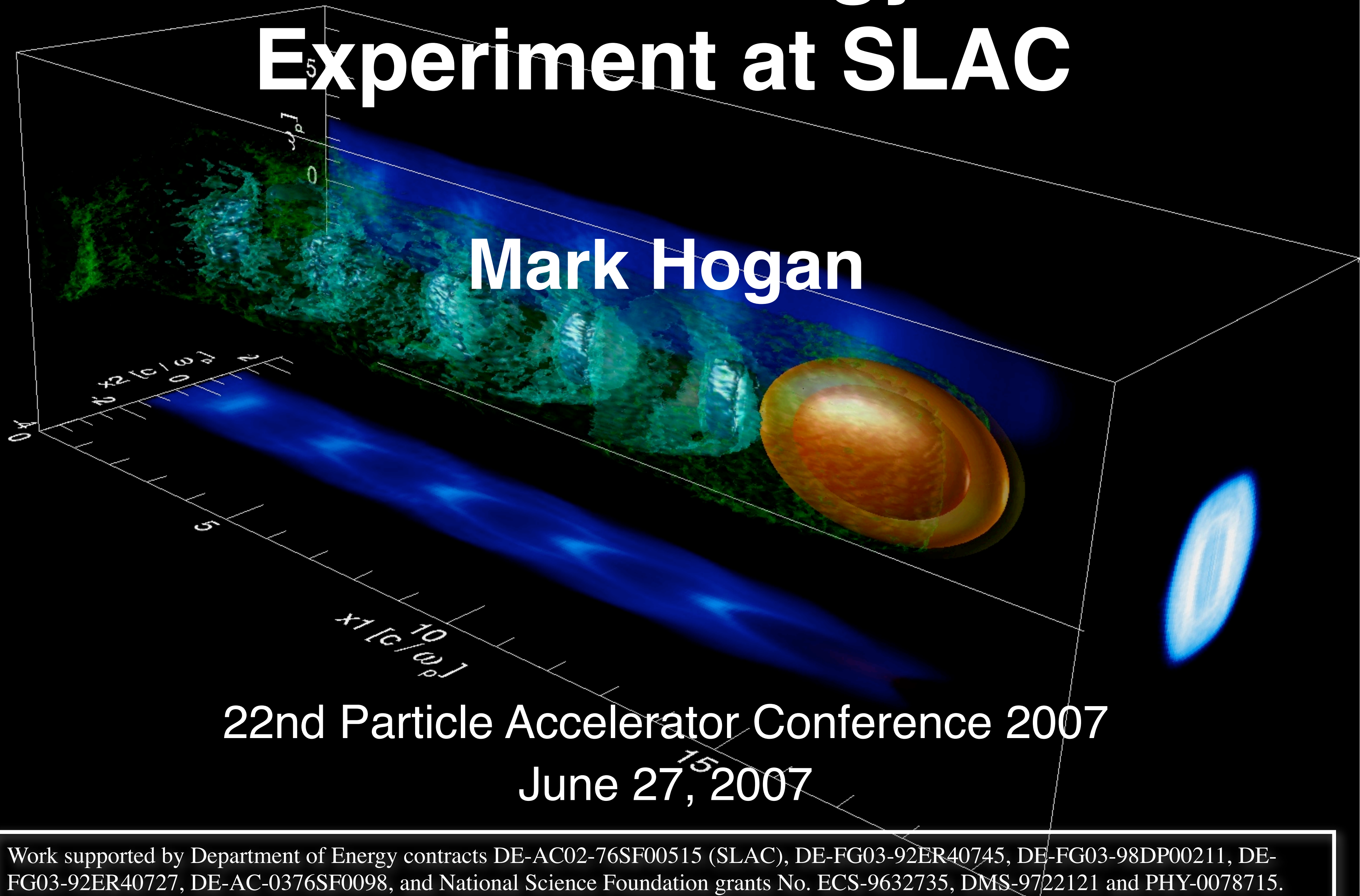
Results of the Energy Doubler Experiment at SLAC



Mark Hogan

22nd Particle Accelerator Conference 2007

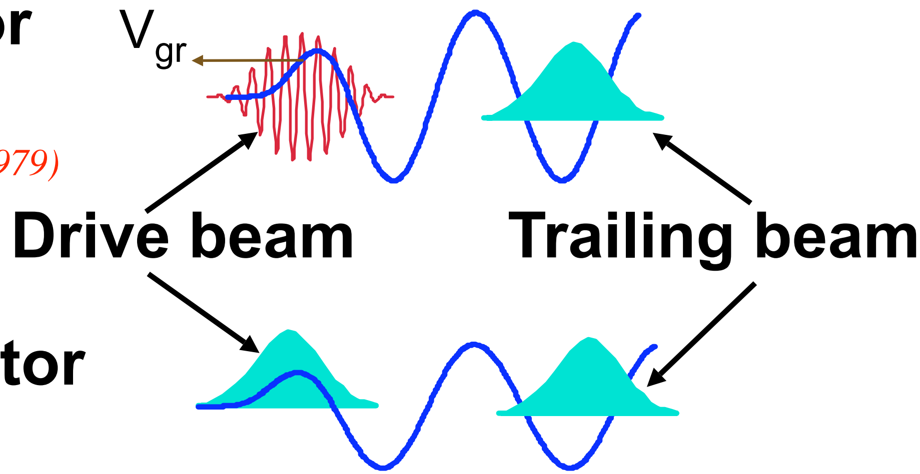
June 27, 2007

Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC), DE-FG03-92ER40745, DE-FG03-98DP00211, DE-FG03-92ER40727, DE-AC-0376SF0098, and National Science Foundation grants No. ECS-9632735, DMS-9722121 and PHY-0078715.

Why Plasma Accelerators?

- **Laser Wake Field Accelerator**
  A single short-pulse of photons
  T. Tajima and J. M. Dawson Phys. Rev. Lett. 43, 267 - 270 (1979)

- **Plasma Wake Field Accelerator**
  A high energy electron bunch
  P. Chen et.al. Phys. Rev. Lett. 54, 693 - 696 (1985)



- **Wake: phase velocity = driver velocity**

Large wake for:

laser amplitude $a_o = eE_o/m\omega_o c \sim 1$ *or*

beam density $n_b \sim n_o$

Accelerating Field:

$30 GeV/m(10^{17}/n_o)^{1/2}$

Plasma Accelerators Showing Great Promise!

Laser Driven Plasma Accelerators:

- Accelerating Gradients > 100GeV/m (measured)
- Narrow Energy Spread Bunches
- Interaction Length limited to cm's

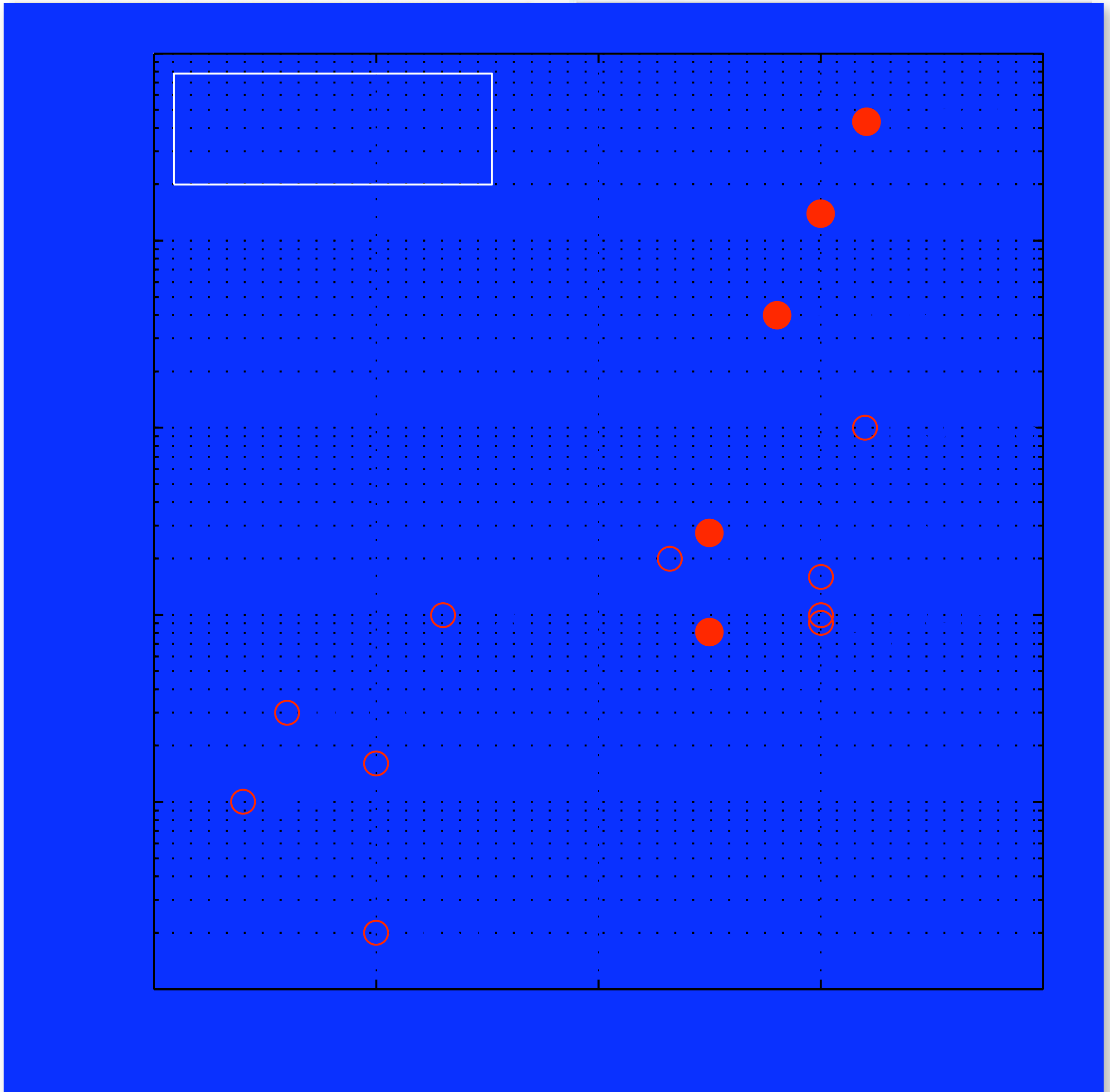
Beam Driven Plasma Accelerators:

Large Gradients:
- Accelerating Gradients > 50 GeV/m (measured!)
- Focusing Gradients > MT/m
- Interaction Length not limited

Unique SLAC Facilities:
- FFTB
- High Beam Energy
- Short Bunch Length
- High Peak Current
- Power Density
- e- & e+

Scientific Question:
- Can one make & sustain high gradients in plasmas for lengths that give significant energy gain?

Plasma Accelerators Showing Great Promise!



Laser Driven Plasma Accelerators:

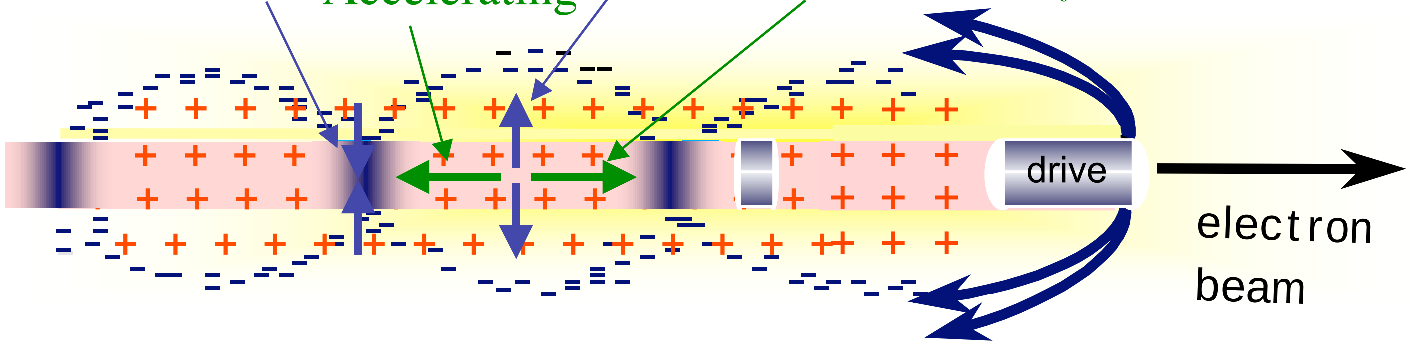
- Accelerating Gradients > 100GeV/m (measured)
- Narrow Energy Spread Bunches
- Interaction Length limited to mm's

Beam Driven Plasma Accelerators:

Large Gradients:
- Accelerating Gradients > 30 GeV/m (measured!)
- Focusing Gradients > MT/m
- Interaction Length not limited

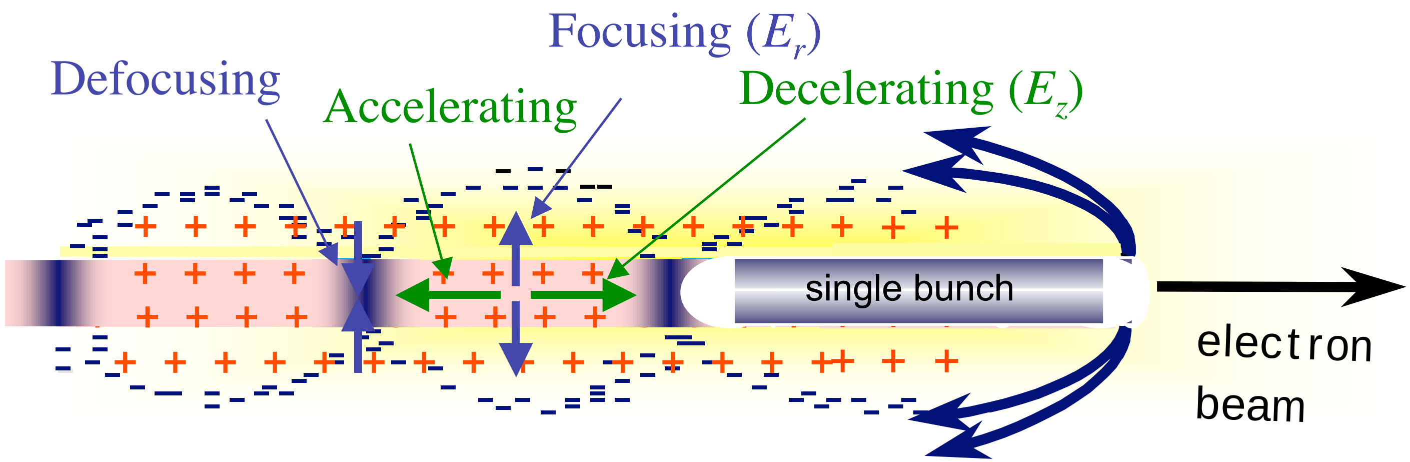
Unique SLAC Facilities:
- FFTB
- High Beam Energy
- Short Bunch Length
- High Peak Current
- Power Density
- e- & e+

Scientific Question:
- Can one make & sustain high gradients in plasmas for lengths that give significant energy gain?



