The Ion Collapse Problem in Plasma Wakefield Accelerators

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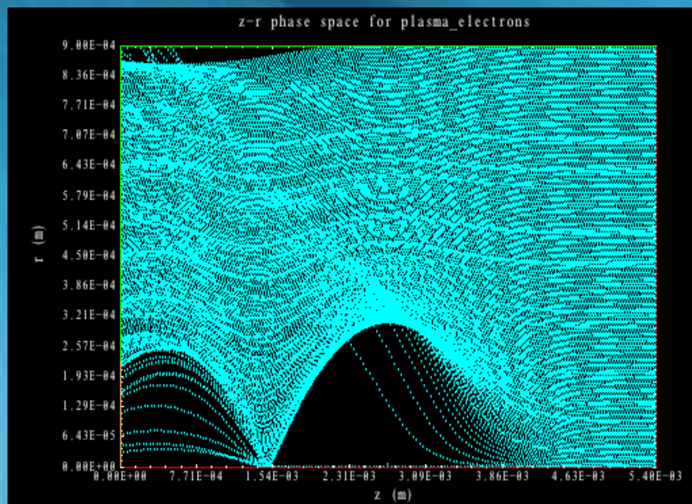
Introduction

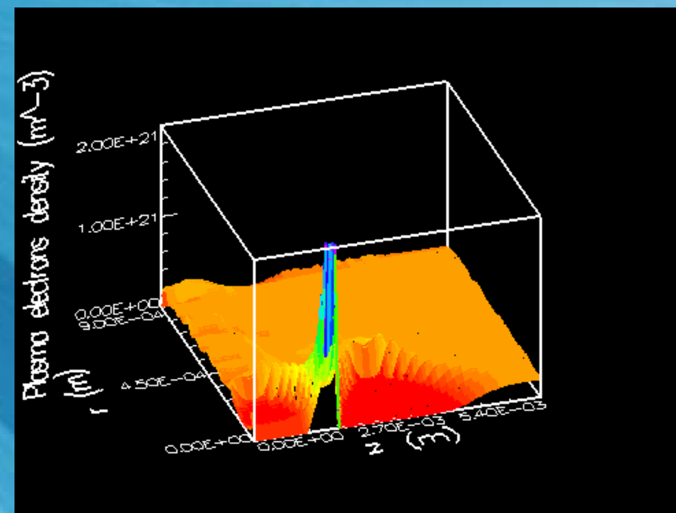
- Plasma wakefield accelerators are commonly conceived now in the “blow-out regime” $n_b >> n_0$
- Plasma electrons completely rarefied from beam channel
  - No net focusing force
  - Induced EM accelerating field

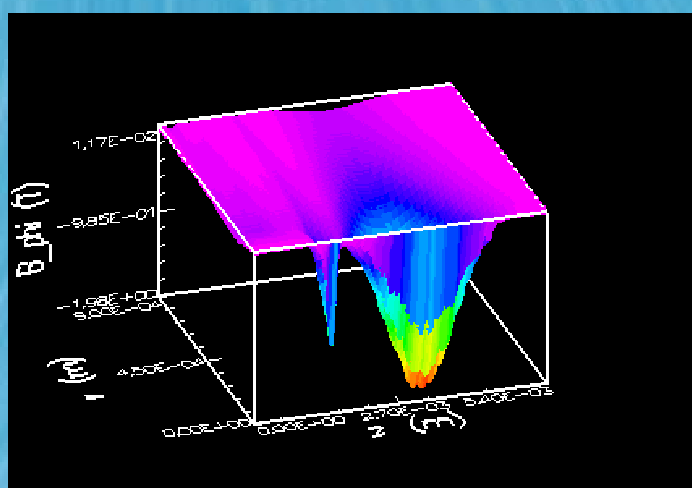
$$F_{r,EM} = -e\left[E_r - H_\phi\right] \cong 0$$
$$E_{z,EM} \neq f(r)$$

