Experiments with e^+ at FFTB*

*Final Focus Test Beam (SLAC)

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Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

ALEGRO
Advanced LinEar collider study GROup

MAX-PLANCK-GESELLSCHAFT

OUTLINE

✧e^+ bunches in plasmas/wakefields driven by a e^+ bunch

✧Experiments with long e^+ bunch (700μm) and low plasma density ($<10^{13}$cm^{-3})

✧Experiments with long e^+ bunch (700μm) and high plasma density ($<5\times10^{14}$cm^{-3})

✧Thin passive plasma lens

✧ Acceleration

✧Conclusions

Comparisons/analogies with e^- bunch results

OUTLINE

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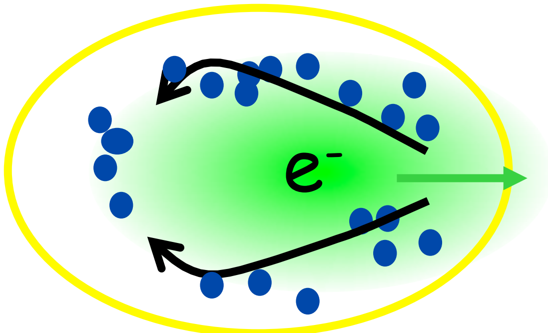
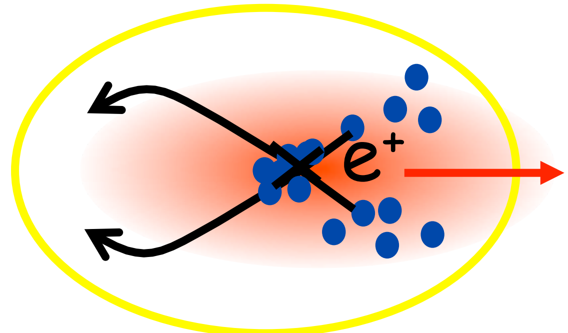
e^- & e^+ BEAM NEUTRALIZATION



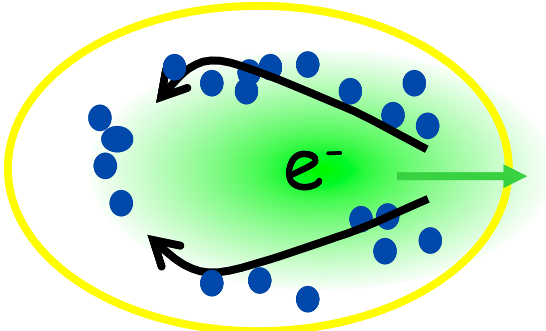


e^- & e^+ BEAM NEUTRALIZATION

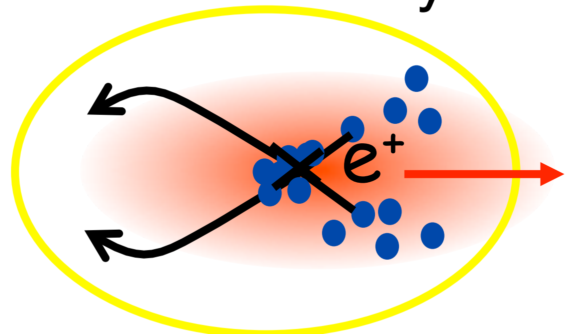
- ✧Main difference(s) in the transverse plane
- ✧Focusing ⇔ space charge neutralization
- ✧Impact emittance/charge/energy spread
- ✧Has to do with the bunch
- ✧e^+ can be accelerated in plasmas

e^- & e^+ BEAM NEUTRALIZATION

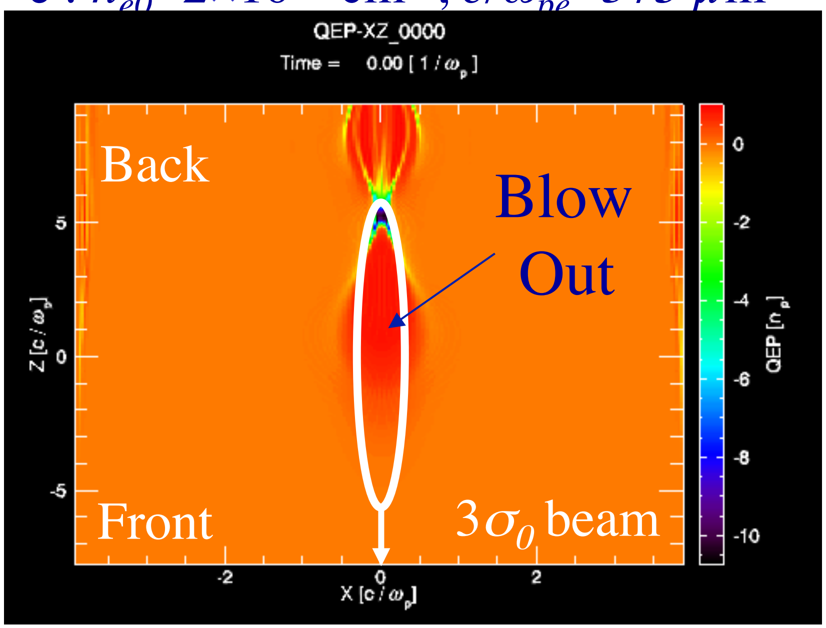
3-D QuickPIC simulations, plasma e^- density:



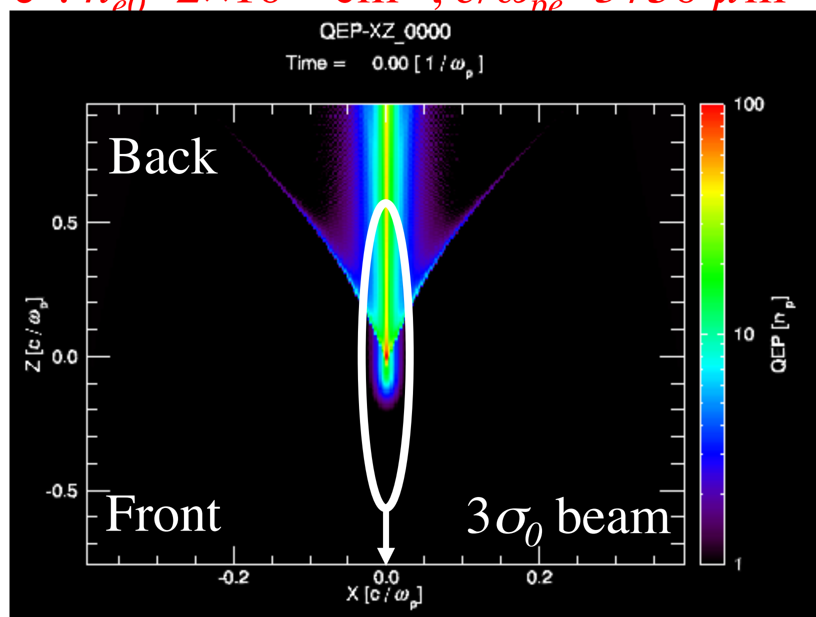
σ_r=35 μm
σ_r=700 μm
N=1.8×10^{10}
d=2 mm



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



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

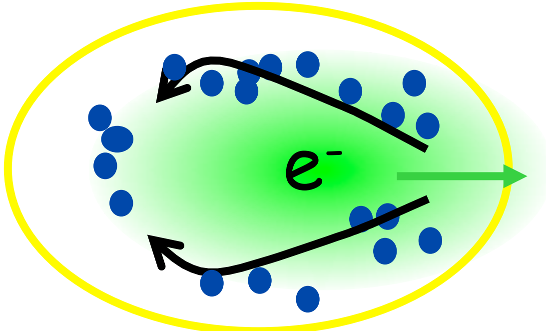


- Uniform focusing force (*r*,*z*)

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

e^- & e^+ BEAM NEUTRALIZATION

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



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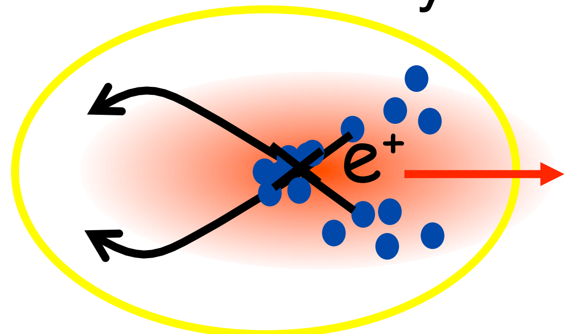

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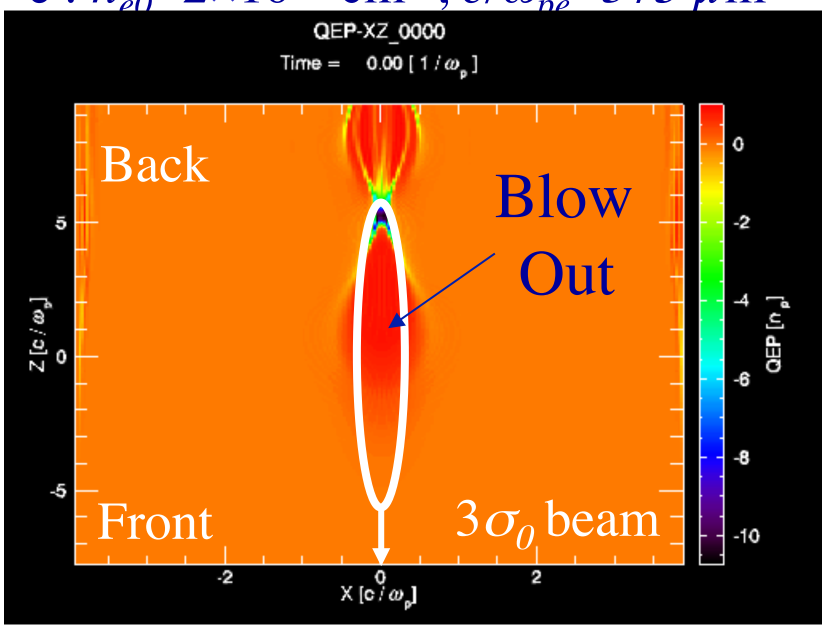

