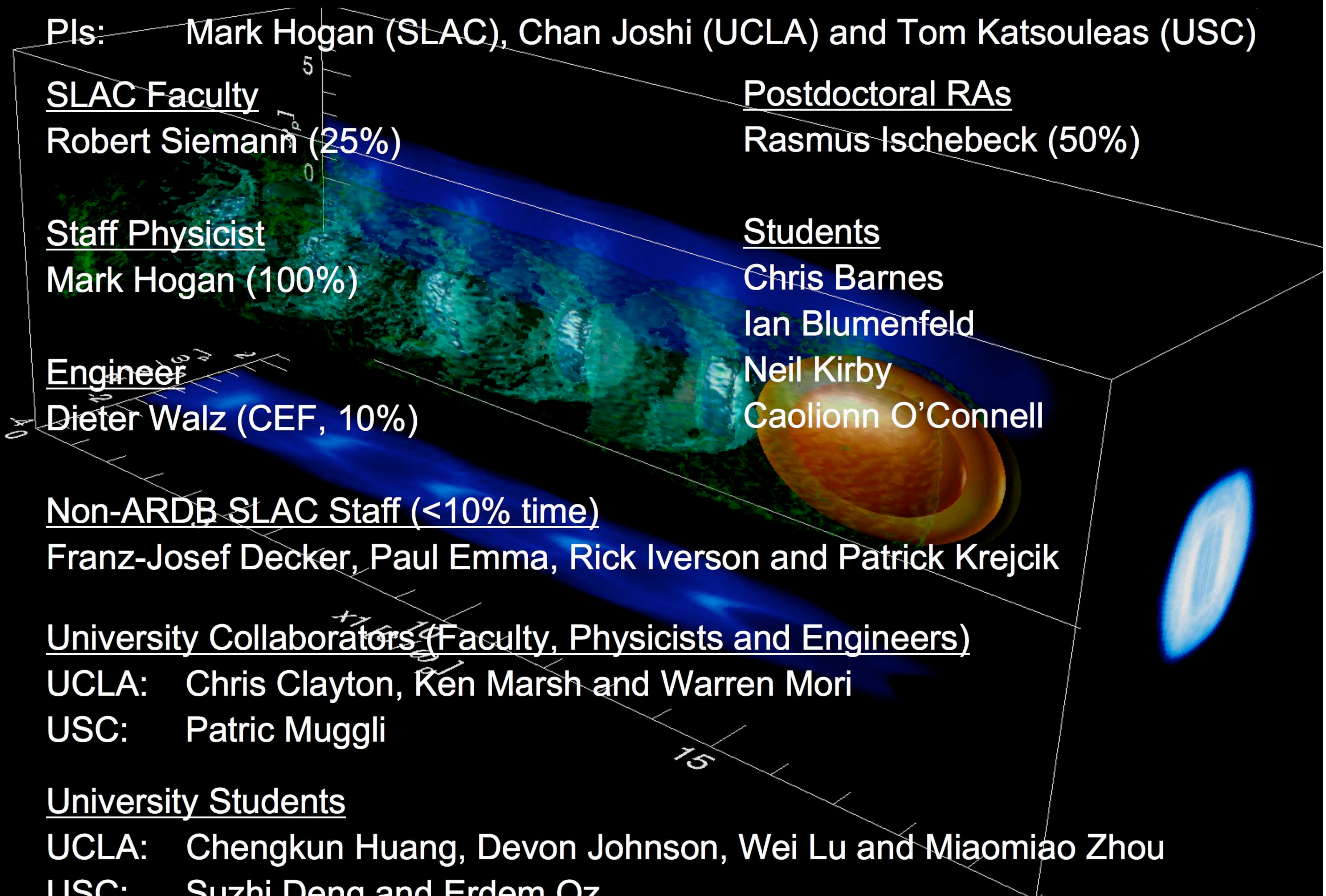
Plasma Wakefield Acceleration in the FFTB (E-164X & E-167)



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USC: Patric Muggli

<u>University Students</u>
UCLA: Chengkun Huang, Devon Johnson, Wei Lu and Miaomiao Zhou
USC: Suzhi Deng and Erdem Oz

Outline

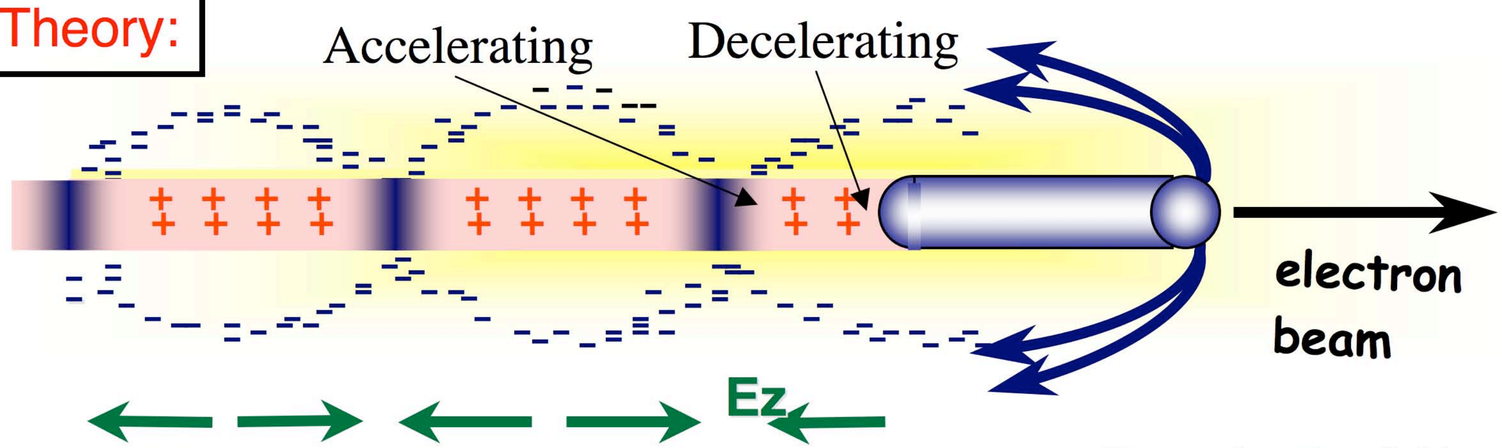
- Introduction to PWFA
- Building on previous work
- Short bunches
  - How we make & measure them
  - Need a plasma to match them
- Phase space retrieval via LiTrack
- Multi-GeV energy gain
- Future directions
- Conclusion

PWFA:
Plasma Wakefield Acceleration

❑ Looking at issues associated with applying the large focusing (MT/m) and accelerating (GeV/m) gradients in plasmas to high energy physics and colliders

❑ Built on E-157 & E-162 which observed a wide range of phenomena with both electron and positron drive beams: focusing, acceleration/de-acceleration, X-ray emission, refraction, tests for hose instability…

Linear PWFA Theory:



- $E_{z,linear} \propto \dfrac{N}{\sigma_z^2}$ ⇨ Short bunch!
- For $k_p\sigma_r << 1$ and $k_p\sigma_z \cong \sqrt{2}$ or $n_p \propto \dfrac{1}{\sigma_z^2}$

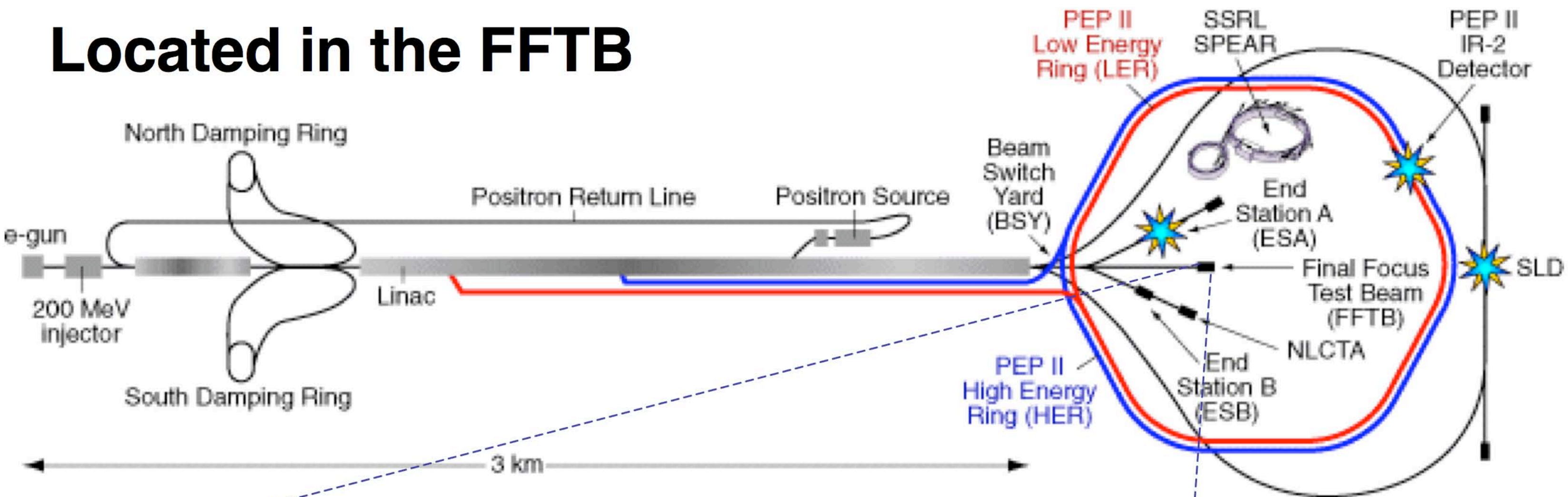
E_z: accelerating field
N: # e^-/bunch
σ_z: gaussian bunch lengt
k_p: plasma wave numbe
n_p: plasma density
n_b: beam density

