A Quick Look at Laser Wakefield Accelerators

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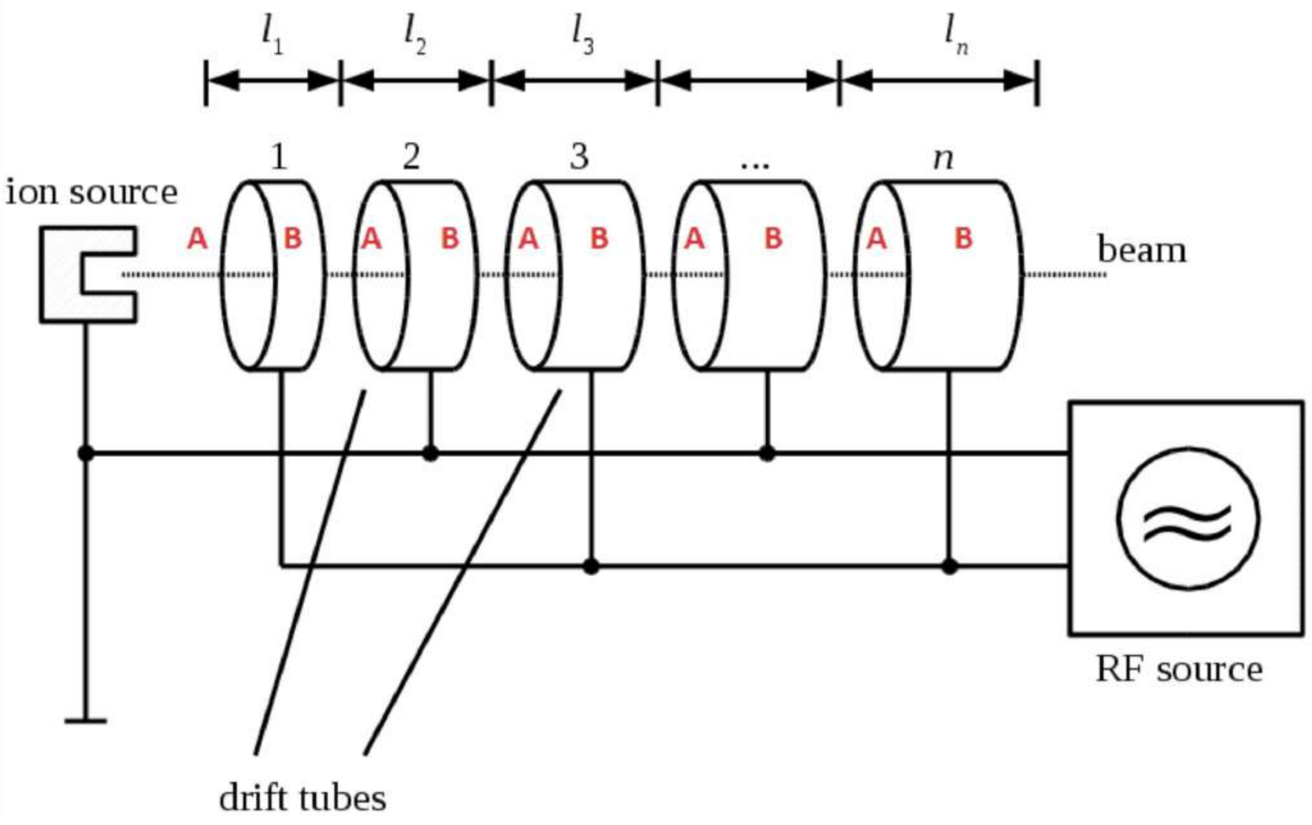
Existing Accelerator Issues

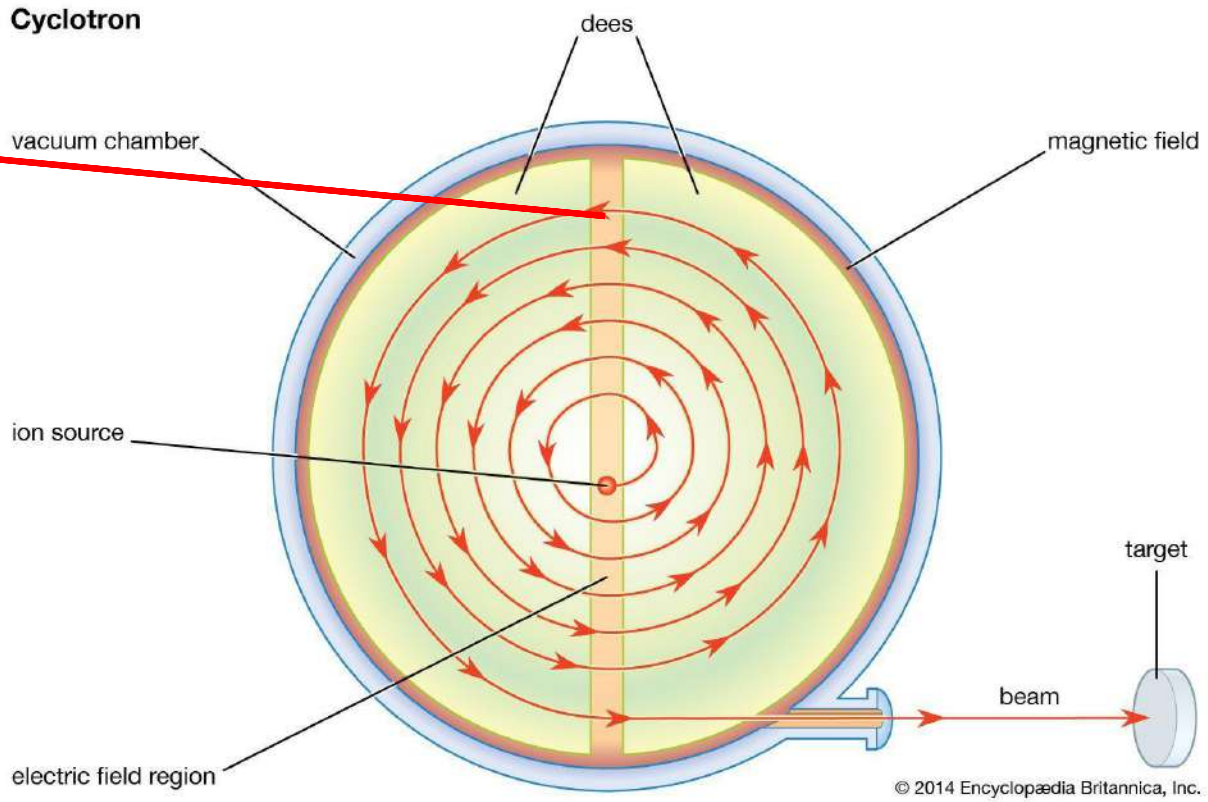
Ionization Limits

- Require high voltages to achieve reasonable acceleration gradient
- Limited to E fields of 100 MV/m
- Needs to be long



Radiation Losses

Pesky cyclotron radiation!



GeV Electron Sources and FELs

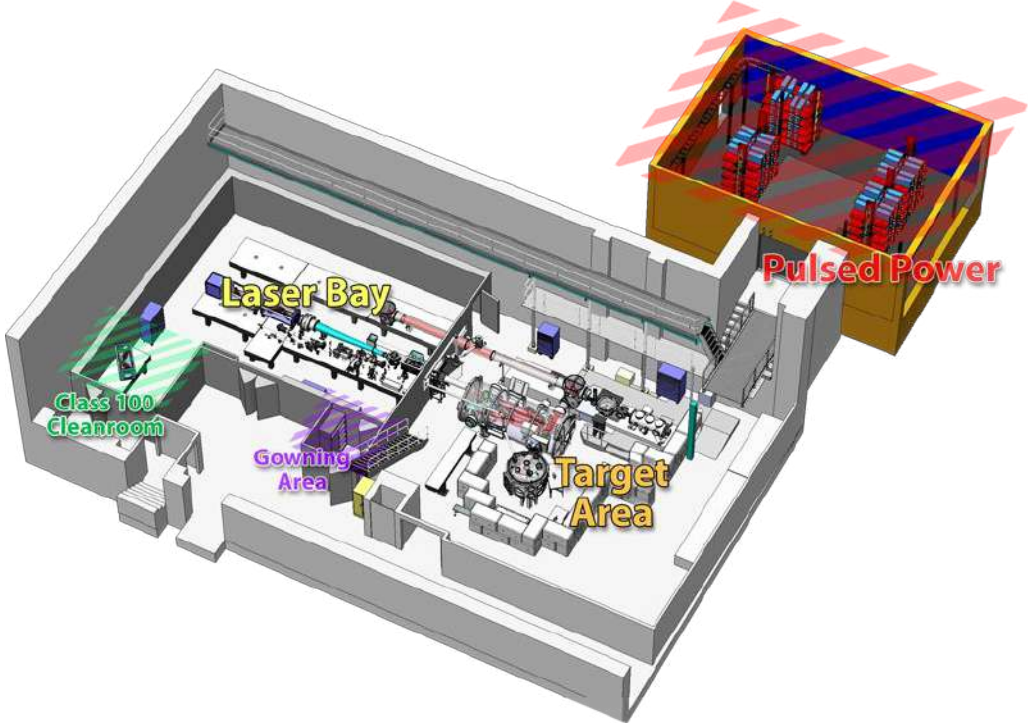
- Long wait time
- Expensive
- Inaccessible
- Large

SLAC
3.2 km long

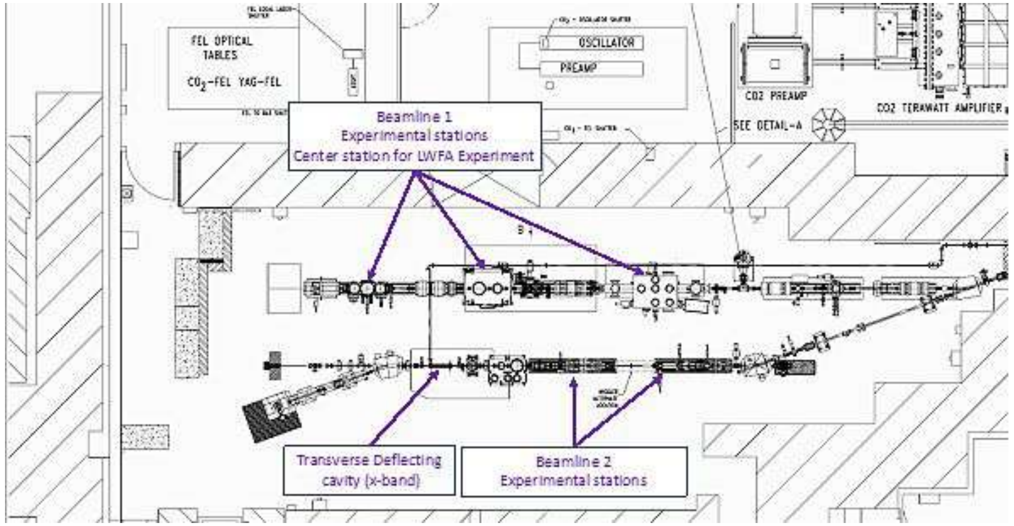
DESY XFEL
3.3 km long

LWFA size requirements

Room size only needs to on the order of magnitude of the size of a laser!