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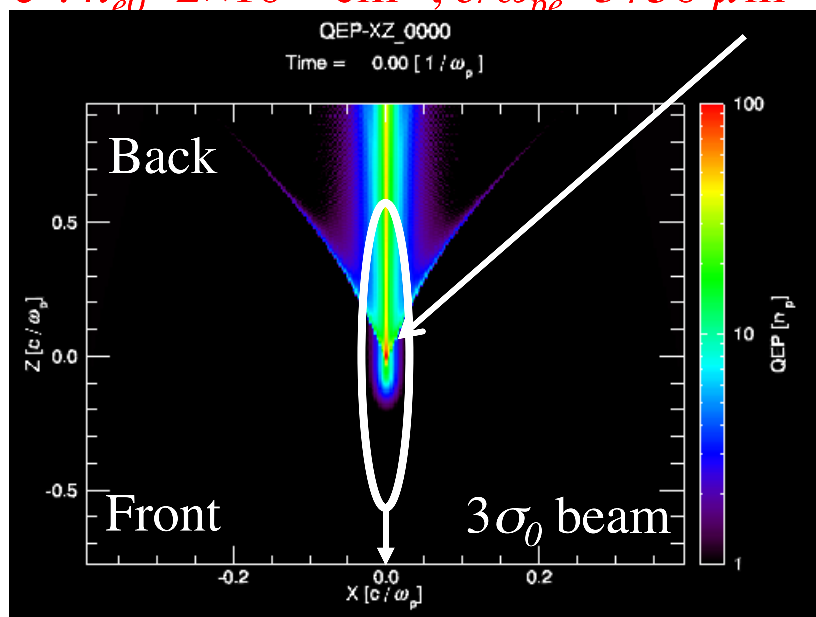
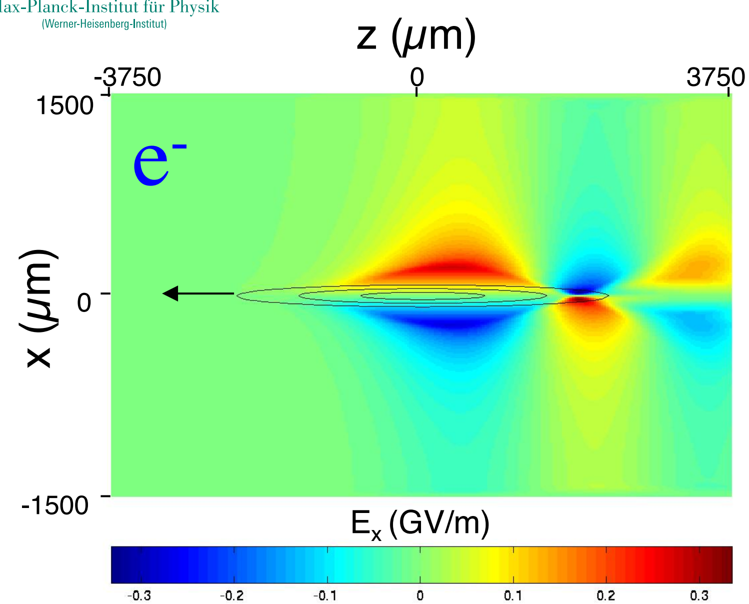
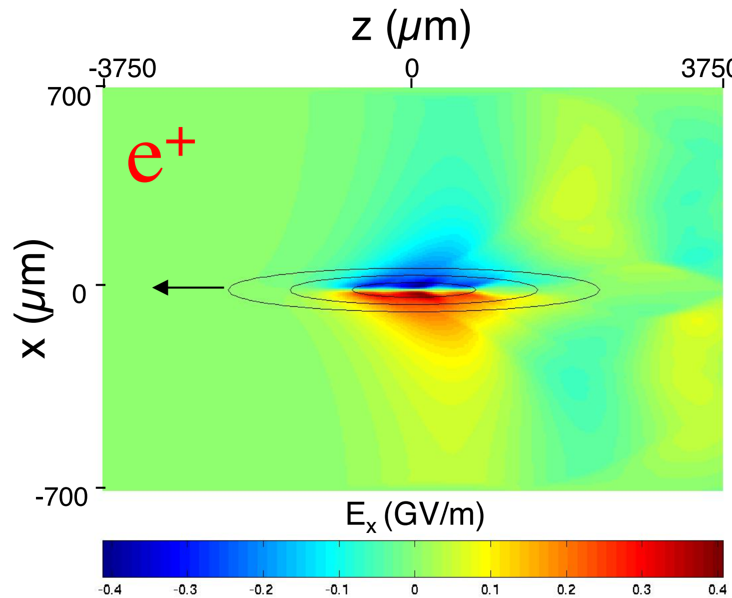


- Uniform focusing force (r,z)
- Non-uniform focusing force (r,z)

