Progress and Future of the Plasma Wakefield Accelerator

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Work supported by US Dept. of Energy

OUTLINE

- Motivation/Introduction
- Experimental results
  - e^- transverse dynamics (focusing)
  - β-tron radiation
  - acceleration

  } Long e^- bunch

  - acceleration
  - β-tron radiation

  } Short e^- bunch

  - e^+ transverse dynamics
  - e^+ acceleration

  } Long e^+ bunch
- Future at FACET
- Multi-bunch, low energy PWFA results
- Summary and Conclusions

P. Muggli and M.J. Hogan, Comptes Rendus Physique, 10(2-3), 116 (2009).

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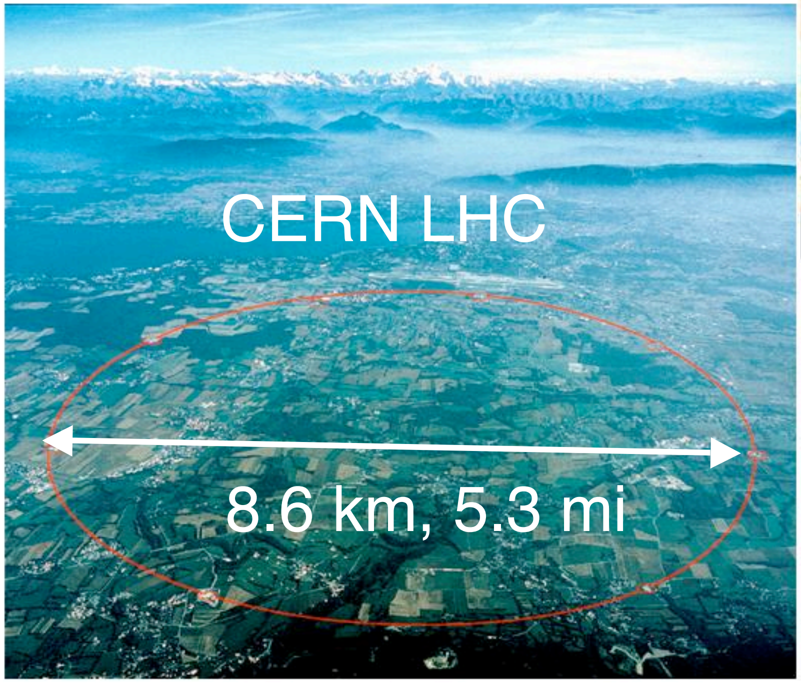
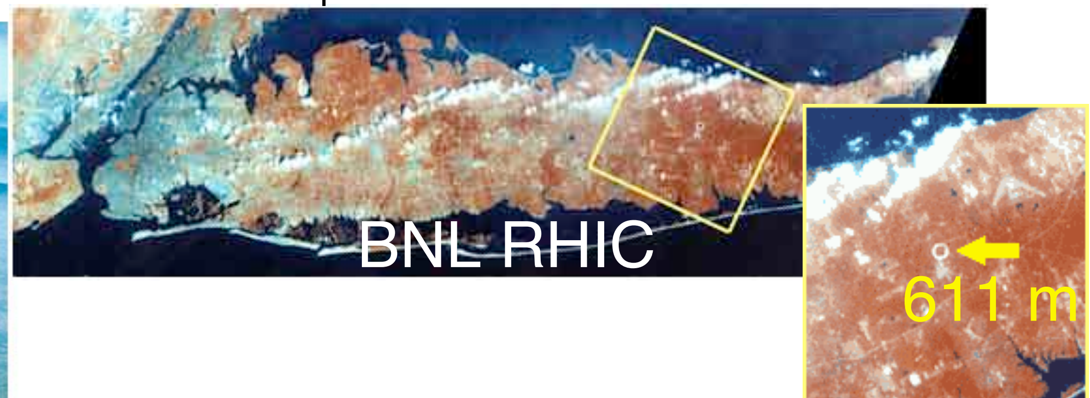
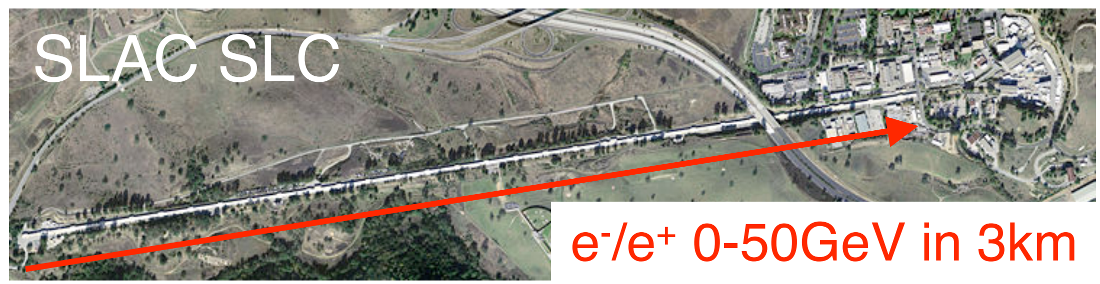
PARTICLE ACCELERATORS



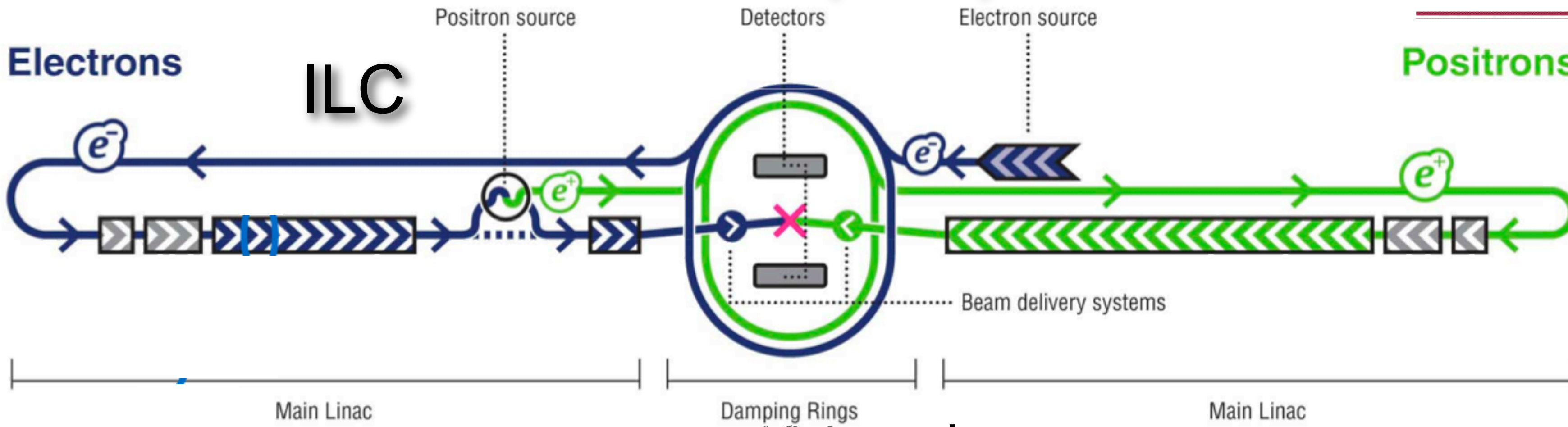
"The 2.4-mile circumference RHIC ring is large enough to be seen from space"





- Some of the largest and most complex (and most expensive) scientific instruments ever built!
- All use rf technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?

FUTURE LEPTON (e^-/e^+) COLLIDER

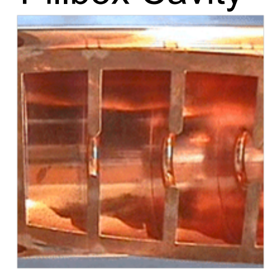


≈40 km site

- Linear accelerator to avoid synchrotron radiation limitation ($\sim\gamma^4/r^2\sim E^4/m^4r^2$)
- Energy frontier: 1-3 TeV, e^-/e^+
- Accelerator length with (cold) rf technology:

$$\frac{1\ \text{TeV}}{<50\ \text{MeV/m}} > 20\ \text{km/side!}$$

Pillbox Cavity

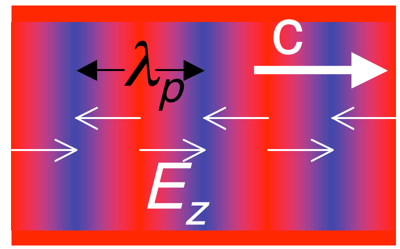


Is there a high-gradient alternative to rf technology?
Plasmas?

WHY PLASMAS?

- Relativistic Plasma Wave (Electrostatic):

$$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\varepsilon_0} \qquad k_pE_z=\frac{\omega_{pe}}{c}E_z=\frac{n_e e}{\varepsilon_0}$$



$$\underline{E}_z=\left(\frac{m_ec^2}{\varepsilon_0}\right)^{1/2}n_e^{1/2}\cong 100\sqrt{n_e\left(cm^{-3}\right)}=\underline{1\,GV/m}$$

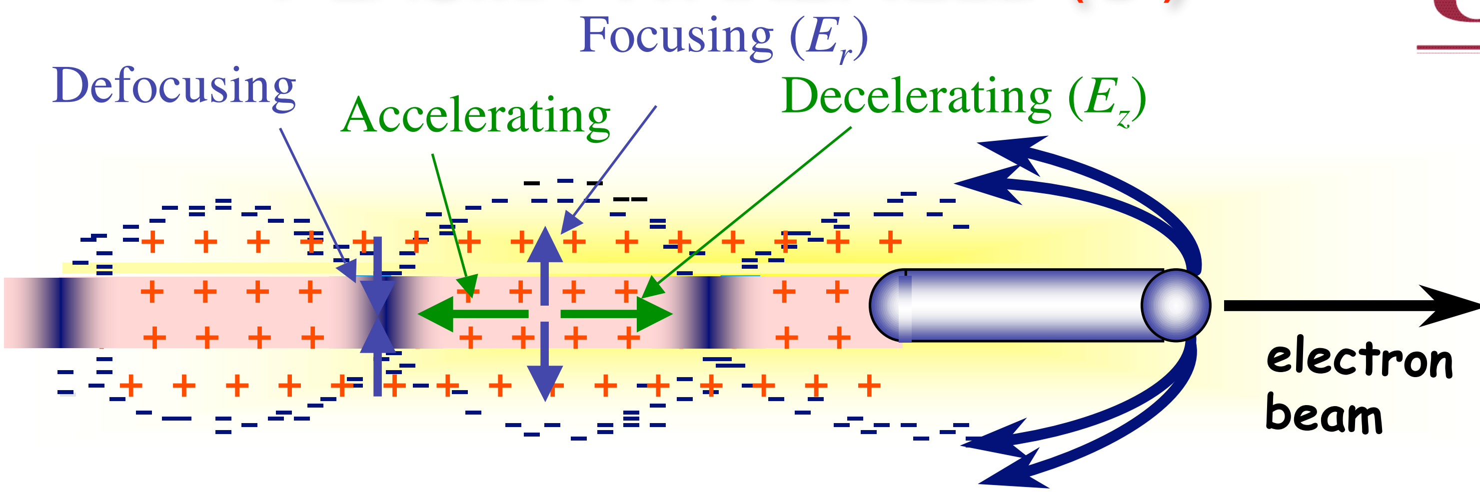
"Cold Wavebreaking" Field

$n_e=10^{14}$ cm^{-3}

LARGE
Collective response!

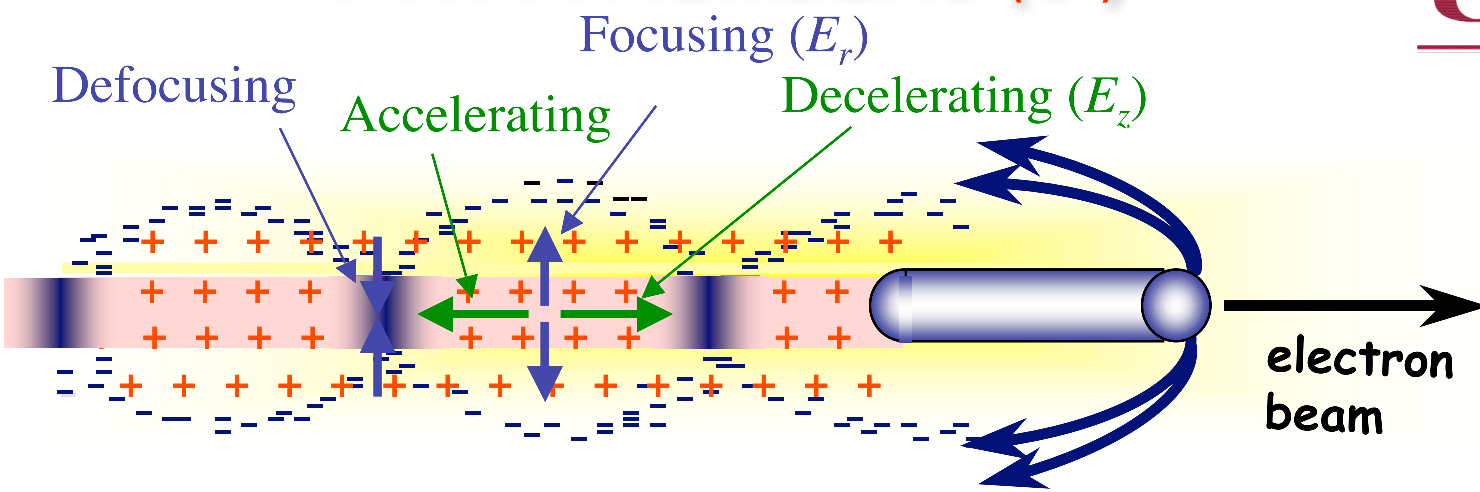
- Plasmas can sustain very large (collective) E_z-field, acceleration
- Plasmas are already (partially) ionized, difficult to "break-down"
- High gradient, high energy plasma accelerator? **Yes**
- Plasmas wave or wake can be driven by:
    - Intense laser pulses (LWFA)
    - Short particle bunch (PWFA)

PLASMA WAKEFIELD (e^-)



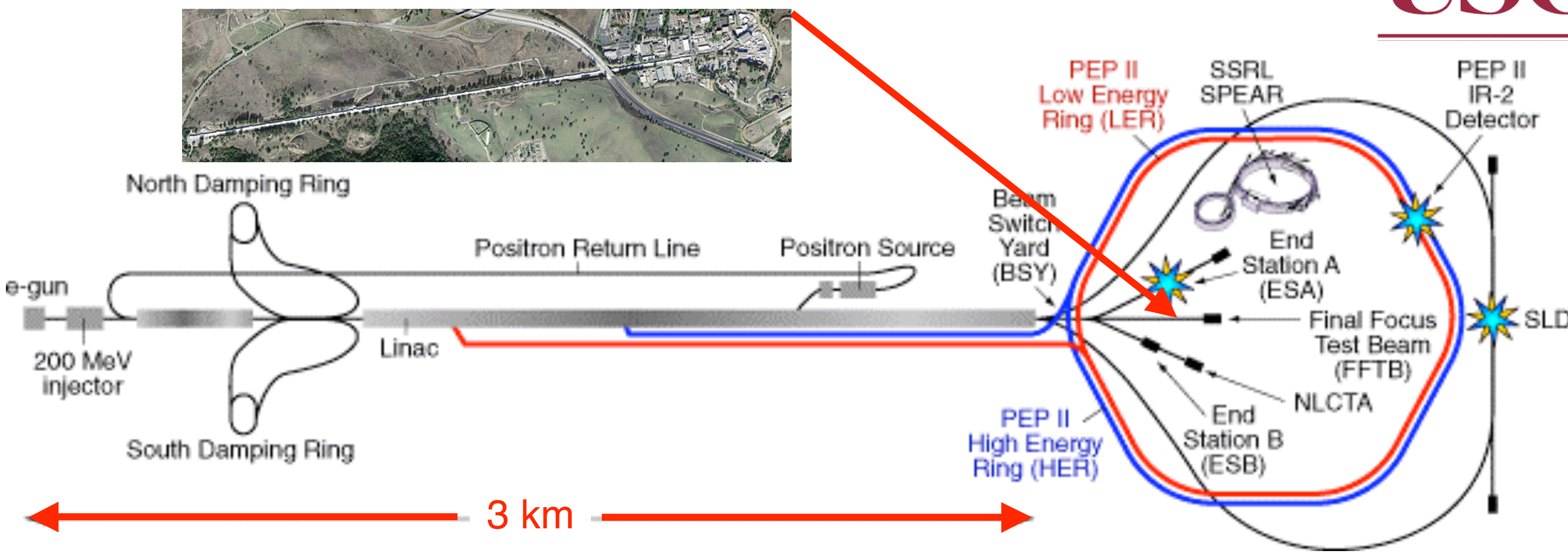
- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces => energy loss + focusing
- Plasma e^- rush back on axis => energy gain
- Optimize for acceleration, focusing (plasma lens), radiation (β-tron)
- Plasma Wakefield Accelerator (PWFA): high-frequency, high-gradient, strong focusing beam-driven accelerator

PWFA NUMBERS (e^-)



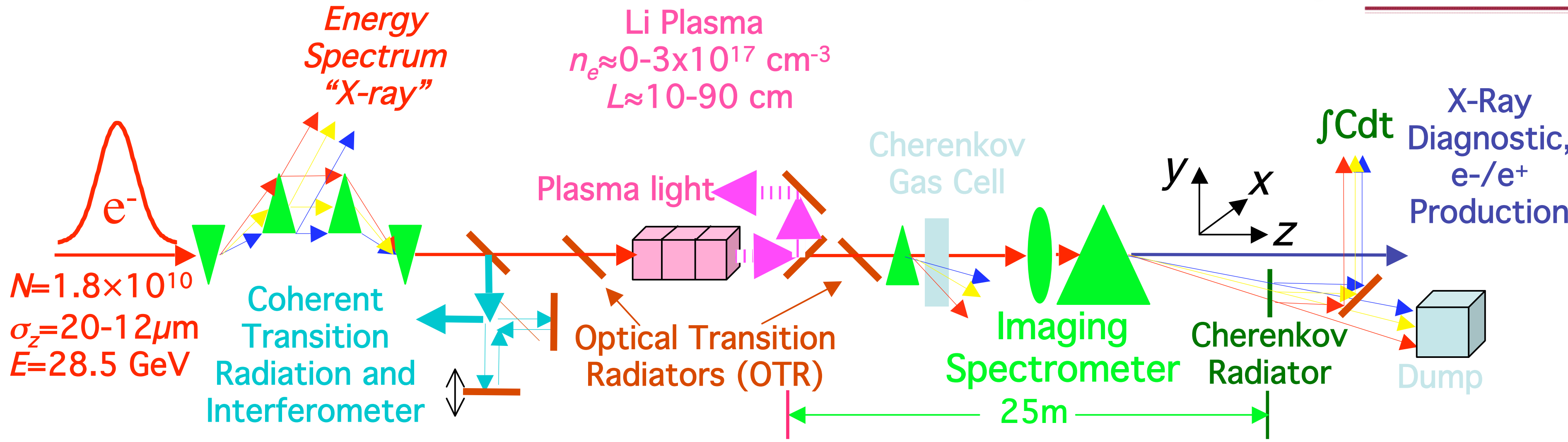
- **Linear theory (n_b<<n_e) scaling:** $$E_{acc} \cong 110(MV/m)\frac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2} \approx N/\sigma_z^2$$
  $@\ k_{pe}\sigma_z \approx \sqrt{2}$ (with $k_{pe}\sigma_r$ <<1)
- **Focusing strength:** $$\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c} = 3kT/m \times n_e(10^{14}\,cm^{-3})$$ (n_b>n_e)
- $N=2\times10^{10}$: σ_z=600 μm, $n_e=2\times10^{14}$ cm^{-3}, E_{acc}~100 MV/m, B_θ/r=6 kT/m
  σ_z= 20 μm, $n_e=2\times10^{17}$ cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m
- Conventional accelerators: E_{acc}<150 MV/m, B_θ/r<2 kT/m