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e⁻ expelled by space charge forces => energy loss + focusing (>MT/m)
  (ion channel formation $r_c \approx (n_b/n_e)^{1/2}\sigma_r$
- Plasma e⁻ rush back on axis => energy gain (>GeV/m)
- Linear scaling: $E_{acc} \cong 110(MeV/m)\frac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2}$ $\approx 1/\sigma_z^2$
  @ $k_{pe}\sigma_z \approx \sqrt{2}$
- Plasma Wakefield Accelerator (PWFA) = Transformer

Booster for high energy accelerator



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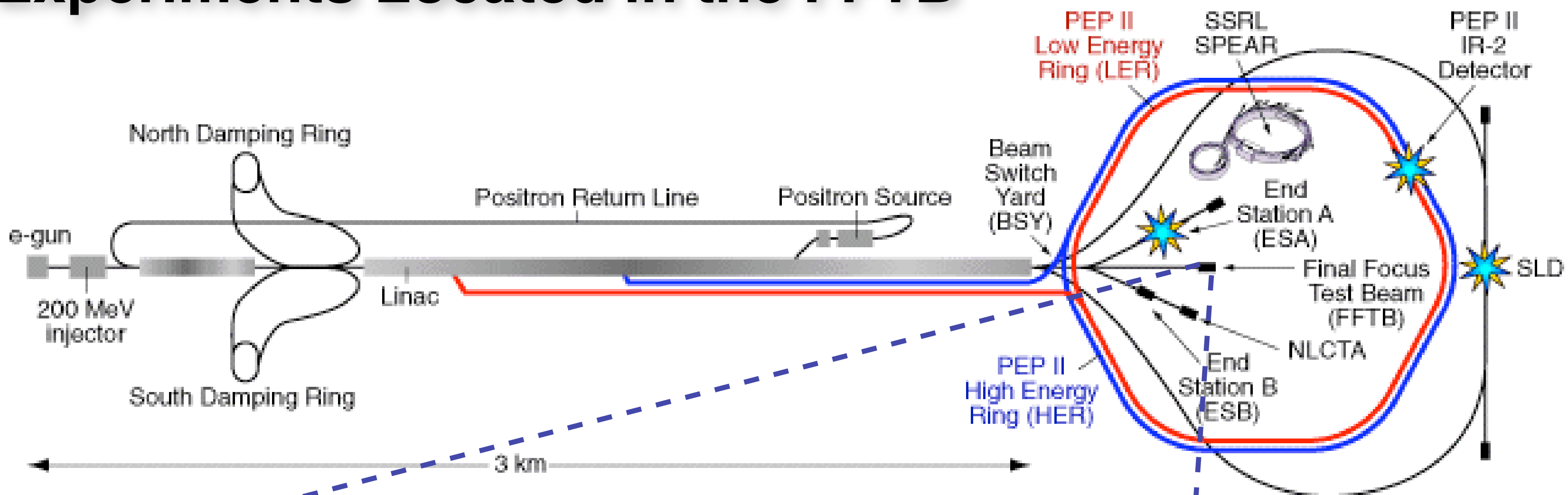
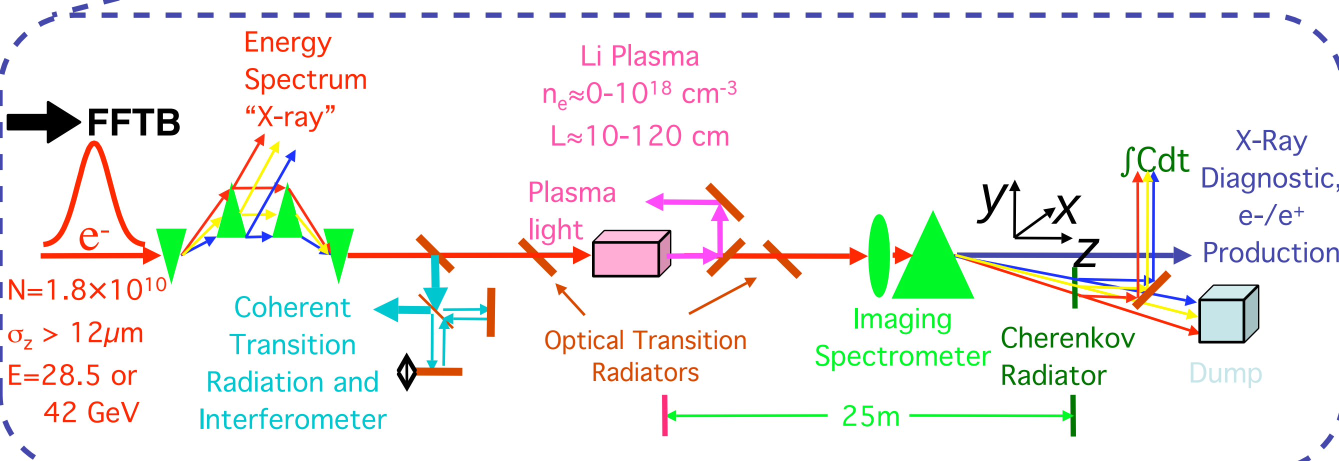
- Plasma Wakefield Accelerator (PWFA) = Transformer
  Booster for high energy accelerator

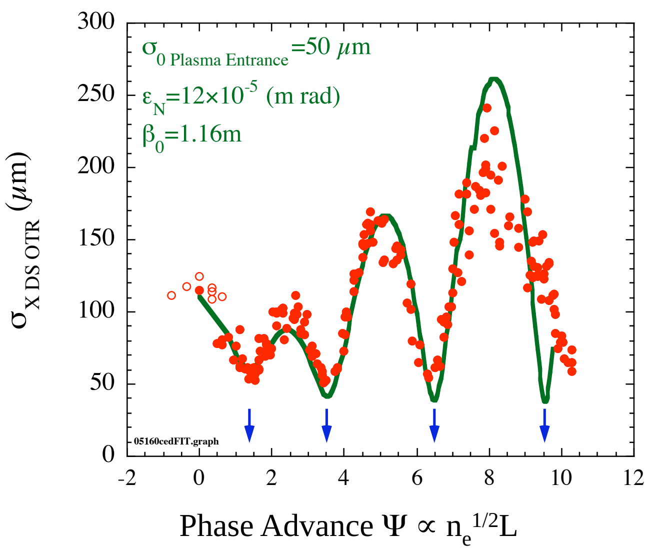
Experiments Located in the FFTB





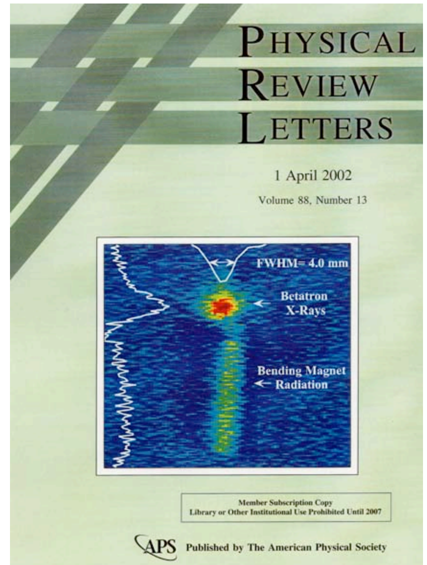
E-157/162 Beam-Plasma Experimental Results

Focusing e-



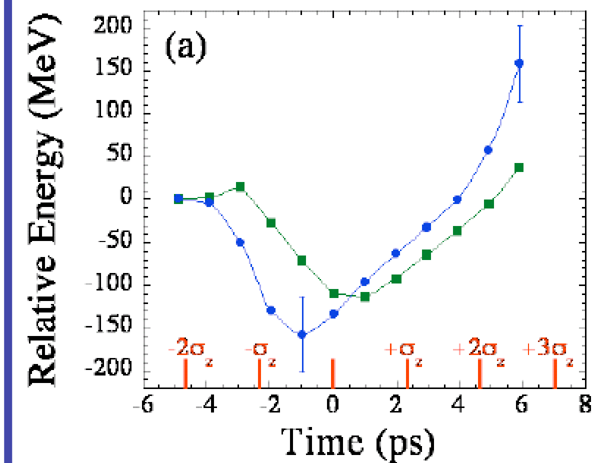
Phys. Rev. Lett. **88**, 154801 (2002)

X-ray Generation



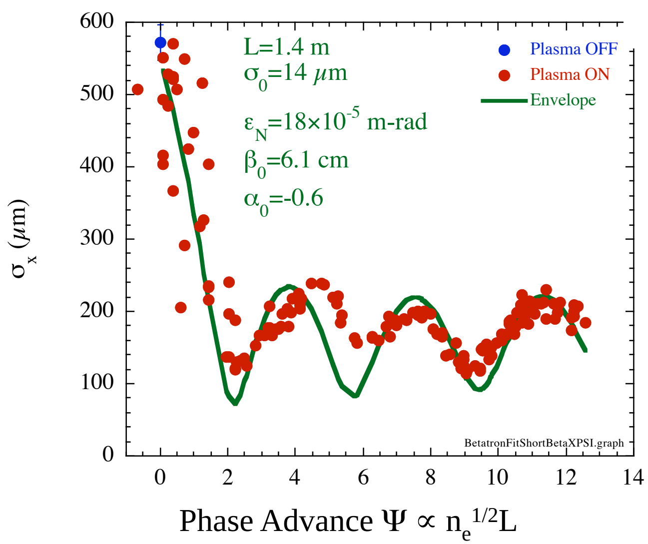
Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e-



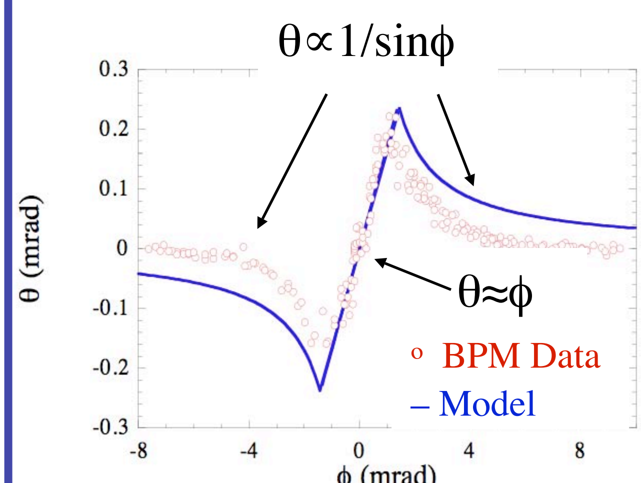
Phys. Rev. Lett. **93**, 014802 (2004)

Matching e-



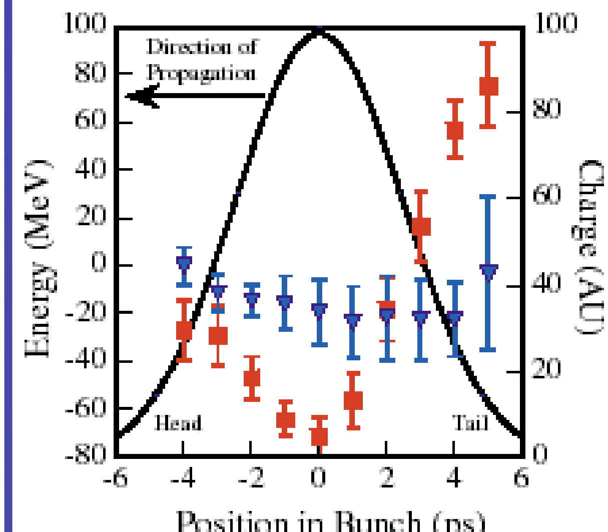
Phys. Rev. Lett. **93**, 014802 (2004)

Electron Beam Refraction at the Gas–Plasma Boundary



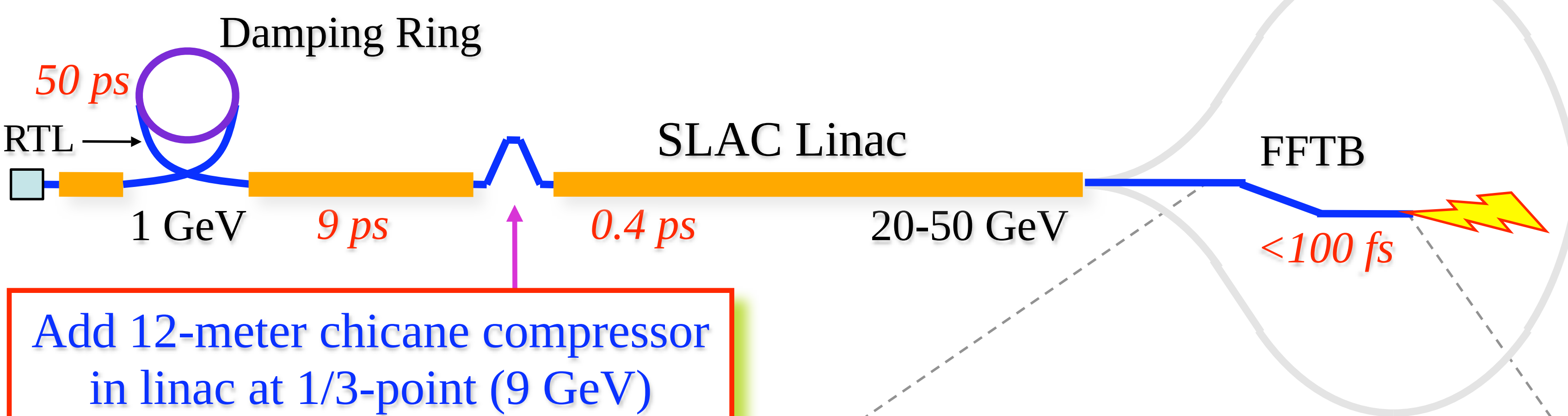
Nature **411**, 43 (3 May 2001)

Wakefield Acceleration e+

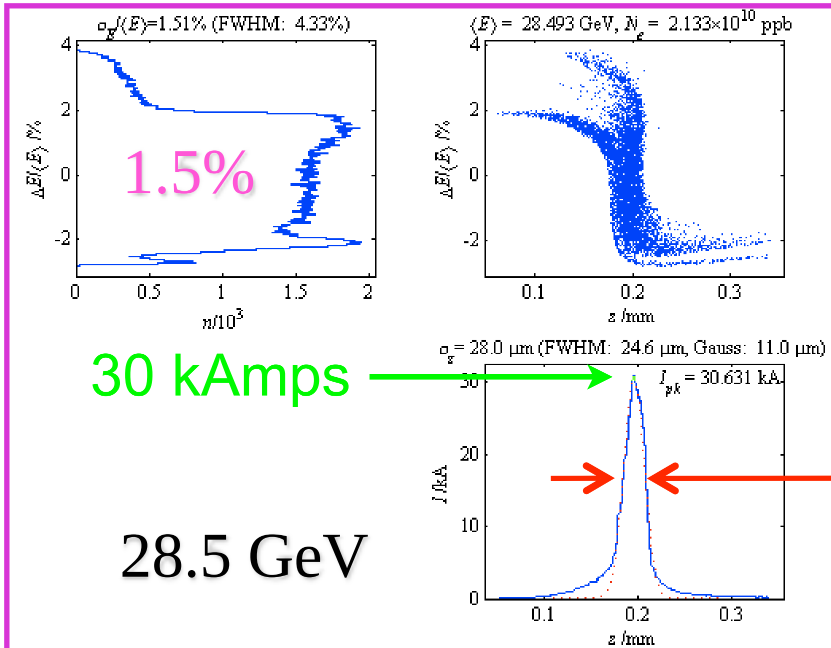


Phys. Rev. Lett. **90**, 214801 (2003)

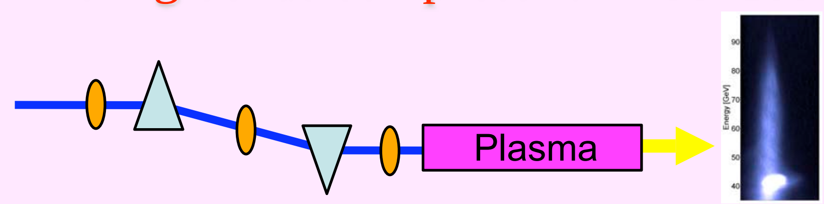
Short Bunch Generation in the SLAC Linac



Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)



Existing bends compress to **<100 fsec**



80 fsec FWHM

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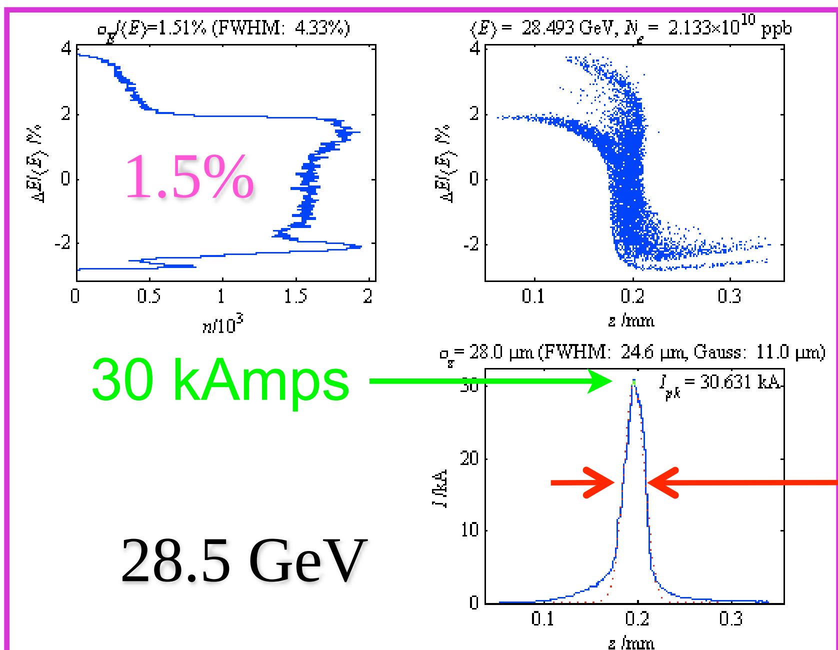

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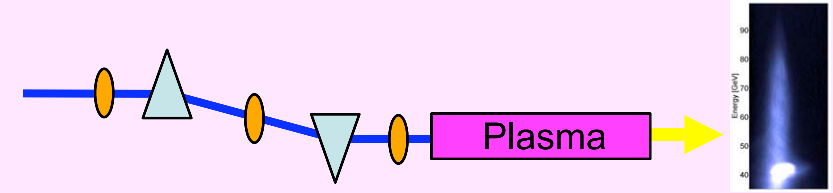
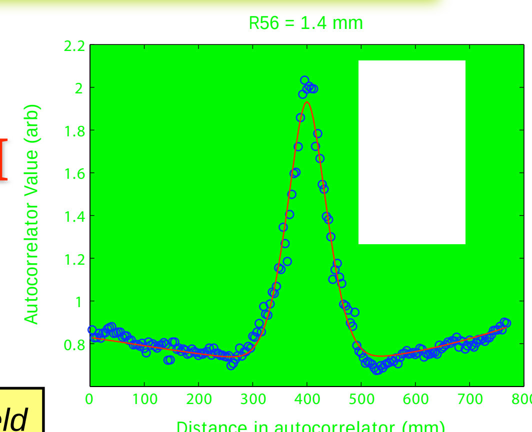
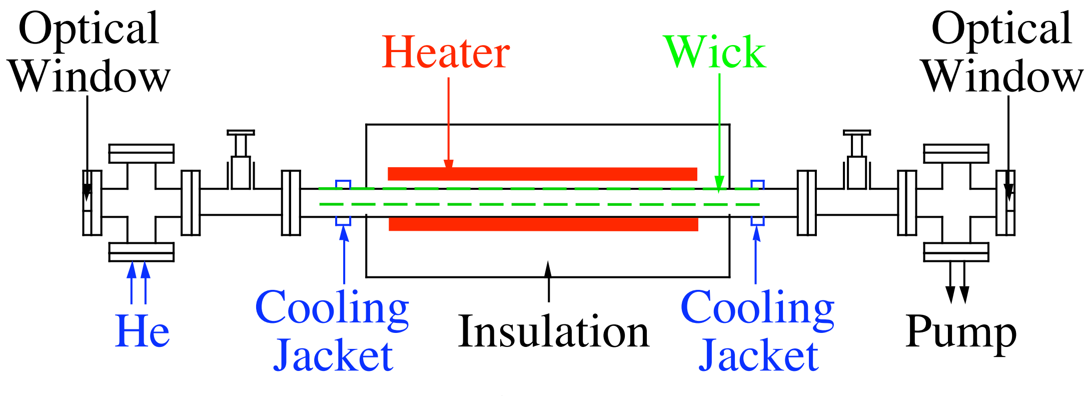


