Recent Electron Beam Driven Plasma Wakefield Accelerator Results

Presented by Patric Muggli

for the *E-164X* Collaboration:

C. Barnes, F.-J. Decker, P. Emma, M. J. Hogan, R. Iverson, P. Krejcik, C. O'Connell, P. Raimondi, H. Schlarb, R.H. Siemann, D. Walz

Stanford Linear Accelerator Center

C. E. Clayton, C. Huang, C. Joshi, D. Johnson, W. Lu, K. A. Marsh, W. B. Mori

University of California, Los Angeles

S. Deng, T. Katsouleas, P. Muggli , E. Oz

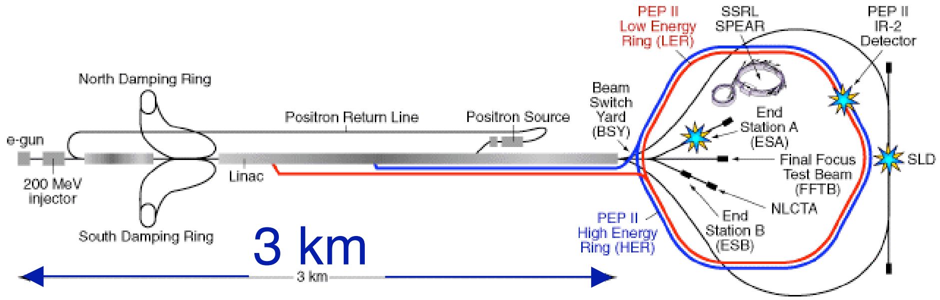
University of Southern California

OUTLINE

- Introduction to PWFA
- Long bunch PWFA results
- Short bunch production
- Short bunch PWFA results
- Conclusions
- Future

ACCELERATING FIELDS

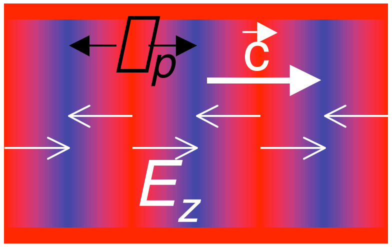
- Fields in rf cavities
- SLAC: ≈200, 70 MW Klystrons
  ≈50 GeV e^-/e^+ in ≈3 km
  Average gradients ≈17 MV/m



- Limited by rf breakdown ≤200 MV/m(?)
- Next linear collider (ILC): ≈35 MV/m(?)
- Relativistic Plasma Wave:
- $\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \qquad k_p E = \frac{\omega_{pe}}{c} E = \frac{n_e e}{\varepsilon_0}$

$$E = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \cong 100\sqrt{n_e\left(cm^{-3}\right)} = 1\, GV/m$$

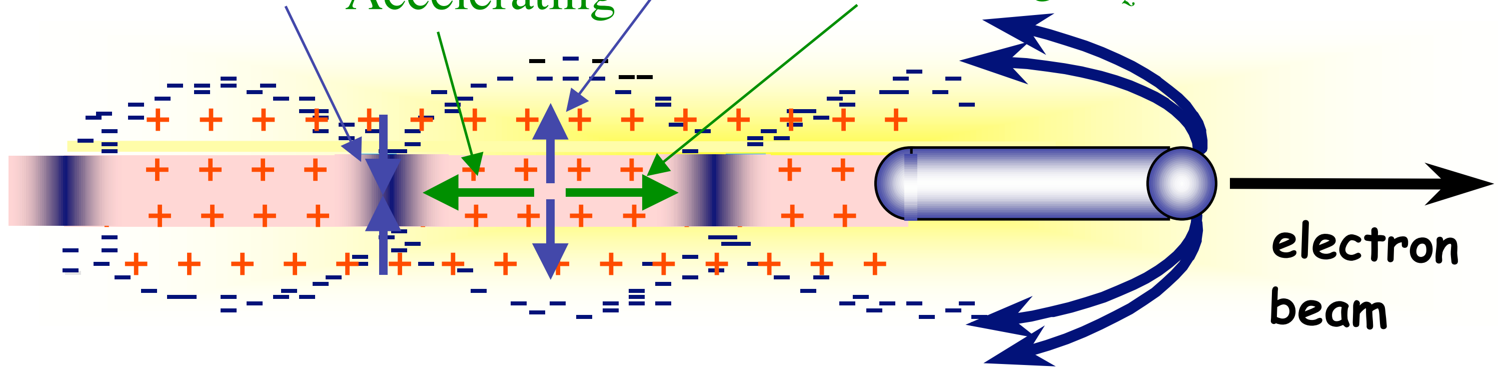
@ $n_e = 10^{14}$ cm^{-3} ($f_{pe} \approx 100$ GHz)



LARGE
Collective response!

- High gradient, high-energy plasma accelerator?

PLASMA WAKEFIELD (e$^-$)



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

  $@\ k_{pe}\sigma_z \approx \sqrt{2}\ or\ n_e \approx 10^{14}\ cm^{-3}$
- Plasma Wakefield Accelerator (PWFA) = Transformer

  Booster for high energy accelerator

PLASMA WAKEFIELD FIELDS (E-162, e^-)

Typical parameters:

<u>e^-- beam:</u>

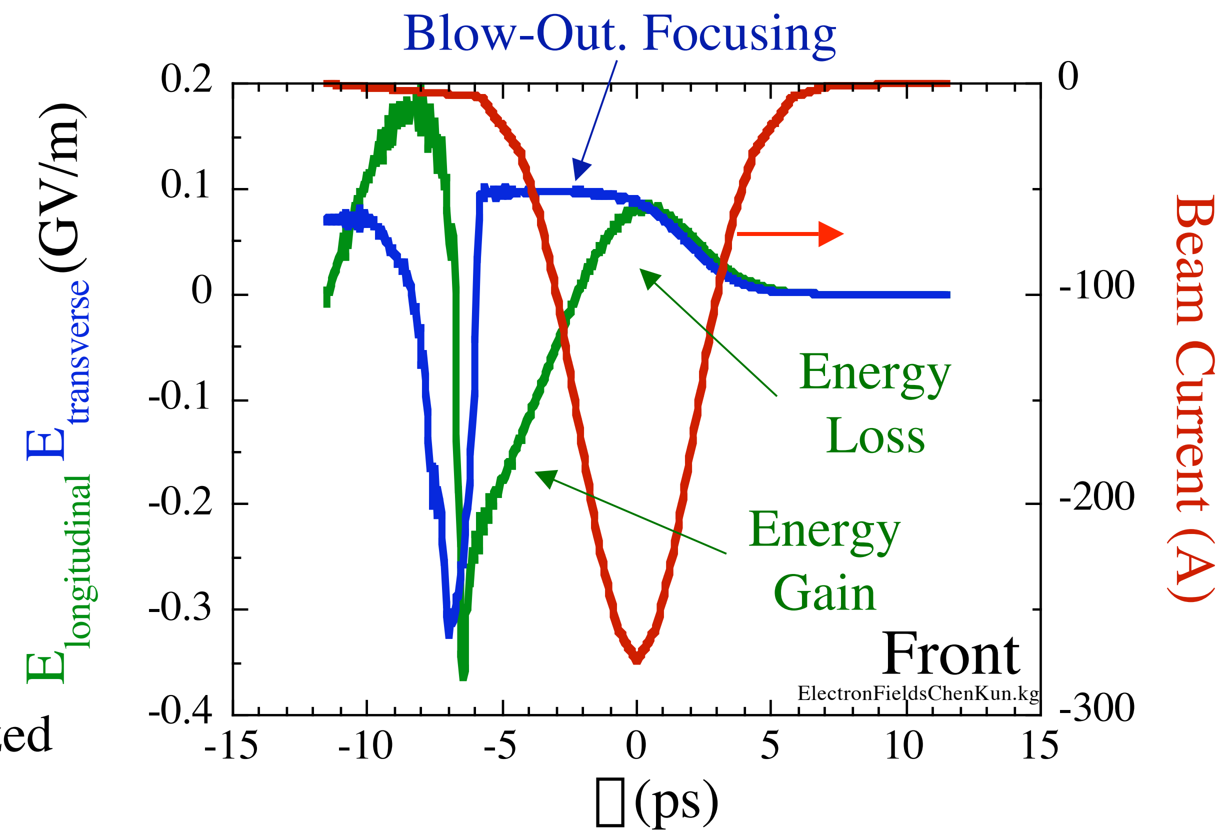
E	28.5 GeV
N	2×10^{10} e^-
σ_z	0.63 mm (2.1 ps)
$\sigma_x=\sigma_y$	70 μm
n_b	4×10^{14} cm^{-3}
ε_{xN}	5×10^{-5} m-rad
ε_{yN}	0.5×10^{-5} m-rad

<u>Plasma:</u>

n_e	$0\text{-}2\times10^{14}$ cm^{-3}
L	1.4 m, laser ionized

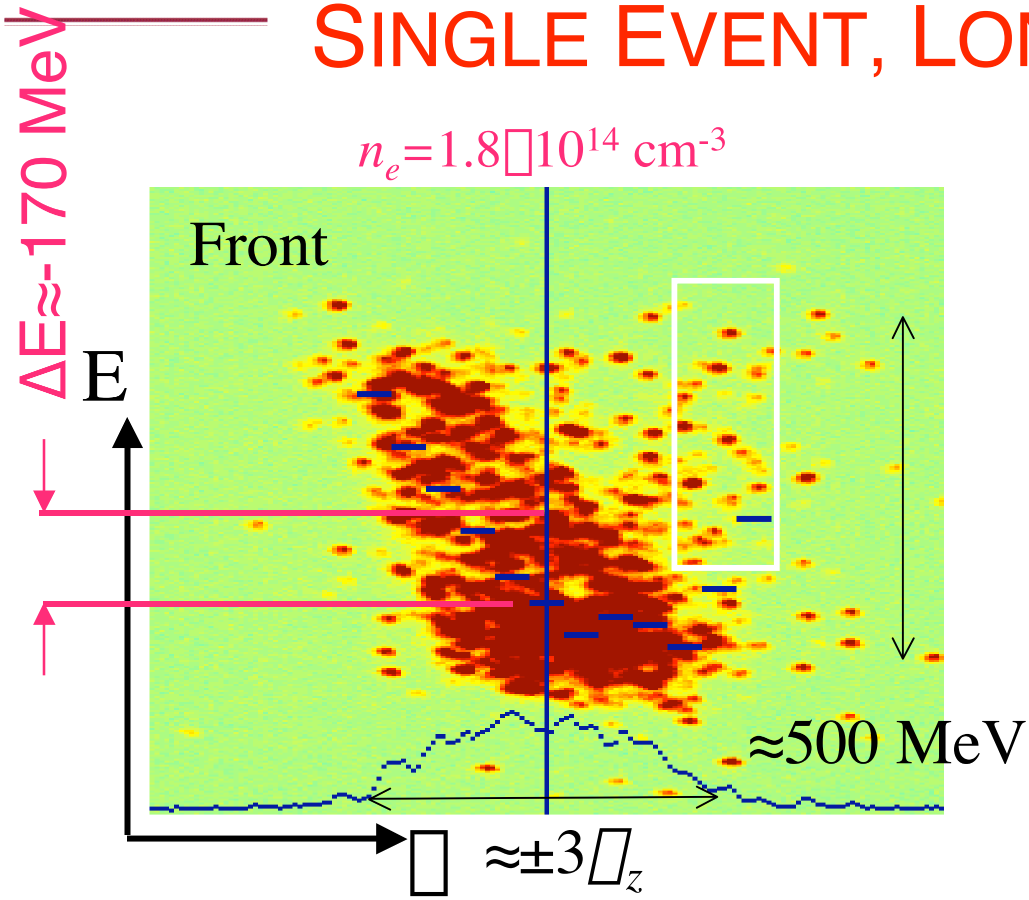
2-D PIC Simulation OSIRIS

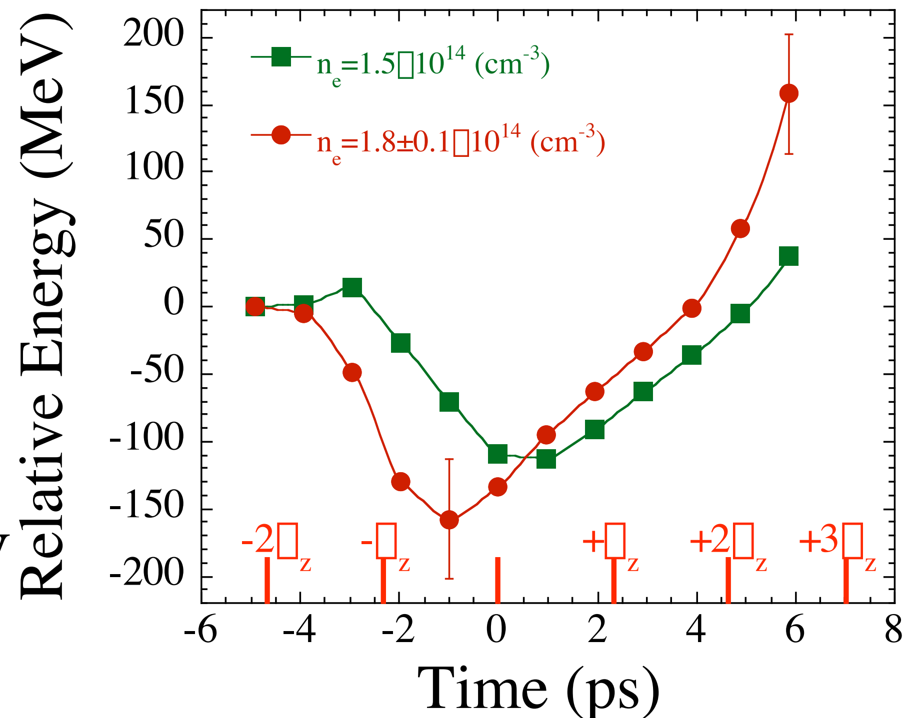
$n_e=1.5\times10^{14}$ cm^{-3}



- Experiment: $n_b>n_e$ => non linear, blow-out regime
  - Uniform focusing field (r,z)
  - Large decelerating/accelerating fields

SLICE ANALYSIS RESULTS
SINGLE EVENT, LONG BUNCH (σ_z≈730 µm)



