# A Short (55 min) Course in Laser Plasmas Induced By ELI-SCALE Lasers

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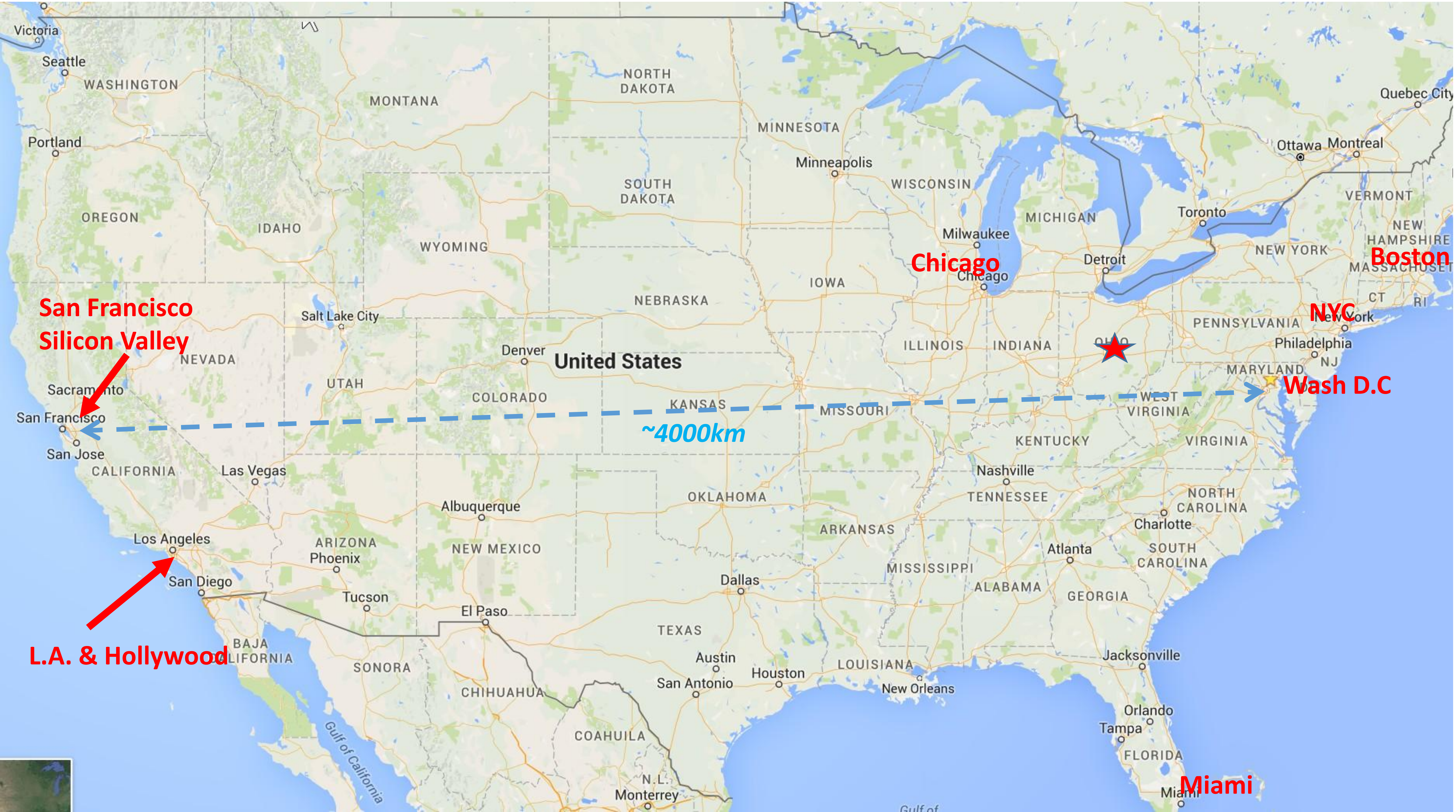


San Francisco
Silicon Valley

L.A. & Hollywood

Chicago

Boston

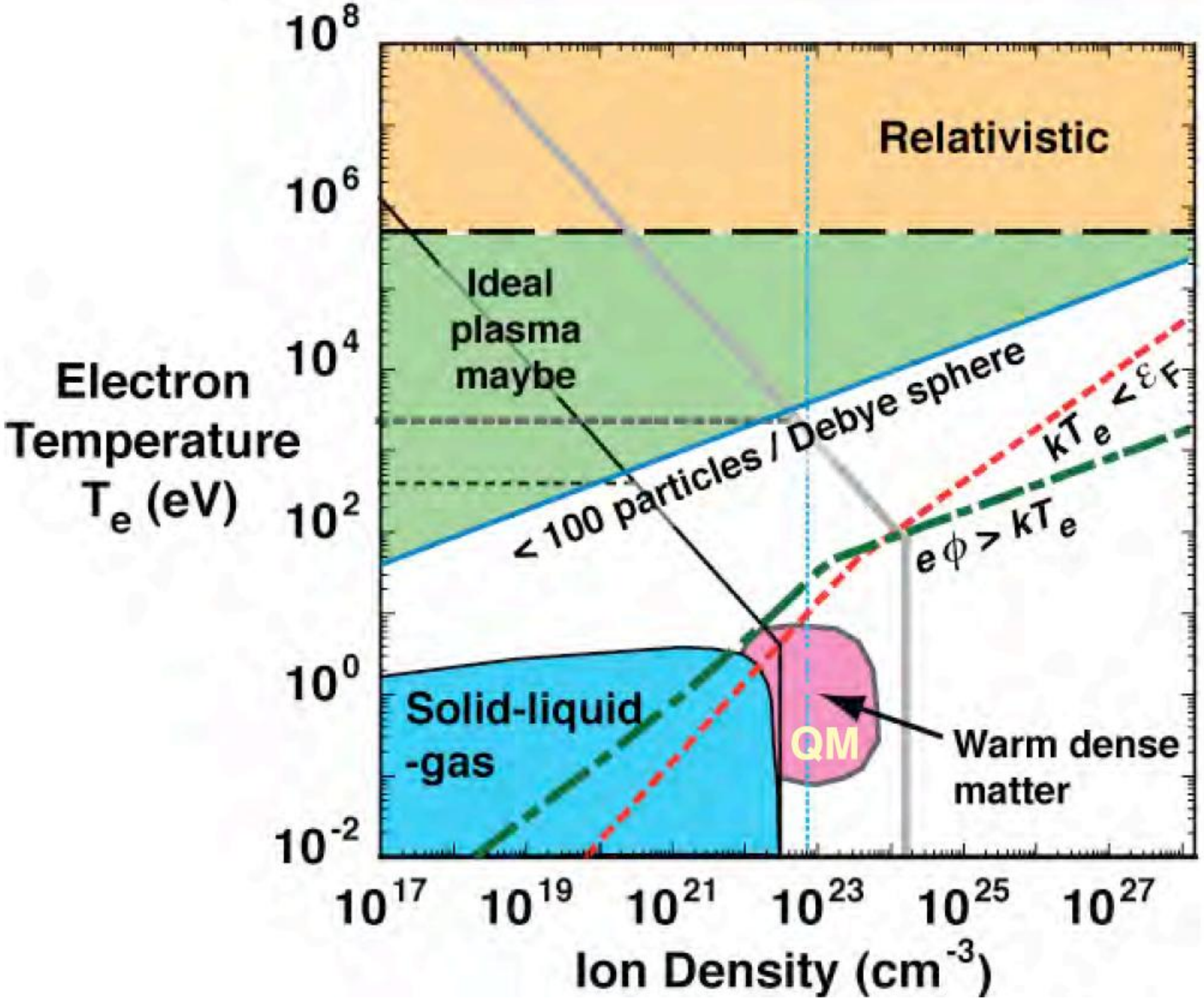
NYC

Wash D.C

Miami

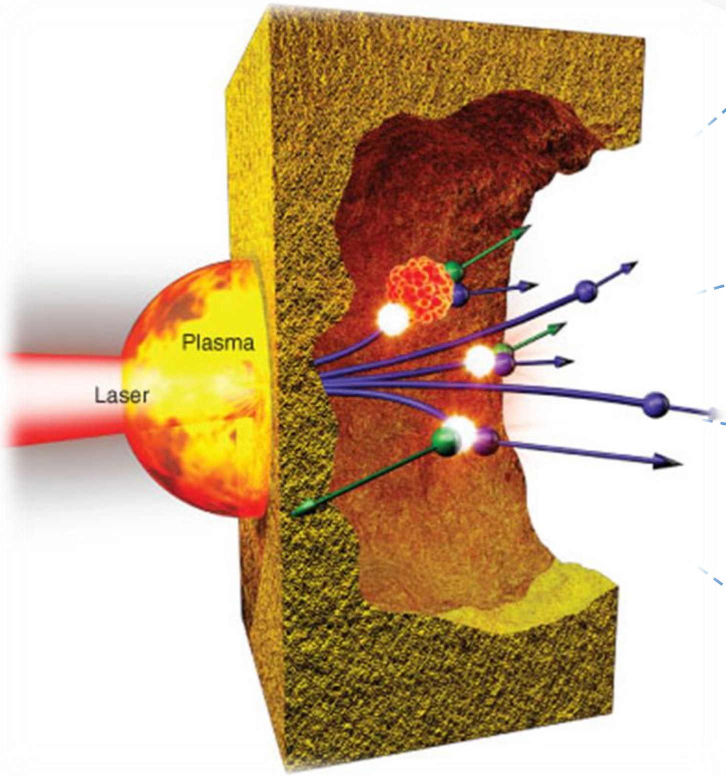
~4000km

# Physics connections within and beyond HEDP



Quark-gluon plasmas

# Laser plasma interactions can provide table-top sources including electron, x-ray, γ-ray, ion, and positron beams



**Monochromatic Kα x-rays**
Fast electrons create vacancies via electron impact ionization process in the cold target

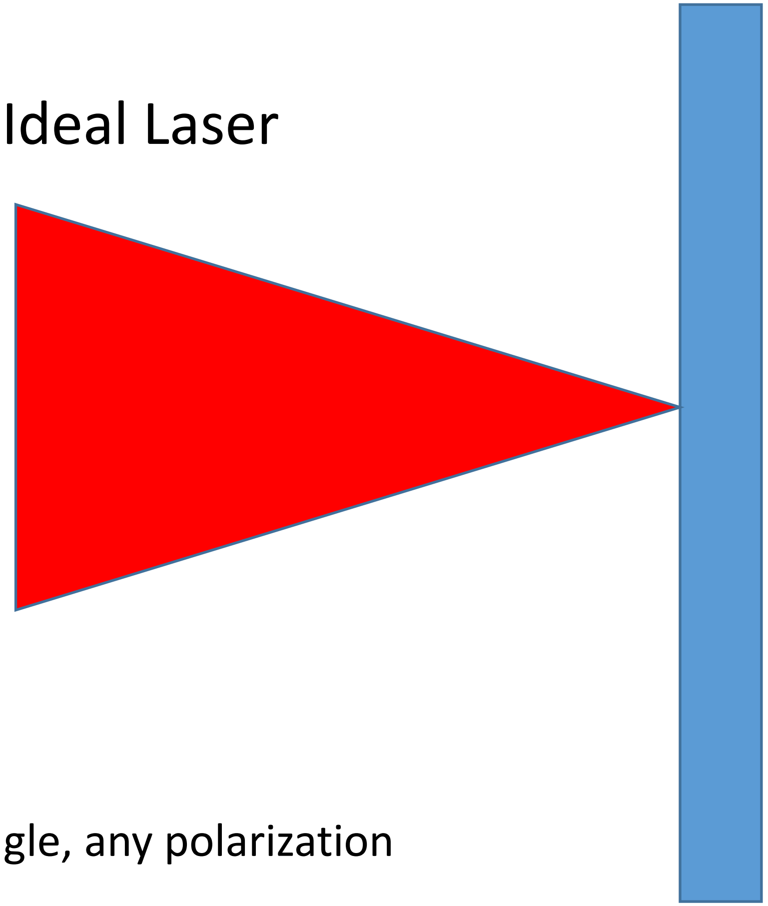
**Bremsstrahlung radiation**
Broadband MeV x-ray emission via multiple Coulomb collisions during transit through the target material

**Ion acceleration**
Charge separation fields due to a collective displacement of a large number of electrons accelerate ions

**Positron production**
Pair production due to the interaction of atomic nuclei with either Bremsstrahlung radiation or relativistic electrons

Picture: courtesy of Kwei-Yu Chu and Lawrence Livermore National Laboratory

Understanding laser-generated electron beam characteristics (source size, energy distribution, divergence) is the key to advancing these radiation or particle sources