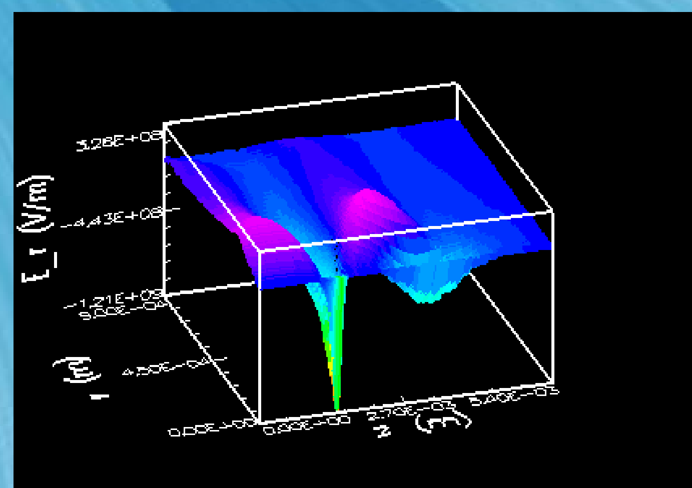
- *Uniform* ion density left behind, give net *linear* focusing $F_{r,i} = -2\pi e^2 n_i r$

Pictorial of the physics (OOPIC)







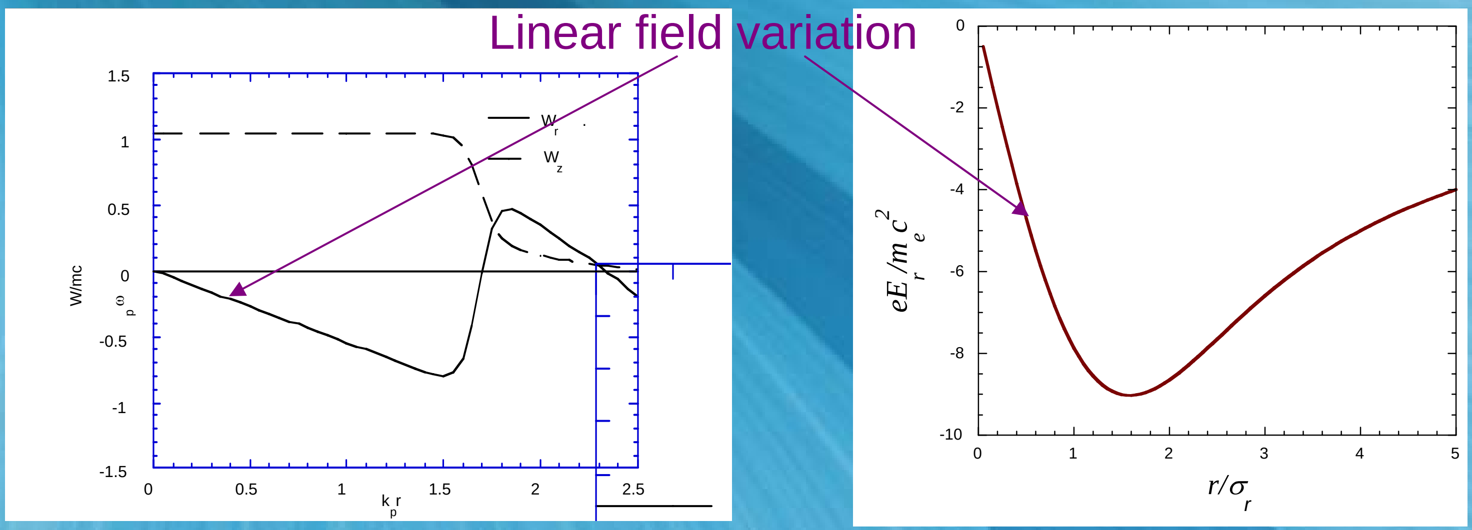


$$n_{b,\max} = 20 n_0$$

All species experience different transverse forces

- *Plasma* electrons experience
  - First electrostatic component of beam field
  - Magnetic component of beam field (oops, longitudinal!)
  - Restoring electrostatic force of plasma ions
- *Beam* electrons experience
  - After blowout, only *electrostatic forces* from ions
- *Ions*, after blowout, dominated by
  - Electrostatic component of beam field
  - If $n_{b,\max} = (m_i / m_e) n_0$, then *violent ion* response