e^- & e^+ FOCUSING FIELDS*





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

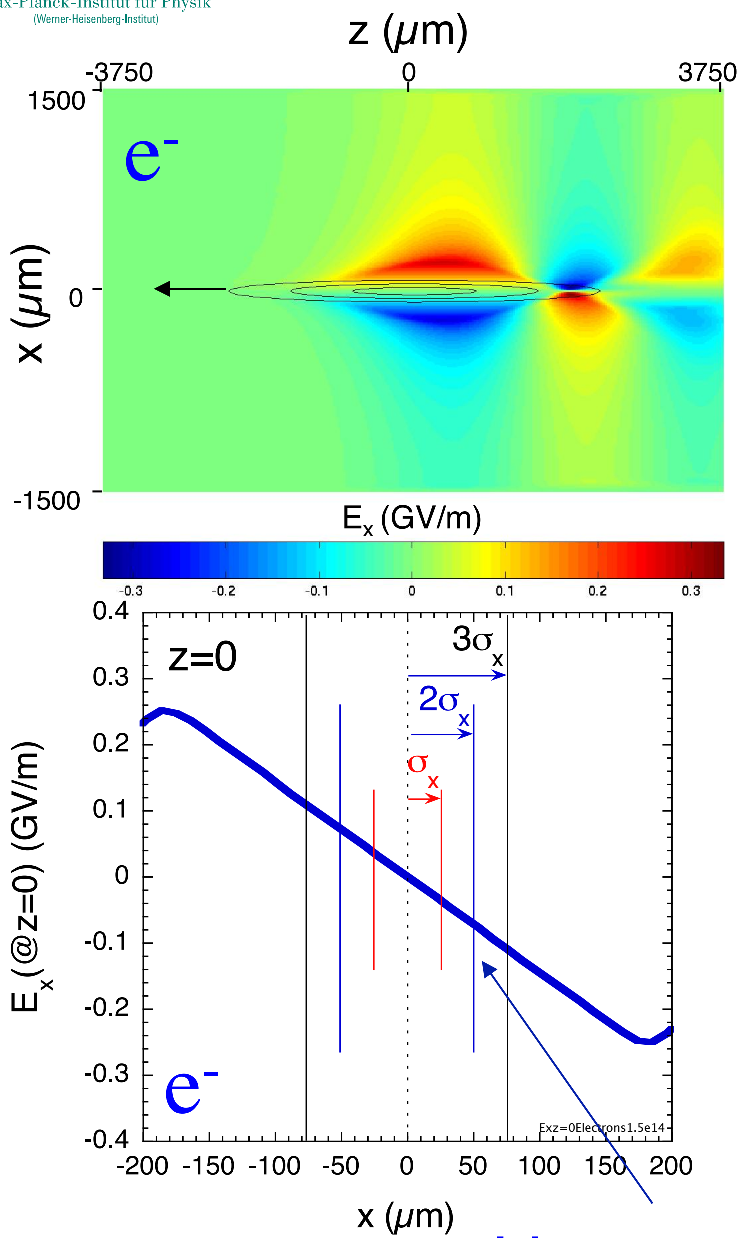
$\sigma_z=730\ \mu m$

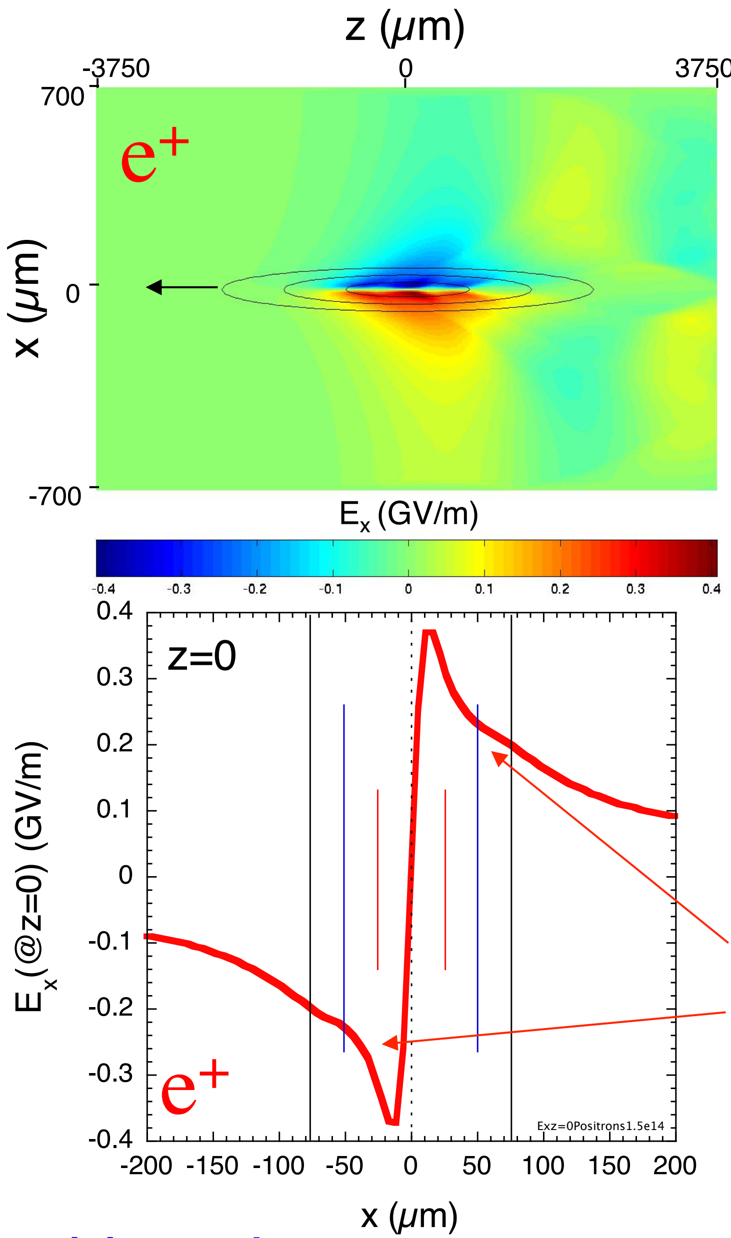
$N=1.9\times10^{10}\ e^+/e^-$

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

*QuickPIC

e⁻ & e⁺ FOCUSING FIELDS*





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

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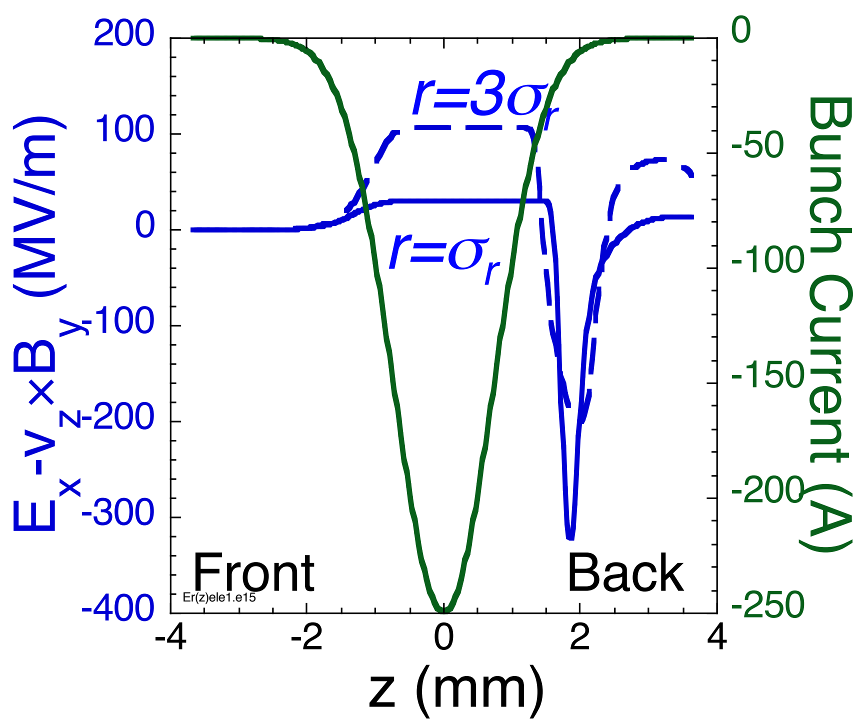
*QuickPIC

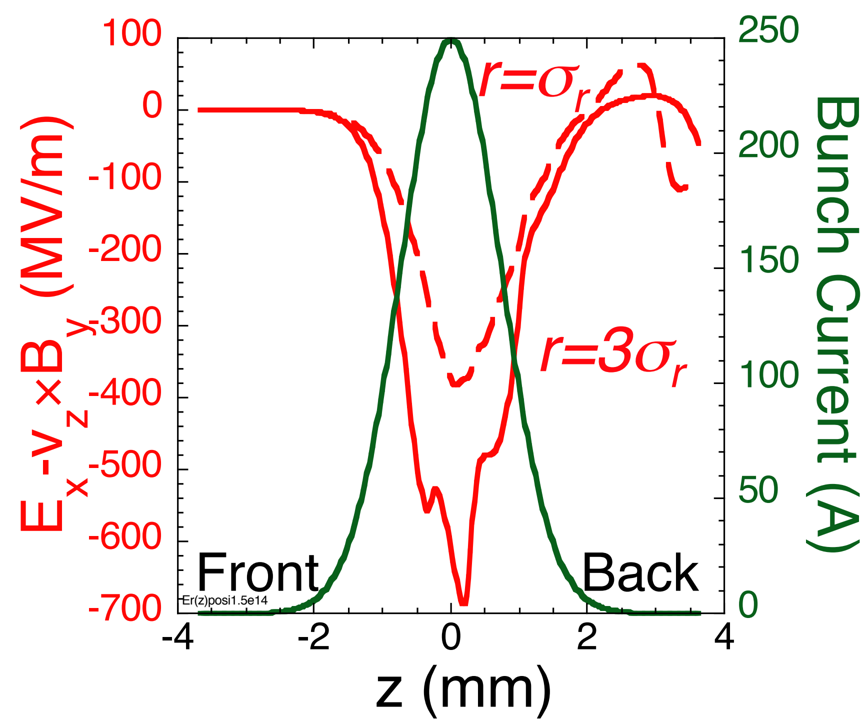
Non-linear, abberations

Linear, no abberations

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!

OUTLINE

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✧Experiments with long e^+ bunch (700μm) and high plasma density (<$5\text{x}10^{14}$cm^{-3})

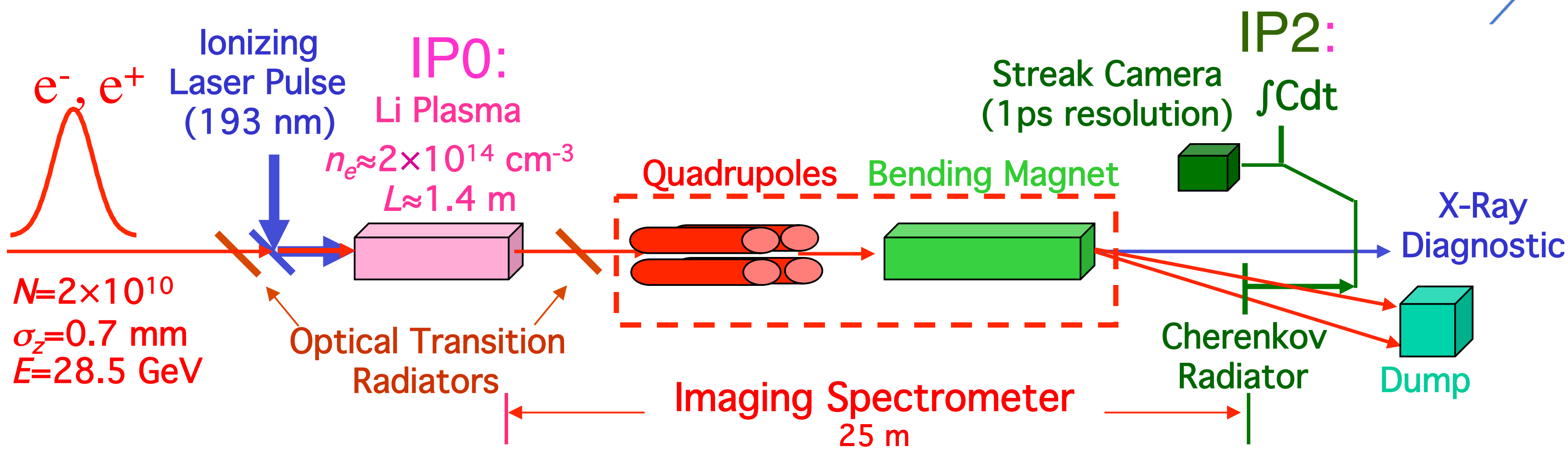
✧Thin passive plasma lens

✧ Acceleration

✧Conclusions

Comparisons/analogies with e^- bunch results

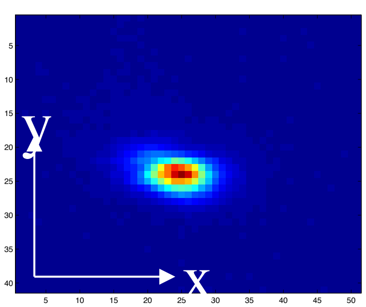
EXPERIMENTAL SET UP

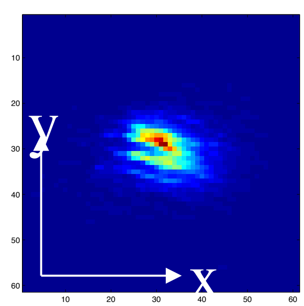


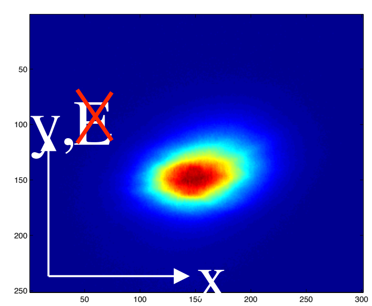
- Optical Transition Radiation (OTR)
- CHERENKOV (aerogel)

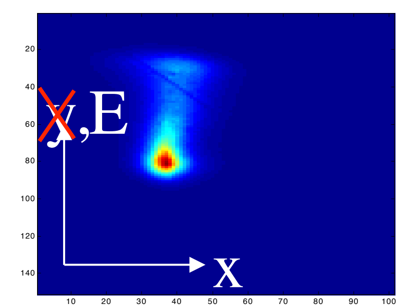
E-157:

E-162:









- 1:1 imaging, spatial resolution <9 μm

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

CHARACTERISTICS OF FFTB EXPTS

Single e^+ bunch:

σ_z~700μm (~2.3ps)
σ_r~30-100μm (round @ plasma entrance)
N~2x10^{10} (Q~3nC)
E=28.5GeV
ε_{Nx}~50(210)mm-mrad
ε_{Ny}~5 (150)mm-mrad

Plasma:

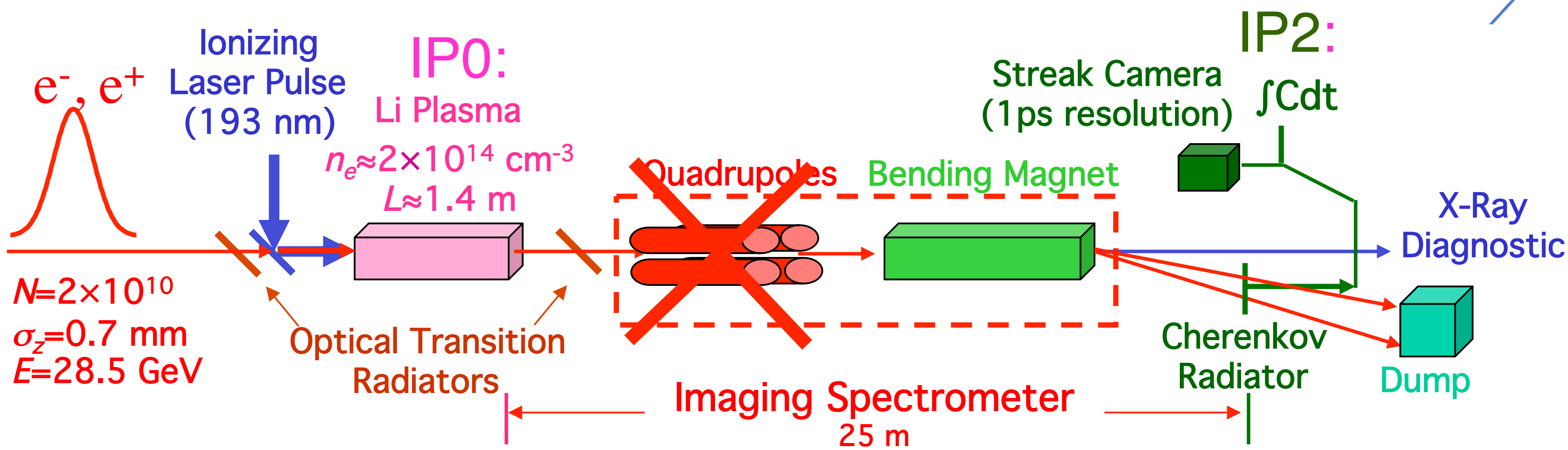
Lithium heat-pipe oven*
UV laser ionization
n_e~10^{11}-5x10^{14}cm^{-3}
L=1.4m
dia.~5mm
Ionization fraction <15%

n_b/n_e~1

Experiments w/wo imaging magnetic spectrometer

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

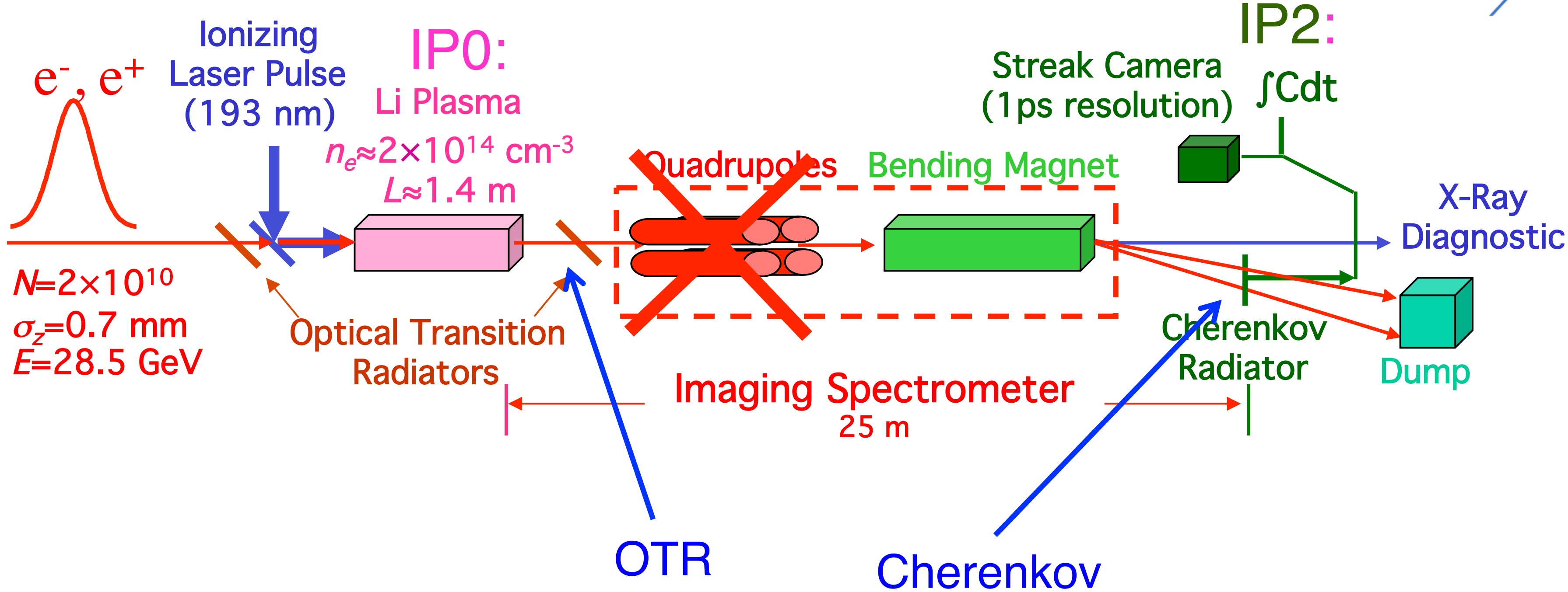
EXPERIMENTAL SET UP



✧Low plasma density results: $n_e < 10^{13}$cm^{-3}

✧No imaging spectrometer

EXPERIMENTAL SET UP



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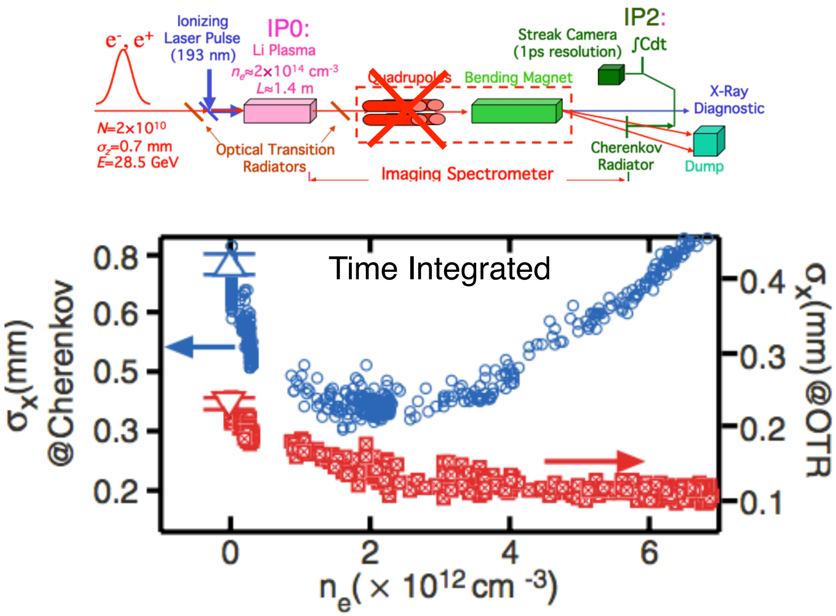
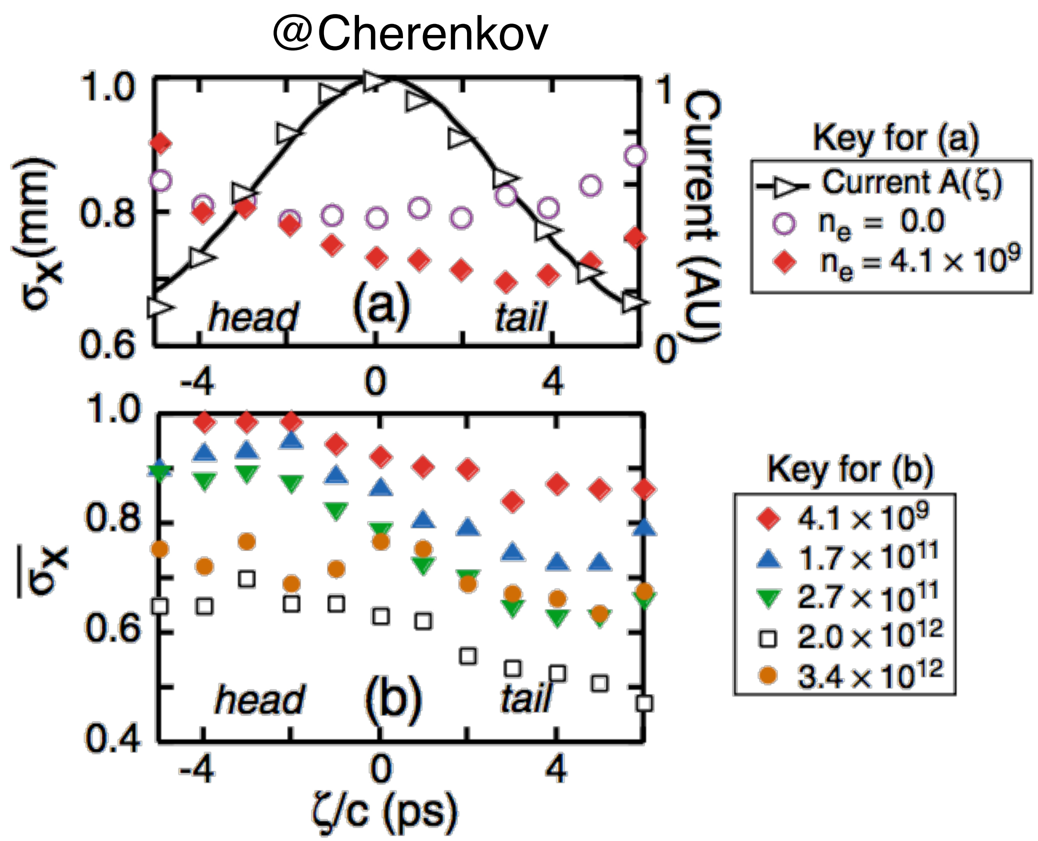
TRANSVERSE SIZE





Distance from plasma exit:
OTR: ~0.9
Cherenkov: ~12m

✧Focusing along the bunch
✧Over-focusing

✧Focusing at both locations
✧Same focusing as with e⁻ @ ~7xn_e

Hogan, Phys. Rev. Lett. 90, 205002 (2003).

