UCI University of California, Irvine

X-ray Laser Wakefield Acceleration in Nanotubes

Sahel Hakimi[1], Xioamei Zhang[2], Deano Farinella[1], Calvin Lau[1], Youngmin Shin[3], Jonathan Wheeler[4], Peter Taborek[1], Gerard Mourou[4], Franklin Dollar[1], Toshiki Tajima[1]

[1] *University of California, Irvine, CA, United States*
[2] *Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai, China*
[3] *Northern Illinois University and Fermi National Accelerator Laboratory, US*
[4] *Ecole Polytechnique, France*

Fermilab

UCIRVINE

Acceleration in Crystals and Nanostructures 2019

Outline

- Motivation and Background
- Simulation Results
  - X-Ray laser driven wakefield
  - Scalings
  - Addition of Lattice force
- Discussion and conclusions

Advantage of Plasma Accelerators

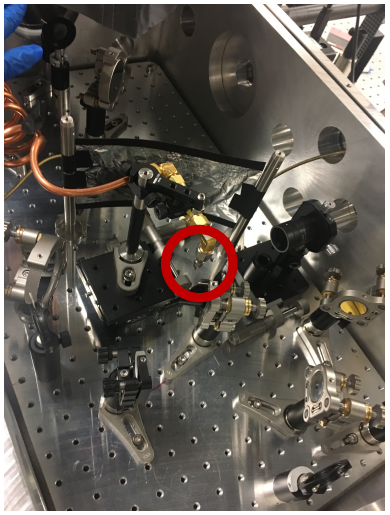
- Material breakdown (~100MV/m)
- Increasing size and cost

  or

- Increasing acceleration gradients

$$E_{TD} = \frac{m_e c \omega_p}{e} = 96\sqrt{\mathrm{n_e(cm^{-3})}}\,\frac{\mathrm{V}}{\mathrm{m}} \sim 100\mathrm{GV/m}$$

