The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2052-44

Summer College on Plasma Physics

10 - 28 August 2009

Positron-Plasma Interactions

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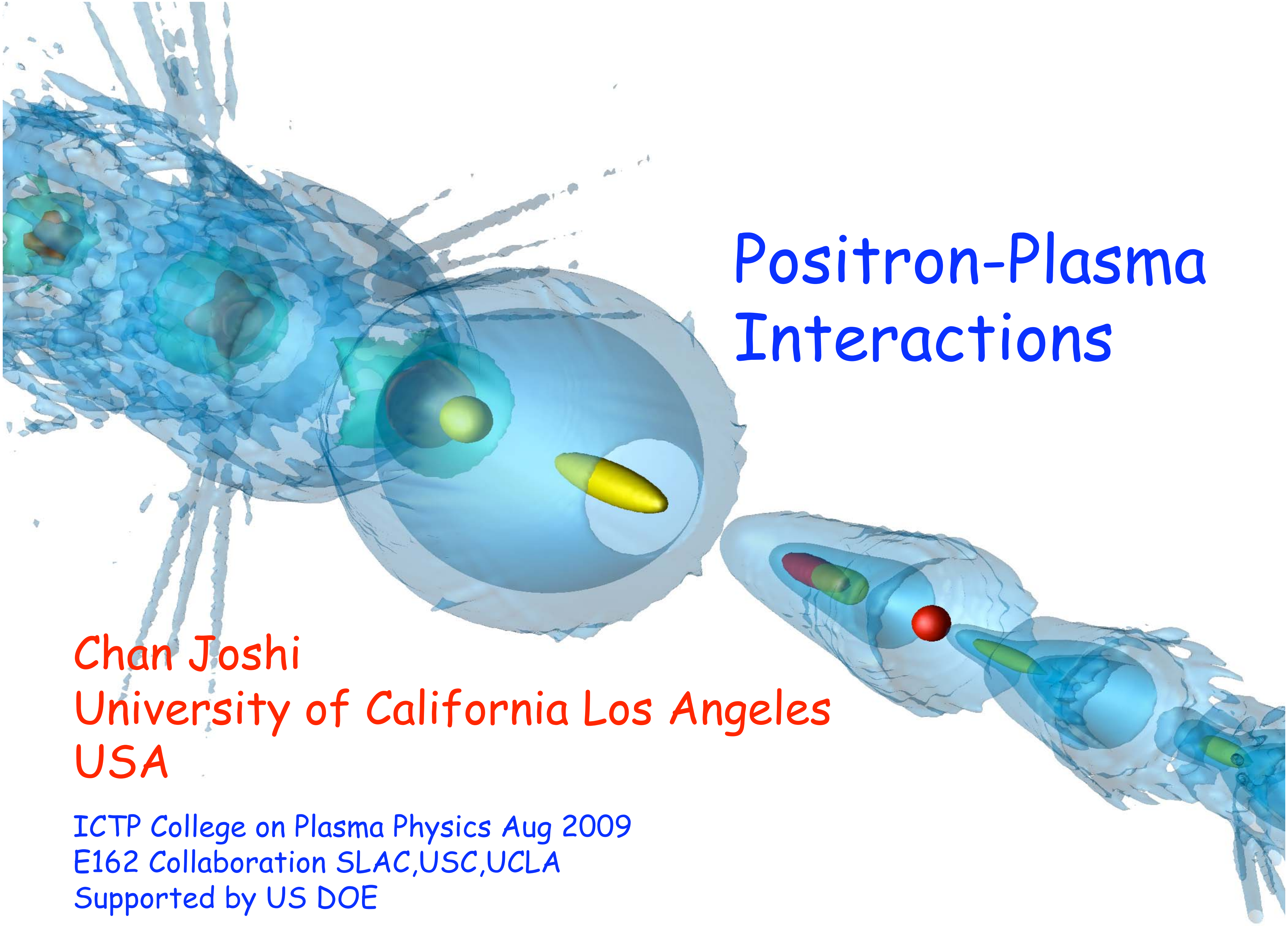


Positron-Plasma Interactions

Chan Joshi
University of California Los Angeles
USA

ICTP College on Plasma Physics Aug 2009
E162 Collaboration SLAC,USC,UCLA
Supported by US DOE

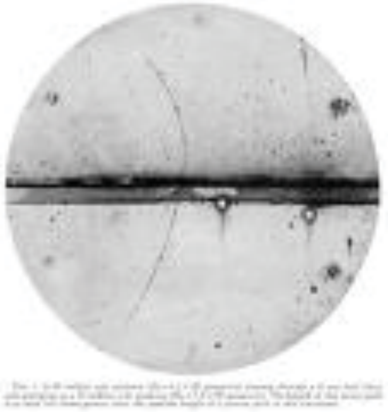
Discovery of Positron

Phys .Rev. vol 43, #6, 1933

Postulated by Dirac in 1928 : Relativistic QM Wave Equation

Carl Anderson

Cloud Chamber track
Produced by a positron

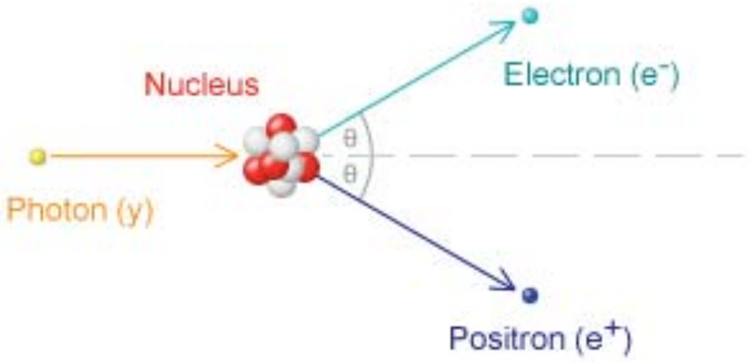


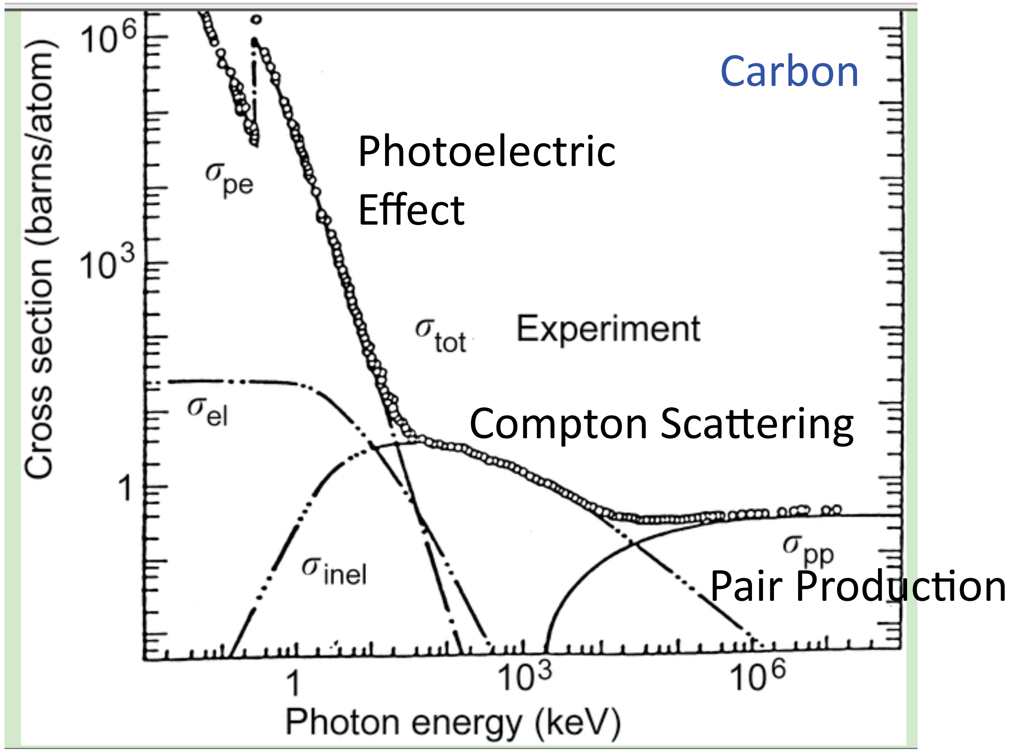
Pb plate

The Positive Electron

"On August 2, 1932, during the course of photographing cosmic-ray tracks... the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron... It is concluded, therefore, that the magnitude of the charge of the positive electron which we shall henceforth contract to positron is very probably equal to that of a free negative electron which from symmetry considerations would naturally be called a negatron." -Carl Anderson

Positron Generation in Laboratory



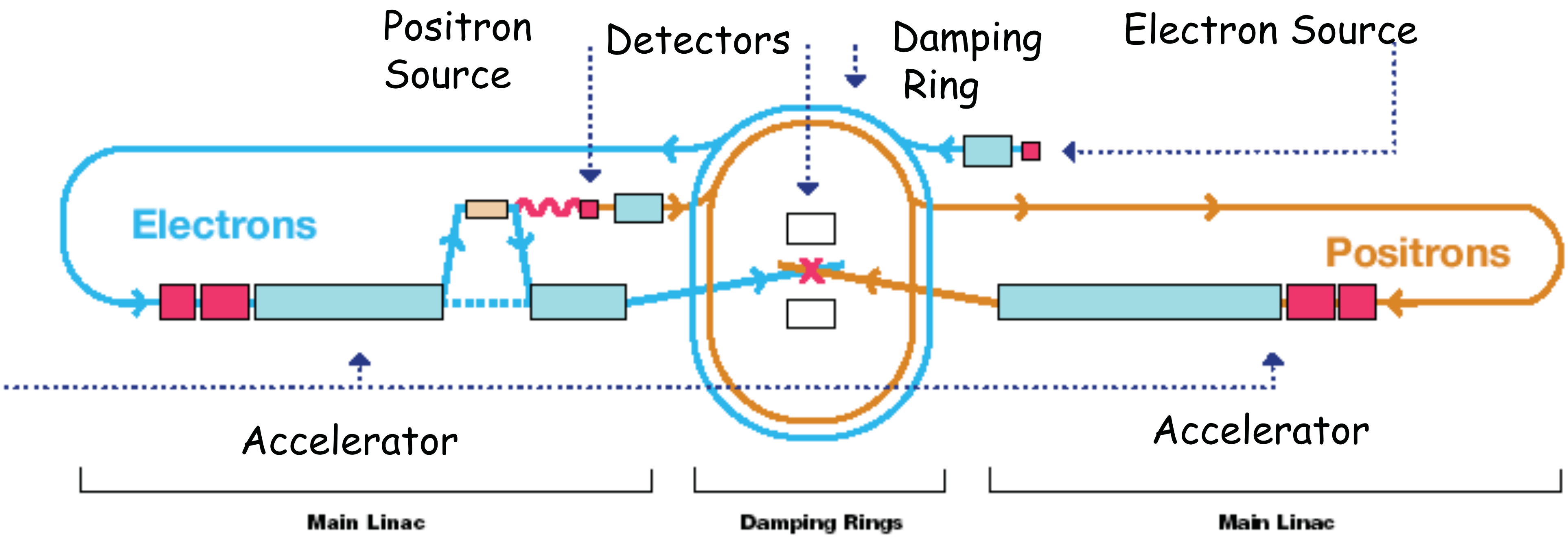


Beam of multi-MV photon traverses a thin (few mm-cm) high Z target.

Photons decay into electron-positron pairs

Positrons can escape the target without annihilation and be collected.

International Linear Collider



31 km , 500 GeV CM $ 20B + !!!

Positron Beam Source Requirements

Production: !50 GeV electron beam, 1.5 cm period , 100m helical undulator with K = 1 , Polarization 60% , 1e14 positrons/s

250 GeV, Total average beam power 20 MW

Can we miniaturize a high energy collider?

Conventional Accelerator

Copper Structure with irises

Powered by microwaves

Energy Gain 20 MV/m
Structure Diameter 10cm

Plasma Accelerator

Ionized Gas
Lifetime, few picoseconds
Powered by a Laser or electron beam pulse
Energy Gain 20 GV/m
Diameter 0.1-l mm

NETWORKING IN THE IMMUNE SYSTEM • NANOTECH BATTERIES

SCIENTIFIC AMERICAN

How to Protect New Orleans from Future Storms

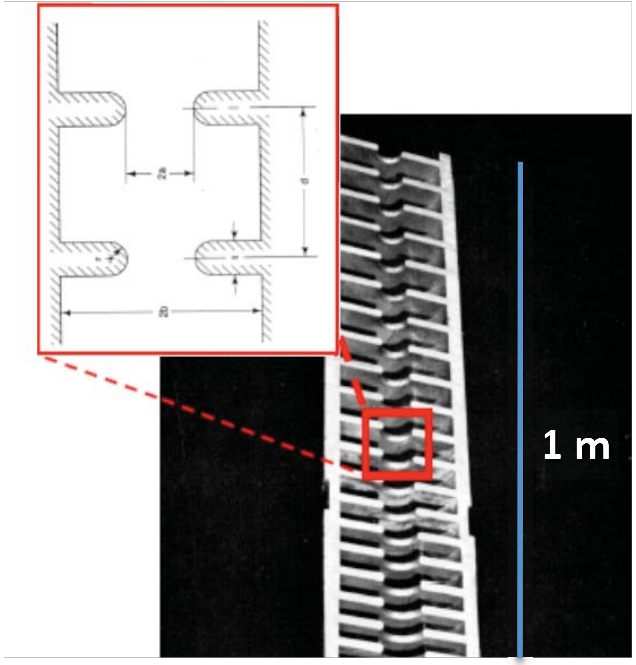
Big Physics Gets Small

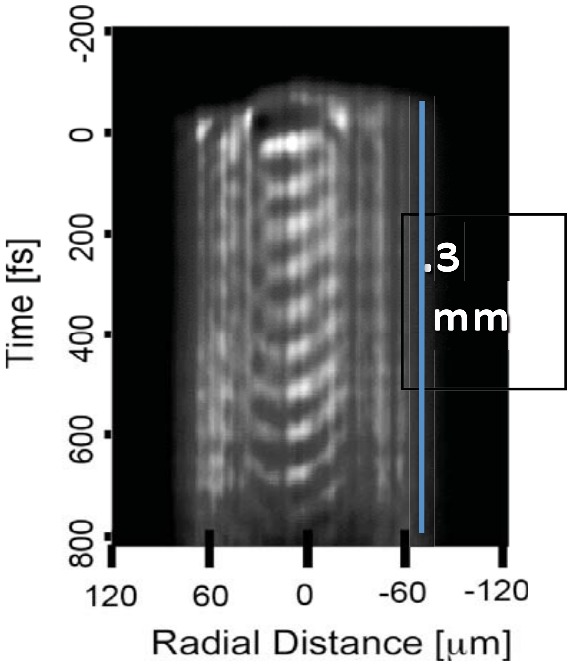
Tabletop Accelerators Make Particles Surf on Plasma Waves

How to Stop Nuclear Terrorists

Guess Who Owns Your Genes?

