Experiments in (e^-/e^+) beam driven PWA

Patric Muggli
University of Southern California
muggli@usc.edu

Work supported by US Dept. of Energy

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

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

Stanford Linear Accelerator Center

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

University of California, Los Angeles

T. Katsouleas, E. Oz, P. Muggli

University of Southern California

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

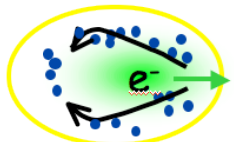
and

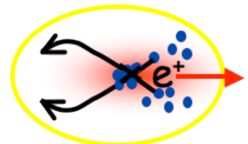
M. Babzien, K. Kusche, J. Park, D. Stolyarov, V. Yakimenko

Brookhaven National Laboratory, Upton, Long Island, NY

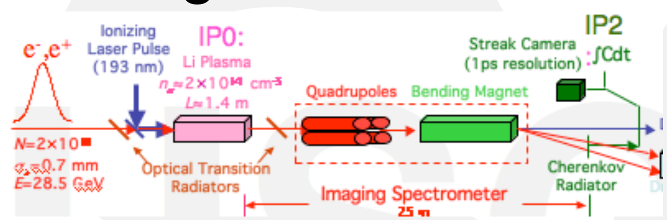
OUTLINE

- Plasma Wakefield Accelerator (PWFA) for e^+



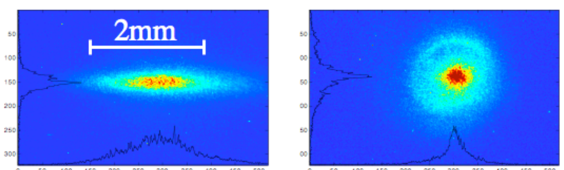


- Experimental Setup & Diagnostics

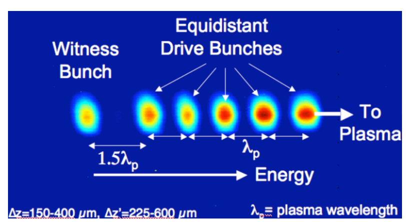


- Experimental results for e^- & e^+ bunches (SLAC)

e+



- Multi-bunch PWFA (ATF)



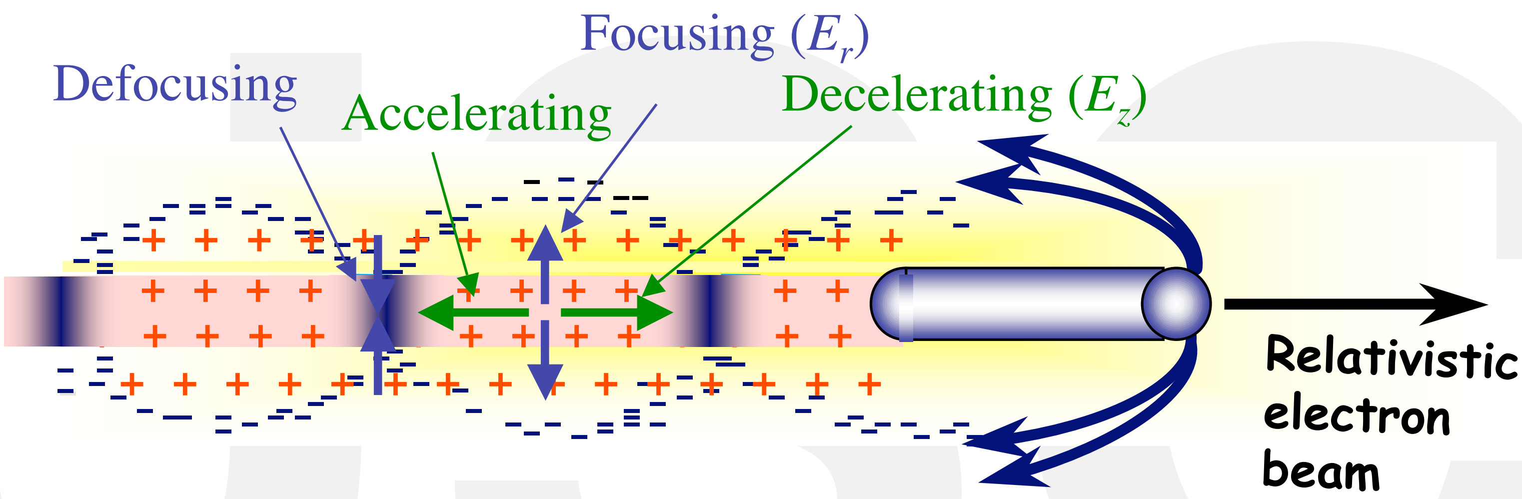
- Conclusions

Review of High-energy Plasma Wakefield Experiments
P. Muggli and M.J. Hogan, Comptes Rendus Physique, 10(2-3), 116 (2009).

PLASMA WAKEFIELD ACCELERATOR* 101

USC UNIVERSITY OF SOUTHERN CALIFORNIA

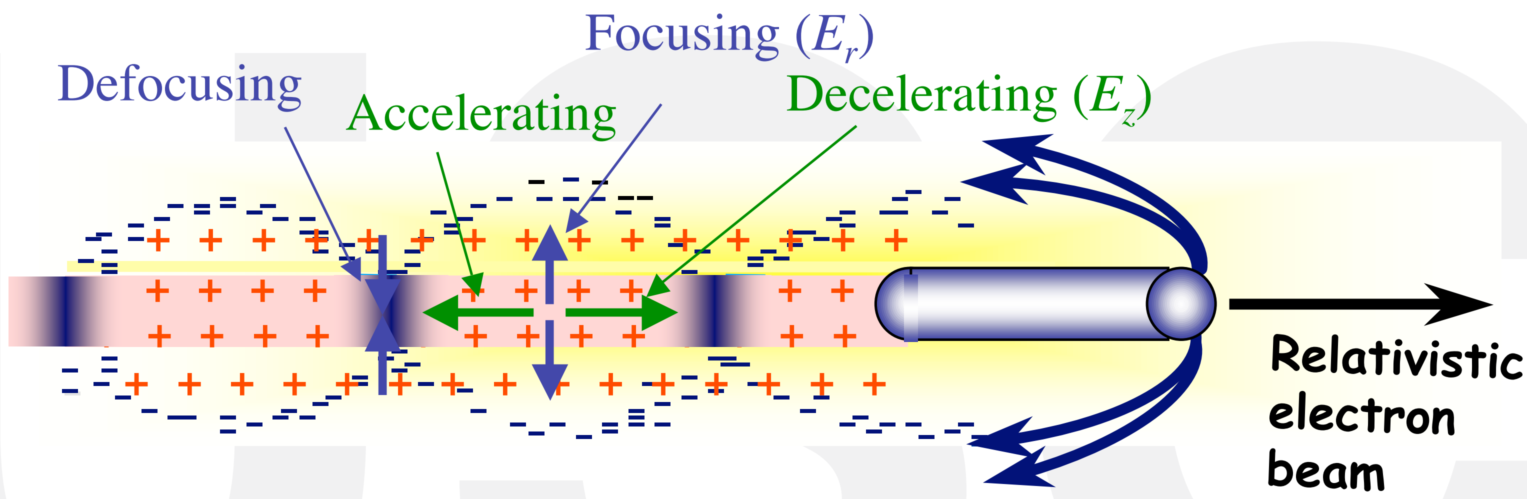
- Two-beam, co-linear, plasma-based accelerator



- 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

PLASMA WAKEFIELD ACCELERATOR* 101

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

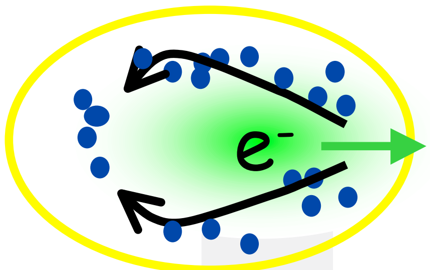


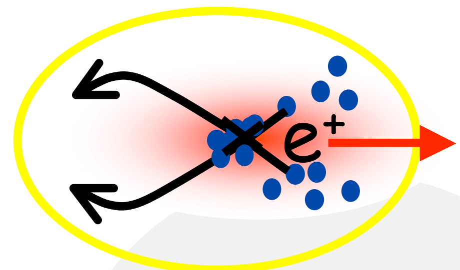
Single bunch experiments:
Bunch (e^-/e^+) covers all phases of the "rf" wave or wake

Ultra-relativistic e^- (γ=50,000) "don't" dephase …

e^- & e^+ BEAM PWFA

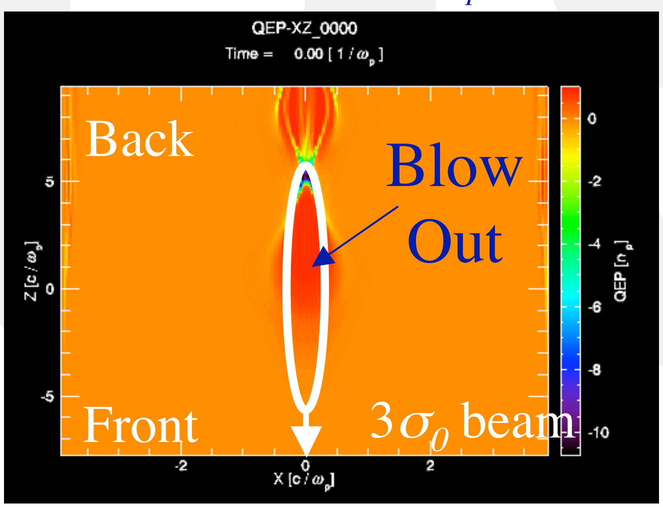
♦ Transverse dynamics, emittance preservation?





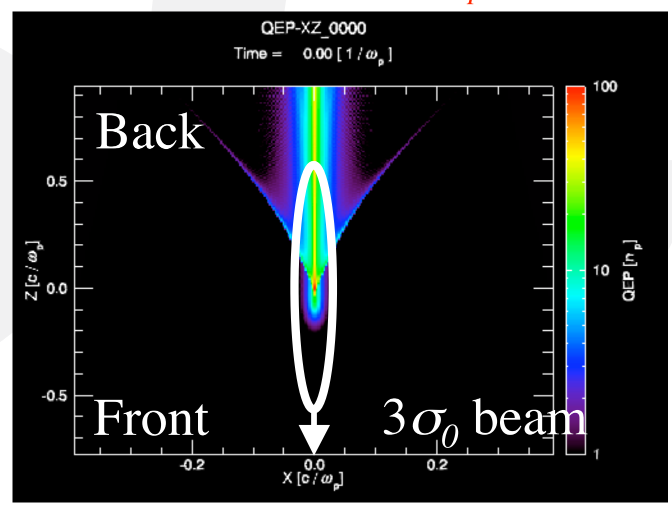
3-D QuickPIC simulations, plasma e^- density:

e^-: n_{e0}=2×10^{14} cm^{-3}, c/ω_p=375 μm



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

e^+: n_{e0}=2×10^{12} cm^{-3}, c/ω_p=3750 μm

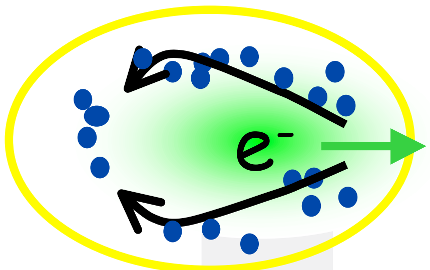


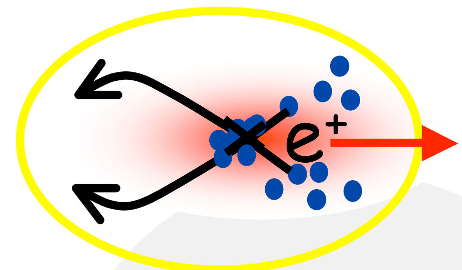
- Uniform focusing force (r,z)
- Free of geometric aberrations
- Emittance preserved

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

e^- & e^+ BEAM PWFA

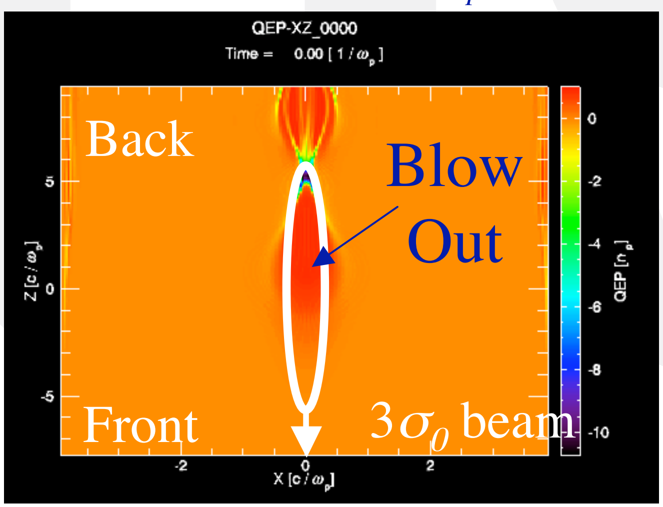
- Transverse dynamics, emittance preservation?





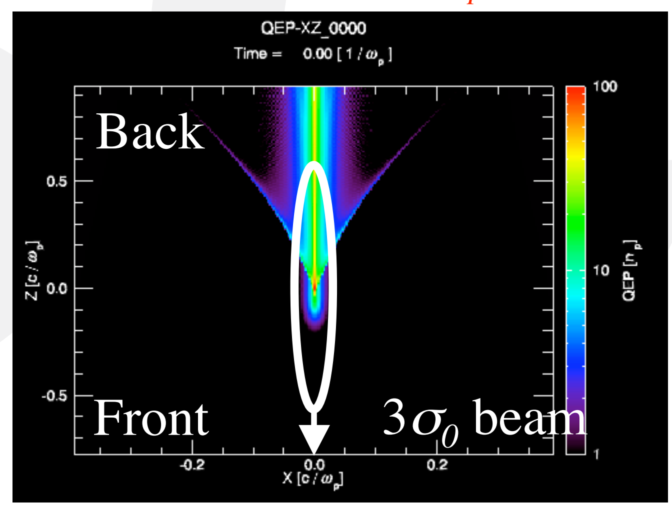
3-D QuickPIC simulations, plasma e^- density:

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

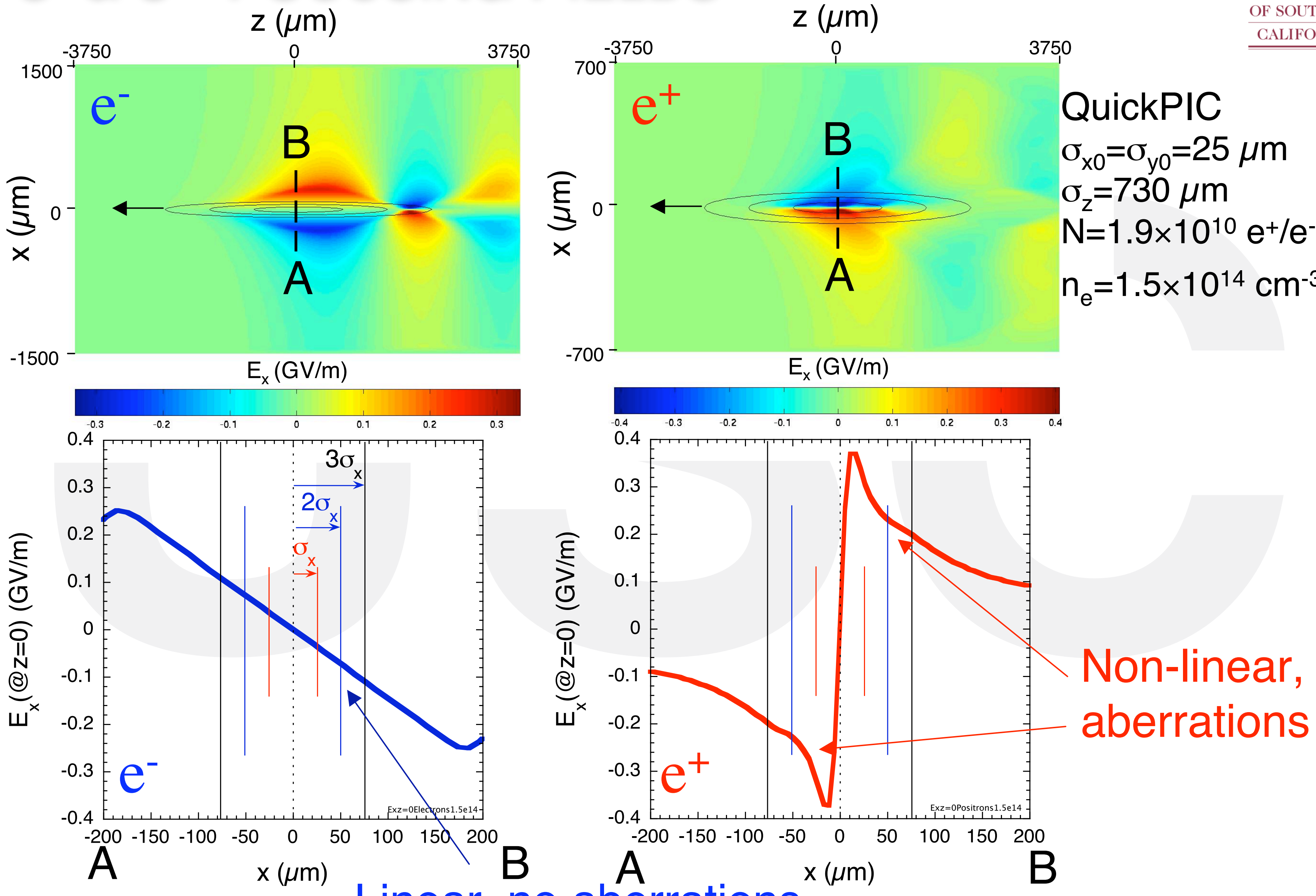
e^+: $n_{e0}=2\times10^{12}$ cm^{-3}, $c/\omega_p=3750\ \mu$m



