E-164

Presented by

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E-162 Collaboration:

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and E-164+X:

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OUTLINE

- Past year: -E-162, PWFA with long e^-, e^+ bunches: $\sigma_z \approx 700\ \mu m$
- Next year: -E-164 PWFA with short e^- bunches: $\sigma_z \approx 100\ \mu m$
- 5^+ years: -E-164 PWFA with ultra-short e^- bunches: $\sigma_z \approx 20\ \mu m$
  -Long term ideas

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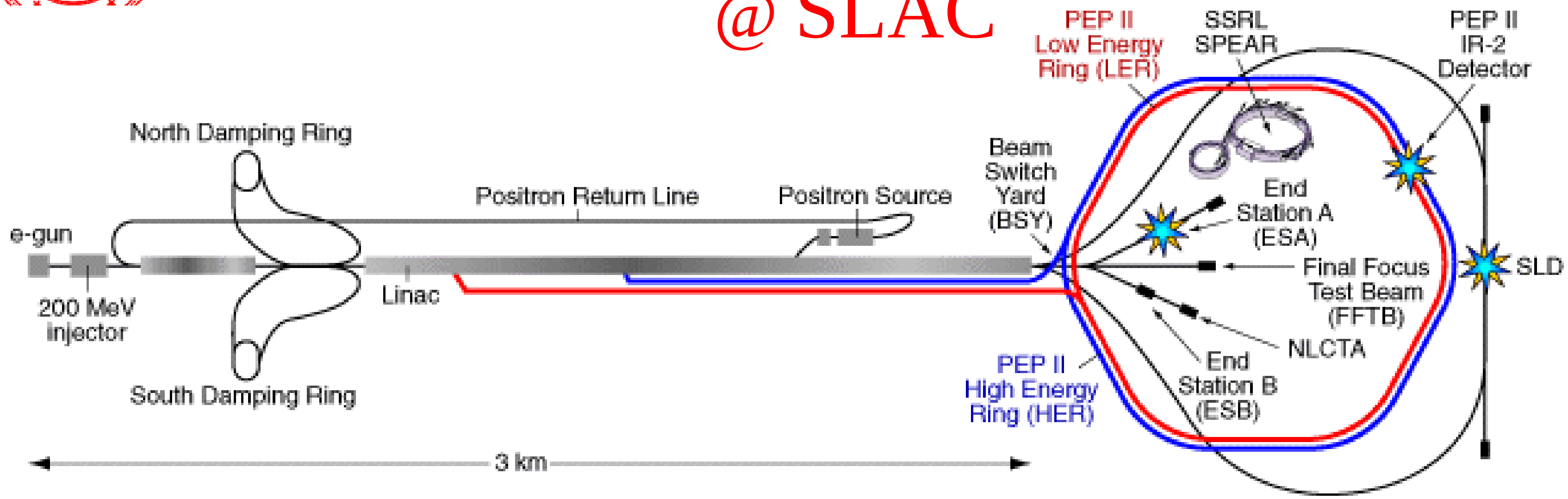
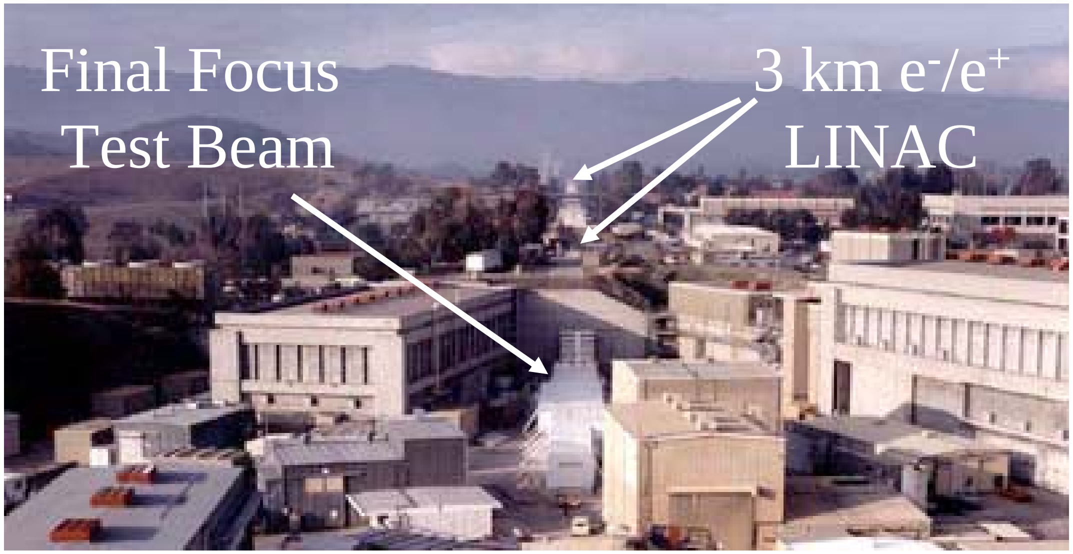
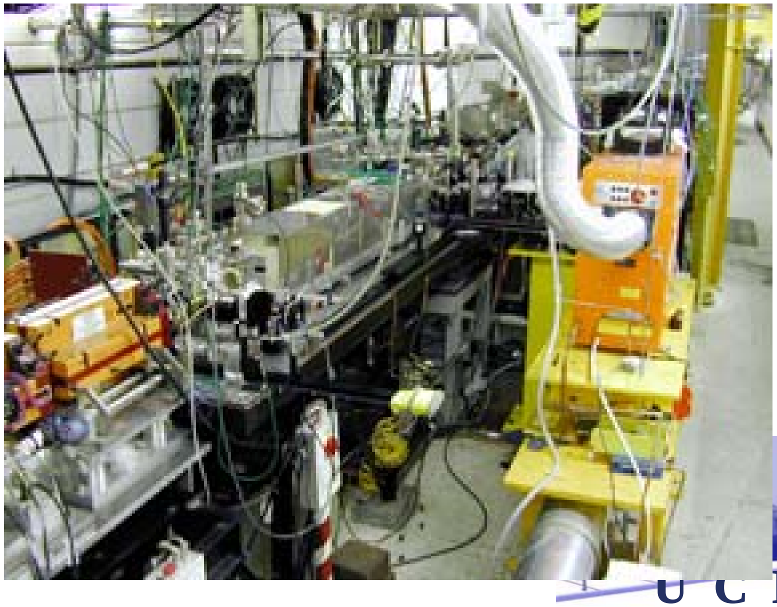
PLASMA WAKEFIELD EXPERIMENT @ SLAC



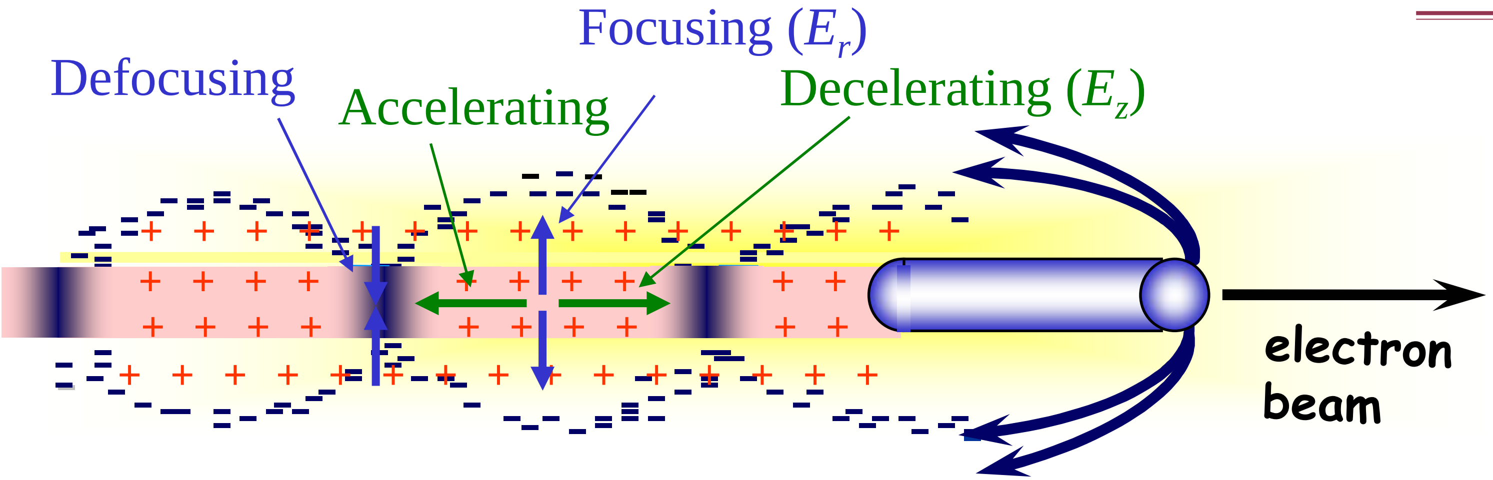
3 km for 50 GeV e^- and e^+

1 m for 1 GeV?