CSI: Washington (George, that is)

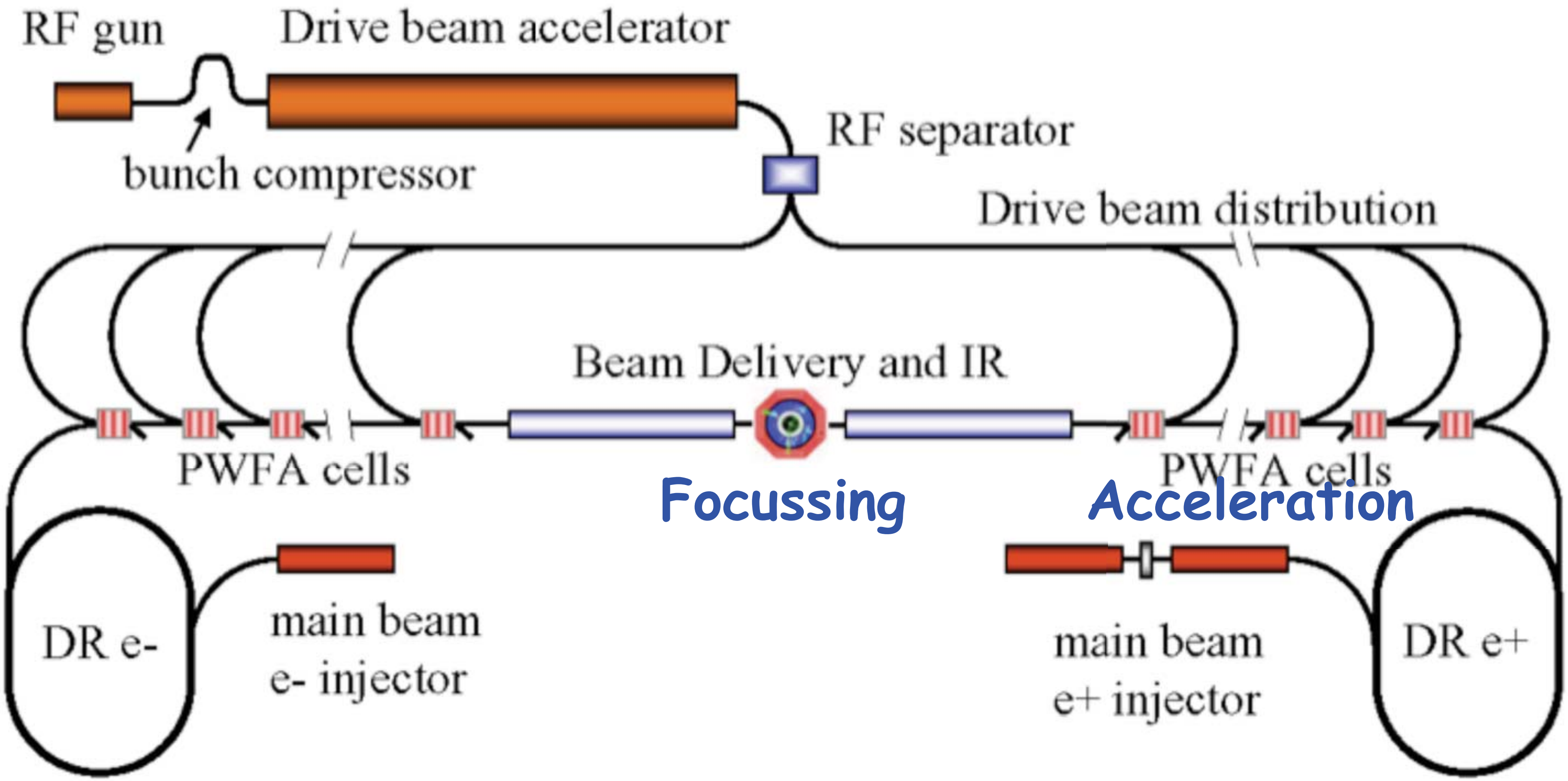




C. Joshi Sc. Am. Feb. 2006

M.Downer U.Texas

Plasma Wakefield Accelerator Linear Collider



Focussing

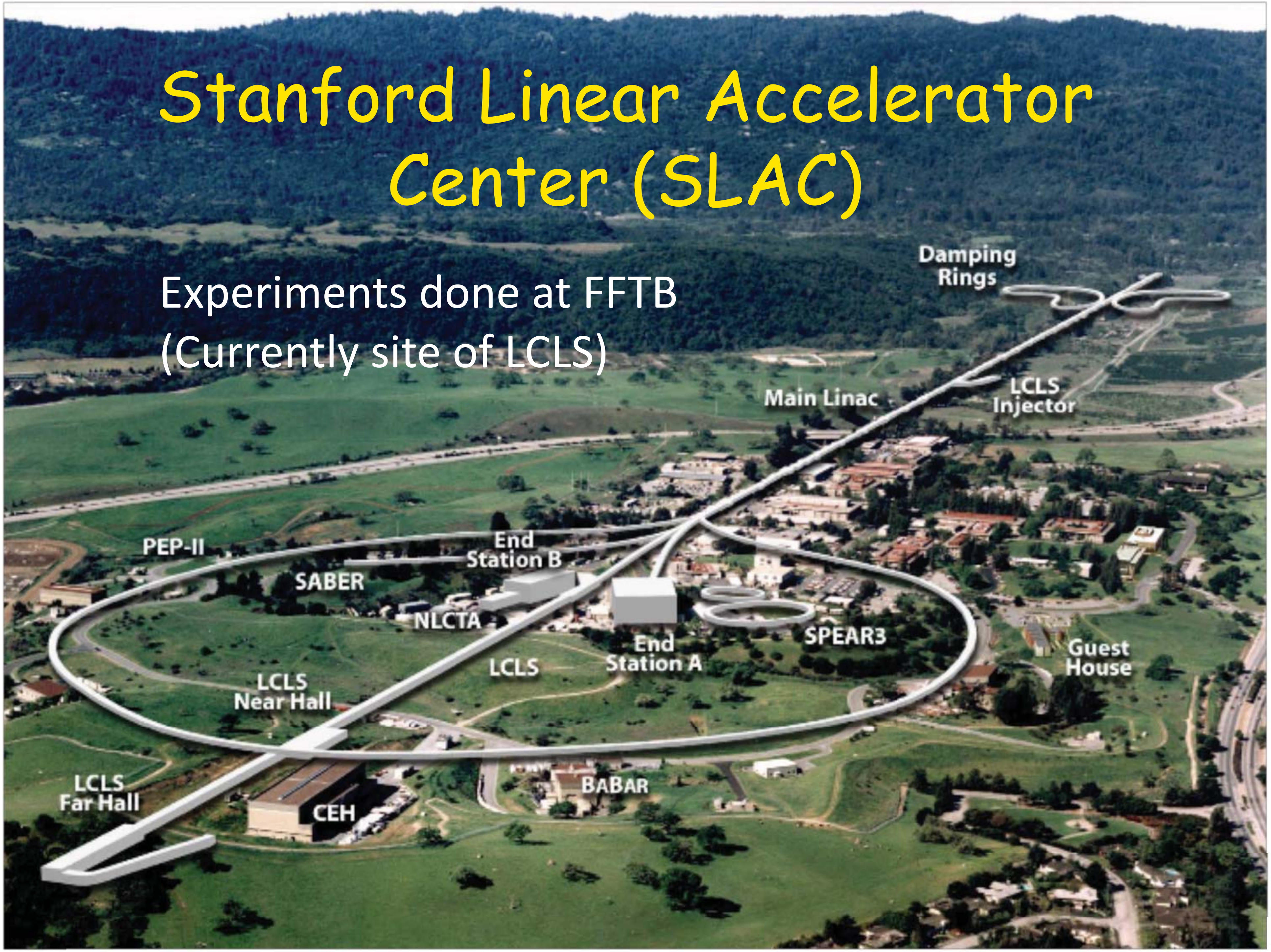
Acceleration

Generation

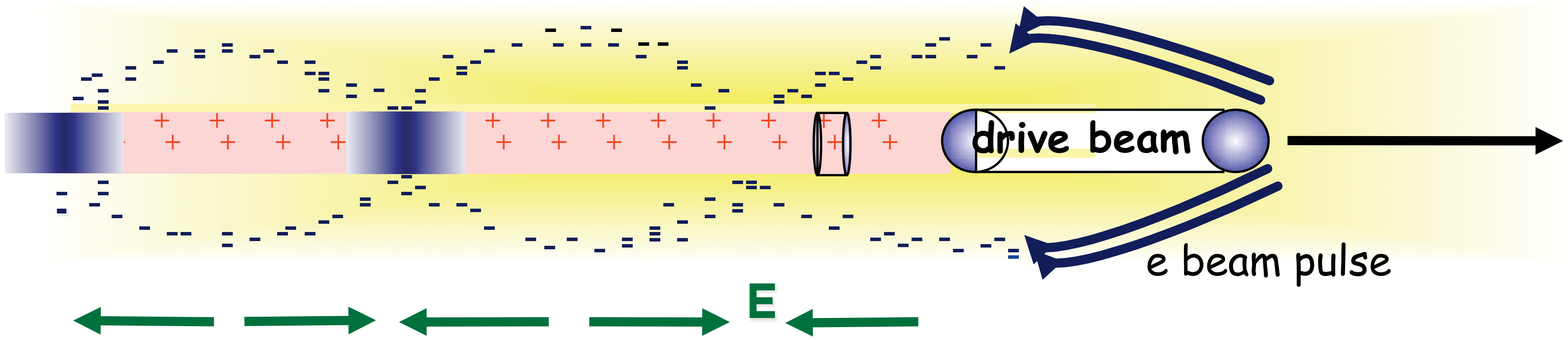
A. Seryi et al PAC Conf Proc.2009

Stanford Linear Accelerator Center (SLAC)

Experiments done at FFTB
(Currently site of LCLS)



Plasma Wakefield Acceleration Concept

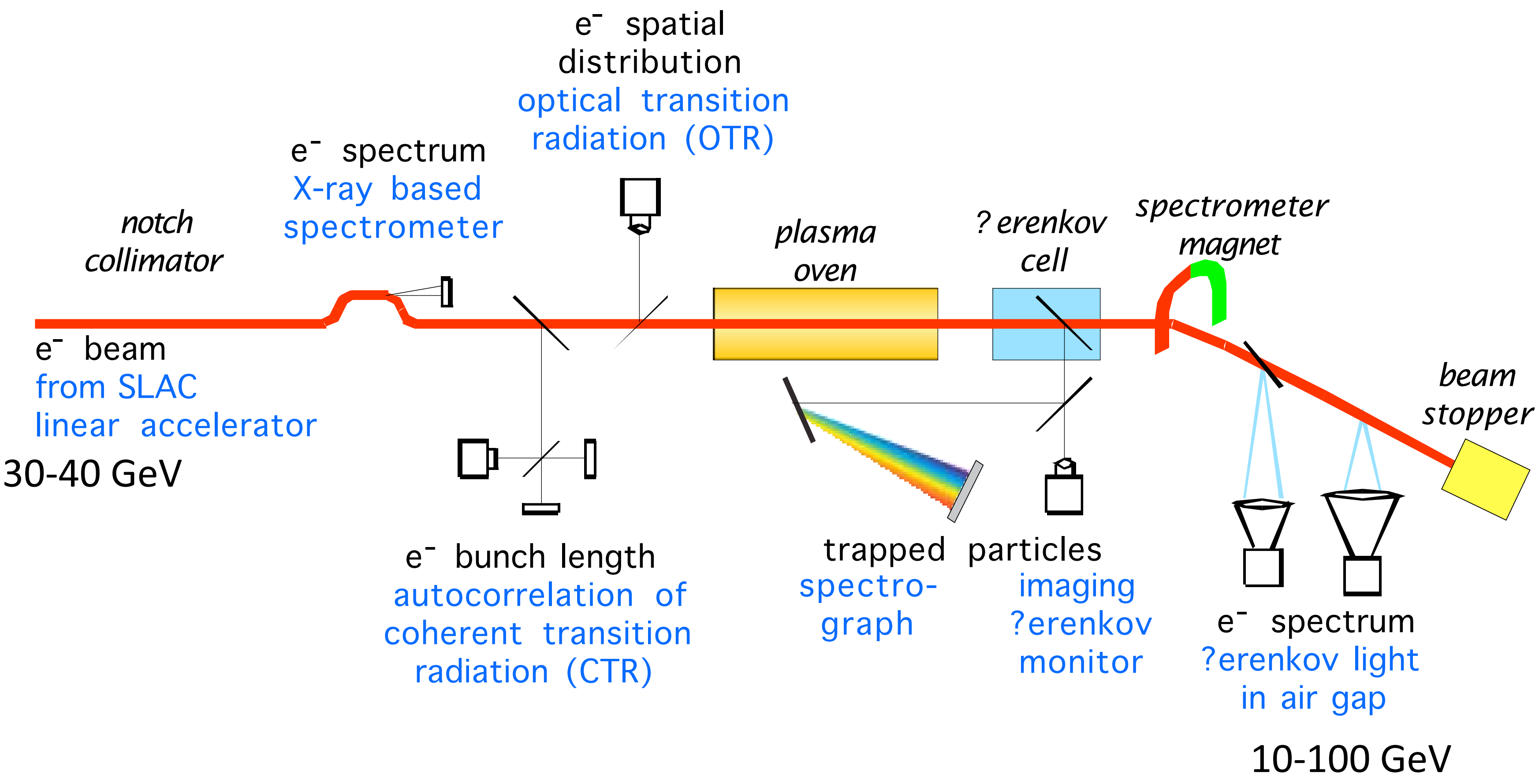


- Space charge force of the beam pulse displaces plasma electrons
- Plasma ion channel exerts restoring force => space charge wake

No dephasing between the particles and the wake

P.Chen et.al.PRL(1983)

Experimental Setup



e⁻ spatial distribution
optical transition radiation (OTR)

e⁻ spectrum
X-ray based spectrometer

notch collimator

plasma oven

? erenkov cell

spectrometer magnet

e⁻ beam
from SLAC linear accelerator
30-40 GeV

beam stopper

e⁻ bunch length
autocorrelation of coherent transition radiation (CTR)

