Demonstration of Energy Gain Larger than 10GeV in a Plasma Wakefield Accelerator

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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

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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

OUTLINE

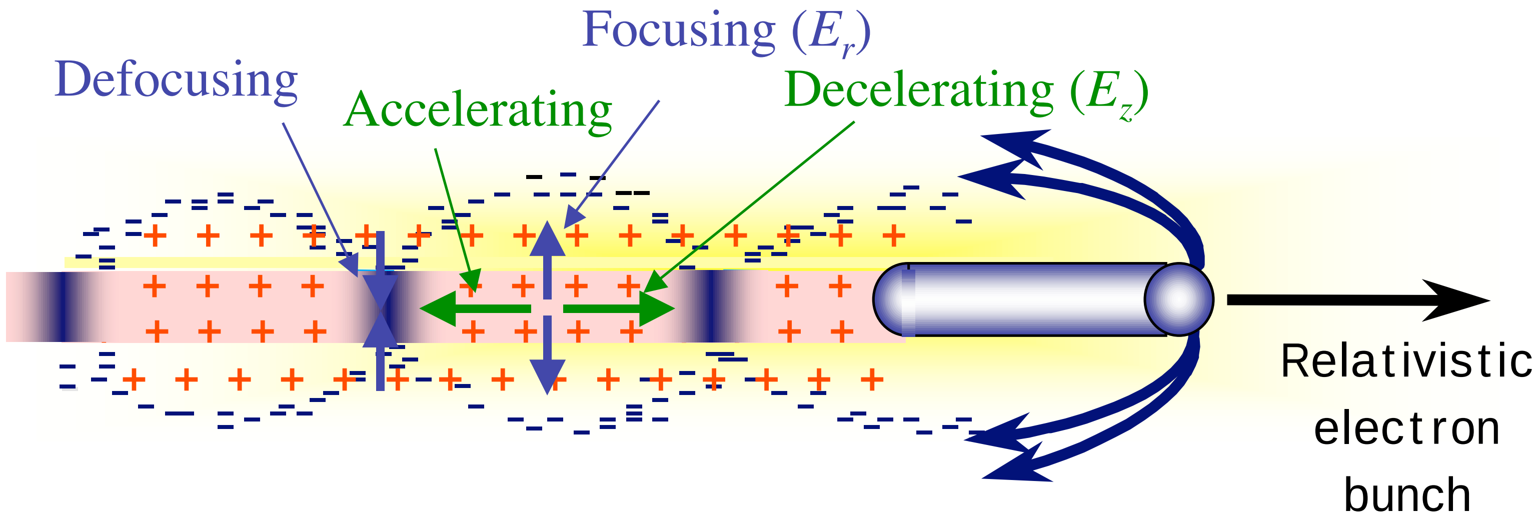
- Motivation
- Introduction to plasma wakefield accelerator (PWFA)
- Experimental setup
- e^- energy gain
- Summary/Conclusions

MOTIVATION

- Could an accelerating structure with a gradient significantly larger (×10, …, ×1000) than that reached in present rf cavities (<200 MV/m) be created and can it lead to large energy gain (1-100 GeV)?
- Plasmas can sustain very large electric fields (10-100 GV/m)
  - Relativistic plasma waves or wakes: **E**//**k**, electrostatic
  - No fabricated structure
  - Operation a very high frequency (THz), high gradient
- Laser-driven plasma accelerator: high charge, control and stability (V. Malka, Monday)
- beam-driven, plasma wakefield accelerator or PWFA

PLASMA WAKEFIELD ACCELERTAOR (e^-)

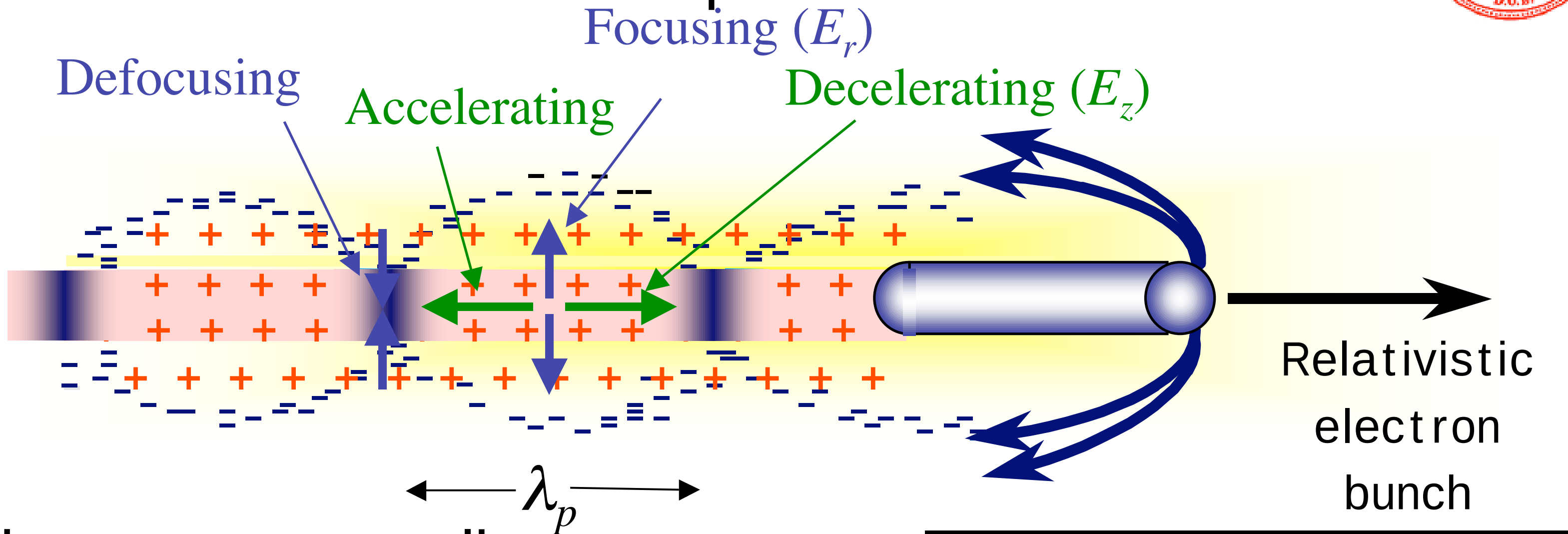
PWFA = beam-driven plasma accelerator



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces => energy loss + focusing
- Plasma e^- rush back on axis => energy gain
- Extract energy from the front, transfer to the back
- Focusing + acceleration = large energy gain
- Single bunch => particles at all phases

PWFA SCALING

PWFA = beam-driven plasma accelerator



- Linear theory ($n_b<<n_e$) scaling:

When $k_{pe}\sigma_z=(2\pi/\lambda_p)\sigma_z\approx\sqrt{2}$ (with $k_{pe}\sigma_r<<1$)

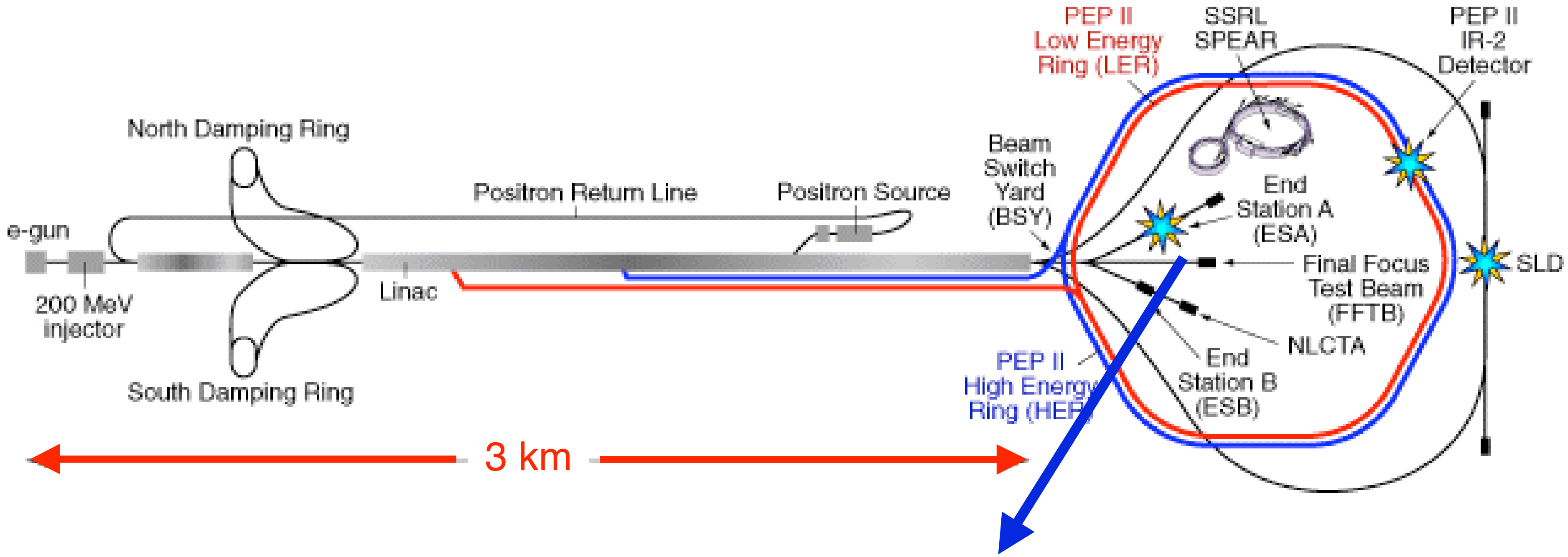
$$E_{acc}\cong 110(MeV/m)\frac{N/2\times10^{10}}{(\sigma_z(\mu m)/600)^2} \approx 1/\sigma_z^2$$

- Focusing strength: ($n_b>n_e$)

$$\frac{B_\theta}{r}=\frac{1}{2}\frac{n_e e}{\varepsilon_0 c}=3kT/m\times n_e(10^{14}cm^{-3})$$

N=1.8×10^{14}	"Long"	"Short"
σ_z (μm)	≈730	20-40
n_e (cm^{-3})	1.0×10^{14}	0.7×10^{17}
E_{acc} (GV/m)	≈0.1	>10
f (GHz)	90	2400
λ_p (μm)	3333	125
B_θ/r (kT/m)	3	2100

PWFA @ SLAC



Final Focus Test Beam (FFTB) parameters:

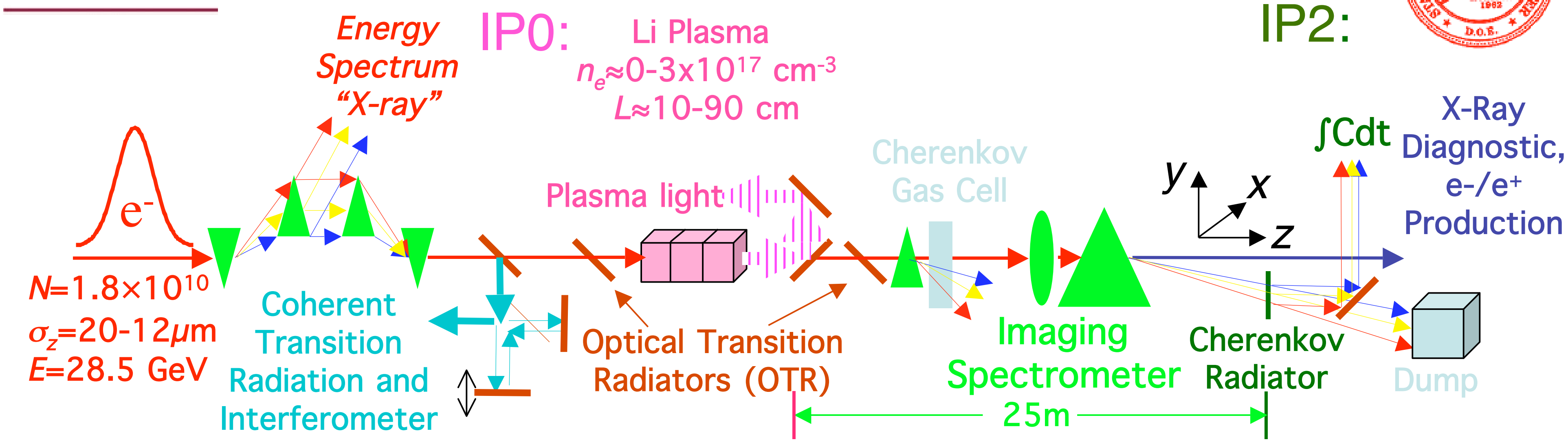
E_0=28.5 or 42 GeV

N=1.6-1.8×10^{10} e^-/bunch

σ_z=14-40 μm (ultra-short bunches)

$\sigma_{x,y}\approx$10 μm

EXPERIMENTAL SET UP (GENERIC)



Energy Spectrum "X-ray"

IP0:

Li Plasma

$n_e \approx 0\text{-}3\times10^{17}$ cm^{-3}

$L \approx 10\text{-}90$ cm

IP2:

e$^-$

$N=1.8\times10^{10}$

$\sigma_z=20\text{-}12\mu m$

$E=28.5$ GeV

Coherent Transition Radiation and Interferometer

Plasma light

Optical Transition Radiators (OTR)

Cherenkov Gas Cell

Imaging Spectrometer

25m

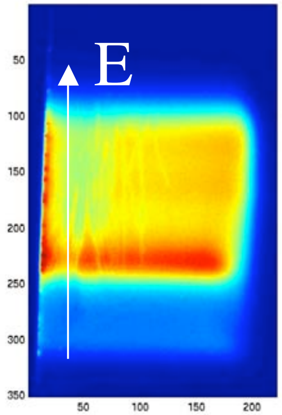
$\int$Cdt

X-Ray Diagnostic, e-/e+ Production

Cherenkov Radiator

Dump

- X-ray Chicane

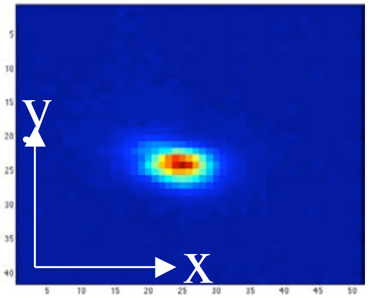


-Energy resolution ≈60 MeV

- Coherent Transition Radiation (CTR)

- CTR Energy≈I_{peak}≈$1/\sigma_z$

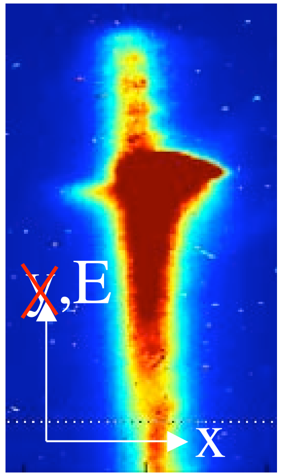
- OTR



-Spatial
-resolution ≈9 μm

- Cherenkov (aerogel)

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



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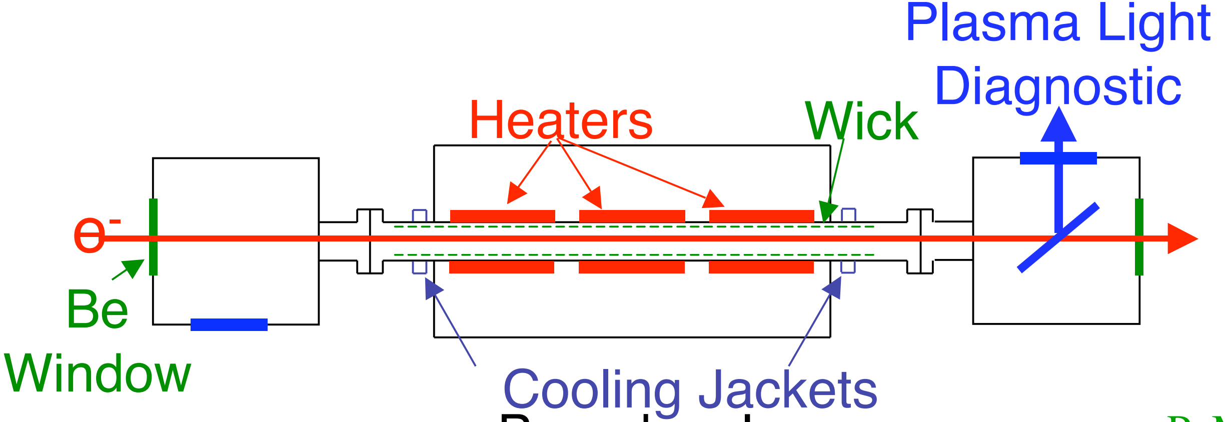
"PLASMA SOURCE"

