# PARTICLE DRIVEN PLASMA WAKEFIELD ACCELERATORS

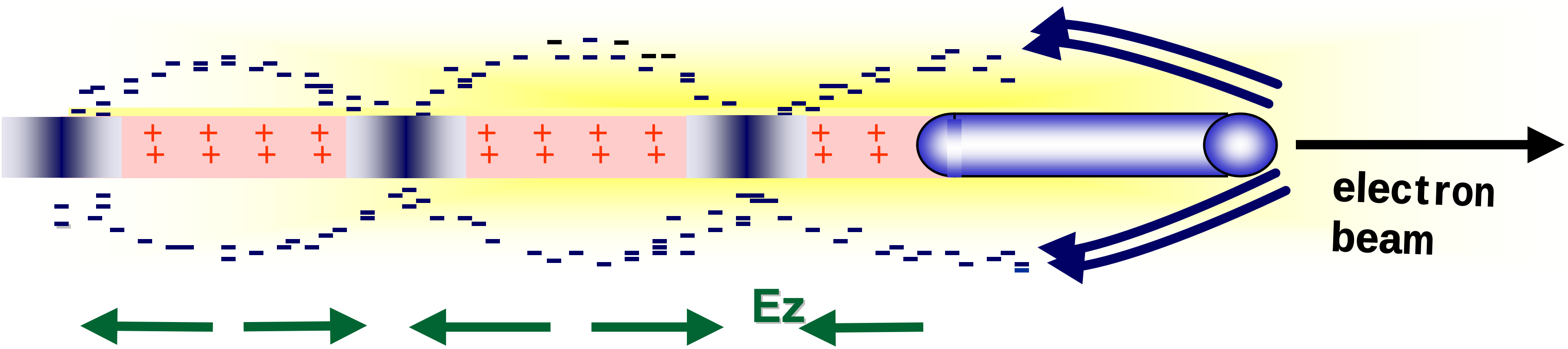
by

C. Joshi

University of California Los Angeles

# Physical Principles of the Plasma Wakefield Accelerator

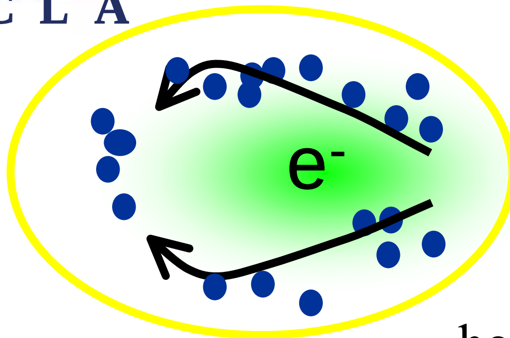
- Space charge of drive beam displaces plasma electrons

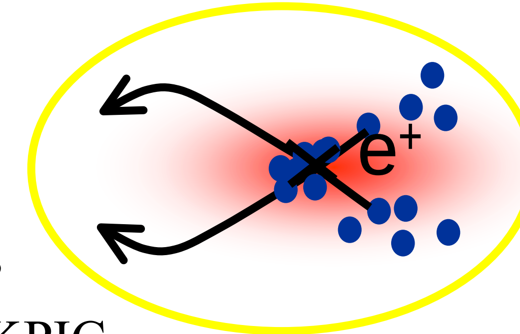



- Plasma ions exert restoring force => Space charge oscillations
- Wake Phase Velocity = Beam Velocity (like wake on a boat)
- Wake amplitude $\propto N_b / \sigma_z^2$
- Transformer ratio $E_{z,\,acell}/E_{z,\,decell}$

P.Chen,J.Dawson et.al P.R.L.(1981)

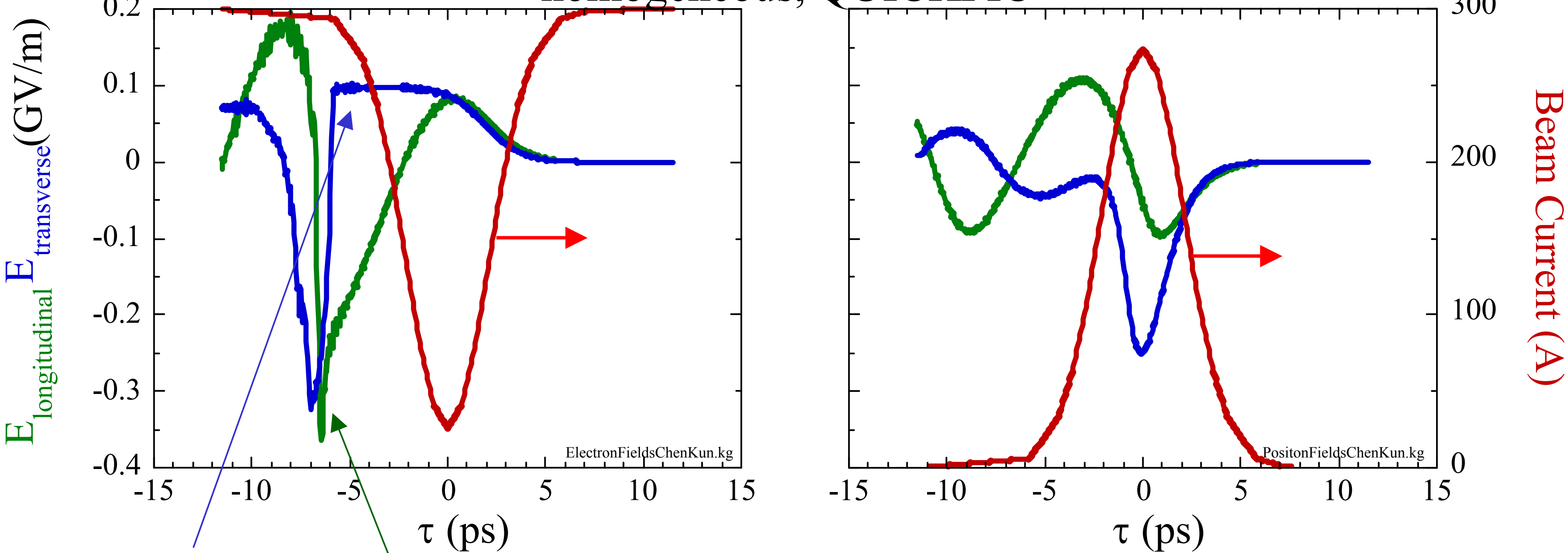
# WAKEFIELD FIELDS for $e^-$ & $e^+$




$n_e$=1.5×10$^{14}$ cm$^{-3}$

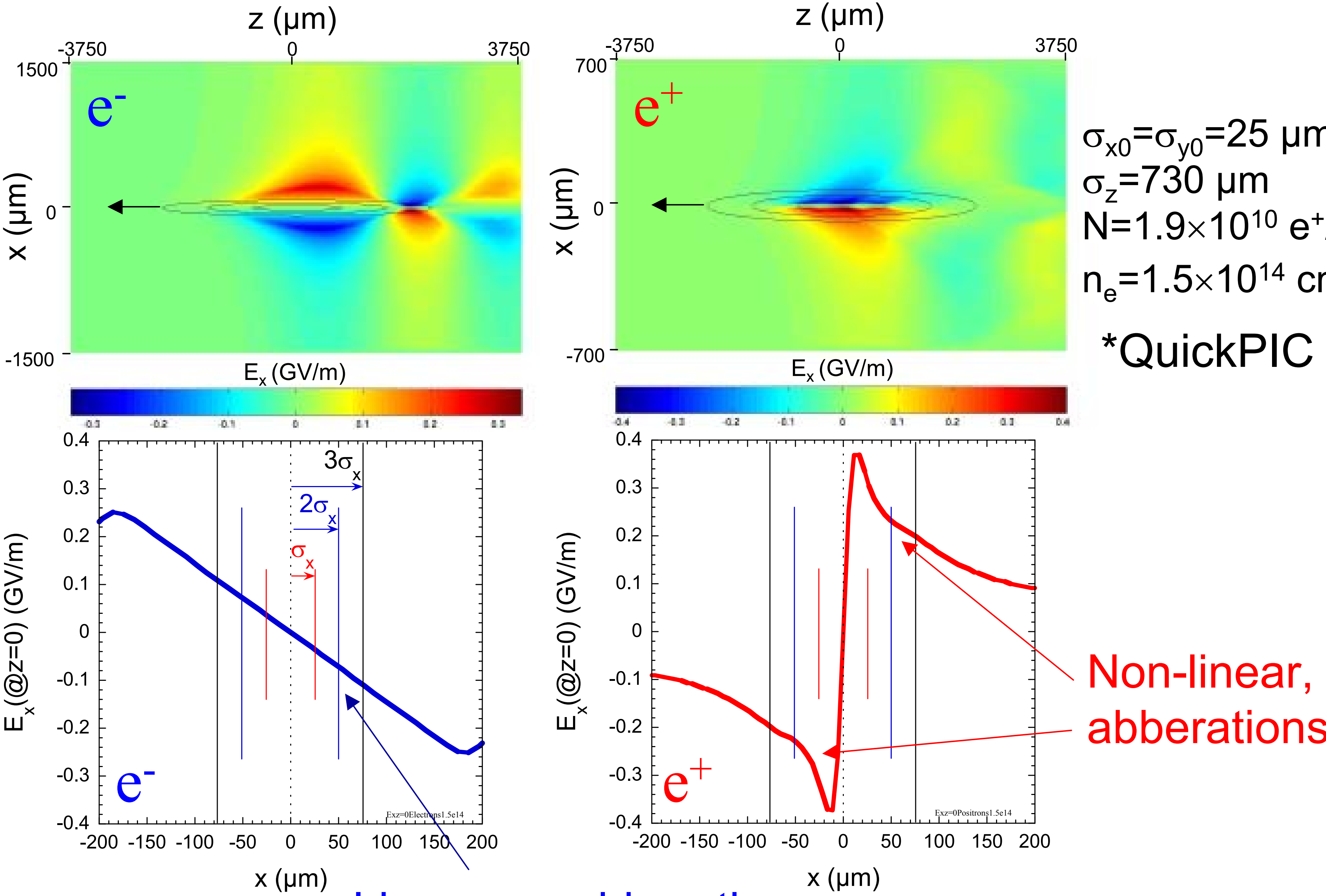
homogeneous, QUICKPIC




- Blow-Out
- Accelerating "Spike"

- Fields vary along r, stronger
- Less Acceleration

# $e^-$ & $e^+$ FOCUSING FIELDS*




$\sigma_{x0}=\sigma_{y0}=25\ \mu m$

$\sigma_z=730\ \mu m$

$N=1.9\times10^{10}\ e^+/e^-$

$n_e=1.5\times10^{14}\ cm^{-3}$

*QuickPIC

UCLA

# Physical Effects of Plasma Fields on the Beam

| TRANSVERSE ($E_r$) | APPLICATION |
| --- | --- |
| Deflection | Beam Steering |
| Focusing/Defocusing | Plasma Lenses |
| Periodic Oscillations | Plasma Wigglers |
| Emission of Betatron Radiation | Positron Production |

| LONGITUDINAL ($E_z$) | |
| --- | --- |
| Acceleration | High Gradient Accelerators |
| Deceleration | Beam Dumps |

# Proof of Principle PWFA Experiment @ ANL

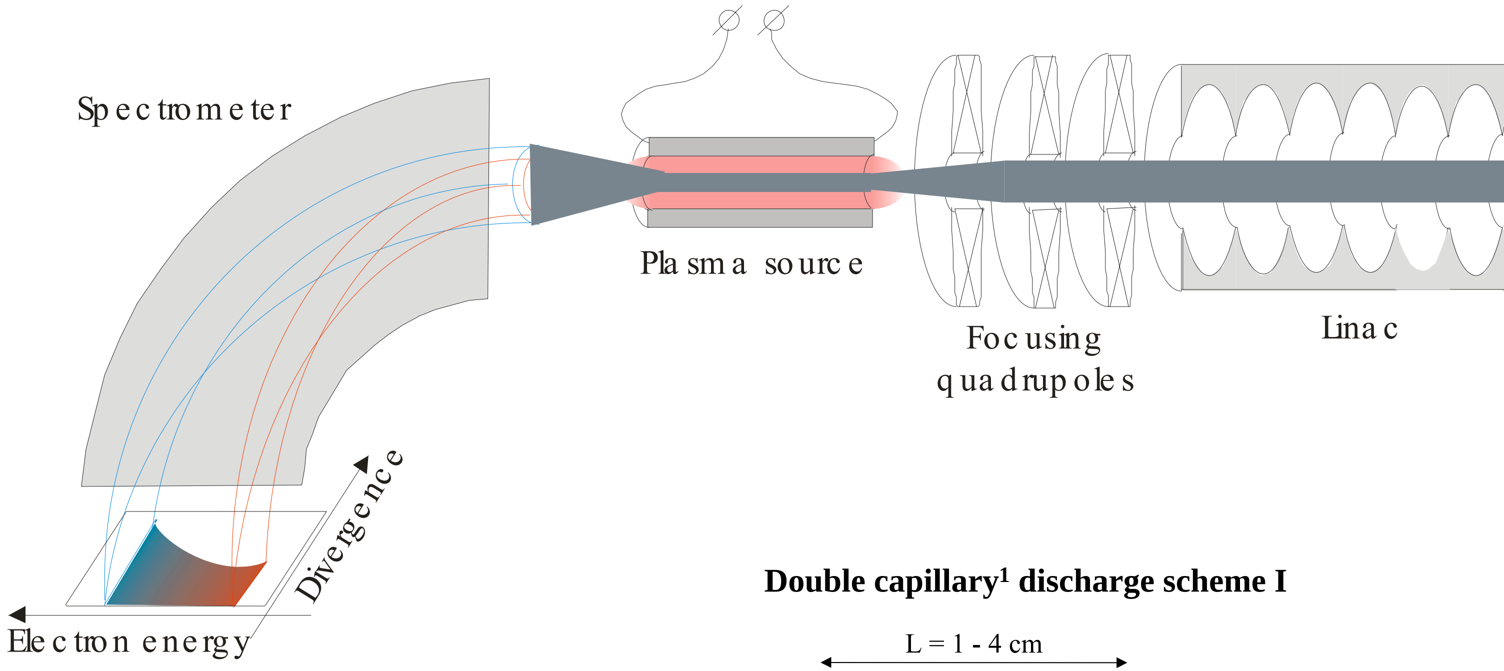
- Performed in 1987 at ANL at AATF
- Drive and witness beam configuration
- 1.6 MeV/m acceleration fields
- Transverse deflection of witness beam by driver wake also observed

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

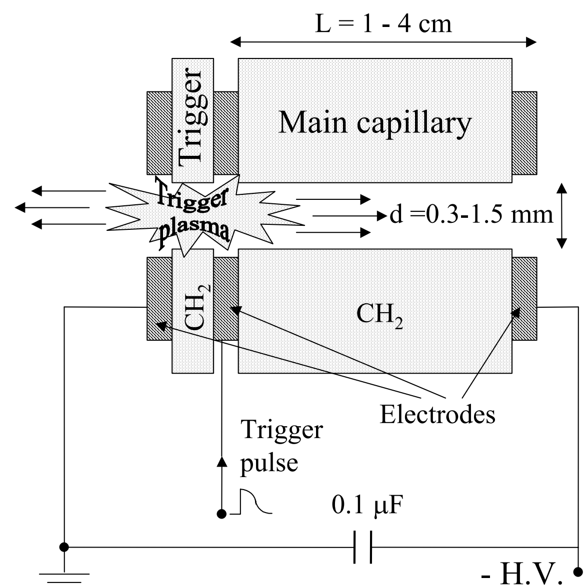
Witness beam centroid as a function of delay time in proof-of-principle PWFA measurement

"Experimental Observation of Plasma Wake-field Acceleration", J.B. Rosenzweig, *et al.*, *Phys. Rev. Letterss* **61**, 98 (1988 ).