PLASMA WAKEFIELD (e^-)



Focusing (E_r)

Defocusing

Accelerating

Decelerating (E_z)

electron beam

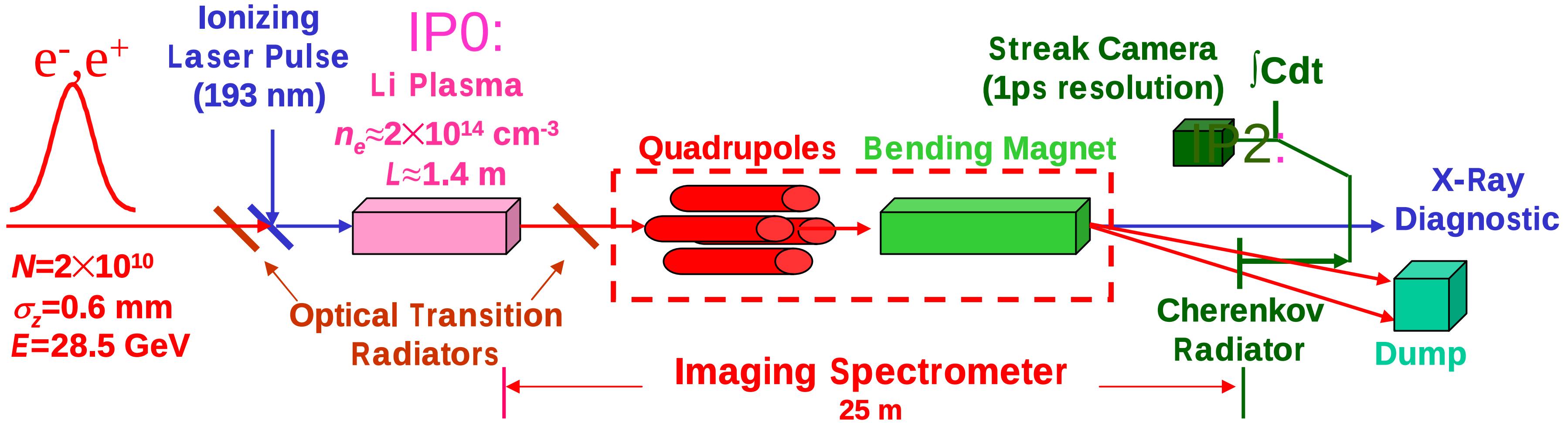
- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces => energy loss, focusing

  (ion channel formation $r_c \approx (n_b/n_e)^{1/2}\sigma_r$)
- Plasma e^- rush back on axis => energy gain
- Linear scaling: $E_{acc} \cong 110(MeV/m)\dfrac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2}$ $\approx 1/\sigma_z^2$

  @ $k_{pe}\sigma_z \approx \sqrt{2}$
- Plasma Wakefield Accelerator (PWFA) = Transformer

  Booster for high energy accelerator

EXPERIMENTAL SET UP



e^-,e^+

Ionizing
Laser Pulse
(193 nm)

IP0:
Li Plasma
$n_e \approx 2\times10^{14}$ cm^{-3}
$L \approx 1.4$ m

Streak Camera
(1ps resolution)

∫Cdt

IP2:

Quadrupoles

Bending Magnet

X-Ray
Diagnostic

$N = 2\times10^{10}$
$\sigma_z = 0.6$ mm
$E = 28.5$ GeV

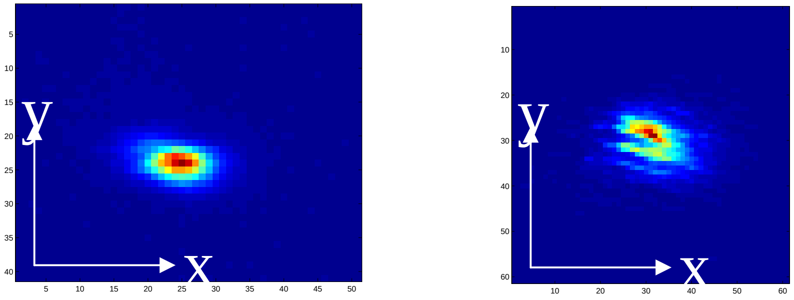
Optical Transition
Radiators

Cherenkov
Radiator

Dump

Imaging Spectrometer
25 m

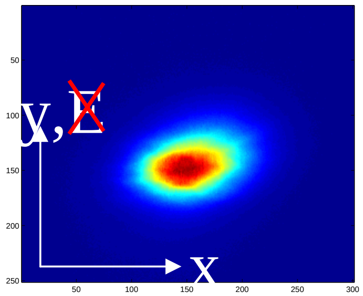
- Optical Transition Radiation (OTR)



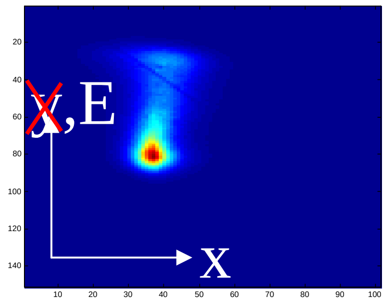
- 1:1 imaging, spatial resolution <9 µm

- CHERENKOV (aerogel)

E-157:



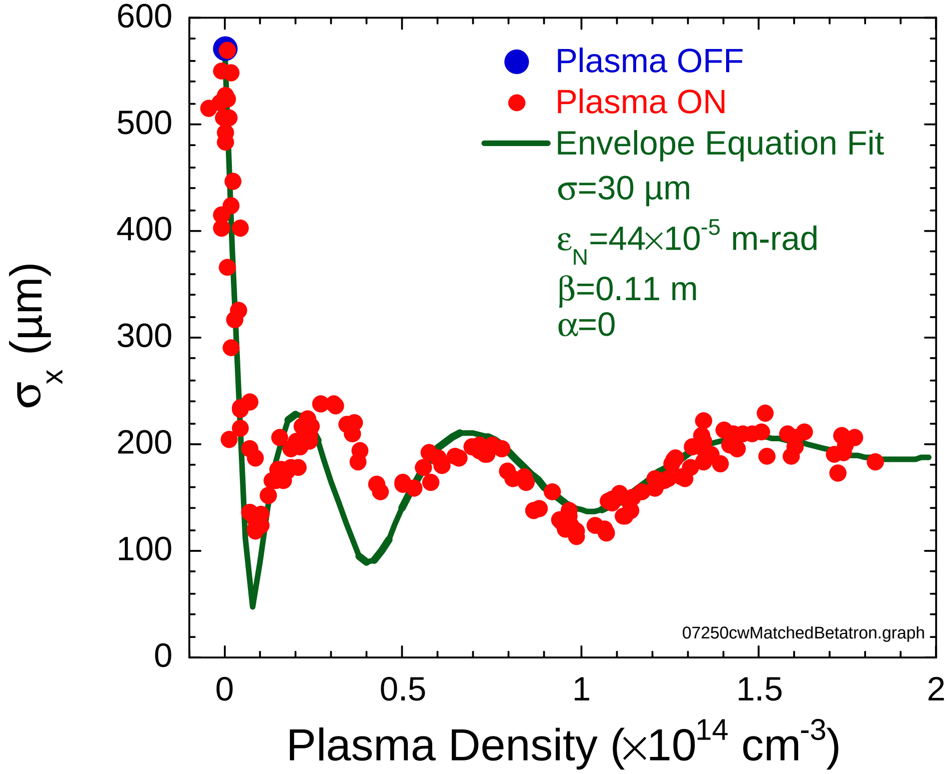
E-162:



- Spatial resolution ≈100 µm
- Energy resolution ≈30 MeV
- Time resolution: ≈1 ps

CHANNELING OF e^-

OTR Images ≈1m downstream from plasma



Envelope equation:

$$\frac{\partial^2\sigma}{\partial z^2}+\left(K^2-\frac{\varepsilon^2}{\sigma^3}\right)\sigma^2=0$$

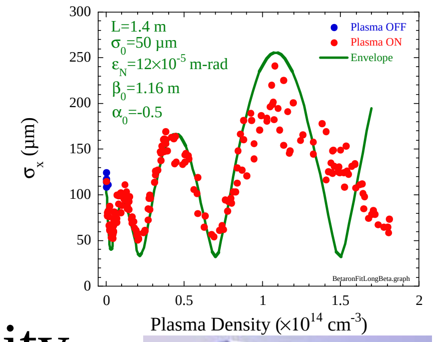
In an ion channel:

$$K=\frac{\omega_{pe}}{\sqrt{2\gamma c}}\propto\left(n_e\right)^{1/2}$$

Beam-plasma matching:

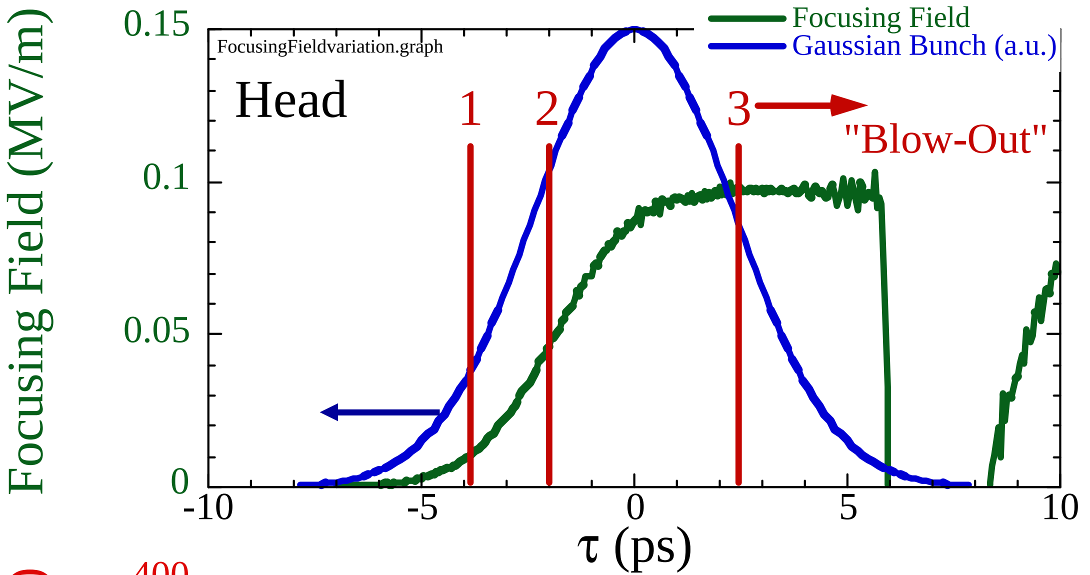
$$K^2=\frac{n_e e^2}{\varepsilon_0 m_e 2\gamma c^2}=\frac{\varepsilon^2}{\sigma^4}$$

Not matched



- $n_{e,\,matched}=2.5\times10^{14}$ cm^{-3}
- σ insensitive to n_e at matching, stabilize hose instability
- Channeling of the beam over 1.4 m or >12β_0