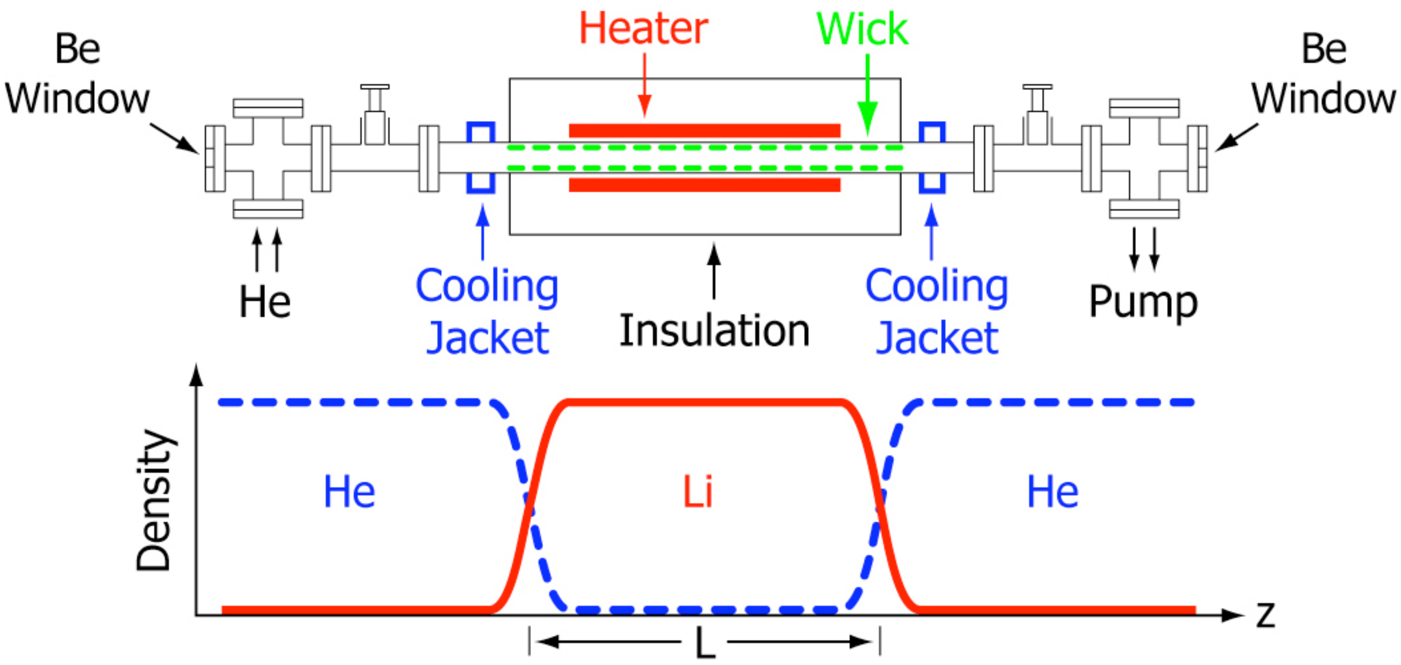
trapped particles
spectro-graph

imaging ?erenkov monitor

e⁻ spectrum
?erenkov light in air gap

10-100 GeV

Lithium Plasma Source



Lithium Oven Diagram

How it works:

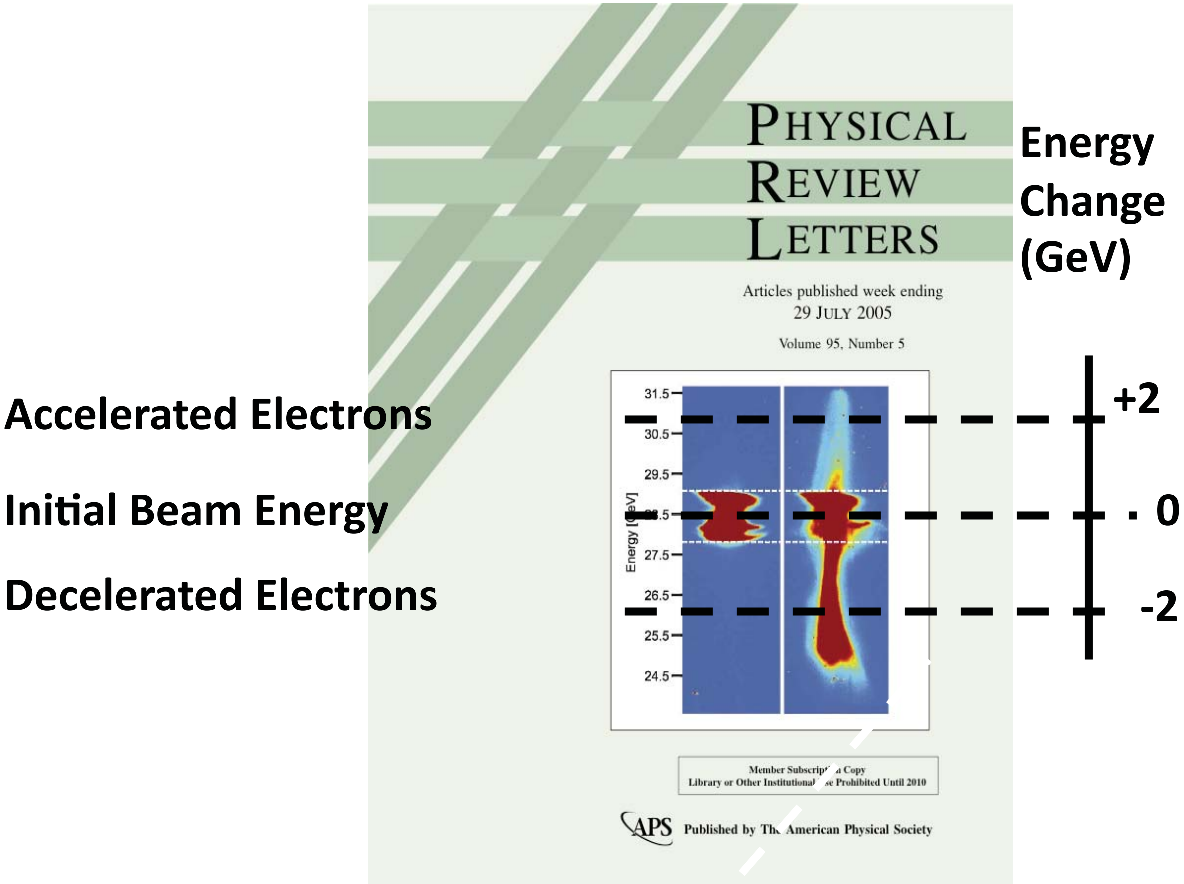
1) Heated to 800^{o}C to vaporize solid Li.

2) Li vapor diffuses out to the He transition region and condenses on wick.

3) The molten Li wicks back to center, vaporizes and begins the process again.

- Be (low-Z) windows separate the He from the FFTB beam line vacuum.
- The He pressure determines the Li vapor density, and the heater power determines the Li vapor length

BREAKING THE 1 GeV BARRIER



PHYSICAL REVIEW LETTERS

Articles published week ending
29 JULY 2005

Volume 95, Number 5

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Accelerated Electrons

Initial Beam Energy

Decelerated Electrons

Energy Change (GeV)

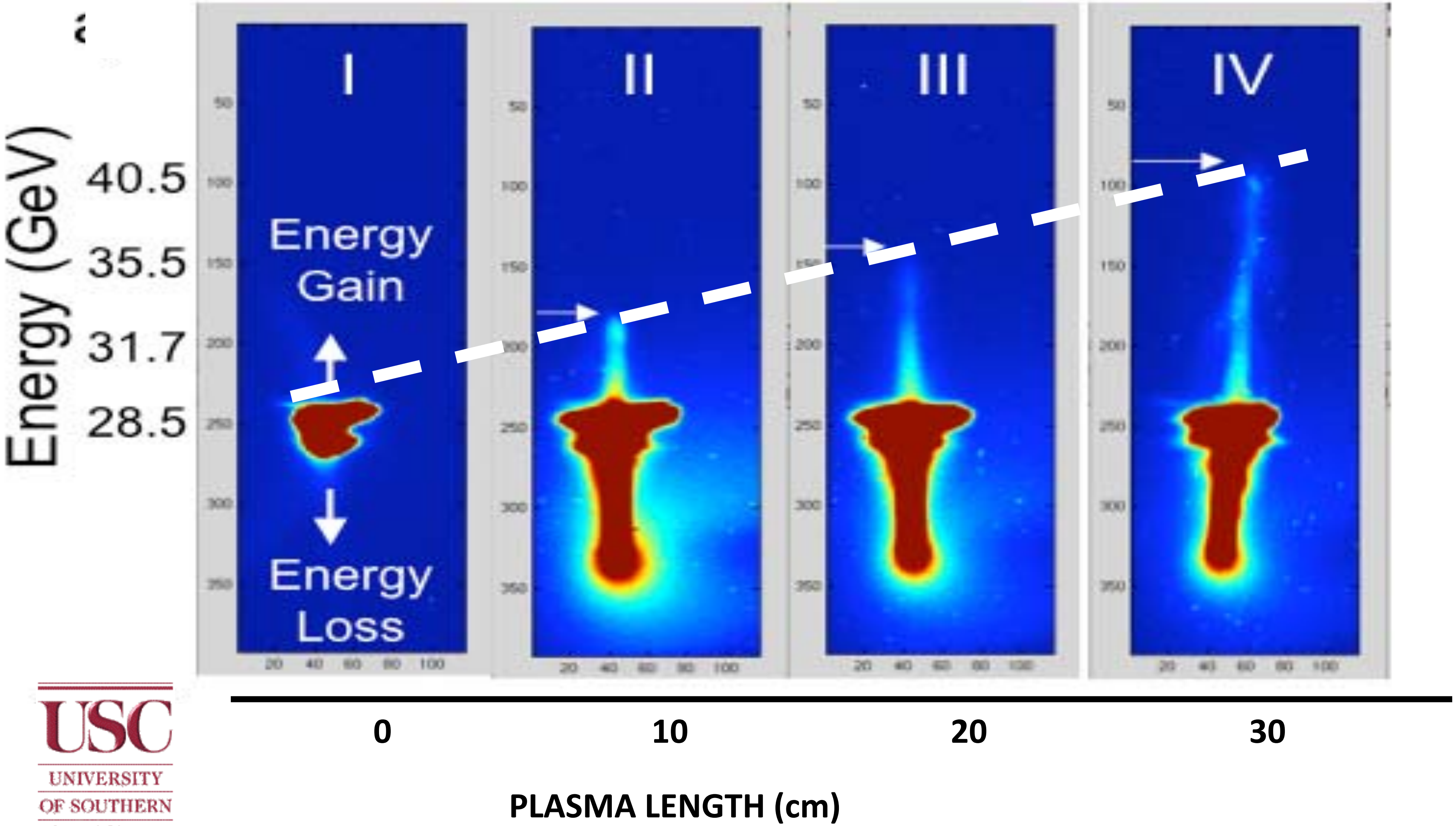
+2

0

-2

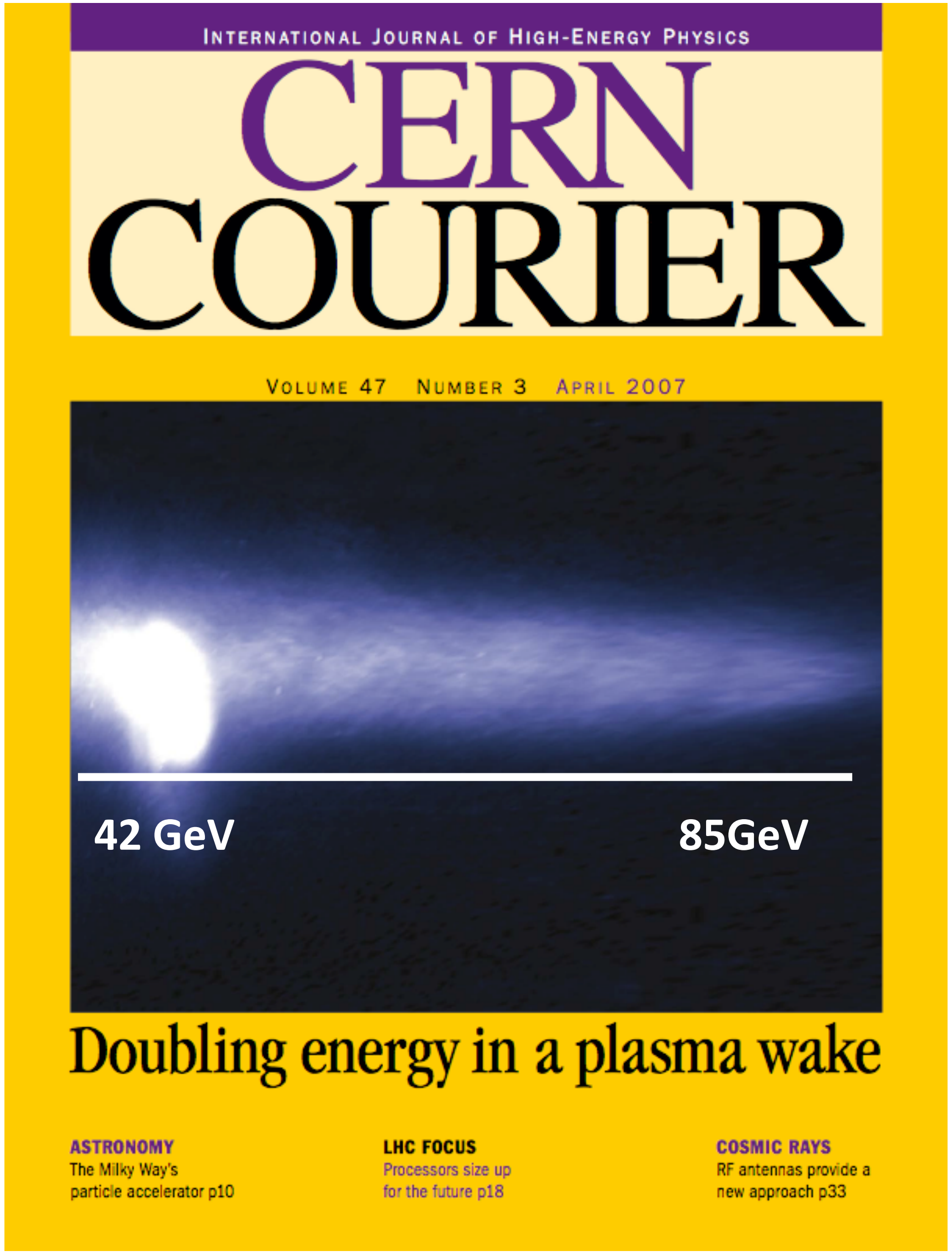
$n_e \approx 3.5\times10^{17}\ \mathrm{cm}^{-3}$ $L \approx 10$ cm, $N \approx 1.8\times10^{10}$, $\tau \approx 50$ fs

Energy Gain Scales Linearly with Length



Spectacular Progress in Plasma Wakefield Acceleration

Energy Doubling of 42 Billion Volt Electrons Using an 85 cm Long Plasma Wakefield Accelerator



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 47 NUMBER 3 APRIL 2007

Doubling energy in a plasma wake

ASTRONOMY
The Milky Way's
particle accelerator p10

LHC FOCUS
Processors size up
for the future p18

COSMIC RAYS
RF antennas provide a
new approach p33

Nature v 445,p741 (2007)

But What About Positrons?