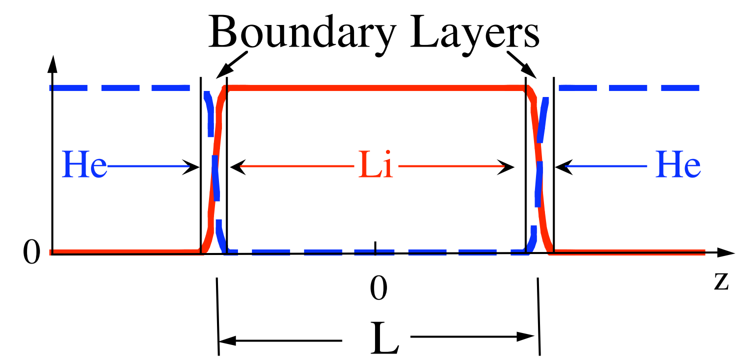
80 fsec FWHM



FRPMS063 Ian Blumenfeld

Plasma Source Starts with Metal Vapor in a Heat-Pipe Oven





Peak Field For A Gaussian Bunch:

$$E = 6GV/m \frac{N}{2x10^{10}} \frac{20\mu}{\sigma_r} \frac{100\mu}{\sigma_z}$$

Ionization Rate for Li:

$$W_{Li}\left[s^{-1}\right] \approx \frac{3.60x10^{21}}{E^{2.18}\left[GV/m\right]} \exp\left(\frac{-85.5.}{E\left[GV/m\right]} \right)$$

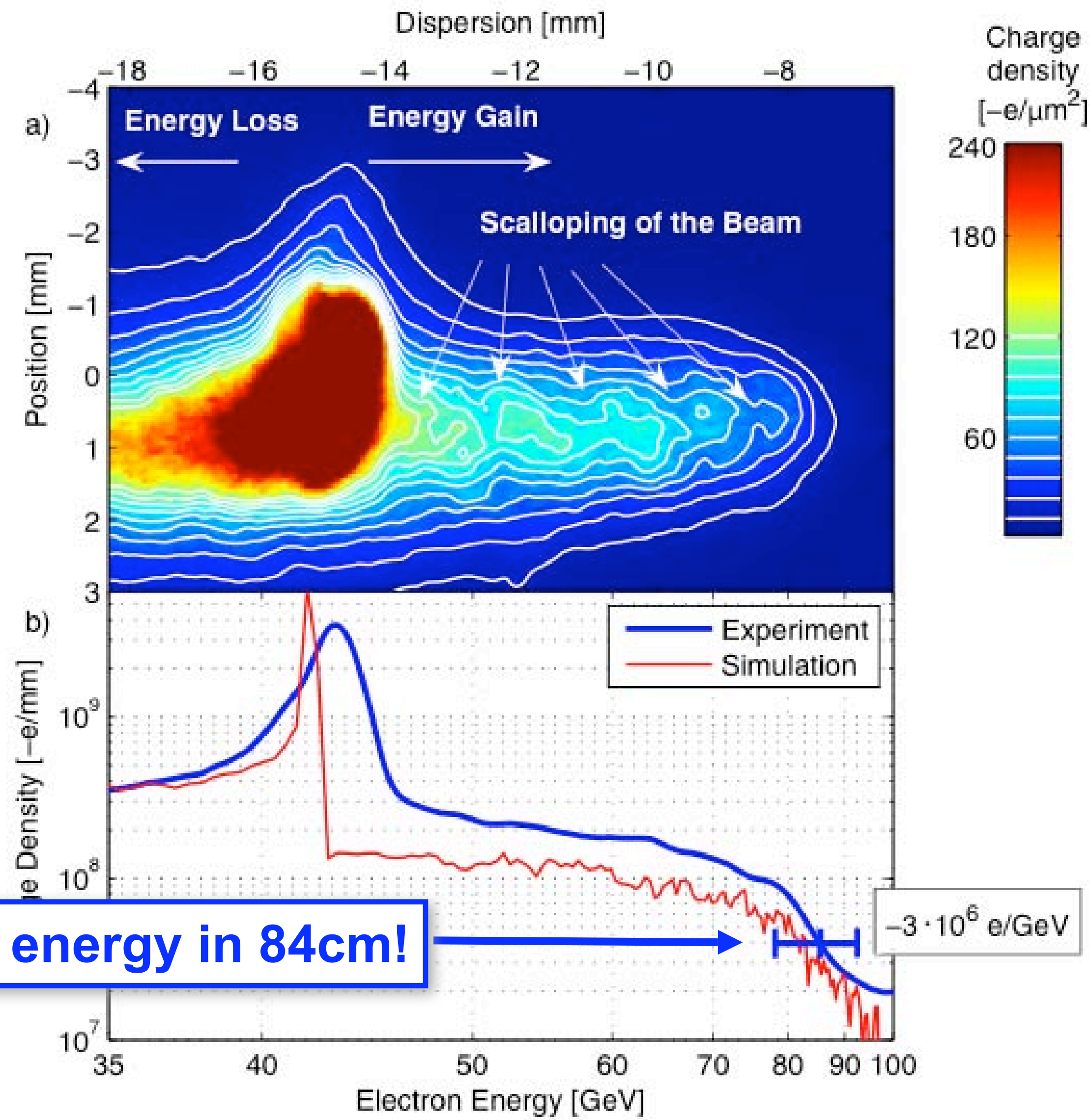
See D. Bruhwiler et al, Physics of Plasmas 2003

Space charge fields are high enough to field (tunnel) ionize - no laser!

- No timing or alignment issues
- Plasma recombination not an issue
- However, can't just turn it off!
- Ablation of the head

E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB

- Linac running all out to deliver compressed 42GeV Electron Bunches to the plasma
- Record Energy Gain
- Highest Energy Electrons Ever Produced @ SLAC
- Significant Advance in Demonstrating Potential of Plasma Accelerators

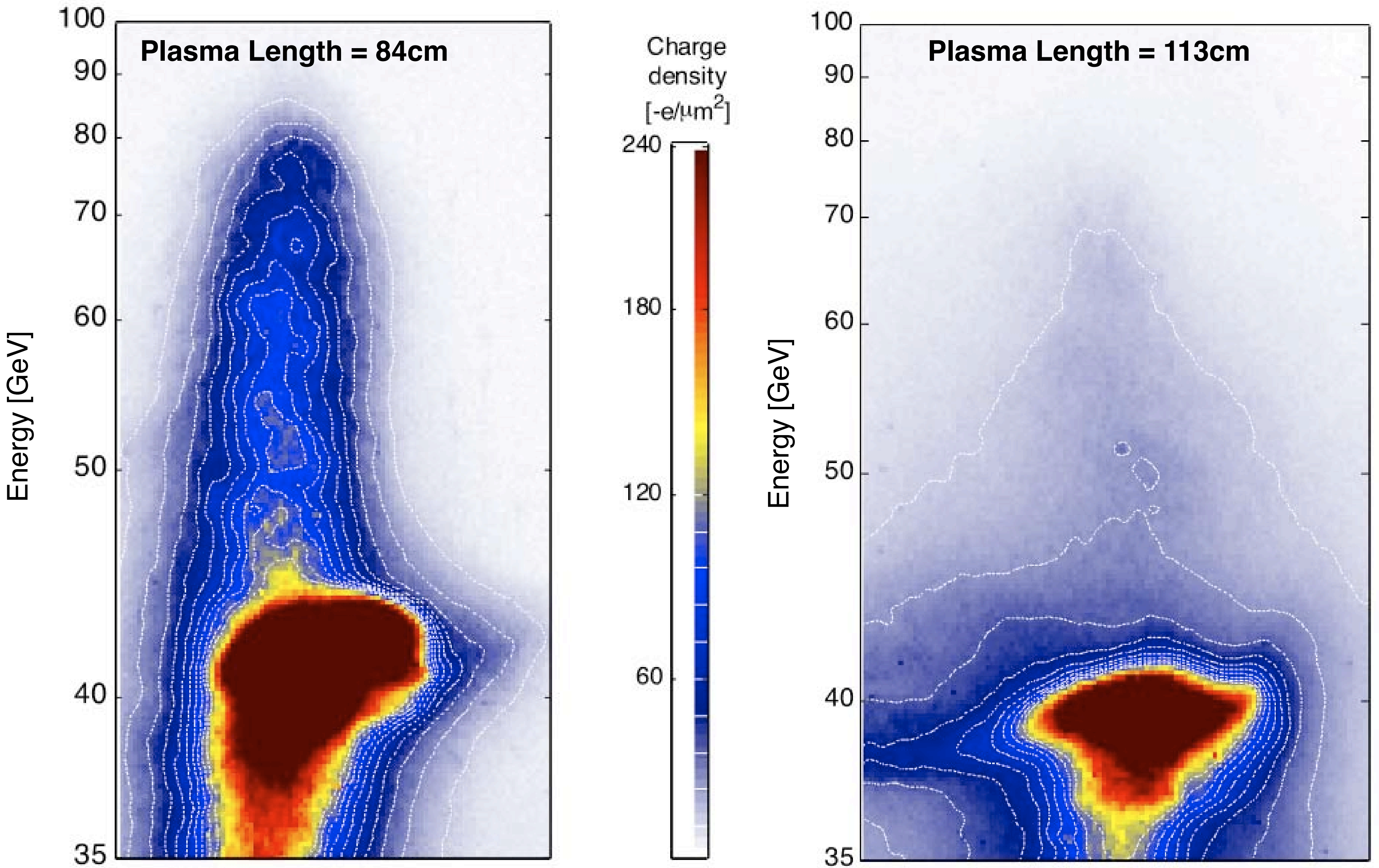


Some electrons double their energy in 84cm!

<u>*Nature*</u> ***445*** *741 15-Feb-2007*

FRPMS067 Rasmus Ischebeck

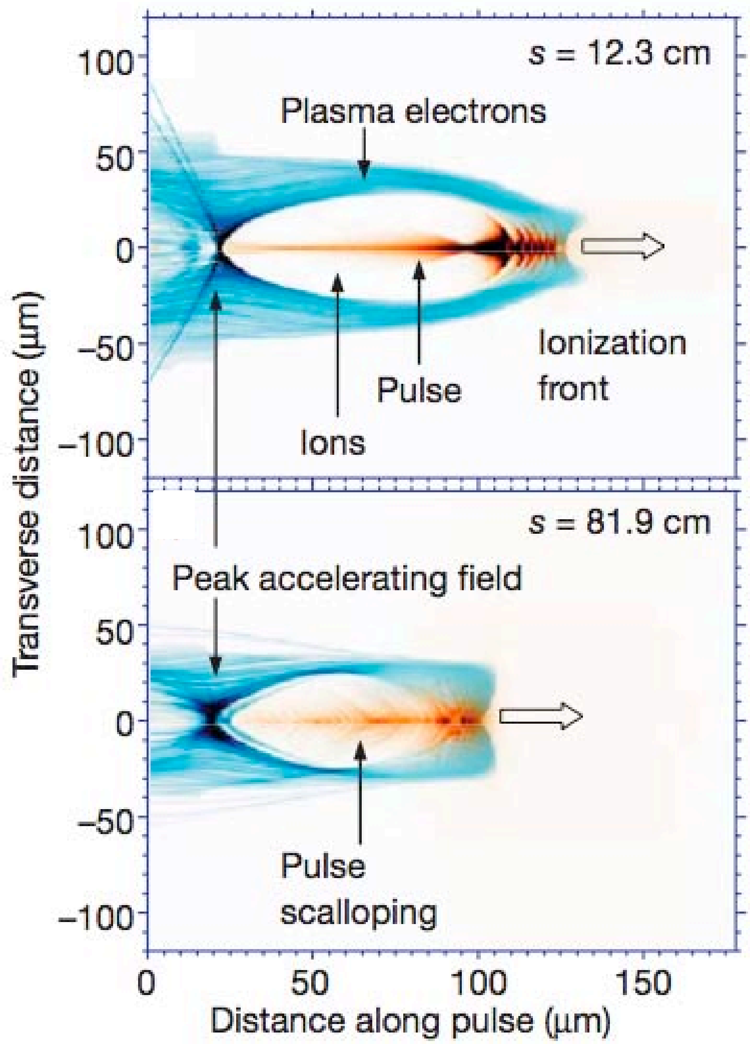
Can you just make the plasma longer?