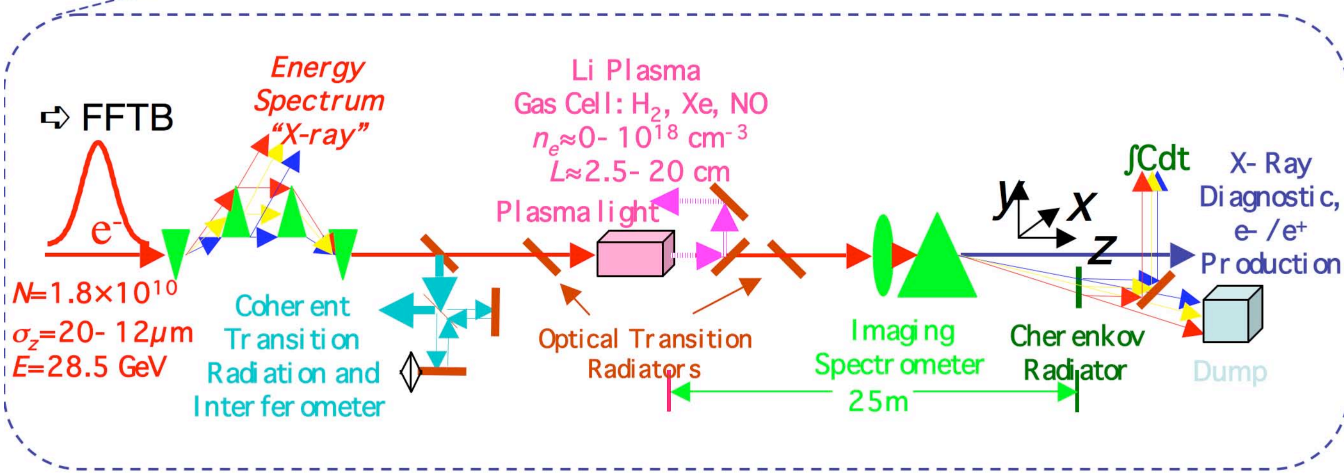
❑ A single bunch from the linac drives a large amplitude plasma wave which focus and accelerates particles

❑ For a single bunch the plasma works as an energy transformer and transfers energy from the head to the tail

PWFA Experiments @ SLAC Share Common Apparatus

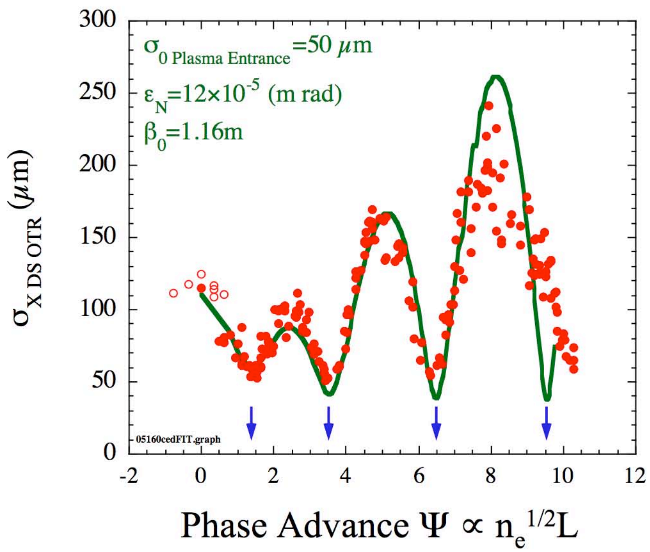
Located in the FFTB





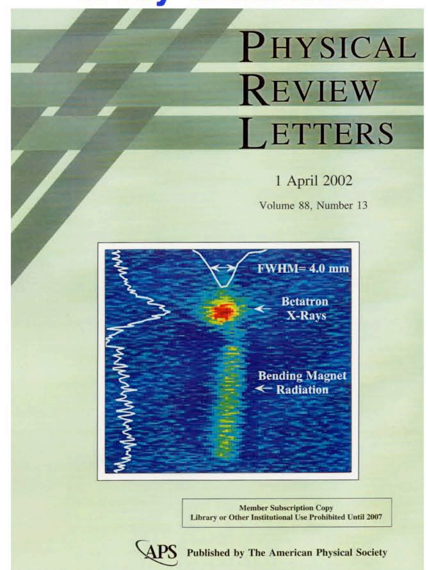
Beam-Plasma Experimental Results (6 Highlights)

Focusing e⁻



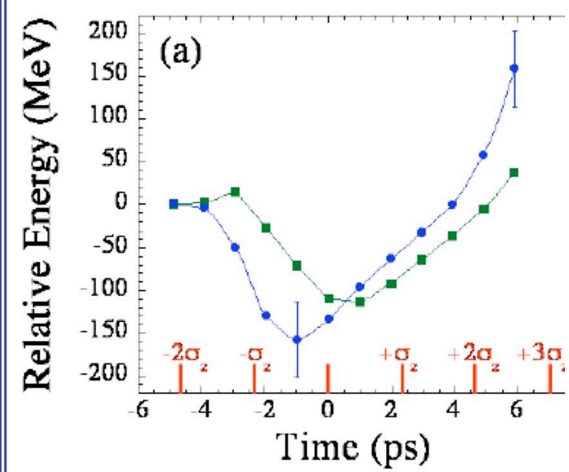
Phys. Rev. Lett. **88**, 154801 (2002)

X-ray Generation



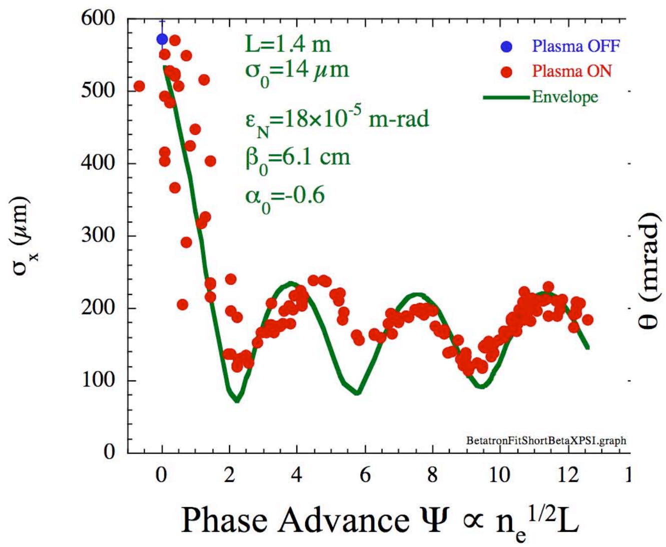
Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e⁻



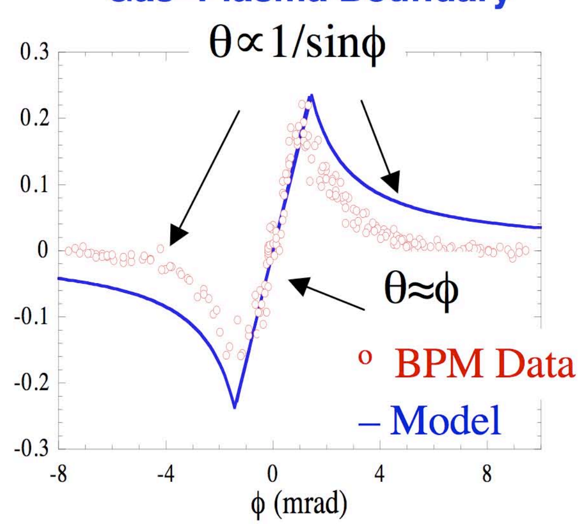
Phys. Rev. Lett. **93**, 014802 (2004)

Matching e⁻



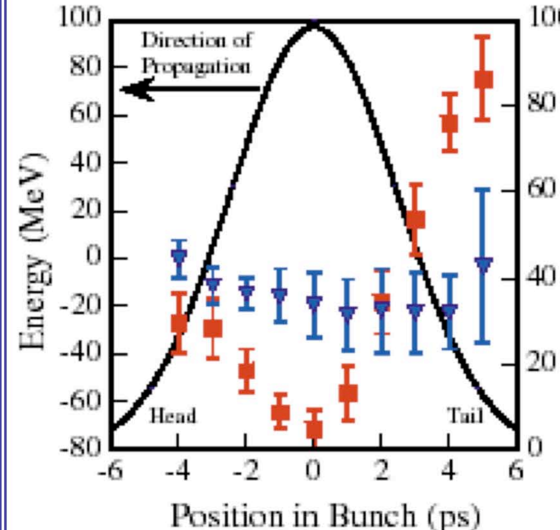
Phys. Rev. Lett. **93**, 014802 (2004)

Electron Beam Refraction at the Gas–Plasma Boundary



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

Wakefield Acceleration e⁺



Phys. Rev. Lett. **90**, 214801 (200

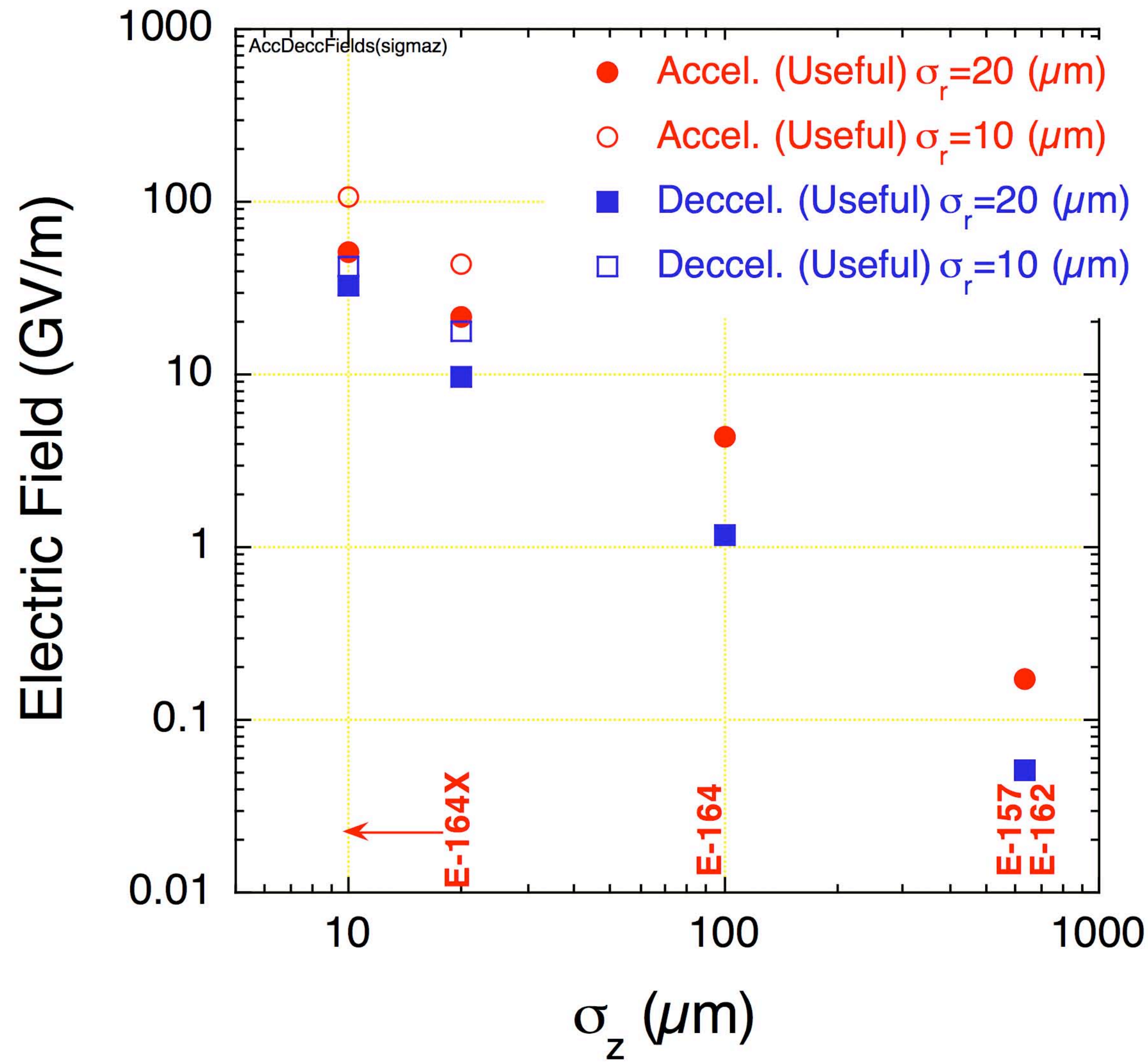
Numerical Simulations: Bunch Length Scaling E-157 to E-164X

