Positron Transport, Focusing and Acceleration Using Plasma Techniques

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Work supported by US Dept. of Energy

Collaboration:

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University of California, Los Angeles

T. Katsouleas, X. Li, P. Muggli, E. Oz

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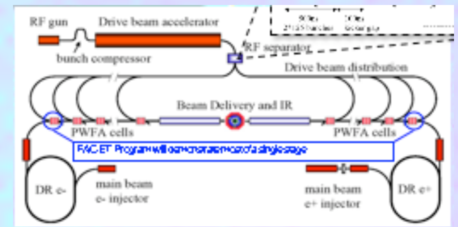
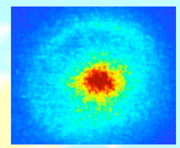
OUTLINE

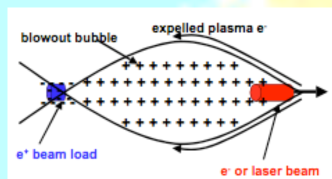
- Plasma Wakefield Accelerator (PWFA), collider, e^-



- e^+ beam transport and focusing



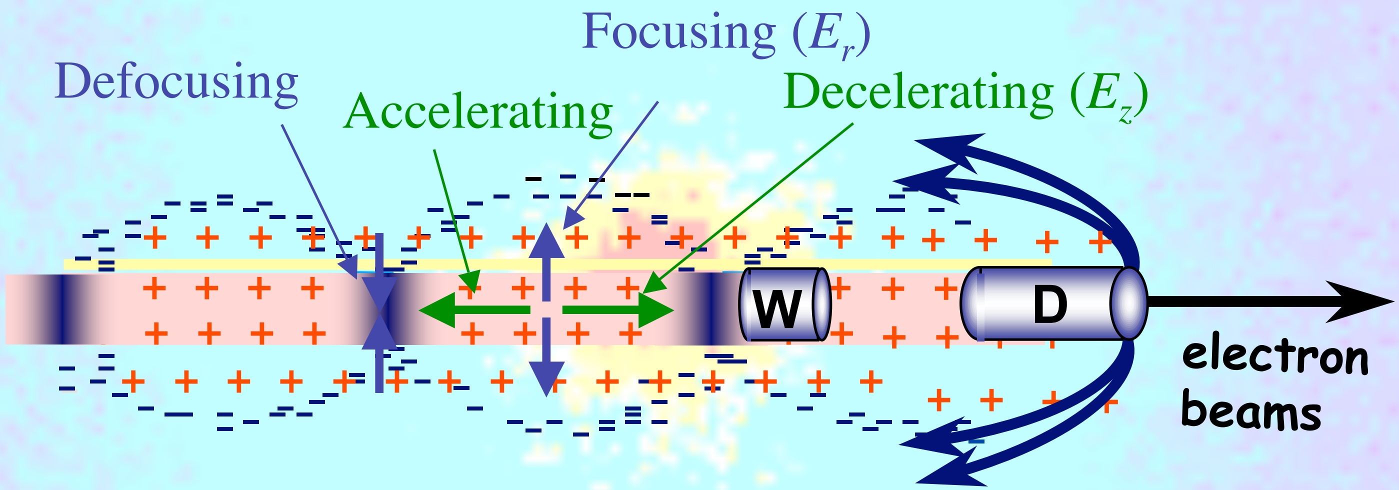
- e^+ acceleration



- Conclusions

PLASMA WAKEFIELD ACCELERATOR* 101

- Two-beam, co-linear, plasma-based accelerator

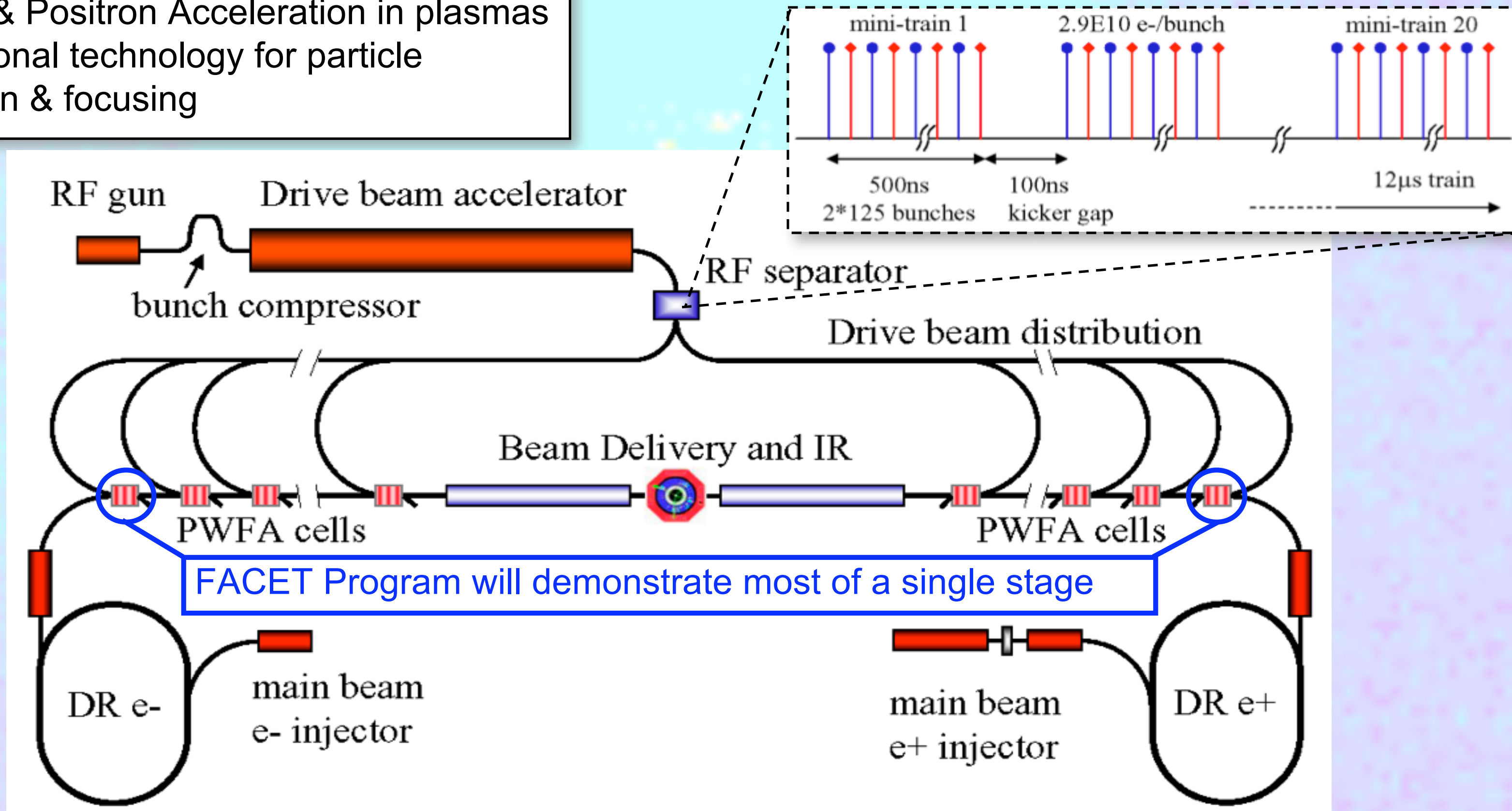


- Deceleration, acceleration, focusing by plasma
- Accelerating field/gradient scales as $n_e^{1/2}$
- Typical: $n_e \approx 10^{16}$-10^{17} cm^{-3}, $\lambda_p \approx 150$ µm, $f_p \approx 2$ THz, $E > 10$ GV/m
- High-gradient, high-efficiency energy transformer

PWFA-LC Concept (an example)

July 7, 2008

- TeV CM Energy
- 10's MW Beam Power for Luminosity
- Electron & Positron Acceleration in plasmas
- Conventional technology for particle generation & focusing



♦ FACET*@SLAC: single, 1m-long, +25 GeV stage, e^- and e^+

*Facilities for Accelerator Science and Experimental Test Beams

PWFA-LC Concept (an example)

July 7, 2

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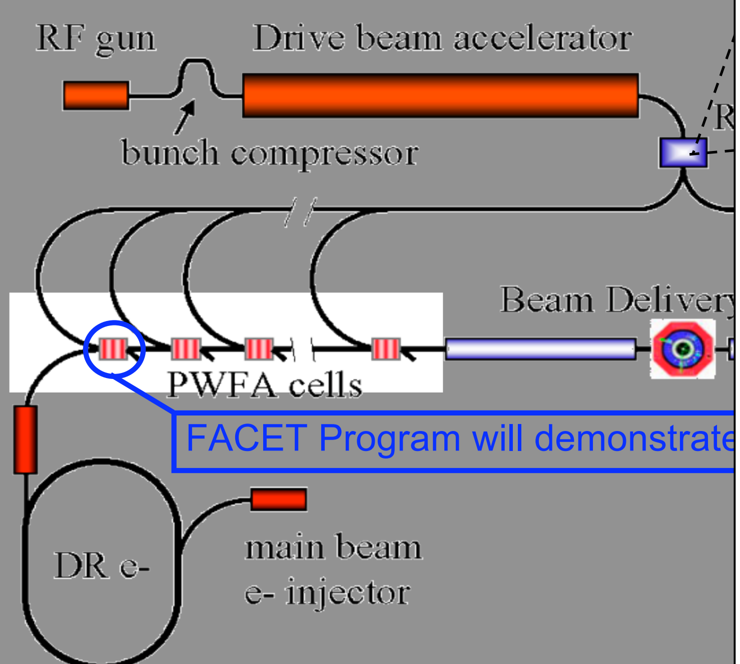
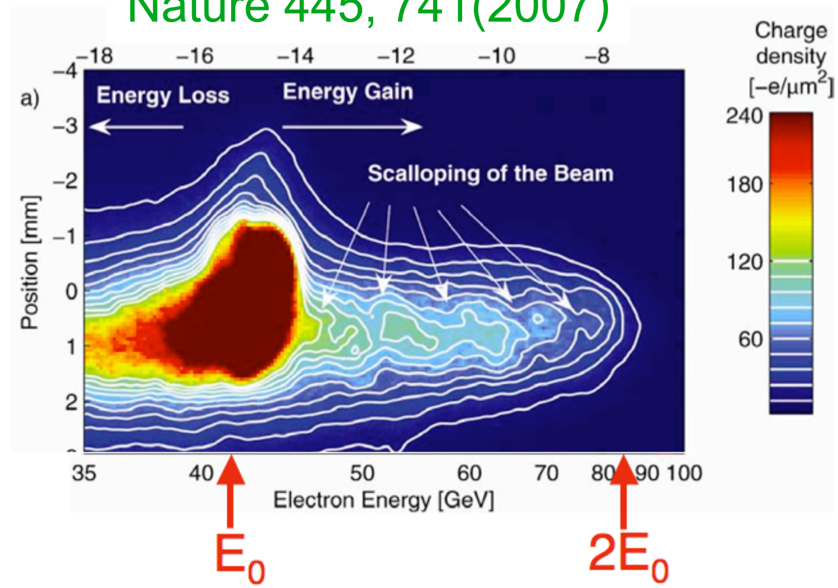


- FACET*@SLAC: single, 1m-l
- e+ at SLAC only!

*Facilities for Accelerator Science a

- e^-

Nature 445, 741(2007)



- Energy doubling of 42 GeV e^-
- Plasma length: 85 cm
- Accelerating gradient: 50 GeV/m
- Agreement with simulations

PWFA-LC Concept (an example)

July 7, 2

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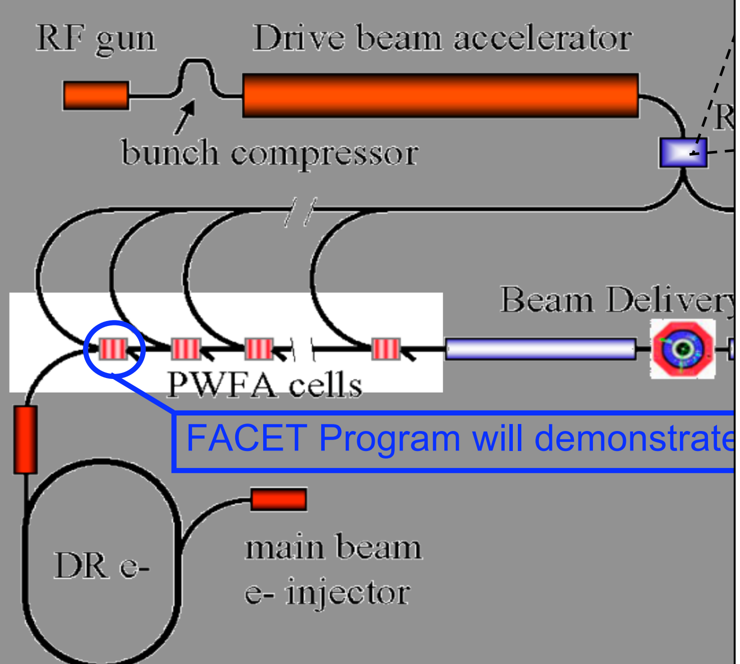
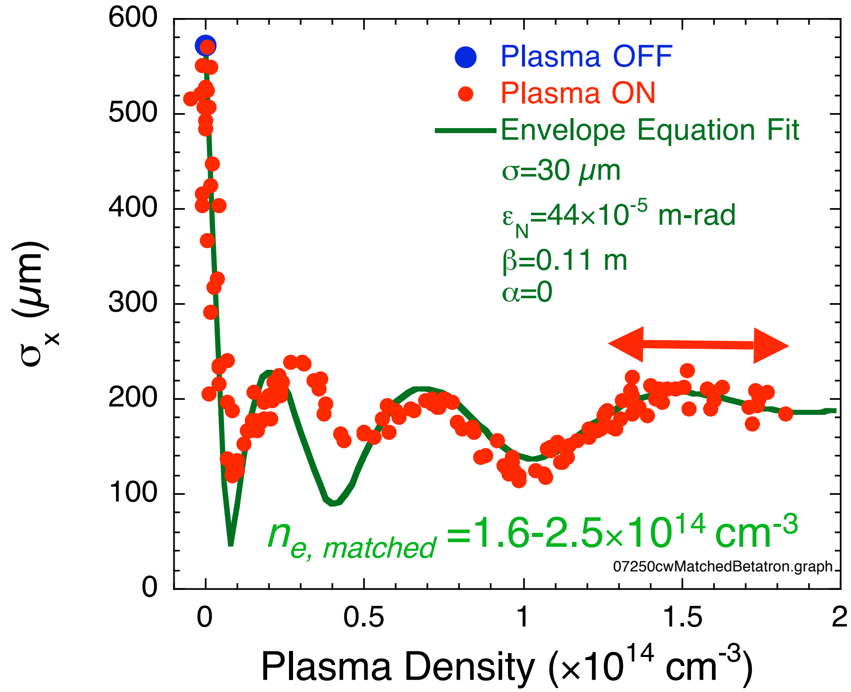


♦ FACET*@SLAC: single, 1m-l

♦ e+ at SLAC only!

*Facilities for Accelerator Science a

♦ e^- PRL 93, 014802 (2004)



♦ Linear focusing force $n_b > n_e$

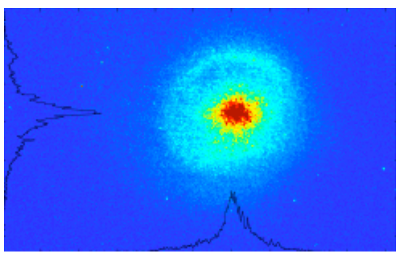
♦ Emittance preservation

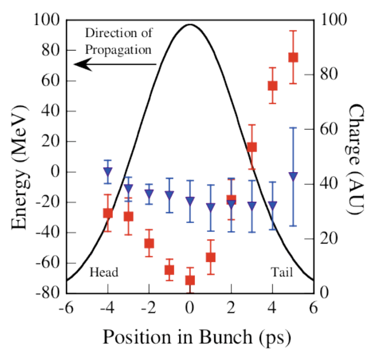
♦ The case of e^- bunches in PWFA is well understood and favorable

PWFA-LC Concept (an example)

- e^+

?