TPW



BNL ATF

UT3

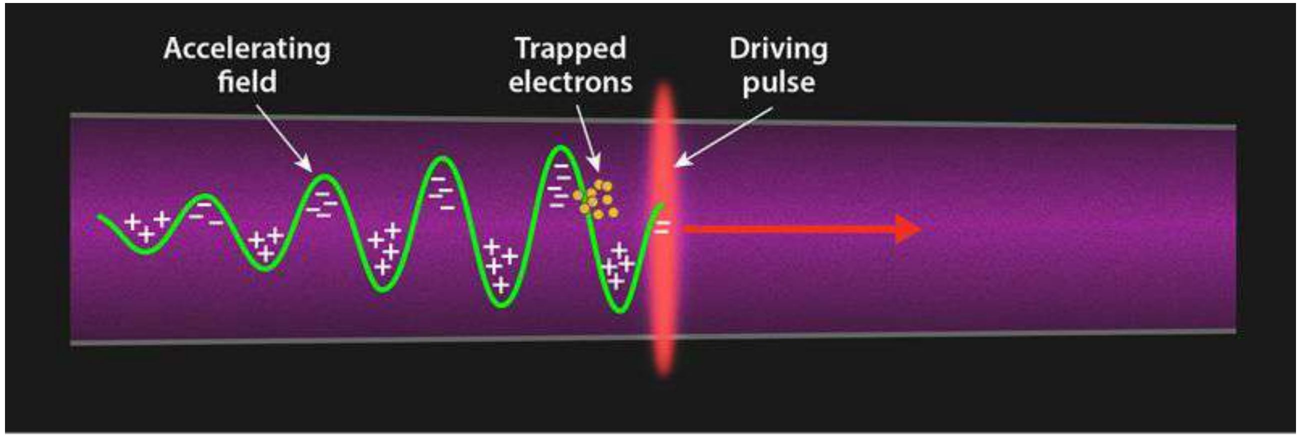
WHAT LWFA IS TACKLING

- High energy accelerator inaccessibility
- Skyrocketing cost of experiments
- Accelerator size
- High brightness-low charge applications

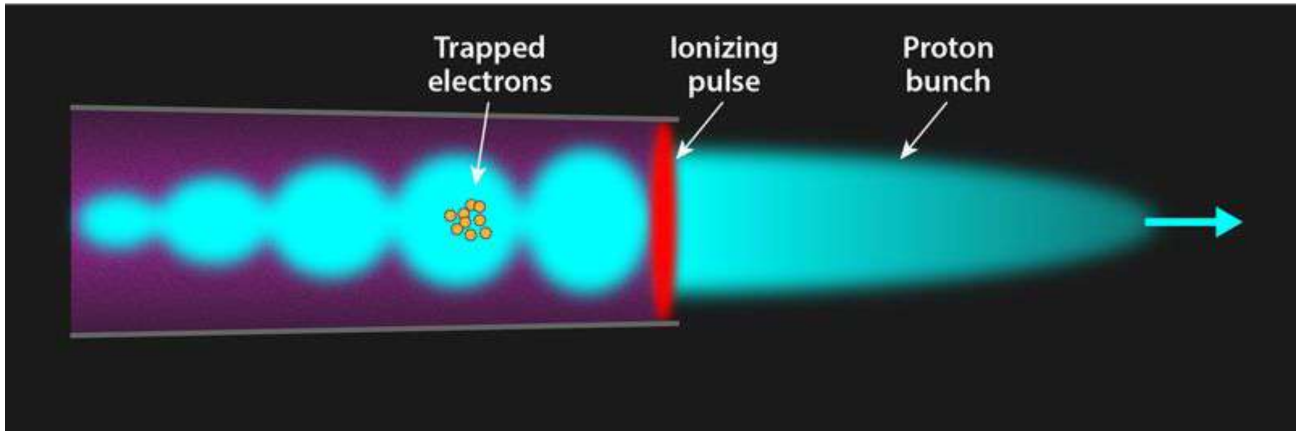
Laser Wakefield Accelerators (LWFA)

Plasma wakefield accelerators

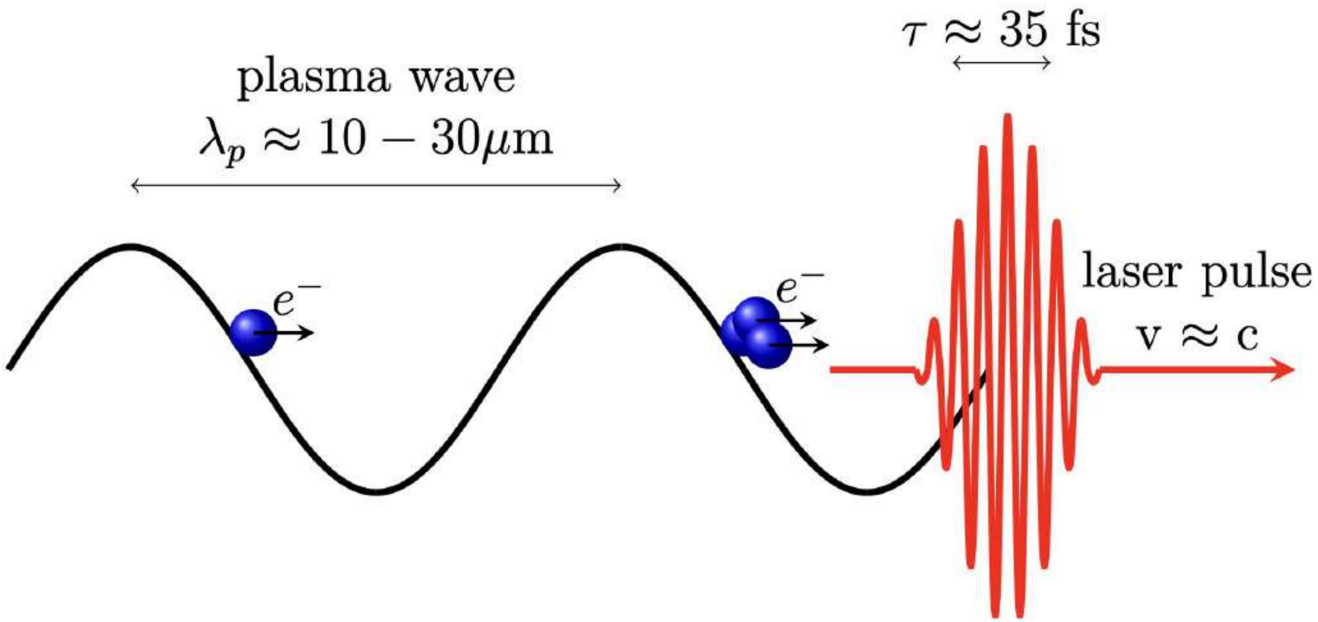
Laser Driver



Proton Driver



What Are LWFAs?



<u>Purposes</u>

- Accelerate Electrons
- Generate x-rays
- Provide affordable MeV-GeV electron sources
- First proposed in 1979