SLAC's **2 miles** long LINAC



UCI's wakefield experiment **~ 10's of microns** long

Laser-Driven Plasma Accelerators

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

… lasers of power density 10^{18} W/cm^2…

… plasmas of densities 10^{18} cm^{-3}…

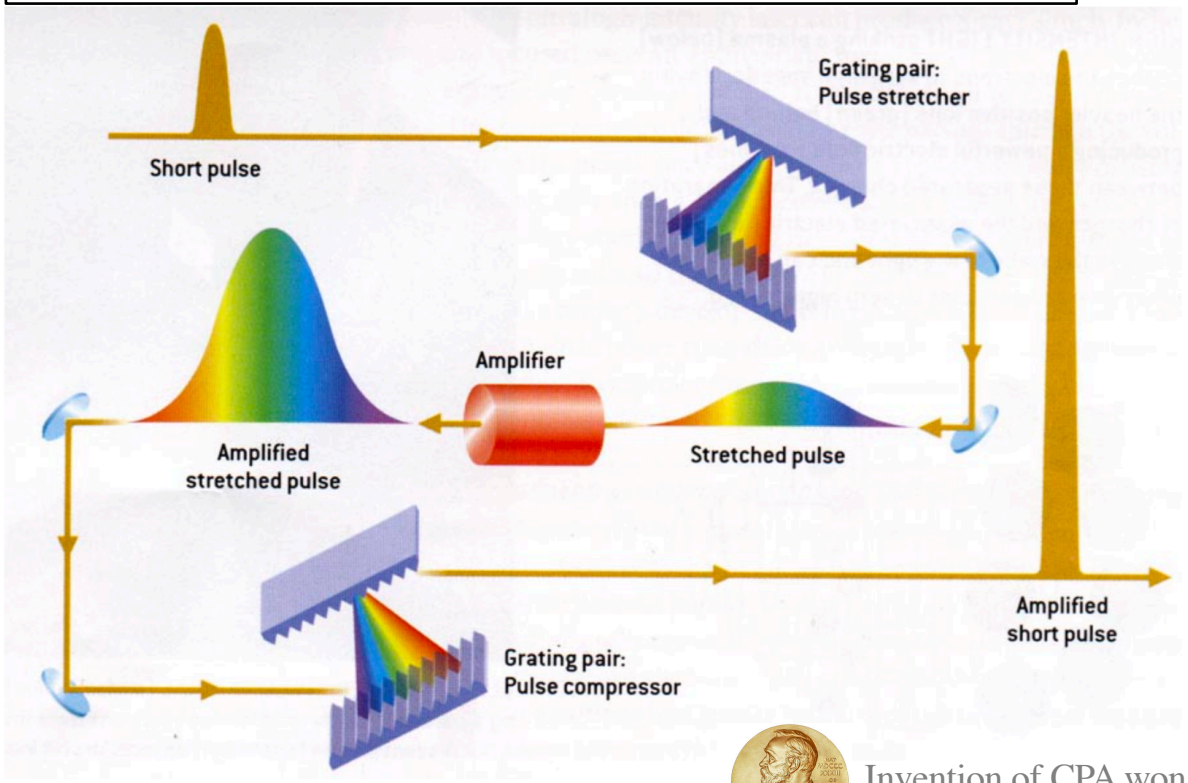
Chirped Pulse Amplification

Volume 56, number 3 OPTICS COMMUNICATIONS 1 December 1985

COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES ☆

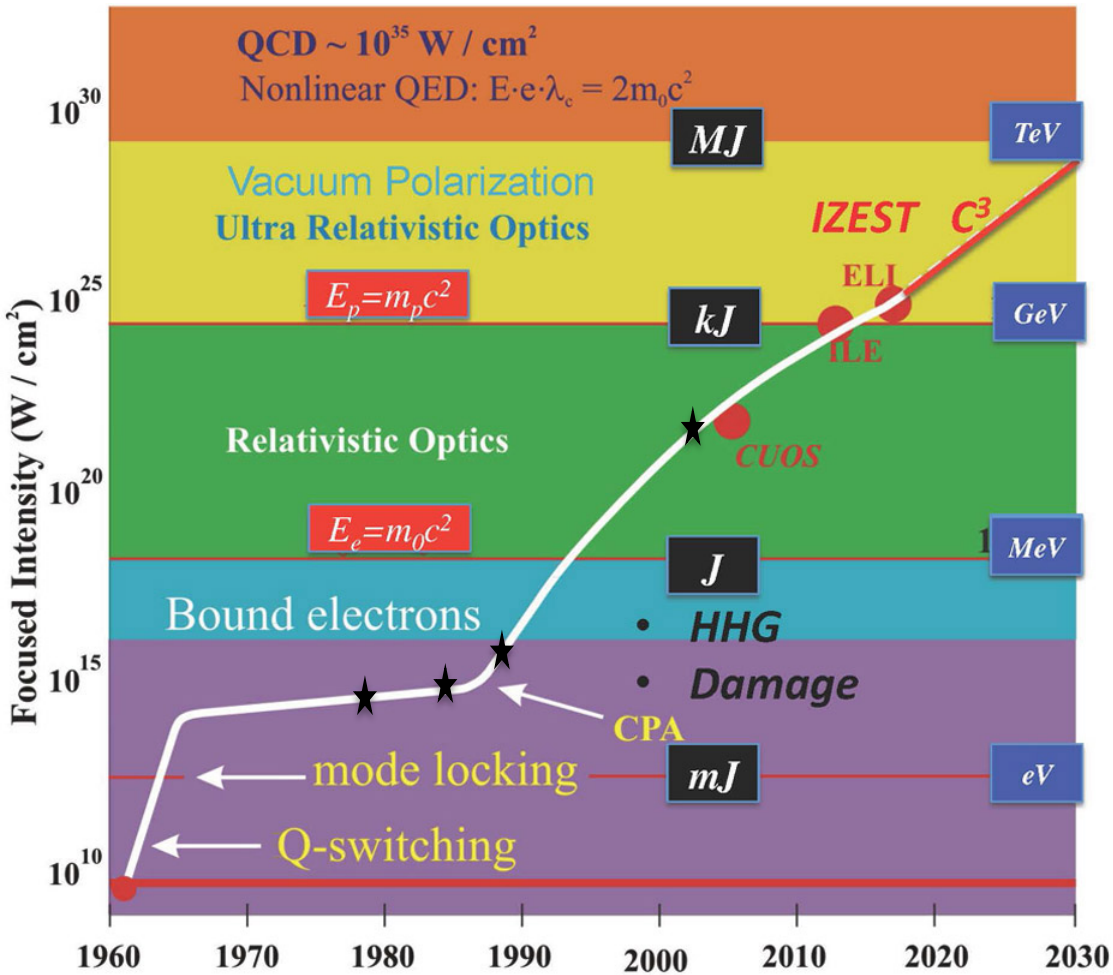
Donna STRICKLAND and Gerard MOUROU

Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, USA



Invention of CPA won the Nobel prize in 2018

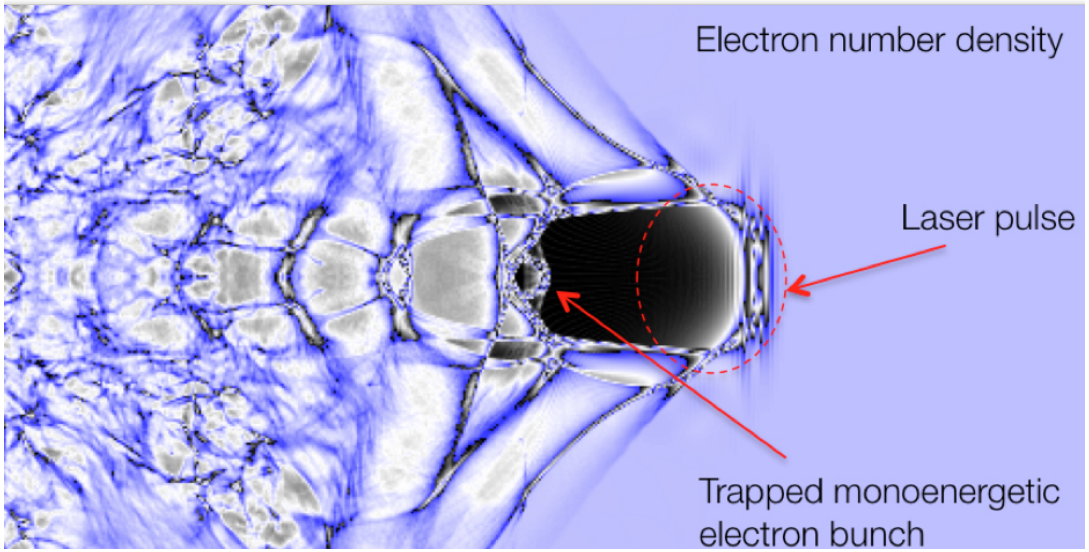
Chirped Pulse Amplification



Tajima T, Mourou G. PRAB. 2002

Laser Wakefield Acceleration (LWFA)

Bubble regime

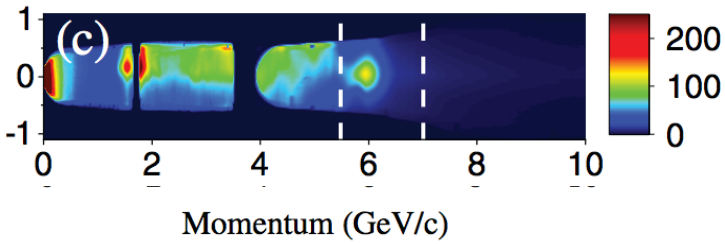


Nature 2004

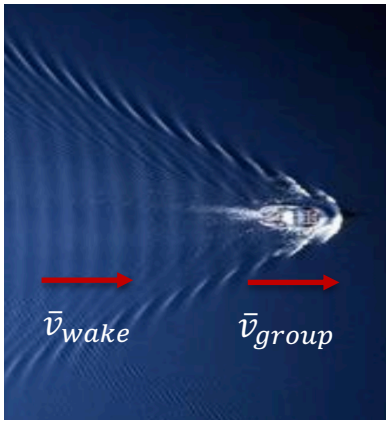
Current Challenges

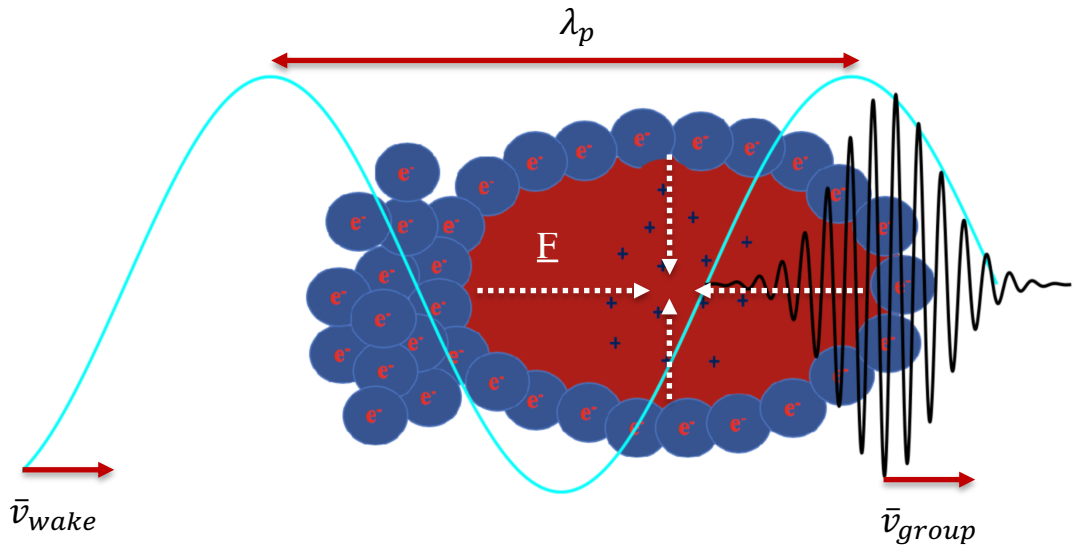
- Laser defocusing
  - Guiding
- Dephasing
  - Density tailoring
- Beam loading
  - Electron beam shaping

[7.8GeV, Phys. Rev. Lett. 122, 084801 (2019)]