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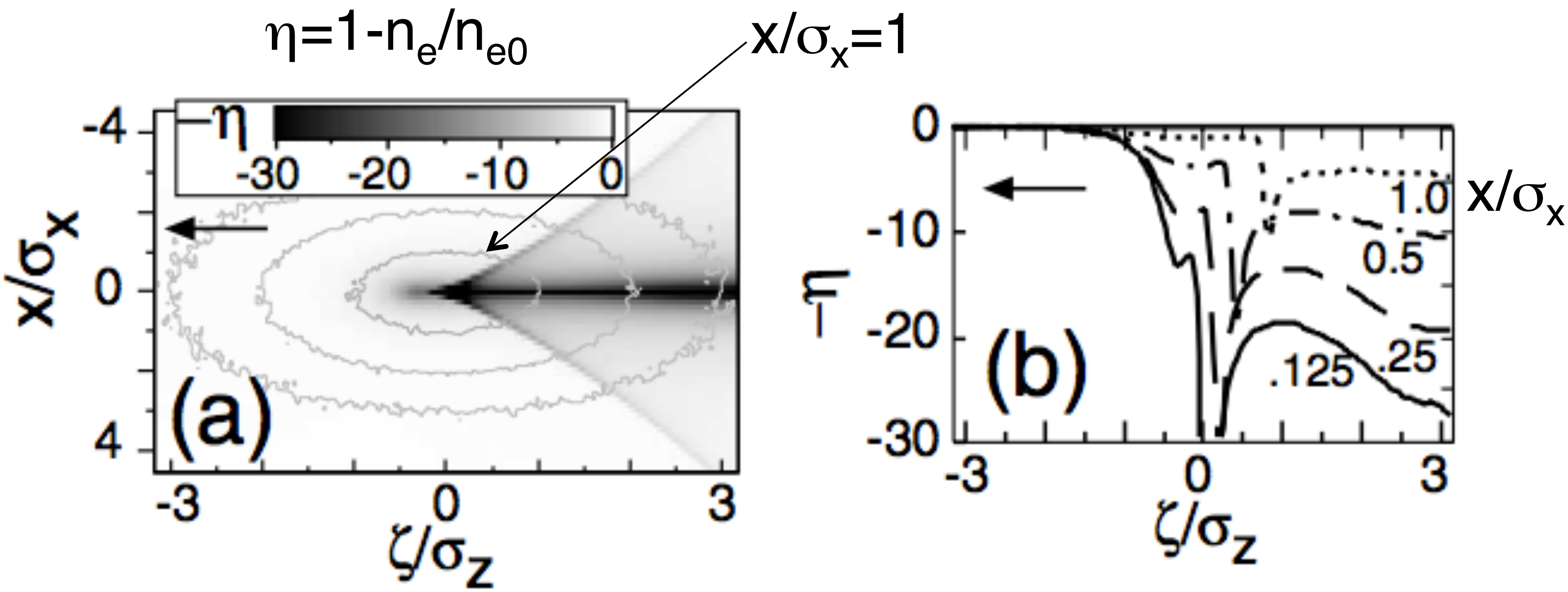
PLASMA DENSITY



$z=0$, $n_{e0}=10^{11}cm^{-3}$

✧No "bubble", "blow-out"

✧High plasma e- charge density near axis

✧Charge density cab ne locally very high $n_e/n_{e0}>>1$

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Hogan, Phys. Rev. Lett. 90, 205002 (2003).

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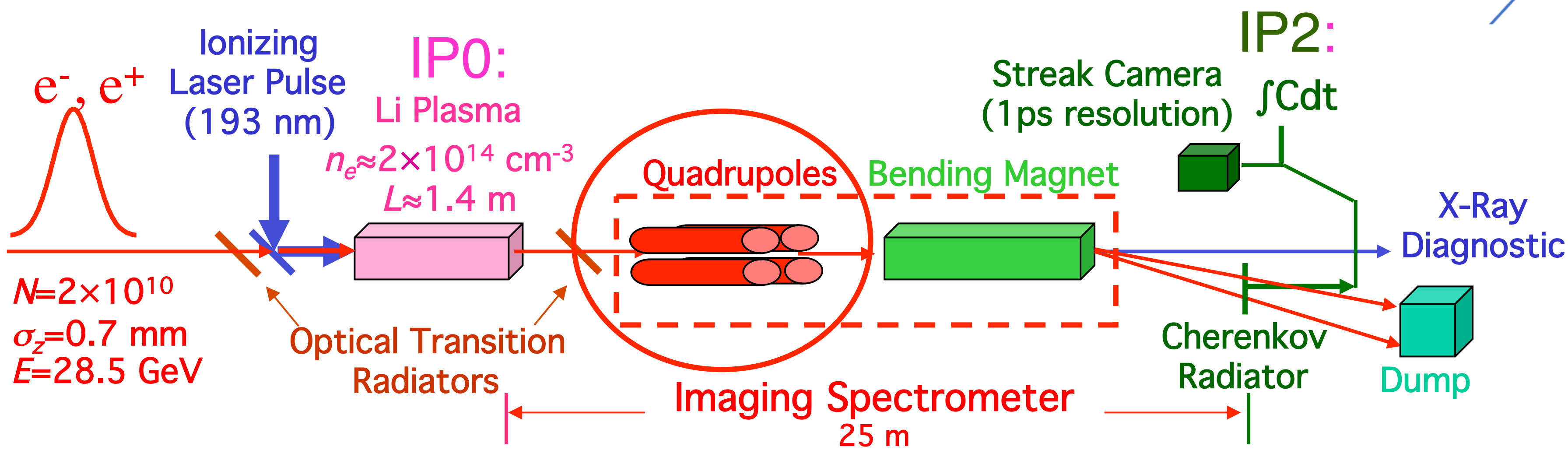

- ✧High plasma density results: $10^{13}<n_e<5\times10^{14}$cm^{-3}
- ✧Imaging spectrometer

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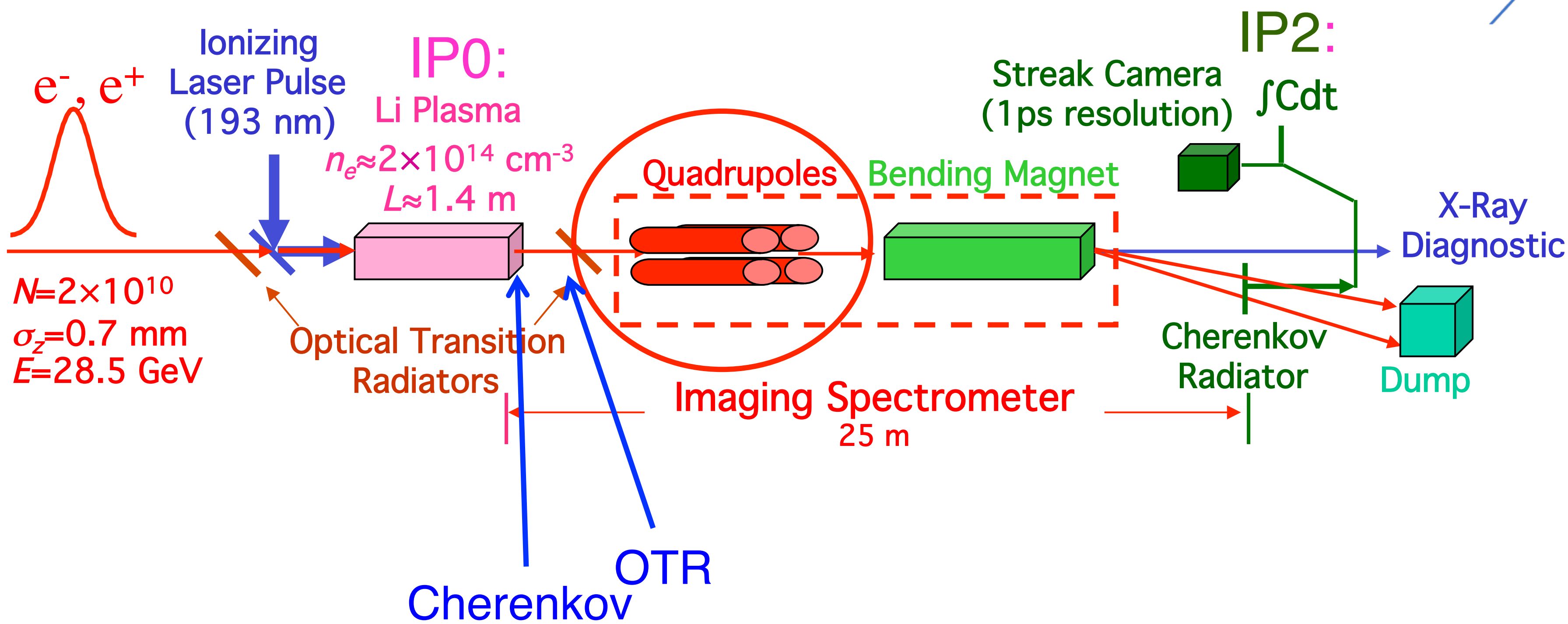


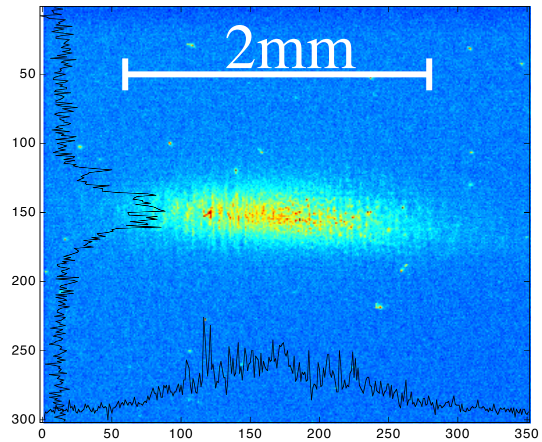
- High plasma density results: $10^{13}<n_e<5x10^{14}cm^{-3}$
- Imaging spectrometer