Proton beams in plasmas <=> Positron beams in plasmas

Witness bunch **Drive bunch**

e^- & e^+ FOCUSING FIELDS

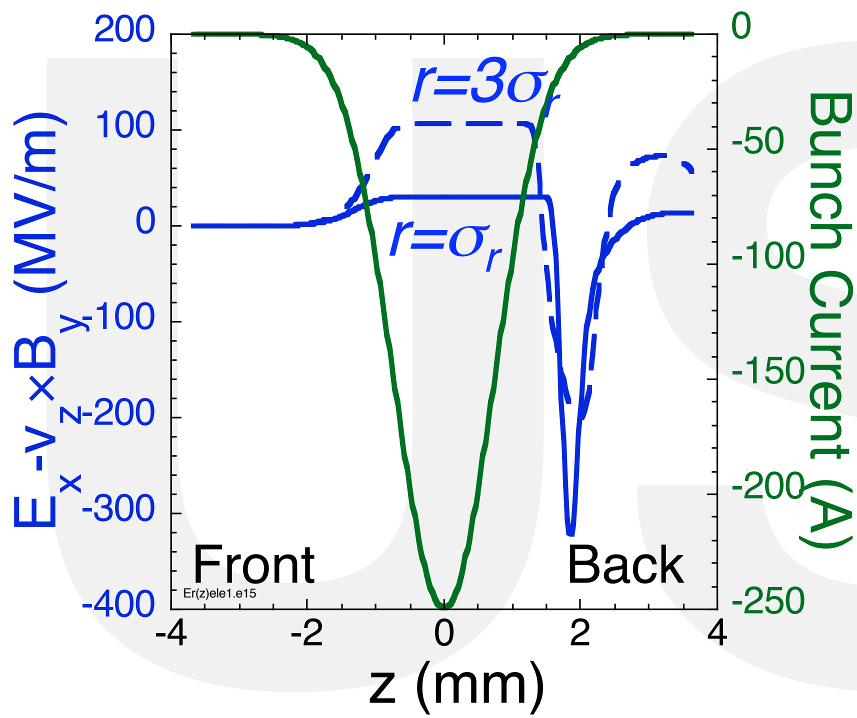


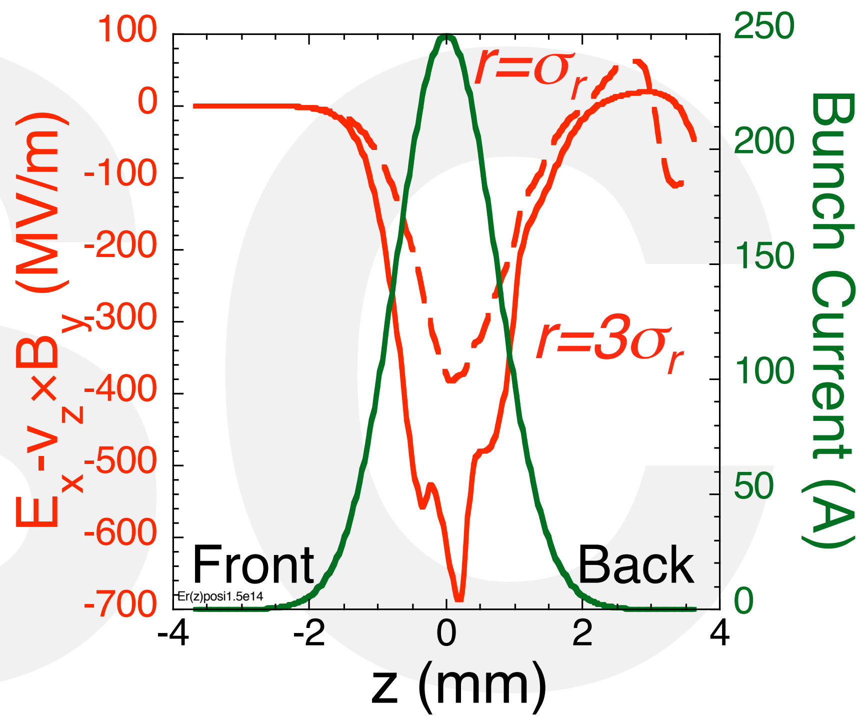
P. Muggli, PPA 09. 09/12/17

e^- & e^+ FOCUSING FIELDS

USC UNIVERSITY OF SOUTHERN CALIFORNIA

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





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

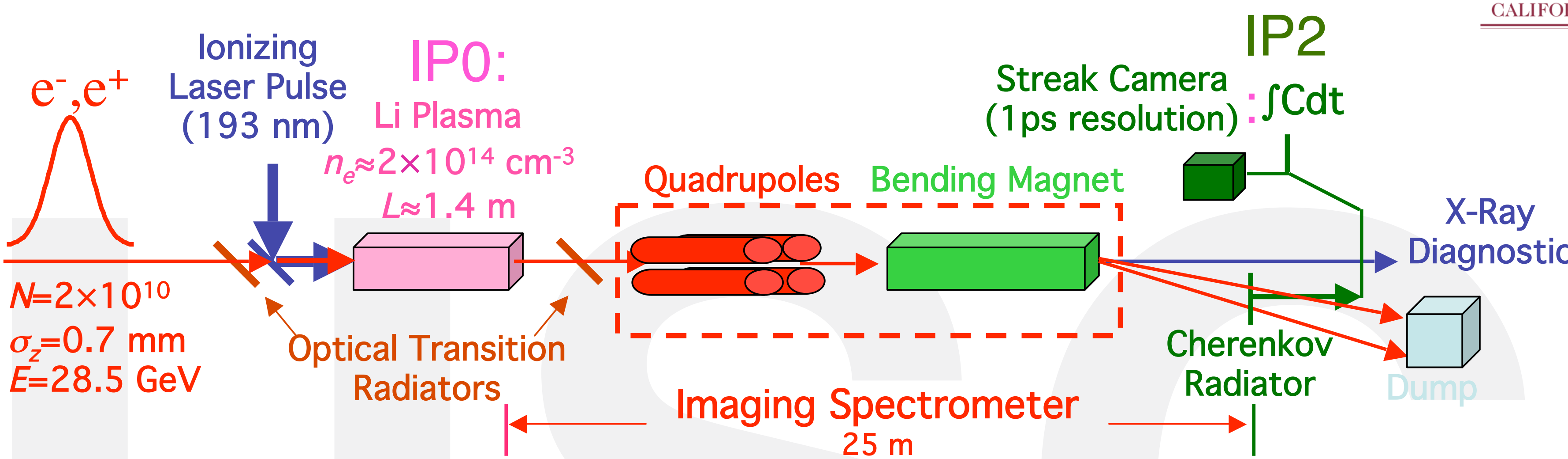
- Non-uniform focusing force (*r,z*)
- Stronger focusing force

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

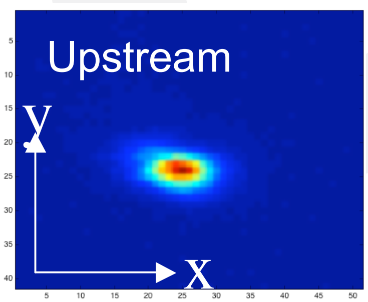
♦ Emittance growth expected

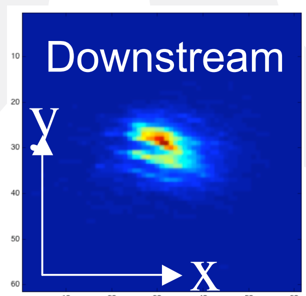
EXPERIMENTAL SET UP

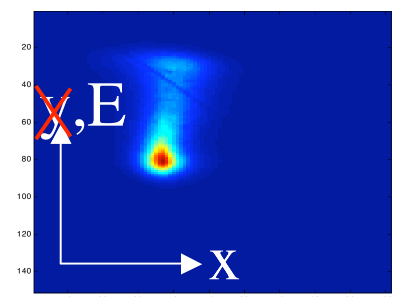
UNIVERSITY OF SOUTHERN CALIFORNIA



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





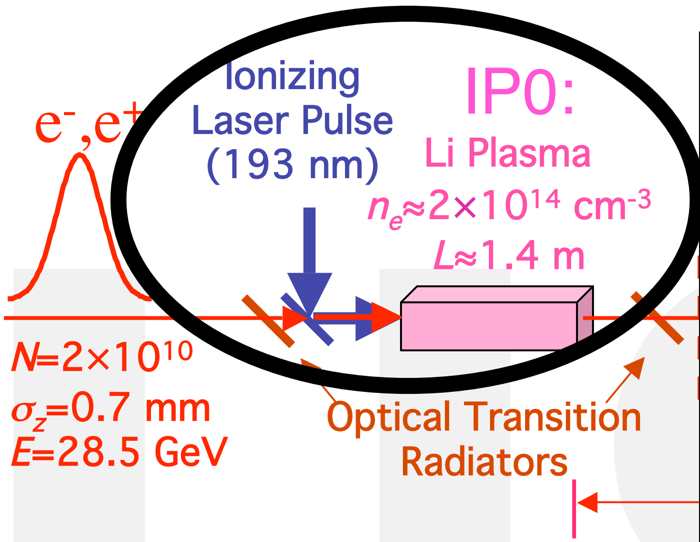


- 1:1 imaging, spatial resolution <9 μm

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

EXPERIMENTAL SET UP

USC UNIVERSITY OF SOUTHERN CALIFORNIA



Plasma:

Lithium vapor in heat-pipe oven

ϕ_1=5.4eV, ϕ_2=75.6eV

Laser-ionized, λ=157nm (excimer)

-variable density

Field ionized, E>6GV/m, ~100fs

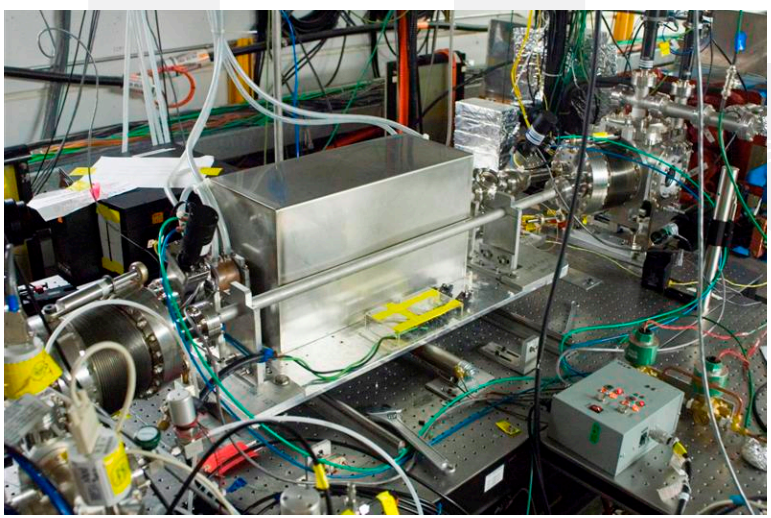
-need ON/OFF

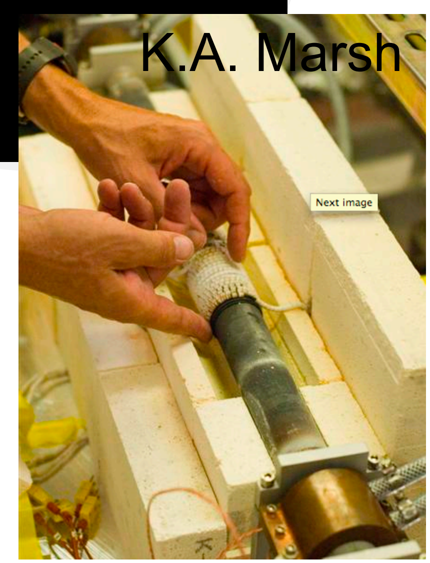
-long time constant

Variable length

Field-free

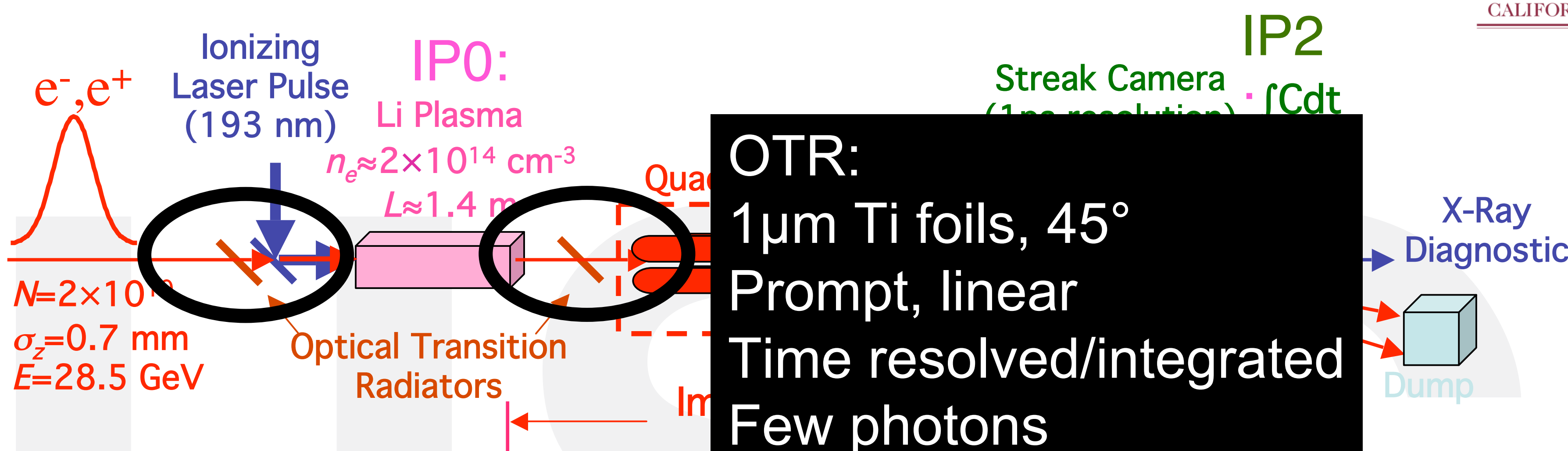
Very reproducible





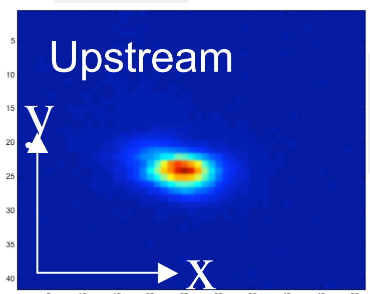
P. Muggli et al., IEEE Trans. on Plasma Science 27(3), pp. 791-799 (1999).

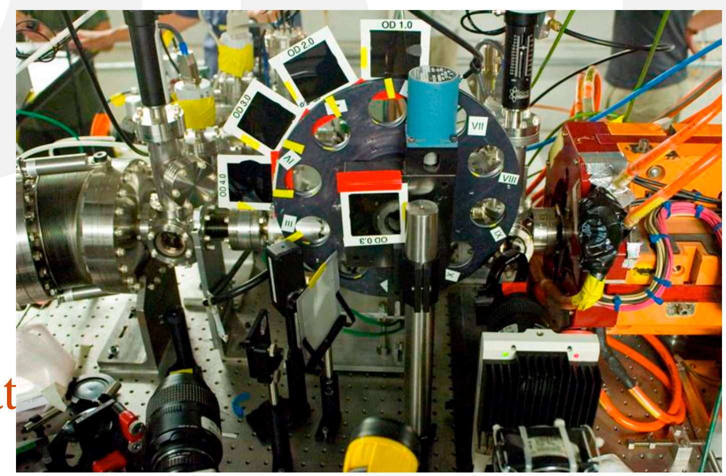
Experimental Set Up

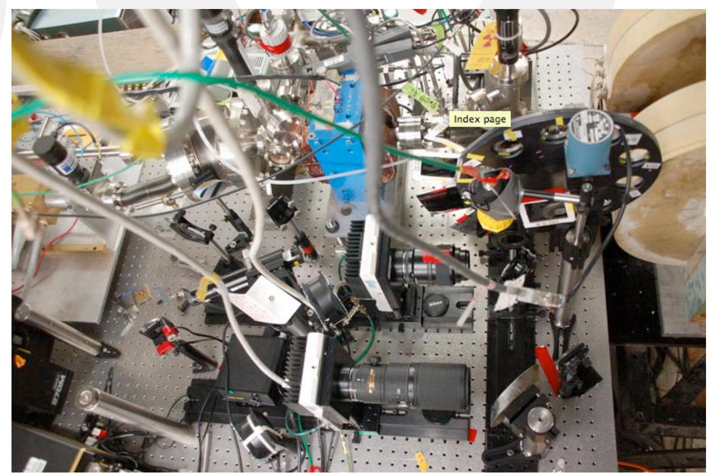


OTR:
1µm Ti foils, 45°
Prompt, linear
Time resolved/integrated
Few photons
~µm resolution
Before and after plasma

- Optical Transition Radiation (OTR)