PWFA EXPERIMENTS @ SLAC

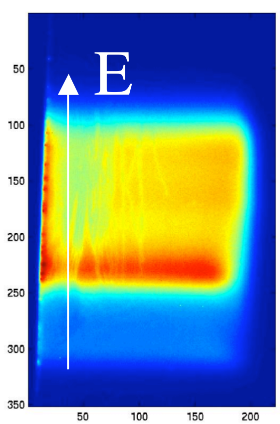


Long-bunch Experiments		Short-bunch experiments
e^-/e^+ 28.5 GeV	$N \approx 1.2\text{-}1.8 \times 10^{10}$/bunch	e^- 28.5, 42 GeV
$\sigma_z \approx 700\ \mu m$		$\sigma_z \approx 30\text{-}20\ \mu m$
$\sigma_r \approx 30\ \mu m$	$k_{pe}\sigma_z \approx \sqrt{2}$	$\sigma_r \approx 10\ \mu m$
$n_e \approx 2 \times 10^{14}$ cm^{-3}	0.1-100 GV/m	$n_e \approx 1\text{-}3 \times 10^{17}$ cm^{-3}
$L_p \approx 1.4$ m		$L_p \approx 10, 20, 30, 60, 90, 120$ cm
Pre-ionized		Field-ionized

EXPERIMENTAL SET UP (GENERIC)

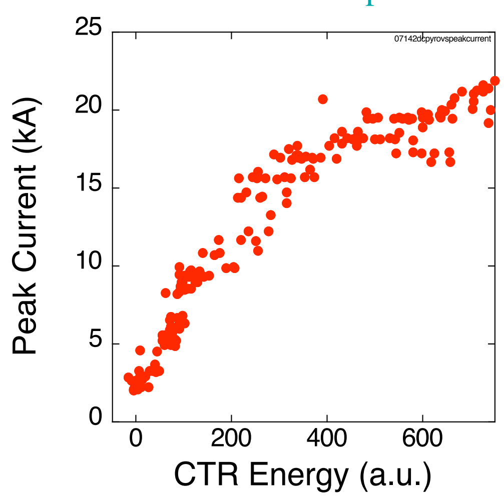


- X-ray Chicane

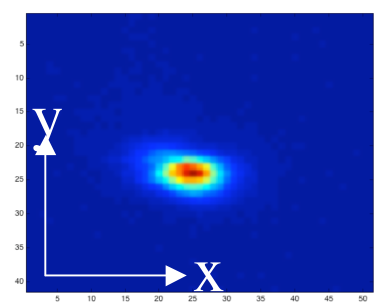


- Coherent Transition Radiation (CTR)

- CTR Energy≈I_{peak}≈$1/\sigma_z$



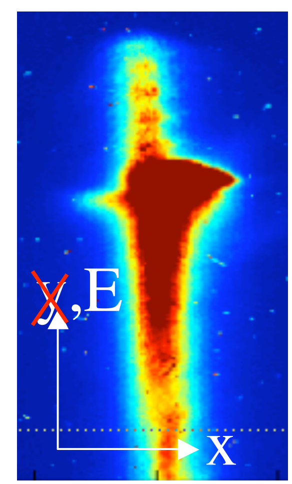
- OTR



-Spatial
-resolution ≈9 μm

- Cherenkov (aerogel)

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



P. Muggli, 09/21/09

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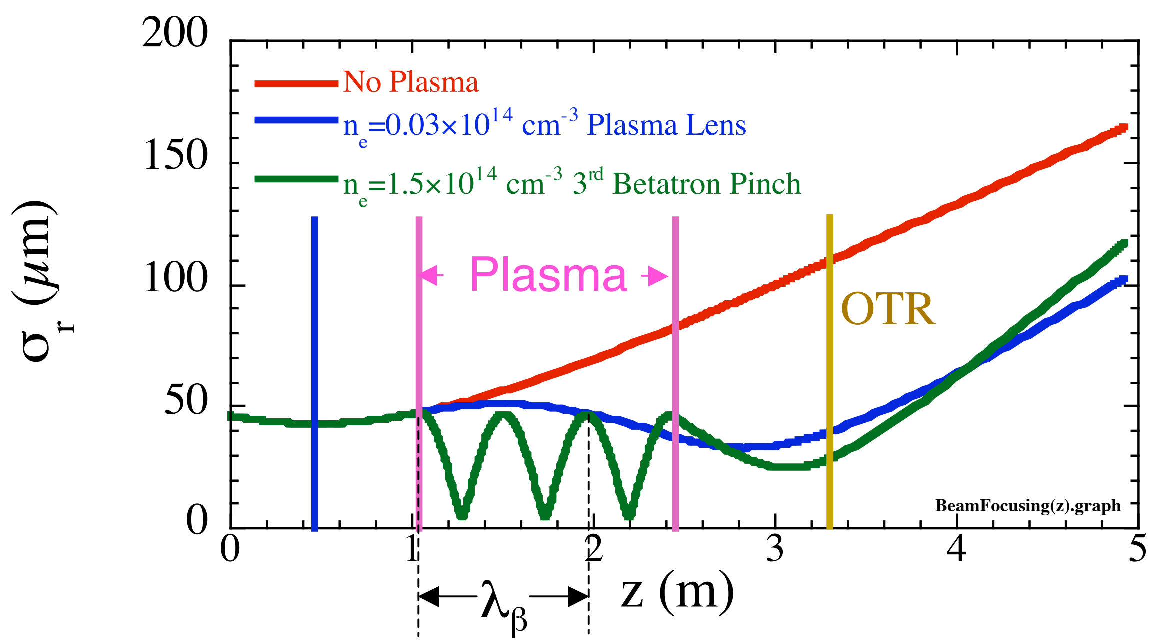
PLASMA FOCUSING OF e^-

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

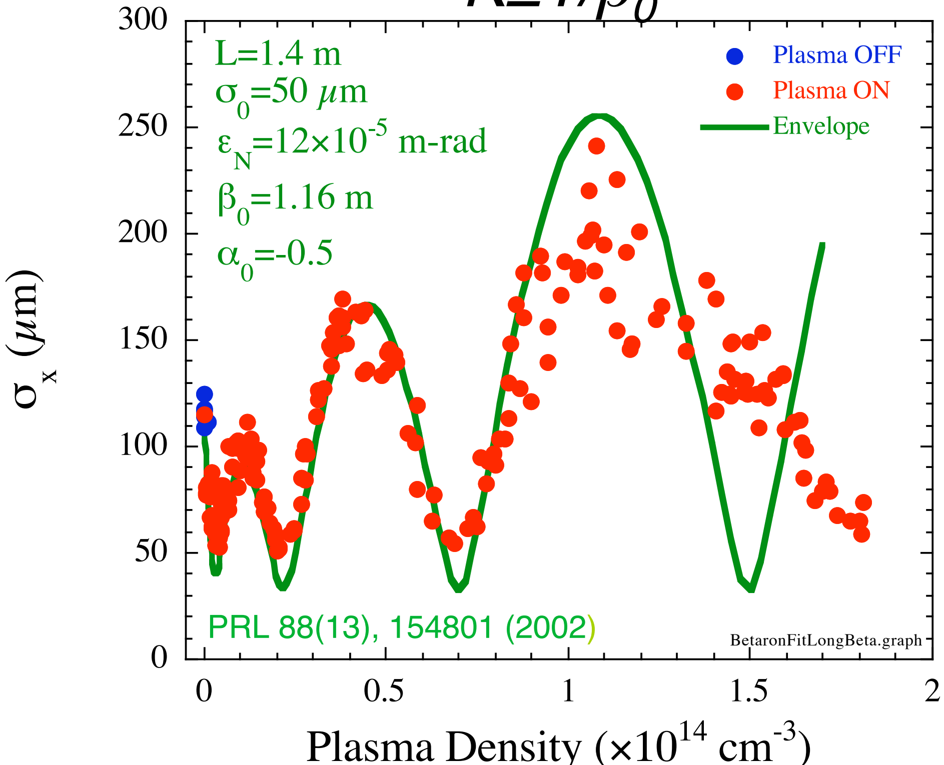
@ $n_e=2\times10^{14}$ cm^{-3}

- Multiple foci (betatron oscillation) within the plasma
- $\sigma_{x,y}(z)$ at fixed n_e => $\sigma_{x,y}(n_e)$ at fixed z

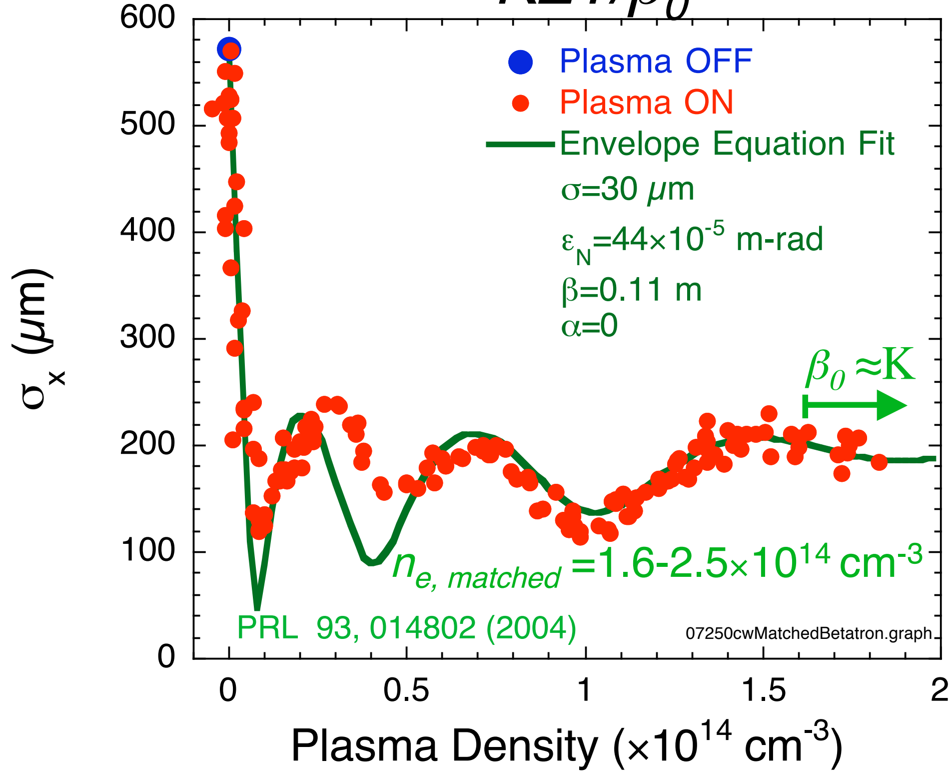
FOCUSING OF e^-

OTR Images ≈1m downstream from plasma

$K \geq 1/\beta_0$



$K \leq 1/\beta_0$

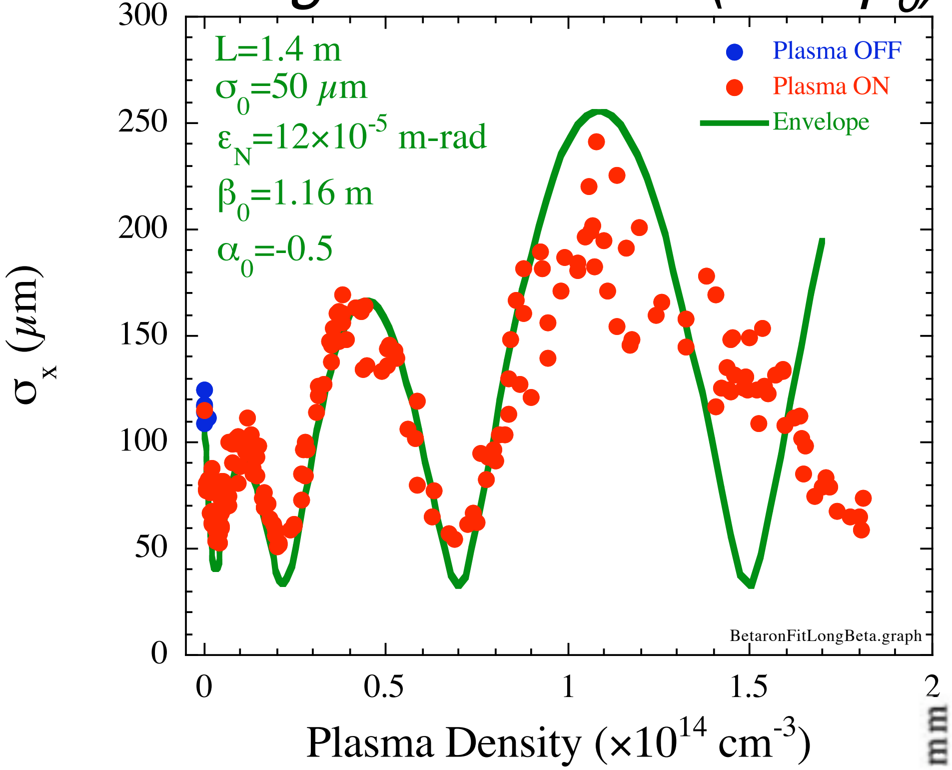


- Focusing of the beam well described by a simple model ($n_b > n_e$): Plasma = Ideal Thick Lens
- No emittance growth observed as n_e is increased
- Stable propagation over L=1.4 m up to as n_e =1.8×10^{14}cm^{-3}
- Channeling of the beam over 1.4 m or >12β_0

=> Matched Propagation over long distance!

β-TRON RADIATION IN PLASMAS

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



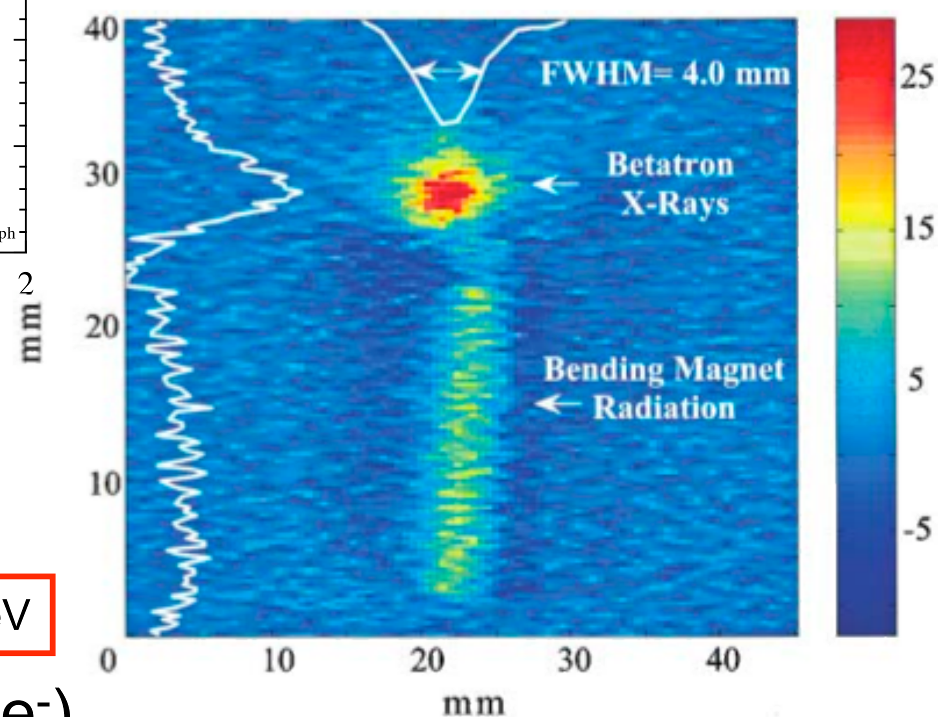
$n_e = 1.5\times10^{14}\ cm^{-3}$ $\lambda_\beta \cong 0.91\ m$ $N_{\lambda_\beta} \cong 1.5$

Wang, PRL 88, 2002

Ion column:

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

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



$\hbar\omega_c \approx keV$

>6x10[5] photons @ 14.2±0.014 keV

- x-rays from a plasma wiggler (e^-)

P. Muggli, 09/21/09

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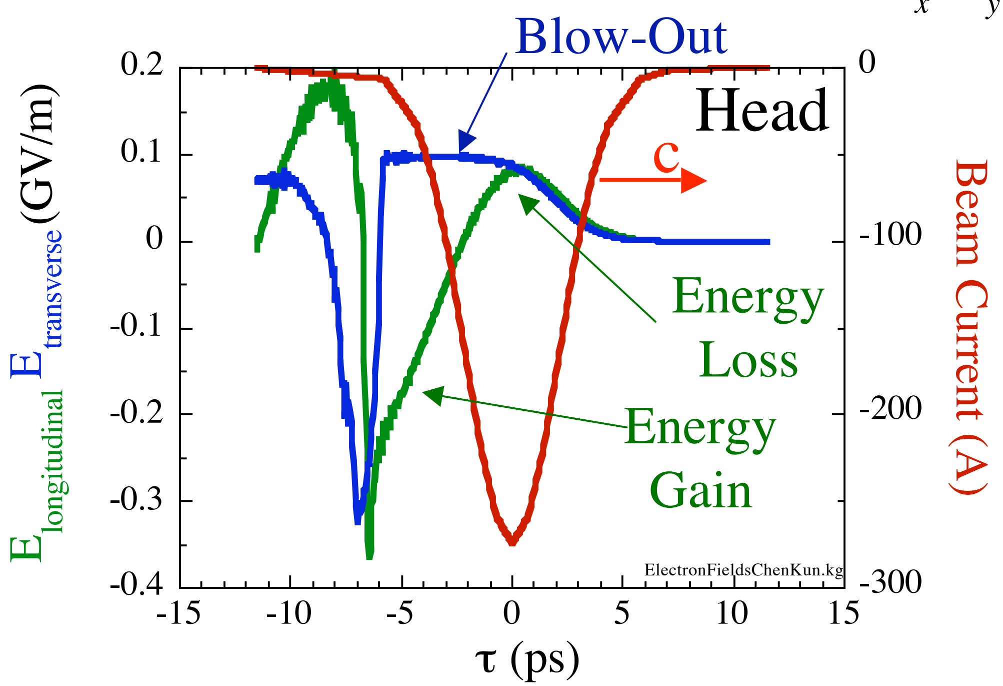
PLASMA WAKEFIELD FIELDS (e^-)