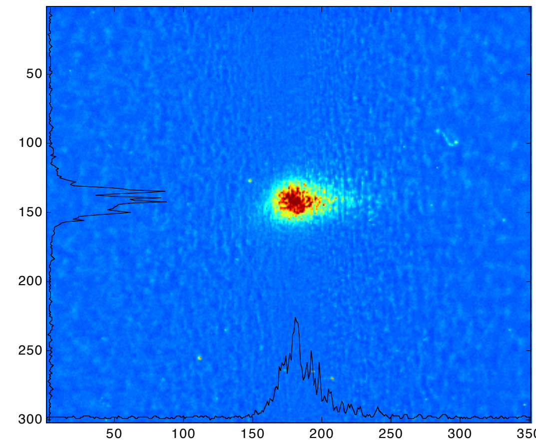
FOCUSING OF e^-/e^+

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

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

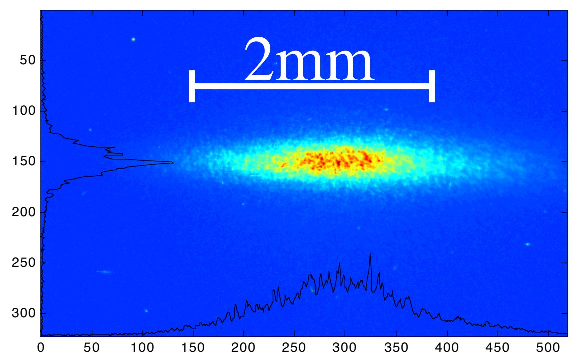
e^-

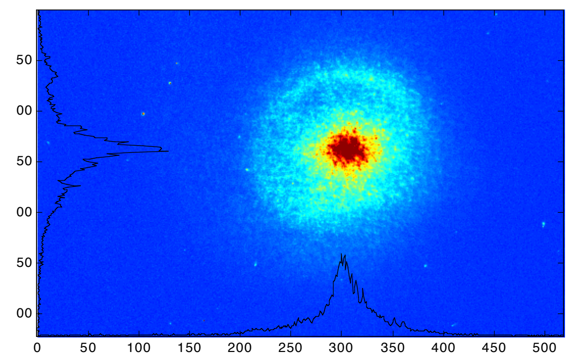




- Ideal Plasma Lens in Blow-Out Regime

e^+





- Plasma Lens with Aberrations

- Qualitative differences

Fit for Beams with Halo

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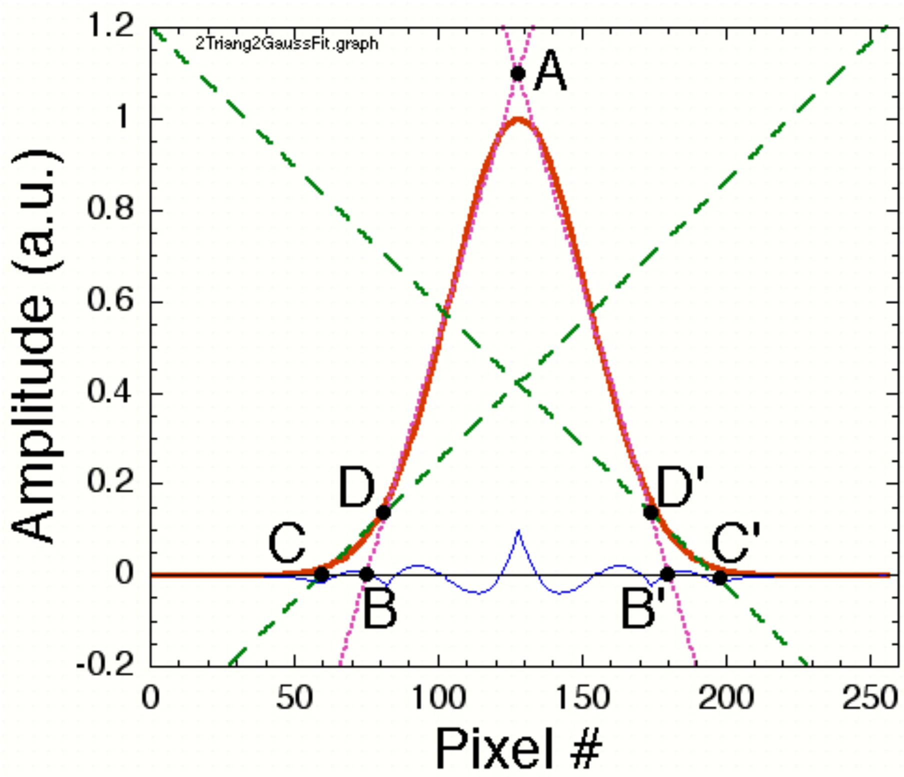

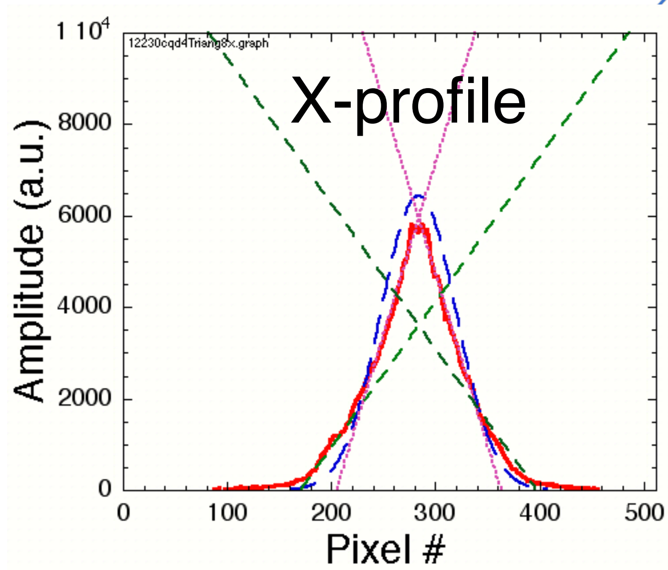

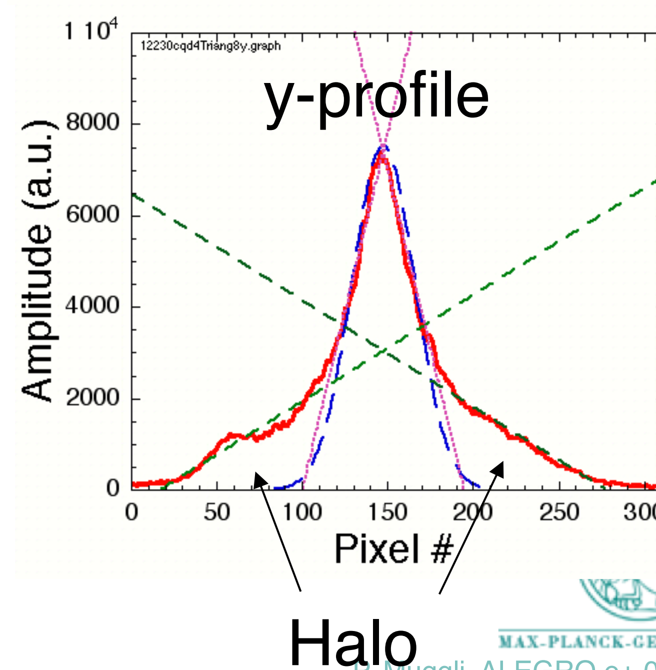

Beam Size=FWHM (BAB')
Charge in the Peak=Area(BAB')
Charge in the Halo=2*Area(CDB)

Muggli, Proc. PAC'2003, 1915

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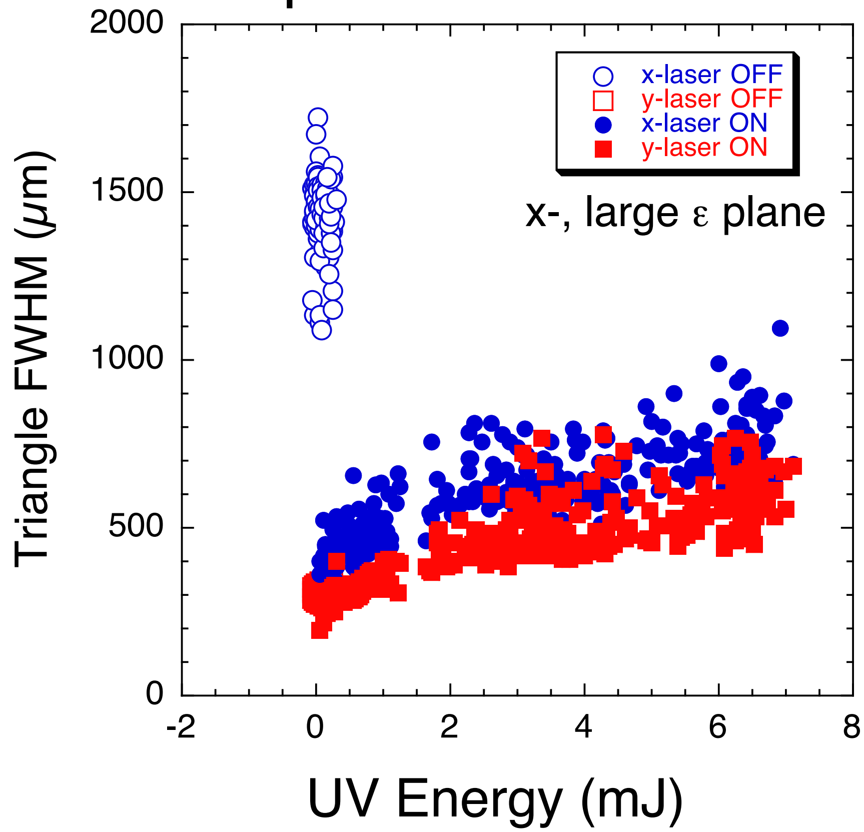
EXPERIMENT / SIMULATIONS

Muggli, Phys. Rev. Lett. 101, 055001 (2008)