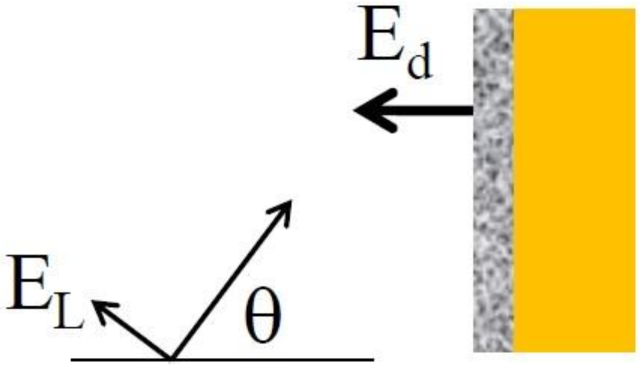
Target of any material, any thickness

Ideal Laser

Any angle, any polarization

- Vacuum (or Brunel: not-so-resonant, resonant) Heating
  - Ignore B-field
  - E-field accelerates electrons near surface
  - Requires some p-component of light (E poking surface)

$$E_d = 2E_L \sin\theta$$

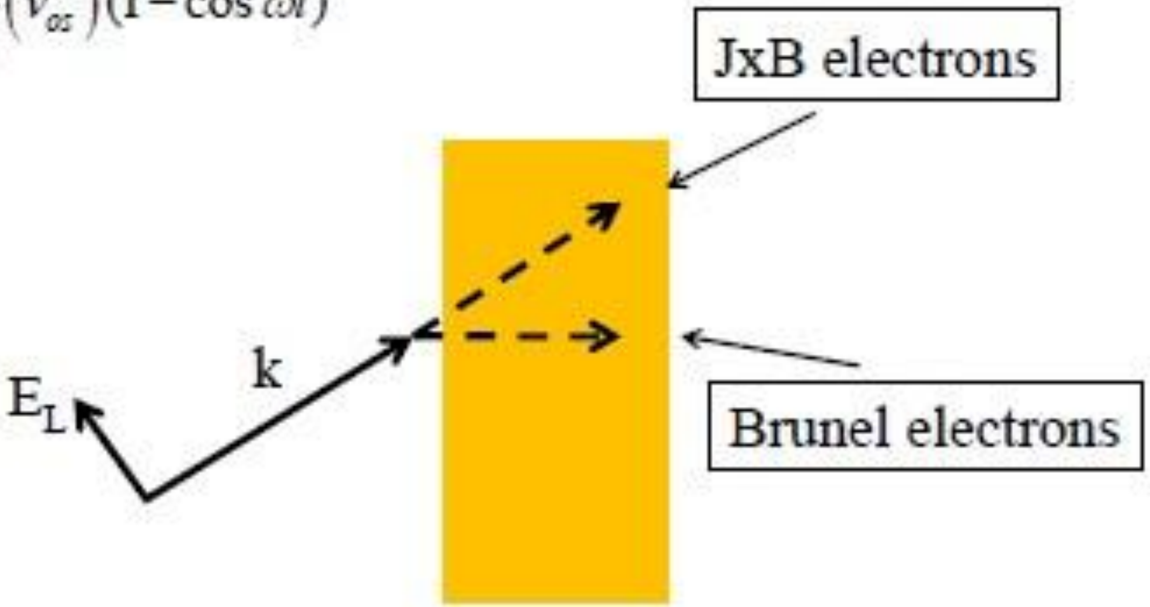


  - Electrons slammed into surface w/ $v \sim v_{os} \sin\theta$

# J x B Heating

- Very high intensities the v x B force becomes important
- Accelerates electrons along k-vector
- Accelerates electrons at twice laser frequency

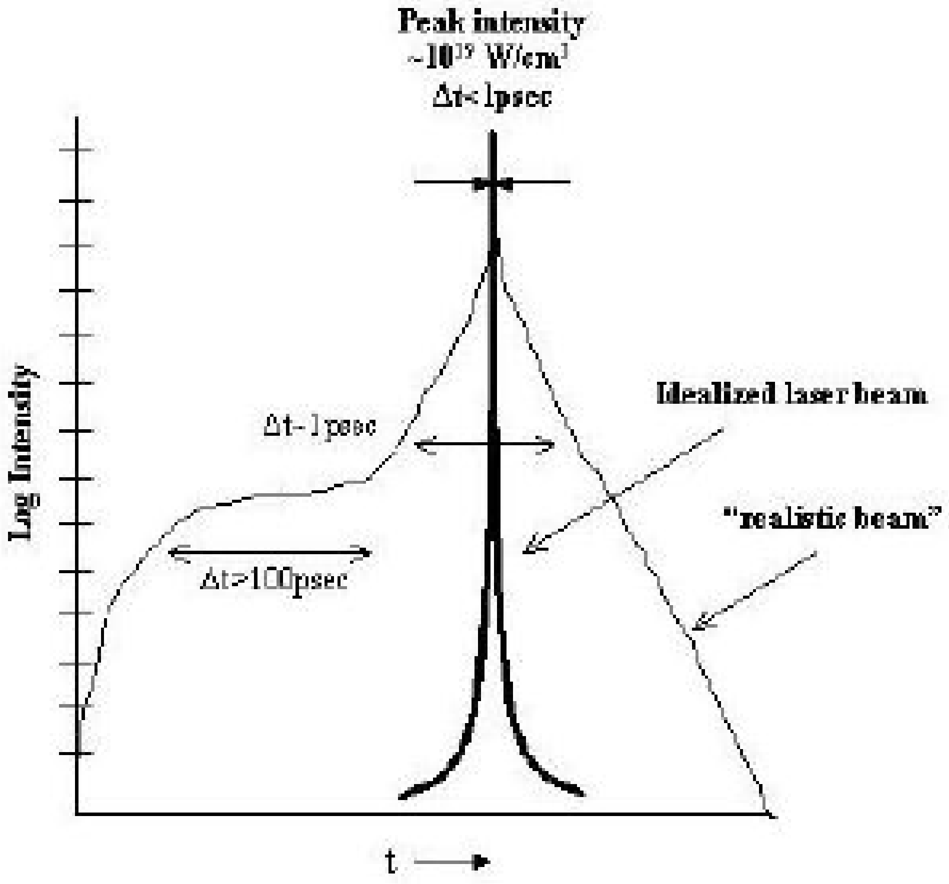
$$F_z \approx \frac{\partial}{\partial z}\left(v_{os}^2\right)(1-\cos\omega t)$$



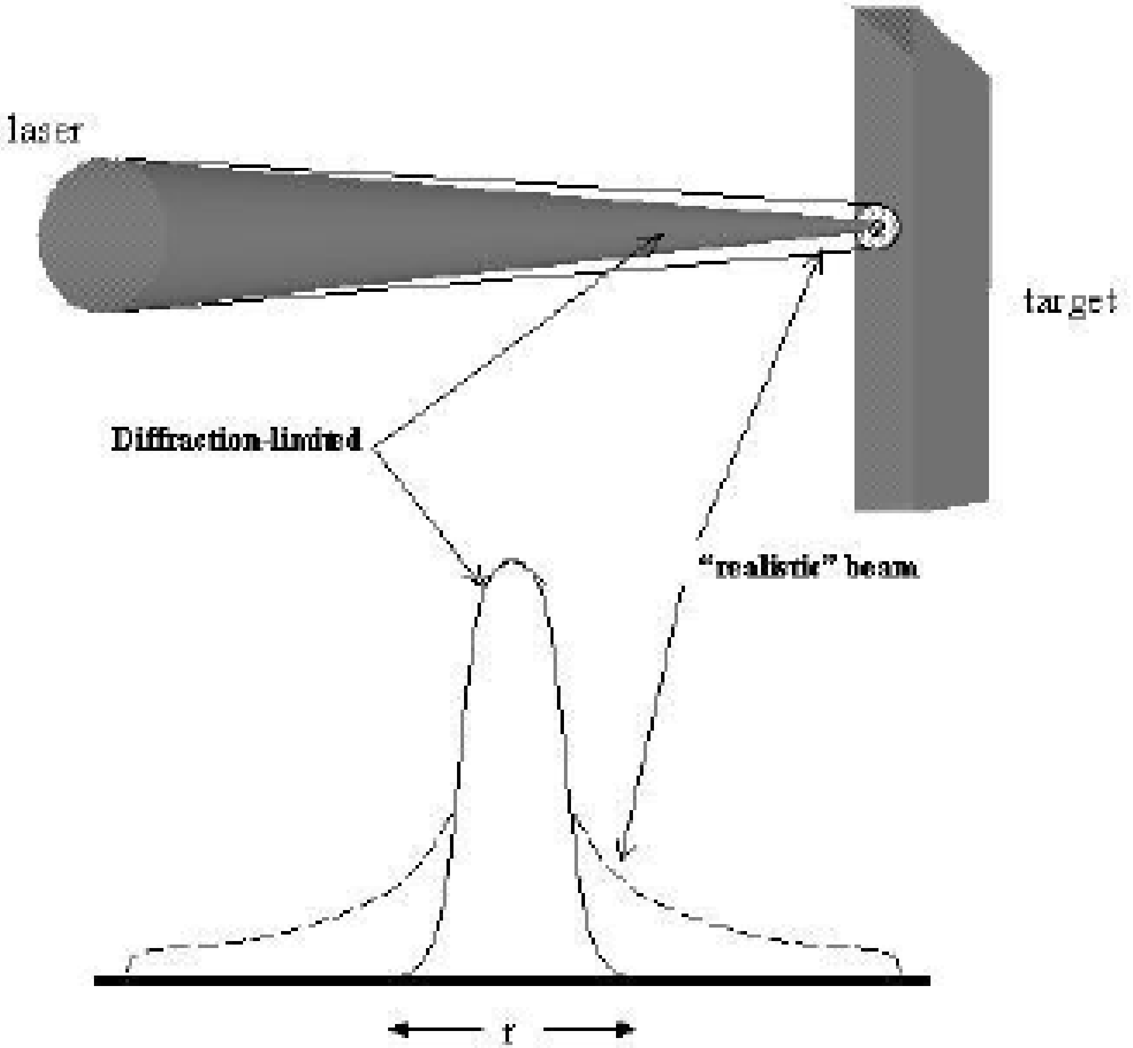
# Laser Interactions in the real world

- In a perfect world
  - Laser interacts with solid density
  - High current burst of electrons transports energy
- In the real world
  - Energy before main pulse
    - Main short pulse interacts with low density plasma NOT solid
  - Big lasers don't focus perfectly
  - Generation of electrons & subsequent transport messy
  - Most diagnostics are time-integrated

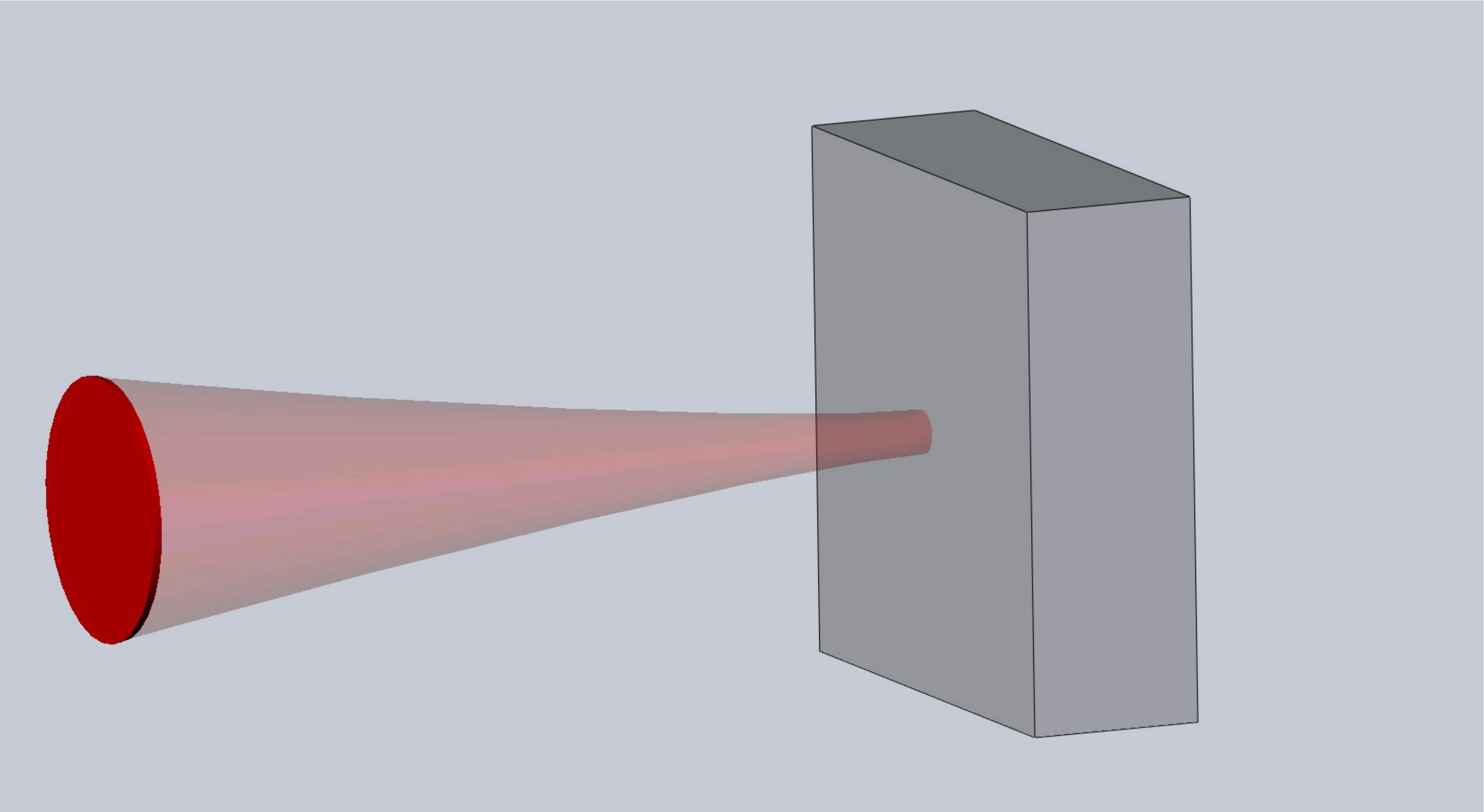
# Real Pulses


Peak intensity
~$10^{19}$ W/cm$^2$
Δt<1psec
Idealized laser beam
Δt~1psec
"realistic beam"
Δt>100psec
Log Intensity
t