Physics of LWFA





- Ponderomotive Force
- Density perturbation
- Wake creation
- Particle trapping

$$a_0 = \frac{eE}{m_e \omega_l c}$$

$$\omega_p^2 = \frac{4\pi n_e e^2}{m_e}$$

$$\lambda_p = \frac{2\pi c}{\omega_p}$$

Physics of LWFA

- Wake velocity

$$\bar{v}_{group} = c\sqrt{1-(n_e/n_c)}$$

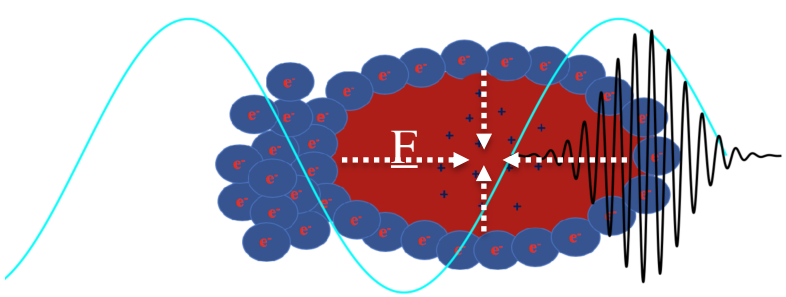
n_e is the electron density in plasma ($10^{18-19} cm^{-3}$)
n_c is the critical density of the laser ($10^{21} cm^{-3}$)

- Energy gain

$$\epsilon_e = 2a_0^2 m_e c^2 (\frac{n_c}{n_e})$$

- Acc. length

$L_d \propto \left(\frac{n_c}{n_e^{3/2}}\right)$;	$L_{pd} \propto \left(\frac{n_c}{n_e^{3/2}}\right)$;	$Z_r = \frac{\pi w_0^2}{\lambda}$
Dephasing	Depletion	Diffraction



TeV/cm acc. gradient

- Energy gain and acc. length dependence on target density
- Increasing energy gain via critical density

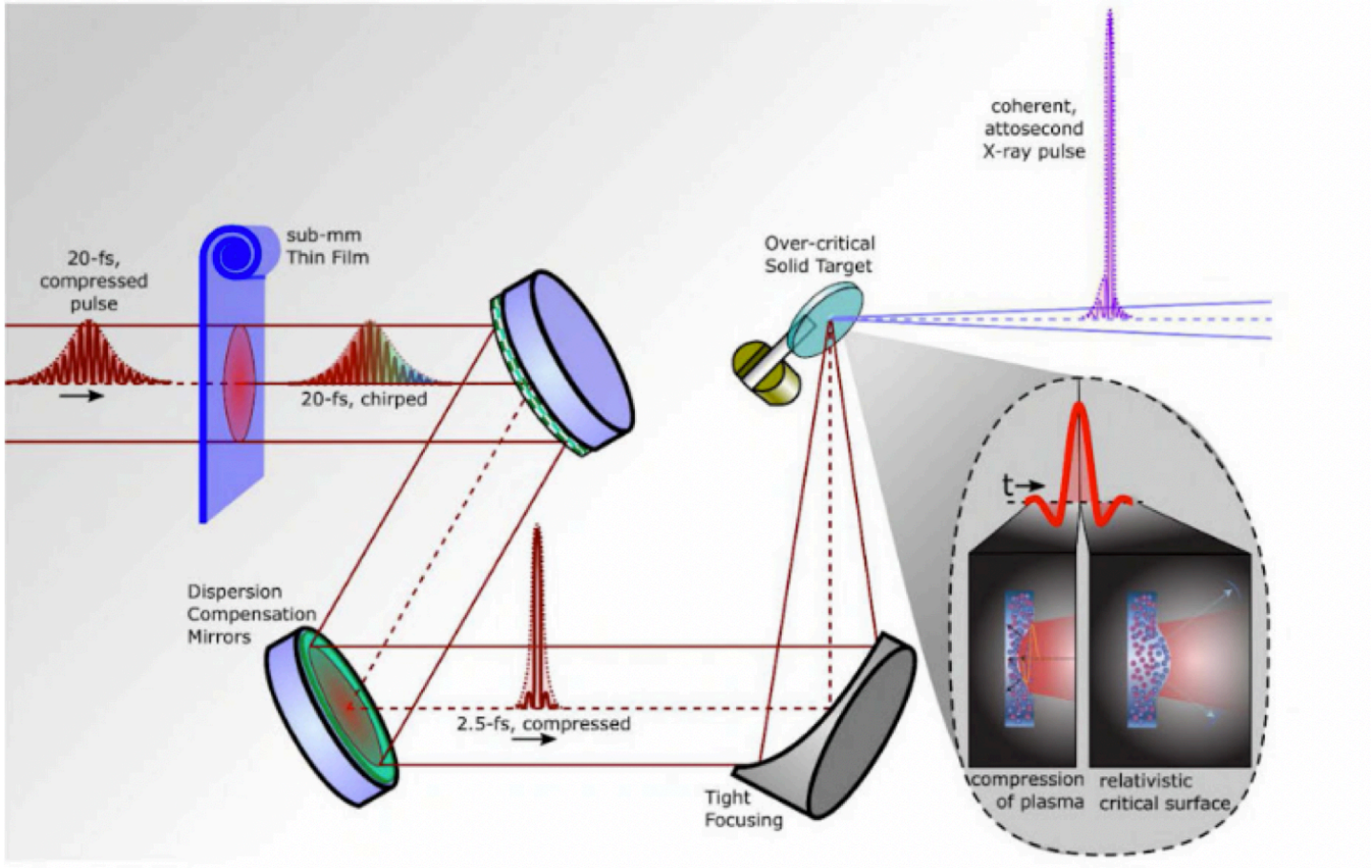
$$\epsilon_e = [1\text{MeV}]\left(\frac{n_c}{n_e}\right)$$