# PWFA Experiment at ATF




**Double capillary[1] discharge scheme I**




The plasma flow in the main capillary is turbulent.The time of the plasma propagation through the main capillary can be estimated as:

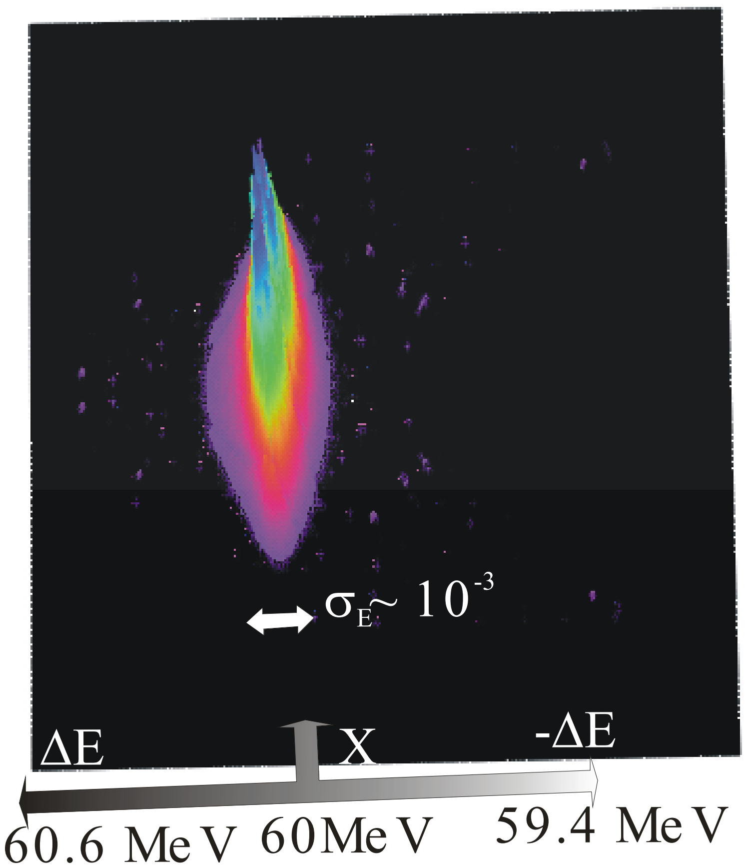
$$t = \frac{d}{k\xi c_s(0)} \exp\left(\frac{kL}{d}\right)$$

Where k and ξ are dimensionless turbulent heat conductivity and viscosity.
$k = 0.048$, $\xi = 0.25$,
$c_s = 4\times10^5$ cm/s.
For d = 300 μm, L = 1.4 cm
t = 60 μs.

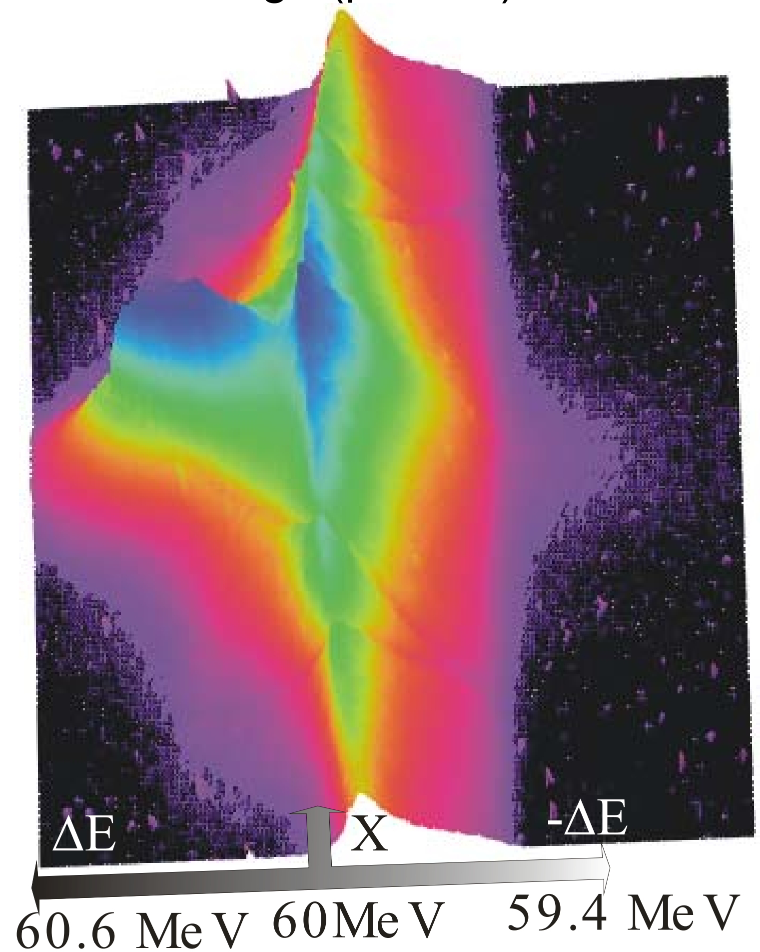
[1]D. Kaganovich *et al.* Appl. Phys. Lett. **71,** 2925 (1997).

# PWFA data from ATF

Discharge (plasma) off




Discharge (plasma) on




Energy distribution and transverse beam phase space dramatically changed after a 60 MeV, 0.5 nC, 3 ps (FWHM) e-beam passes through 17 mm of ~$10^{17}$ plasma.

# First measurement of PWFA in the "blowout regime"

- Measurement at ANL AWA facility in 1999
- First creation of witness and drive beams in RF photogun
- Average acceleration of 25 MV/m in 12 cm of $10^{13}$ $cm^{-3}$ plasma, with $n_b > 2.5 n_p$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Streak camera trace of drive and witness beams

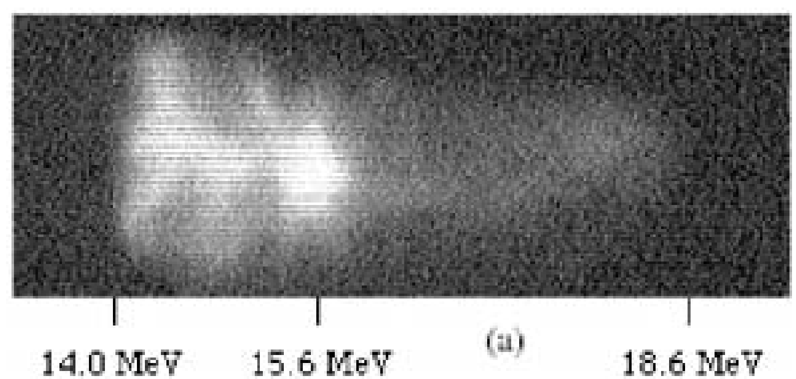
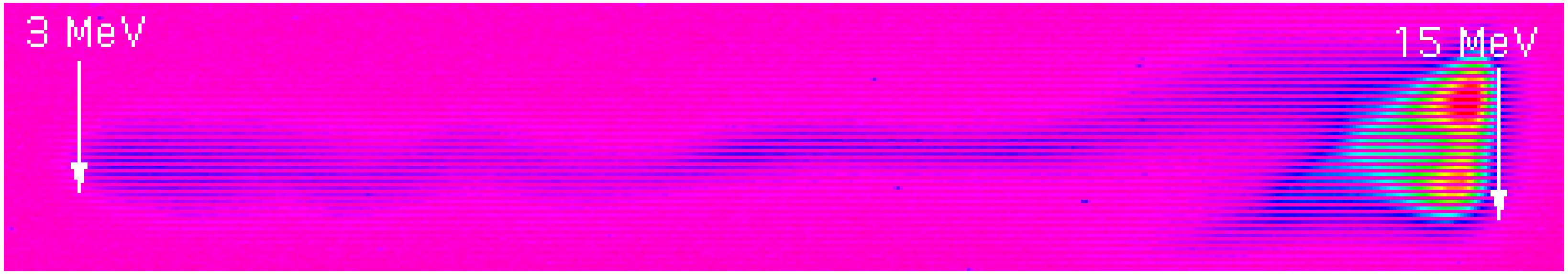



Image of electron beam after plasma in spectrometer

"Observation of plasma wakefield acceleration in the underdense regime" N. Barov, J. B. Rosenzweig, M. E. Conde, W. Gai, and J. G. Power *Physical Review Special Topics Accelerators and Beams* **3** 011301 (2000).

# High gradient PWFA with compressed beam @ A0




Spectrometer image of beam after 8 cm of plasma

- First use of compressed beam in PWFA experiment at FNAL A0 photoinjector (2001)
- Deceleration observed at 150 MeV/m, with beam nearly stopped in plasma
- Acceleration recently observed at 132 MeV/m (2003)
- New experiments with witness beam

# E-162/E-164/E-164X

## Collaborations:

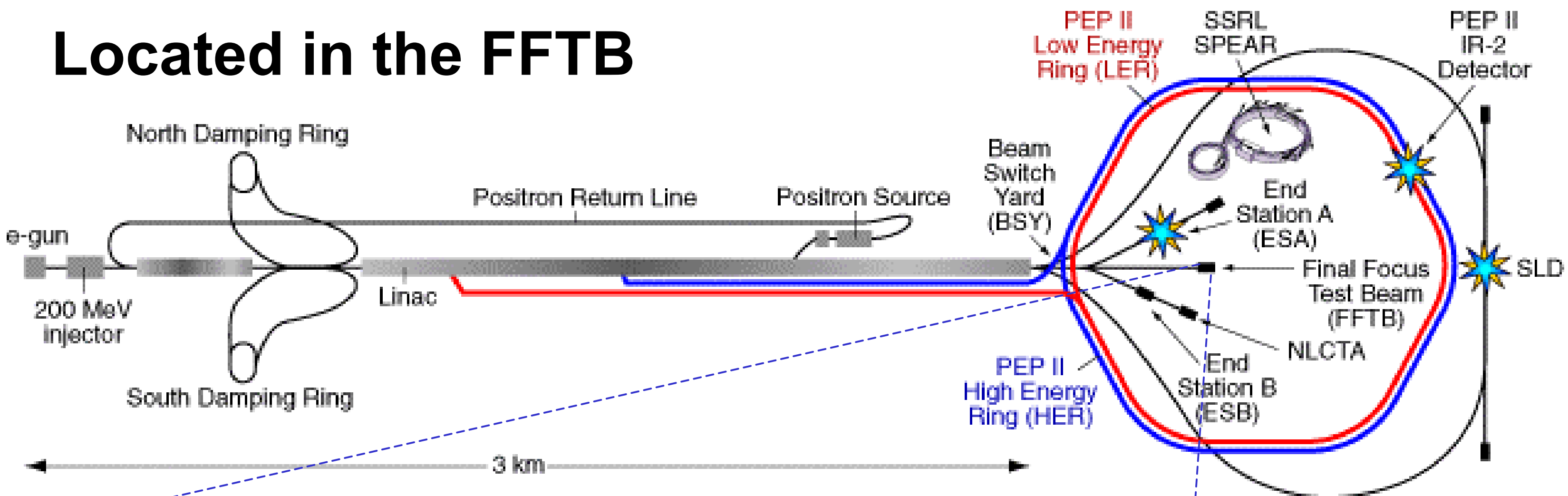
**C. Barnes, F.-J. Decker, P. Emma, M. J. Hogan, R. Iverson, P. Krejcik, C. O'Connell,**
**P. Raimondi, R.H. Siemann, D. Walz**
***Stanford Linear Accelerator Center***

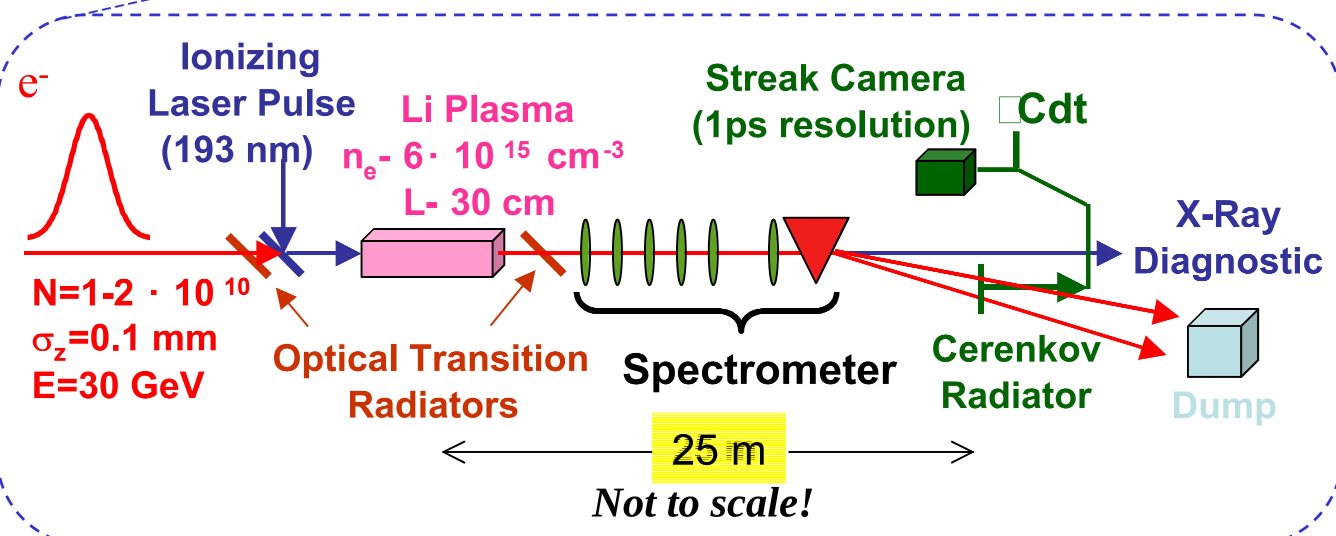
**B. Blue, C. E. Clayton, C. Huang, C. Joshi, D. Johnson, K. A. Marsh, W. B. Mori, W. Lu**
***University of California, Los Angeles***

**T. Katsouleas, S. Lee, P. Muggli, E. Oz**
***University of Southern California***

# PWFA Experiments @ SLAC

## Located in the FFTB

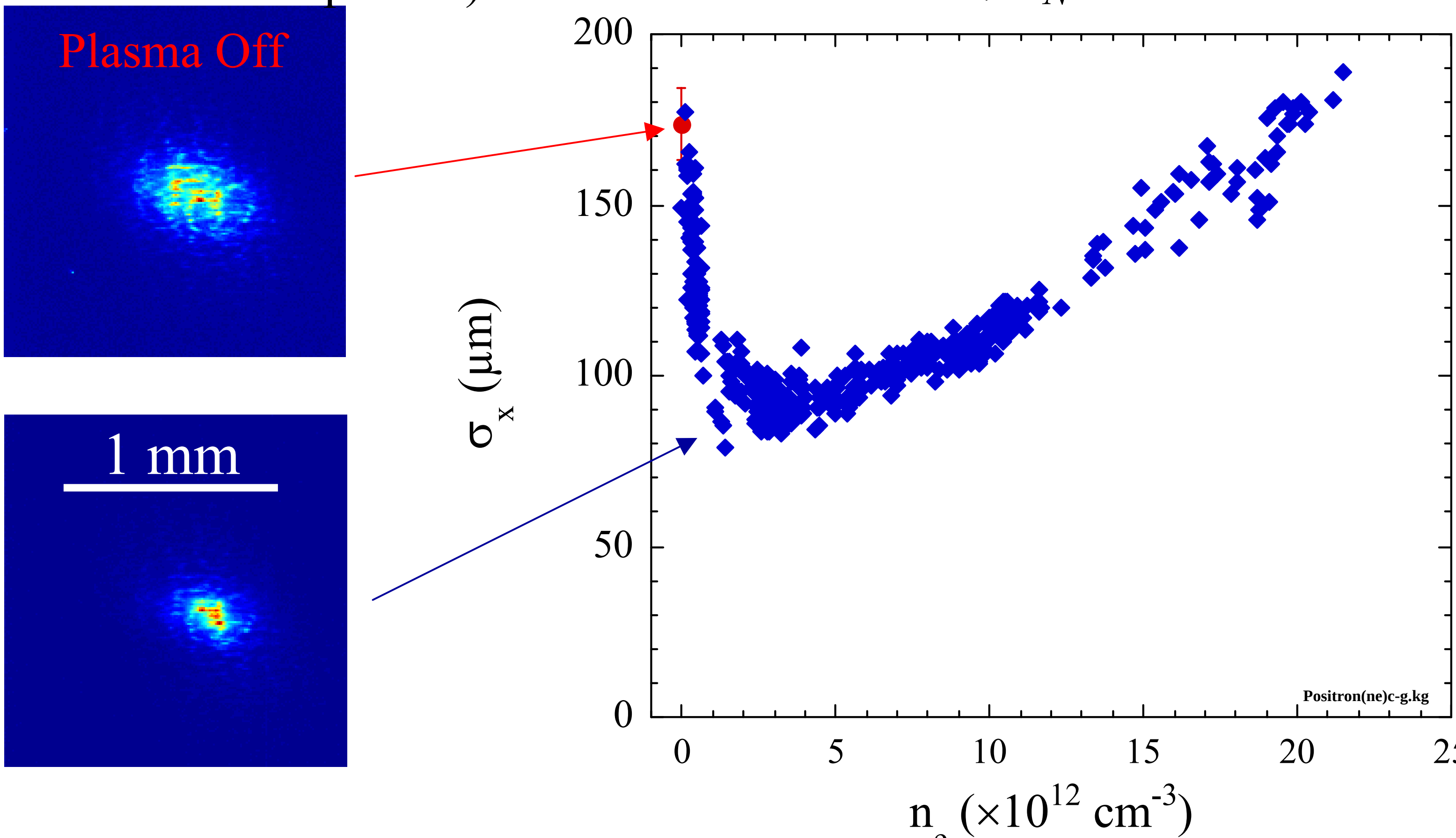



# FOCUSING OF $e^+$

OTR Images
(≈1m downstream from plasma)