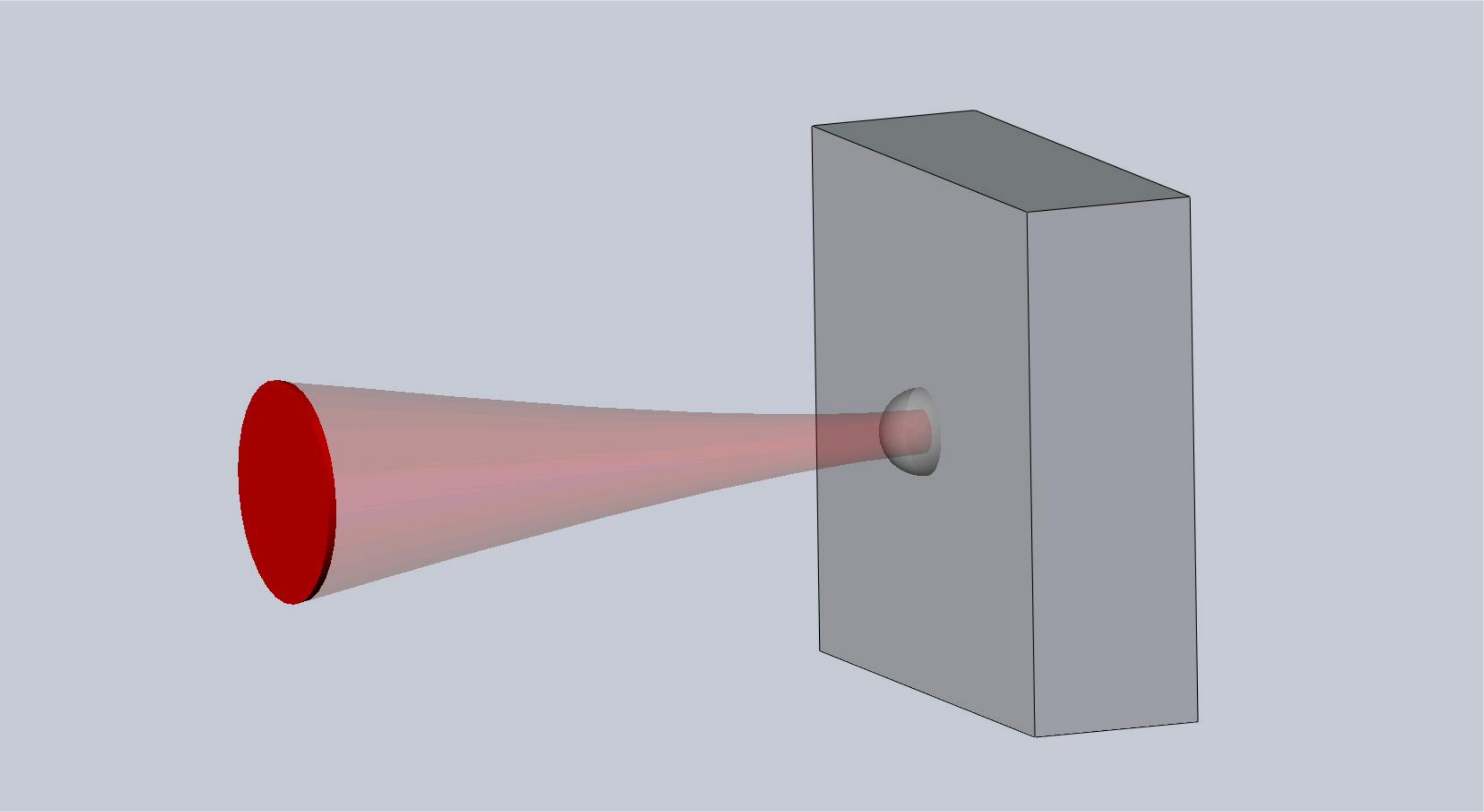
# Real Beams



# Typical experimental target is a thin metal foil (Al, Cu, Au, etc.)



# Expanding “pre-plasma” is formed at the laser focus by “pre-pulse”



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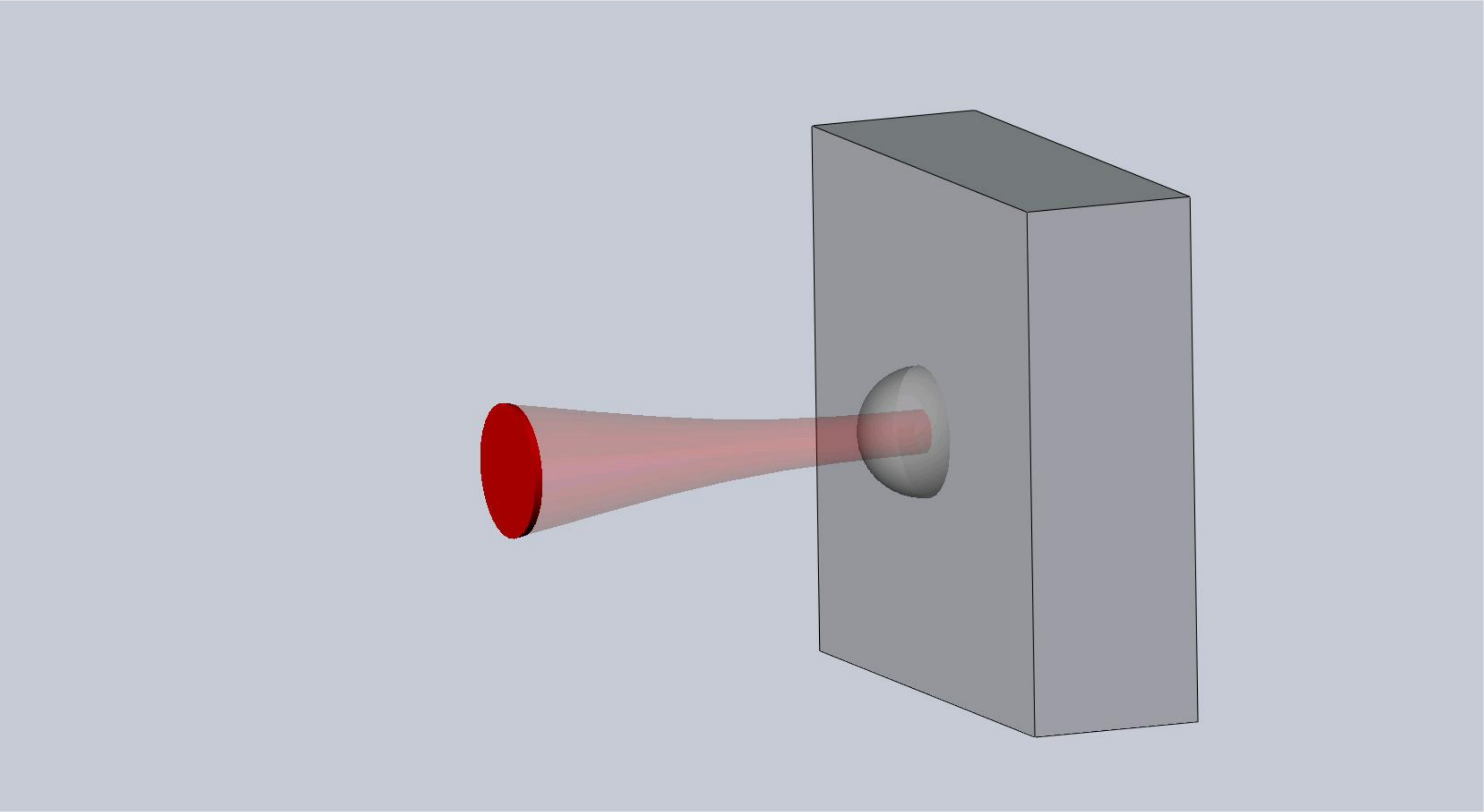

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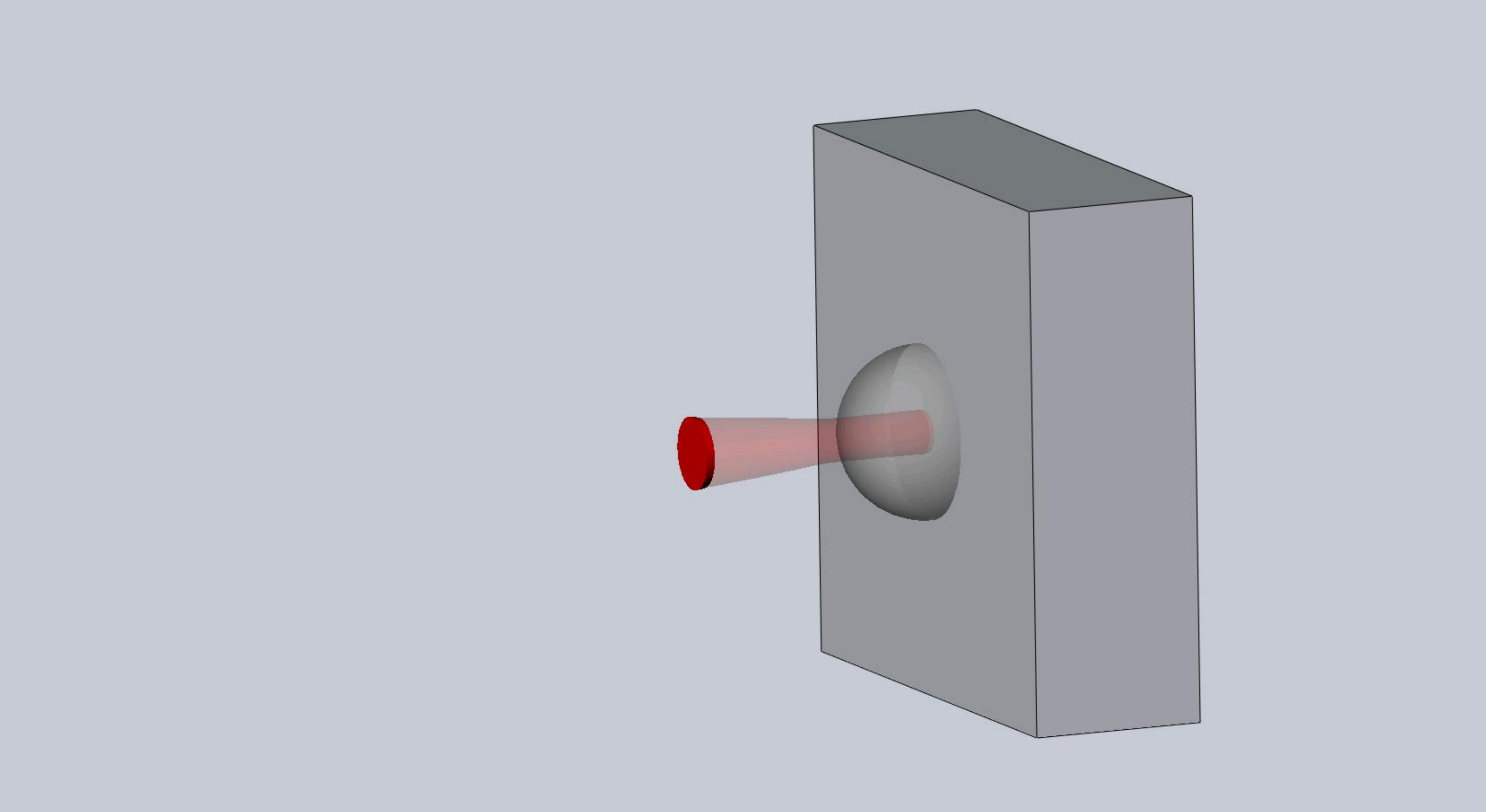
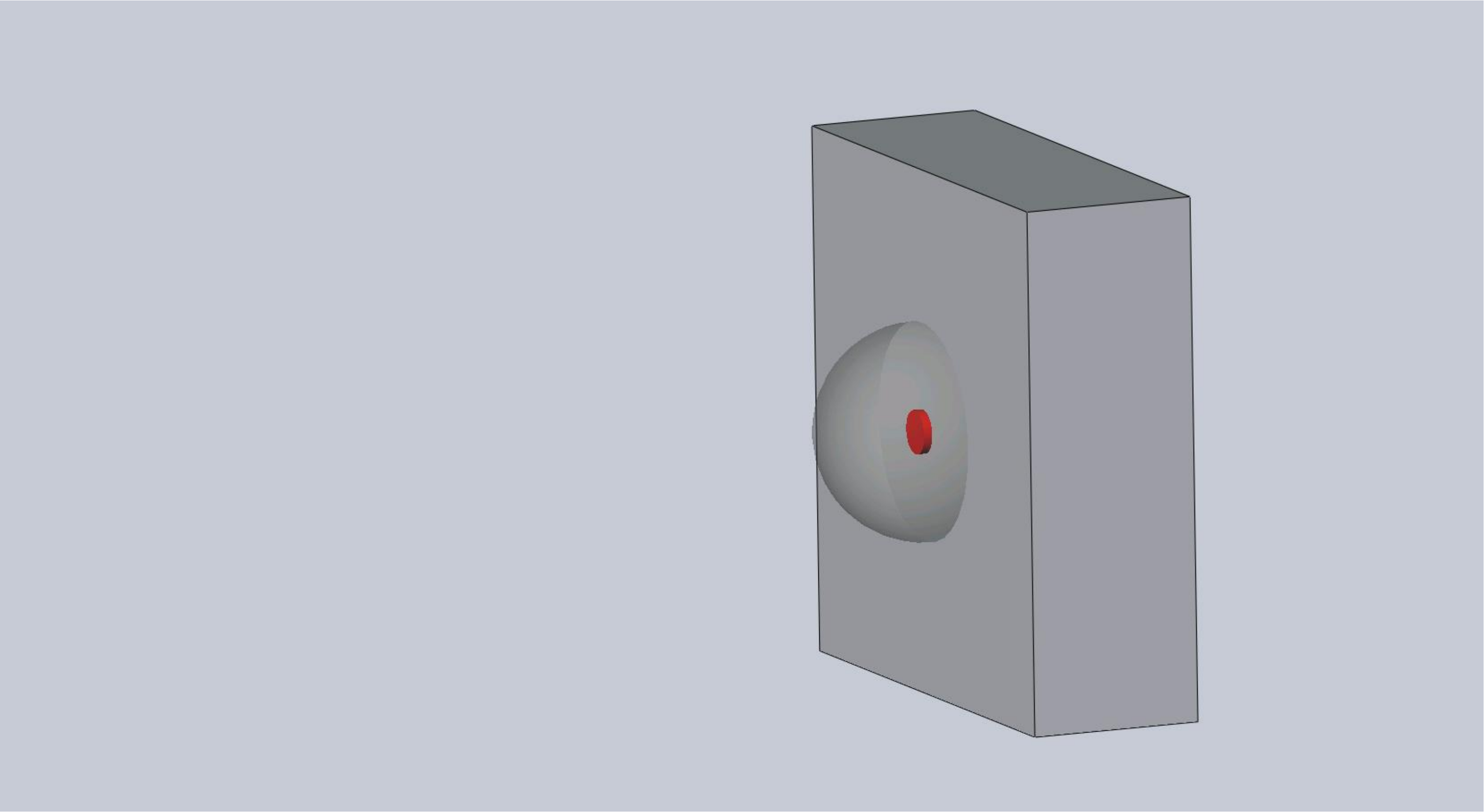
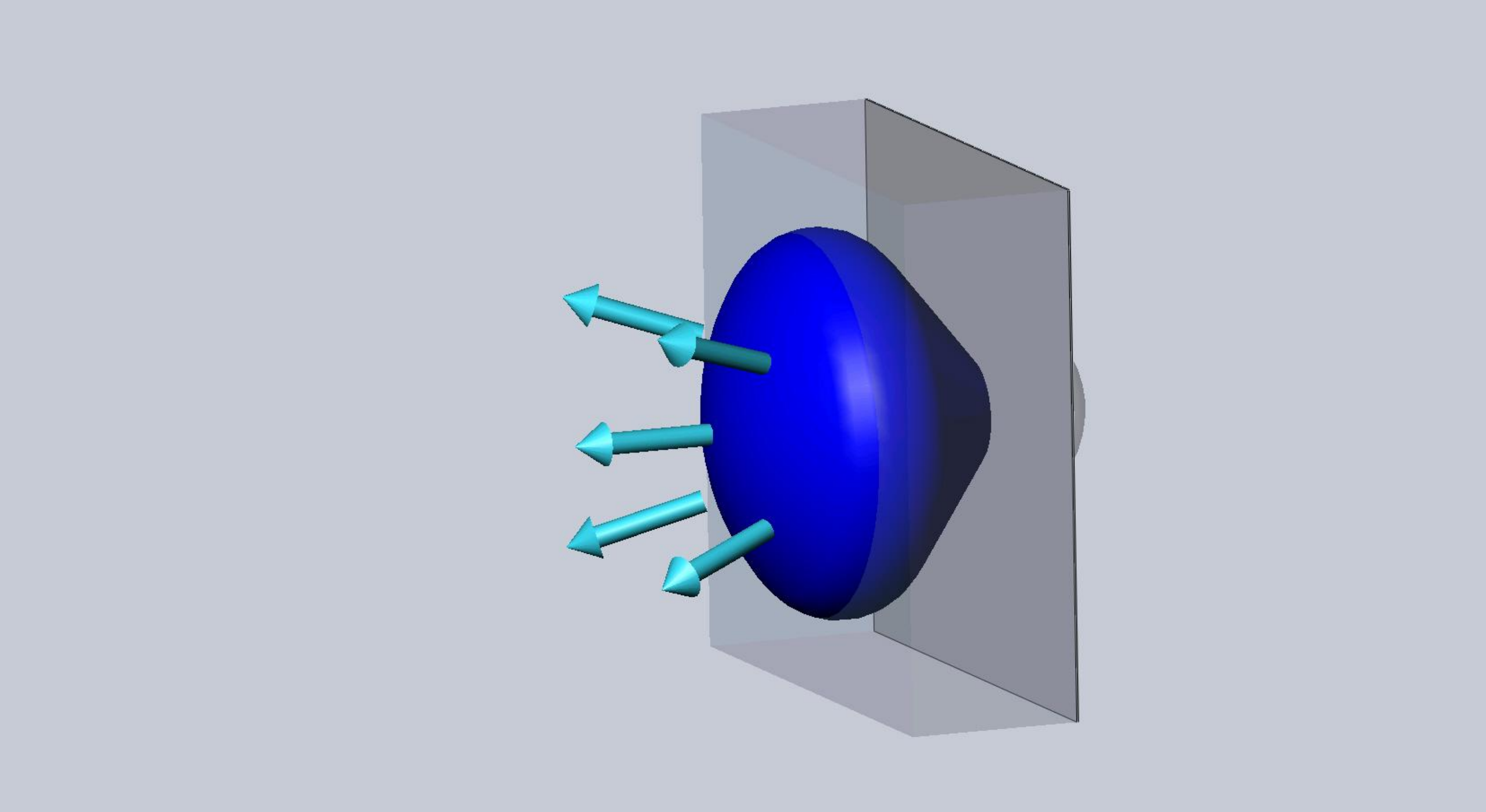