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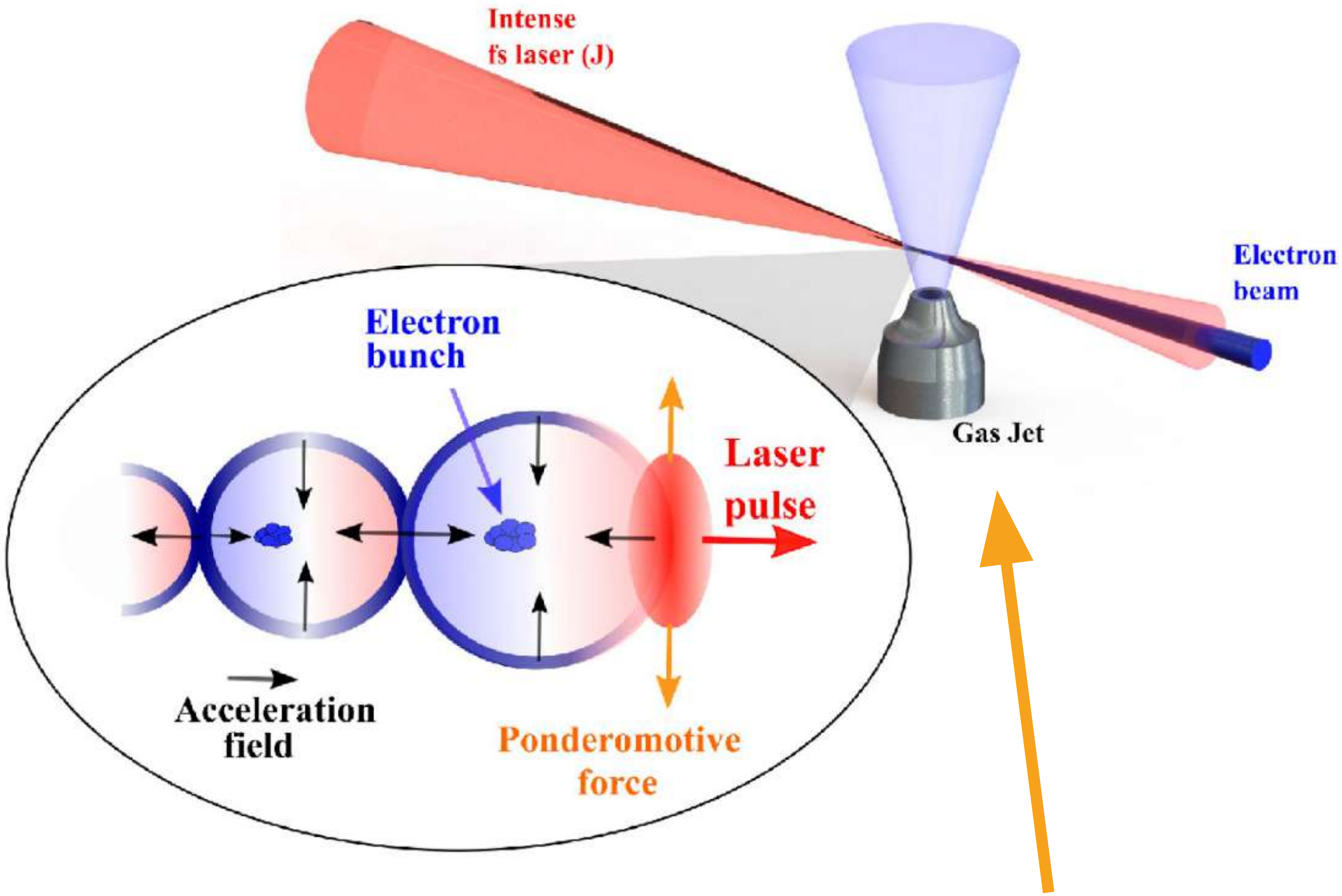
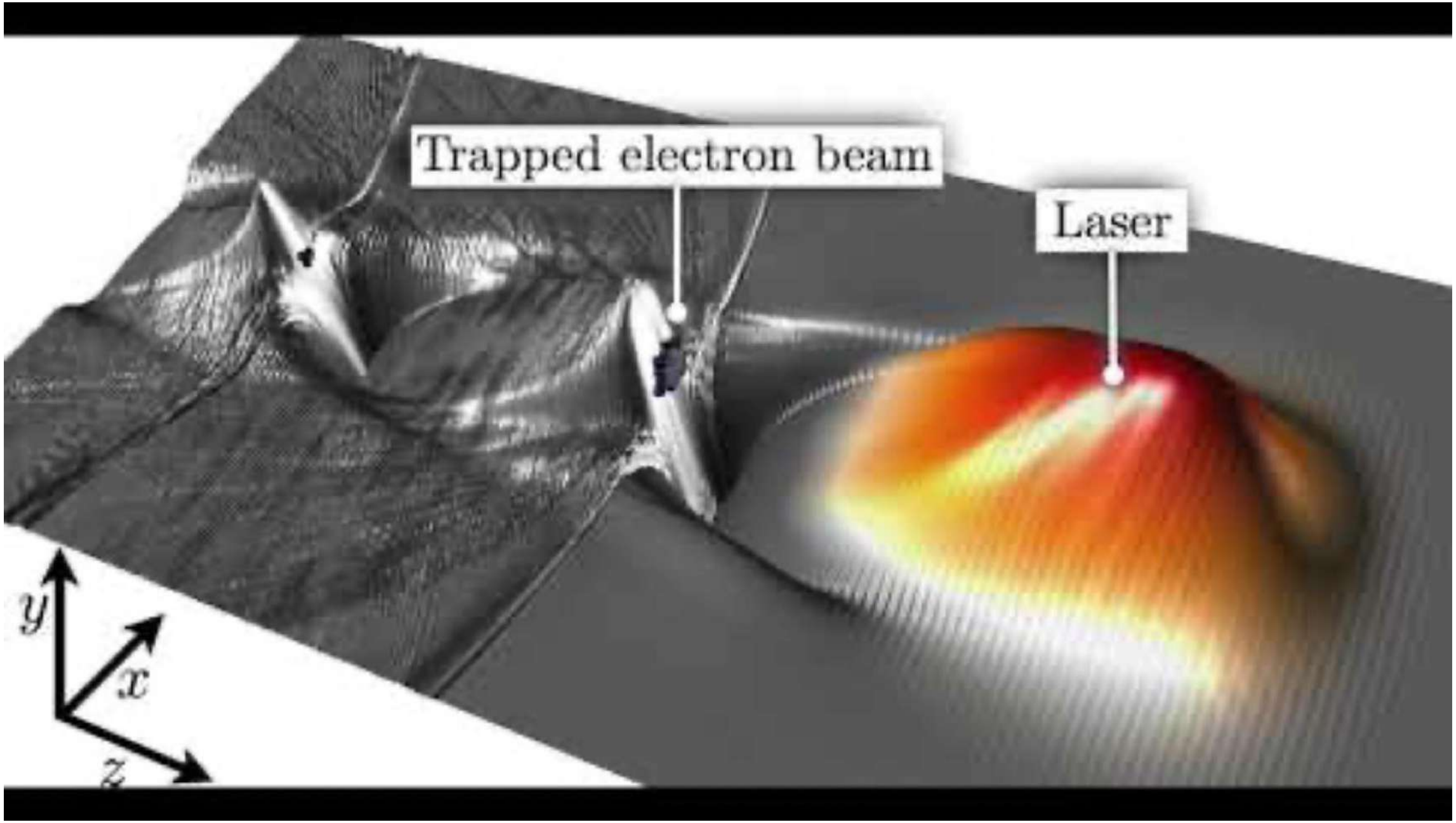


Gas jet size is around ~ 1-2 cm
E > TeV/m

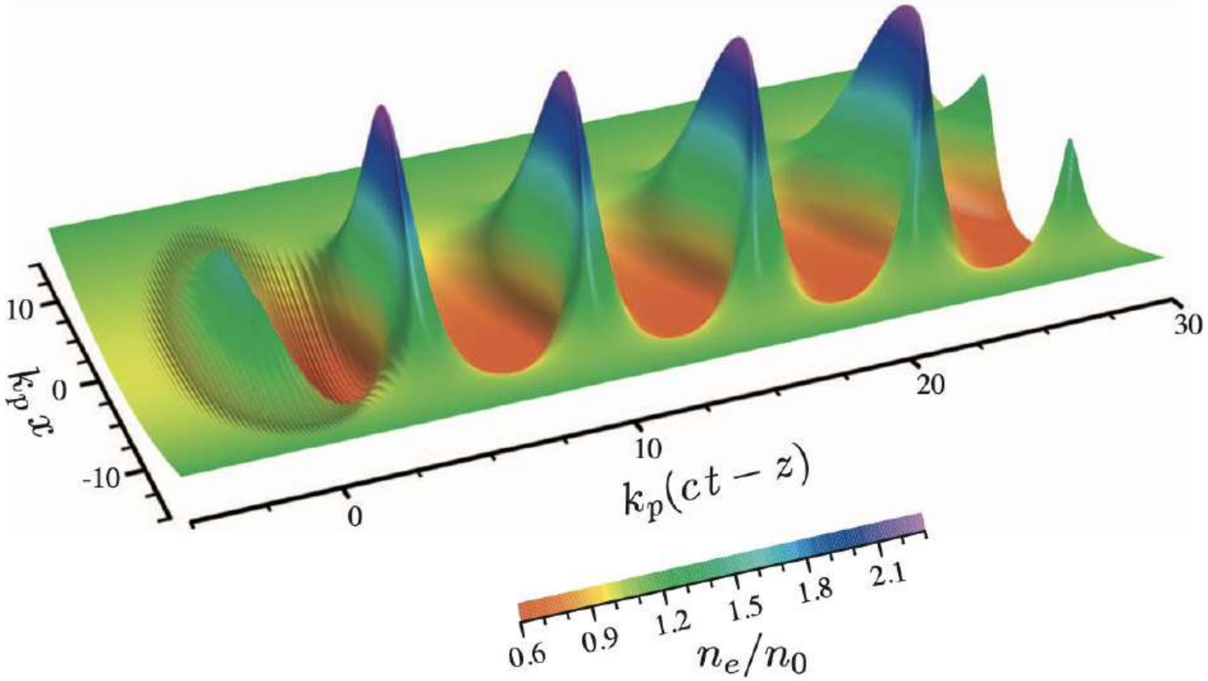
What Does This Look Like?



LWFA Basics

LASER-PLASMA INTERACTION

- The laser's field perturbs the plasma
- Creates plasma wake



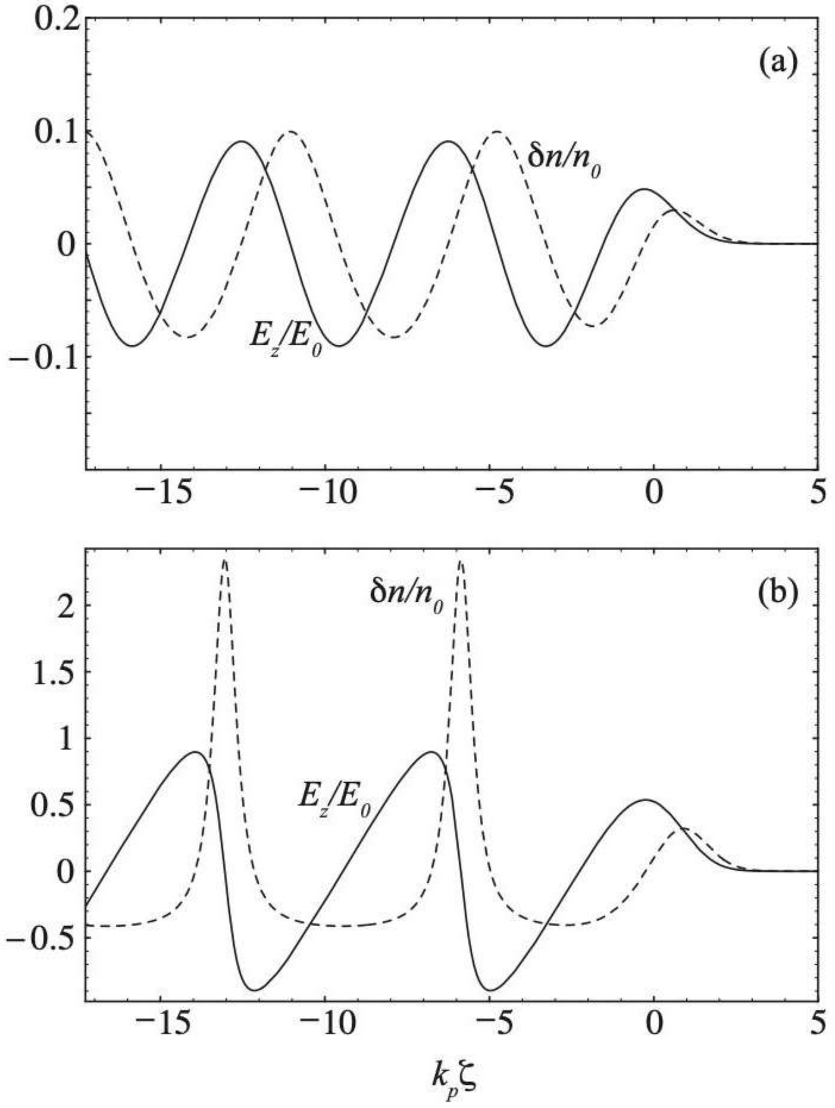
$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$$

Plasma Wake

As laser strength increases, the plasma waves experience wave-breaking

$$E_{max} = m_e \omega_p v_{phase}/e$$

This occurs because the work done by the electric becomes comparable to the relativistic mass

