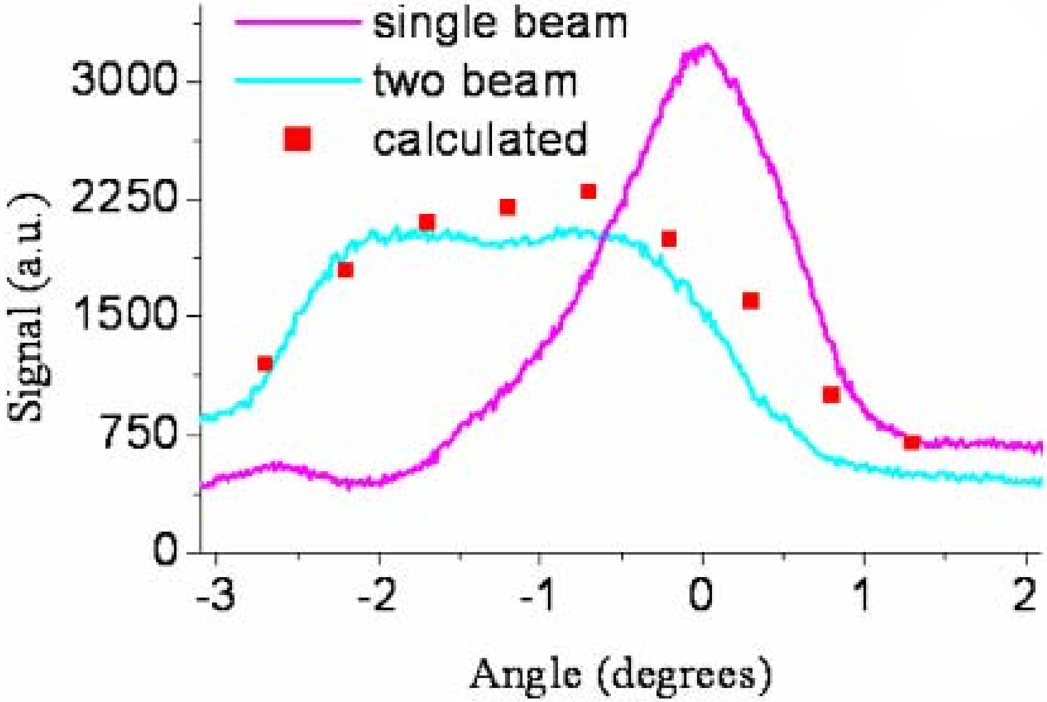
2-beam, zero delay



Cross-correlation of laser wakefield accelerated electron beam

Analysis predicts observed deflection





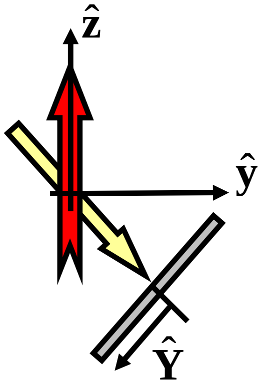
f(θ,γ) – distribution function $f(\theta,\gamma) = g(\theta)\exp(-\alpha\gamma)$

Perturbed by incident laser $\theta \to \theta + \theta_D(\gamma)$

Convolution of angle and energy is used to obtain the angular profile of the electron beam when acted on by the second laser pulse