Positron Focusing by Plasma : Need a transverse electrostatic field

Positron Acceleration by Plasma: Need a longitudinal field

Intense Beams of Positrons for Positron-Plasma Interaction

Only place in the world to study this topic !!

SLAC
NATIONAL ACCELERATOR LABORATORY
New SLAC National Accelerator Laboratory logo

N = 4 x 10^{10}

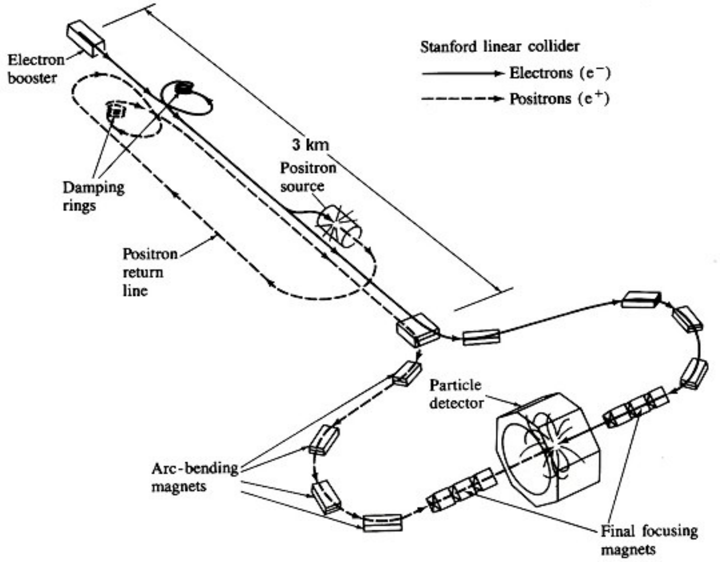
Energy 50 GeV

Rep Rate 60 HZ

Energy/pulse 320 J
Focal Spot Size 1 micron

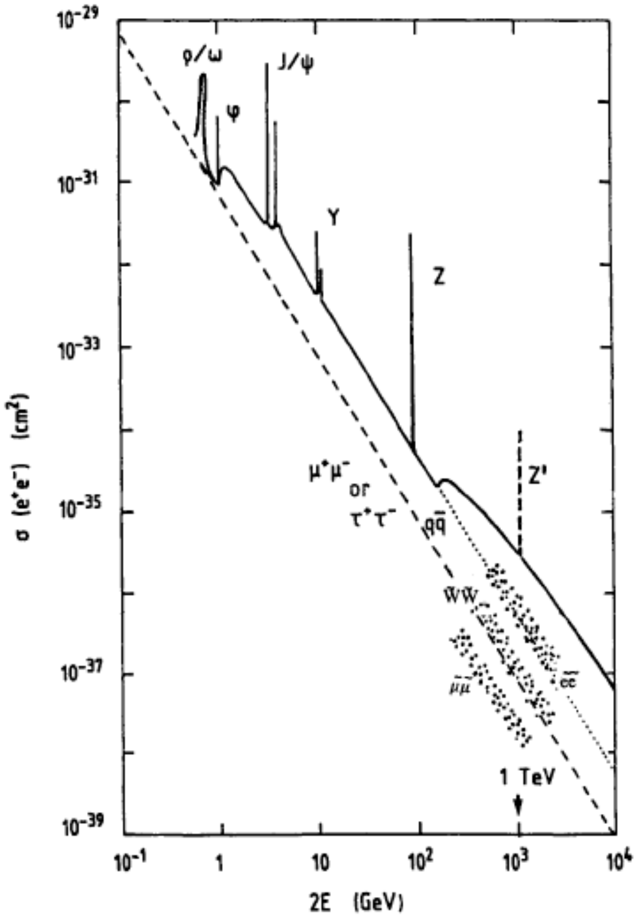
Pulse Width 4 ps

Focused Intensity 8 x 10^{21} W/cm^2



Comparable to the most intense laser beams to-date

Positron-Electron Annihilation



Why don't the positrons annihilate with plasma electrons?

For fixed target collisions CM Energy must exceed 2.muon rest mass = 210 MeV

$$E^2 - (pc)^2 = E^2_{cm}$$

$$\left(\gamma_b mc^2 + 0.511\right)^2 - \left(\gamma_b mc^2\right)^2 = E^2{}_{cm}$$

$$\gamma_b mc^2 = 43.69\ \ GeV\ \ , \qquad E_{cm} = 210\ \ MeV$$

Below this threshold in current experiments.

Bhabha cross section that will scatter positrons also very small

Even above this energy cross-section too small

Linear Plasma Wakefield Theory

In the linear regime plasma response to both electrons and positrons very similar

$$(\partial_t^2 + \omega_p^2)\frac{n_1}{n_o} = \mp\ \omega_p^2\left(\frac{n_b(t)}{n_o}\right)$$

Large wake if beam density $n_b \sim n_o$

$t_{pulse} \sim pi.w_p^{-1}$

100fs $(10^{17}/n_o)^{1/2}$ and spot size c/ω_p:

$\Rightarrow Q/\tau_{pulse}$ = 1nCoul/100fs (~10 kA) beam

$$\nabla \bullet E = -4\pi e n_1 \Rightarrow \quad eE = \frac{n_1}{n_o}\sqrt{\frac{n_o}{10^{16}cm^{-3}}}\,10\,GeV/m\,\cos\omega_p(t - z/c)$$

But interesting wakes are in the nonlinear blowout regime…

Linear wake fields driven by e^- and e^+ beams

e^- Beam

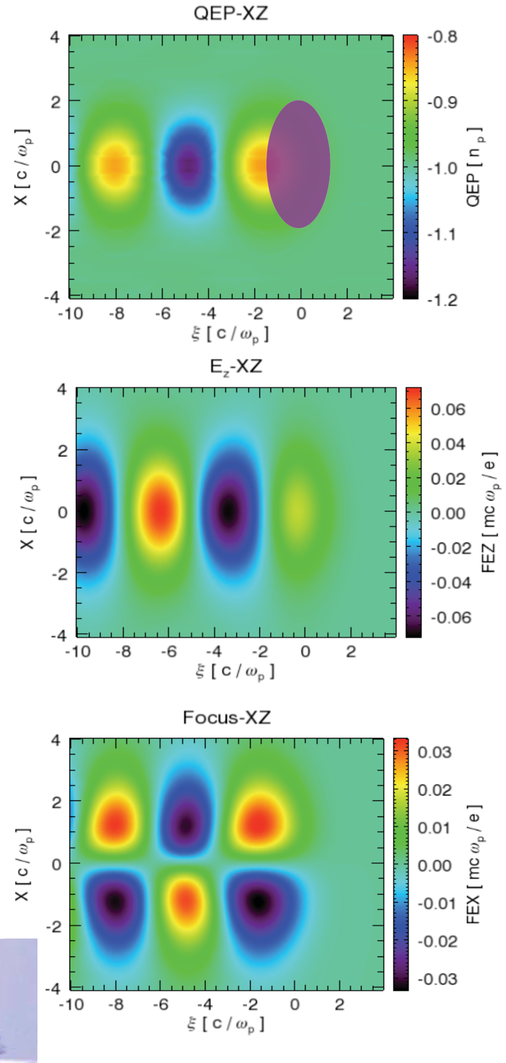
$n_b << n_p$

e^+ Beam

Plasma Density

Accelerating Field

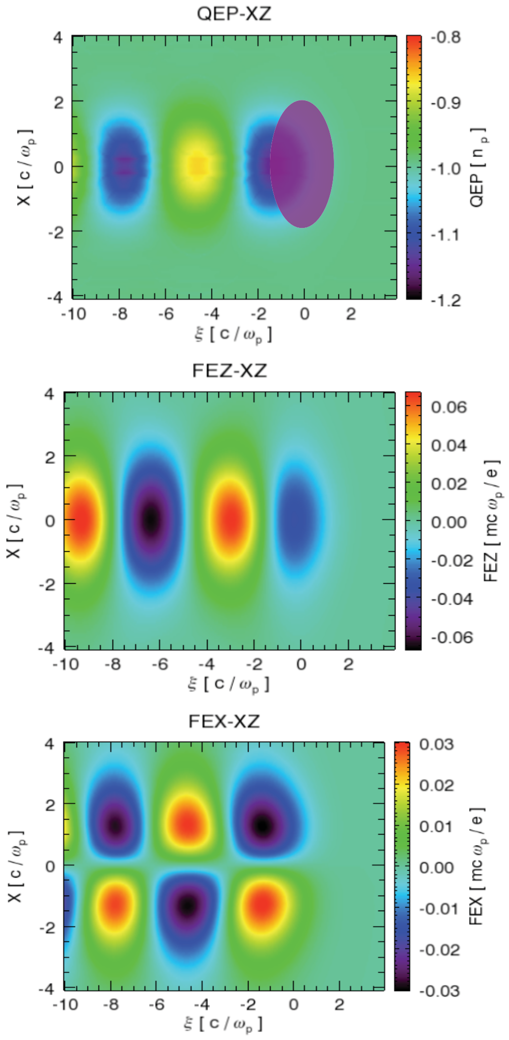
Focusing Field



$$n_b = n_0 e^{\frac{-r^2}{2\sigma_r^2}} e^{\frac{-z^2}{2\sigma_z^2}}$$

$$\sigma_r = 1.0 k_p^{-1}$$

$$\sigma_z = 1.0 k_p^{-1}$$



QuickPIC simulations

By Weiming An and Warren B. Mori UCLA

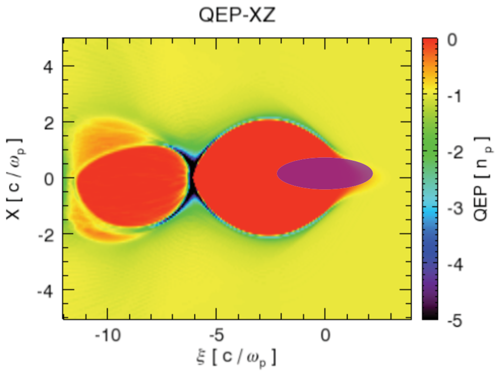
Nonlinear wake fields driven by e^- and e^+ beams

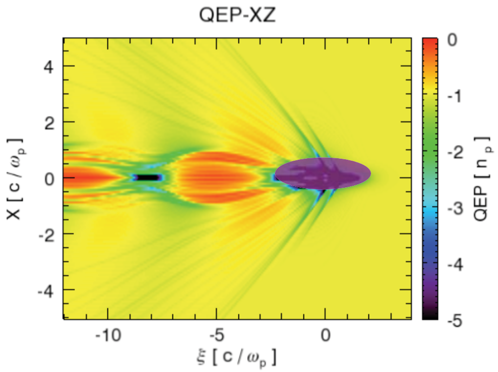
e^- Beam

$n_b >> n_p$

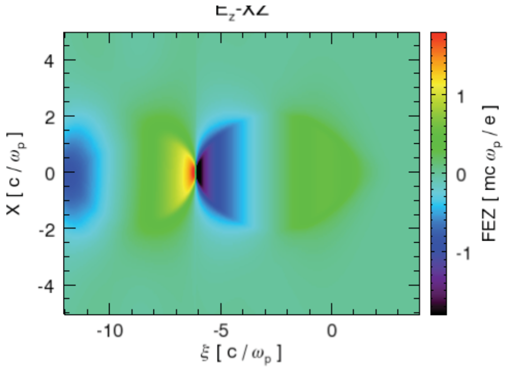
e^+ Beam

Plasma Density





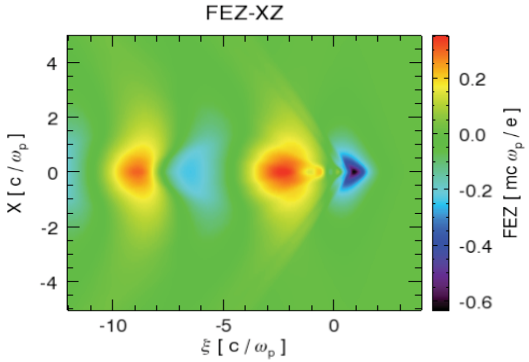
Accelerating Field



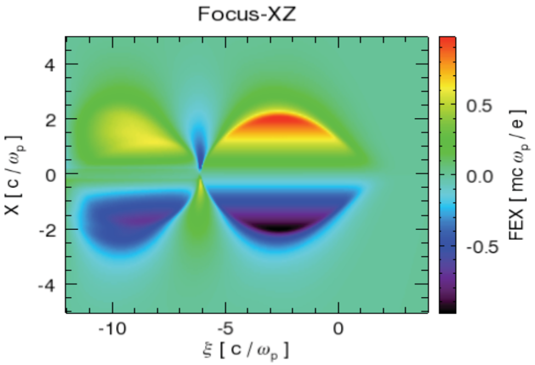
$$n_b = n_0 e^{\frac{-r^2}{2\sigma_r^2}} e^{\frac{-z^2}{2\sigma_z^2}}$$