$\times 10^6$ $\times 10^3$

$$L \propto \left(\frac{n_c}{n_e}\frac{1}{\sqrt{n_e}}\right)$$

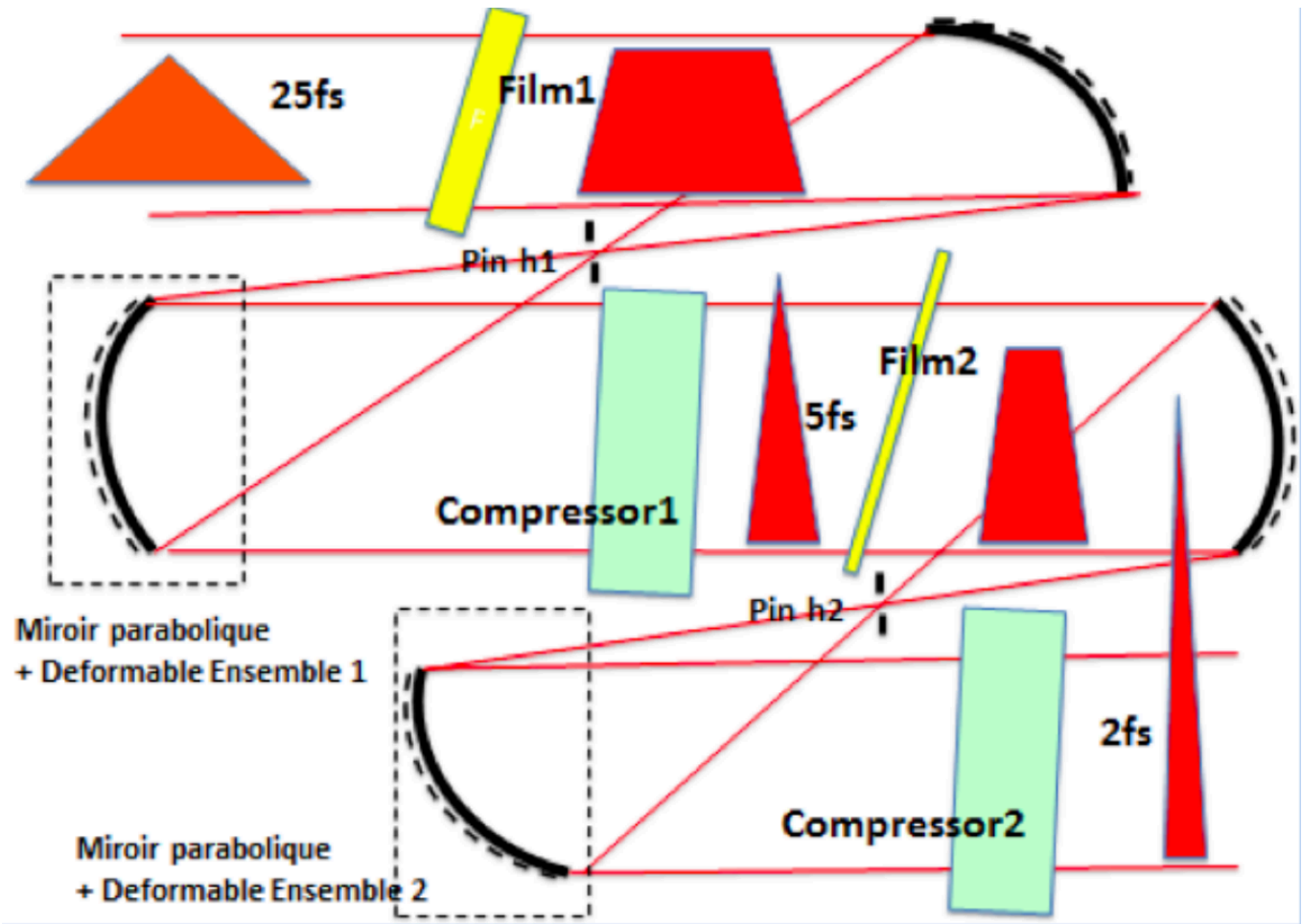
Optical laser (800nm)	X-ray laser (1nm)
$n_c \approx 10^{21}\ \text{cm}^{-3}$	$n_c \approx 10^{27}\ \text{cm}^{-3}$
$n_e \approx 10^{18}\ \text{cm}^{-3}$	$n_e \approx 10^{21}\ \text{cm}^{-3}$
$n_c/n_e = 10^3$	$n_c/n_e = 10^6$

Next Generation X-ray Lasers



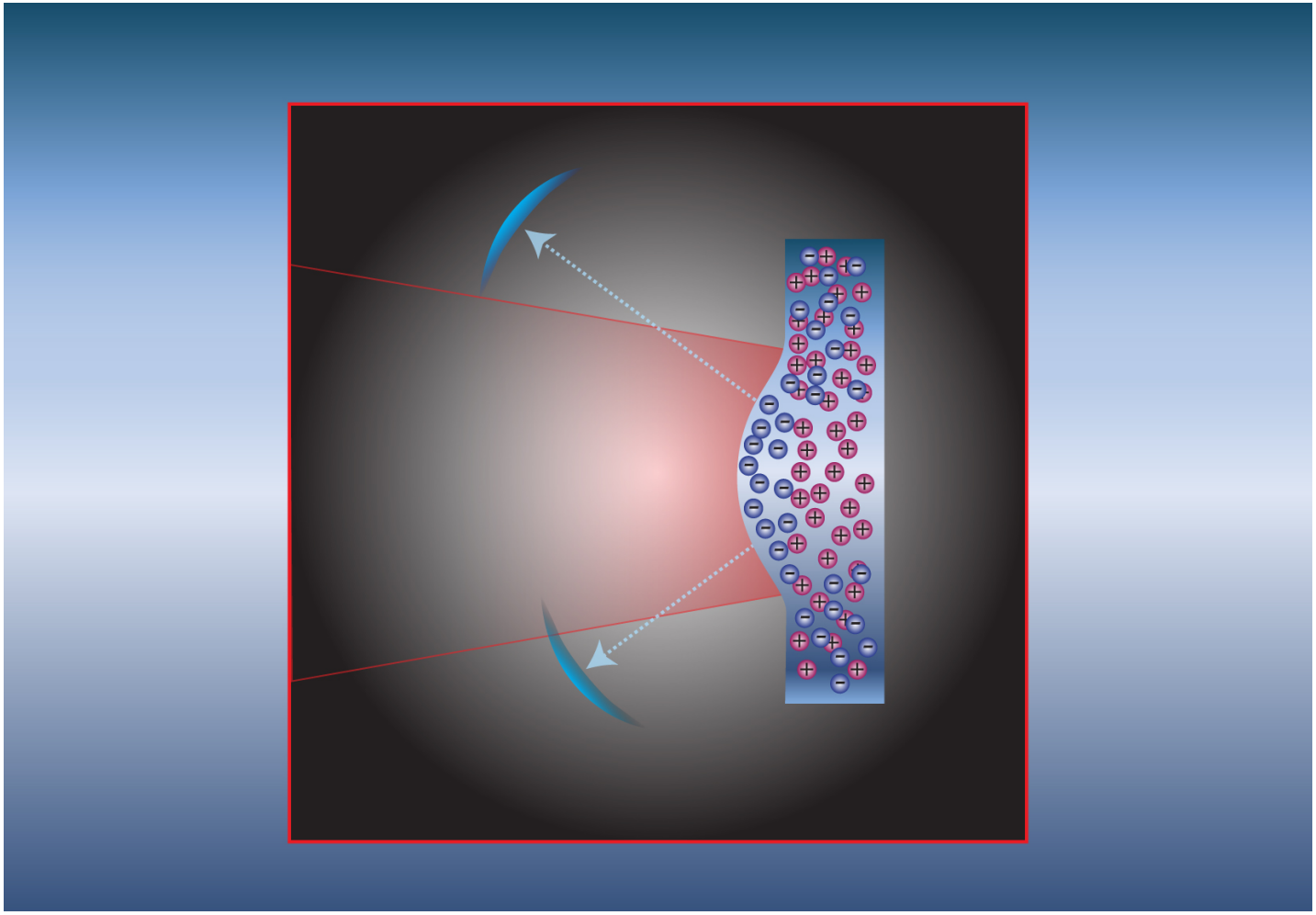
Wheeler J, Mourou G, Tajima T. Technology and Applications of Advanced Accelerator Concepts 2016

Thin Film Compression



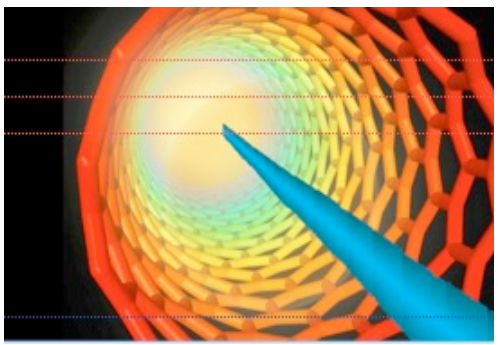
Mourou G, Mironov S, Khazanov E, Sergeev A. The European Physical Journal Special Topics. 2014