- Less studied
- e^+ beams not widely available!
- More challenging!

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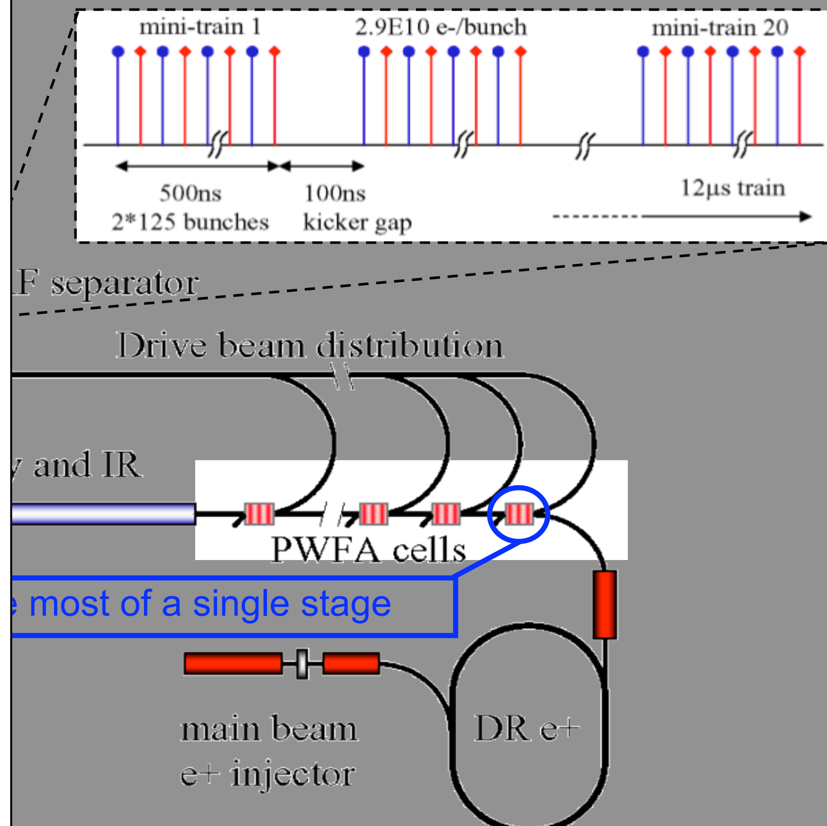
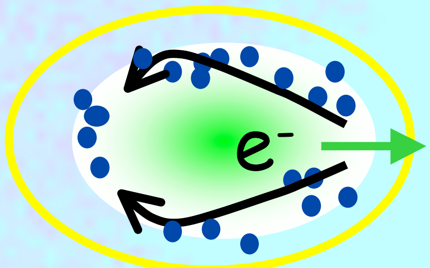


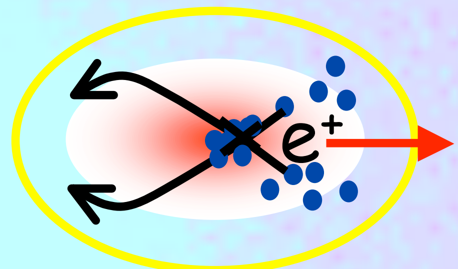
ong, +25 GeV stage, e^- and e^+

nd Experimental Test Beams

e^- & e^+ BEAM NEUTRALIZATION, "FOCUSING"

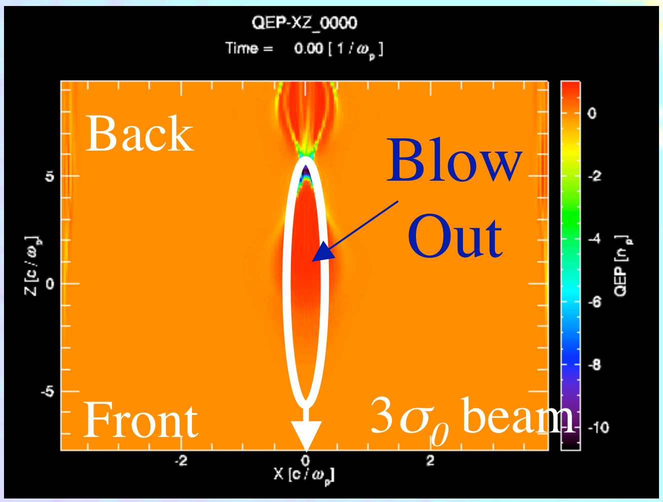
- Transverse dynamics, emittance preservation?





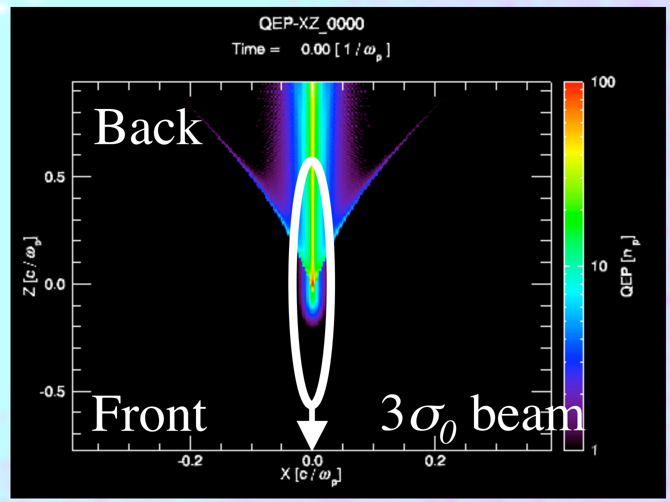
3-D QuickPIC simulations, plasma e^- density:

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



$\sigma_r=35\ \mu$m
$\sigma_r=700\ \mu$m
$N=1.8\times10^{10}$
$L=2$ mm

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



- Uniform focusing force (*r*,*z*)
- Free of geometric aberrations
- Emittance preserved

- Non-uniform focusing force (*r*,*z*)
- Emittance growth?

e^- & e^+ FOCUSING FIELDS

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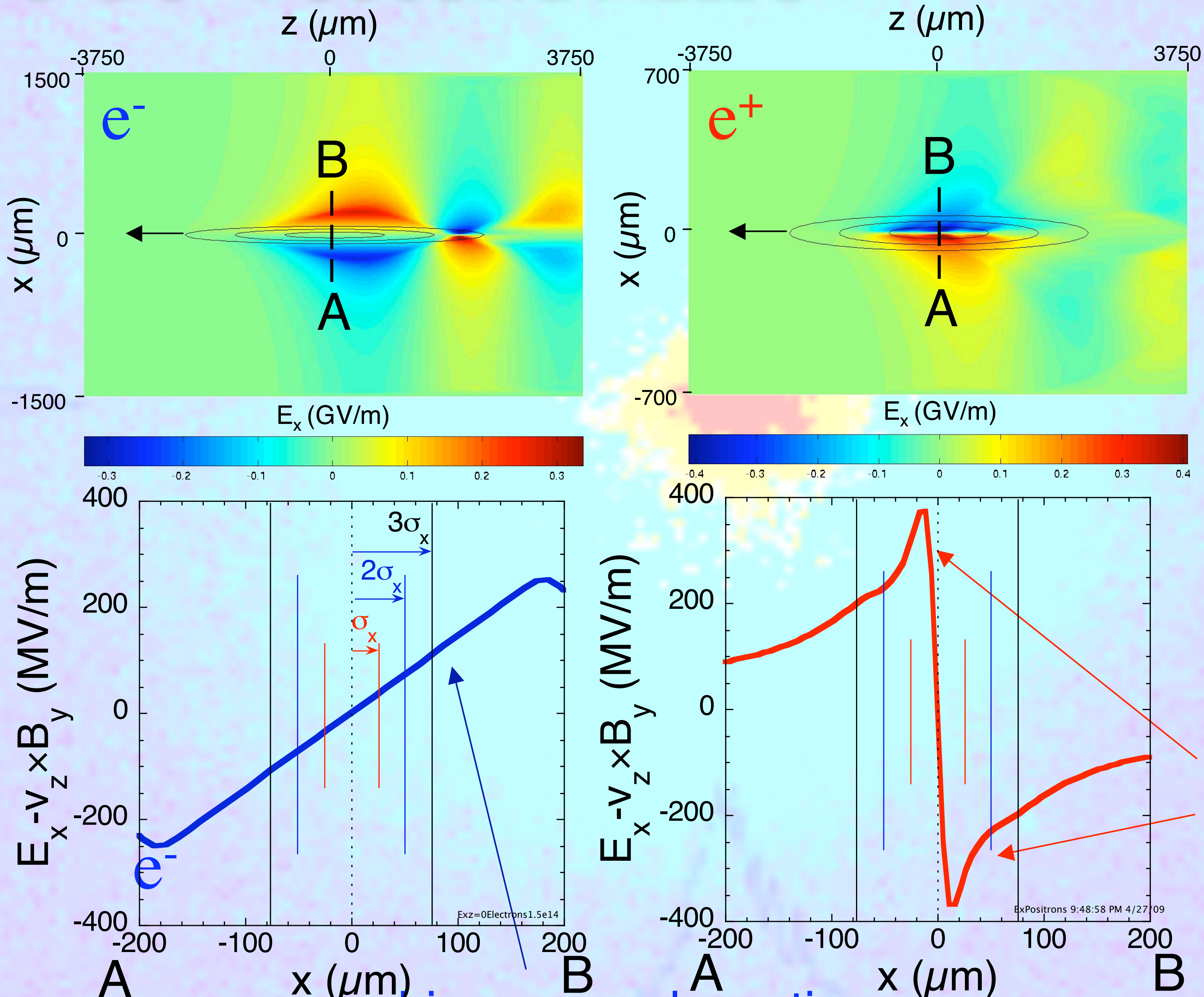


QuickPIC
$\sigma_{x0}=\sigma_{y0}=25\ \mu m$
$\sigma_z=730\ \mu m$
$N=1.9\times10^{10}\ e^+/e^-$
$n_e=1.5\times10^{14}\ cm^{-3}$

Non-linear, aberrations

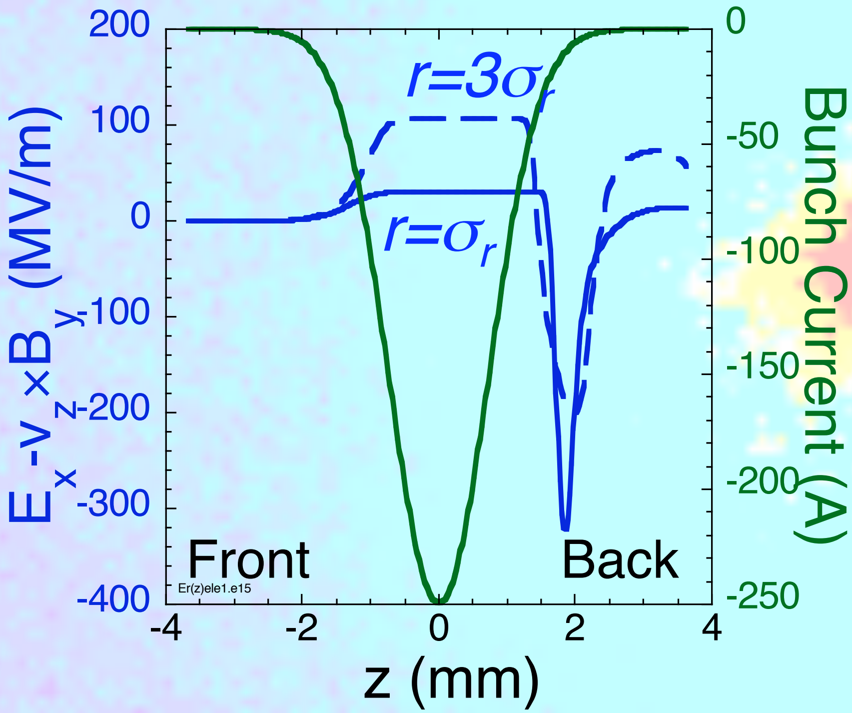
Linear, no aberrations

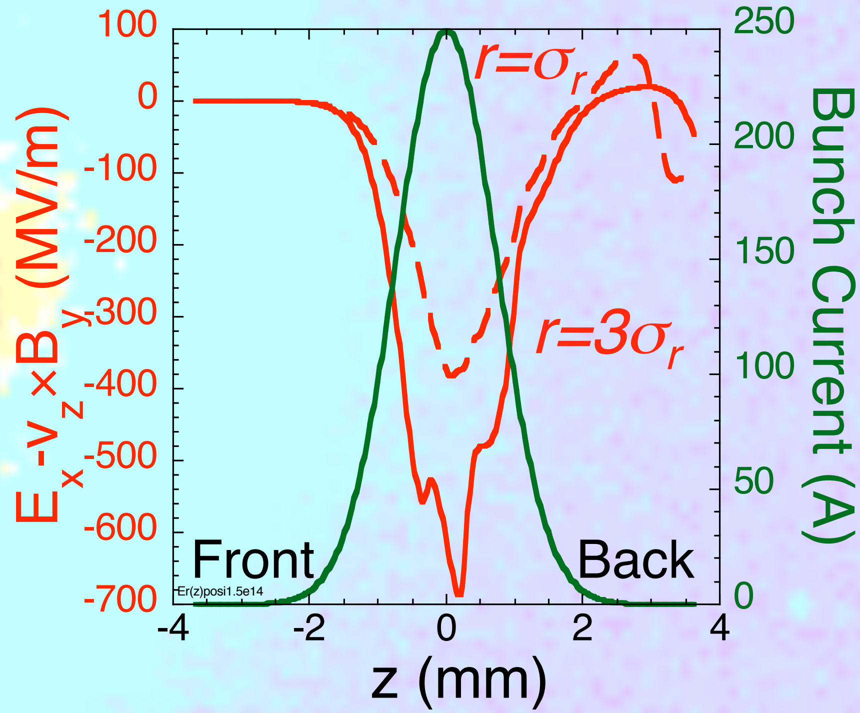
P. Muggli, PAC 09. 05/04/09

PAC09 VANCOUVER

e^- & e^+ FOCUSING FIELDS

QuickPIC: $\sigma_{x0}\approx\sigma_{y0}\approx 25\ \mu m$, $\varepsilon_{Nx}\approx 390\times10^{-6}$, $\varepsilon_{Ny}\approx 80\times10^{-6}$ m-rad, $N=1.9\times10^{10}\ e^+$, $\sigma_z\approx 730\ \mu m$, $n_e=1.5\times10^{-6}$, $L\approx 1.1$ cm





- Uniform focusing force (*r,z*)
- Weaker focusing force

- Non-uniform focusing force (*r,z*)
- Stronger focusing force

♦ e^+: focusing fields vary along r and z!