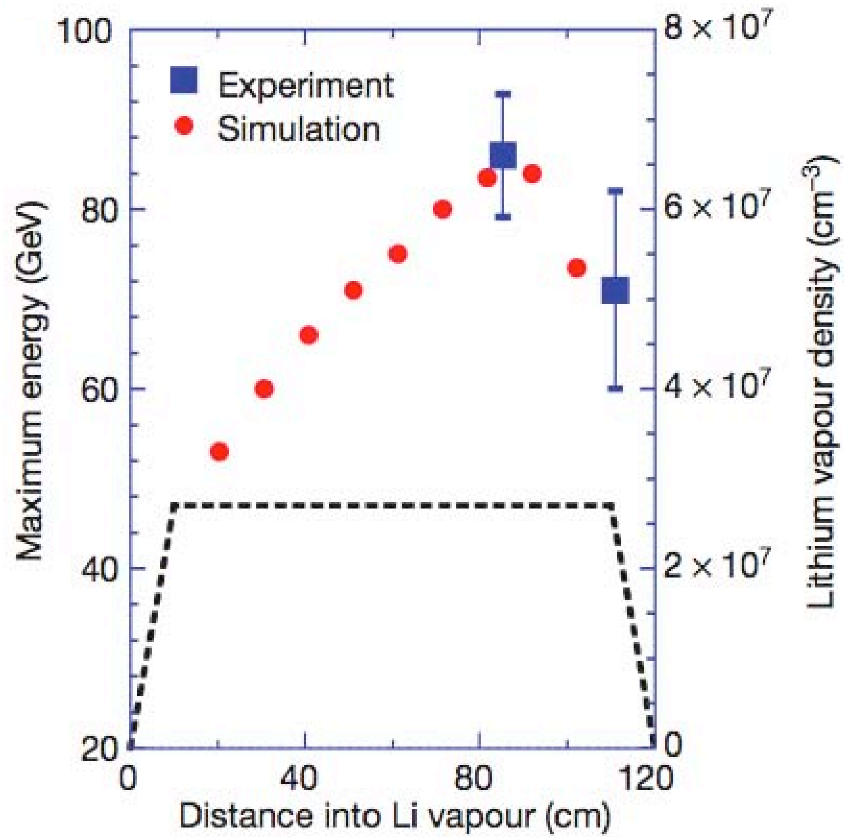


THPMS033 Patric Muggli

THPMS040 Ian Blumenfeld

Energy Gain Limited by Head Erosion





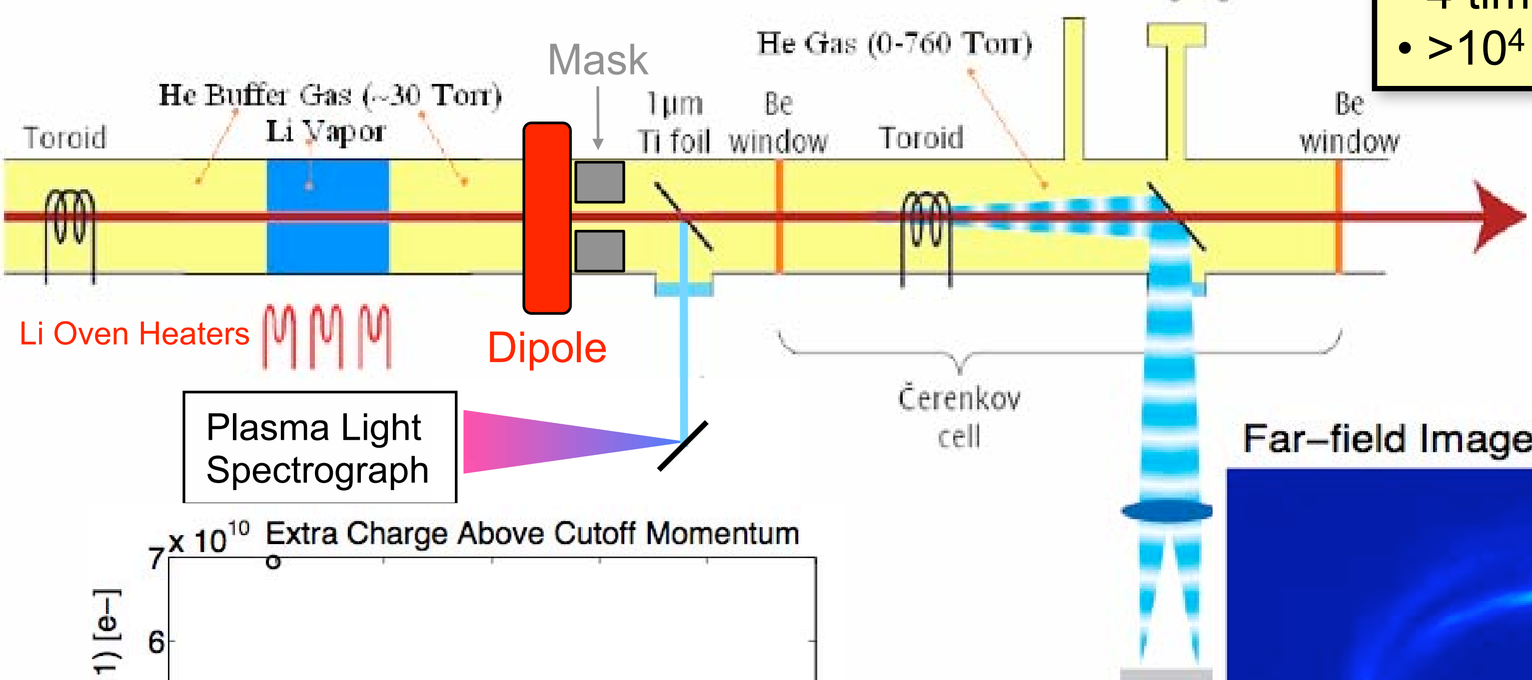
THPMS029 Miaomiao Zhou

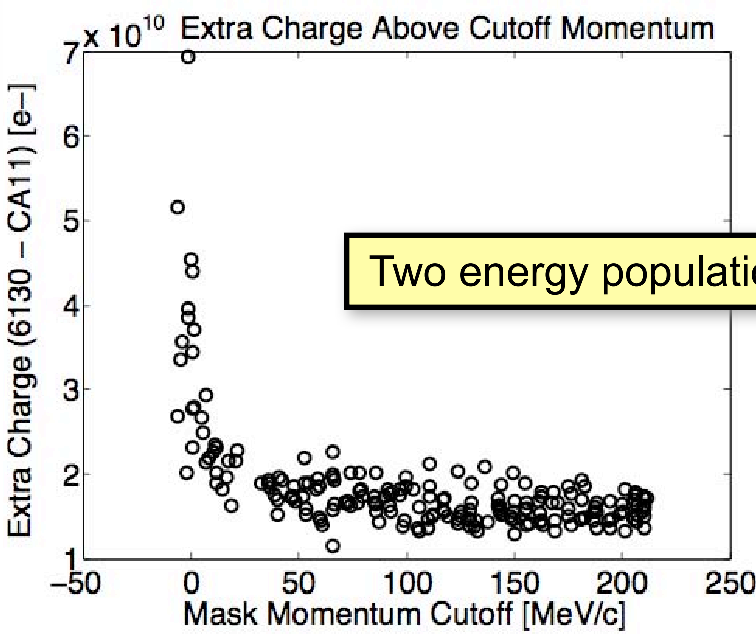
Near term solution will likely involve either a low density pre-ionization or integrated permanent magnet focusing. Longer term – get a better emittance

New Phenomena: Trapped Particles

Electrons Are Trapped at He Boundaries and Accelerated Out of the Plasma

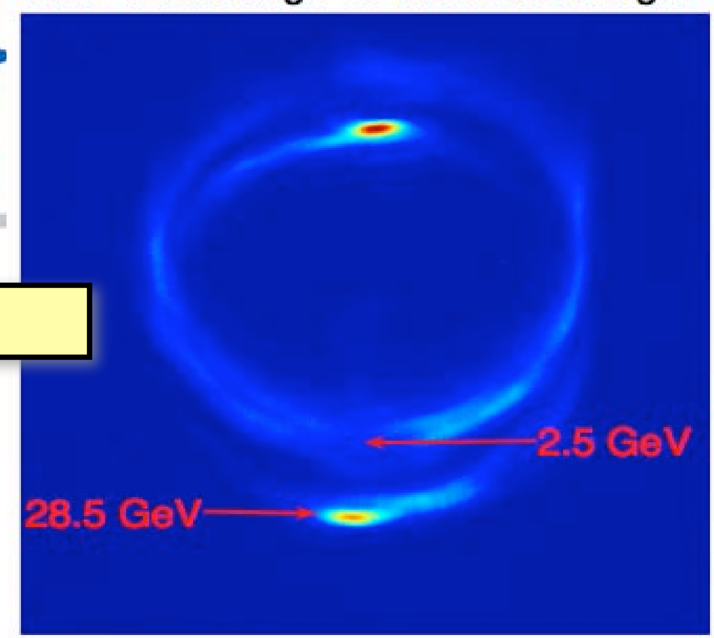
Two Main Features
- 4 times more charge
- $>10^4$ more light!





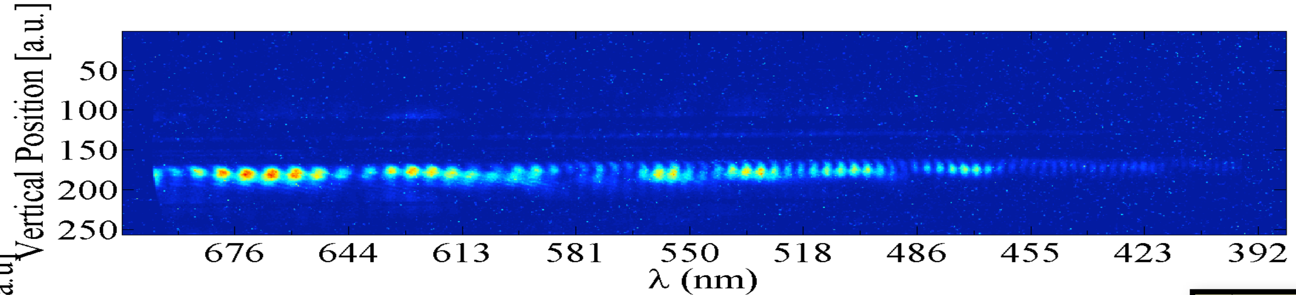
Two energy populations (MeV & GeV)

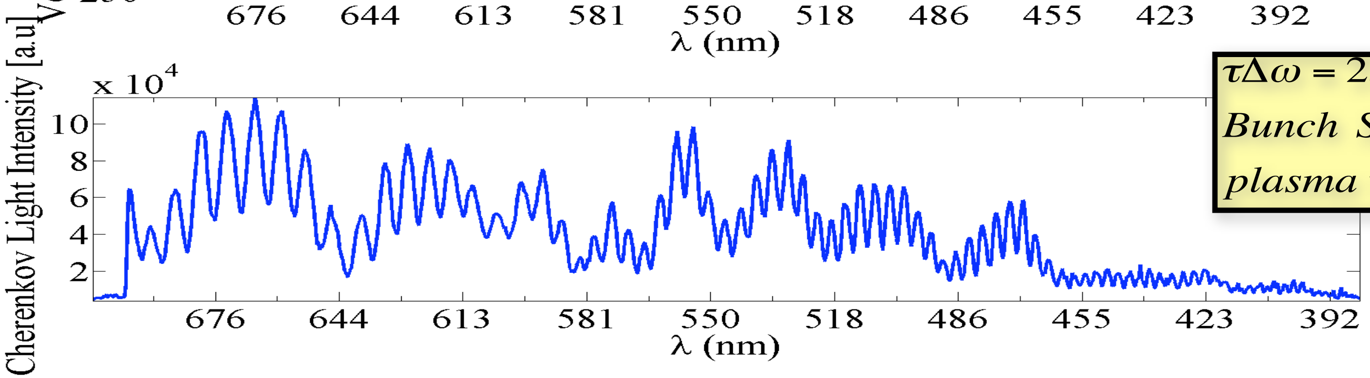
Far–field Image of Cherenkov Light



Note: Primary beam is also radiating!

Visible Light Spectrum Indicates Time Structure of Trapped Electrons





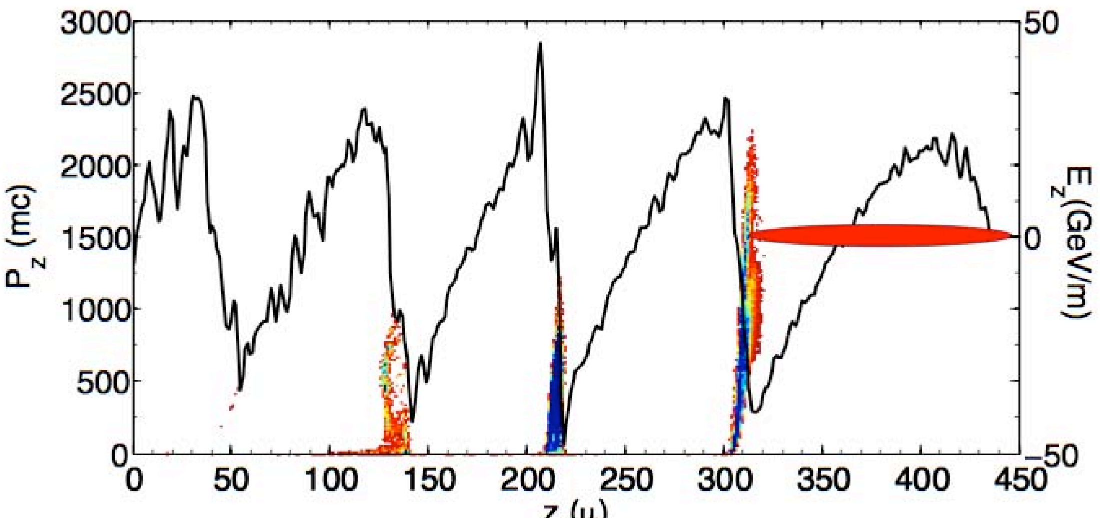
$$\tau \Delta\omega = 2\pi$$

$$Bunch\ \ Spacing = c\tau \approx 70\ \mu,$$

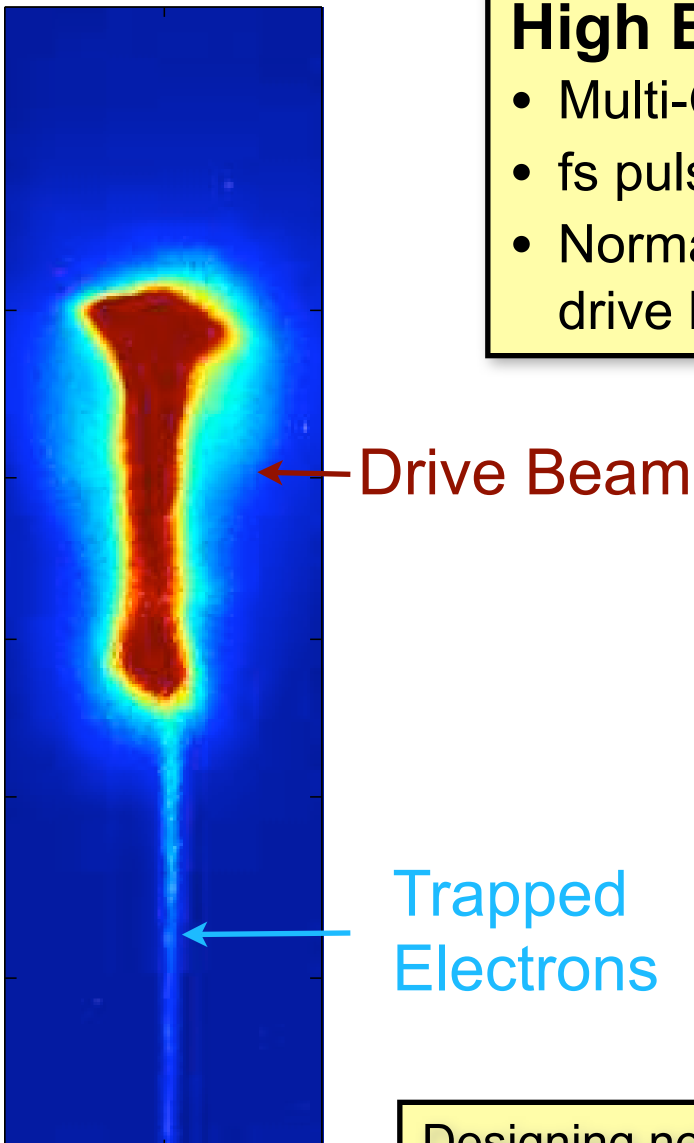
$$plasma\ wavelength,\ \lambda_p = 64\ \mu.$$

OSIRIS Simulations:

- He electrons in several buckets
- Spaced at plasma wavelength
- Bunch length ~fs

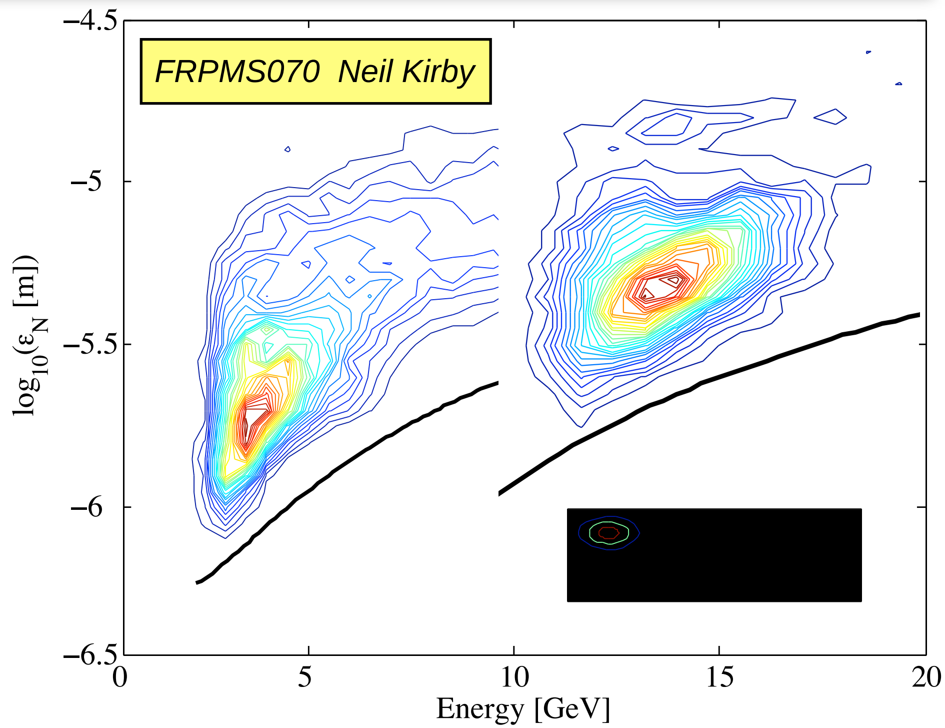


Trapped Particles



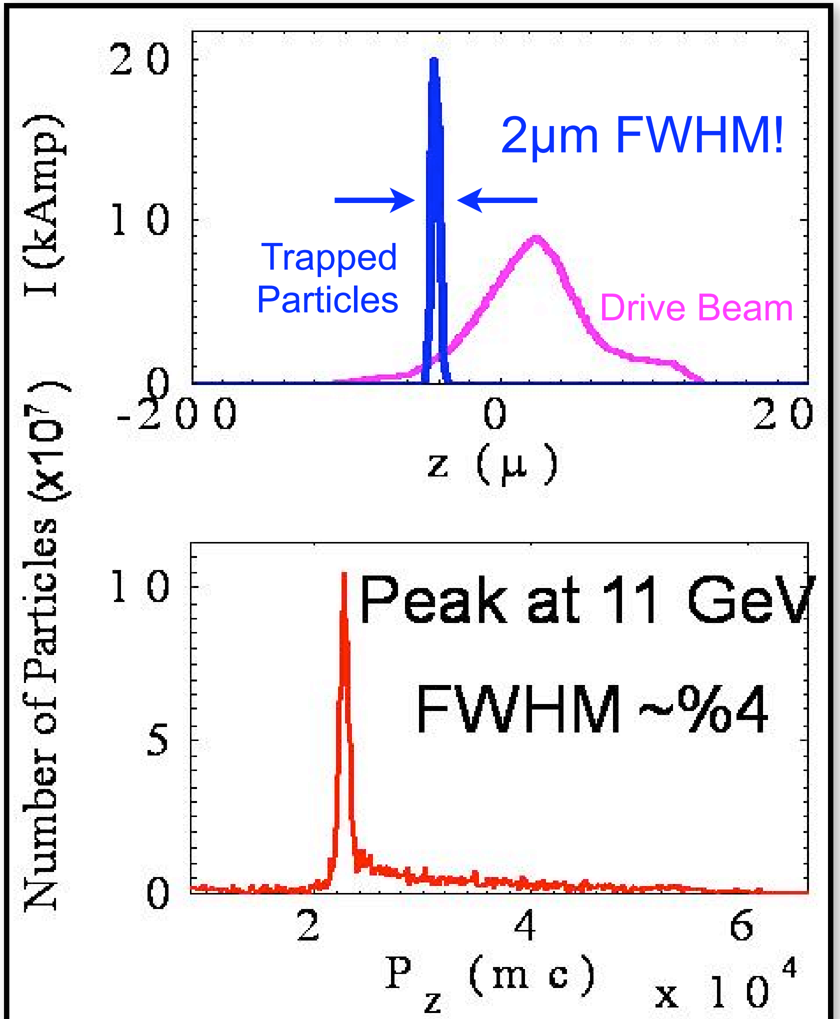
High Brightness Electron Source?