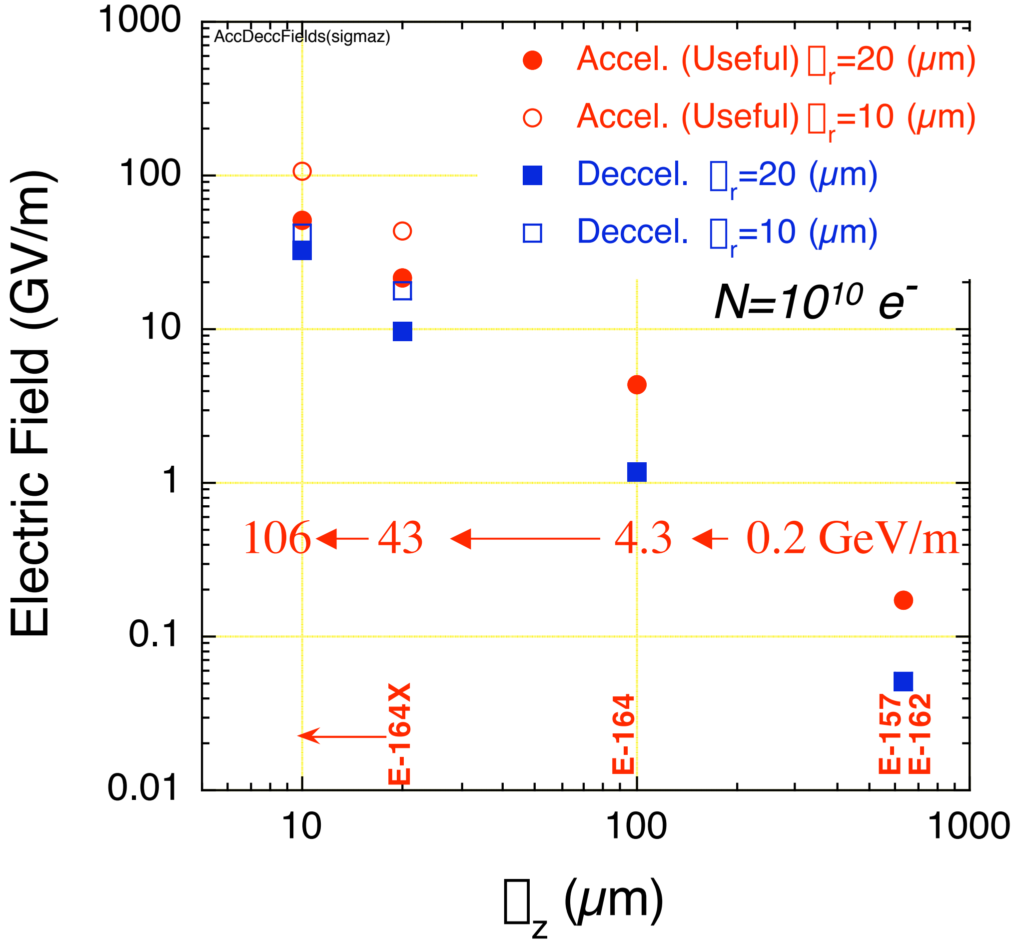


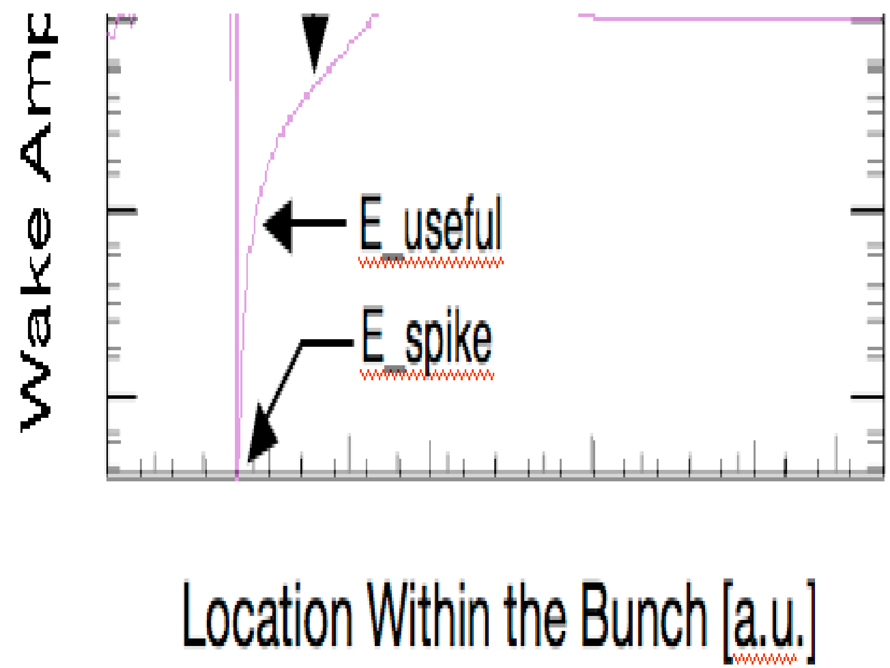
- Time resolution needed, but shows the physics
- Energy gain smaller than, hidden by, incoming energy spread
- Peak energy gain: 279 MeV, L=1.4 m, ≈200 MeV/m

e^-: P. Muggli *et al.*, PRL 2004
e^+: B. Blue *et al.*, PRL 2003

NUMERICAL SIMULATIONS: E-164/X , e^-

Gradient≈1/σ_z^2? (N=cst)





- E-164X: σ_z=20-10 μm: >100 GV/m gradient!

  (σ_r dependent! $k_p\sigma_r$≈1)

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

PLASMA WAKEFIELD FIELDS (e^-)

Typical parameters:

e^-- beam:

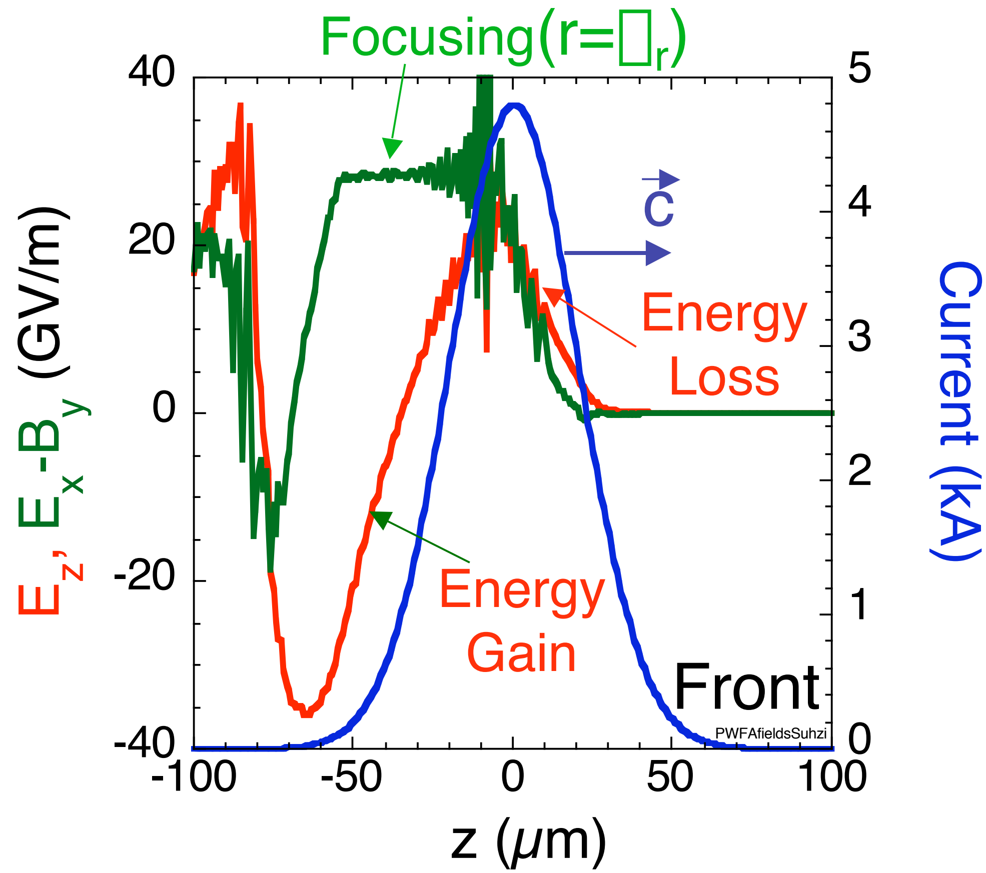
E	28.5 GeV
N	1.8×10^{10} e^-
σ_z	20 μm (70 fs)
$\sigma_x=\sigma_y$	15 μm
n_b	2.5×10^{17} cm^{-3}
ϵ_{xN}	5×10^{-5} m-rad
ϵ_{yN}	0.5×10^{-5} m-rad

Plasma:

$n_e=n_0$	0-3.5×10^{17} cm^{-3}
L	$\approx$10 cm

3-D PIC Simulation OSIRIS

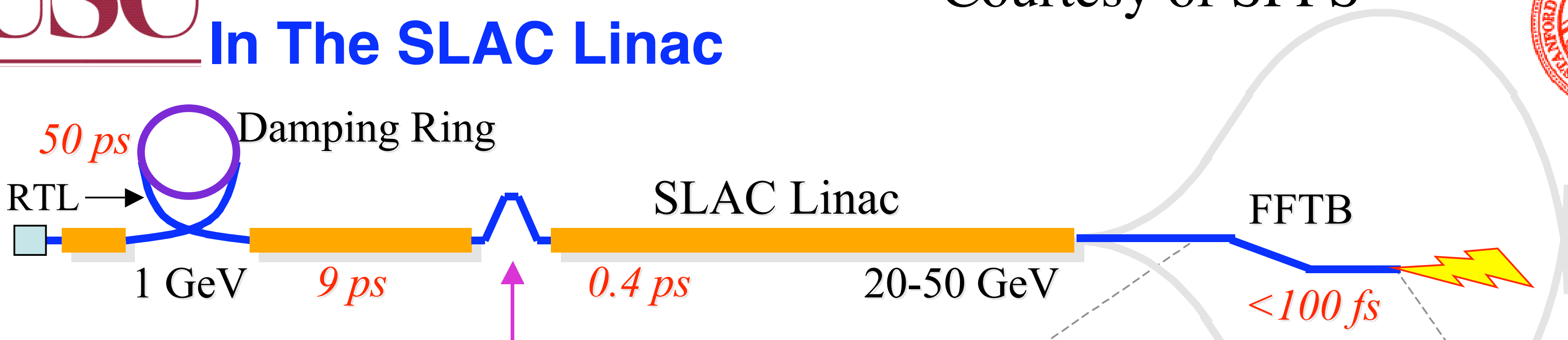
$N=10^{10}$ e^-, $n_e=2.1\times10^{17}$ cm^{-3}, $L=3$ cm



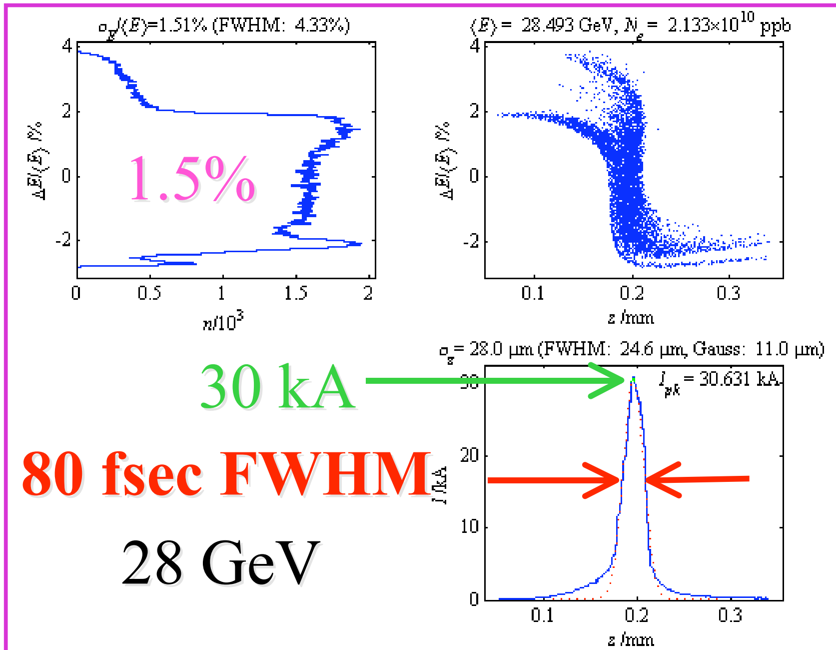
- Much larger accelerating field
- Reach $k_p\sigma_r\approx1$, ($\approx$"linear" theory)

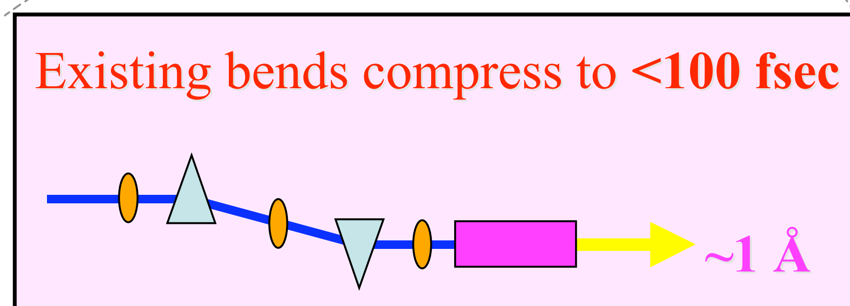
Short Bunch Generation In The SLAC Linac