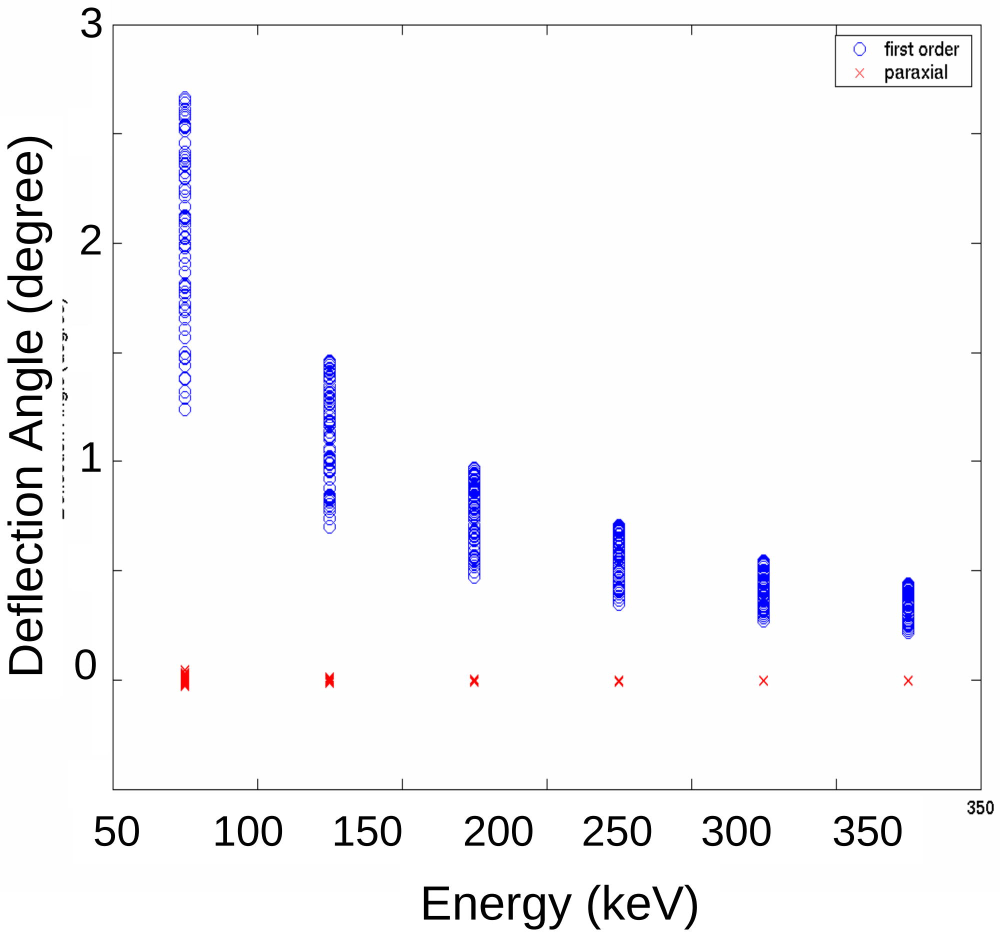
Banerjee *et al*., Phys. Rev. Lett. **95**, 035004 (2005)

Agreement requires inclusion of longitudinal fields



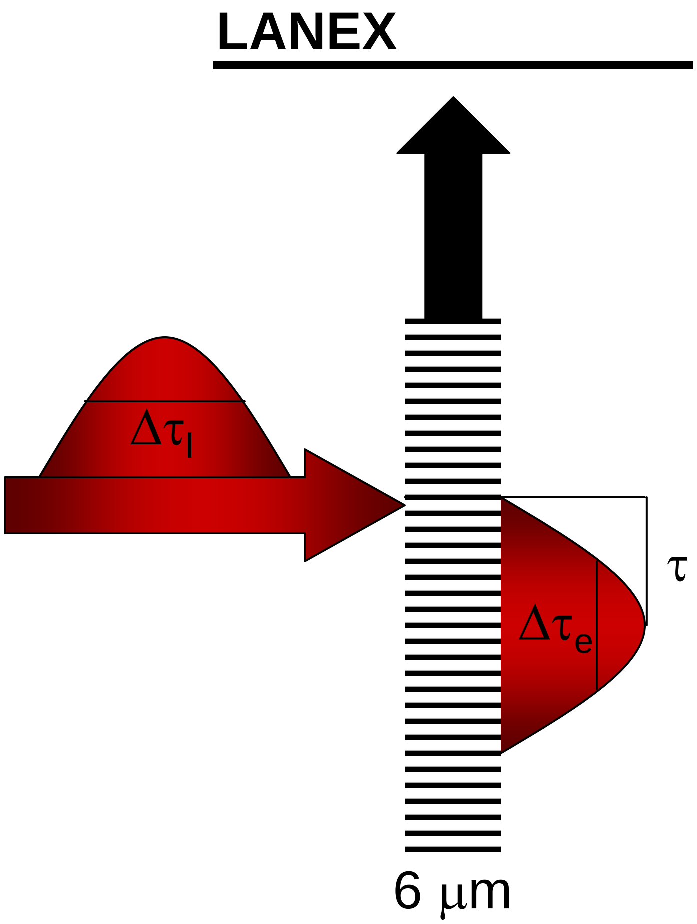
Including the first non-paraxial term [E_z/B_z] reproduces the experimentally observed result. The paraxial result shows no deflection.

$$\frac{E_z}{E_x} \sim \frac{B_z}{B_y} \sim 0.1$$



S. Sepke and D. Umstadter, Opt. Lett. 31, 1447 (2006).

Simulations of Beam Conditioning



Simulate electrons colliding with an ultraintense, 30-fs laser at 90 degrees to separate 1-3 MeV electron beams. Electron are diagnosed by a “LANEX” screen.