# Main laser pulse interacts with “pre-plasma” rather than sharp interface

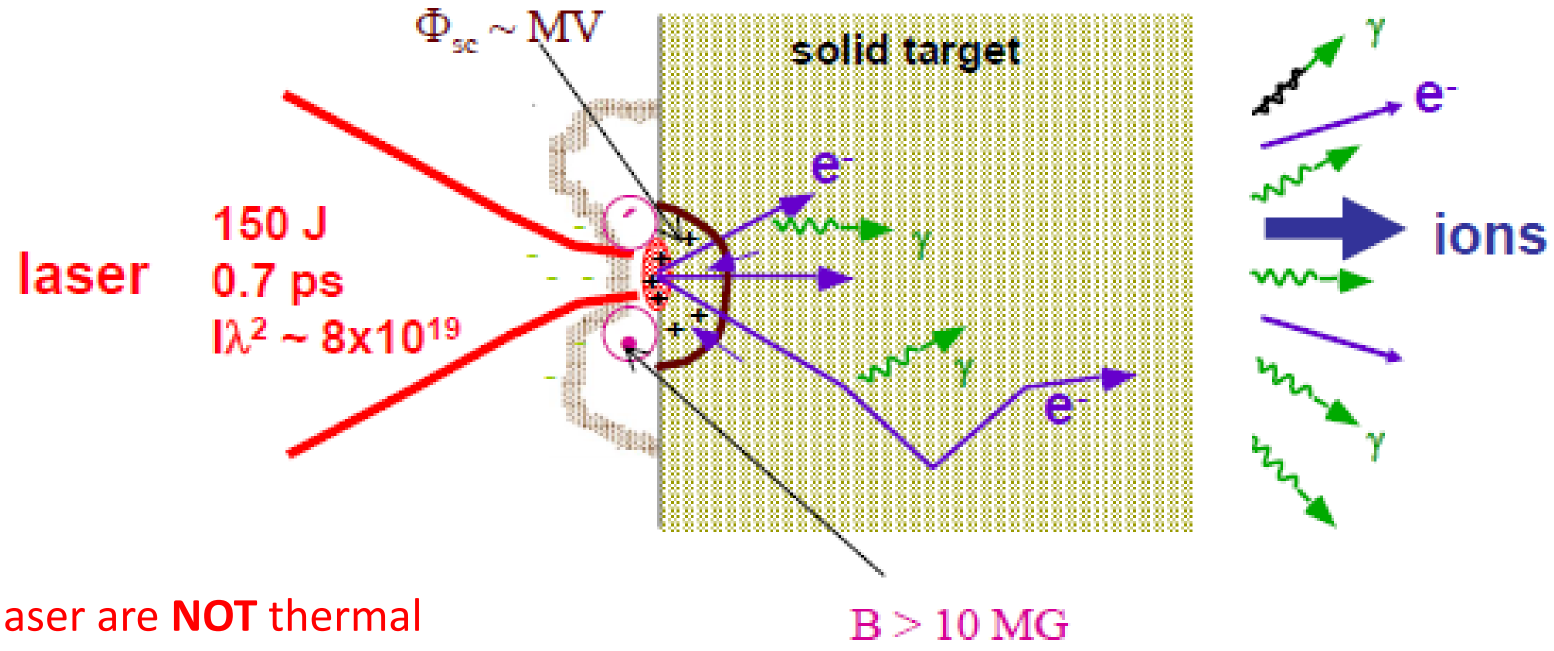


# Laser-plasma interaction creates relativistic electron jet



# Transport Issues

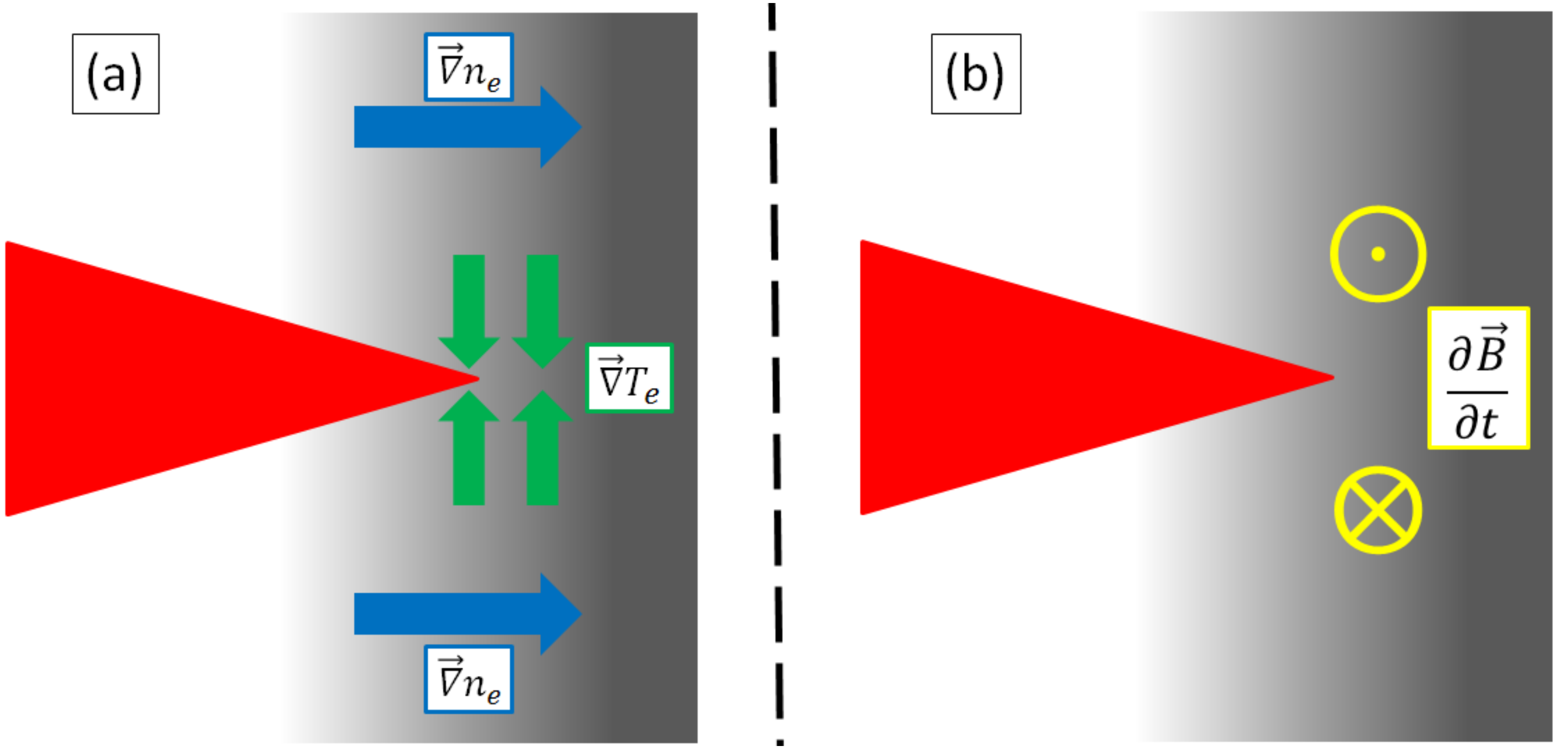
- All the preceding processes generate “hot” electrons
- Hotter than surrounding background electrons
- How do they propagate in high densities?



Electrons excited by laser are **NOT** thermal

**BIG** disconnect between ion temperature—conduction electron temperature—laser-excited electron

# A curl of thermal and density gradients produce large B fields



**In general: whenever there is a misalignment of "electron drivers" there will be induced magnetic fields.**

**These magnetic fields can be enormous—many hundreds of MEGA Guass**

# *First thing about laser-plasmas you need to understand and memorize*

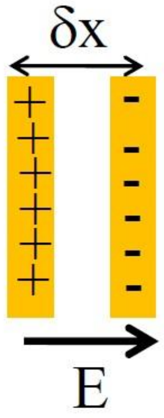
- Complex index of refraction → absorption or no propagation
- When driving frequency = plasma frequency
  - Index becomes complex
  - k-vector imaginary component → no propagation inside
  - Light is reflected
- Critical Density $n_c$ = density where $\omega=\omega_p$
- For light w/ wavelength = 1 micron → $n_c = 10^{21}$ cm$^{-3}$

$$n_c = \frac{m\varepsilon_o\omega_L^2}{e^2} = \frac{m\omega_L^2}{4\pi e^2} \approx 1.1x10^{21}\lambda^{-2}(\mu m)cm^{-3}$$

- Higher frequency (shorter $\lambda$) → penetrates to higher density

# Second thing about laser plasmas you need to understand and memorize

- Consider a uniform plasma & 1-D
- Number density $n_e$
- Surface charge density $\sigma = en\delta x$
- Electric field $E = \sigma/\varepsilon_o$
- Newton's law for a test particle, e



