Beam-plasma Physics
Experiments at the FFTB

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OUTLINE

- Introduction to plasma wakefield/Motivation
- Propagation of e^--beams in plasmas
- Radiation source/Plasma wiggler
- e^- energy gain
- Trapped particles
- Two-bunch experiment
- What about e^+ in plasmas?
- Summary/Conclusions

THANK YOU
to my colleagues
of the *E-167* Collaboration:

I. Blumenfeld, F.-J. Decker, P. Emma, M. J. Hogan, R. Iverson, R. Ischebeck, N.A. Kirby, P. Krejcik, R.H. Siemann, D. Walz

Stanford Linear Accelerator Center

D. Auerbach, C. E. Clayton, C. Huang, C. Joshi, K. A. Marsh, W. B. Mori, W. Lu, M. Zhou

University of California, Los Angeles

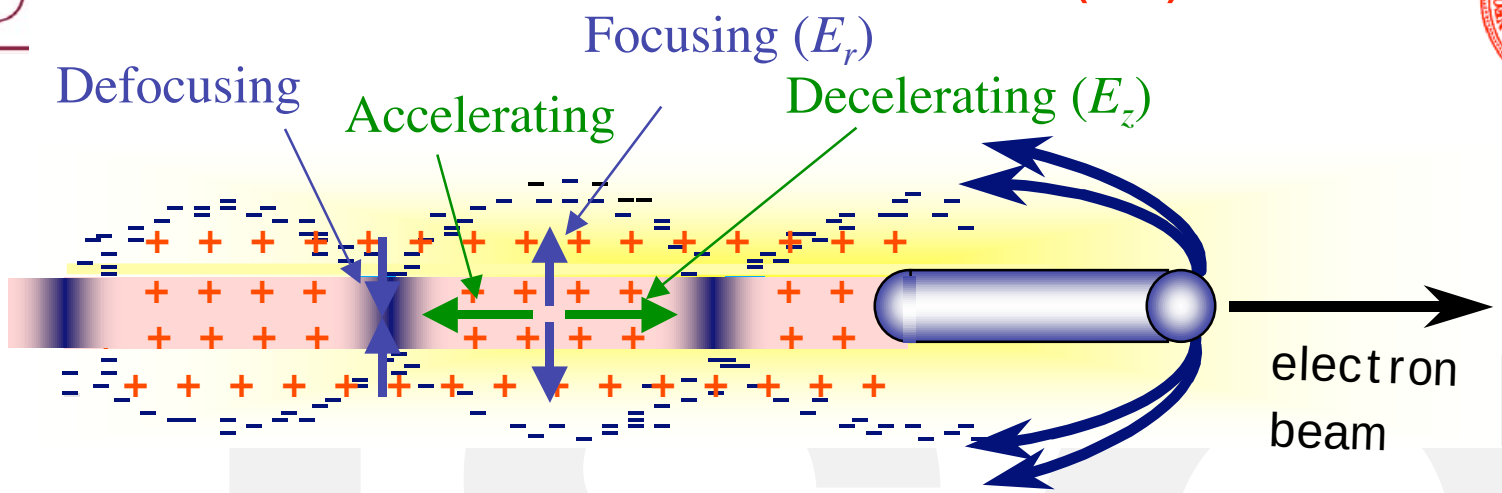
T. Katsouleas, E. Oz, P. Muggli

University of Southern California

and of the *E-157/162/164/164X* Collaborations

THANK YOU
to SLAC

PLASMA WAKEFIELD (e^-)

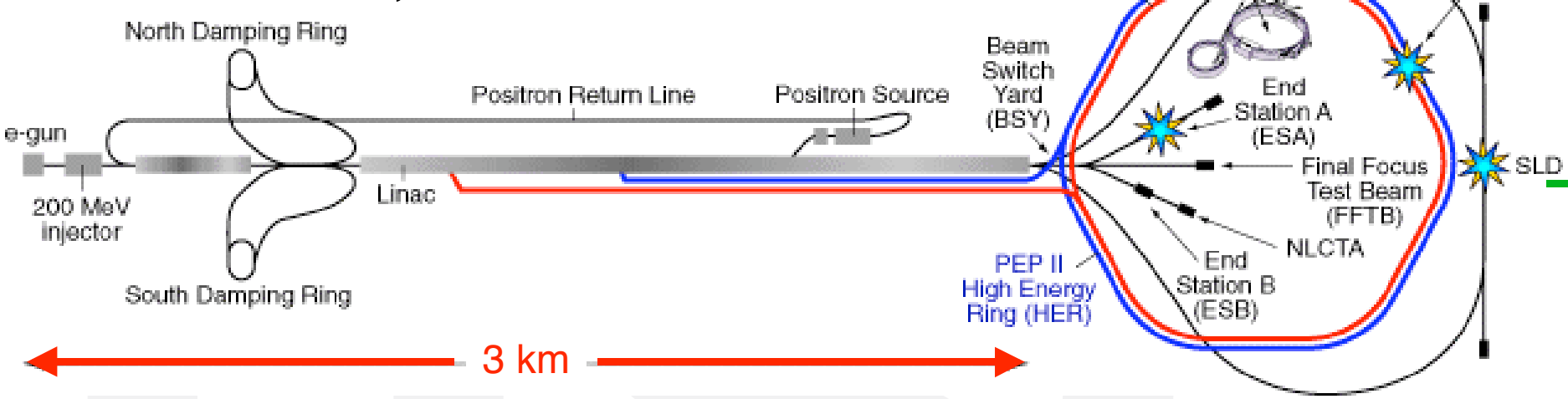


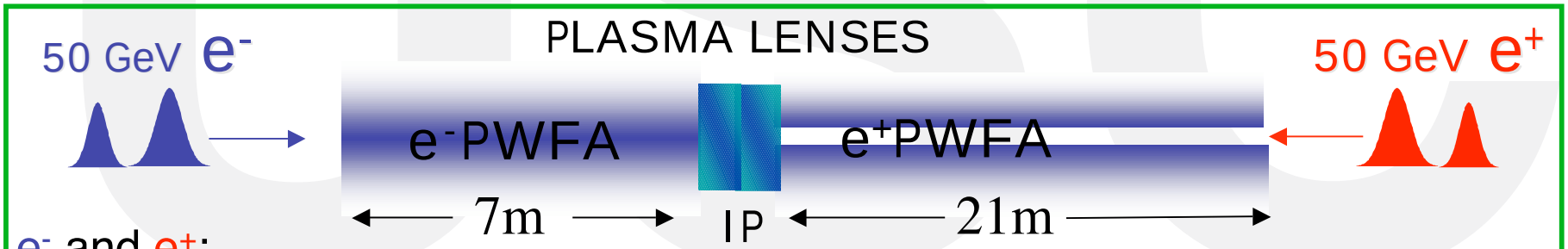
- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces => energy loss + focusing
- Transverse oscillations => radiation keV to MeV photons
- Plasma e^- rush back on axis => energy gain
- Large wakefield => trapping of plasma e^-
- Optimize for acceleration or focusing or radiation source
- PWFA: high-frequency, high-gradient, strong focusing beam-driven accelerator

PLASMA AFTERBURNER

(SLC EXAMPLE)

100+ GeV, e-/e+ Collider



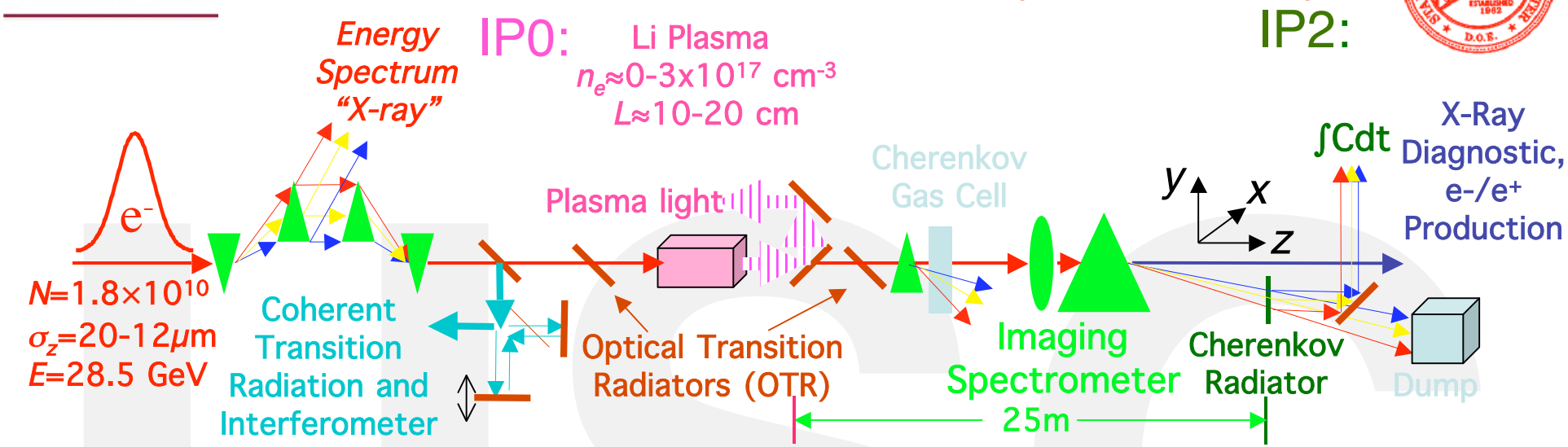


e- and e+:

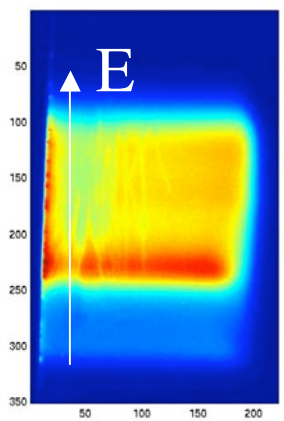
Driver bunches:	σ_z=63 μm, σ_r=5 μm, N=3×10^{10} e-/e+, 50 -> 0 GeV
Witness bunches:	σ_z=32 μm, σ_r=5 μm, N=1×10^{10} e-/e+, 50 -> 100+ GeV
Delay:	d=200 μm
Plasma:	n_e=1.8 ×10^{16} cm^{-3}, L=7, 21 m
Accelerating gradient:	8, 3 GV/m

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

EXPERIMENTAL SET UP (GENERIC)



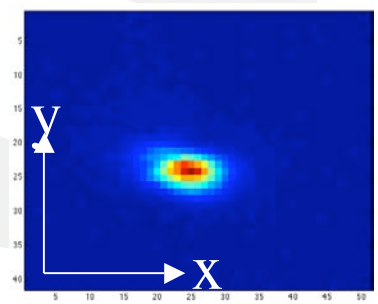
- X-ray Chicane



-Energy resolution ≈60 MeV

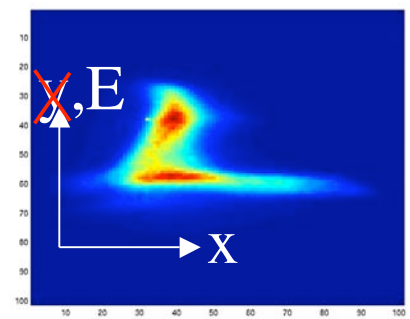
- Coherent Transition Radiation (CTR)
  - CTR Energy≈I_{peak}≈$1/\sigma_z$

- OTR



-Spatial
-resolution ≈9 μm

- Cherenkov (aerogel)



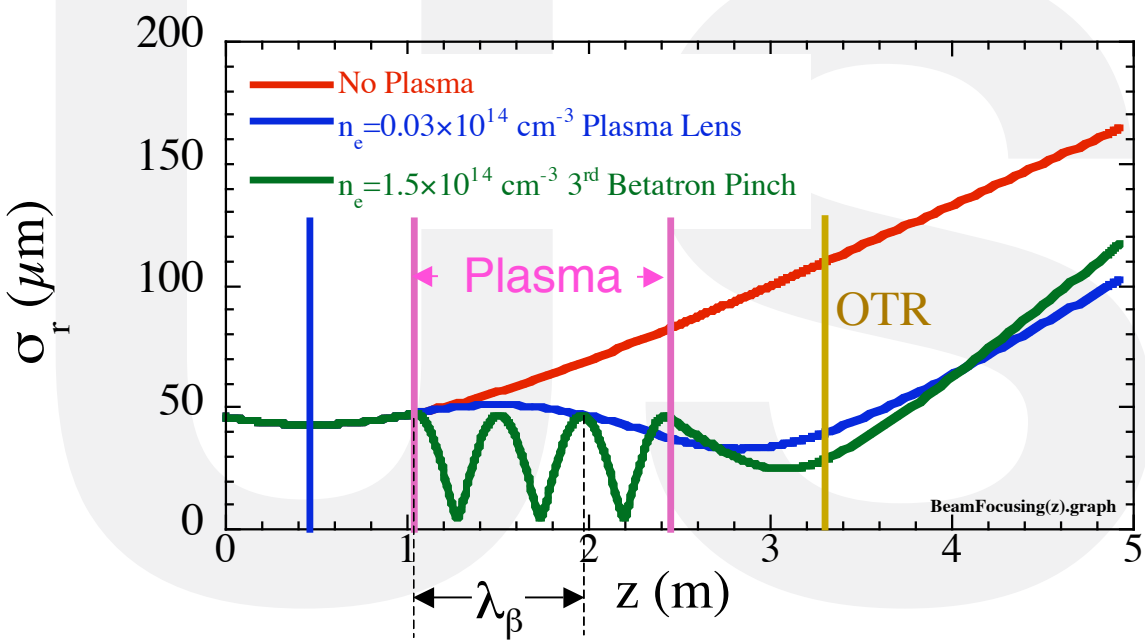
- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV

PROPAGATION OF e^-

Beam Envelope Model for Plasma Focusing

Plasma Focusing Force > Beam "Emittance Force"

$(\beta_{beam}=1/K > \beta_{plasma})$



Envelope equation:

$$\frac{\partial^2\sigma}{\partial z^2} + K^2\sigma = \frac{\varepsilon^2}{\sigma^3}$$

In an ion channel:

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

with a focusing strength:

$$W = \frac{E_r}{rc} = \frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c}$$

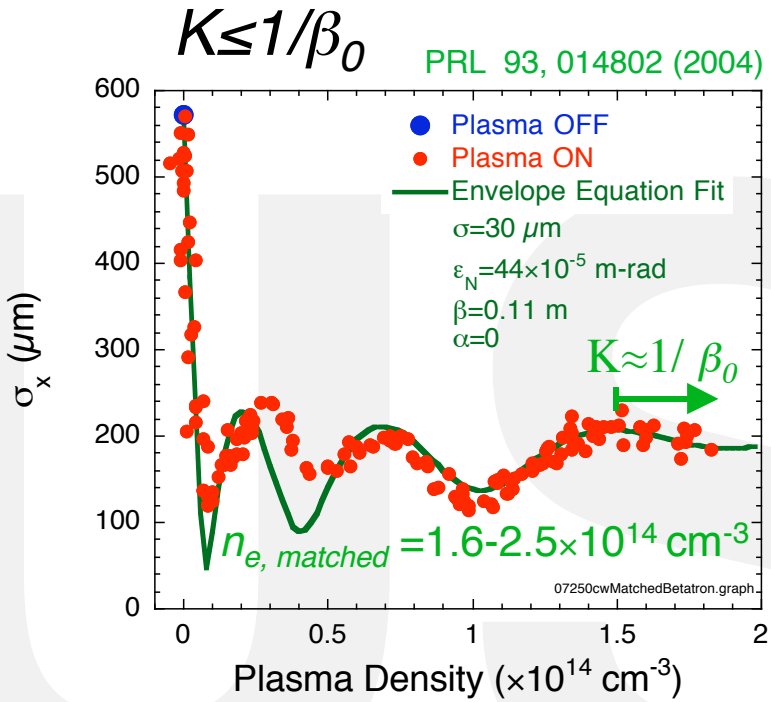
=6 kT/m @ $n_e=2\times10^{14}$ cm^{-3}

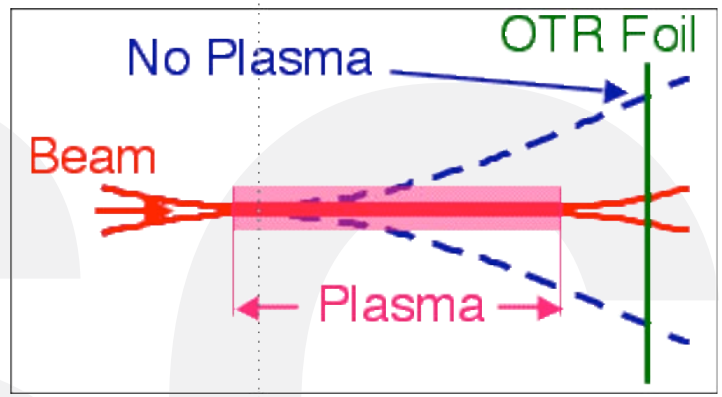
=6 MT/m @ $n_e=2\times10^{17}$ cm^{-3}

- Multiple foci (betatron oscillation) within the plasma
- Synchroton "betatron" radiation

