Ultra-Intense Beam Effects in Plasma Wakefields

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Outline

- Ultra-high intensity electron beams
- Plasma wakefields in the blowout regime
- Beam field-induced ionization
- Scaling of PWFA fields up to very high charge
- Ion collapse, implications for linear colliders and other plasma accelerators

Ultra-high intensity electron beams

- In recent year high energy beams (e.g. SLAC FFTB), have been produced with unprecedented intensity

  N_b=3x10^{10}, σ_z=20 μm, σ_x=10 μm
- Ultra-high transverse electric fields in vacuum

$$E_{r,\max} \cong \frac{2r_e m_e c^2}{\sigma_x \sigma_z} \approx 170\ \text{GV/m (present example)}$$

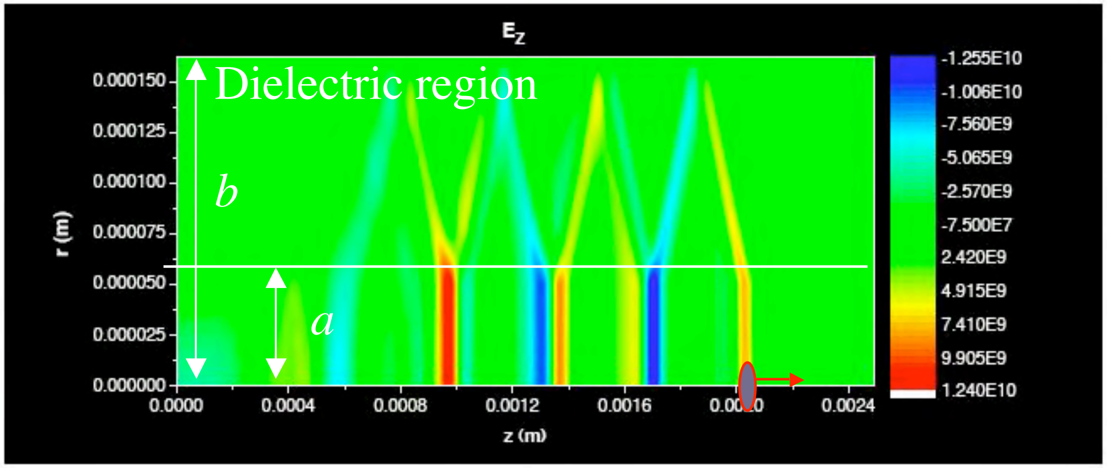
- What is the utility of this “hot” beam?
- High energy density, ultra-fast physics…

Wakefield accelerators

Example 1: Dielectric wakefields

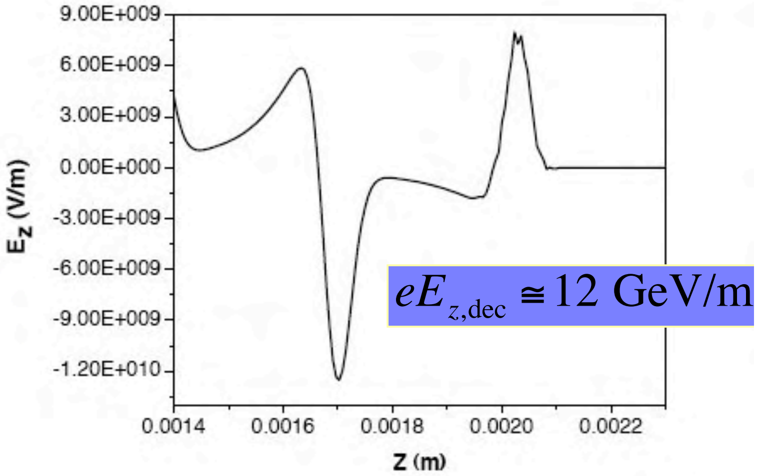
$$eE_{z,\text{dec}} \cong -\frac{2N_b r_e m_e c^2}{\sqrt{2\pi}\,\sigma_z a}\,\frac{\sqrt{\varepsilon-1}}{\varepsilon}$$

Note: $a \gg \sigma_x$



Simulated GV/m Cerenkov wakes for typical FFTB parameters (OOPIC -- Tech-X)

Contour plot showing E_z for a = 50 μm



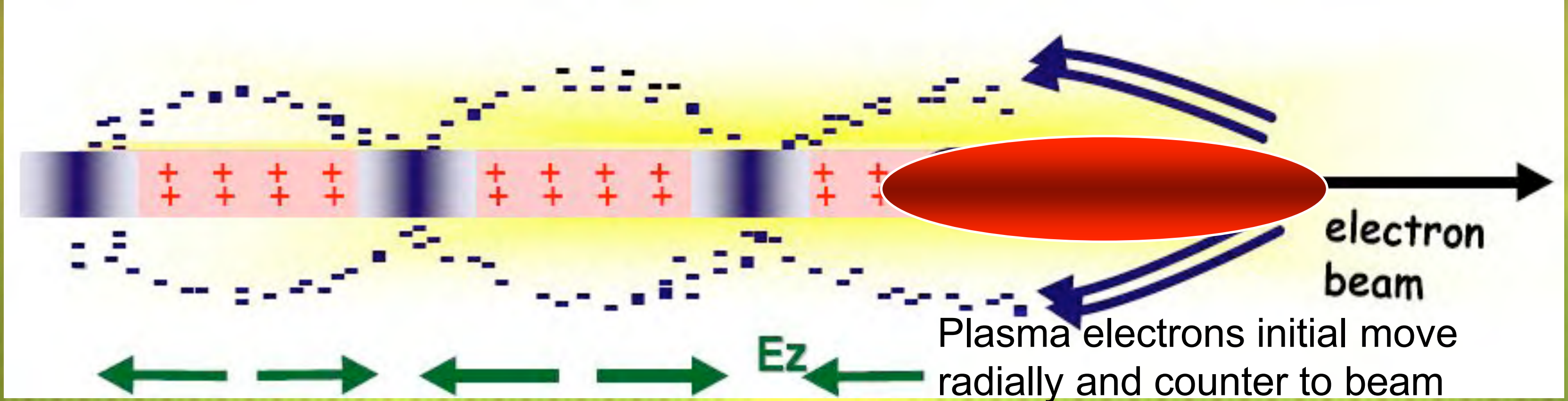
$eE_{z,\text{dec}} \cong 12$ GeV/m

Line out of E_z at r = 10 μm with a = 50 μm

Experiment at SLAC searching for breakdown (G. Travish, WG4)

Evading the material limits…

- For fields > several GV/m, materials breakdown and you have plasma
- **Ex. 2: Plasma Wakefield Acceleration (PWFA)**
- E-beam shock-excites plasma wave $\sigma_z < k_p^{-1}$ $k_p = \sqrt{4\pi r_e n_0}$
- Plasma electron motion mainly radial $\sigma_r < k_p^{-1}$
- Same *linear* scaling as Cerenkov wakes, maximum field strength goes as $E \propto e^2 N_b k_p^2 \propto N_b \sigma_z^{-2}$