E-164X:

σ_z = 10 - 20 μm

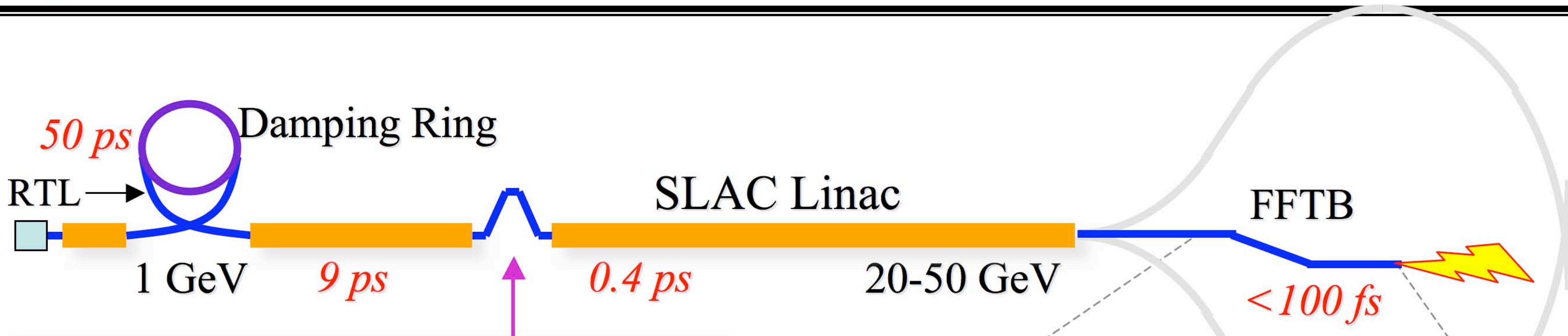
> 10 GeV/m gradient!

(σ_r dependent! $k_p\sigma_r \approx 1$)

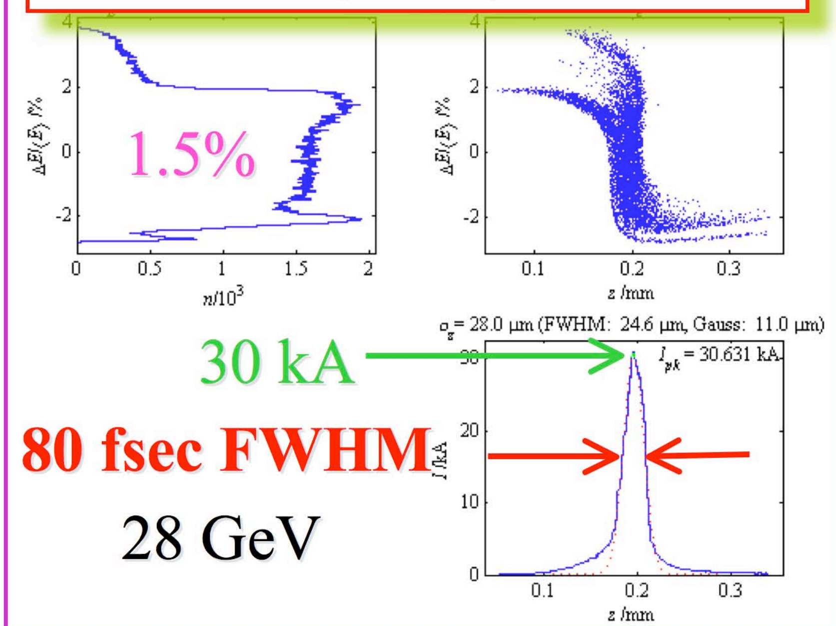


f_p=2 .8 THz, W=3MT/m @ $n_e=10^{17}$ cm^{-3}

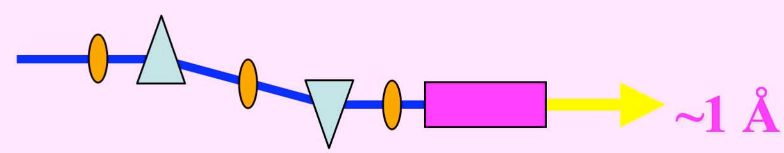
Short Bunch Generation In The SLAC Linac



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

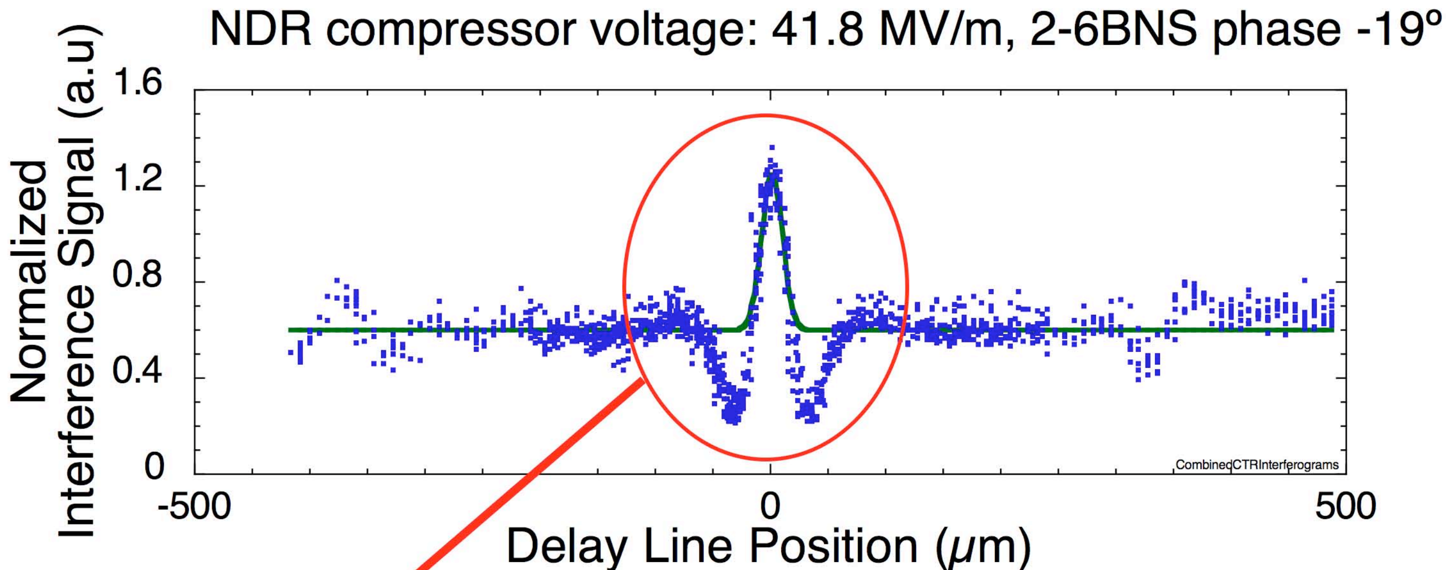


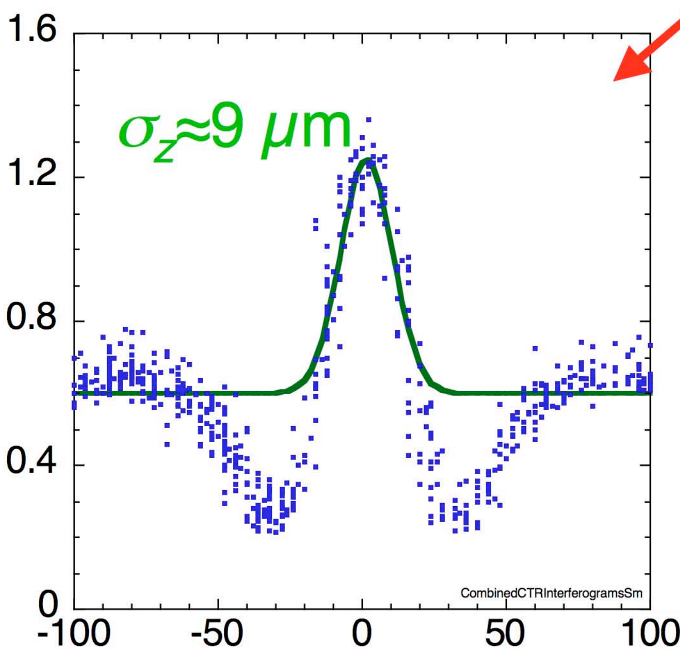
Existing bends compress to **<100 fsec**

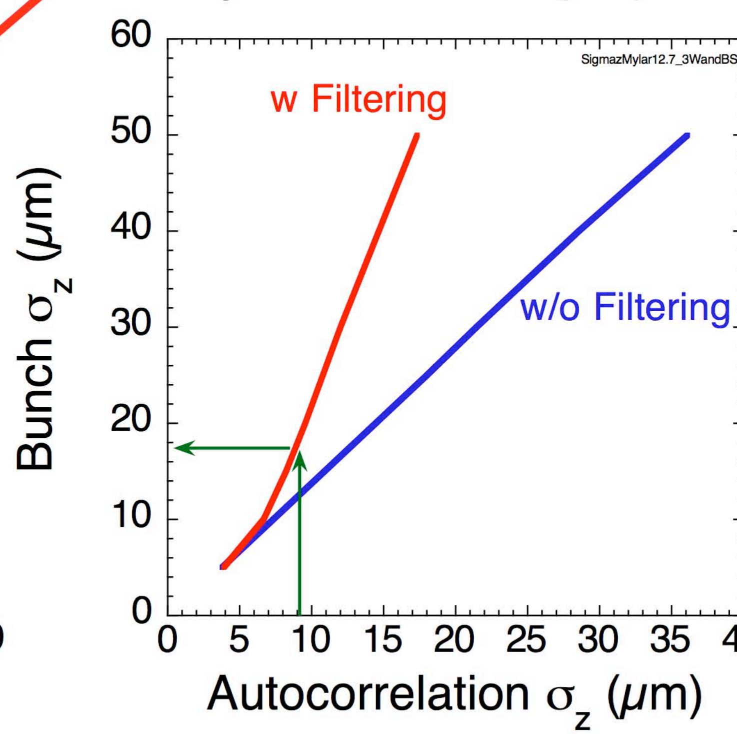


- Bunch length/current profile is the convolution of an incoming energy spectrum and the magnetic compression
- Dial FFTB R_{56}, measure incoming energy spectrum.