♦ Emittance growth expected

EXPERIMENTAL SET UP

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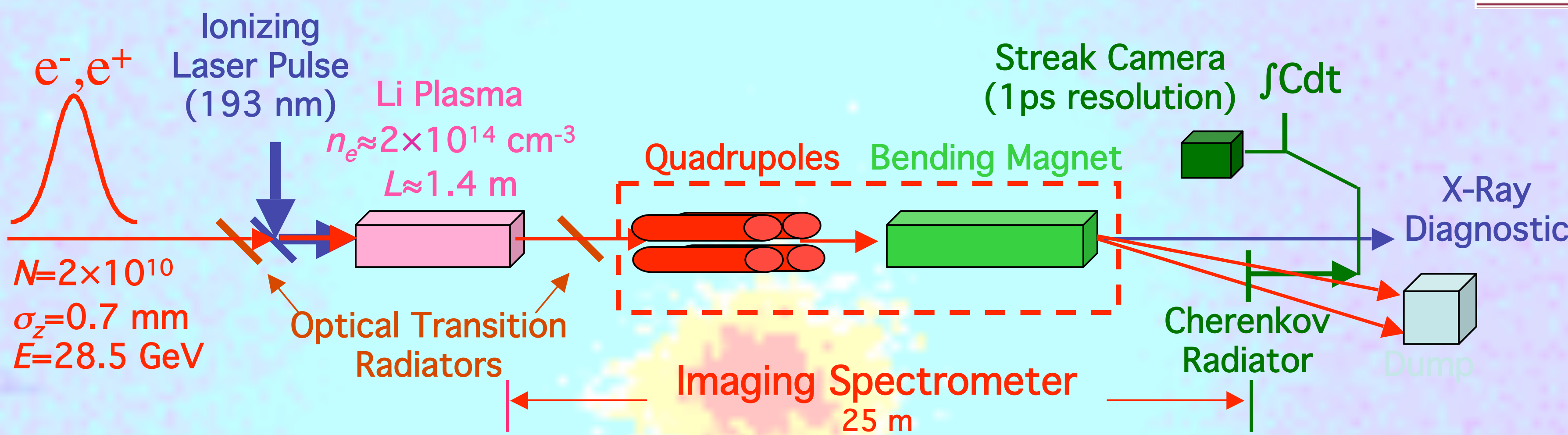
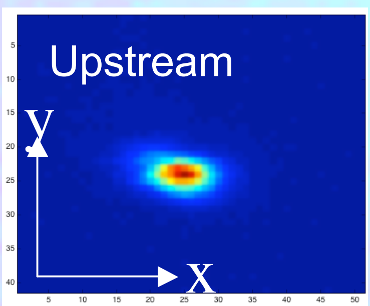
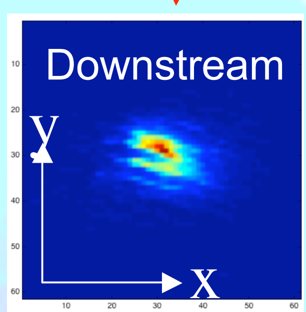
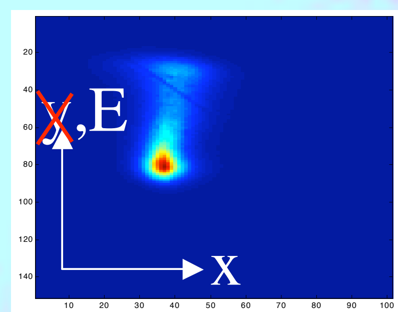


- Optical Transition Radiation (OTR)
- CHERENKOV (aerogel)







- 1:1 imaging, spatial resolution <9 μm

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

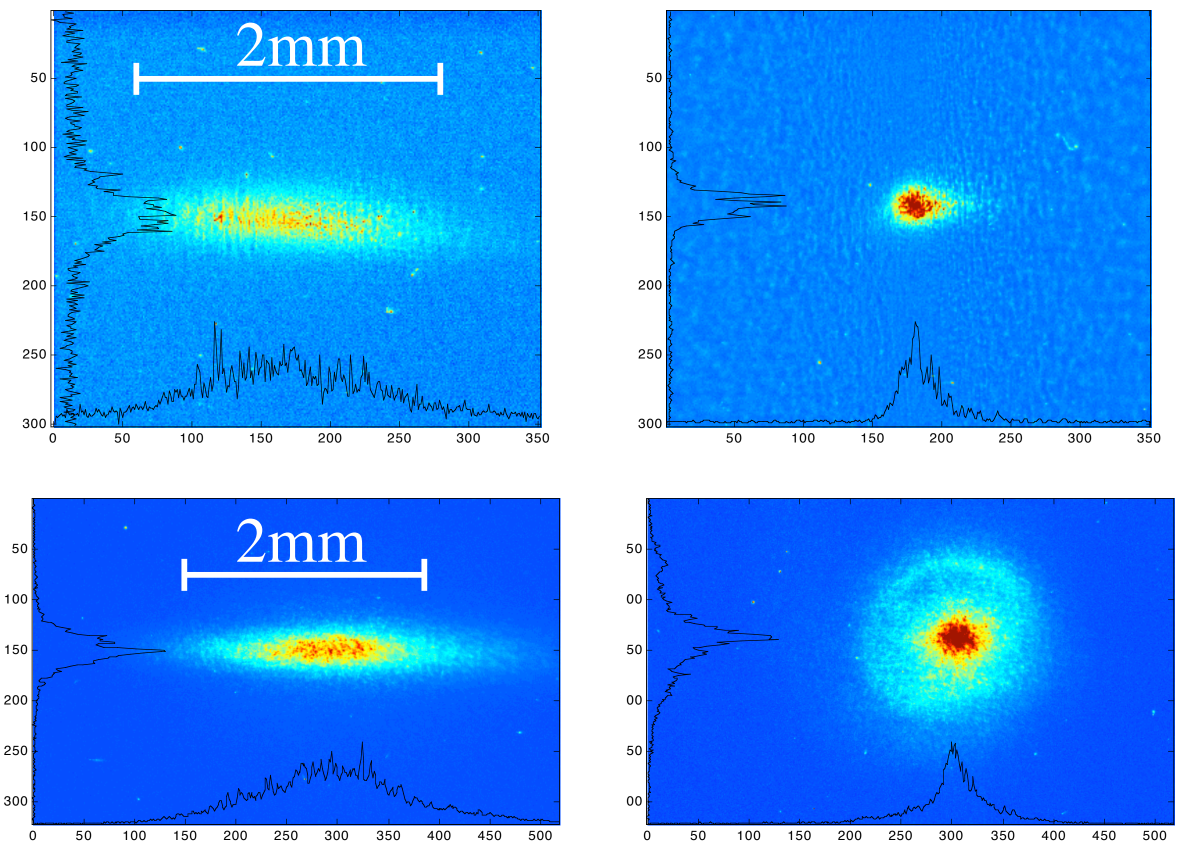
PAC09 VANCOUVER

FOCUSING OF e^-/e^+

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

n_e=0 | n_e≈10^{14} cm^{-3}

e^- | e^+



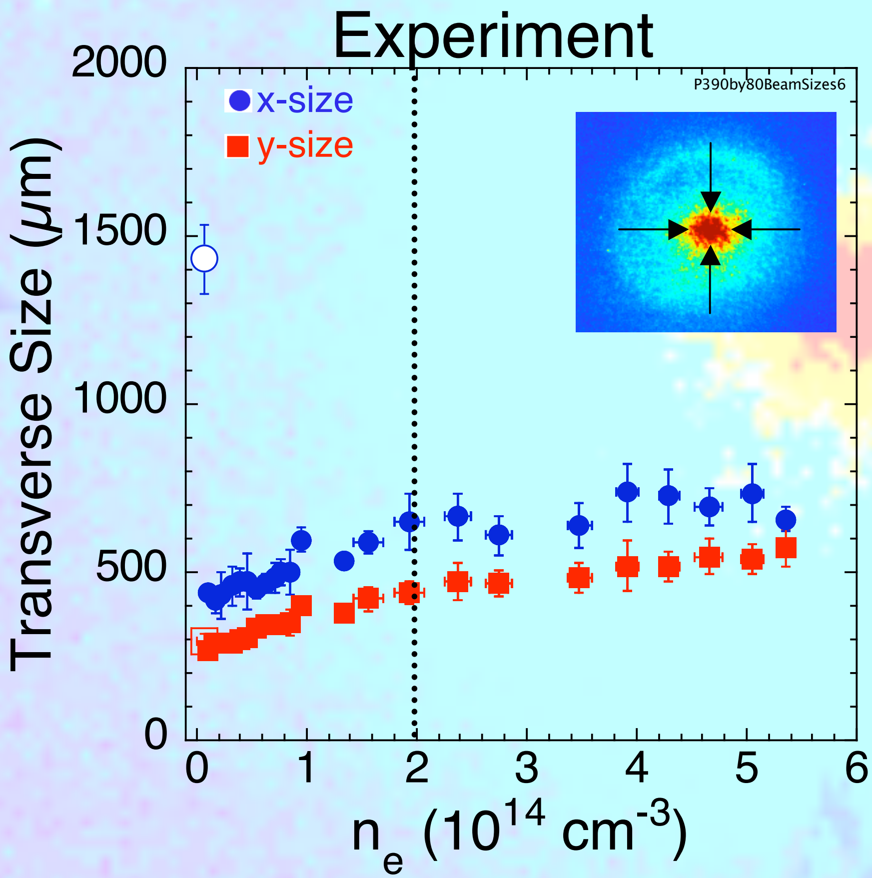
- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations, Halo Formation

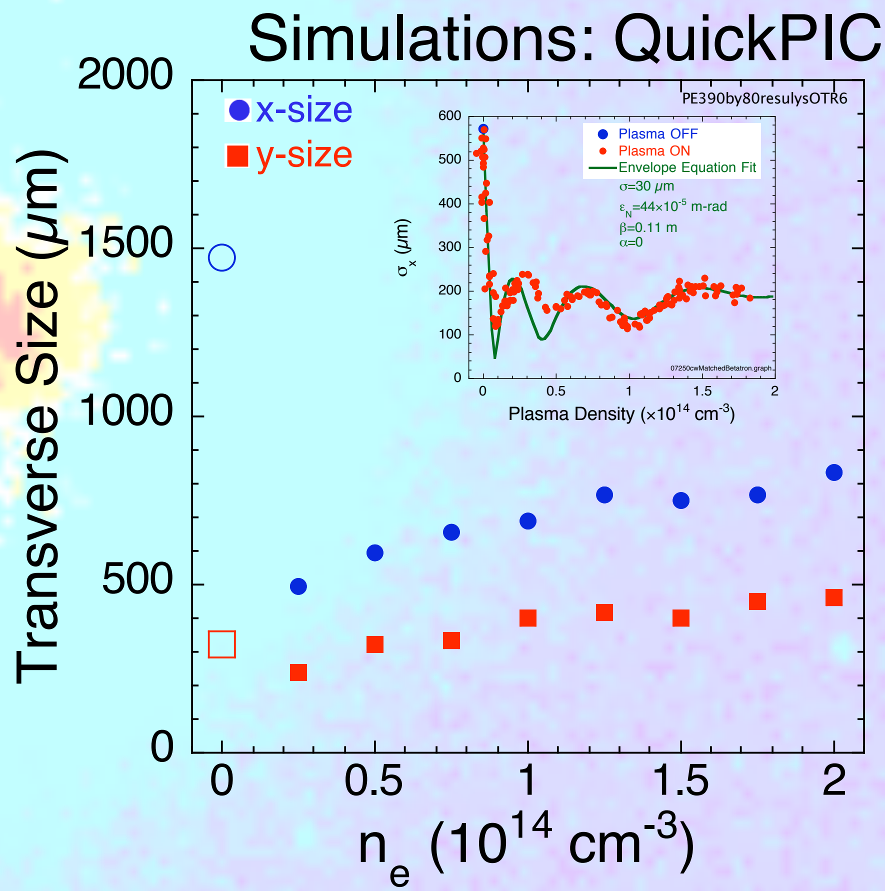
- Qualitative differences

EXPERIMENT/SIMULATIONS: BEAM SIZE

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

Downstream OTR

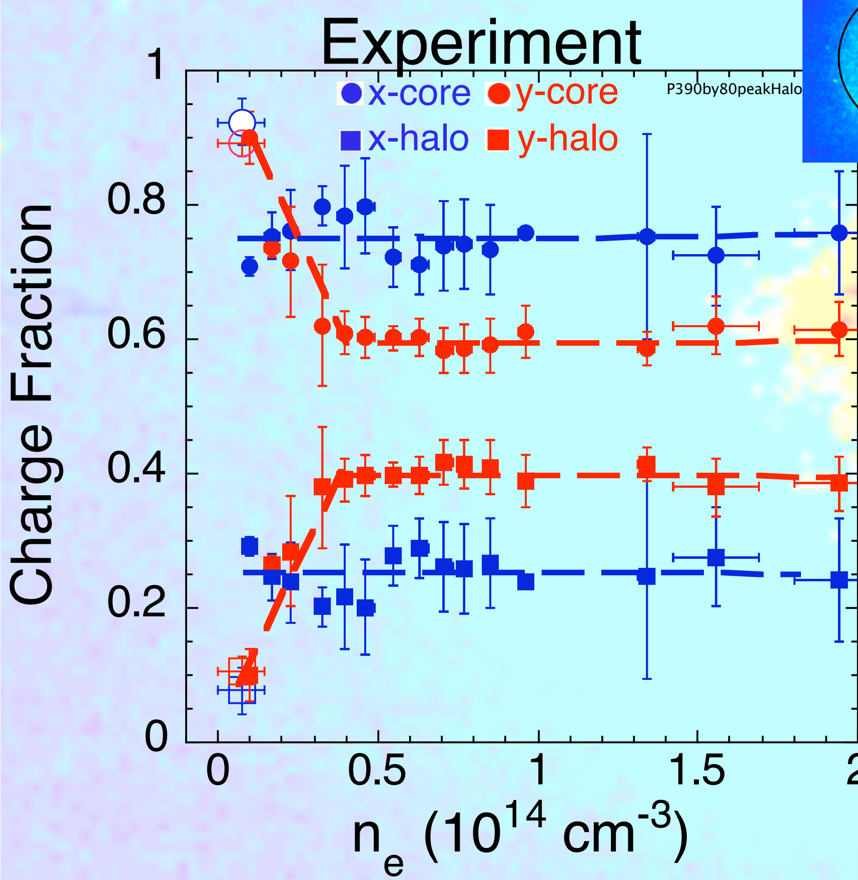


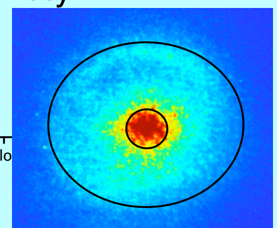


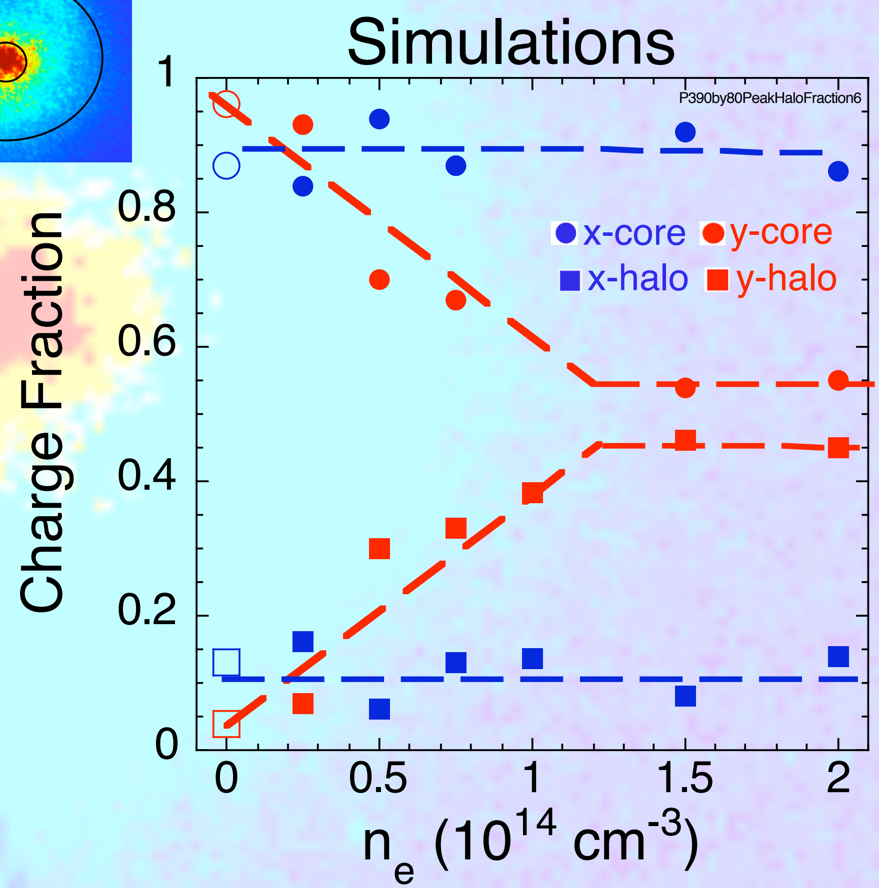
- Excellent experimental/simulation results agreement!
- The beam is ≈round with $n_e \neq 0$