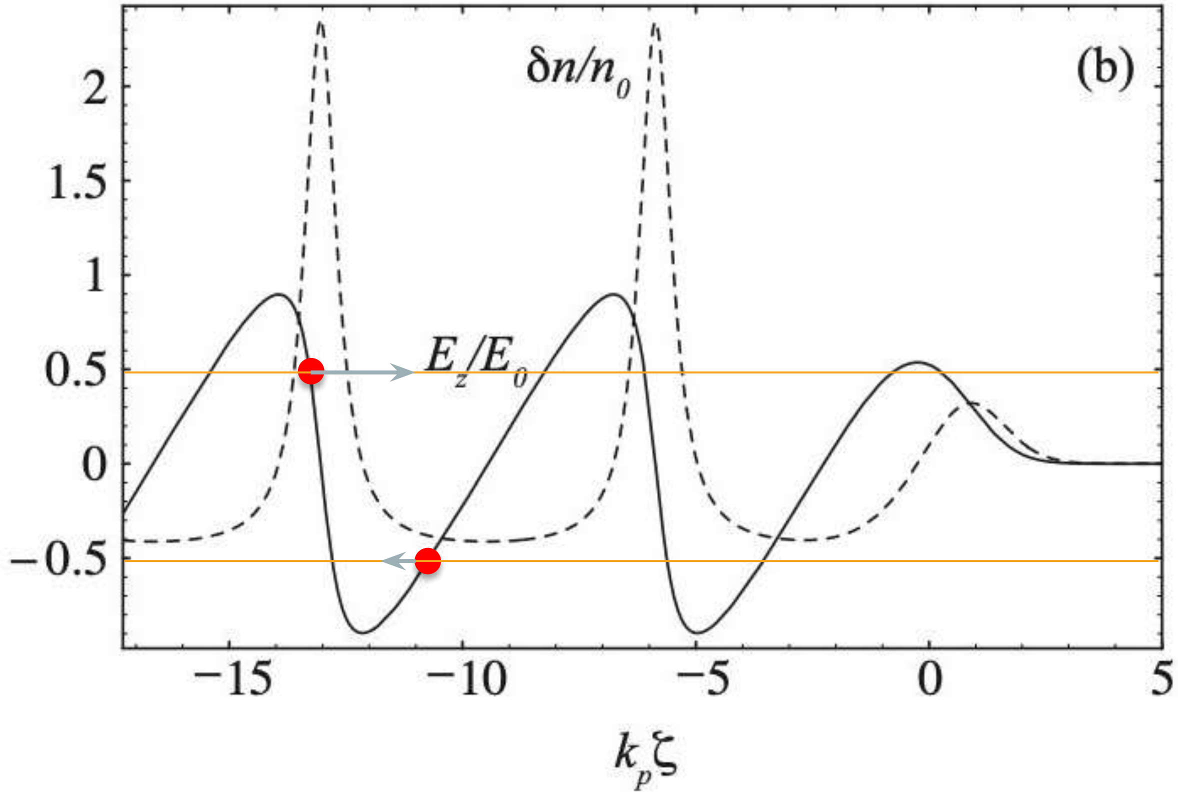


$a)\ a_0 = 0.5$
$b)\ a_0 = 2$

Ponderomotive Force

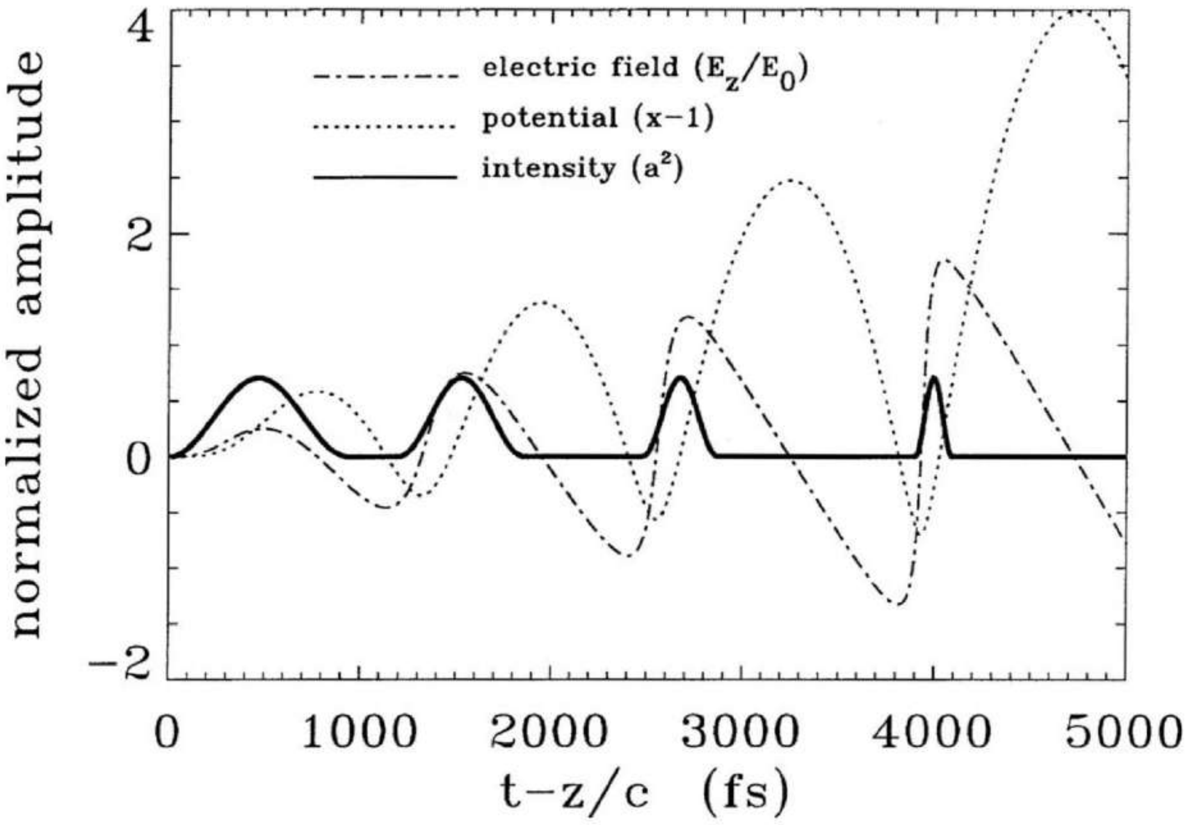
$$F_p = -m_e c^2 \nabla(\frac{a^2}{2})$$

- Requires the steepest gradients possible.
- We need a high-powered laser!
- Requires nonlinear interactions!



Beat Wave and Multi-Pulse LWFA

- Constituted the earliest LWFA experiments
- Needed when only low powered lasers were available
- Multiple pulses fire consecutively to resonantly excite plasma wakes



Self-modulated LWFA

- When laser is strong enough to drive nonlinear wakes in a single pulse
- Not strong enough to completely void space of electrons
- Laser is modulated by nonlinear interactions with the plasma

Forward Raman Instability

- Scattering occurs when laser strongly interacts with the plasma
- This is sign of resonant energy transfer
- Laser-plasma is said to be coupled

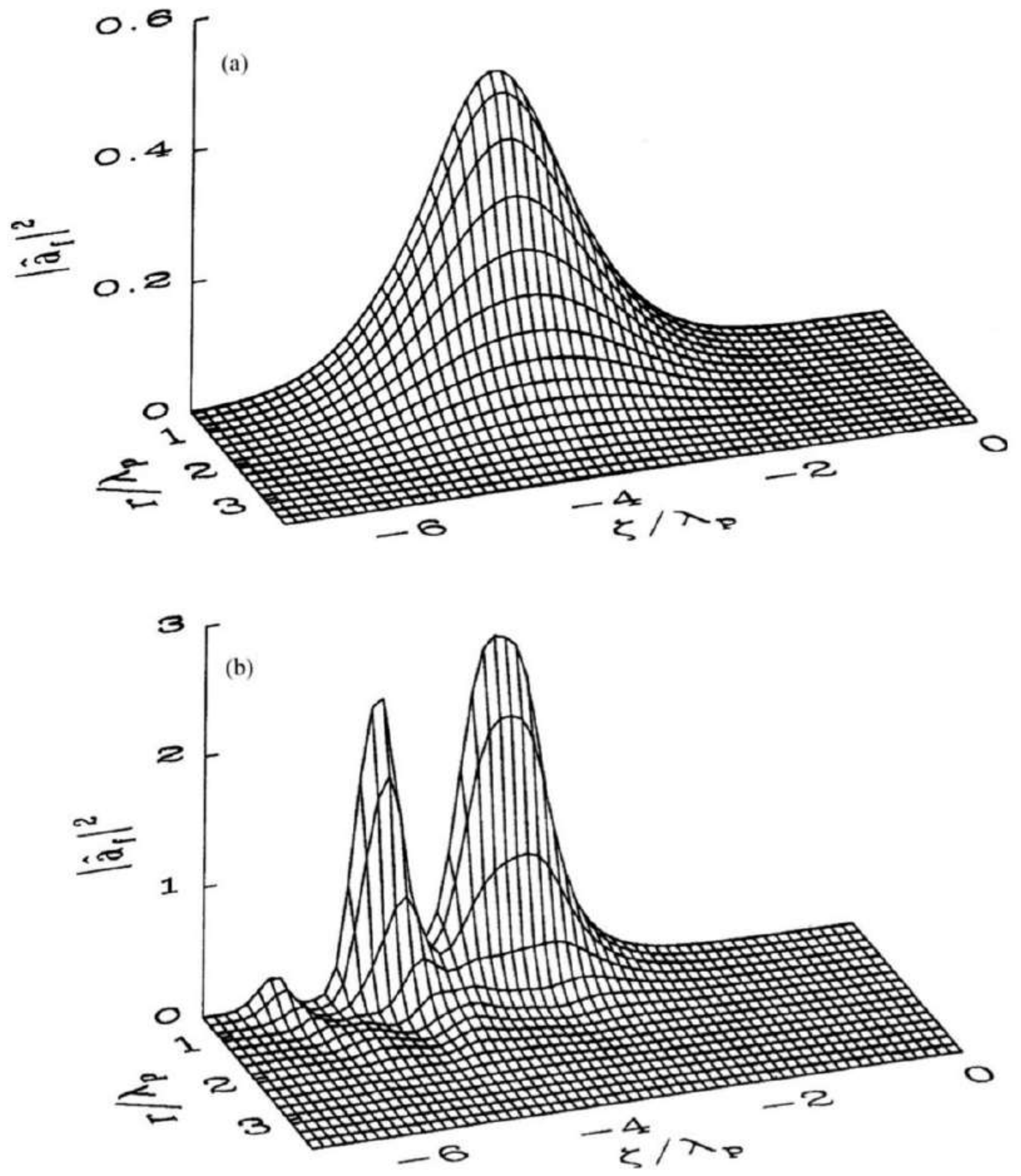


FIG. 15. Normalized laser intensity $|a|^2$ for the self-modulated LWFA case at (a) $c\tau=2Z_R$ and (b) $c\tau=3.2Z_R$. Laser pulse is moving to the right. From Krall *et al.*, 1993