Plasma electrons initial move radially and counter to beam

The modern PWFA: operation in the blow-out regime

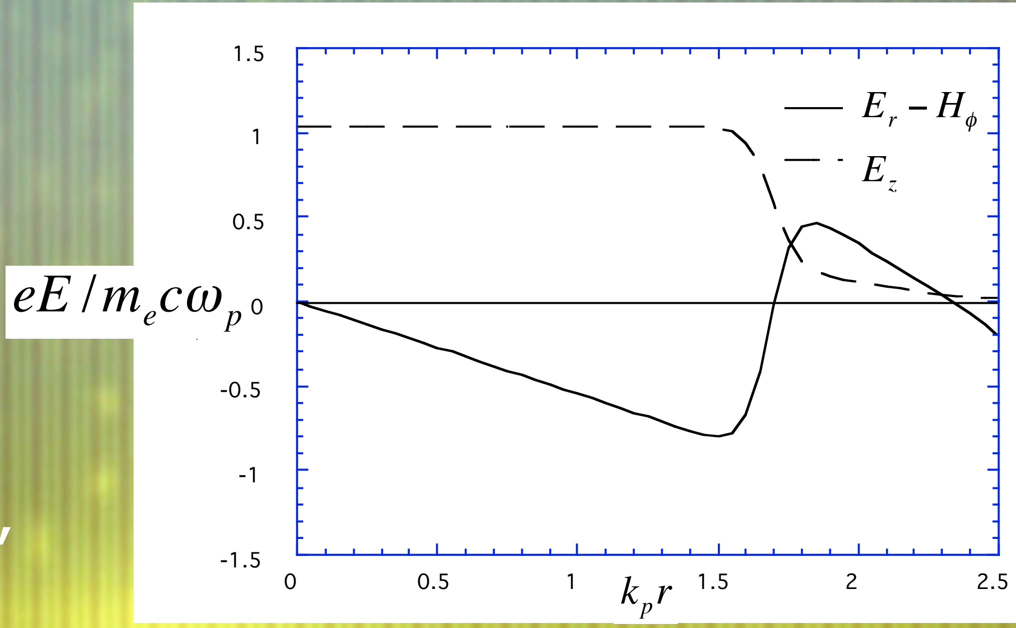
- Plasma wakefield accelerators are commonly conceived now in the "blow-out regime" $n_b >> n_0$
- Plasma electrons completely rarefied from beam channel
  - No net focusing force $F_{r,EM} = -e\left[E_r - H_\phi\right] \cong 0$
  - Induced EM accelerating field $E_{z,EM} \neq f(r)$
- Uniform (?) ion density left behind, give net *linear* focusing

$$F_{r,i} = -2\pi e^2 n_i r$$

- Matched β-function in plasma very small, giving sub-μm beam σ_x

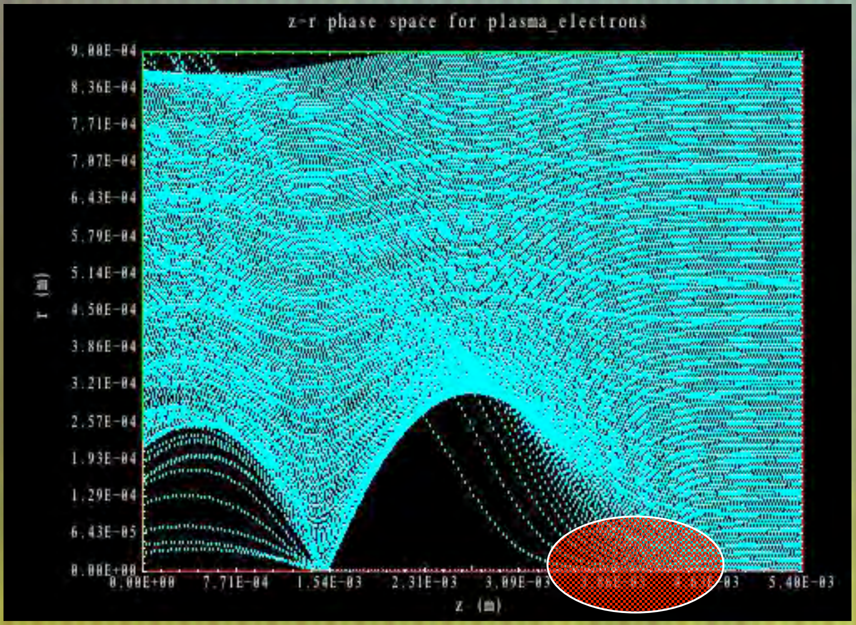
“Linear” fields seen by beam

- High quality fields inside of plasma-electron rarefaction
- Acceleration independent of *r*
  - Past ‘wave-breaking’
- Focusing linear in *r*

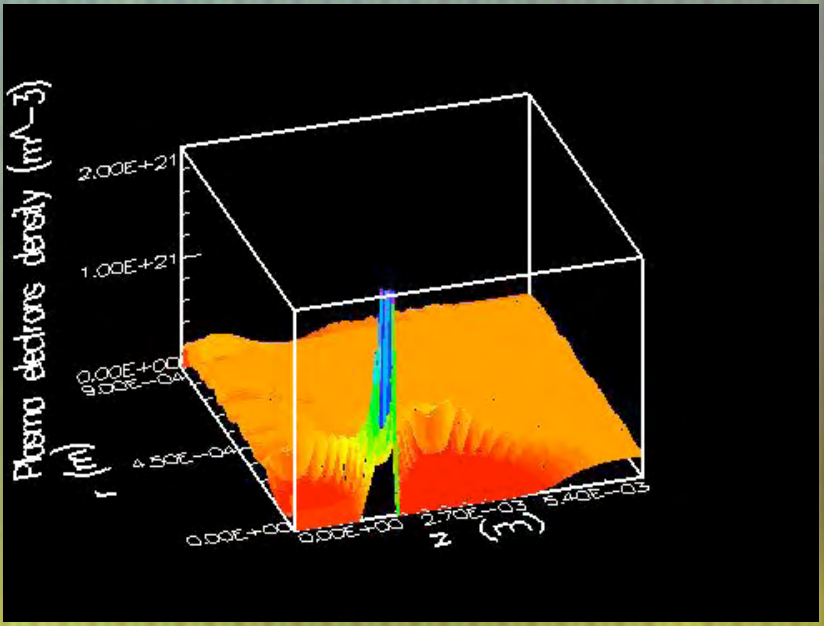


Fields inside plasma electron rarefaction region

Pictorial of the nonlinear plasma response (OOPIC)



Plasma electron distribution (*r*,*z*)



Plasma electron density (*r*,*z*)

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

Gauging the beam intensity needed for nonlinearity

- Ratio of beam density to plasma density (blowout) related to dimensionless measure of nonlinearity
$$\frac{n_b}{n_0} \approx \frac{\tilde{Q}}{\left(k_p \sigma_x\right)^2}$$
- Normalized charge (beam charge in cubic plasma skin-depth)
$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_0} = 4\pi k_p r_e N_b \begin{cases} <<1, & \text{linear regime} \\ >1, & \text{very nonlinear} \end{cases}$$
- Measure of field amplitude
  - Ratio of beam fields to induced plasma fields
  - Measure of magnetic field onset

Scaling of PWFA with respect to beam charge/plasma density

- From 1993 it was noted* in simulations that in the blowout regime the maximum field excited in PWFA scaled approximately as coherent Cerenkov radiation

$$eE_{z,dec} = e^2 N_b \int \left(n(k)-1\right)/n(k)\,dk \Rightarrow e^2 N_b k_p^2$$

- For finite bunch length, we must choose

$$k_p \sigma_z \leq 2$$

- Thus we have scaling with bunch length $$eE_{z,dec} \cong \frac{4e^2 N_b}{\sigma_z^2}$$

- Is this linear "Cerenkov" scaling really valid in blowout? Linear PWFA theory supports, but scenario v. nonlinear

*J.B. Rosenzweig, in *Proceedings of the 1992 Linear Accelerator Conference*, (AECL-10728, Chalk River, 1993).