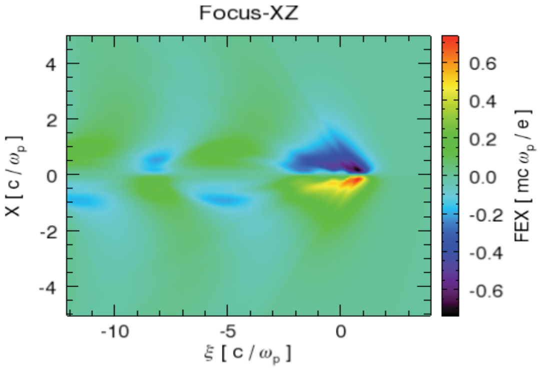
$$\sigma_r = 0.2 k_p^{-1}$$

$$\sigma_z = 1.0 k_p^{-1}$$



Focusing Field



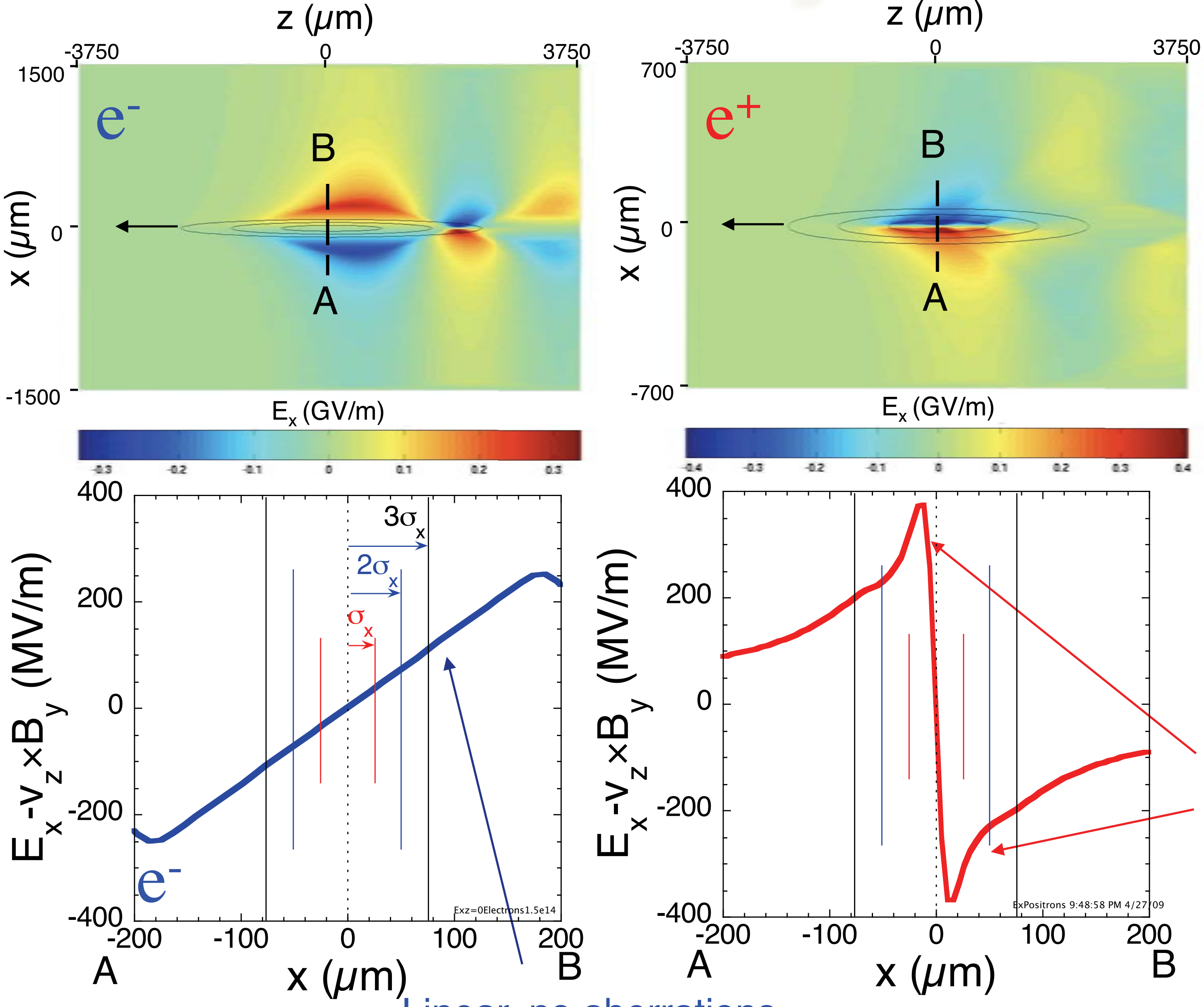


UCLA

QuickPIC simulations

By Weiming An and Warren B. Mori UCLA

e^- & e^+ Focusing Fields



Non-linear, aberrations

Linear, no aberrations

QuickPIC

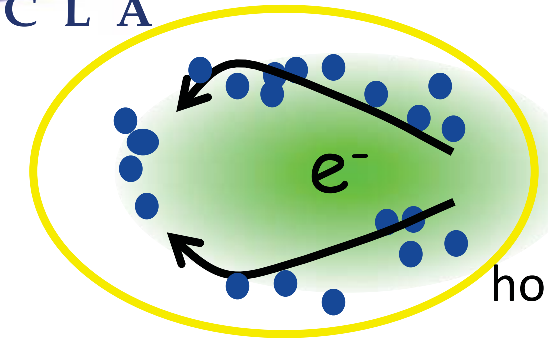
$\sigma_{x0}=\sigma_{y0}=25\ \mu m$

$\sigma_z=730\ \mu m$

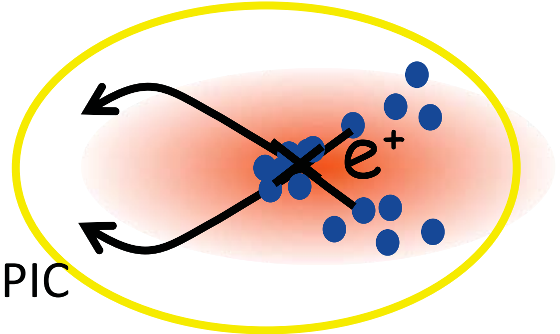
$N=1.9\times10^{10}\ e^+/e^-$

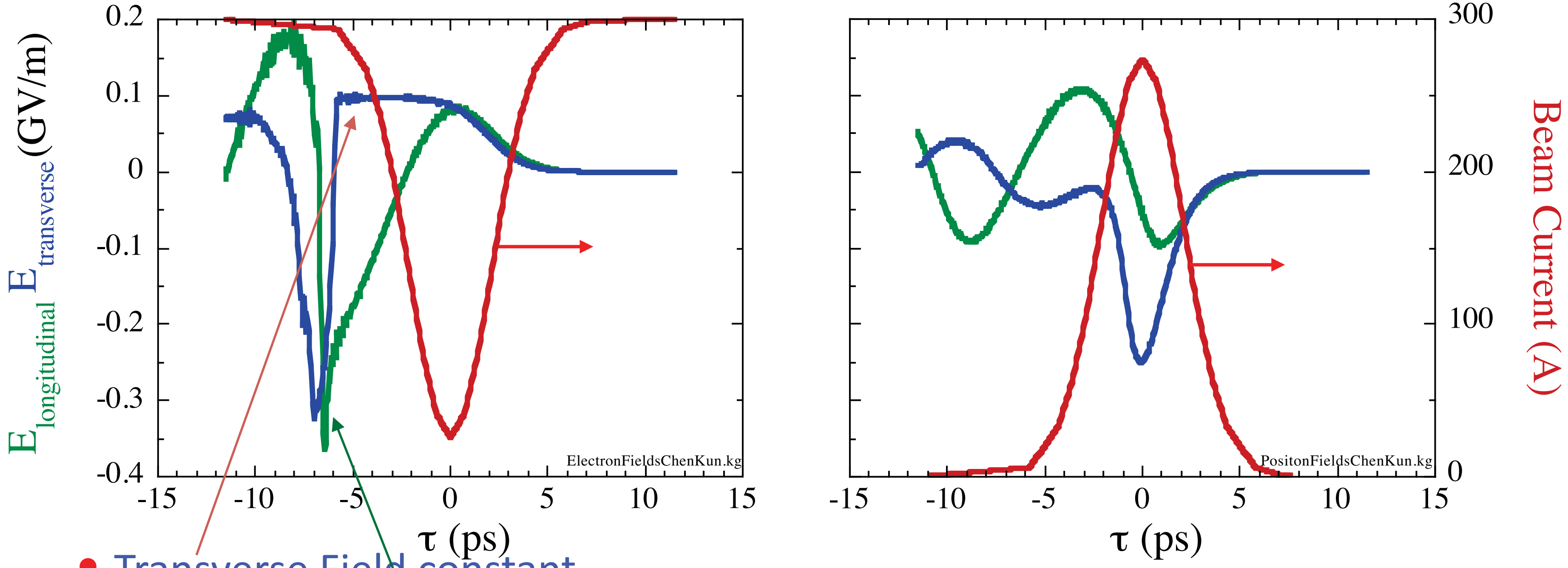
$n_e=1.5\times10^{14}\ cm^{-3}$

WAKEFIELD FIELDS for e^- & e^+



n_e=1.5×10^{14} cm^{-3}
homogeneous, QUICKPIC

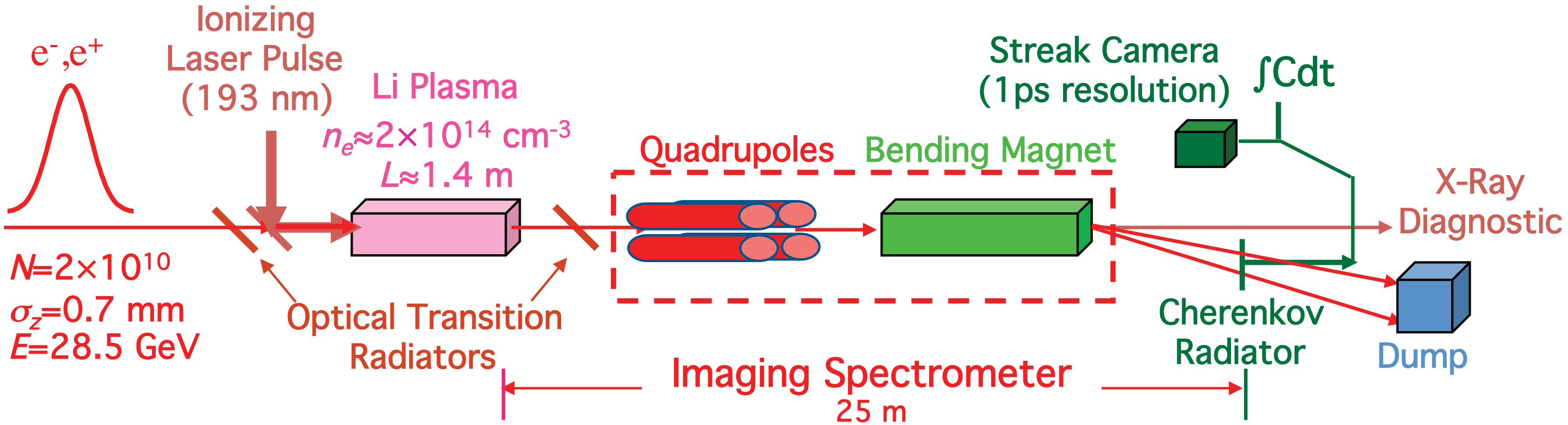




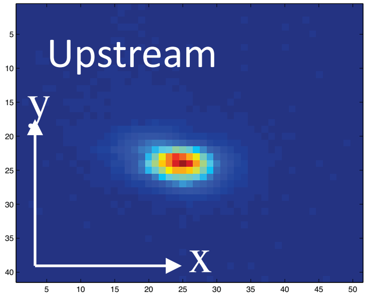
- Transverse Field constant
After Plasma electrons Blown-Out
- Longitudinal field Shows
Accelerating "Spike"

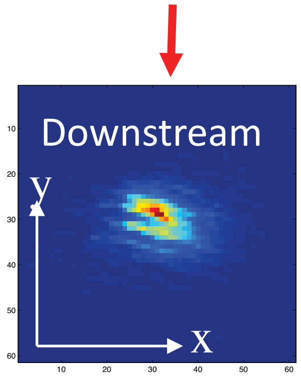
- Fields vary along r, stronger
- Less Acceleration