First Measurement of SLAC Ultra-short Bunch Length!







Autocorrelation

$\sigma_z \approx 9\ \mu m$

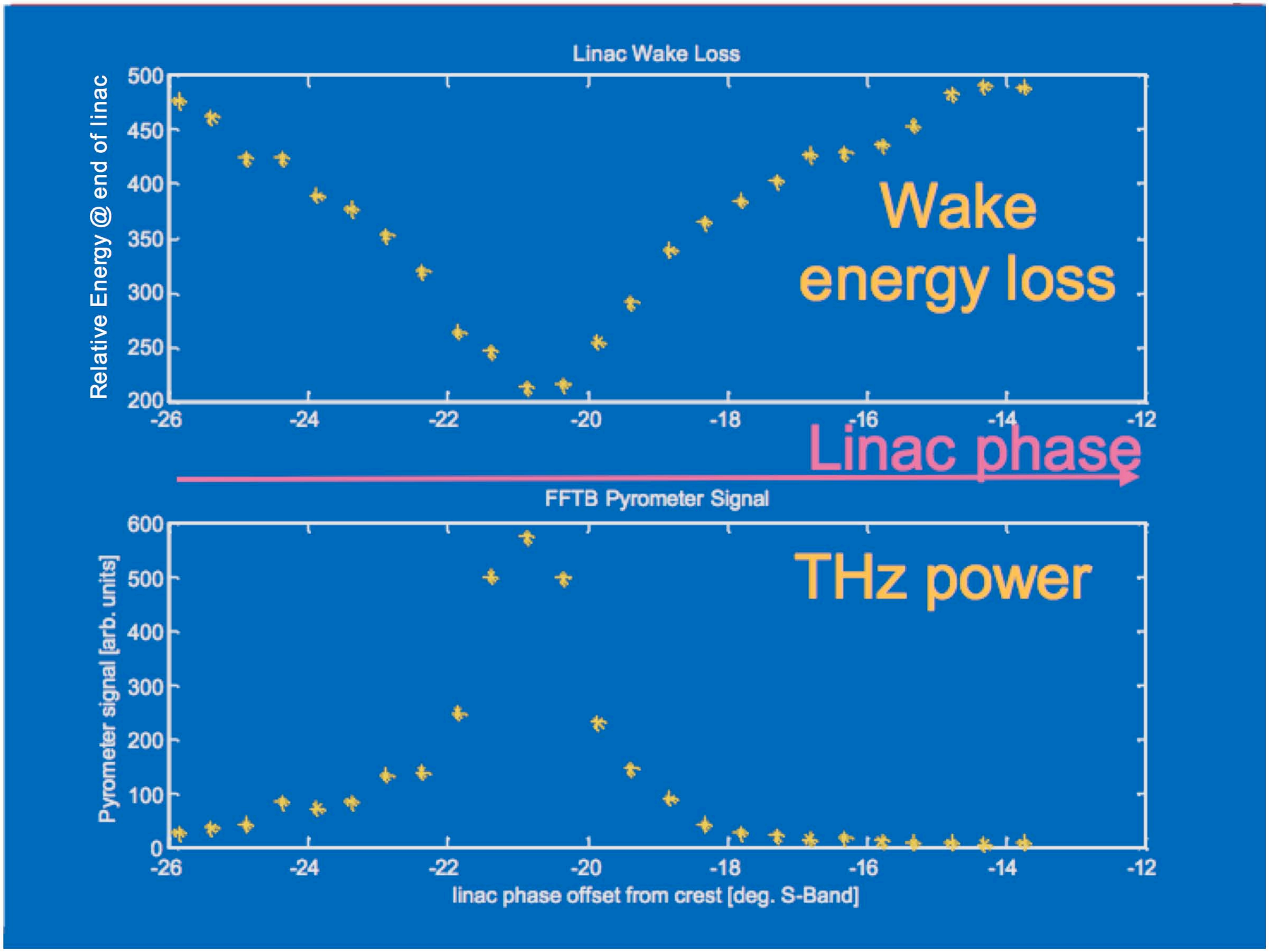
Gaussian Bunch

$\sigma_z \approx 18\ \mu m$

or

$\tau \approx 60$ fs

CTR Energy Correlates with Bunch Length



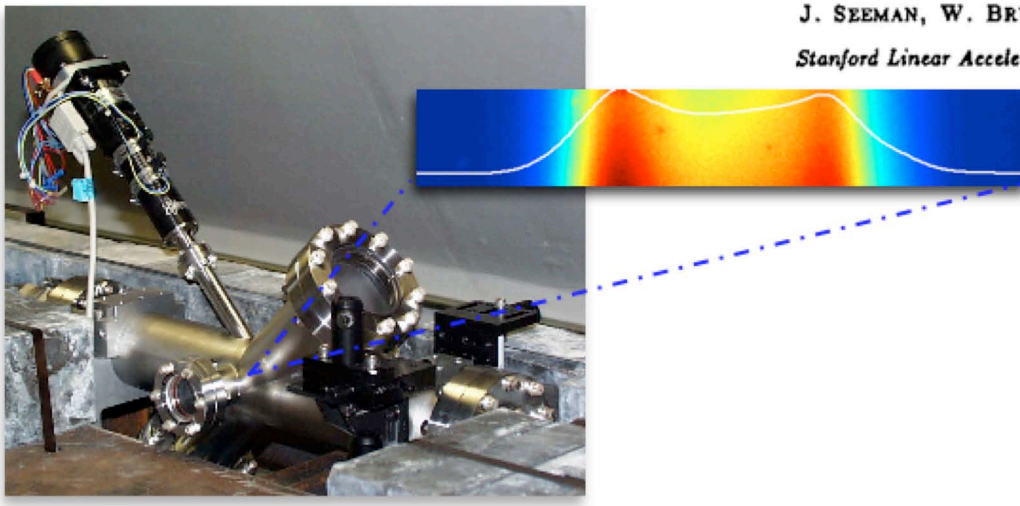
Non-Invasive Energy Spectrometer Upstream of Plasma

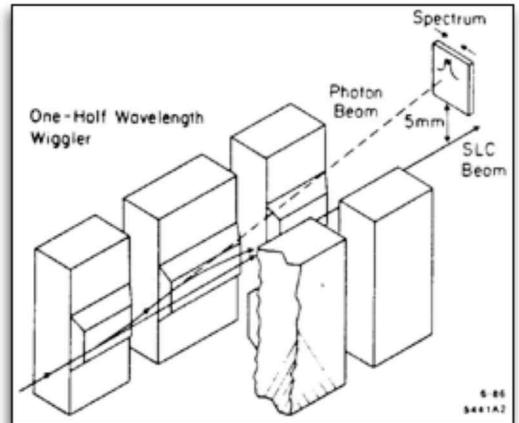
SLC ENERGY SPECTRUM MONITOR USING SYNCHROTRON RADIATION*

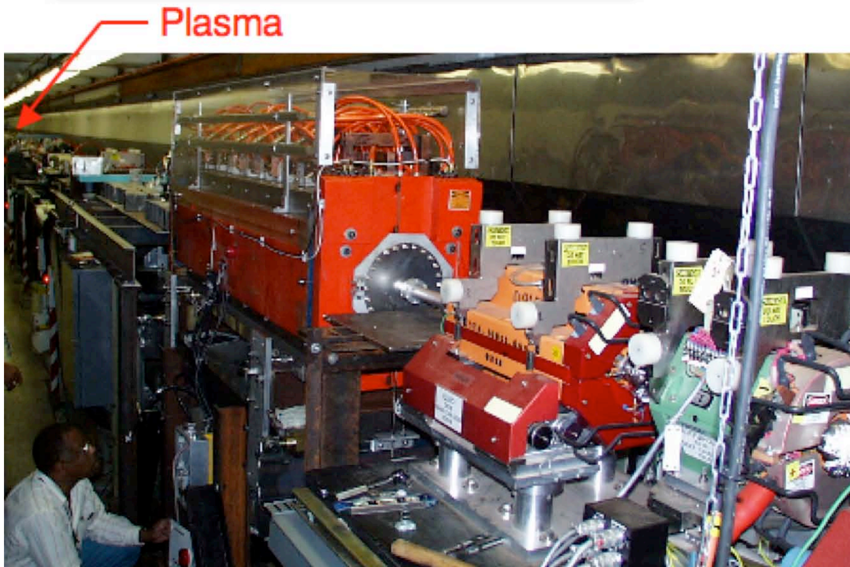
J. SEEMAN, W. BRUNK, R. EARLY, M. ROSS, E. TILLMANN and D. WALZ