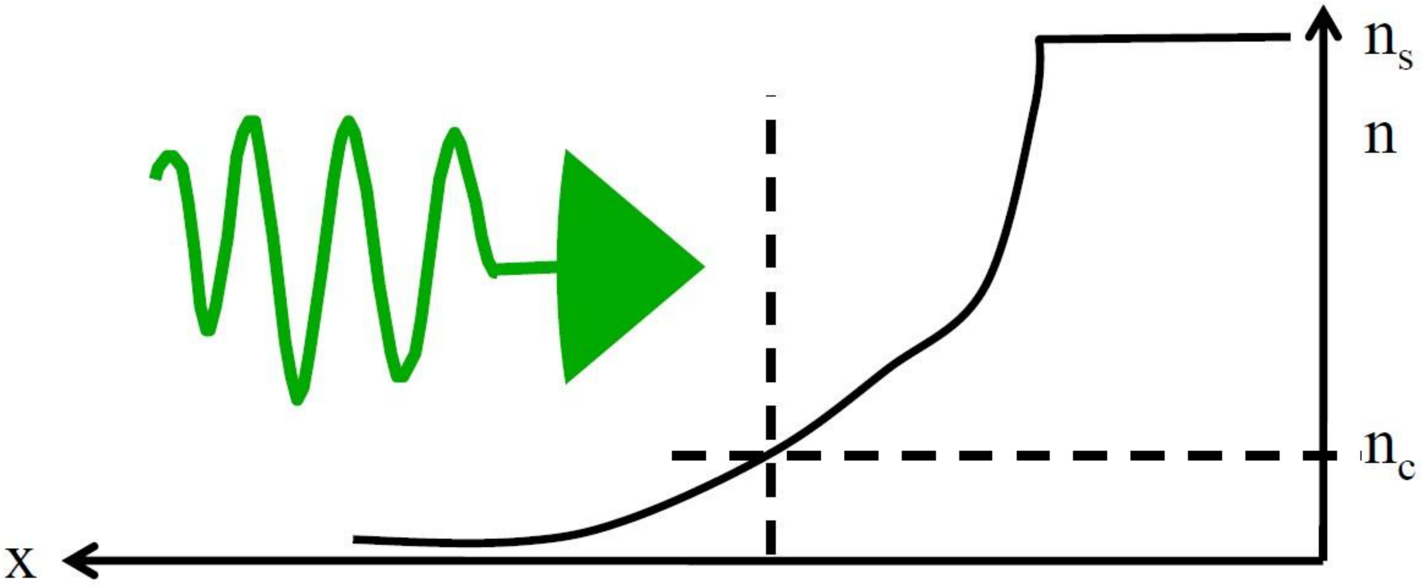
$$m\frac{d^2\delta x}{dt^2} = -eE = -\frac{e^2 n_e \delta x}{\varepsilon_o}$$

$$\delta x = \delta x_o \cos \omega_p t$$

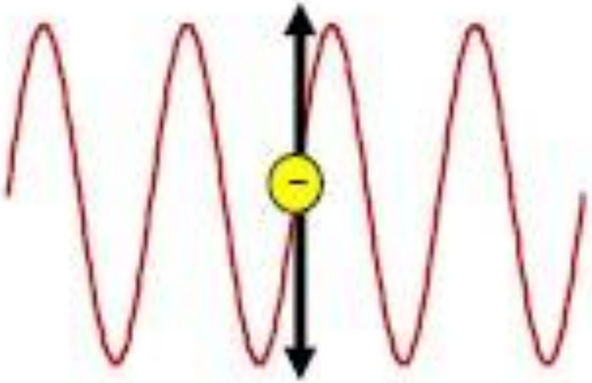
$$\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_o}} = \sqrt{\frac{4\pi n_e e^2}{m}} = 5.64x10^4 \sqrt{n_e(cm^{-3})} s^{-1}$$

# The Action is at Critical Density

- Whatever the density profile, light will propagate up to $n_c$
- Light couples to electrons most strongly at $n_c$
- If intensity is high enough (relativistic) → $\gamma n_c$
- For solid density → above critical density
  - Different laser interactions
- Question is always → what is the density profile?



# WIGGLING ELECTRONS



$$E(\vec{r},t) = E_o(\vec{r},t)\cos\omega t$$

$$F = -eE(\vec{r},t) = ma$$

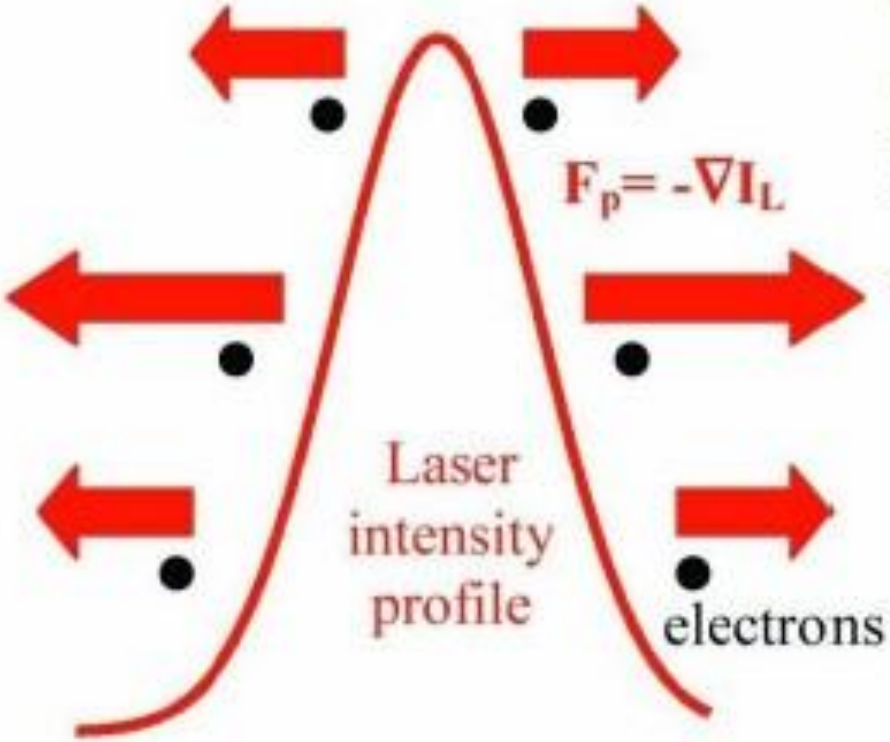
$$\langle KE \rangle \approx U_p(\vec{r})$$

$$U_p(\vec{r}) = \frac{e^2\left|E_o(\vec{r})\right|^2}{4m\omega^2} \sim I\lambda^2$$

$U_p$ ~ few eV @ I ~ $10^{13\text{-}14}$ Wcm$^{-2}$

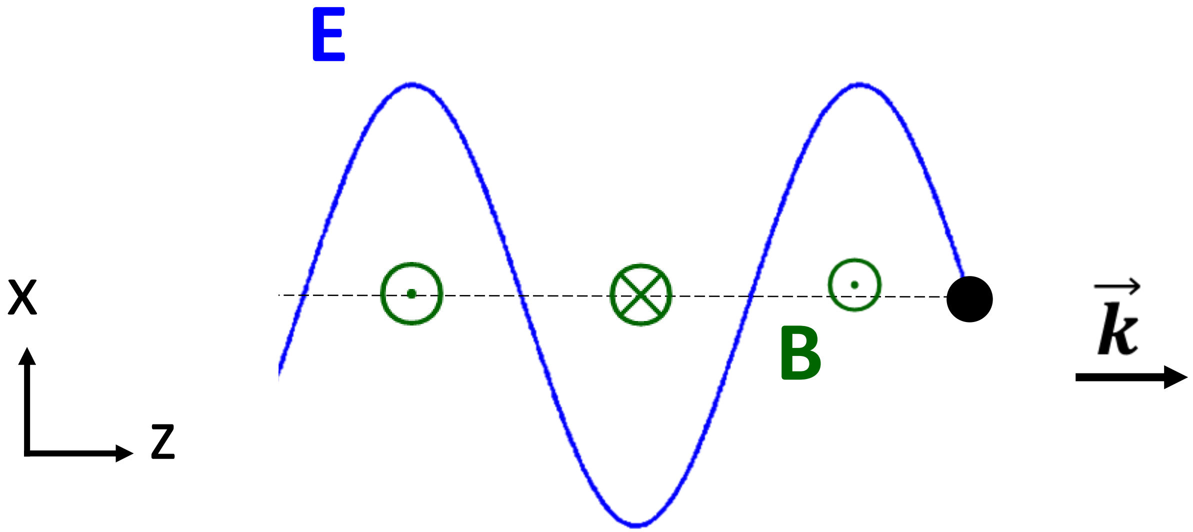
# Ponderomotive Force

Force on charged particles → Gradient of intensity



Average over an optical period to get a quasi-static force …. Varies as the pulse envelope varies in time

# When an electron interacts with an intense laser, the Lorentz force due to the laser B field plays an important role



- In a plane wave, cB = E
- When $v_x$<<c, -$ev_xB$ << -eE, Lorentz force is often neglected
- This is a significant effect when $I\lambda^2 > 10^{18}$ μm$^2$ W/cm$^2$

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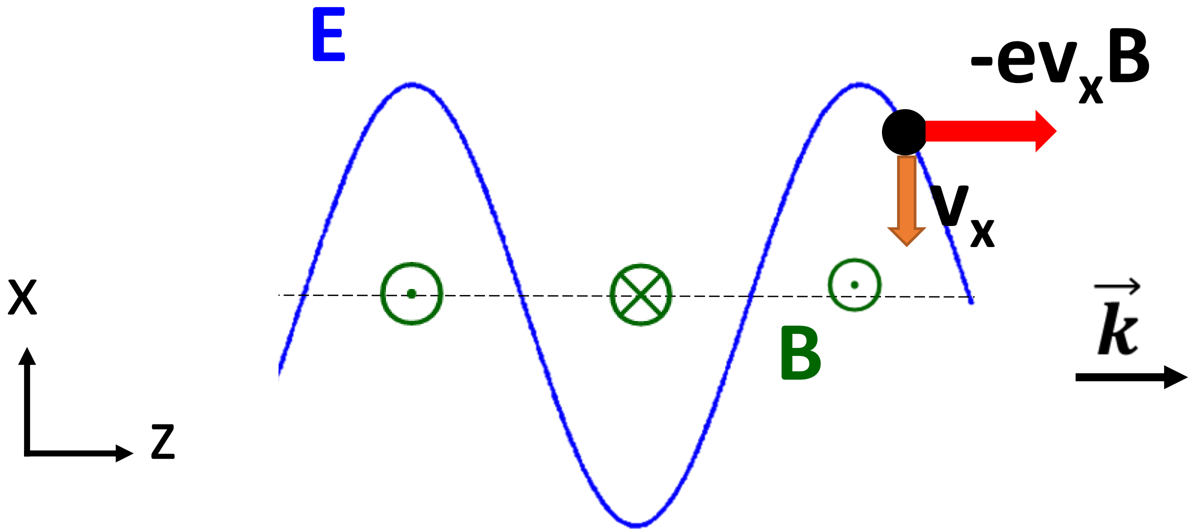

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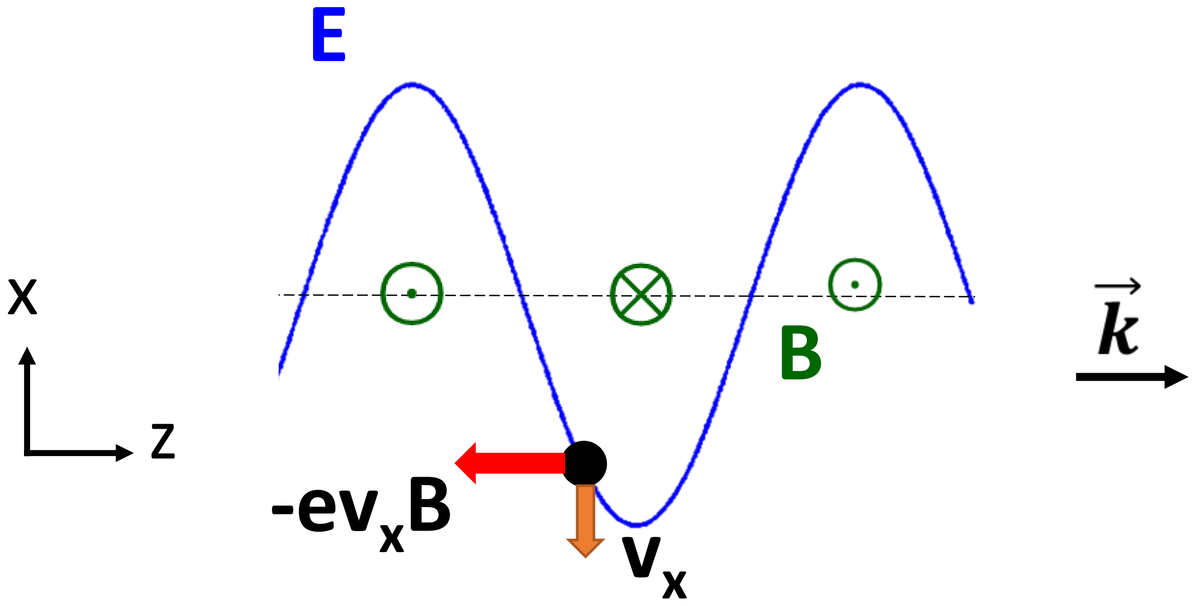

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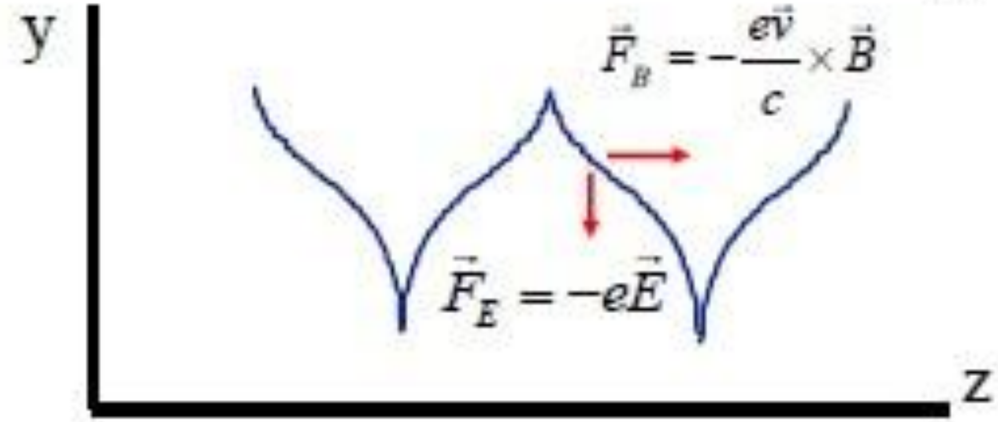
# Relativistic Intensities

Intensity rises → electron moves faster → relativistic

$$KE = E_T - E_0 = (\gamma - 1)E_o \qquad \gamma = \left[1 + \frac{I\lambda^2}{1.37x10^{18}\,Wcm^{-2}}\right]^{1/2}$$



Trajectory has forward motion due to magnetic force in plane polarized beam

- **At $10^{21}$ Wcm$^{-2}$ quiver energy is 13 MeV scaling as $I^{1/2}$**
- **Electric field is 100 kV/nm or 180 a.u.**
- **field ionizes bound electrons with up to 4 keV binding energy**