PROPAGATION OF e^-

OTR Images ≈1m downstream from plasma





Matching condition:

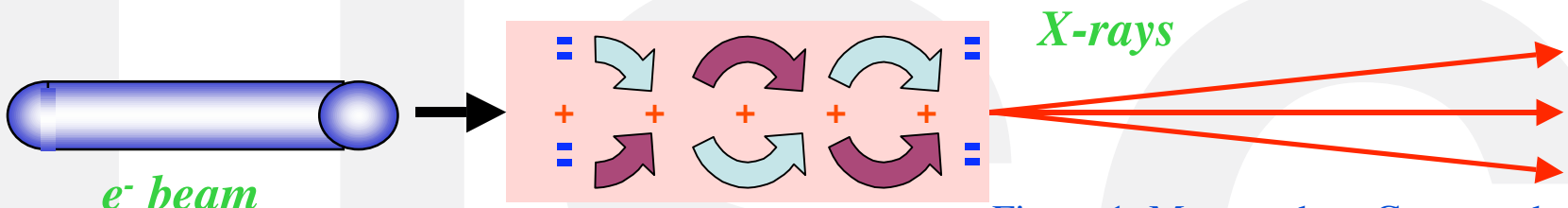
$$\frac{\sigma^2 n_e}{\varepsilon\gamma} = \frac{\varepsilon_0 m_e c}{2e^2}$$

- Focusing of the beam well described by a simple model ($n_b > n_e$): Plasma = Ideal Thick Lens
- No emittance growth observed as n_e is increased
- Stable propagation over L=1.4 m up to as n_e =1.8×10^{14}cm^{-3}
- Channeling of the beam over 1.4 m or >12β_0

  => Matched Propagation over long distance!

Positron Production from Betatron X-rays

- Plasma ion column acts as a "Plasma Wiggler" lead to X-ray synchrotron radiation.
- X-ray synchrotron radiation from electrons betatron oscillations.



N_p=3e17 cm^{-3}, γ=56000, r_0=10 μm,
B_θ/r= 9 MT/m , λ_β= 2cm

1) Wiggler strength:

$$K = \frac{\gamma\omega_\beta}{c} r_o = 173$$

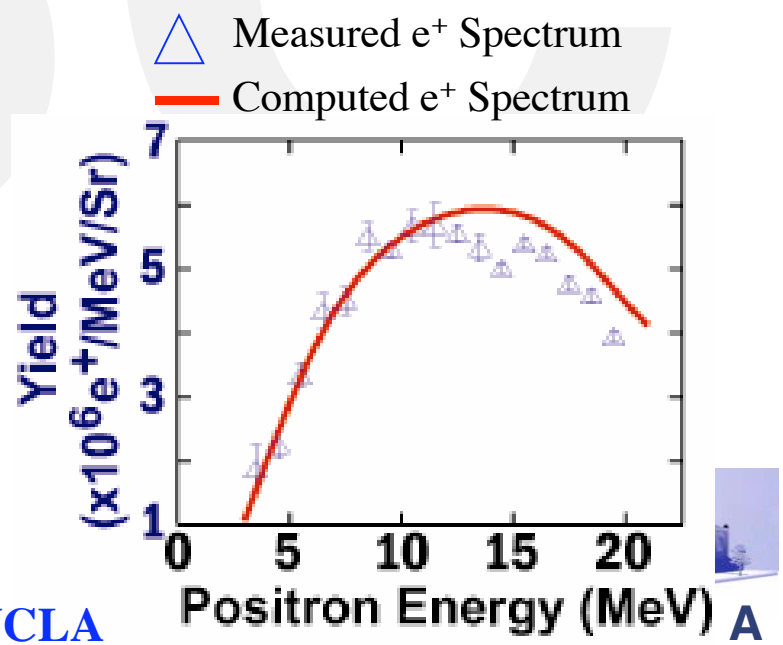
2) Critical frequency on-axis (K>>1):

$$\omega_c = \frac{3\omega_\beta^2\gamma^3}{2c} r_o = 49.6 MeV$$

3) Particle energy loss:

$$\frac{dE}{dz} = \frac{1}{3} r_e m_e c^2 \gamma^2 k_\beta^2 K^2 = 4.3 GeV/m \quad \approx r_0^2 \gamma^2 n_e^2$$

Figure 1: Measured vs. Computed e$^+$ Spectra: N_p=1E17, R_x=7μm and R_y=5μm with N_b=7.2E9 electrons in the ion column

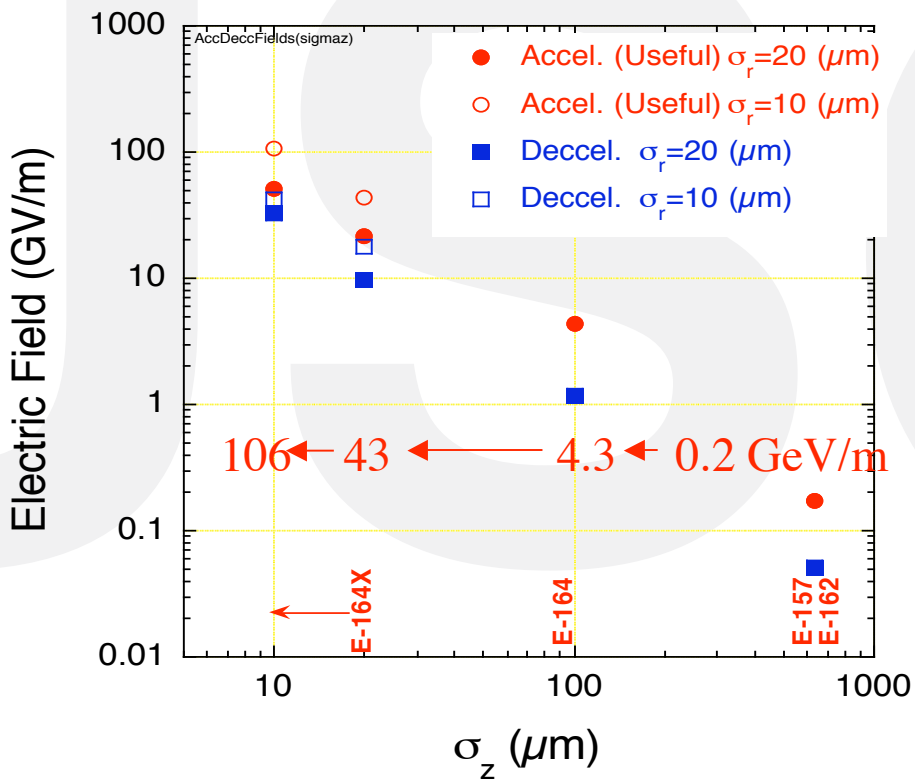


Courtesy of Devon Johnson, UCLA

ACCELERATING GRADIENT SCALING

Linear Theory: $E_{acc} \cong 110(MeV/m)\dfrac{N/2\times 10^{10}}{(\sigma_z/0.6mm)^2}$ $\approx 1/\sigma_z^2$

@ $k_{pe}\sigma_z \approx \sqrt{2}$ $(with\ k_{pe}\sigma_r << 1)$

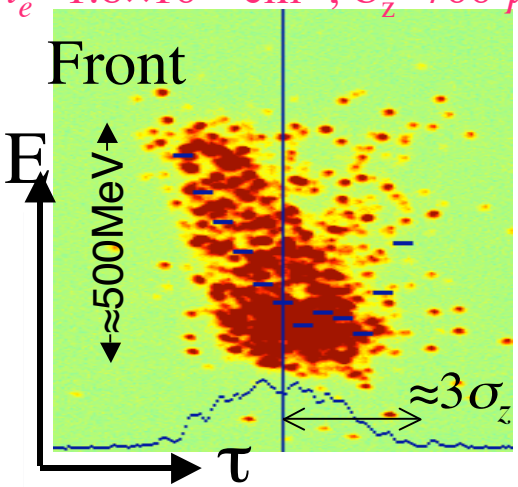


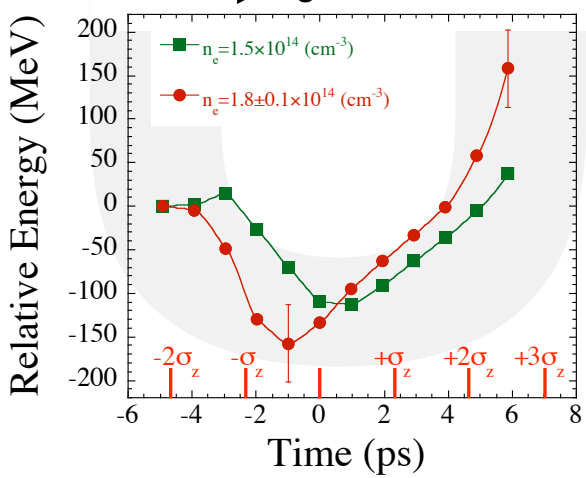
Simulation using OSIRIS, for non-linear regime: $n_b > n_0$