*J.B. Rosenzweig, et al., Nuclear Instruments and Methods A **410** 532 (1998).

*N. Barov, J.B. Rosenzweig, M.E. Conde, W. Gai, and J.G. Power, *Phys. Rev. Special Topics – Accel. Beams* **3** 011301 (2000).

* S. Lee *et al*., Phys. Rev. ST Accel. Beams **4**, 011001 (2002).

Scaling in PWFA Experiments

- Shorter beams through compression $\tilde{Q}\uparrow$
- Ex: Large fractional energy gain and loss at UCLA/FNAL A0 experiment
- 15 MeV Beam, Q=5 nC, σ_z=2 ps (600 μm)
- Beam nearly stopped in 7 cm of plasma

- Accelerating wake is also stable; good efficiency

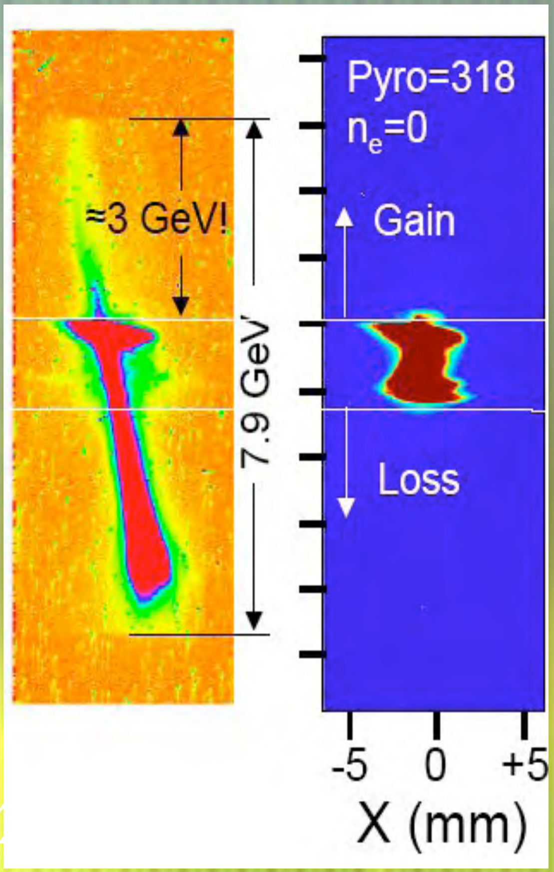
Acceleration to > 24.3 MeV (~130 MeV/m), 60% gain.

Ultra-high gradient PWFA: E164 experiment at SLAC FFTB

- Use extremely short beam
  - σ_z=20 μm
- Beam causes field ionization to create dense plasma
- Over 4 GeV(!) energy gain over 10 cm: 40 GV/m fields
- Self-trapping of plasma electrons due to enormous fields, ionization
- New experiments in nonlinear regime reported by Hogan
- Is “linear scaling obeyed?

$$\tilde{Q} = 80$$

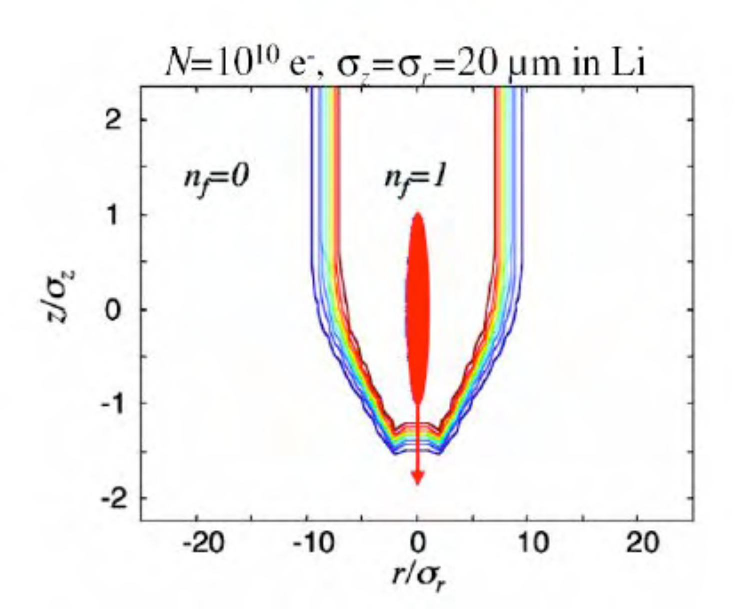
M. Hogan, et al.



plasma **No plasma**

Aspect of intense beam PWFA: plasma creation by beam-based ionization

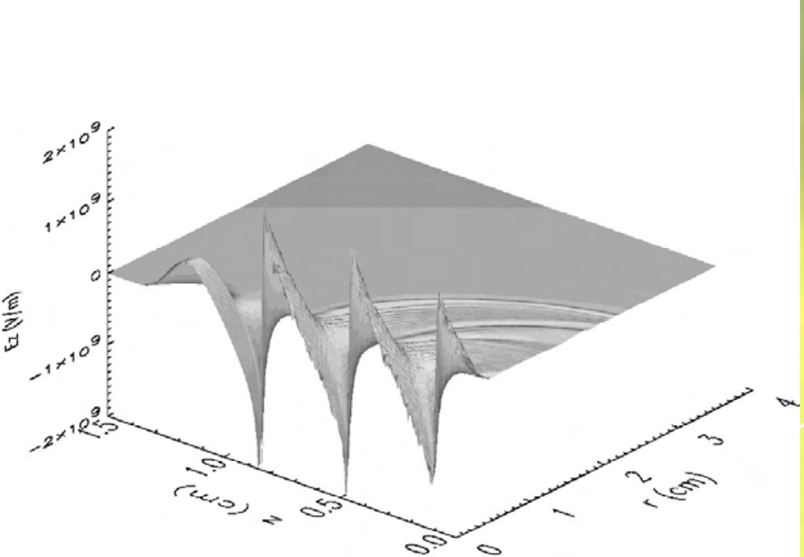
- E164 uses Li source
  - 1st ionization 5.4 eV
  - 2nd ionization 75.6 eV
- First ionization threshold field 6.8 GV/m
- Second ionization threshold >250 GV/m

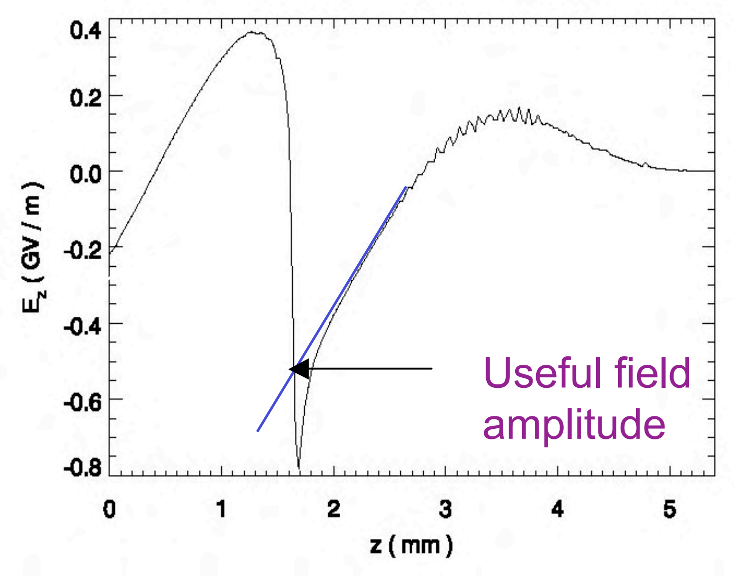


Fractional ionization in E164 experiment

Nonlinear plasma response: what do we know about it?

