



Electron Beam Driven Plasma Wakefield Accelerators

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E-162/E-164/E-164X Collaboration:

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OUTLINE



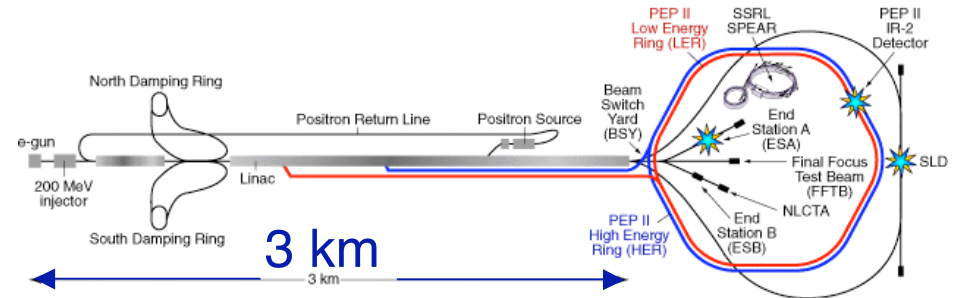
- Motivation: plasmas as particle accelerators
- Introduction to the Plasma Wakefield Accelerator (PWFA)
- Acceleration of e^-
- Plasma afterburner or energy doubler for a linear collider
- Conclusions and future



ACCELERATING FIELDS



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



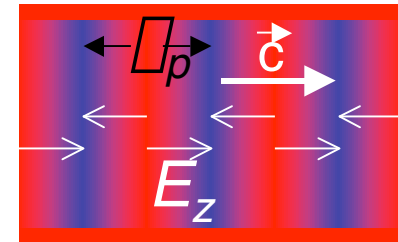
- Limited by rf breakdown ≤ 200 MV/m
- Next linear collider: ≈ 25 MV/m

Relativistic Plasma Wave:

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0} \quad k_p E = \frac{\rho_{pe}}{c} E = \frac{n_e e}{\epsilon_0}$$

$$\underline{E} = \frac{\epsilon_0 m_e c^2}{\epsilon_0} n_e^{1/2} \approx 100 \sqrt{n_e (\text{cm}^{-3})} = \underline{1 \text{ GV/m}}$$

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

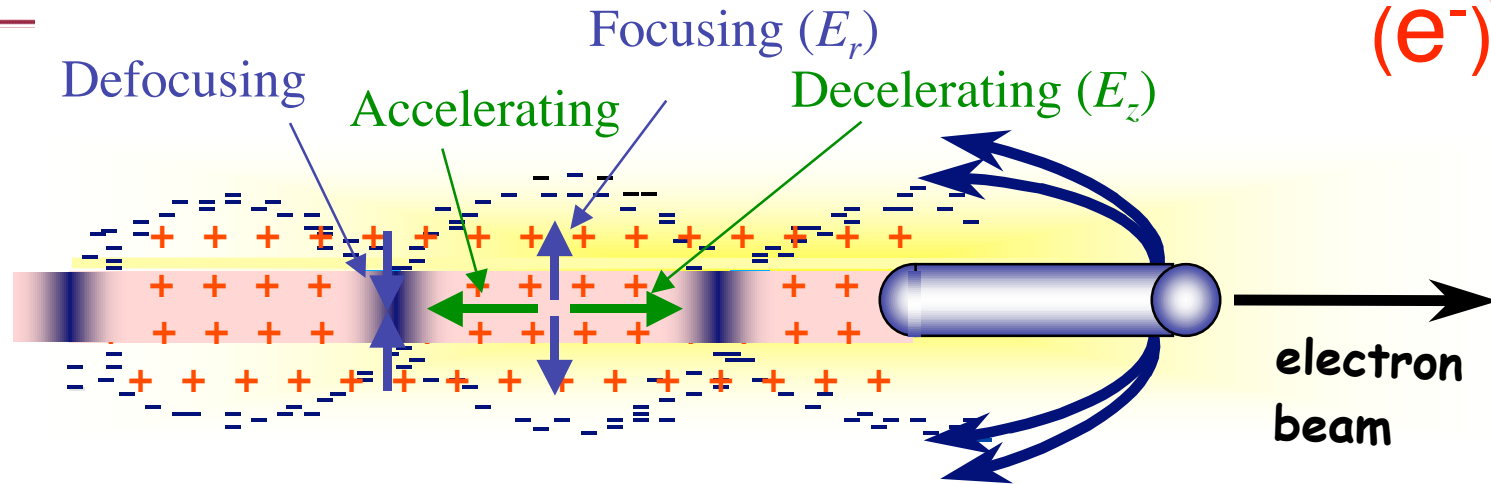


LARGE
Collective response!

- High gradient, high-energy plasma accelerator?



BEAM-DRIVEN PLASMA WAKEFIELD



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces \Rightarrow energy loss + focusing
(ion channel formation $r_c \approx (n_b/n_e)^{1/2} \lambda_p$)
- Plasma e^- rush back on axis \Rightarrow energy gain

- Linear scaling: $E_{acc} \approx 110 (MeV/m) \frac{N/2 \times 10^{10}}{(\lambda_z / 0.6mm)^2} \approx 1/\lambda_z^2$
 $@ k_p \lambda_z \approx \sqrt{2} \quad (n_e \approx 1.5 \times 10^{14} \text{ cm}^{-3} \text{ for } \lambda_z = 700 \mu\text{m})$

- Plasma Wakefield Accelerator (PWFA) = Transformer

Booster for high energy accelerator



Typical parameters:

e^- - beam:

E 28.5 GeV

N $1.8 \times 10^{10} e^-$

σ_z 20 μm (70 fs)

$\sigma_x = \sigma_y$ 15 μm

n_b $2.5 \times 10^{14} \text{ cm}^{-3}$

σ_{xN} $5 \times 10^{-5} \text{ m-rad}$

σ_{yN} $0.5 \times 10^{-5} \text{ m-rad}$

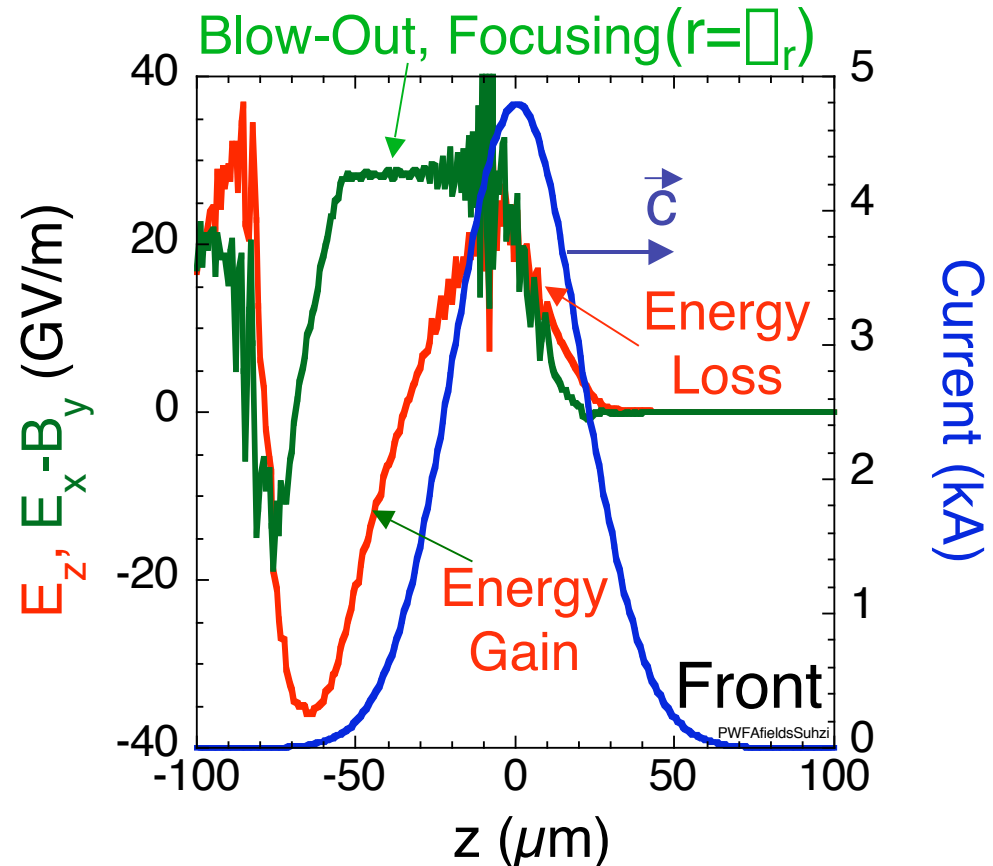
Plasma:

$n_e = n_0$ 0-3.5 $\times 10^{17} \text{ cm}^{-3}$

L $\approx 10 \text{ cm}$

3-D PIC Simulation OSIRIS

$n_e = 2.1 \times 10^{17} \text{ cm}^{-3}$

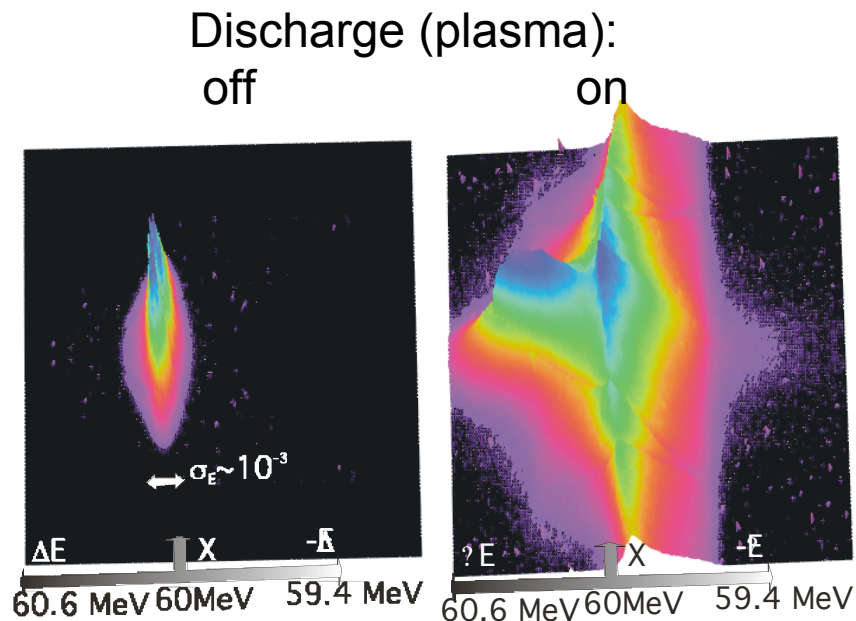


- Experiment: $n_b > n_e \Rightarrow$ non linear, blow-out regime
 - Uniform focusing field (r, z)
 - Large decelerating/accelerating fields