$N$=1.9×10[10], $\varepsilon_N$>5×10[-5] m-rad

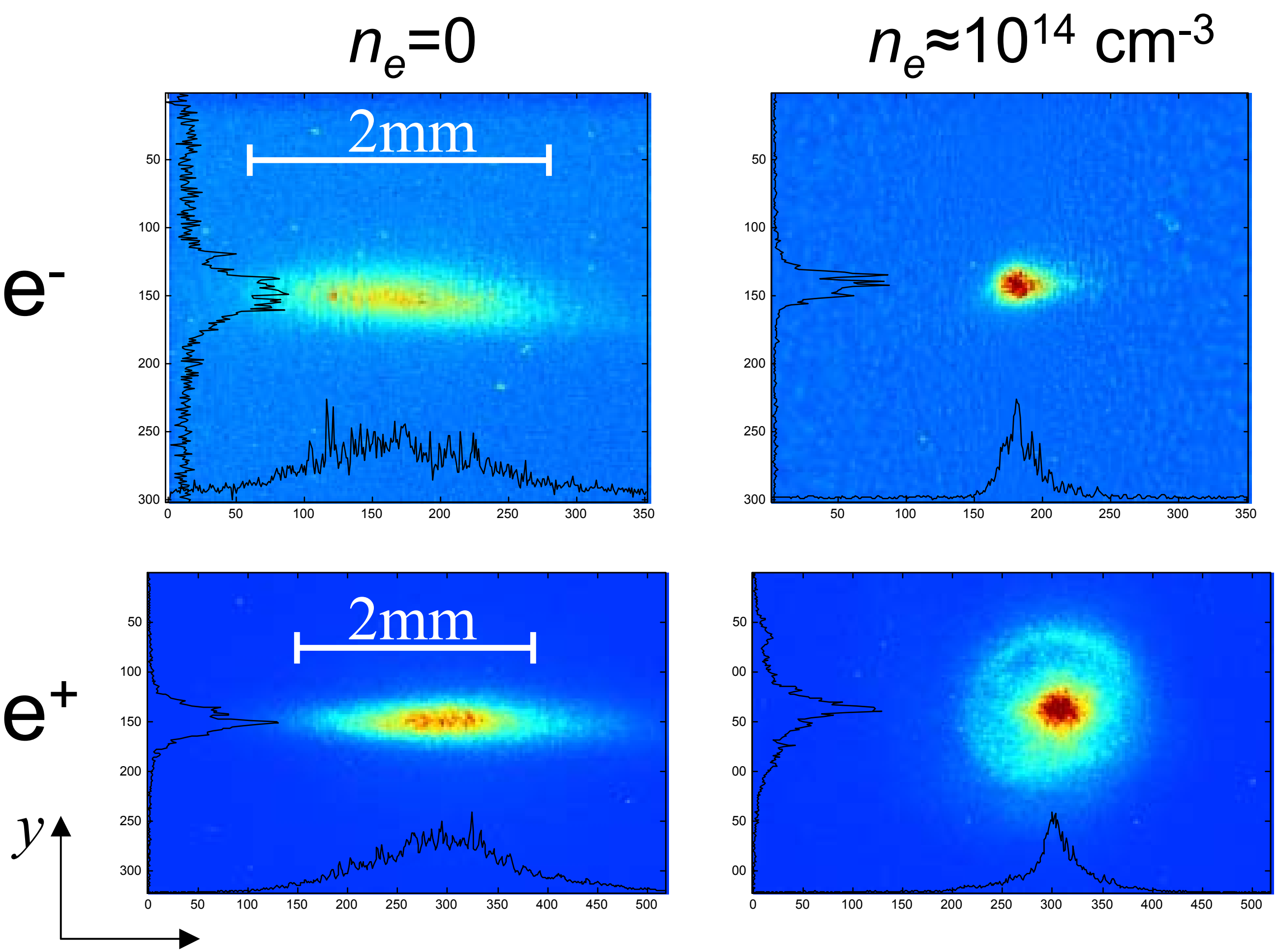



- Overall focusing at low plasma densities

M.J. Hogan *et al.*, PRL, 2002

# FOCUSING OF $e^-/e^+$

- OTR images ≈1m from plasma exit ($\varepsilon_x \neq \varepsilon_y$)

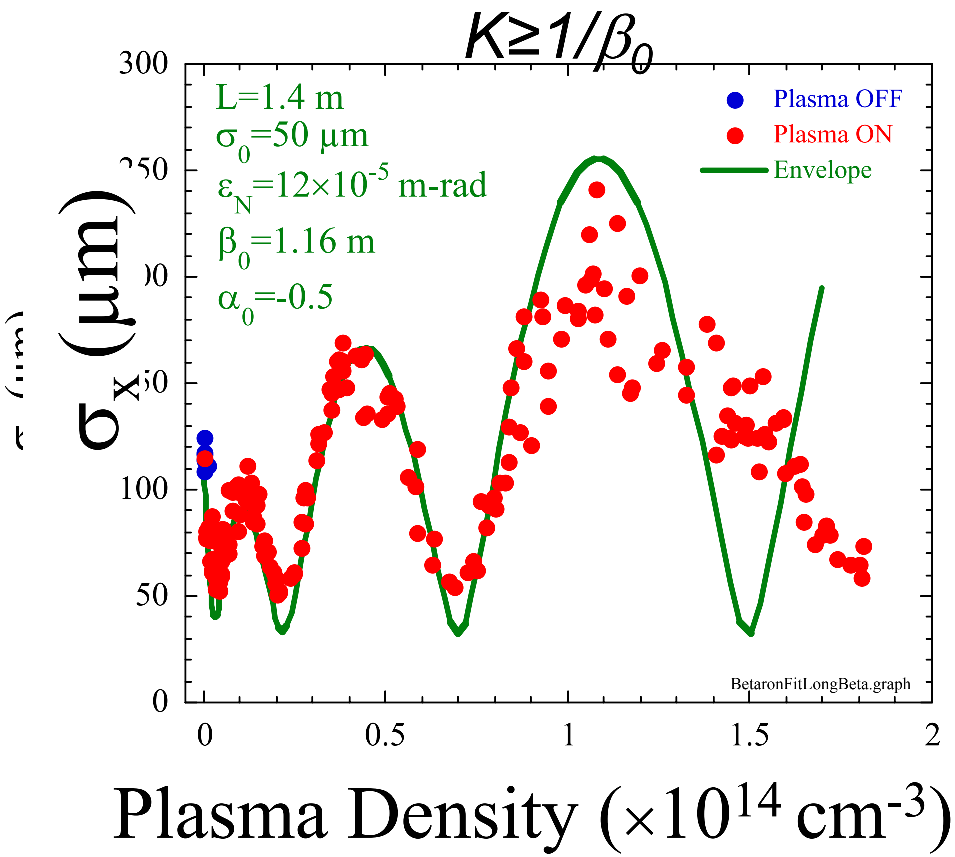


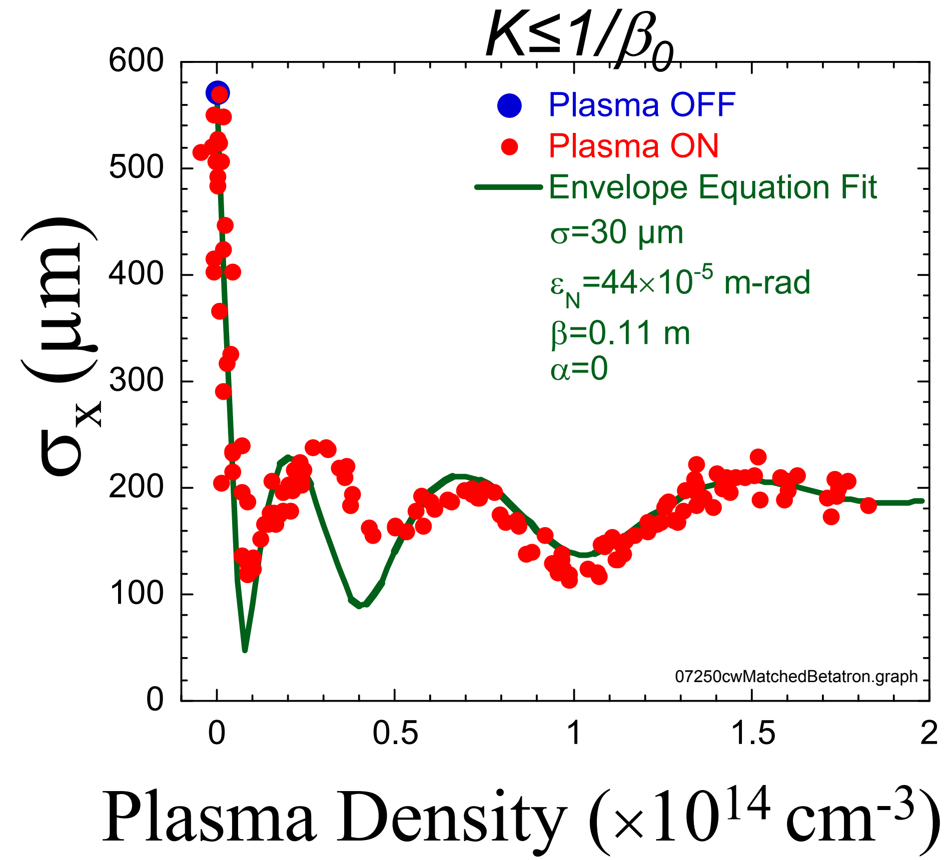

- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations

- $e^+$: halo formation from non uniform focusing (focusing abberations)

# FOCUSING OF e⁻

OTR Images ≈1m downstream from plasma




- Focusing of the beam well described by a simple model ($n_b > n_e$):
  Plasma = Ideal Thick Lens
- Channeling of the beam over 1.4 m or $>12\beta_0$

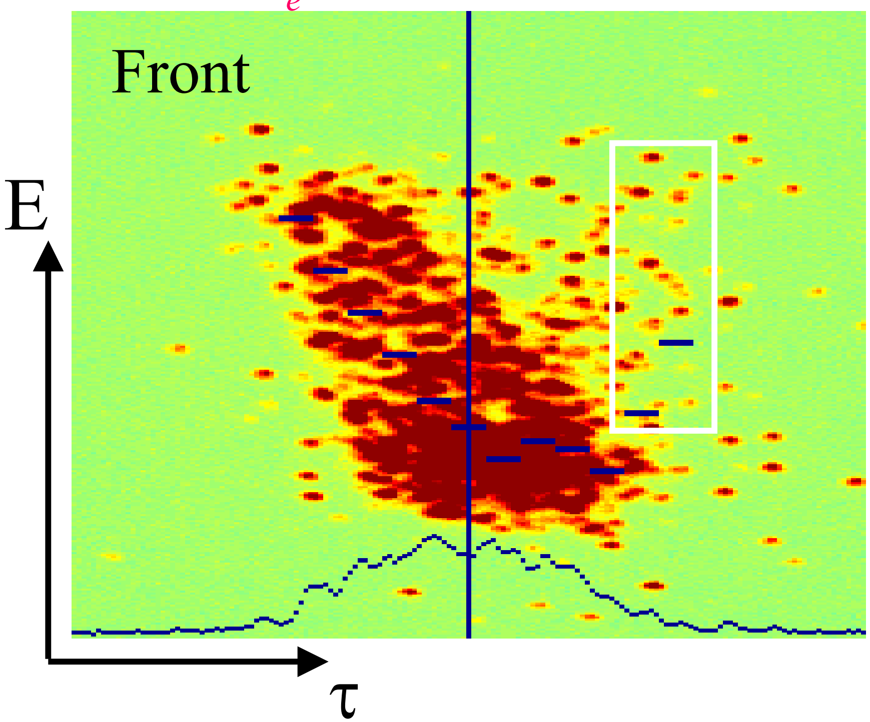
C.E. Clayton *et al.*, PRL, 2001


**S.Wang et.al. P.R.L.**

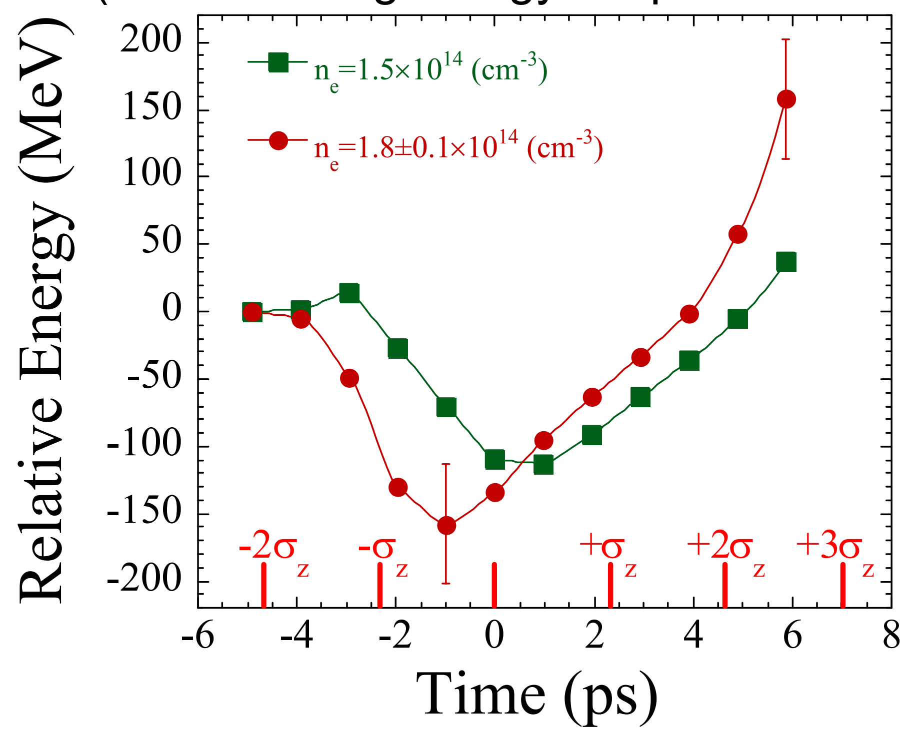
# $e^-$ ENERGY GAIN/LOSS

## ps slice analysis results

$n_e=1.8\times10^{14}$ cm$^{-3}$




(with incoming energy chirp subtracted)




- Energy gain by particles ≈279 MeV in the last (-6 ps) 1 ps slice
- Peak accelerating gradient ≈200 MeV/m ($L$=1.4 m)

P. Muggli *et al.*, PRL, 2004

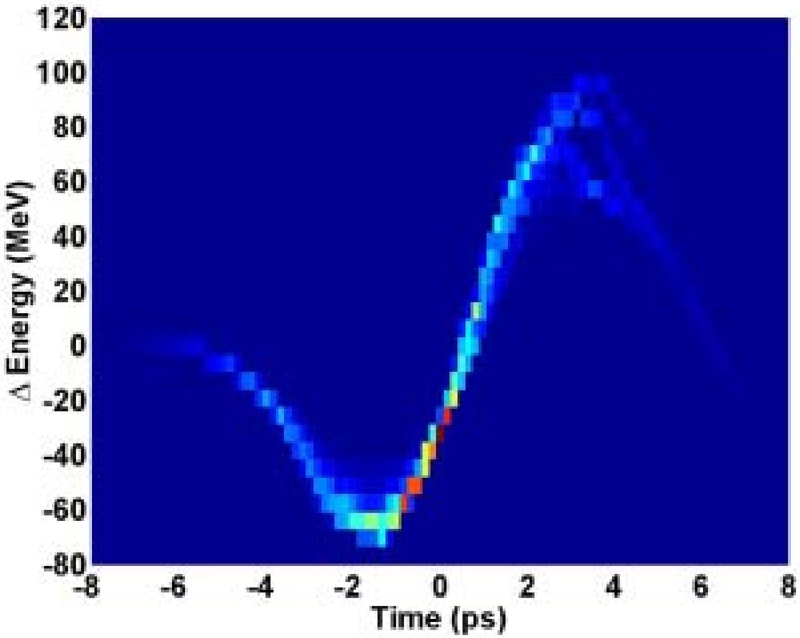
USC

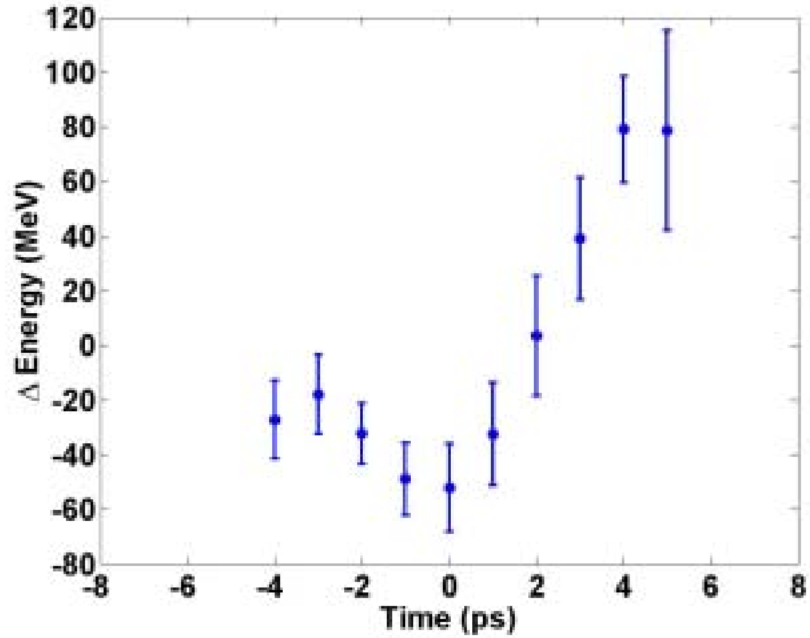
U C L A

# Energy Gain of a Positron Beam

Excellent agreement between simulation and experiment of a positron beam which has passed through a 1.4 m PWFA

| | Peak Energy Loss | Peak Energy Gain |
|---|---|---|
| OSIRIS Simulation Prediction: | 64 MeV | 78 MeV |
| Experimental Measurement: | 65±10 MeV | 79±15 MeV |