# Transport Issues

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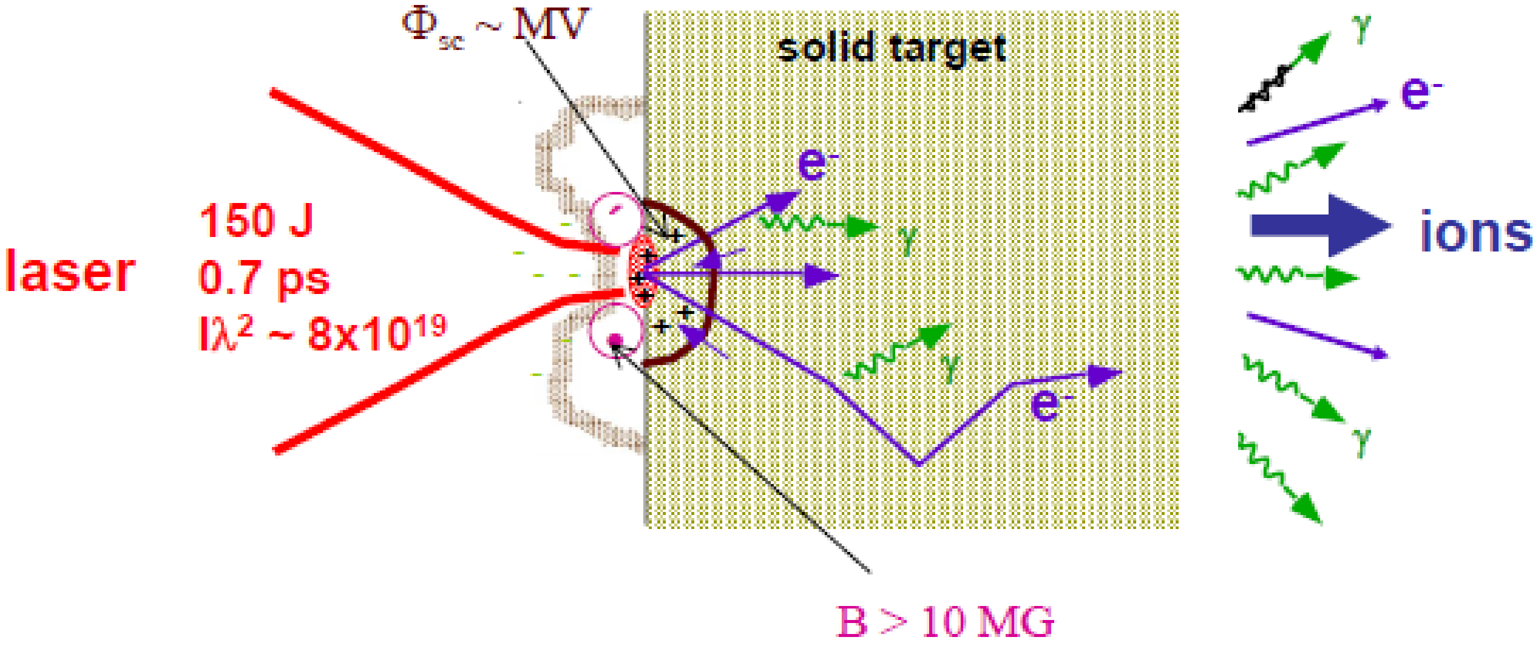


# Charge Separation Issues

- Start with neutral solid target
- Laser ionizes & creates hot electrons
- High speed electrons want to stream into solid BUT
- Hot electrons move away from positive ions
  - Massive electric fields build up & stop electrons
  - We know they stream into material
  - HOW?
- Recall solid density contains lots of low energy electrons
  - So called cold or background or plasma electrons
  - These supply charge & current neutralization

# Hot vs Cold electrons

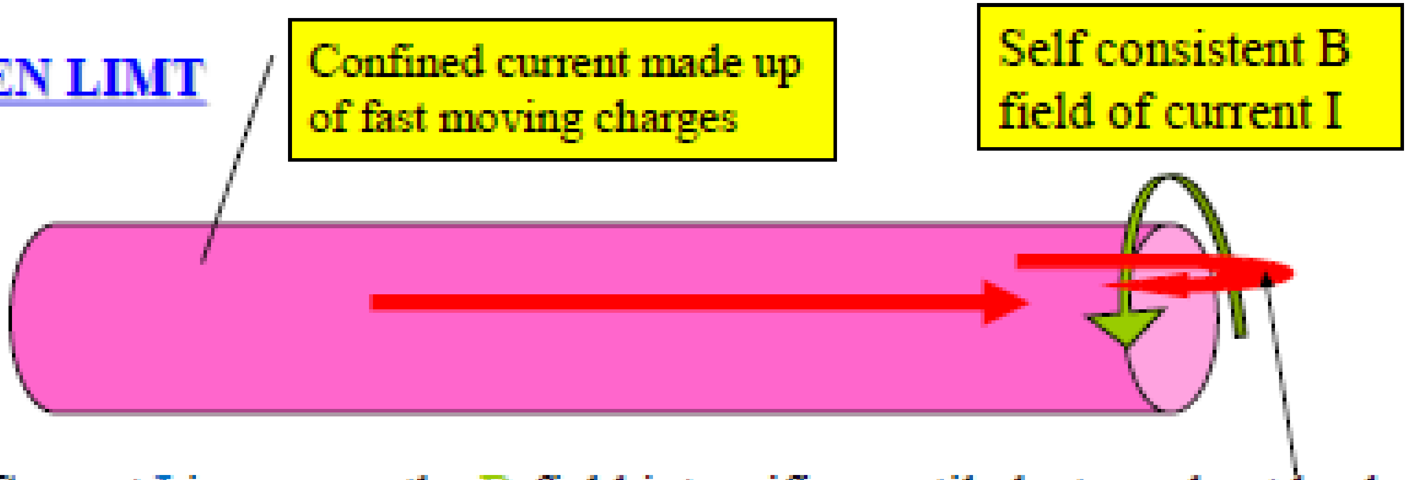
- Laser generated hot electrons ~ MeV energies
- Background cold electrons ~ temperature of material
  - Hot electrons couple to material weakly
  - Lower energy hot electrons couple to material
  - Temperature rises for cold electrons & resistivity changes
- Typical experiments → mega-amperes of hot electrons

$$\vec{j}_h = -en_h\vec{v} \approx -en_h\vec{c}$$

- Low density but very high speed
- Can a net current flow?

# Current Issues

## ALFVEN LIMT

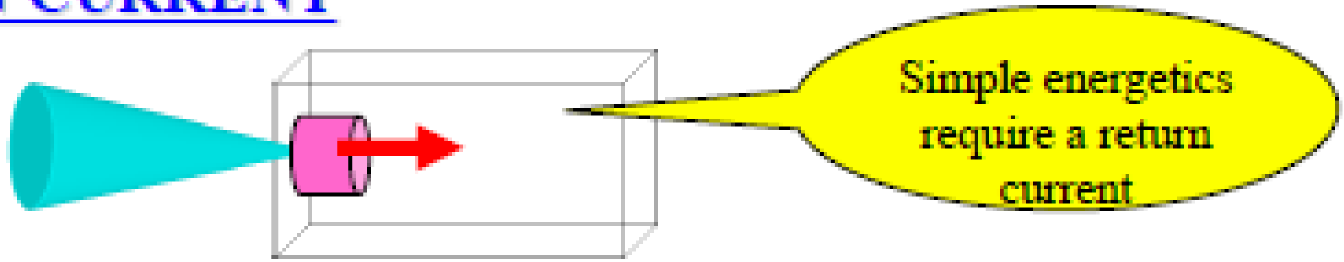


Confined current made up of fast moving charges

Self consistent B field of current I

Current I increases, the B-field intensifies, until electrons bent back upon themselves by v x B forces. In vacuum →17 βγkA

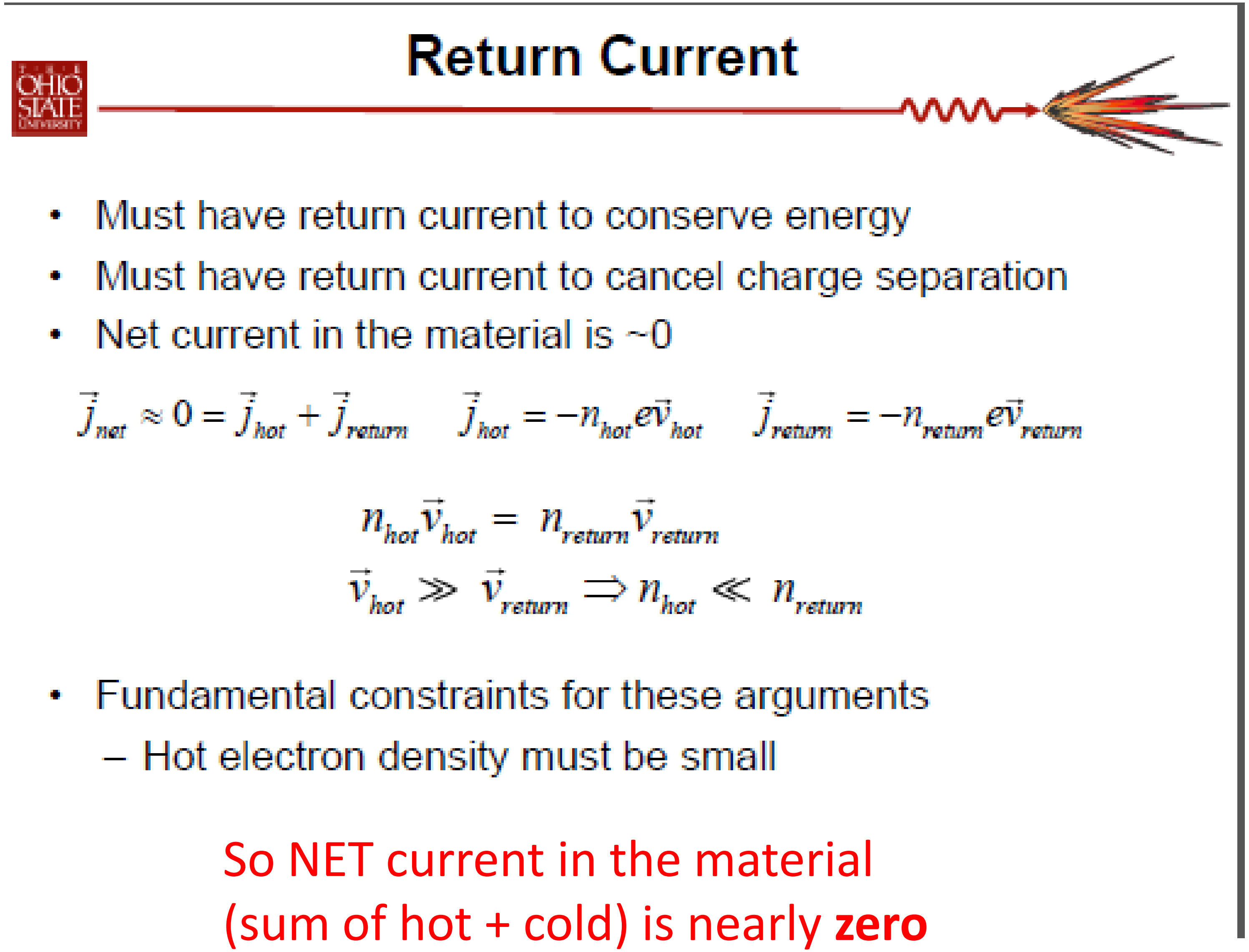
## RETURN CURRENT



Simple energetics require a return current

1 ps laser pulse focused to spot ~30 μm, absorbed intensity of $10^{18}$ W/cm$^2$ → energy per pulse ~7J, ($10^{14}$ fast $e^-$ @200keV); bunch ~60 μm in length (RMS 200 keV fast $e^-$ range in Al); magnetic field on surface of cylinder ~3200 MG →*magnetic field energy of 5 kJ!*

--A.Bell, et al., Plasma Phys Control Fusion 39 653 (1997)



# Return Current

- Must have return current to conserve energy
- Must have return current to cancel charge separation
- Net current in the material is ~0

$$\vec{j}_{net} \approx 0 = \vec{j}_{hot} + \vec{j}_{return} \qquad \vec{j}_{hot} = -n_{hot} e \vec{v}_{hot} \qquad \vec{j}_{return} = -n_{return} e \vec{v}_{return}$$

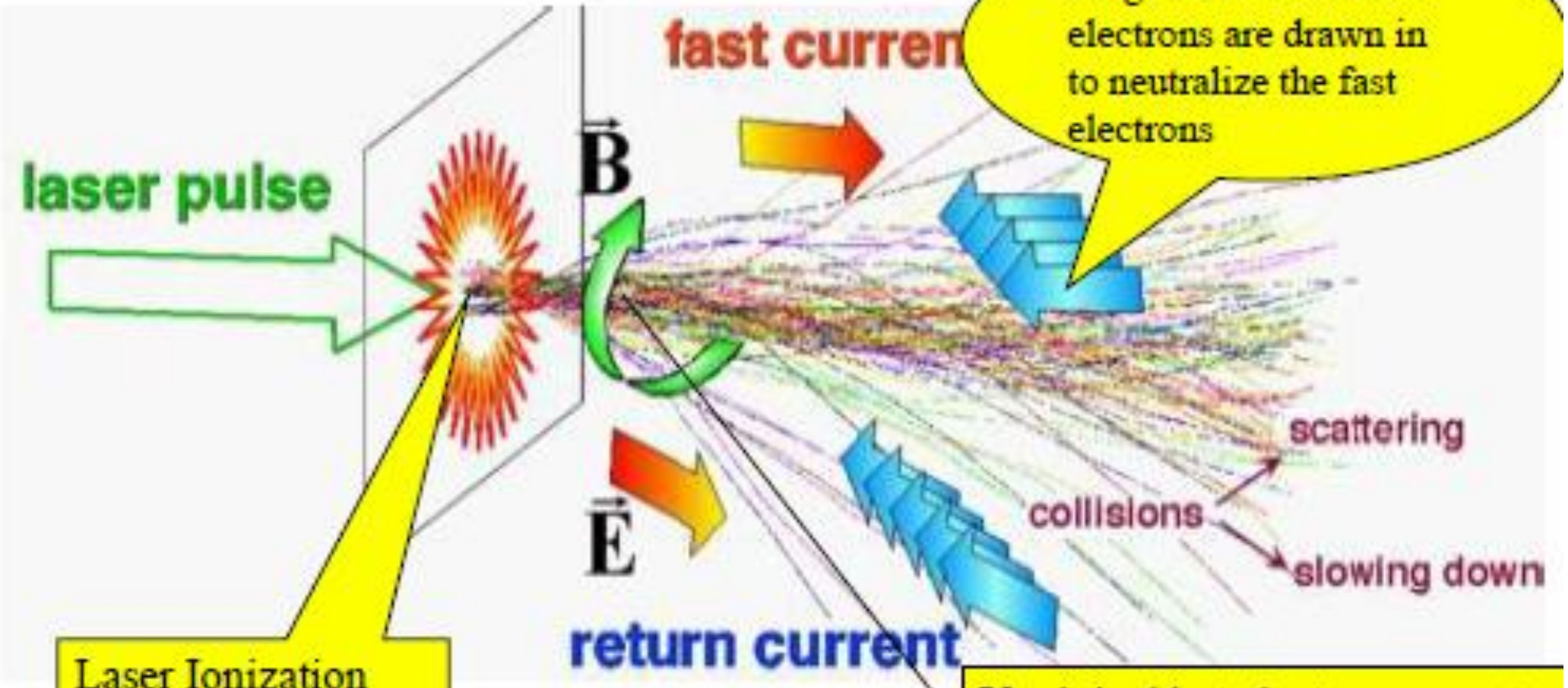
$$n_{hot} \vec{v}_{hot} = n_{return} \vec{v}_{return}$$

$$\vec{v}_{hot} \gg \vec{v}_{return} \Rightarrow n_{hot} \ll n_{return}$$

- Fundamental constraints for these arguments
  - Hot electron density must be small