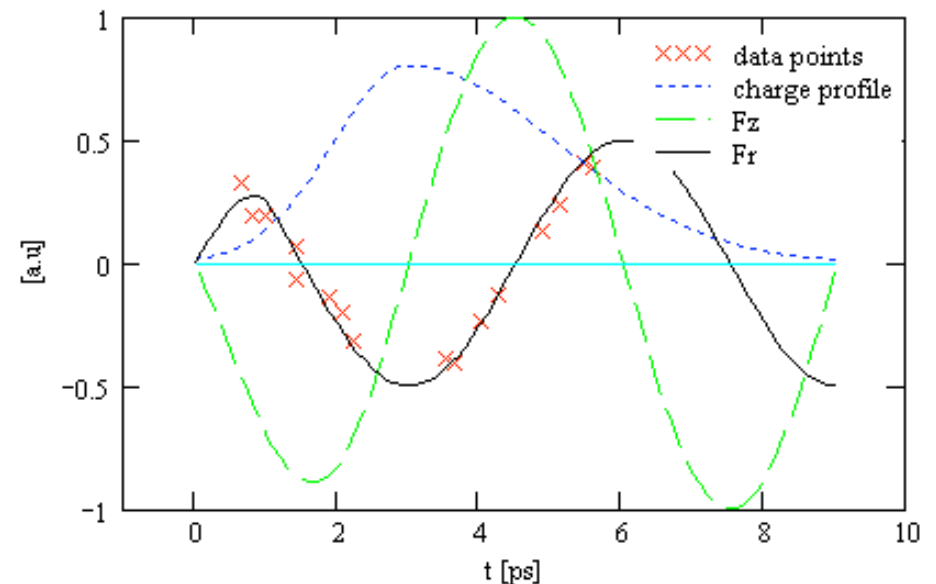
LONGITUDINAL TRANSVERSE WAKE FIELDS



Courtesy of Vitaly Yakimenko, Brookhaven Nat. Lab.



60 MeV, 0.5 nC, 3 ps (FWHM) e-beam
17 mm of $\sim 10^{17}$ plasma.



- Confirms wakefield structure

Courtesy of Nick Barov, Northern Illinois University

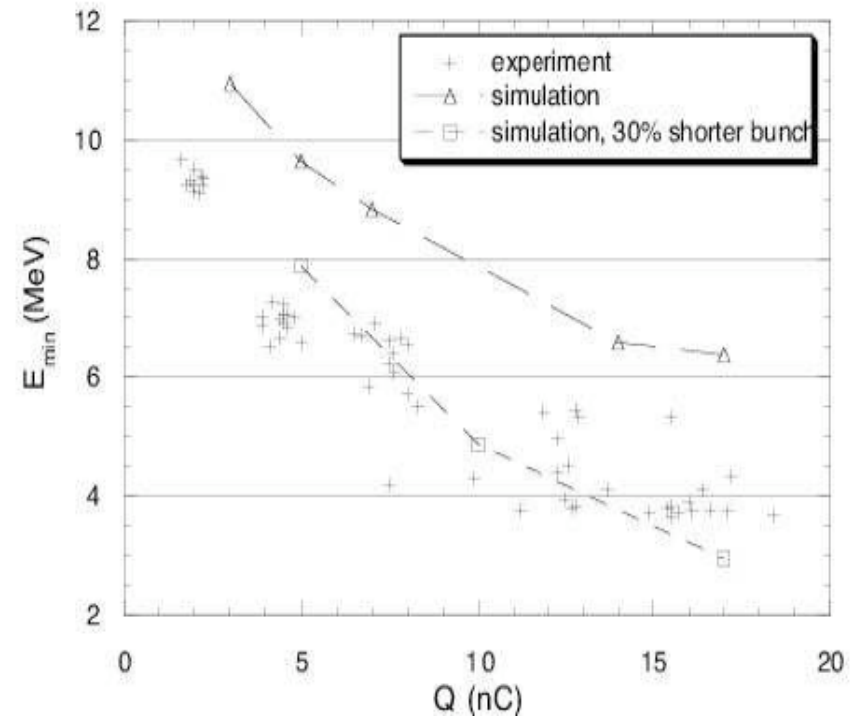
A0 photoinjector: 15 MeV, 1-8 nC, compressed to < 3 ps

Plasma: $\approx 1.1 \times 10^{14} \text{ cm}^{-3}$ over $\approx 7 \text{ cm}$

Accelerated electrons; gradient is 130 MeV/m.

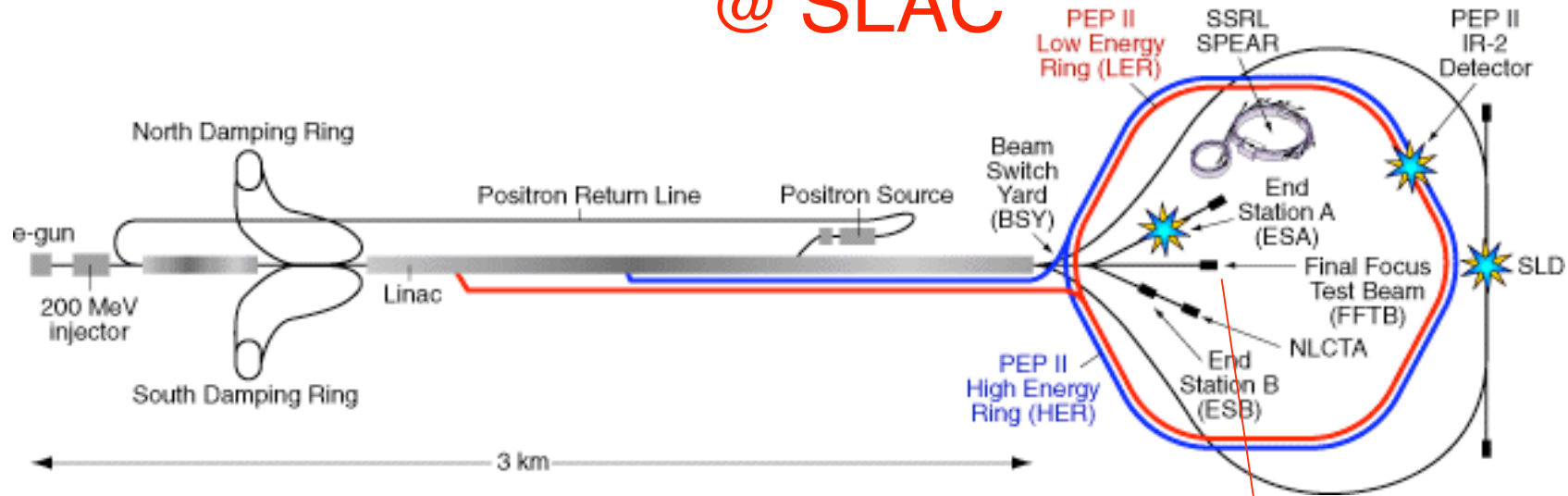


Background shot with no plasma (taken with smaller camera iris).



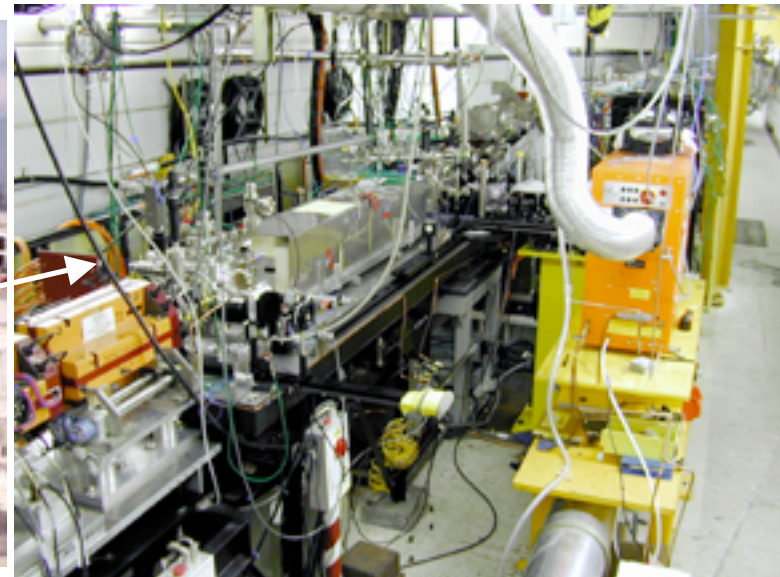
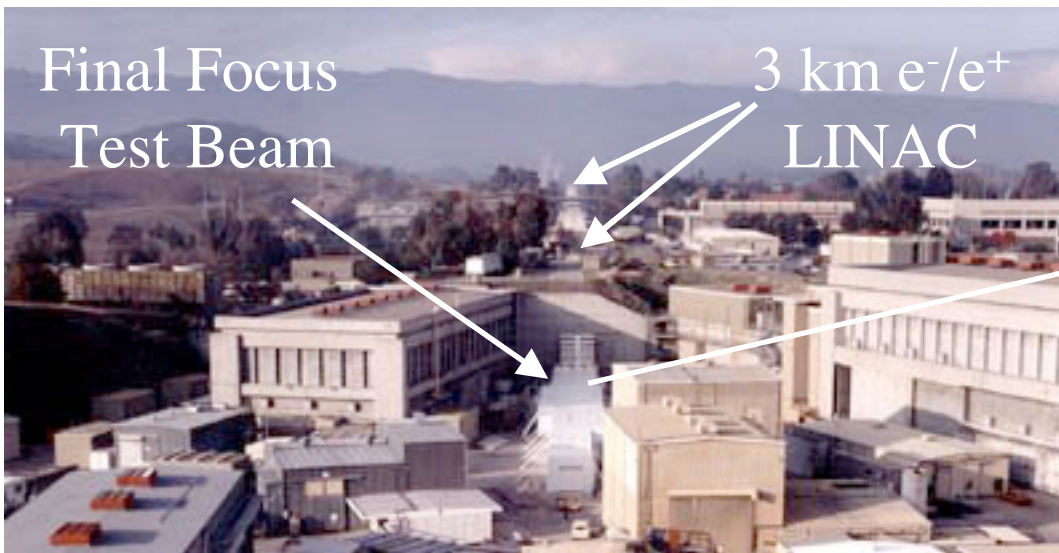
- High-gradient acceleration/deceleration
- Good agreement experiment/simulation

PLASMA WAKEFIELD EXPERIMENT @ SLAC



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

add 1 GeV over <1 m?