- Lithium vapor in a heat-pipe oven



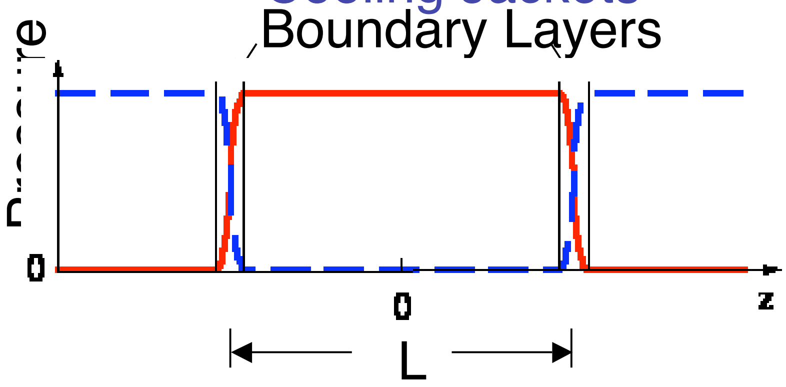
n_0=0.5-3.5×10^{17} cm^{-3}

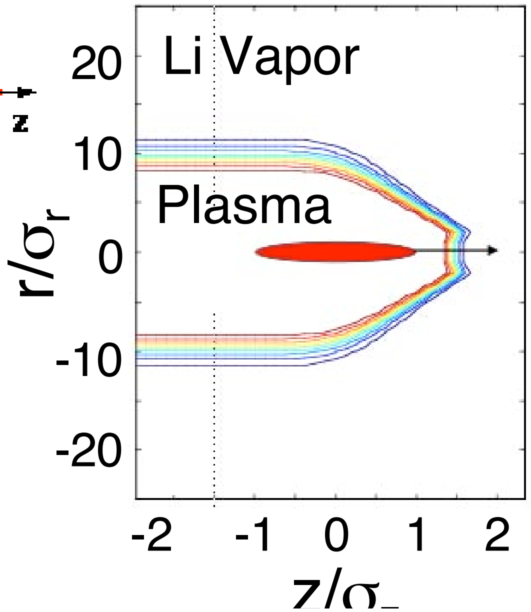
T=700-1050°C

L=13-22-31-90 cm

P_{He}≈1-40 T

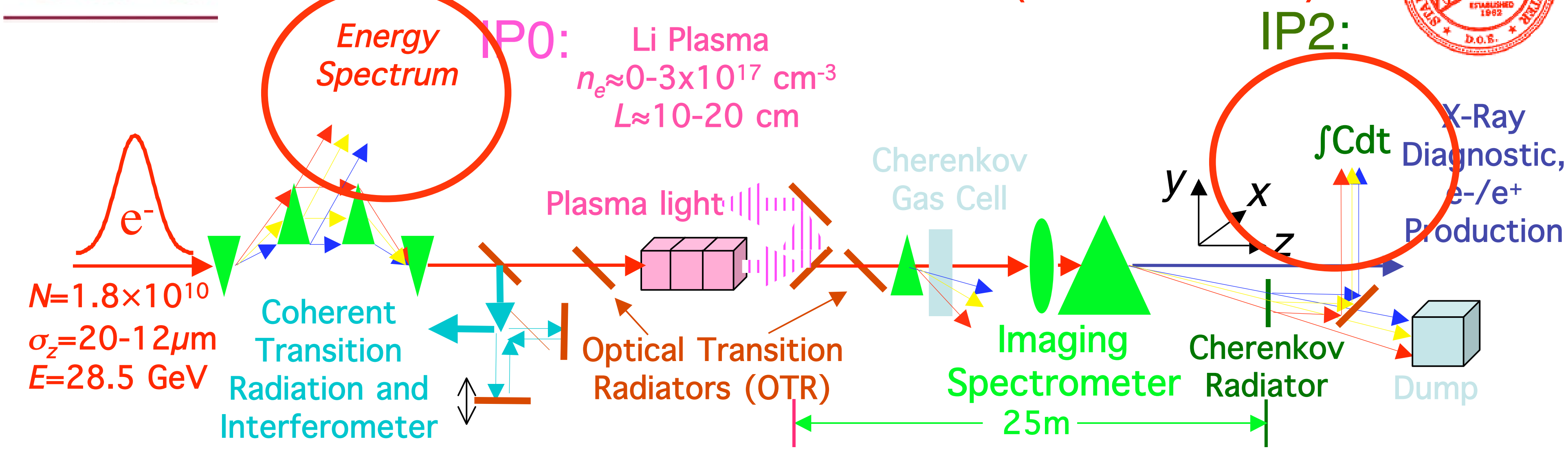
P. Muggli *et al.*, IEEE TPS (1999)





- Tunnel-ionization:
  - - Lithium: low Z, low IP (5.4 eV)
  - - Ultra-short bunch E_r field > 6GV/m
  - - $n_e=n_{o,\,Li}$
  - - Plasma very "reproducible"

EXPERIMENTAL SET UP (GENERIC)



Energy Spectrum

IP0: Li Plasma

$n_e \approx 0\text{-}3 \times 10^{17}$ cm^{-3}

$L \approx 10\text{-}20$ cm

IP2:

e^-

$N = 1.8 \times 10^{10}$

$\sigma_z = 20\text{-}12\,\mu m$

$E = 28.5$ GeV

Coherent Transition Radiation and Interferometer

Plasma light

Optical Transition Radiators (OTR)

Cherenkov Gas Cell

Imaging Spectrometer

25m

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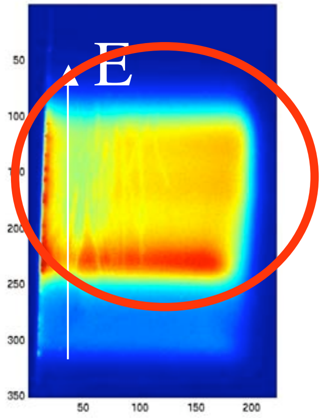
- X-ray Chicane

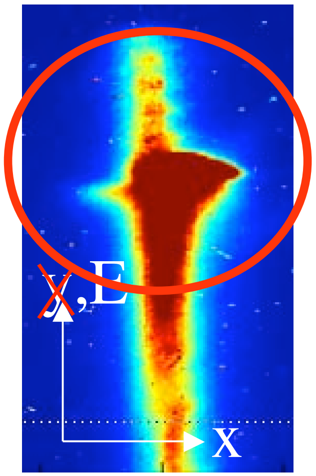


-Energy resolution ≈60 MeV

Compare events with similar incoming longitudinal characteristics

- Cherenkov (aerogel)

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



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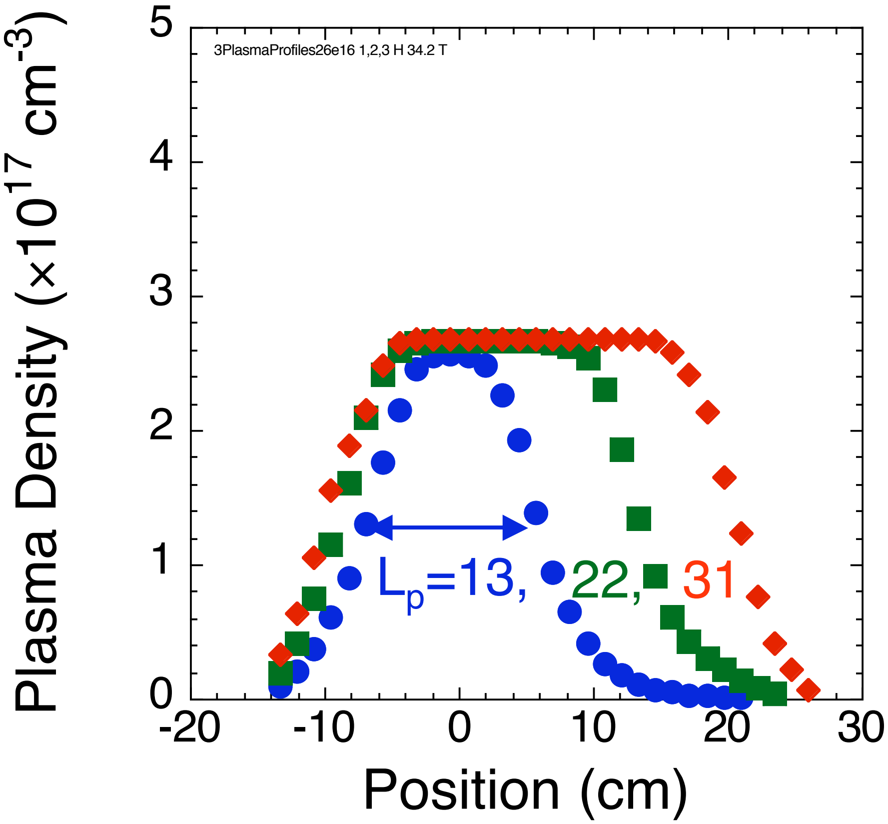
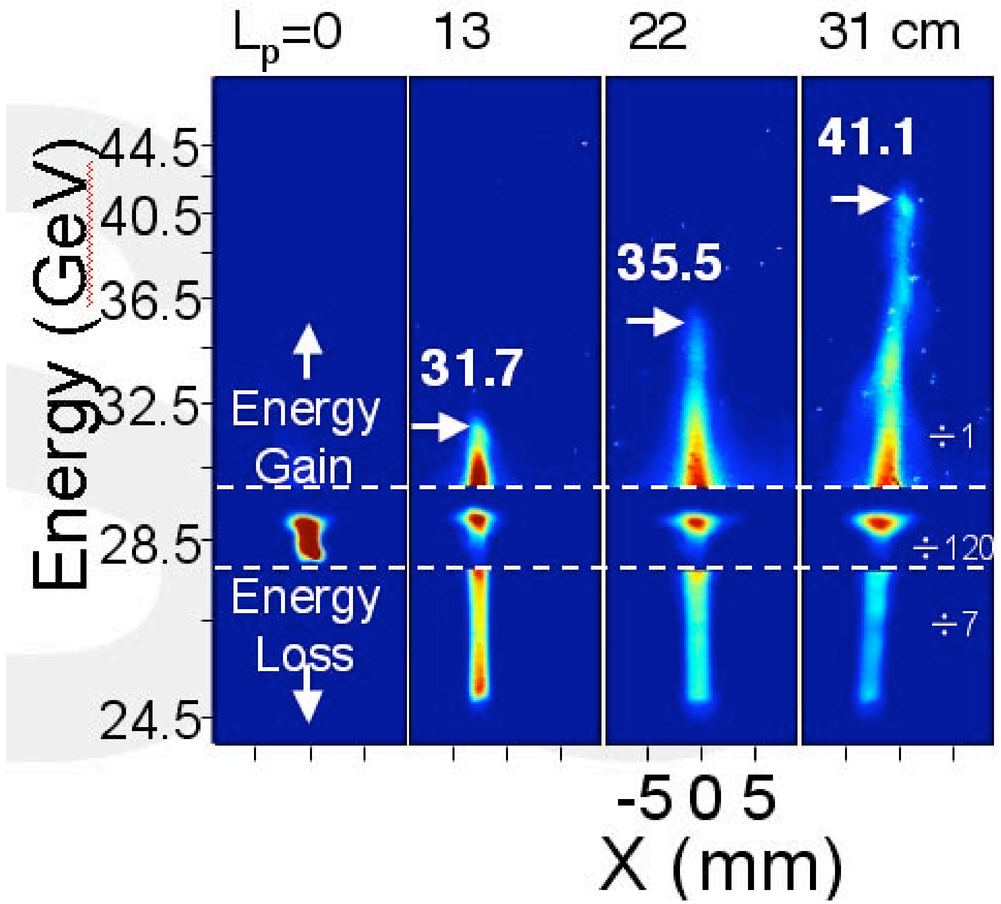
ENERGY GAIN VS. PLASMA LENGTH

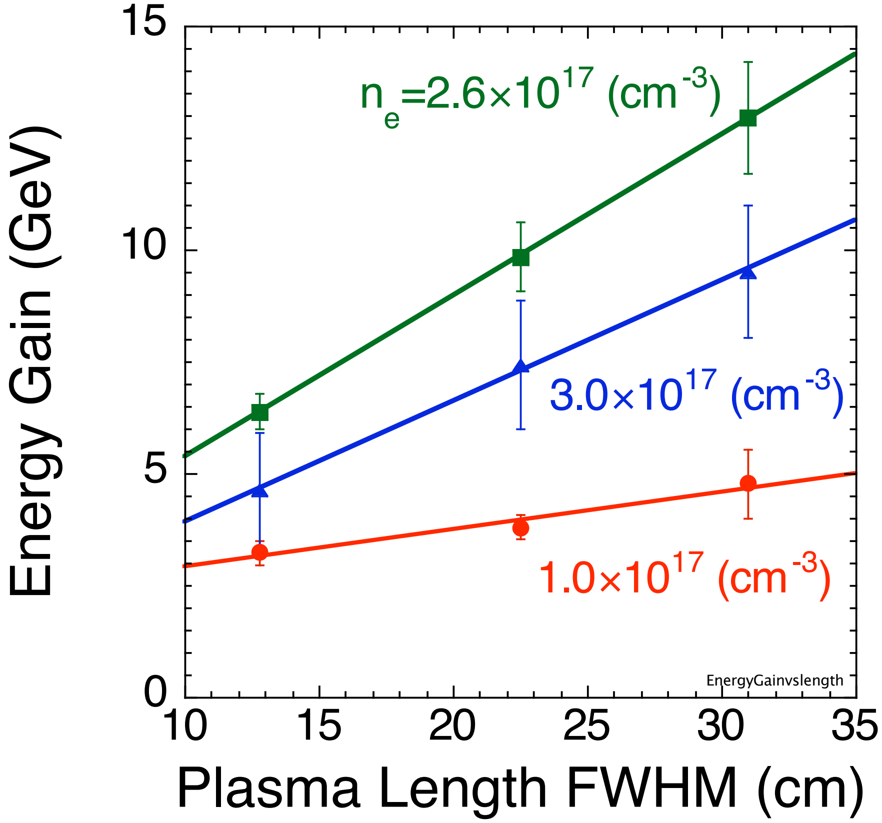
E_0=28.5 GeV, n_e=2.7×10^{17}cm^{-3}

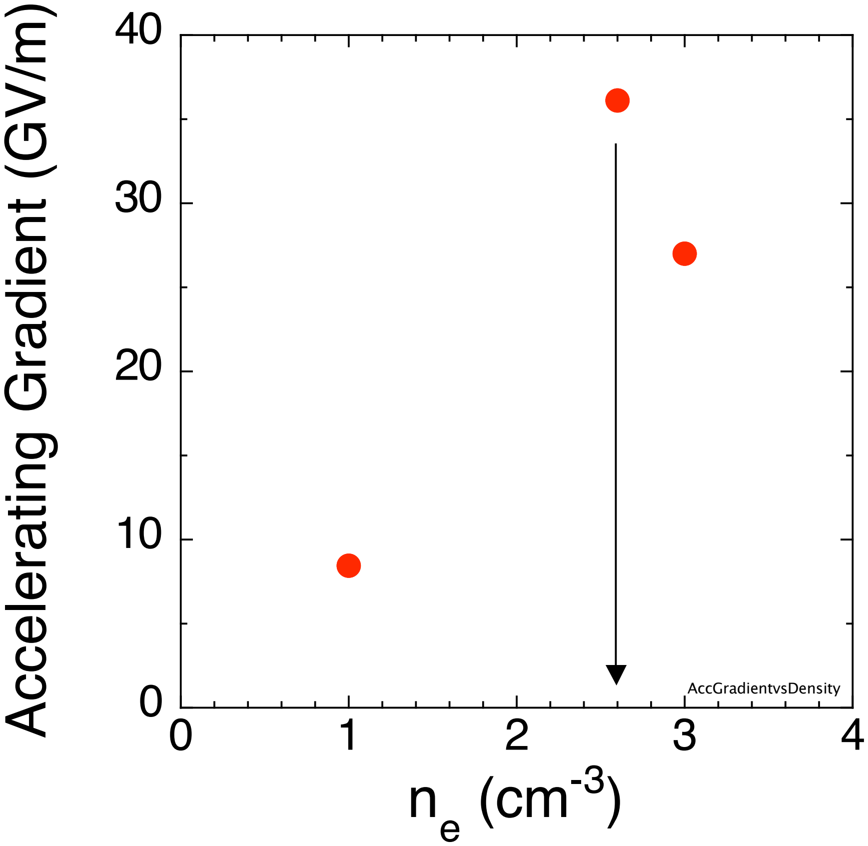




- Energy gain increases with plasma length (L_p)
- Energy gain reaches 13.6 GeV with L_p=31 cm!