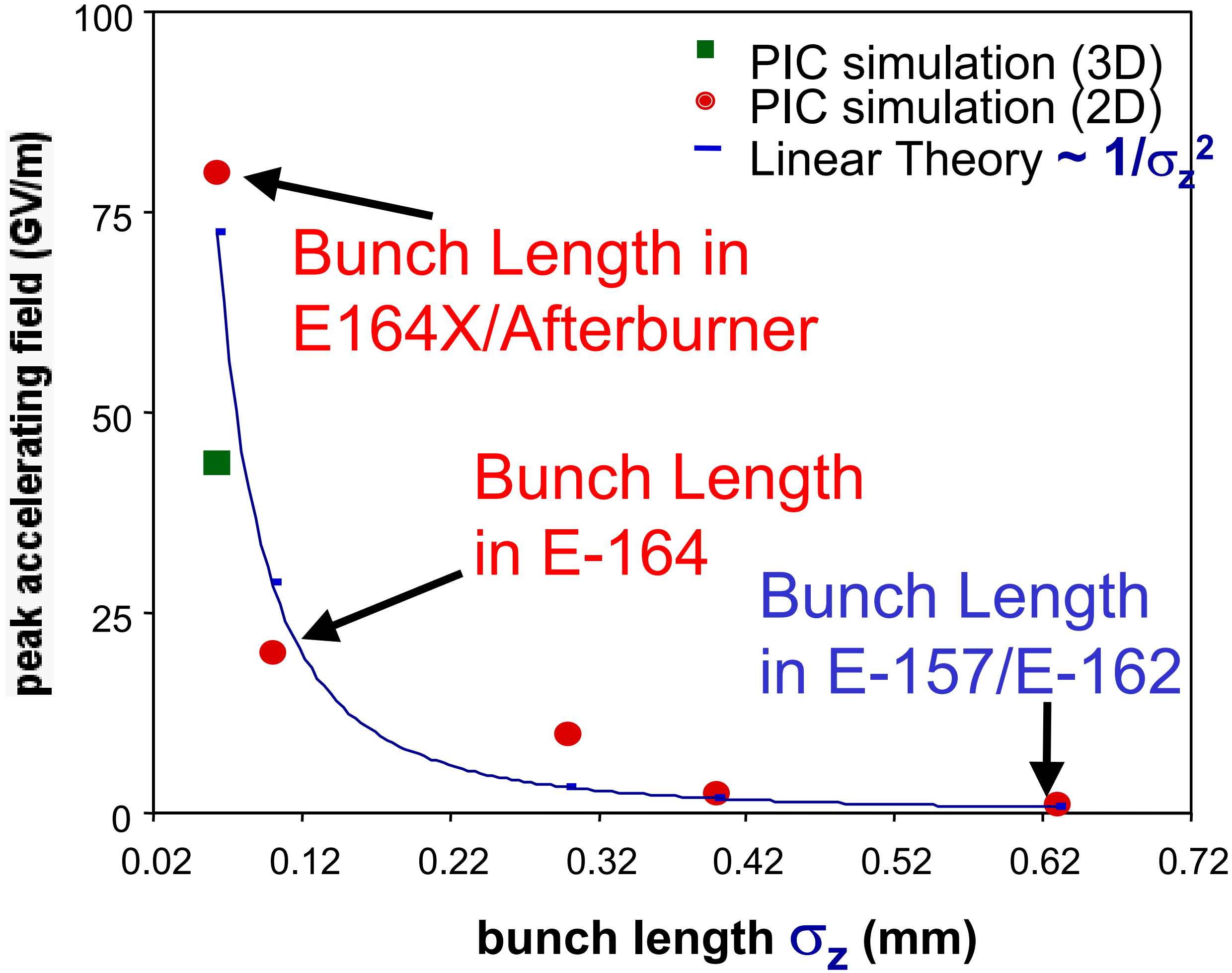



$5\times10^{8}$ $e^{+}$ in 1 ps bin at +4 ps

**B.Blue et.al. Phys. Rev. Lett. (2003)**

# Expected Gradient / Scaling

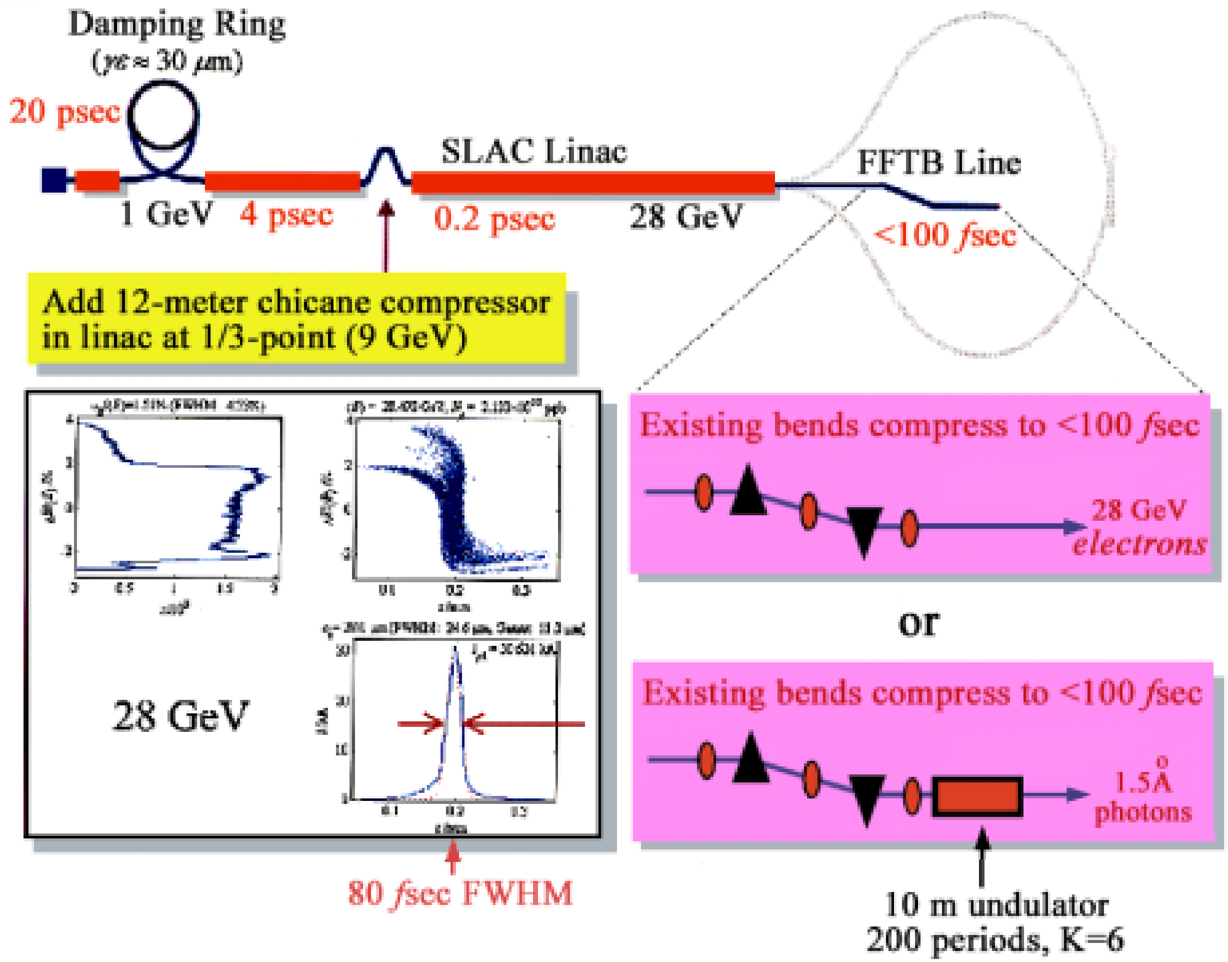



- E-164X: $\sigma_z$=20-10 µm: >10 GV/m gradient!

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

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

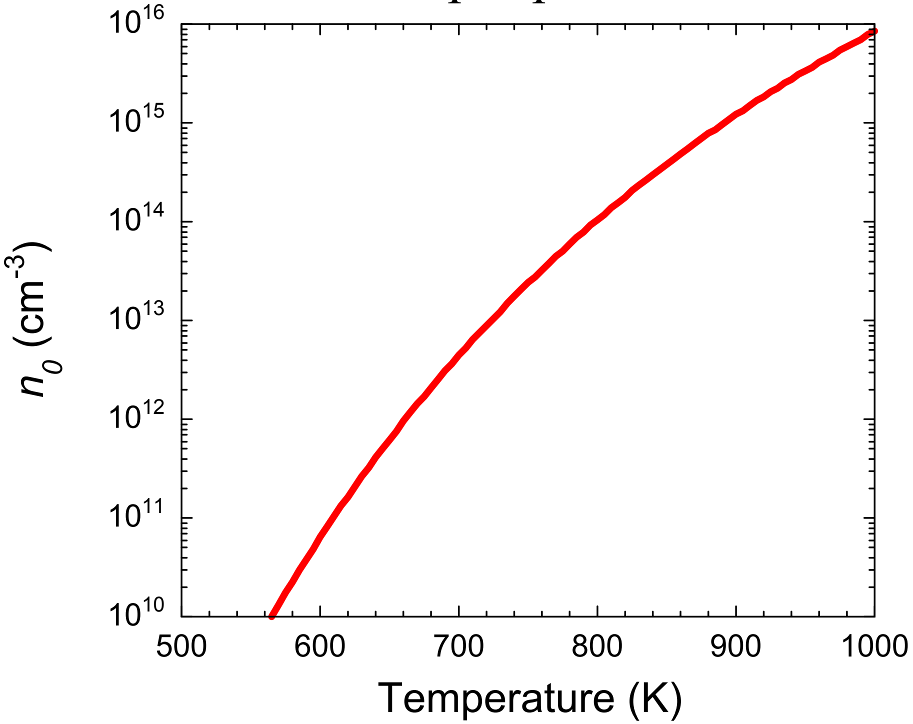
# Sub-Picosecond Pulse Source



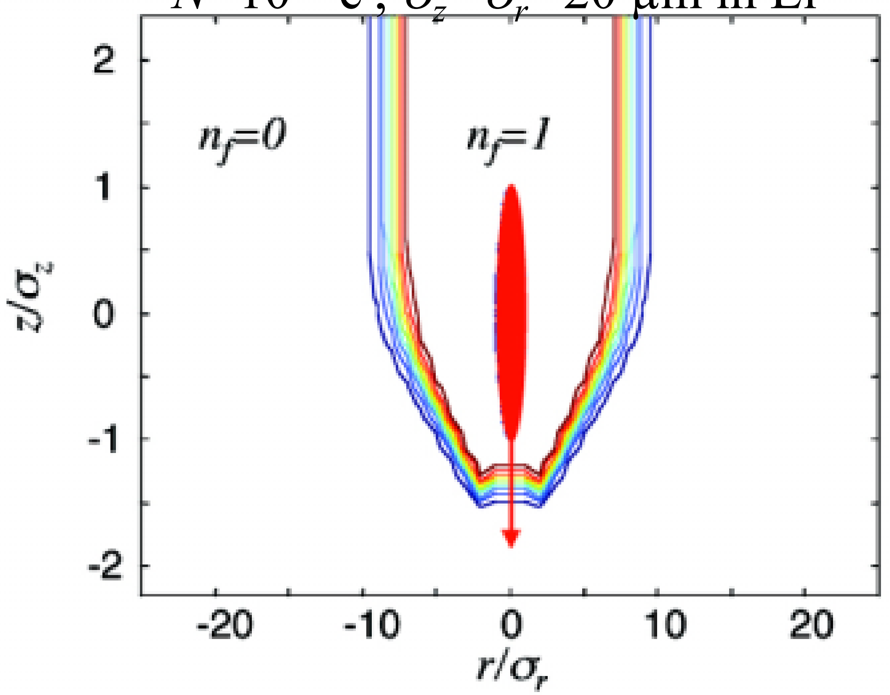
# BEAM-IONIZED PLASMA

- Short bunch, $E_r \approx 5.2\times10^{-19} N/\sigma_z \sigma_r$ *(GV/m)* > tunneling field (Kyldish, ADK)

Lithium vapor pressure curve

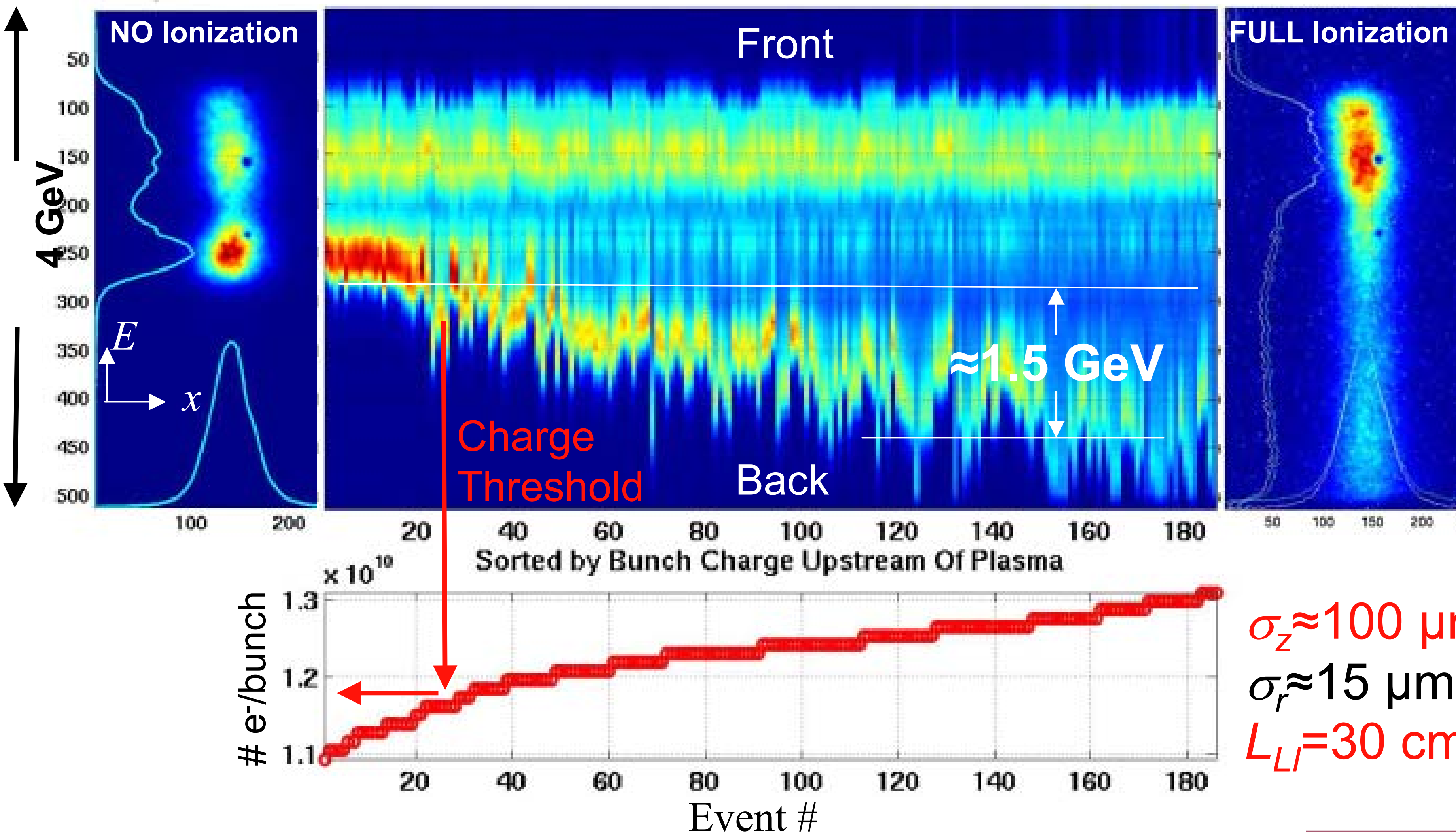



$N$=$10^{10}$ e$^-$, $\sigma_z$=$\sigma_r$=20 µm in Li



# $e^-$-BEAM FIELD-IONIZATION

Beam images dispersed in energy




$\sigma_z \approx 100\ \mu m$

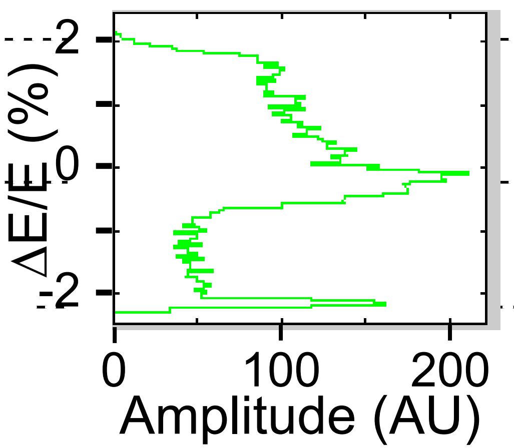
$\sigma_r \approx 15\ \mu m$

$L_{LI} = 30\ cm$

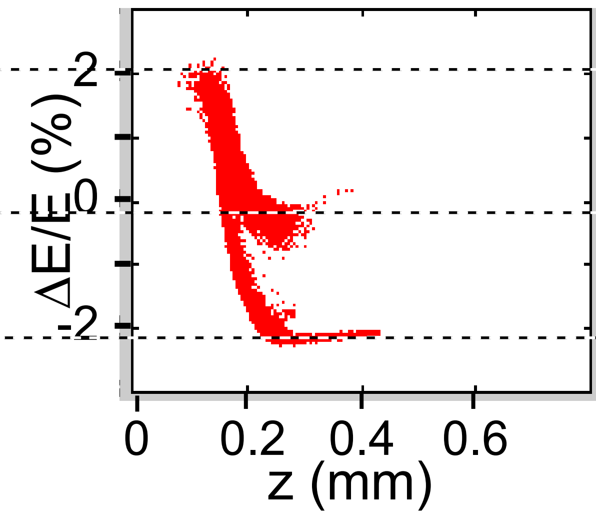
- > 4 GeV/m Energy Loss in Beam Ionized Plasma
  (near threshold)