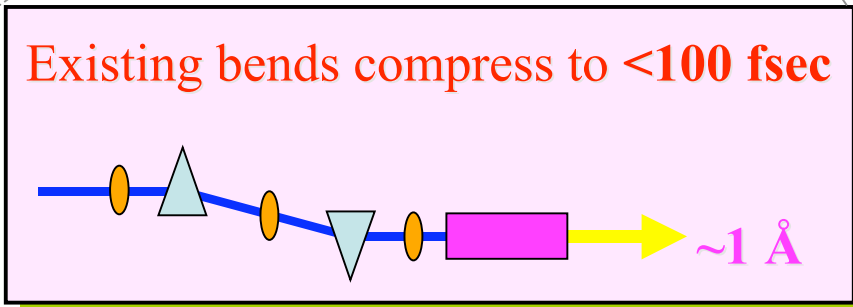
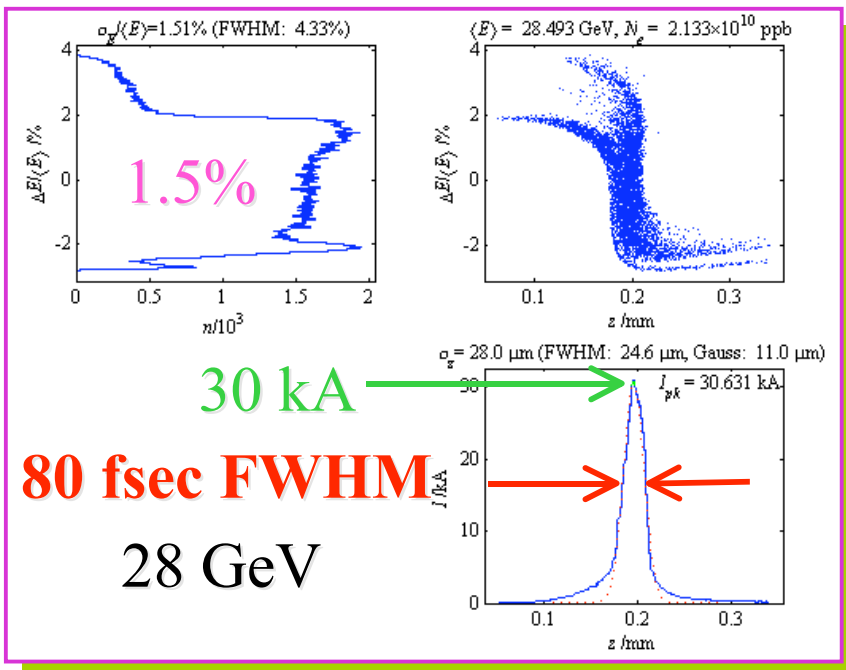


USC Short Bunch Generation In The SLAC Linac

Courtesy of SPPS



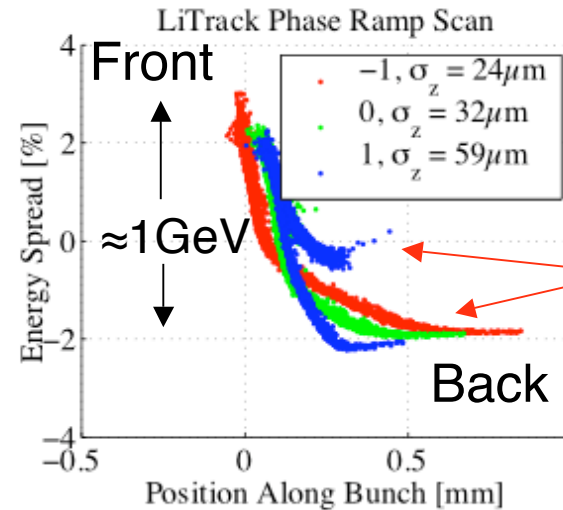
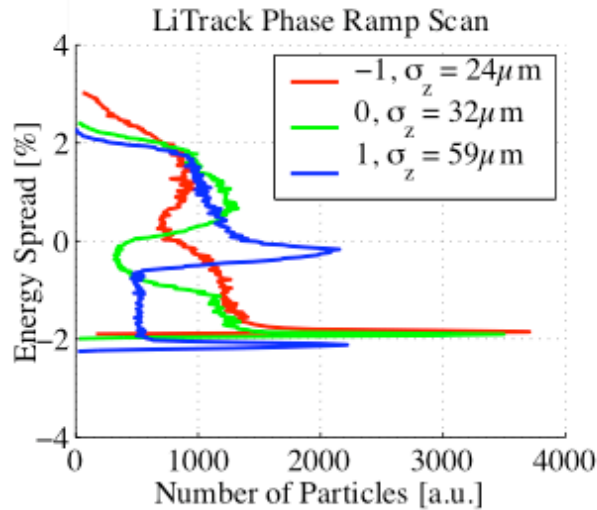
Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)



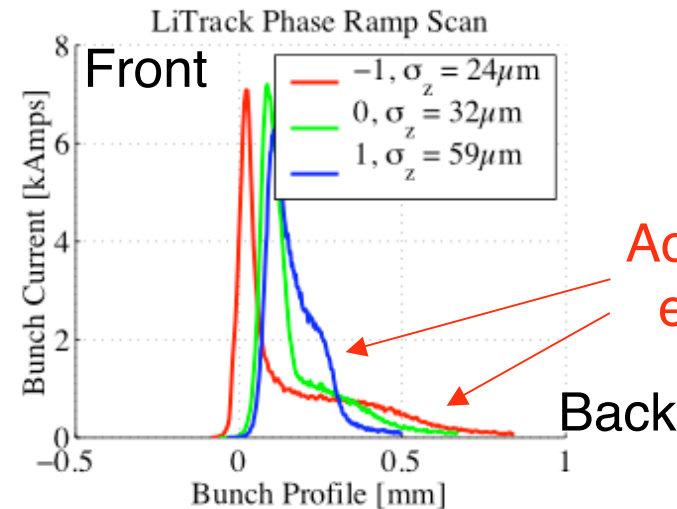
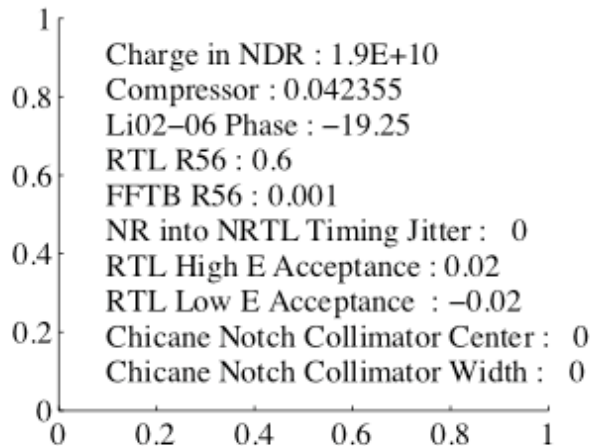
- Bunch length/current profile is the convolution of an incoming energy spectrum and the magnetic compression
- Dial FFTB R_{56} , measure incoming energy spectrum.



e⁻ BUNCH MANIPULATION



Accelerated electrons



Accelerated electrons

➔ Energy spectrum \leftrightarrow phase space \leftrightarrow current profile

➔ PWFA: accelerate e⁻ in the back of the bunch



e⁻-BEAM FIELD-IONIZATION

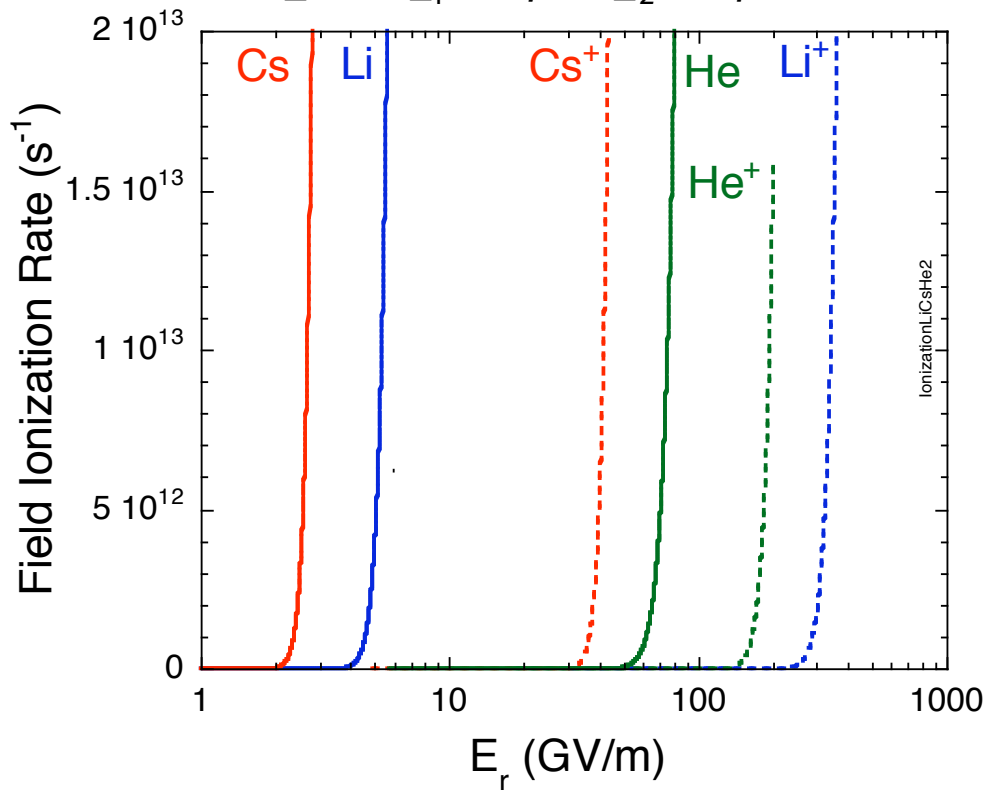


Ionization rate (ADK model):