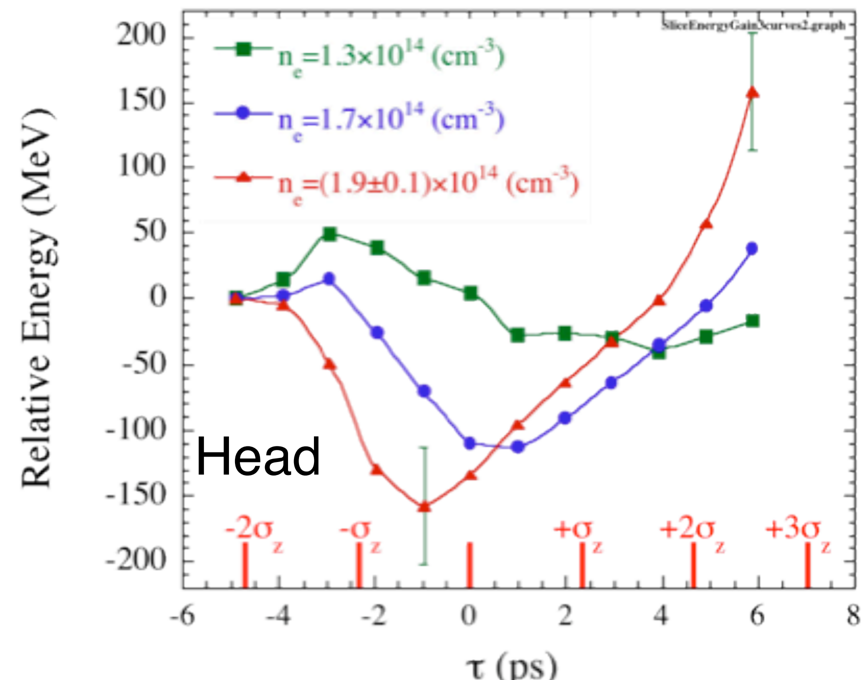
P. Muggli et al., Phys. Rev. Lett. 93, 014802 (2004).

E_0	28.5 GeV	n_b	4×10^{14} cm^{-3}
N	2×10^{10} e^- or e^+	ε_{xN}	5×10^{-5} m-rad
σ_z	0.63 mm (2.1 ps)	ε_{yN}	0.5×10^{-5} m-rad
$\sigma_x=\sigma_y$	70 μm		

2-D PIC Simulation QUICPICK

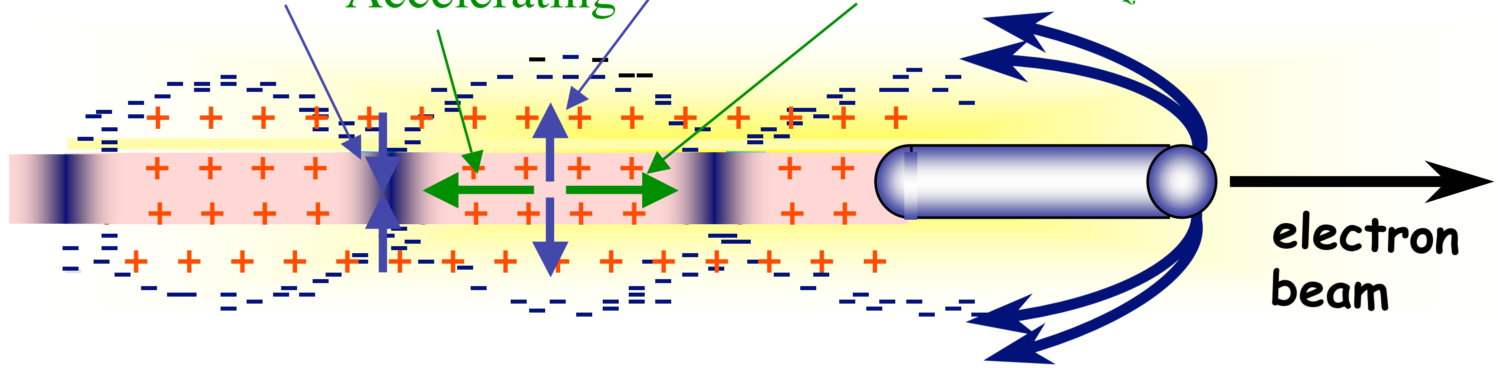
$n_e=1.5\times10^{14}$ cm^{-3}, $N=1.8\times10^{10}$ e^-





- Energy gain smaller than, hidden by, incoming energy spread
- Time resolution needed, but shows the physics
- Peak energy gain: 279 MeV, L=1.4 m, ≈200 MeV/m

PLASMA NUMBERS (e^-)



- Linear theory scaling: $E_{acc} \cong 110(MV/m)\frac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2}$ $\approx N/\sigma_z^2$

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

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

- $N=2\times10^{10}$: σ_z=600 μm, $n_e=2\times10^{14}$ cm^{-3}, $E_{acc}\approx$100 MV/m, B_θ/r=6 kT/m

  σ_z= 20 μm, $n_e=2\times10^{17}$ cm^{-3}, $E_{acc}\approx$ 10 GV/m, B_θ/r=6 MT/m

Short Bunches!

- Conventional: E_{acc}<150 MV/m, B_θ/r<2 kT/m

+plasma field ionization!

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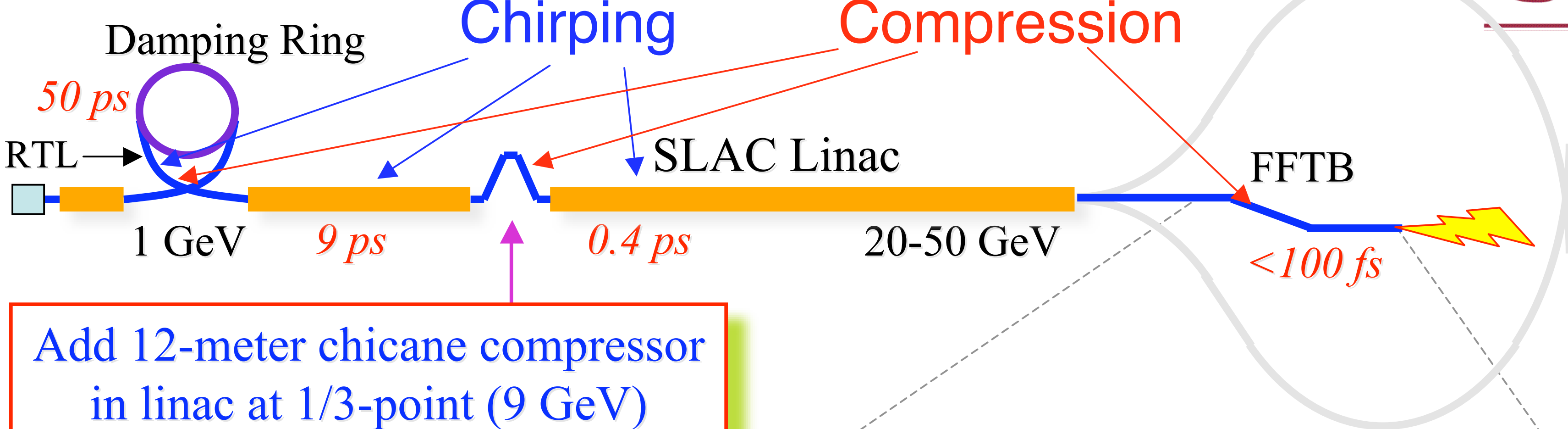
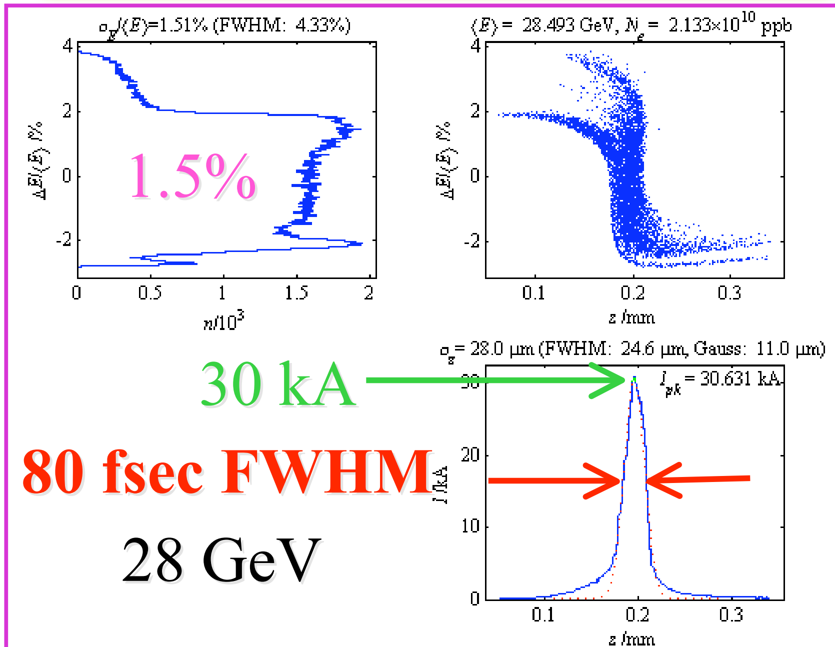
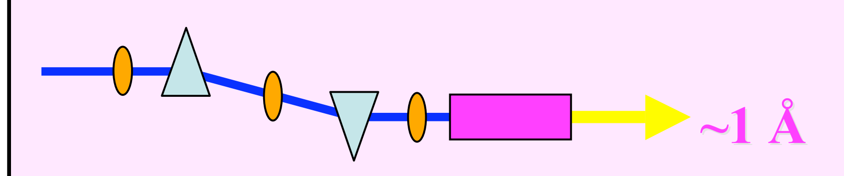
Short Bunch Generation In The SLAC Linac



Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)





- Bunch magnetic compression (N=cst) by a factor of ≈730/25≈29!

$$E_{acc} \cong 110(MV/m)\frac{N/2\times 10^{10}}{(\sigma_z/0.6mm)^2}$$

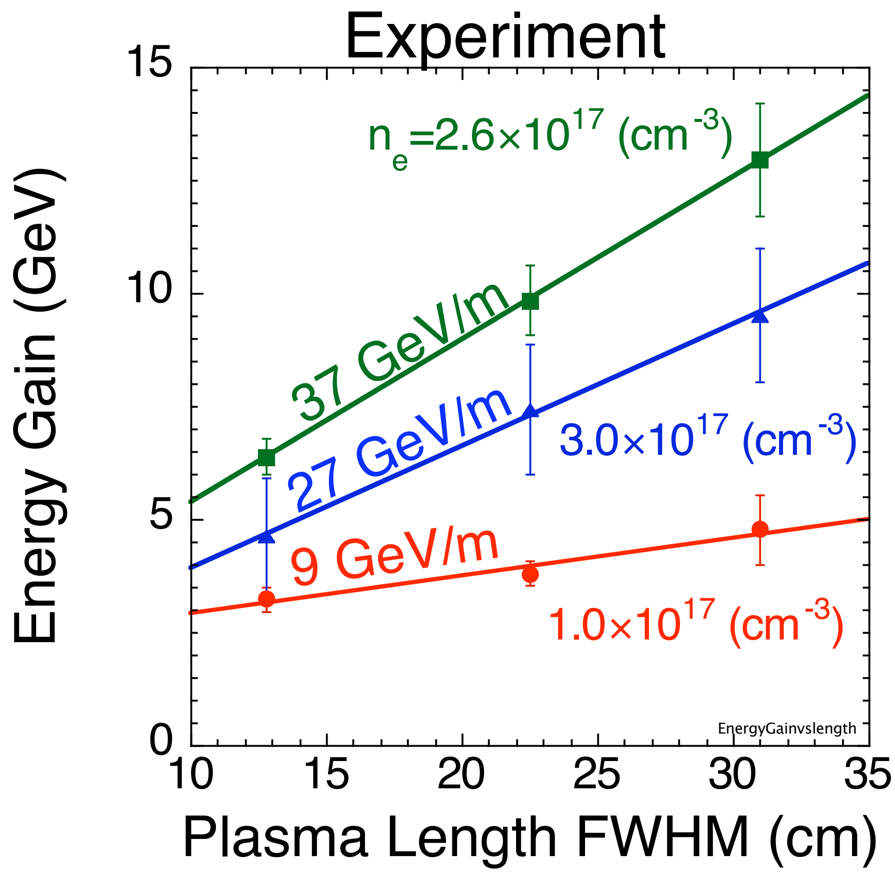
- $E_{r,\ bunch}$> 6GV/m, filed-ionize Li!

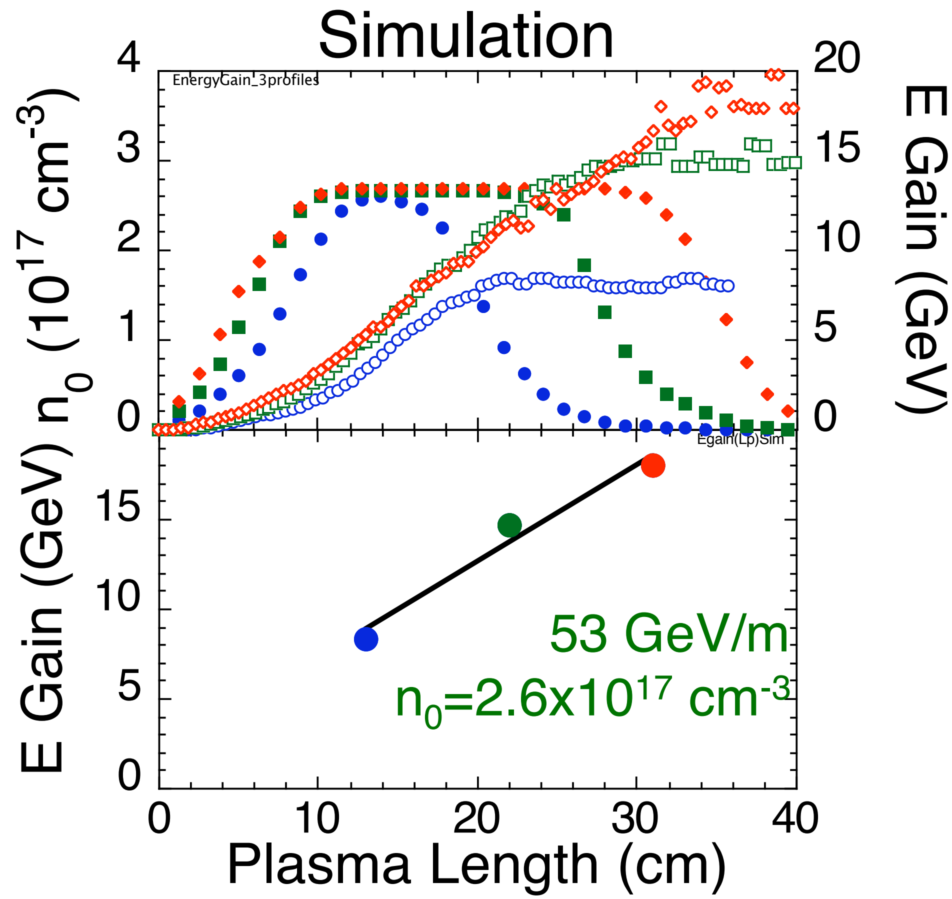
Courtesy of SPPS

SCALING WITH PLASMA LENGTH

$$\text{Accelerating Gradient} = \frac{\text{Energy Gain}}{\text{Plasma Length}}$$

E_0=28.5 GeV
$\sigma_z \approx 25\ \mu m$



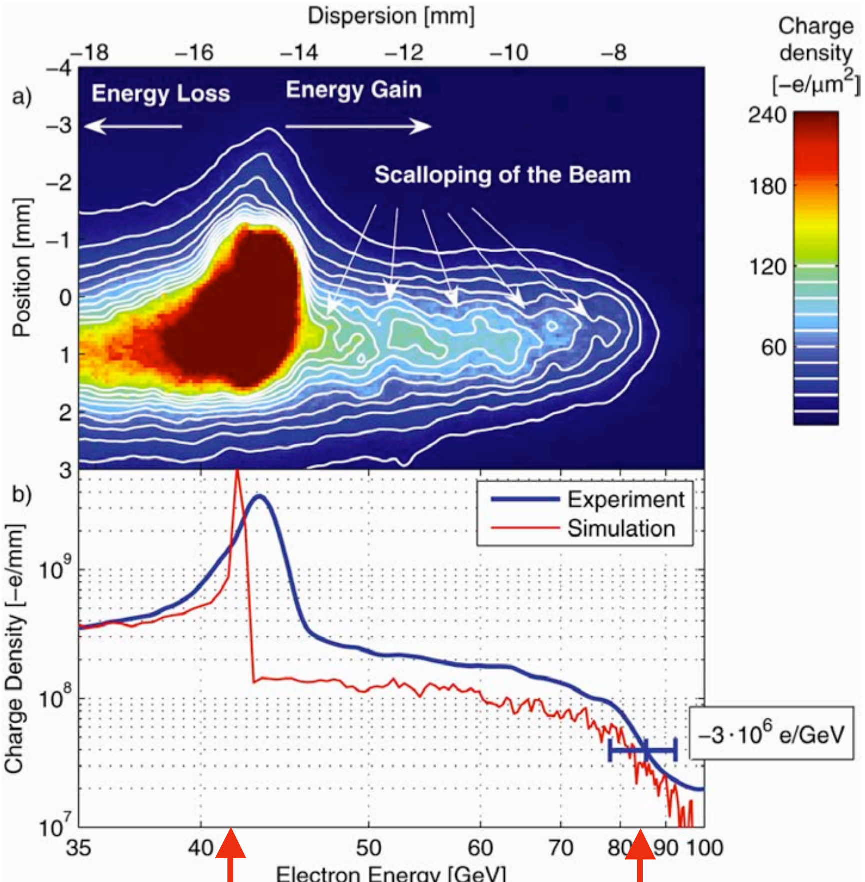


- Energy gain scales linearly with L_p, optimum $n_e \approx 2.6\text{x}10^{17}$ cm^{-3}
- Experimental accelerating gradient: $E_{acc} \approx 37$ GeV/m (max. avg.)