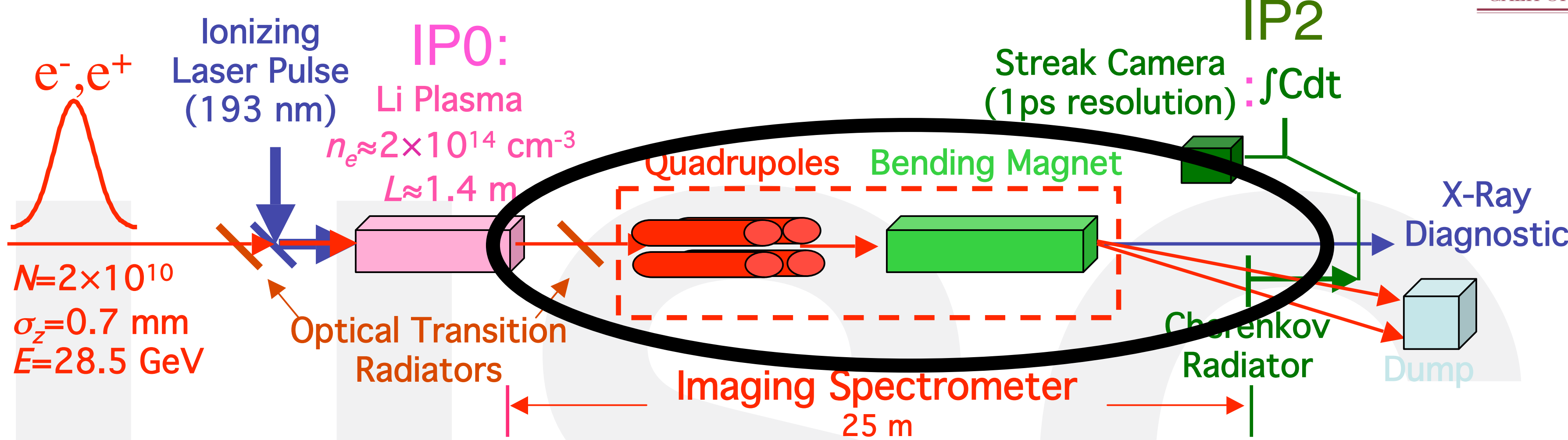






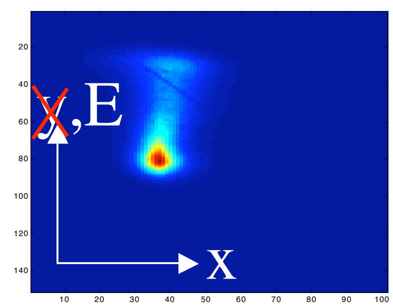
- 1:1 imaging, spat

EXPERIMENTAL SET UP



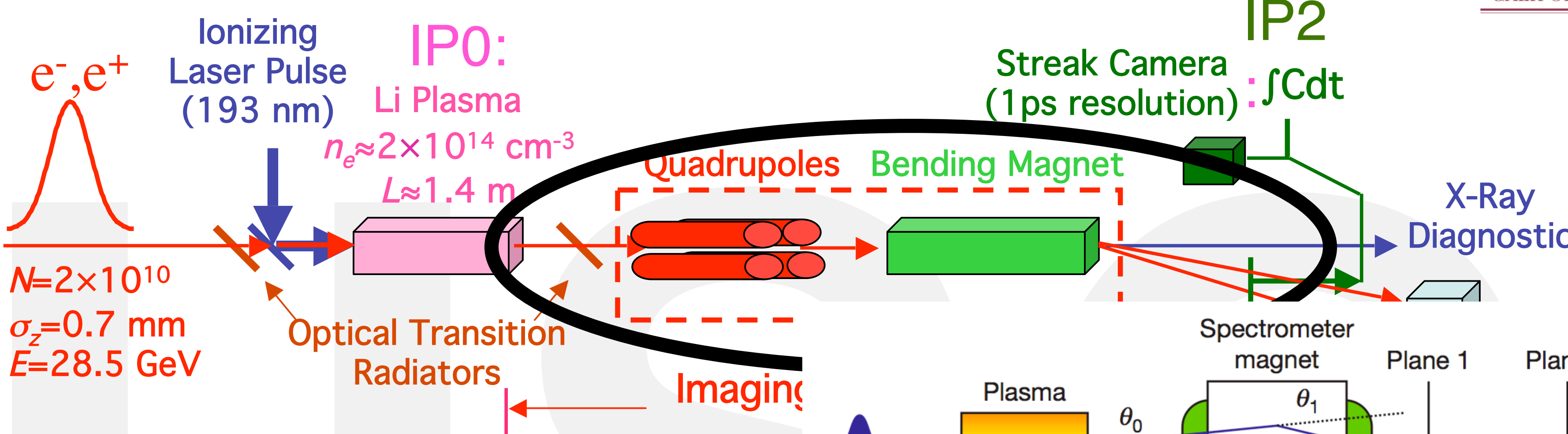
Imaging Spectrometer: Small ΔE
Transverse field ~ Longitudinal fields
NECESSARY to remove p_{perp}-ΔE ambiguity
$\beta_y\varepsilon_y<<(\eta_y\Delta E/E_0)^2$

- CHERENKOV (aerogel)

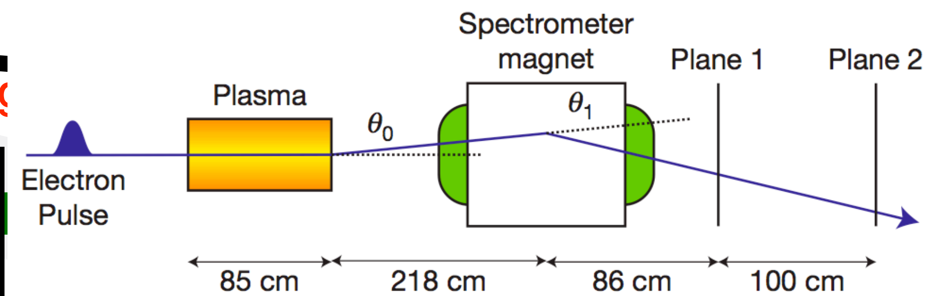


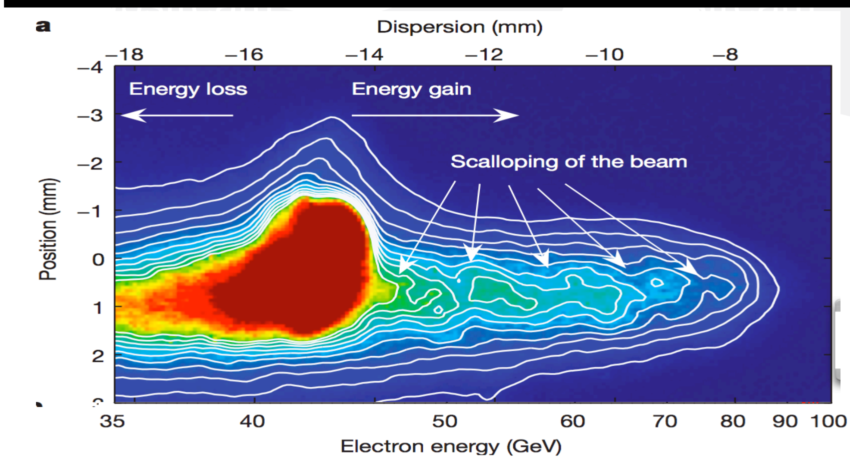
- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV
- Time resolution: ≈1 ps

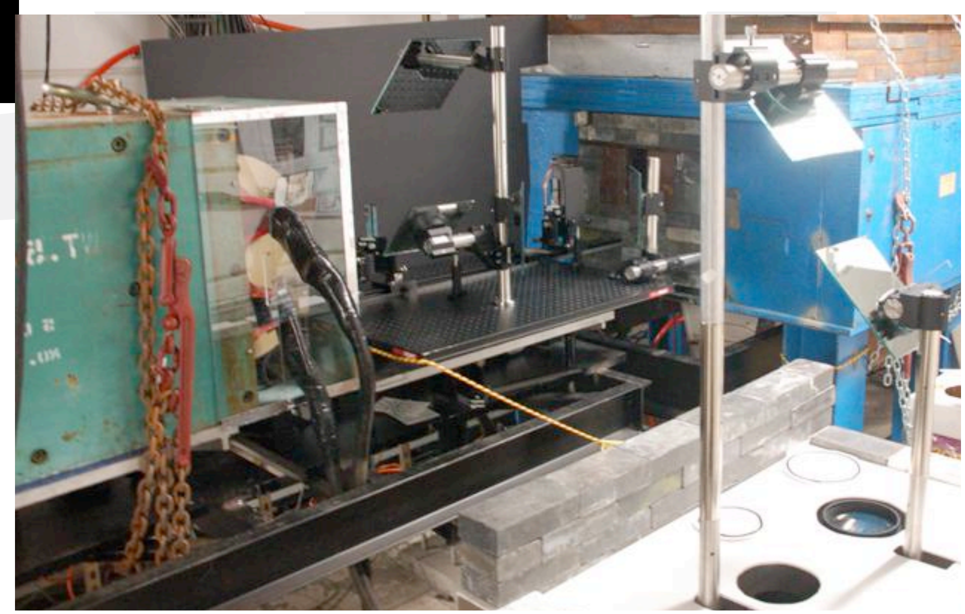
EXPERIMENTAL SET UP



Two-screen Spectro: Large ΔE NECESSARY to remove p_{perp}-ΔE ambiguity



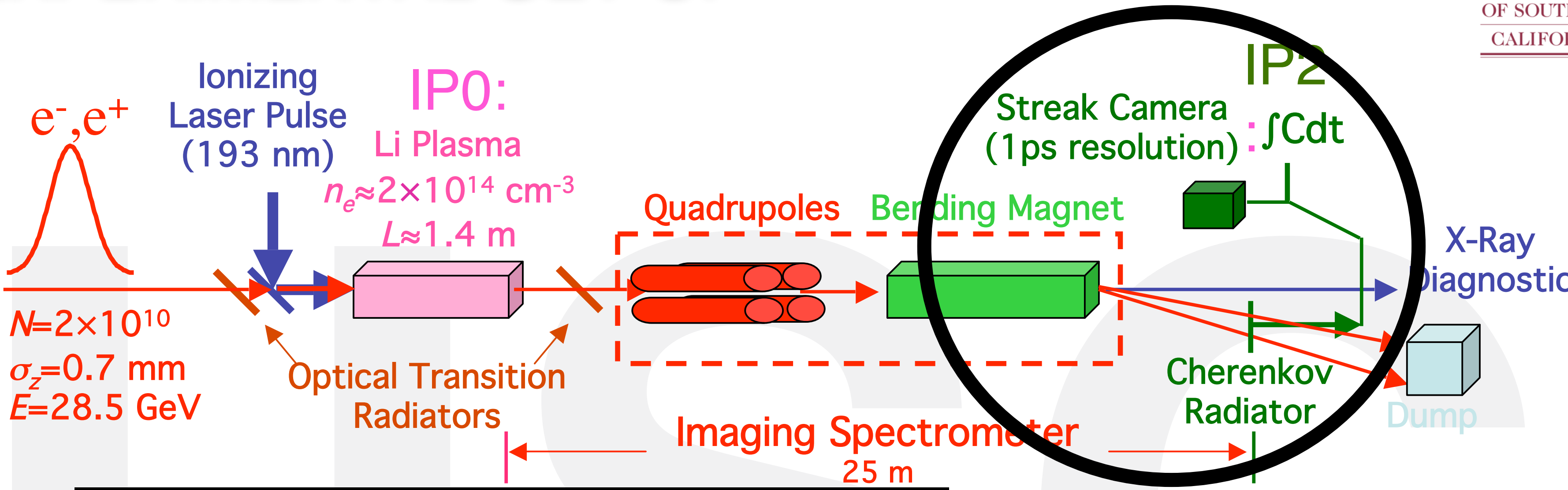




P. Muggli, PPA 09. 09/12/17

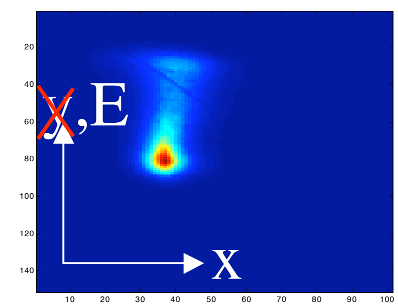
EXPERIMENTAL SET UP

USC UNIVERSITY OF SOUTHERN CALIFORNIA



Cherenkov Radiator:
Aerogel, n=1.009, θ_c≈8°
Many photons
-beam large-x, dispersed-y
Prompt, linear
Time resolved/integrated
Emit in a cone: $\cos\theta_c$≈1/n
Limited spatial/energy resolution
$\Delta r=L^*\cos\theta_c$

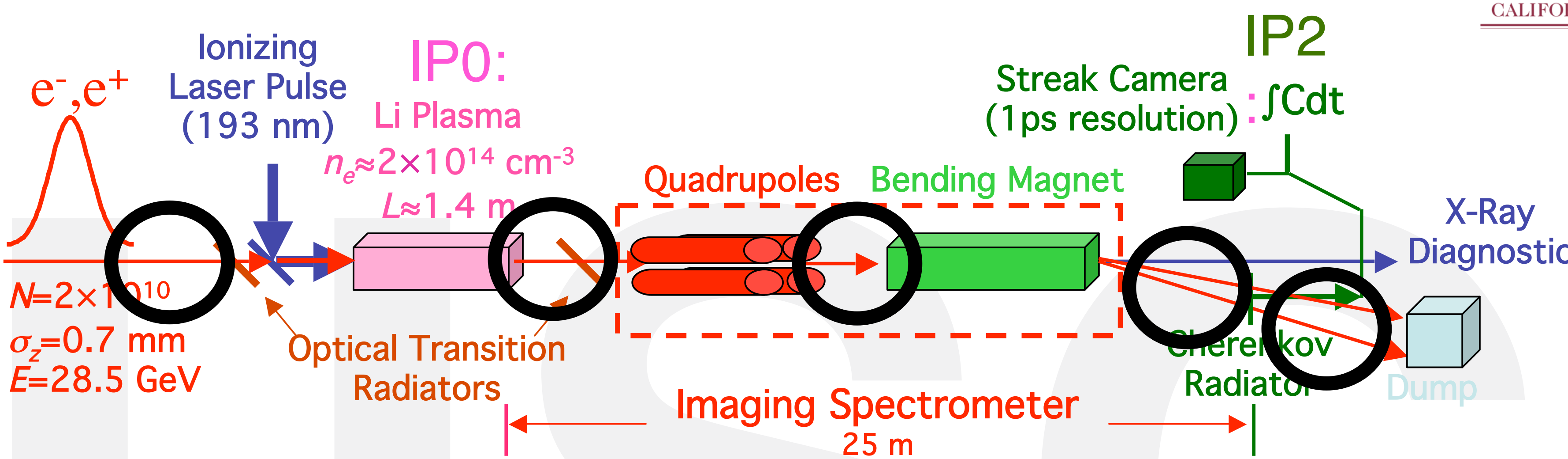
- CHERENKOV (aerogel)



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

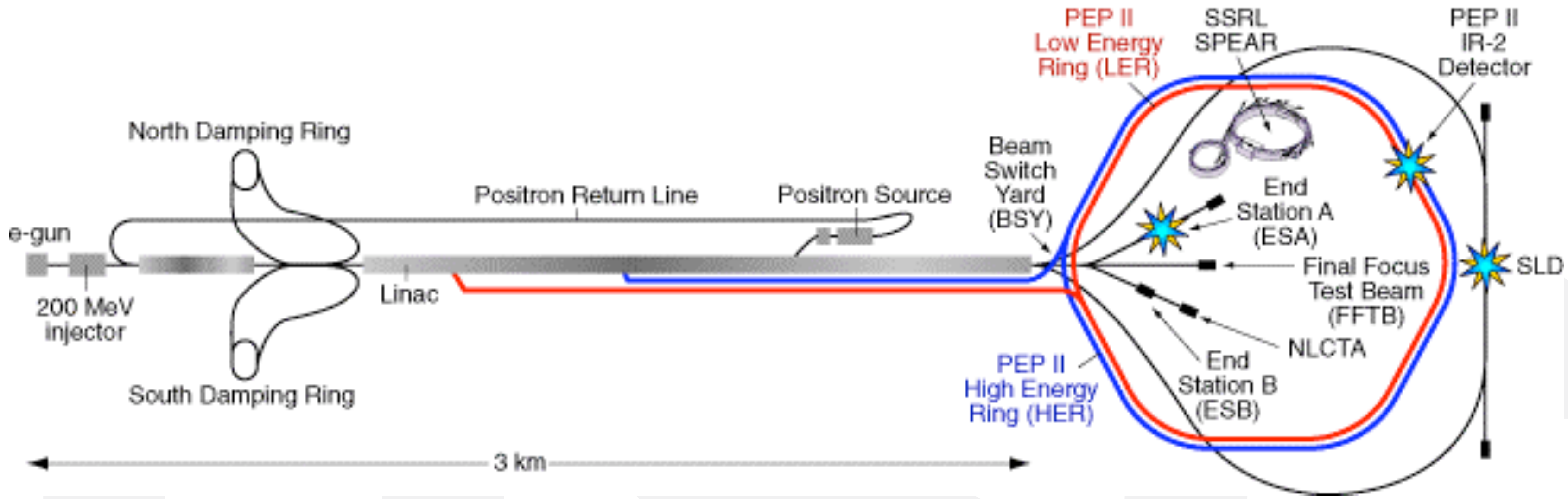
EXPERIMENTAL SET UP

USC
UNIVERSITY
OF SOUTHERN
CALIFORNIA



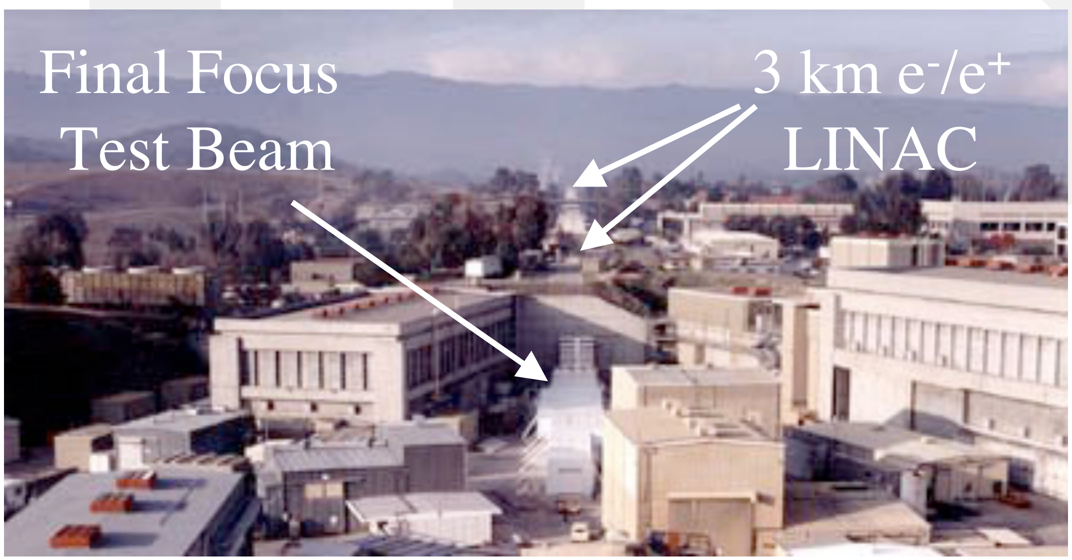
Beamline diagnostics:
As many as possible
BPM, wires, OTRs, etc.