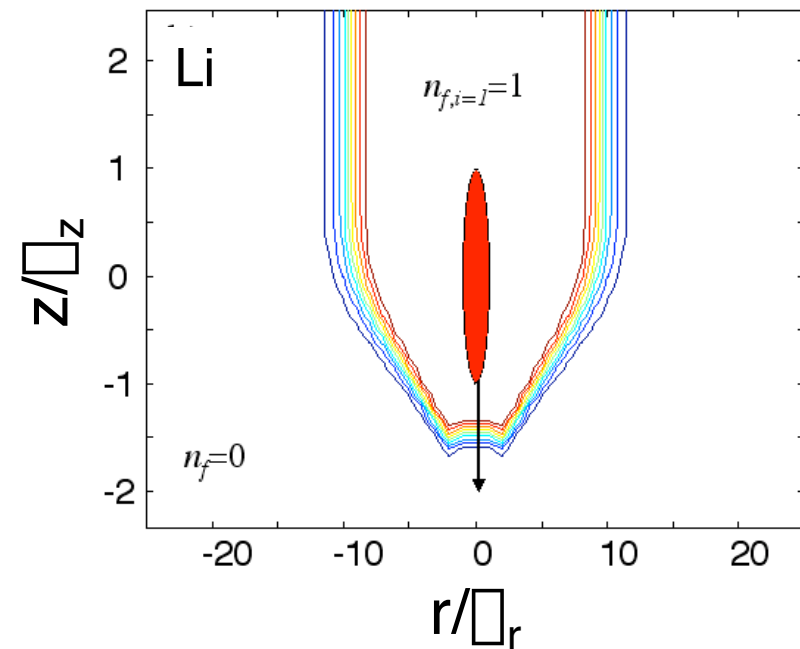
$$E_r \approx 5.2 \times 10^{19} \frac{N}{\sigma_r \sigma_z} \approx 35 \text{ GV/m}$$

$$N = 2 \times 10^{10}, \sigma_r = 25 \mu\text{m}, \sigma_z = 12 \mu\text{m}$$

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



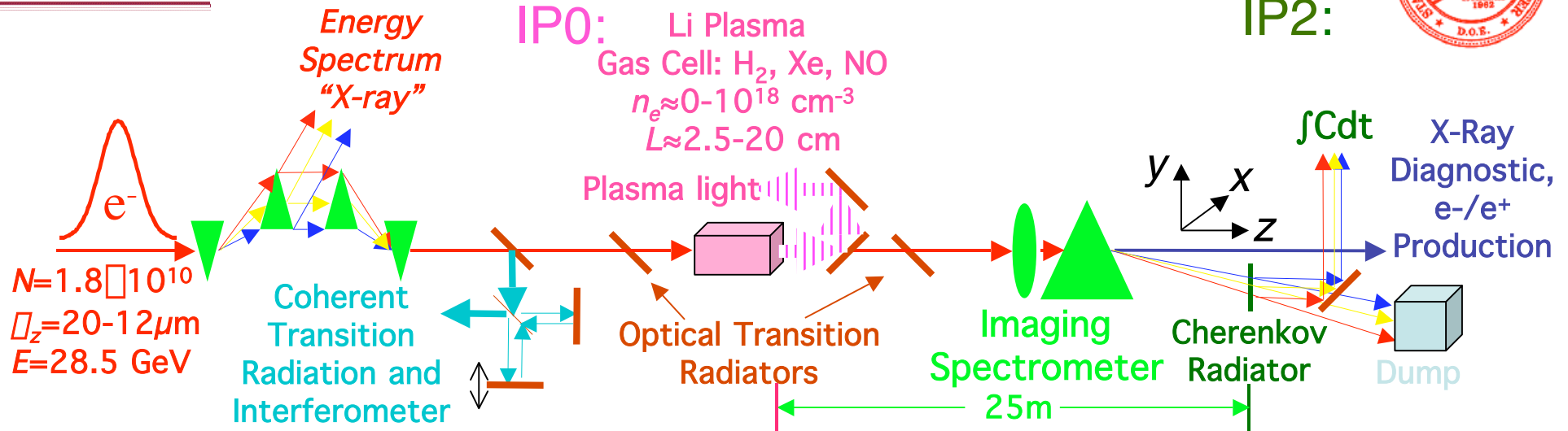
σ_i = ionization potential = 5.45 eV for Li
 E = electric field in GV/m
 n^* = effective quantum number = $Z/(2\sigma_i)^{1/2}$



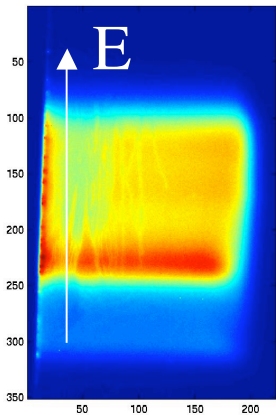
- Threshold process, lithium for plasma
- Short bunches can field-ionize their own plasma and create their own accelerating structure (E-164X, after-burner?)

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

EXPERIMENTAL SET UP



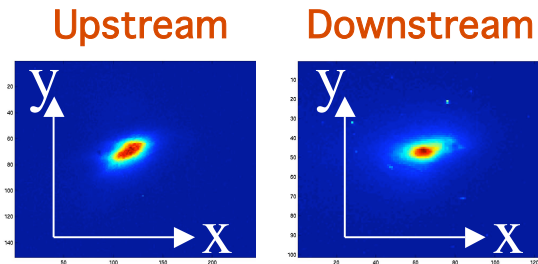
- X-ray Chicane



-Energy resolution $\approx 60 \text{ MeV}$

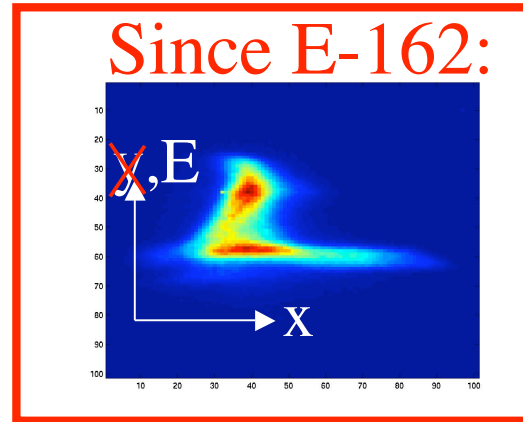
P. Muggli, APS-DPB 08/28/05

- Optical Transition Radiation (OTR)

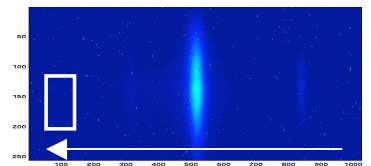


-1:1 imaging, spatial resolution $\approx 9 \mu\text{m}$

- Cherenkov (aerogel)
- Plasma Light

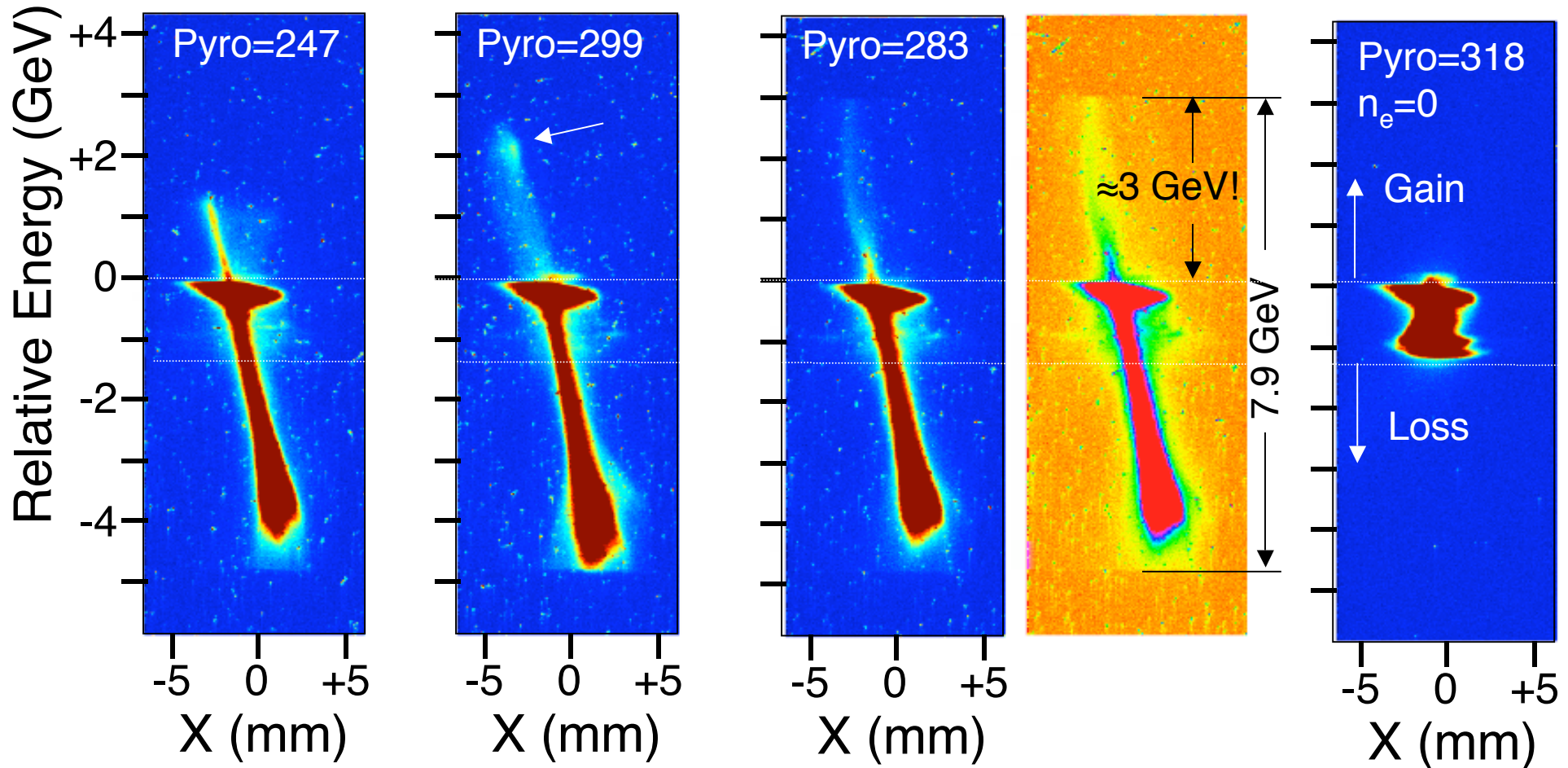


- Spatial resolution $\approx 100 \mu\text{m}$
- Energy resolution $\approx 30 \text{ MeV}$



$n_e \approx 2.55 \times 10^{17} \text{ cm}^{-3}$ RESULTS (e⁺)

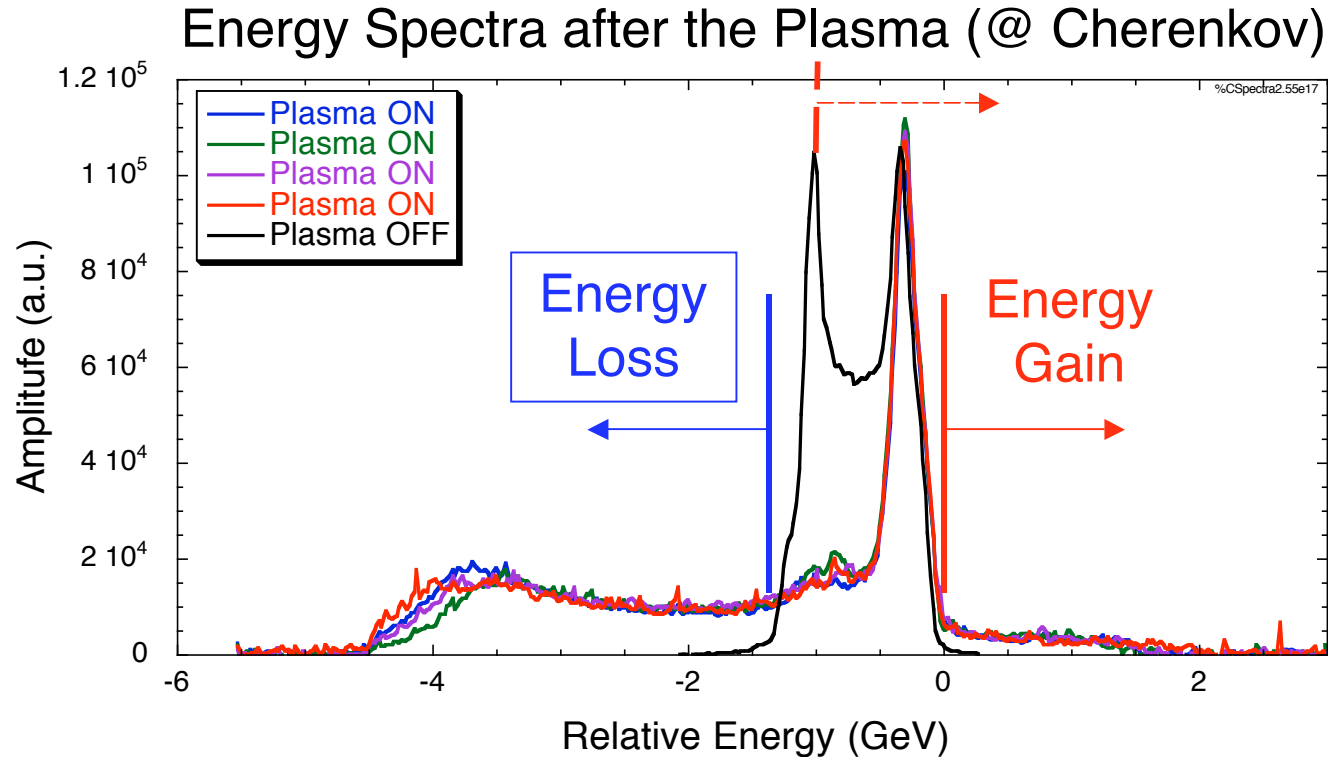
Field-ionized Lithium, $L \approx 10 \text{ cm}$, $N \approx 1.8 \times 10^{10}$