# EXPERIMENTAL BEAM-IMAGE AGREES WELL WITH SIMULATION OF SUBPICOSECOND BEAM

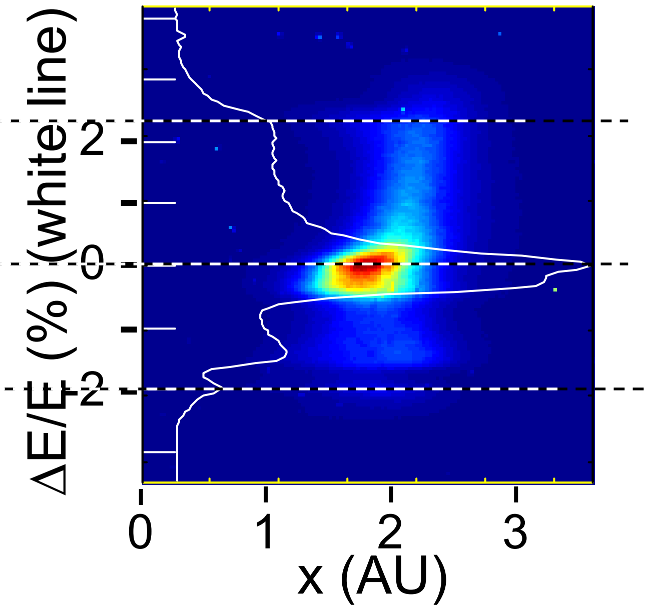
ENERGY SPECTRUM



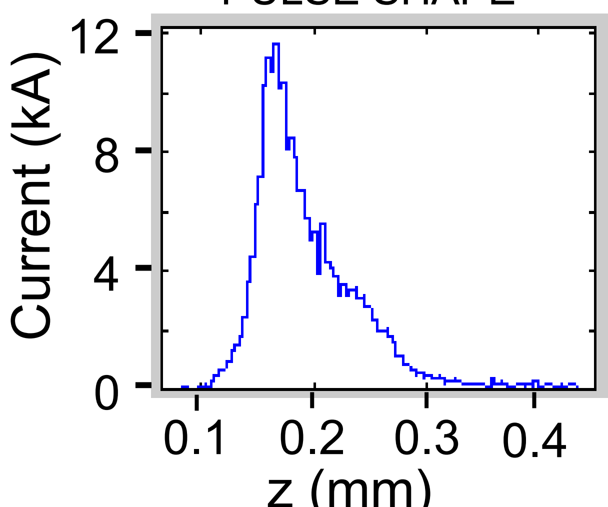

PHASE SPACE




SPECTROMETER IMAGE

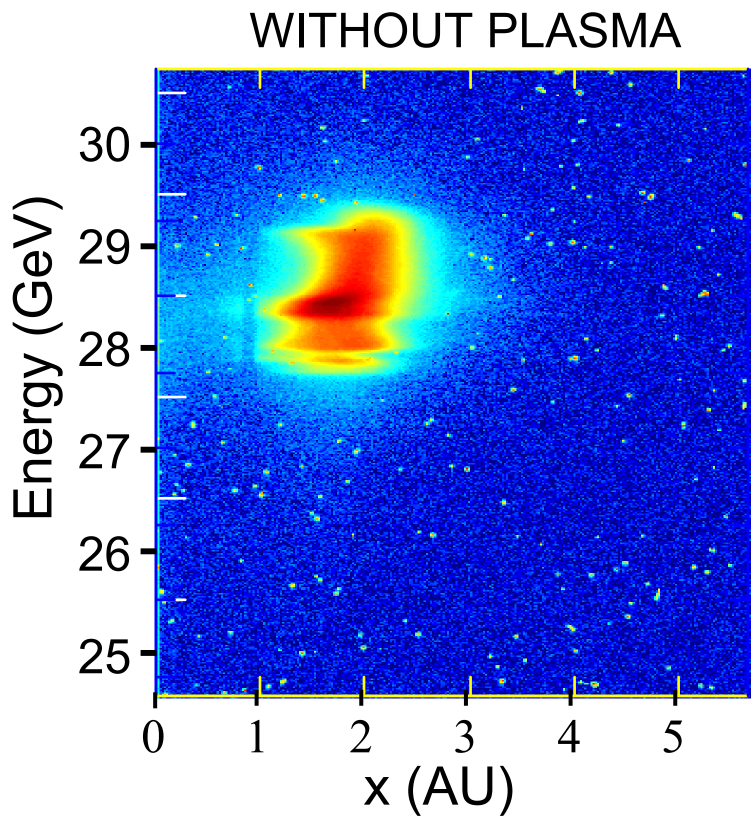


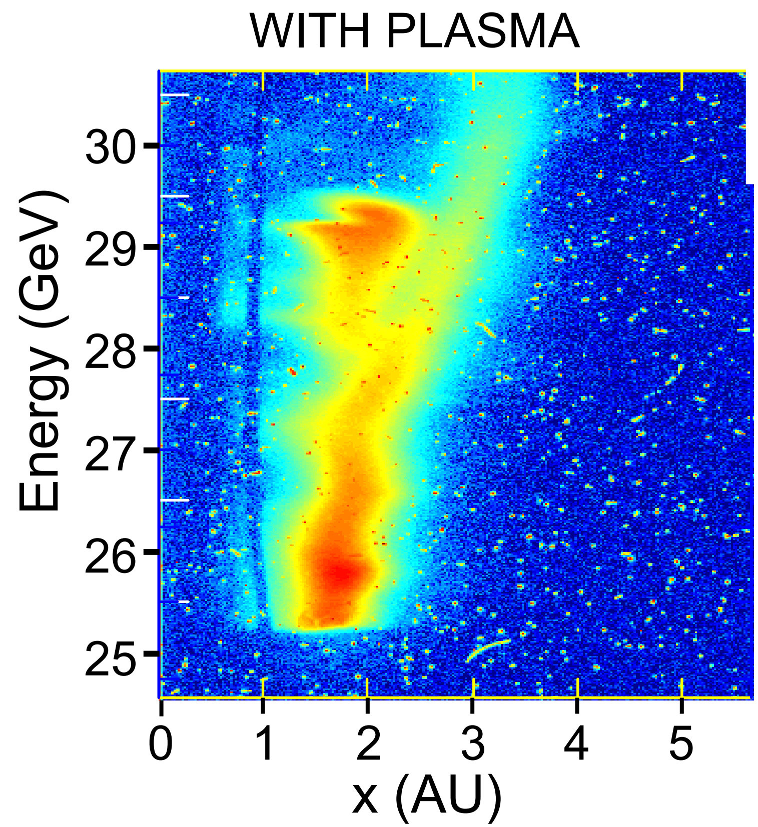

PULSE SHAPE




UCLA

# E-164 (Run II):First signature of energy gain



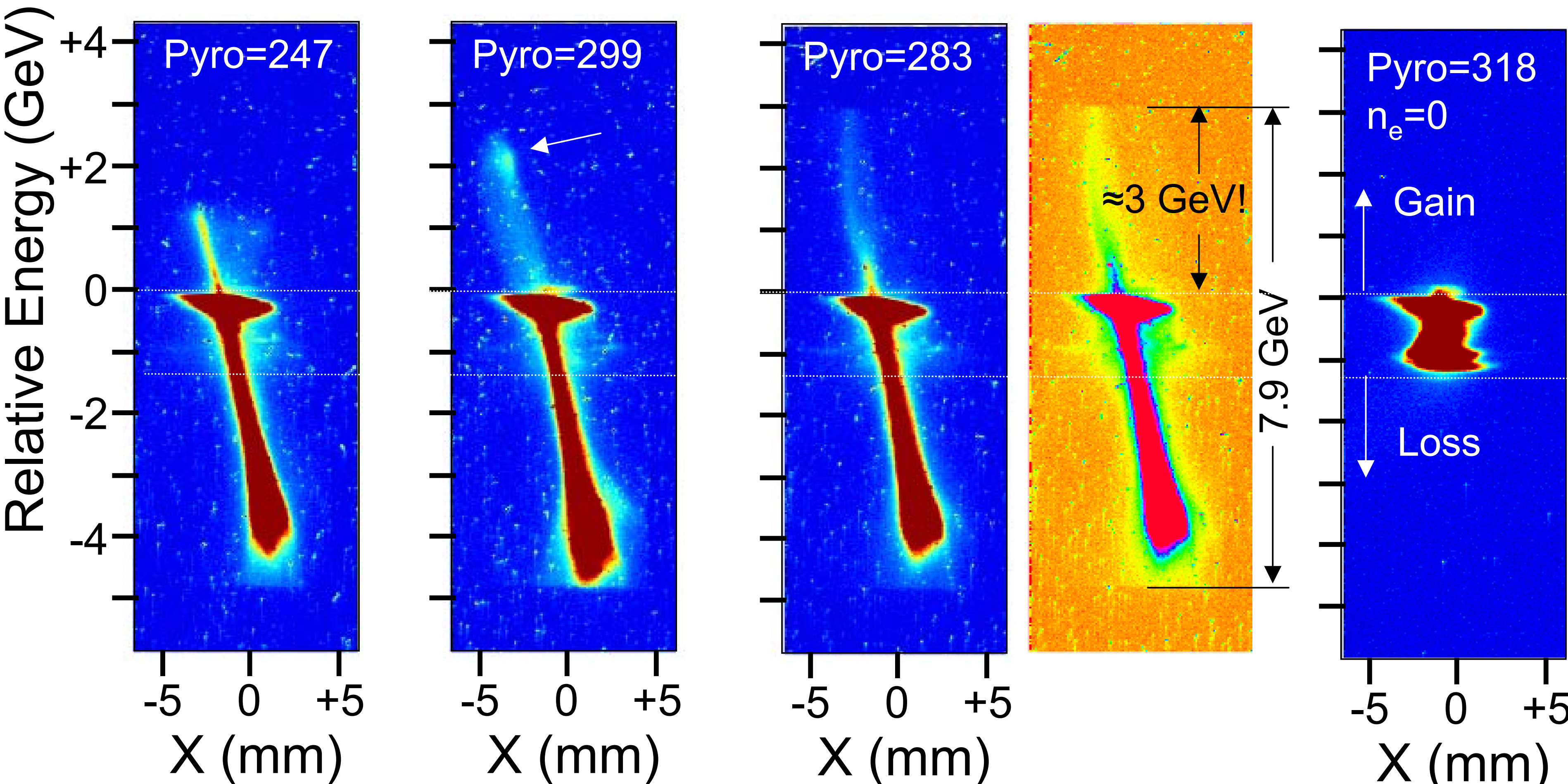




$n_e = 3 \times 10^{16}$ cm$^{-3}$, L = 15 cm, N = $1.8 \times 10^{10}$

- Energy loss of ~ 2.5 GeV
- Energy gain of ~ 2 GeV

# E164X Breaks GeV Barrier

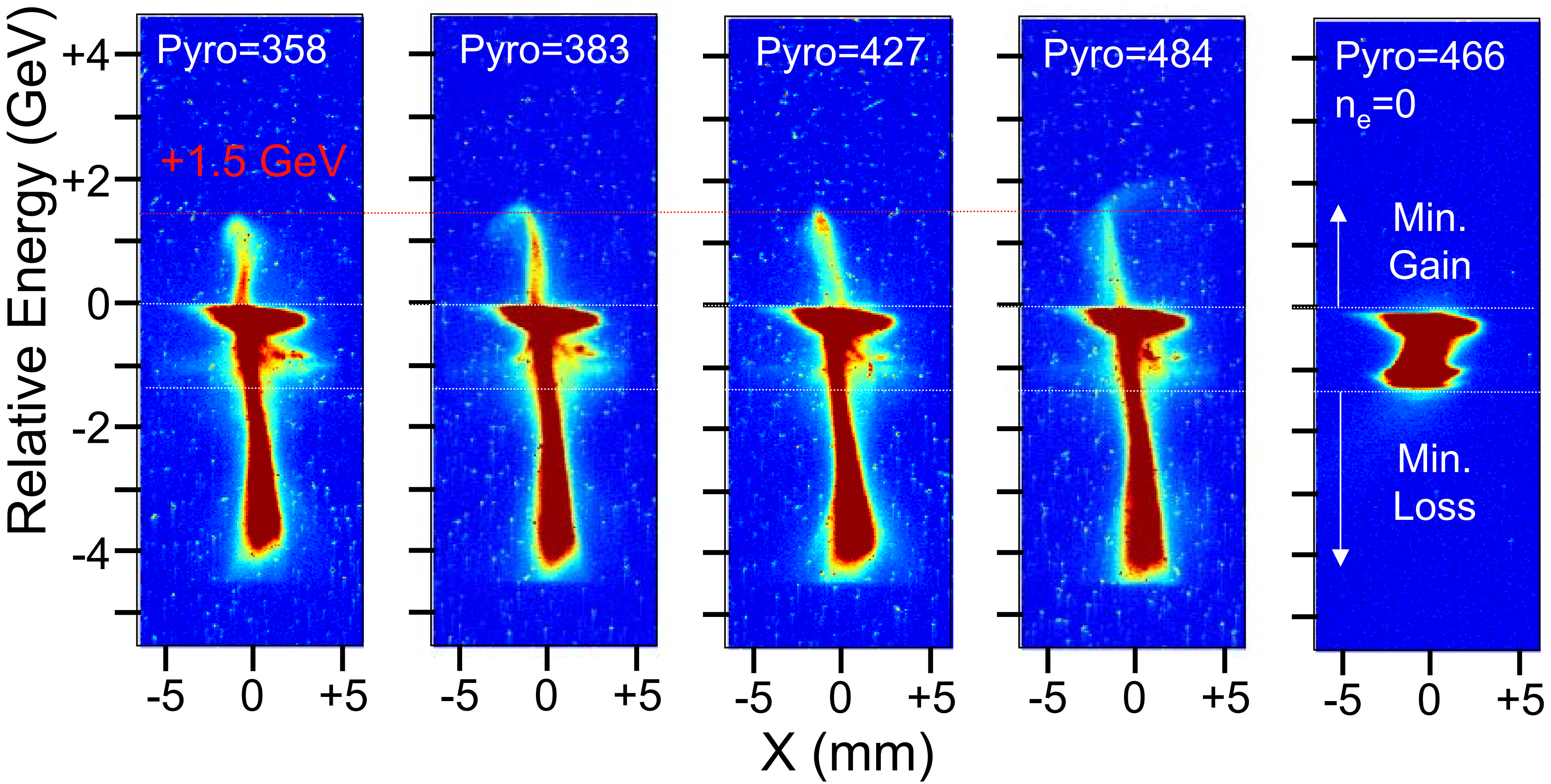
L≈10 cm, N≈ $1.8 \times 10^{10}$




- Energy gain reaches ≈ 4 GeV
- $n_e \approx 2.55 \times 10^{17}\ cm^{-3}$

# $n_e \approx 3.5\times10^{17}$ cm$^{-3}$ RESULTS

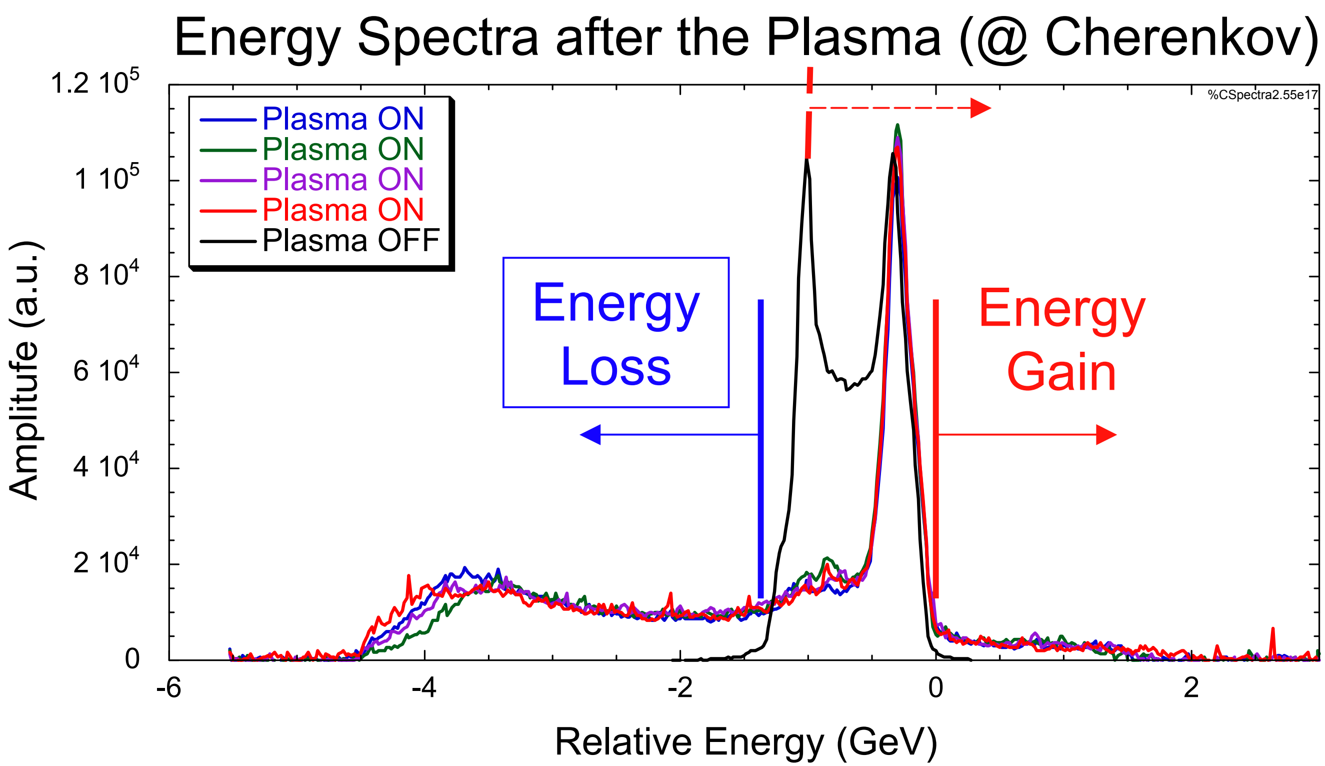
L≈10 cm, N≈ $1.8\times10^{10}$




- Many similar events in a data set
- Acceleration with significant charge: 2.5 GeV

# $n_e \approx 3.5 \times 10^{17}$ cm$^{-3}$ ENERGY SPECTRA

$L \approx 10$ cm, $N \approx 1.8 \times 10^{10}$