So NET current in the material
(sum of hot + cold) is nearly **zero**

# The Picture



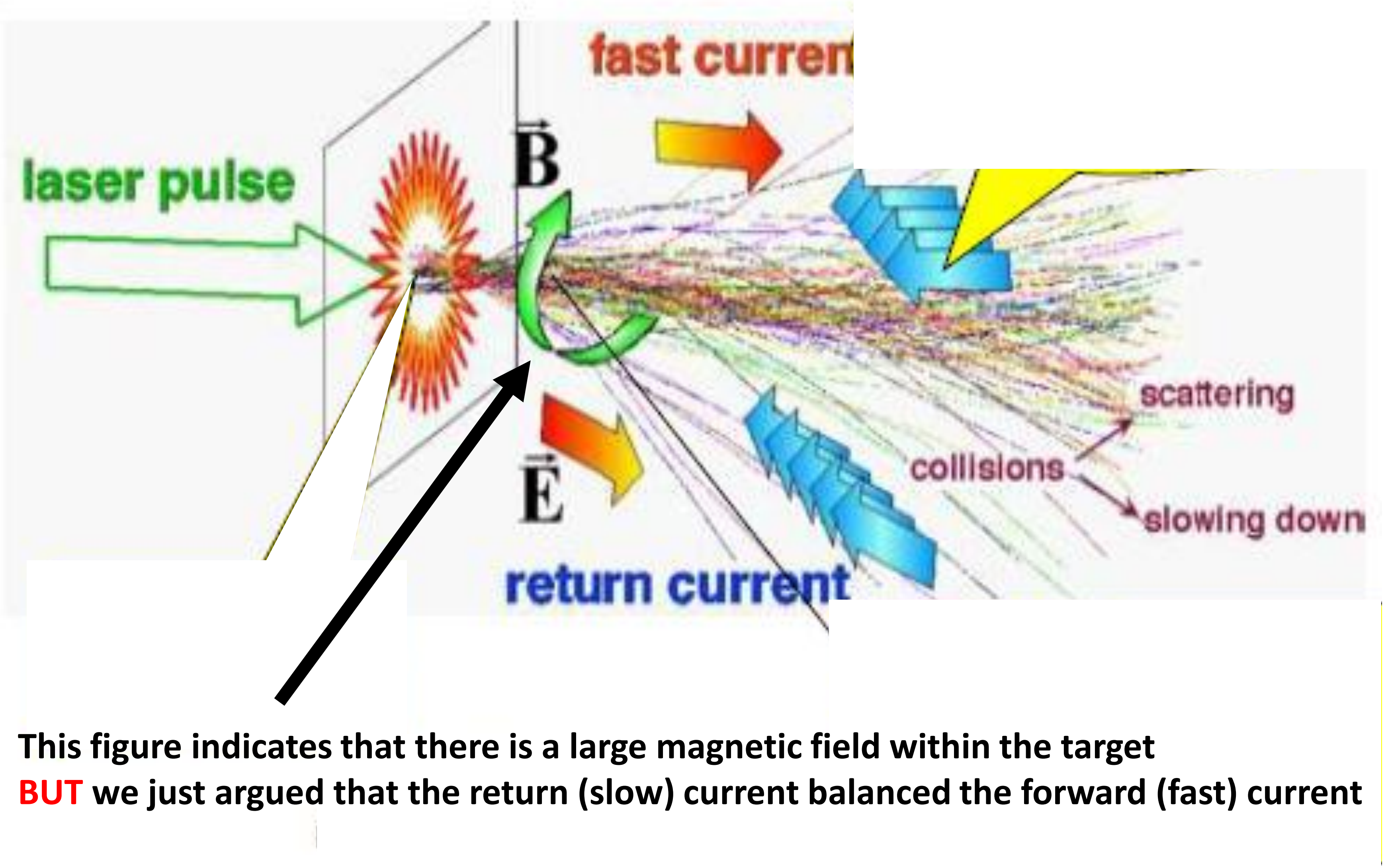
Large number of slow electrons are drawn in to neutralize the fast electrons

Laser Ionization creates fast forward electron stream

If original hot electron current exceeds Alfven limit, filaments into many small components, each separated by return currents

Hybrid PIC model ( Paris)
L Gremillet G Bonnaud,
F Amiranoff POP 9,941,(2002)

# The Picture



This figure indicates that there is a large magnetic field within the target

**BUT** we just argued that the return (slow) current balanced the forward (fast) current

# But wait, there’s more….

- Return current → cold, slow moving electrons
  - Coulomb cross section big
  - Resistivity big → much bigger than for hot electrons
  - Cold electrons “see” high resistivitiy
  - Set up electric field E=ηj
  - This field slows down the hot electrons
  - Known as Ohmic inhibition

**AND**

$$\frac{\partial \vec{B}}{\partial x} = -\vec{\nabla} \text{ X } \vec{E}$$

# Transport Issues

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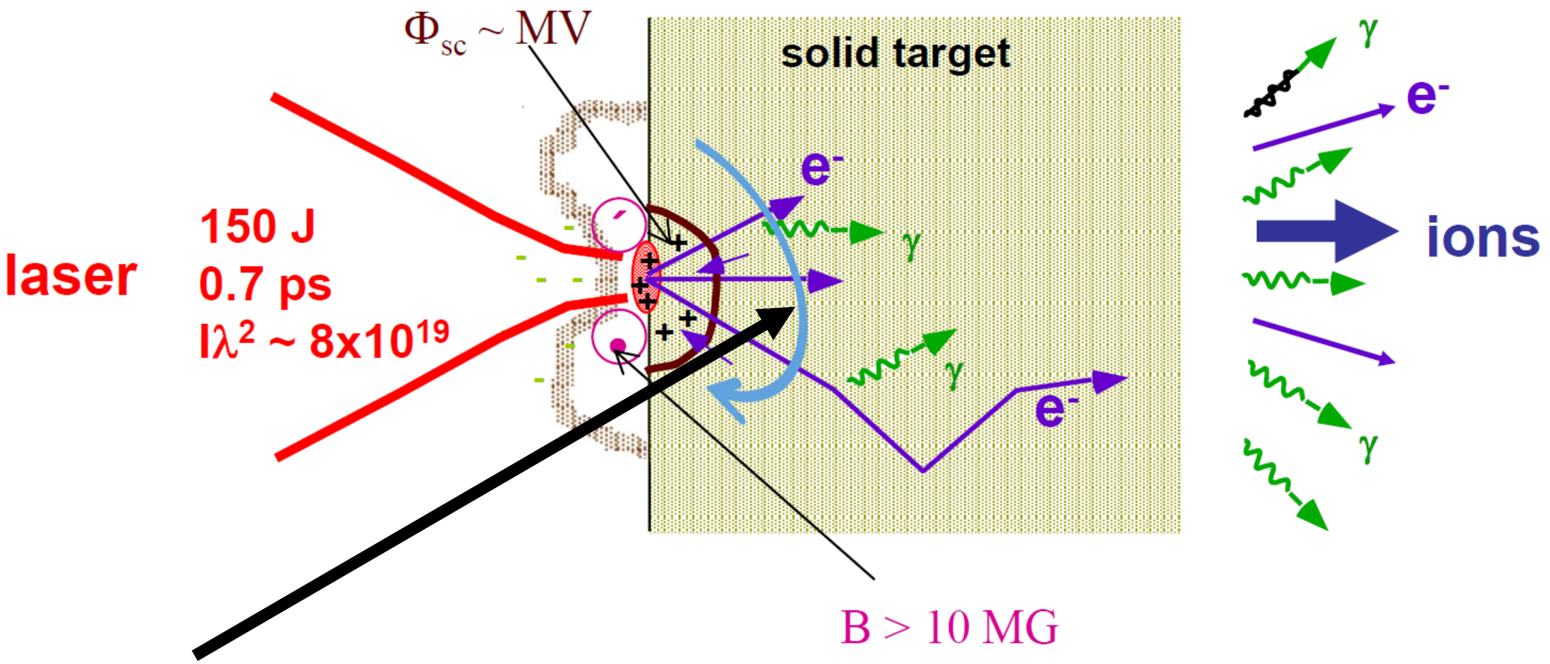
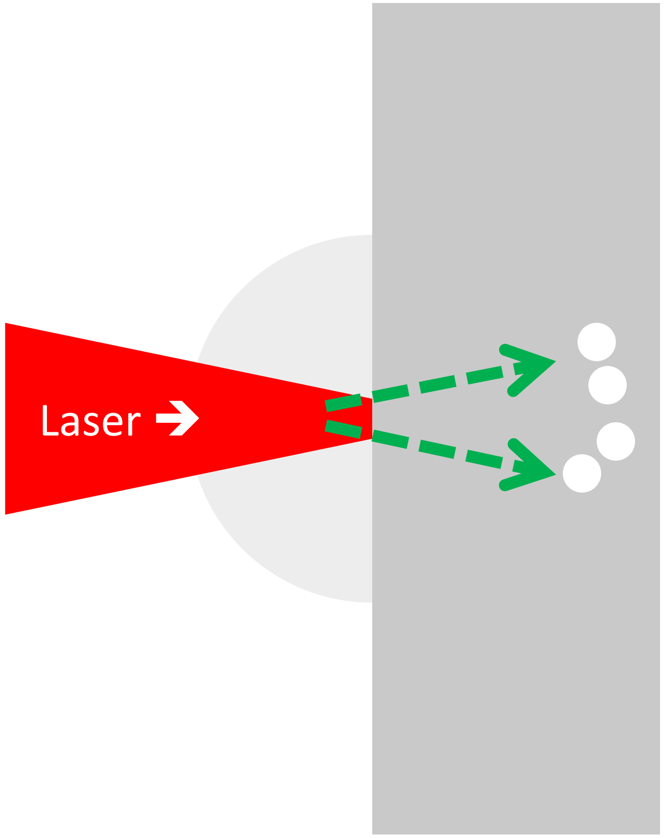
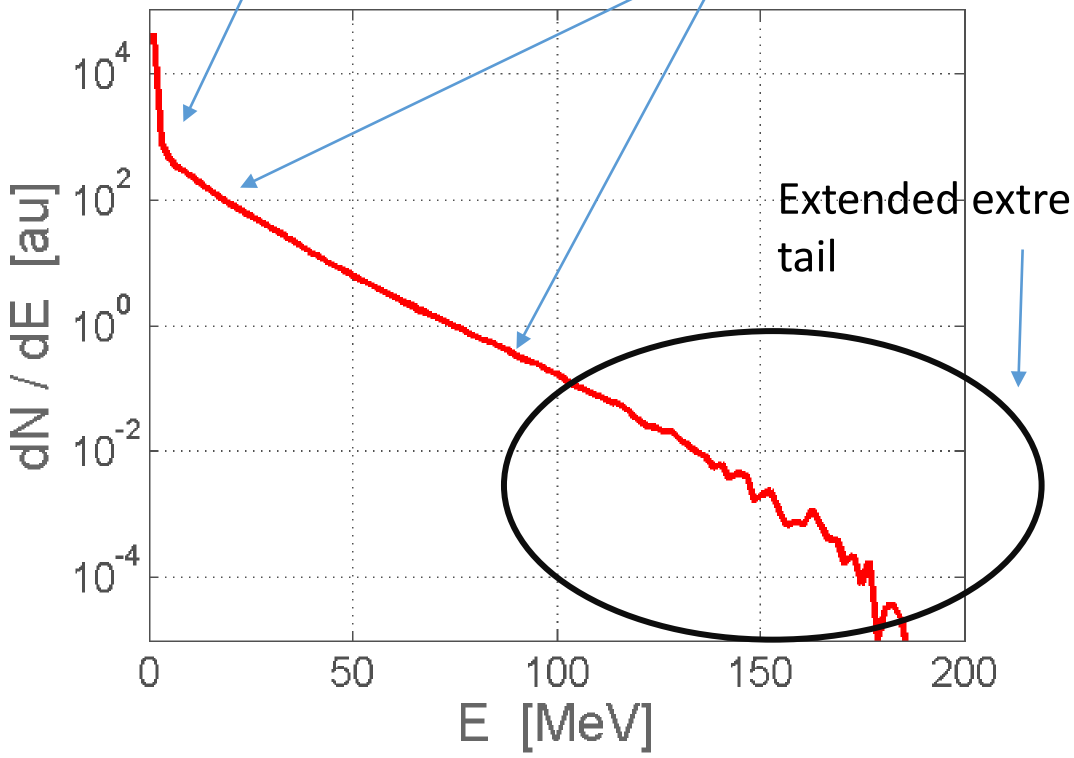