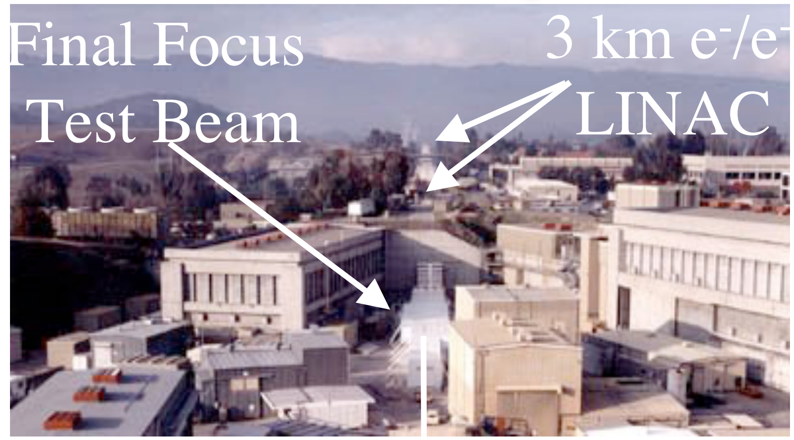
e^- ENERGY DOUBLING

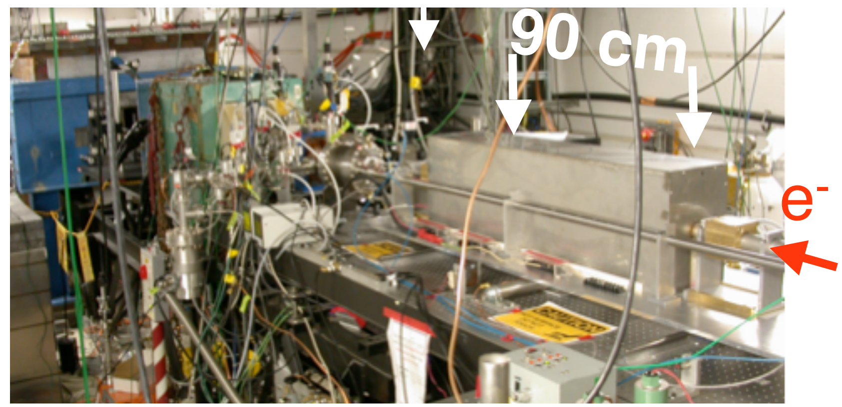
I. Blumenfeld *et al.*, Nature 445, 2007

E_0=42 GeV



E_0 $2E_0$





- Energy doubling of e^- over L_p≈85 cm, 2.7x10^{17} cm^{-3} plasma
- Unloaded gradient ≈52 GV/m (≈150 pC accel.)

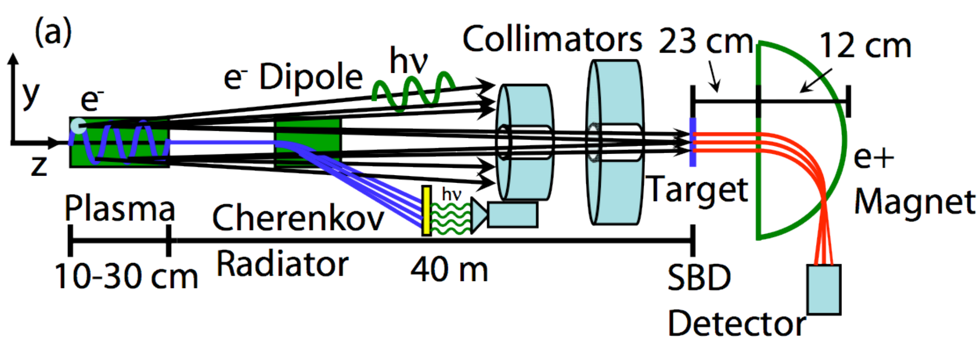
e^+ FROM e^- β-TRON RADIATION

$n_e = 10^{17}\ cm^{-3}$ $\lambda_\beta \cong 0.035\ m$ $N_{\lambda_\beta} \cong 8\left(L_p = 30\ cm\right)$

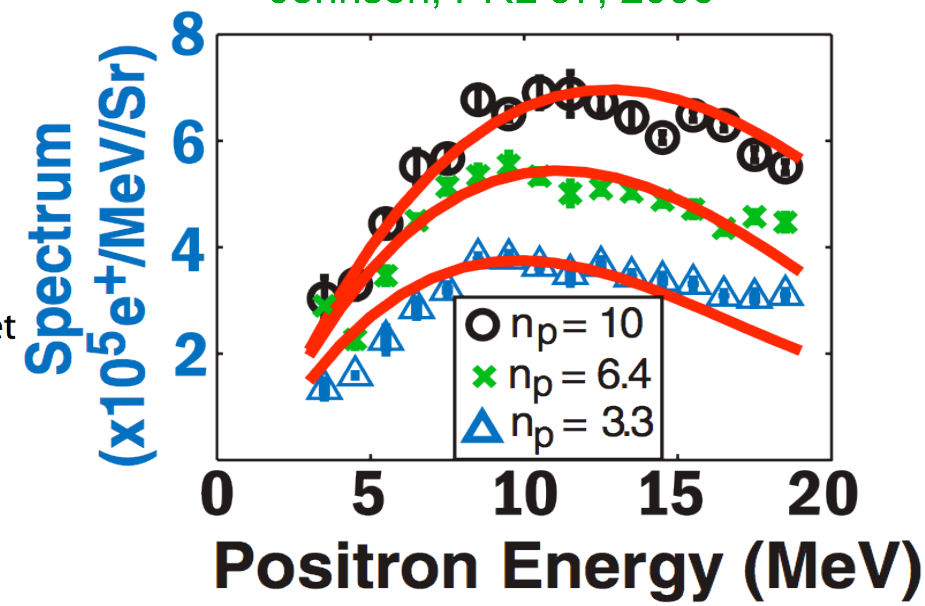
$\hbar\omega_c\left(\propto n_e\right) \approx 10\ MeV > 2m_e c^2$

Produce e^-/e^+ pairs!

Johnson, AAC 06, Proceedings



Johnson, PRL 97, 2006



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

P. Muggli, 09/21/09

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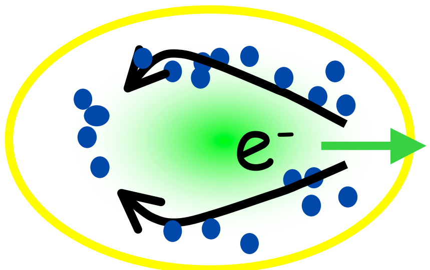
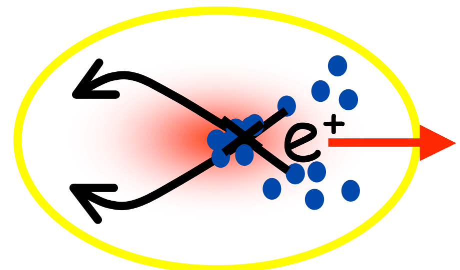
e^- & e^+ BEAM NEUTRALIZATION, "FOCUSING"

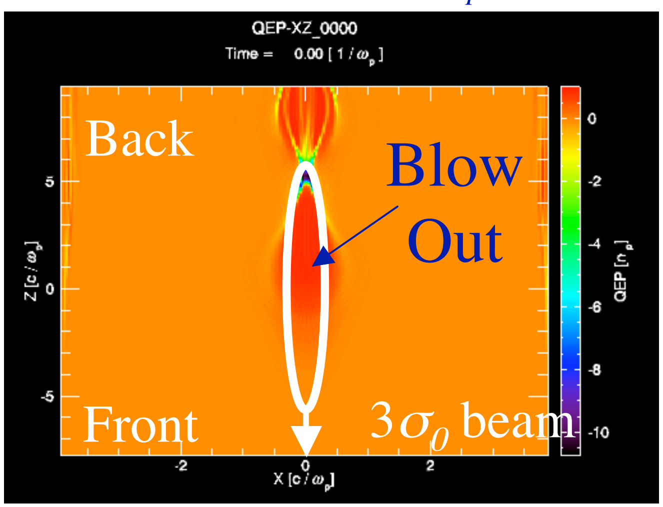
- Transverse dynamics, emittance preservation?





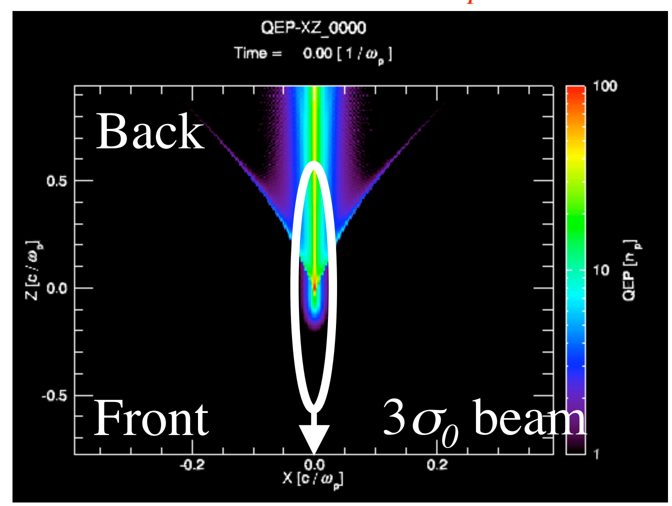
3-D QuickPIC simulations, plasma e^- density:

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

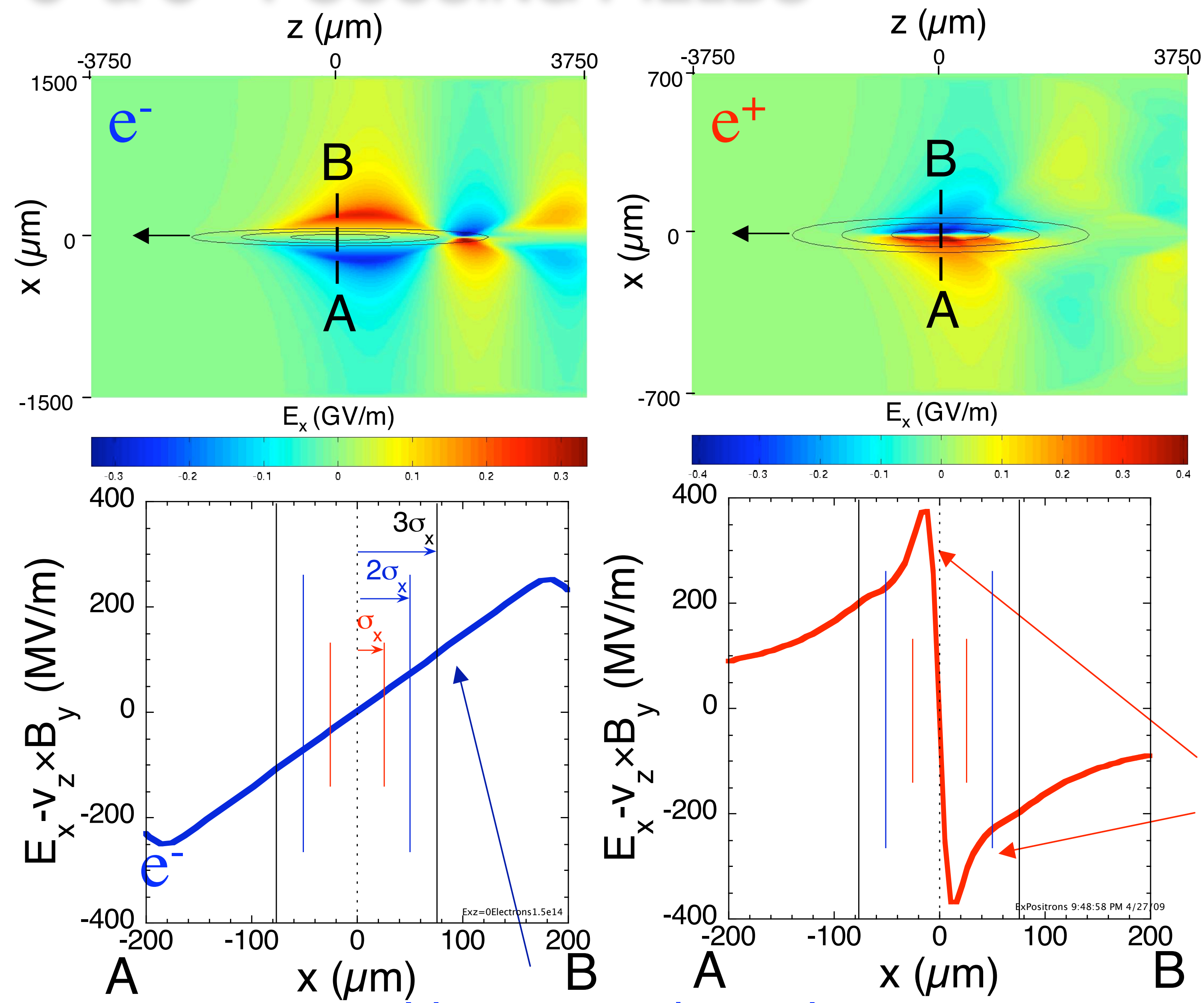
e^+: $n_{e0}=2\times10^{12}$ cm^{-3}, $c/\omega_p=3750\ \mu$m