Input Parameters

Laser	**Electrons**
$\Delta\tau_l = 30$ fs	$\Delta\tau_e = 30$ fs
$w_0 = 10\ \mu m$	$D = 6\ \mu m$
$a_0 = [2.5, 5.625]$	$E \in [100, 7000]$ keV
$\lambda_0 = 1\ \mu m$	$\Delta E = 100$ keV
$\xi = 90°$	$\Delta y = 1.5\ \mu m$
$\varepsilon = 0.0159$	$T_e = 18$ MeV
	$2x10^6$ electrons

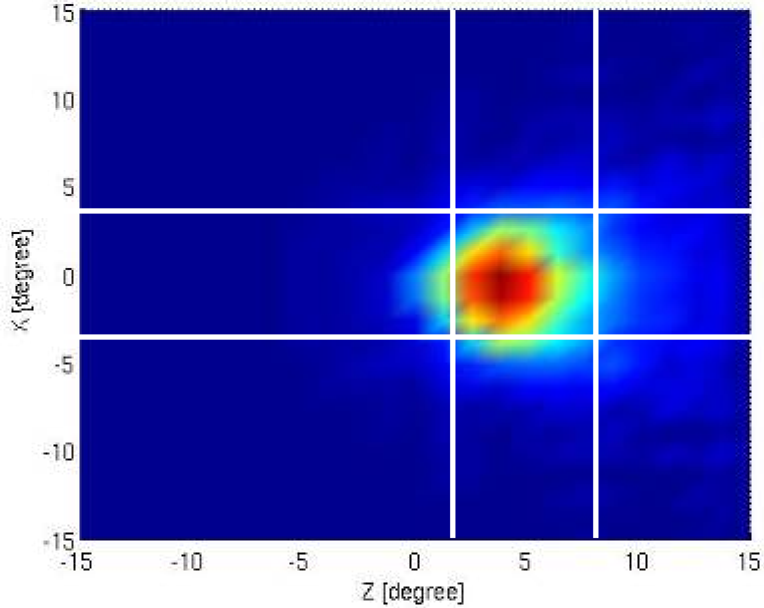
Imaging the Conditioned Electrons: 1.2--MeV Electron Beam

To analyze the resulting electron beam, the particles are tallied on a simulated LANEX. The signal is proportional to the number of actual electrons striking the screen.

$$f(E,t)=exp\left(-\frac{(t-\tau)^2}{\Delta\tau_e^2}\right)\left\{exp\left(-\frac{E-\Delta E/2}{T_e}\right)-exp\left(-\frac{E+\Delta E/2}{T_e}\right)\right\}$$

Each simulation particles carries the energy distribution function: T_e=18 MeV

a_0=2.5, E$\in$[0.5, 1.5] MeV, 3.5° to 8.5°



Summary of Beam Conditioning Simulations

- Best conditioned electron beams are produced when the laser and electron durations are matched.

- Maximum deflection occurs when the electron bunch collides with the centre of the laser pulse: τ = -10 fs.