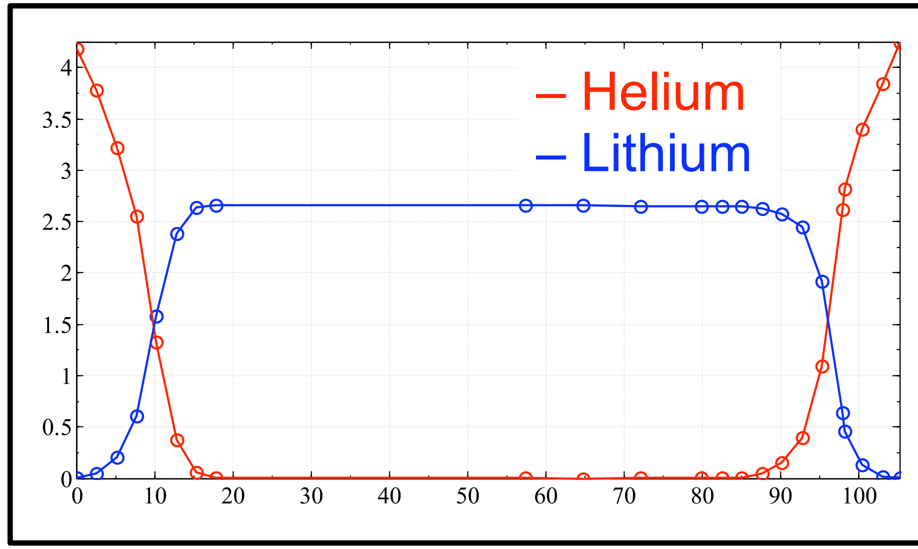
- Multi-GeV Energy
- fs pulse length
- Normalized Emittance 10 smaller than the drive beam



Designing next generation experiments to better understand and produce more of them!

Can Be Optimized by Varying Beam and Plasma Parameters





Ionization level	Ionization Energy (eV) He	Li	Ar
1st	24.587	5.392	15.759
2nd	54.416	75.638	27.629
3rd		122.451	40.74

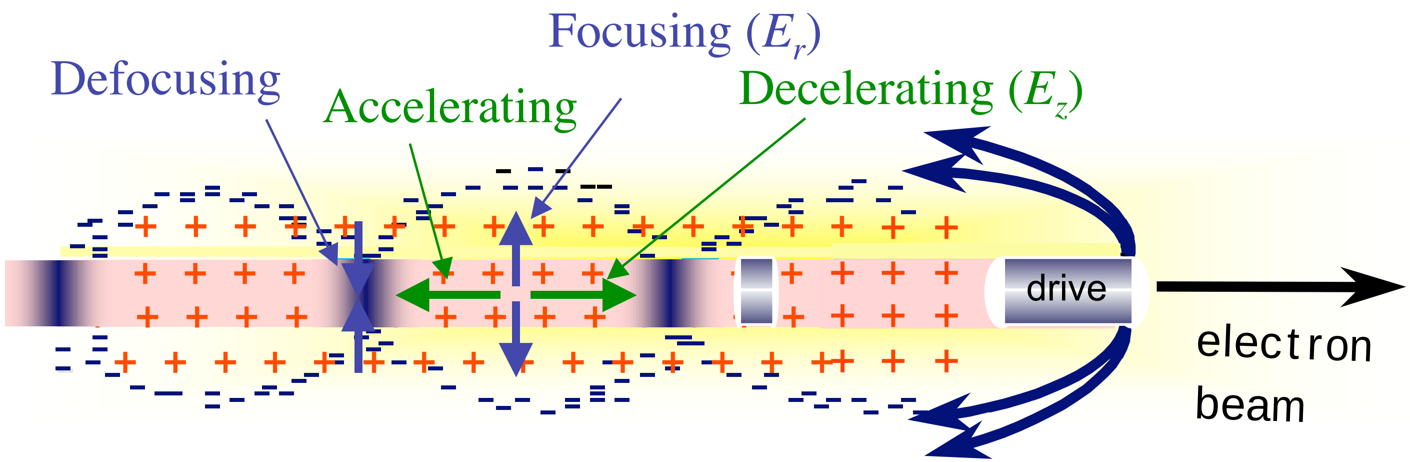
THPMS035 Erdem Oz

What's Next?

Next generation experiments will focus on two major themes:

- Two Bunch Experiments
  - ➡ Accelerate an electron bunch with narrow energy spread and preserved emittance – not just particles
- High Gradient Positron Acceleration
  - ➡ Need both for a collider
  - ➡ Two bunch positron experiments will follow

Recall Why We Want Drive + Witness Bunch

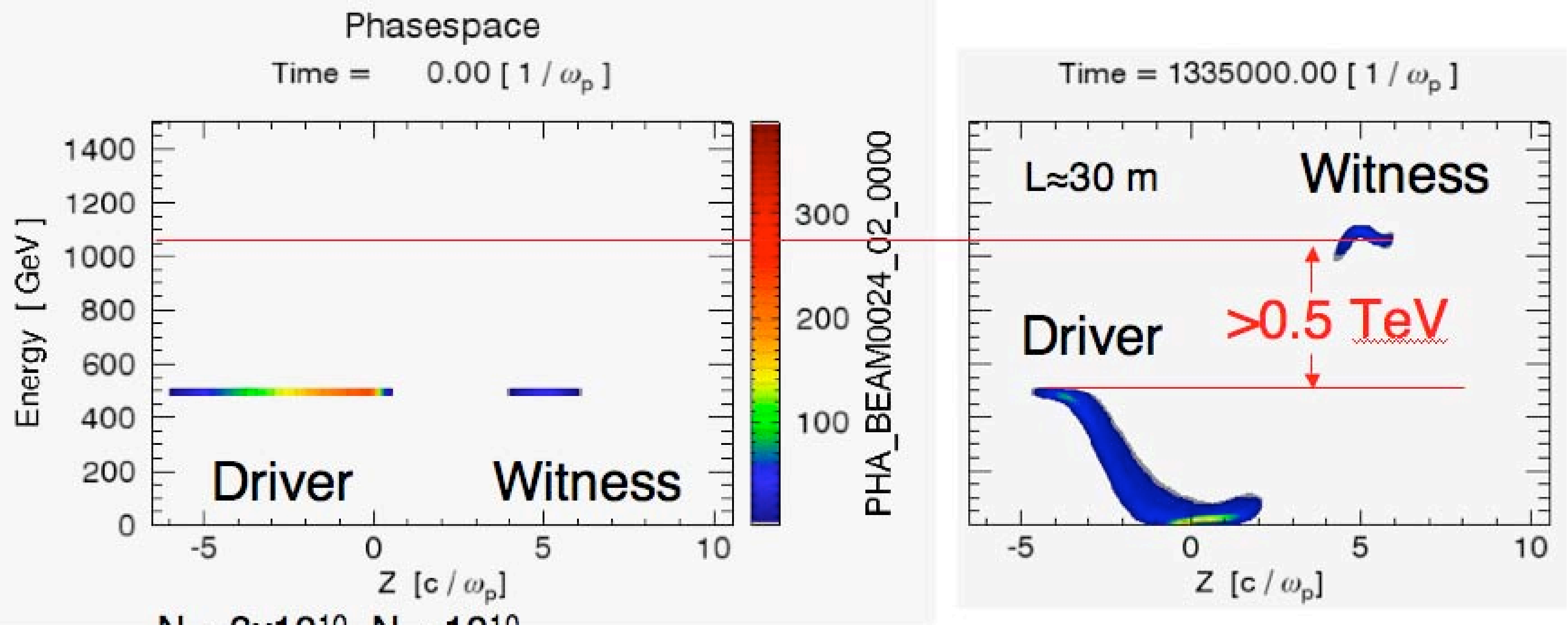


- Plasma Wakefield Accelerator (PWFA) = Transformer
  Booster for high energy accelerator

Recall Why We Want Drive + Witness Bunch

Simulations by C. Huang, UCLA

THPAS053 Chengkun Huang



$N_D=3\times10^{10}$, $N_w=10^{10}$,

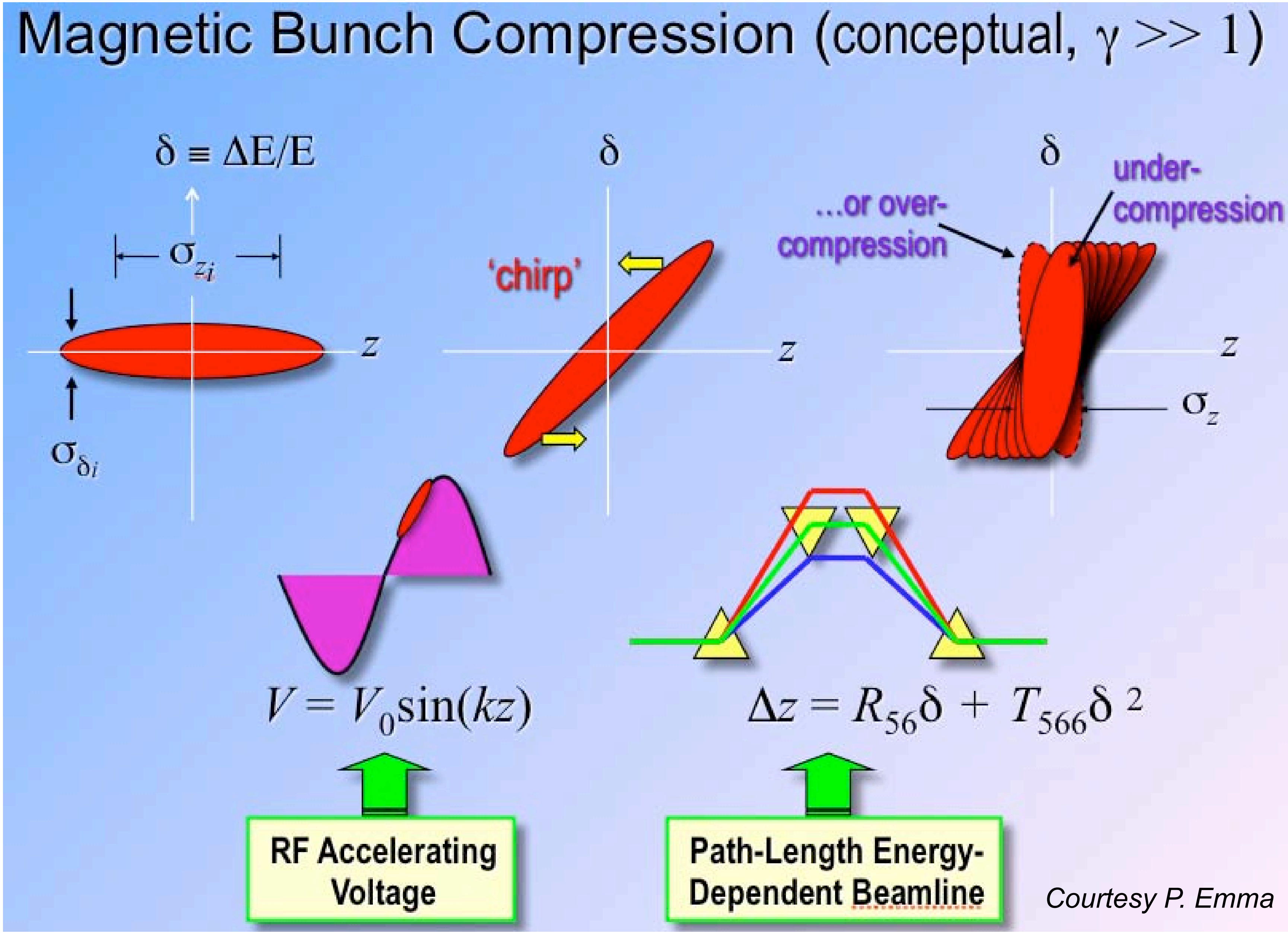
$\varepsilon_{Nx}=\varepsilon_{Ny}=2230\times10^{-6}$ m-rad, $\sigma_x=\sigma_y=15\ \mu m$, (beam matched to the plasma)

$\sigma_{zD}=145\ \mu m$, $\sigma_{zW}=10\ \mu m$, $\Delta z=100\ \mu m$

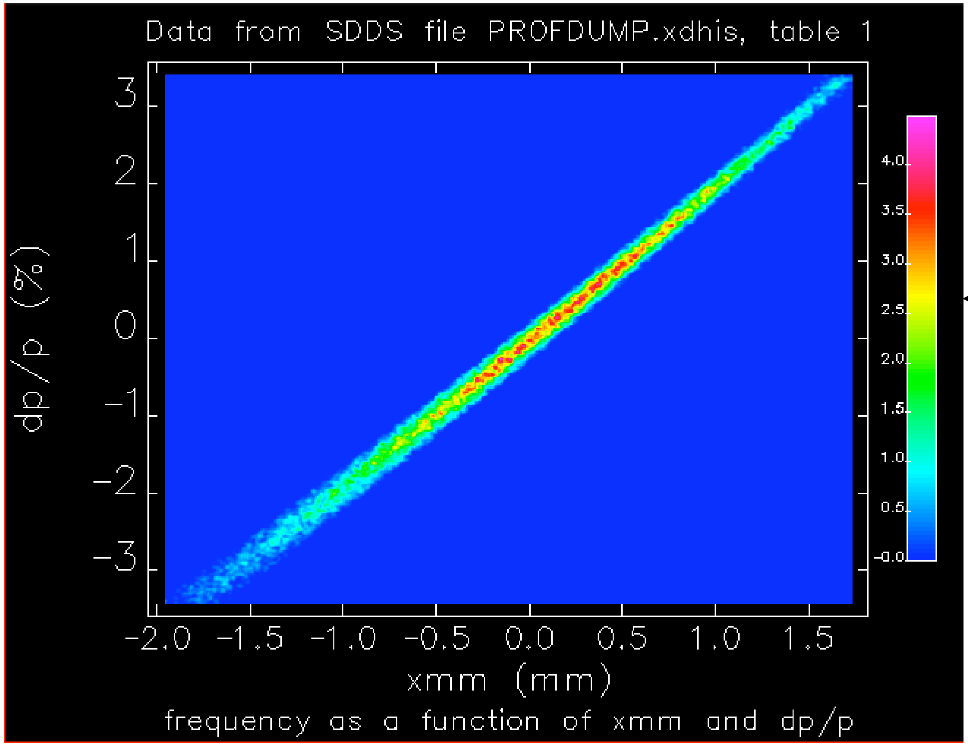
$N_e=5.66\times10^{16}\ cm^{-3}$, $L_p=30$ m

Doubling 500GeV in 30m! (simulation)

Creating Two Bunches: Use a Notch Collimator

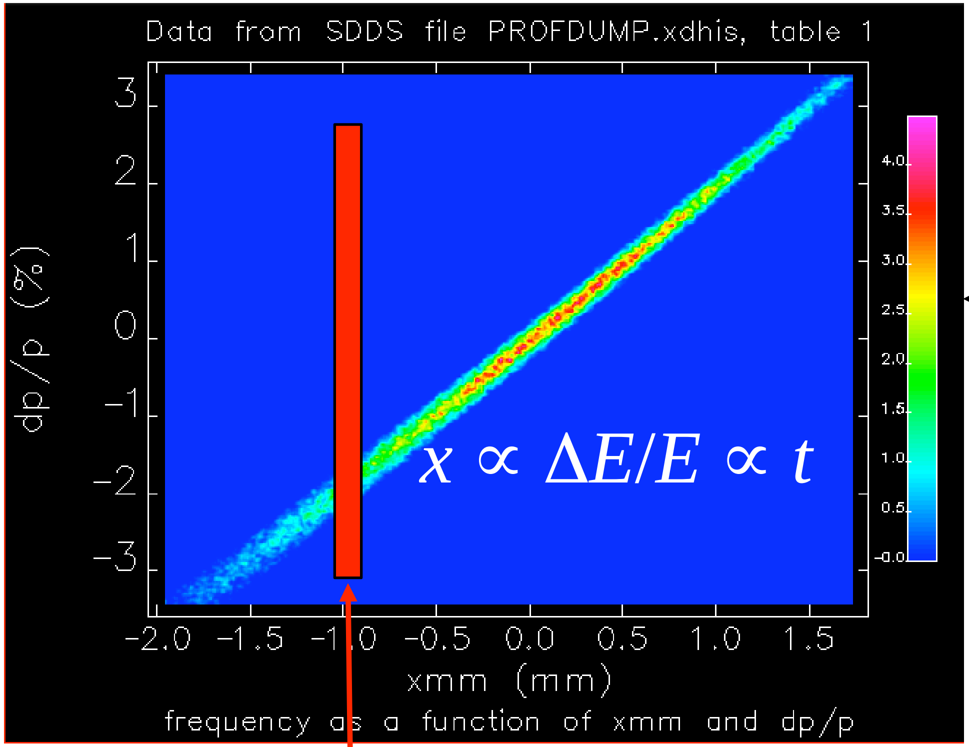


Exploit Position-Time Correlation on e⁻ bunch to create separate drive and witness bunch