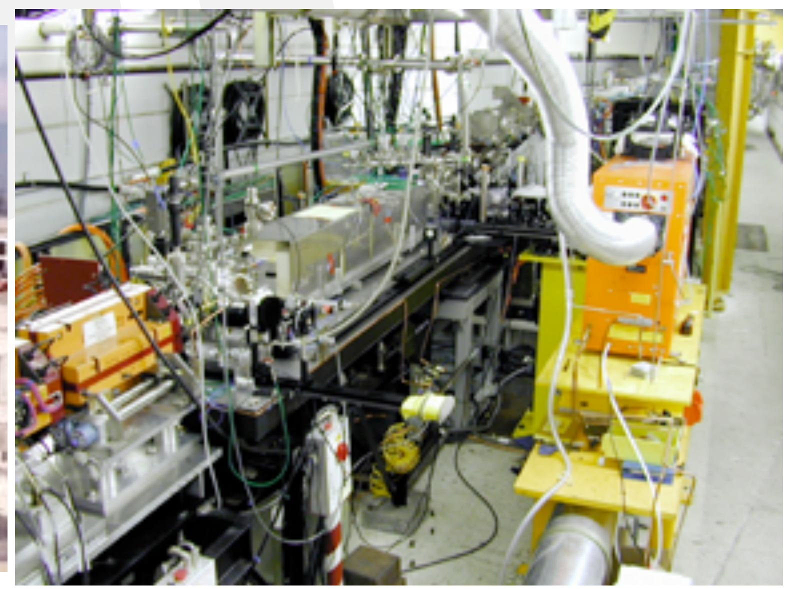
PLASMA WAKEFIELD EXPERIMENT @ SLAC



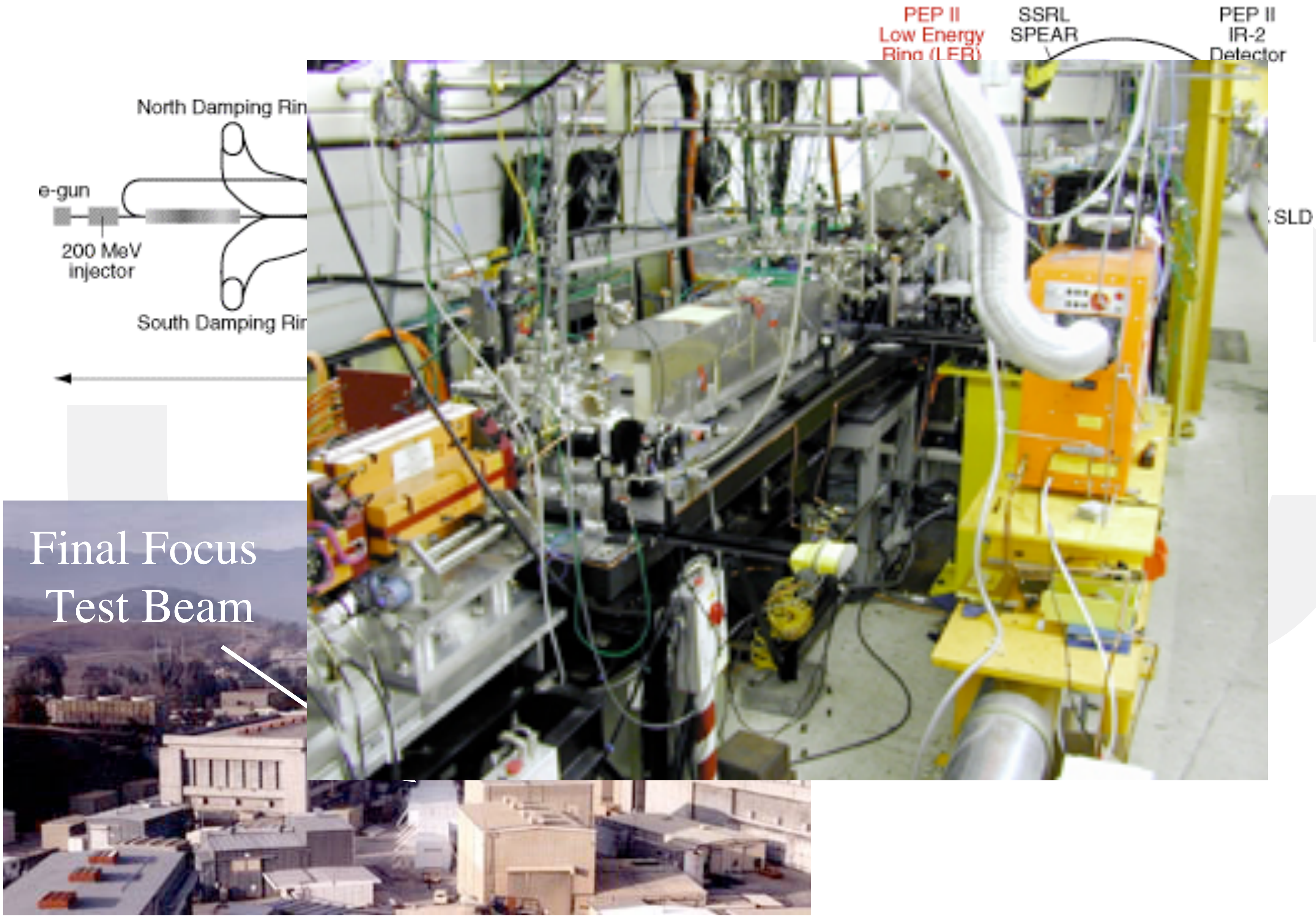
3 km for 50 GeV

1 m for 1 GeV?





PLASMA WAKEFIELD EXPERIMENT @ SLAC

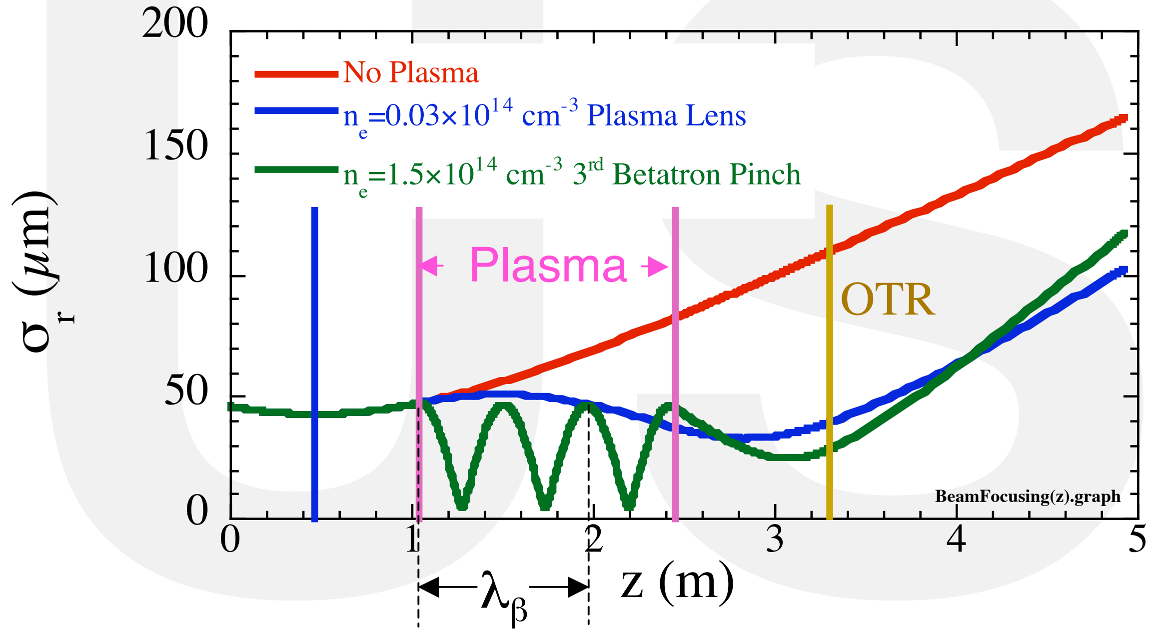


P. Muggli, PPA 09. 09/12/17

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=2×10^{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

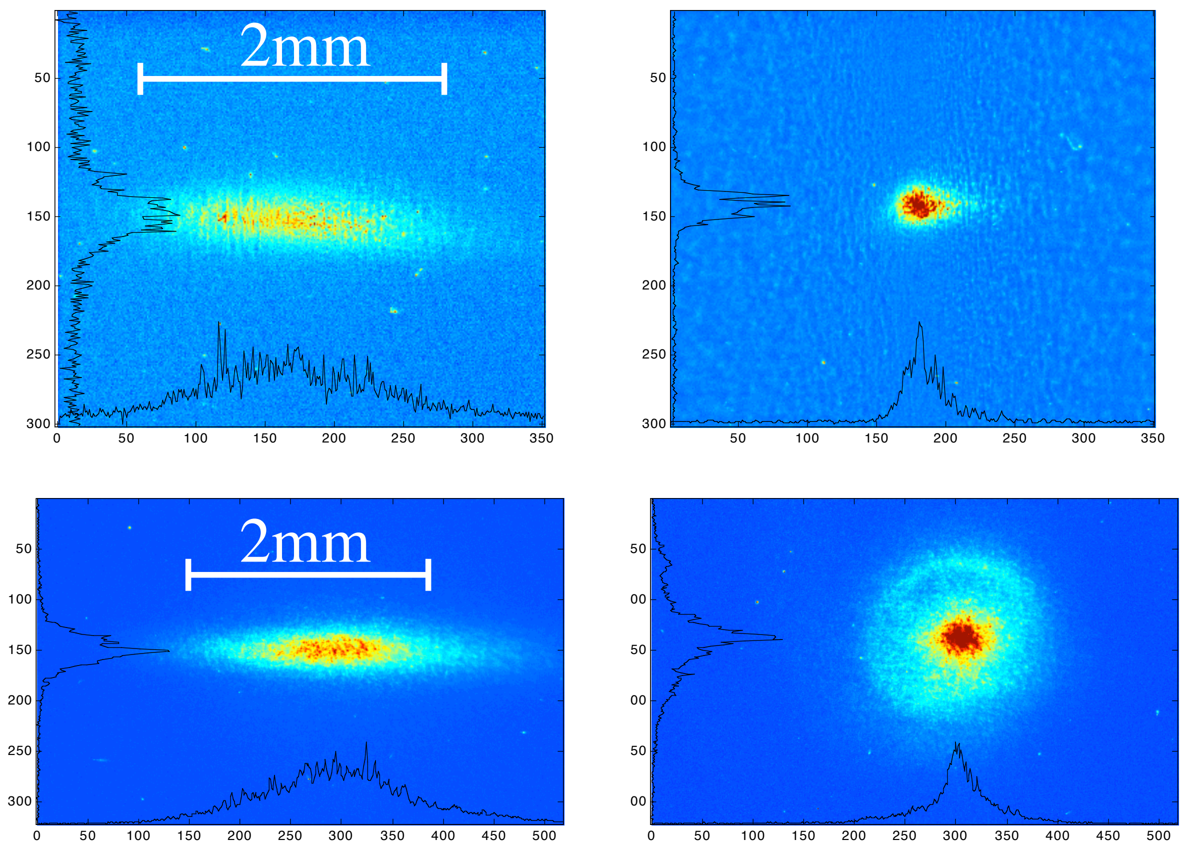
FOCUSING OF e^-/e^+

- 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^+

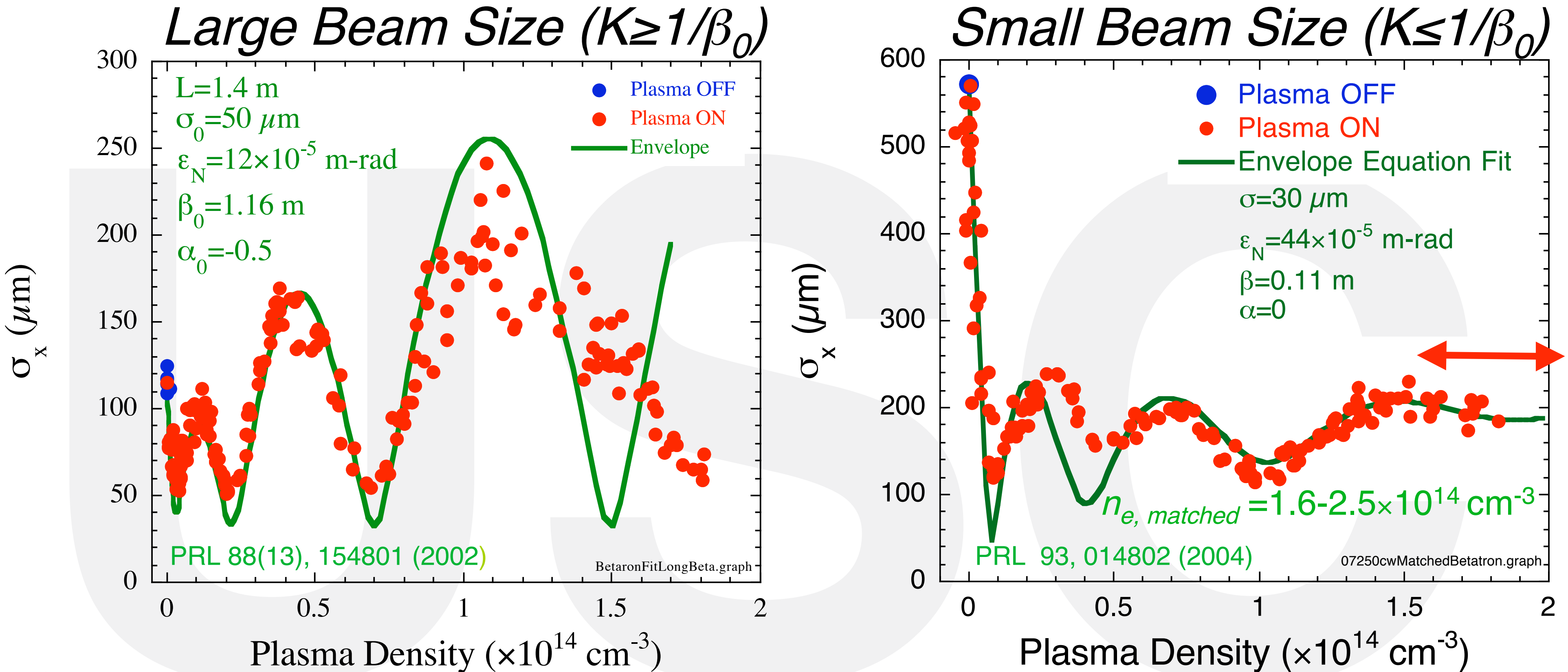


- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations, Halo

- Qualitative differences

FOCUSING OF e^-

OTR Images ≈1m downstream from plasma



- 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

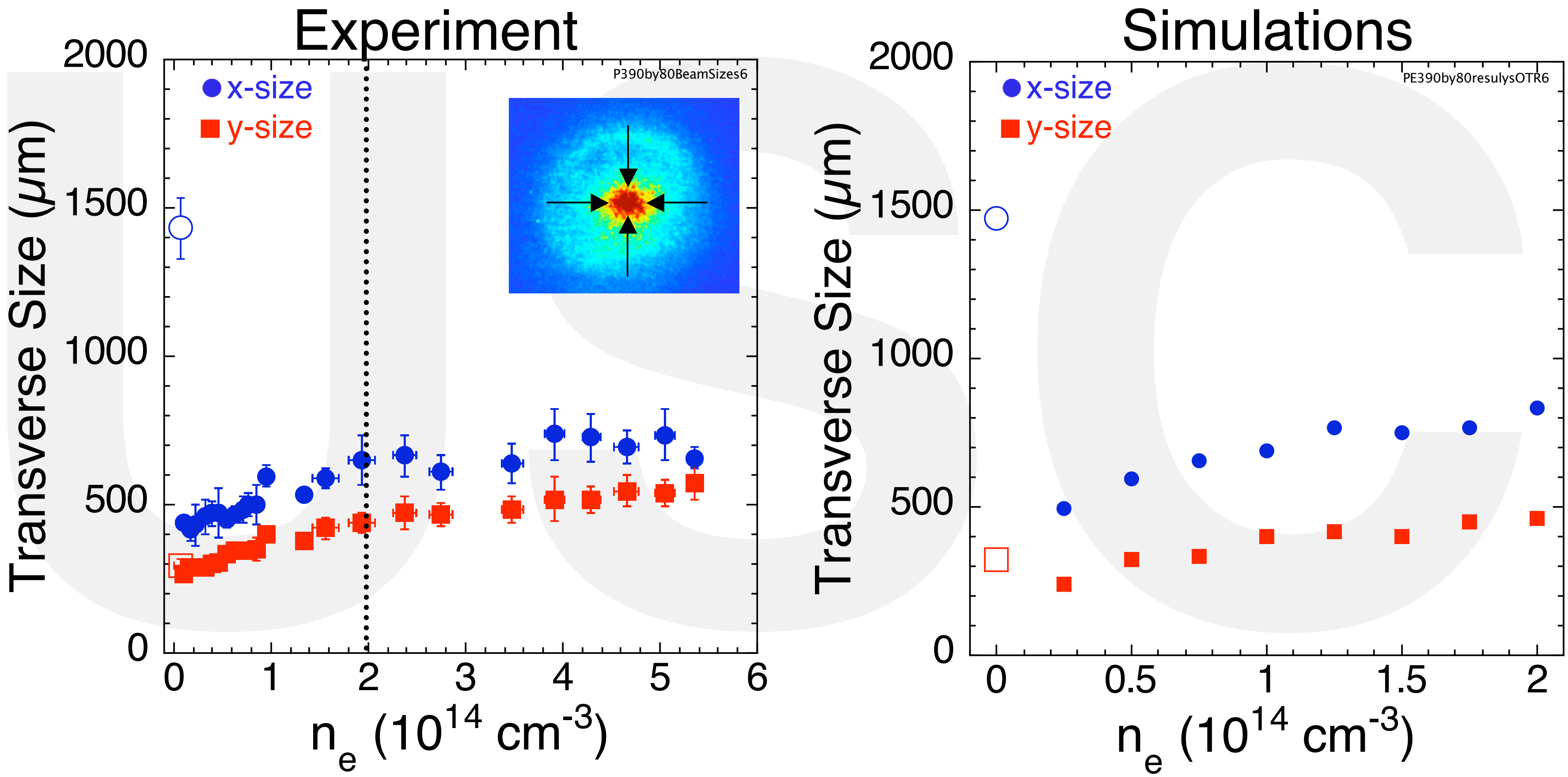
=> Matched Propagation over long distance!