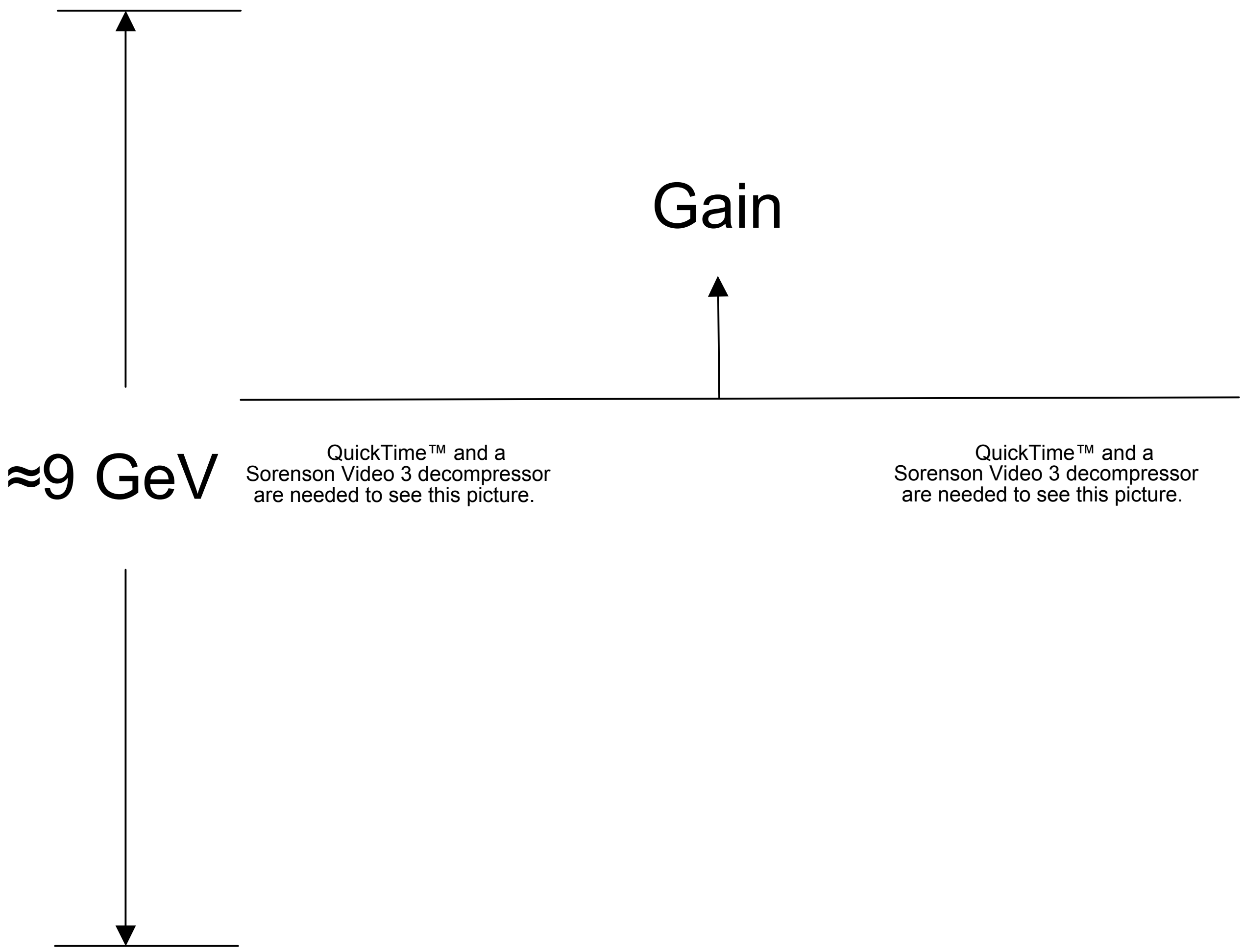



- Variations from incoming energy spectrum variations
- Charge Fraction at E>0: 6.8-7.9% of total charge!
- Peak energy gain above the beam head: ≈1.5 GeV

  total gain: 2.5 GeV

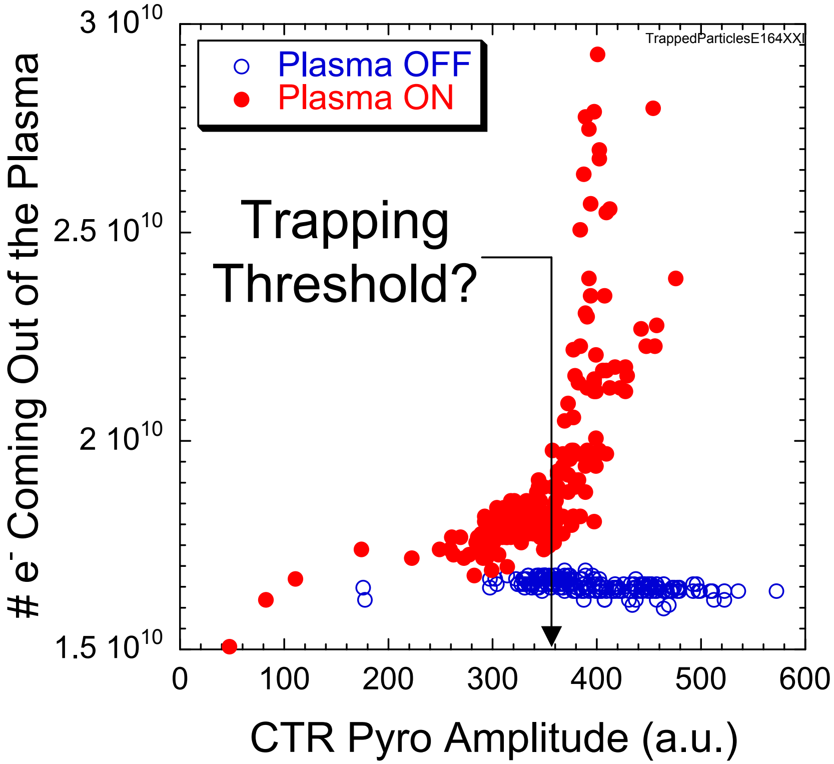
$n_e \approx 2.11 \times 10^{17}\ cm^{-3}$

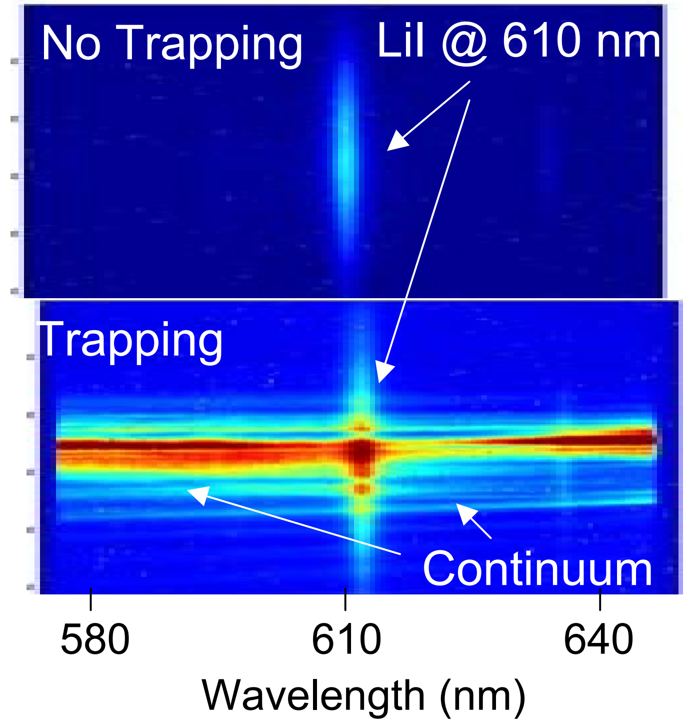
$L \approx 10\ cm$, $N \approx 1.8 \times 10^{10}$




➡ Very consistent acceleration, varies with incoming parameters

# TRAPPING OF PLASMA e⁻



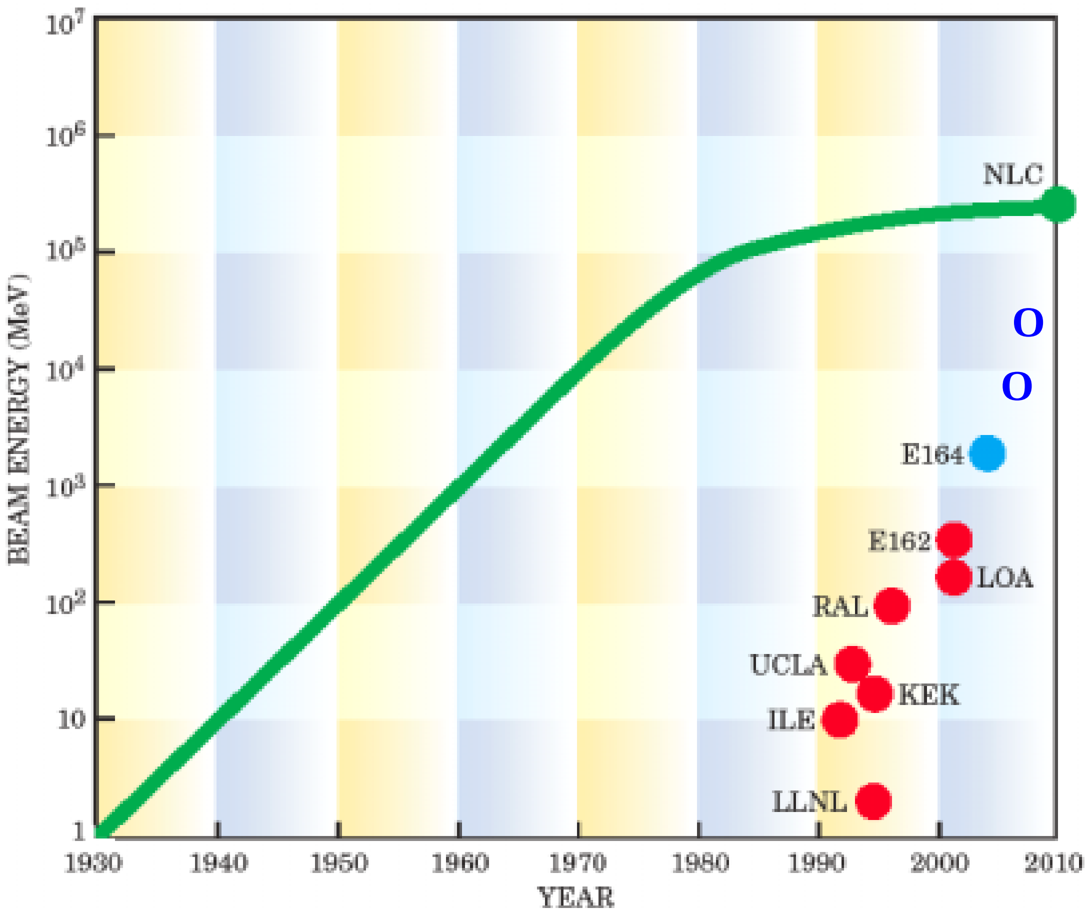




## Evidence for plasma $e^-$ trapping:

- Excess charge after the plasma
- Excess light from OTR screen
- Continuum light emission on plasma light spectrum

Dark current limit for the PWFA?

# Plasma Accelerators and the Livingston Curve

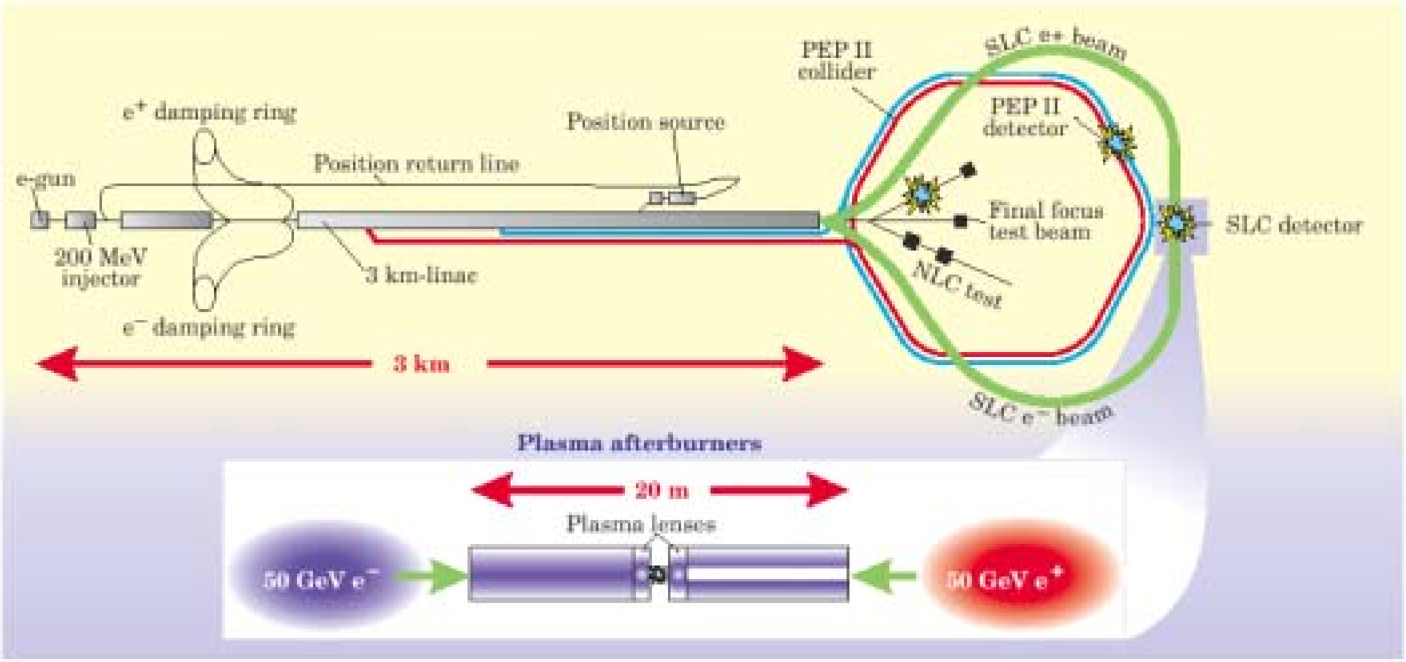


# Beam-Driven Plasma Wakefield Accelerators

## Ultimate Goal

Double the Energy of a Collider Using Plasma After-Burner Sections Placed Before IP.