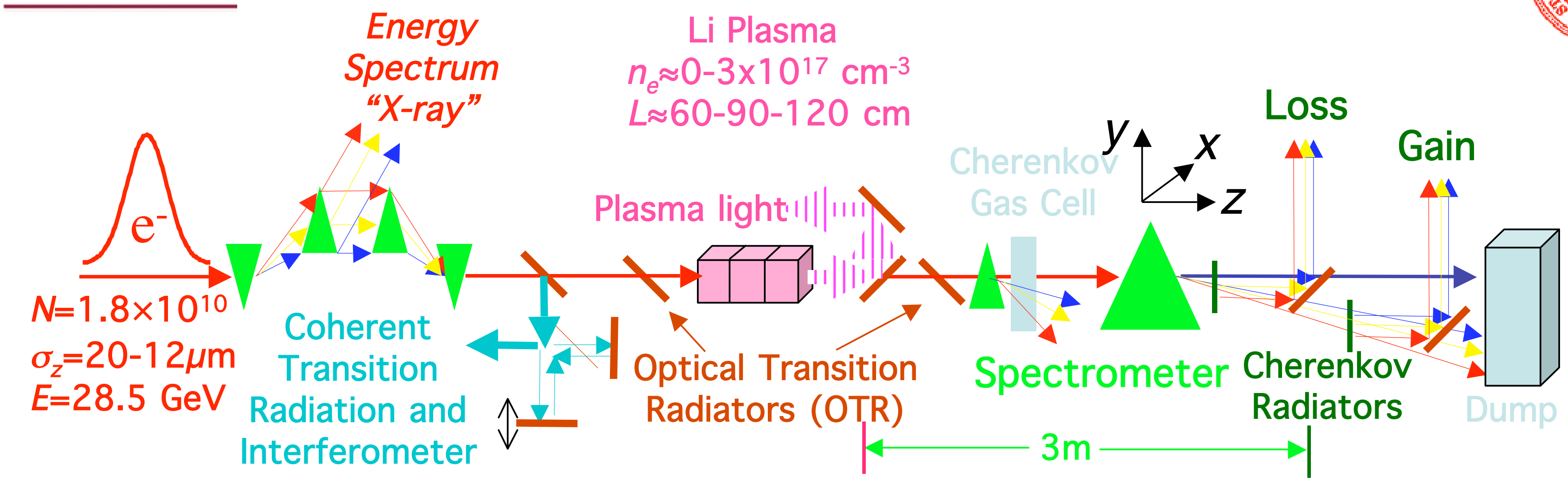
ENERGY GAIN VS. PLASMA LENGTH





- Largest gain with $n_e=2.6\times10^{17}$cm^{-3} (∀ L_p, for $\sigma_z\approx20\ \mu$m)
- Accelerating gradient of 36 GV/m over L_p=31 cm (unloaded: 7% accelerated charge)

EXPERIMENTAL SET UP


Energy Spectrum "X-ray"

Li Plasma
$n_e \approx 0\text{-}3\times10^{17}$ cm^{-3}
$L \approx 60\text{-}90\text{-}120$ cm

e^-
$N = 1.8\times10^{10}$
$\sigma_z = 20\text{-}12\,\mu m$
$E = 28.5$ GeV

Coherent Transition Radiation and Interferometer

Plasma light

Optical Transition Radiators (OTR)

Cherenkov Gas Cell

Spectrometer

Loss

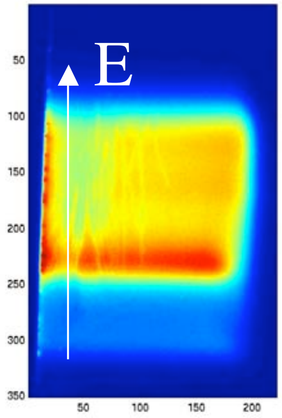
Gain

Cherenkov Radiators

Dump

3m

- X-ray Chicane

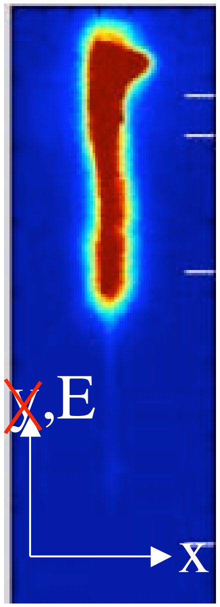


-Energy resolution ≈60 MeV

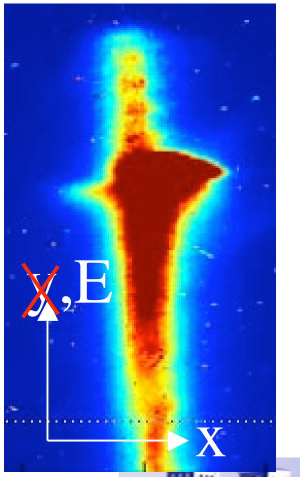
High Energy Gain-Loss Measurements FOV ≈3 GeV to >100 GeV

- Cherenkov (air)

Loss

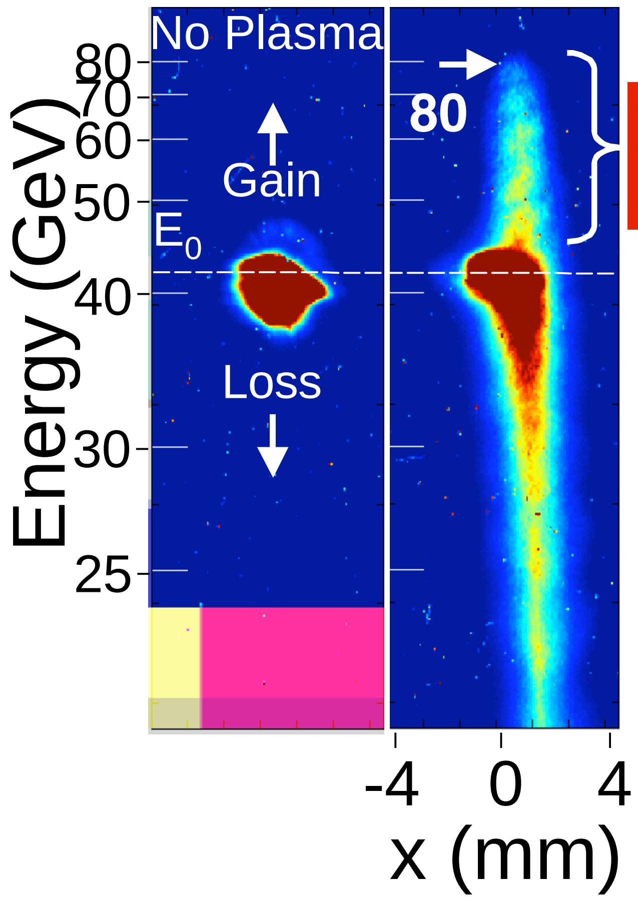


Gain

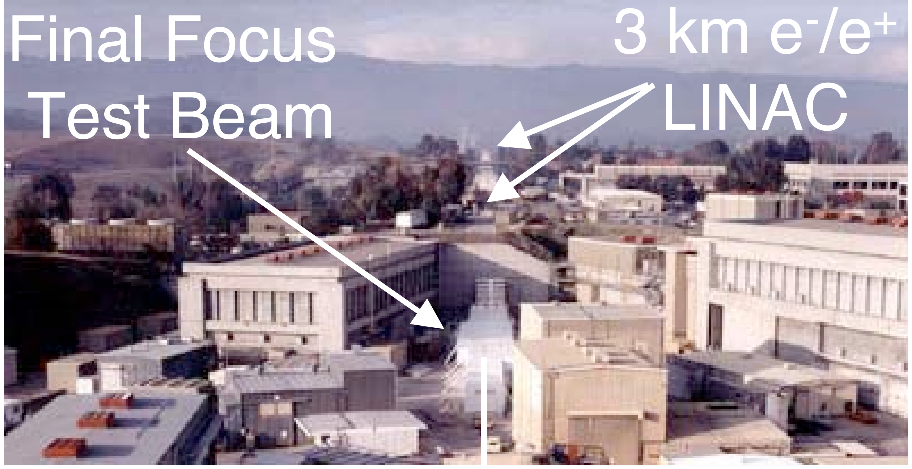


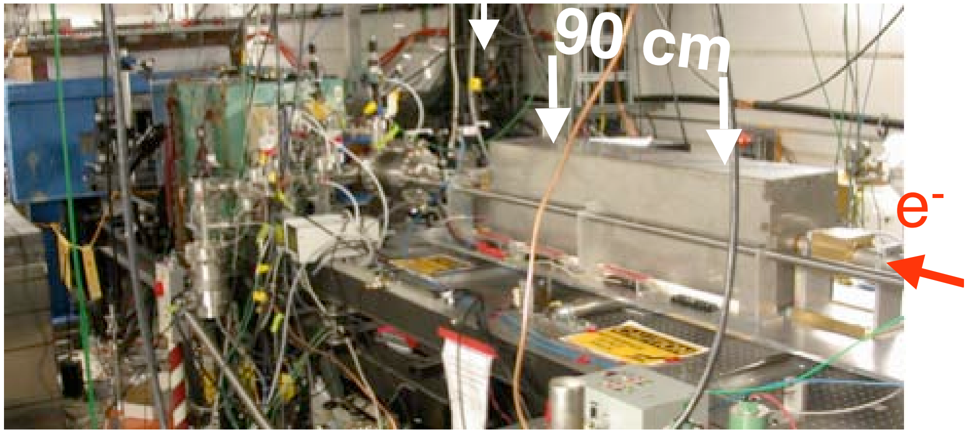
ENERGY GAIN

E_0=42 GeV, N=1.75 ×10^{10} e^-, n_e=2.6×$10^{17}$$cm^{-3}$, L_p=90 cm



≈9.6x10^8 e^-
≈154 pC

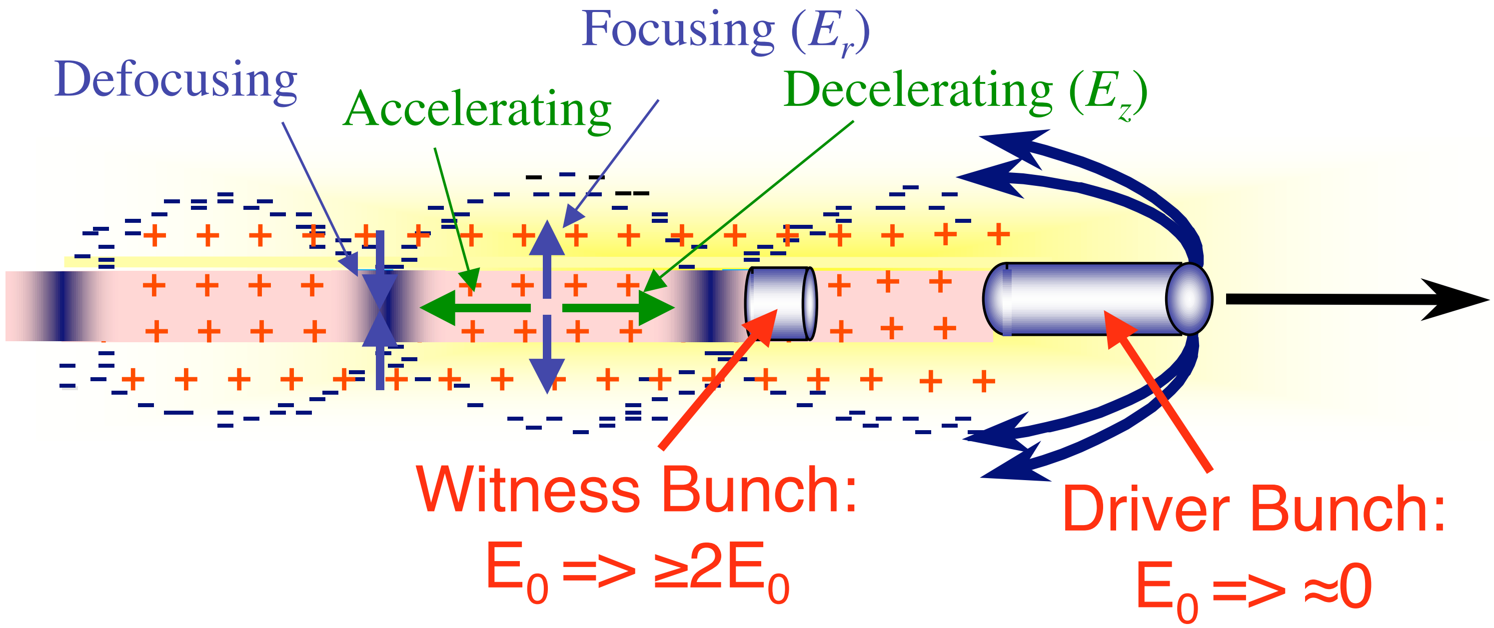




- Energy gain 38 GeV over ≈90 cm of plasma! or 42GV/m!
- PWFA = extremely simple and compact accelerator

FUTURE EXPERIMENT

- 2-Bunch PWFA



Witness Bunch:
$E_0 \Rightarrow \geq 2E_0$

Driver Bunch:
$E_0 \Rightarrow \approx 0$

- Driver bunch: high-charge (*3N*), modest emittance, shaped?
- Witness bunch: lower charge (*N*), good emittance
  beam loading for $\Delta E/E \ll 1$

- Typical 2- bunch PWFA parameters:

$n_e \approx 10^{16}$ cm^{-3}, $f_{pe} \approx 900$ GHz, $\lambda_{pe} \approx 300$ μm
$G \approx 10\text{-}20$ 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

USC

SUMMARY / CONCLUSIONS

- ❖ First plasma accelerator with >1GeV energy gain
- ❖ Energy gain up to 38 GeV in ≈90 cm, 42 GV/m over 90 cm
- ❖ Measured important scalings:

Bunch length: σ_z=730 μm W=200 MV/m, σ_z≈20 μm W=42 GV/m

Optimum plasma density: $n_e=1.8\text{x}10^{14}$ cm^{-3} $n_e= 2.6\text{x}10^{17}$ cm^{-3}

Plasma length: 13.6 GeV 31 cm (E_0=28.5 GeV), 38 GeV, 85 cm, (E_0=42 GeV)

- ❖ Energy gain increases linearly with plasma length
- ❖ Stable and reproducible acceleration

Next steps:

- ➢Two-bunch experiment (ΔE/E<1)
- ➢High-gradient positrons acceleration

SABER
South Arc Beam Experimental Region

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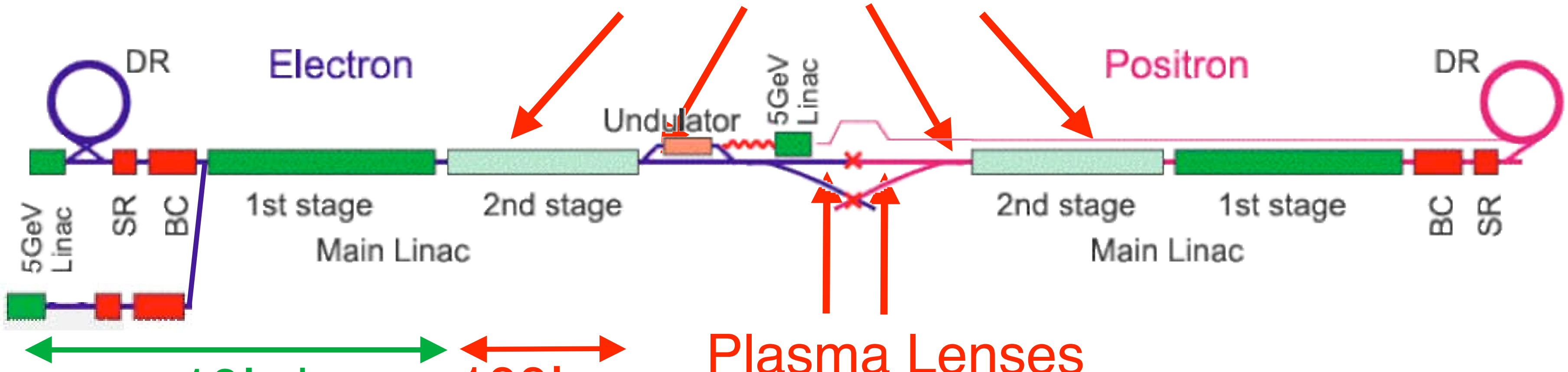
FUTURE RESEARCH?

PLASMA AFTERBURNER

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



Large Gradient Plasma Accelerators

Plasma Lenses

≈ 10's km ≈ 100's m

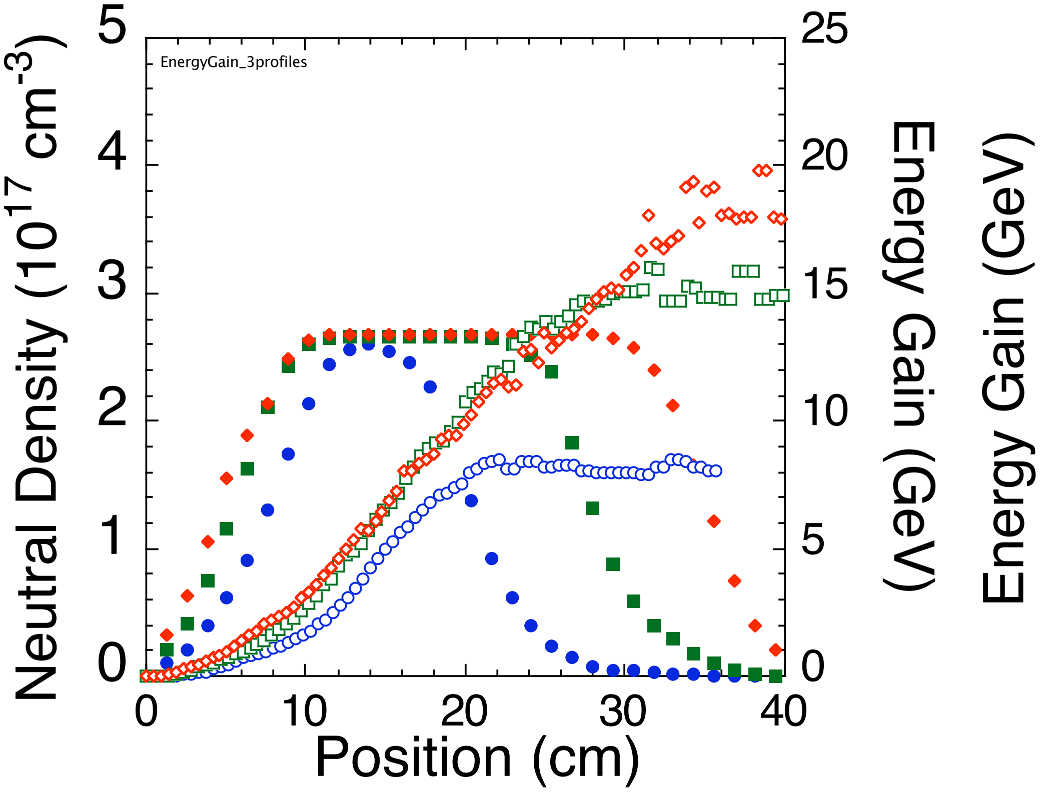
Double the gradient and reduce size?

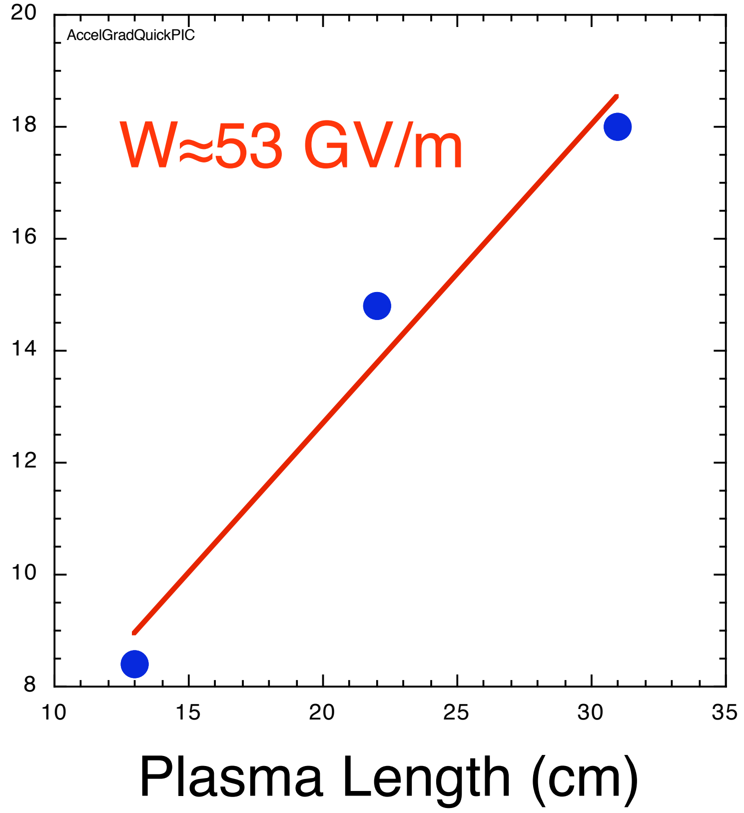
Double the energy and extend the energy frontier?