Transverse fields

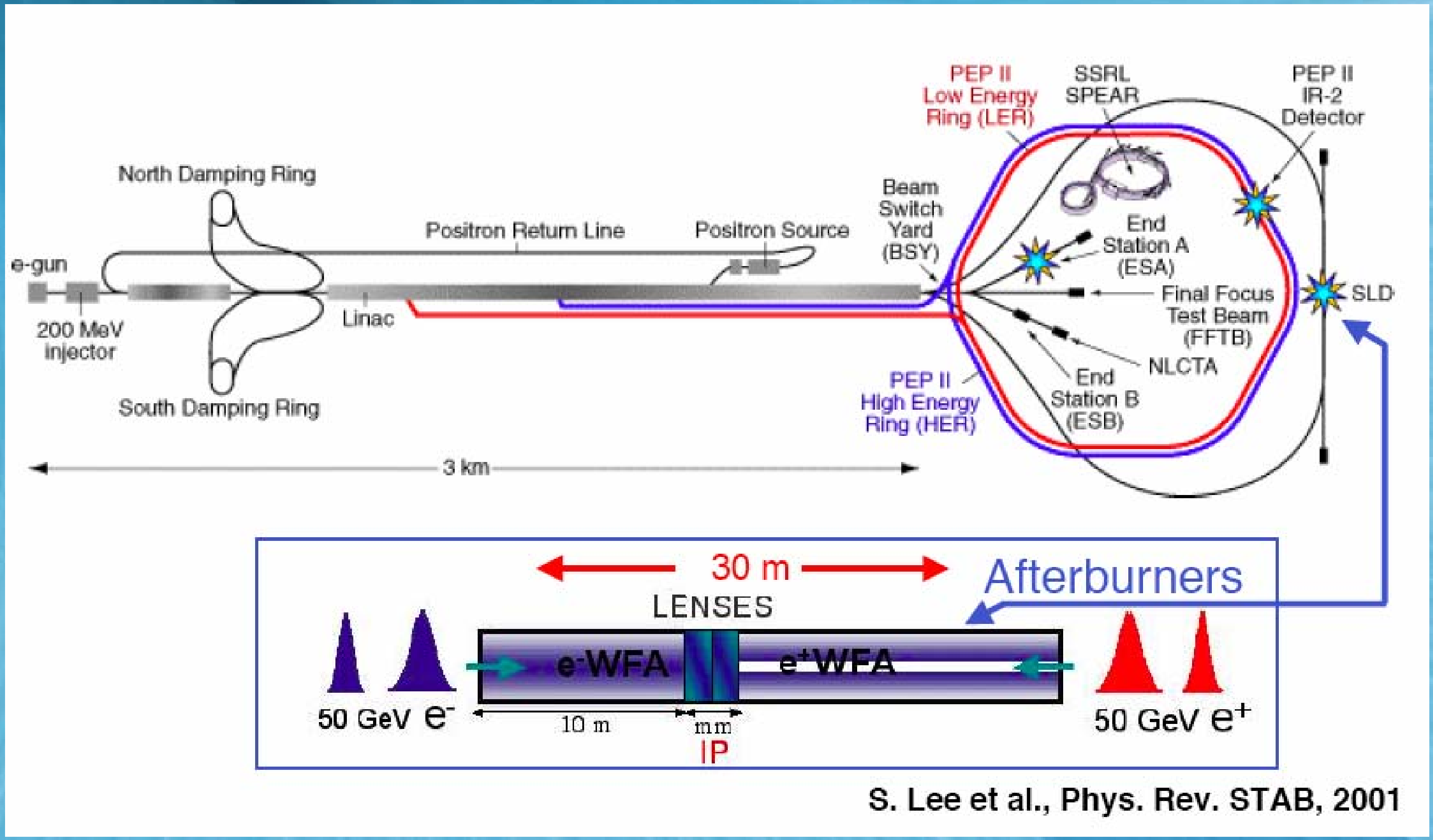


Net force on beam electrons inside of blowout region

Net force on plasma ions inside of blowout region

- Fields inside of beam, in blowout
  - Focus beam — linear focusing forces due to *stationary* ions
  - But... collapse ion distribution — nonlinear focusing due to beam