Much of the research could be done at SLAC




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

# Critical Issues

Beam Loading

Transverse Beam Dynamics (hosing,radiation)

**Beam head Erosion**

Plasma Source Development

Beginning to end Modeling

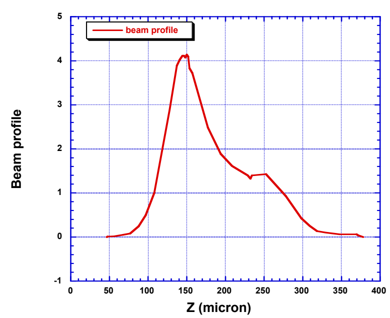
**High Gradient Acceleration of Positrons**

**High Demagnification plasma Lenses**

Large Transformer Ratio

# First 100 GeV PWFA Simulation : QuickPIC

C.Huang et.al.

<table>
<tr><th></th><th>E164X</th><th>Afterburner</th></tr>
<tr><td>Plasma Density</td><td>$n=1.6E17cm^{-3}$</td><td>$n=5.66E16cm^{-3}$</td></tr>
<tr><td>Beam charge</td><td>$N=1.8E10^{10}$</td><td>$N_{drive}=3E10^{10}$, $N_{trailing}=1E10^{10}$</td></tr>
<tr><td>Beam Profile</td><td>Longitudinal:<br><br><br>Transverse: Gaussian profile, $\sigma_r$= 12μm = $0.9c/\omega_p$</td><td>Longitudinal:<br><br>Drive beam : wedge shape, L=145μm=$6.5c/\omega_p$<br><br>Trailing beam : Gaussian profile, $\sigma_z$= 10μm = $0.45c/\omega_p$<br><br>Transverse: Gaussian profile, $\sigma_r$= 15μm = $0.67c/\omega_p$</td></tr>
</table>

# Drive Beam Erosion and Transverse Stability of Trailing Beam

QuickTime™ and a MPEG-4 Video decompressor are needed to see this picture.

# Evolution of Plasma Wake

QuickTime™ and a MPEG-4 Video decompressor are needed to see this picture.

# Energy Change of the Drive and Trailing Beams

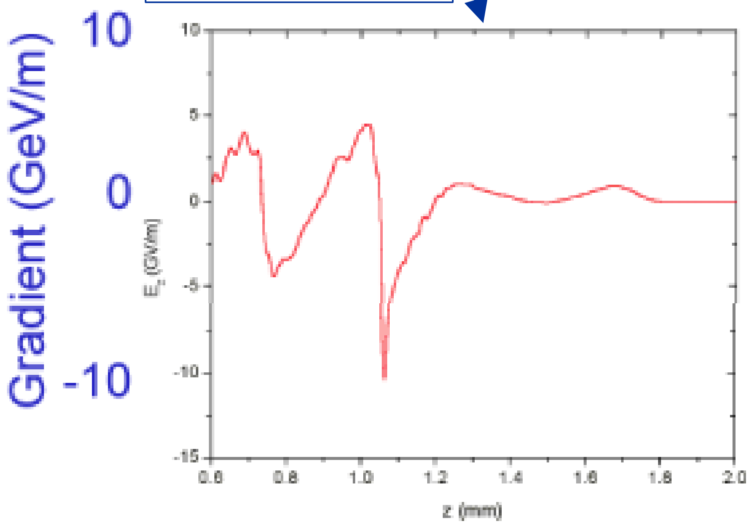
QuickTime™ and a MPEG-4 Video decompressor are needed to see this picture.

# CONCLUSIONS

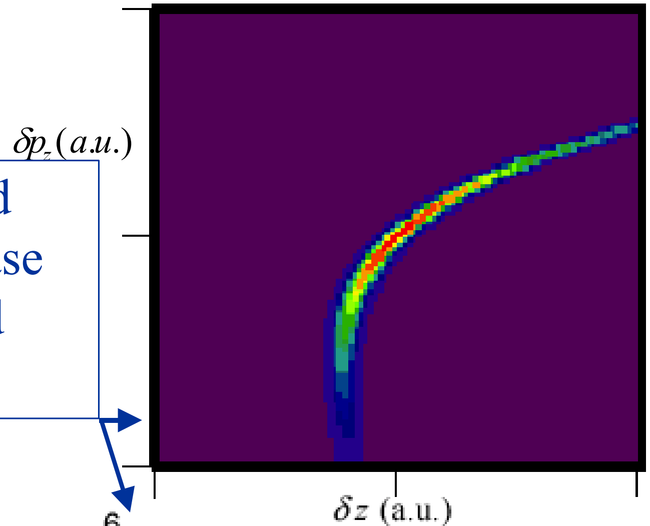
- For the 1st time: gain > 1 GeV in a plasma accelerator!
- Maximum energy gain observed:> 4 GeV over 10 cm!
- Accelerating gradient > 40 GeV/m over ≈10 cm!
- Acceleration very consistent and repeatable
- Maximum energy gain limited by the energy acceptance of the FFTB!
- Energy gain trends: largest at $\approx 2.55\times10^{17}$ $cm^{-3}$, more charge at higher densities.
- Observed trapped particles
- **Opinion:Energy Doubling with Reasonable Beam Loading Efficiency and Energy Spread @50-100GeV Level Achievable for Electrons within 2-4 Years**

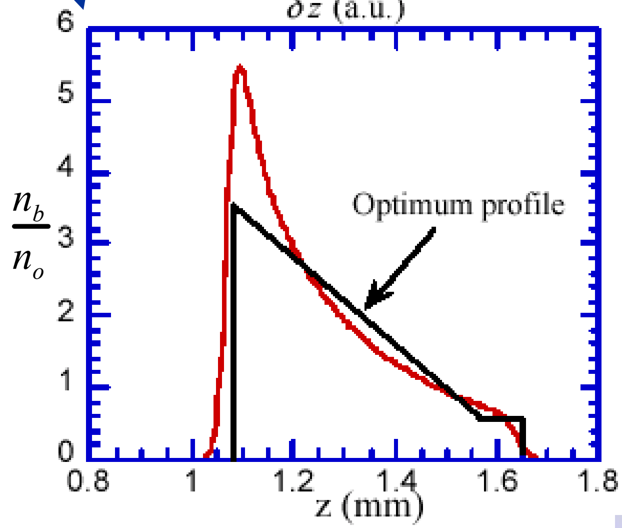
# Shaped bunch PWFA can be studied at ORION

Simulated Wake




Simulated beam phase space and shape



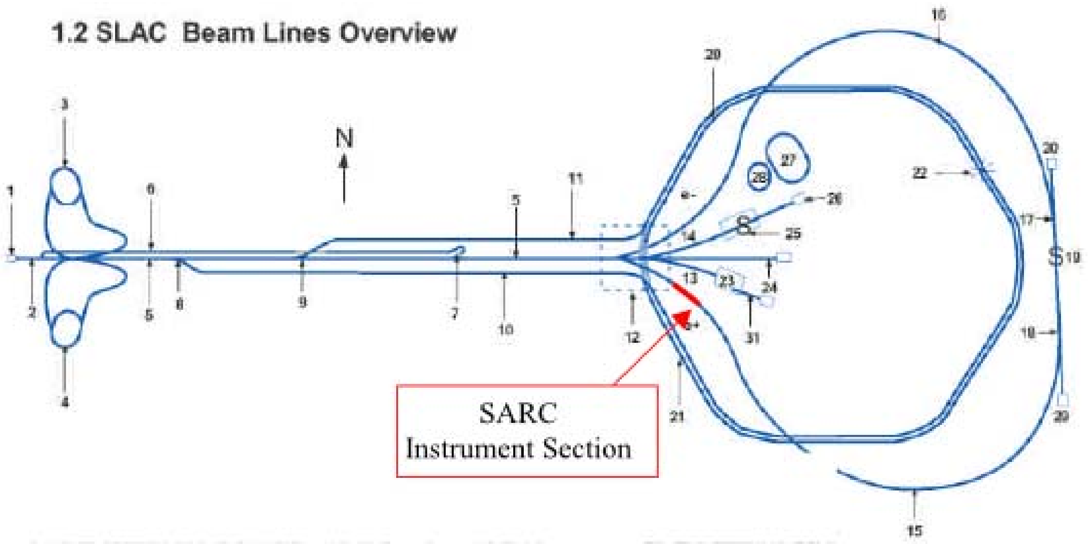



Figure 1. Location of the Instrument Section close to the beginning of the SARC

**Courtesy P. Krejcik, P. Emma**

# Transition trapping injection

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Simulation of beam captured in UCLA/FNAL transition trapping expt.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Plasma source UCLA/FNAL transition trapping expt. (side view)

- Trapping of plasma electrons based on density transition; phase mixing near boundary
- Density tailored to produce very low energy spread injected beam
- Plasma now installed on beamline at FNAL A0

M. C. Thompson, J. B. Rosenzweig, H. Suk, “Plasma density transition trapping as a possible high-brightness electron beam source”, Phys. Rev. ST. – Accel. Beams, **7**, 011301 (2004)

# Observation of nonlinear plasma wakefields @ ANL

- Measurements at AATF
- Wave steepening into sawtooth form
- Wakes persist for 10’s of wavelengths
- Harmonics also observed in transverse deflection wakes

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Witness beam centroid as a function of delay time in nonlinear PWFA measurement

"Experimental Measurement of Nonlinear Plasma Wake-fields", J. B. Rosenzweig, *et al.*, *Phys. Rev. A - Rapid Comm.* **39**, 1586 (1989).

# Underdense beam guiding

- Measurement at ANL AWA facility in 1997
- Underdense plasma ($n_b > n_p$)
- Guiding shown over 12 times $\beta^*$
- First step to blow-out regime of PWFA

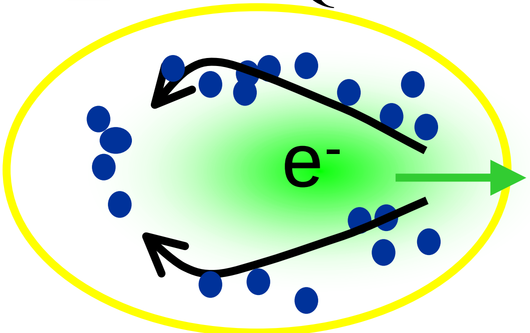
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Time resolved focusing of beam using streak camera at end of plasma, showing guiding in beam core

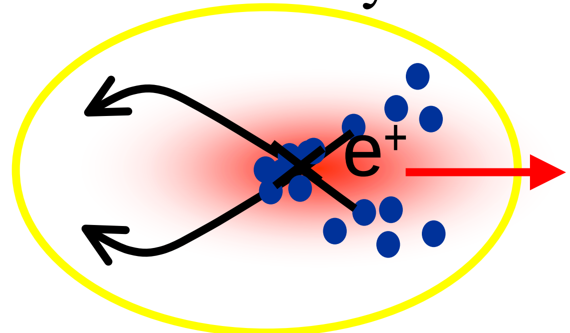
"Propagation of Short Electron Pulses in a Plasma Ion Chanel" N. Barov, M.E. Conde, W. Gai, and J.B. Rosenzweig, *Physical Review Letters*. **80**, 81 (1998).

# $e^-$ & $e^+$ BEAM NEUTRALIZATION

3-D QuickPIC simulations, plasma $e^-$ density:

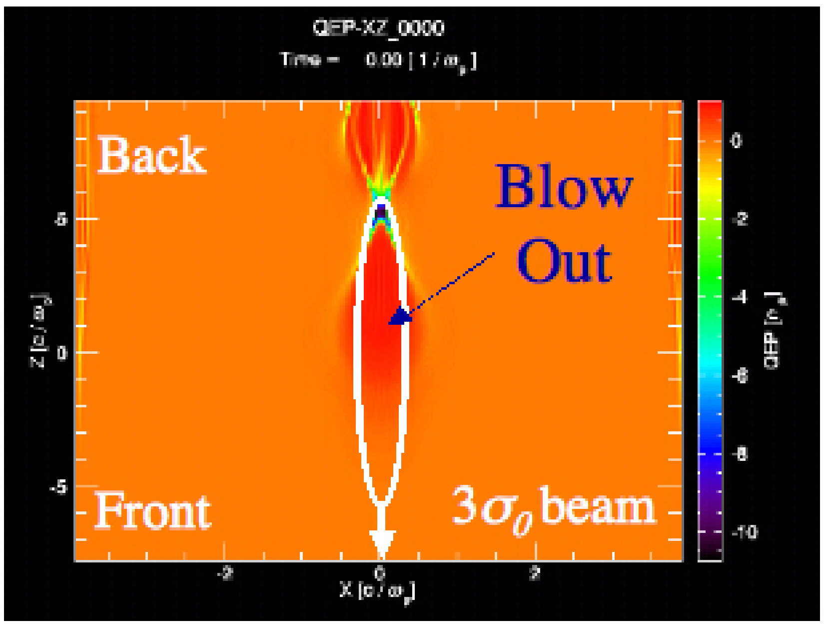


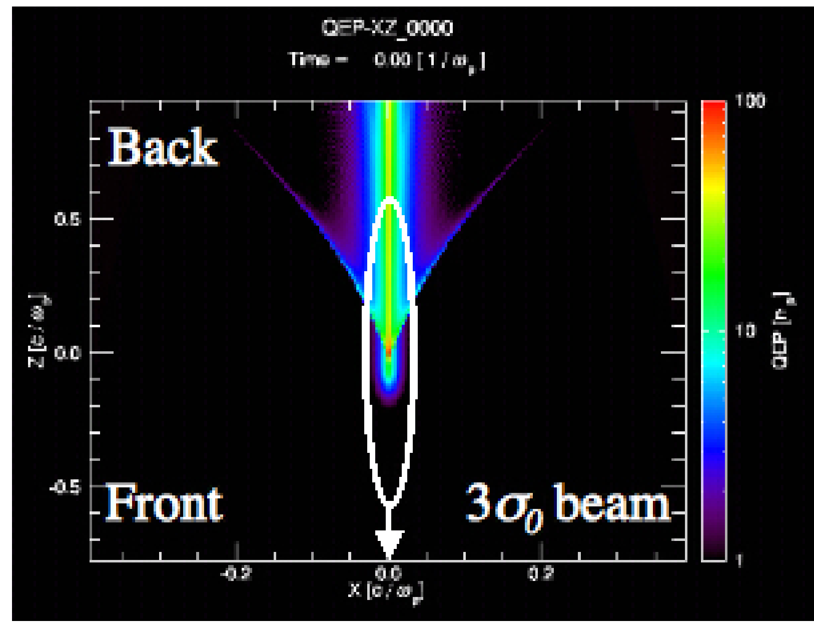

$\sigma_r$=35 μm
$\sigma_z$=700 μm
$N$=1.8×10$^{10}$
$d$=2 mm




$e^-$: $n_{e0}$=2×10$^{14}$ cm$^{-3}$, $c/\omega_p$=375 μm

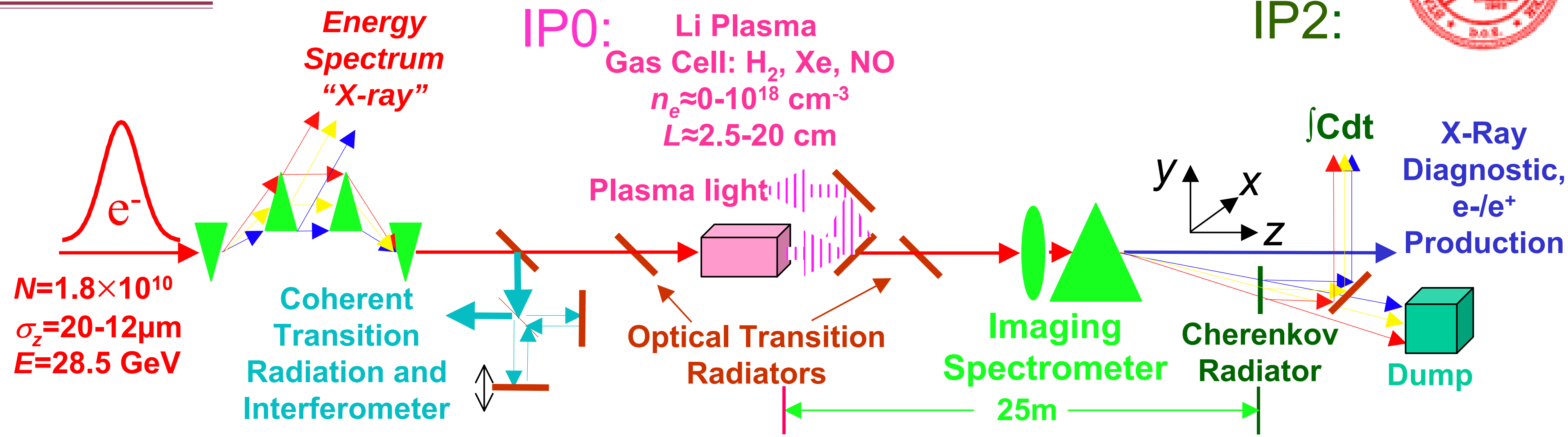
$e^+$: $n_{e0}$=2×10$^{12}$ cm$^{-3}$, $c/\omega_p$=3750 μm