ENERGY GAIN VS. PLASMA LENGTH

3-D Simulations using QuickPIC

E_0=28.5 GeV, N=1.8×10^{10} e^-, n_e=2.7×10^{17}cm^{-3}

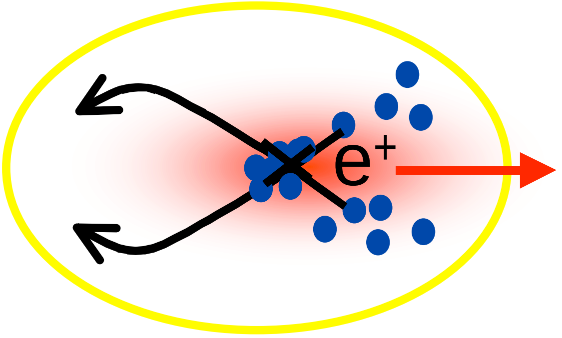




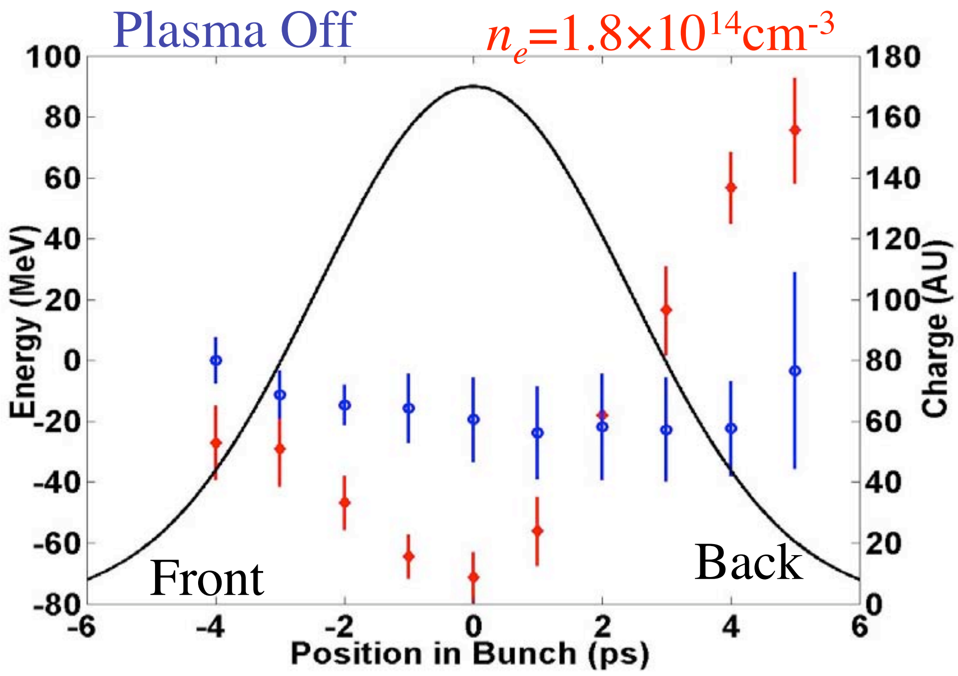
- Energy gain increases with plasma length (L_p)
- Gradient ≈53 GV/m

FUTURE RESEARCH

➡ e^+ wake gradient, emittance growth in plasma



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



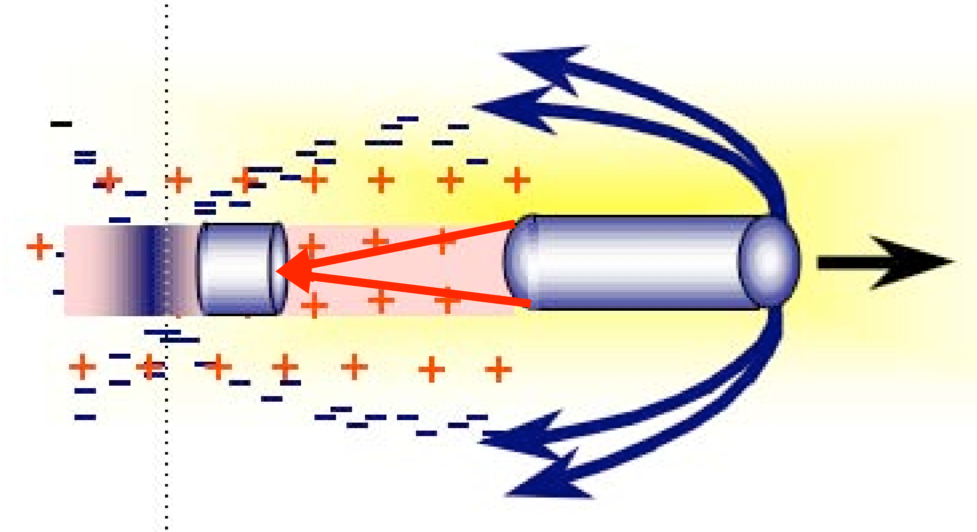
- Hollow plasma channel
- More stringent beam parameters
- **SABER**
  South Arc Beam Experimental Region

- Loss ≈ 70 MeV (over 1.4 m)
- Gain ≈ 75 MeV
- Plasmas do accelerate e^+
- Excellent agreement with simulations!

PRL 90, 214801, (2003)

FUTURE RESEARCH

- Plasma ions motion (J. B. Rosenzweig, *et al.* PRL. **95**, 195002 (2005))



- Significant when n_b/n_e>>1
- Degrades beam emittance and focusing
- Improves with: larger σ_r, higher ε, higher A, etc.

- Synchrotron radiation, beam plasma matching
- Preservation of emittance and polarization (<<X_0)
- Evolution, stability of the bunch/wake over long plasma lengths
- Real accelerator: beam loading, optimization, …

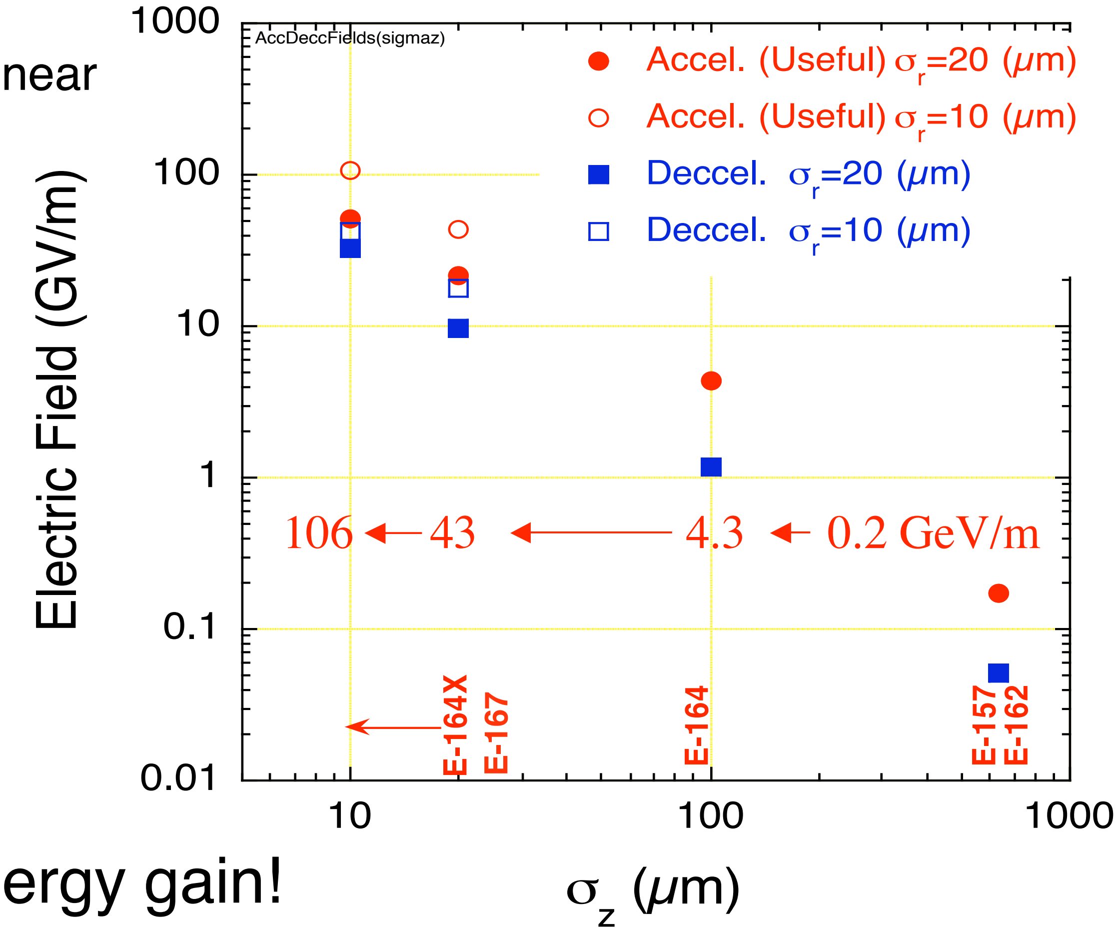
Patric Muggli,EPAC'06 06/28/06

ACCELERATING GRADIENT SCALING

Linear Theory: $E_{acc} \cong 110(MeV/m)\dfrac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2}$ $\approx 1/\sigma_z^2$

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

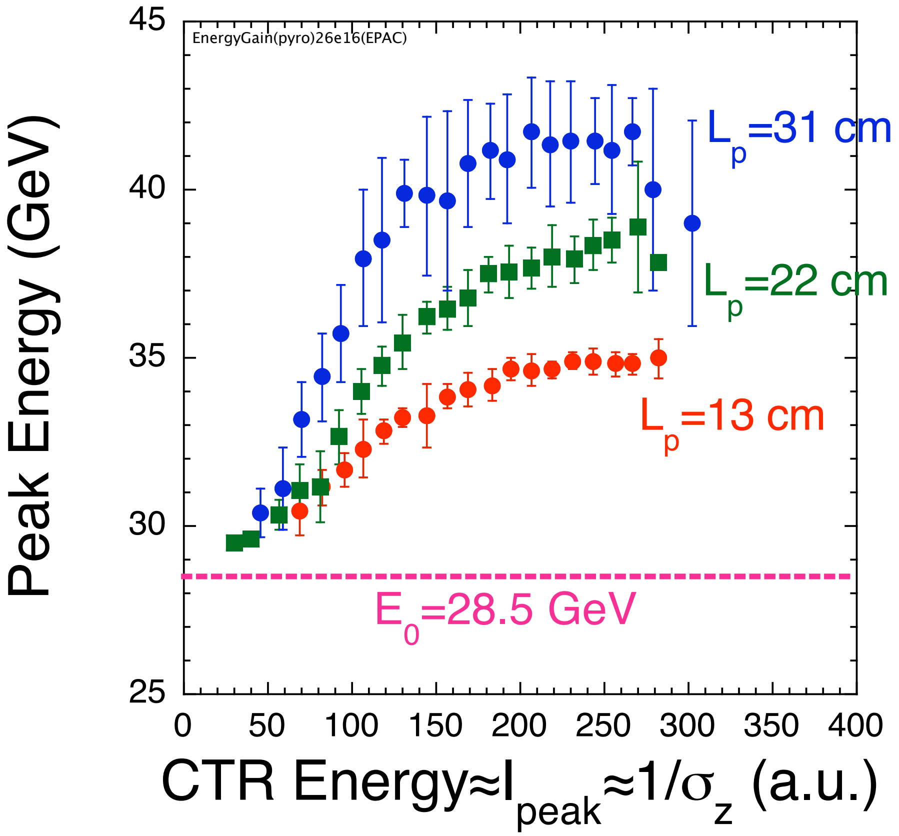
Simulation using OSIRIS, for non-linear regime: $n_b > n_0$



- Measure energy gain!

ENERGY GAIN VS. BUNCH LENGTH

$n_e=2.6\times10^{17}cm^{-3}$

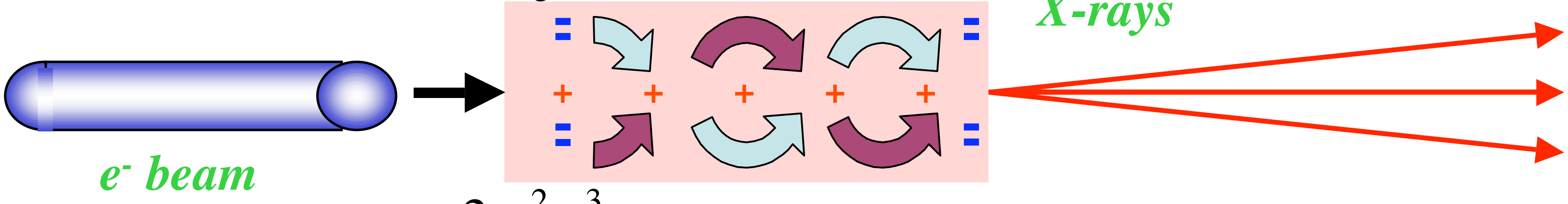


- Energy gain increases bunch peak current or σ_z^{-1}
- Energy gain reaches 13? GeV with L_p=31 cm!

FUTURE RESEARCH

Synchrotron radiation

$$K = \frac{\gamma\omega_\beta}{c} r_o = f\left(\sqrt{n_e}, r_o, \gamma\right) = 94$$



$$\omega_c = \frac{3\omega_\beta^2\gamma^3}{2c} r_o = f\left(n_e, r_o, \gamma^2\right) = 64\,MeV$$

$$\frac{dE}{dz} = \frac{1}{3} r_e m_e c^2 \gamma^2 k_\beta^2 K^2 = f\left(n_e^2, r_o^2, \gamma^2\right) = 334\,MeV/m$$

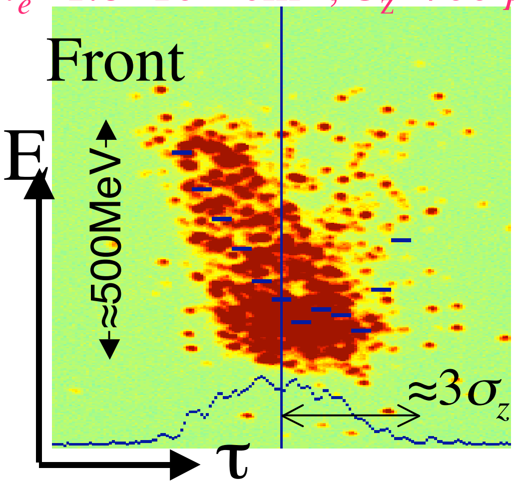
n_e=2x10^{16} cm^{-3}
r_0=10 μm
E=125 GeV

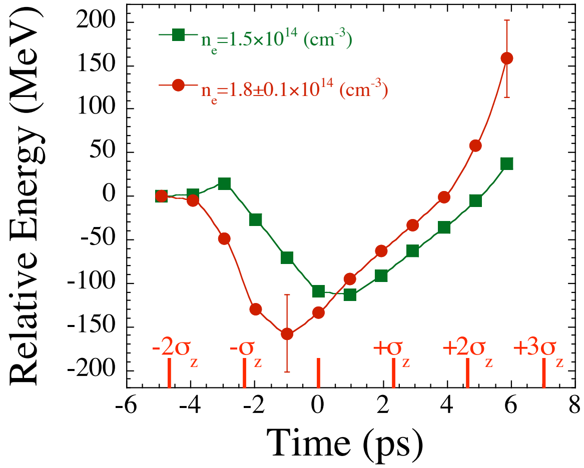
- Decreases with beam radius r_0 (compromise with ions motion)
- Negligible when compared to accelerating gradient (≈10 GV/m)
- Interesting as a source of gamma rays for positron production?