Courtesy of SPPS



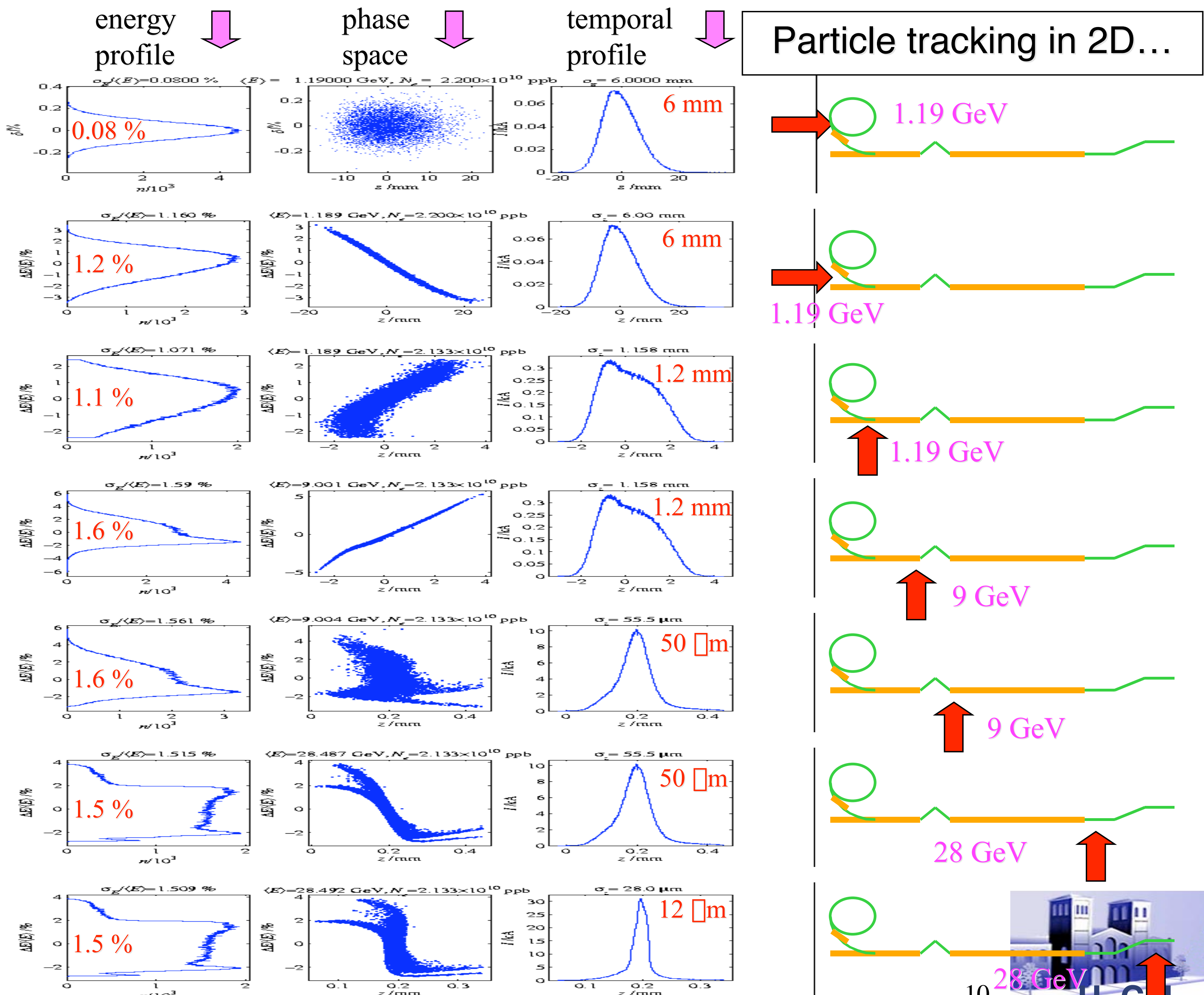
Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)





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

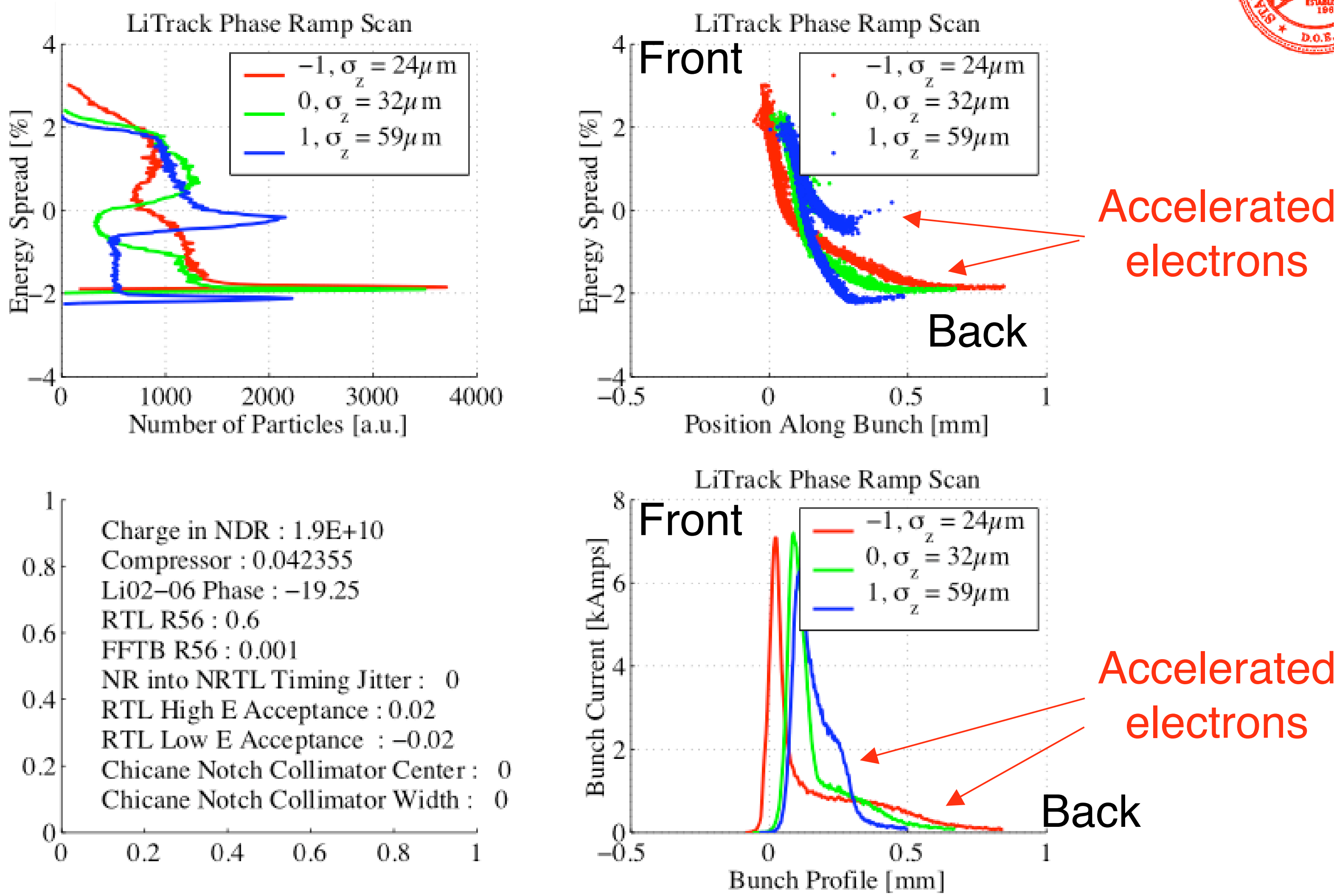
Particle tracking in 2D…



Courtesy of SPPS

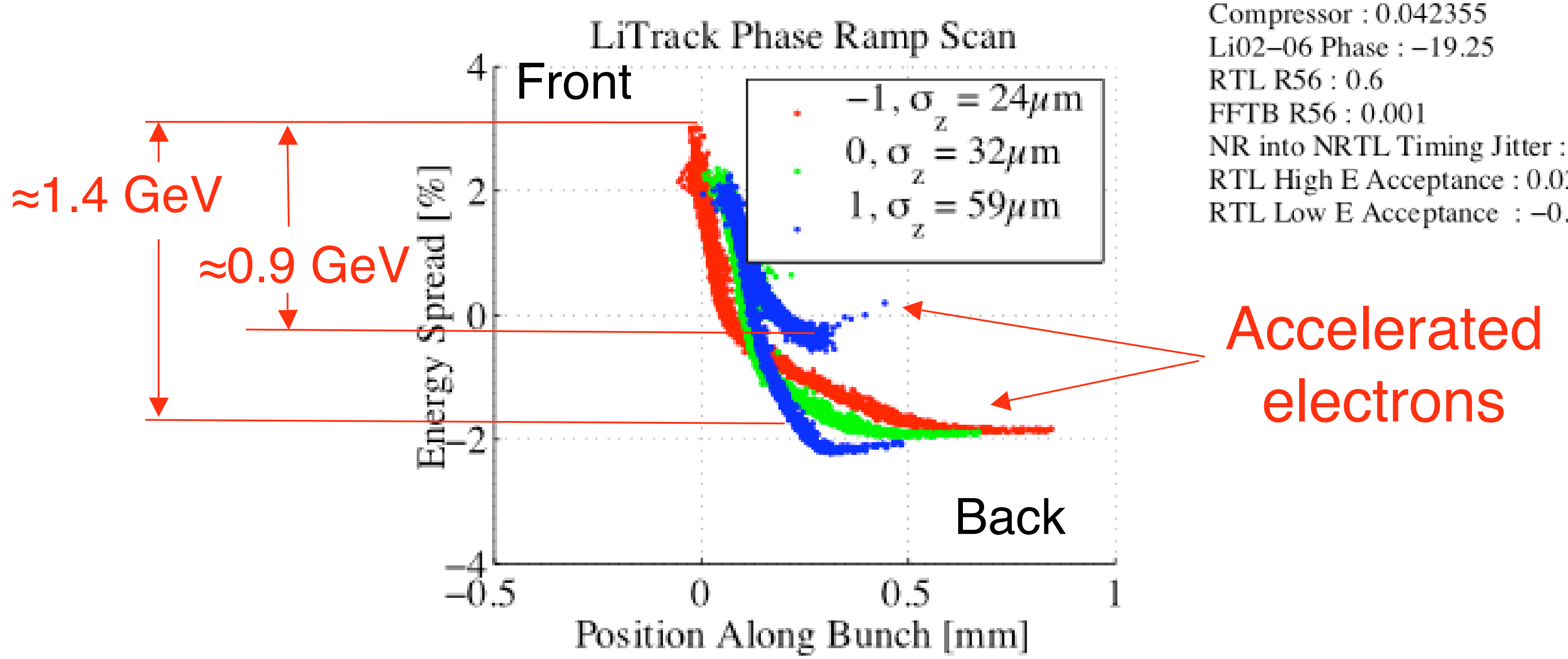
e^- BUNCH MANIPULATION

LiTrack:
K. Bane,
P. Emma



- Energy spectrum <-> phase space <-> current profile
- PWFA: accelerate e^- in the back of the bunch

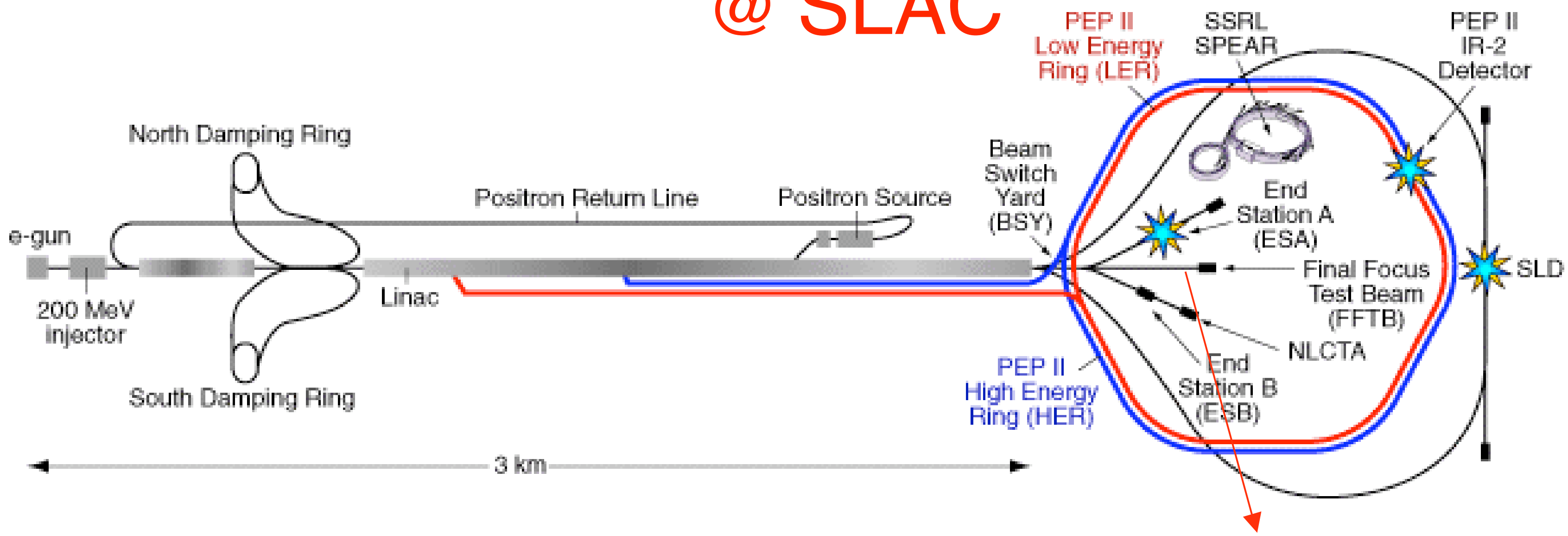
ACCELERATED e^-



Charge in NDR : 1.9E+10
Compressor : 0.042355
Li02–06 Phase : −19.25
RTL R56 : 0.6
FFTB R56 : 0.001
NR into NRTL Timing Jitter : 0
RTL High E Acceptance : 0.02
RTL Low E Acceptance : −0.02