EXPERIMENT/SIMULATIONS: HALO FORMATION

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







- Very nice qualitative agreement
- Simulations to calculate emittance

e^+: SLICE EMITTANCE (SIMULATIONS)

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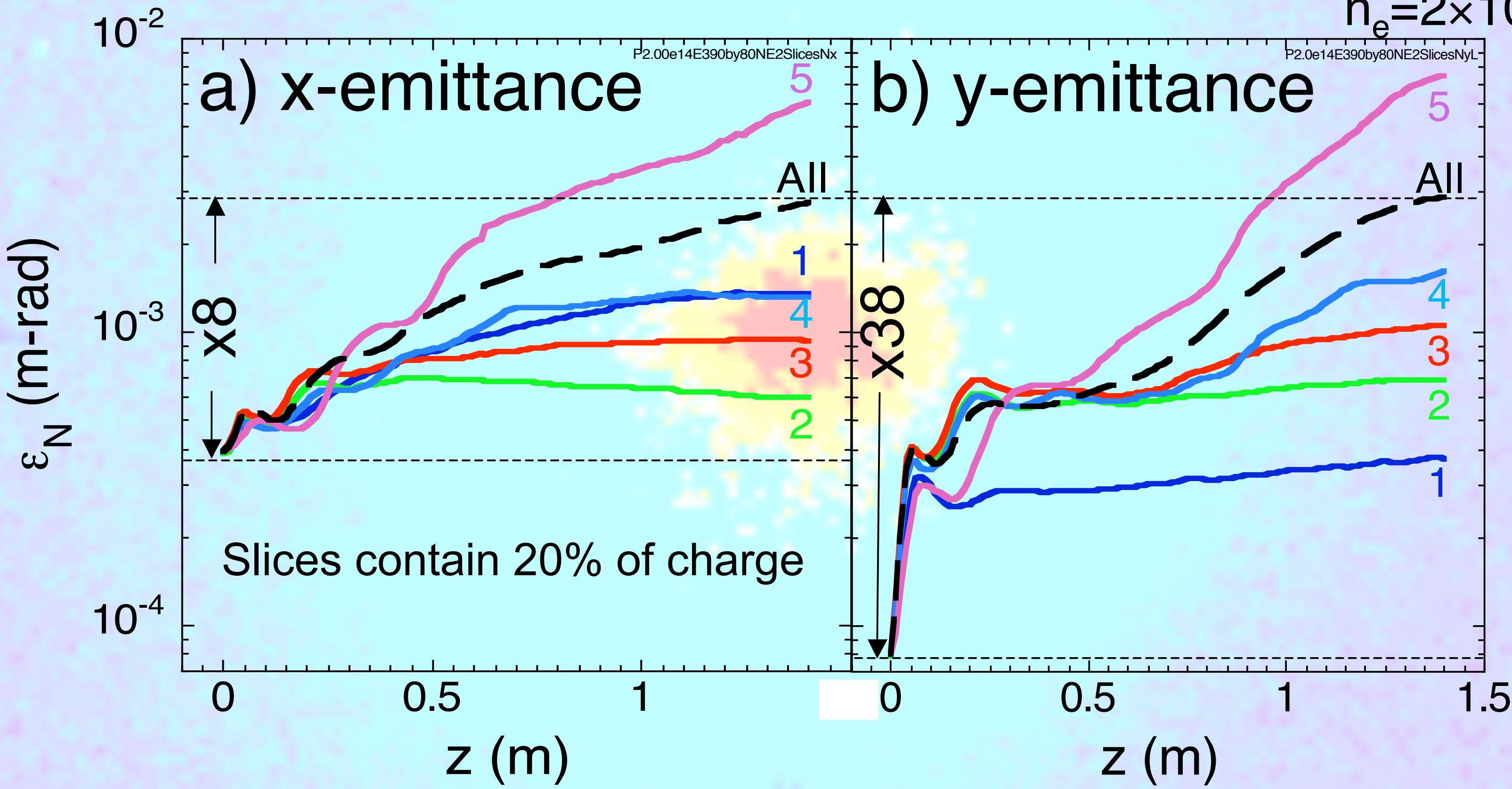
$\sigma_{x0} \approx \sigma_{y0} \approx 25\ \mu m$, $\varepsilon_{Nx} \approx 390 \times 10^{-6}$, $\varepsilon_{Ny} \approx 80 \times 10^{-6}$ m-rad, $N = 1.9 \times 10^{10}$ e^+, $L \approx 1.4$ m

$n_e = 2 \times 10^{14}$ cm^{-3}



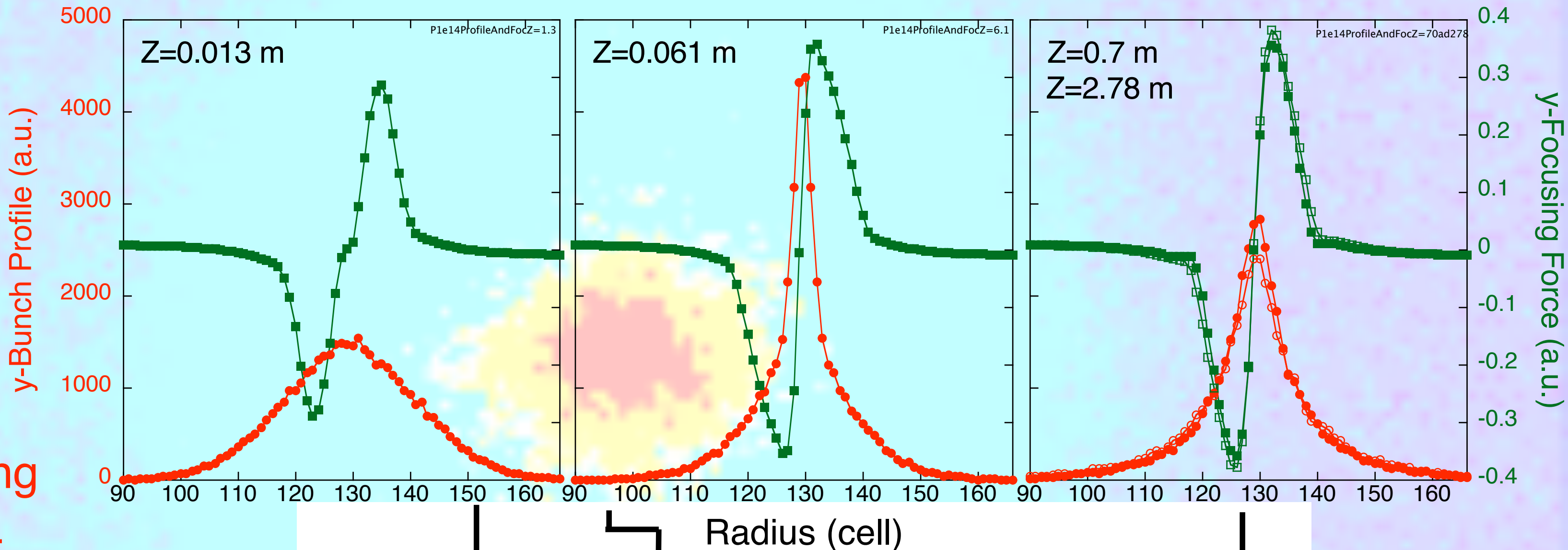
♦ The e^+ beam exits the plasma with ≈equal emittances <u>and</u> ≈equal transverse sizes

FR8RPF025

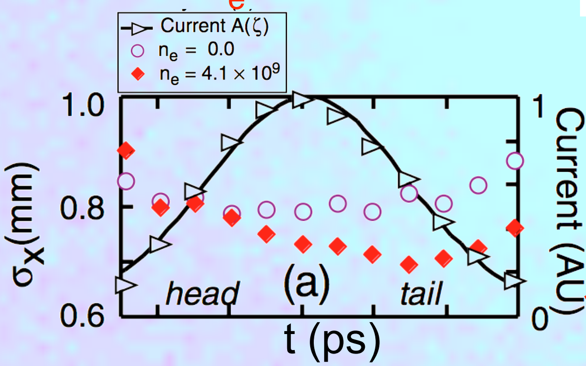
P. Muggli *et al.*, PRL 101, 055001 (2008).

Beam/Field Evolution

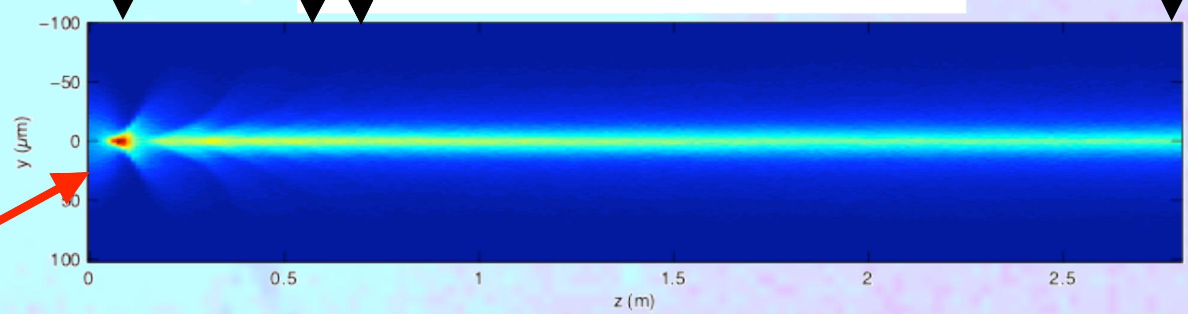
$\sigma_{x0}=\sigma_{y0}=25\mu m$, $\varepsilon_{Nx}=390\times10^{-6}$, $\varepsilon_{Ny}=80\times10^{-6}$ m-rad, $N=1.9\times10^{10}$



Initial focusing for small n_eL



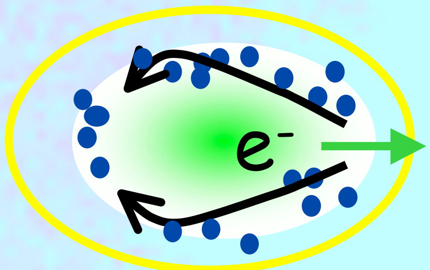
Hogan, PRL 90 (2003)

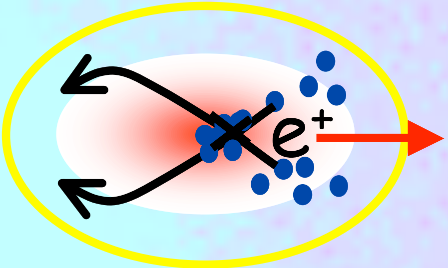


- Dynamic focusing, beam becomes non Gaussian
- Beam size and focusing field “stop” at z≈0.7 m, “self matching”

e^+: ACCELERATION

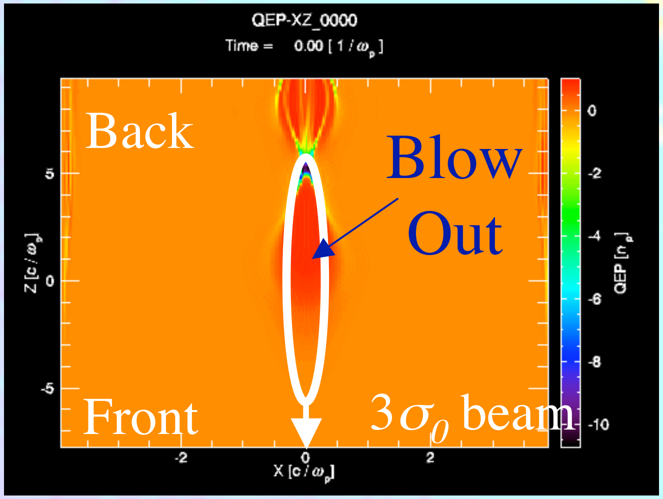
♦ Possible?





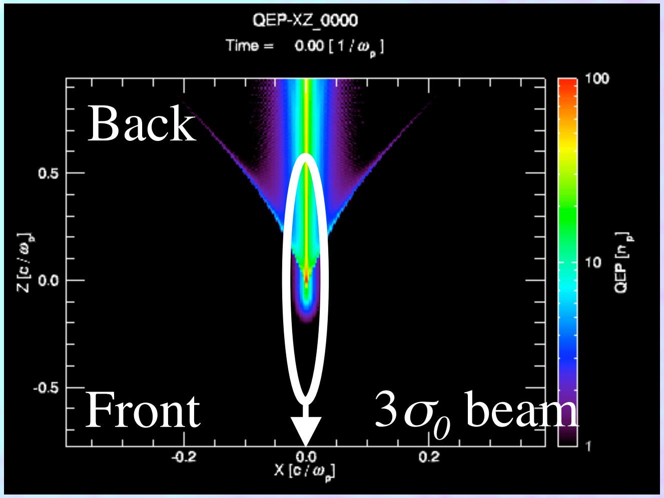
3-D QuickPIC simulations, plasma e^- density:

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



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

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



- Plasma e^- density spike "pushes" beam e^-
- Plasma e^- density spike "pulls" beam e^+

♦ YES!

EXPERIMENTAL SET UP

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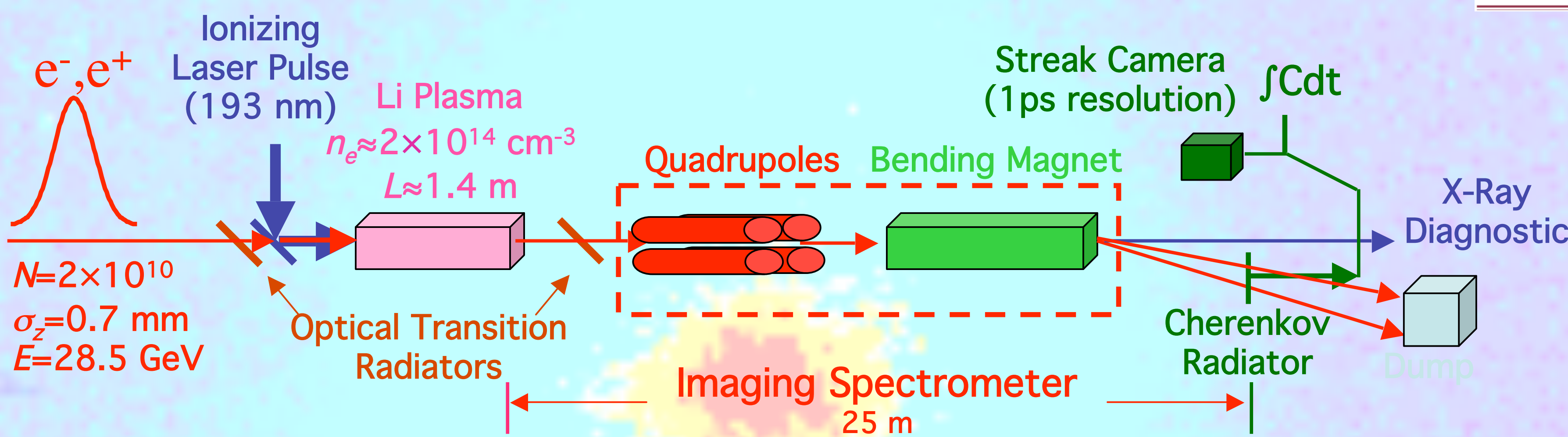

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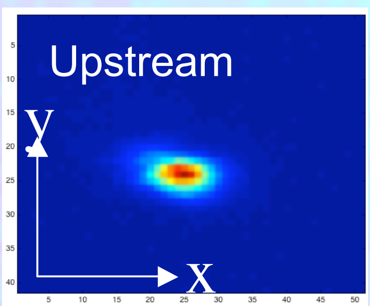