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

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

e^- & e^+ Focusing Fields



QuickPIC

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

$\sigma_z=730\ \mu m$

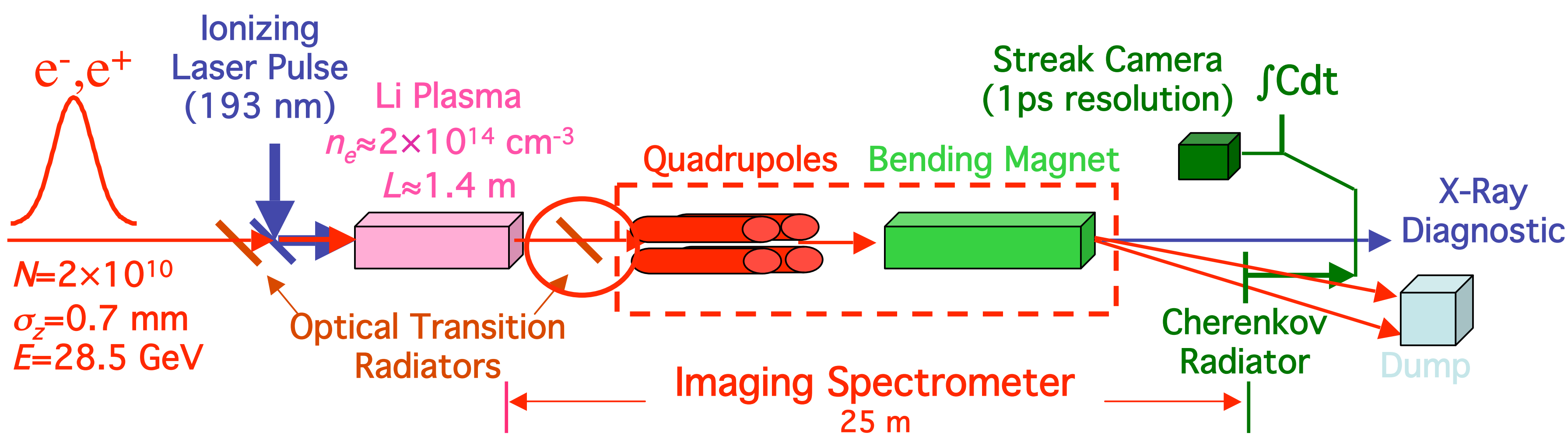
$N=1.9\times10^{10}\ e^+/e^-$

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

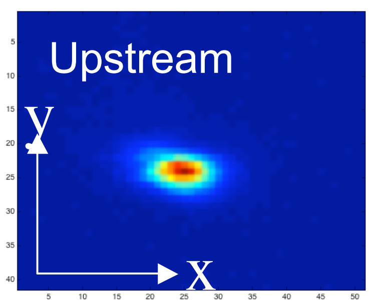
Non-linear, aberrations

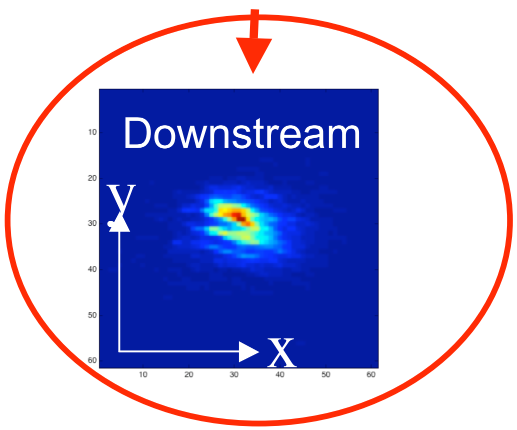
Linear, no aberrations

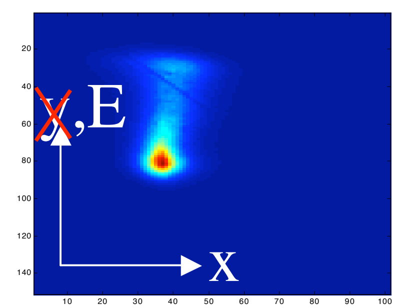
EXPERIMENTAL SET UP



- 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

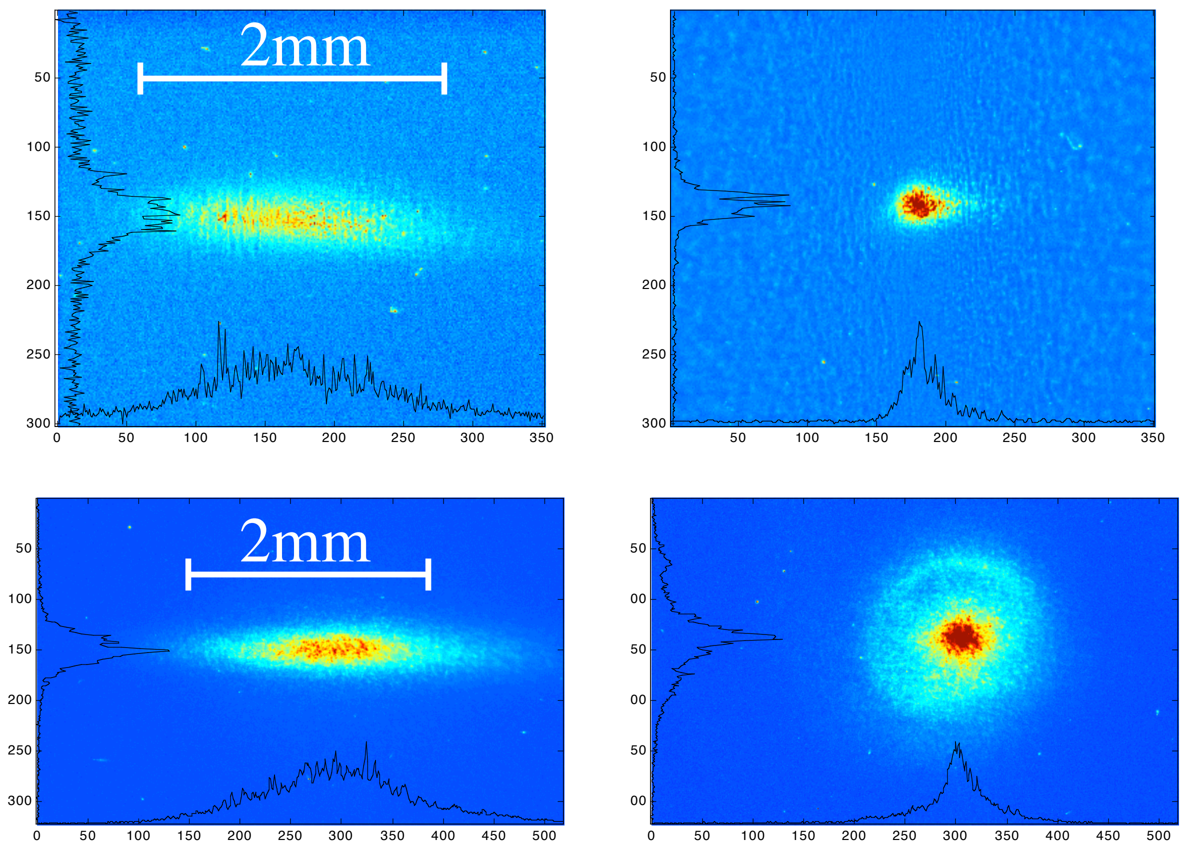
FOCUSING OF e^-/e^+

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

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

e^-

e^+



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

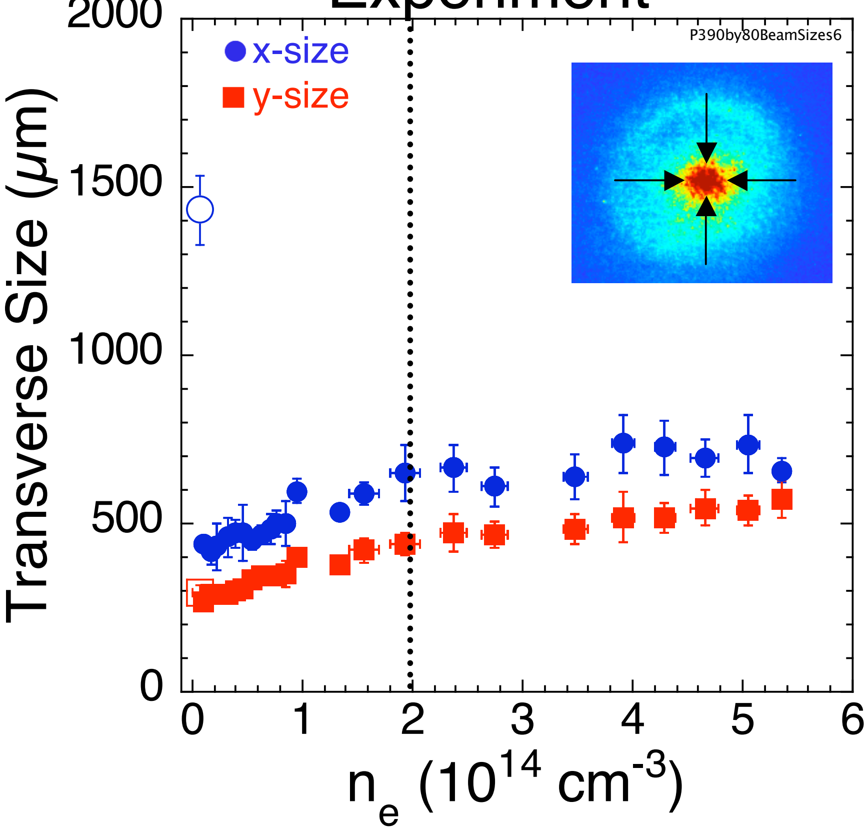
- Qualitative differences

EXPERIMENT/SIMULATIONS: BEAM SIZE

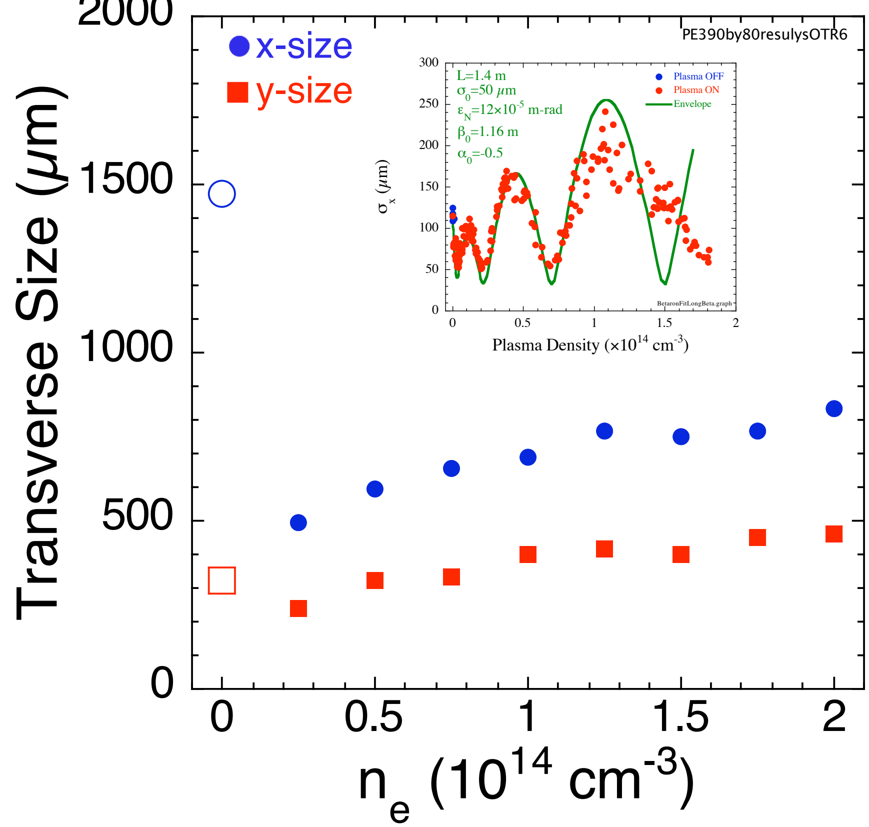
$\sigma_{x0}=\sigma_{y0}=25\mu m$, $\varepsilon_{Nx}=390\times10^{-6}$, $\varepsilon_{Ny}=80\times10^{-6}$ m-rad, $N=1.9\times10^{10}$ e^+, $L=1.4$ m

Downstream OTR

Experiment



Simulations: QuickPIC



- Excellent experimental/simulation results agreement!
- The beam is ≈round with $n_e\neq0$

P. Muggli, 09/21/09

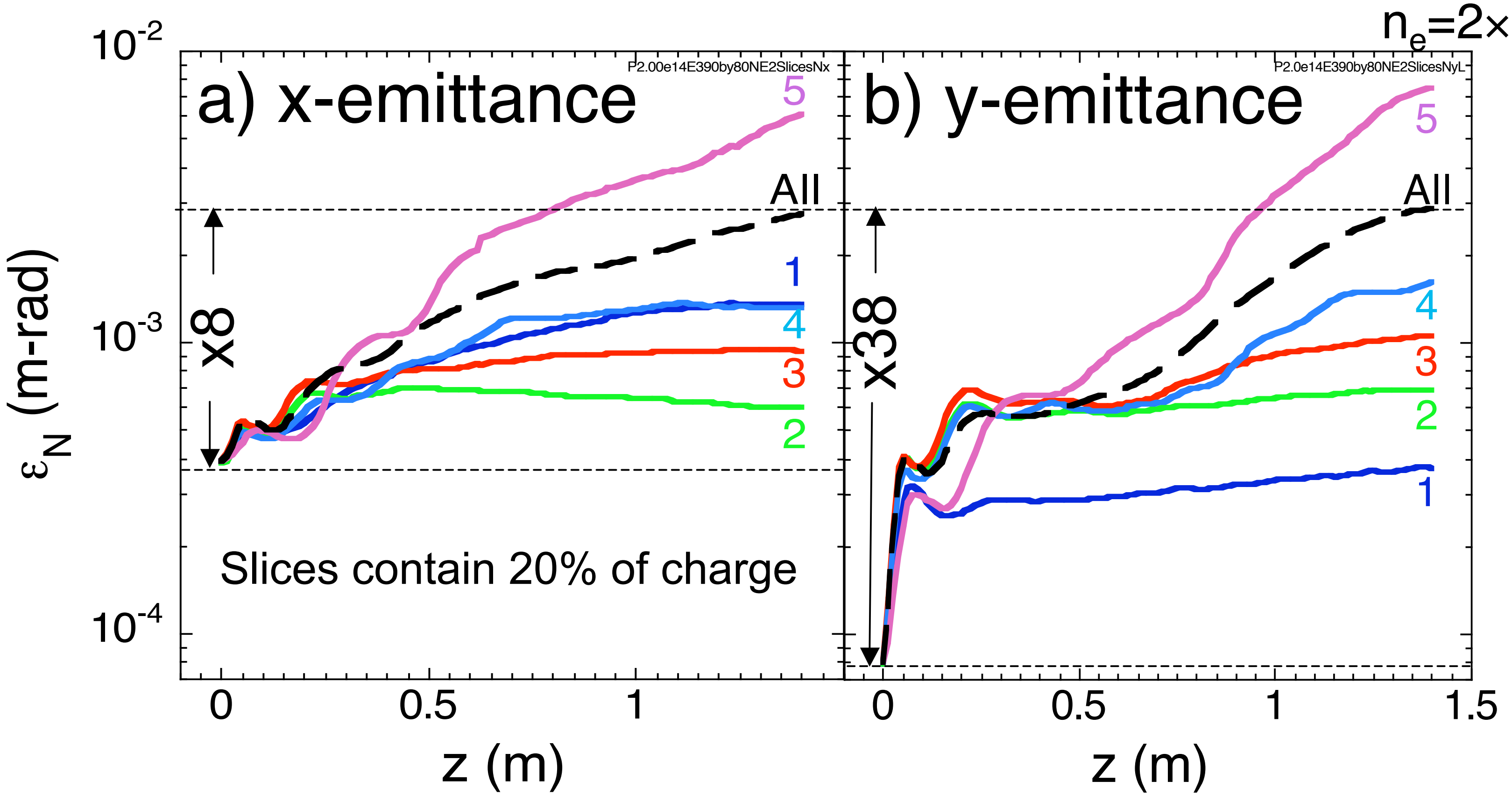
e^+: Slice Emittance

(SIMULATIONS)

USC

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

$n_e=2\times10^{14}$ cm^{-3}

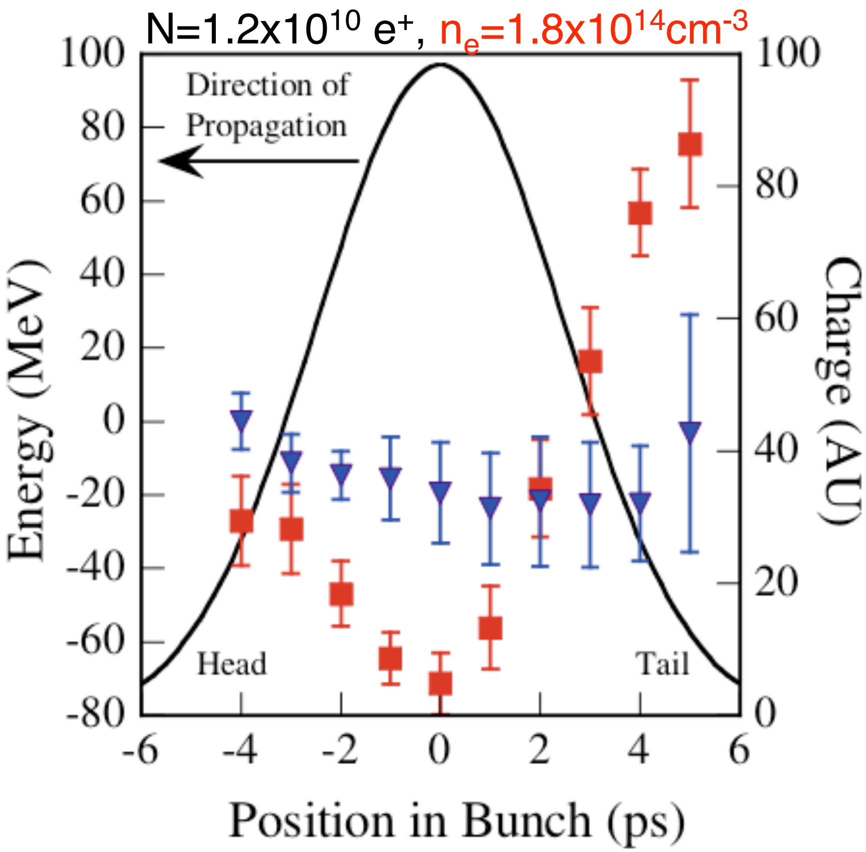


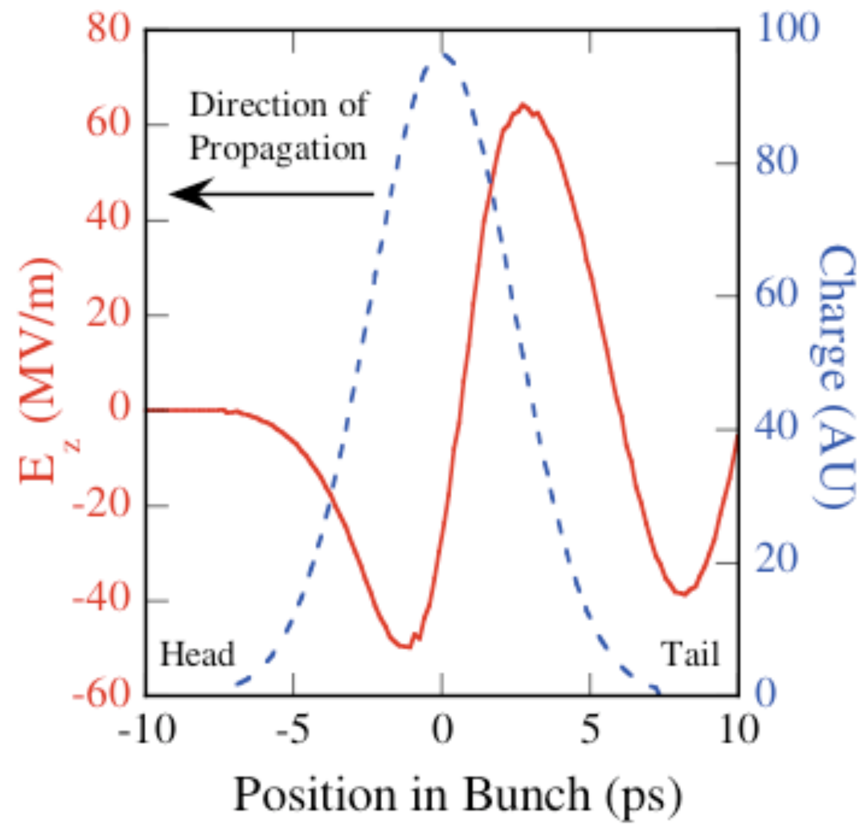
- Large emittance growth
- The e^+ beam exits the plasma with ≈equal emittances <u>and</u> ≈equal transverse sizes

P. Muggli, 09/21/09

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

e^+ ACCELERATION PRE-IONIZED, LONG BUNCH





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

- Energy gain and loss ≈80 MeV over 1.4 m
- Good agreement with numerical simulations

Outline

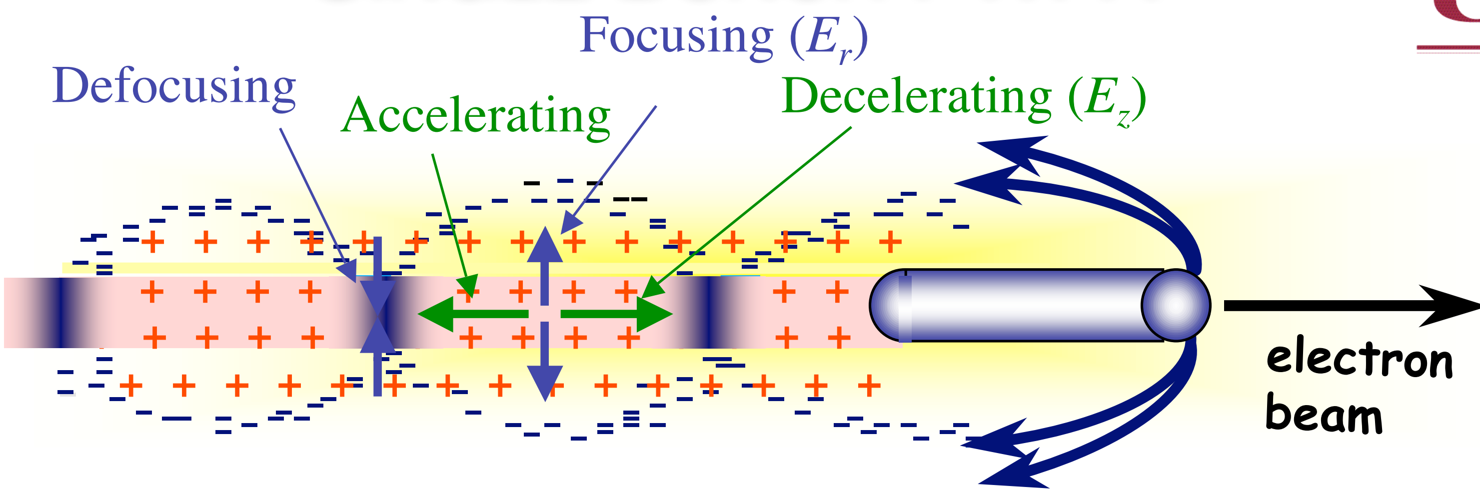
- Motivation/Introduction
- Experimental results
  - e^- transverse dynamics (focusing)
  - β-tron radiation
  - acceleration