The “Afterburner”



- Double (or more) energy of conventional linear collider
- Exciting recent experimental results
- T. Raubenheimer gave talk at AAC04 on using concept at NLC

Some NLC numbers applied to afterburner scenario

Bunch population N_b	1.5×10^{10} (driver) 0.5×10^{10} (accelerating)
Bunch length σ_z	35 μm (driver/accelerating)
Normalized beam energy γ	5×10^{5} (250 GeV)
Accelerating beam emittances $\varepsilon_{n,x(y)}$	4×10^{-6} m-rad (4×10^{-8} m-rad)
Driving beam emittance $\varepsilon_{n,x}$	4×10^{-7} m-rad
Plasma ion density n_0	2×10^{16} cm^{-3}
Ion charge state Z	1 (hydrogen)

- Raubenheimer's linear collider scenario
- Equilibrium beam is very much denser than assumed! Beam density is *thousands* of times plasma
- Problem worse with energy

$$n_b \propto \sigma_x^{-2} = (\beta\varepsilon)^{-1} = \sqrt{\frac{\varepsilon_n}{2\pi r_e n_0 \gamma}}$$

Ion collapse

- Look at "linear" field region insider of beam $$E_r = -2\pi e n_{b,0} r = -\frac{eN_b}{\varepsilon_{n,x}\sigma_z}\sqrt{r_e n_0 \gamma}\, r$$
- Ion equations of motion $$\xi = z - v_b t \cong z - ct$$

$$r'' = \frac{d^2 r}{d\xi^2} = -\frac{Z r_a N_b}{A\varepsilon_{n,x}\sigma_z}\sqrt{r_e n_0 \gamma}\, r = -k_i^2 r$$

- Phase advance inside of beam

$$\Delta\phi = k_i \Delta\xi \cong k_i \sqrt{2\pi}\sigma_z = \sqrt{\frac{2\pi Z r_a N_b \sigma_z}{A\varepsilon_{n,x}}}\left(r_e n_0 \gamma\right)^{1/4}$$

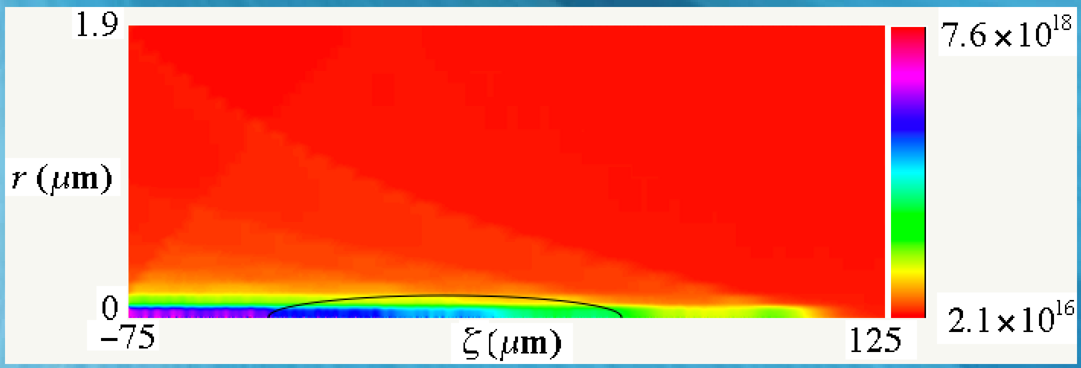
- If this is $\pi/2$, total collapse. For our case:

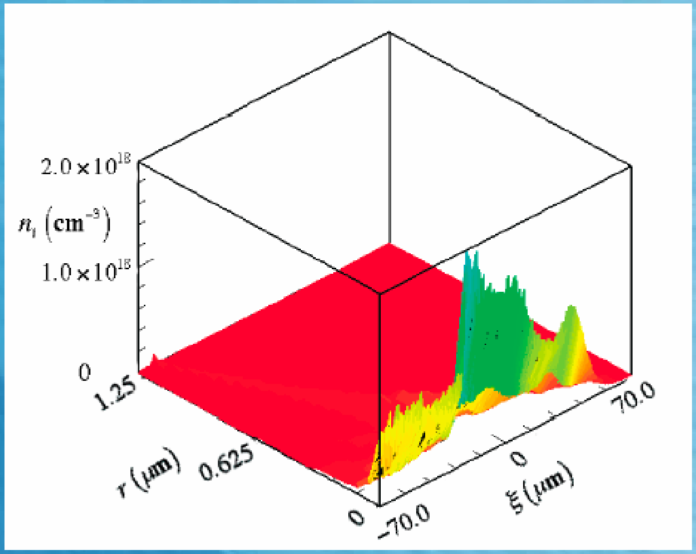
$$\Delta\phi = 6.45!$$

Why wasn’t this found before?

- S. Lee et al. analysis *not* self-consistent
- Chose beam size to be 25 μm
- Self consistent beam size is 0.18 μm for 4E-7 m-rad emittance
- Assumed beam is less dense by factor of 20,000
- Ion collapse phase advance is 0.1.

OOPIC simulations: afterburner driver





Two views of ion density in OOPIC simulation

- Self-consistent simulations, including mobile ions
- Density spike is >100 times ambient!
- Effect on beam matching and emittance disastrous

$$\frac{d\varepsilon_n}{dz} = 6 \times 10^{-4} \text{ m-rad/m}$$

- 100% emittance growth in 1 mm propagation

Accelerating beam

- Parameters set by collider needs
- Asymmetric emittances $\varepsilon_{n,x} >> \varepsilon_{n,y}$
- Beta-function same in *x* and *y, a*symmetric equilibrium beam sizes $\sigma_x >> \sigma_y$
- Electric field at beam transverse edges is same
- Collapse proceeds first by *vertical* motion

$$E_y = -\frac{4\pi e n_{b,0}}{(1+R)} y = -\frac{2eN_b\sqrt{r_e n_0 \gamma}}{\varepsilon_{n,y}\sigma_z(1+R)} y \approx -\frac{2eN_b}{\varepsilon_{n,y}\sigma_z}\sqrt{\frac{r_e n_0 \gamma}{\varepsilon_{n,y}\varepsilon_{n,x}}} y, \quad R = \sqrt{\frac{\varepsilon_{n,x}}{\varepsilon_{n,y}}} >> 1.$$

- Ion equation of motion $y'' = -\frac{2Zr_a N_b}{A\sigma_z}\sqrt{\frac{r_e n_0 \gamma}{\varepsilon_{n,y}\varepsilon_{n,x}}} y = -k_{i,y}^2 y$
- Ion wavenumber larger by $2^{1/2}$ for equal $\sqrt{\varepsilon_{n,y}\varepsilon_{n,x}}$
- For afterburner case: $\Delta\phi_y \cong 6.26$

Can ion motion be mitigated?

- Problematic solutions
  - Smaller beam charge (smaller wakes)
  - Lower energy (its an afterburner!)
  - Shorter bunch: not really, w/constraint $k_p\sigma_z = \sqrt{2}$

$$\Delta\phi = \sqrt{\frac{Zr_a N_b}{A\varepsilon_{n,x}}}(\pi\gamma)^{1/4}$$

Independent of bunch length

  - Less dense plasma? (smaller wakes, also ineffective)
  - Run *much* higher emittance
    - But...can't do it with trailing beam!

Solutions (and dissolutions)

- Are there better knobs?
  - Larger mass (*A*) ions?
- More revolutionary directions
  - Hollow plasma fiber (already needed for positrons)
  - Try vastly different beam parameters?
    - Scaling is “unnatural”, beam charge too big? We need to look...
    - Need completely different LC-consistent parameter set