(D.K. Johnson, PAC'05 and PRL to come)

e^- ACCELERATION

n_e=1.8×10^{14} cm^{-3}, σ_z≈700 μm

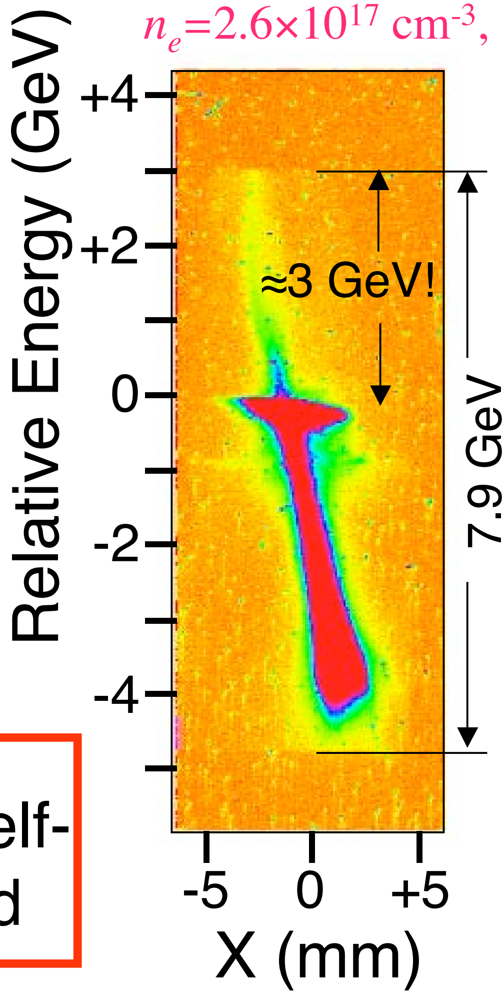


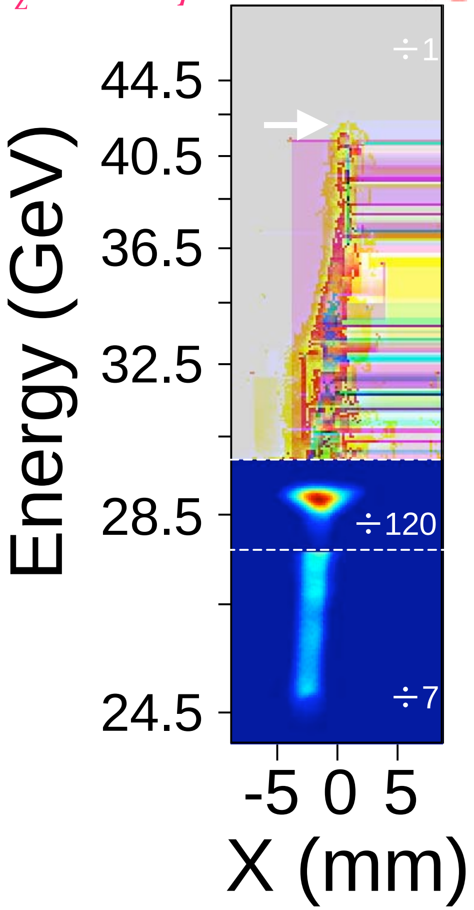


Pre- | Self-

Ionized

n_e=2.6×10^{17} cm^{-3}, σ_z≈20-30 μm



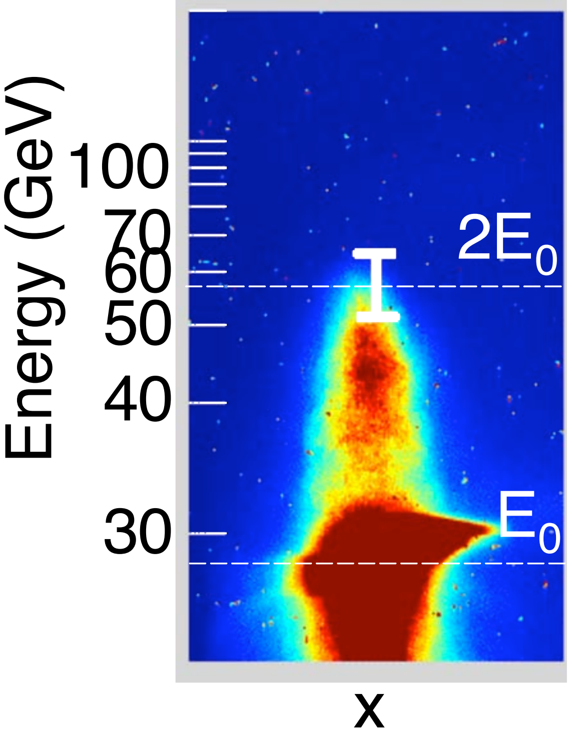


- Gain≈280 MeV, L_p=1.4m
  Gradient≈200 MV/m
  PRL 93, 014802 (2004)
- Gain≈4 GeV, L_p=10cm
  PRL 95, 054802 (2005)
- Gain≈14 GeV, L_p=32cm
  Gradient≈40 GV/m
- Scaling with bunch length and plasma length

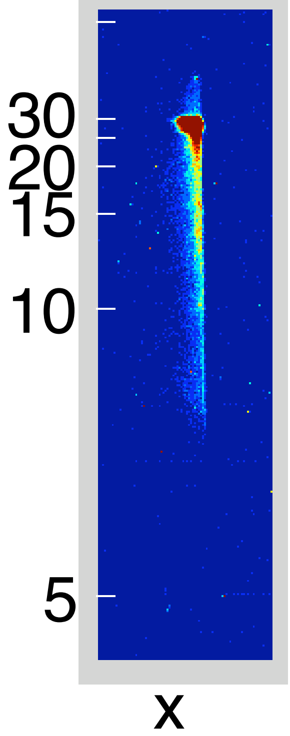
e^- ENERGY DOUBLING EXPERIMENT

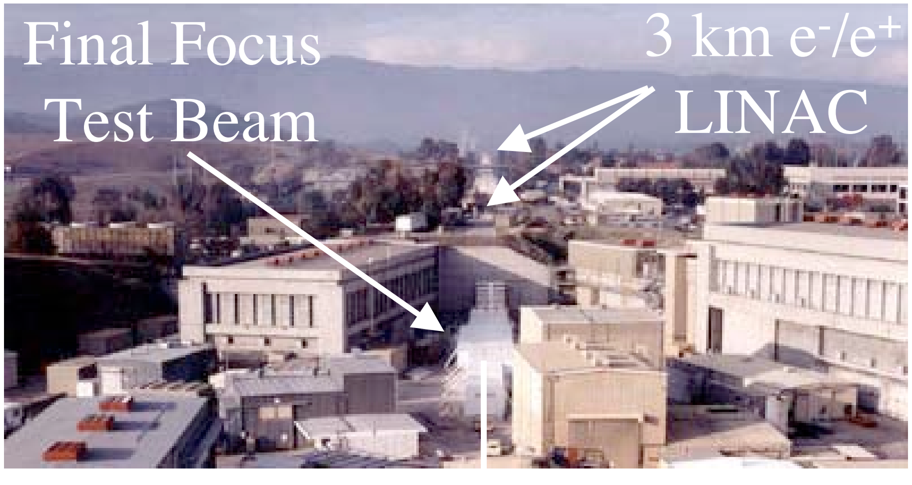
$L_p\approx60cm,\ n_e=2.6\times10^{17}\ \mathrm{cm}^{-3},\ \sigma_z\approx20\text{-}30\ \mu m$

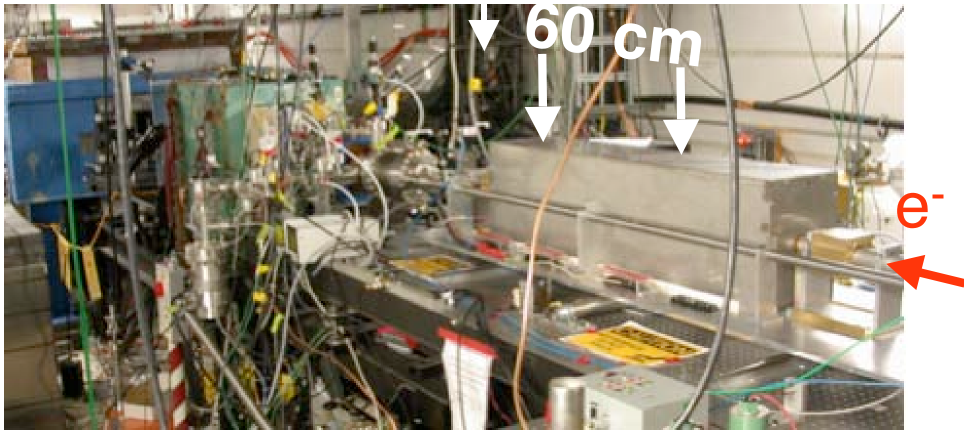
High-dispersion Image
for Energy
Gain Measurement



Low-dispersion Image
for Energy
Loss Measurement







- Large energy loss and gain, as expected

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?

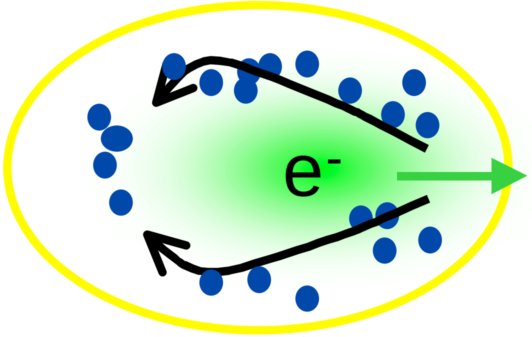
Possible new experiments at SABER :

- 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)

e^- & e^+ ASYMMETRY IN PLASMAS

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

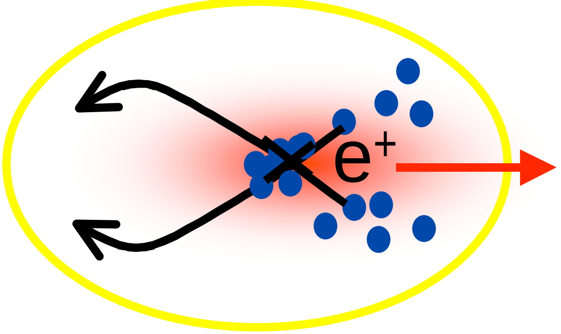


σ_r=35 μm

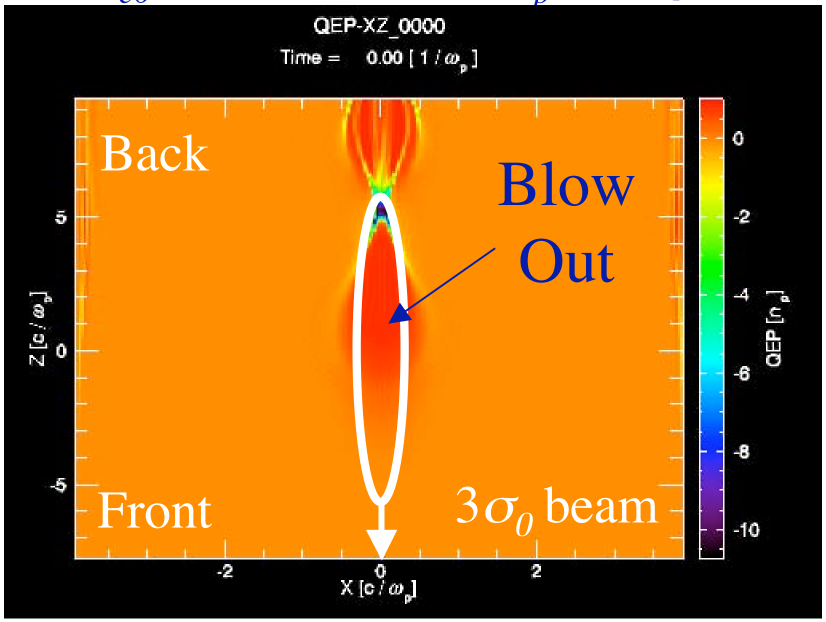
σ_r=700 μm

N=1.8×10^{10}

d=2 mm

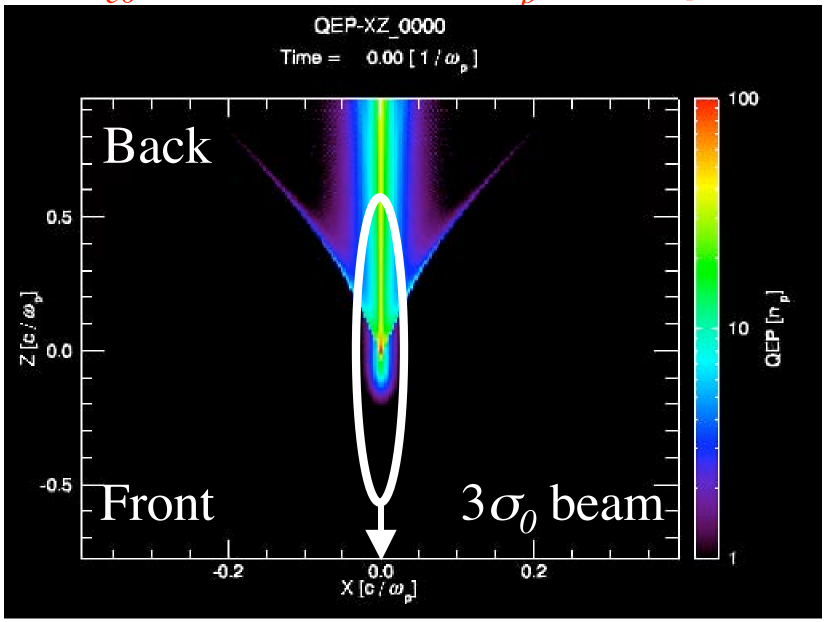


e^-: $n_{e0}=2\times10^{14}$ cm^{-3}, c/ω_p=375 μm



- Uniform focusing force (r,z)

e^+: $n_{e0}=2\times10^{12}$ cm^{-3}, c/ω_p=3750 μm



- Non-uniform focusing force (r,z)

e$^+$ PLASMA FOCUSING

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

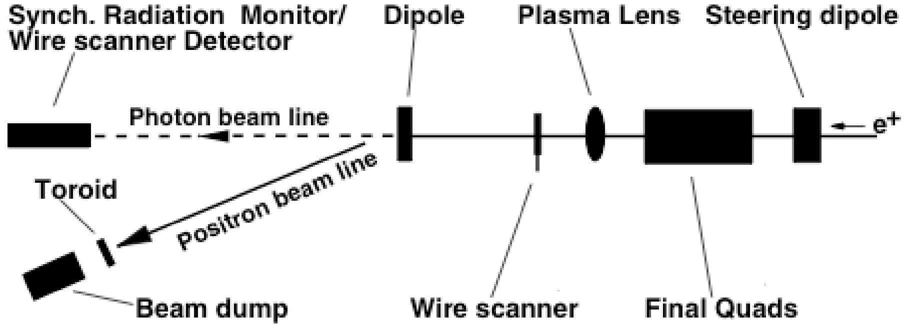


FIG. 1. Schematic layout of the SLAC Plasma Lens experiment at the FFTB. "Final Quads" are conventional focusing quadrupole magnets. The positron beam is deflected towards the dump by the magnetic dipole.

- 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}

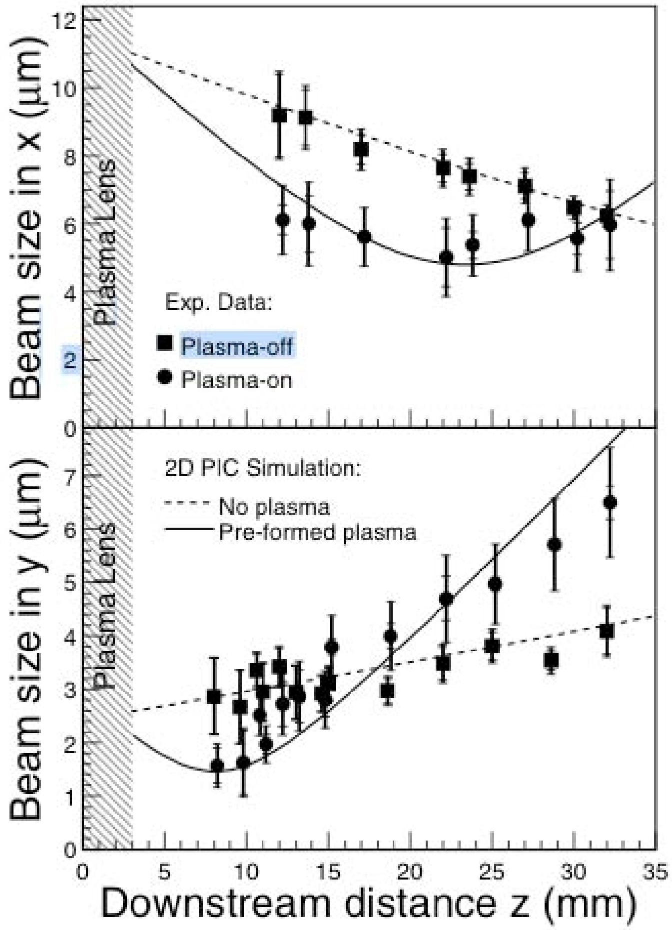


FIG. 3. Measured beam envelope Gaussian widths in the x and y dimensions, with and without plasma focusing. Inner error bars indicate the statistical uncertainty, and outer error bars indicate the quadrature sum of statistical and systematic uncertainties. The curves represent the particle-in-cell simulations.