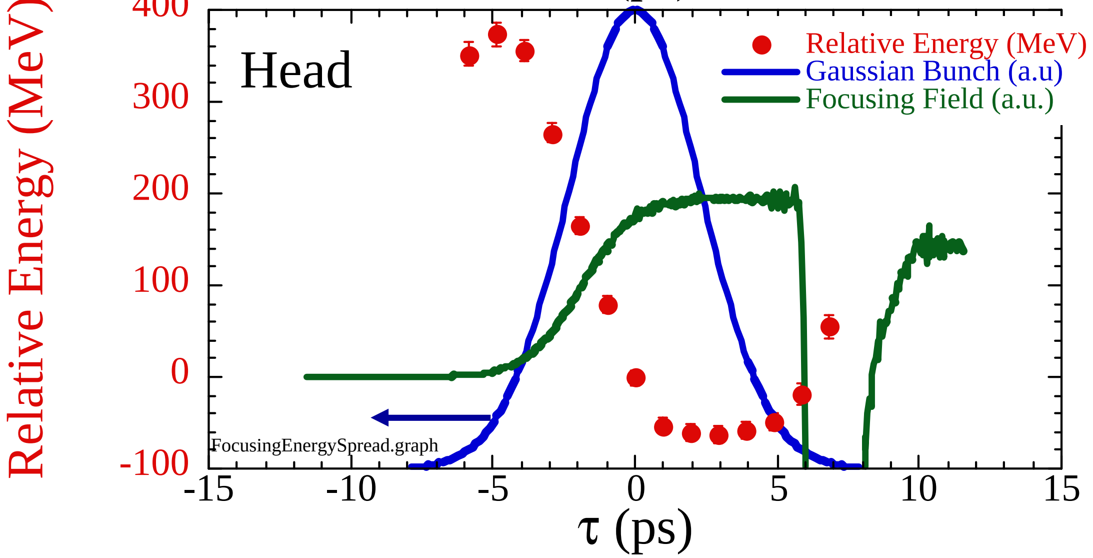
DYNAMIC FOCUSING WITHIN e^- BUNCH



- Channel Formation

⇓

Dynamic Focusing

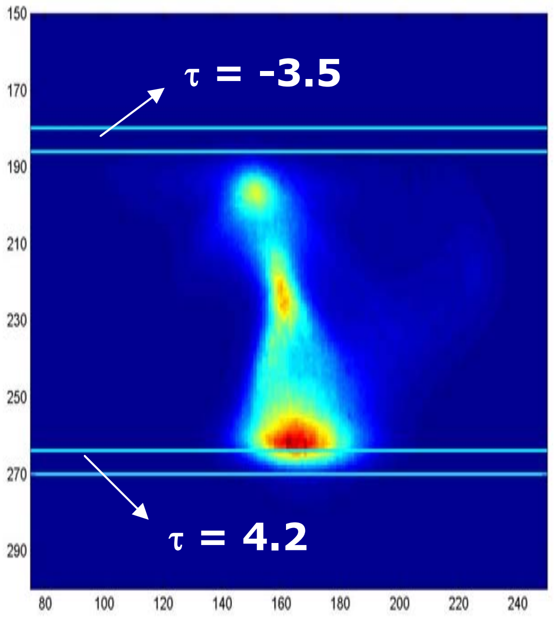


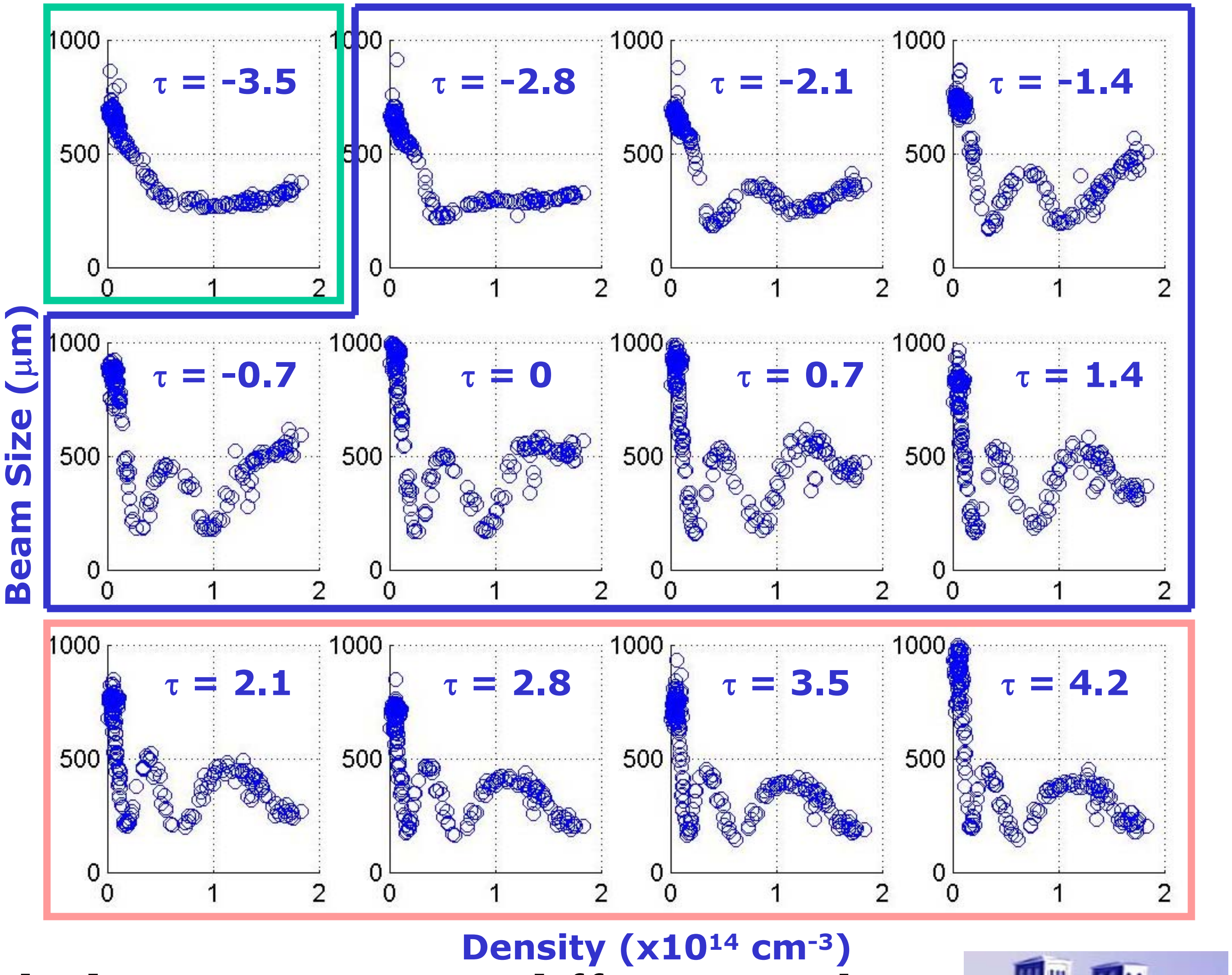
- Correlated Energy Spread

⇓

Space-Time Correlation after Energy Dispersion

DYNAMIC FOCUSING WITHIN e$^-$ BUNCH





☐ = **Head**

☐ = **Middle**

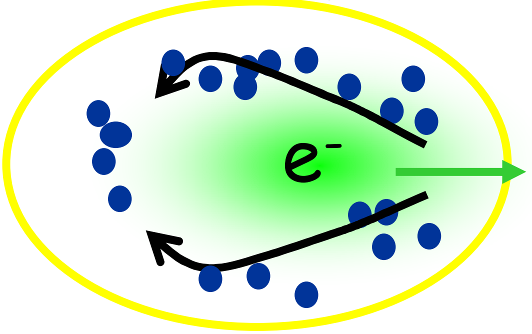
☐ = **Blowout**

- Different *t* or *z* bunch slices experience a different number of betatron oscillations

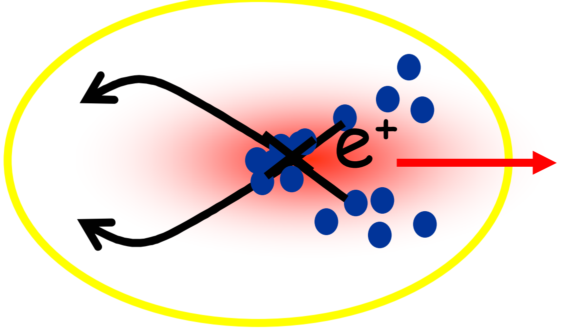
C. O'Connell *et al.*, PRST-AB (2002)

e^- & e^+ BEAM NEUTRALIZATION

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



σ_r=35 μm
σ_r=700 μm
N=1.8×10^{10}
d=2 mm



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

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

Blow Out

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

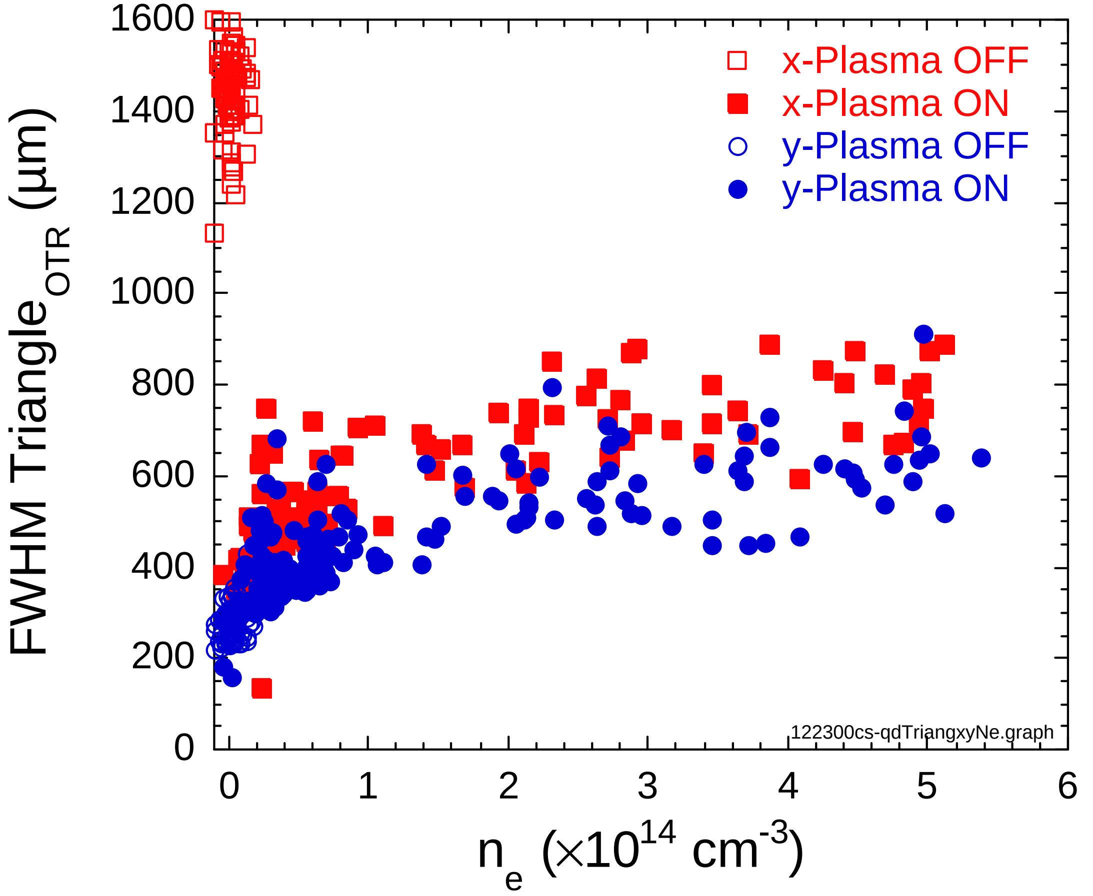
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