e^-

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 $n_e\neq0$

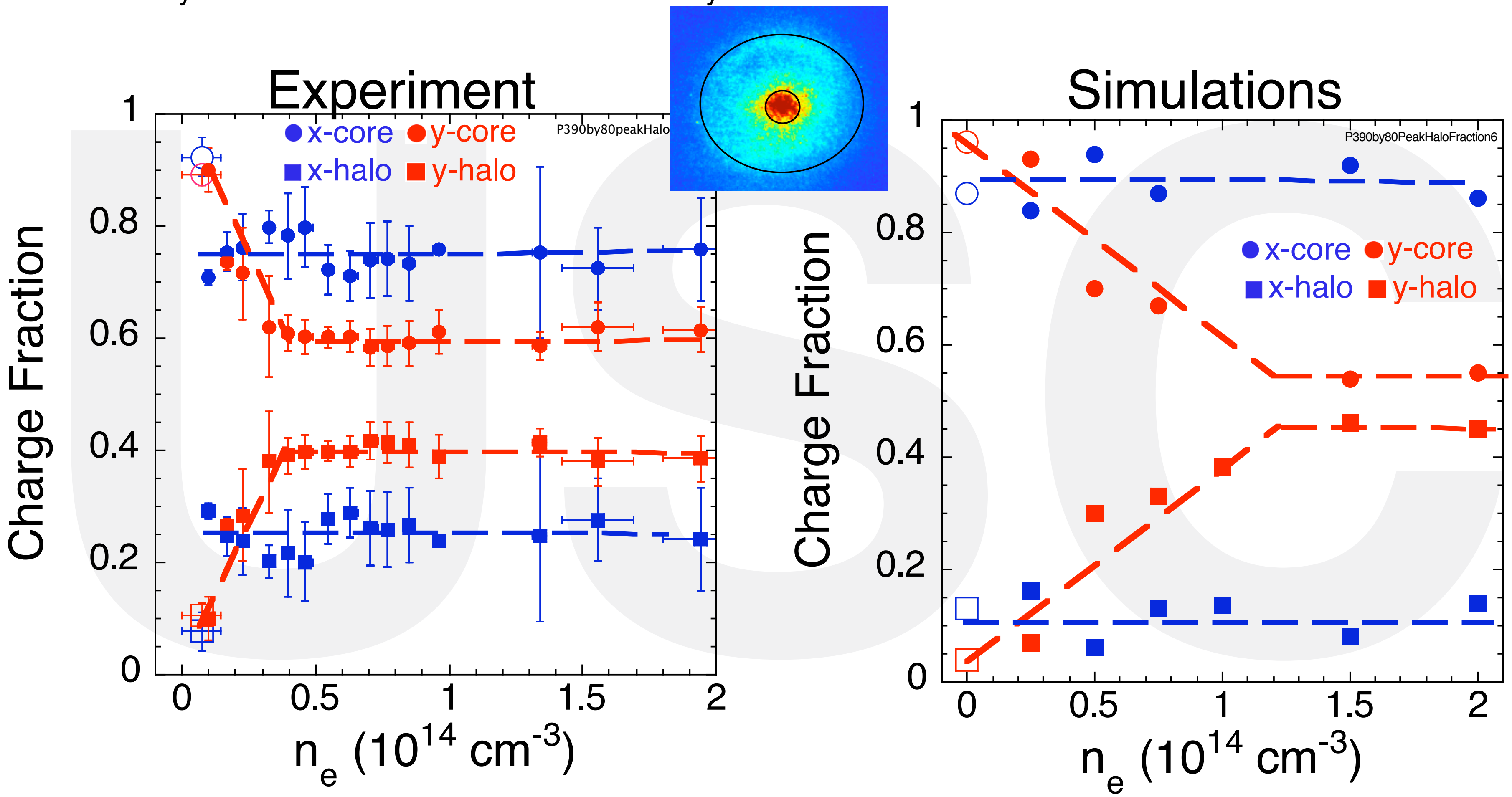
P. Muggli *et al.*, PRL 101, 055001 (2008).

e^+

EXPERIMENT/SIMULATIONS: HALO FORMATION

USC UNIVERSITY OF SOUTHERN CALIFORNIA

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



- Very nice qualitative agreement
- Simulations to calculate emittance

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

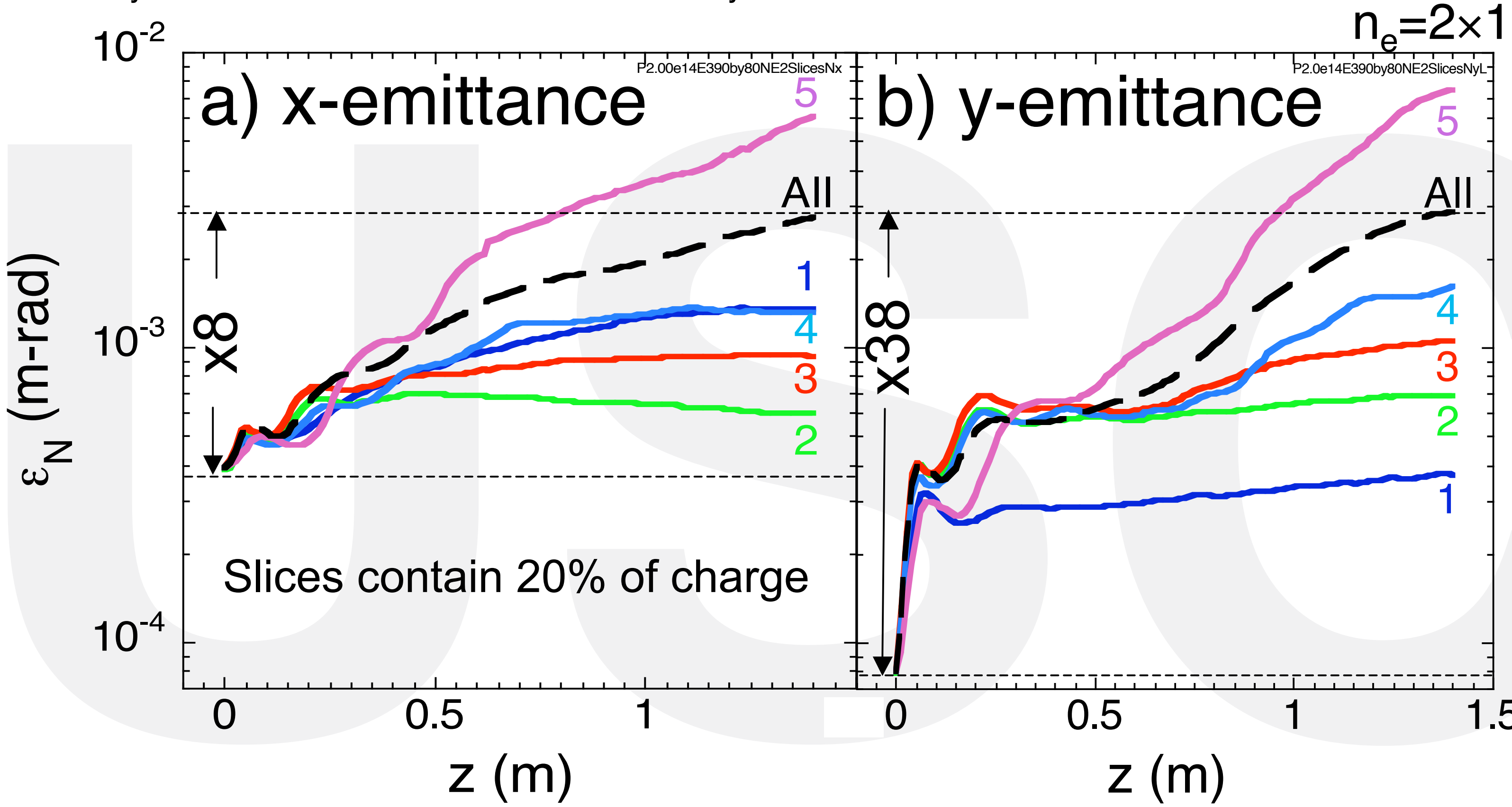
e^+

e^+: SLICE EMITTANCE (SIMULATIONS)

UNIVERSITY OF SOUTHERN CALIFORNIA

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

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

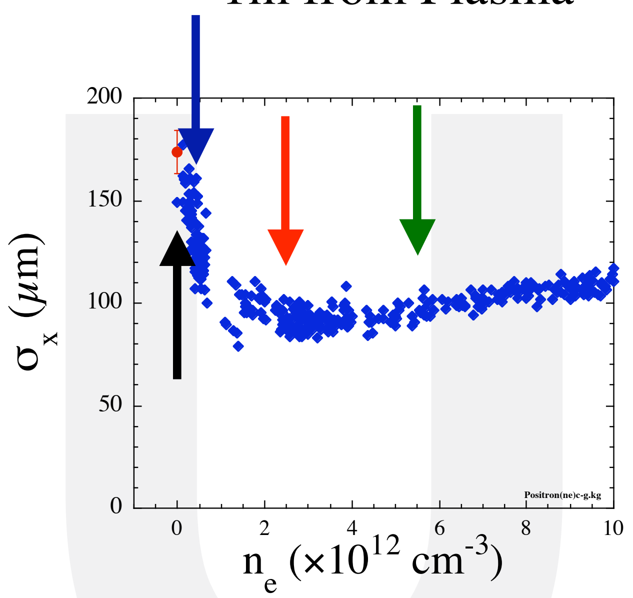


♦ The e^+ beam exits the plasma with ≈equal emittances and ≈equal transverse sizes

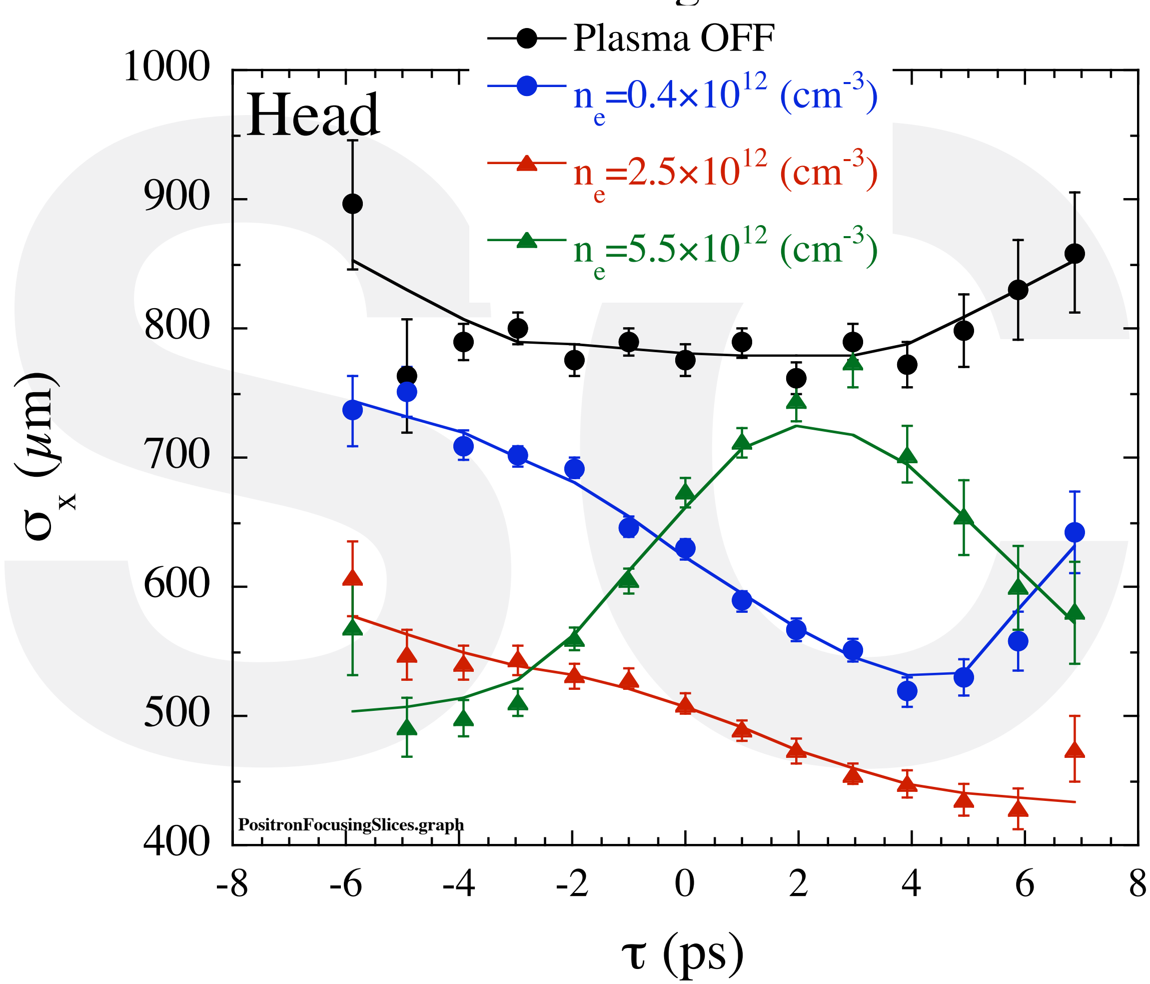
P. Muggli *et al.*, PRL 101, 055001 (2008).