- Measure energy gain!

e⁻ ACCELERATION

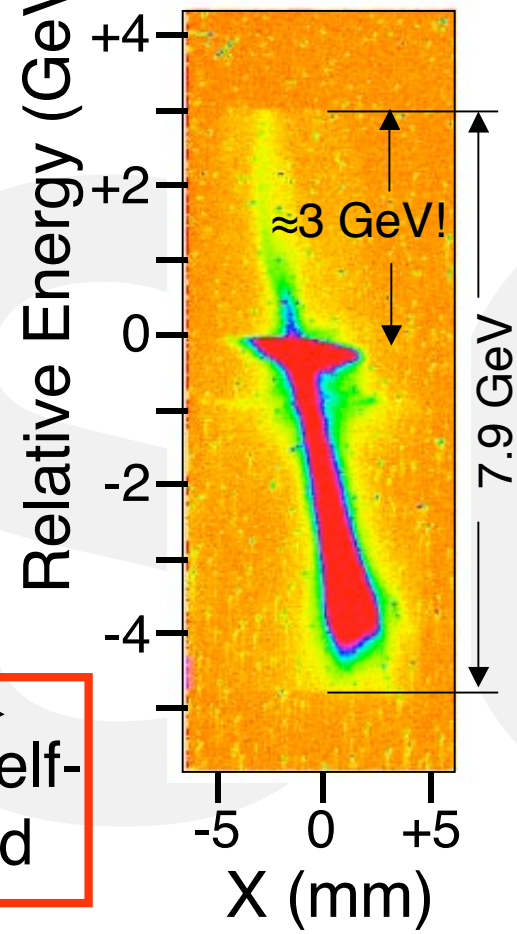
n_e=1.8×10^{14} cm^{-3}, σ_z≈700 μm

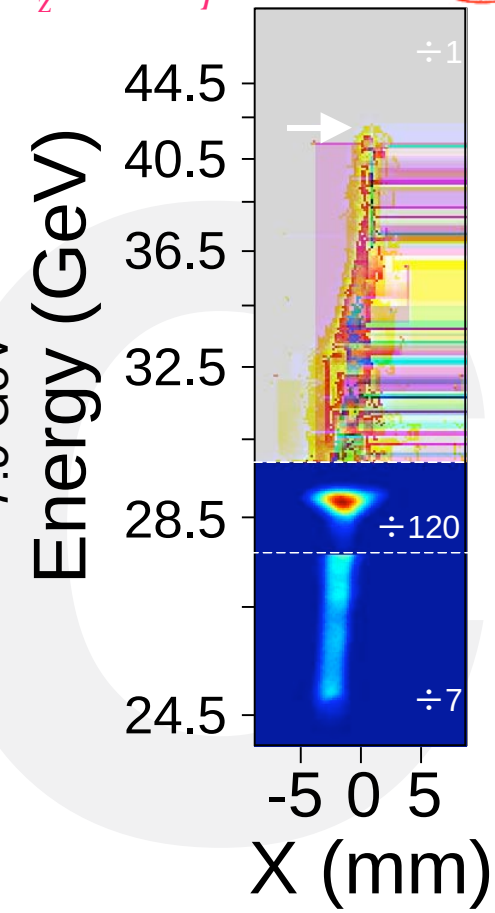




Pre- | Self-
Ionized

n_e=2.6×10^{17} cm^{-3}, σ_z≈20-30 μm

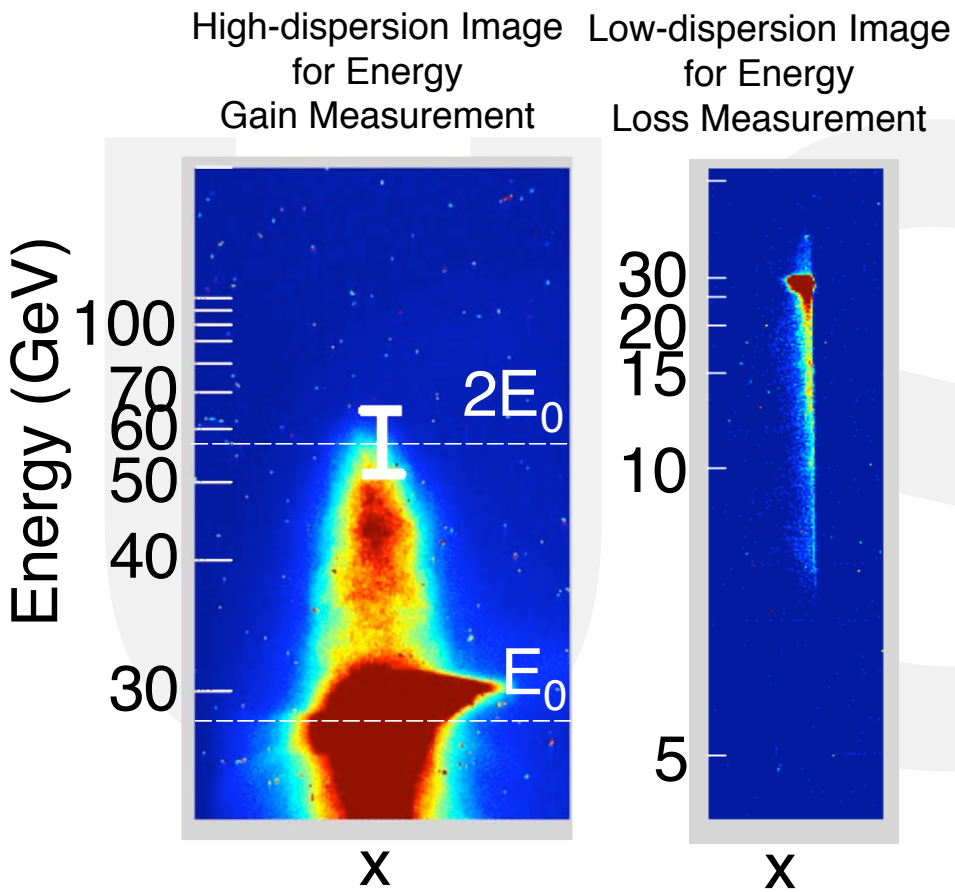


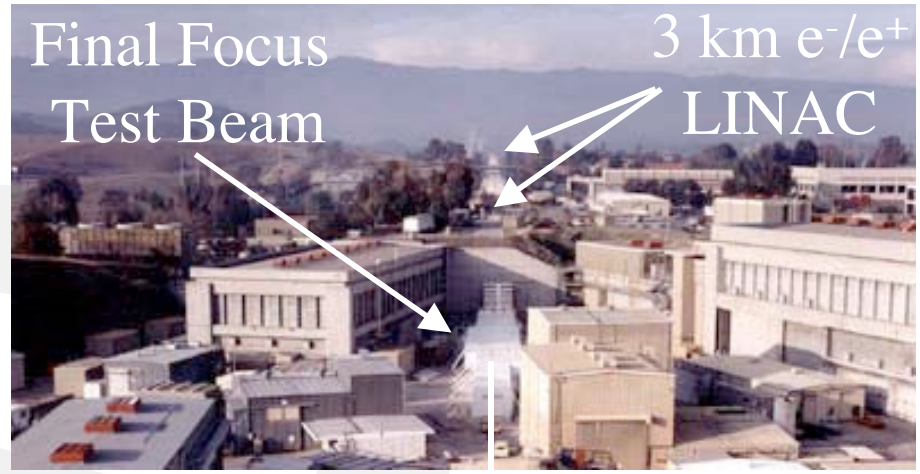


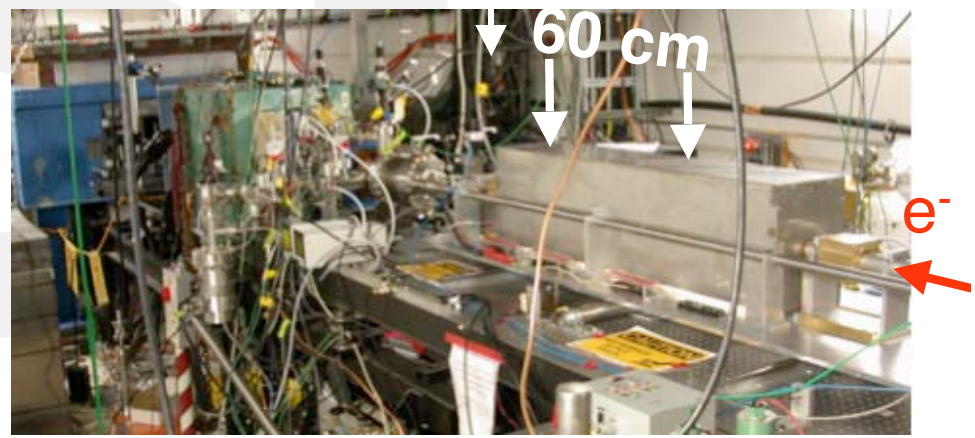
- Gain≈280 MeV, L_p=1.4m
  Gradient≈200 MV/m
  PRL 93, 014802 (2004)
- Gain≈4 GeV, L_p=10cm
  Gradient≈40 GV/m
  PRL 95, 054802 (2005)
- Gain≈14 GeV, L_p=32cm
- Scaling with bunch length and plasma length