- Plasmas do focus e$^+$

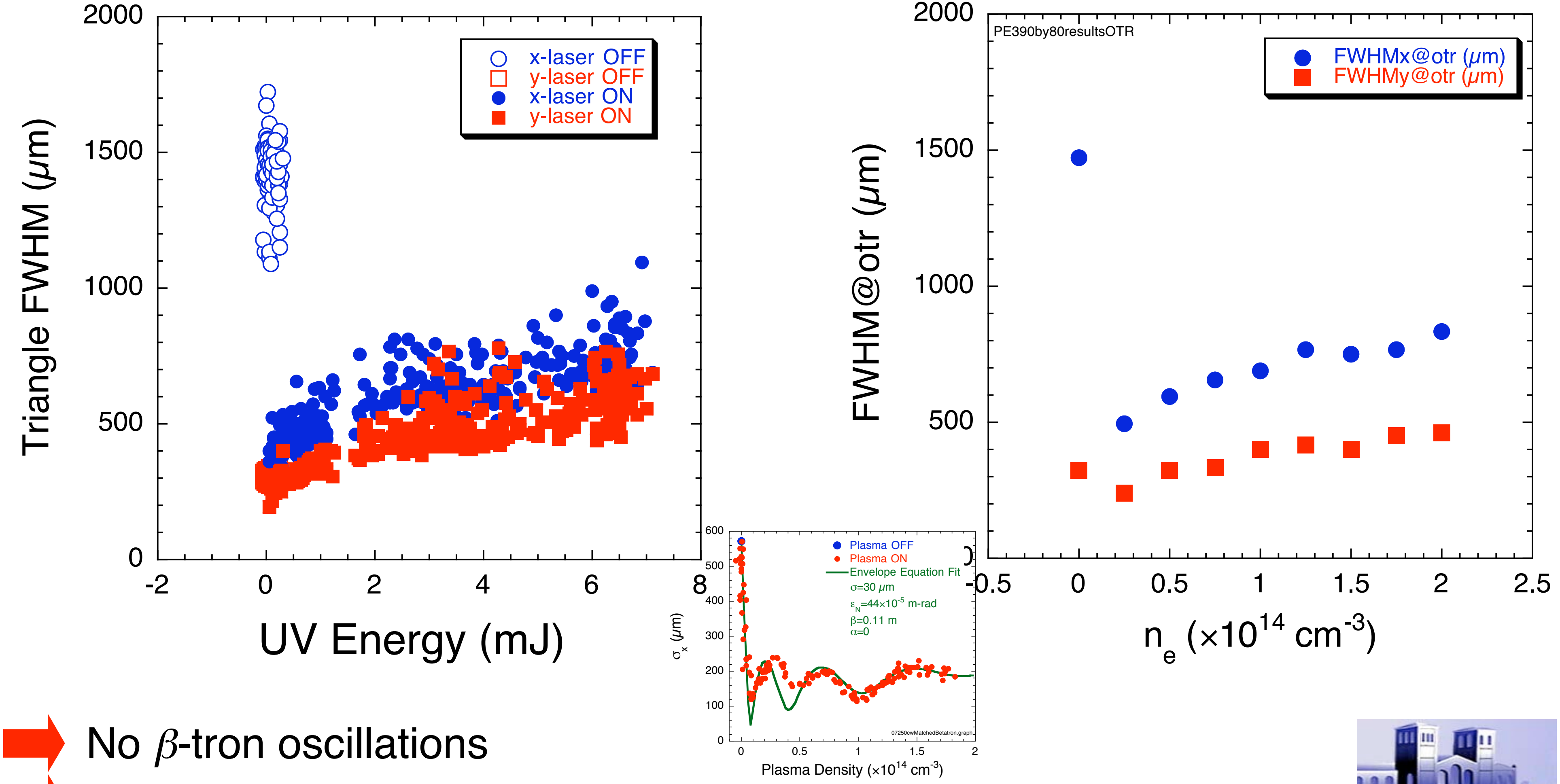
e^+ Propagation

$\sigma_{x0}=\sigma_{y0}=25\mu m$, $\varepsilon_{Nx}=390\times10^{-6}$, $\varepsilon_{Ny}=80\times10^{-6}$ 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!

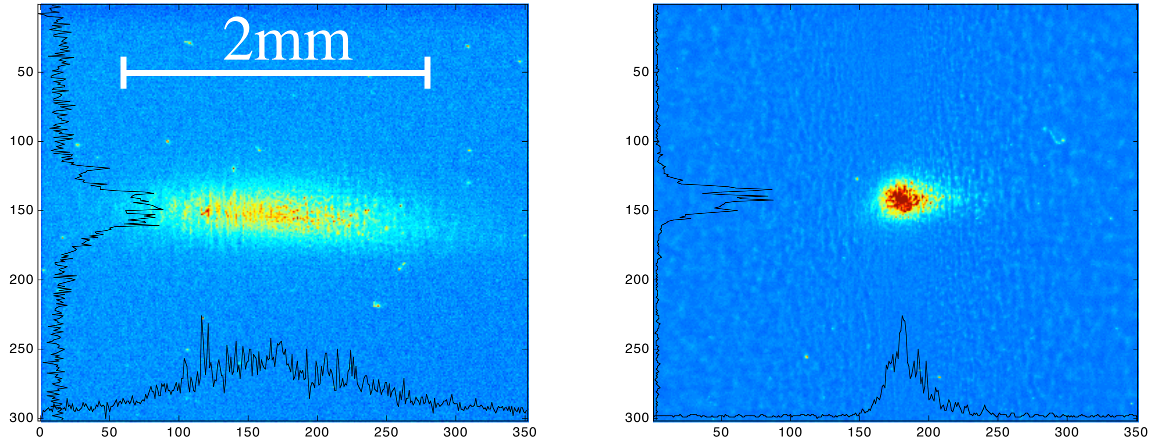
FOCUSING OF e^-/e^+

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

$n_e=0$

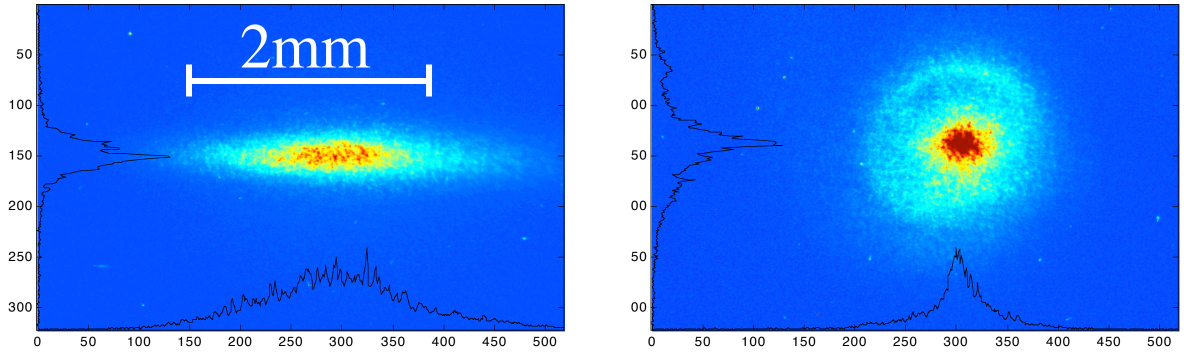
$n_e \approx 10^{14}$ cm^{-3}

e^-



- Ideal Plasma Lens in Blow-Out Regime

e^+



- Plasma Lens with Aberrations

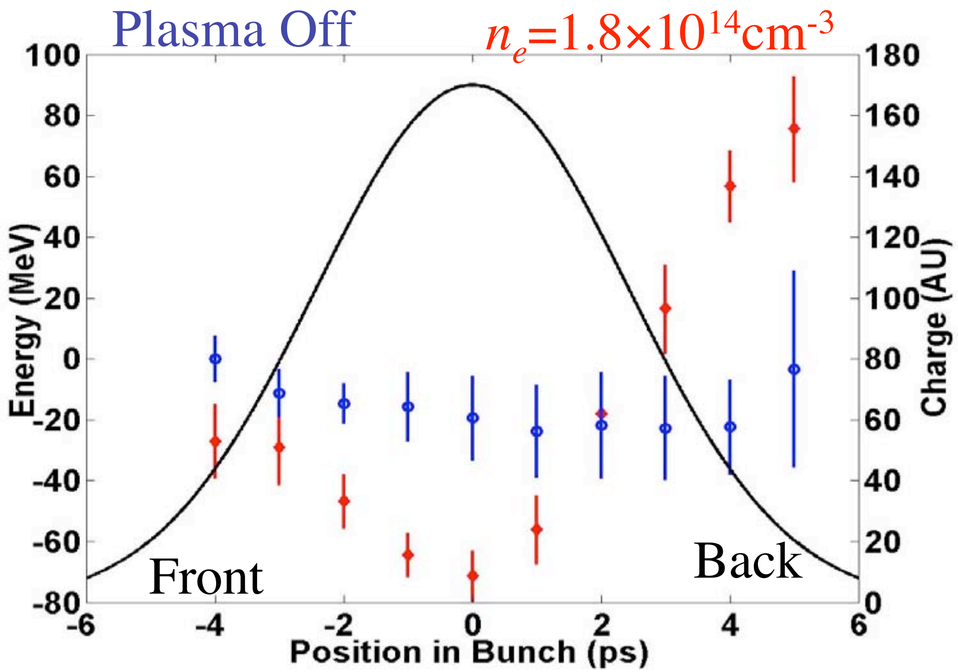
➡ Qualitative differences

ENERGY LOSS/GAIN e^+

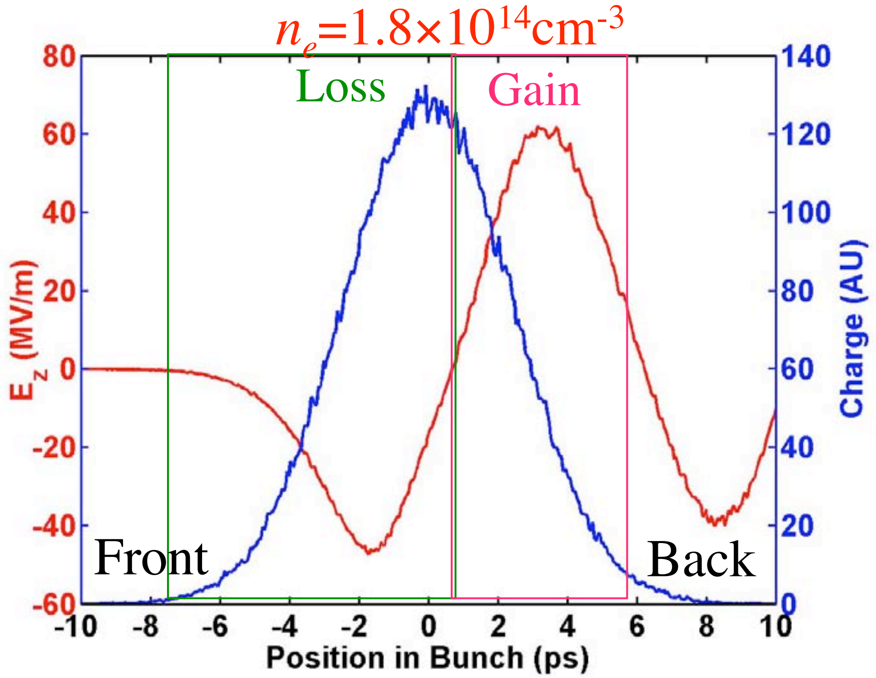
$\sigma_z \approx 730\ \mu m$

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

Experiment



2-D Simulation



- Loss ≈ 70 MeV
- Gain ≈ 75 MeV

(over 1.4 m)

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

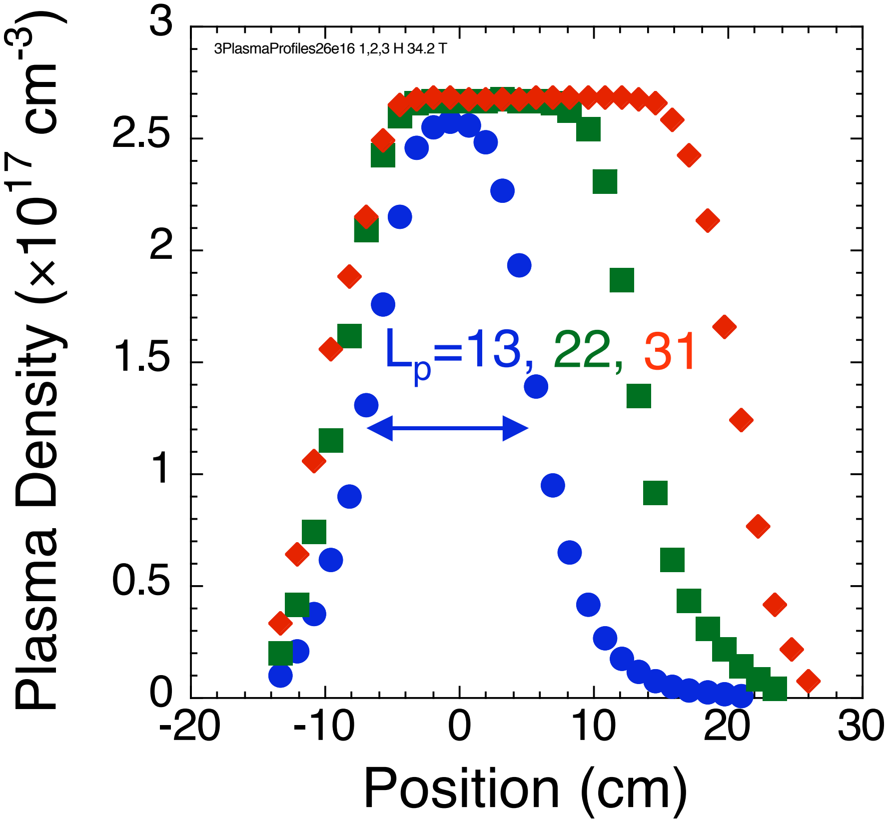
➡ Excellent agreement!

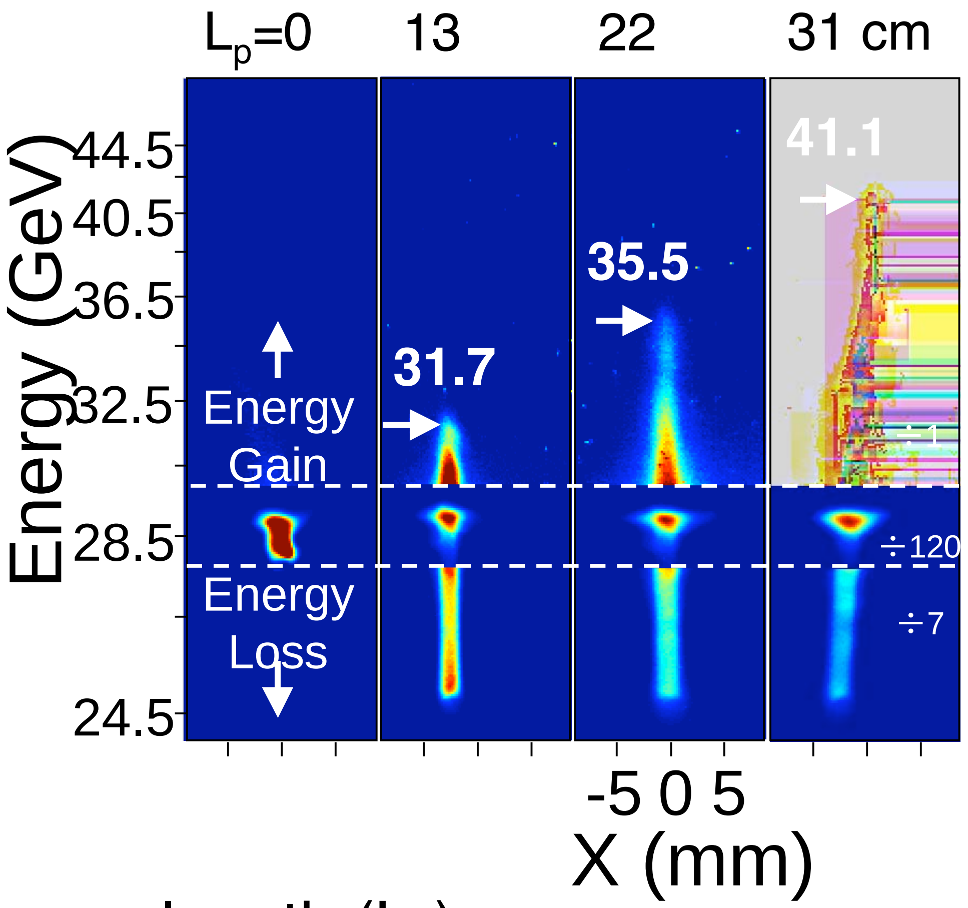
➡ Plasmas do accelerate e^+

PRL 90, 214801, (2003)

ENERGY GAIN VS. PLASMA LENGTH

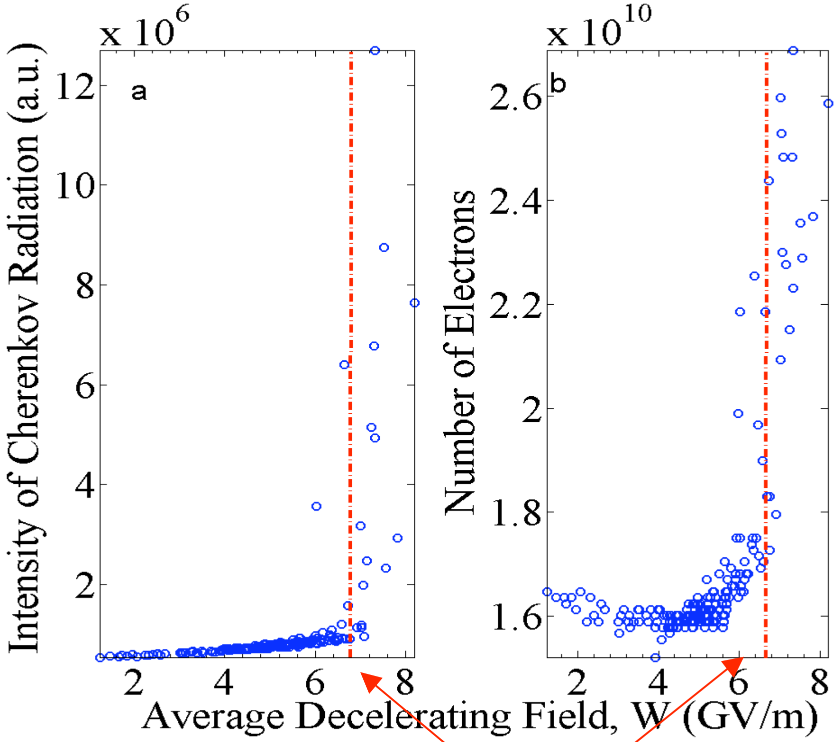
E_0=28.5 GeV, n_e=2.7×10^{17}cm^{-3}





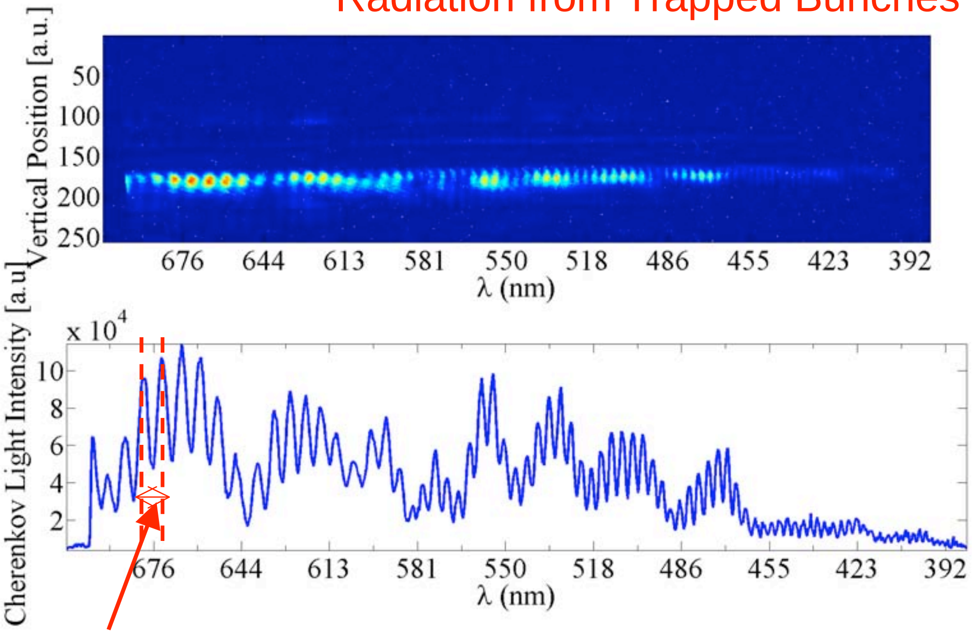
- Energy gain increases with plasma length (L_p)
- Energy gain reaches 13.6 GeV with L_p=31 cm!