Access to *time* coordinate along bunch

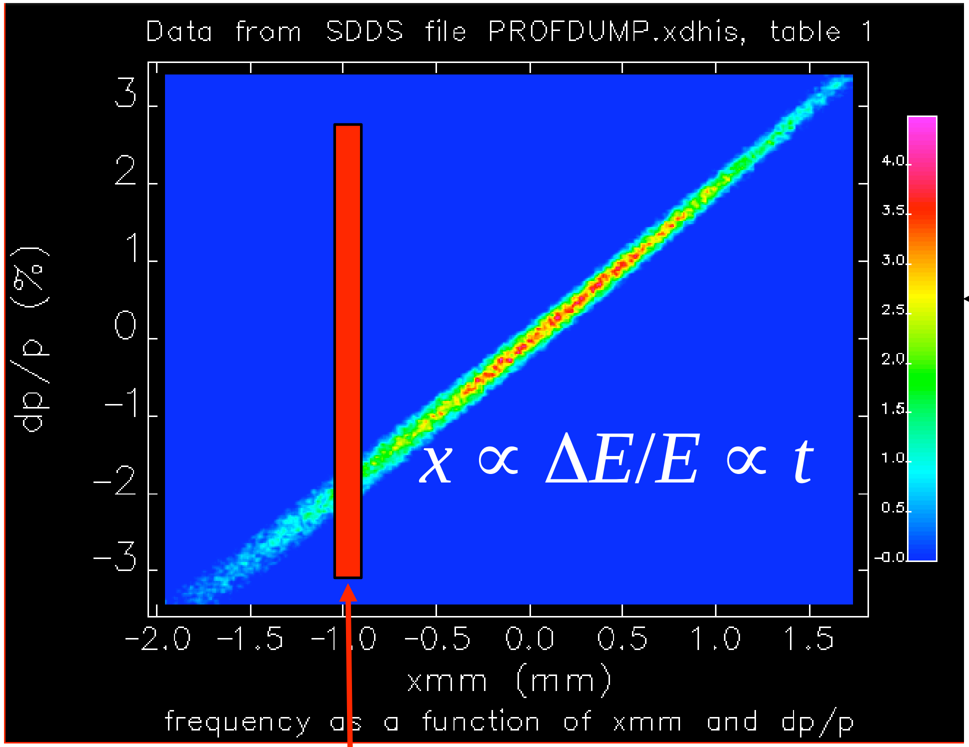
Exploit Position-Time Correlation on e⁻ bunch to create separate drive and witness bunch



Access to *time* coordinate along bunch

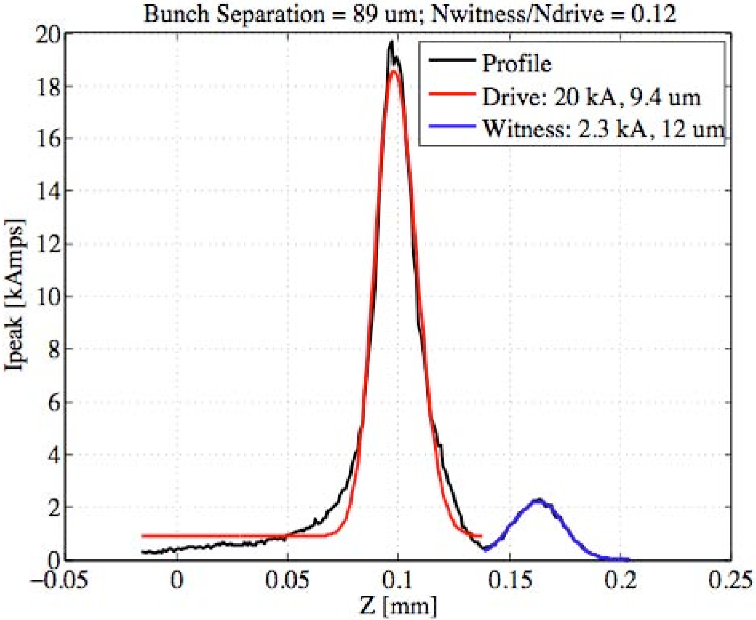
1. Insert tantalum blade as notch collimator

Exploit Position-Time Correlation on e⁻ bunch to create separate drive and witness bunch

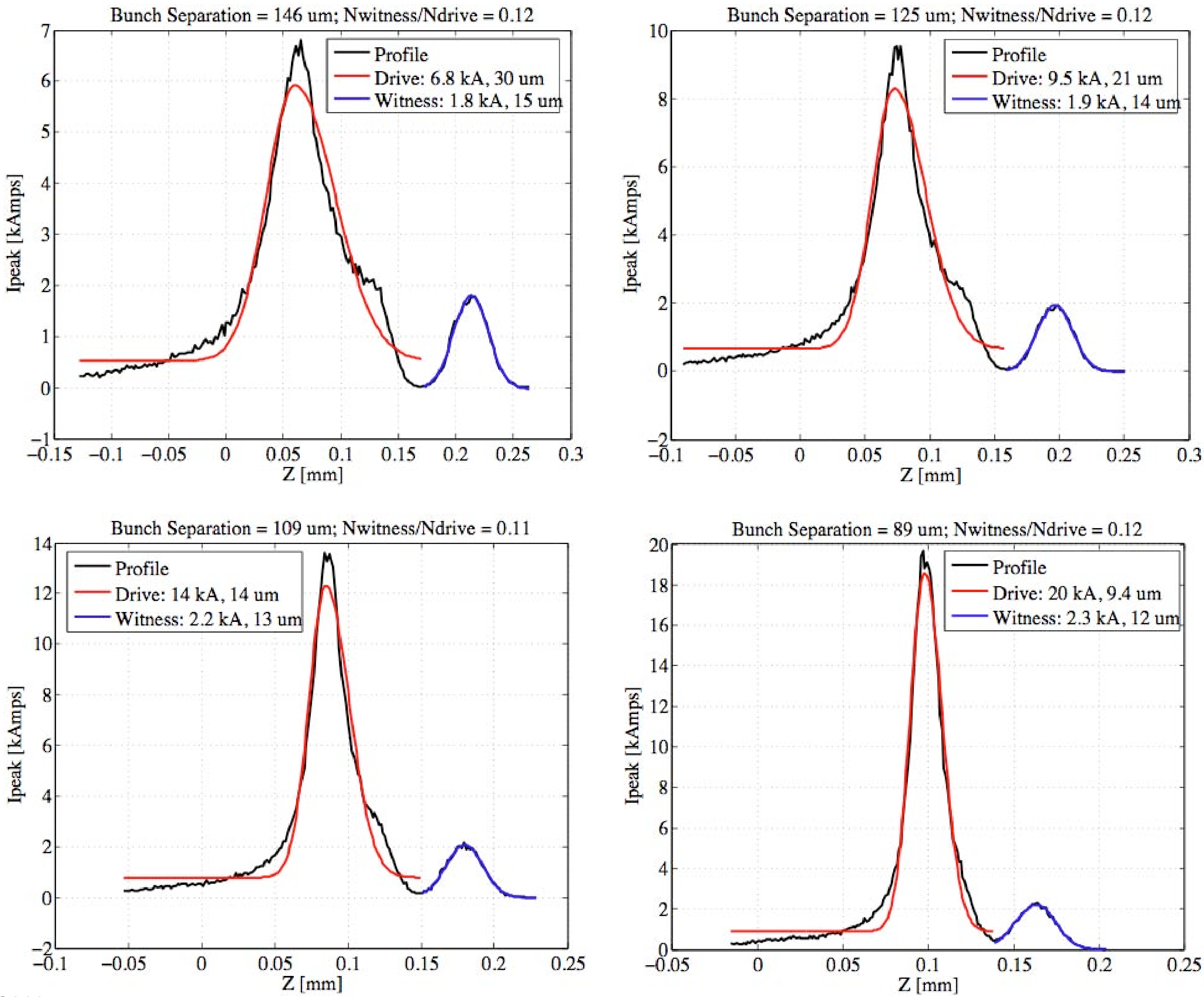


Access to *time* coordinate along bunch

1. Insert tantalum blade as notch collimator
2 Do not compress fully to preserve two bunches separated in time

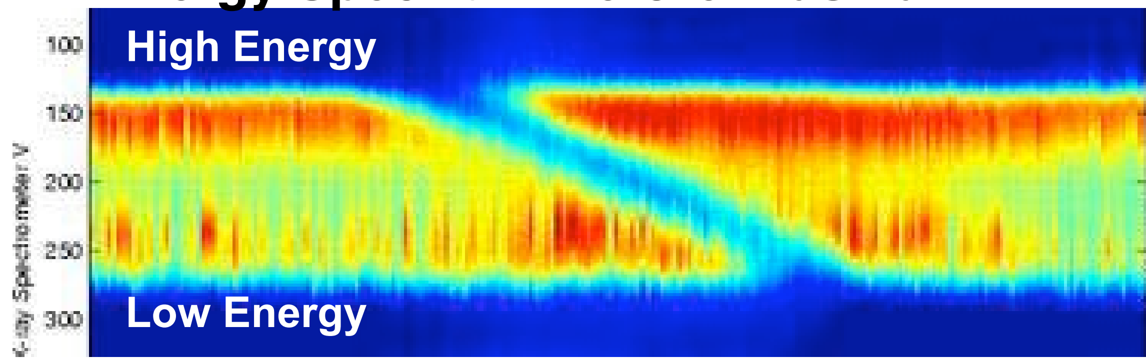


Change Incoming Chirp to Change Bunches

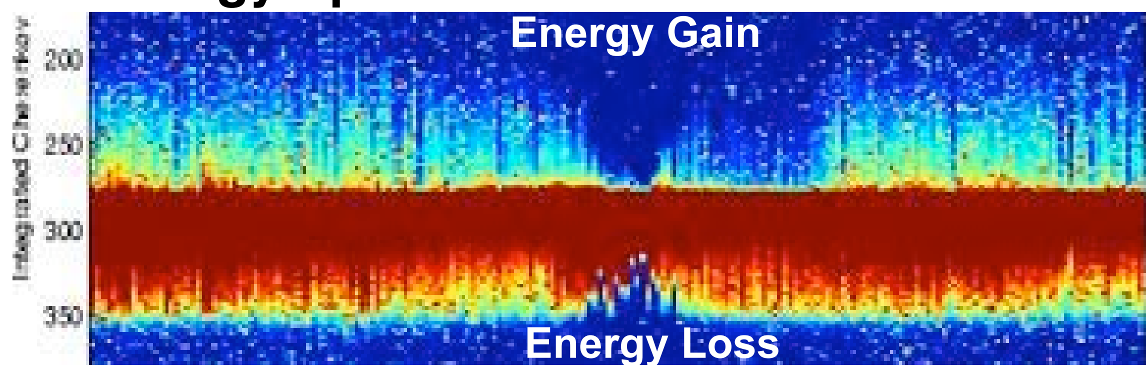


Test of Notch Collimator - December 2005

Energy Spectrum Before Plasma:



Energy Spectrum After Plasma:

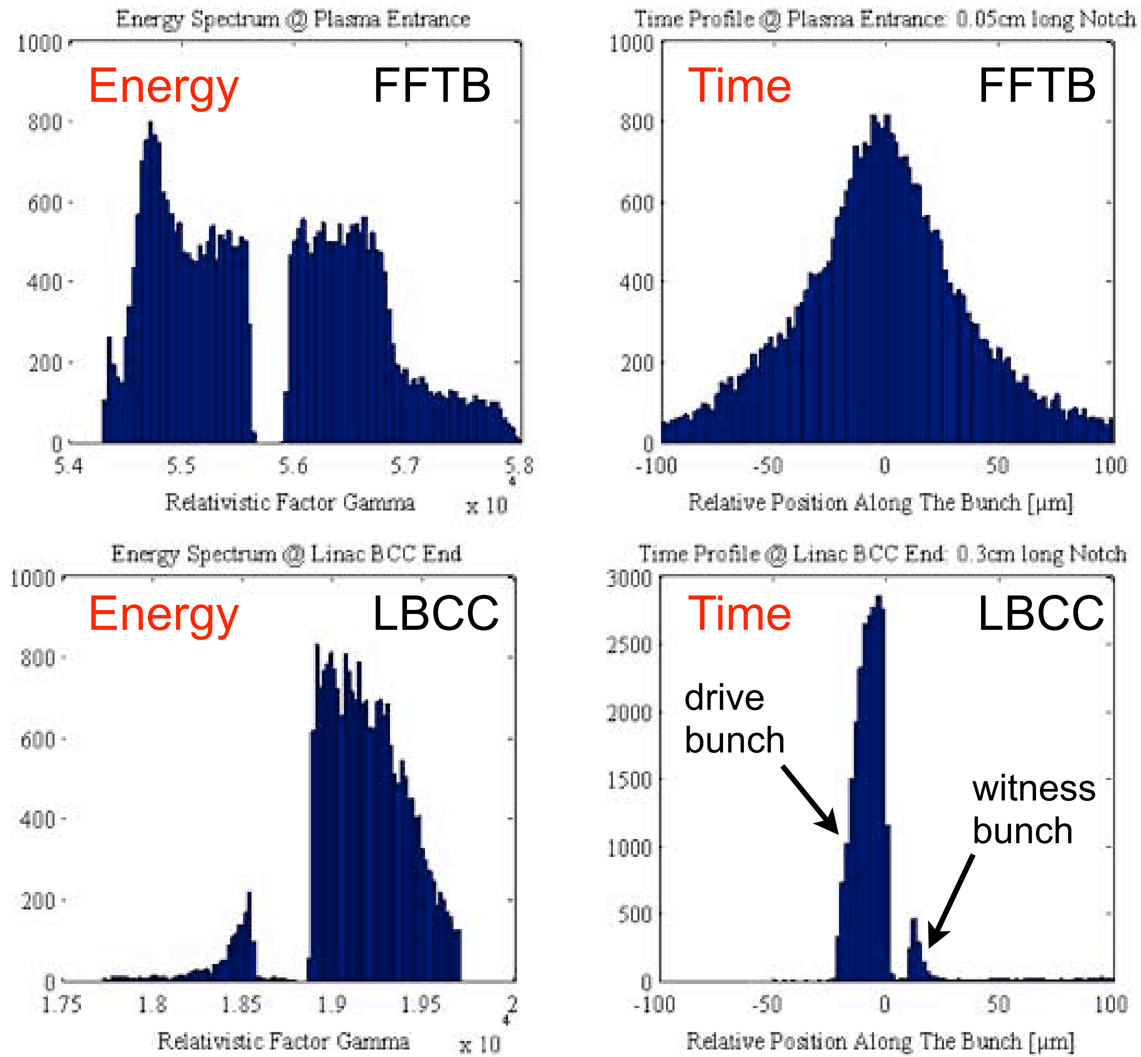


Shot # (Time) →

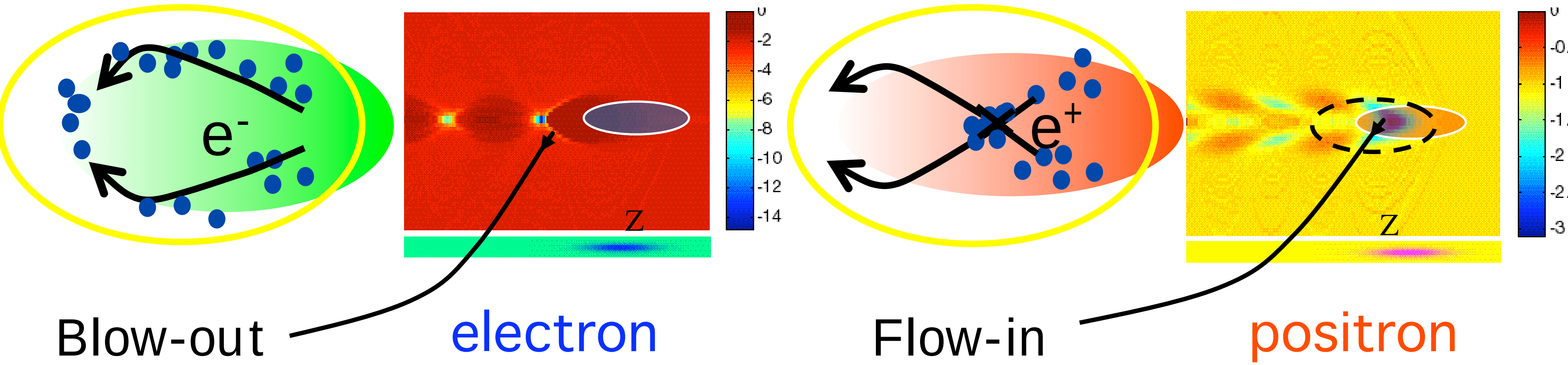
- Acceleration correlates with collimator location (Energy)
- No signature of temporally narrow witness bunch - yet!
- Collimated spectra more complicated than anticipated
- **Will be a major component of long term program @ SABER**
- **The only technique that will work for positrons too!**