e^+

FOCUSING OF e^+: LOW n_e



N=1.9×10^{10}



- Focusing dynamics

M. J. Hogan, PRL 90, 205002 (2003)

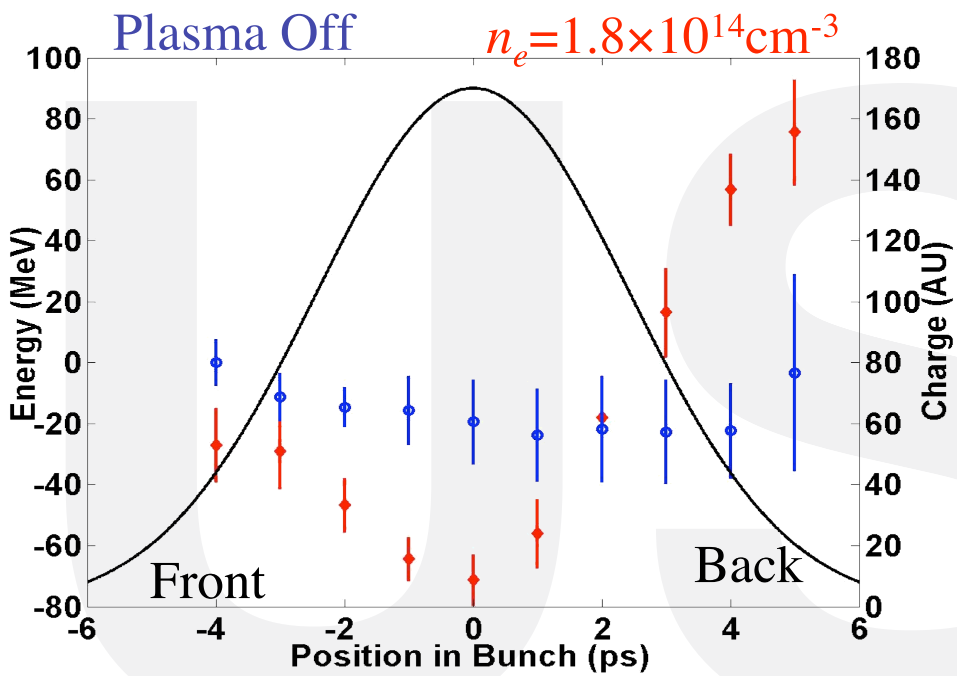
e^+

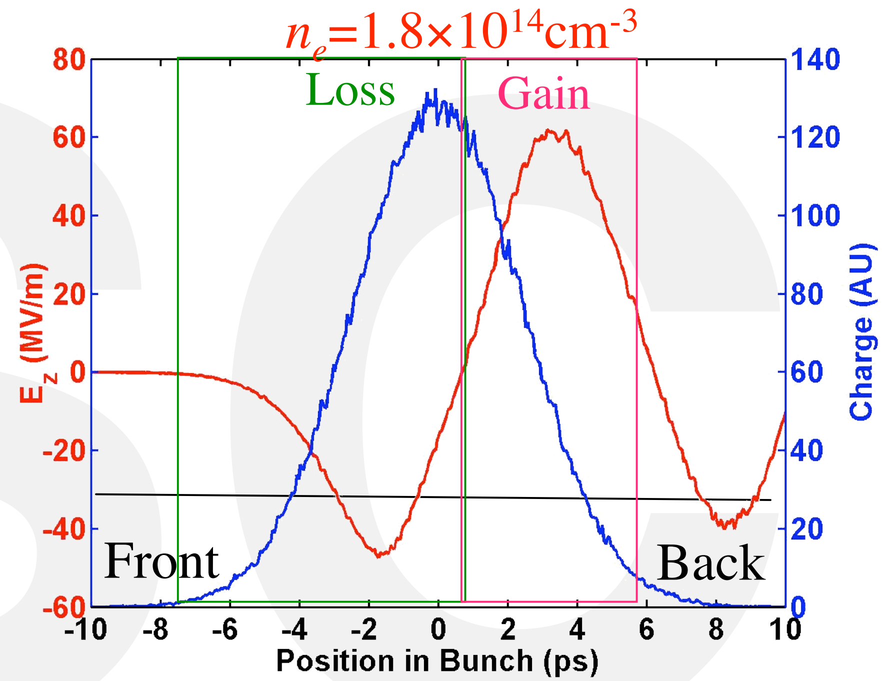
ENERGY LOSS/GAIN e^+

Experiment

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

2-D Simulation





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

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

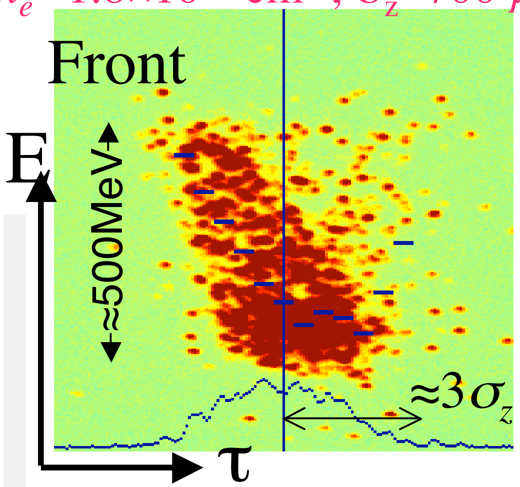
➡ Excellent agreement!

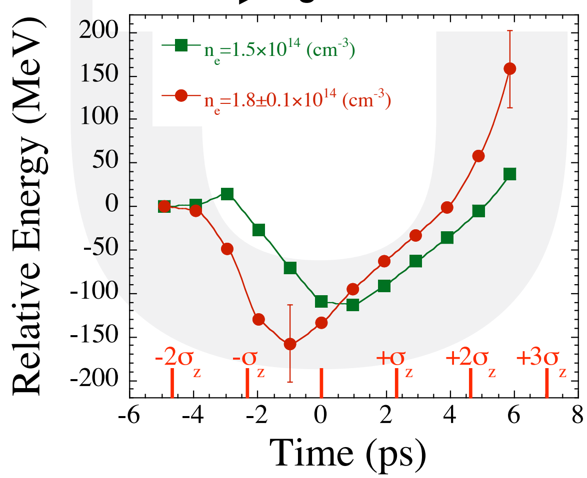
PRL 90, 214801, (2003)

e^+

e^- ACCELERATION

n_e=1.8×10^{14} cm^{-3}, σ_z≈700 μm



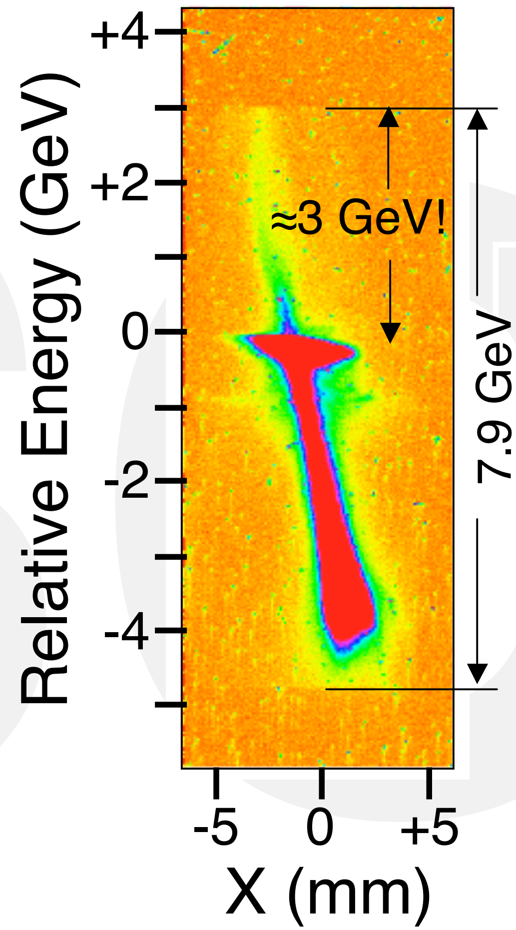


- Gain≈280 MeV, L_p=1.4m
  Gradient≈200 MV/m

Muggli et al., PRL 93, 014802 (2004)

Long	Short
Bunch	
Pre-	Self-
Ionized	
ΔE<	ΔE>>
ΔE_0	

n_e=2.6×10^{17} cm^{-3}, σ_z≈20-30 μm



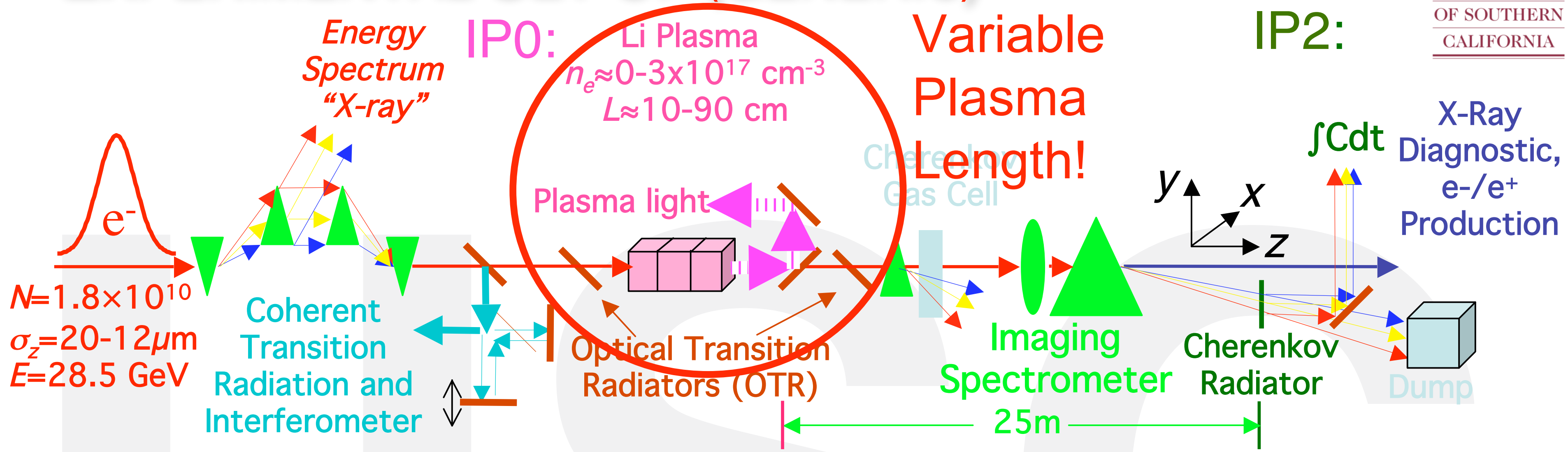
- Gain≈4 GeV, L_p=10cm
- Gradient≈40 GV/m

Hogan et al., PRL 95, 054802 (2005)

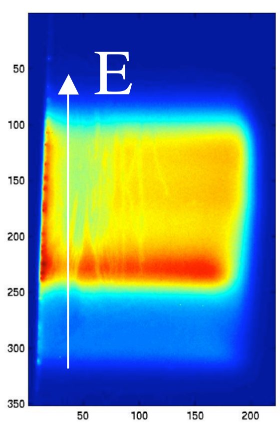
- No time resolution needed anymore!!!!

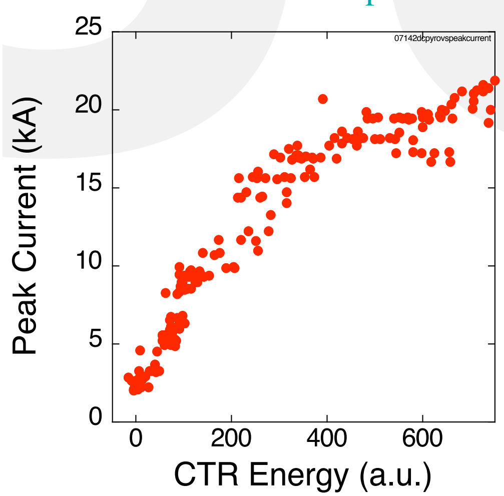
EXPERIMENTAL SET UP (GENERIC)

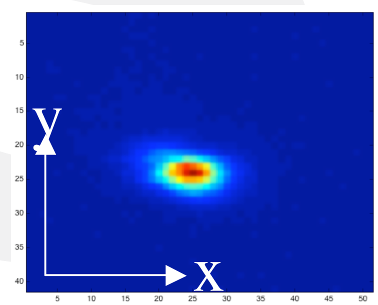
USC
UNIVERSITY OF SOUTHERN CALIFORNIA

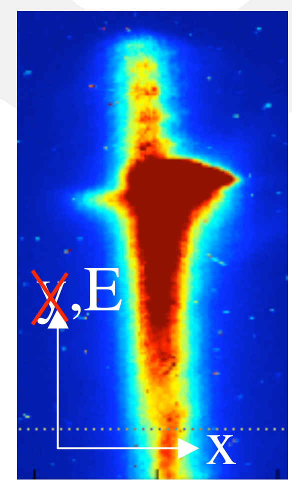


- X-ray Chicane
- Coherent Transition Radiation (CTR)
  - CTR Energy≈I_{peak}≈$1/\sigma_z$
- OTR
  - Spatial
  - resolution ≈9 µm
- Cherenkov (aerogel)
  - Spatial resolution ≈100 µm
  - Energy resolution ≈30 MeV



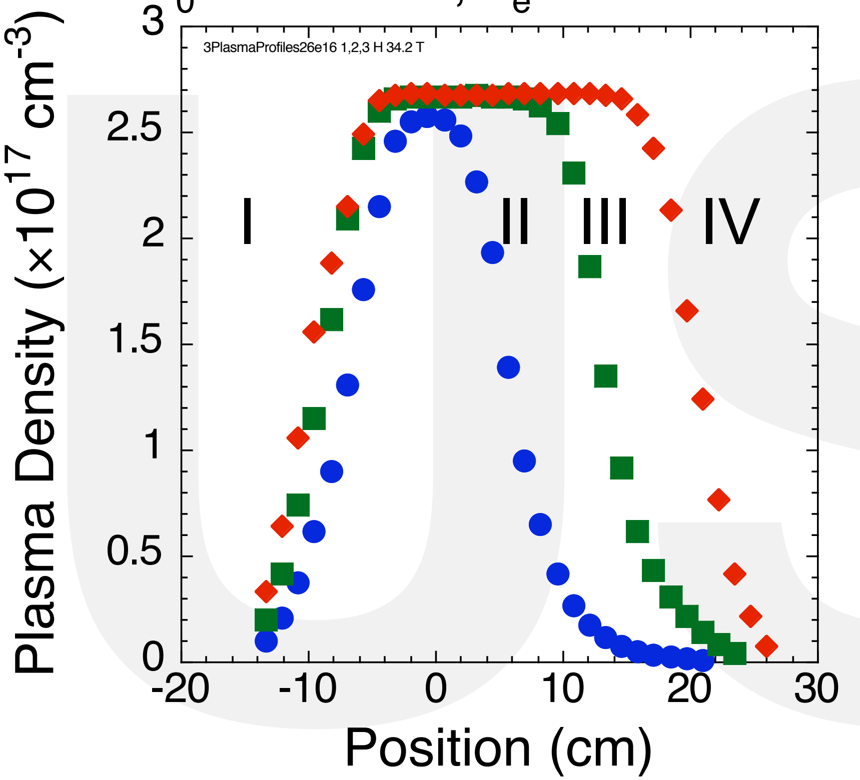






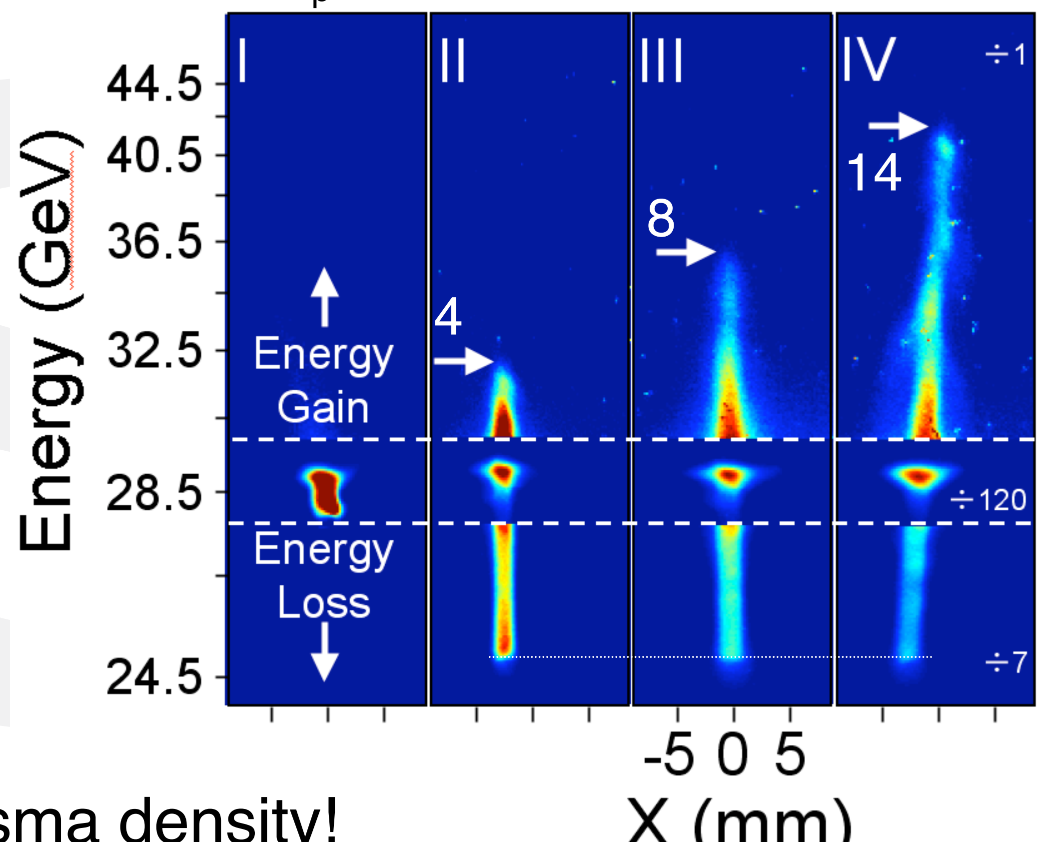
$\sigma_z \approx 25\ \mu m$: SCALING WITH PLASMA LENGTH

E_0=28.5 GeV, n_e=2.7x10^{17} cm^3



Same incoming beam! $\sigma_z \approx 25\ \mu m$

L_p=0, 13, 22, 31 cm

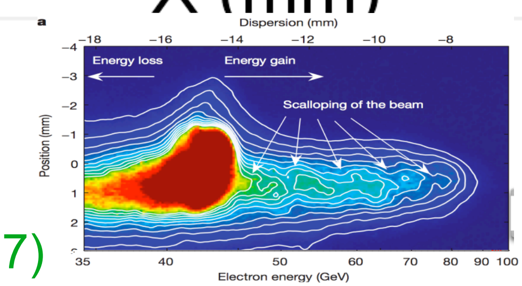


➡ Energy gain scales with plasma density!