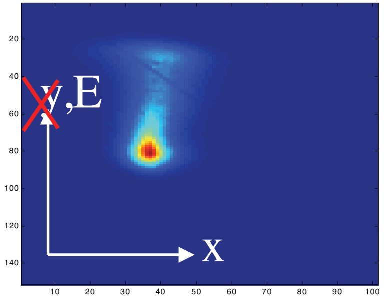
EXPERIMENTAL SET UP



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

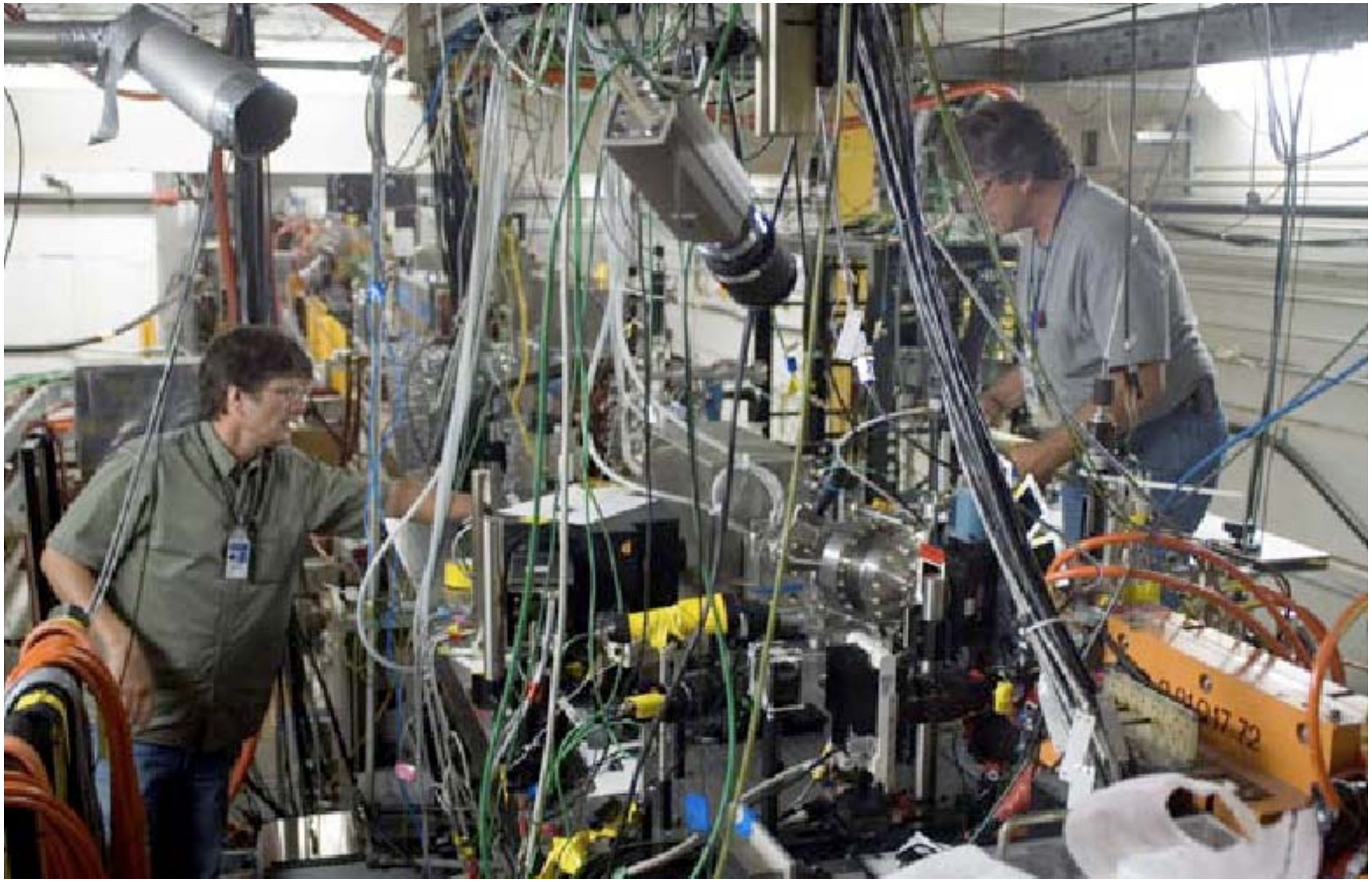






- 1:1 imaging, spatial resolution <9 μm

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

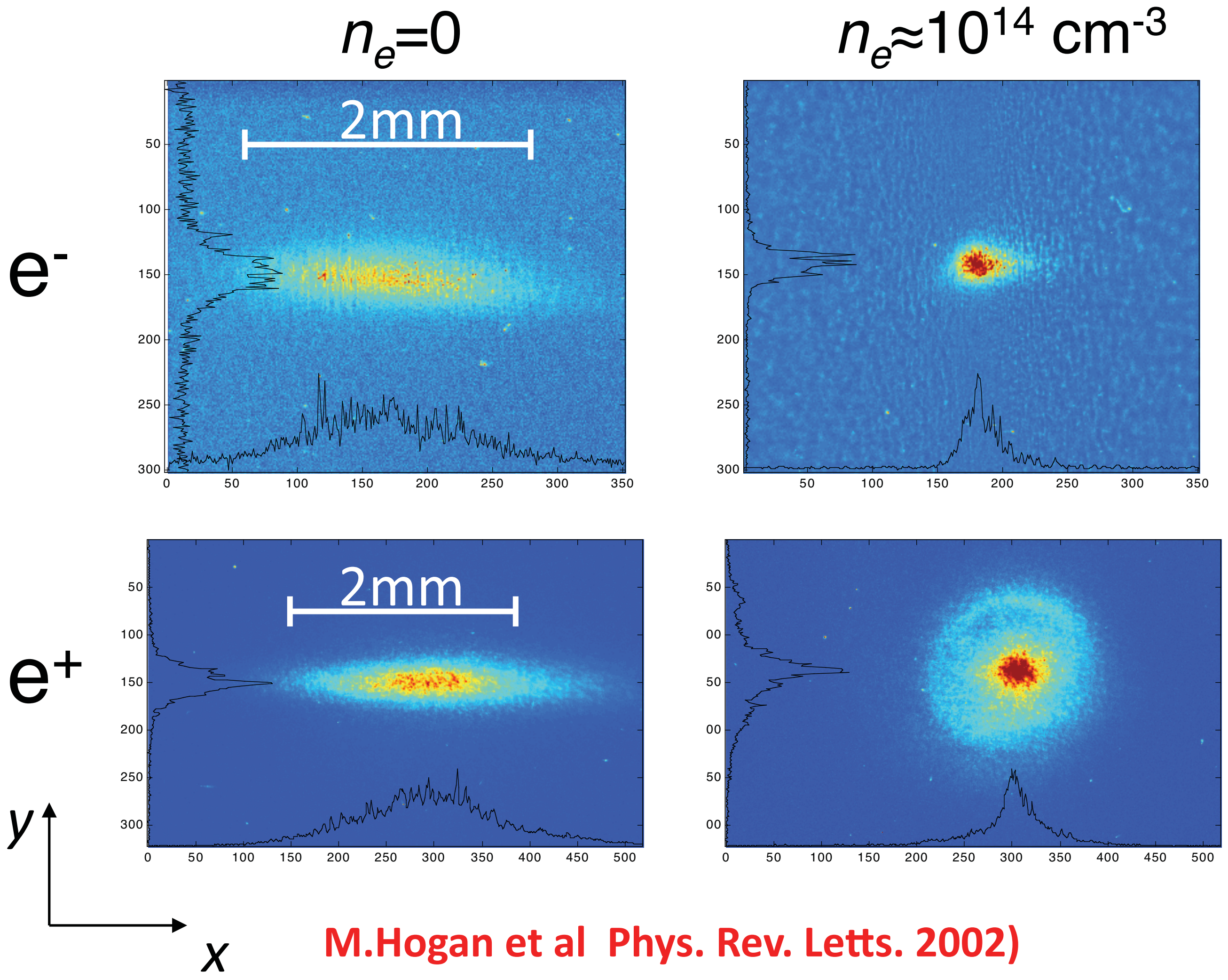


Life of an experimentalist

From: Chan Joshi, UCLA Personal archives

FOCUSING OF e^-/e^+

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



- *Ideal Plasma Lens in Blow-Out Regime*

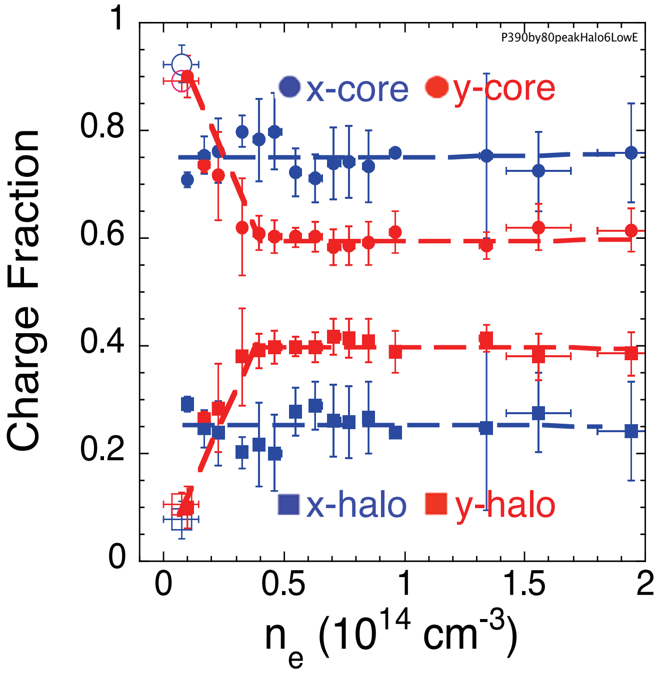
- *Plasma Lens with Aberrations (Halo Formation)*

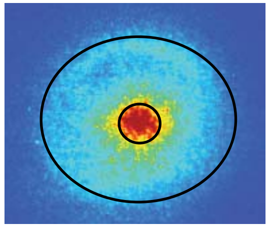
M.Hogan et al Phys. Rev. Letts. 2002)
P.Muggli et al Phys. Rev .Letts 101 055001, (2008),

EXPERIMENT/SIMULATIONS: HALO FORMATION

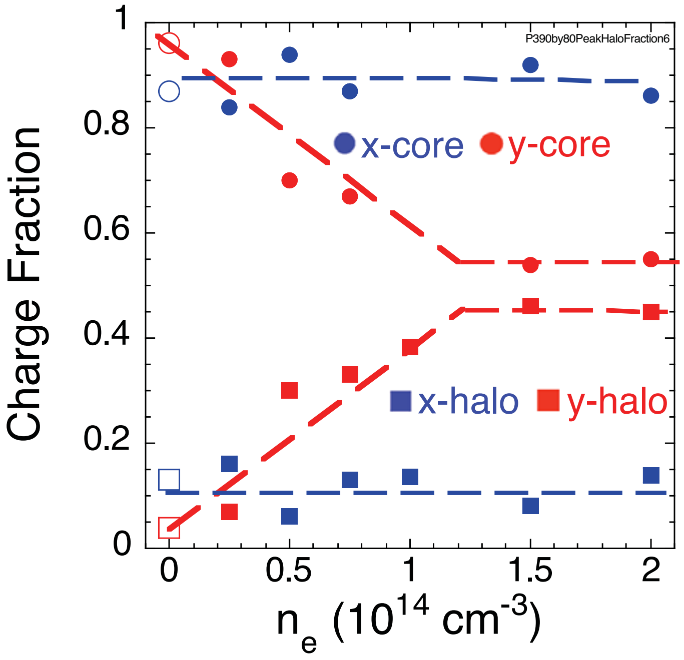
$\sigma_{x0} \approx \sigma_{y0} \approx 25\ \mu m$, $\varepsilon_{Nx} \approx 390\times10^{-6}$, $\varepsilon_{Ny} \approx 80\times10^{-6}$ m-rad, $N = 1.9\times10^{10}$ e^+, $L \approx 1.4$ m

Experiment





Simulations

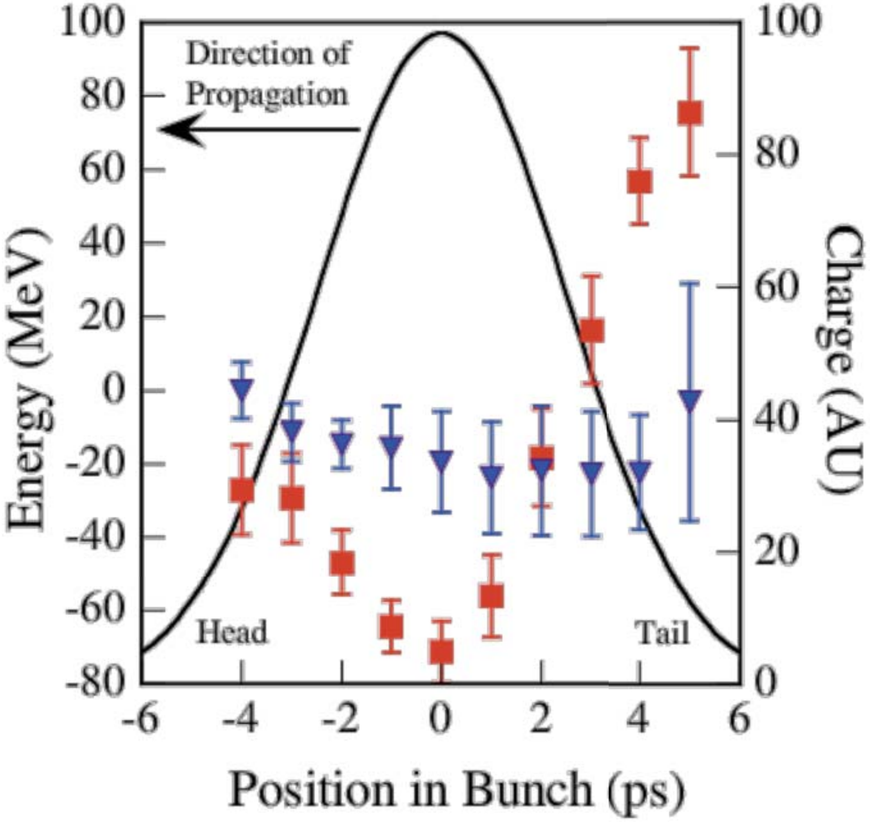


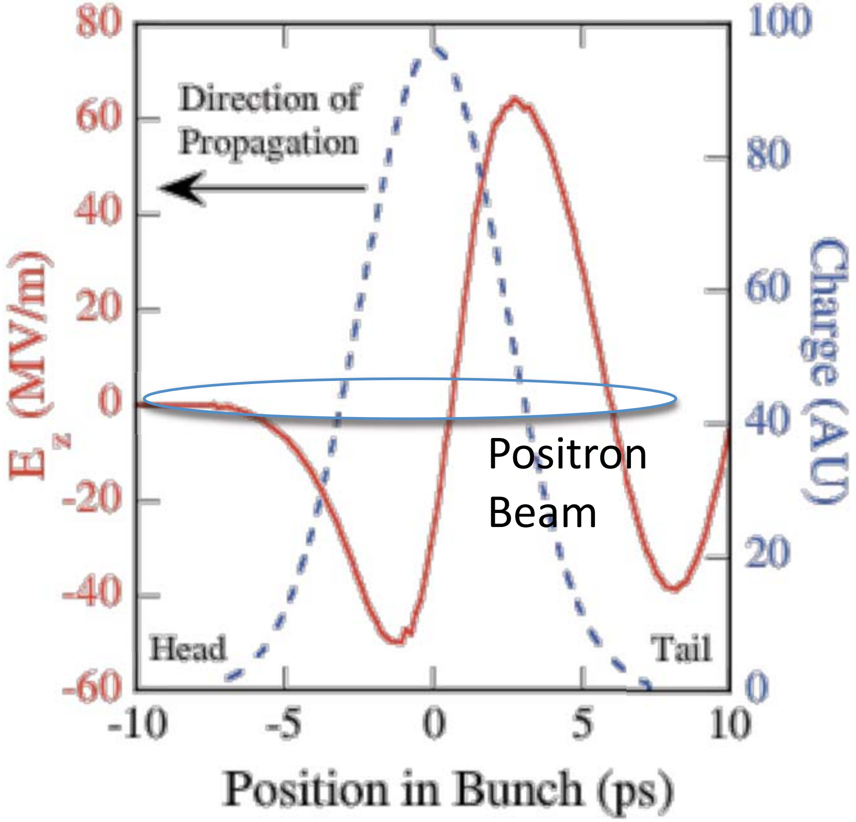
Positron Acceleration

Time Resolved Spectrum

Wake Structure in Plasma

$N=1.2\times10^{10}$ e^+, $n_e=1.8\times10^{14}cm^{-3}$,
L=1.4 m





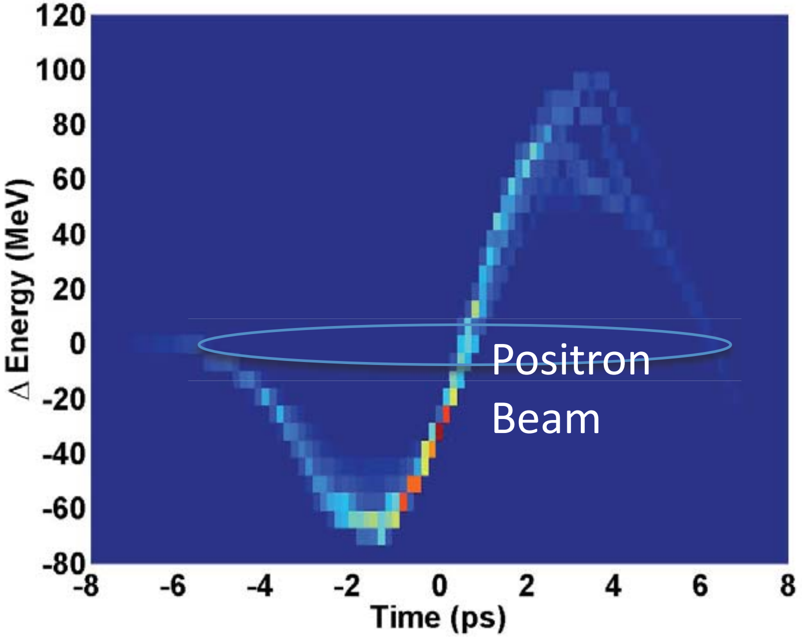
B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (2003).