- Uniform focusing force (r,z)

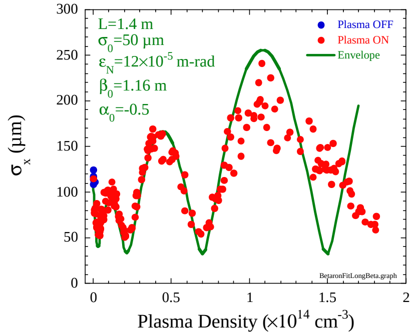
- Non-uniform focusing force (r,z)

FOCUSING OF e^-/e^+: HIGH n_e

- from OTR images ≈1m from plasma exit



for e^-:



- Focusing limited by emittance growth due to plasma focusing aberrations?

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

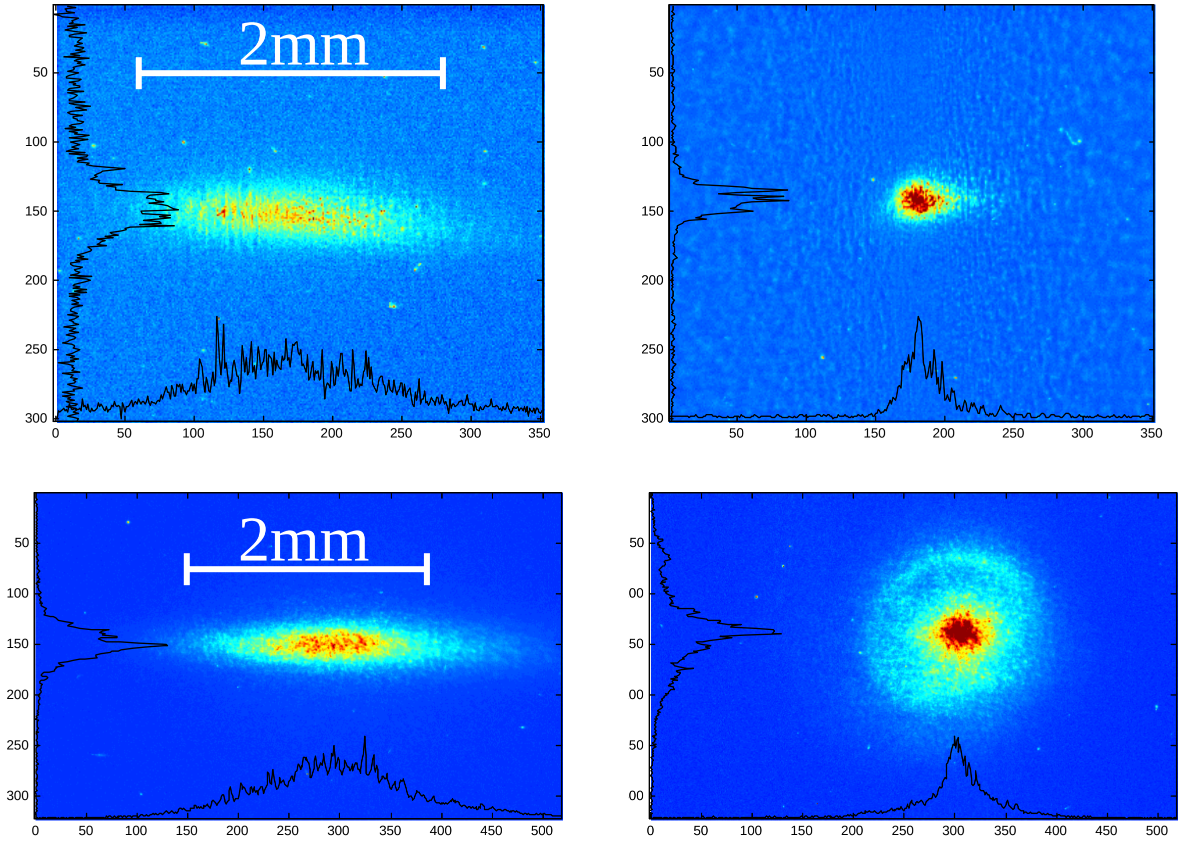
FOCUSING OF e$^-$/e$^+$

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

n_e=0 $n_e \approx 10^{14}$ cm^{-3}

e$^-$

e$^+$

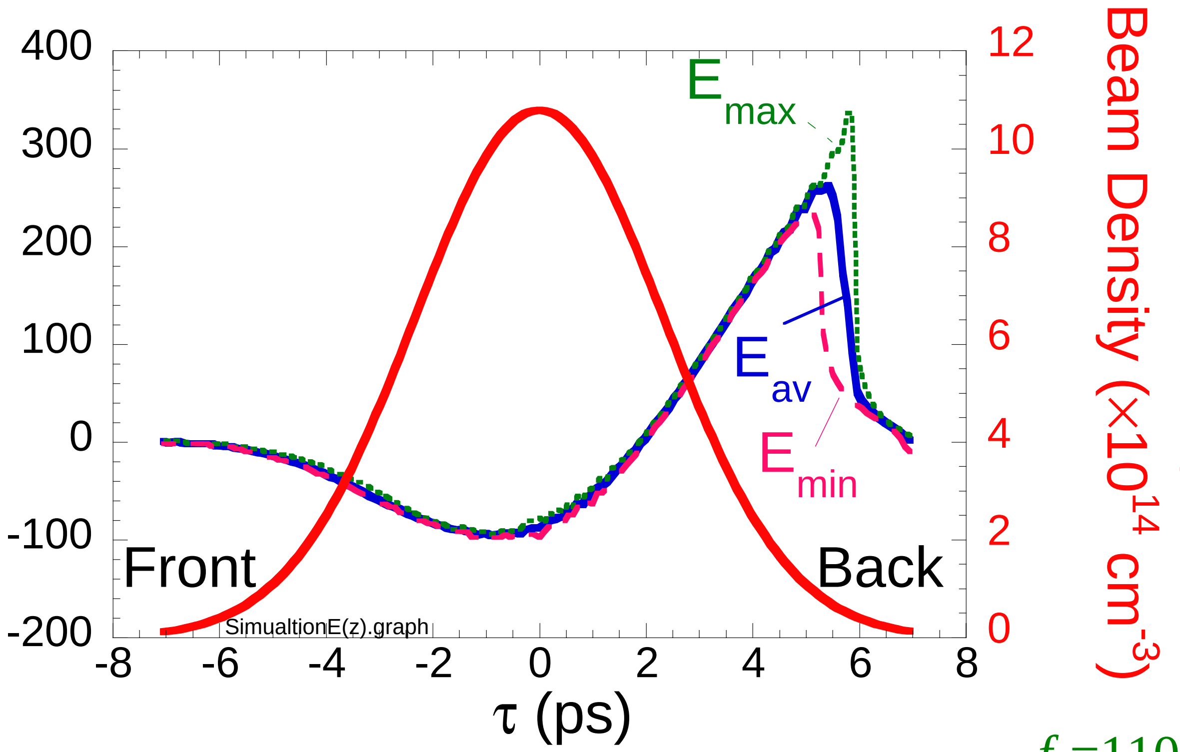


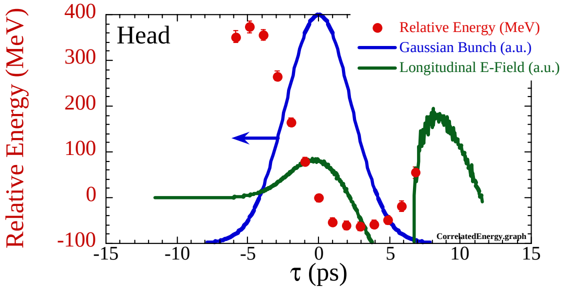
- Ideal Plasma Lens in Blow-Out Regime

- Plasma Lens with Aberrations

EXPECTED ENERGY LOSS/GAIN, e^-

2-D OSIRIS PIC simulation: L=1.4 m, n_e=1.5×10^{14} cm^{-3}, σ_z=40 µm



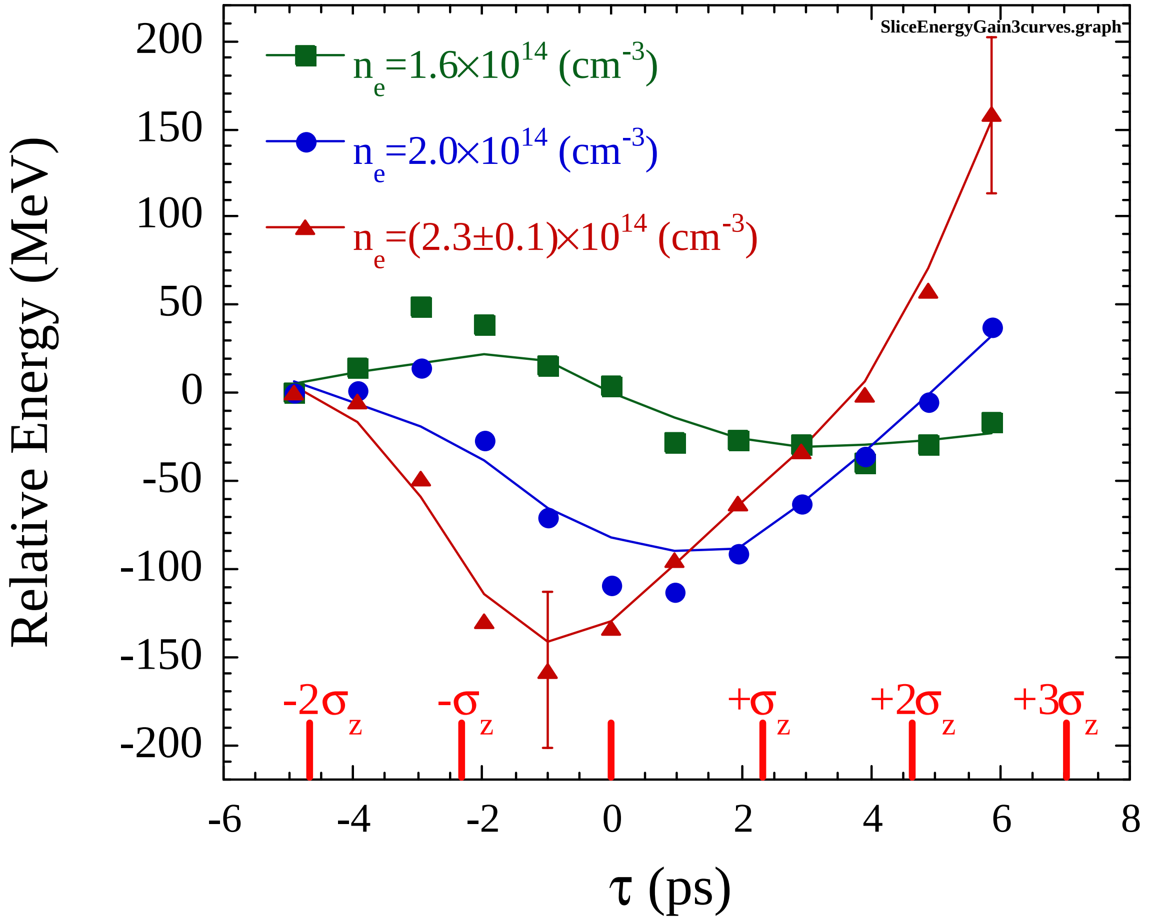


f_p=110 GHz @ n_e=1.5×10^{14} cm^{-3}