Self-modulated LWFA

- As laser modulates, some electrons spend more time in the accelerating stage than others
- Terrible energy distribution

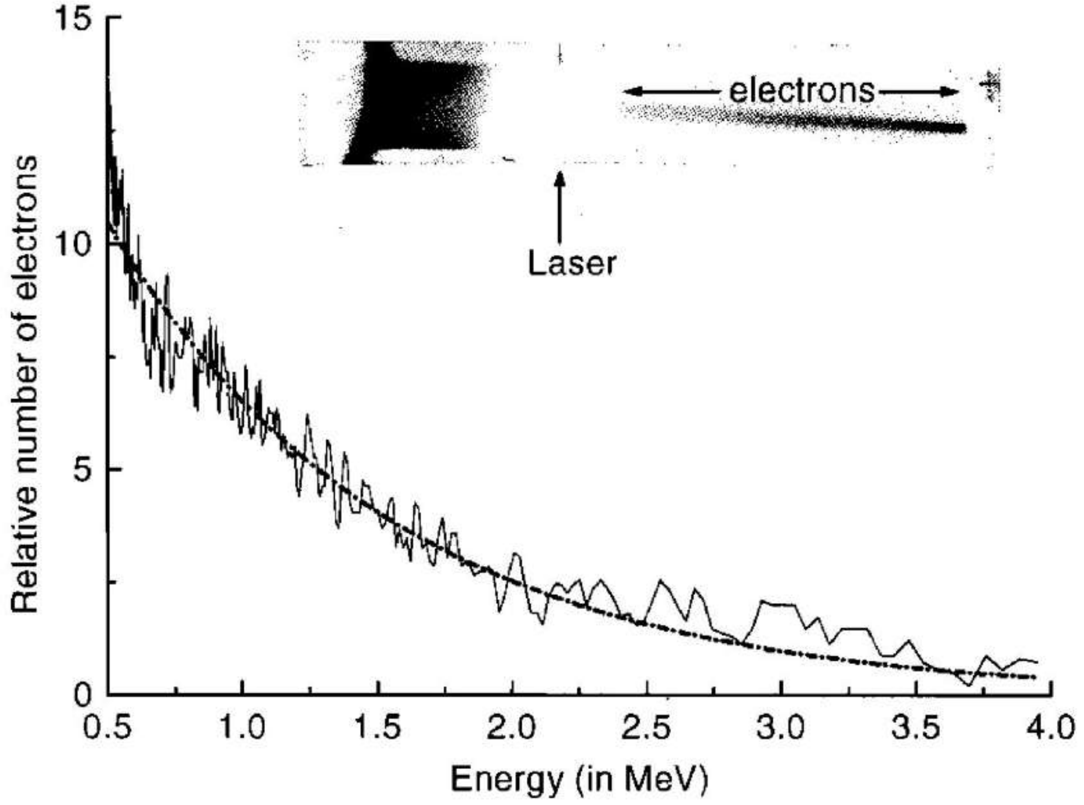


FIG. 9. Energy spectrum of accelerated electrons using direct exposure x-ray film. The dashed curve is an exponential fit to the data.

CHIRPED PULSE AMPLIFICATION (CPA)

- First demonstrated in 1985
- Allows the generation of ultrapowerful and ultrashort beams
- An intensity of ~ $2E18\ W/cm^2$ required for nonlinear effects

MAINE *et al.*: GENERATION OF PEAK POWER PULSES BY CPA

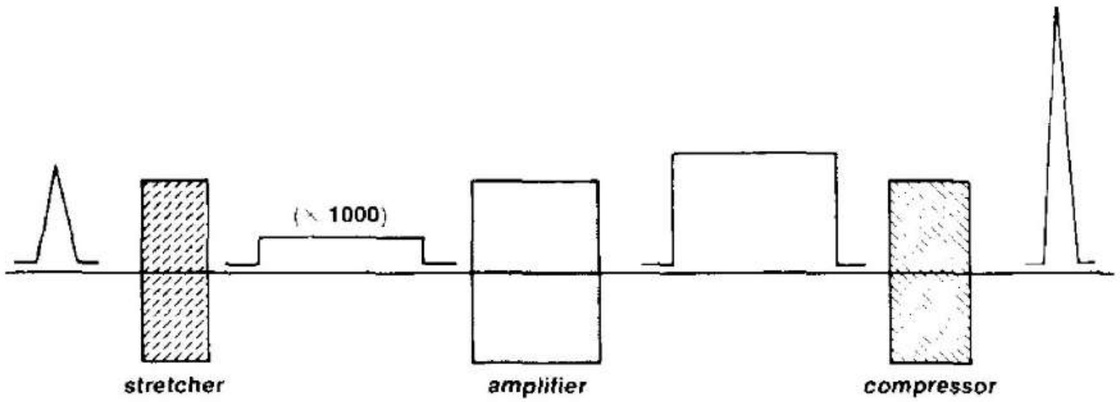


Fig. 1. Chirped pulse amplification technique.

Stretcher and Compressor Layout

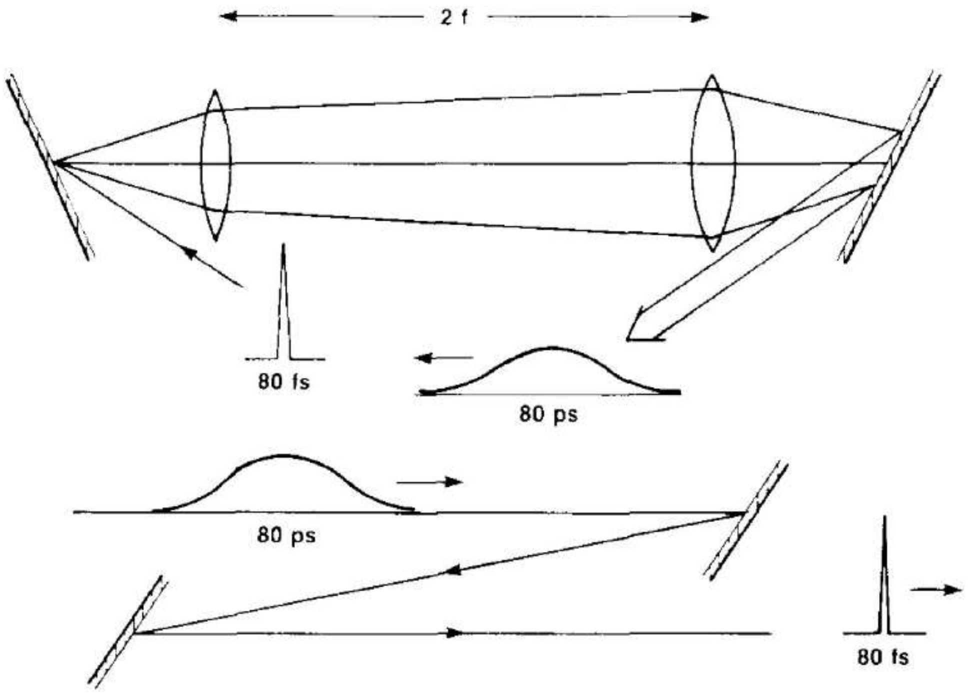
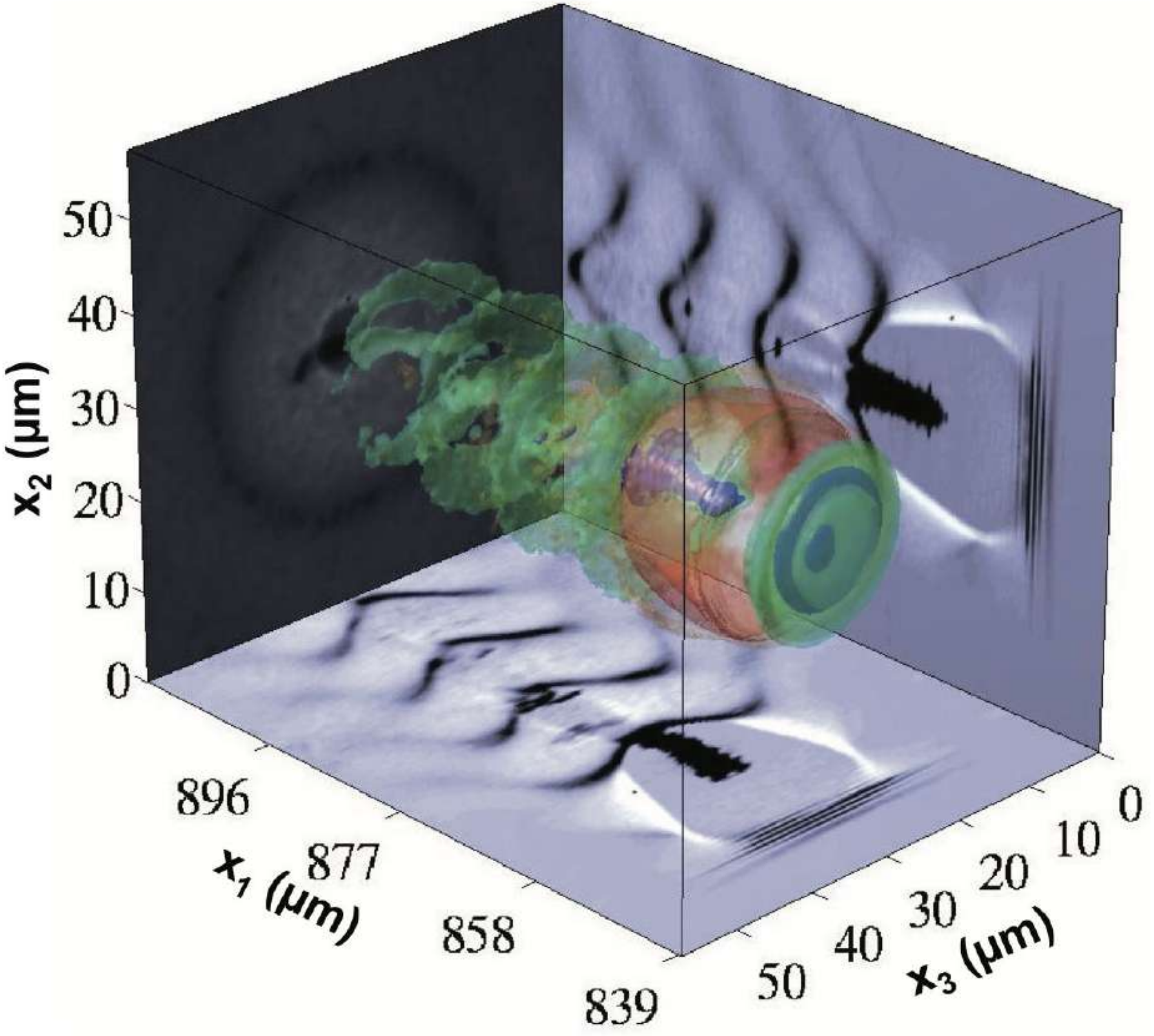


Fig. 11. Expansion–compression setup.