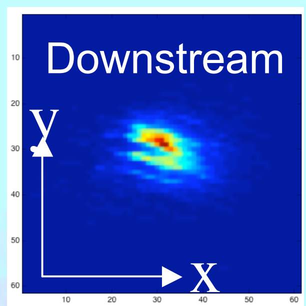

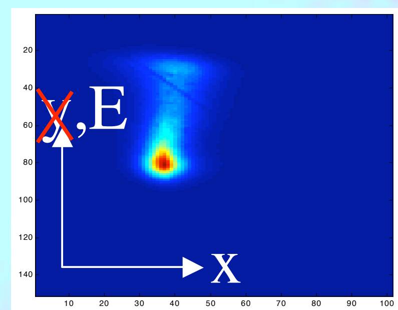

- 1:1 imaging, spatial resolution <9 μm

- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV
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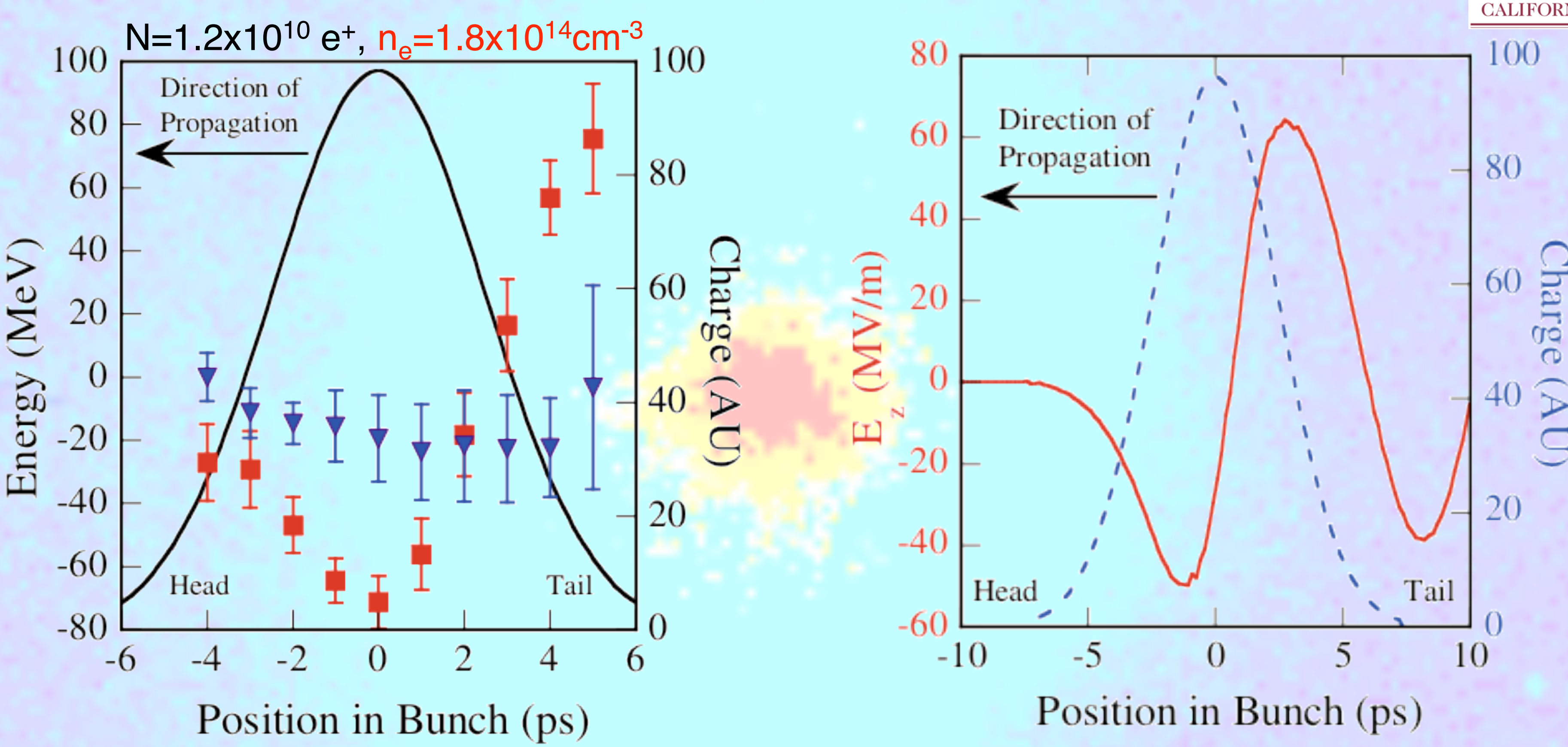
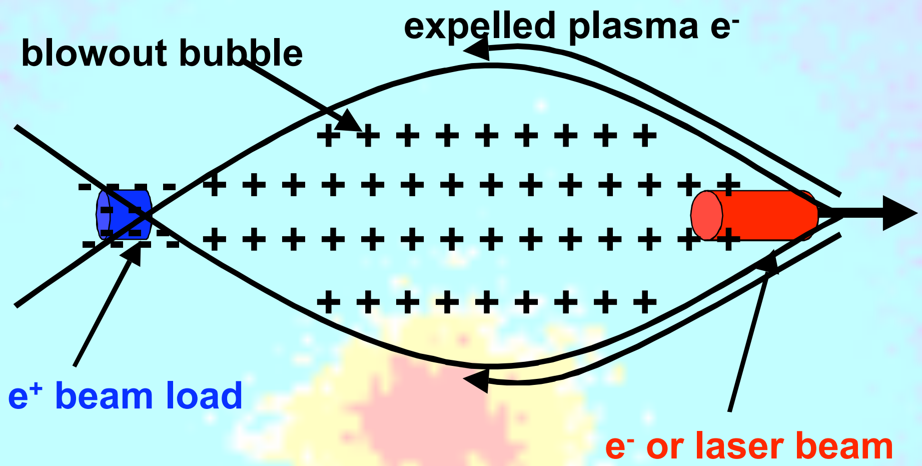
e^+: ACCELERATION



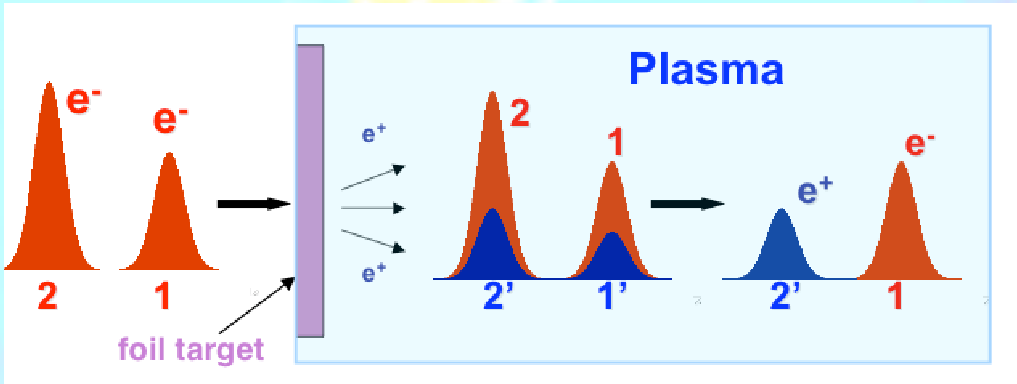
B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (2003).

- Energy gain and loss ≈80 MeV over 1.4 m (long, ≈700 μm bunches)
- Good agreement with numerical simulations
- High gradient acceleration not demonstrated

e^+ ACCELERATION ON e^- WAKE



Wang, PRL 101, 124801 (2008)



- Test of e^+ acceleration on e^- wake
- Injection on e^+ on e^- wake

CONCLUSIONS

- e^+/plasma interaction much less studied than e^-/plasma
- Focusing force on e^+ bunches in nonlinear
- Emittance growth for single e^+ bunch in uniform plasma
- Possible remedies include hollow plasma channel, linear wake, transverse bunch shaping, drive-witness bunch, …
- e^+ can be accelerated in plasmas
- e^+ accelerated on e^- or laser wake
- Emittance preservation/acceleration more challenging for e^+ than for e^- in plasma-based accelerators
- e^+/plasma interaction @ FACET

- Thank you to my collaborators:

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University of Southern California

- And thank You!

Work supported by US Dept. of Energy

Laser and Plasma Accelerators Workshop 2009

Kardamili, June 22-26 2009

Topics

- Plasma accelerators and the energy frontier
- One to ten GeV laser-plasma accelerator technology
- Computer modelling of laser and plasma accelerators
- Physics and applications of laser/beam - plasma interactions
- Fundamental physics and relativistic astro-physics with intense laser and particle beams

Deadline of **May 24th** for

- Early registration
- Abstract Submission

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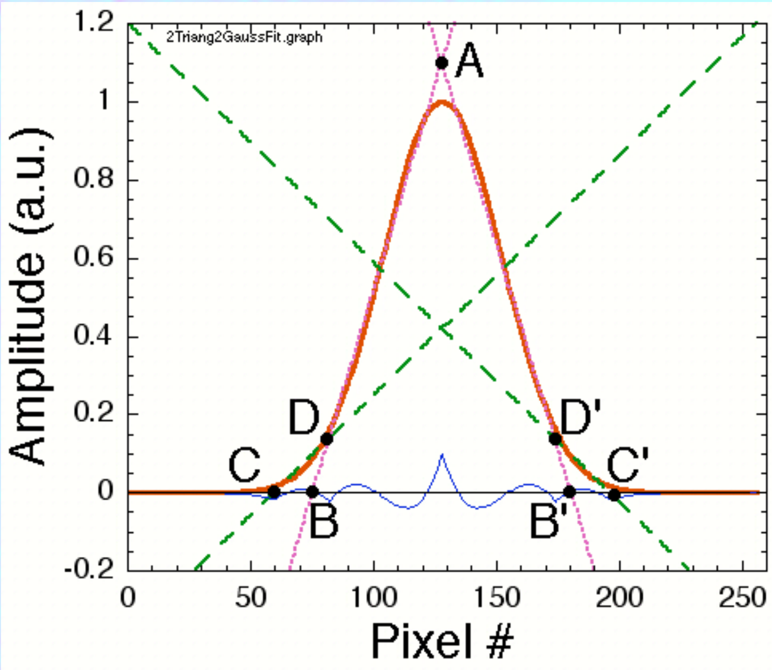
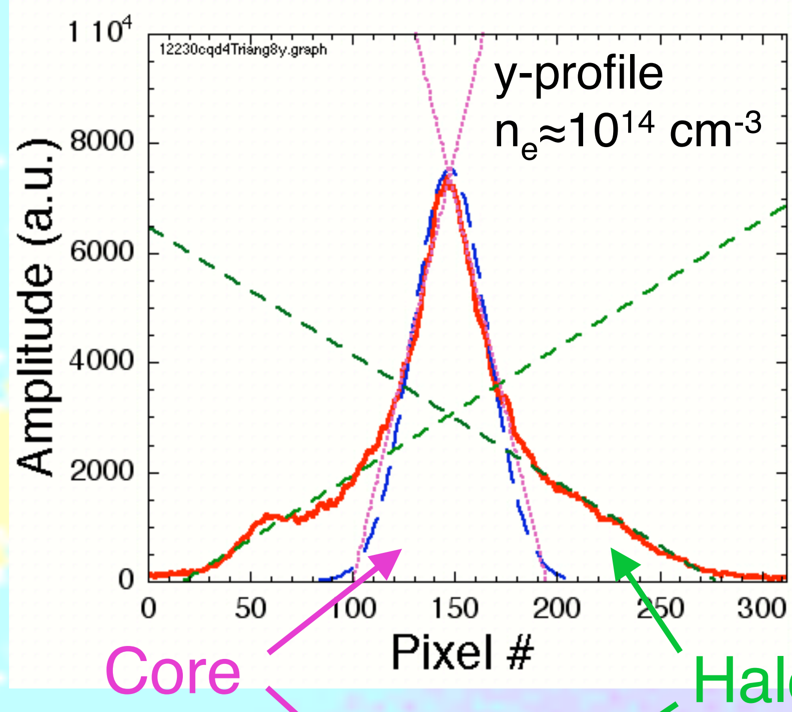
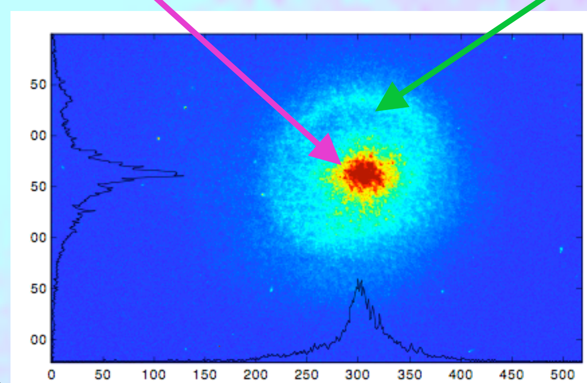
FIT FOR BEAMS WITH HALO





Beam Size=FWHM (BAB')
Charge in the Peak=Area(BAB')
Charge in the Halo=2*Area(CDB)



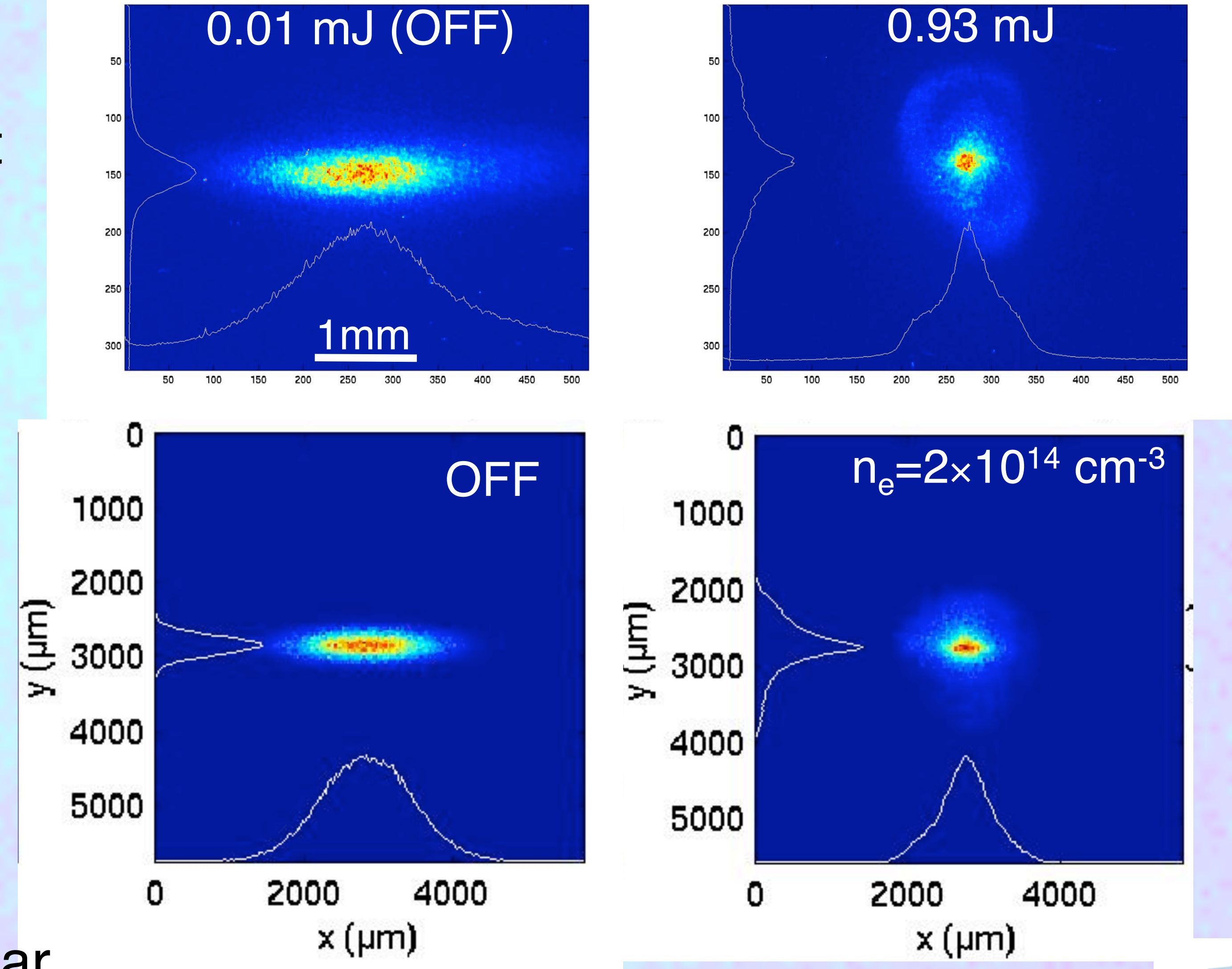
- Use fit to describe:
    - core size
    - relative charge in core and halo
- Apply to experimental and simulation images