- Expected energy loss: 95 MeV (average)
- Expected energy gain: 260 MeV (average), 335 MeV (peak)
- Expected energy gain < incoming correlated energy spread => need time discrimination

ENERGY GAIN/LOSS AVERAGE, e^-

ps slice analysis results



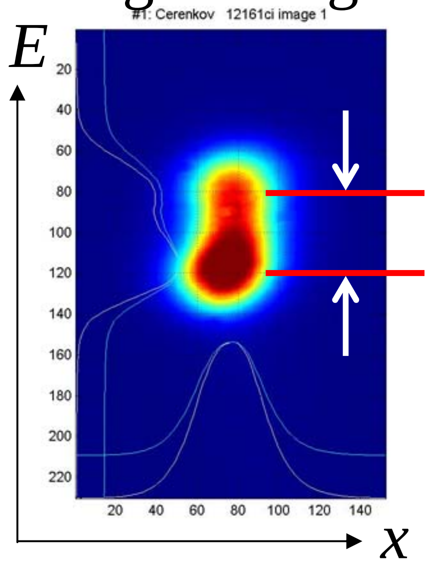
- Average energy loss (slice average): 159±40 MeV
- Average energy gain (slice average): 156 ±40 MeV (≈3×10^7 e^-)
- Events/particles to more than 250 MeV

P. Muggli, SLAC-DoE, 04/10/03

ENERGY LOSS/GAIN LOW CHARGE, e+USC

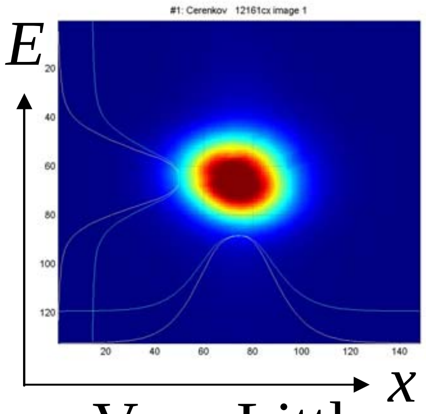
Cerenkov images => energy spectrum

Design Charge: 2×10^{10}



Energy Spread≈1.5%

Low Charge: 1.2×10^{10}



Very Little Energy Spread

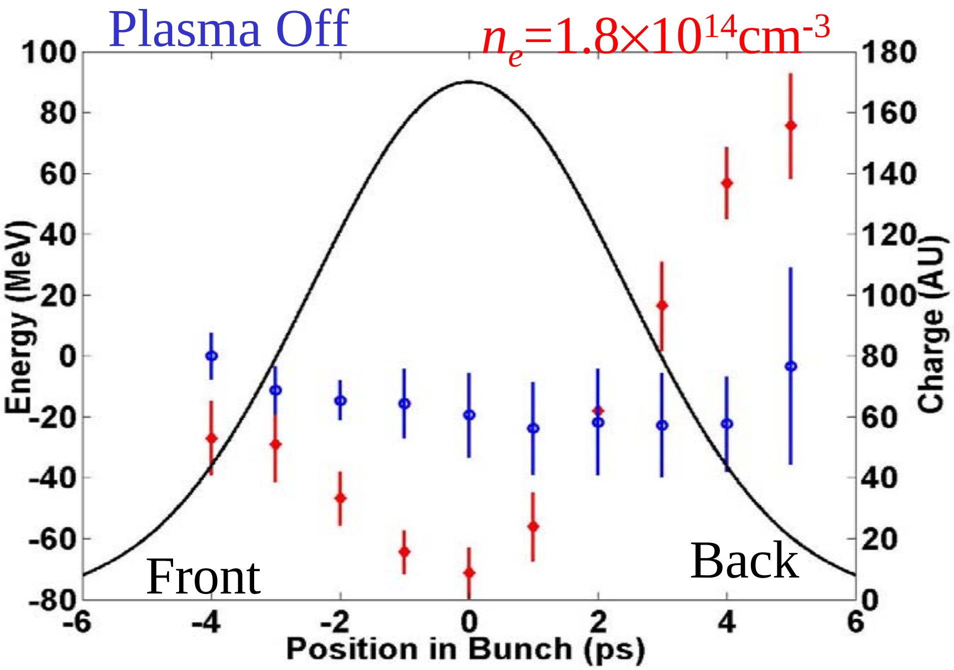
e^+- beam:	
E	28.5 GeV
N	1.2×10^{10} e^+
σ_z	0.73 mm
σ_r	40 µm
ε_{rN}	12×10^{-5} m rad