a_0	E ± ΔE (MeV)	e^- (10^8)*
2.5	1.20±0.45	9.02
5.6	2.35±0.45	7.03

***Initial electron beam – 5 nC**

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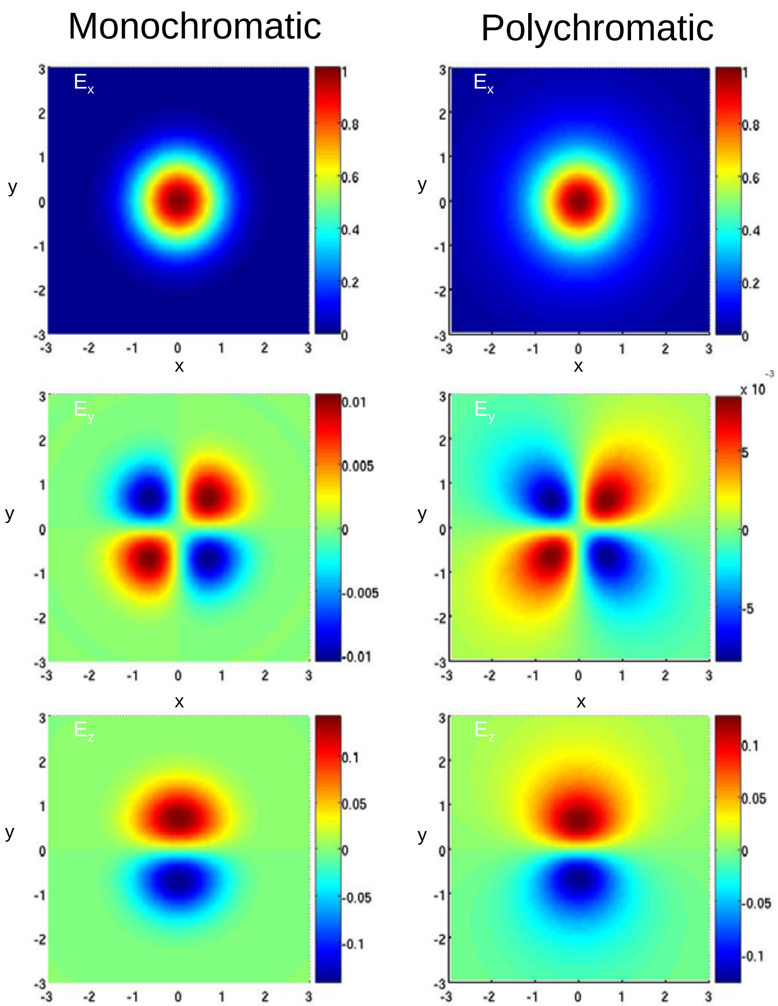
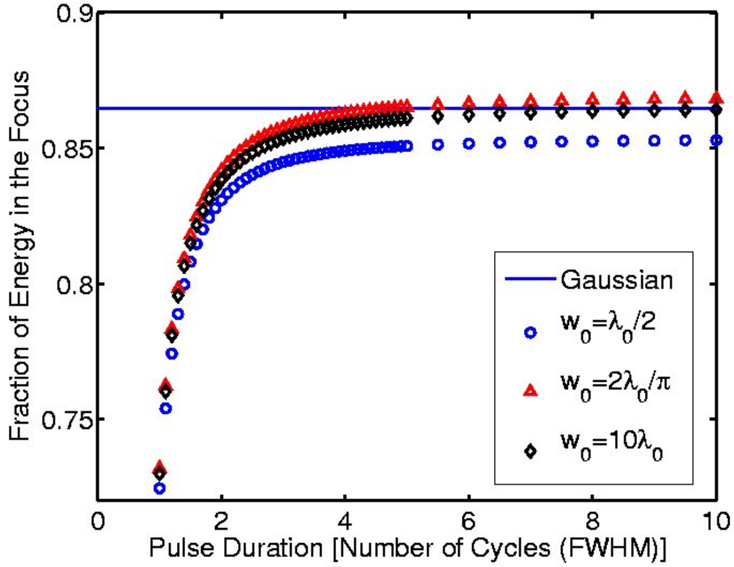
Exact Solutions for the Fields of Few-Cycle, Focused Laser Pulses

The Focal Plane Laser Fields



- Detailed vector model using the angular spectrum of plane waves
- Two complimentary solutions allowing for tight and loose focusing and all pulse durations.
- Save 3-4 orders of magnitude in computation time.
- Few-cycle pulses broaden the laser focus and decrease the energy in the nominal focus.