e^- ENERGY DOUBLING EXPERIMENT

$L_p \approx 60cm$, $n_e = 2.6\times10^{17}$ cm^{-3}, $\sigma_z \approx 20\text{-}30\ \mu m$

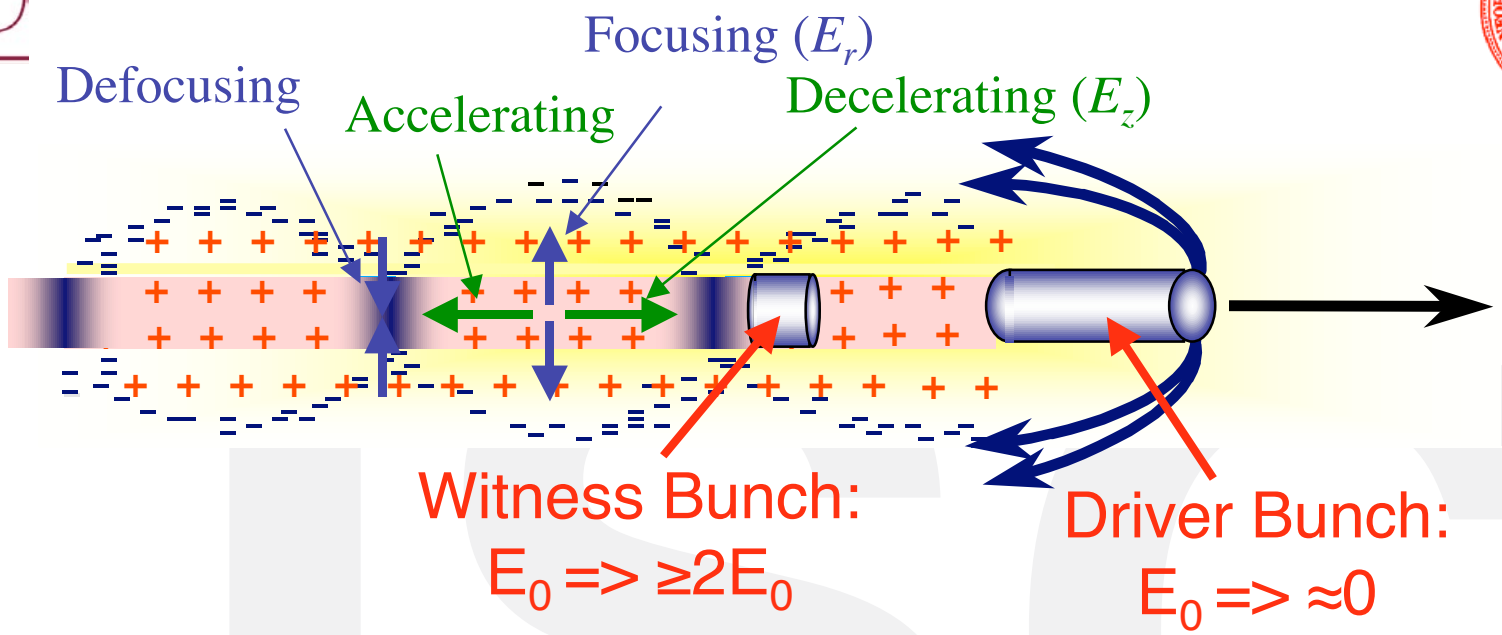






- Large energy loss and gain, as expected

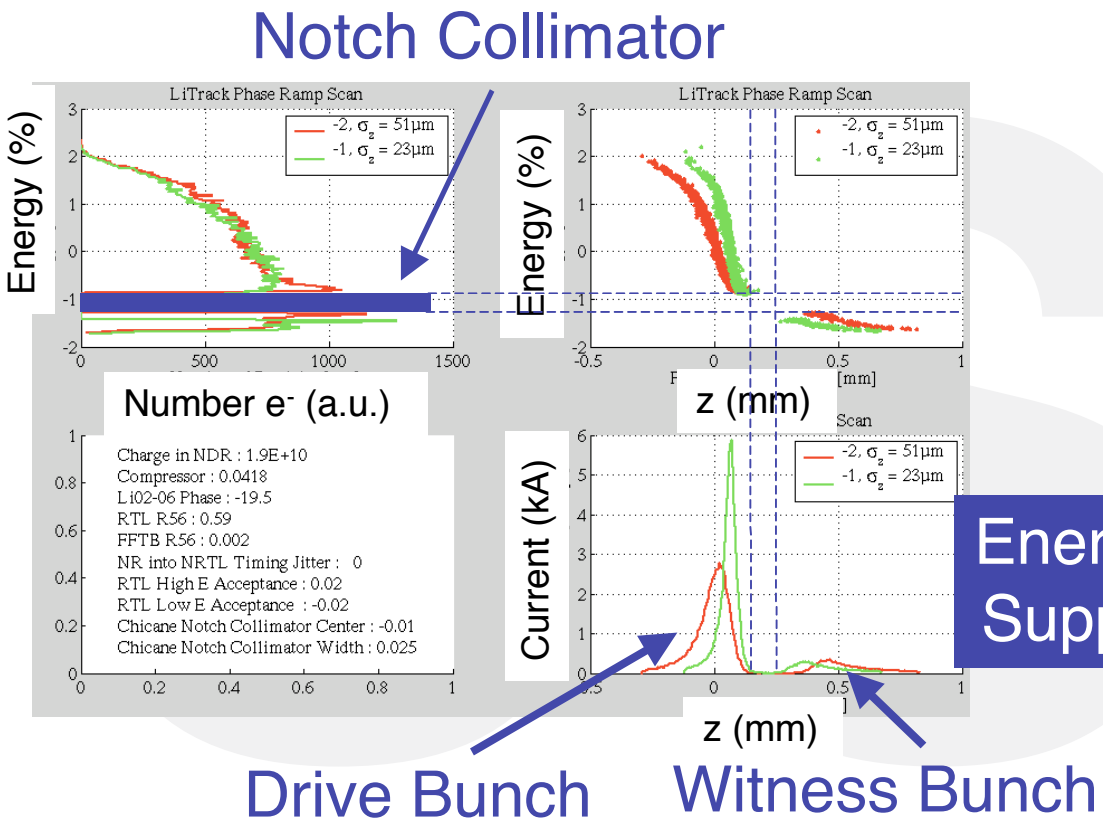
PLASMA WAKEFIELD ACCELERATOR

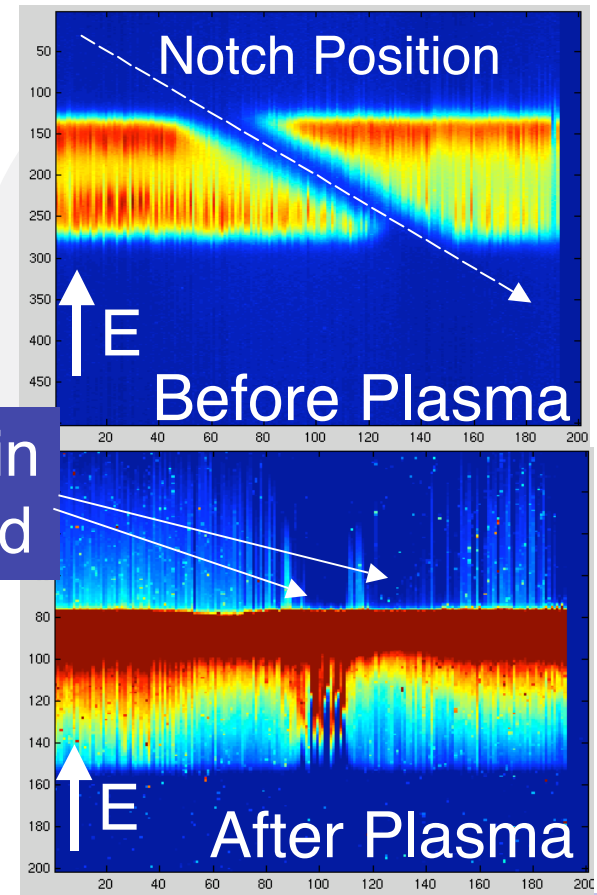


- Driver bunch: high-charge (*3N*), modest emittance, shaped?
- Witness bunch: lower charge (*N*), good emittance
  ion column focusing preserves emittance
  beam loading for $\Delta E/E \ll 1$
- Plasma provides focusing and acceleration
- Typical PWFA parameters: $n_e \approx 10^{16}$ cm^{-3}, $f_{pe} \approx 900$ GHz, $f_{pe} \approx 300$ μm
  $G \approx 10$-20 GeV/m
  $N \approx 0.5 \times 10^{10}$ e$^-$
  $\sigma_D \approx 60$ μm, $\sigma_W \approx 30$ μm, $\Delta t \approx 150$ μm