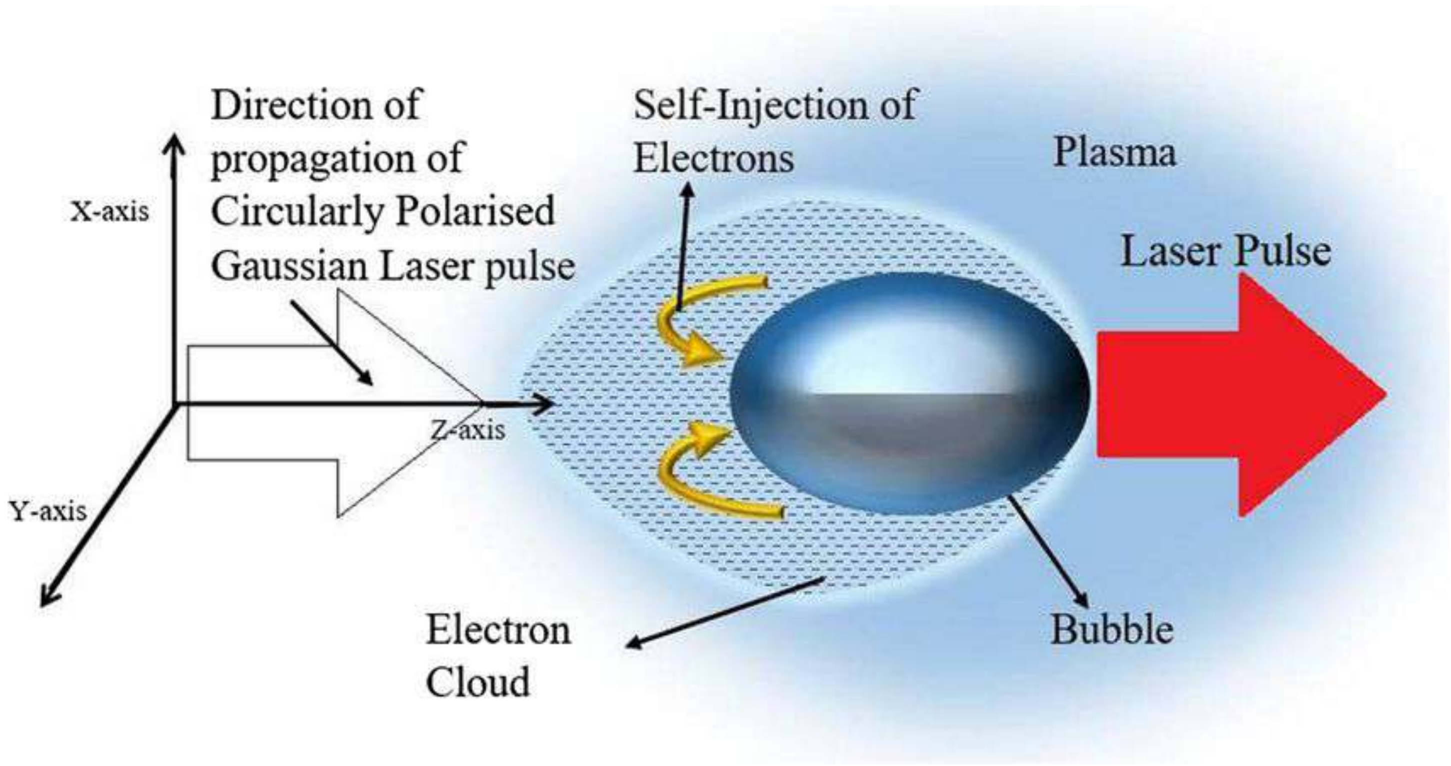
- Can now readily obtain TW class, fs pulsed lasers
- UT3's 30 TW laser can produce >80 MeV electrons

Bubble Regime LWFA

- Laser is powerful enough to create a bubble completely void of electrons in the initial wake period
- Forms quasi-monoenergetic distributions
- First demonstrated in 2004

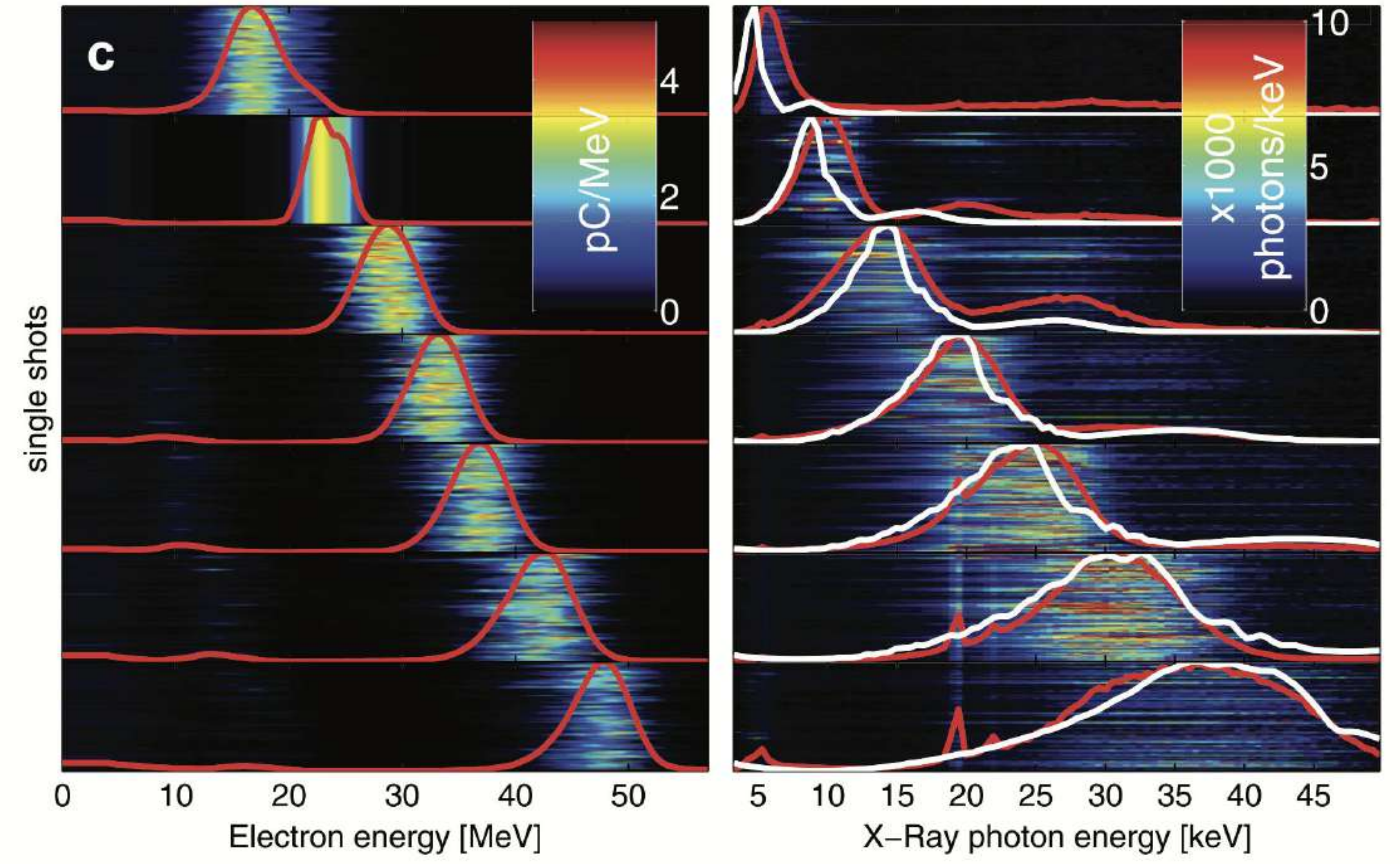


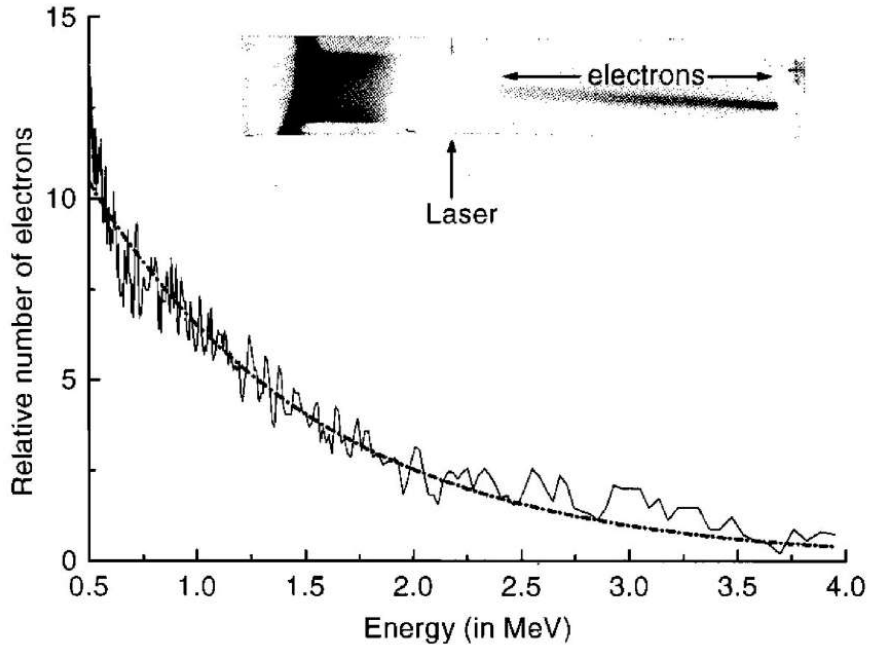
Bubble Structure



Bubble Regime

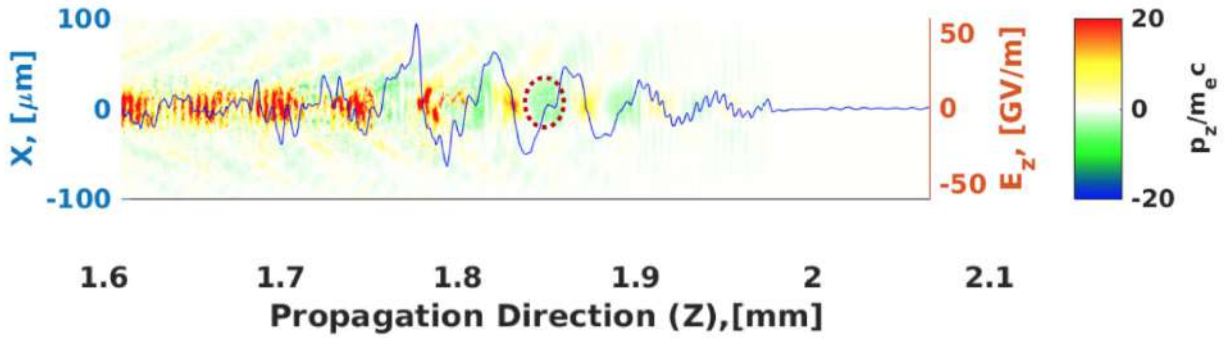
Self-Modulated Regime





Electron Injection

Direct Laser Acceleration (DLA)