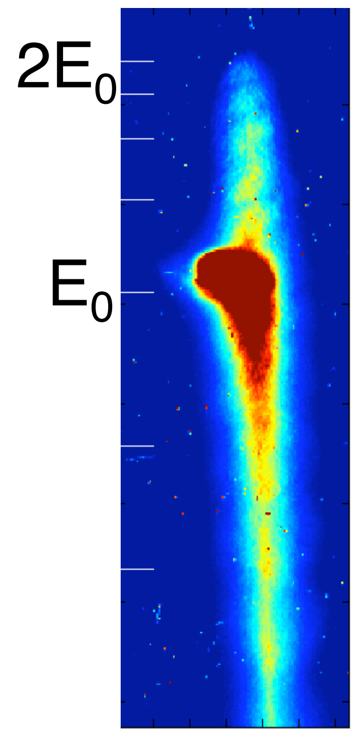
  } Long e^- bunch
  - acceleration
  - β-tron radiation

  } Short e^- bunch
  - e^+ transverse dynamics
  - e^+ acceleration

  } Long e^+ bunch
- Future at FACET
- Multi-bunch, low energy PWFA results
- Summary and Conclusions

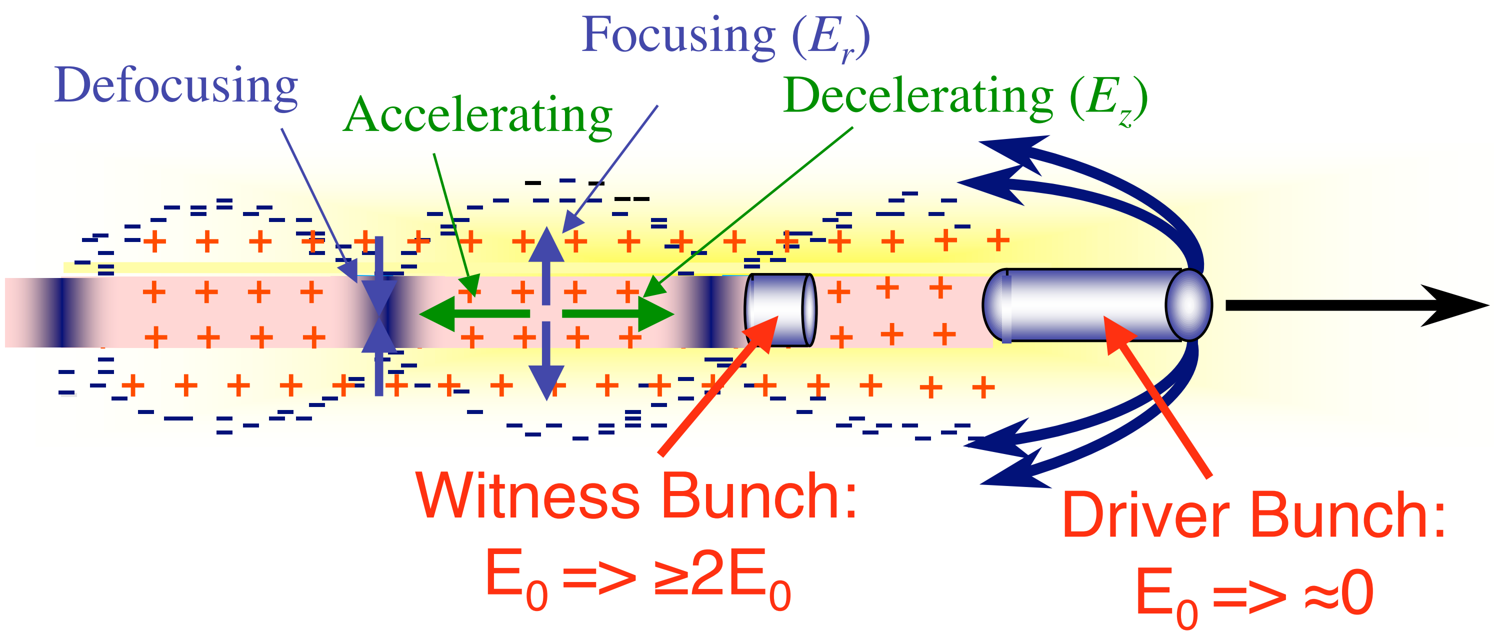
SINGLE BUNCH PWFA

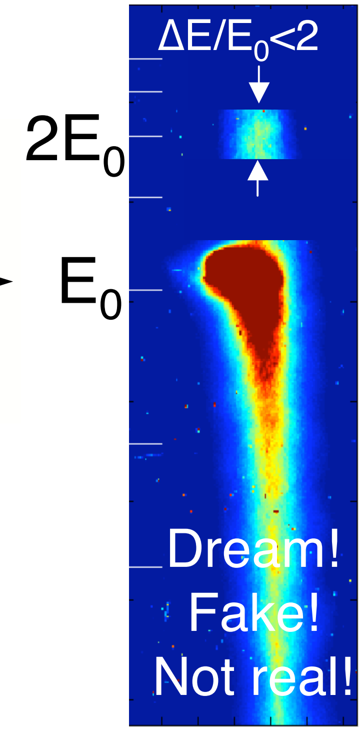




- Particles at all phase, large energy spread (100%)

2-BUNCH PWFA

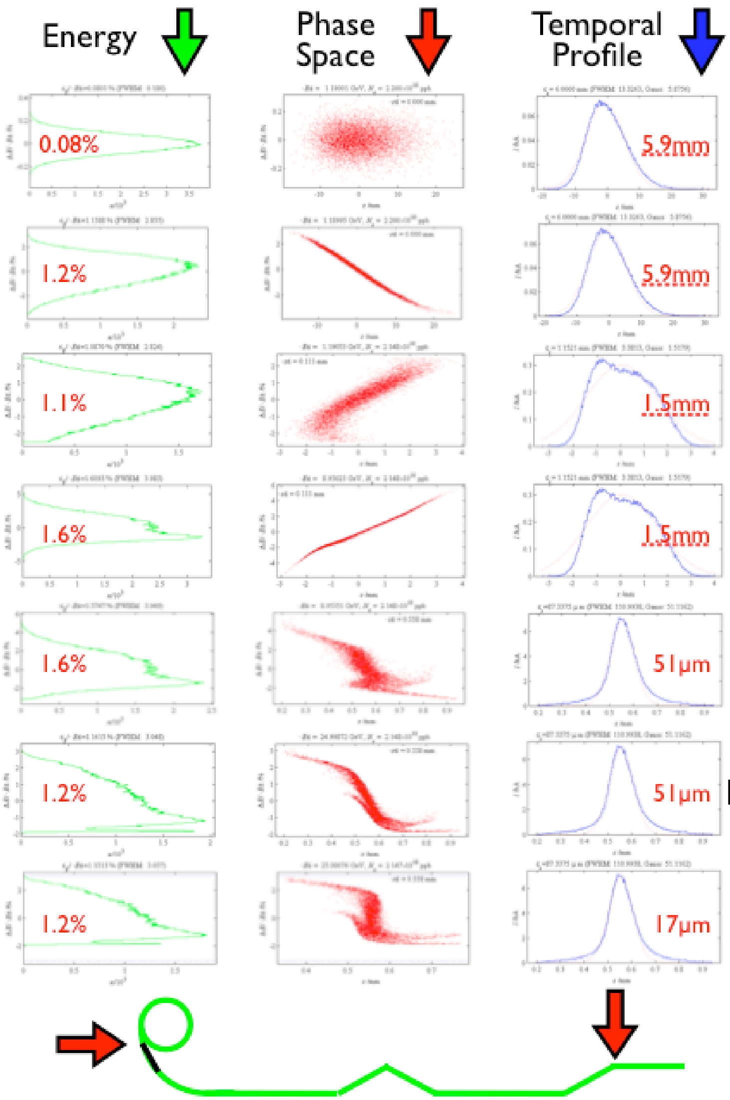




- Really important experiment! (psychologically)
- Driver bunch: high-charge (*3N*), modest emittance, shaped?
- Witness bunch: lower charge (*N*), good emittance, shorter
  beam loading for $\Delta E/E \ll 1$

P. Muggli, 09/21/09

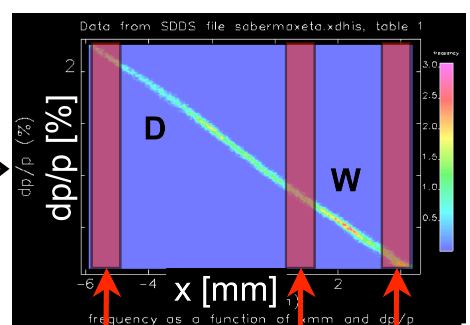
Two Bunches Generation



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

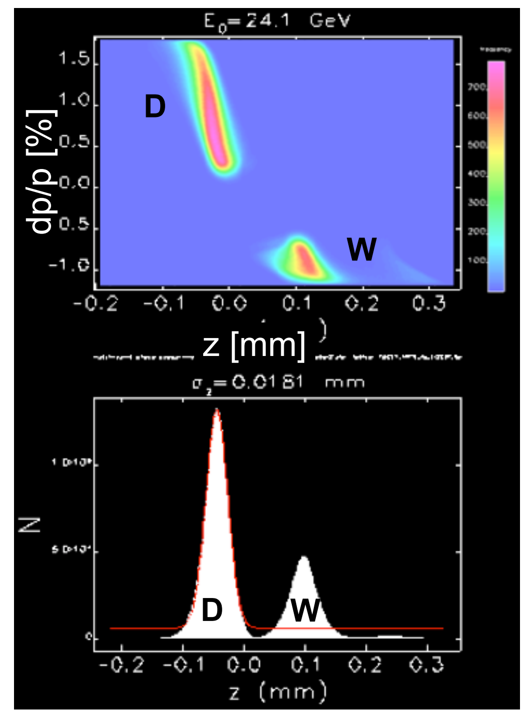
Disperse the beam in energy

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



...selectively collimate

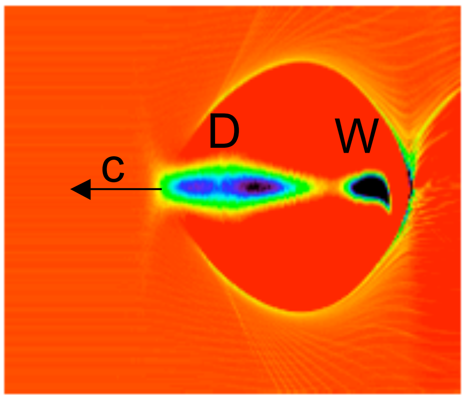
Adjust final compression

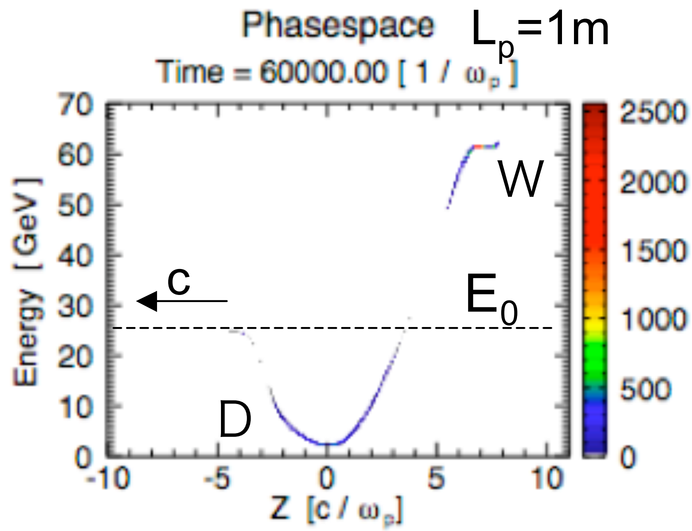


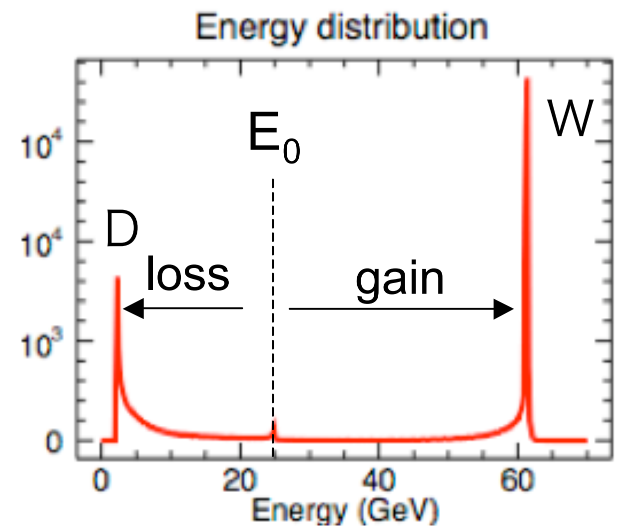
M. Hogan, SLAC

BEAM LOADING & EFFICIENCY

Simulations by C. Huang







n_p= 1×10^{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)

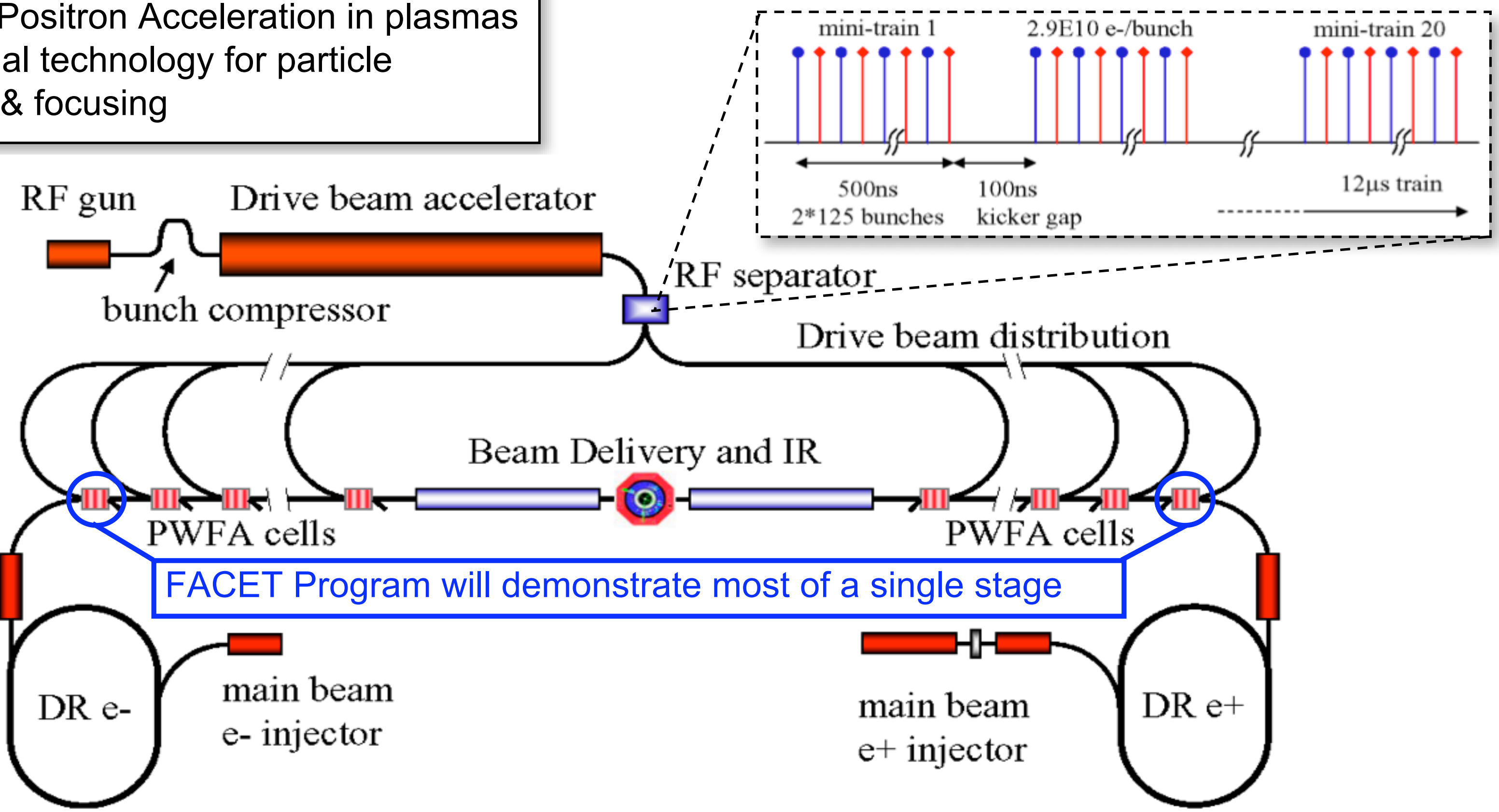
1% Energy spread
Efficiency from drive to trailing bunch ~48%!