TRAPPING OF PLASMA e^-



Clear threshold
at ~7 GV/m

Interference of Coherent
Radiation from Trapped Bunches



$$\tau\Delta\omega = 2\pi$$

$$\textit{Bunch Spacing} = c\tau \approx 70\ \mu,$$

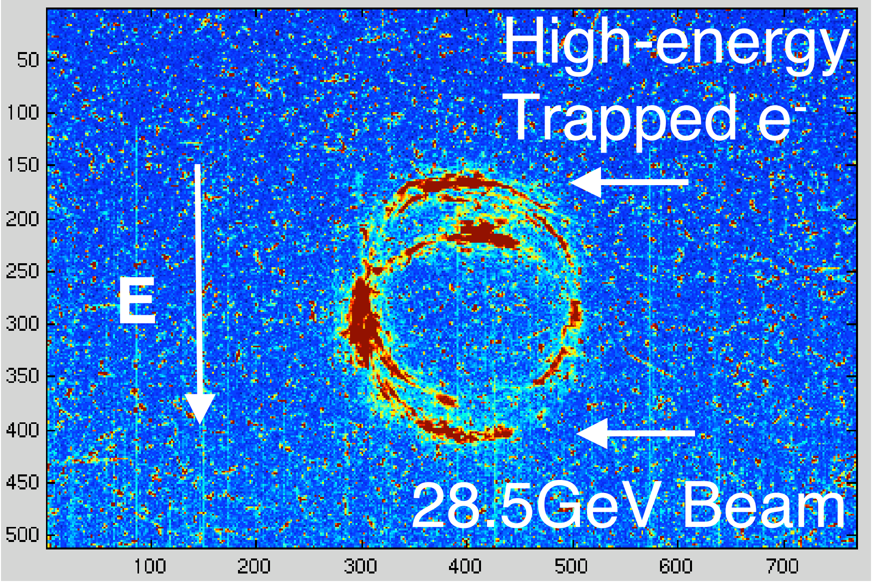
$$\textit{plasma wavelength}, \lambda_p = 64\ \mu.$$

- Trapping above a threshold wake amplitude ≈7GV/m
- Excess charge of the order of the beam incoming charge (1.6x10^{10} e^-)
- Evidence for two (or more) short bunches of trapped particles

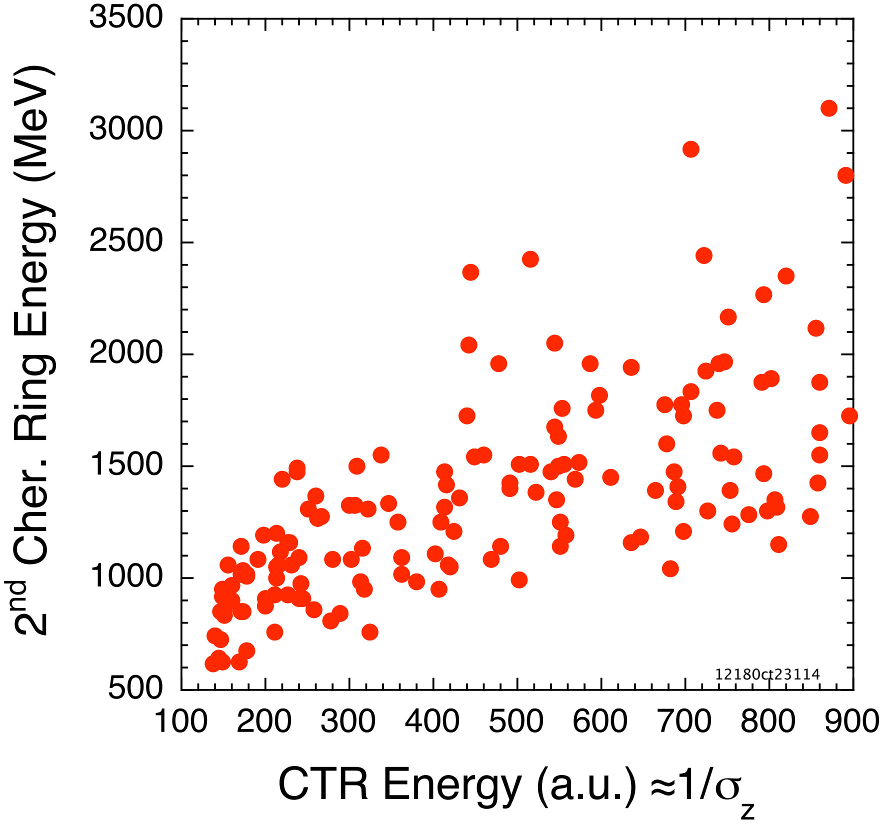
Courtesy Erdem Oz, USC

TRAPPING OF PLASMA e^-

Cherenkov Cell Image



L_p=32cm, n_e=2.6x10^{17} cm^{-3}



- High-energy, narrow ΔE/E trapped particle bunches

SCIENCE TOPICS FOR SABER

SABER:
- Short ($\sigma_z<30\mu$m) e^- and e^+ bunches
- High peak current (>10kA, $N\approx 2\times 10^{10}$/bunch)
- Small ($\sigma_{x,y}<10\mu$m) transverse size

Topics:
- e^+-beam/plasma physics
- Beyond energy doubling?
- Ionization/wake excitation by e^+ , hollow plasmas
- Transport/acceleration in long plasmas (e^-/e^+)
- Beam quality (ε?, $\Delta E/E$?, …), ion motion
- Beam/plasma matching
- γ-ray source/e^+ source
- Radiation from e^+ in plasmas
- Focusing/plasma lens
- 2-bunch experiments/head erosion/stability
- Hollow plasmas for e^+ beams
- Experiments fo early SABER?

UCLA

e^+ PLASMA FOCUSING

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

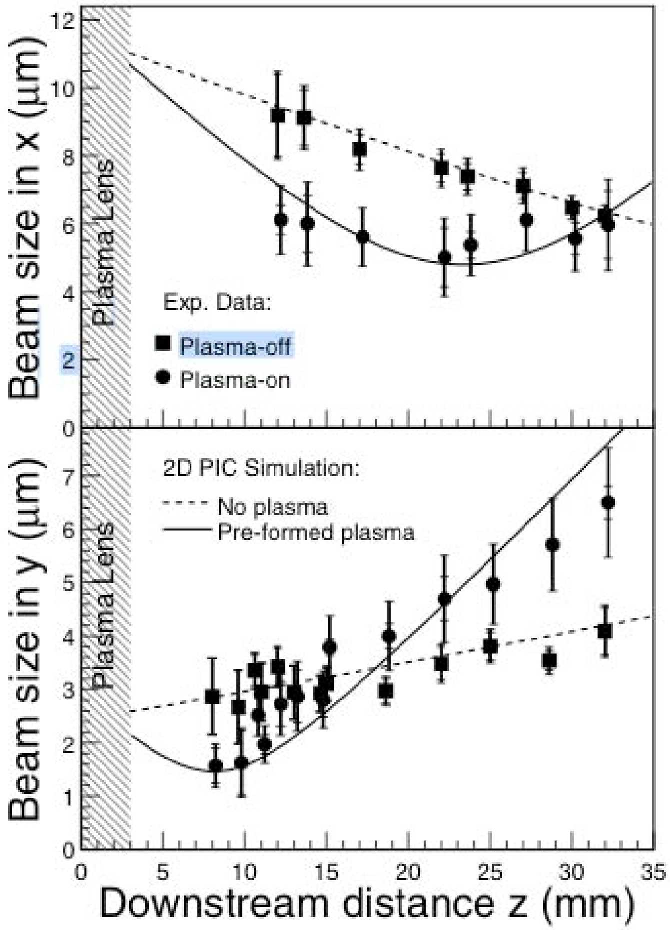


FIG. 3. Measured beam envelope Gaussian widths in the x and y dimensions, with and without plasma focusing. Inner error bars indicate the statistical uncertainty, and outer error bars indicate the quadrature sum of statistical and systematic uncertainties. The curves represent the particle-in-cell simulations.

M.J. Hogan *et al.*, PRL 2006

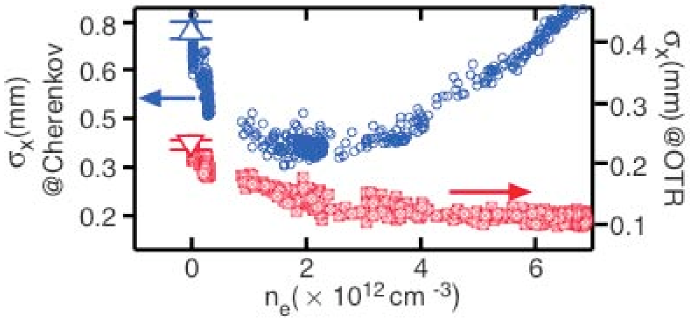


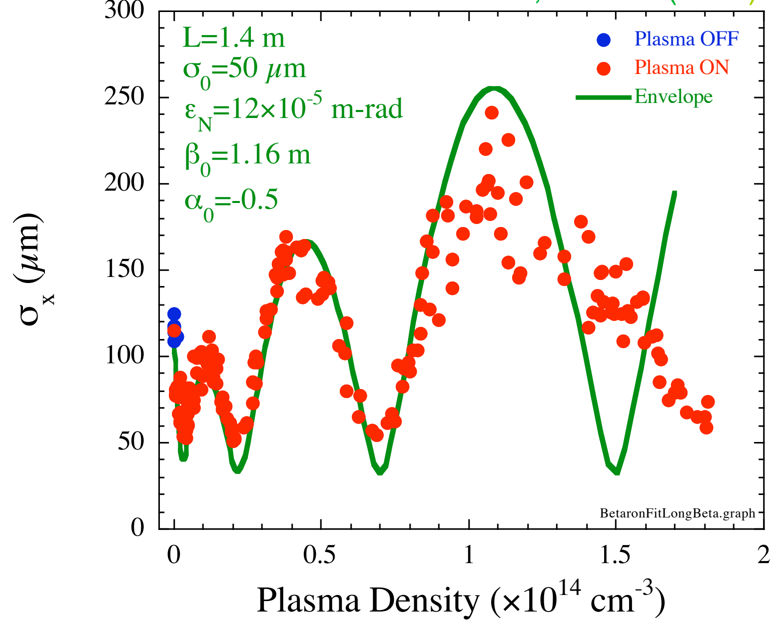
FIG. 1 (color). Time-integrated measurements of the positron beam spot size in the x direction vs n_e from the two profile monitors downstream of the plasma exit. The symbols at zero density are the mean no-plasma spot sizes at the Cherenkov radiator (△) and OTR (▽) for 50 pulses. The bars indicate the error of the mean.

- Plasmas do focus e^+

PROPAGATION OF e^-

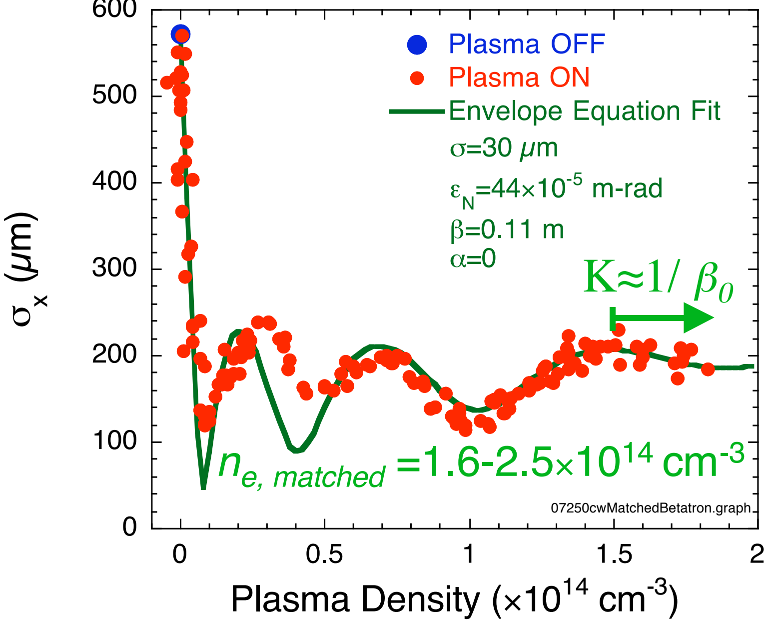
OTR Images ≈1m downstream from plasma

$K \geq 1/\beta_0$



PRL 88, 154801 (2002)

$K \leq 1/\beta_0$



PRL 93, 014802 (2004)

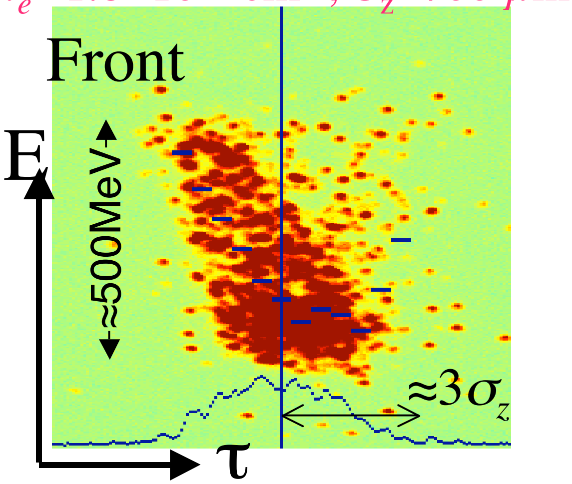
- Focusing of the beam well described by a simple model ($n_b > n_e$):
- No emittance growth observed as n_e is increased
- Stable propagation over L=1.4 m up to as n_e =1.8×10^{14}cm^{-3}
- Channeling of the beam over 1.4 m or >12β_0

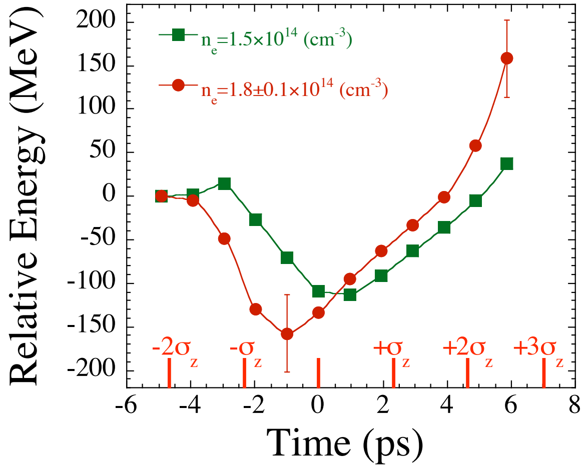
  => Matched Propagation over long distance!

Plasma
=
Ideal Thick Lens

e^- ACCELERATION

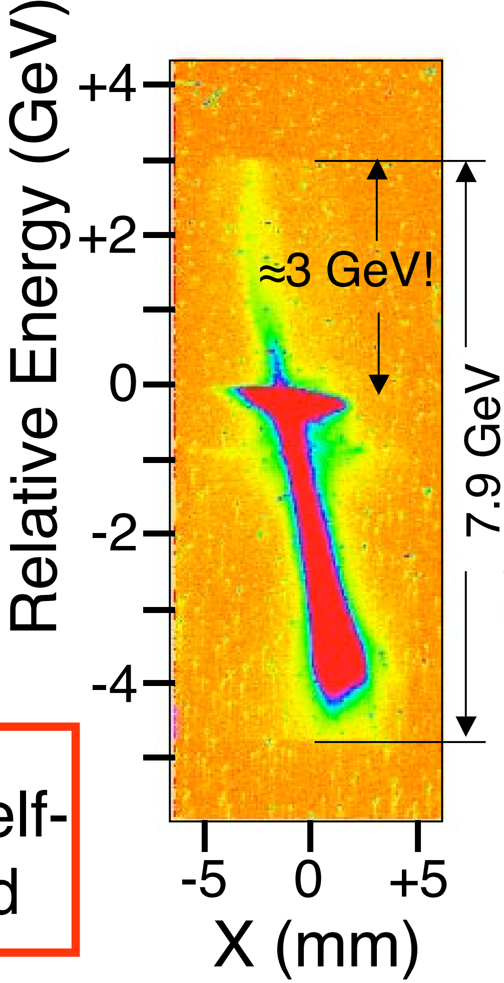
$n_e=1.8\times10^{14}$ cm^{-3}, $\sigma_z\approx700\ \mu$m

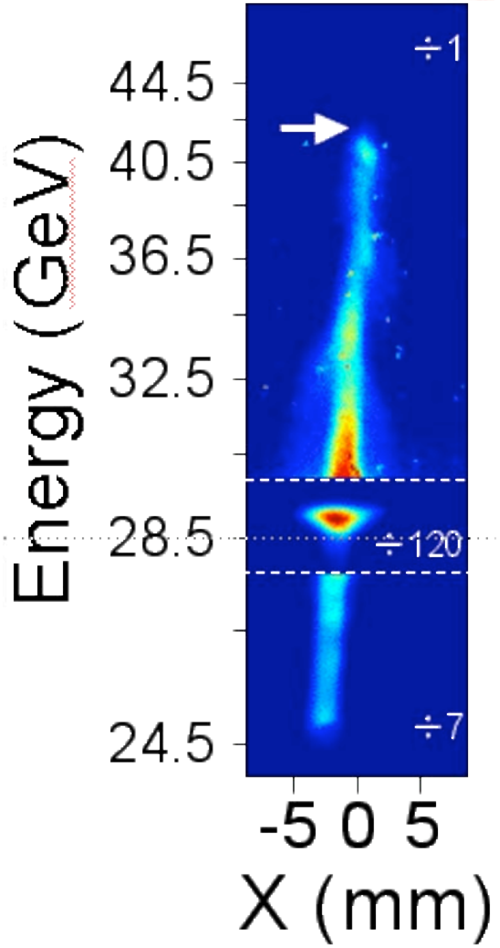




Pre- | Self-
Ionized

$n_e=2.6\times10^{17}$ cm^{-3}, $\sigma_z\approx20$-$30\ \mu$m





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

MOTIVATION / QUESTIONS

➡ Could an accelerating structure with a gradient significantly larger (×10, …, ×1000) than that reached in present rf cavities be created and can it lead to large energy gain (1-100 GeV)?