- Relativistic plasma motion
- Artifacts in both physics and modeling
  - Electric field spike (sensitive to mesh)
- Good focal qualities of blow-out regime fall apart in the spike region
- Beam loading eliminates the spike
  - Very little stored energy in spike region (narrow)
- The spike can be *many* times the "useful" field amplitude
- Nearly everything known from simulations; *very little analytical work*





δ-function nonlinear plasma response

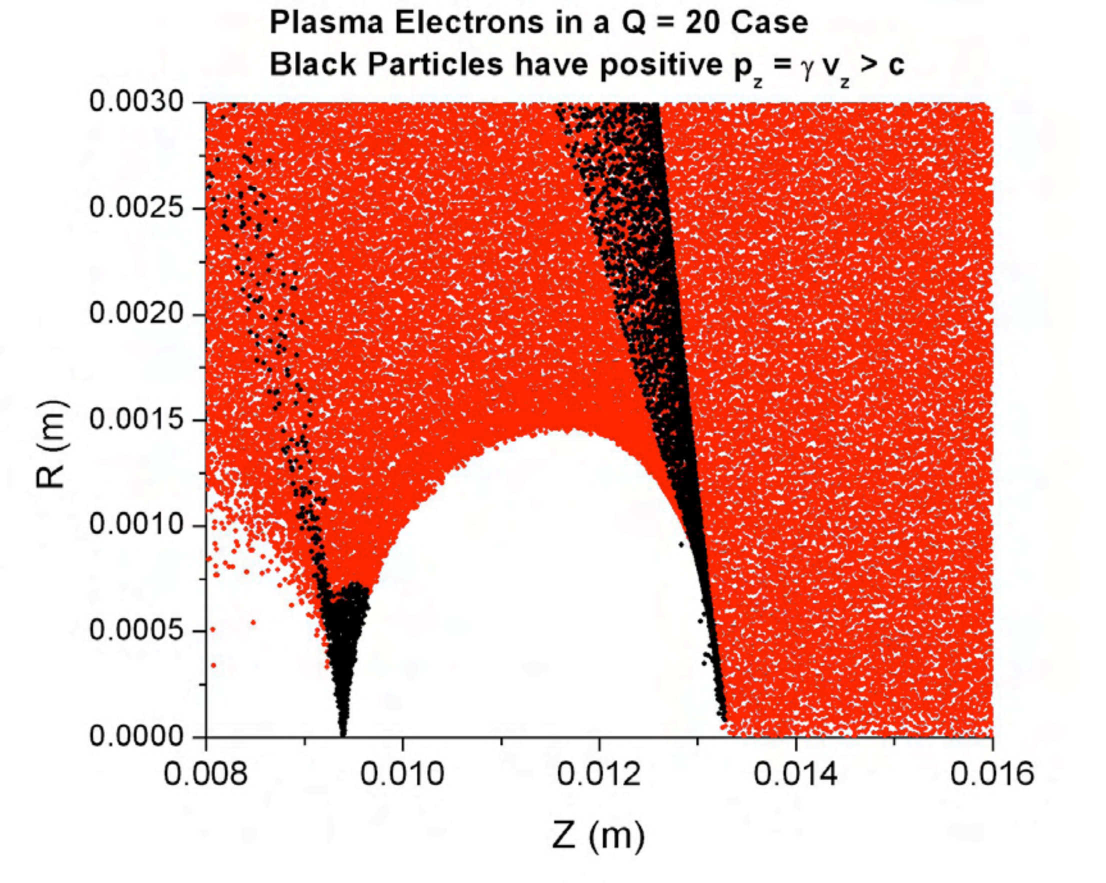
- Ultra-short beam; exact analysis possible
- Fully relativistic, nonlinear plasma response
  - N. Barov, J. B. Rosenzweig, M. C. Thompson, and R. B. Yoder "Energy loss of a high charge bunched electron beam in plasma: Analysis" Phys. Rev. ST Accel. Beams 7, 061301 (2004)
- Model problem gives new physics insight
- Plasma decelerating field response: identical to linear regime!
- Scaling in field preserved $E_z \propto k_p \tilde{E}_z \propto k_p^2$
- *New plasma electron physical phenomena*:
  - Strong initial *forward* longitudinal motion
  - Density increase (snowplow) gives coupling increase
  - Cancels decrease in (inductive) coupling due to relativistic velocity saturation (J_r same)

Nonlinear scaling: simulation

- Verify new physical phenomena for short, narrow beam
  $(k_p\sigma_z = 0.11,\ k_p a = 0.2 \text{ for snowplow study})$
- Need to extend results to realistic finite length beam $k_p\sigma_z = 1.1$
- Examine *averag*e energy loss
  - Connect with δ-beam
  - Measures efficiency of wave excitation
- Examine peak accelerating field
  - Connect with previous work (S. Lee, et al.)
  - Dangerous (spike!)
- Look at scaling
  - Also *experimental* scaling (constant emittance)
  - J. B. Rosenzweig, N. Barov, M. C. Thompson, and R. B. Yoder "Energy loss of a high charge bunched electron beam in plasma: Simulations, scaling, and accelerating wakefields" Phys. Rev. ST Accel. Beams 7, 061302 (2004),