S. Sepke and D. Umstadter, Opt. Lett. 31, 1447 (2006).

Also, see POSTER Session this afternoon

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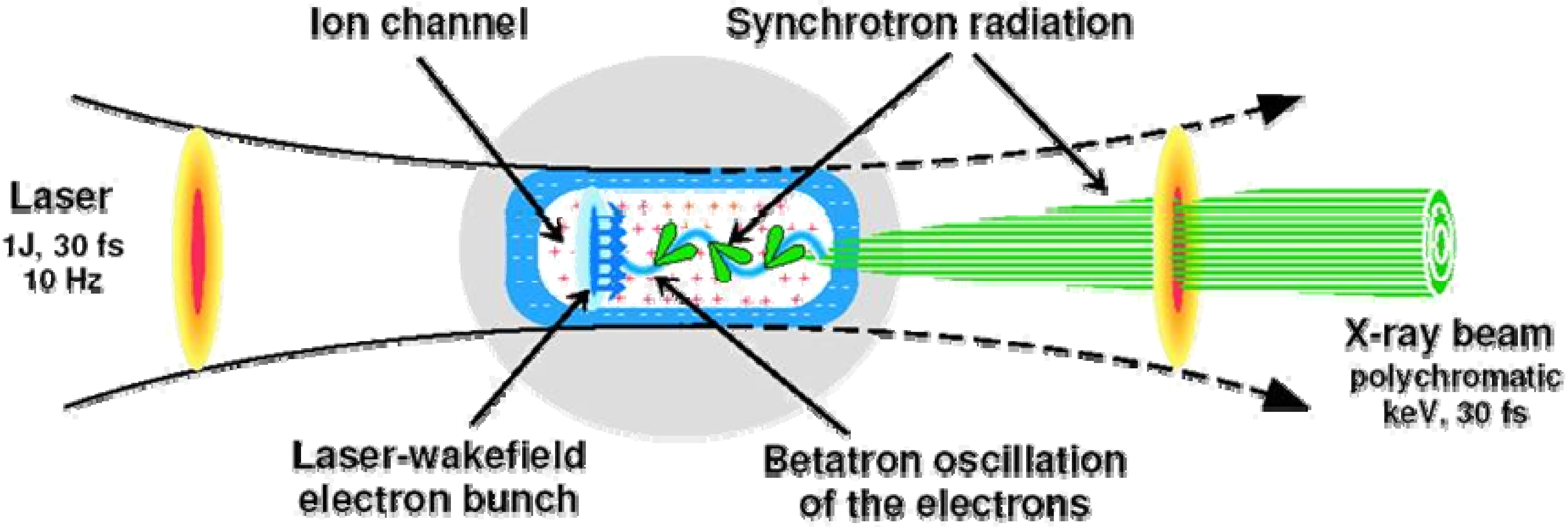
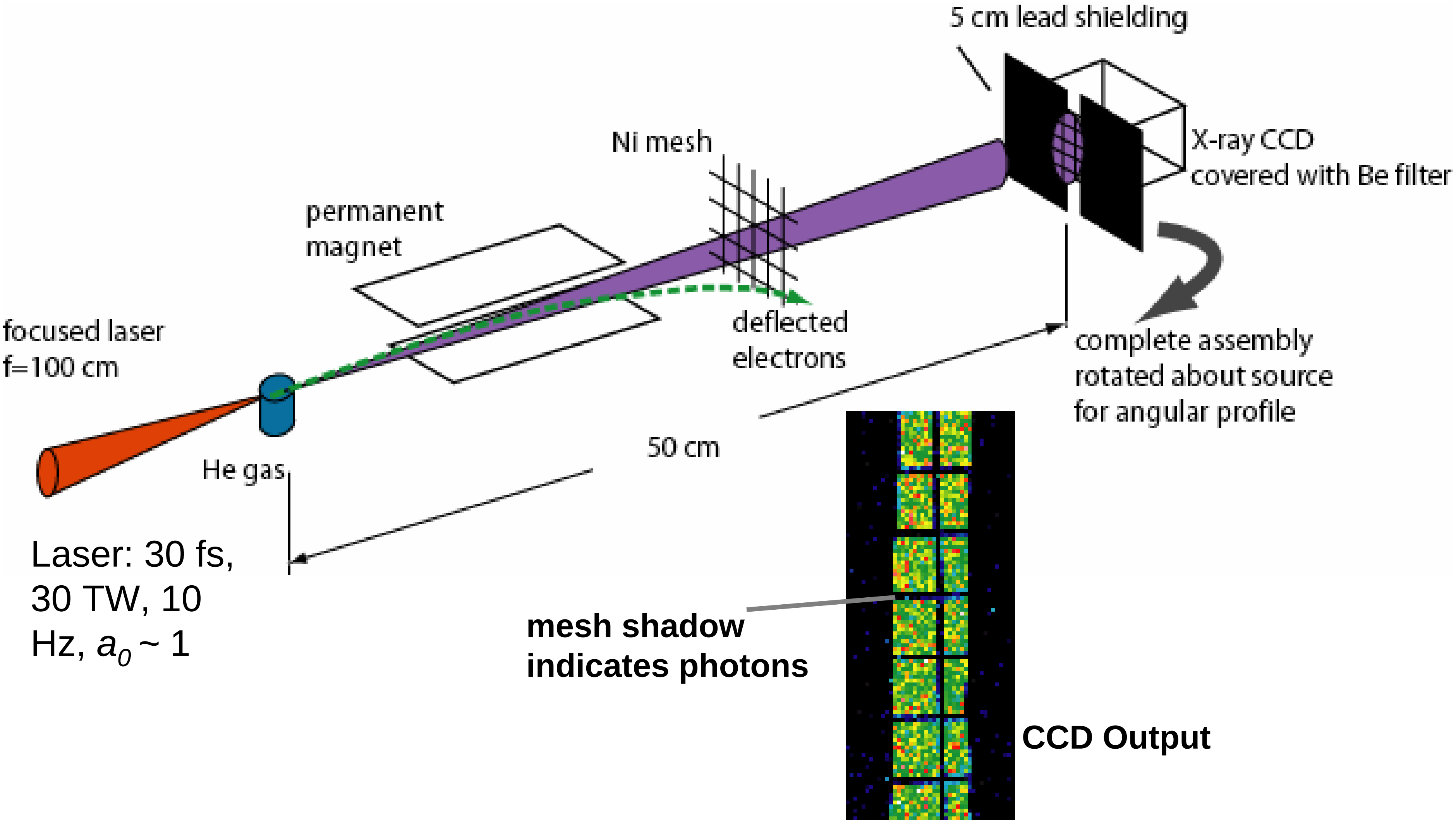
Single-Pulse Drives Electron Betatron Oscillations