➔ Energy gain reaches $\approx 3+1 \text{ GeV}$, gradient $\approx 40 \text{ GeV/m}$

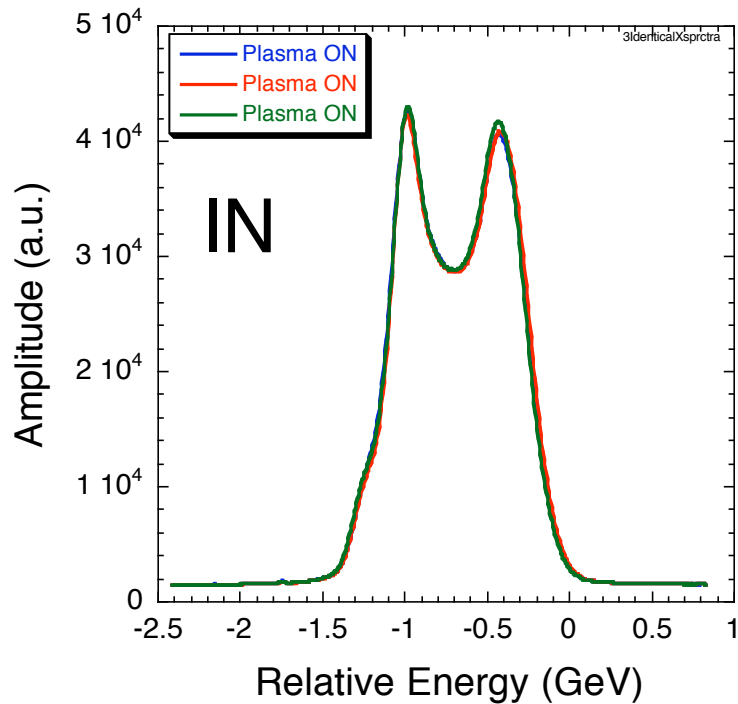
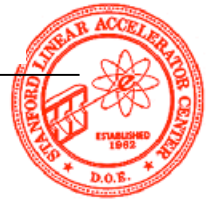
➔ Energy gain depends on the details of the incoming beam (x,y,z)

Field-ionized Lithium, $L \approx 10 \text{ cm}$, $N \approx 1.8 \times 10^{10}$



- ➔ Variations from incoming energy spectrum variations
- ➔ Charge Fraction at $E > 0$: 6.8-7.9% of total charge, $\approx 250 \text{ pC}$
- ➔ Peak energy gain above the beam head: $\approx 1.5 \text{ GeV}$
total gain: $1.5 + 1 \text{ GeV}$

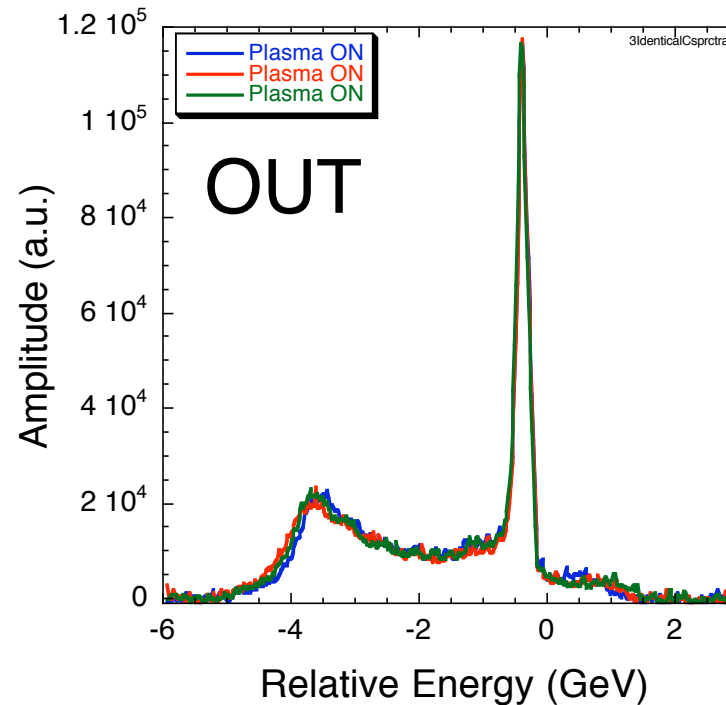
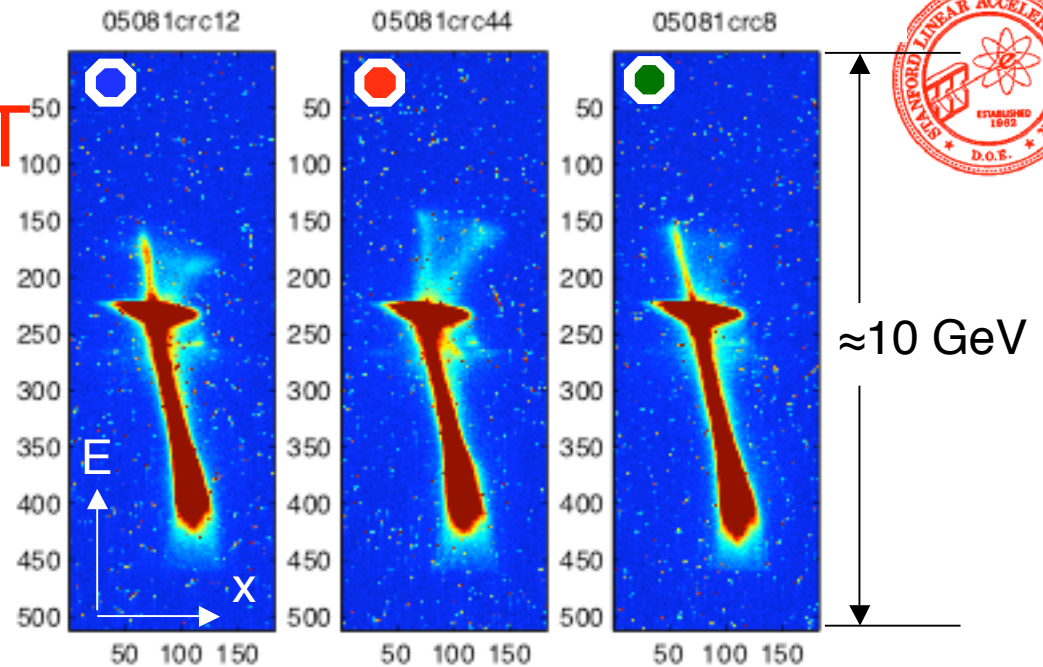
SIMILAR IN, SIMILAR OUT



Identical incoming
energy spectra/events



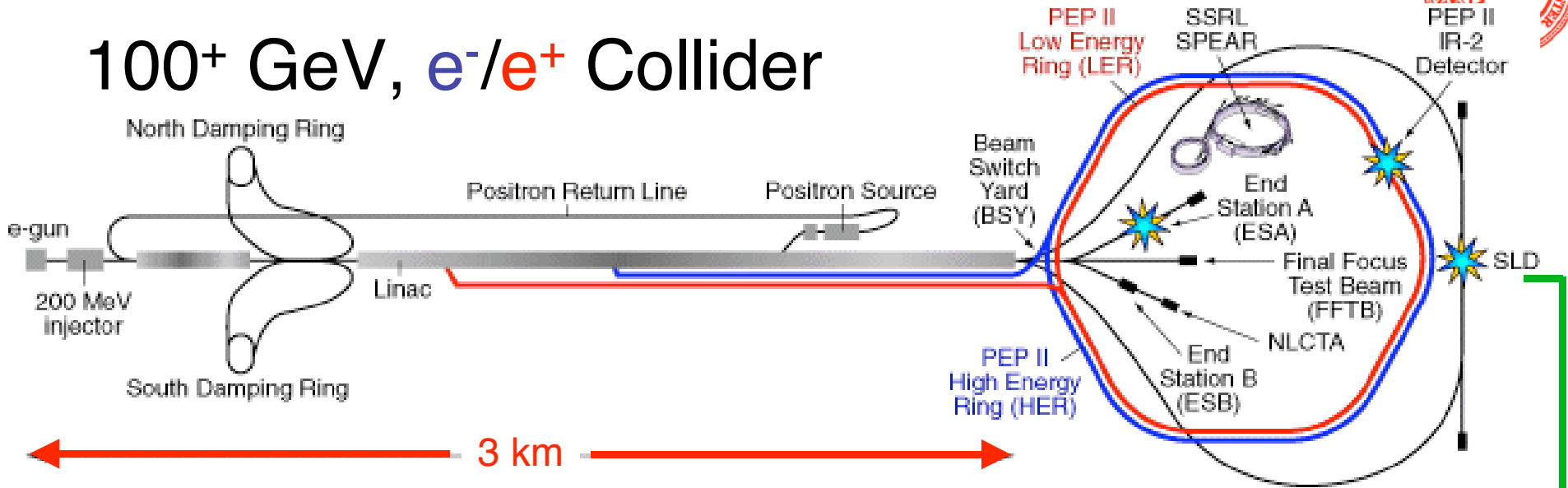
“Identical” outgoing
energy spectra/events



PLASMA AFTERBURNER (EXAMPLE)