Snowplow observed in simulation

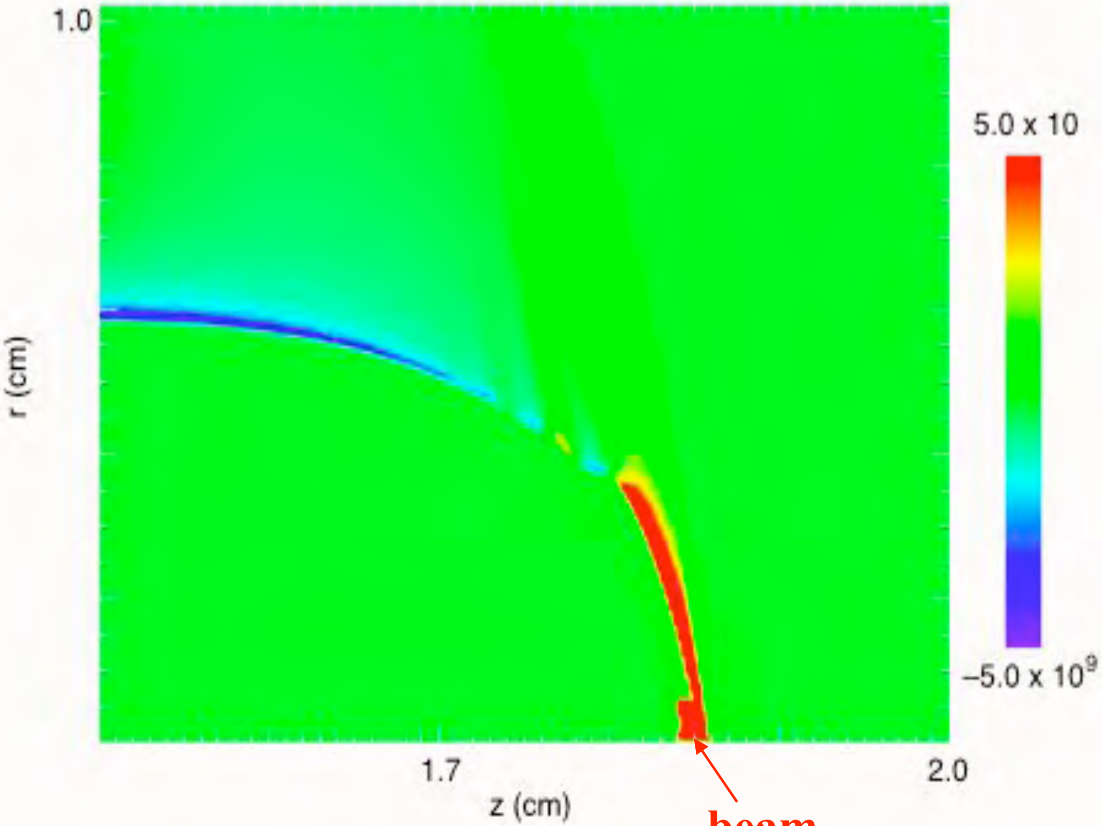
Microscopic view:
Electron momenta



MAGIC simulation shows clear snowplow;
Initial longitudinal momentum is *forward.*

Macroscopic picture: current density

OOPIC

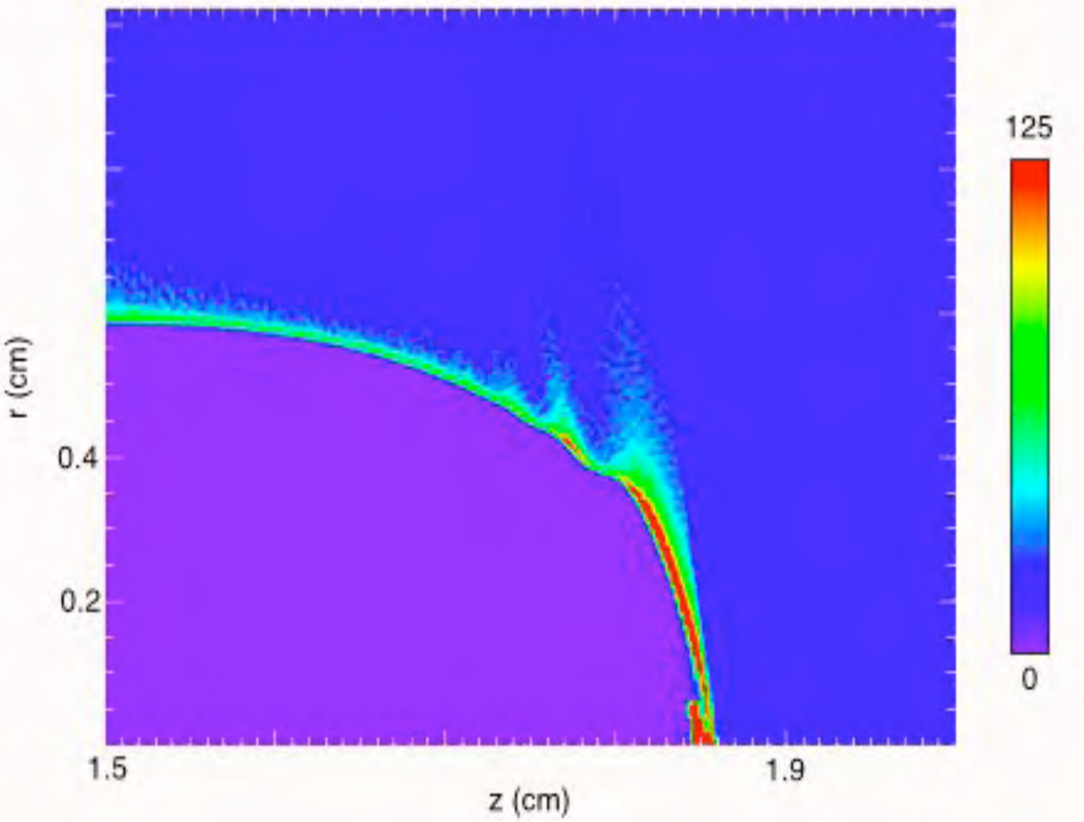


$\tilde{Q} = 200$

Longitudinal current density J_z

Macroscopic picture: electron density

OOPIC

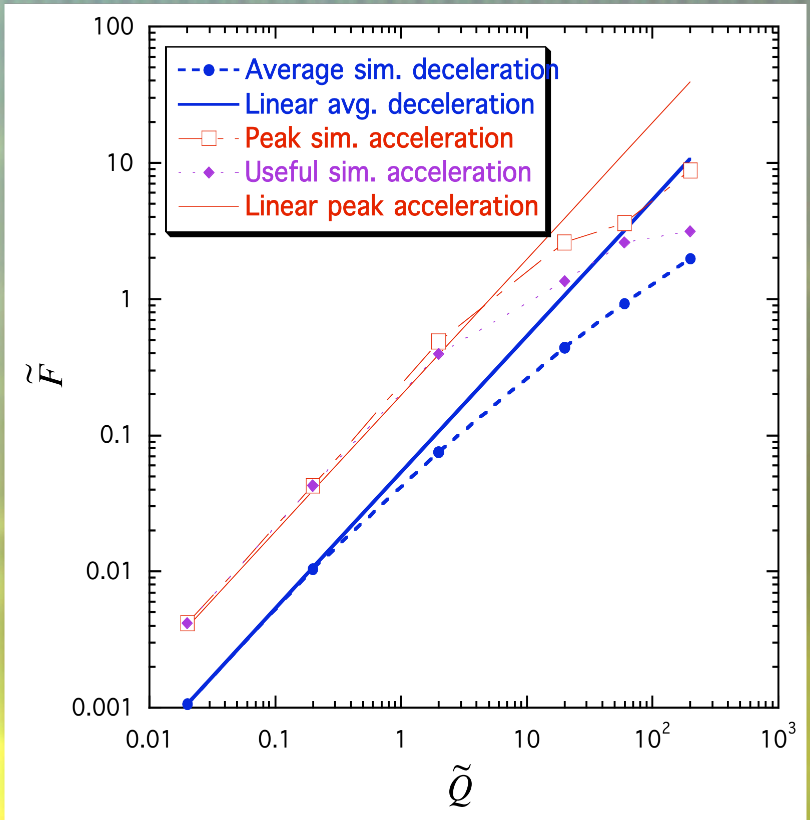


$\tilde{Q} = 200$

Electron density (ambient=15)