- Lower charge allows for better time dispersed energy measurements

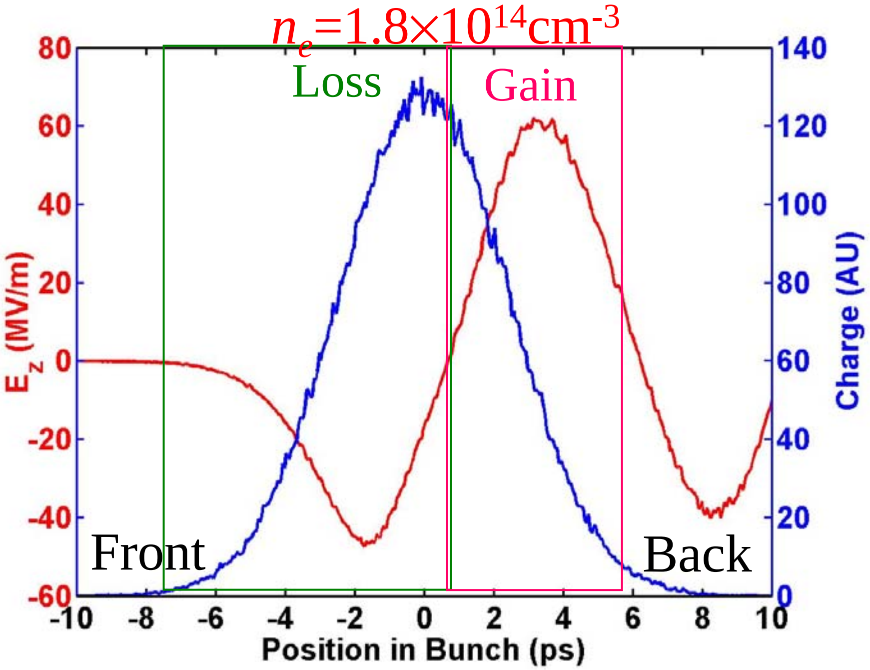
ENERGY LOSS/GAIN LOW CHARGE e^+

N=1.2×10^{10} e^+

Experiment



2-D Simulation



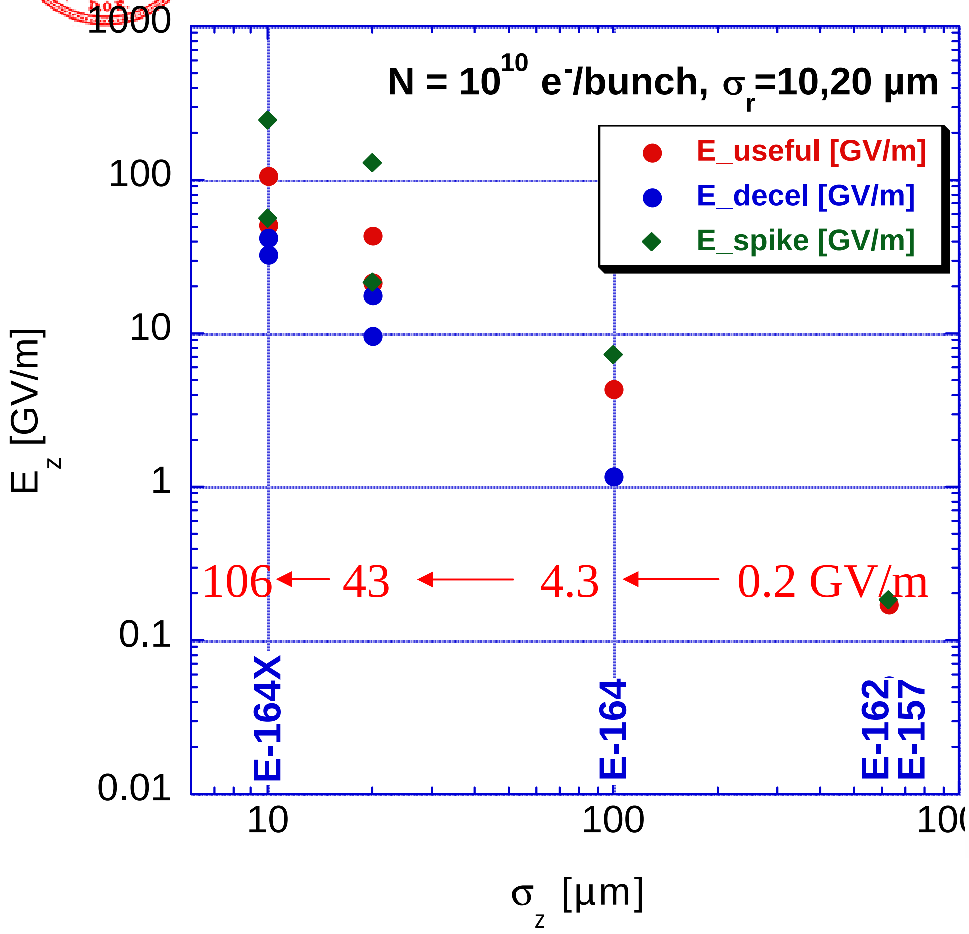
- Loss ≈ 50 MeV
- Gain ≈ 75 MeV

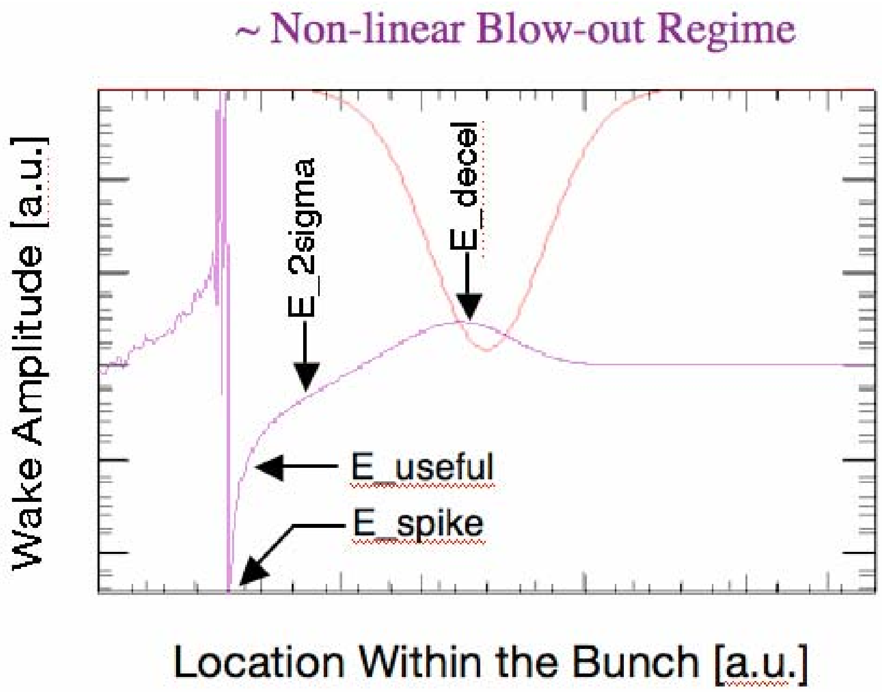
- Loss ≈ 45 MeV/m × 1.4 m=63 MeV
- Gain ≈ 60 MeV/m × 1.4 m=84 MeV

- Excellent agreement!