Higher atomic mass

- Larger mass mitigates motion as $\Delta\phi \propto (Z/A)^{1/2}$
- Potential amelioration <10?
- Consider also multiple ionization
  - Beam surface fields are >1 TV/m!
  - 2nd ionization in Li is uniquely large: 76 eV

$$W_{ADK}\left[s^{-1}\right] \approx 1.52 \times 10^{15} \frac{4^{n^*}\varepsilon_0}{n^*\Gamma(2n^*)} \left(20.5\frac{\varepsilon_0^{3/2}}{F}\right)^{2n^*-1} \exp\left(-6.83\frac{\varepsilon_0^{3/2}}{F}\right)$$

ε_0 : ionization pot'l (eV)

F : electric force (GeV/m)

  - Example: Li exponent factor 0.016 for 2nd
  - High *A* materials may easily be doubly (and not uniformly) ionized

Experimental scenarios

- New proposal to NSF from UCLA
- Three options:
  - ATF experiment
    - Partial and full collapse scenarios
    - Ion motion detection
  - SABER, high ion energy
  - DARHT-like; ultra-long pulse, fusion scenario

ATF experiment

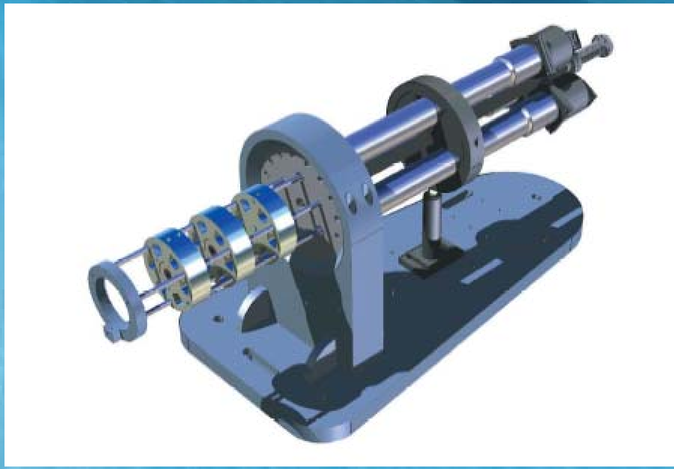
N_b	1.25×10^{10}
σ_z	1 mm
Norm. energy γ	141 (71 MeV)
Norm. emittance $\varepsilon_{n,x}$	2×10^{-6} m-rad
Plasma density n_0	10^{14} cm^{-3}
Ion charge state Z	1 (hydrogen)
Norm. beam density n_b/n_0	68
Matched β-function	0.9 cm

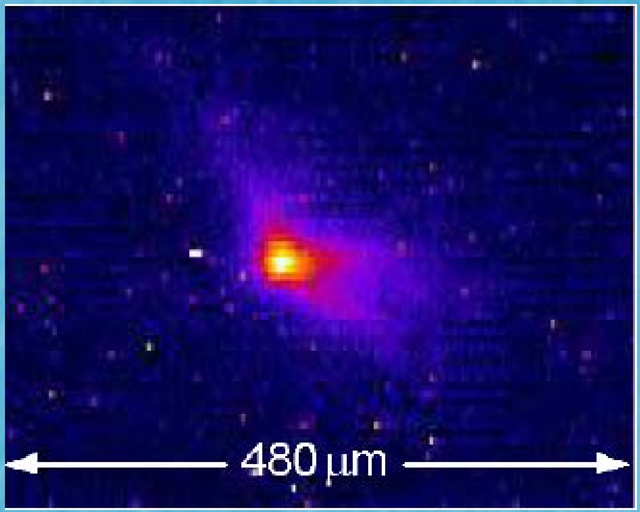
- 1st phase uses high charge (2 nC) uncompressed beam
- Measure ejected ions (H+) up to 750 eV
- Proposed to NSF

Velocity distributions from OOPIC: ions, plasma and beam e$^-$s

UCLA/FNAL plasma source

ATF experiment II





UCLA permanent magnet quadrupole
Buil t for LLNL PLEIADES

- 2nd phase dense capillary plasma $n_0 = 10^{16}\ \mathrm{cm}^{-3}$
- Denser beam due to higher ion focusing fields...
- “Long” beam $k_p\sigma_z = 19$
- Complete collapse $\Delta\phi = 1.9$
- Higher ion energies: 3.5 keV
- More difficult to β–match
  - Use PMQ array developed for ICS