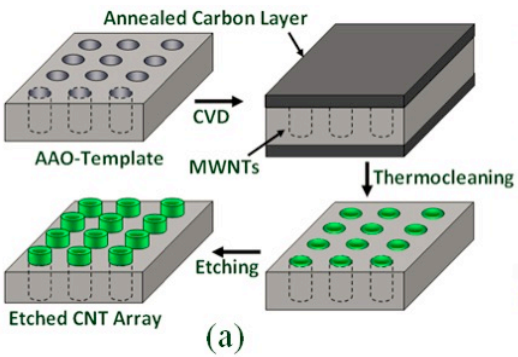
Relativistic Compression

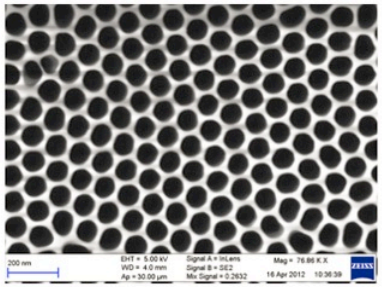


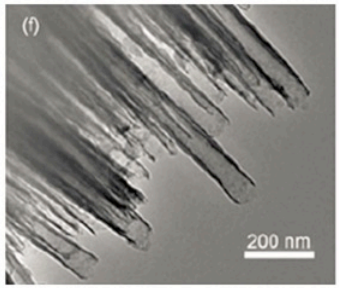
Naumova NM, Nees JA, Sokolov IV, Hou B, Mourou GA. Physical review letters. 2004

Advantages of Nanotubes







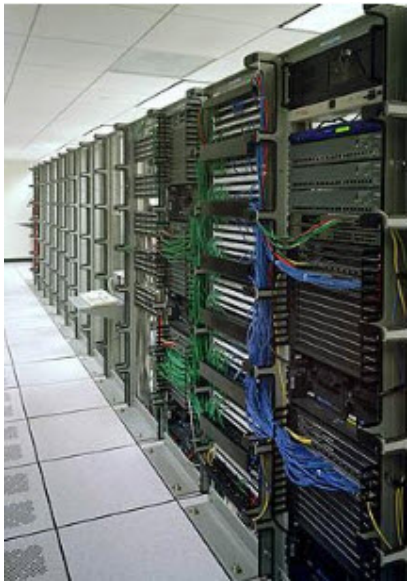


- High density ⟷ Higher acceleration gradient
- Provides a mean to guide laser and the accelerated beam
- Avoid slow-down of electrons due to collisions
- Intact in time of ionization

Lazarowich RJ, Taborek P, Yoo BY, Myung NV. Journal of applied physics. 2007

Epoch Simulations

- QED 2D Particle-in-cell simulations
  - Developed by Chris Brady, Keith Bennett, Christopher Ridgers, Roland Duclous
  - Available for free and is open source
- Examined 1 and 1000 nm wavelengths
- Simulations performed on the UCI HPC cluster

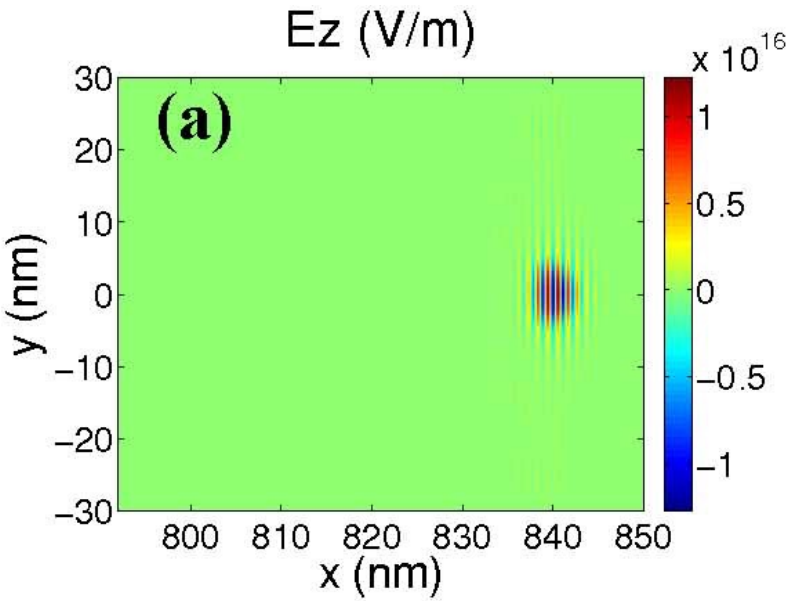


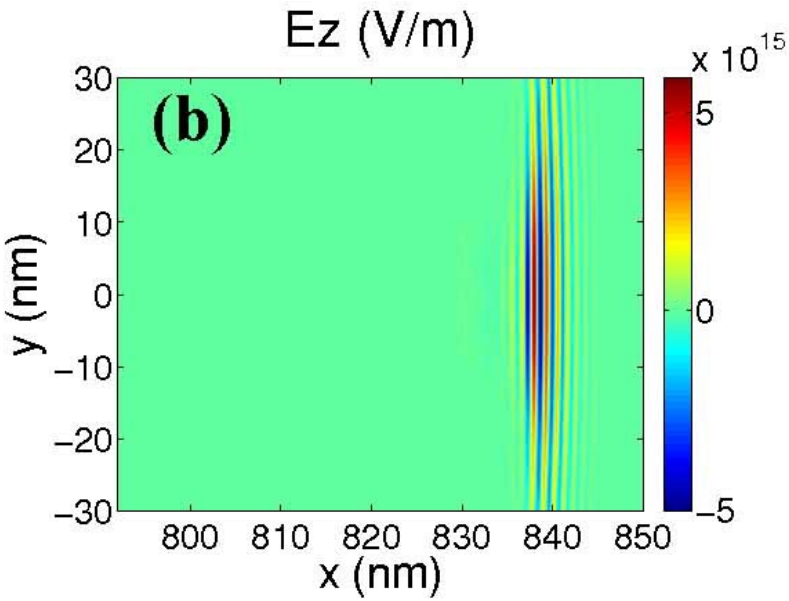
Simulation Parameters

- Moving box simulation with 3000 x 500 cells
  - 60 x 100 nm (μm) box size
- 10 particles per cell
- Normalized vector potential $a_0 = 4$
  - Corresponding to intensity of 2.2×10^{25} Wcm^{-2} (5×10^{18} Wcm^{-2})
- Focal size of $5\lambda_L$
- Plasma wall density of 5×10^{24} cm^{-3} (5×10^{18} cm^{-3})

Zhang X, Tajima T, Farinella D, Shin Y, Mourou G, Wheeler J, Taborek P, Chen P, Dollar F, Shen B. PRAB. 2016