**Large internal magnetic fields arising from CURL of the Ohmic electric field due to return current**

# The typical electron energy spectrum is quite broad



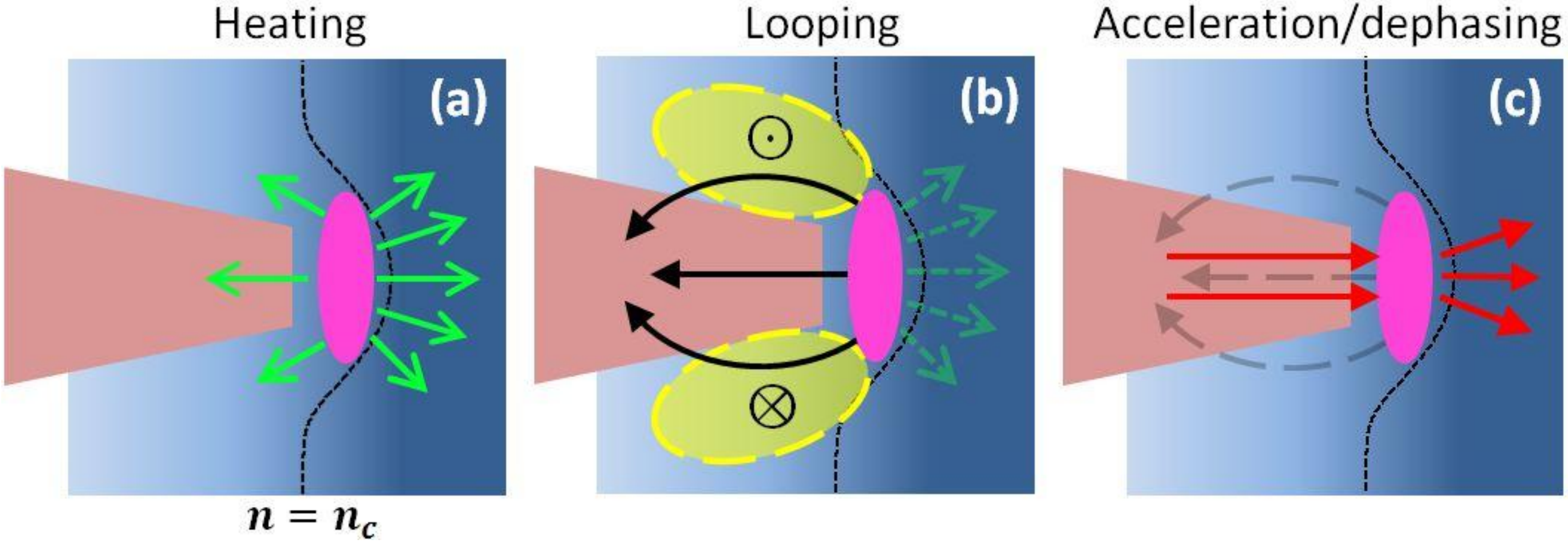


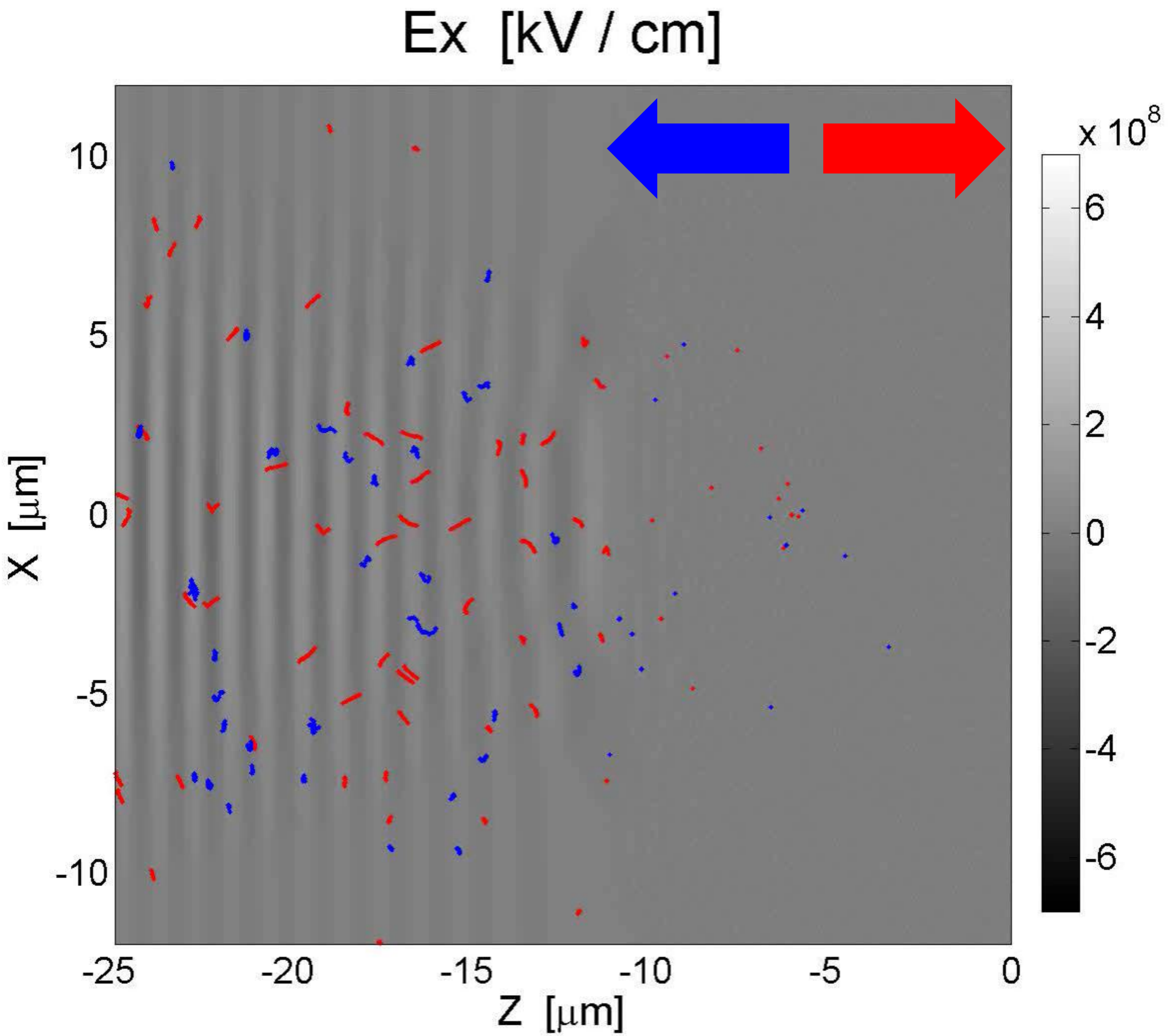
Target expansion (Link)

Ponderomotive Heating (Wilks)

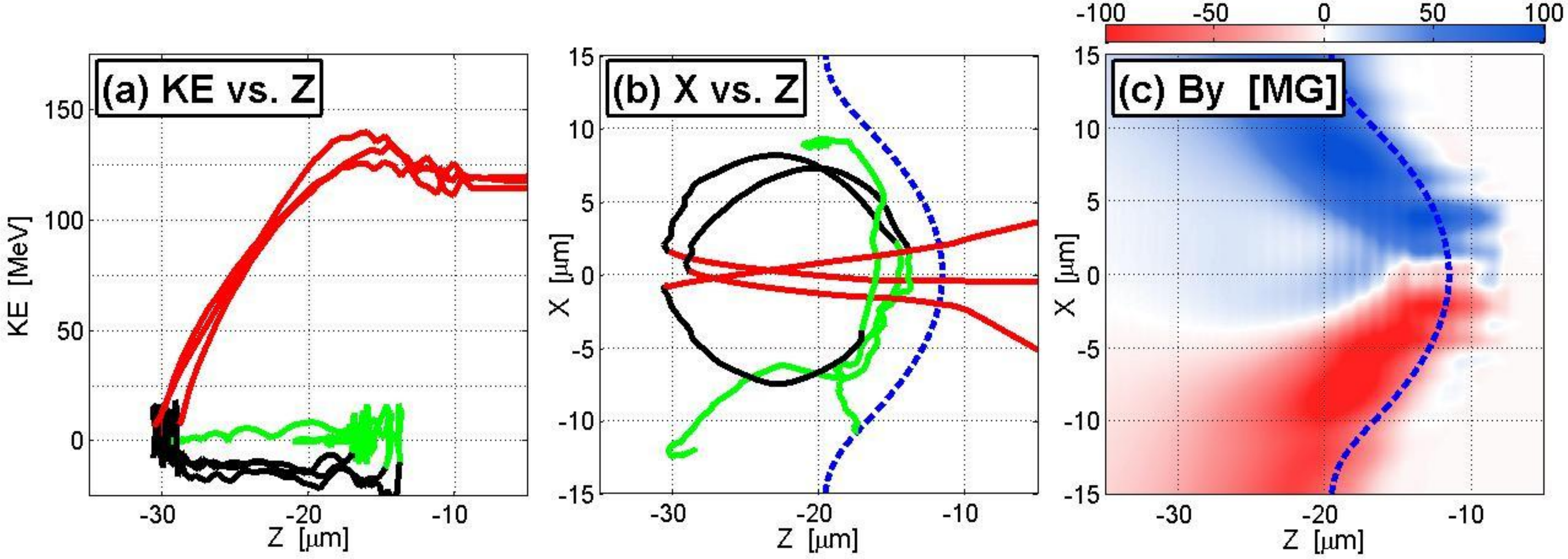
Extended extreme high energy tail

# “Loop-injected direct acceleration” is a simple 3 step injection mechanism




Ex [kV / cm]
x 10^8
6
4
2
0
-2
-4
-6
10
5
0
-5
-10
X [μm]
-25
-20
-15
-10
-5
0
Z [μm]

# Sample tracks show LIDA mechanism

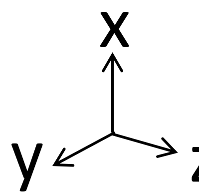


**Green** shows early heating stage

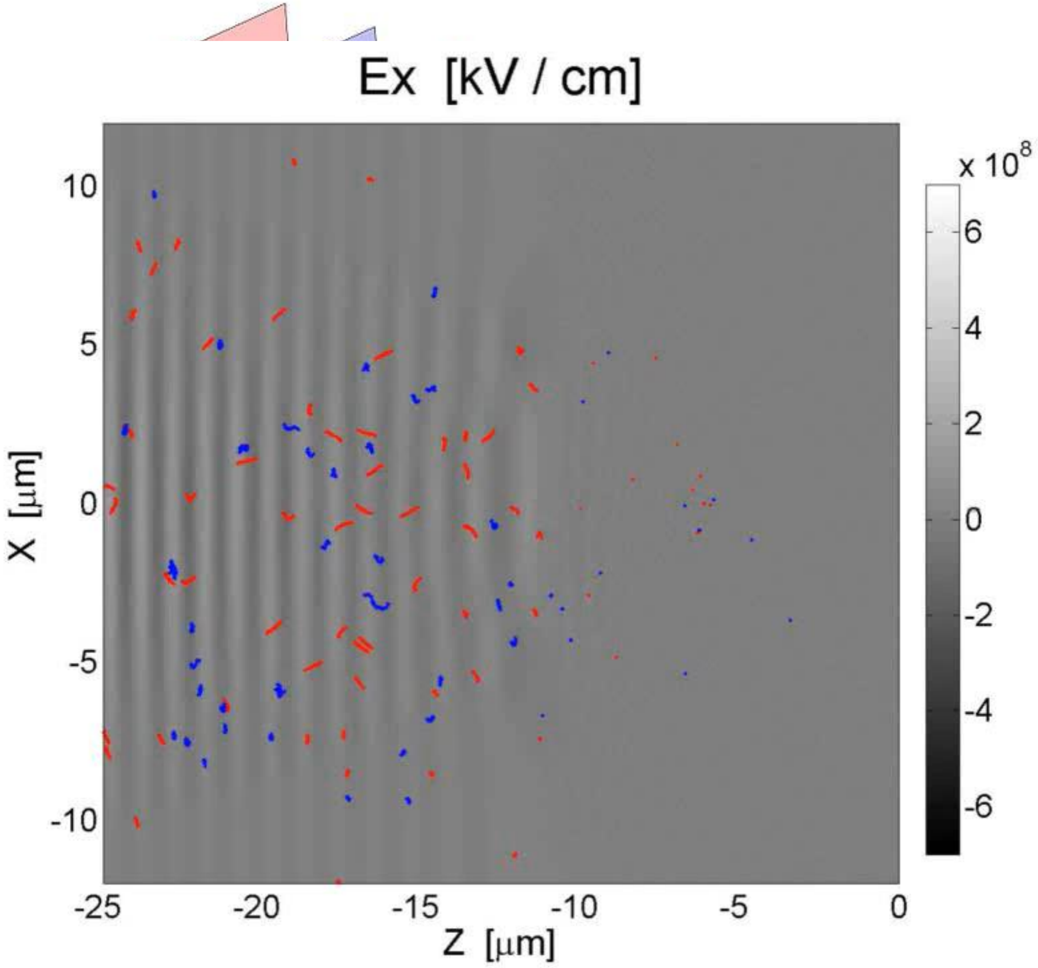
shows looping stage

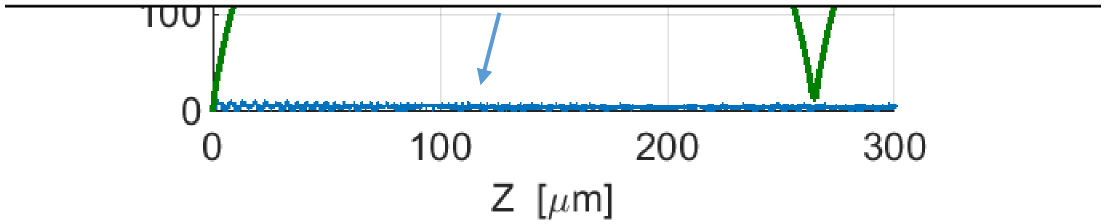
**Red** shows DLA and dephasing stage

# Electron can be accelerated to high energies by direct laser acceleration using a high intensity laser



λ = 800nm





# LIDA dominates “hot tail”