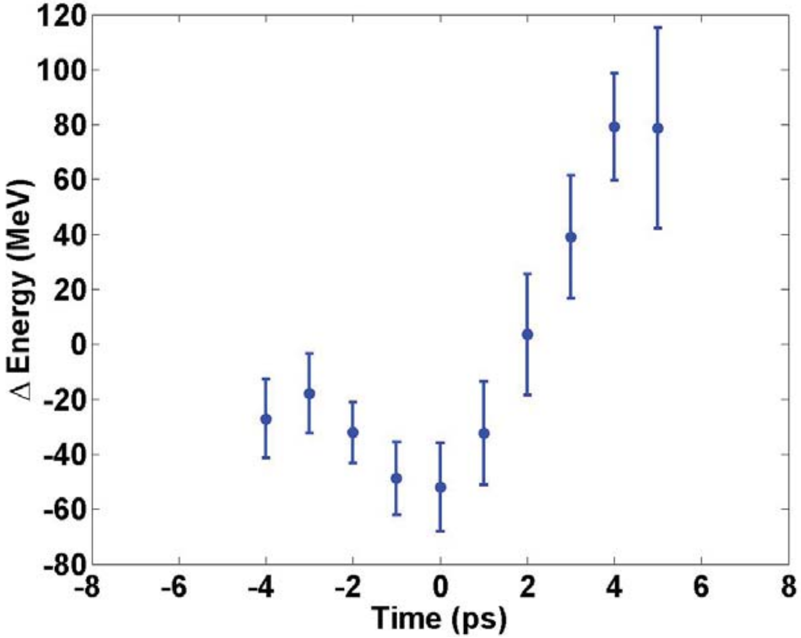
Energy Gain & Loss of Positrons in a Plasma Wake

OSIRIS Simulation Prediction:

Experimental Measurement:

	Peak Energy Loss	Peak Energy Gain
Simulation	64 MeV	78 MeV
Experiment	65±10 MeV	79±15 MeV





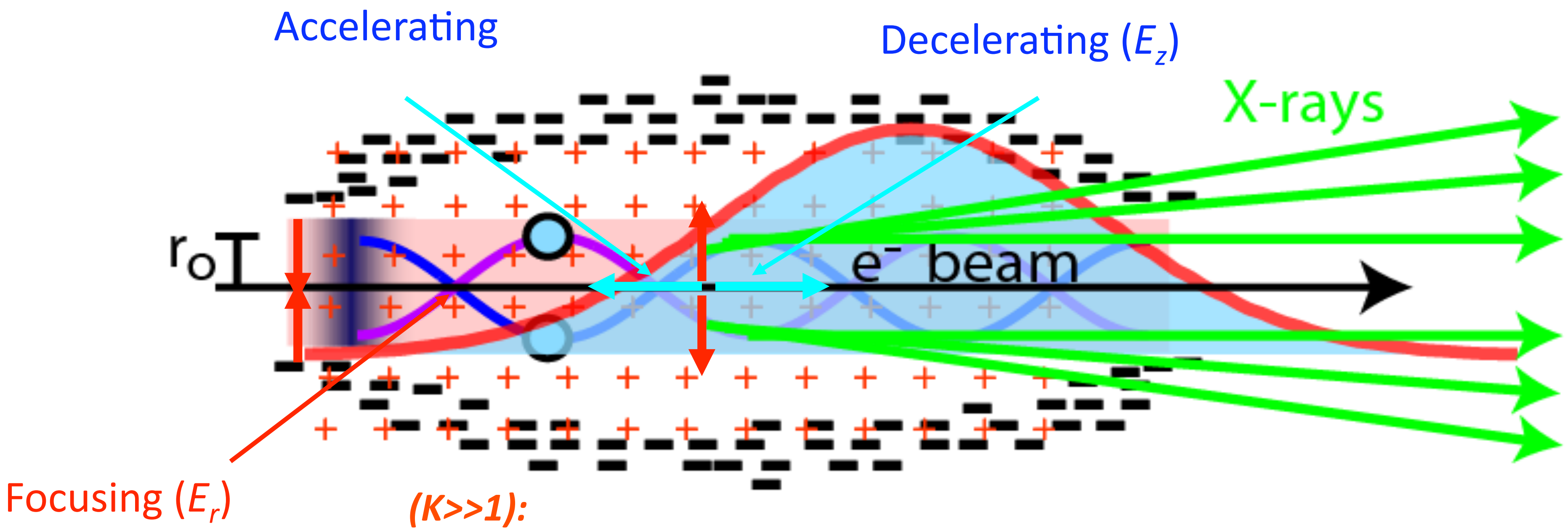
5×10^8 e^+ in 1 ps bin at +4 ps

(Brent Blue et al Phys,Rev.Letts 2002)

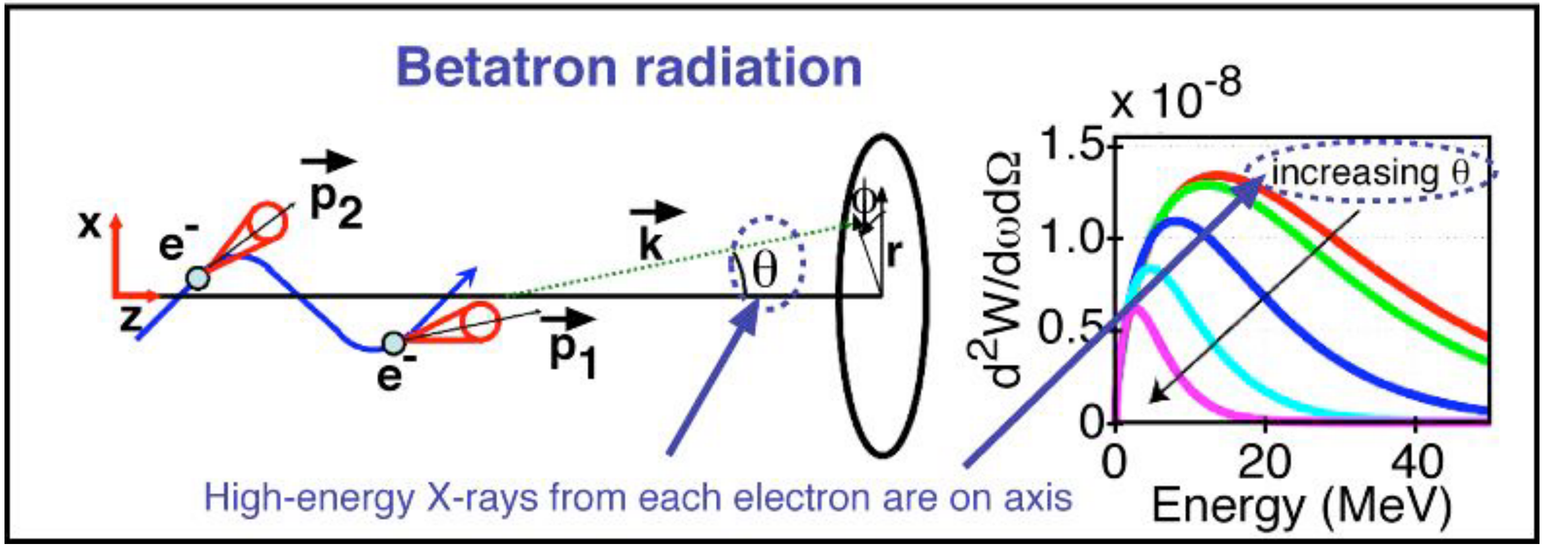
Positron Production Using Plasmas

Plasma Wiggler for MeV X-ray Production

- Positron production needs 50 MV X-Rays
- Use an ion column produced by a dense electron beam as a wiggler
- If $n_b > n_{pe}$, all plasma e^- are blown-out creating an ion column. Betatron motion in this wiggler produces X-ray radiation.



For "high-K" wigglers, high-energy photons are emitted in the near forward direction



Scaling Laws for Betatron radiation

Wiggler strength:

$$K = \frac{\gamma\omega_\beta}{c} r_o = f\left(\sqrt{n_p}, r_o, \sqrt{\gamma}\right) = 173$$

Critical frequency on-axis

$$\omega_c = \frac{3\omega_\beta^2\gamma^3}{2c} r_o = f\left(n_p, r_o, \gamma^2\right) = 49.6 MeV$$

Larmor Formula
Energy Loss:

$$\frac{dE}{dz} = \frac{1}{3} r_e m_e c^2 \gamma^2 k_\beta^2 K^2 = f\left(n_p^2, r_o^2, \gamma^2\right) = 4.3 GeV/m$$

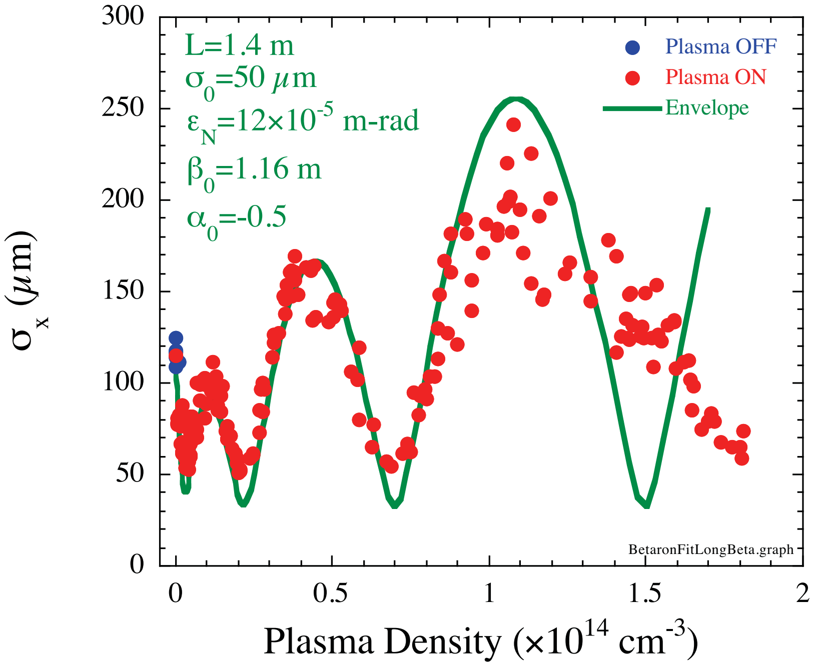
Typical Parameters

n_{pe}=$3x10^{17}$ cm^{-3}, γ=56000, r_0=10 μm:

Giving: ***E_r=27 GV/m, λ_β=2cm B/r= 9 MT/m***

β-TRON RADIATION IN PLASMAS

Beam Envelope Oscillations in Ion Column



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

$\hbar\omega_c \approx keV$ $n_e = 1.5 \times 10^{14}\ cm^{-3}$

Betatron Radiation Spot

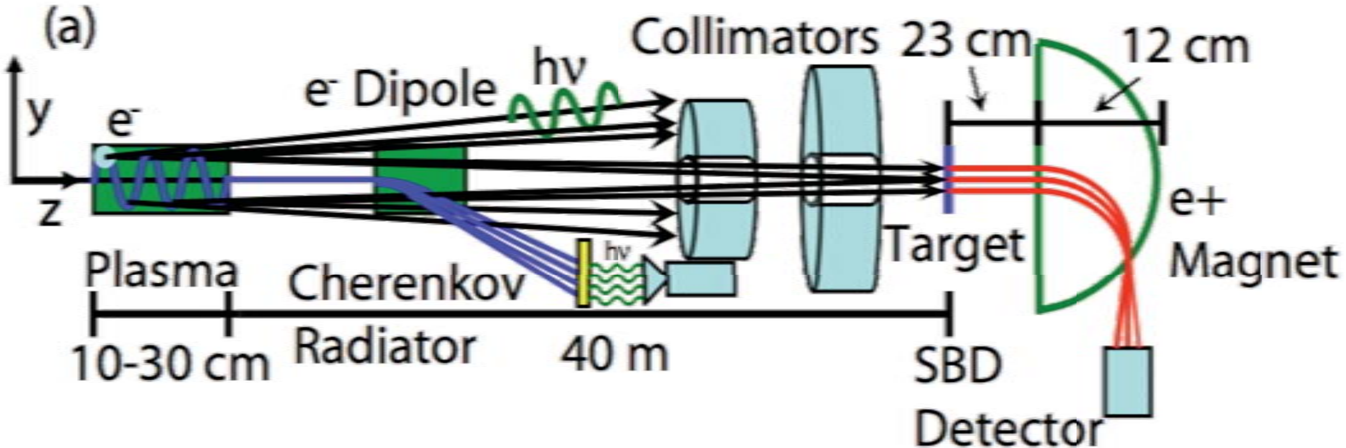

PHYSICAL
REVIEW
LETTERS

1 April 2002

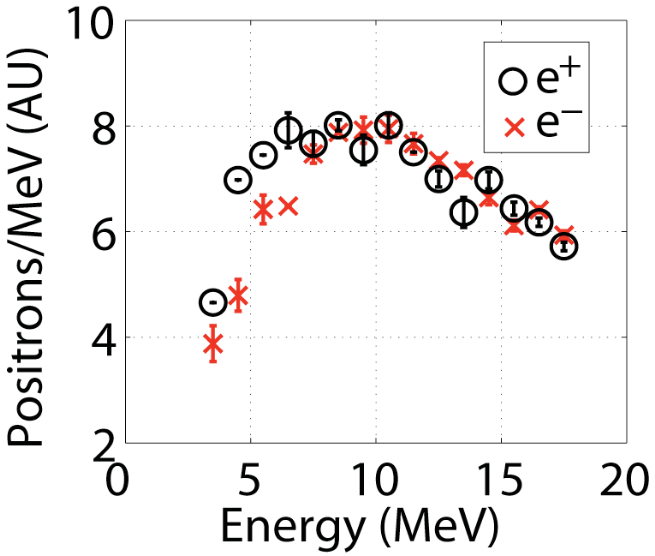
APS Published by The American Physical Society