Experimental Setup and X-ray Signal

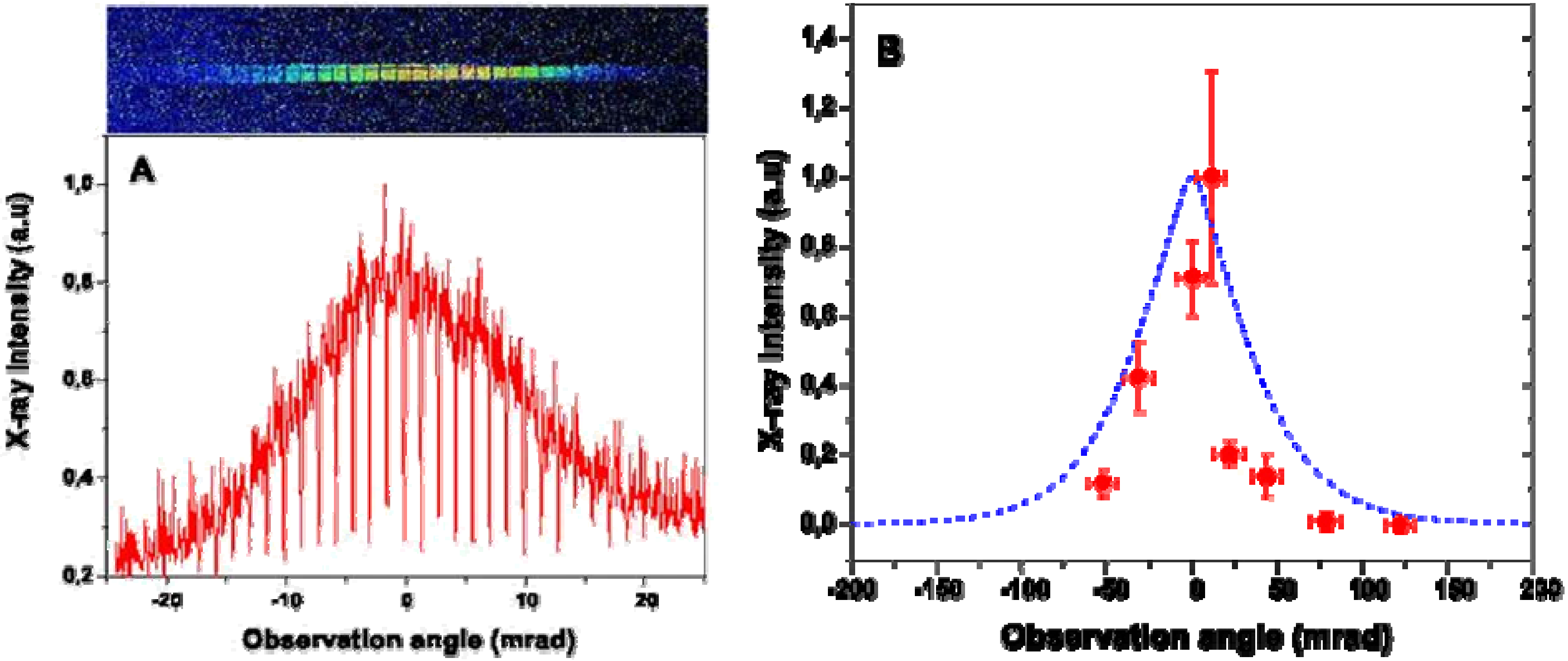


Laser: 30 fs, 30 TW, 10 Hz, $a_0 \sim 1$

mesh shadow indicates photons

CCD Output

A Well-Collimated Beam of keV-Energy X-Rays are Emitted