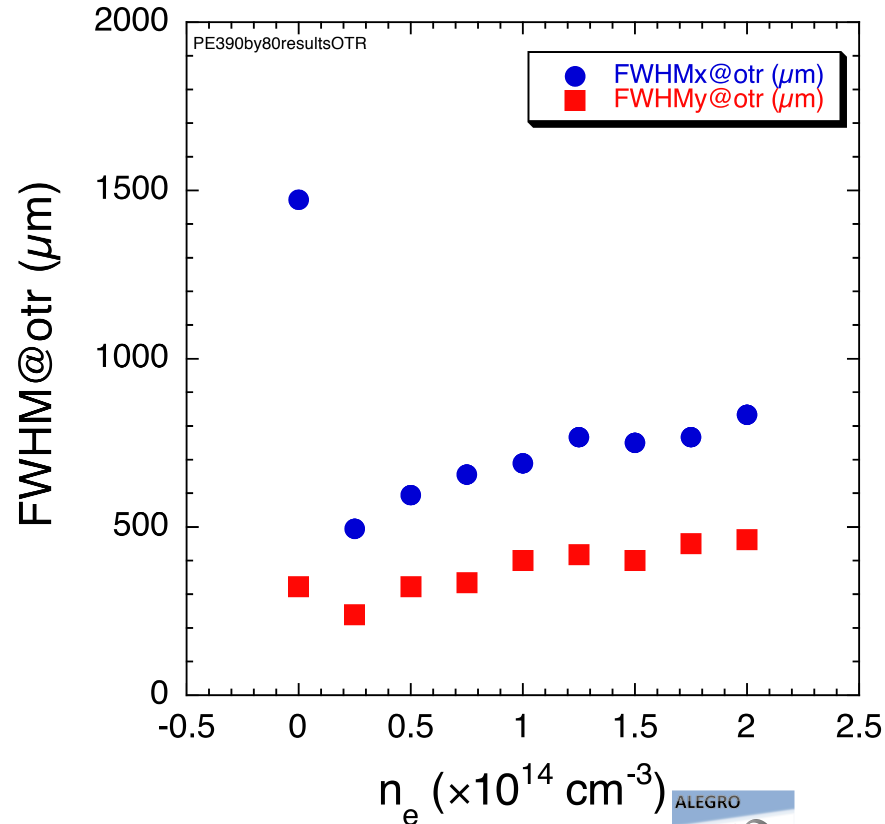
σ_{x0}≈65 σ_{y0}≈48 μm, ε_{Nx}≈115×10^{-6}, ε_{Ny}≈184×10^{-6} m-rad, N≈1.9×10^{10} e^+, L≈1.4 m

Downstream OTR

Experiment



Simulation



- Excellent experimental/simulation results agreement!

EXPERIMENTAL/SIMULATION RESULTS

σ_{x0}≈65 σ_{y0}≈48 μm, ε_{Nx}≈115×10^{-6}, ε_{Ny}≈184×10^{-6} m-rad, N≈1.9×10^{10} e^+, L≈1.4 m

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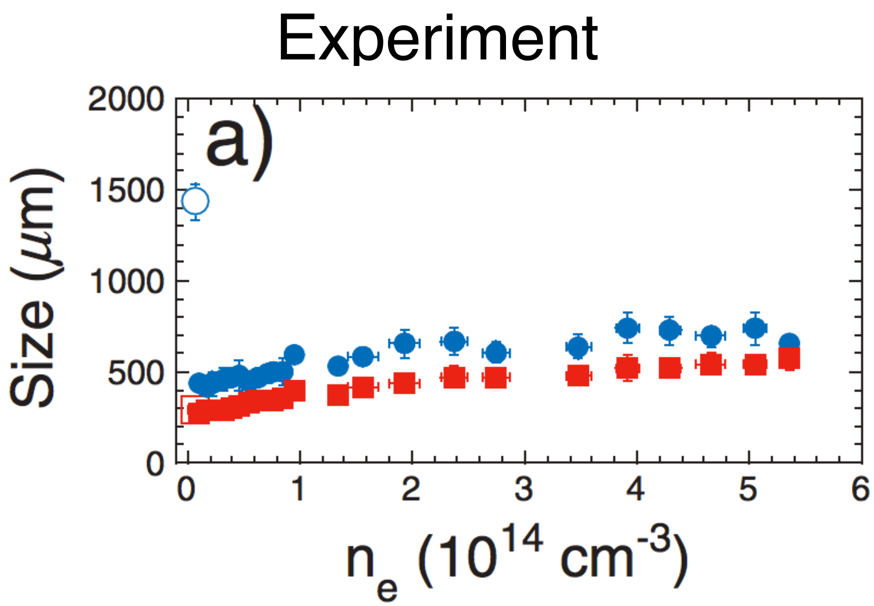
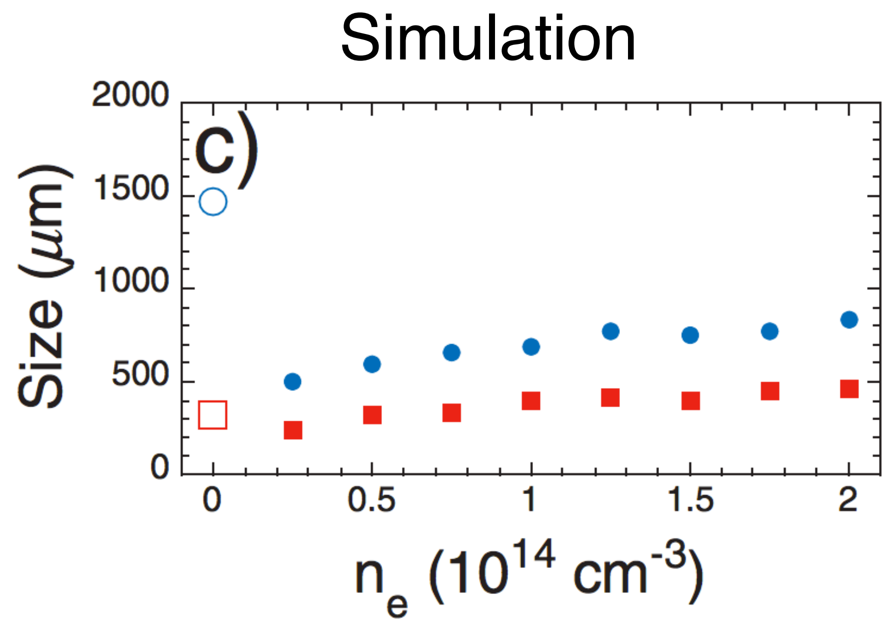




Muggli, Phys. Rev. Lett. 101, 055001 (2008)

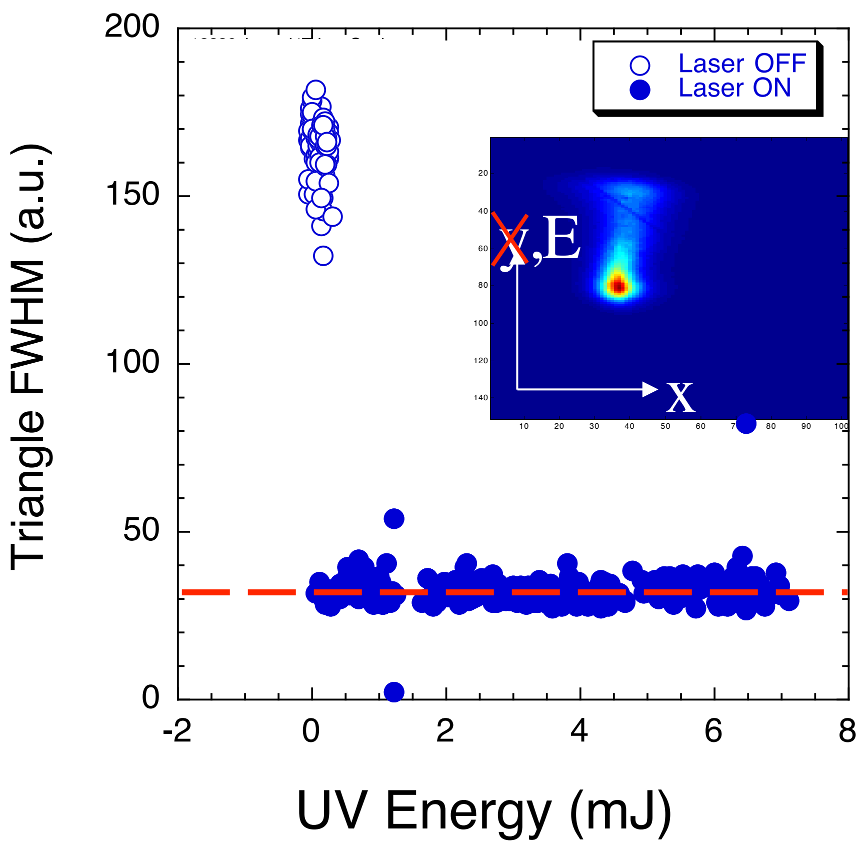
- Defocusing in x and y "low" ε in both planes, larger σ
- No distinctive features (β-tron oscillations)
- Excellent experimental/simulation results agreement!