Guided vs. Unguided

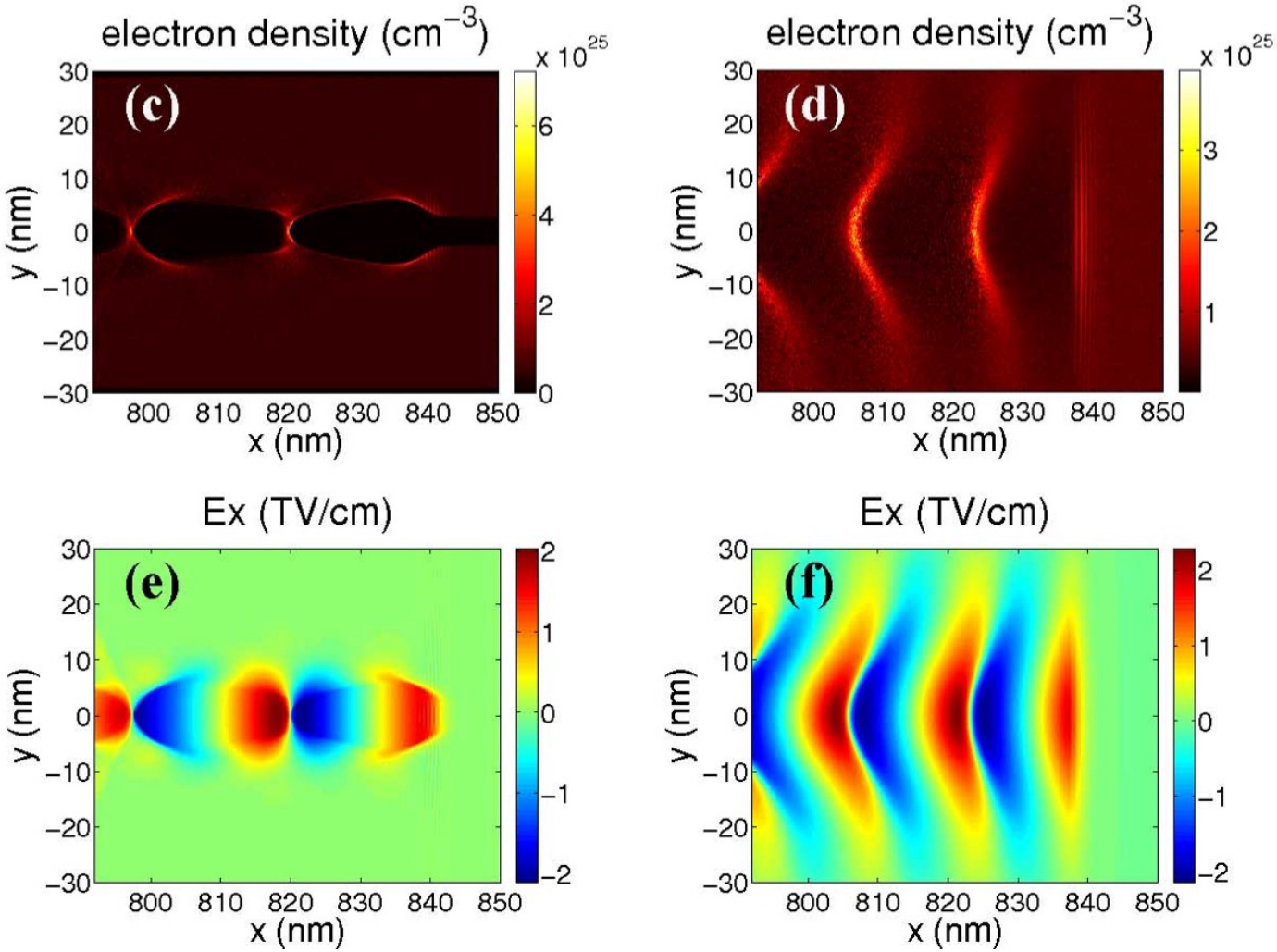




Nanotube radius of 5 nm

Zhang X, Tajima T, Farinella D, Shin Y, Mourou G, Wheeler J, Taborek P, Chen P, Dollar F, Shen B. PRAB. 2016

Guided vs. Unguided

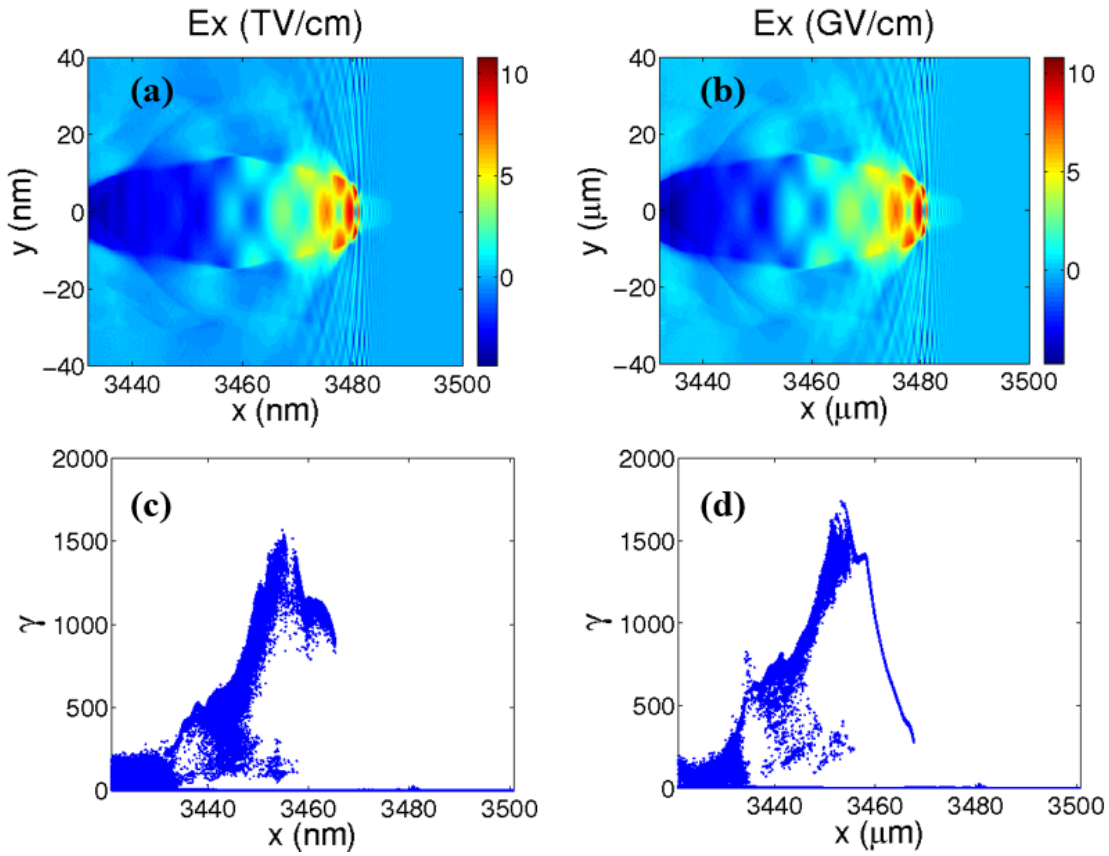


Zhang X, Tajima T, Farinella D, Shin Y, Mourou G, Wheeler J, Taborek P, Chen P, Dollar F, Shen B. PRAB. 2016