Scaling of fields with charge

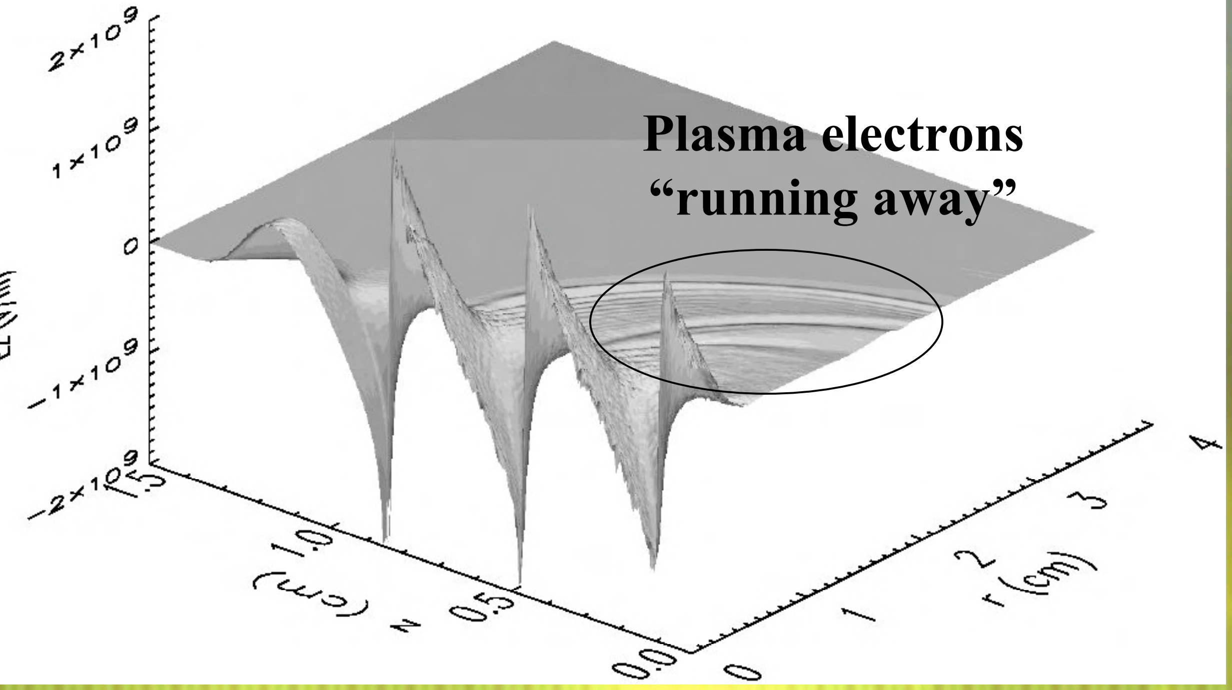
- Compare with predictions of linear theory
- Fields saturates at high charge
  - Snow-plow loses effectiveness
  - Fields only a *few times wave-breaking* are possible
- Peak does not saturate as fast
  - We are misled by the spike
- Little field growth for $\tilde{Q} > 20$
- Useful acceleration falling more rapidly than average deceleration
  - Energy going into electrons that do not contribute to accelerating field



$$\tilde{F} = E_z / E_{WB} = eE_z m_e c\omega_p$$

The less-than-useful plasma electron excitations

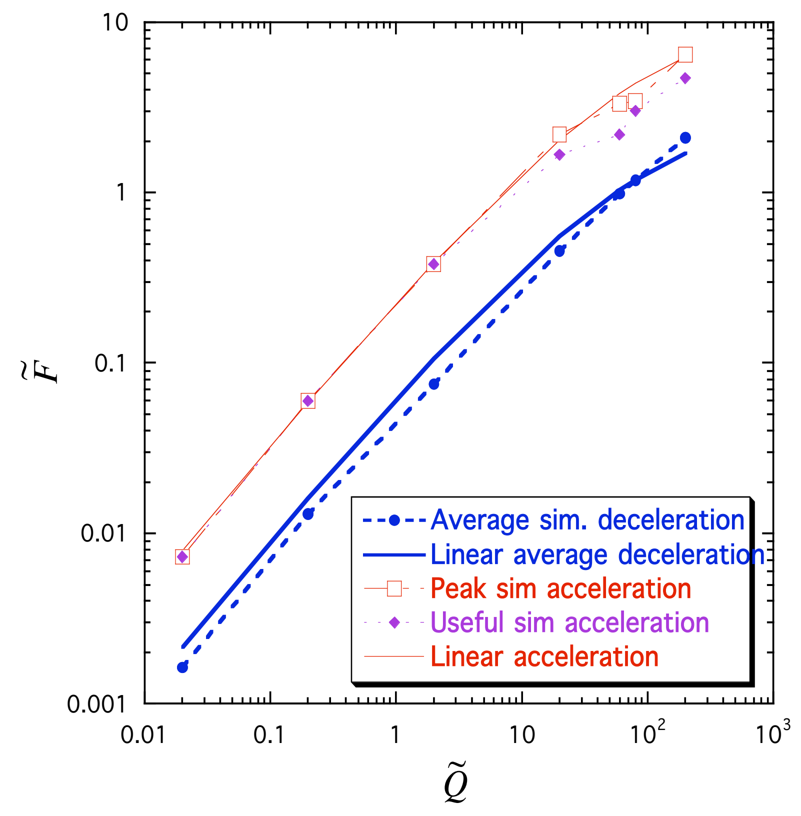
$$\tilde{Q} = 20$$



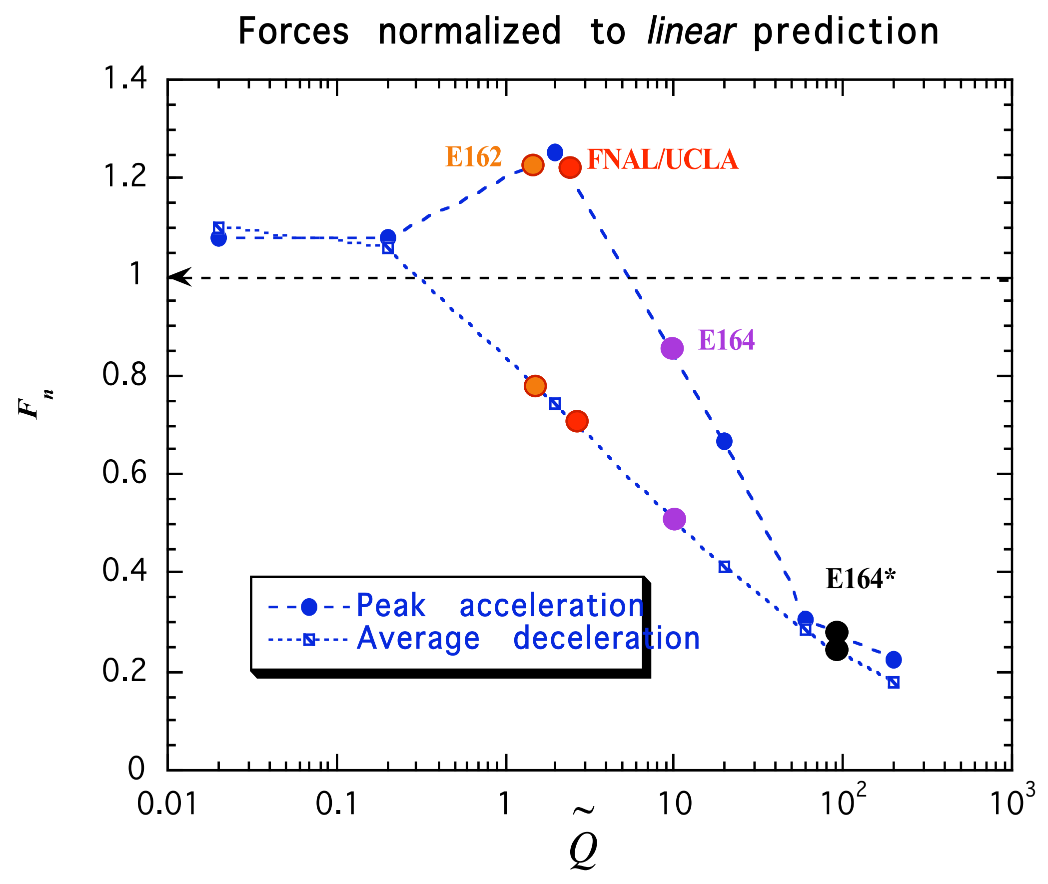
Plasma electrons "running away"

Experimental scaling

- Going to higher *Q*~ by compression does not scale transverse beam size
- Emittance is constant
- Beam eventually is wide
  - $k_p\sigma_r > 1$
- Blowout effects markedly diminish
- NOT $1/\sigma_z^2$ scaling!