- High efficiency and narrow $\Delta E/E_0$ while > energy doubling
- Potential for high efficiency accelerator (beam+PWFA)
- Ultra-relativistic beams: NO dephasing
- NO new physics required

PWFA-LC CONCEPT (an example)

July 7, 2008, A. Seryi, M. Hogan, T. Raubenheimer

- 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^+

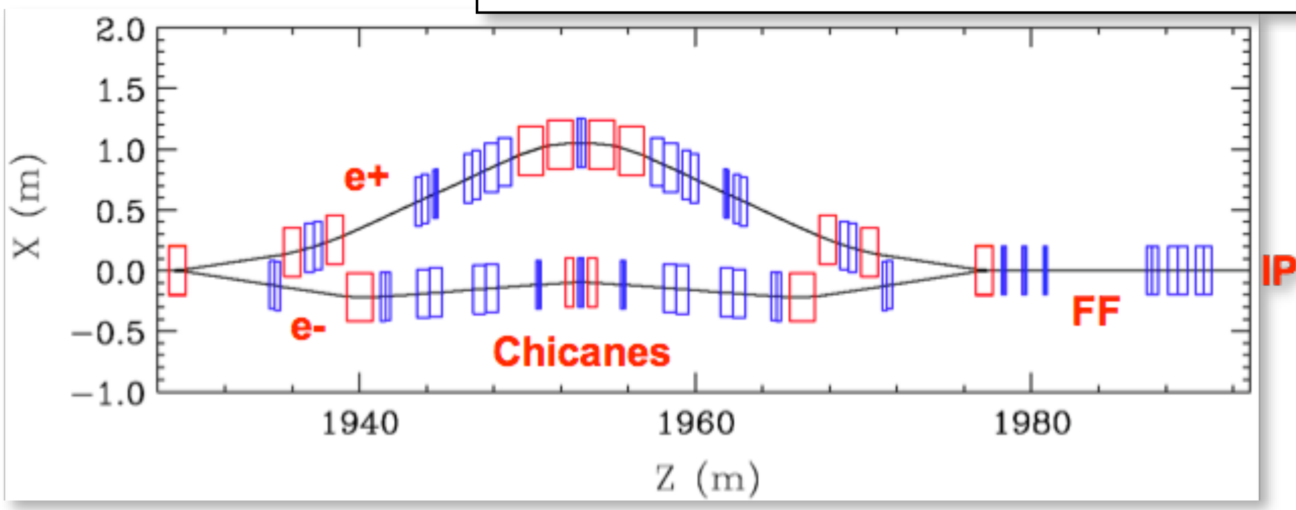
*Facilities for Accelerator Science and Experimental Test Beams

e^-/e^+ Drive/Witness Train

USC

- Accelerate e^+ bunch on e^--bunch driven wake
- Sailboat chicane:

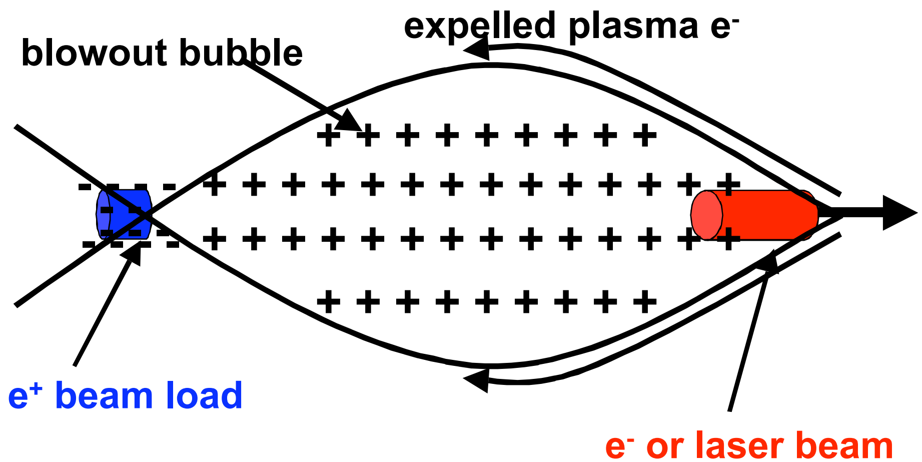
> - Extract e^- & e^+ from damping rings on same linac pulse
> - Accelerate bunches to sector 20, 5cm apart
> - Use 'Sailboat Chicane' to put them within 100μm at entrance to plasma
> - Large beam loading of e^- wakes with high charge e^+ beams
>
> M. Hogan, SLAC

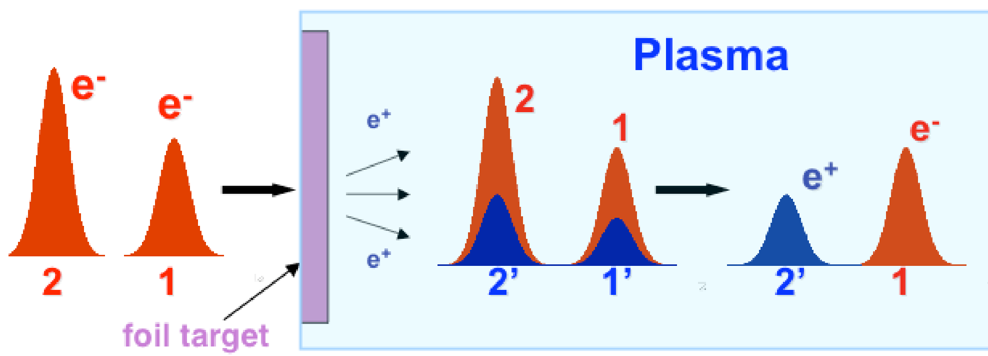


- True injection of e^+ bunch in high gradient plasma wake
- High current e^+ bunches available at FACET only!!!
- Neutral e^-/e^+ beams in plasmas, astrophysics

e^+ ACCELERATION ON e^- WAKE

Wang, PRL 101, 124801 (2008)





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

OUTLINE

- Motivation/Introduction
- Experimental results
  - e^- transverse dynamics (focusing)
  - β-tron radiation
  - acceleration

  } Long e^- bunch
  - acceleration
  - β-tron radiation

  } Short e^- bunch
  - e^+ transverse dynamics
  - e^+ acceleration

  } Long e^+ bunch
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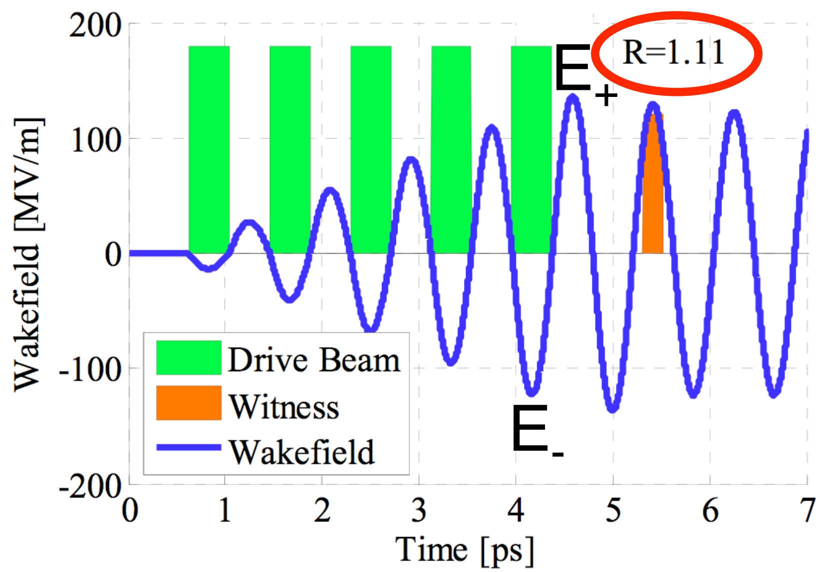
MULTIBUNCH PWFA

Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

σ_r=125 μm, n_e=1.8x10^{16} cm^{-3}, λ_p=250 μm E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm≈λ_p

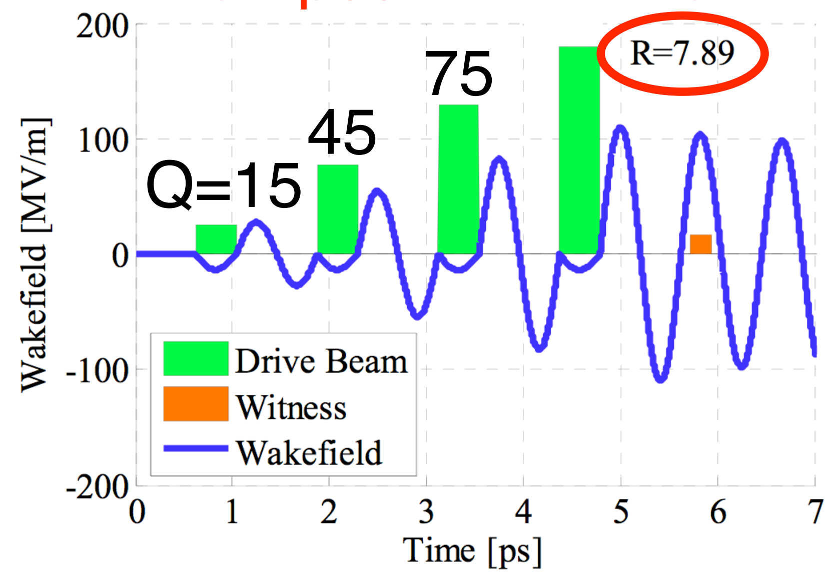
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*



*Tsakanov, NIMA, 1999

➡ R=7.9 => multiply energy by ≈8 in a single PWFA stage!

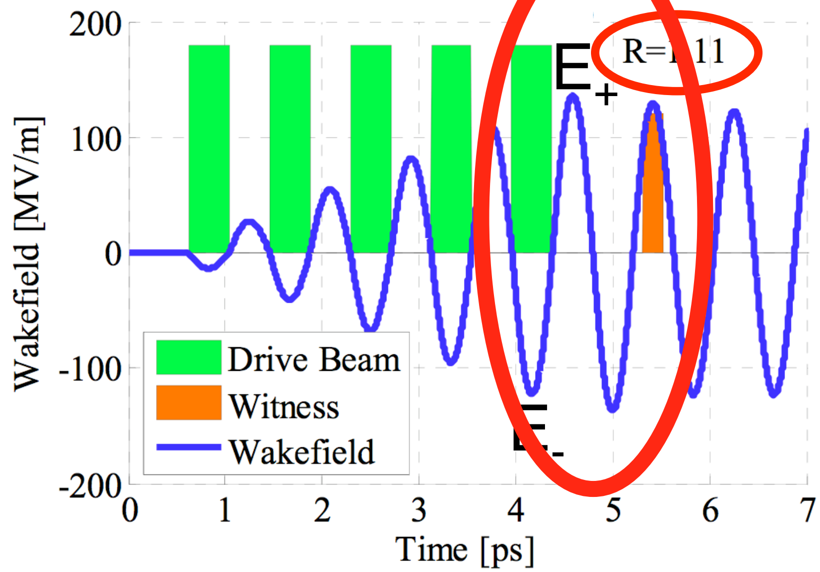
2-BUNCH PWFA

Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

σ_r=125 μm, n_e=1.8x10^{16} cm^{-3}, λ_p=250 μm E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm≈λ_p

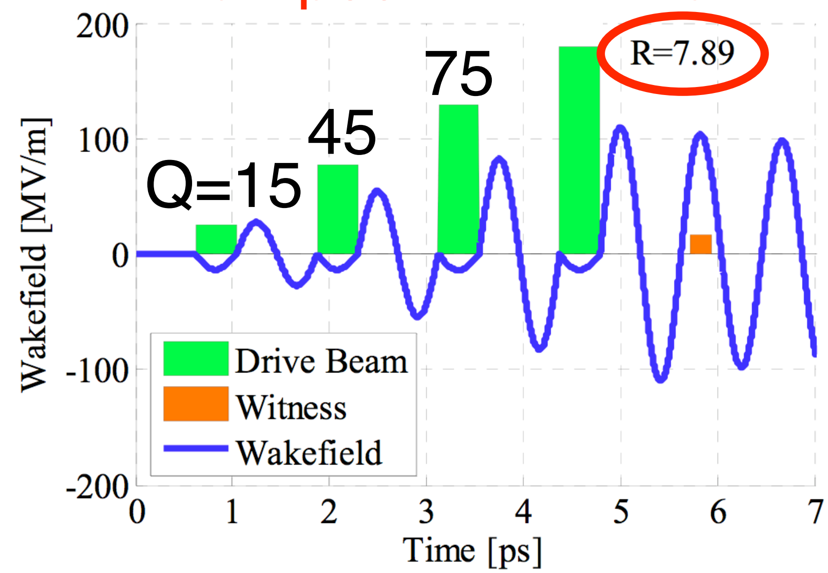
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*



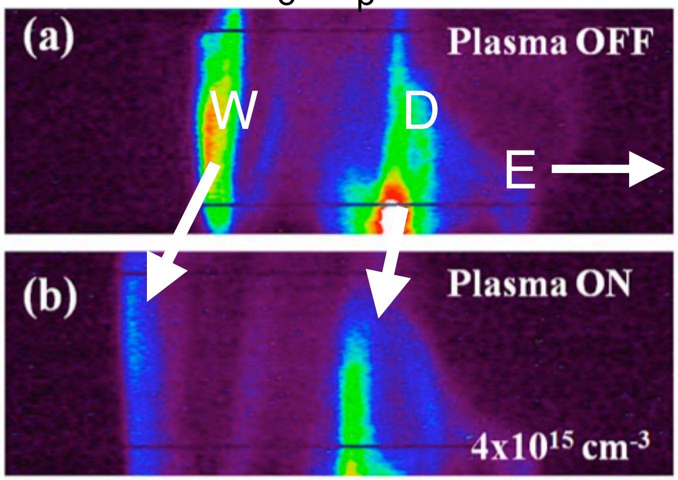
*Tsakanov, NIMA, 1999

- Resonant excitation of wakefields
- Large transformer ratio and energy gain (>2)

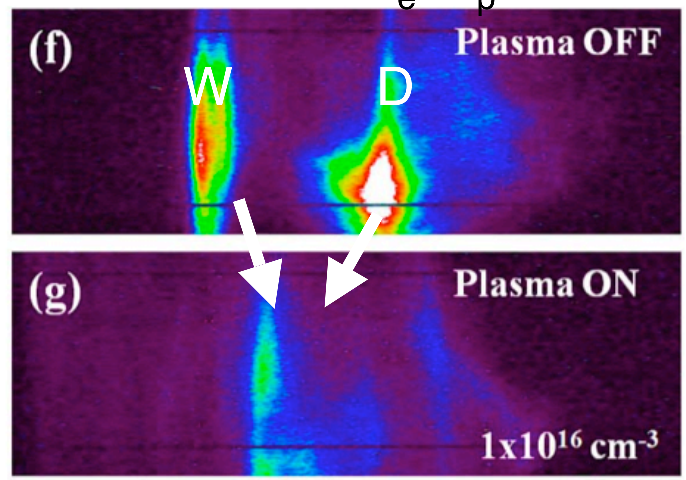
2-BUNCH RESULTS

Kallos, PRL 2008, PhD, IEEE NPSS Thesis Award 09

Low n_e: $\lambda_p > \Delta z$

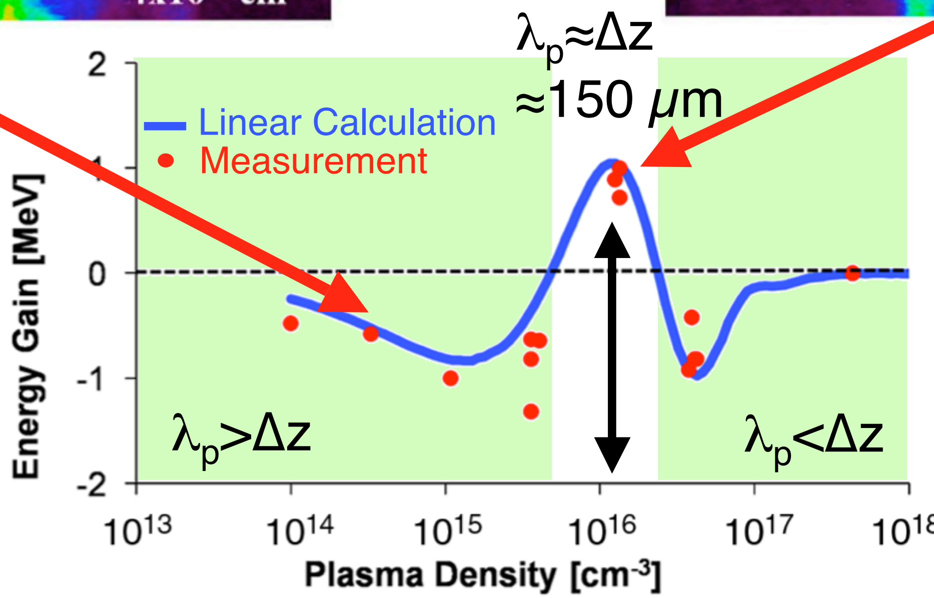


"Resonant" n_e: $\lambda_p \approx \Delta z$



Loss

Gain



E_{gain}=+0.9 MeV

E_{loss}=-1.0 MeV

ΔE=+1.9 MeV

L_p=6 mm

$G_{unloaded}$=315 MeV/m

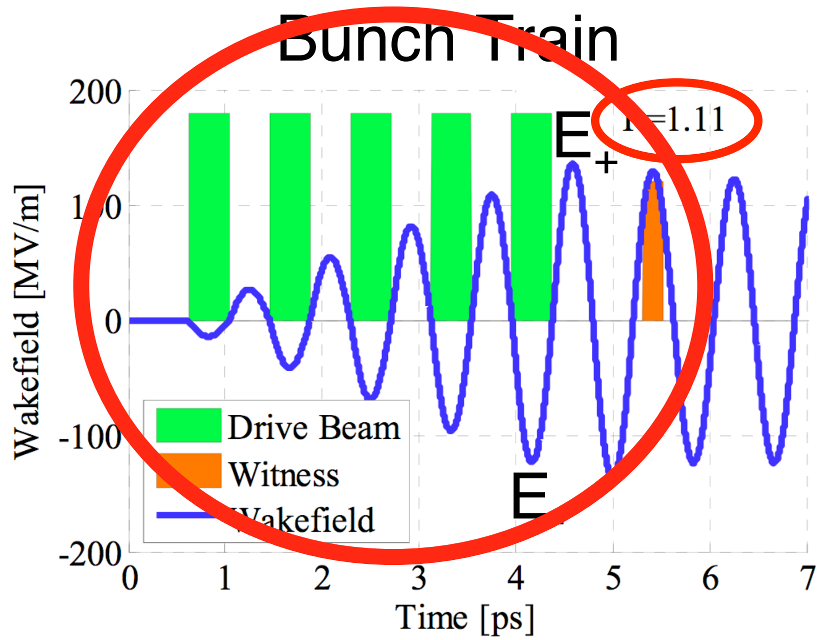
➡ First large gradient acceleration of a witness bunch

MULTIBUNCH PWFA

Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

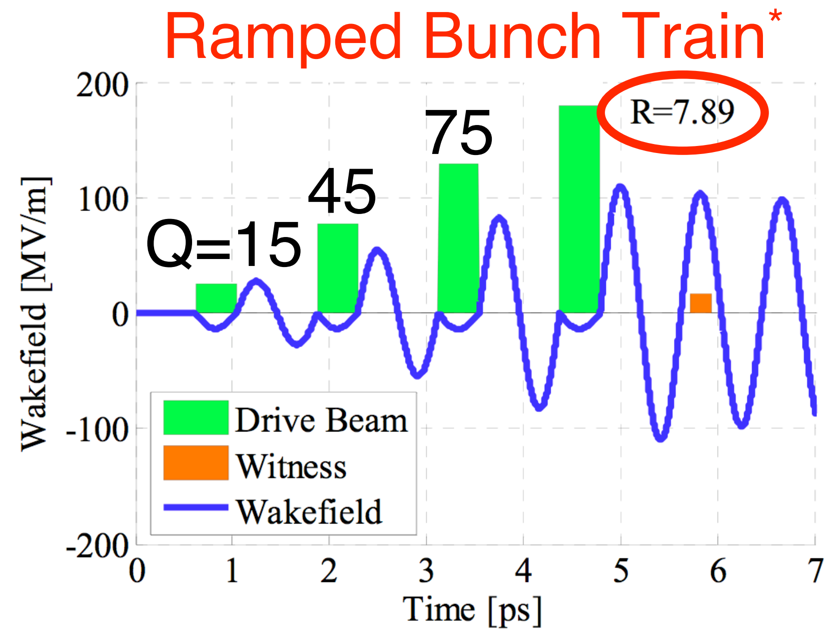
σ_r=125 μm, n_e=1.8x10^{16} cm^{-3}, λ_p=250 μm E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm≈λ_p