ELEGANT & SHOWER (EGS4) Simulations

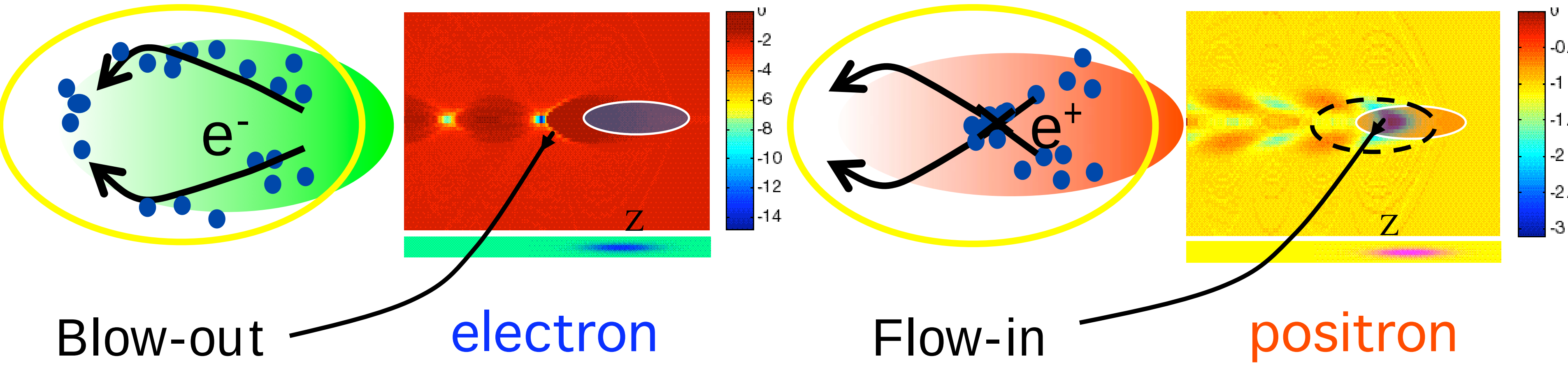
- FFTB provided better access for test than the linac chicane (LBCC)
- 1D simulations not adequate
- 3D models using ELEGANT & SHOWER (EGS4) reproduce measured spectra from tests in 2005
- Simulations show can create two bunches in the chicane!
- Only technique that will work for *both* e- & e+
- Collimator optimization in progress



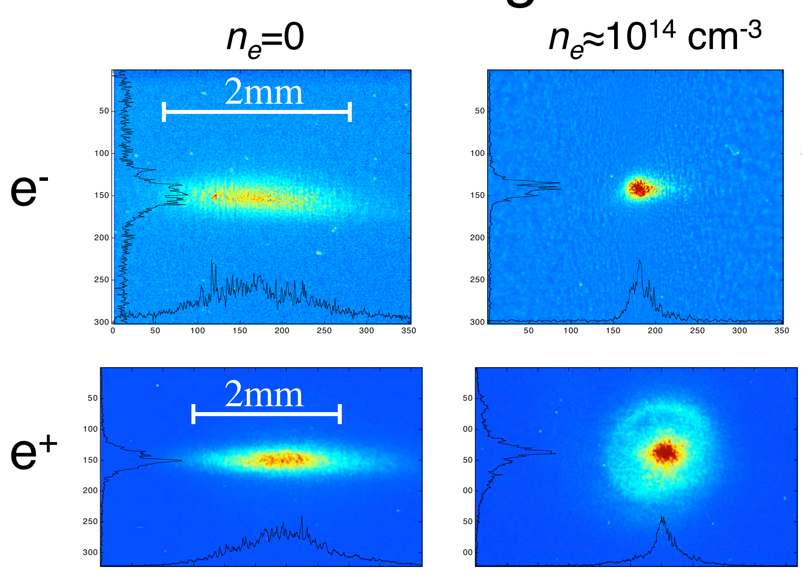
THPMS034 Patric Muggli


e-
Blow-out
0
-2
-4
-6
-8
-10
-12
-14
z
electron
e+
Flow-in
0
-0.5
-1
-1.5
-2
-2.5
-3
z
positron

PWFA Mechanism Different For A Positron Beam

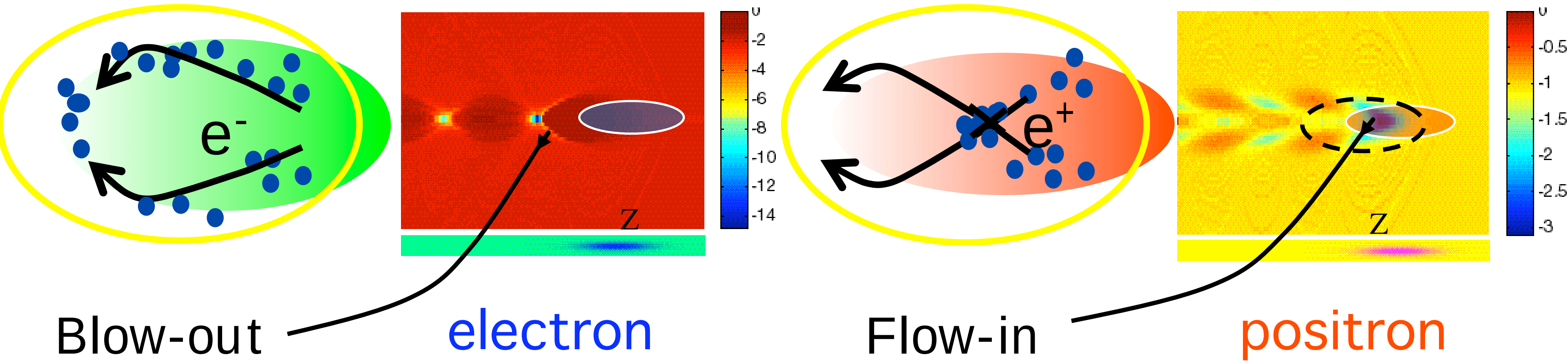


Positron Focusing varies with radius

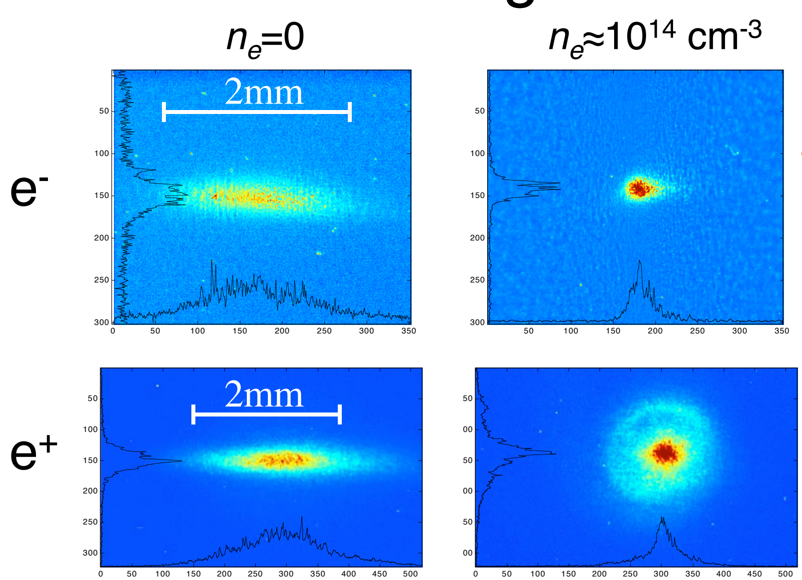


- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations

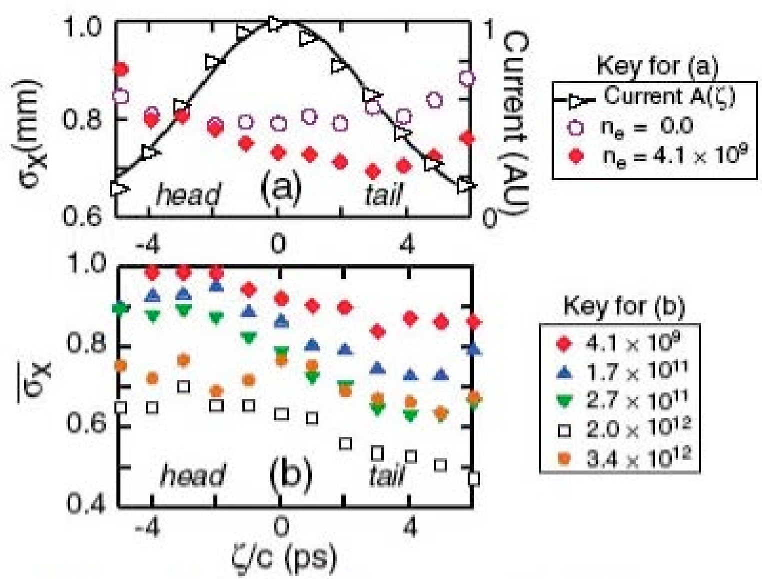
E-162 Data



Positron Focusing varies with radius and position along the bunch



- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations

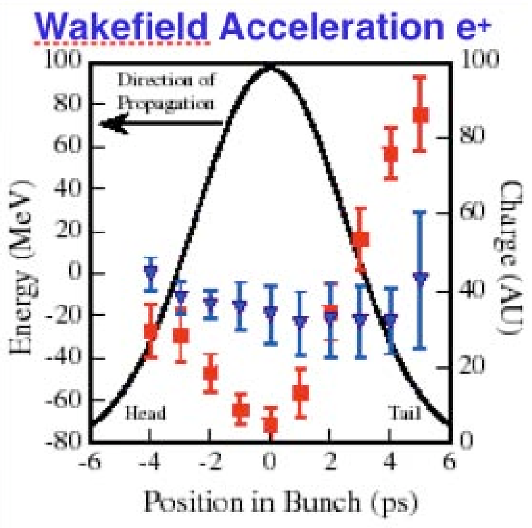


(M.J. Hogan *et al.*, PRL 2003)

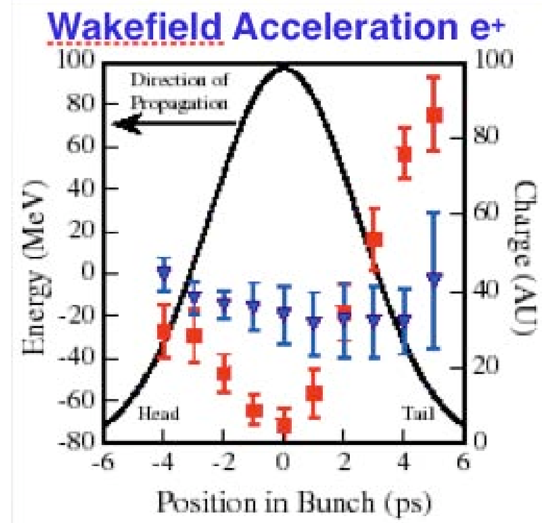
E-162 Data

PWFA Mechanism Different For A Positron Beam

Although the wakes are more complicated, have demonstrated positron acceleration with long bunches and low density (E-162)



Phys. Rev. Lett. **90**, 214801 (2003)



Phys. Rev. Lett. **90**, 214801 (2003)

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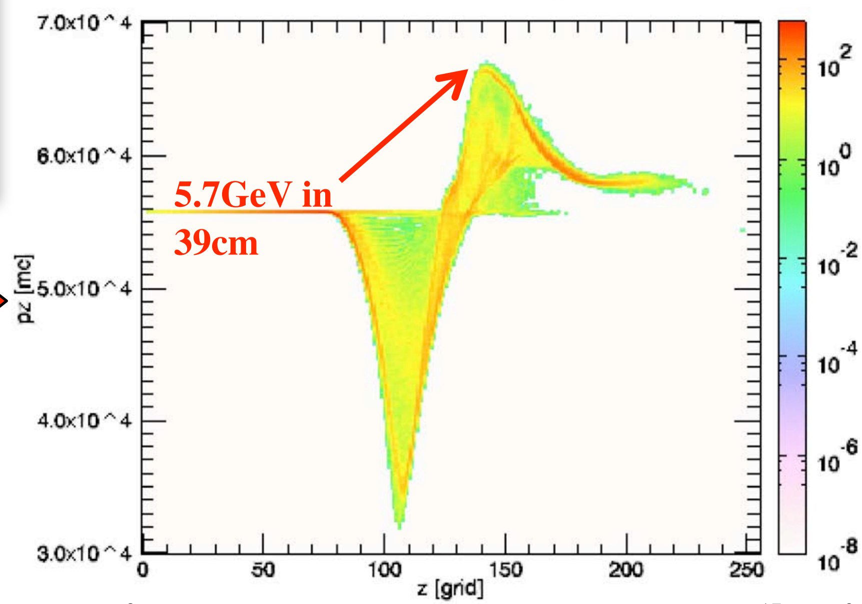
A Compelling Question:
Can the large amplitude wakes measured for electrons be created and sustained for a positron drive beam?

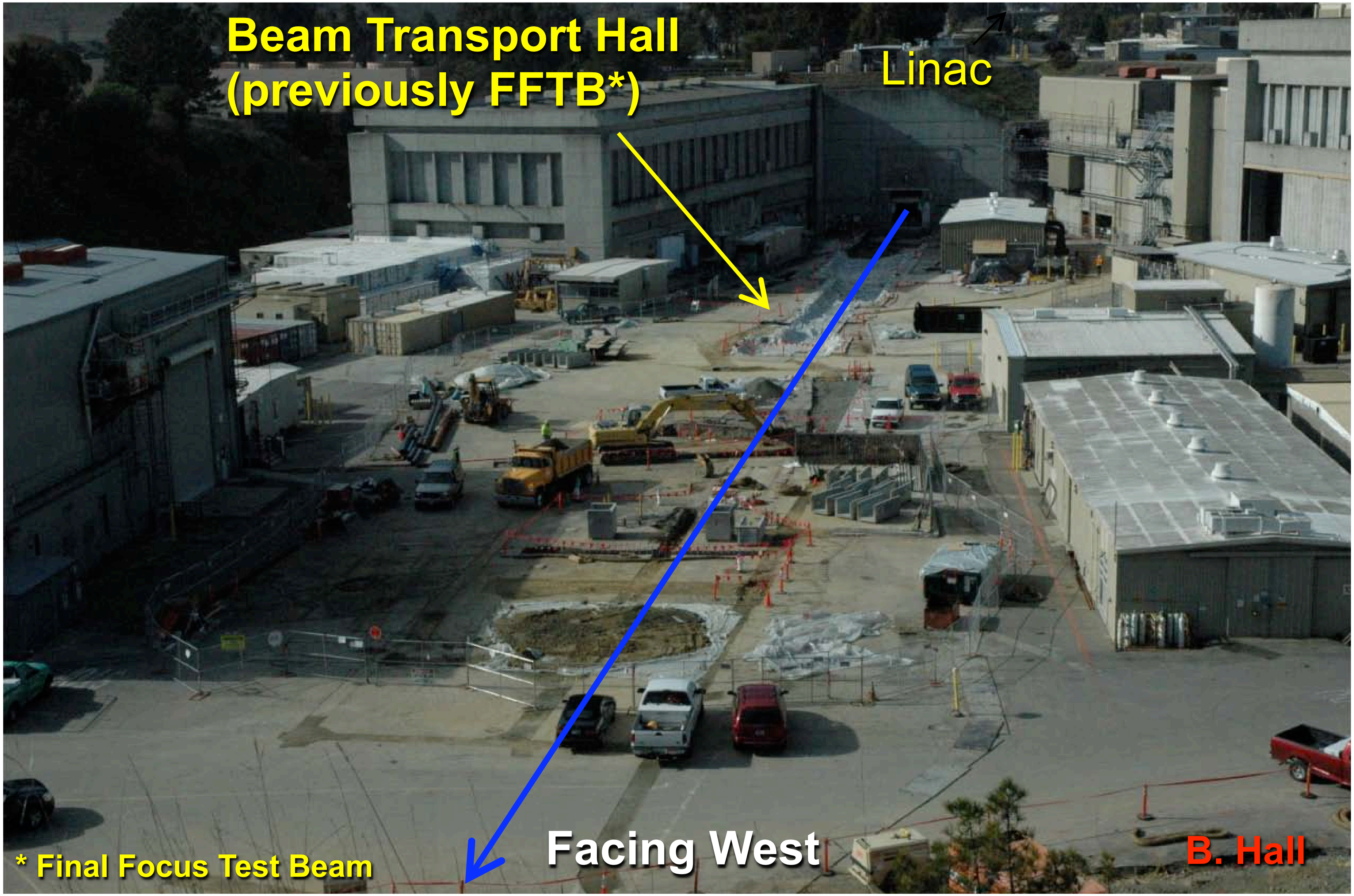
Evolution of a positron beam/wakefield and final energy gain in a **self-ionized** plasma



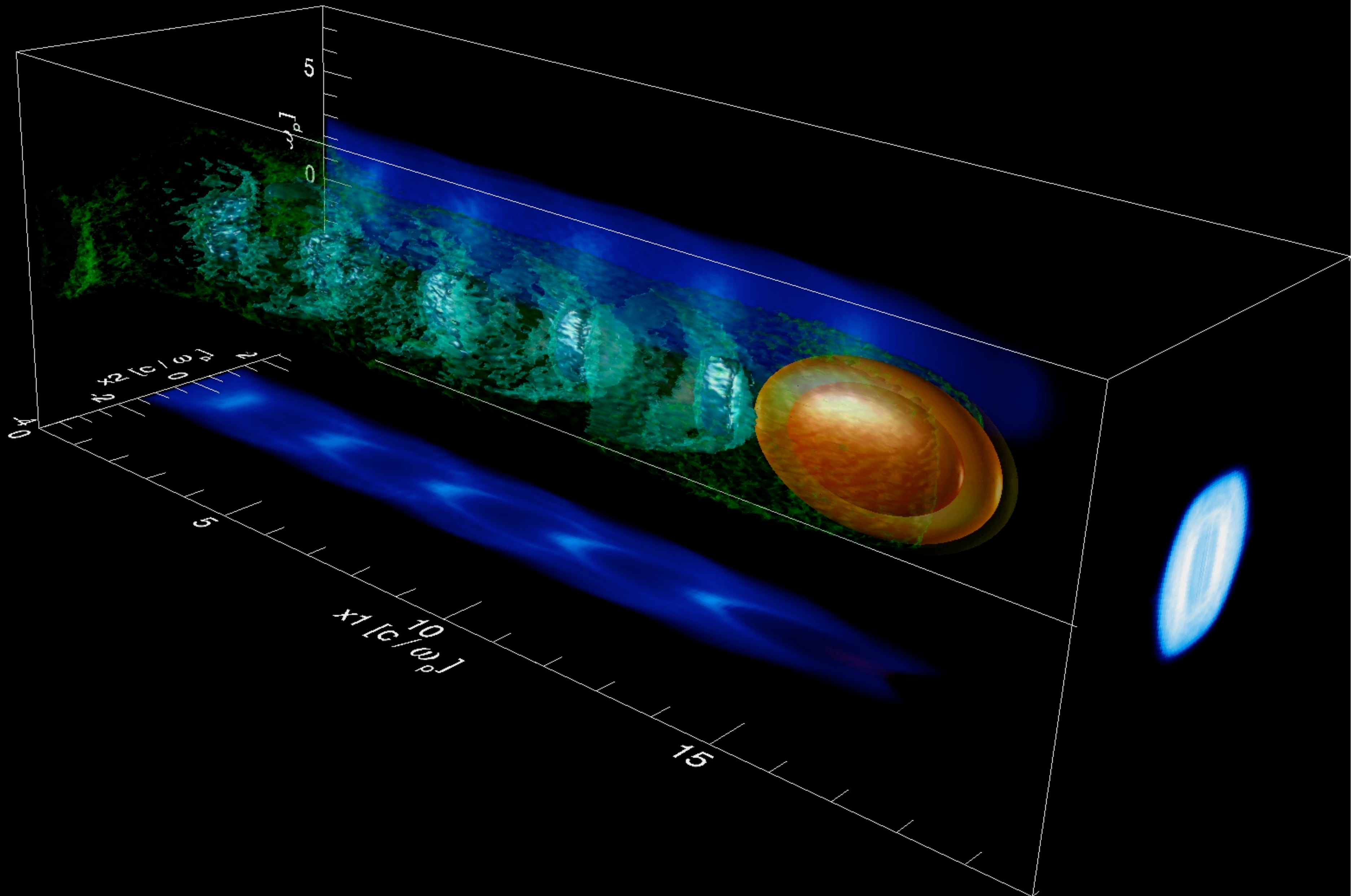
$N_b = 8.79 \times 10^9, \sigma_r = 11\mu m, \sigma_z = 19.55\mu m, n_p = 1.8 \times 10^{17} cm^{-3}$

Will require iteration with plasma source development to minimize emittance growth (hollow channel plasma?)