2-BUNCH GENERATION

Notch collimator in the dispersive region of the FFTB dogleg





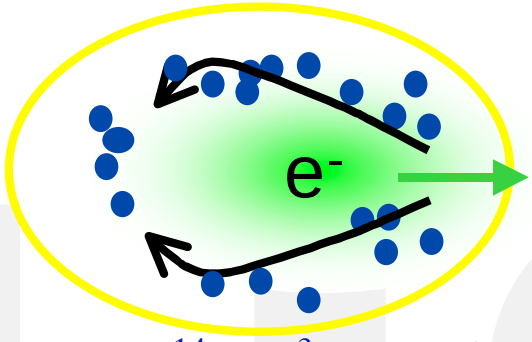
Energy Gain Suppressed

- Work in progress, transferred to SABER?

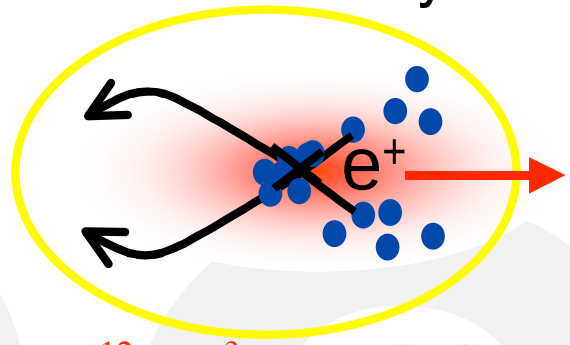
Litrack, K. Bane, P. Emma

e^- & e^+ ASYMMETRY IN PLASMAS

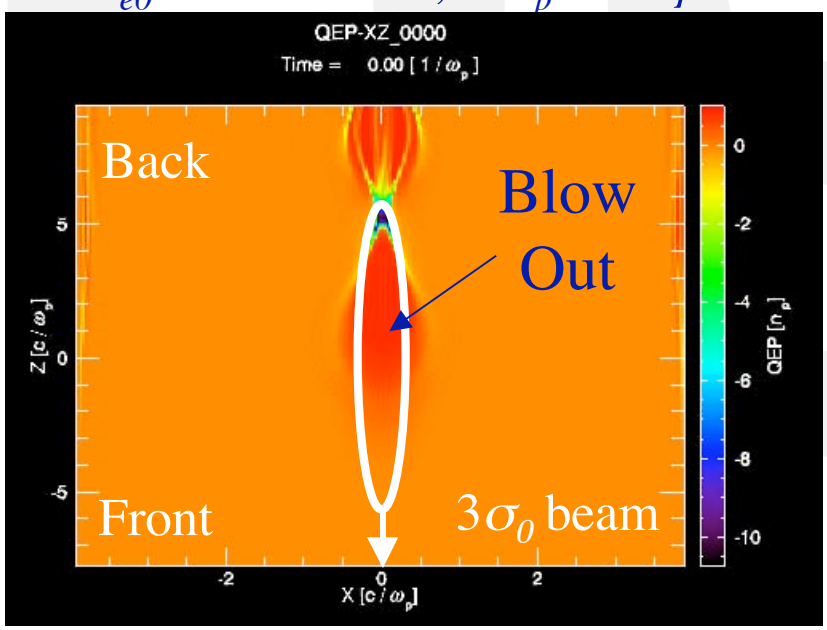
3-D QuickPIC simulations, plasma e^- density:



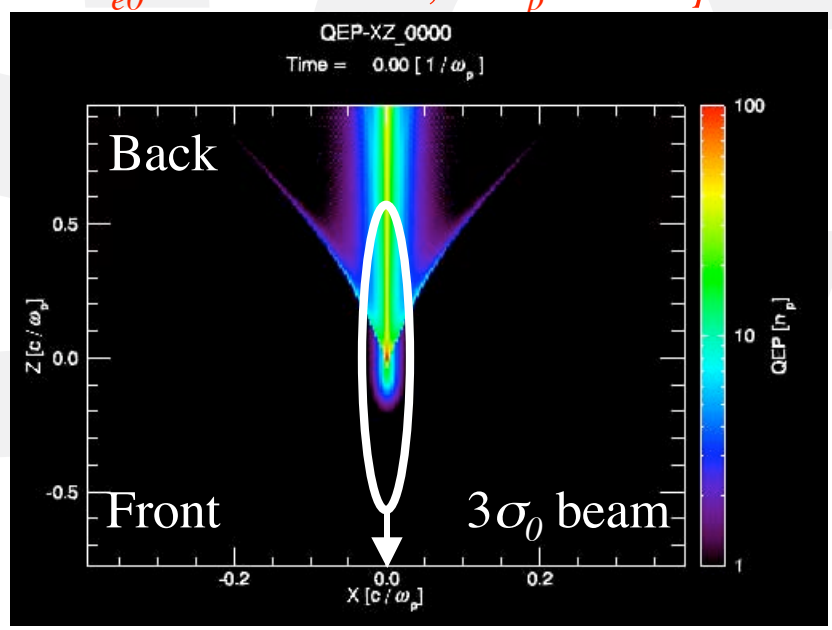
σ_r=35 μm
σ_r=700 μm
N=1.8×10^{10}
d=2 mm



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



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

e^+ PLASMA FOCUSING

E-150: J.S.T Ng *et al.*, PRL 2001

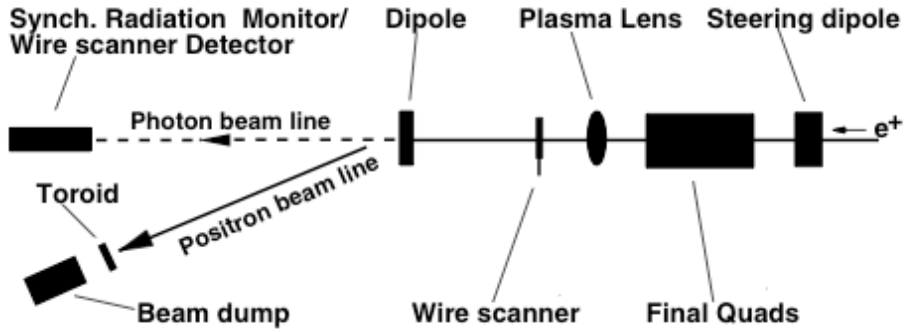


FIG. 1. Schematic layout of the SLAC Plasma Lens experiment at the FFTB. "Final Quads" are conventional focusing quadrupole magnets. The positron beam is deflected towards the dump by the magnetic dipole.