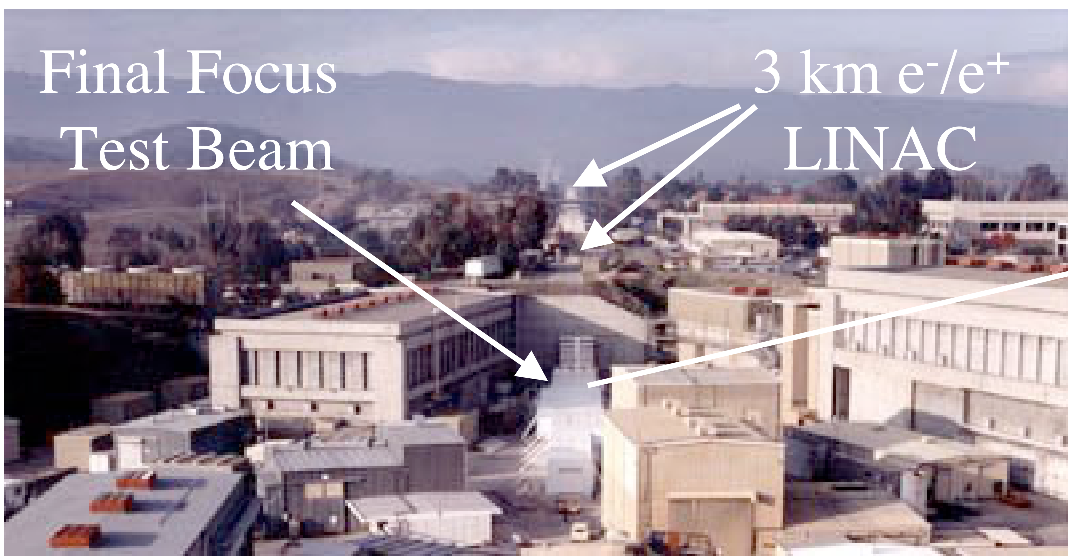
- PWFA: accelerate e^- in the back of the bunch
- Accelerated e^- originate from 0.9-1.4 GeV below the bunch max. energy!
- Quote energy above the bunch head/front energy, analysis will reveal real energy gain

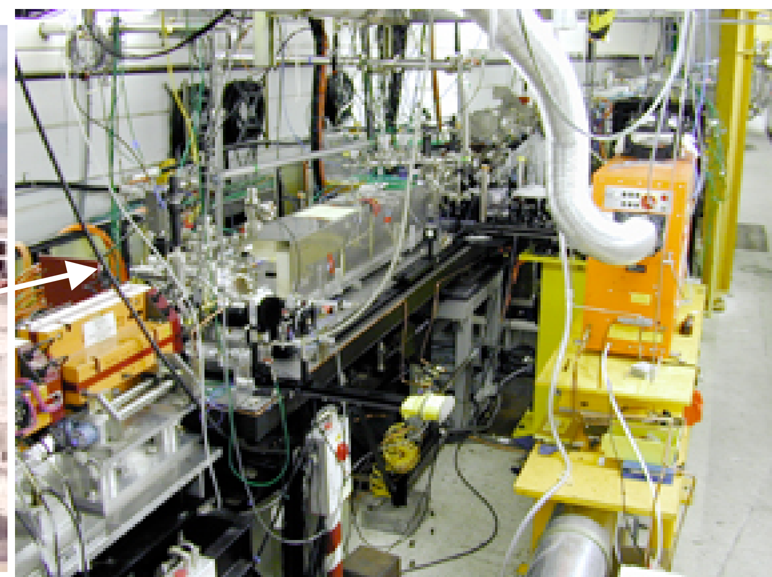
Plasma Wakefield Experiment @ SLAC



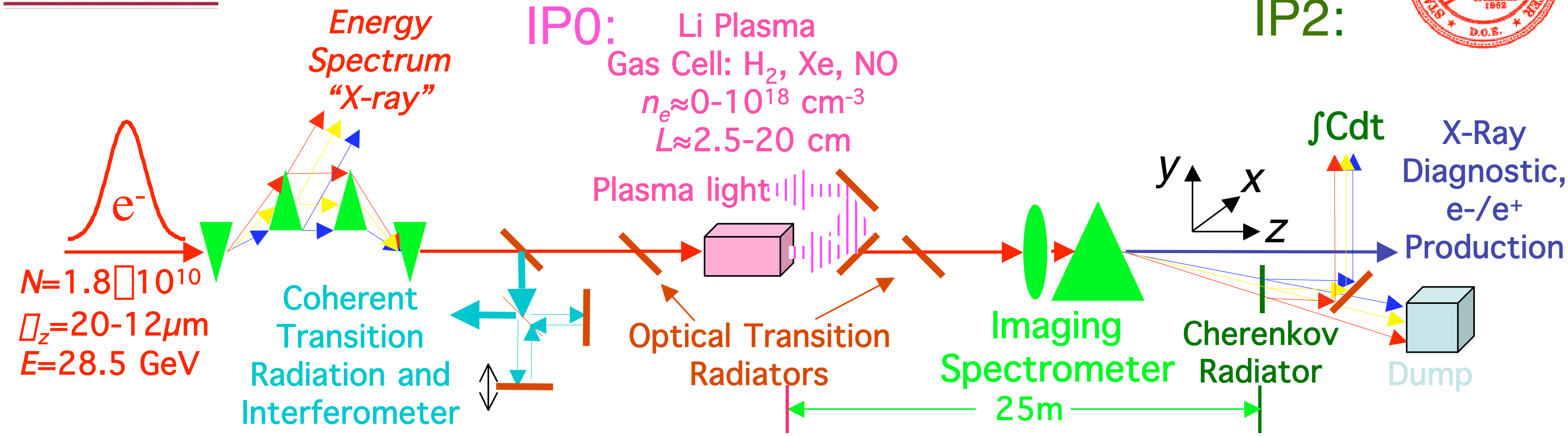
3 km for 50 GeV e^- and e^+

add 1 GeV over <1 m?

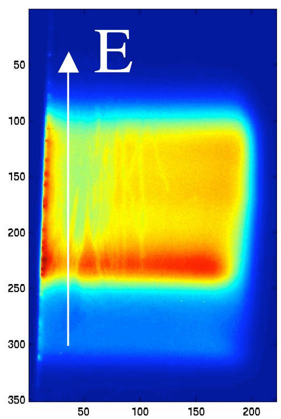




EXPERIMENTAL SET UP



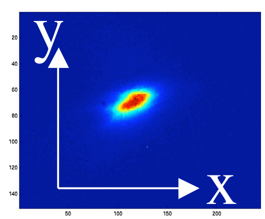
- X-ray Chicane



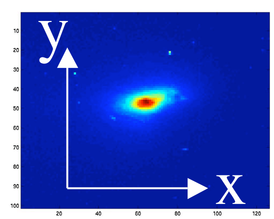
-Energy resolution ≈60 MeV

- Optical Transition Radiation (OTR)

Upstream



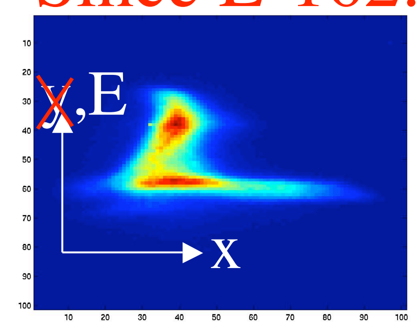
Downstream



-1:1 imaging, spatial resolution ≈9 μm

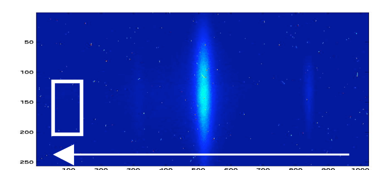
- Cherenkov (aerogel)

Since E-162:



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

- Plasma Light



ENERGY SPECTROMETER

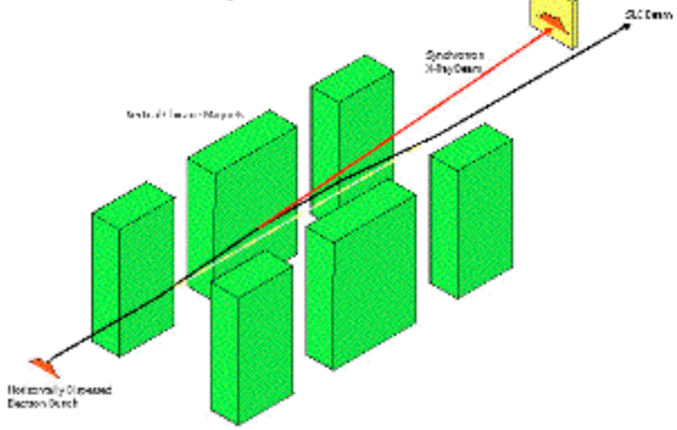
(NON-INVASIVE, UPSTREAM OF PLASMA)

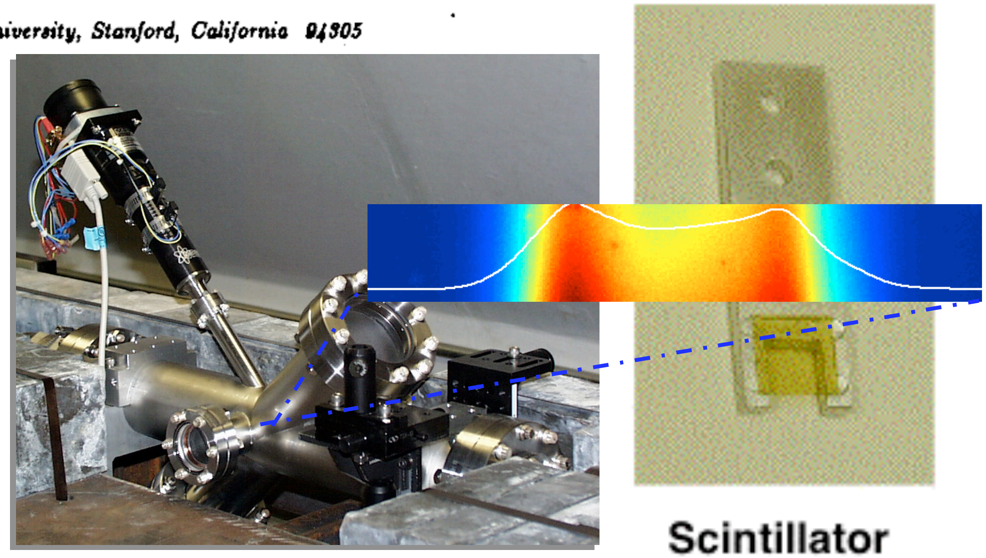
SLC ENERGY SPECTRUM MONITOR USING SYNCHROTRON RADIATION*

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

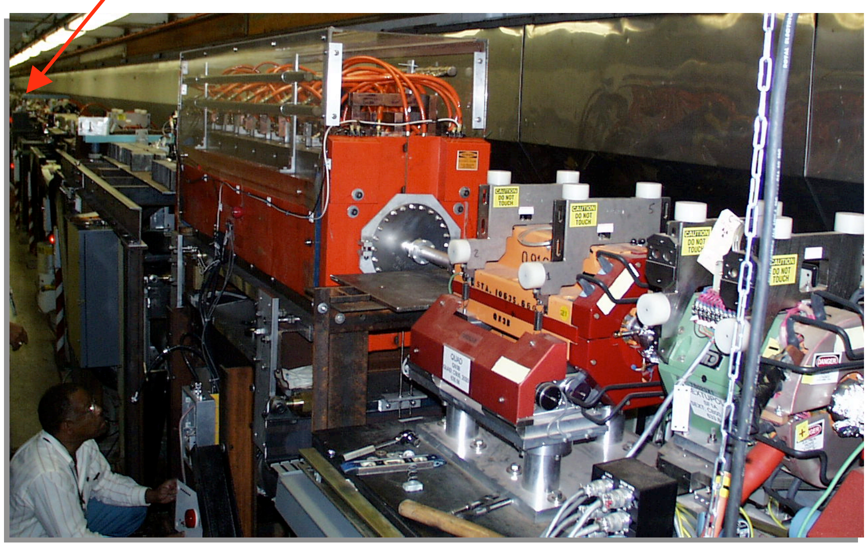
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

SLAC – PUB – 3945
April 1986





Plasma

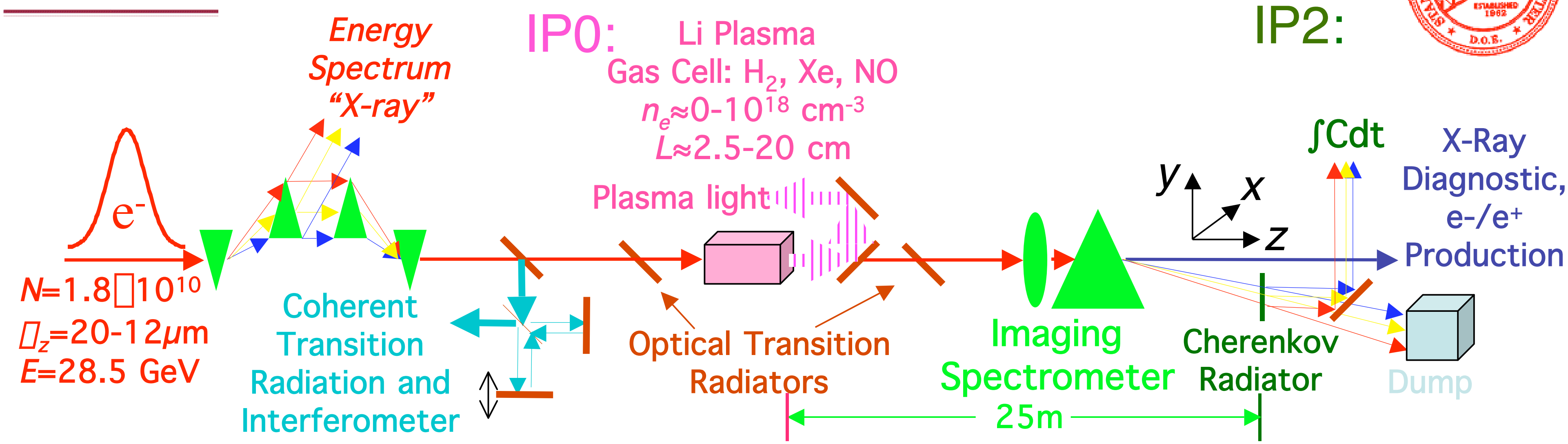


e⁻

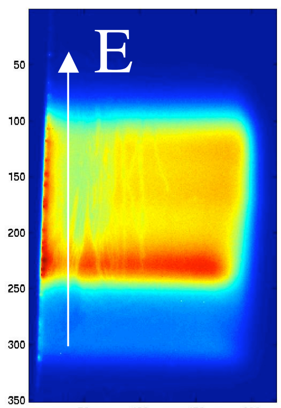
- Measure incoming bunch spectrum

C.D. Barnes
PhD. Thesis
Stanford 2004

EXPERIMENTAL SET UP

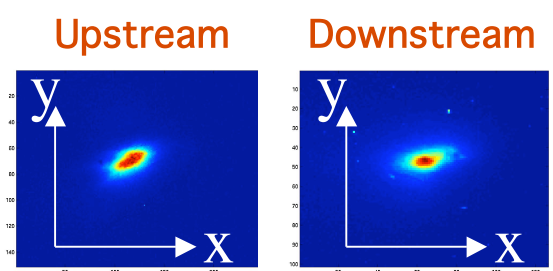


- X-ray Chicane



-Energy resolution ≈60 MeV

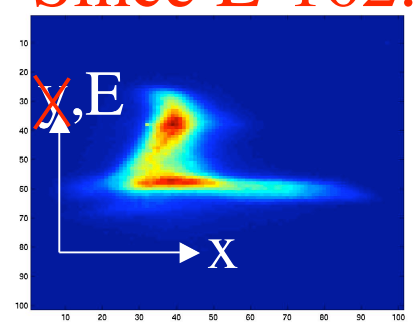
- Optical Transition Radiation (OTR)