LWFA comparison

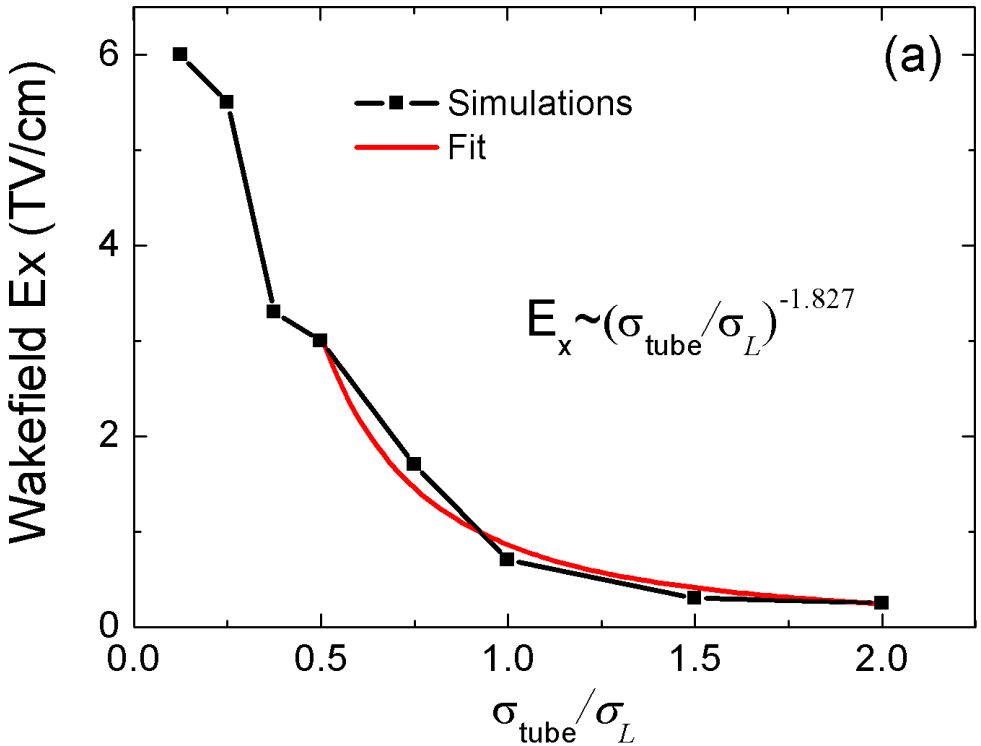
1 nm and 1000 nm laser confined in tubes of diameter $5\lambda_L$ and intensity $a_0 = 10$

Maintaining laser wavelength to plasma wavelength ratio preserves wakefield structure



Zhang X, Tajima T, Farinella D, Shin Y, Mourou G, Wheeler J, Taborek P, Chen P, Dollar F, Shen B. PRAB. 2016

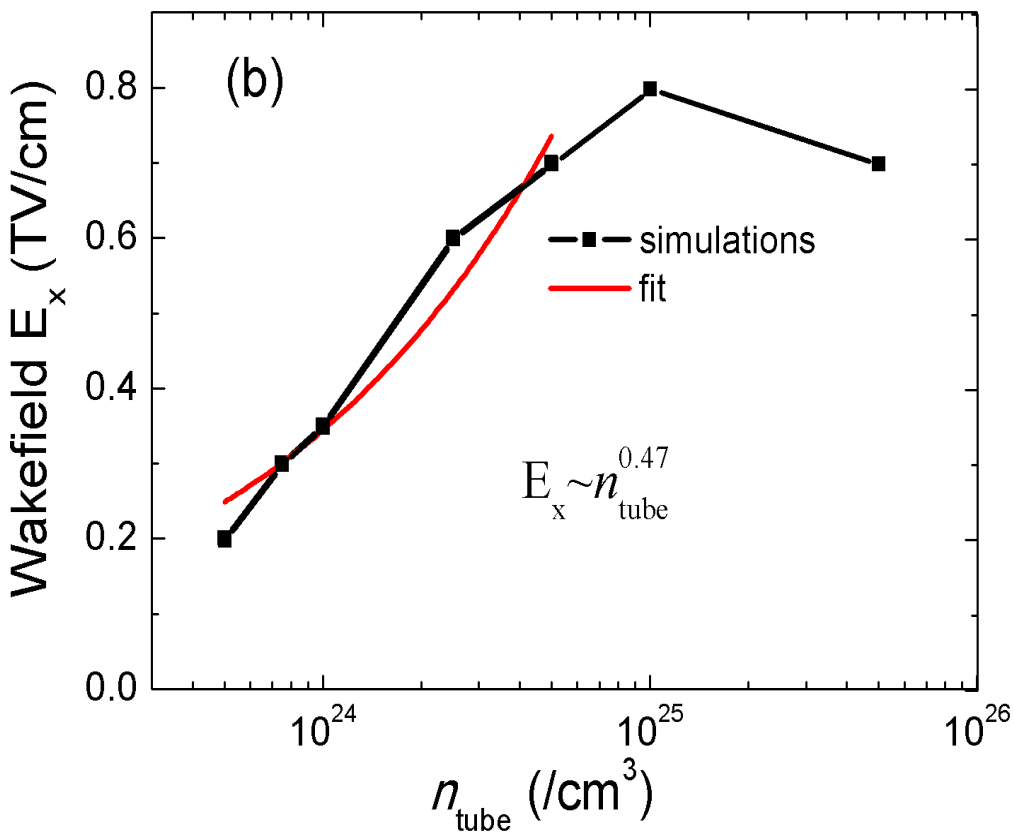
Scalings



Increasing radius ratio decreases effective density

Zhang X, Tajima T, Farinella D, Shin Y, Mourou G, Wheeler J, Taborek P, Chen P, Dollar F, Shen B. PRAB. 2016

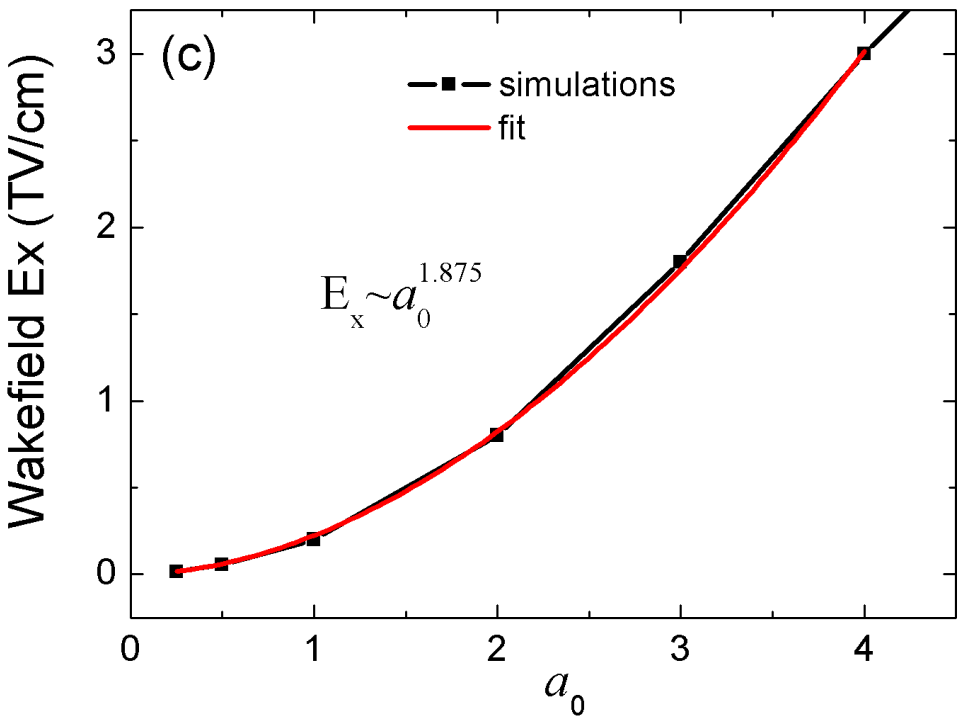
Scalings



The wakefield scales with the tube wall density as $E_x \propto n_{tube}^{0.47}$ in the low density region, which in principle agrees with the theory expected as $E_x \propto \sqrt{n}$ in the uniform density case