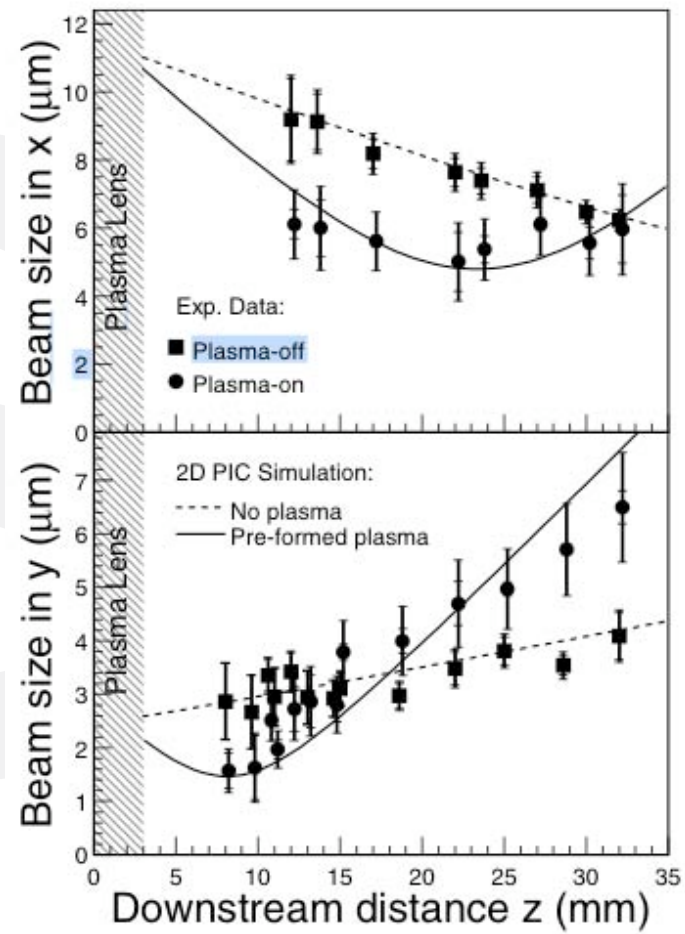


FIG. 3. Measured beam envelope Gaussian widths in the x and y dimensions, with and without plasma focusing. Inner error bars indicate the statistical uncertainty, and outer error bars indicate the quadrature sum of statistical and systematic uncertainties. The curves represent the particle-in-cell simulations.

- Plasmas lens experiment

  x: $B_\theta/r \approx 0.7T/\mu m$, f=34mm
  y: $B_\theta/r \approx 4T/\mu m$, f=1.6mm
  L_p=3 mm
  $n_e=5\times10^{17}\ cm^{-3} > n_b=2\times10^{16}\ cm^{-3}$

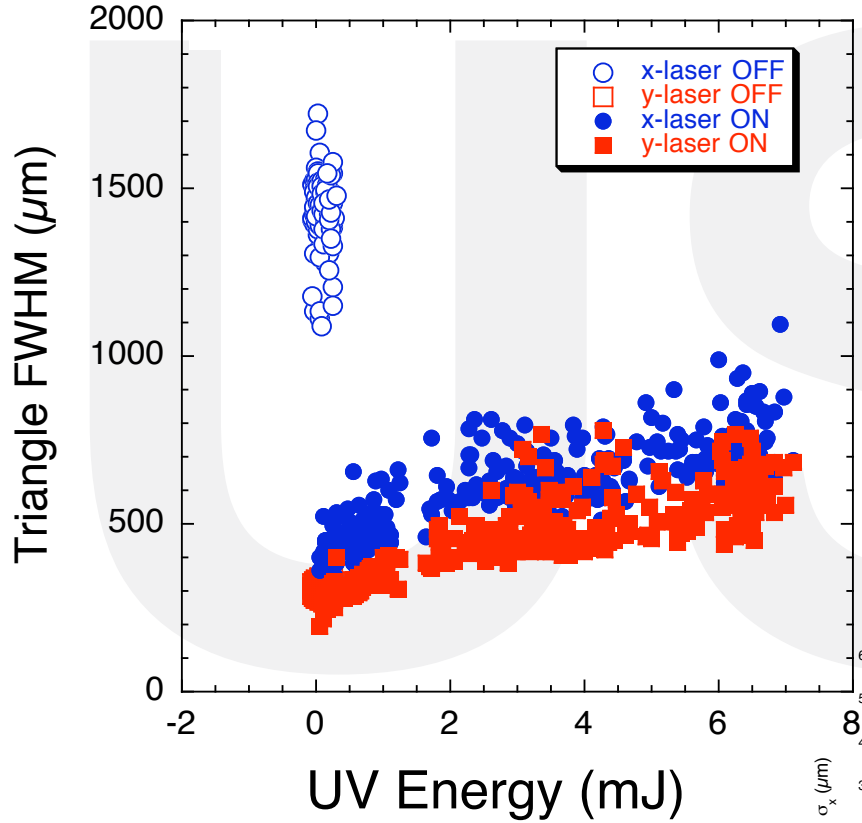
- Plasmas do focus e^+

e^+ Propagation

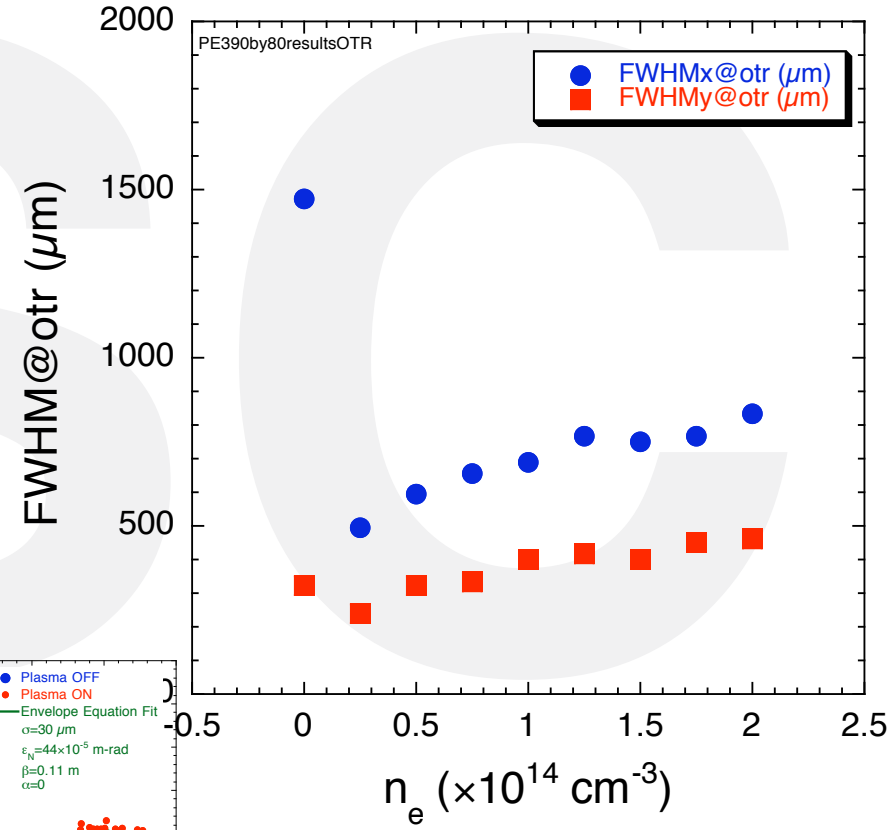
$\sigma_{x0}=\sigma_{y0}=25\mu m$, $\varepsilon_{Nx}=390\times10^{-6}$, $\varepsilon_{Ny}=80\times10^{-6}$ m-rad, $N=1.9\times10^{10}$ e^+, L=1.4 m

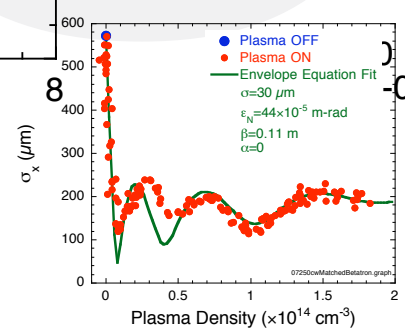
Downstream OTR

Experiment



Simulations





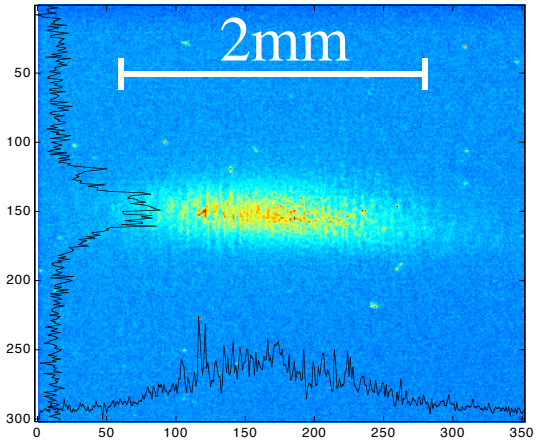
- No β-tron oscillations
- Excellent experimental/simulation results agreement!