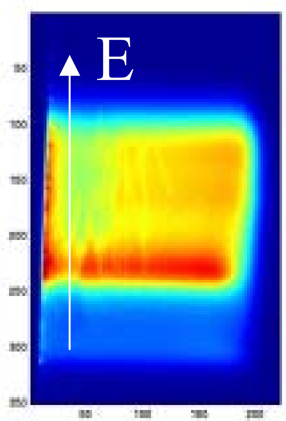




- Uniform focusing force ($r$,$z$)
- Non-uniform focusing force ($r$,$z$)

# EXPERIMENTAL SET UP



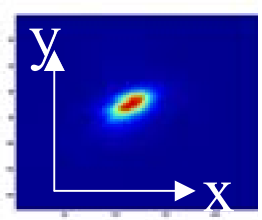

- X-ray Chicane



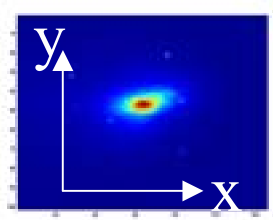

-Energy resolution ≈60 MeV

- Optical Transition Radiation (OTR)

Upstream



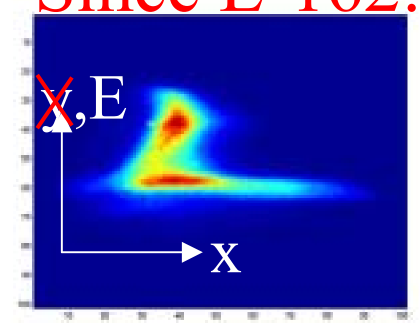

Downstream




-1:1 imaging, spatial resolution ≈9 μm

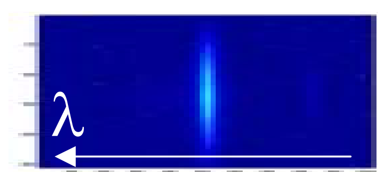
- Cherenkov (aerogel)

Since E-162:



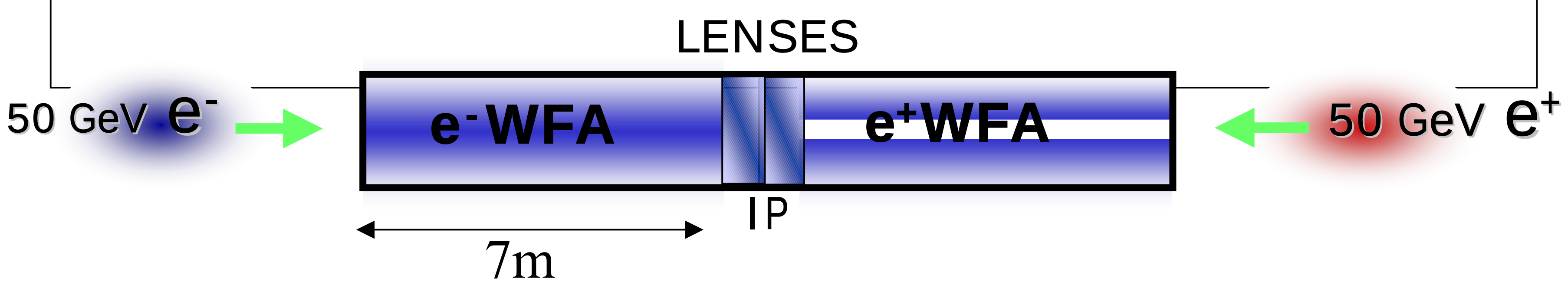

- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV

- Plasma Light



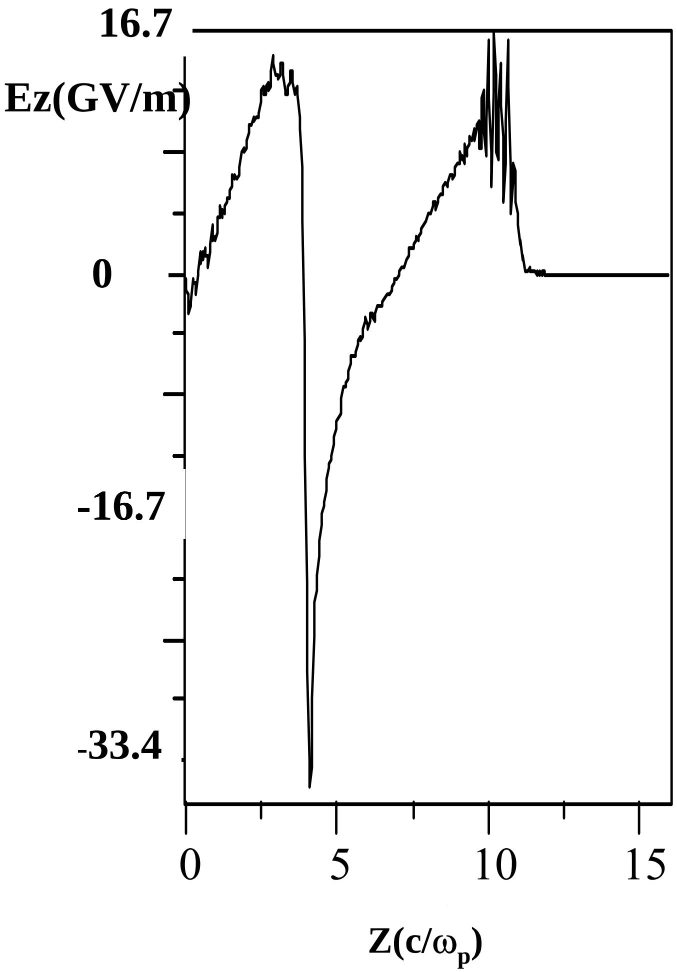
# PLASMA AFTERBURNER

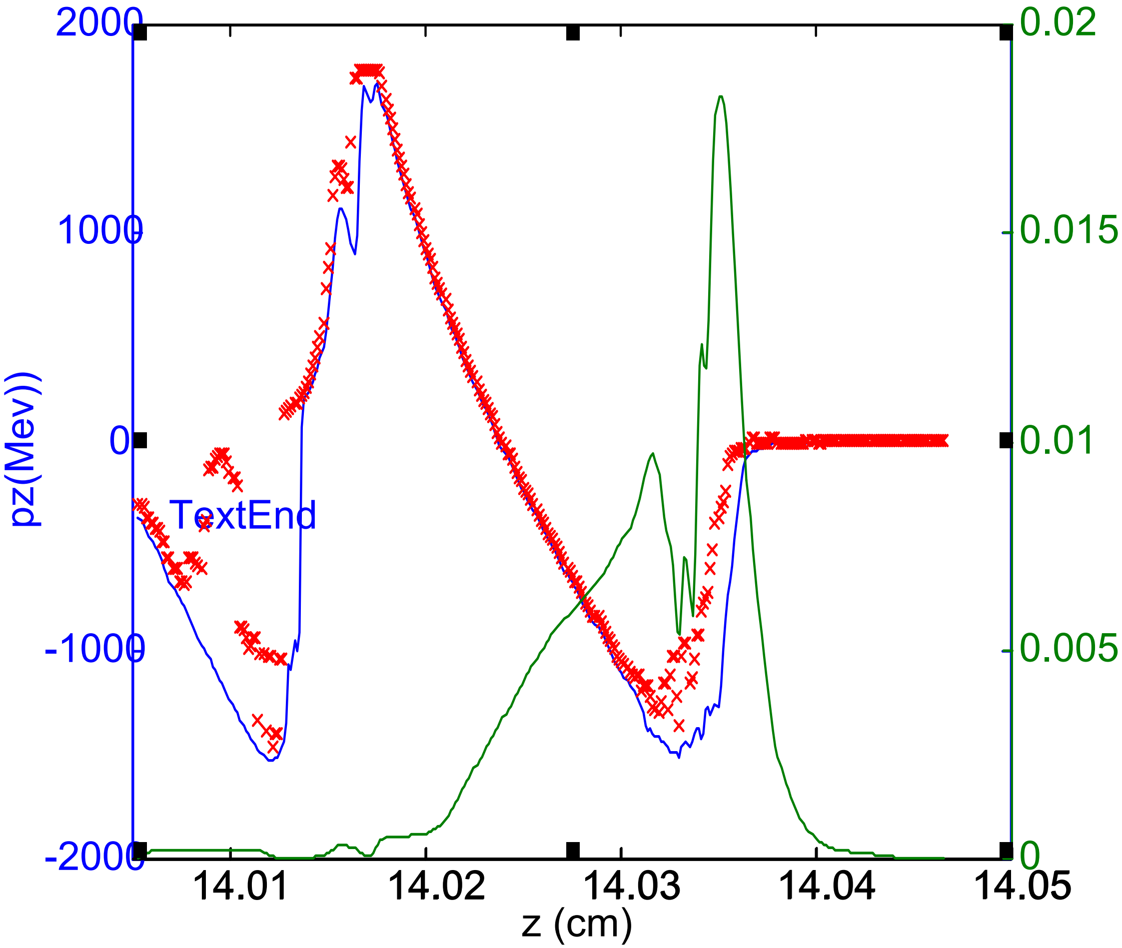
- Double the energy of Collider w/ short plasma sections before IP
- $1^{st}$ half of beam excites wake --decelerates to 0
- $2^{nd}$ half of beams rides wake--accelerates to 2 x $E_o$
- Make up for Luminosity decrease $\propto N^2/\sigma_z^2$ by halving $\sigma$ in a final plasma lens




S. Lee *et al.*, PRST-AB (2001)

# E164X simulation results

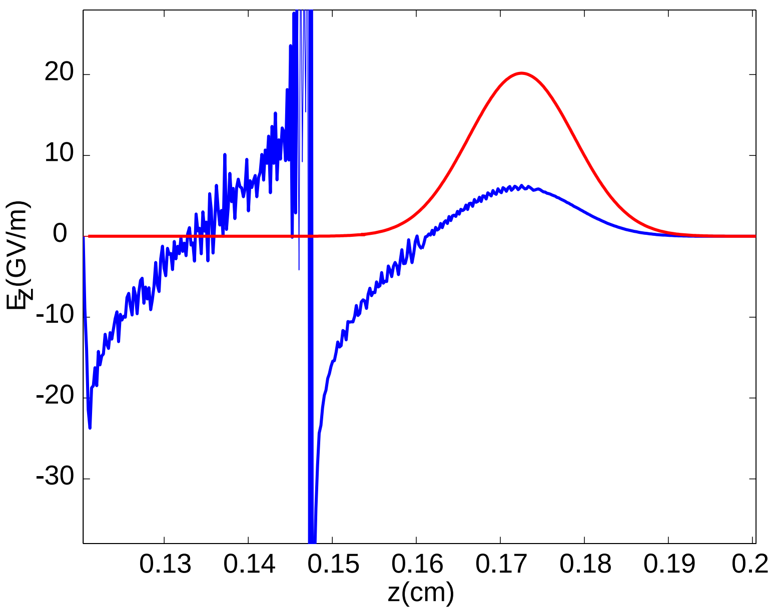


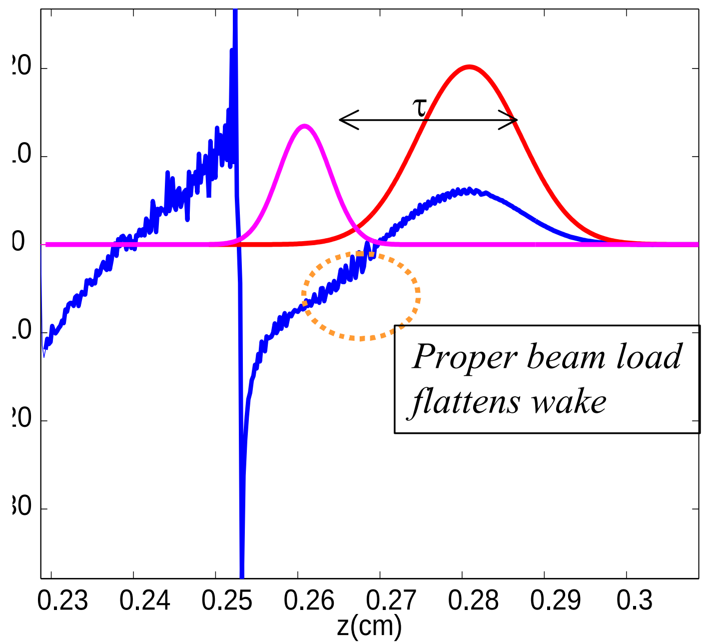
# PIC Simulation of 2 bunch Afterburner Experiment

Hi beam quality requires specialized
infrastructure of ORION beamline

(shorter 2nd bunch, precise phasing $\tau$)



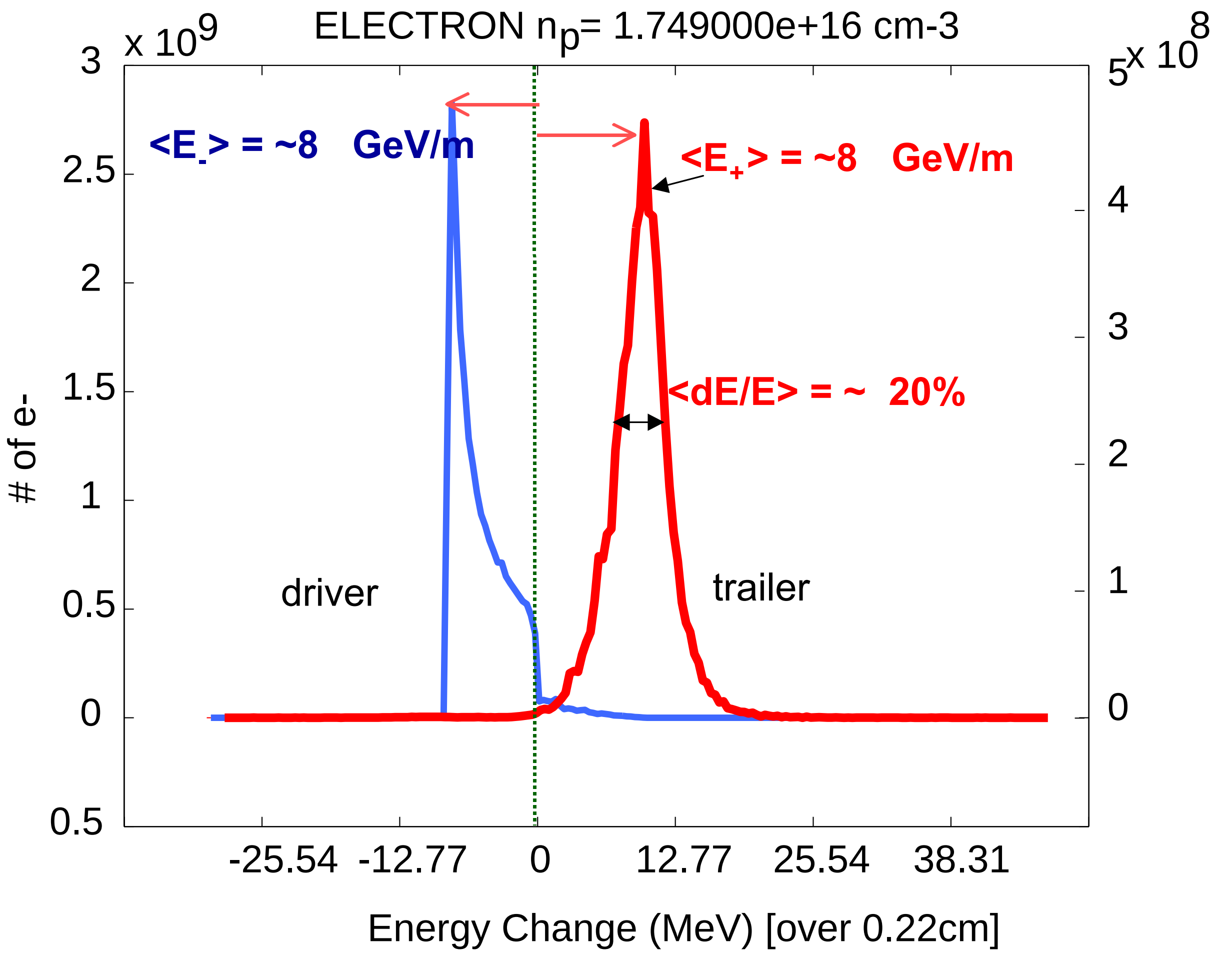

Driving bun ch only




Driving bun ch N=3 $\times 10^{10}$ $\sigma_z$=0.063mm

Trailing bunc h $N^-$ =1 $\times$ 10 $^{10}$ $\sigma_z$(trailing) = $\sigma_z/2$

# Energy distribution of driver & trailer



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