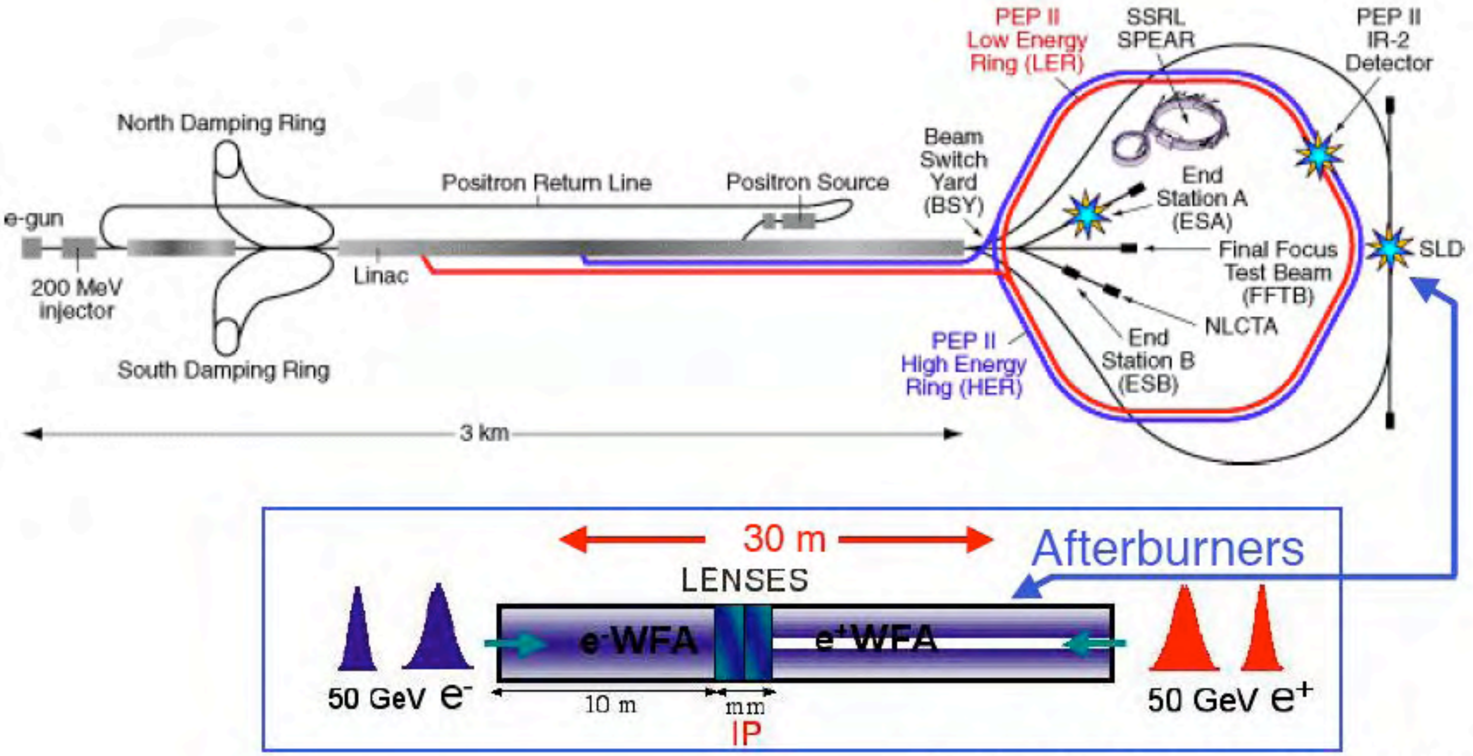


High charge experiments



- Experiments transition from $\tilde{Q}$~2 to near 100
- Peak field still near to "scaling" for E164
- E164 -> E164X loses a factor of 3 off linear scaling (this is worse if you look at the useful field, not the spike)
- Still *very large* fields!

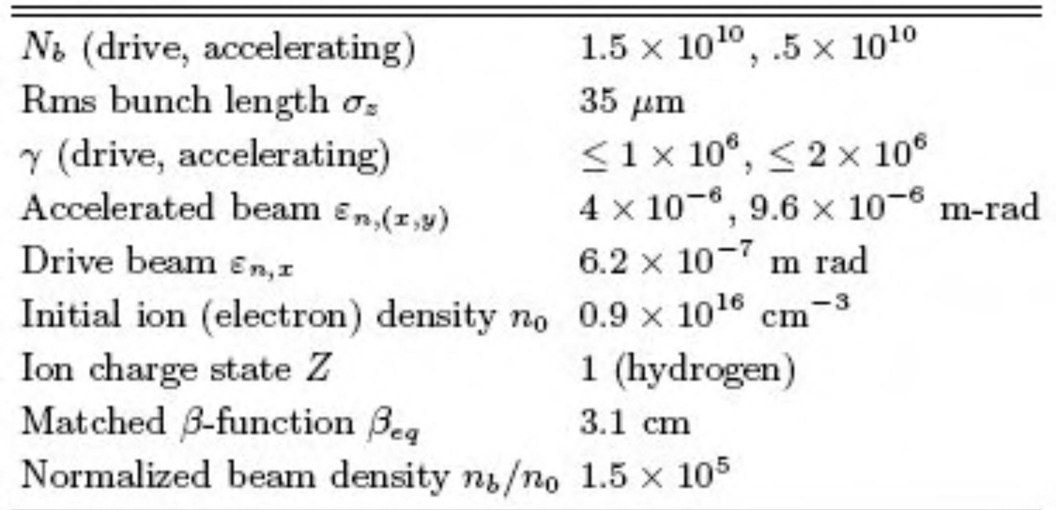
Converting high fields to a collider: the "Afterburner"



S. Lee et al., Phys. Rev. STAB, 2001

- Double (or more) energy of conventional linear collider
- Lots of exciting recent experiments
- T. Raubenheimer examined using concept at ILC (AAC'04)

Some NLC numbers applied to afterburner scenario



N_b (drive, accelerating)	1.5×10^{10}, $.5 \times 10^{10}$
Rms bunch length σ_z	35 μm
γ (drive, accelerating)	$\leq 1 \times 10^6$, $\leq 2 \times 10^6$
Accelerated beam $\varepsilon_{n,(x,y)}$	4×10^{-6}, 9.6×10^{-6} m-rad
Drive beam $\varepsilon_{n,x}$	6.2×10^{-7} m rad
Initial ion (electron) density n_0	0.9×10^{16} cm^{-3}
Ion charge state Z	1 (hydrogen)
Matched β-function β_{eq}	3.1 cm
Normalized beam density n_b/n_0	1.5×10^5