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



$50 \text{ GeV } e^-$

LENSES

$50 \text{ GeV } e^+$

e^- -PWFA

7m

IP

e^+ -PWFA

21m

e^- and e^+ :	
Driver bunches:	$\sigma_z=63 \mu\text{m}, \sigma_r=5 \mu\text{m}, N=3 \times 10^{10} e^-/e^+, 50 \rightarrow 0 \text{ GeV}$
Witness bunches:	$\sigma_z=32 \mu\text{m}, \sigma_r=5 \mu\text{m}, N=1 \times 10^{10} e^-/e^+, 50 \rightarrow 100^+ \text{ GeV}$
Delay:	$d=200 \mu\text{m}$
Plasma:	$n_e=1.8 \times 10^{16} \text{ cm}^{-3}, L=7, 21 \text{ m}$
Accelerating gradient:	$8, 3 \text{ GV/m}, \Delta E/E < 10\%$



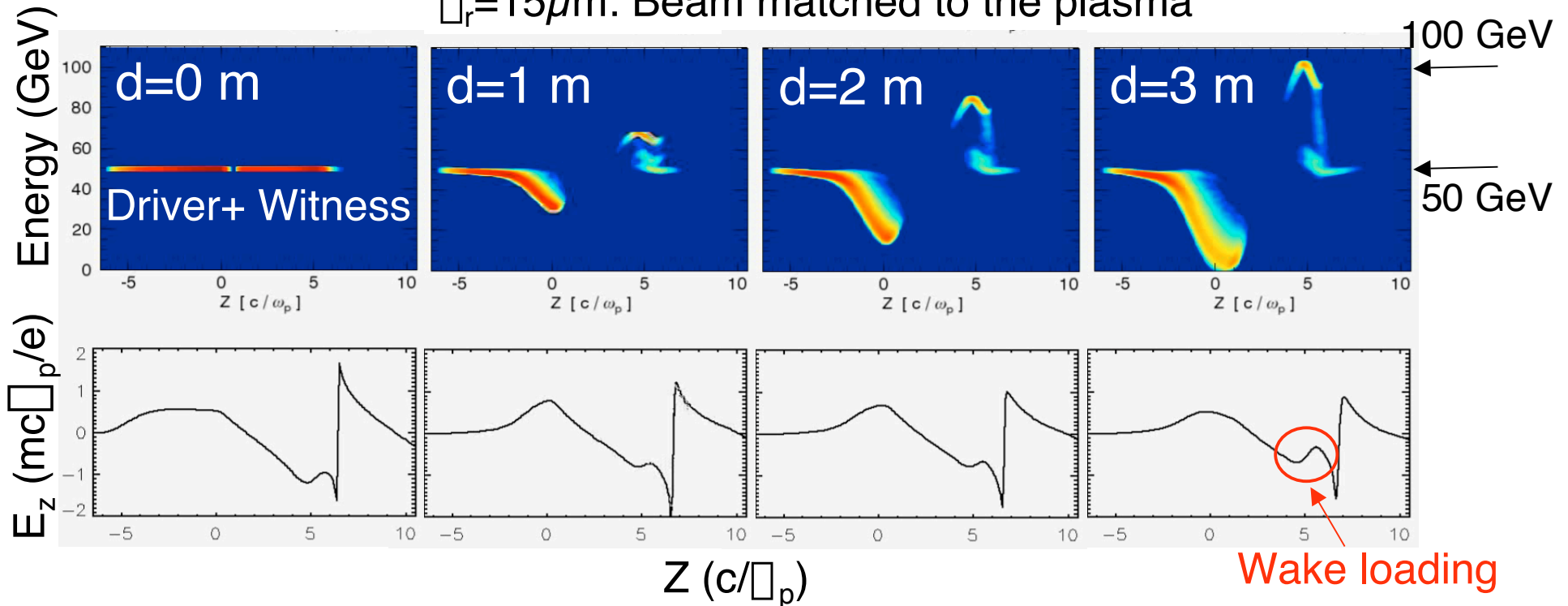
AFTERBURNER SIMULATIONS* (EXAMPLE)

SLC: 50 GeV ->100 GeV



$L_{z,D}=145\mu\text{m}$, $\sigma_{z,W}=10\mu\text{m}$, $N=(3+1)\times 10^{10} e^-$, $\text{delay}=111\mu\text{m}$, $n_e=5.7\times 10^{16} \text{ cm}^{-3}$

$\sigma_r=15\mu\text{m}$: Beam matched to the plasma



- ➔ Energy gain reaches 50 GeV over 3 m!
- ➔ Evolution of the driver bunch and E_z : head erosion

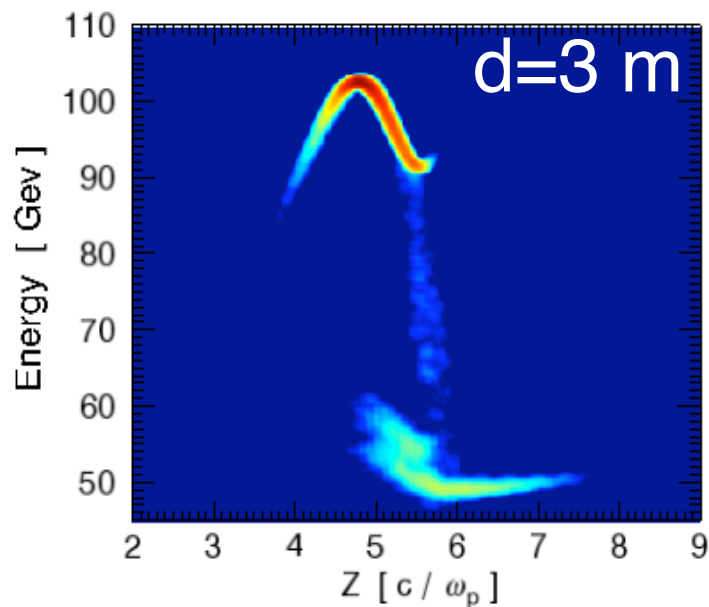
*by Chengkun Huang, QuickPIC



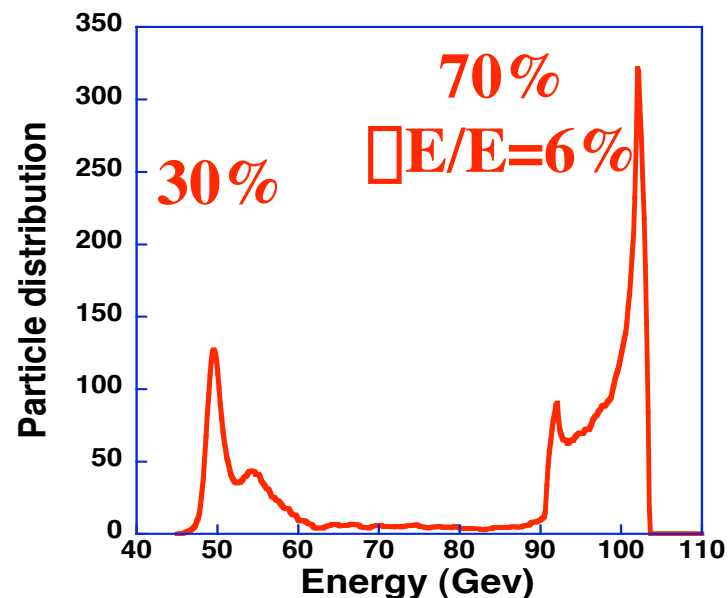
USC AFTERBURNER SIMULATIONS* (EXAMPLE)



Witness Bunch



Energy Spectrum



- ➔ Driver bunch σ_r larger than accelerating bucket
- ➔ Finite energy spread of the accelerated bunch
- ➔ Incoming emittance preserved



Very significant steps towards a plasma afterburner/energy doubler

- Field ionization as a plasma source -> very long, dense plasma
- Acceleration:
 - $\Delta z \approx 730 \mu\text{m}$ e^+ : $\approx 75 \text{ MeV}$ at $\approx 50 \text{ MeV/m}$ ($n_e \approx 1.5 \times 10^{14} \text{ cm}^{-3}$)
 e^- : $\approx 280 \text{ MeV}$ at $\approx 200 \text{ MeV/m}$
 - $\Delta z \approx 20 \mu\text{m}$ e^- : $\approx 4 \text{ GeV}$ at $\approx 40 \text{ GeV/m}$ ($n_e \approx 2.5 \times 10^{17} \text{ cm}^{-3}$)
- First gain $>1 \text{ GV}$ in ANY plasma accelerator(!), very reproducible, limited by energy acceptance of the beam line
- Propagation, matching to the plasma
- ... with very good understanding of the experimental results
- Simulation tools available for meters long, multi-GeV PWFAs