HALO FORMATION

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

Experiment

Simulation



- Very similar

Previous work FFTB@SLAC
Studied all aspects of beam-plasma interaction

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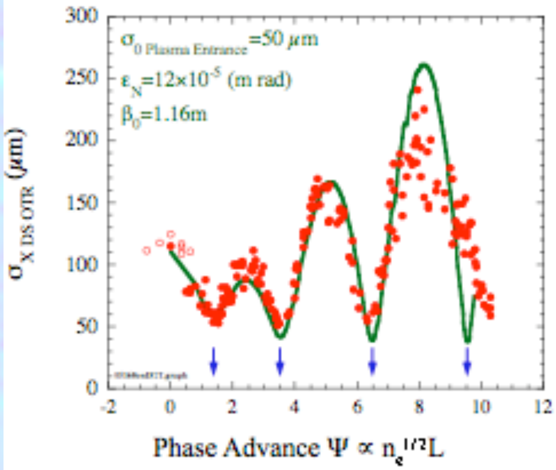
Focusing e-

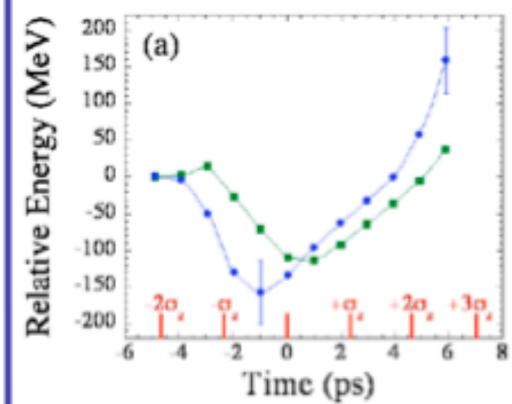


Phys. Rev. Lett. **88**, 154801 (2002)

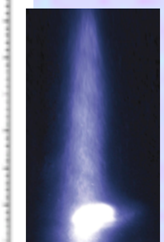
X-ray Generation

Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e-

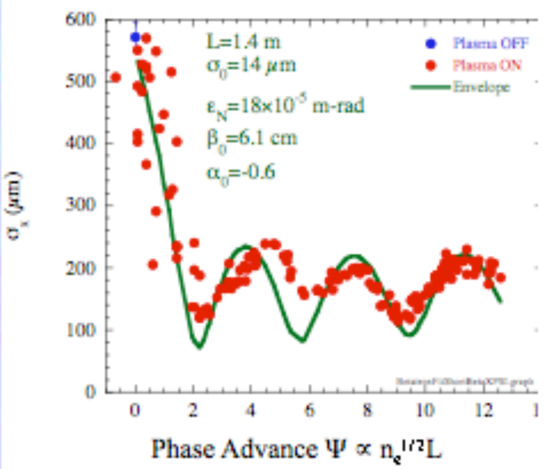


Phys. Rev. Lett. **93**, 014802 (2004)



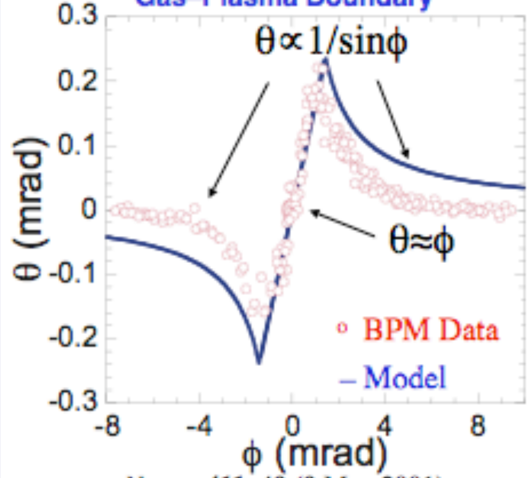
Nature (2007)

Matching e-



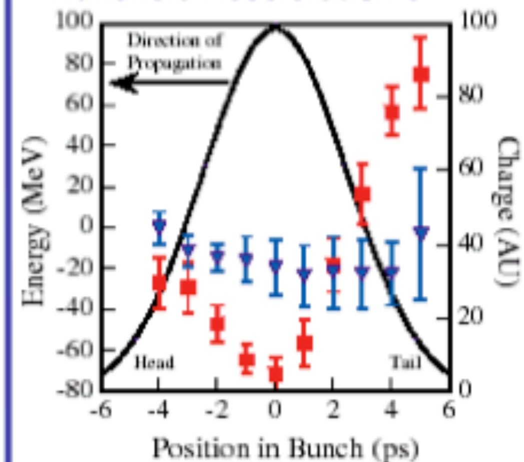
Phys. Rev. Lett. **93**, 014802 (2004)

Electron Beam Refraction at the Gas–Plasma Boundary



Nature **411**, 43 (3 May 2001)

Wakefield Acceleration e+



Phys. Rev. Lett. **90**, 214801 (2003)

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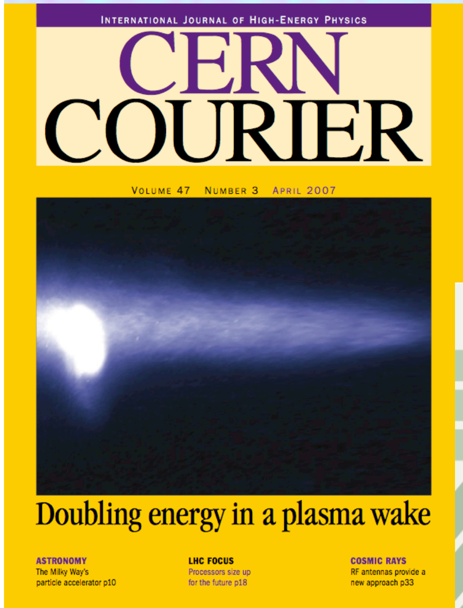
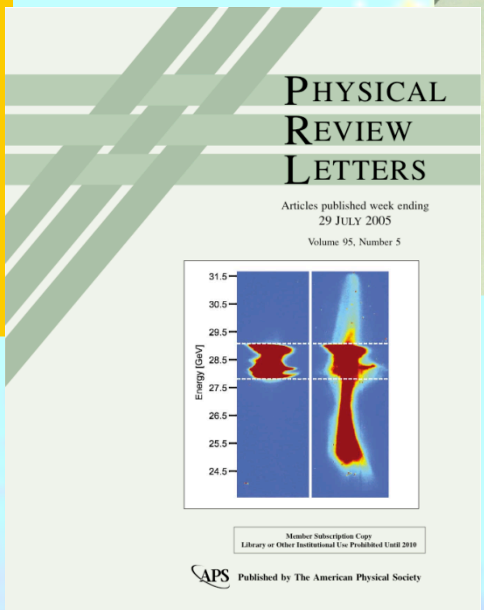
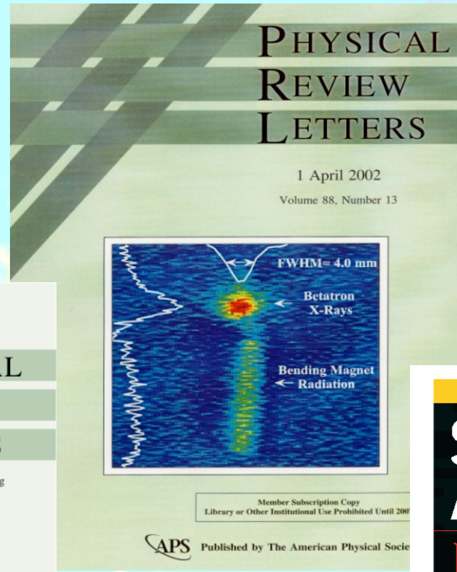
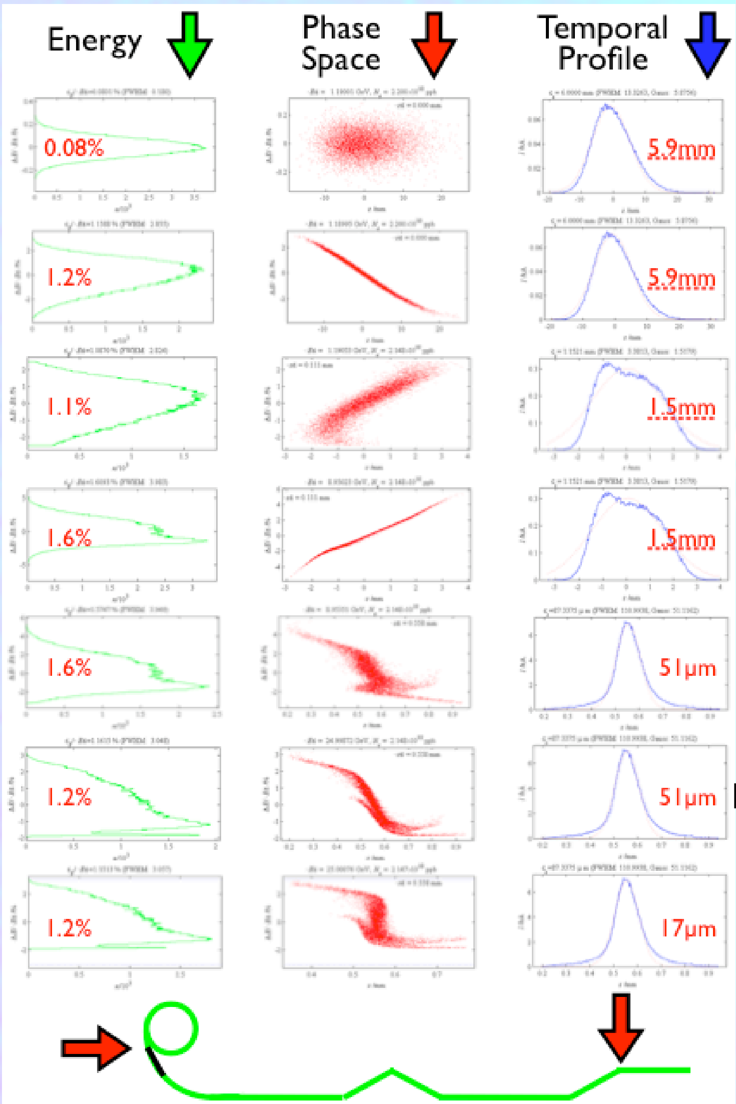
PWFA@FFTB Successes







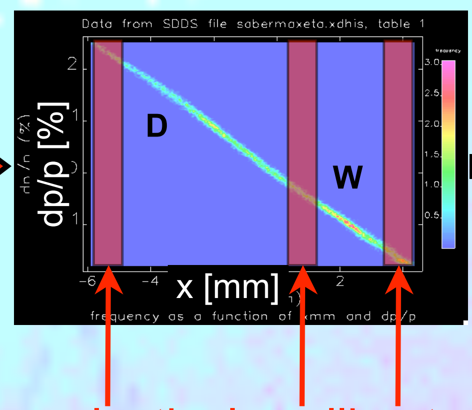
Generate Two Bunches by Selectively Collimating During Bunch Compression Process



Exploit Position-Time Correlation on e⁻ bunch to create separate drive and witness bunch e⁻/e⁻ or e⁺/e⁺