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

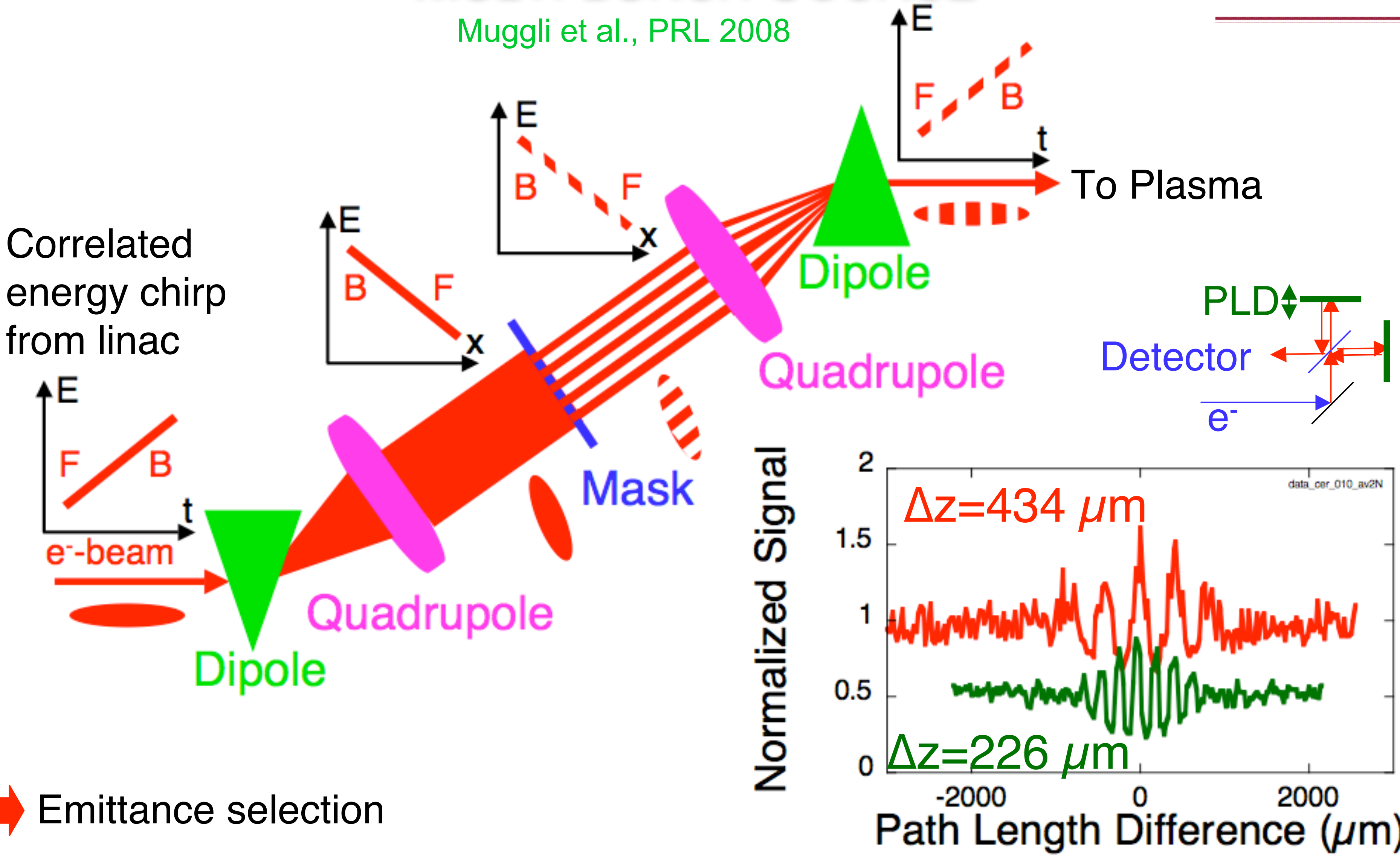


*Tsakanov, NIMA, 1999

- Resonant excitation of wakefields
- Large transformer ratio and energy gain (>2)

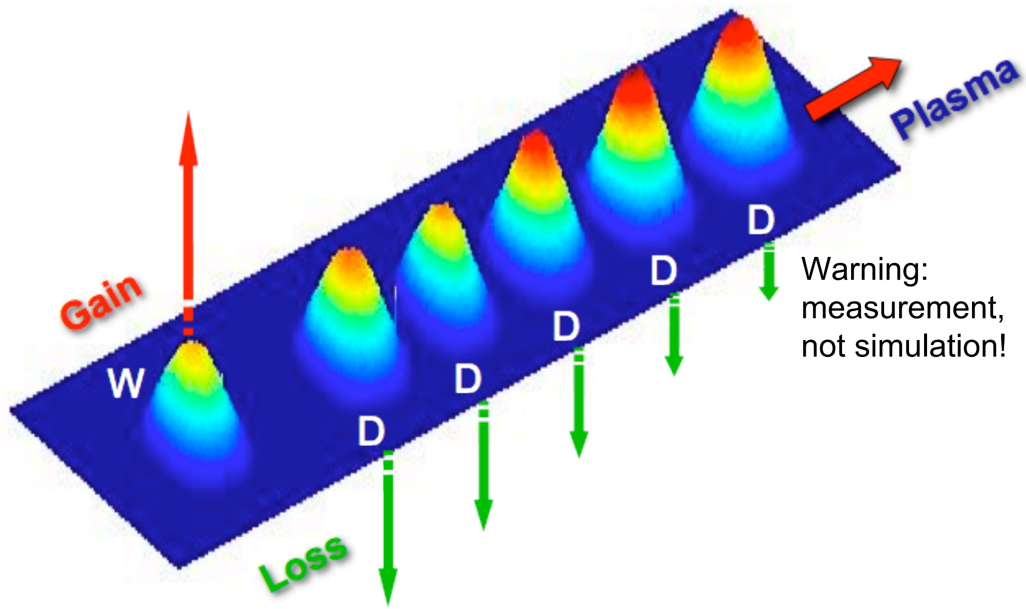
MULTI-BUNCH SOURCE

Muggli et al., PRL 2008



- Emittance selection
- Choose microbunches spacing and widths with mask and beam parameters: N, Δz, σ_z, Q

MULTI-BUNCH TRAIN

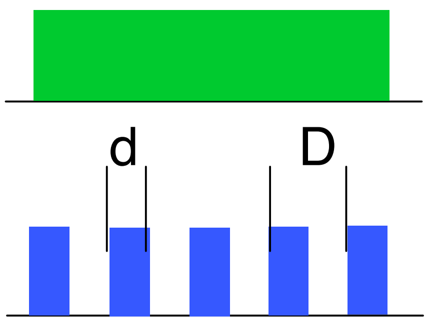


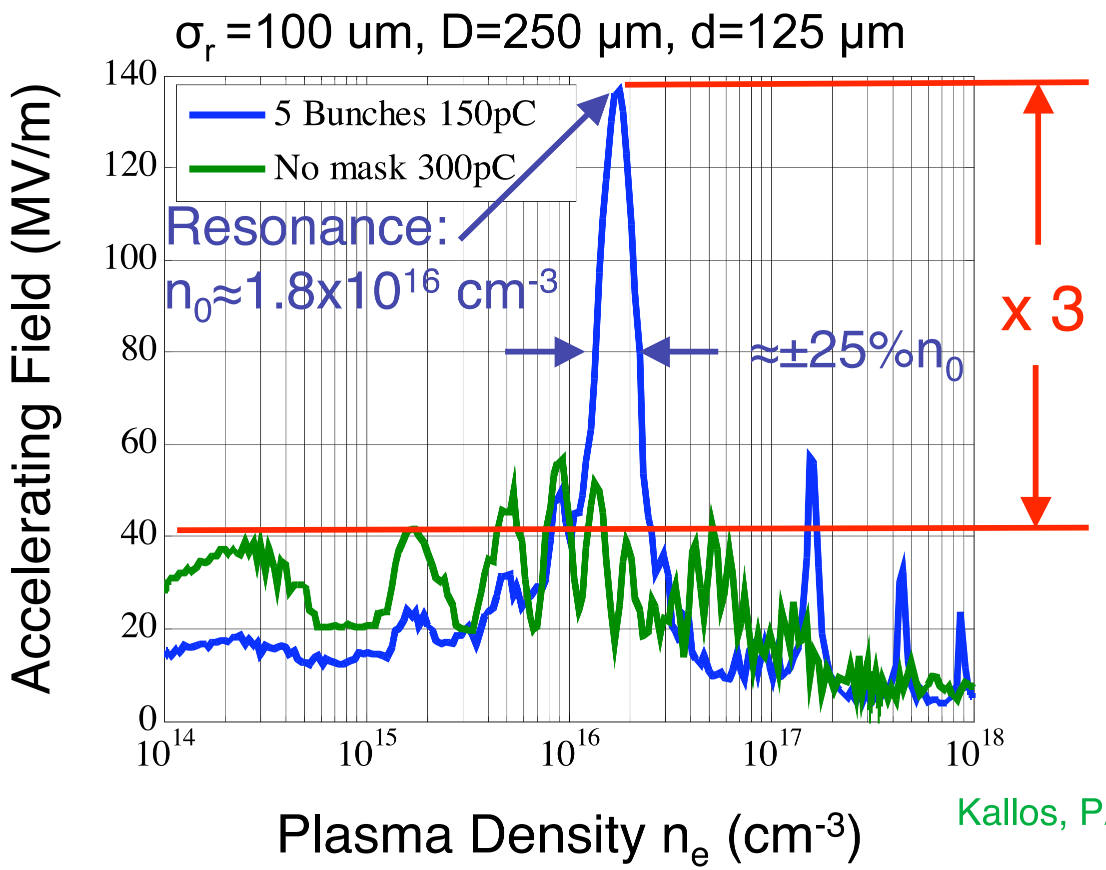
Warning:
measurement,
not simulation!

- E_0=59 MeV
- N=1-5D + 1W, Δz=150-400 μm, $\sigma_z \approx \Delta z/2$, Q≈40 pC/bunch
- Perfect for PWFA, could be used for FEL, fs x-ray streak camera
- Excellent test bed for FACET notch collimator

ACCELERATING FIELD

Linear calculation microbunches with equal charge

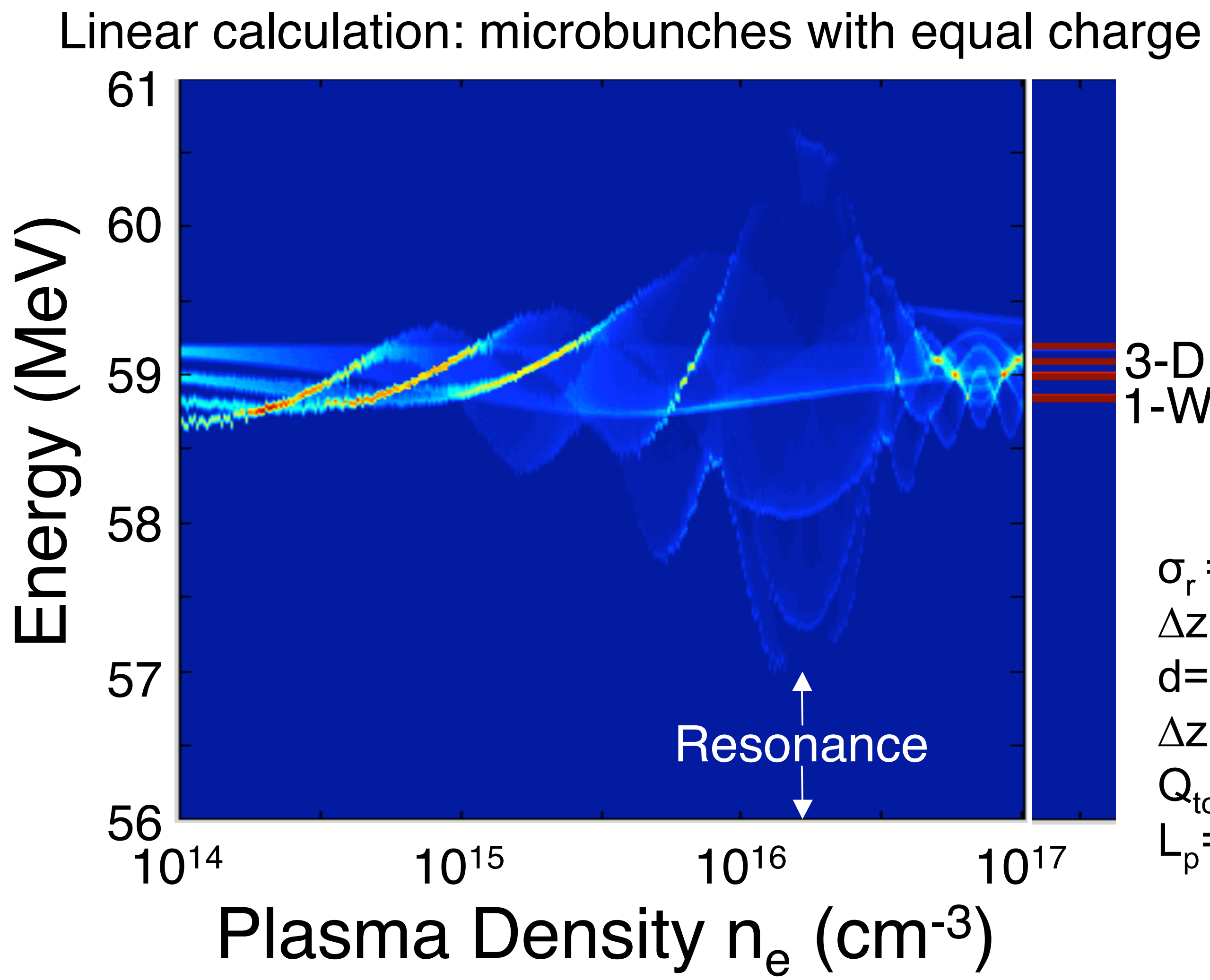




Kallos, PAC'07 Proceedings

- Expect ≈MeV energy gain/loss over 1 cm
- Microbunch resonance clear, and narrow

ENERGY CHANGE



σ_r =100 um,
Δz=250 μm,
d=125 μm
$\Delta z'$=375 μm
Q_{tot}=150 pC
L_p=2 cm

- Resonant excitation of wakefield is the main feature
- Note: case of witness bunch at lowest energy, WRONG CHIRP!

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  - acceleration

    } Long e^- bunch
  - acceleration
  - β-tron radiation

    } Short e^- bunch
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  - e^+ acceleration

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Summary and Conclusions

- PWFA made remarkable progress
  - e^- transverse dynamics (focusing)
  - β-tron radiation
  - acceleration

  } Long e^-, e^+ Short e^-

- PWFA is well understood
- Many more results: multi-GeV trapped e^-, emittance, …
- FACET@SLAC will address PWFA collider issues
  - Acceleration of witness bunch ($\Delta E/E_0$~1%)
  - e^+ …
  - Single, e^-/e^+, +25 GeV PWFA stage
- PWFA physics can be tested/demonstrated at low energy
- PWFA experiments broaden to astrophysics and ICF, fs x-ray streak camera, CSR mitigation, etc.

Collaborations:

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University of California, Los Angeles

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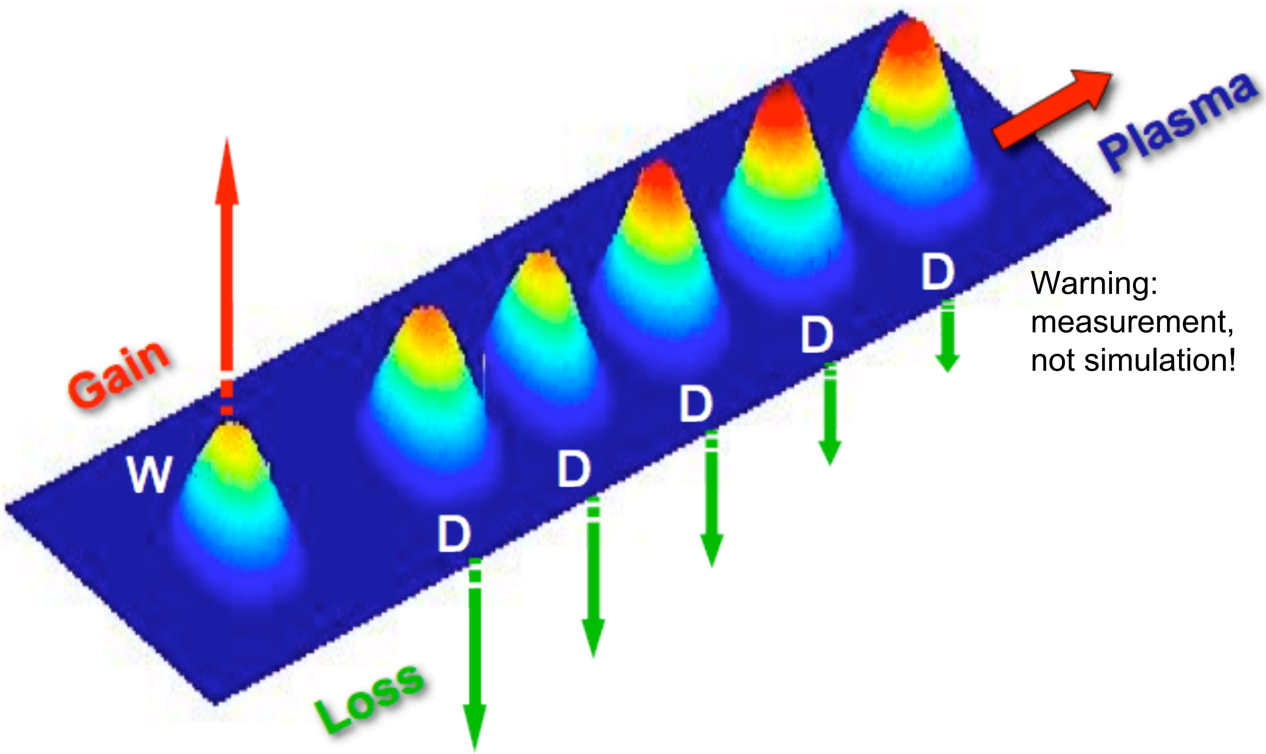
University of Southern California

M. Babzien, K. Kusche, J. Park, D. Stolyarov, V. Yakimenko
Brookhaven National Laboratory, Upton, Long Island, NY

Thank you!

* Principal Investigators

Thank You!



Warning:
measurement,
not simulation!

Work supported by US Dept. of Energy