SLAC SABER experiment

- Very high peak current
  - Not extreme density ratio
  - Ion motion limited to $\Delta\phi \cong 0.5$
- Large ion energies; cusp of fusion scenario
- Examining proposal
  - Coordinate with dielectric wake proposal

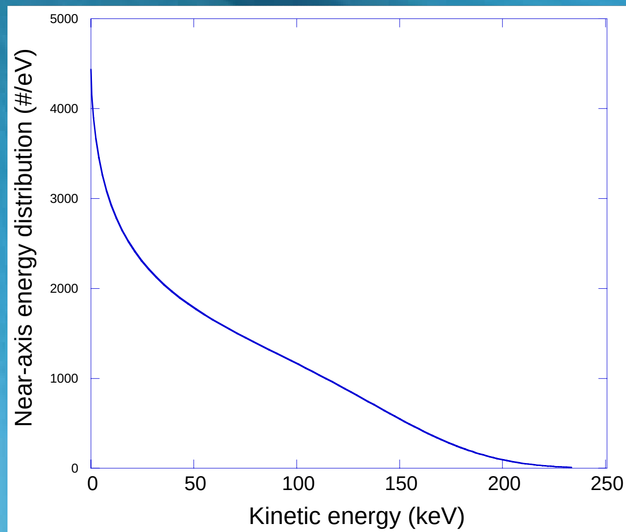
Ion energetics

- Radial force on ion $$ZeE_r = \frac{2ZI_b m_e c^2}{I_0 r}\left[1 - \exp\left(-\frac{r^2}{2\sigma_r^2}\right)\right]$$
- Convert potential energy to kinetic energy

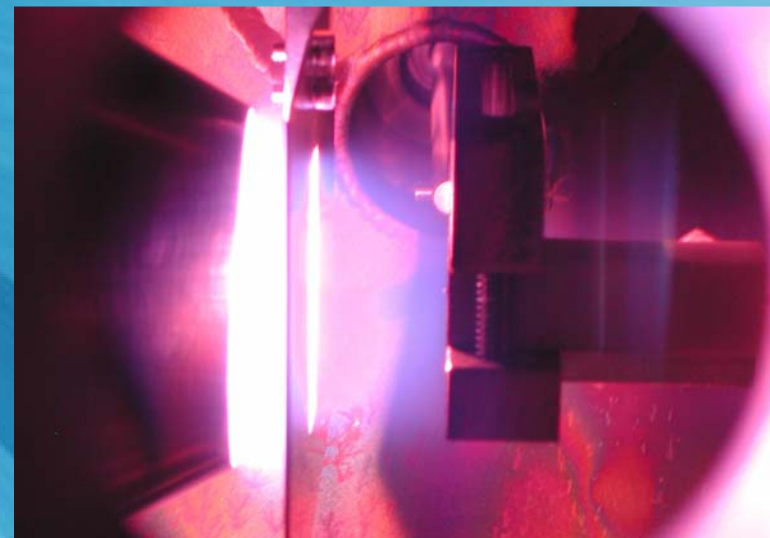
$$q\Phi_{\max} \approx \frac{ZI_b m_e c^2}{2I_0\sigma_r^2} r^2 \bigg|_{\text{beam edge}} \cong \frac{ZI_b m_e c^2}{2I_0}$$

- Depends only on current
  - Must have full collapse
- Fusion > 50 keV
- Rate
- Want long interaction...

Fusion-optimized experiment



Ion energy distribution
Ion energy distribution



UCLA-FNAL plasma lens source

- Use DARHT-like parameters
  - 2 kA, 200 mm-mrad beam, 2 nsec pulses
- Plasma: ~8E12/cc $k_p \sigma_z \approx 160$ $\Delta\phi \cong 20$
  - UCLA-FNAL plasma lens source with D,T admixture
- Rate fusion events/volume QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
  - Event rate during passage: $R = fV \approx 1.6 \times 10^{12}\ \mathrm{sec}^{-1}$

Conclusions

- More work needed on understanding consistency of LC needs and PWFA
  - High energy density scenario!
- On to experiments...