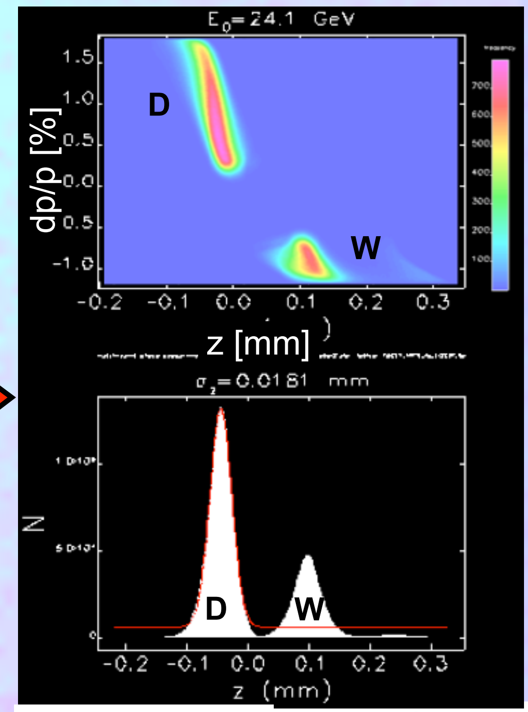
Disperse the beam in energy

$$x \propto \Delta E/E \propto t$$



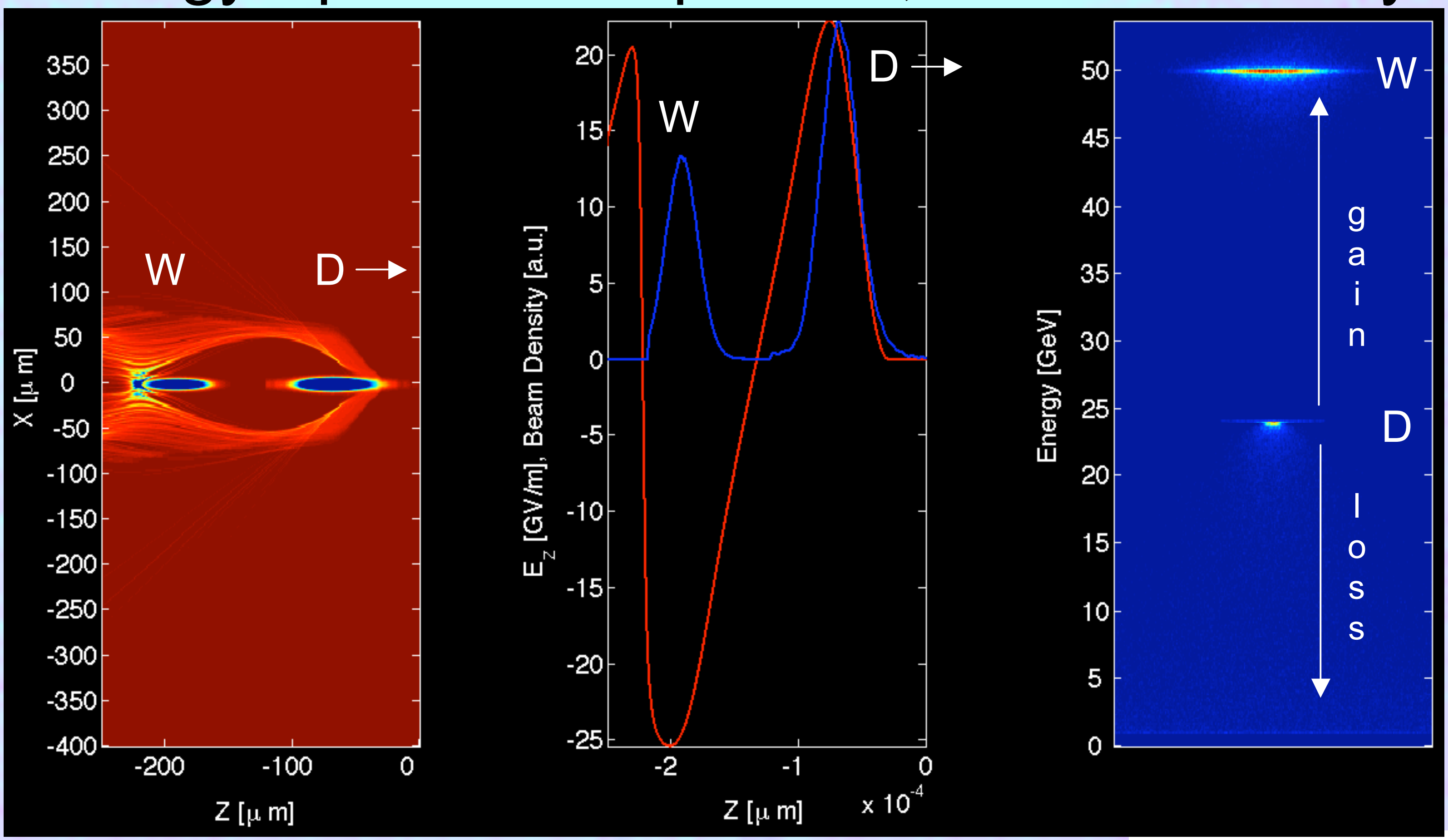
...selectively collimate

Adjust final compression

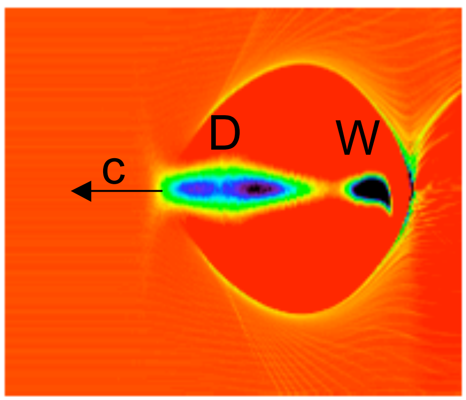


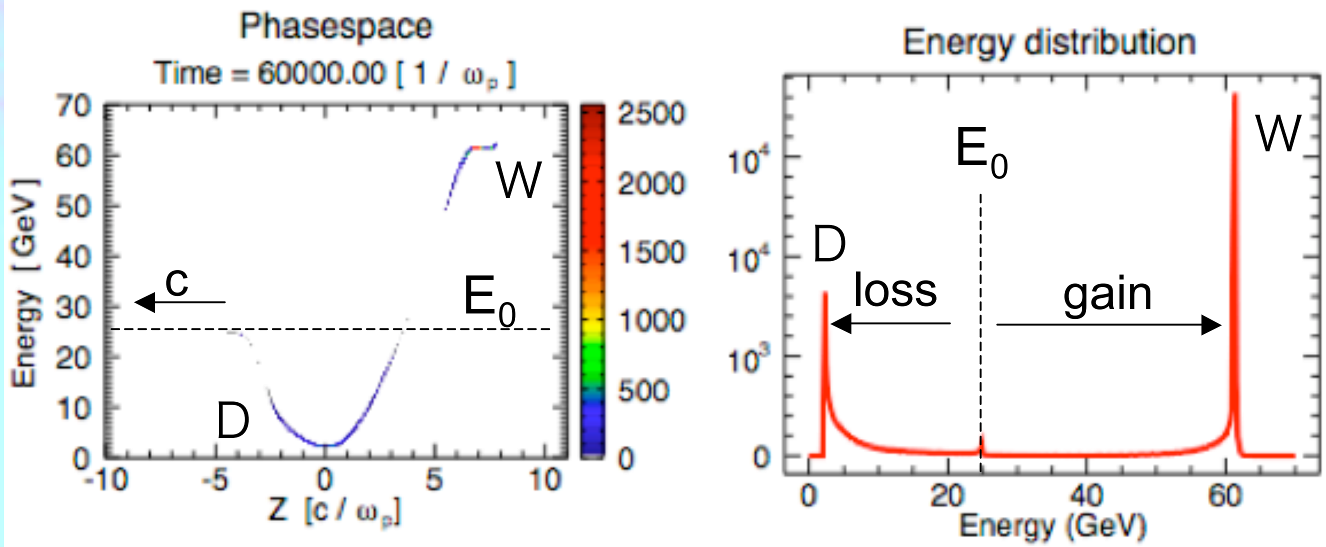
FACET Experiments will accelerate a discrete bunch of particles with narrow energy spread

- Energy Doubling in ~1m
- Energy Spread ~few percent, ~30% efficiency



Beam Loading & Energy Transfer Efficiency





n_p= $1\times10^{17}cm^{-3}$

N_{driver} = 2.9×10^{10}, σ_r= 3 μ, σ_z = 30 μ, Energy = 25 GeV

$N_{trailing}$ = 1.0×10^{10} , σ_r= 3 μ , σ_z = 10 μ, Energy = 25 GeV

Spacing= 110 μ

R_{trans} = $-E_{acc}/E_{dec}$ > 1 (Energy gain exceeds 25 GeV per stage)

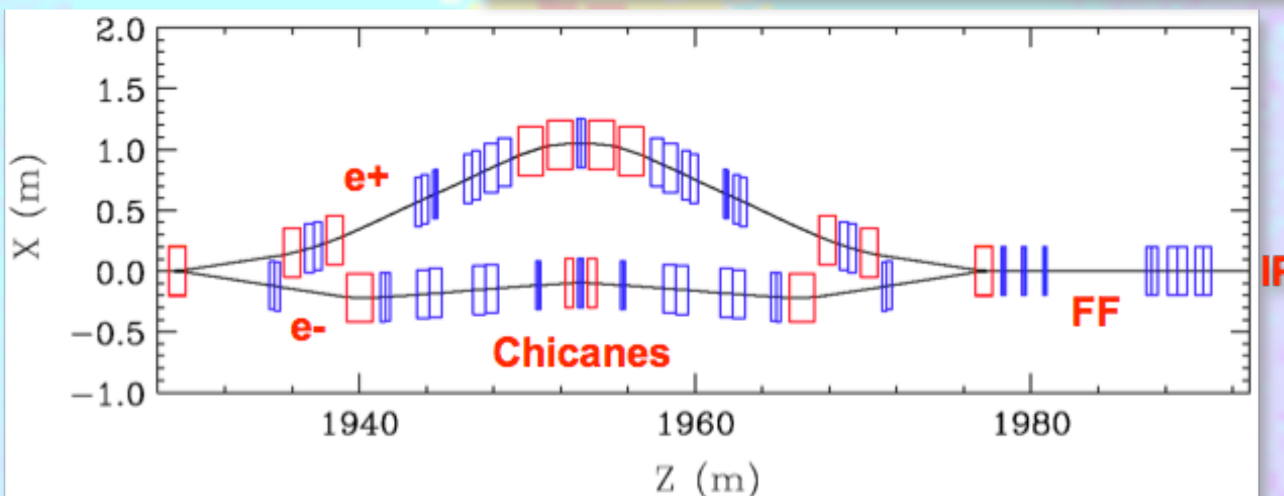
1% Energy spread
Efficiency from drive to trailing bunch ~48%!

- High efficiency and narrow $\Delta E/E_0$ while > energy doubling

Produce Drive/Witness Bunches e^-/e^+

- Extract e^- & e^+ from damping rings on same linac pulse
- Accelerate bunches to sector 20, 5cm apart
- Use 'Sailboat Chicane' to put them within 100μm at entrance to plasma
- Large beam loading of e^- wakes with high charge e^+ beams

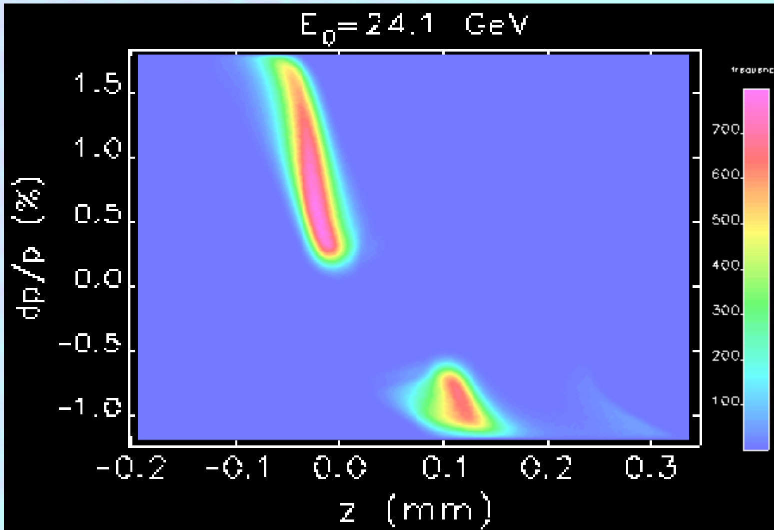
♦ Sailboat chicane:

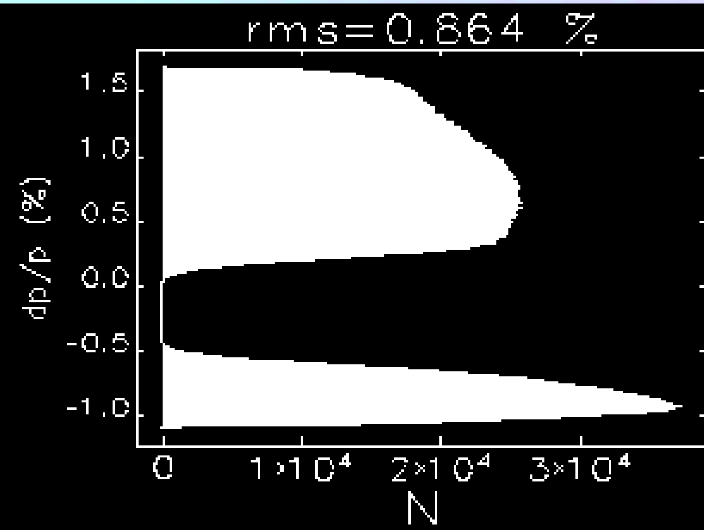


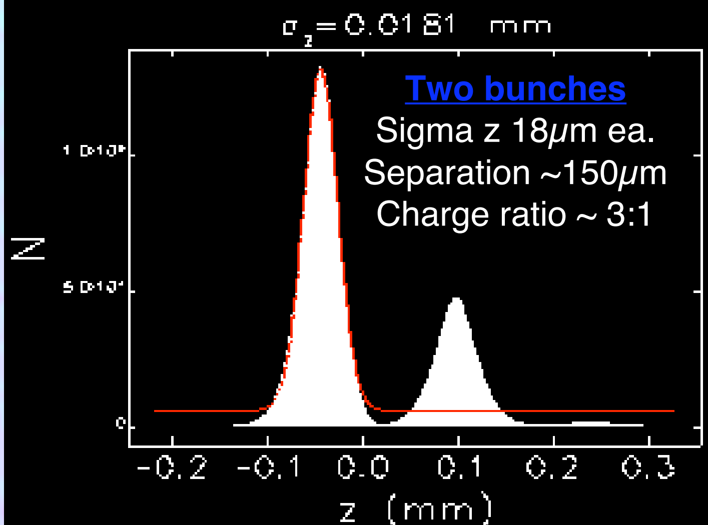
♦ True injection of e^+ bunch in high gradient plasma wake

♦ High current e^+ bunches available at FACET only!!!

Use a combination of 6D particle tracking in ELEGANT combined with EGS4 to simulate the collimator(s)







Challenges:

- Drive bunch needs to both ionize the vapor and drive a large amplitude wake
- Witness bunch needs to be half-plasma period behind the drive bunch (~100μm for 10^{17} e^-/cm^3 plasma)
- Must work for e^- & e^+

NDR exit to FACET IP

VISION

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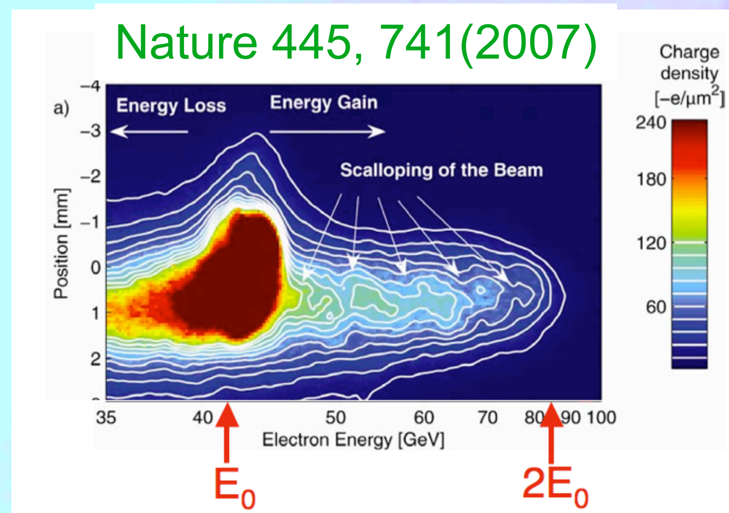
- Beam-driven, Plasma Wakefield Acceleration (PWFA) as a new technology for a future e^-/e^+ Plasma-based LC or PWFA-LC
- Demonstrated Accelerating Gradient: 50 GV/m over 85 cm
  Energy doubling of 42 GeV e^-



Nature 445, 741(2007)

- Build single, e^-/e^+ 25 GeV stage of a (possible) multi-stage PWFA-LC
- Vision: reduce the price of a future e^-/e^+ linear collider to 2-4 b$ (target) by merging the high efficiency of conventional beam generation with the large accelerating gradient of the PWFA

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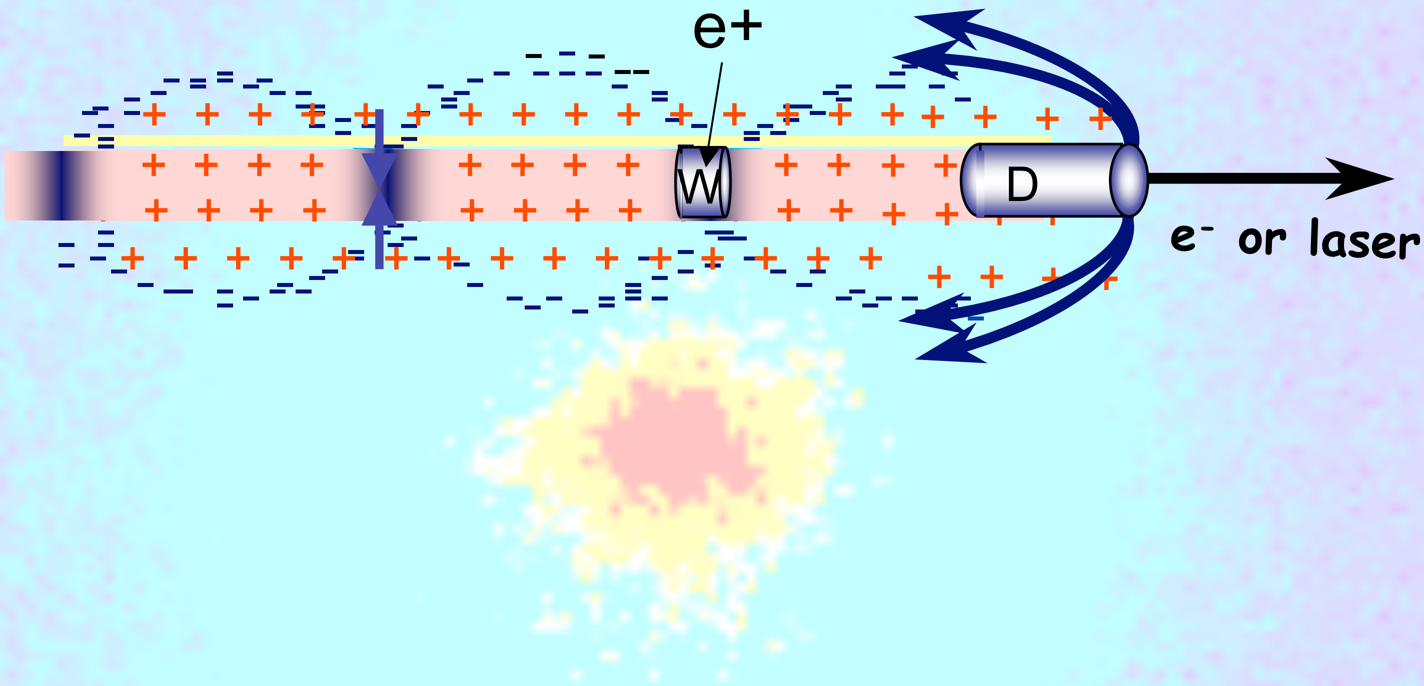
e+
W
D
e⁻ or laser