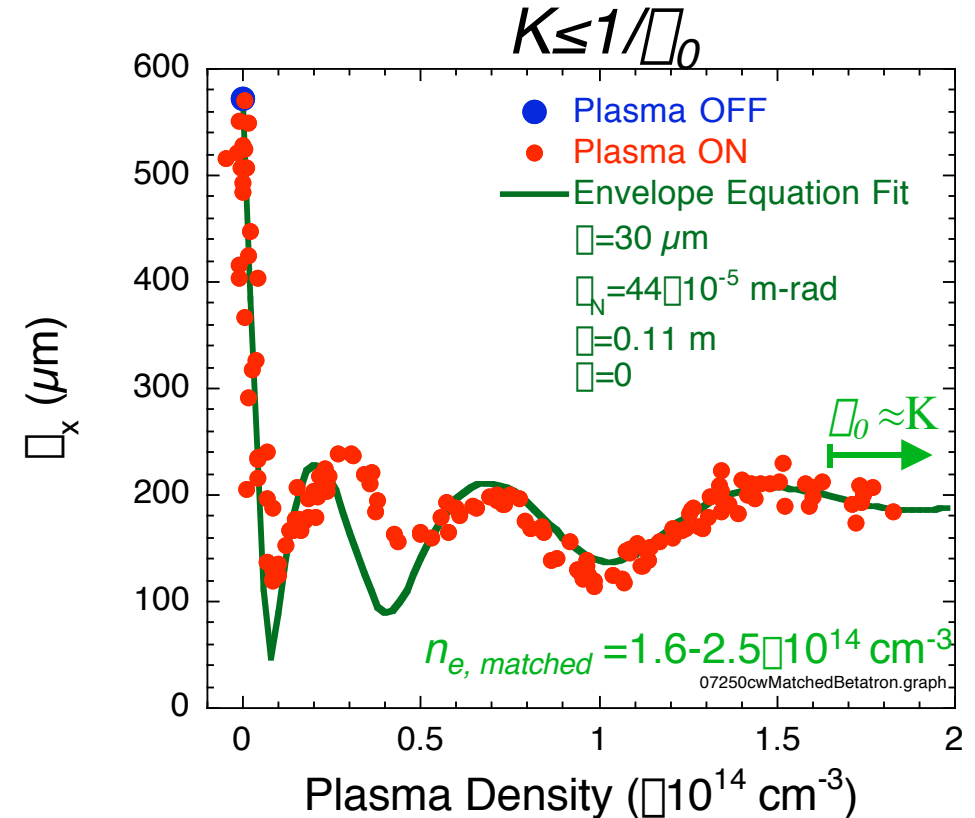
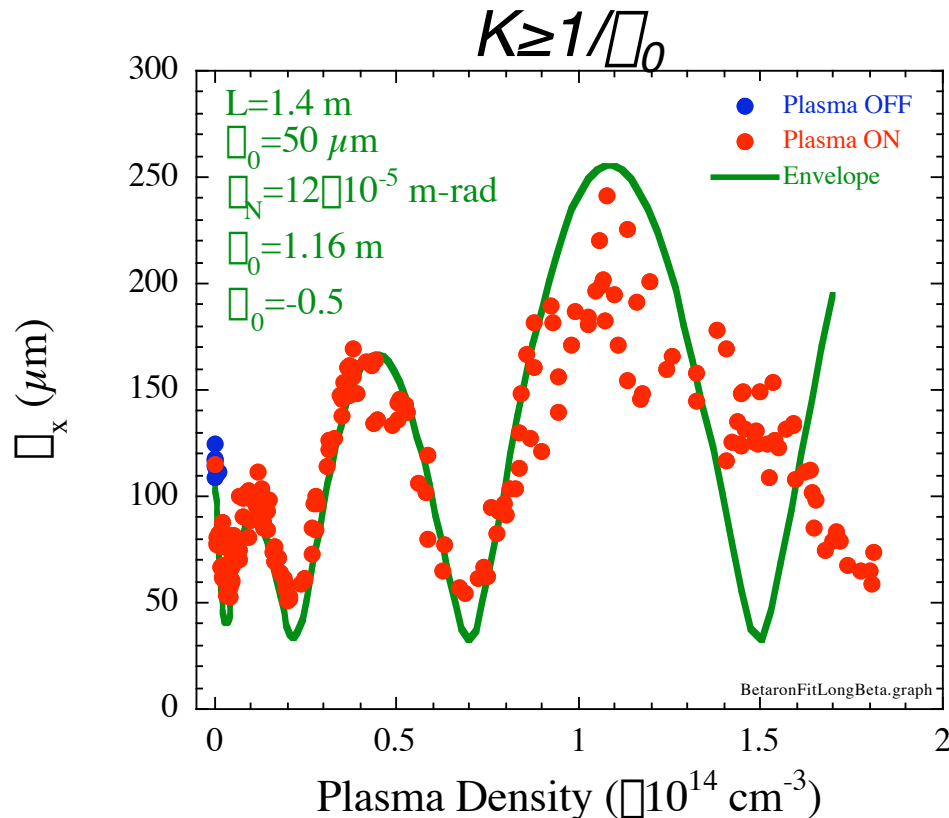
- 2-bunch experiments: beam acceleration, beam loading , energy spread, emittance preservation, wakefield mapping, ...
MOST INTERESTING and VERY IMPORTANT
- Propagation/acceleration over long distances: stability, beam erosion, energy doubling, ...
- Final plasma(?) lenses
- Experiments with positrons ($\sigma_z=20 \mu\text{m}$ not available ...yet!)
- PWFA physics at low (MeV) energies
- Afterburner+collider integration
Advanced Accelerator Concepts workshop 2004:
afterburner for nLC: 1 TeV \rightarrow 2 TeV



MATCHING OF e^- BEAM



OTR Images $\approx 1\text{m}$ downstream from plasma



- Focusing of the beam well described by a simple model ($n_b > n_e$):

Plasma = Ideal Thick Lens

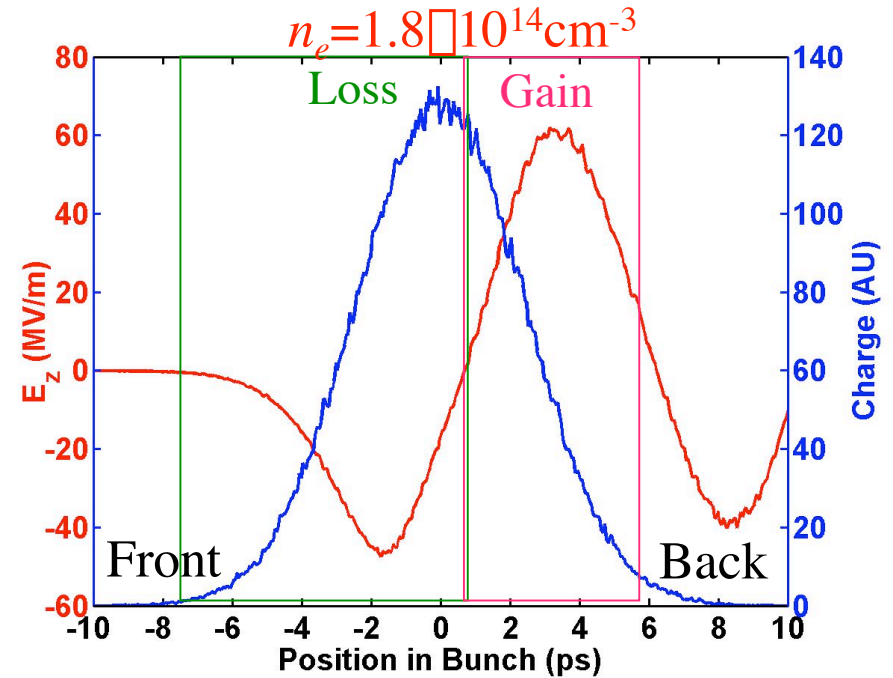
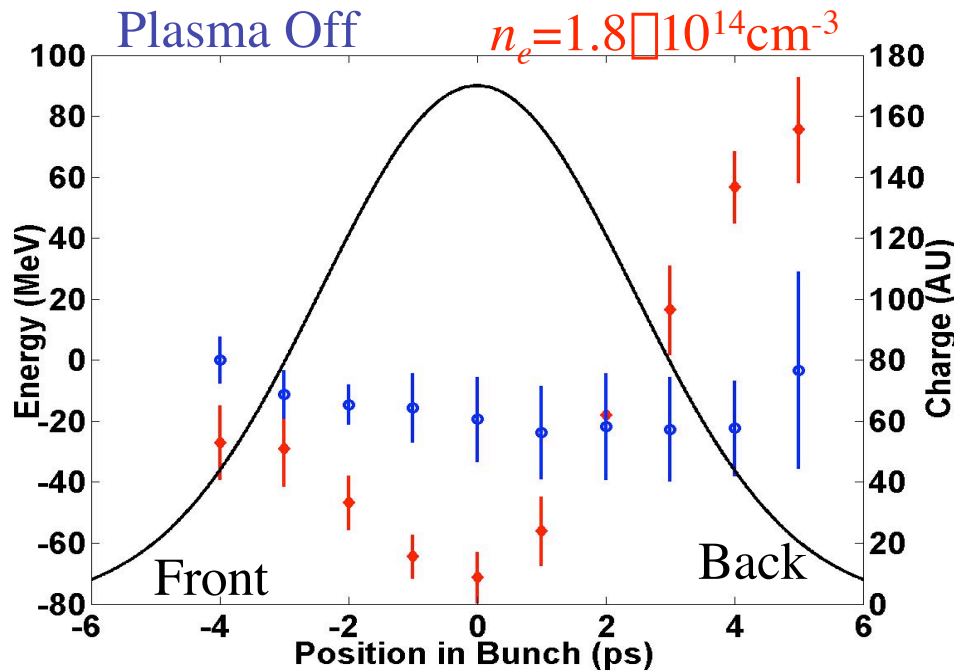
- No emittance growth, stable propagation over $L=1.4\text{ m}$ up to $1.8 \times 10^{14}\text{ cm}^{-3}$
- Channeling of the beam over 1.4 m or $>12\beta_0$
- Beam matched to the plasma!



$N=1.2 \times 10^{10} e^+$

Experiment

2-D Simulation



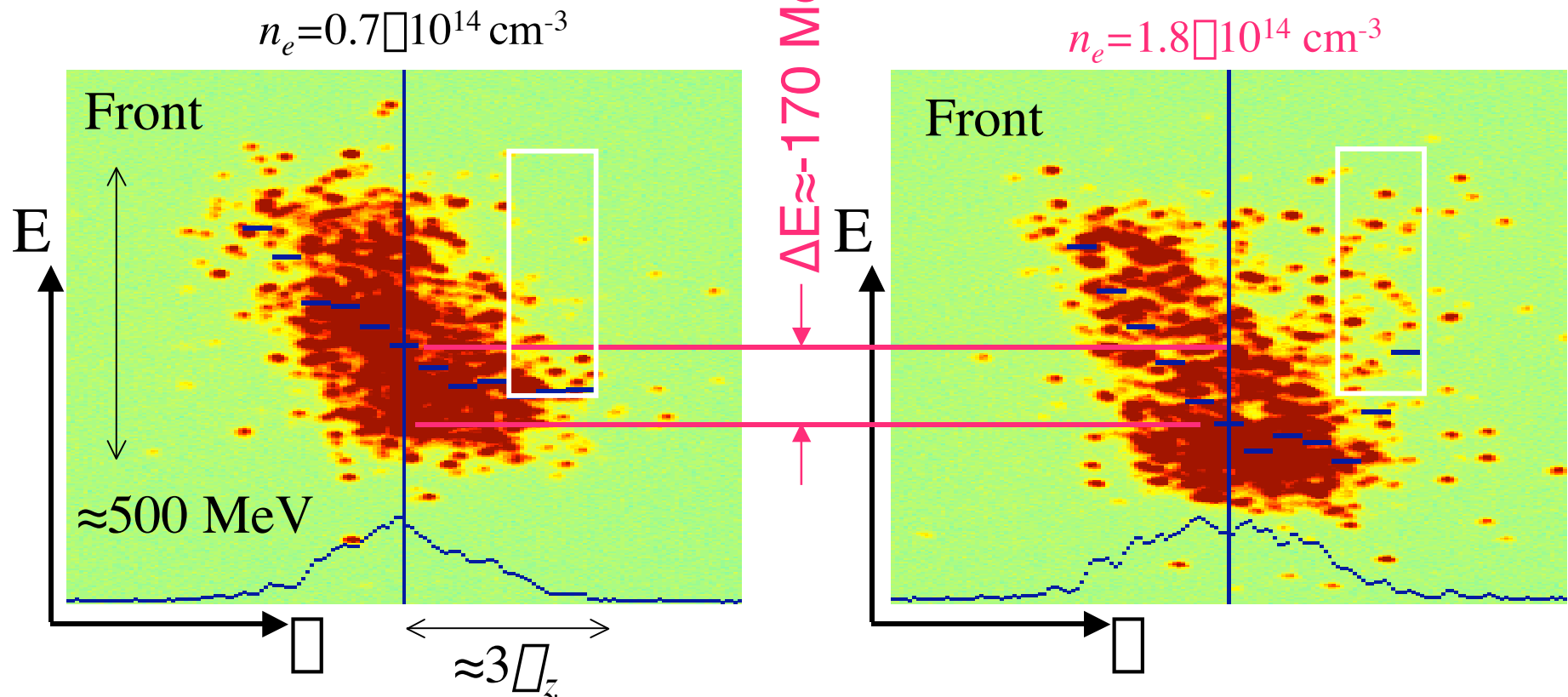
- Loss ≈ 70 MeV (over 1.4 m)
- Gain ≈ 75 MeV

- Loss ≈ 45 MeV/m $\times 1.4$ m = 63 MeV
- Gain ≈ 60 MeV/m $\times 1.4$ m = 84 MeV

• Excellent agreement!