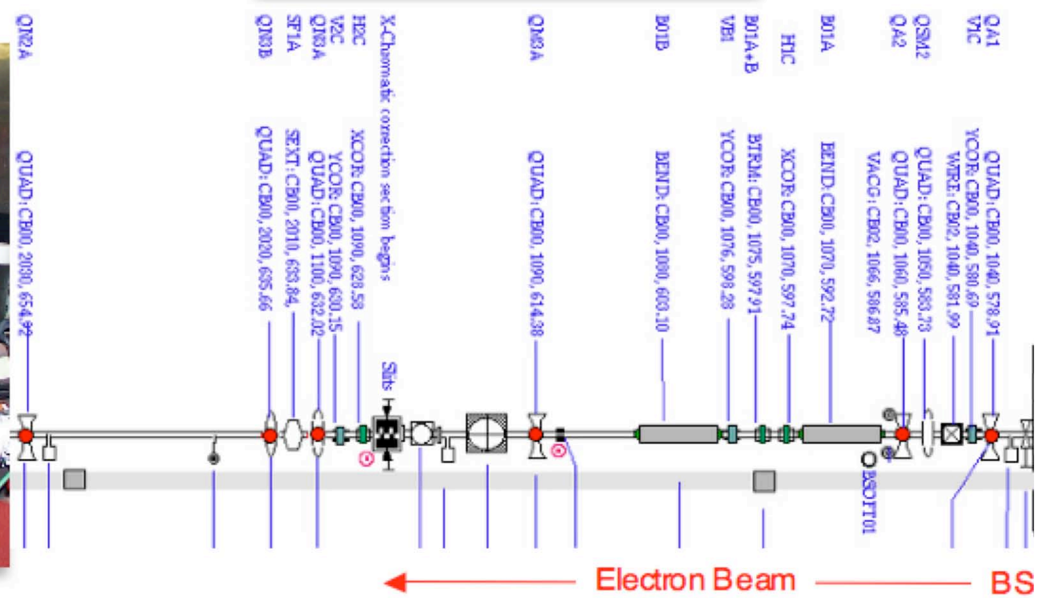
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

SLAC – PUB – 394
April 1986





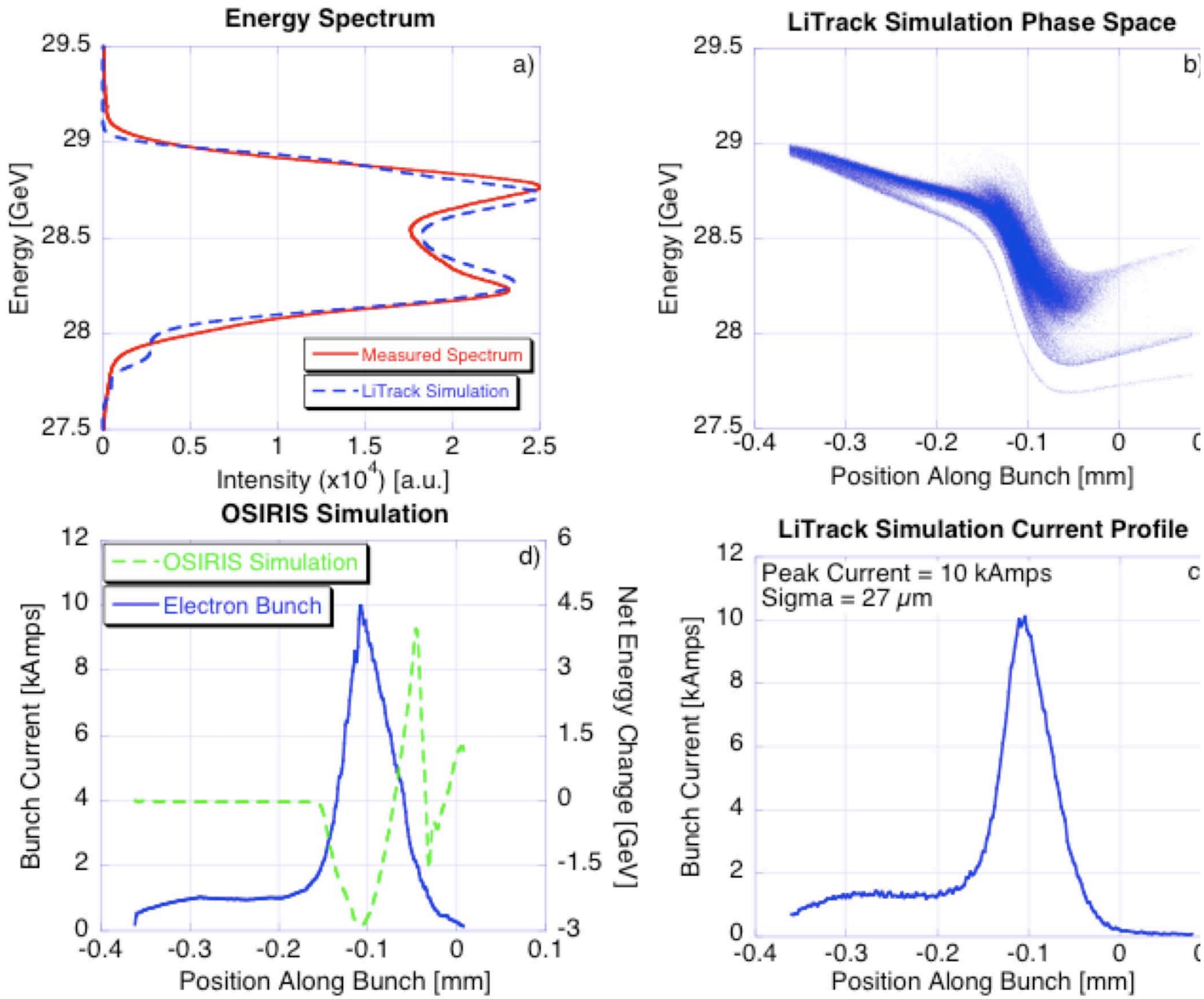




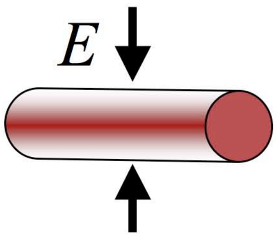
Phase Space Retrieval via LiTrack*

*K. Bane & P. Emma

- **Extension of previous work on SLC**
  - **More compression stages**
  - **More free parameters**
  - **Shorter bunches**
- **Requires good measurements, good intuition or really good guessing!**
- **Not automated (yet!)**
- **Single shot and non-destructive!**



Below 100μm Bunch Length At Threshold For Self-Ionization

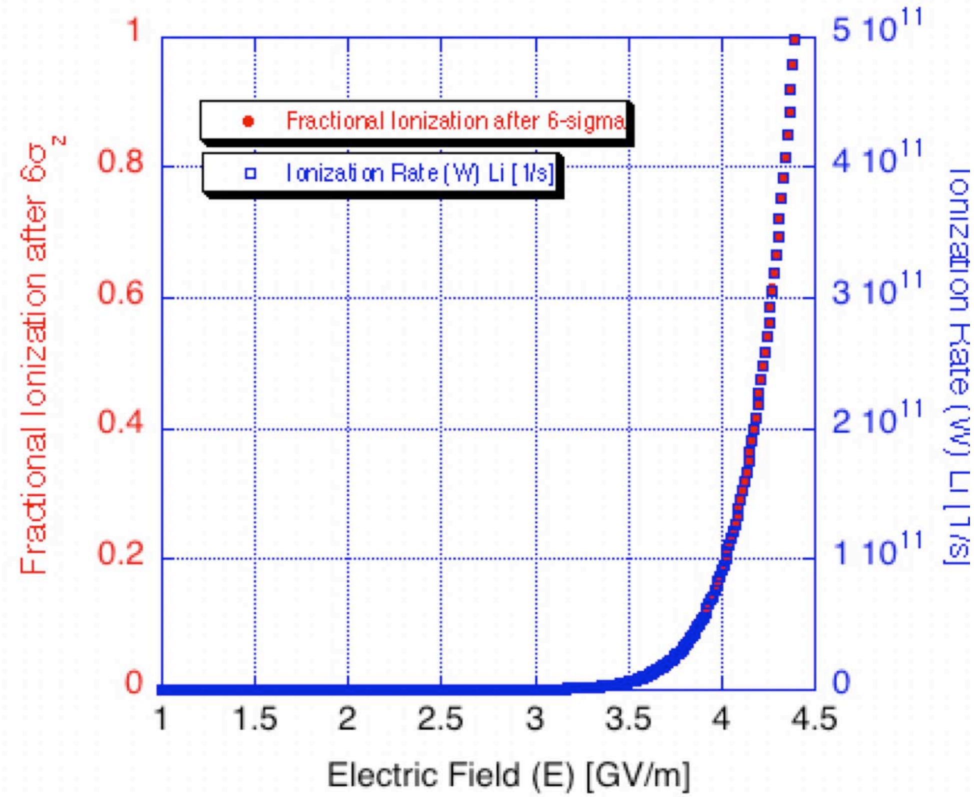


Peak Field For A Gaussian Bunch

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

Ionization Rate for Li

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



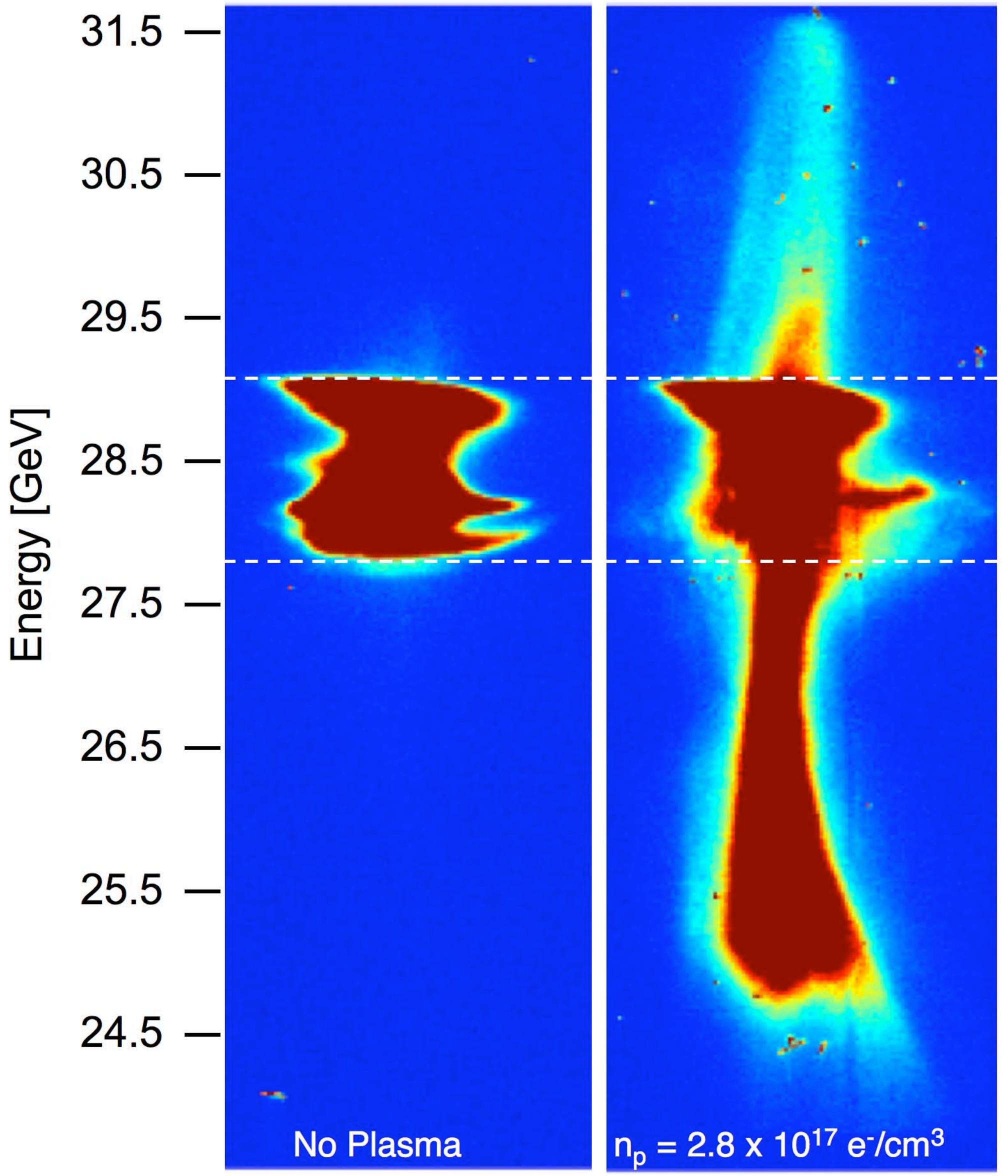
See D. Bruhwiler et al, Physics of Plasmas 2003