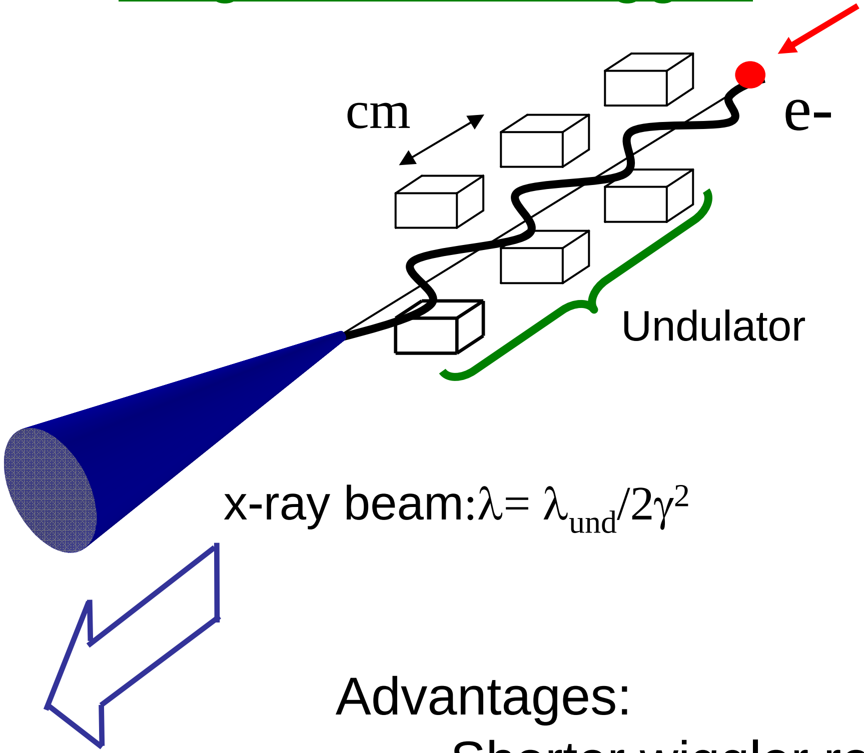


10^{10} photons/shot in a collimated beam

A. Rousse et al., Phys. Rev. Lett. 93, 135005 (2004).

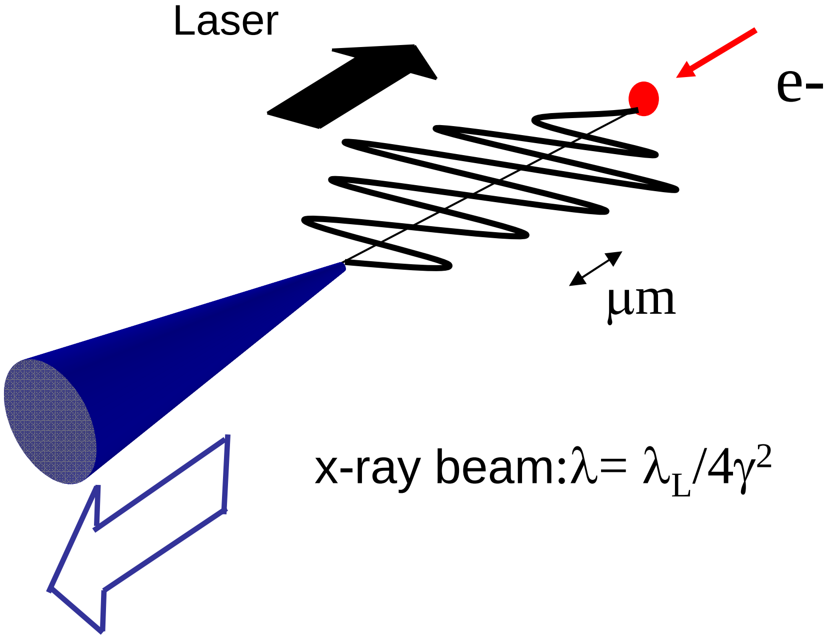
Replacing Magnets with Light Provides Micron-Wavelength Wiggler