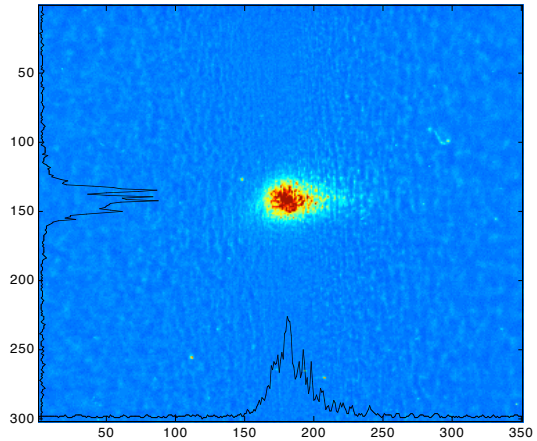
FOCUSING OF e^-/e^+

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

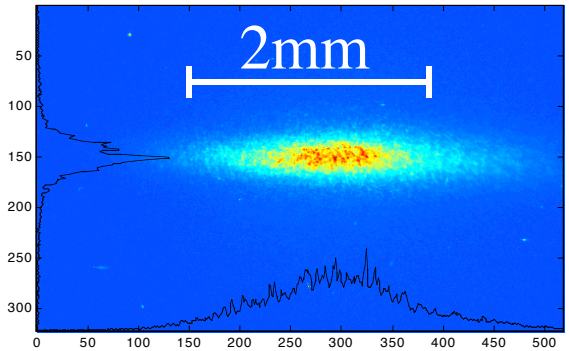
$n_e=0$ | $n_e \approx 10^{14}$ cm^{-3}

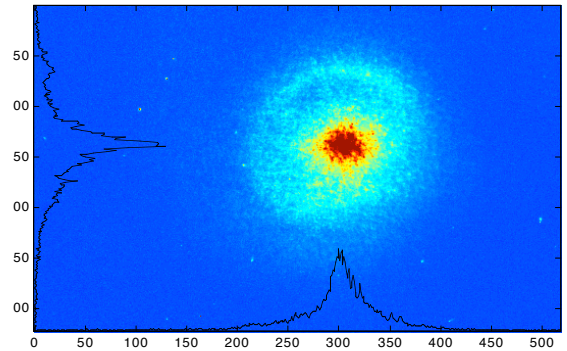
e^-





e^+





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

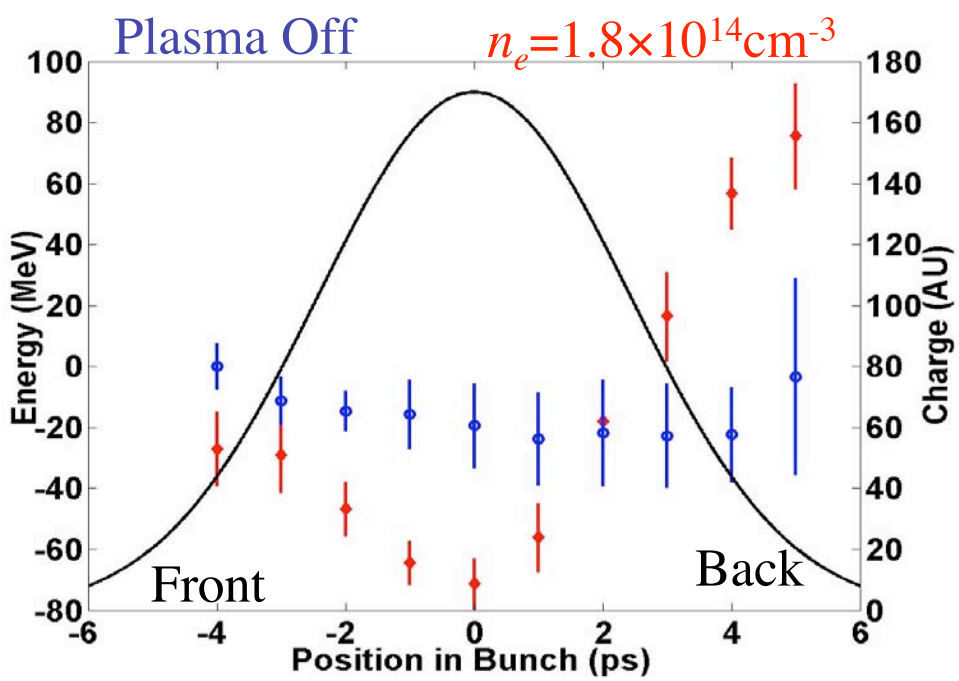
➡ Qualitative differences

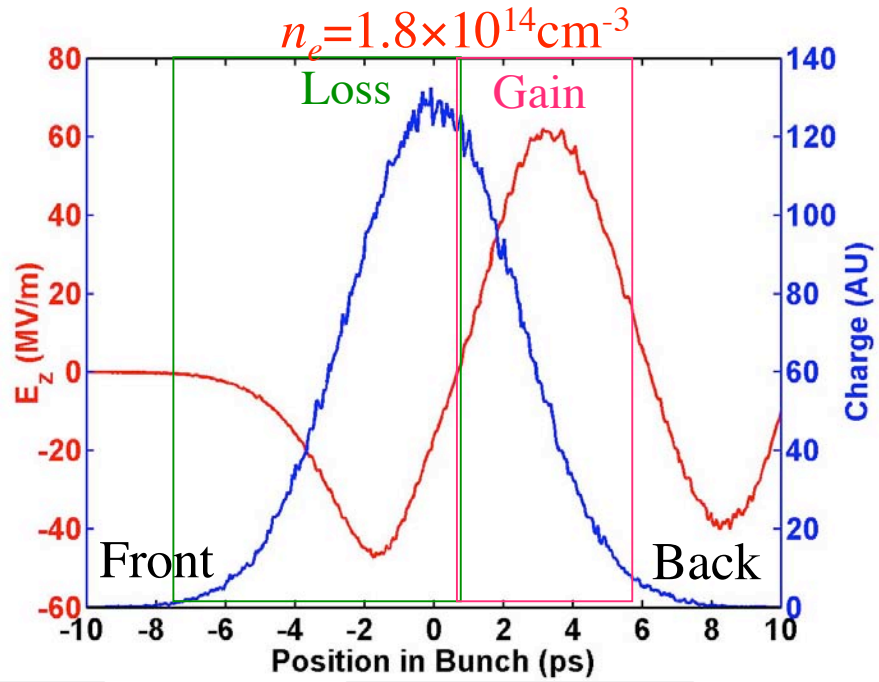
ENERGY LOSS/GAIN e^+

Experiment

$\sigma_z \approx 730\ \mu m$
$N = 1.2\times10^{10}\ e^+$

2-D Simulation





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

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

➡ Excellent agreement!
➡ Plasmas do accelerate e^+

PRL 90, 214801, (2003)

SUMMARY

- We built a very sophysticated PWFA lab in the FFTB and obtained very significant results

- First plasma accelerator to exceed 1GeV energy gain (e^-, 10cm)
- Doubled the energy of e^- linear collider (60cm), reproducible process
- First PWFA experiment in the self-ionized plasma regime
- Demonstrated stable propagation of e^--beam over long plasma length (60cm, $2.6 \times 17 cm^{-3}$, ≈30 beam betatron wavelengths)
- Demonstrated acceleration of e^+ in plasmas
- Observed MeV photons from e^- in plasma wiggler
- Observed trapped particles
-… and much more

- First demonstration of plasma lens for e^+

CONCLUSIONS

- Next E-167 run:
  - Double the energy of 43GeV e^-
  - Beyond energy doubling?
  - Two-bunch experiment
- SABER will be a great facility to study:
  - e^+-beam-plasma physics
  - Ionization/wake excitation by e^+, hollow plasmas
  - γ-ray source/e^+ source, polarized?
  - Radiation from e^+ in plasmas?
- Possible new experiments at SABER :
  - Focusing/plasma lens
  - Ion channel laser
  - Ion motion in PWFA
  - Beam loading (ε?, $\Delta E/E$?, …)
  - … and much more

(to be discussed in the WG)

BEAM-PLASMA PHYSICS WG SCHEDULE

Wednesday:

10:55, Matt Thompson, LLNL,
"Prospect for ultra-high gradient Cherenkov wakefield accelerator experiments at SABER"

11:25, Devon Johnson, UCLA,
"Plasma betatron radiation as a source for positron production" **

13:30, Mark J. Hogan, SLAC,
"Production of two bunches for PWFA experiments at SABER"**

14:00, Chengkun Huang, UCLA,
"QuickPIC simulations of the two-bunch operation regime for SABER"

15:20, Miaomiao Zhou, UCLA,
"Quasi-static simulations of self-ionized plasma wakefield acceleration by SABER relevant electron/positron beams"

16:30, Sven Reiche, UCLA,
"Inverse Compton scattering experiments at SABER"**

Thursday:

08:30, Erdem Oz, USC,
"Plasma dark current in self ionized plasma wakefield accelerators"

10:30, All
WG Summary preparation: NEED YOUR SLIDES!