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

Accelerating Gradient > 27 GeV/m! (Sustained Over 10cm)

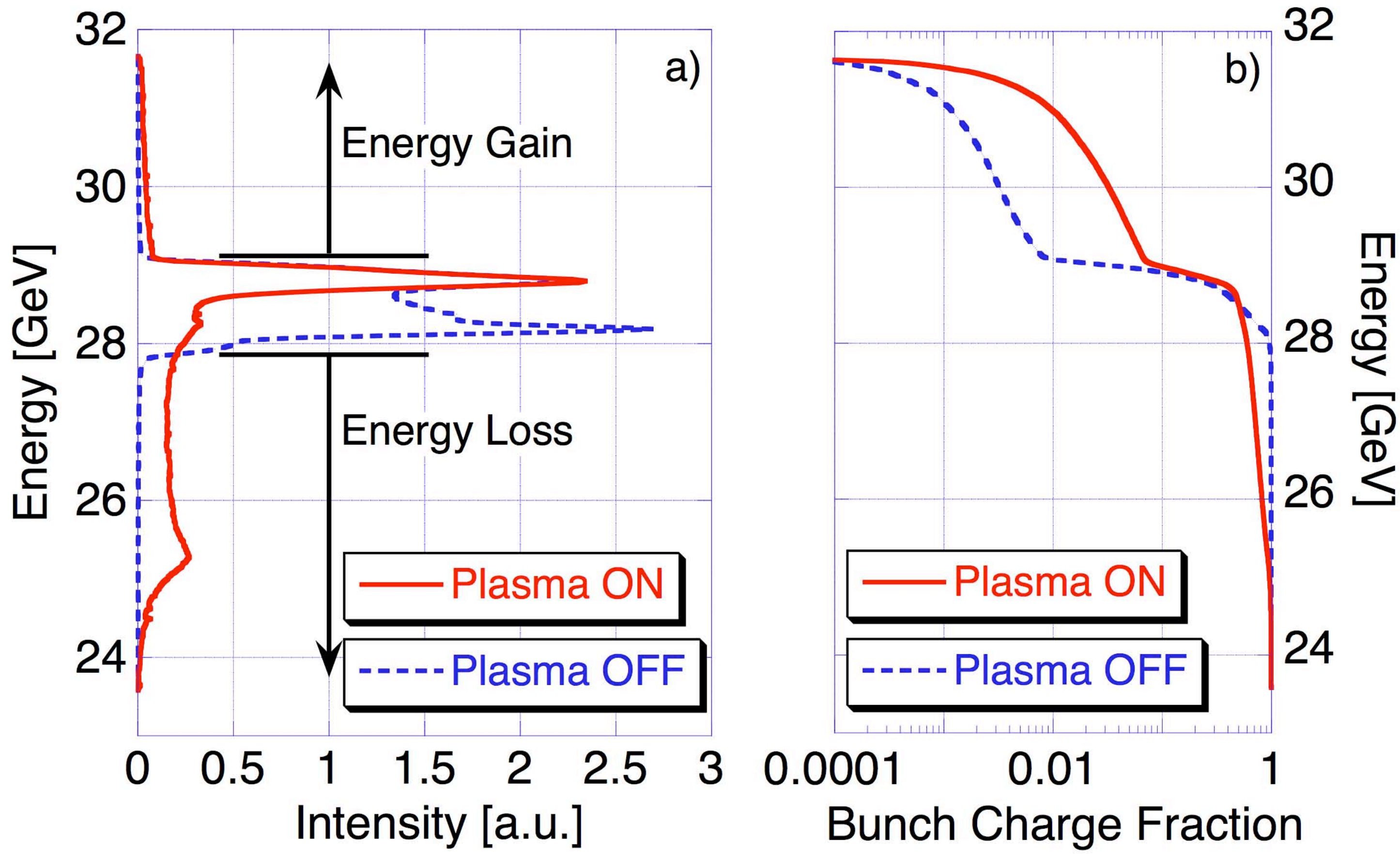


- Large energy spread after the plasma is an artifact of doing single bunch experiments
- Electrons have gained > 2.7 GeV over maximum incoming energy in 10cm
- Confirmation of predicted dramatic increase in gradient with move to short bunches
- First time a PWFA has gained more than 1 GeV
- Two orders of magnitude larger than previous beam-driven results
- Future experiments will accelerate a second “witness” bunch

Accepted for publication Phys. Rev. Lett. 2005

How We Quantify The Data

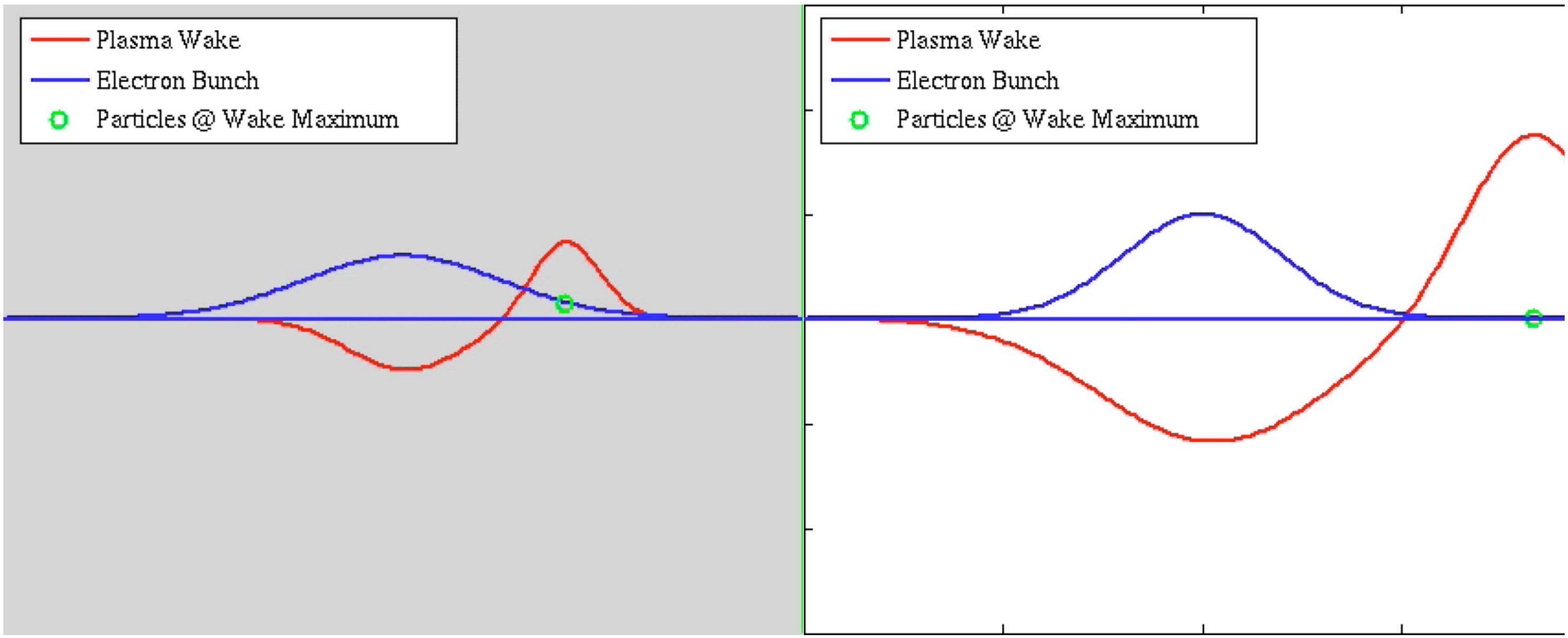
- No longer have time resolution
- Must quantify particles with energies above maximum incoming energy



Note: The head of the bunch (25% of the highest energy electrons in the plasma off case) is below ionization threshold and not affected by the lithium vapor.

A Simple Picture (Cartoon!)