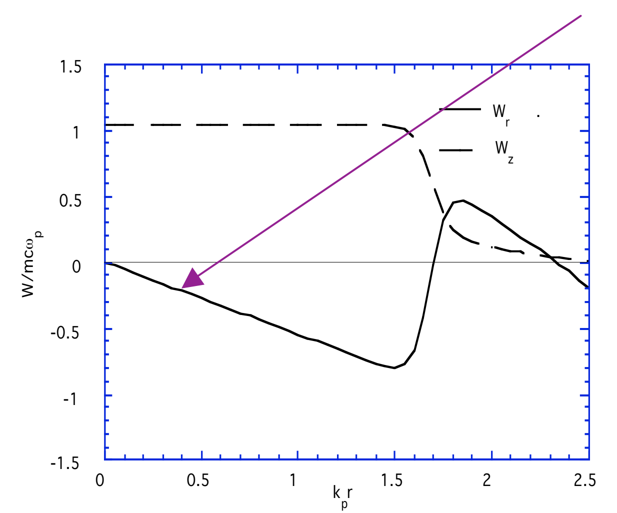
- Raubenheimer's linear collider scenario
- Equilibrium beam is very much denser than assumed! Beam density is *thousands* of times plasma
- Problem worse with energy $n_b \propto \sigma_x^{-2} = (\beta\varepsilon)^{-1} = \sqrt{\dfrac{\varepsilon_n}{2\pi r_e n_0 \gamma}}$

Transverse motion in electrons *and* ions

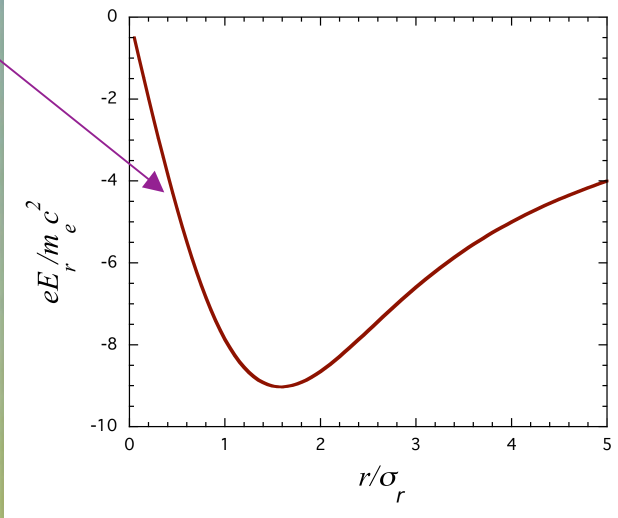
- *Plasma* electrons experience
  - First electrostatic component of beam field
  - Magnetic component of beam field
  - Restoring electrostatic force of plasma ions
- *Beam* electrons experience
  - After blowout, only *electrostatic forces* from ions
- *Ions*, after blowout, dominated by
  - Electrostatic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

Transverse fields

Linear field variation



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 electron beam *and*
  - Focus (collapse!) ion distribution
- Examine first cylindrical drive beam

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 $\xi = z - v_b t \cong z - ct$

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

$$r_a = 1.55 \times 10^{-18} \text{ m}$$

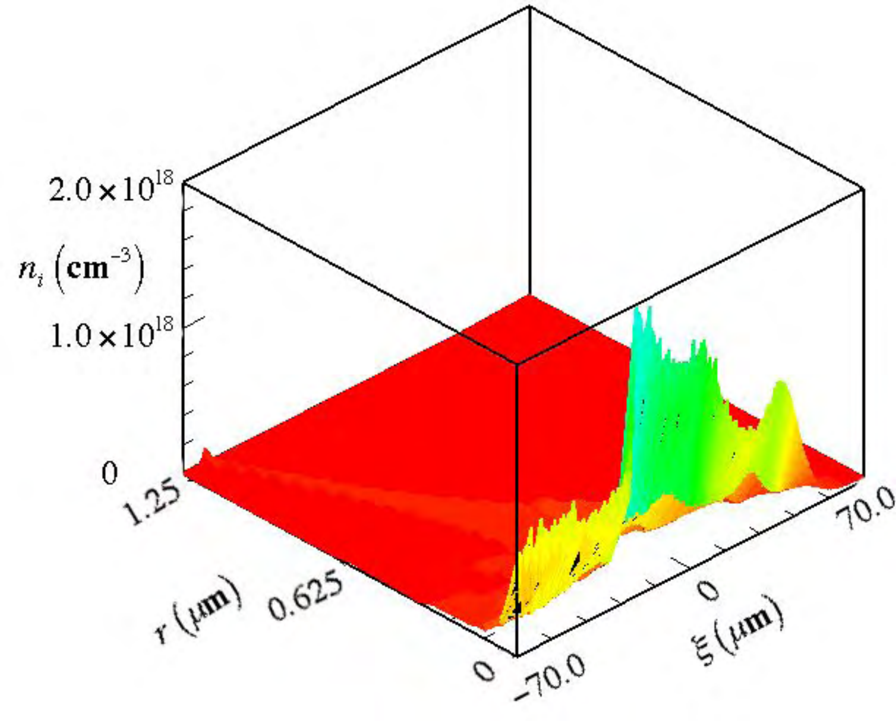
- Phase advance inside of beam

$$\Delta\phi = k_i \Delta\xi \cong k_i \sqrt{2\pi}\,\sigma_z = \sqrt{\frac{2\pi Z r_a N_b \sigma_z \sqrt{r_e n_0 \gamma}}{A \varepsilon_{n,x}}}$$

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

$$\Delta\phi = 6.5!$$

OOPIC simulations: dramatic ion collapse



OOPIC simulation ion ion densityinside of "after-burner" beam (from Rosenzweig, et al., to appear in PRL)

- Density spike is >200 times ambient!
- Effect on beam matching and emittance is disastrous…

Can ion motion be mitigated?

- Problematic solutions
  - Shorter bunch (not possible, depends on $n_0^{1/2}$)
  - Smaller beam charge (smaller wakes)
  - Lower energy (its an afterburner!)
  - Less dense plasma (smaller wakes)
  - Higher atomic number (multiple ionization)
    - Beam field is 1.1 TV/m
- Better knob?
  - Run *much* higher emittance
  - But…can’t do it with trailing beam

Accelerating beam

- Parameters set by collider needs
- Asymmetric emittances $\varepsilon_{n,x} >> \varepsilon_{n,y}$
- Beta-function same in *x* and *y*, asymmetric 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 $\sqrt{\varepsilon_{n,y}\varepsilon_{n,x}}$
- ILC case $\Delta\phi = 6.3$

Outlook

- Try vastly different beam parameters?
  - Scaling is "unnatural", beam charge too big?
  - Look at completely different parameter set
- Plasma fiber (hollow channel)
  - No ions. No focusing… etc.
  - Already needed for positrons
- Ion motion in experiments?
  - E164X? phase advance is 0.16 (9 deg)
  - Look also at LCLS case (more motion)
  - What are signatures? Fusion in D-T?
- Look hard at plasma lens scenarios
- Implications also for *any* plasma accelerator

Conclusions

- Very intense beam effects manifested in PWFA, in collider scenario
  - Field ionization
  - Nonlinear electron motion
  - Ion collapse
- Some effects beneficial, some benign, some disastrous
- Experiments needed
- Pay attention in proposing future scenarios
  - Work to understand options