Future Experiments Require a New Facility: SABER

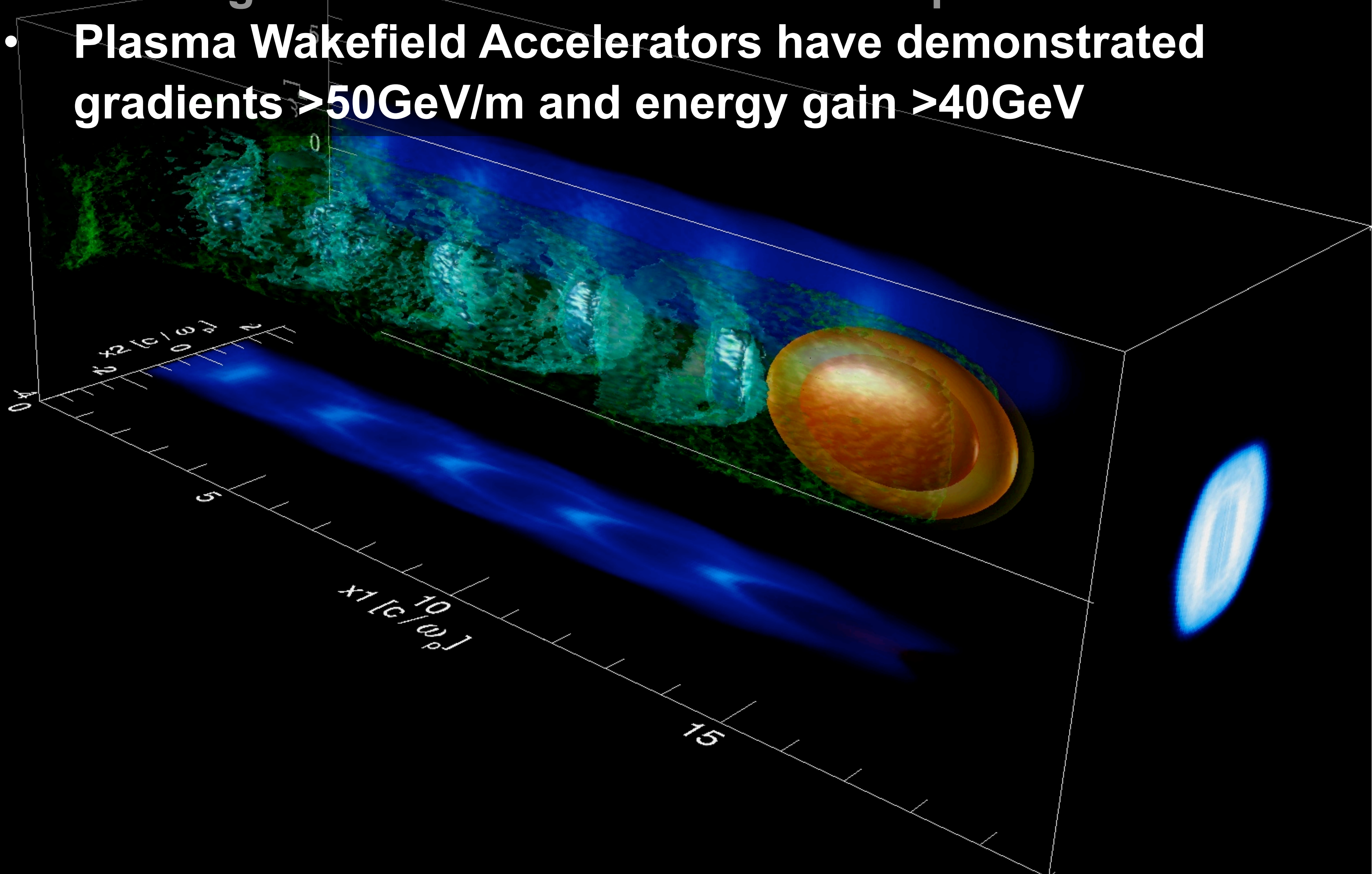


Conclusions:



Conclusions:

- Exciting Time for Plasma Wakefield Experiments
- **Plasma Wakefield Accelerators have demonstrated gradients >50GeV/m and energy gain >40GeV**



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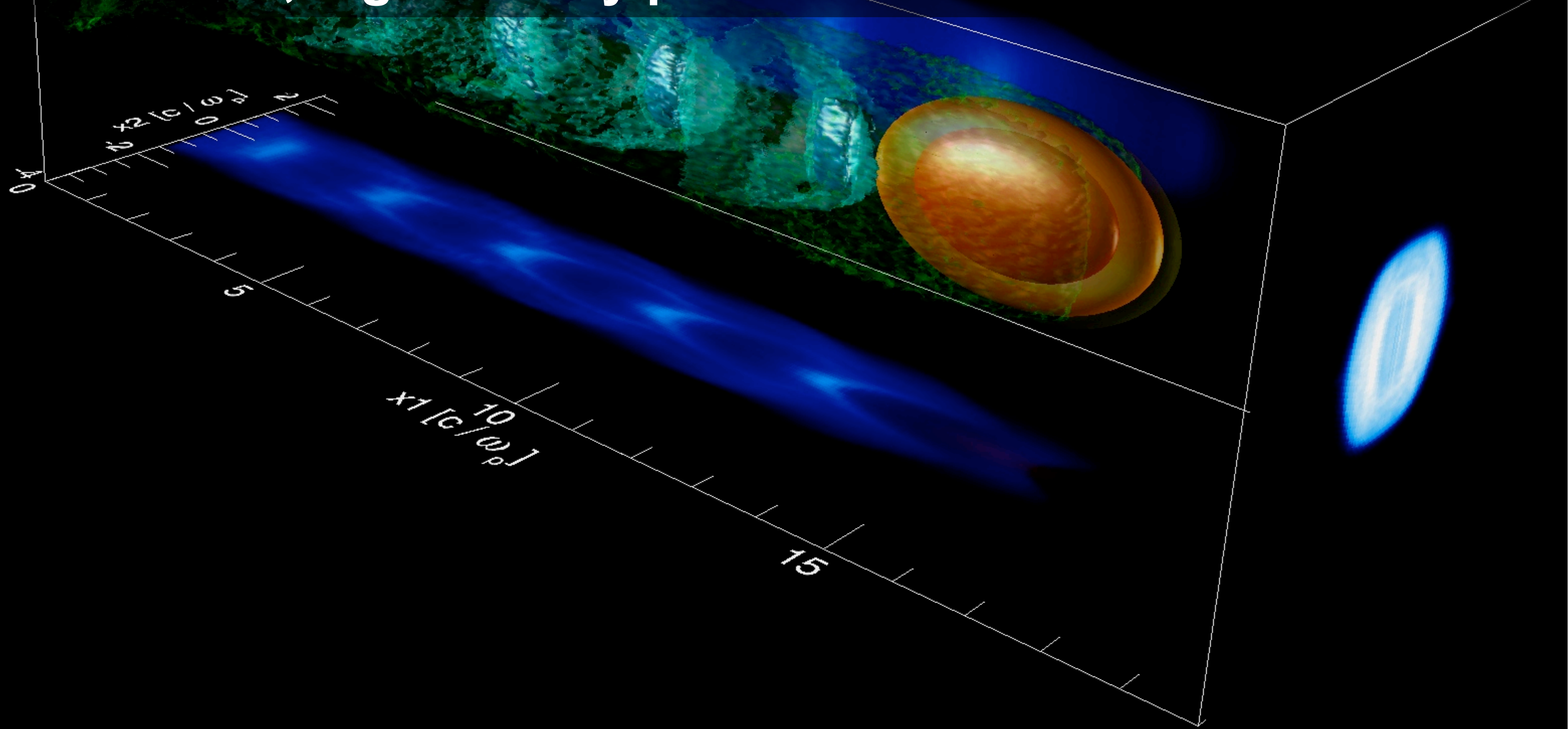

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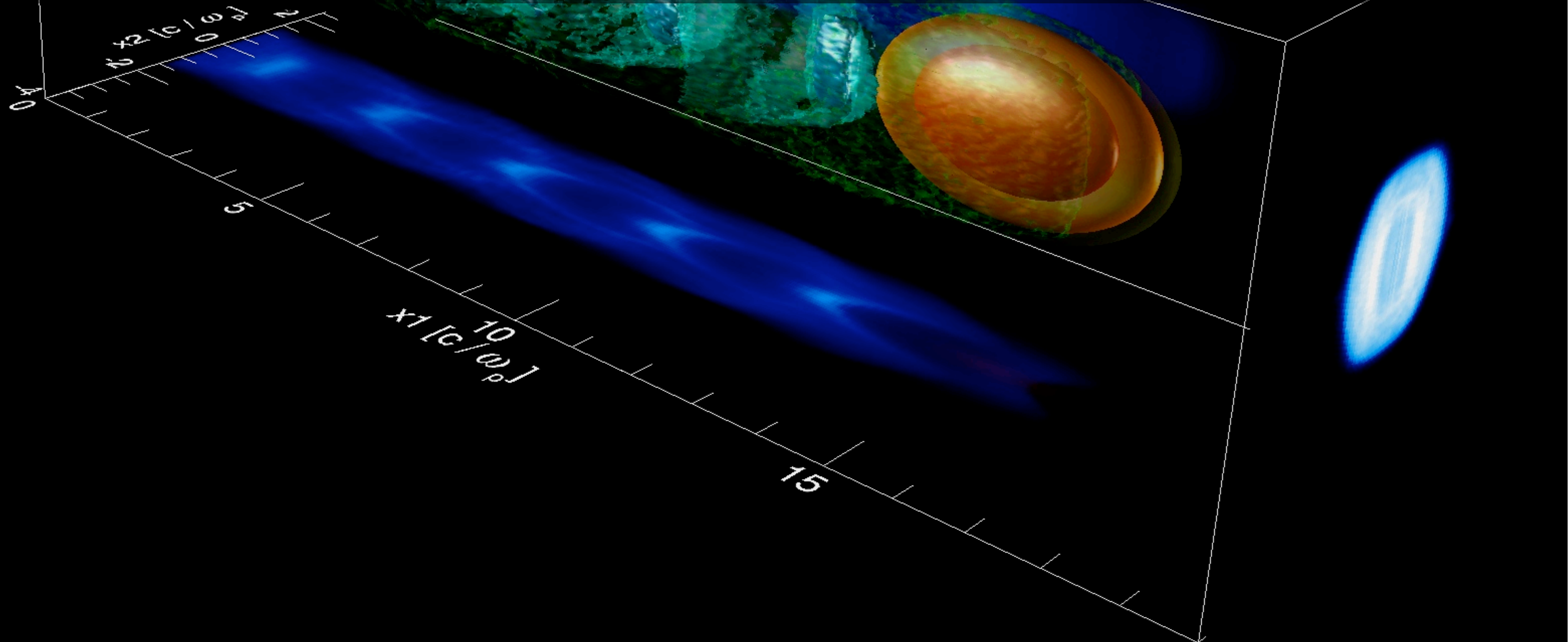

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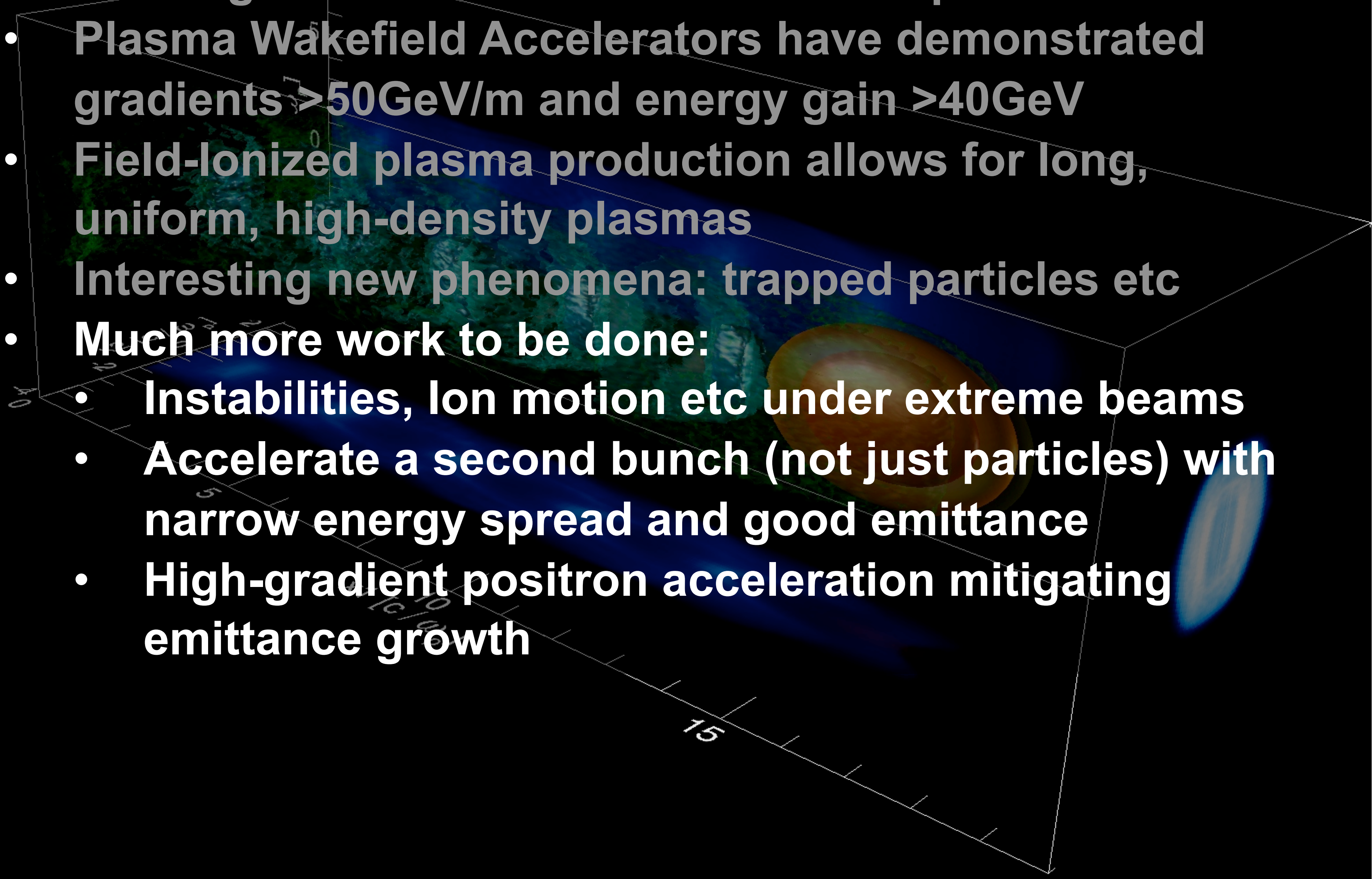
    - High-gradient positron acceleration mitigating emittance growth



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- **Continued progress requires an accelerator research facility to replace the FFTB while providing additional capabilities → SABER**