B. Blue *et al.*, submitted to PRL

NUMERICAL SIMULATIONS: E-164/X , e-



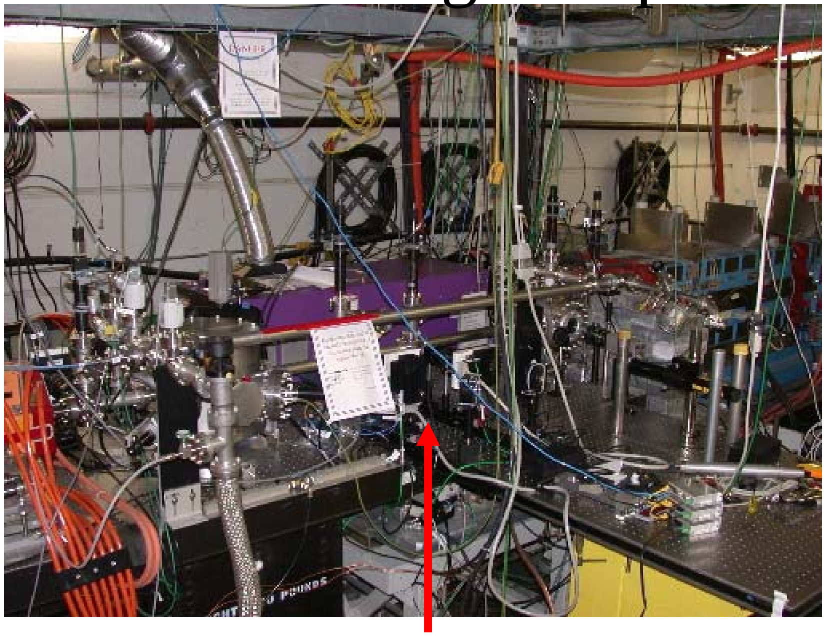


- E-164X: σ_z=20-10 µm: >10 GV/m acceleration! (σ_r dependent!)
- Plasma length, energy gain limited by FFTB dump line acceptance

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

E-164: RIGHT NOW!

Beam tuning set up



OTRs at plasma entrance/exit

Lithium plasma source

UV-photo-ionized plasma

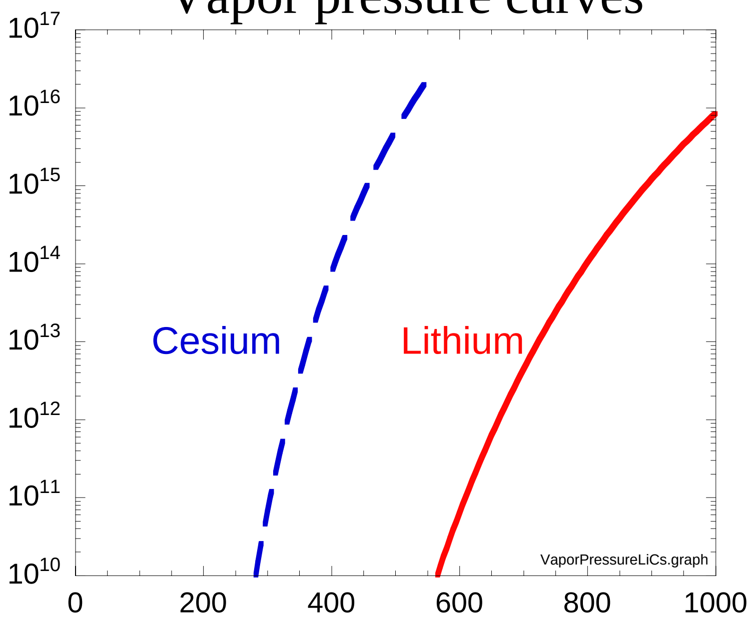
- Goal: >1 GeV over 30 cm (4 GeV/m)
- Plasma length, energy gain limited by FFTB dump line acceptance

$f_p \approx 700$ GHz, W=3MT/m @ $n_e = 5\times10^{15}\ cm^{-3}$

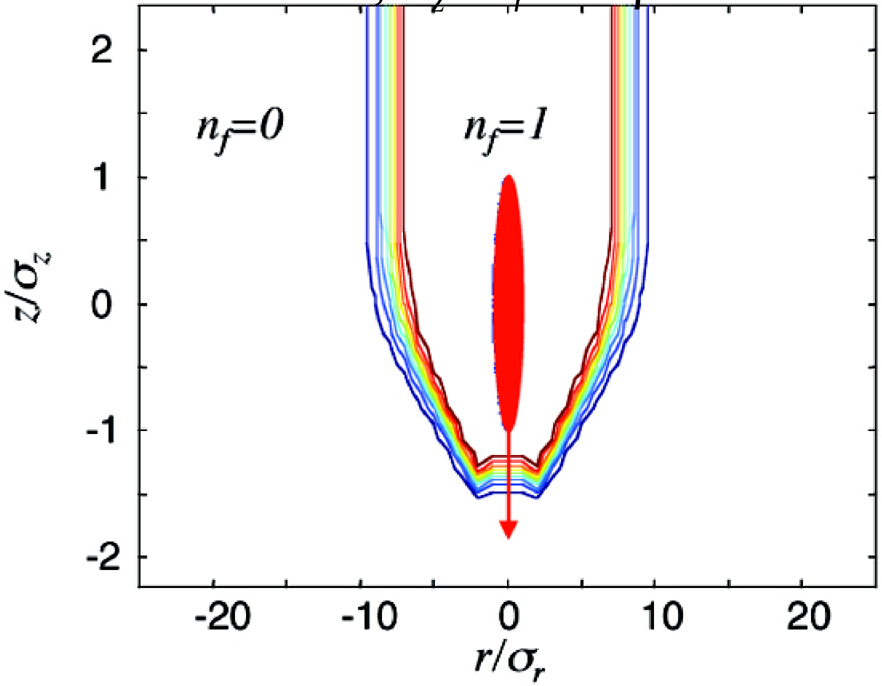
E-164X: BEAM-IONIZED PLASMA

- Plasma source: $n_e L$ limited by laser fluence and absorption
- Relativistic plasma electrons=> $n_e >$ given by $k_p\sigma_z \approx \sqrt{2}$ $n_e \approx 10^{16}$-10^{17} cm^{-3}
- Short bunch, $E_r \approx 5.2\times 10^{-19} N/\sigma_z\,\sigma_r$ (GV/m) > tunneling field (Kyldish, ADK)

Vapor pressure curves



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



- Plasma density = neutral density (n_f=1), easier, more stable!
- Channeling+long plasma+large gradient=large energy gain!

5^+ YEARS

- Propagation in long field ionized plasmas, large energy gains

- Stability against hose the instability

- Two-bunch experiments: - wake loading
  (ORION) - beam quality (ε, $\Delta E/E$, ...)

- ... “Pre-After-Burner”

SUMMARY

- E-157/162 built a PWFA laboratory for 30 GeV beams
- Wealth of important results:
  - Beam refraction, Muggli *et al.*, Nature 2001
  - Electrons transverse dynamics, Clayton *et al.*, PRL 2002
  - High brightness X-ray emission, Wang *et al.*, PRL2002
  - Focusing dynamics, O'Connell *et al.*, PRSTAB 2002
  - Positrons dynamic focusing, Hogan *et al.*, PRL 2003
  - Acceleration of positrons, Blue *et al.*, submitted to PRL
  - Acceleration of electrons, Muggli *et al.*, in preparation
- E-164: 1 GeV energy gain over 30 cm, PWFA σ_z scaling law
- E-164X: Ultra short bunches, ultra-high gradients in field-ionized plasmas
- Two-bunch experiments, hose instability, ultra-high energy gains, after-burner.