Zhang X, Tajima T, Farinella D, Shin Y, Mourou G, Wheeler J, Taborek P, Chen P, Dollar F, Shen B. PRAB. 2016

Scalings



As intensity increases, effective density increases due to larger plasma wavelength

Similar scalings found for different radius ratios

Zhang X, Tajima T, Farinella D, Shin Y, Mourou G, Wheeler J, Taborek P, Chen P, Dollar F, Shen B. PRAB. 2016

Dispersion Relation

- Dispersion relation is modified by the transverse optical frequency

$$\epsilon(k,\omega) = 1 - \frac{\omega_{pi}^2}{\omega^2 - \omega_{TO}^2} - \frac{\omega_{pe}^2}{\omega^2 - k_x^2 v_e^2}; \qquad \omega_{TO}^2 = \frac{K_i}{m}$$

Transverse Optical Frequency

Tajima, T. and Ushioda Phys. Rev. B 1978

Lattice Force simulation and Parameters

- EPOCH PIC code
- Introduction of ionic structure
- Addition of the ionic lattice force

$$\frac{d\widetilde{v_n}}{dt}\hat{x} = \frac{q}{m}\left(\tilde{E} + \widetilde{v_n}\times\tilde{B}\right)\hat{x} - \frac{K_i}{m}(x_n - x_{n0})\hat{x}$$

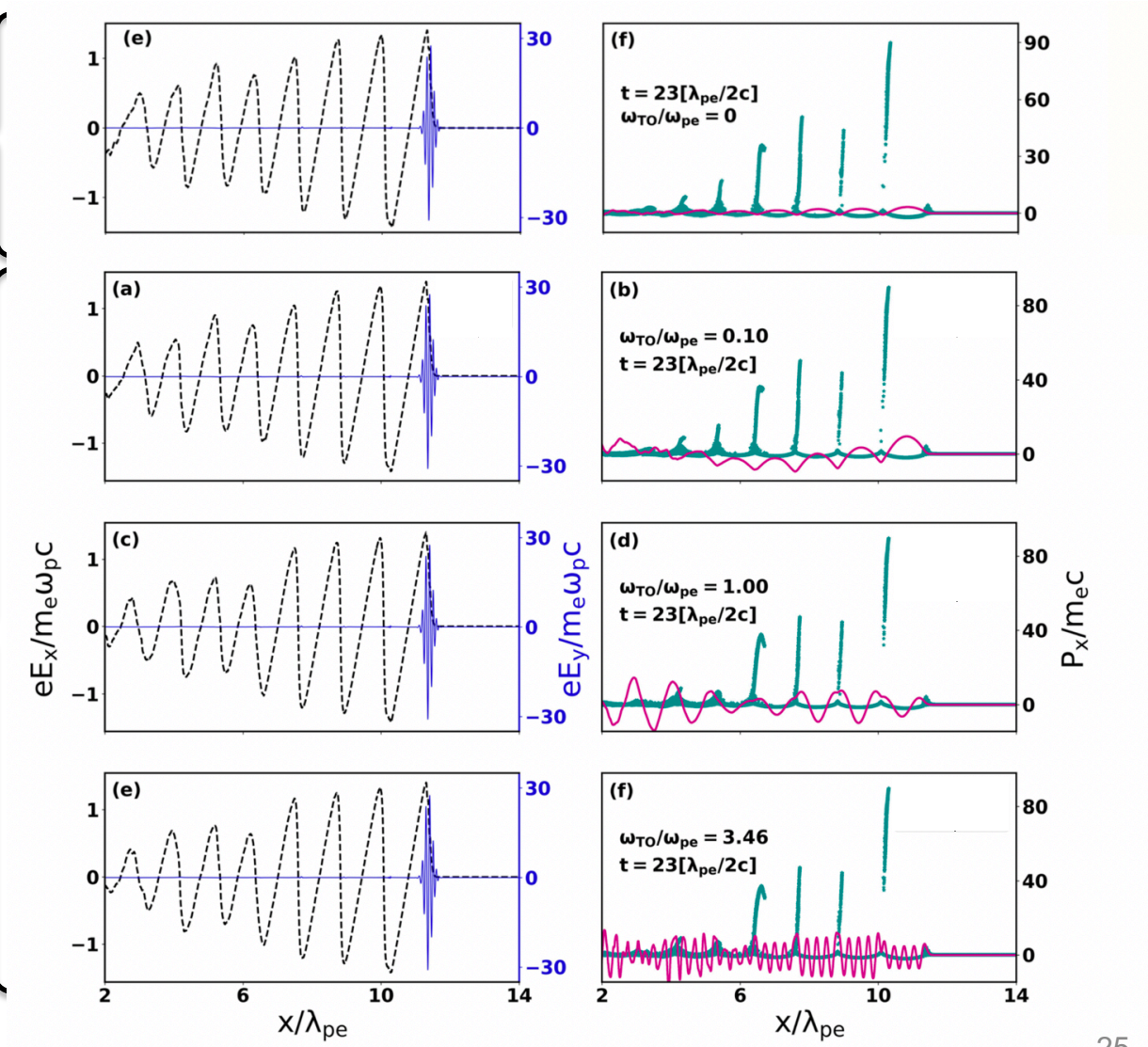
- Parameters
  - $\lambda_l = 10\text{nm}; 125\text{eV}$
  - $n_c = 10^{25}\text{cm}^{-3}; n_e = 10^{23}\text{cm}^{-3}$

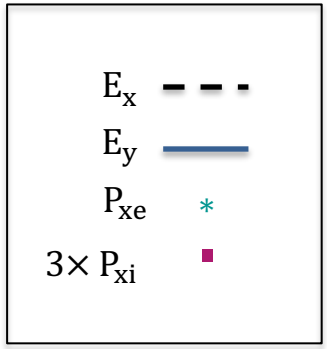
Hakimi S, Nguyen T, Farinella D, Lau CK, Wang HY, Taborek P, Dollar F, Tajima T. Physics of Plasmas. 2018

Simulation Results

without
phonon frequency

with
phonon frequency





Hakimi S, Nguyen T, Farinella D, Lau CK, Wang HY, Taborek P, Dollar F, Tajima T. Physics of Plasmas. 2018

Conclusions

- X-ray photons: $\hbar\omega \gg \phi_e$
  - Metallic plasma at solid density
- Time-scales
  - Passage of X-ray Pulse: attosecond
  - Ionization: femtosecond
- Atom stabilization
- Raster

Conclusions

- Recent proposal of TFC (2014) + RC (2004)
  - Allows high intensity ultrafast X-ray laser

- Crystal + Nanotubes
  - Wakefield acceleration
    - $E_L \sim \frac{\text{TeV}}{\text{cm}}$
    - $\epsilon \sim 1\text{eV over } 2\text{cm}$

TeV acc. on a chip

Thank you