Changing Bunch Length Fixed Plasma Density	Fixed Bunch Length Changing Plasma Density

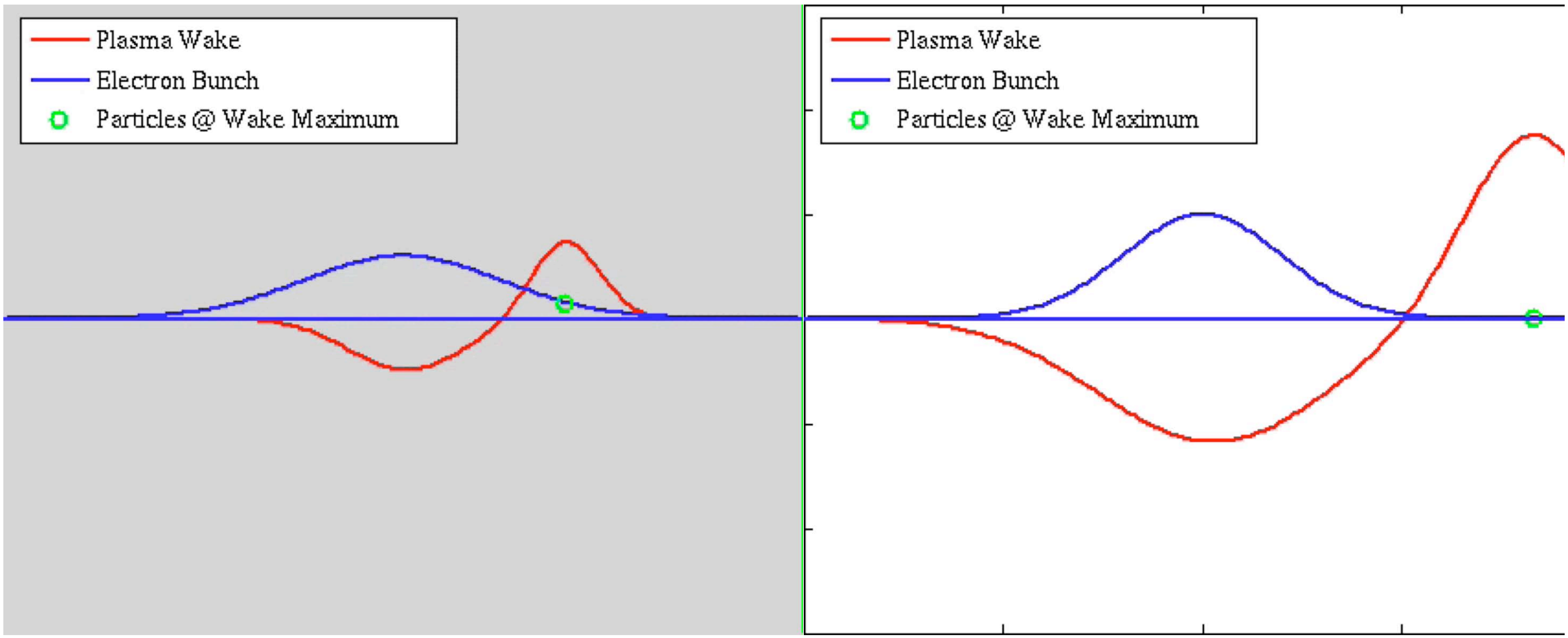


- Wake amplitude increases
- Less of the bunch population samples the Maximum accelerating gradient

- Wake amplitude increases
- More of the bunch population samples the Maximum accelerating gradient

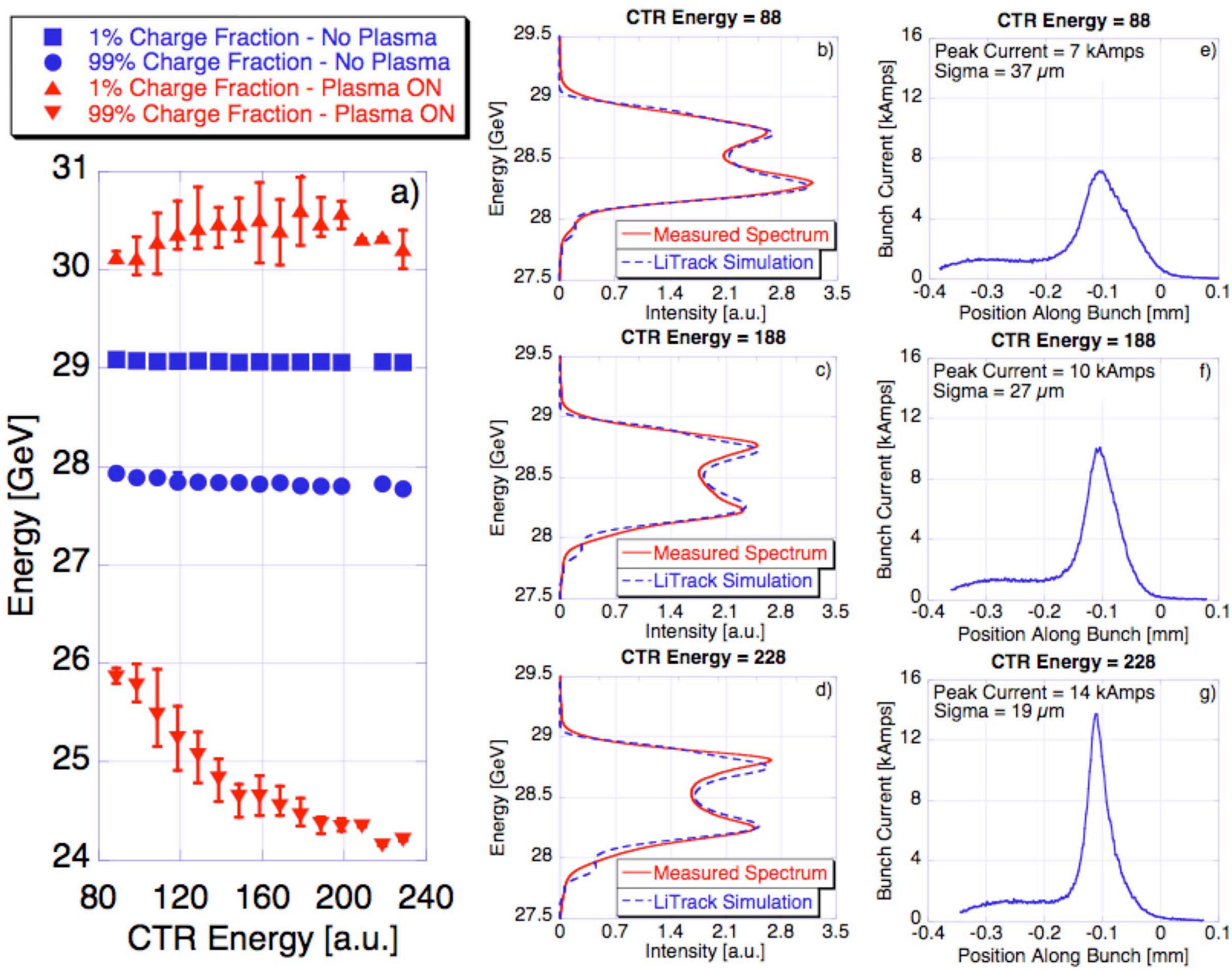
A Simple Picture (Cartoon!)

Changing Bunch Length Fixed Plasma Density	Fixed Bunch Length Changing Plasma Density

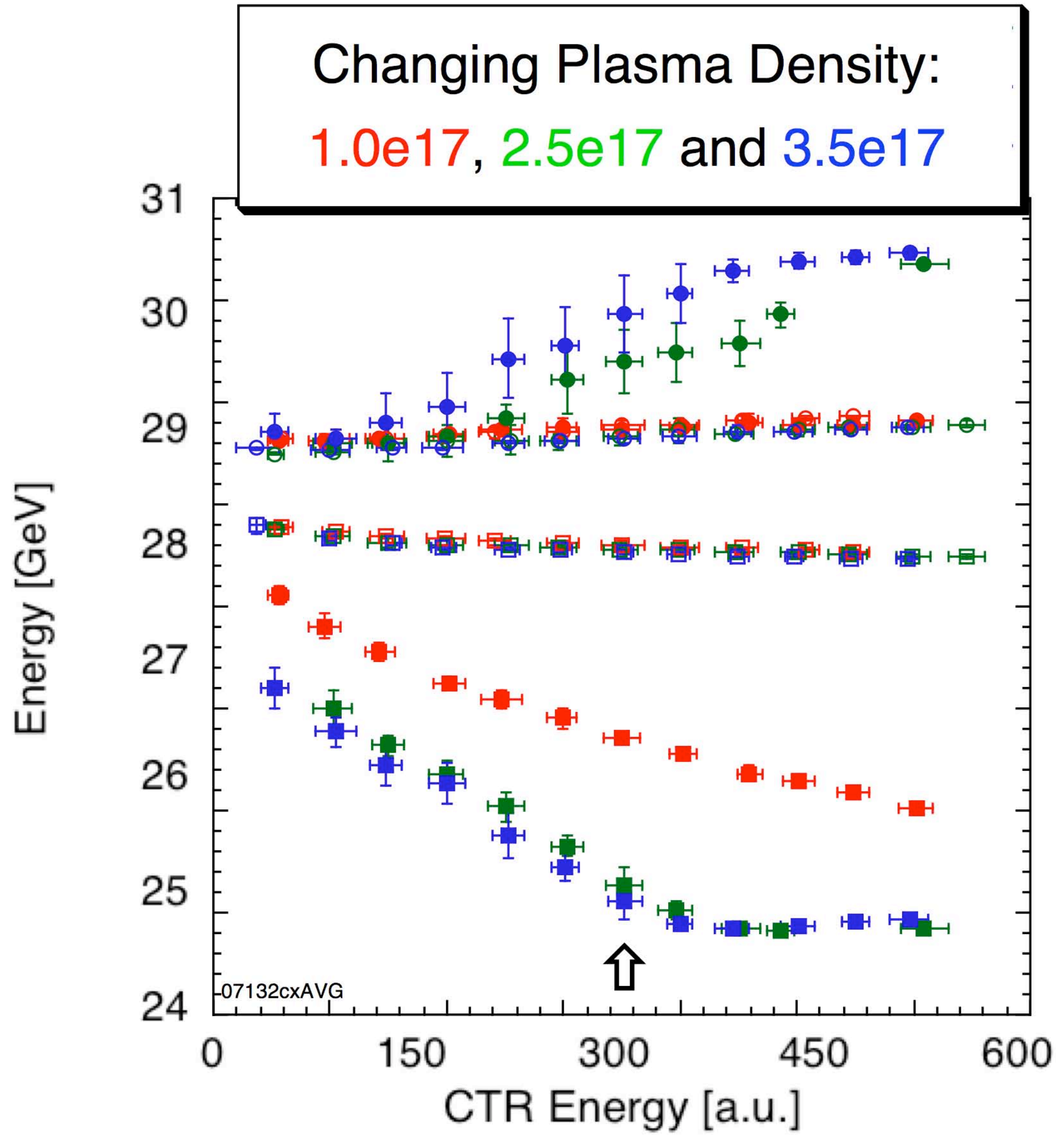


• Wake amplitude increases • Less of the bunch population samples the Maximum accelerating gradient	• Wake amplitude increases • More of the bunch population samples the Maximum accelerating gradient