- ILC: 35-45 MV/m → 28-23 km for 1 TeV!
- CLIC: 150 MV/m → 7 km for 1 TeV!

➡ Could such a structure be used to produce high-quality e^-/e^+ beams?

- E≈GeV/TeV, ΔE/E<<1, ε<<1, …

➡ Could such a structure be made of PLASMA?

WHY PLASMA?

➡ Plasmas can sustain very large electric fields (10-100 GV/m)

- Relativistic plasma waves or wakes: **E**//**k**, electrostatic
- Exist for a a short time (few wave periods)
- Already ionized (H I: 13.6 eV, Li I: 5.4 eV, Li II: 75 eV)

➡ Accelerating "structure" or wake is sustained by the plasma

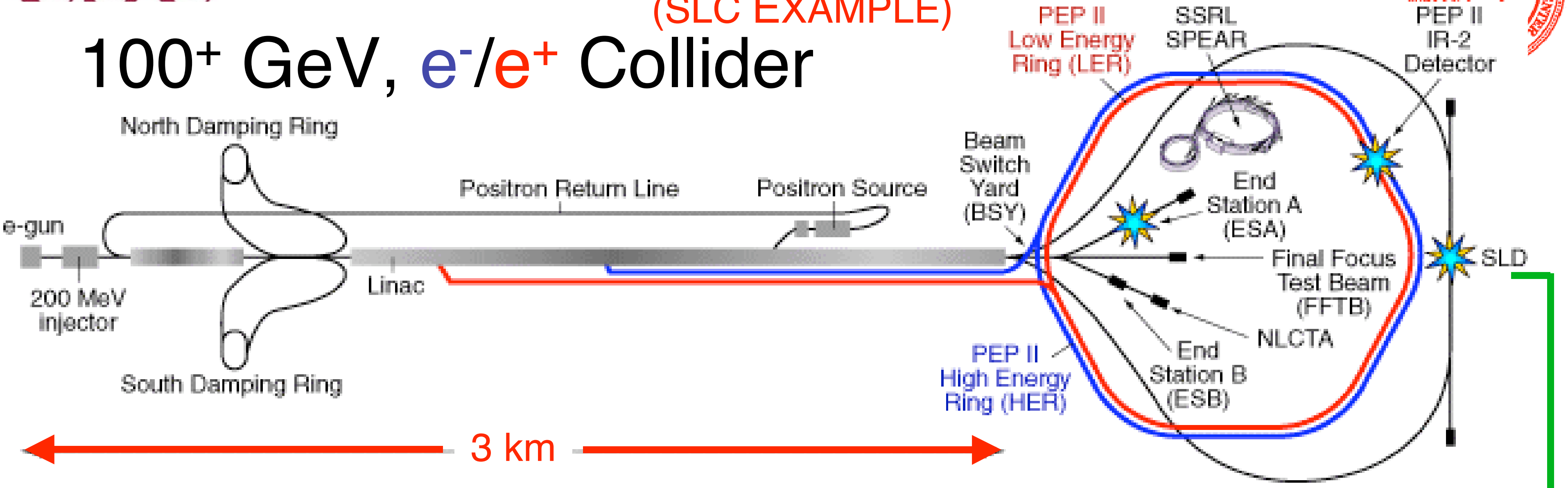
- No fabricated structure
- Operation a very high frequency (THz)
- No damage to the structure

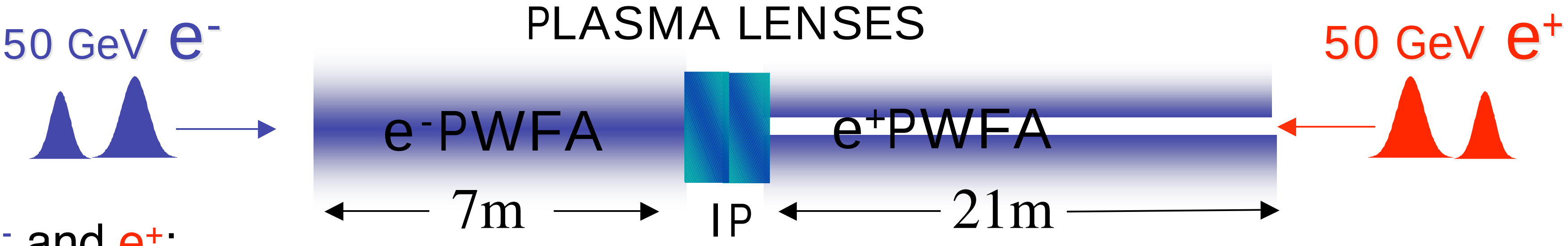
➡ ➡ beam-driven, plasma wakefield accelerator or PWFA

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

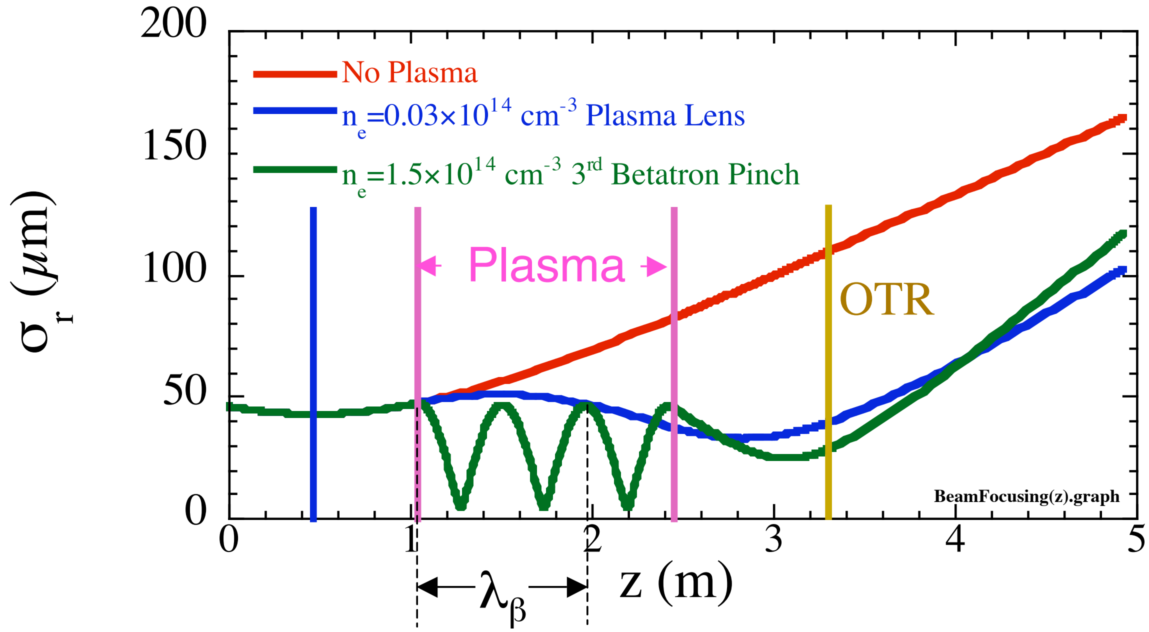
S. Lee *et al.*, PRST-AB (2001)

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:

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

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}

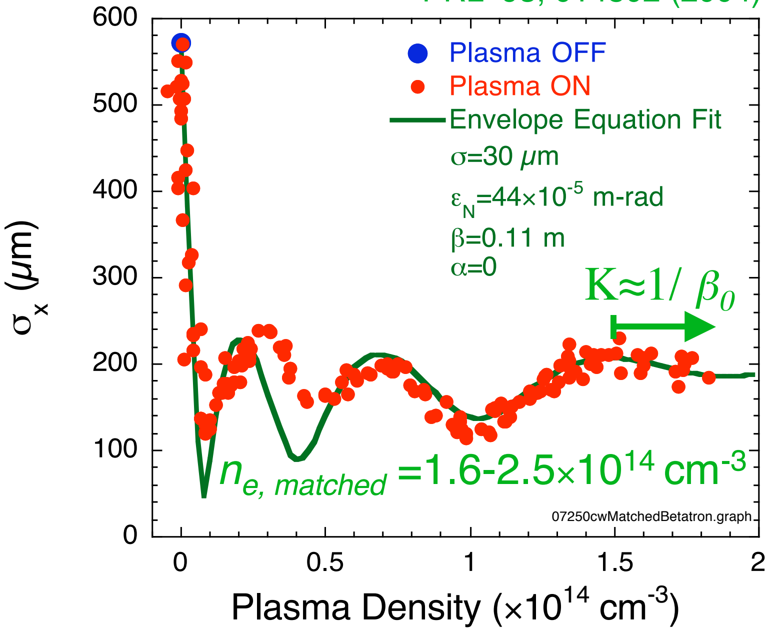
- Multiple foci (betatron oscillation) within the plasma
- Synchroton “betatron” radiation

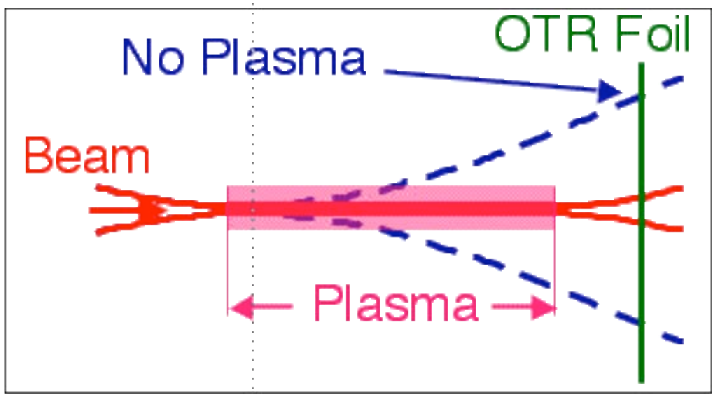
PROPAGATION OF e^-

OTR Images ≈1m downstream from plasma

$K \le 1/\beta_0$

PRL 93, 014802 (2004)





Matching condition:

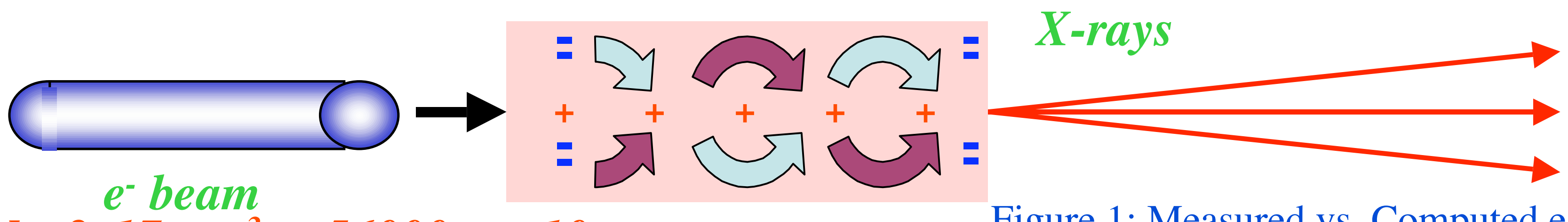
$$\frac{\sigma^2 n_e}{\varepsilon\gamma} = \frac{\varepsilon_0 m_e c}{2e^2}$$

- 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):

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

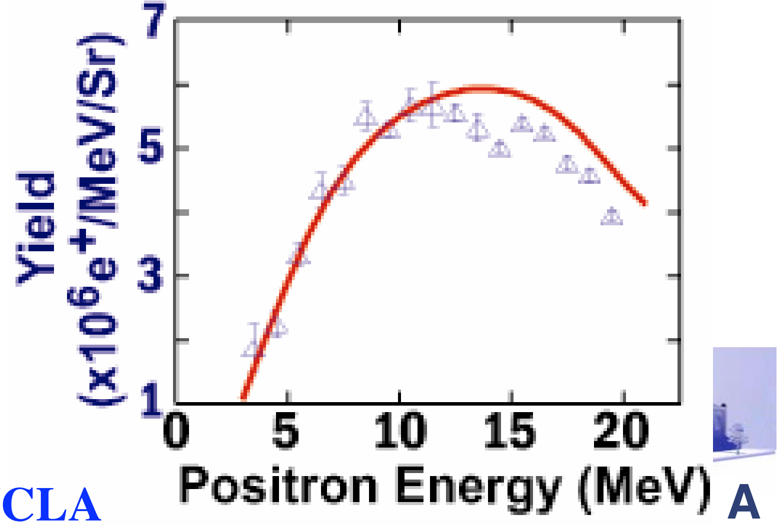
3) Particle energy loss:

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

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

△ Measured e^+ Spectrum

▬ Computed e^+ Spectrum

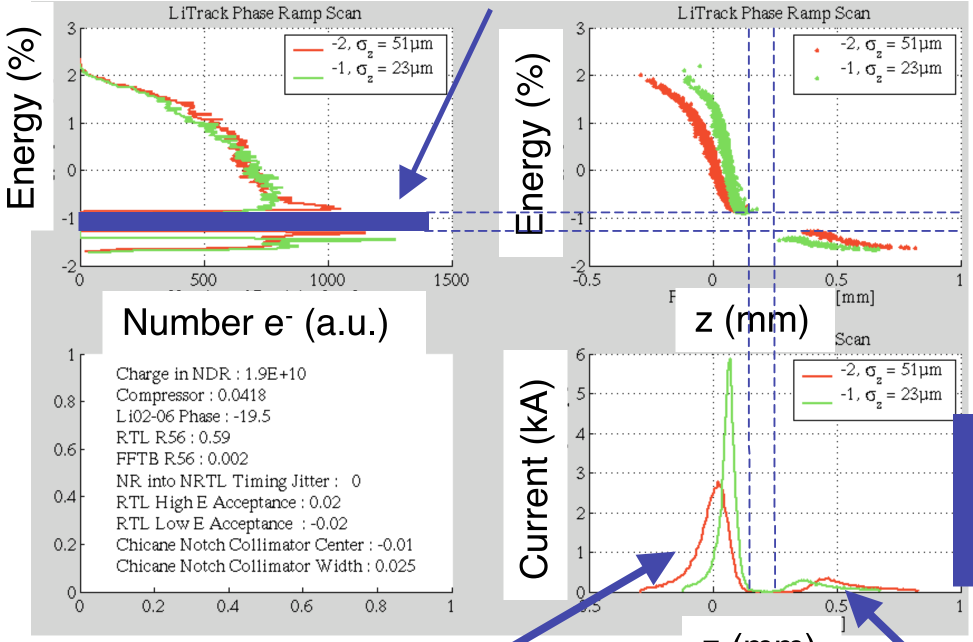


Courtesy of Devon Johnson, UCLA

2-BUNCH GENERATION

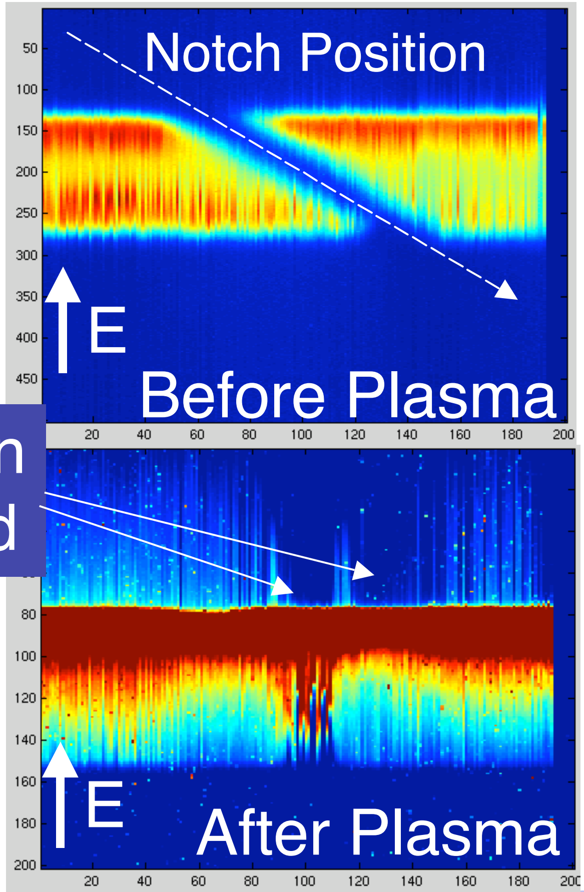
Notch collimator in the dispersive region of the FFTB dogleg

Notch Collimator



Drive Bunch

Witness Bunch



Energy Gain Suppressed

- Work in progress, transferred to SABER?

Litrack, K. Bane, P. Emma