Wang, PRL 88, 2002

β-Tron Radiation Produced Pairs



Johnson, AAC 06, Proceedings



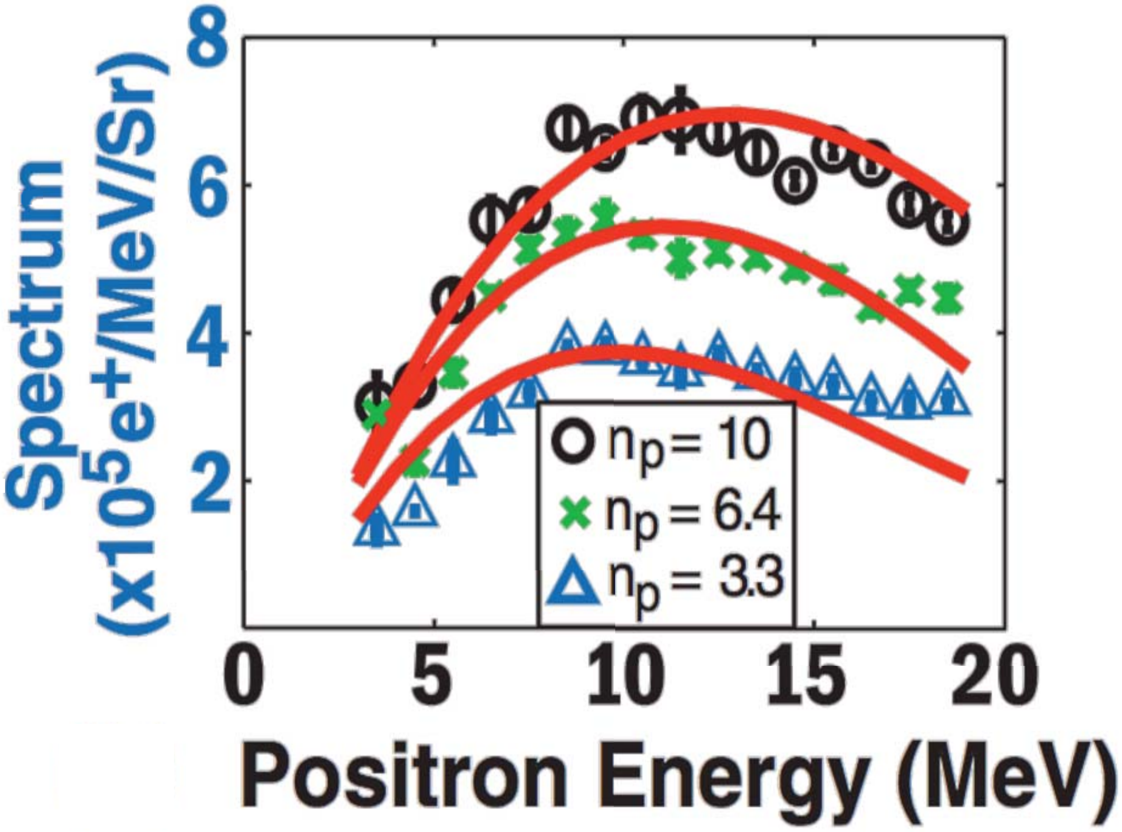
Both electron and positron spectra measured

Johnson, PRL 97, 2006

Measured Positron Spectra Excellent Agreement with Theory

n_{pe} = 3×10^{17} cm^{-3},
γ = 56000,
r_0 = 10 µm:

Giving:
E_r = 27 GV/m,
λ_β = 2cm
B/r = 9 MT/m



D.Johnson et al Phys Rev Letts 97, 175003,(2006)

Summary on Positron Production

- Using a 28 GeV beam radiation loss of 4.2 GeV/m demonstrated.
- Since half the energy is above the critical frequency , 50 MeV photons , this loss represents ~ 500 photons/e
- This is within an order of magnitude of what is needed for a future linear collider
- Open Questions : circularly polarized photons?

Positron-Plasma Interactions: Where to next?

FACET:Facilityfor Second Generation AA Research @SLAC

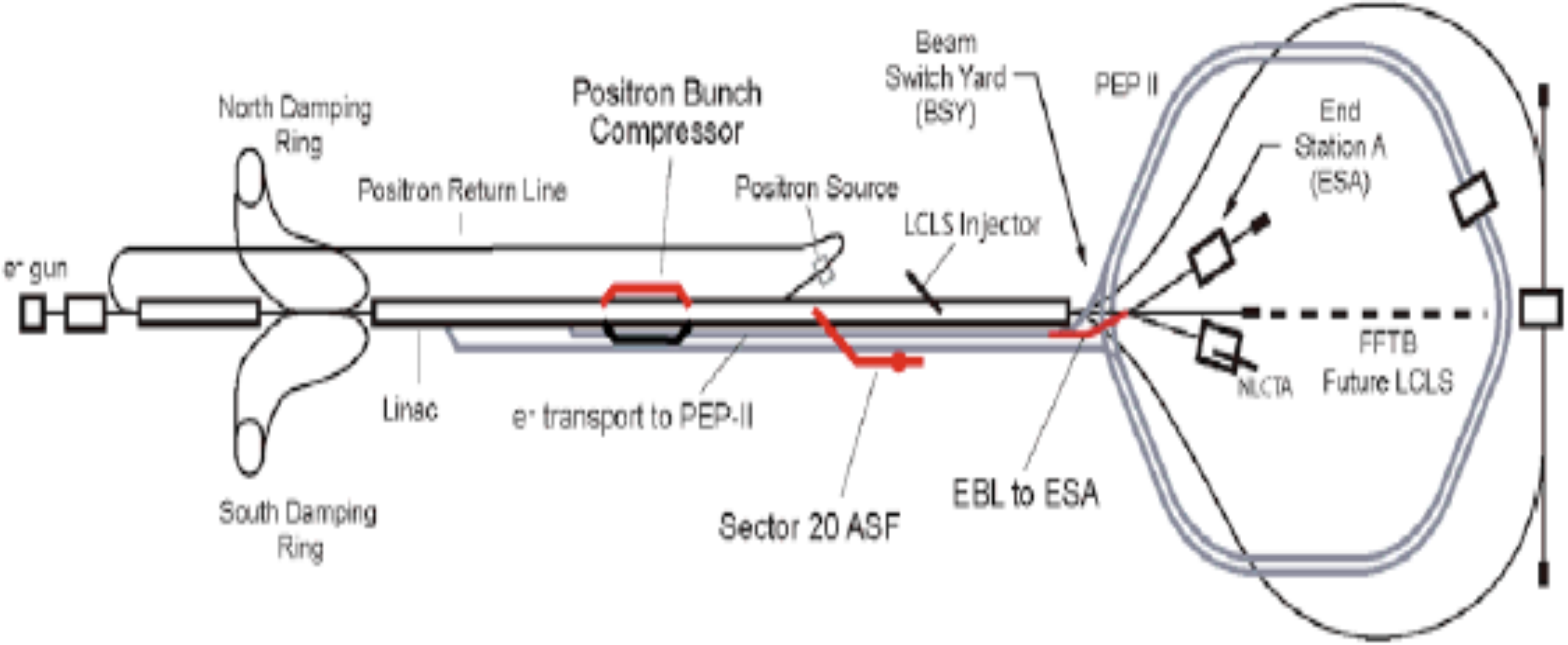
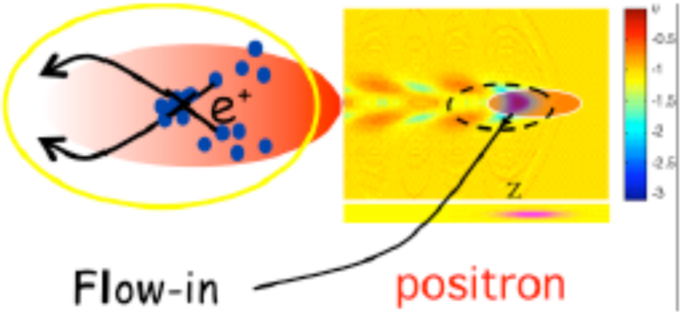
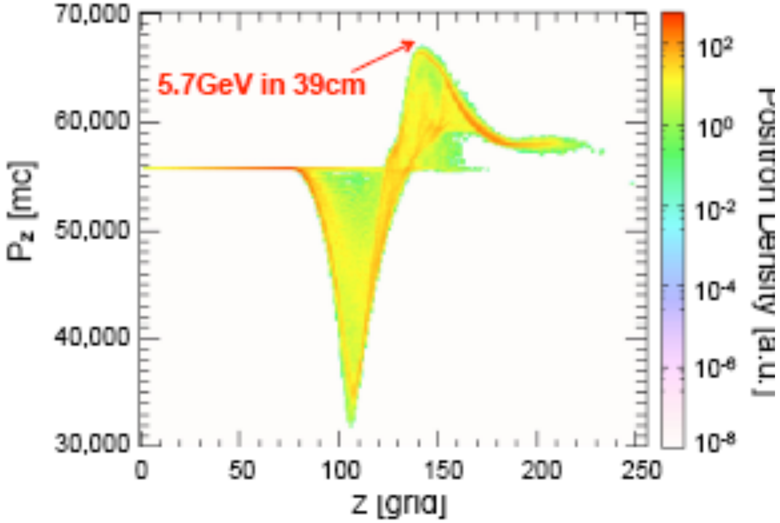


Figure 1-1. Schematic of the SLAC site with proposed FACET modifications to the beam delivery systems.

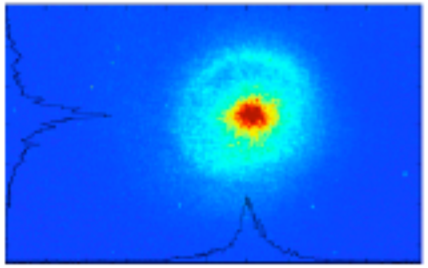
High Gradient Positron Acceleration

- First experiments will attempt to reproduce E-167 with positrons
- Not trivial when consider the difference in plasma electron response

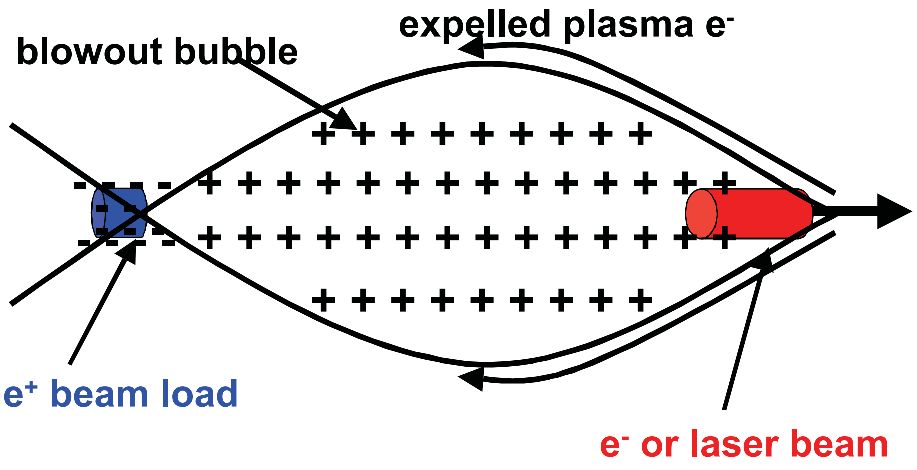


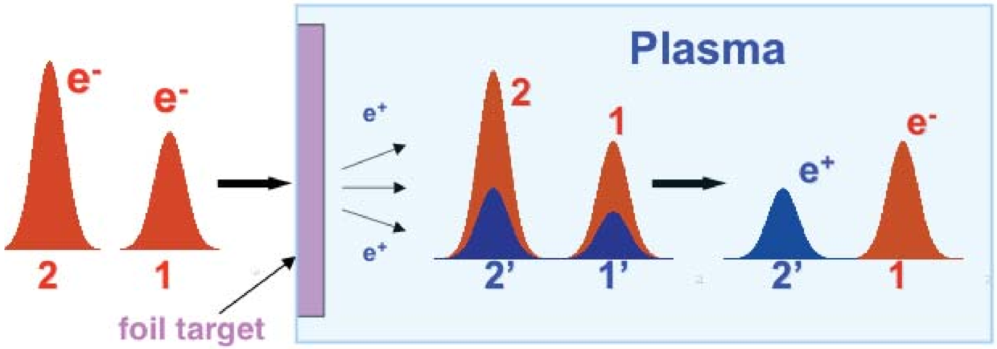


- Second phase will use two bunches to study beam loading of positron wakes (notch collimator will work equally well with e- or e+)
- Measure halo formation and emittance growth with DSOTR & quad scan in x-plane of dispersed beam to isolate accelerating portion of the wake



e^+ ACCELERATION ON e^- WAKE





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

X. Wang, PRL 101, 124801 (2008)

Research program has put Plasma Physics at the Forefront of Science

Acceleration, Radiation Sources, Refraction, Medical Applications

International Journal of High-Energy Physics
CERN COURIER
Volume 47 Number 3 April 2007
Doubling energy in a plasma wake
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Conclusions

Positron-plasma interactions is a rich area of research

Driven by applications to plasma-based accelerators

Good progress to date on experiments and simulations

Nonlinear theory is still lacking

FACET facility will allow next generation experiments to be carried out.

EPILOGUE

John M. Dawson
1930-2001

"This is a story **of Science as a Living Thing** taking Unexpected turns in directions that were never foreseen. Science must have goals, but it must also have the freedom to follow up interesting and unexpected results when they turn up. This is what excites the good young researcher and it is in their hands that our future rests."

John Dawson AIP Conf. Proc. 560 p 3 (2000)
Personal Recollections on the Development of Plasma Accelerators and Light Sources

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