Maximum Energy Gain (at fixed n_p) is Bunch Length Dependent



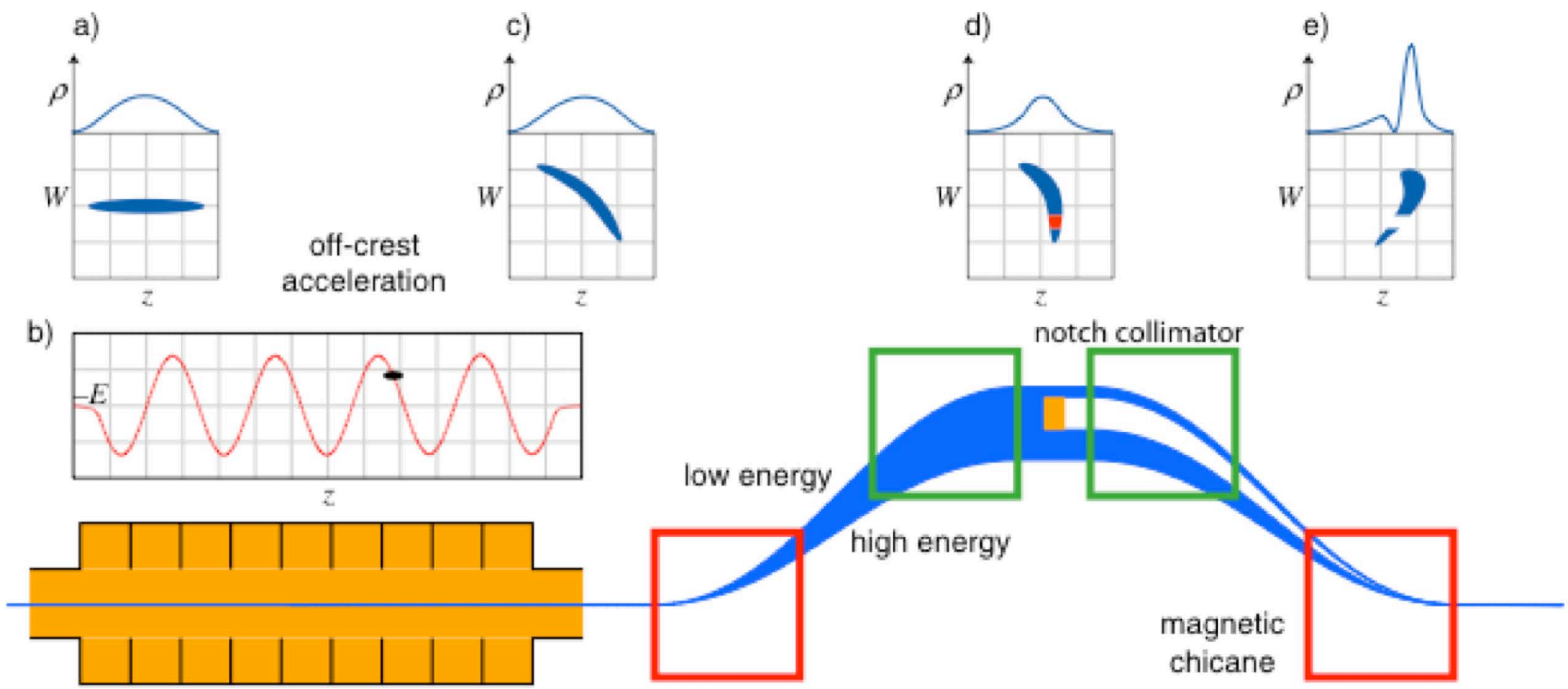
Maximum Energy Gain (at fixed σ_z) is Plasma Density Dependent

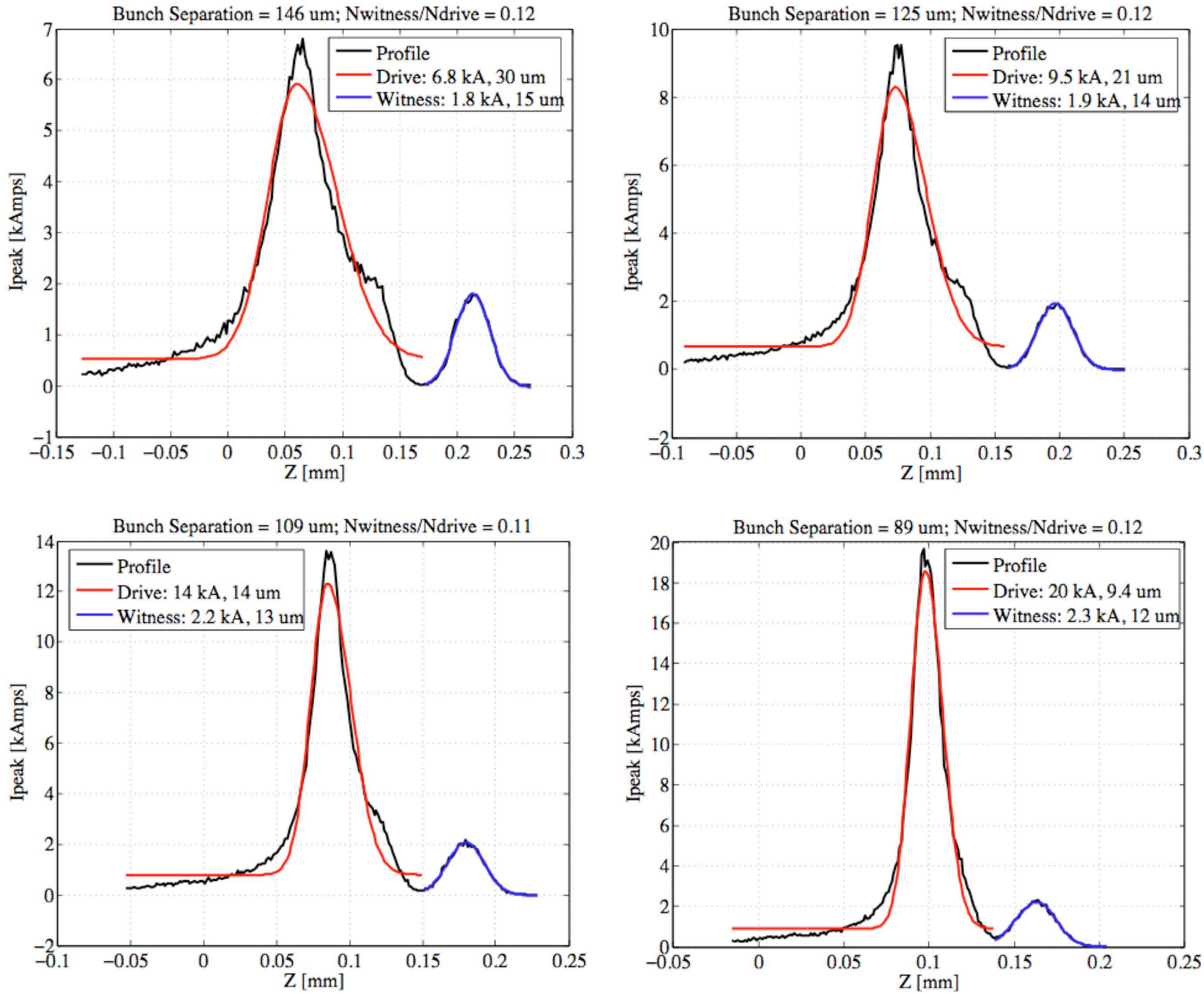


Energy Spread is filling the pipe!

Future Experiments

- **Increased energy aperture in the FFTB (Summer 2005)**
  - Try for 10GeV energy gain!
  - Test for instabilities (electron hose etc…)
- **Two bunches via notch collimator in linac chicane or FFTB (Early 2006)**




Bunch Separation = 146 um; Nwitness/Ndrive = 0.12
Profile
Drive: 6.8 kA, 30 um
Witness: 1.8 kA, 15 um
Ipeak [kAmps]
Z [mm]
Bunch Separation = 125 um; Nwitness/Ndrive = 0.12
Profile
Drive: 9.5 kA, 21 um
Witness: 1.9 kA, 14 um
Ipeak [kAmps]
Z [mm]
Bunch Separation = 109 um; Nwitness/Ndrive = 0.11
Profile
Drive: 14 kA, 14 um
Witness: 2.2 kA, 13 um
Ipeak [kAmps]
Z [mm]
Bunch Separation = 89 um; Nwitness/Ndrive = 0.12
Profile
Drive: 20 kA, 9.4 um
Witness: 2.3 kA, 12 um
Ipeak [kAmps]
Z [mm]

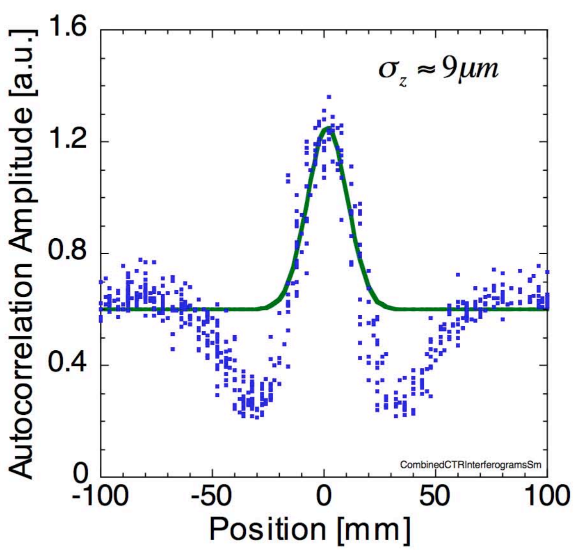
Plasma Wakefield Accelerator Research Summary

Over the past 5 years

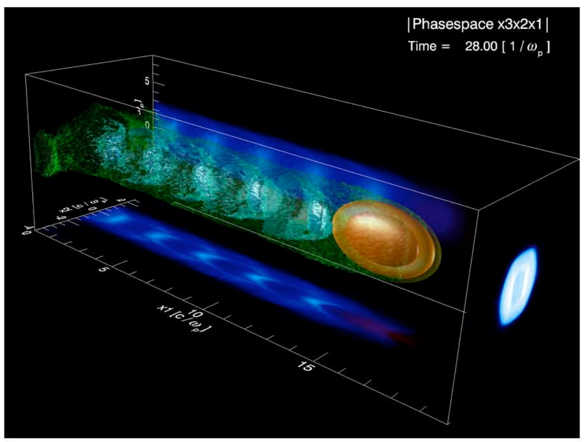
20 Peer reviewed publications *covering all aspects of beam plasma interactions:*
Focusing (e^- & e^+), Transport, Refraction, Radiation Production, Acceleration (e^- & e^+)

This years accomplishments

First measurement of the SLAC Ultra-short Bunch Length



Demonstration of Field Ionized Plasma Source



Measured Accelerating Gradients > 27 GeV/m (over 10cm) in a PWFA