-1:1 imaging, spatial resolution ≈9 μm

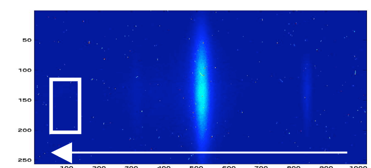
- Cherenkov (aerogel)

Since E-162:



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

- Plasma Light



U C L A

e⁻-BEAM FIELD-IONIZATION

$$E_{r,peak}(r \approx 1.6\sigma_r, z=0) \approx 5.2 \times 10^{-10} \frac{N}{\sigma_r \sigma_z}$$

N=1.8×10^10, σ_r=10 μm, σ_z=20 μm in Li

$E_{r,max}$≈47 GV/m

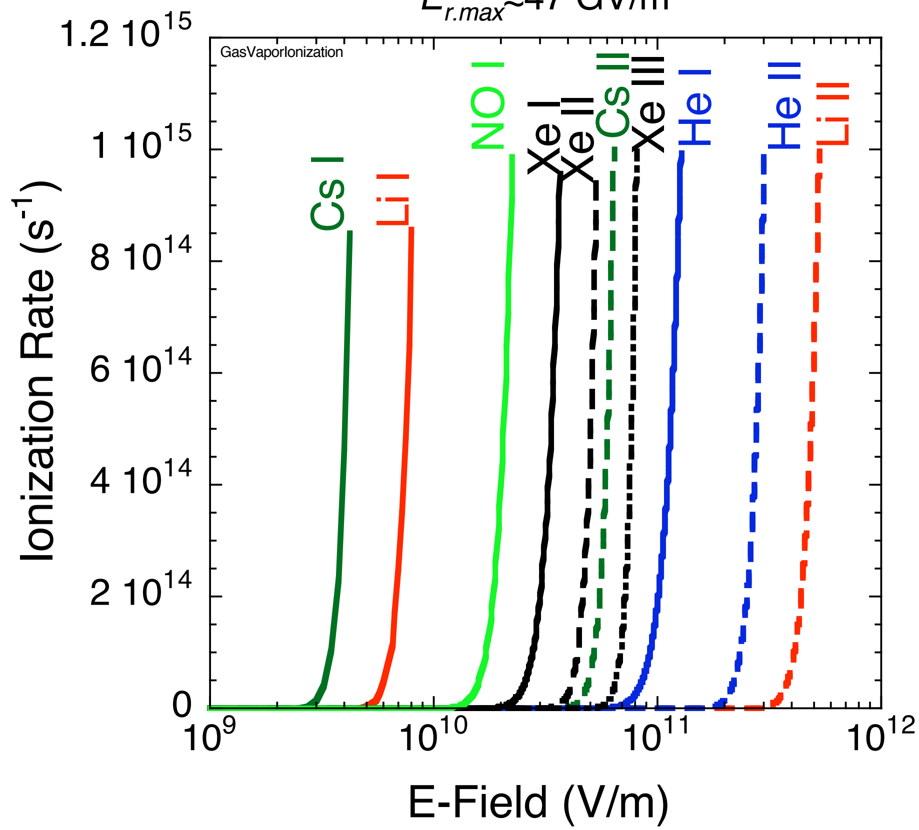
Ionization rate (ADK model):

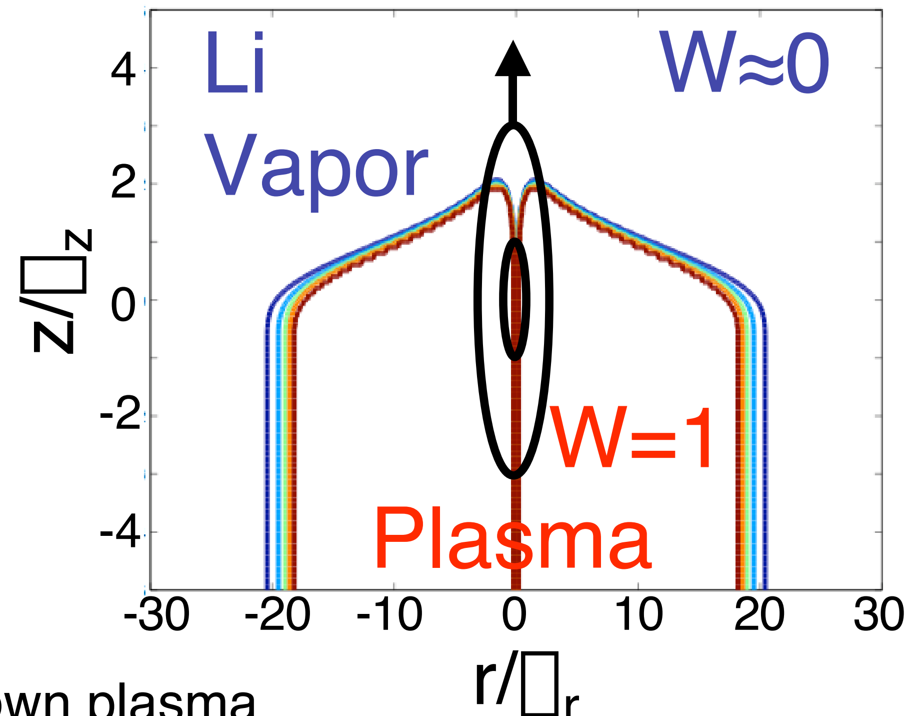
$$W[s^{-1}] \approx 1.52 \times 10^{15} \frac{4^{n^*} \xi_i}{n^* \Gamma(2n^*)} \left(20.5 \frac{\xi_i^{3/2}}{E}\right)^{2n^*-1} e^{\left(-6.83 \frac{\xi_i^{3/2}}{E}\right)}$$

ξ_i= ionization potential = 5.45 eV for Li

E= electric field in GV/m

n^*=effective quantum number =$3.68 Z/\xi_i^{1/2}$

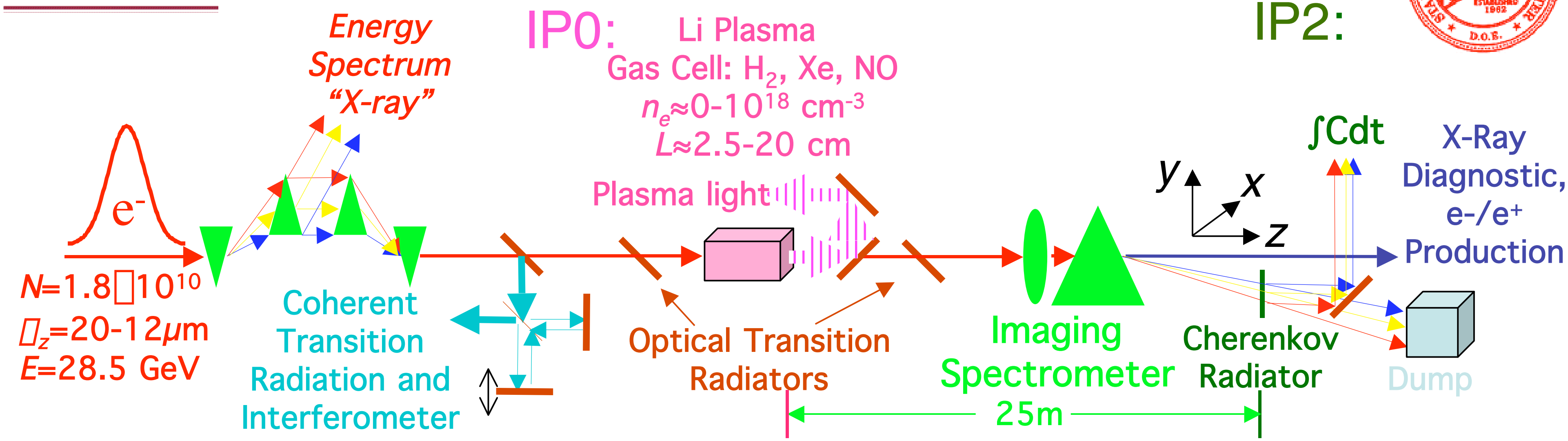




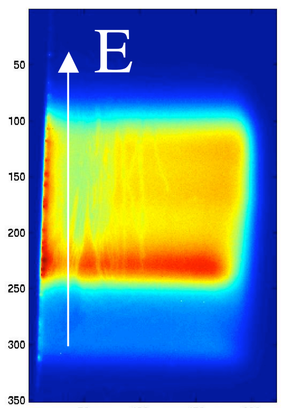
- Threshold process
- Short bunches can field-ionize their own plasma and create their own accelerating structure (E-164X, after-burner?)

see for example D. Bruhweiler et al., Phys. of Plasmas to be published, and P.Muggli et al, AAC-2002 Proceedings

EXPERIMENTAL SET UP



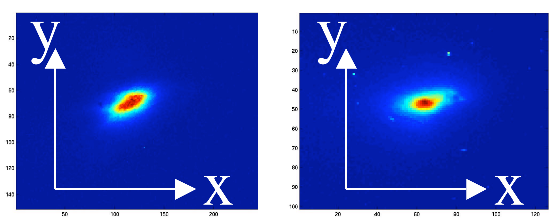
- X-ray Chicane



-Energy resolution ≈60 MeV

- Optical Transition Radiation (OTR)

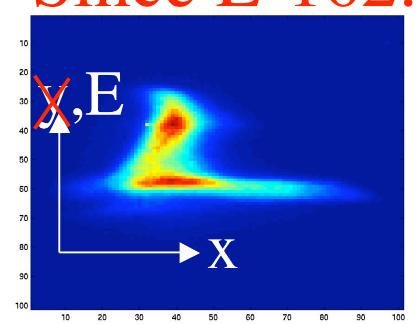
Upstream   Downstream



-1:1 imaging, spatial resolution ≈9 μm

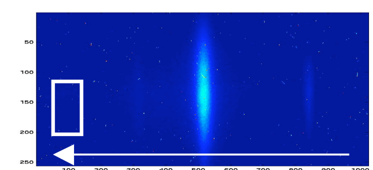
- Cherenkov (aerogel)

Since E-162:



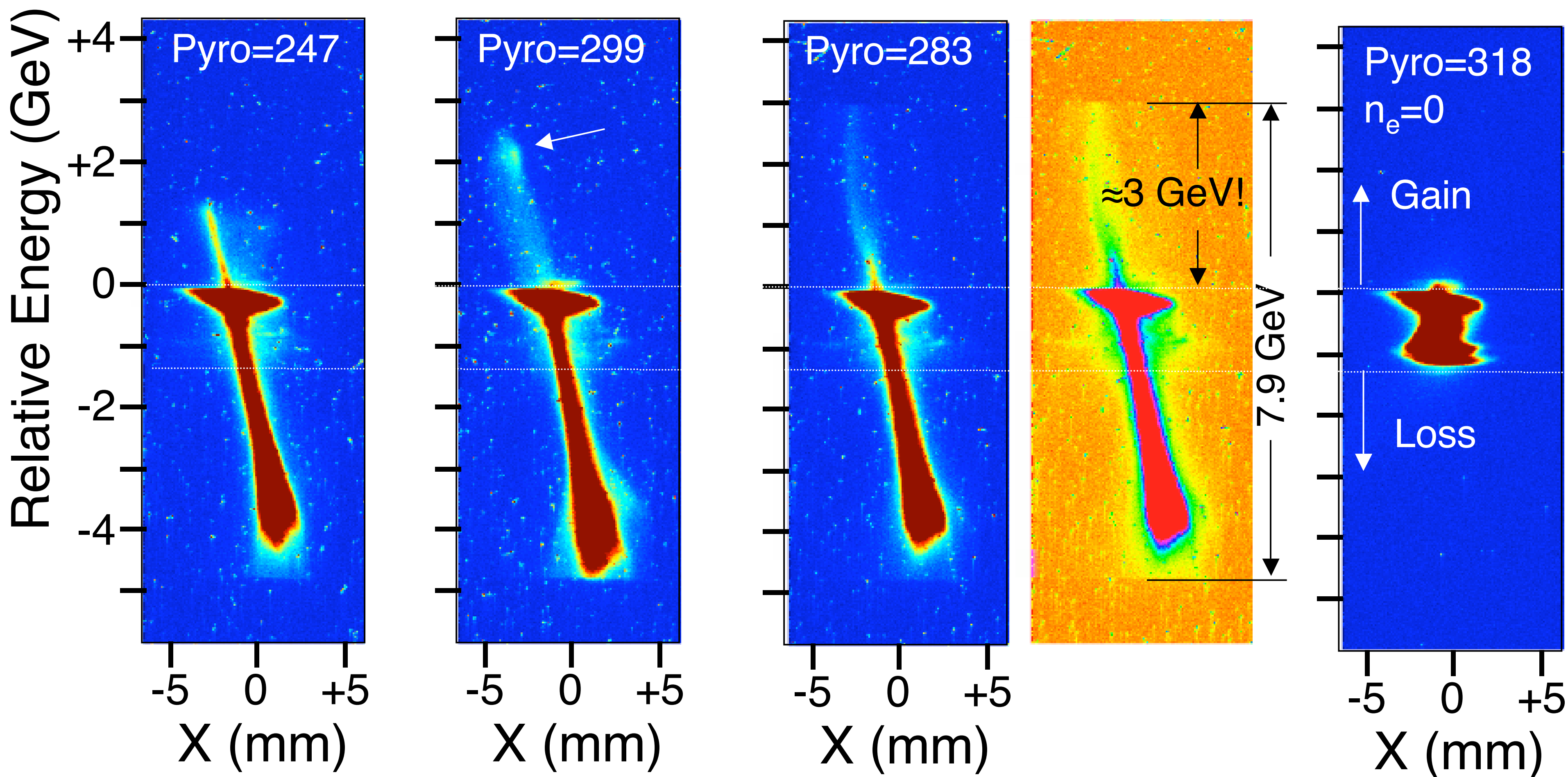
- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV

- Plasma Light



$n_e \approx 2.55 \times 10^{17}$ cm^{-3} RESULTS

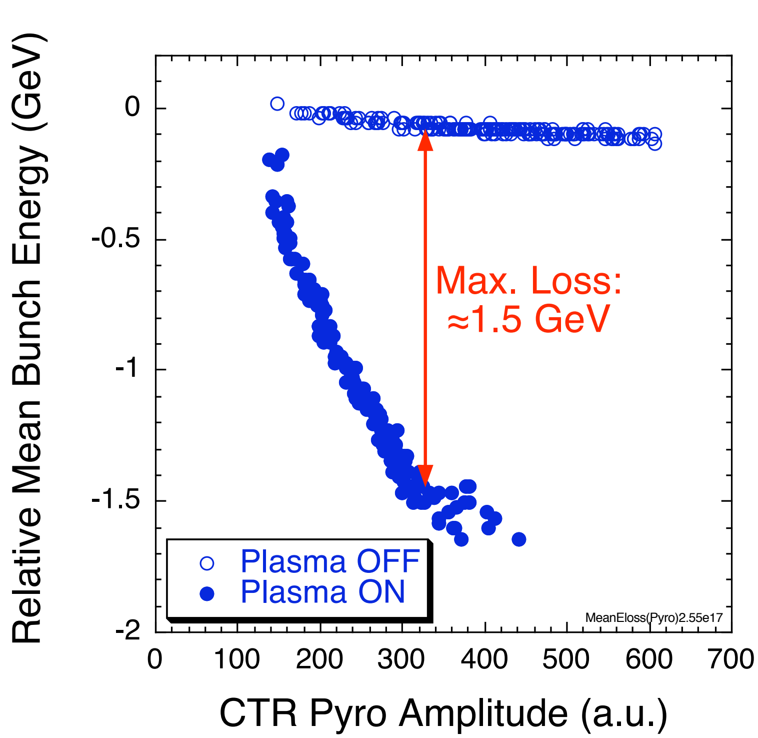
$L \approx 10$ cm, $N \approx 1.8 \times 10^{10}$



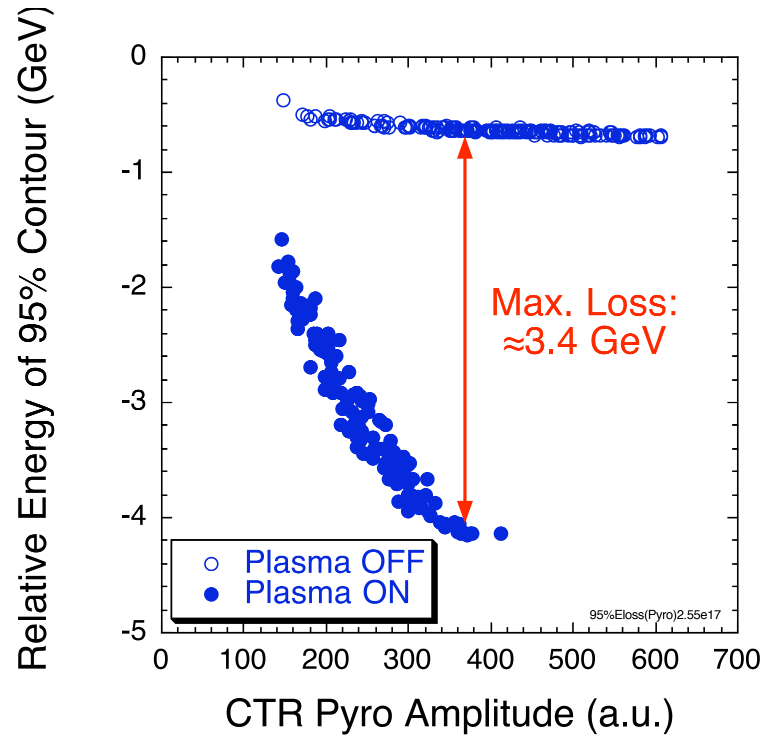
- Energy gain reaches ≈3+1 GeV
- Energy gain depends on the details of the incoming beam (x,y,z)

$n_e \approx 2.55 \times 10^{17}$ cm^{-3} ENERGY LOSS

L≈10 cm, N≈ 1.8×10^{10}



≈$1/\sigma_z$



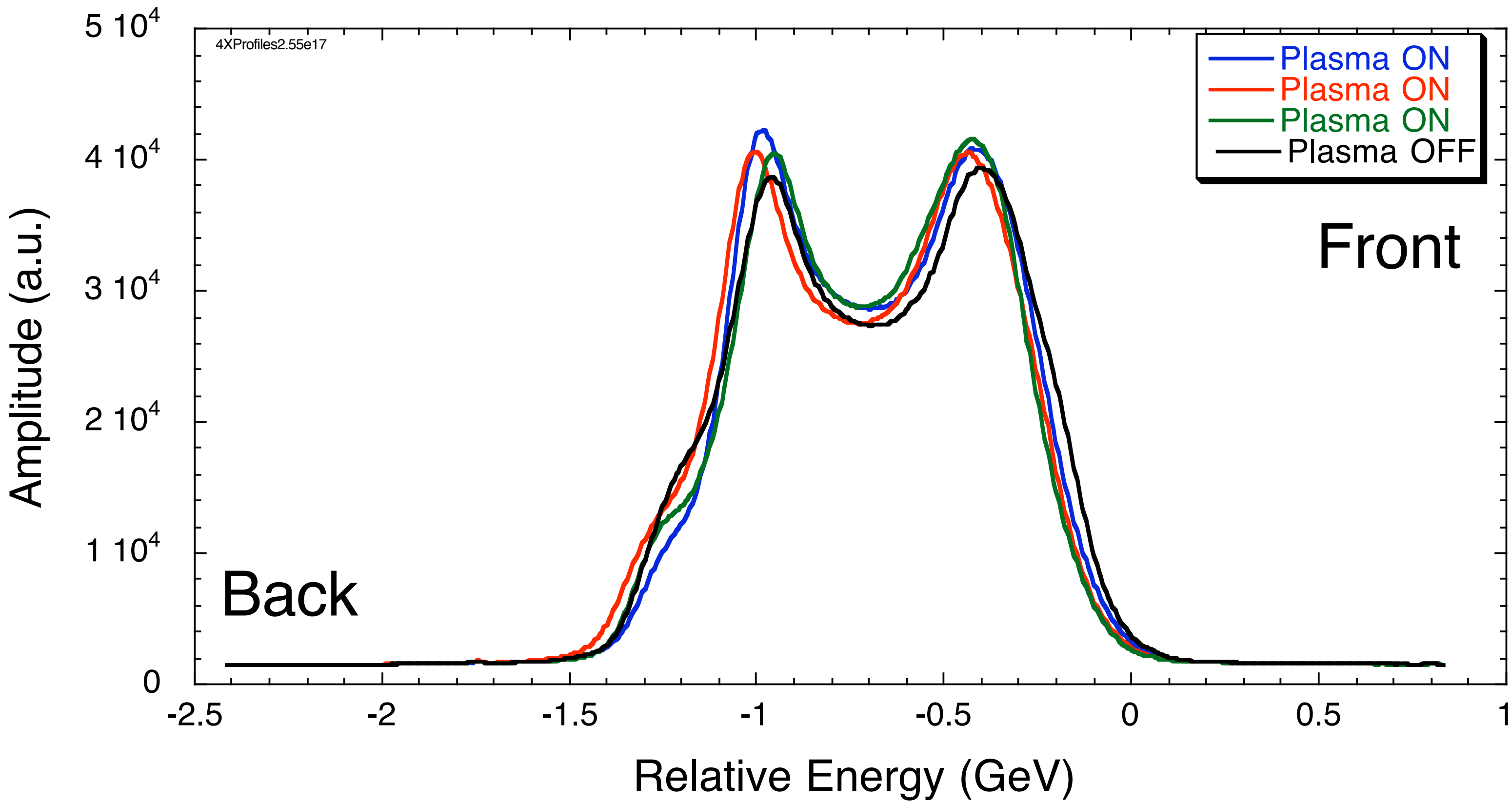
≈$1/\sigma_z$

- Mean energy loss is linear with bunch length
- Peak energy gradient ≥3.4 GeV/10 cm!

$n_e \approx 2.55 \times 10^{17}$ cm^{-3} INCOMING SPECTRA

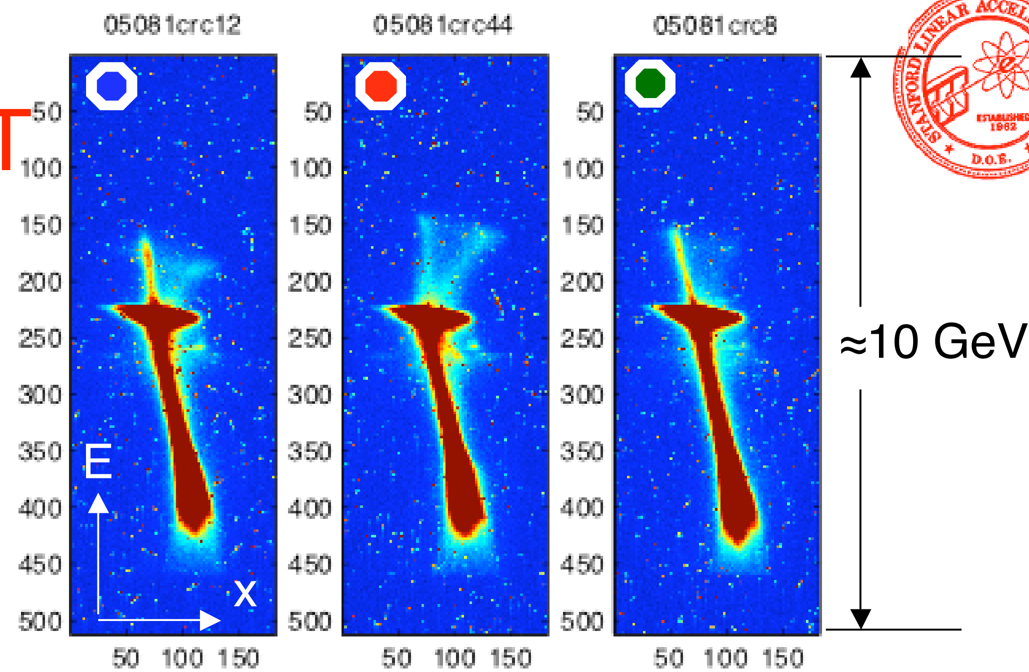
$L \approx 10$ cm, $N \approx 1.8 \times 10^{10}$

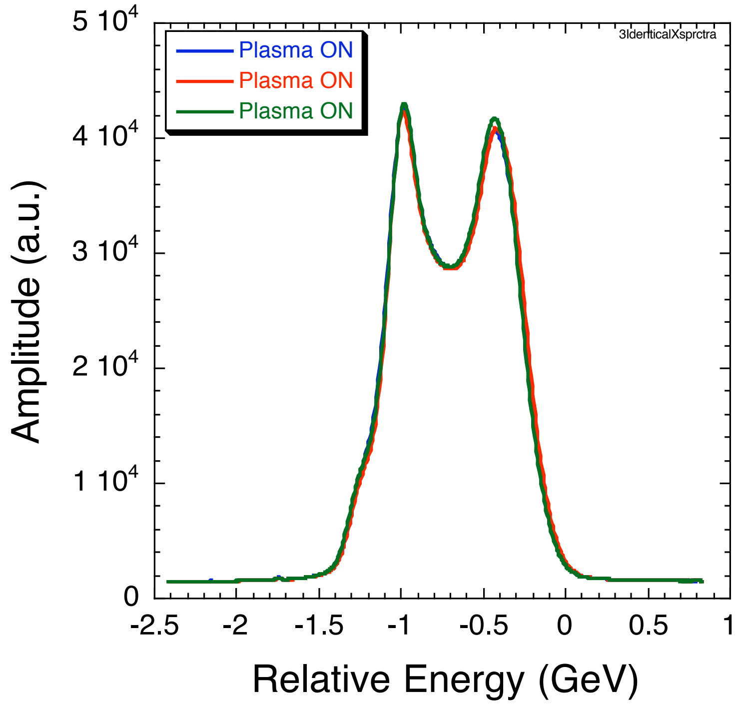
Energy Spectra before the Plasma (@ x-ray chicane)



- Details of the incoming energy spectra are visible
- Matching of incoming energy spectra with LITrack will allow for the unfolding of the effects