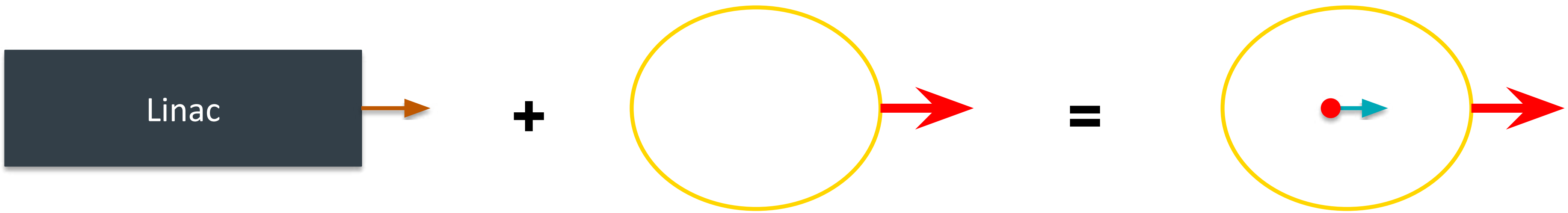


- Electrons that undergo DLA gain longitudinal momentum before interacting with nonlinear fields
- Supported by electrons with frequencies matching the laser frequency

Gas doping

- Inject a small number of heavier atoms into gas mix to alter when ionization occurs
- Nitrogen is commonly used (1%-10%)

External injection



Developing injection scheme

- Traditional LWFA experiments use drive lasers ~ 1 micron
- New CO_2 lasers can now produce TW, fs pulses at 10 microns

CO2 lasers

$$a_0 = \frac{eE_L}{\omega m_e c}$$

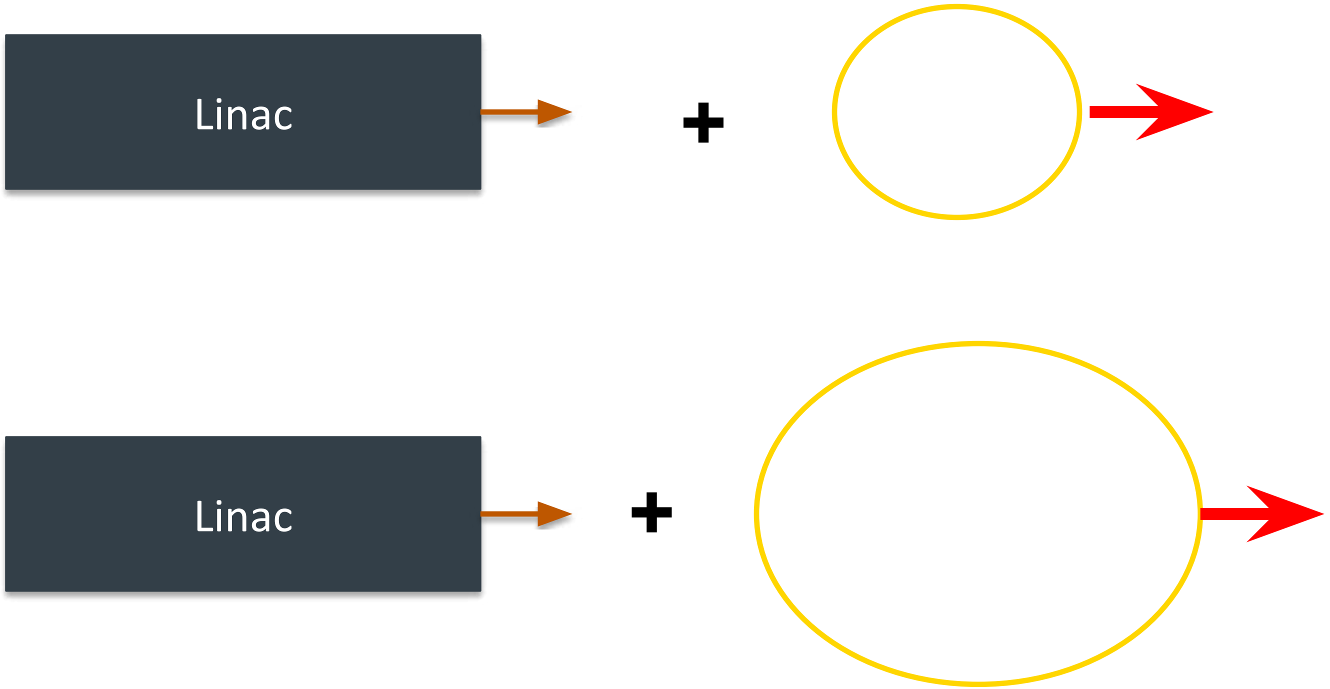
Linear Normalized
Vector Potential Scaling

$$\Phi_{pond} = \frac{m_e c^2}{4e} a_0^2$$

Quadratic Pondermotive
Potential Scaling

$$F_p = -m_e c^2 \nabla(\frac{a^2}{2})$$

100x improvement in pondermotive force!
Larger Bubbles!



Pulse Guiding

Kerr Effect: Nonlinear Self-Foc

- Longer laser-plasma interaction times offer greater attainable energies
- Diffraction must be dealt with

$$E(t) =$$

$$P^{(3)}(t) = \frac{1}{4}\varepsilon_0\chi^{(3)}\mathrm{E}^3 \cos$$

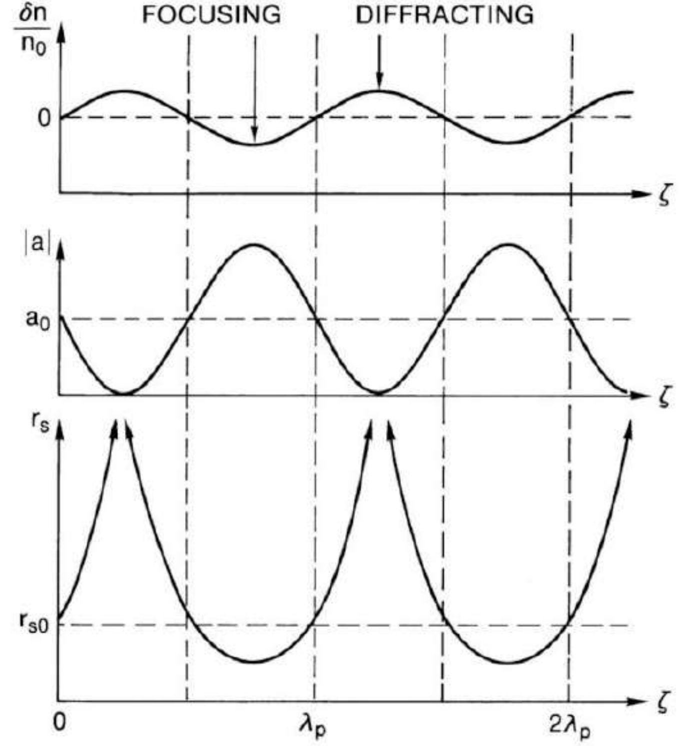


FIG. 34. Schematic of focusing effects of an externally ated plasma wave on an initially uniform low-intensity pulse.

$$n = n_0 + n_2 I$$

The laser's intensity focuses itself!

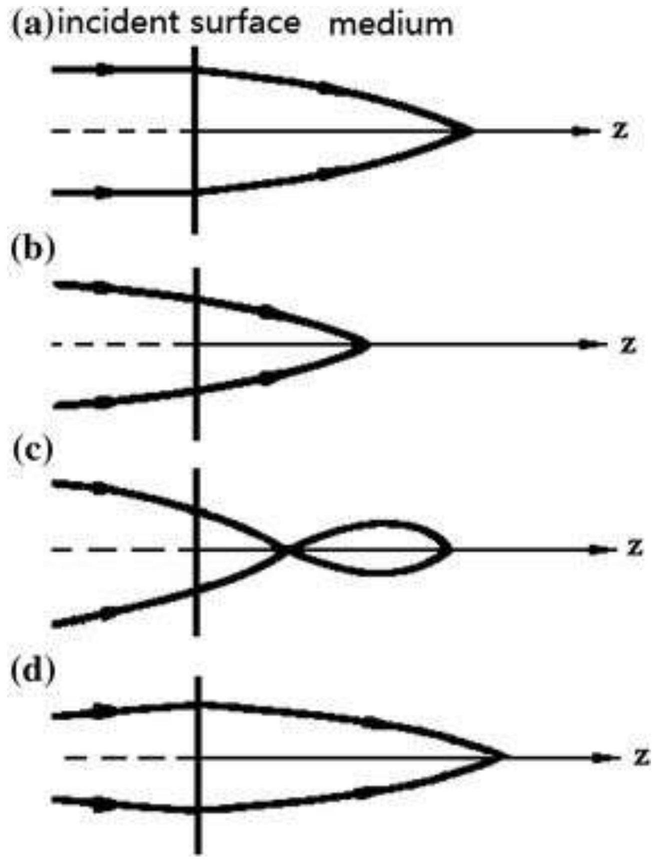
Kerr Effect: Nonlinear Self-Focusing

Parallel

Weakly Converging

Strongly Converging

Weakly Diverging



Plasma Channeling

As light goes from a low to high index of refraction, it bends towards the normal of the interface

Methods:

1. Pre-pulse
    1. Transverse Axial Focusing Probe
    2. Longitudinal pre-pulse
2. Special gas jets

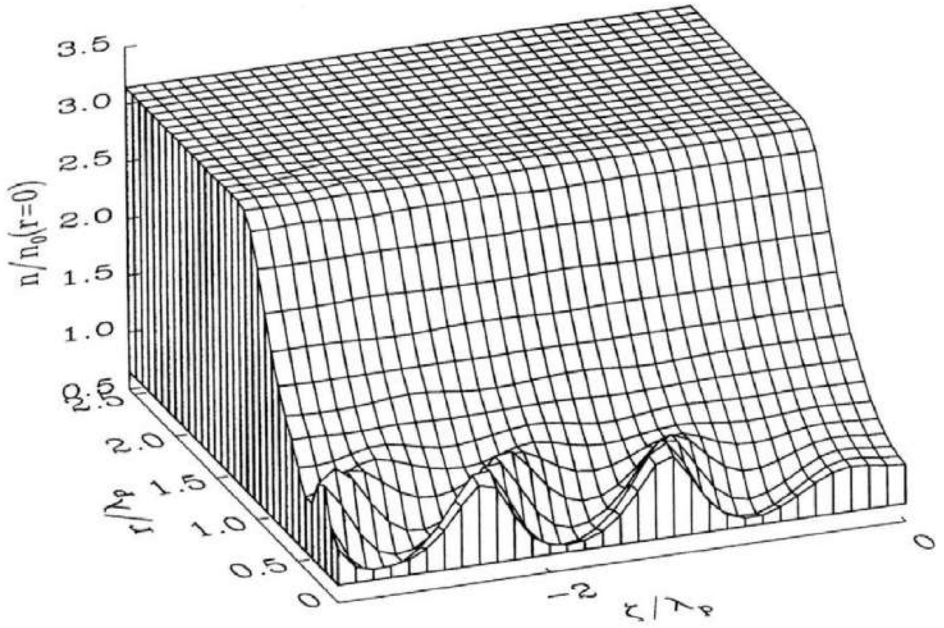
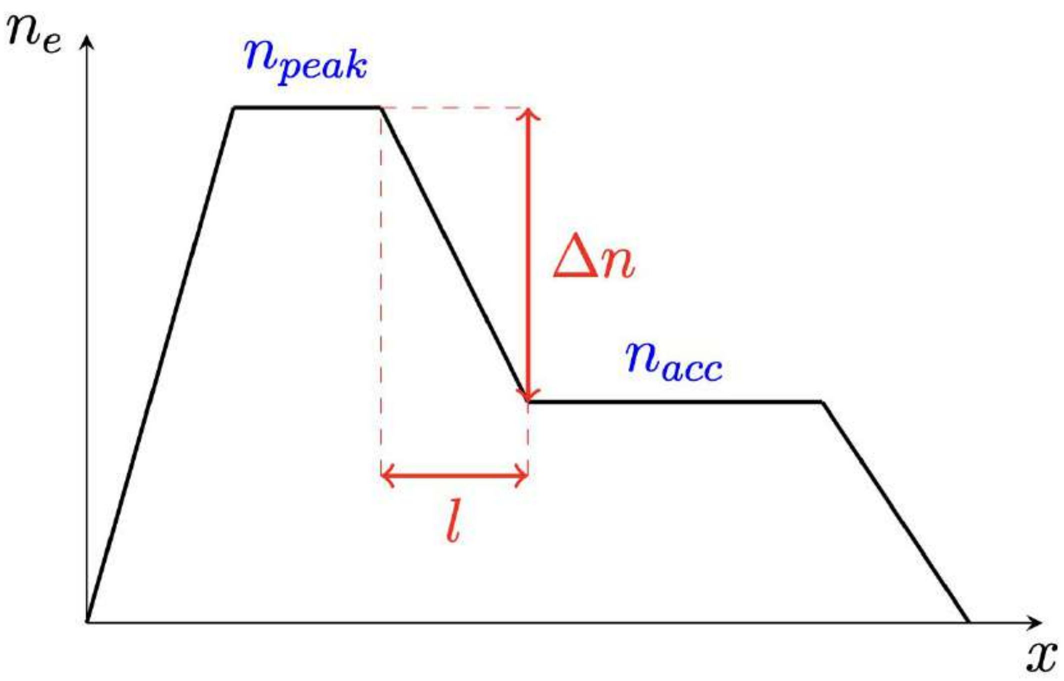


FIG. 29. Plasma electron density n/n_0 at $c\tau=20Z_R$ for a channel-guided LWFA. Initial density profile is parabolic with a depth $\Delta n = \Delta n_c = 1/\pi r_e r_0^2$. From Esarey, Sprangle, *et al.*, 1993.

Gas Jet Density Profile

- Higher density allows for early collection of charge
- Lower density allows for less laser diffraction

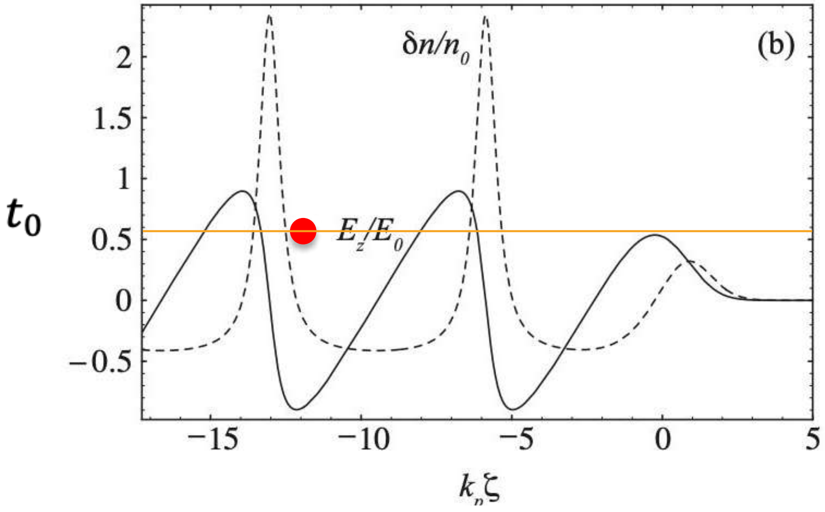


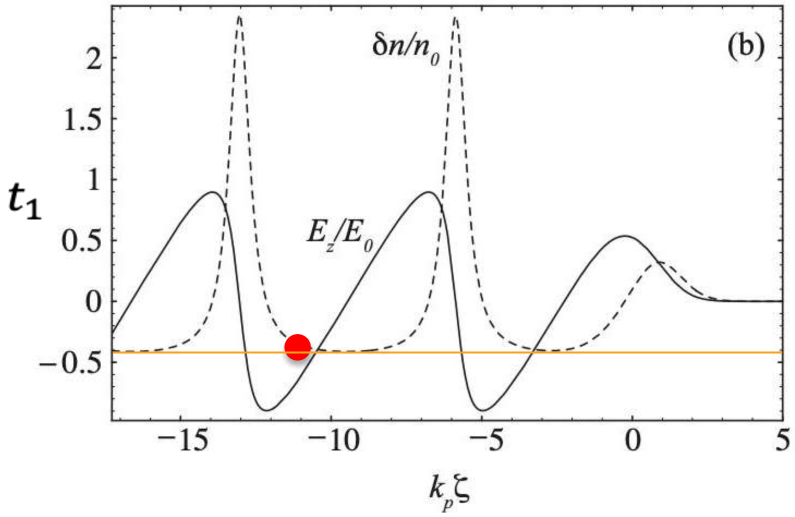
What Must LWFA Overcome?

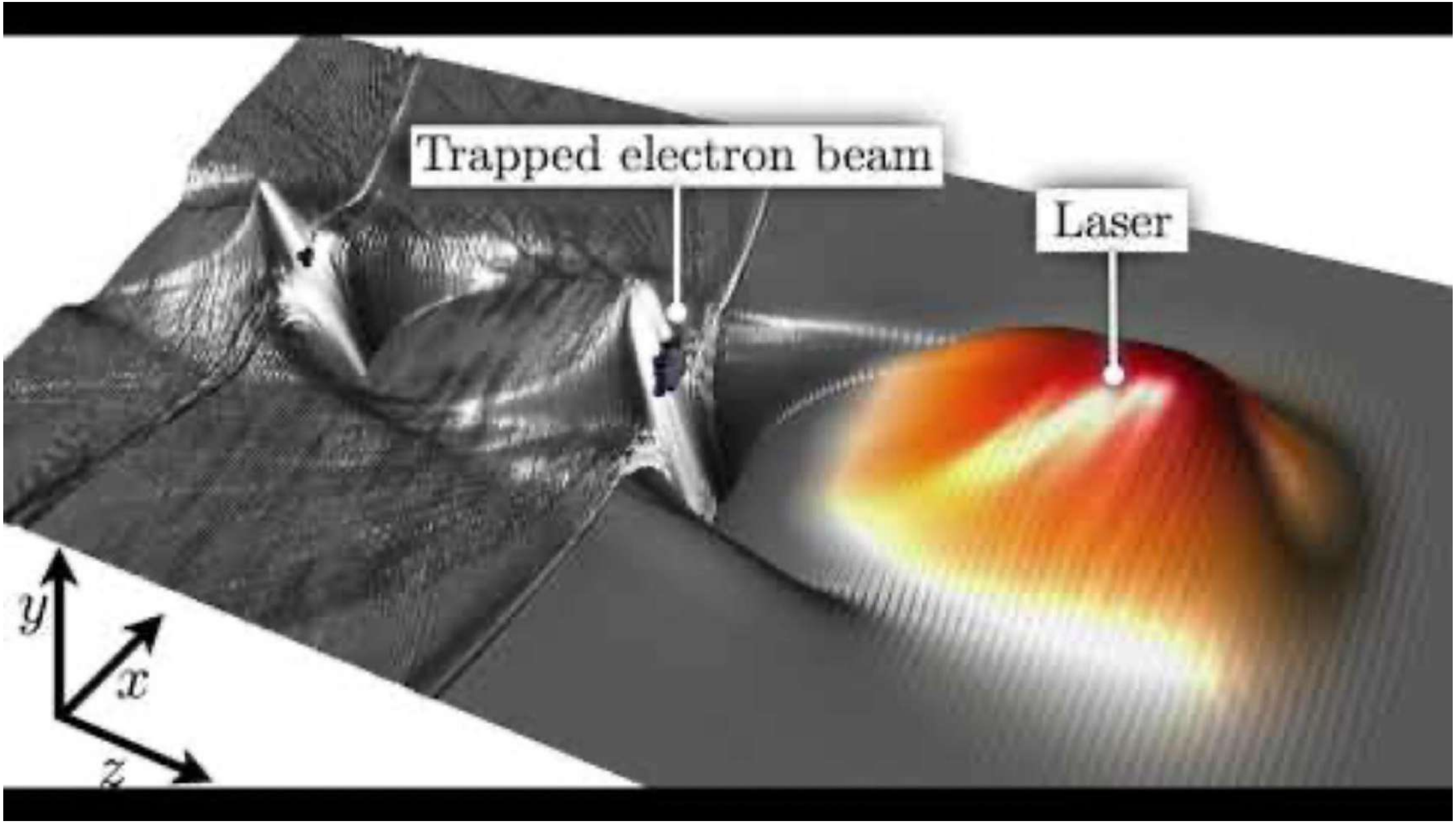
Dephasing and Pump Depletion

- As the electrons accelerate, their group velocity eventually outruns the group velocity of the laser
- Must turn off plasma source once this switchover occurs
- Laser runs out of energy overtime

$$v_g = \sqrt{1 - {n_e}/{n_c}}$$






Trapped electron beam
Laser
y
x
z

THANKS FOR LISTENING!