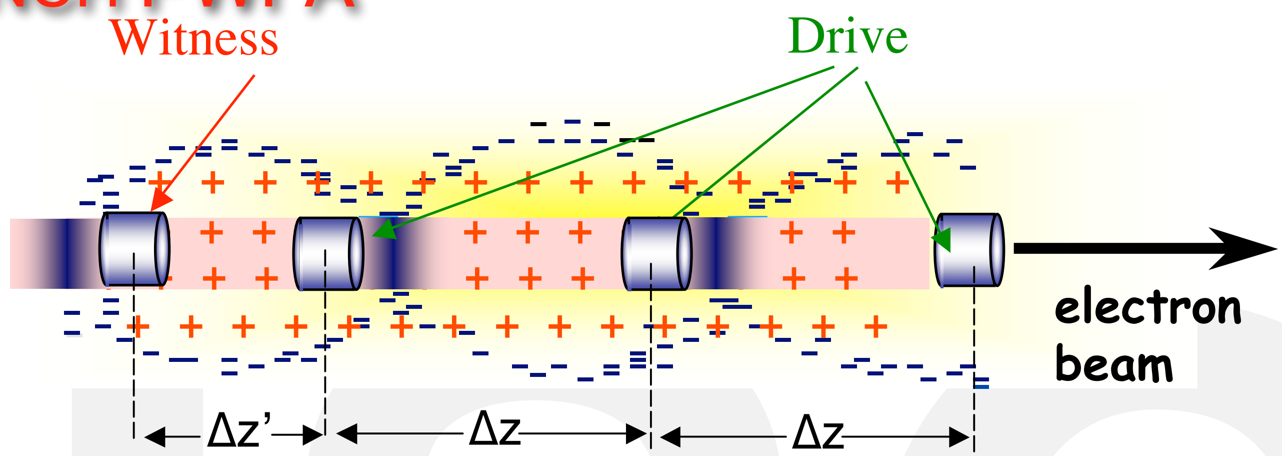
➡ Gain >14 GeV over (only!) L_p=31 cm!

➡ $E_{acc} \approx 45$ GV/m

➡➡ Nature 445, 741(2007)



MULTIBUNCH PWFA



- Bunch spacing/plasma density condition:

  $\Delta z=\lambda_p$ (resonance) $\sigma_z \leq \lambda_p/2$

  $\Delta z' \approx (m+1/2)\lambda_p$

  Plasma wavelength: $\lambda_p = \dfrac{2\pi c}{\omega_{pe}}$ Plasma angular frequency, density n_e: $\omega_{pe} = \left(\dfrac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$

- Wake fields add up (linear theory):

  $E_{z\ N\ bunches} = N \times E_{z\ 1\ bunch}$ (Maximize wakefield!)

- Maximize transformer ratio with "shaping" (beyond energy doubling!)

- Finite energy spread, beam acceleration

MULTIBUNCH PWFA

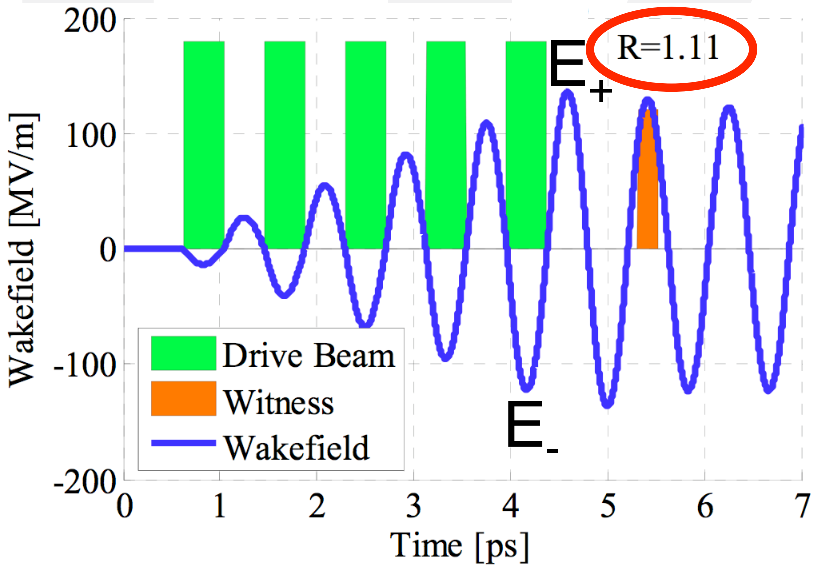
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

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

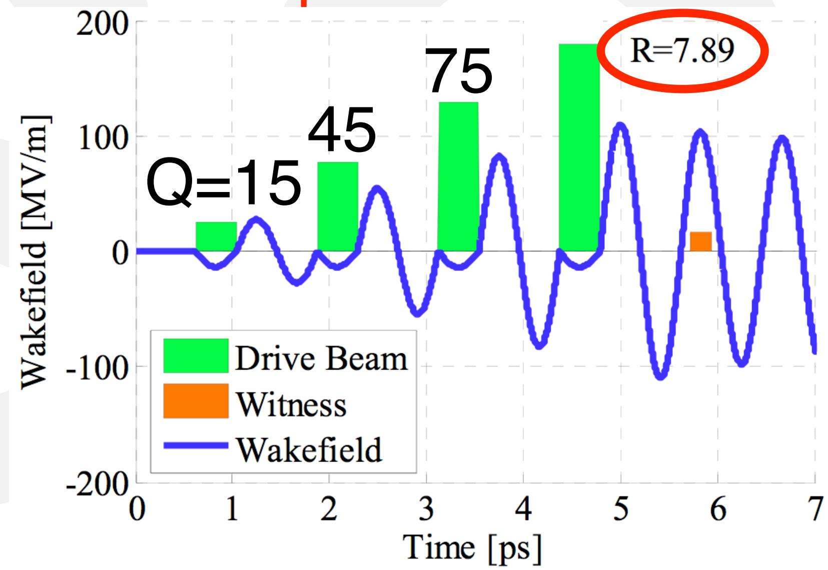
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*



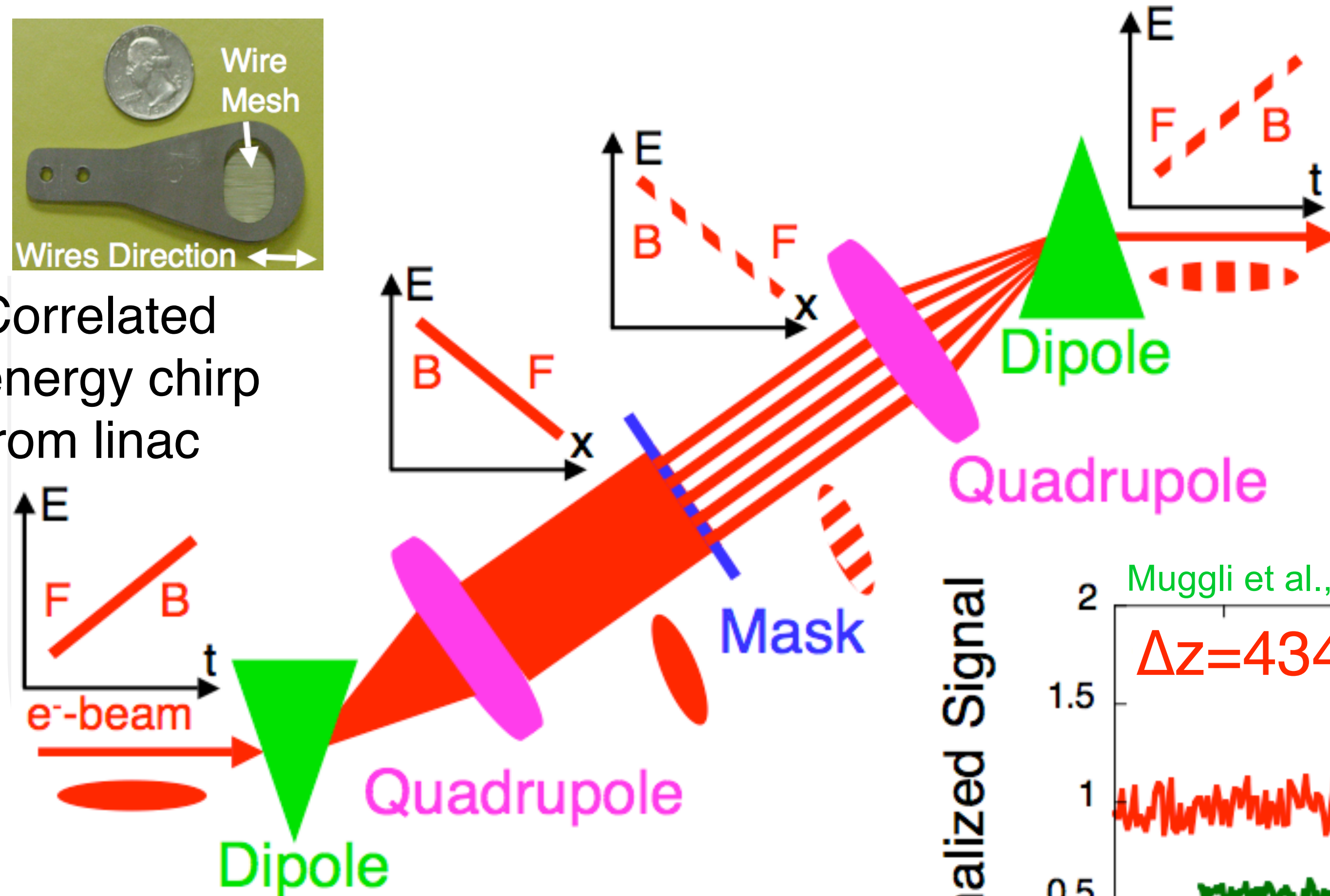
*Tsakanov, NIMA, 1999

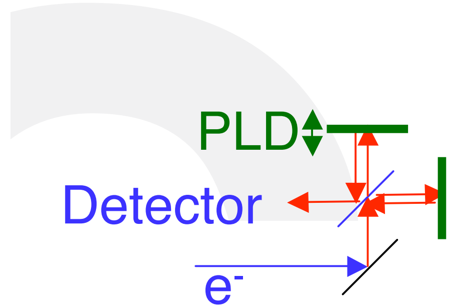
➡ R=7.9 => multiply energy by ≈8 in a single PWFA stage!

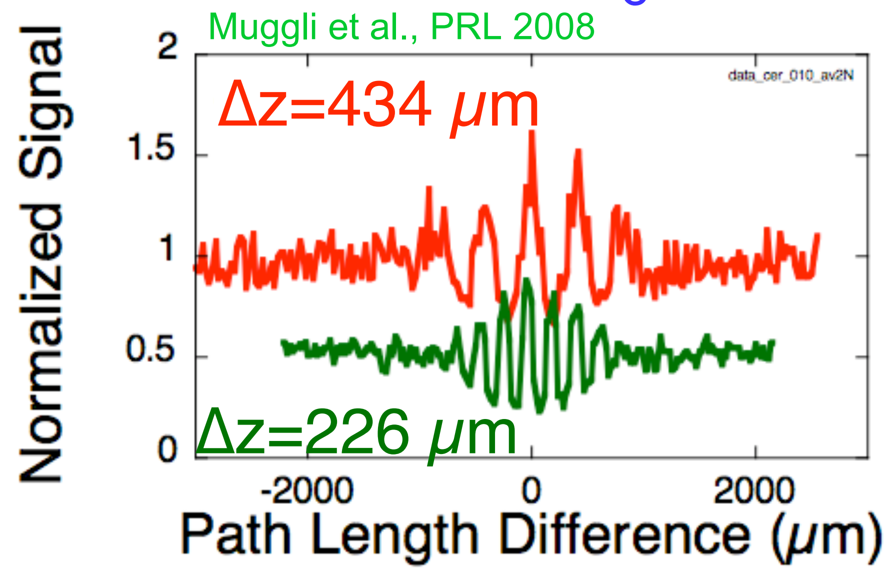
MULTI-BUNCH SOURCE

USC
UNIVERSITY
OF SOUTHERN
CALIFORNIA

Correlated energy chirp from linac



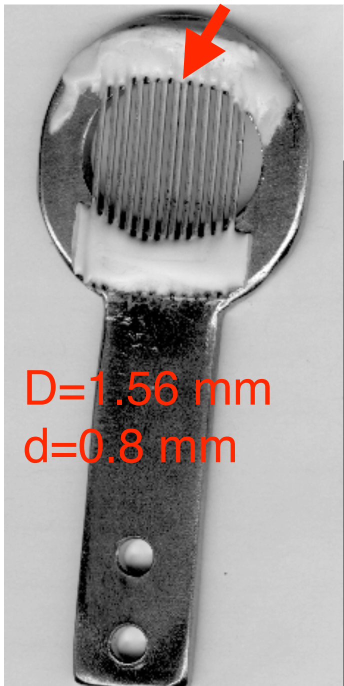


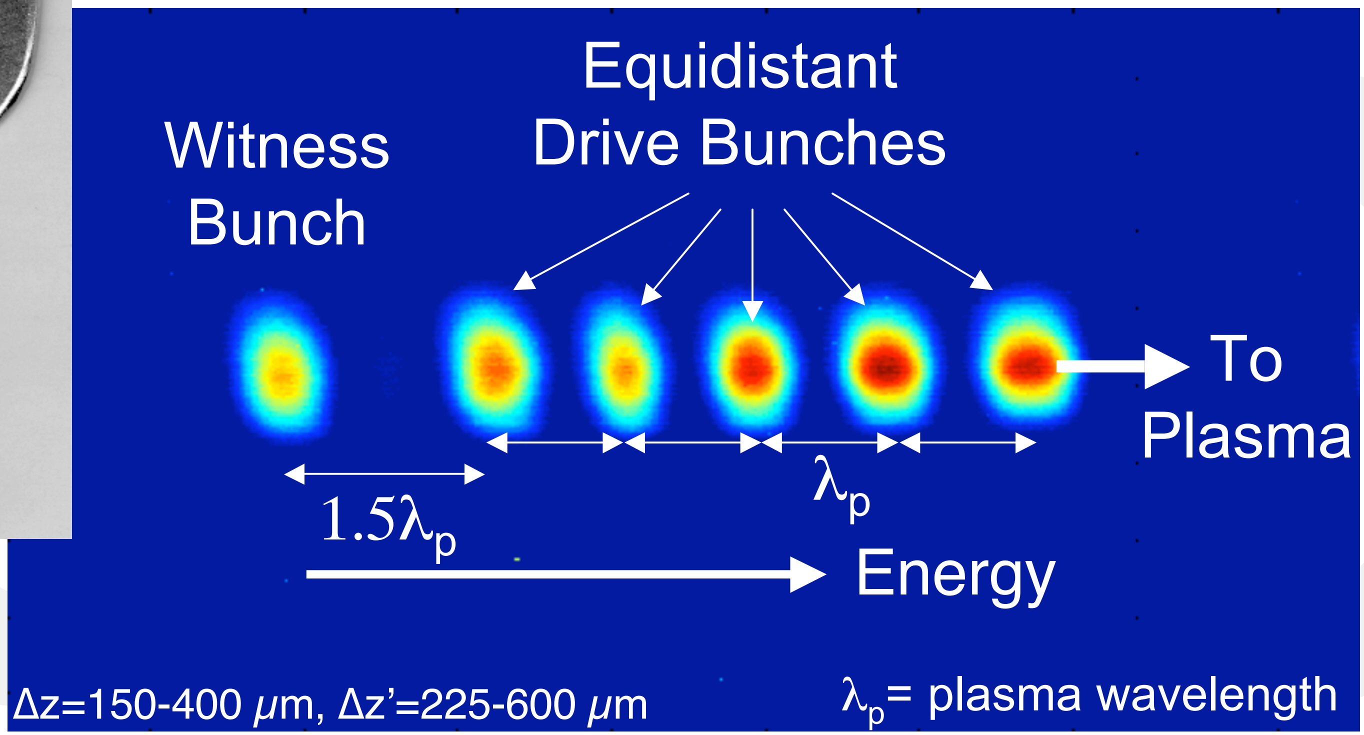


- Emittance selection
- Mask+Slit
- Choose microbunches spacing and widths with mask and beam parameters: N, Δz, σ_z, Q

TRAIN FOR PWFA

Mask with non-equidistant "wires"
Measurement in energy plane

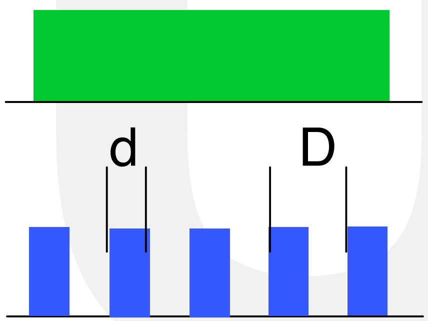


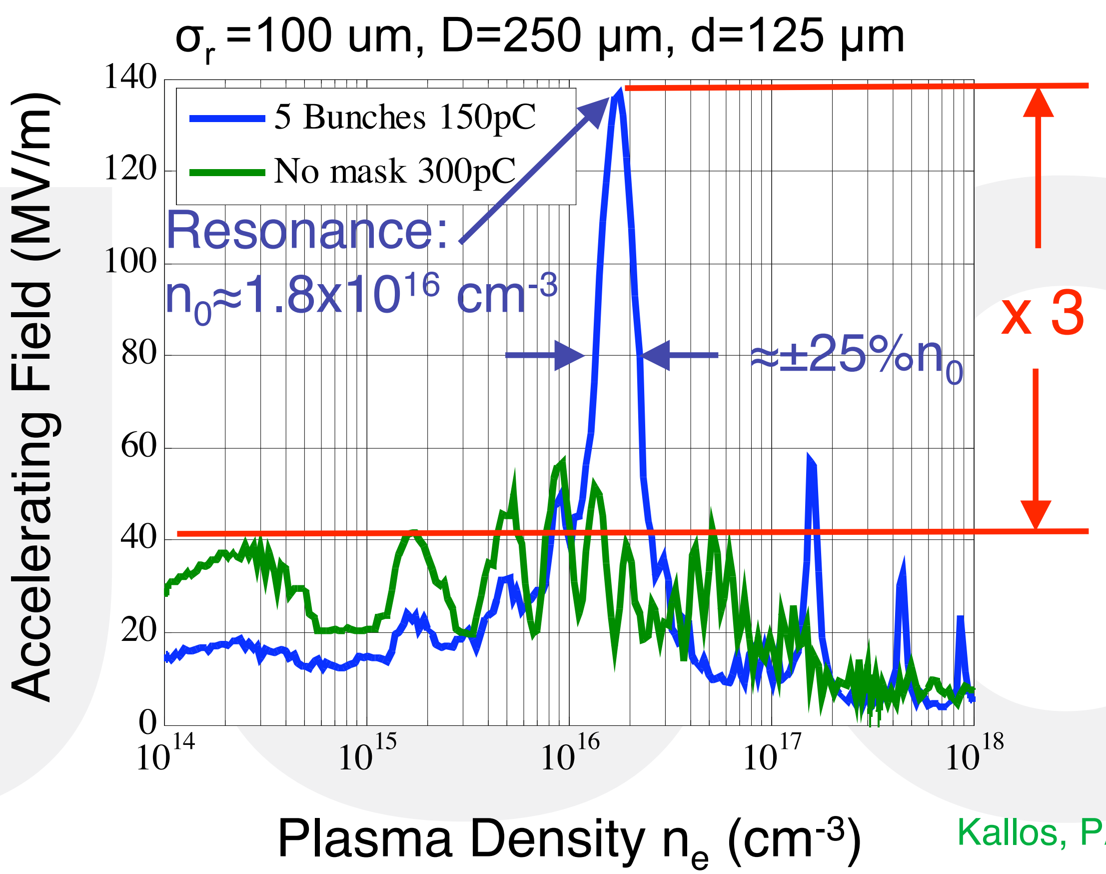


- Generate "ideal" spacing for resonant PWFA
- Charge modulation optimization possible
- Plasma density must be adjusted for resonant excitation