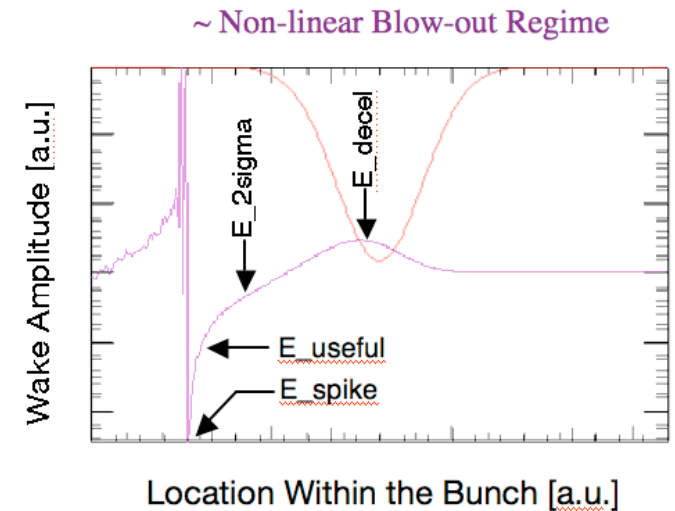
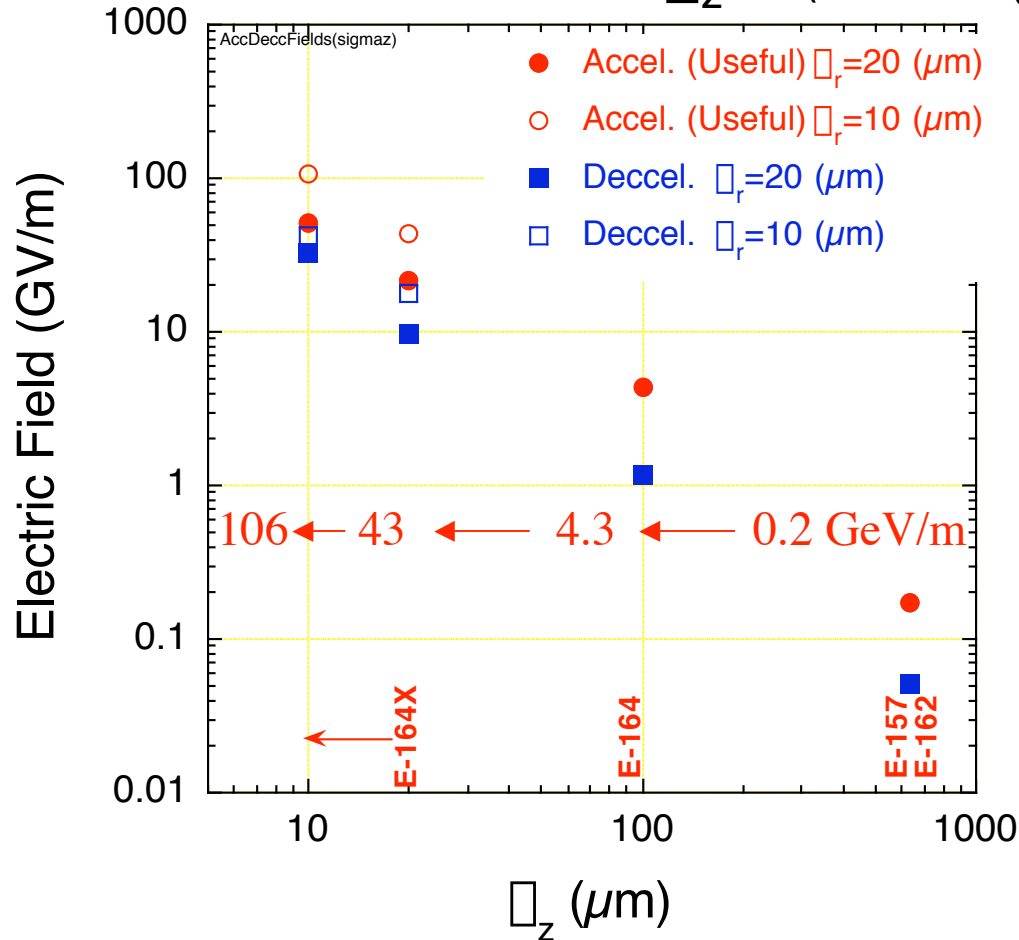
B. Blue *et al.*, PRL, 2003

SLICE ANALYSIS RESULTS SINGLE EVENT



- Select events by n_e , and by position on the streak camera slit
- Use low n_e events as “plasma off”

Gradient $\approx 1/\sigma_z^2$? ($N=cst$, n_e for $k_p \sigma_z = \sqrt{2}$)



- E-162: $\sigma_z = 700 \mu\text{m}$: $\approx 0.2 \text{ GV/m}$
- E-164X: $\sigma_z = 20-10 \mu\text{m}$: $> 10 \text{ GV/m}$!
(σ_r dependent! when $k_p \sigma_r \approx 1$)

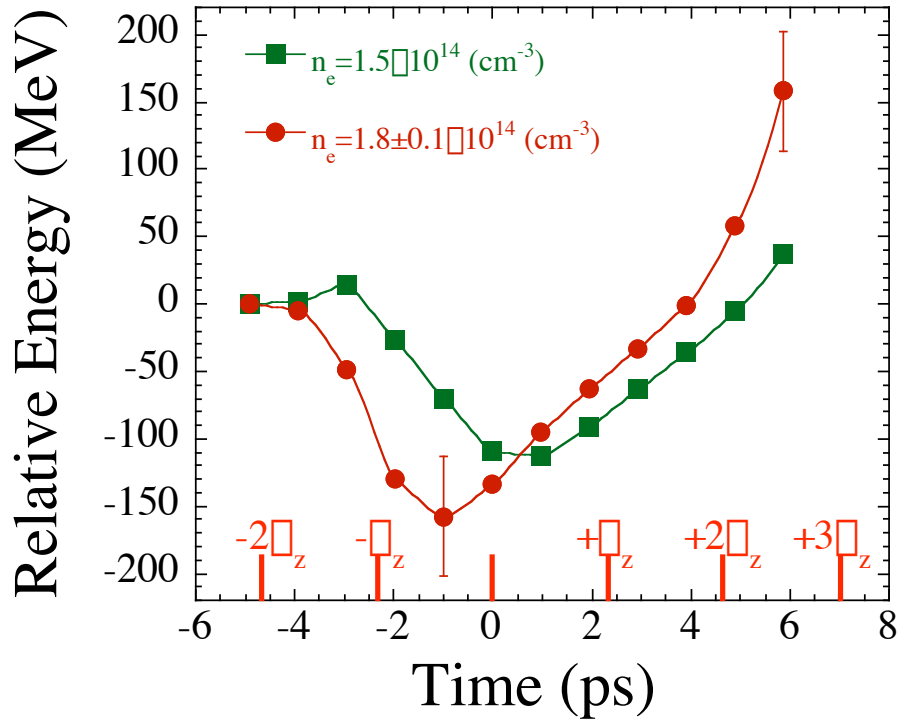
$f_p = 2.8 \text{ THz}$, $W = 3 \text{ MT/m}$ @ $n_e = 10^{17} \text{ cm}^{-3}$

e⁻ ENERGY GAIN/LOSS

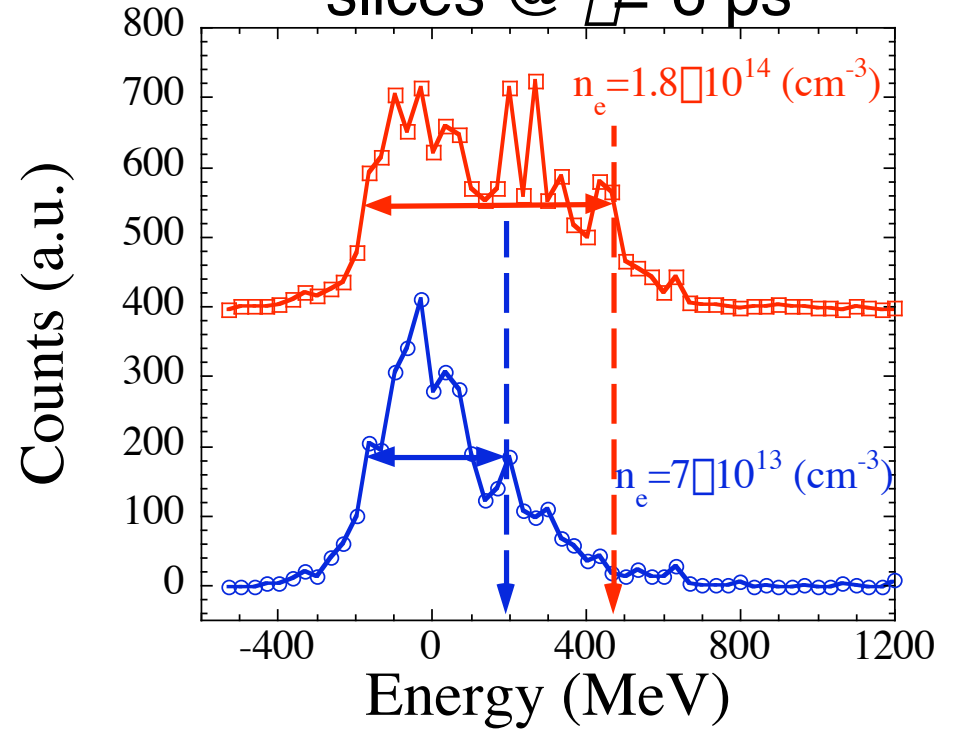
ps slice analysis results



(with incoming energy chirp subtracted)



slices @ $\Delta t = 6 \text{ ps}$



- Average energy loss (slice average): $159 \pm 40 \text{ MeV}$ (@ $n_e = 1.8 \times 10^{14} \text{ cm}^{-3}$)
- Average energy gain (slice average): $156 \pm 40 \text{ MeV}$ ($\approx 3 \times 10^7 e^-$)
- Energy gain by particles $\approx 279 \text{ MeV}$ in the last (-6 ps) 1 ps slice
- Peak accelerating gradient $\approx 200 \text{ MeV/m}$ ($L = 1.4 \text{ m}$)