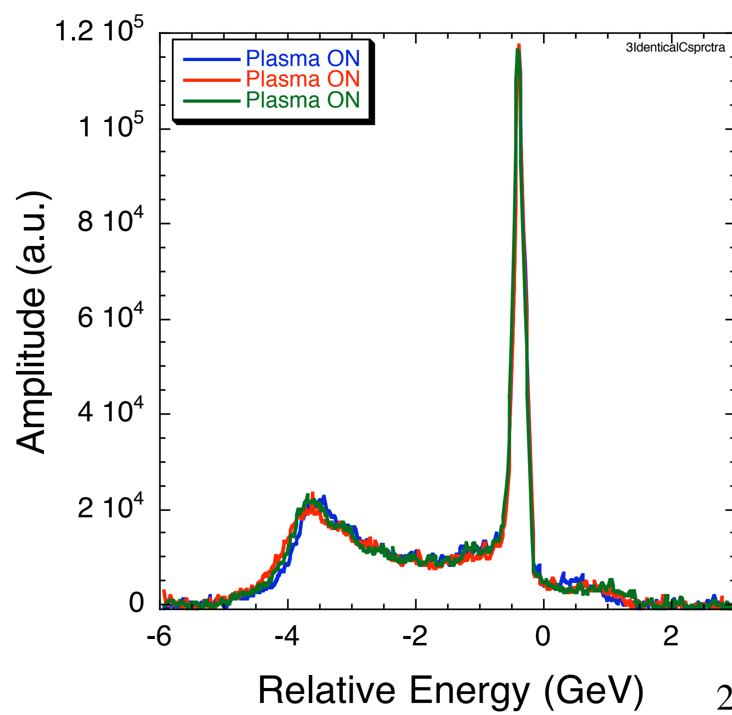
SIMILAR IN, SIMILAR OUT





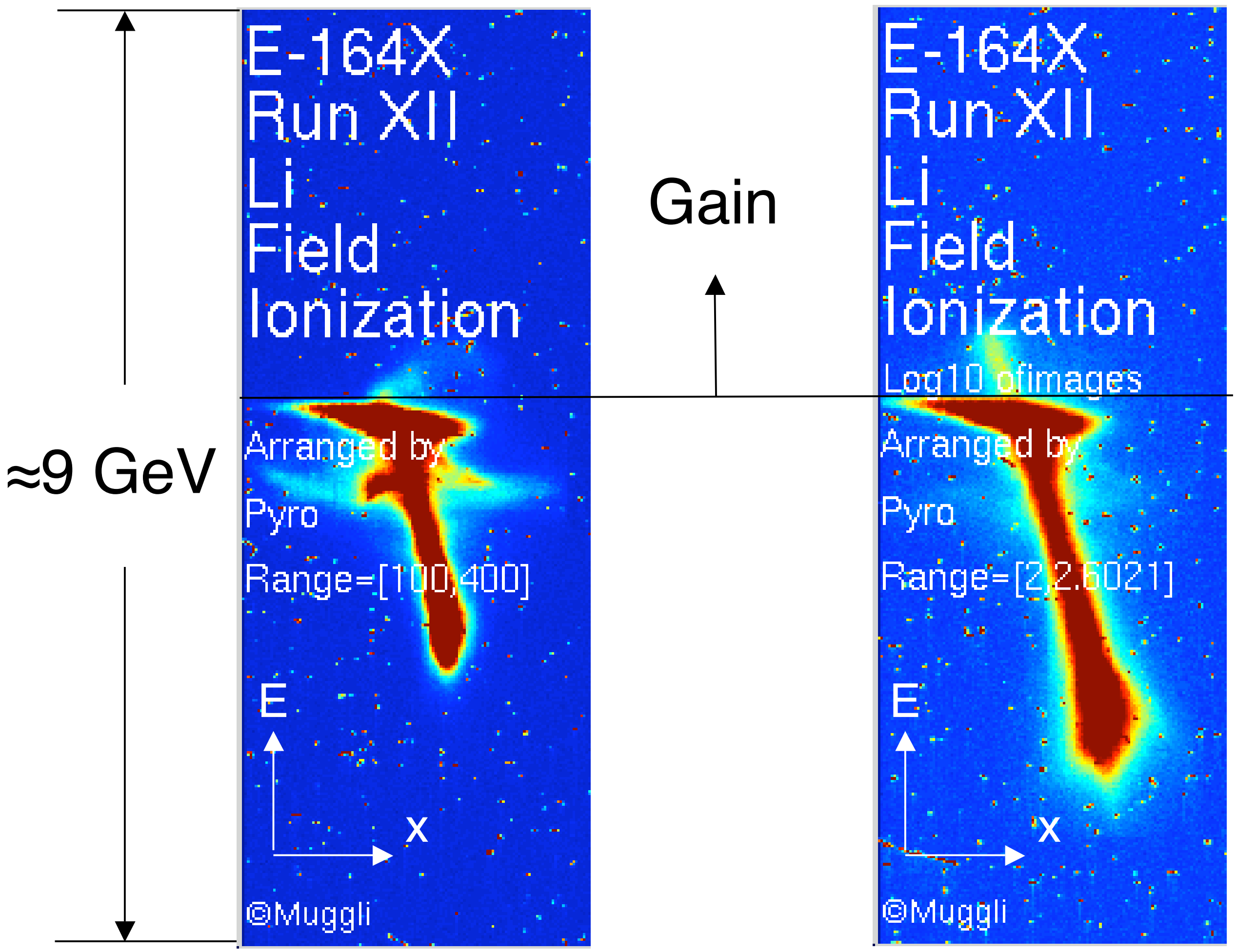
Identical incoming energy spectra/events

"Identical" outgoing energy spectra/events



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

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

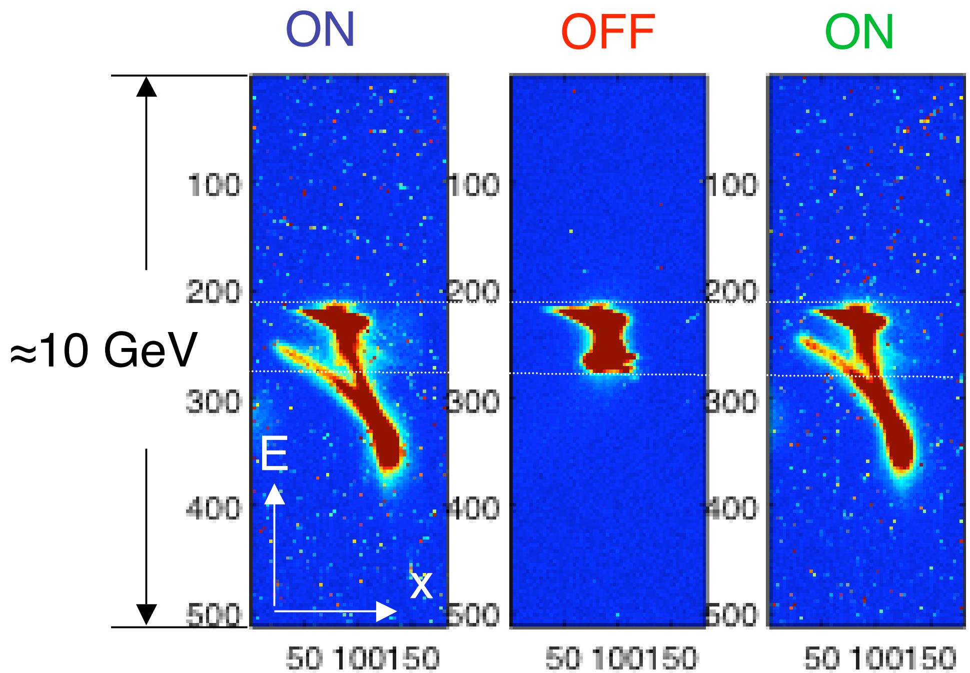


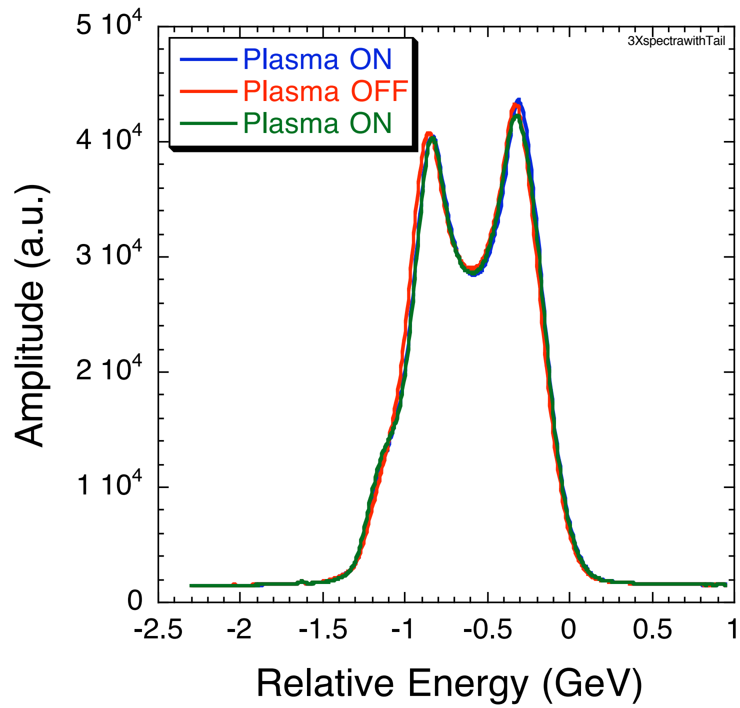
- Very consistent acceleration, varies with incoming parameters

ORIGIN OF ACCELERATED e^-

Find similar incoming bunches with χ^2 on incoming spectra.

$n_e \approx 2.51 \times 10^{17}$ cm^{-3}, $L \approx 10$ cm, $N \approx 1.8 \times 10^{10}$

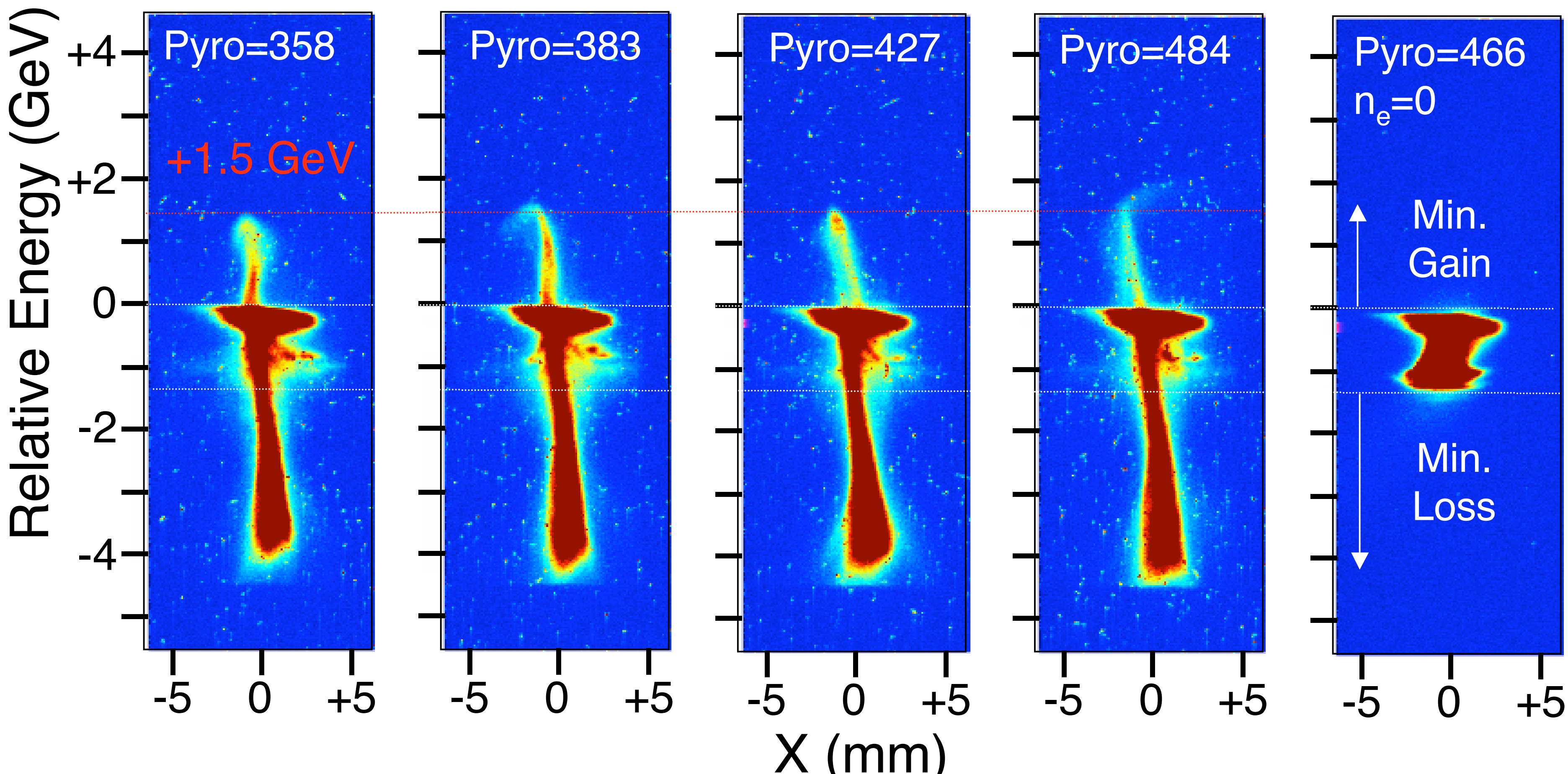




- Confirm: e^+ gain energy from below the head energy
- Retrieve energy of accelerated e^+ from incoming spectra and LITrack simulations

$n_e \approx 3.5 \times 10^{17}$ cm^{-3} RESULTS

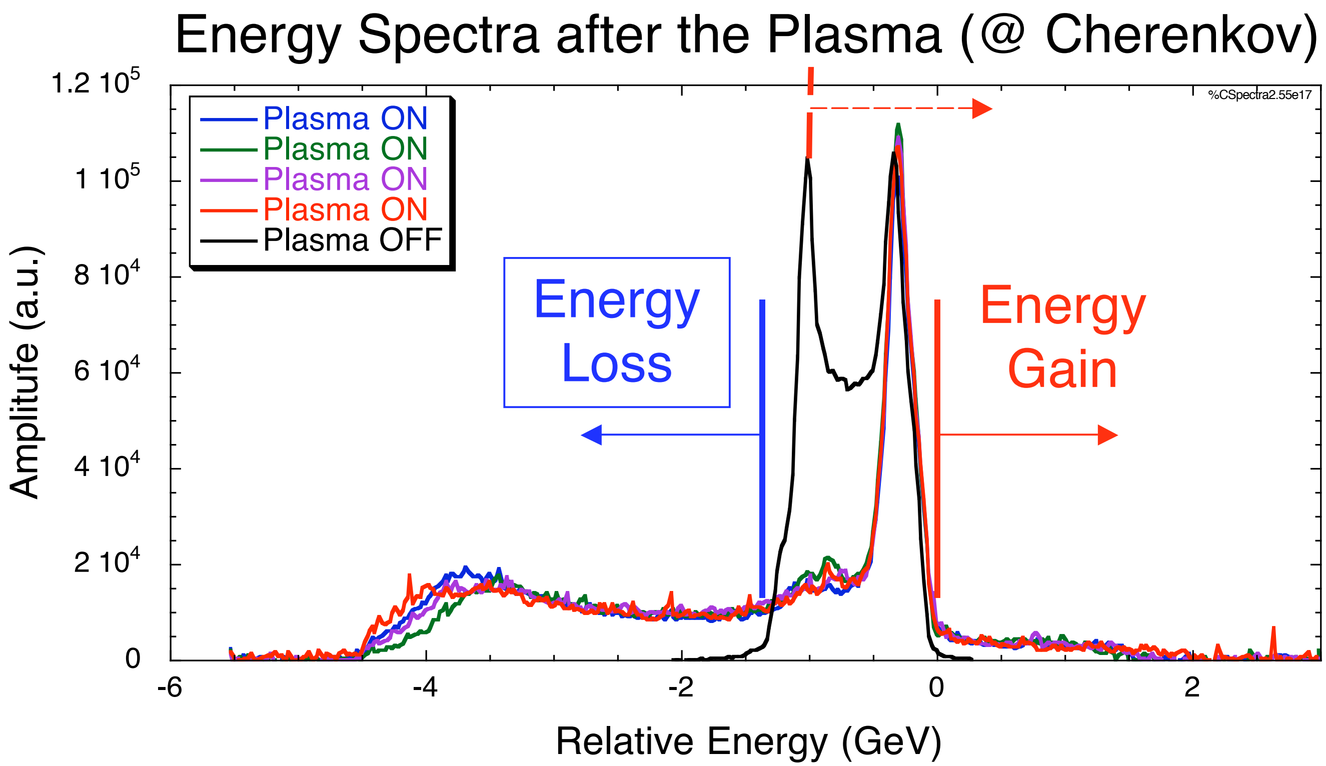
L≈10 cm, N≈ 1.8×10^10



- Many similar events in a data set
- Acceleration with significant charge: ≈1.5+1 GeV
- Lower gain than @ 3.5×10^{17} cm^{-3}