Magnetostatic Wiggler



x-ray beam: $\lambda = \lambda_{und}/2\gamma^2$

Electromagnetic Wiggler

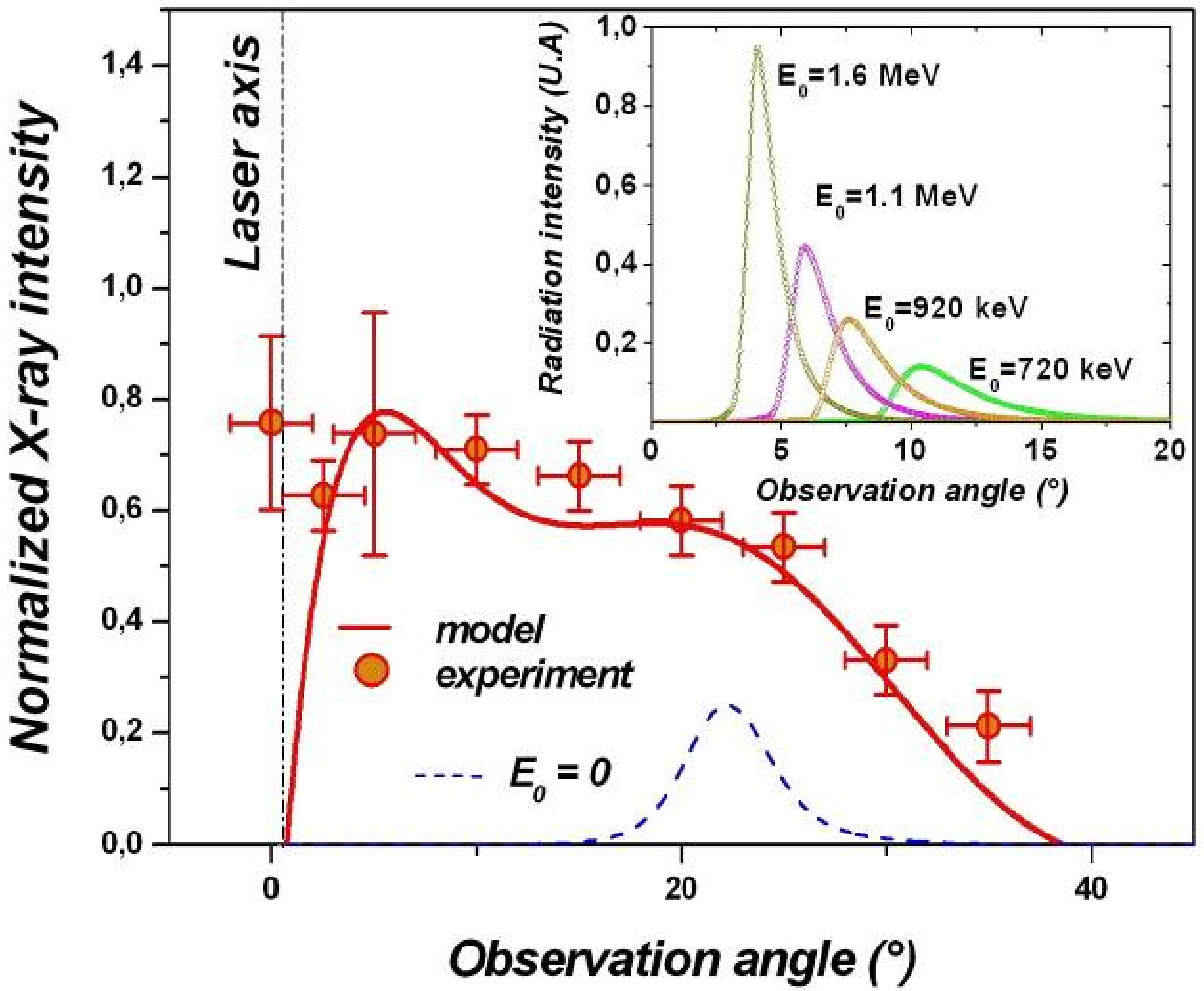


x-ray beam: $\lambda = \lambda_L/4\gamma^2$

Advantages:

- Shorter wiggler region (mm vs. 10 m)
- Shorter wavelength wiggler (micron vs. cm)
- Less energetic electrons (MeV vs. GeV)
- Shorter acceleration length (mm vs. 100 m)

Angular distribution : implies emission by a laser-accelerated electron beam oscillating in a laser wiggler



FOCUS

K. Ta Phouc, et al. *Physical Review Letters,* **91**, 195001-1 (2003).

DIOCLES

EXTREME LIGHT LABORATORY

UNIVERSITY OF Nebraska Lincoln