ACCELERATING FIELD

Linear calculation microbunches with equal charge

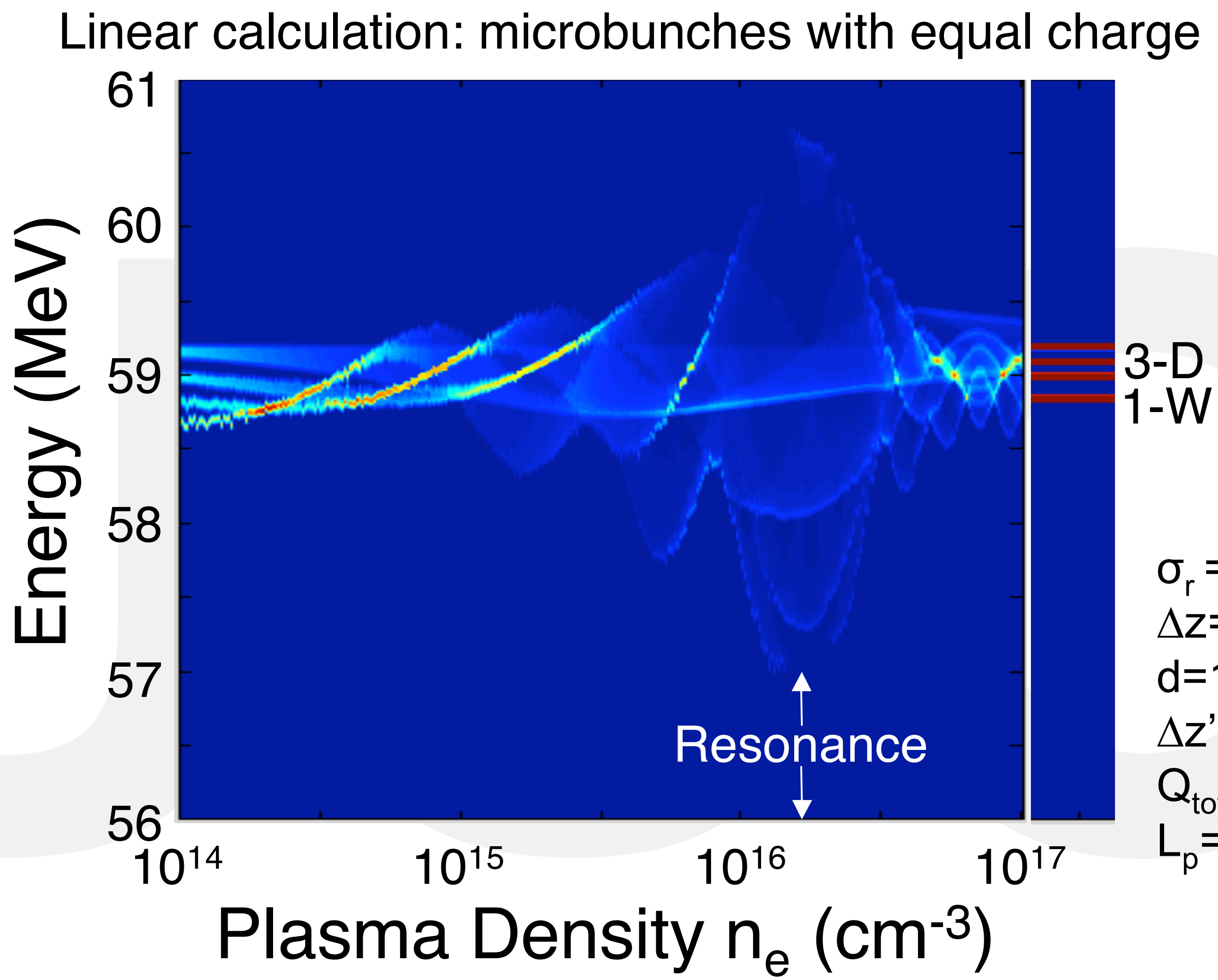




Kallos, PAC'07 Proceedings

- Expect ≈MeV energy gain/loss over 1 cm
- Microbunch resonance clear, and narrow
- Drive larger wakefields with the train ($<Q_0/2$) than with the long bunch!

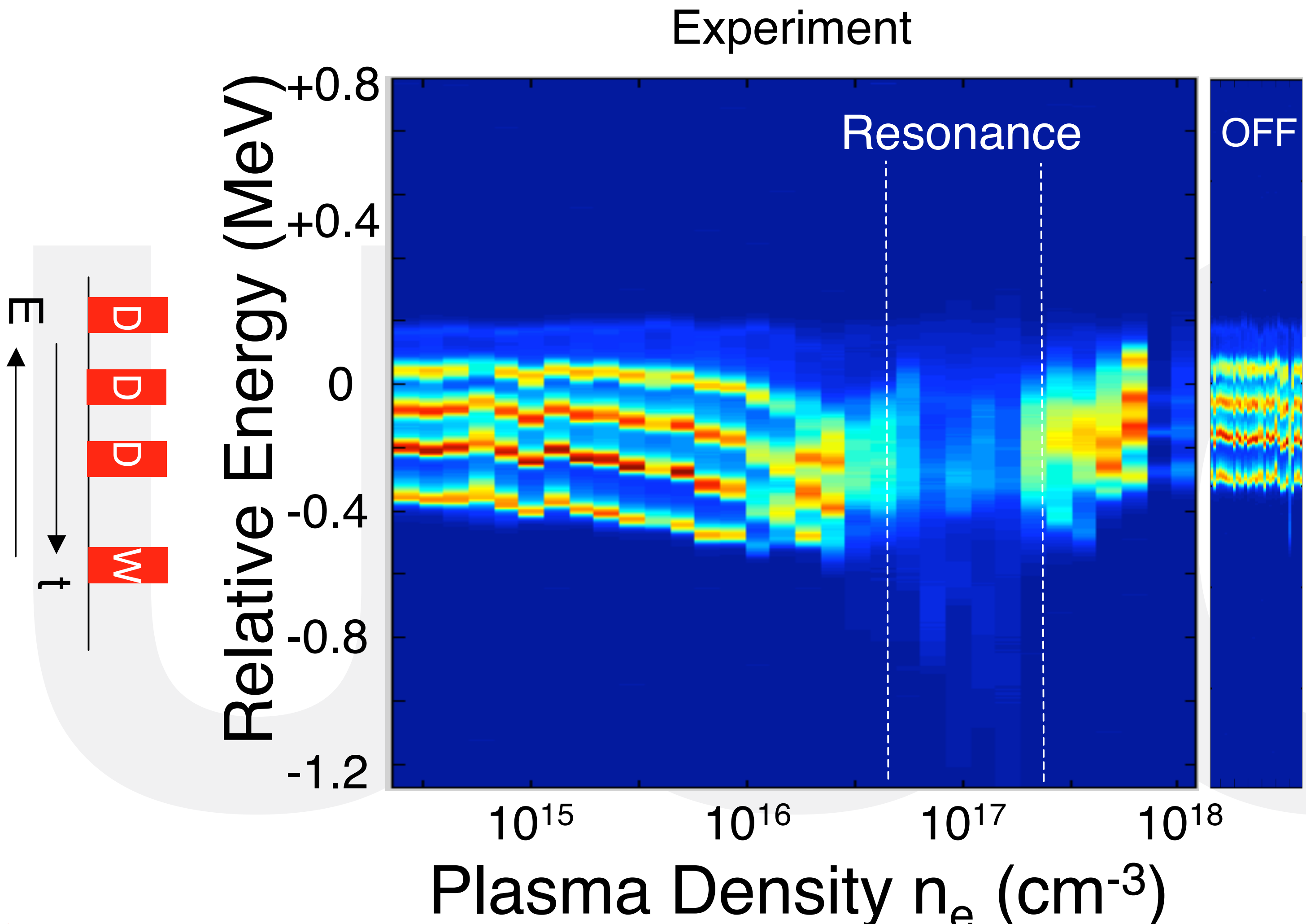
ENERGY CHANGE



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!

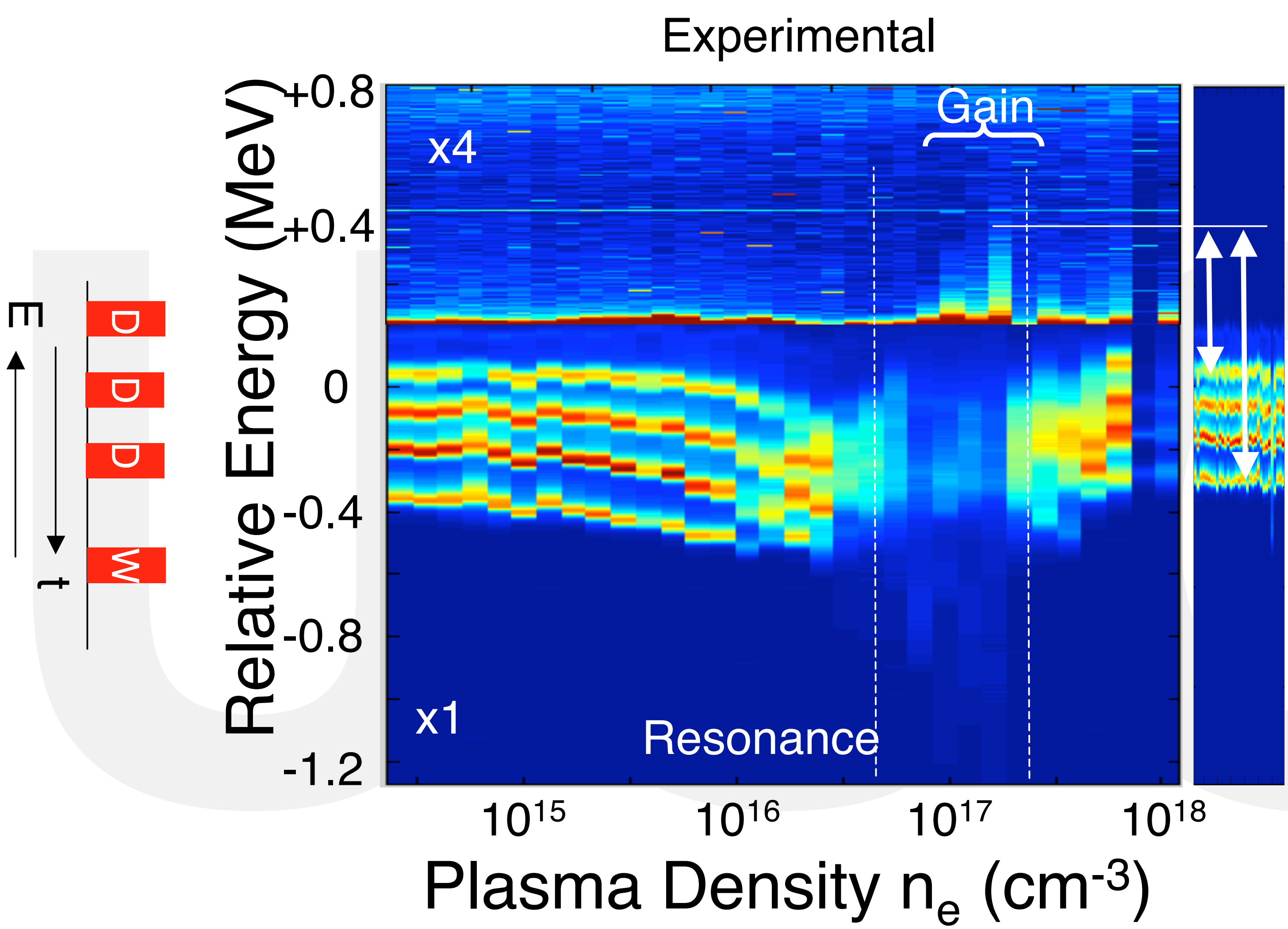
ENERGY CHANGE



- Resonance clearly observed
- Large energy loss, >0.8 MeV or >40MeV/m
- Energy gain?

P. Muggli, PPA 09. 09/12/17

ENERGY CHANGE



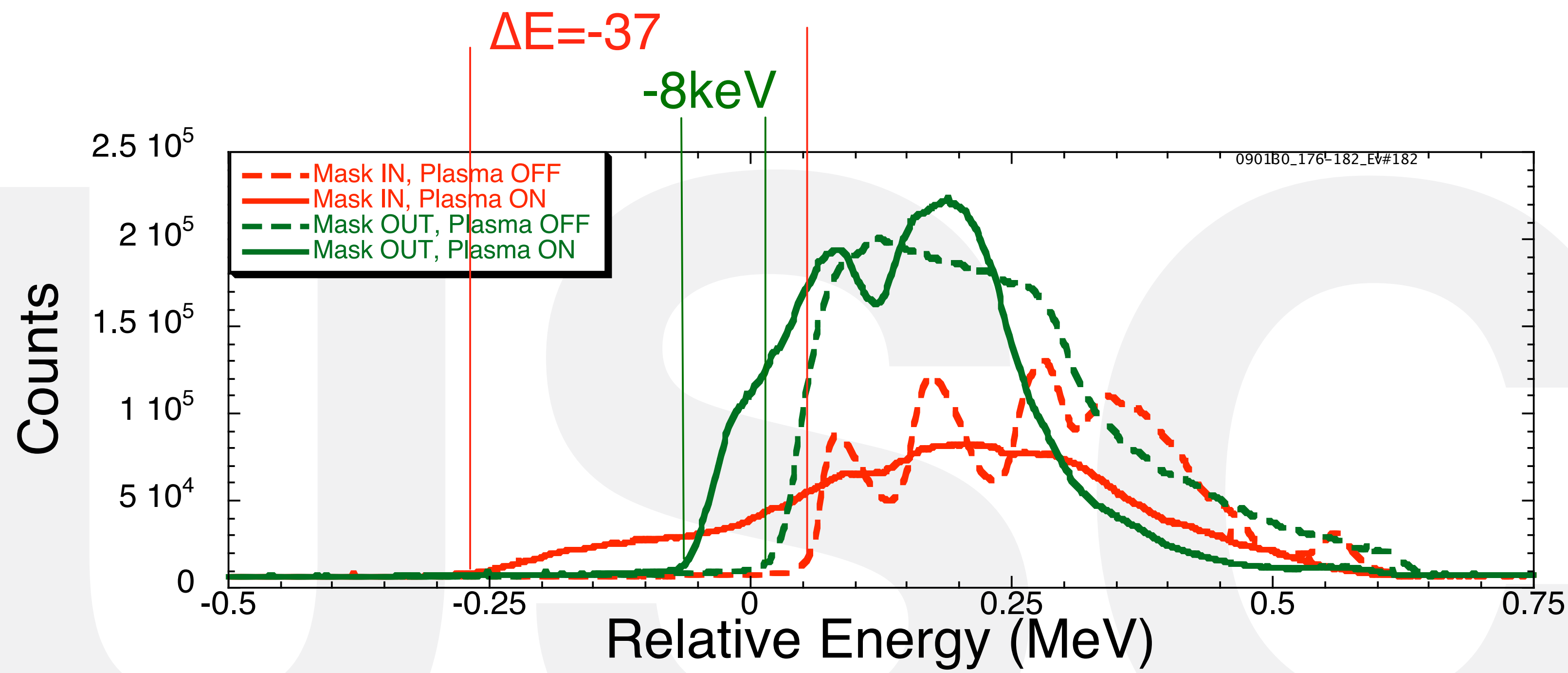
σ_r =100 um,
Δz=350 μm

0.2-0.7 MeV

- Energy gain, up to 0.7 MeV?
- Stability of $\Delta E/E_0$ => stability of Δz!

- More experiments needed!

RESONANT DENSITY INTERACTION



- Much larger loss with microbunches at/near resonance
- Drive large wakefield with half the charge and large n_e
- Decelerating gradient with μbunches ≈18 MV/m

CONCLUSIONS

- Wealth of experience in e^-/e^+ PWFA experiments at SLAC and BNL-ATF
- Very well diagnosed experiments built over time
- "Perfect" plasma source: field free, stable, …
- Many optical diagnostics for info within the bunch (OTR, Cher., CTR)
- Magnetic spectrometer is key
- Understanding "all" aspects of the PWFA is important
- Masking technique for long p^+ bunches?
- Many more results not presented
- Experience acquired with e^-/e^+ transfers to PPA

Thank You!

Mozambique: suggested location for the next PWFA experiments