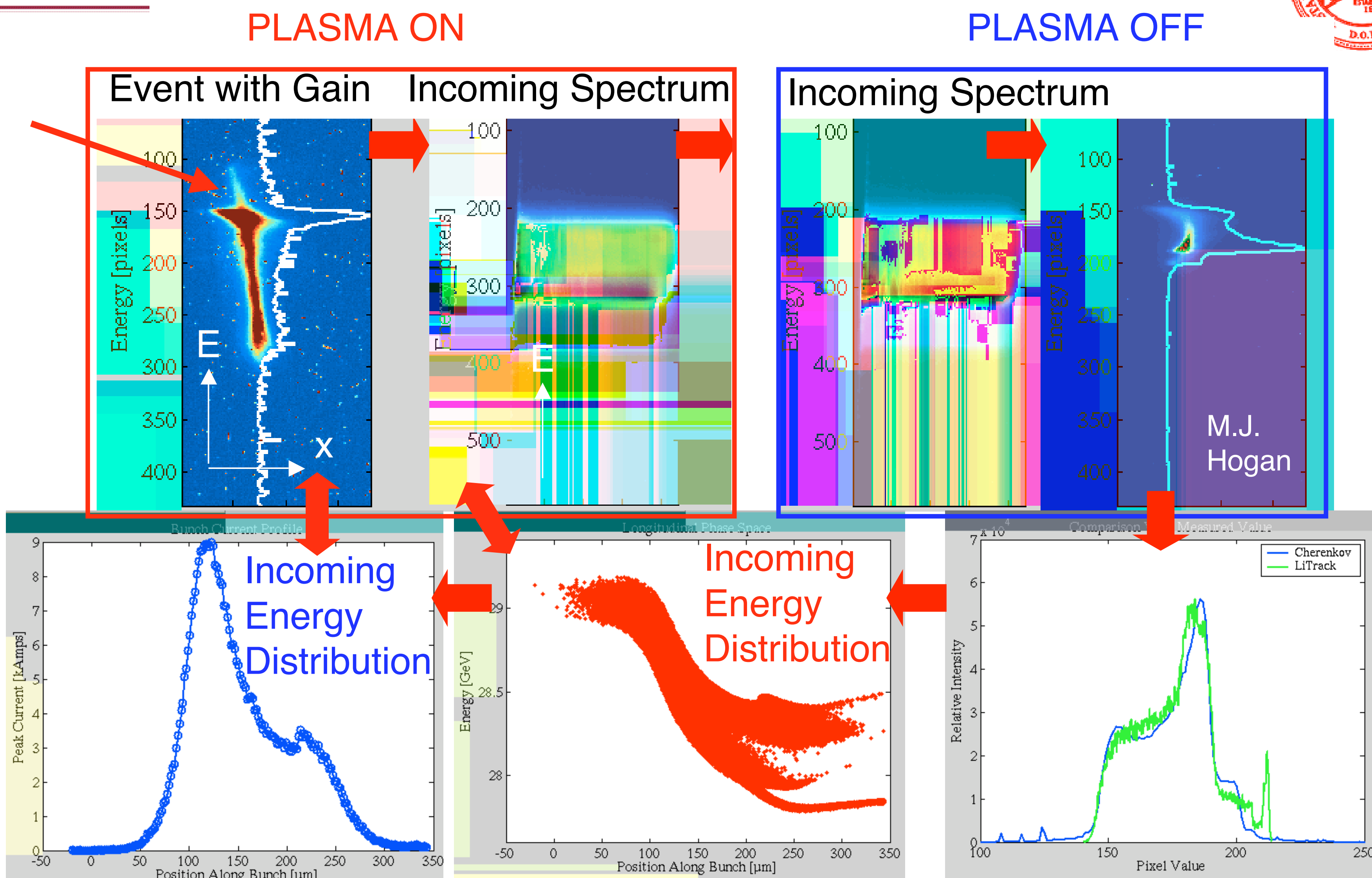
$n_e \approx 3.5 \square 10^{17}$ cm^{-3} ENERGY SPECTRA

L≈10 cm, N≈ 1.8□10^{10}



- Variations from incoming energy spectrum variations
- Charge Fraction at E>0: 6.8-7.9% of total charge or ≈220 pC!
- Peak energy gain above the beam head: ≈1.5 GeV
  total gain: ≈2.5 GeV

ANALYSIS EXAMPLE



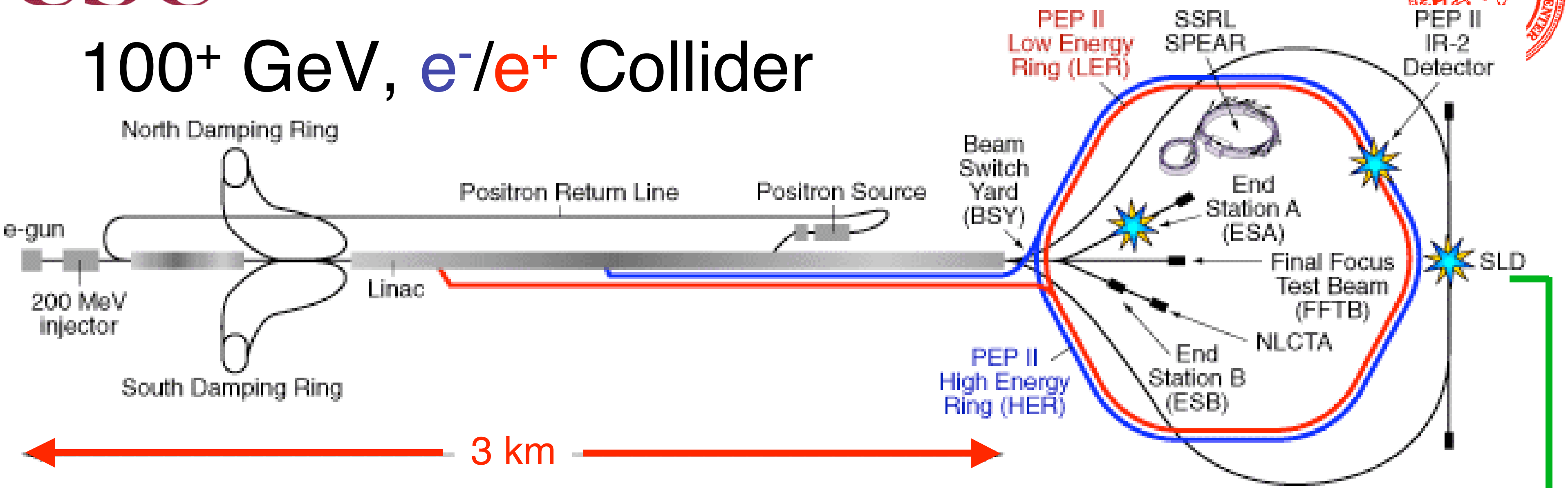
- Retrieve bunch energy distribution/current profile for energy gain events

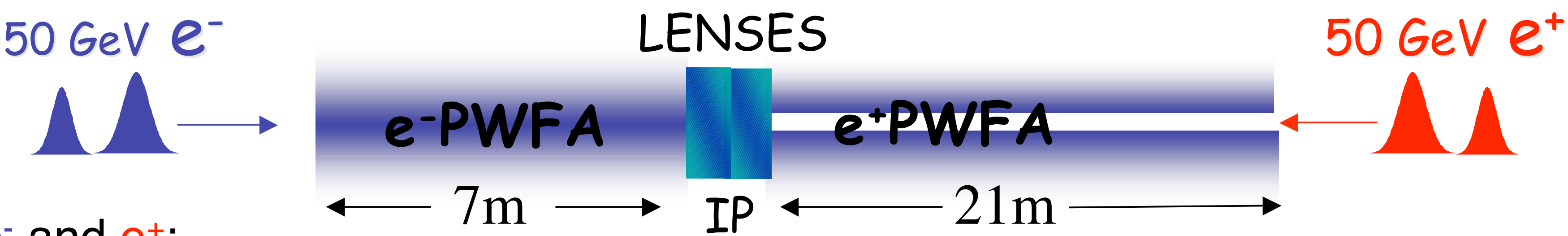
CONCLUSIONS

- 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.
- Data collected is being analyzed in detail to unfold connection between observed energy gain and incoming bunch

PLASMA AFTERBURNER (EXAMPLE)

100^{+} GeV, e^-/e^+ Collider





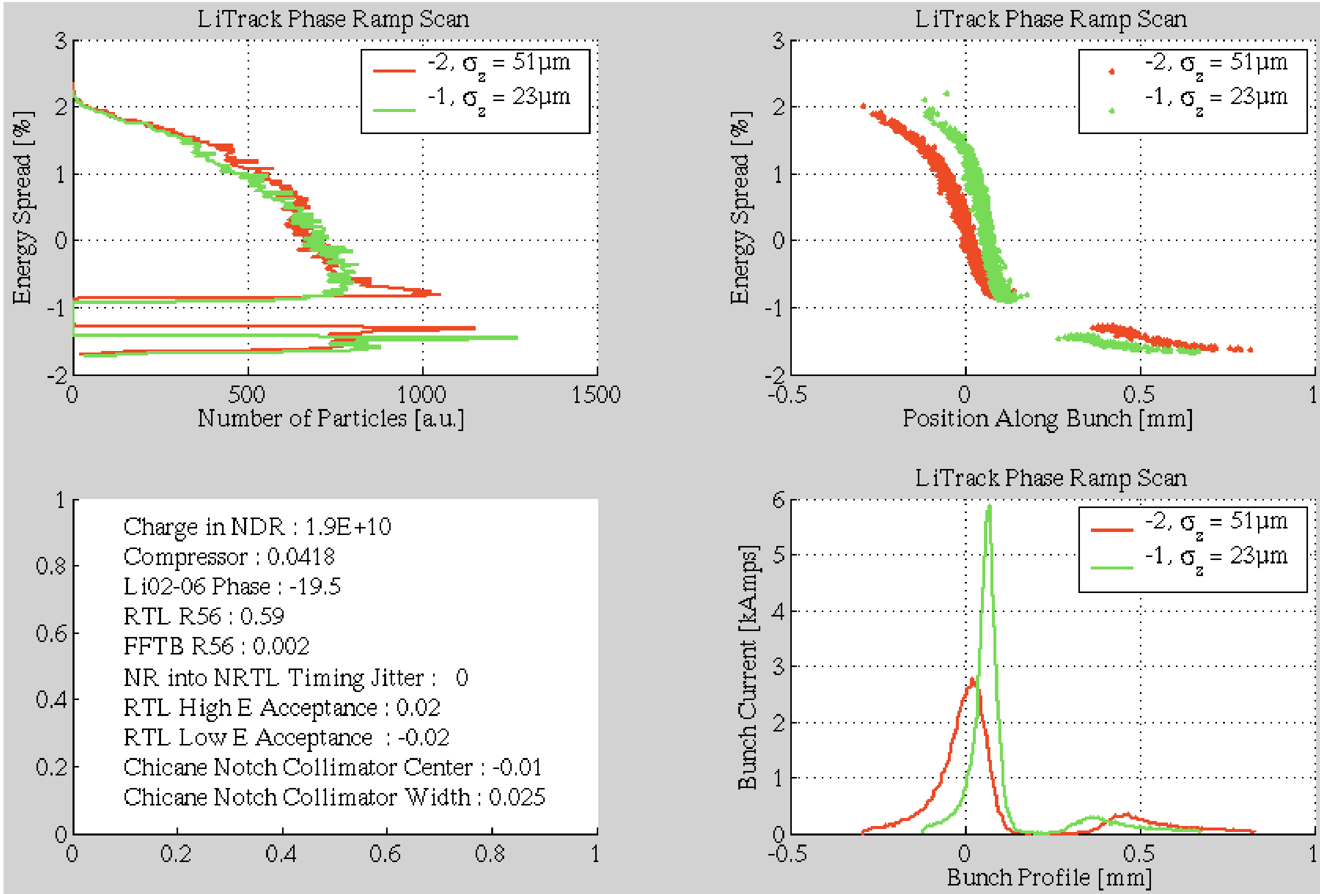
e^- and e^+:

Driver bunches:	σ_z=63 μm, σ_r=5 μm, $N=3\times10^{10}$ e^-/e^+, 50 -> 0 GeV
Witness bunches:	σ_z=32 μm, σ_r=5 μm, $N=1\times10^{10}$ e^-/e^+, 50 -> 100^{+} GeV
Delay:	d=200 μm
Plasma:	$n_e=1.8\times10^{16}$ cm^{-3}, L=7, 21 m
Accelerating gradient:	8, 3 GV/m, $\Delta E/E$ <10%

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

UCLA

NEAR FUTURE



- Notch in the LI10 chicane => 2-bunch experiment!?!
- Beam acceleration with finite energy spectrum (XFEL beams? SLAC, DESY?)
- Long plasma => Large energy gain (2□E_o in 70 cm?)
- Short positron bunches?

SIMULATION CHALLENGE

50 Gev energy gain in 3 meters !

Courtesy of C. Huang, UCLA