e^+ ACCELERATION ON e^- WAKE

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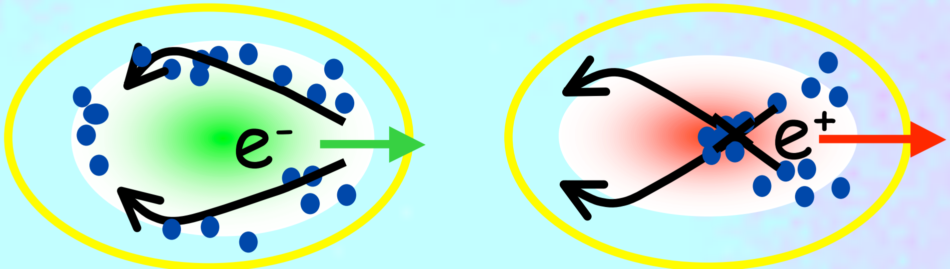
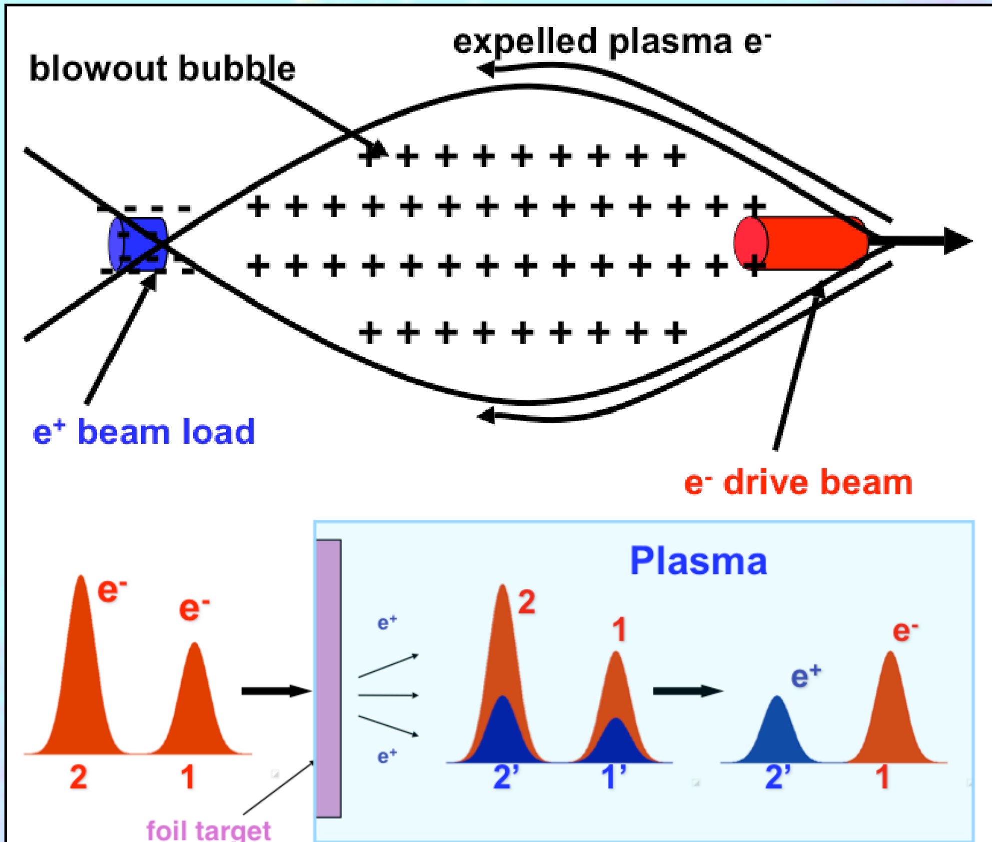
- Asymmetry



- Injection of e^+ on e^- wake
  (or laser wake!)



X. Wang, PRL (2008)

e^+ FROM e^- β-TRON RADIATION IN PLASMAS

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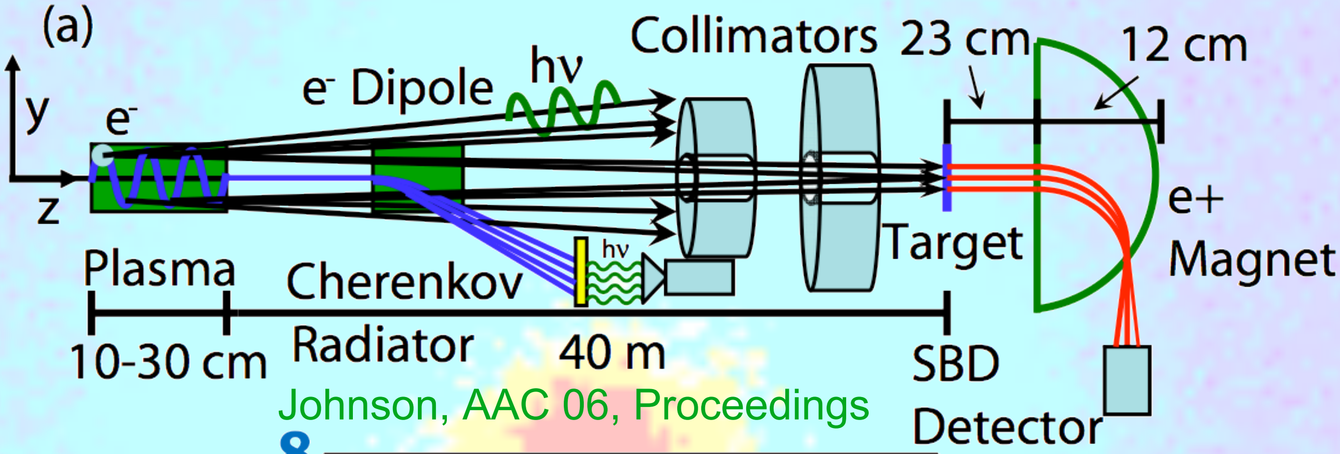
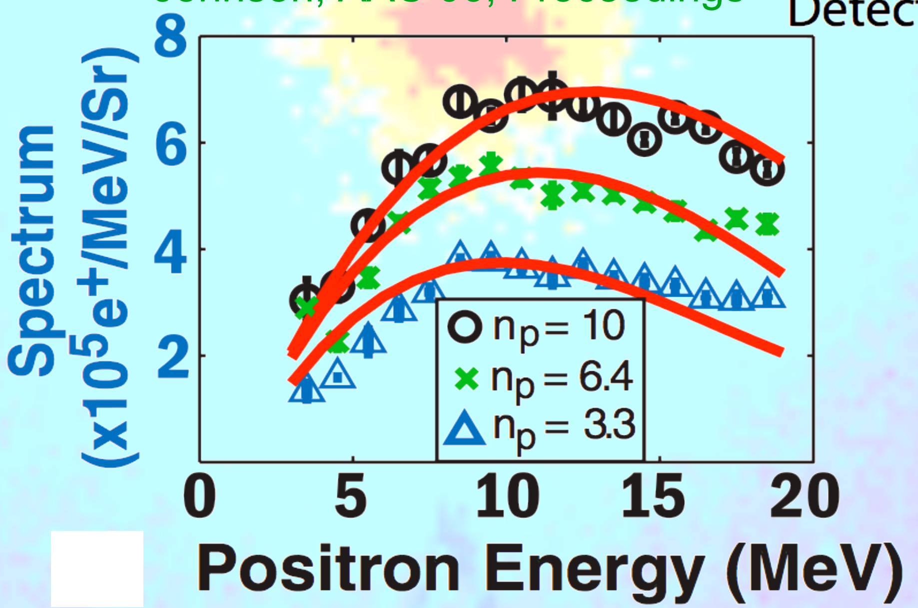


Johnson, AAC 06, Proceedings



- Demonstration of a plasma wiggler e^+ source
- Excellent experiment/calculations agreement

Johnson, PRL 97, 2006

VANCOUVER PAC09

β-TRON RADIATION IN PLASMAS

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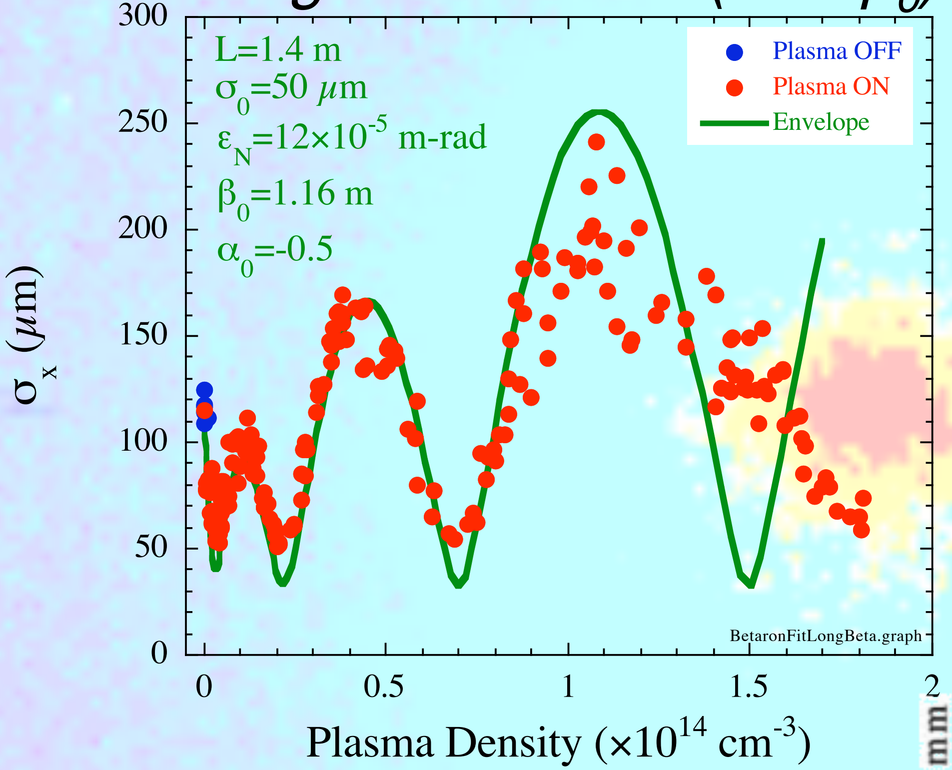
Large Beam Size ($K \geq 1/\beta_0$)



$$n_e = 1.5\times 10^{14}\ cm^{-3}$$

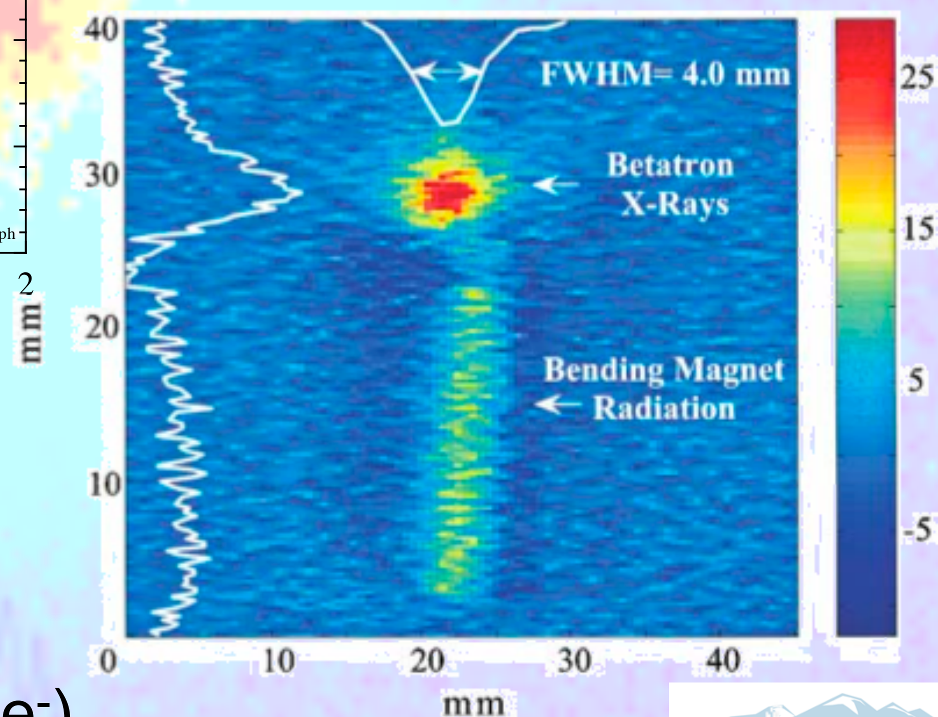
$$\lambda_\beta \cong 0.91\,m \qquad N_{\lambda_\beta} \cong 1.5$$

$$\hbar\omega_c \approx keV$$

Ion column:

$$\lambda_\beta = \frac{\sqrt{8\gamma}\,\pi c}{\omega_{pe}} \propto \frac{1}{n_e^{1/2}}$$

$$\omega_c = \frac{3}{2}\frac{\gamma^3}{c}\omega_\beta^2\sigma_r \propto n_e$$



Wang, PRL 88, 2002

♦ x-rays from a plasma wiggler (e^-)

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e^+ FROM e^- β-TRON RADIATION IN PLASMAS

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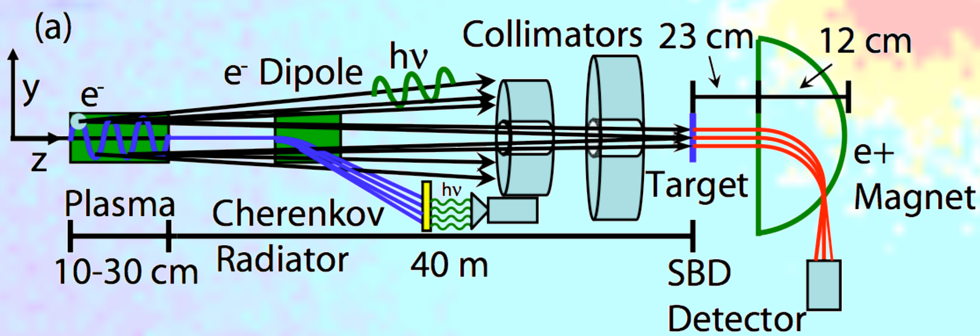
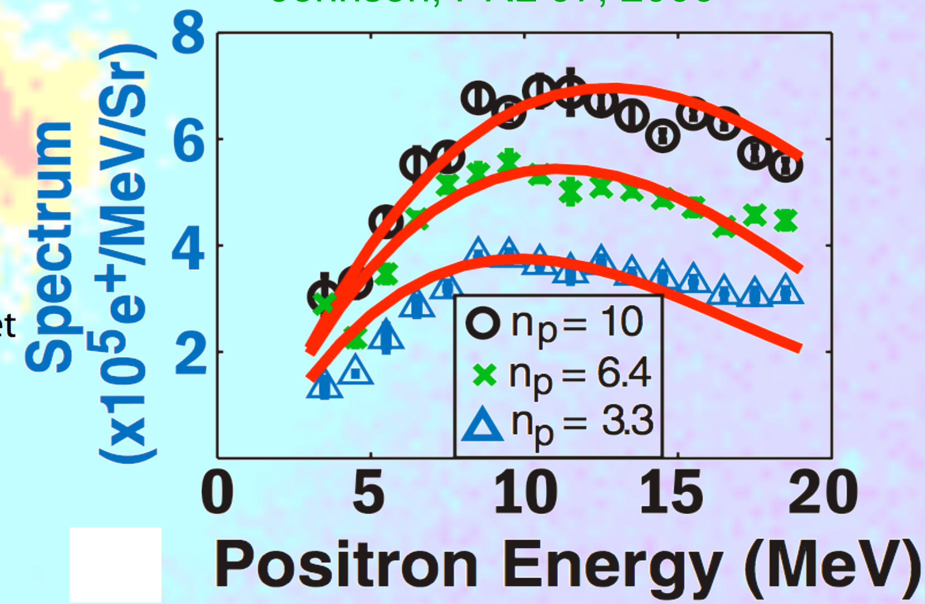
$n_e = 10^{17}\ cm^{-3}$ $\lambda_\beta \cong 0.035\ m$ $N_{\lambda_\beta} \cong 24\ (L_p = 30\ cm)$

$\hbar\omega_c \approx 10\ MeV > 2m_ec^2$ Produce e^-/e^+ pairs!

Johnson, AAC 06, Proceedings



Johnson, PRL 97, 2006



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