EXPERIMENTAL RESULTS e^+

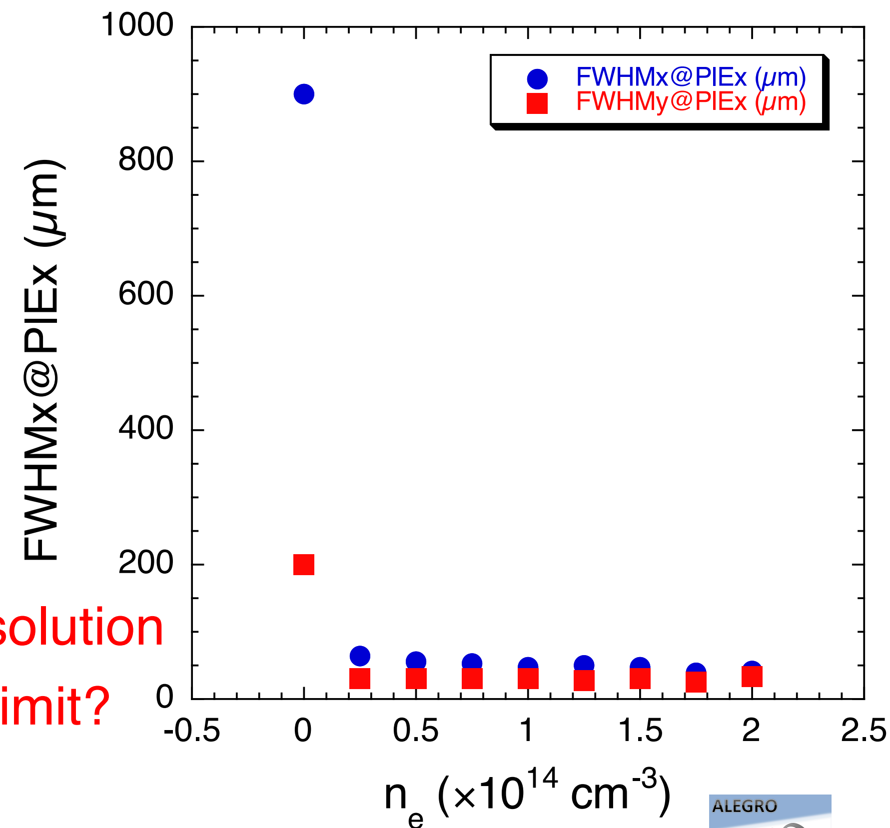
$\sigma_{x0}\approx\sigma_{y0}\approx 25\ \mu m$, $\varepsilon_{Nx}\approx 390\times10^{-6}$, $\varepsilon_{Ny}\approx 80\times10^{-6}$ m-rad, $N=1.9\times10^{10}\ e^+$, $L\approx 1.4$ m

Cherenkov/Plasma Exit

PE390by80results



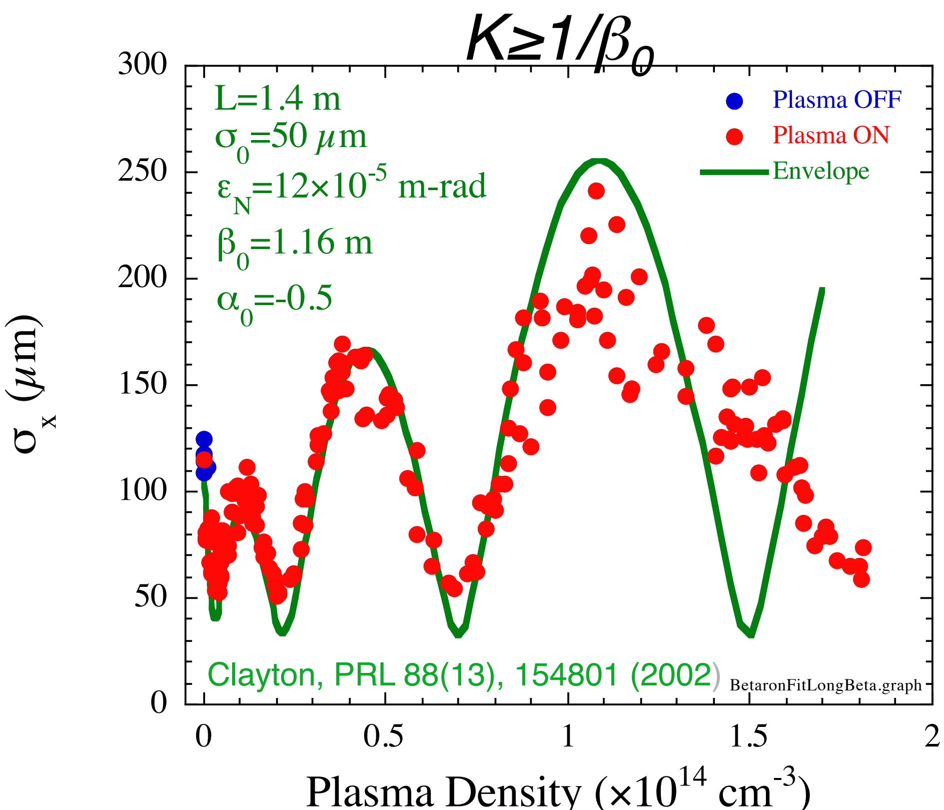
Resolution Limit?

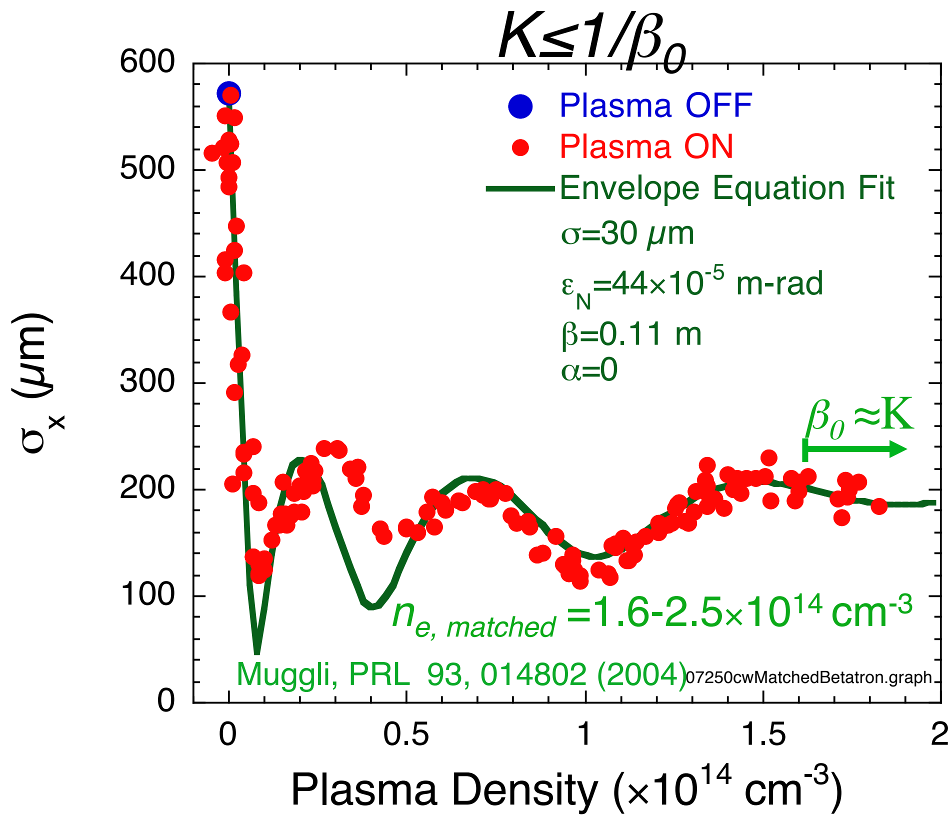


- Strong focusing in x (large ε), defocusing in y (low ε)
- No distinctive features (β-tron oscillations)

FOCUSING OF e^-

OTR Images ≈1m downstream from plasma

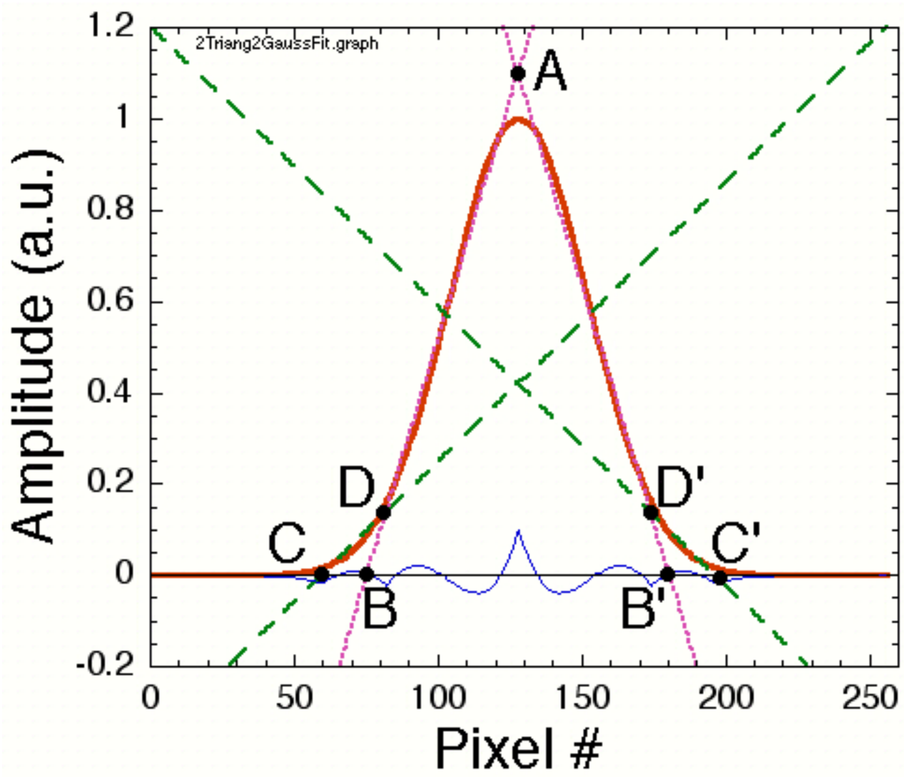


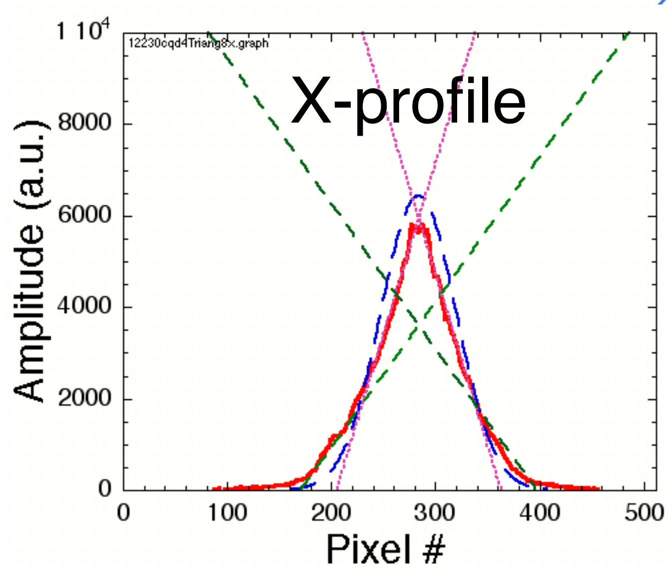


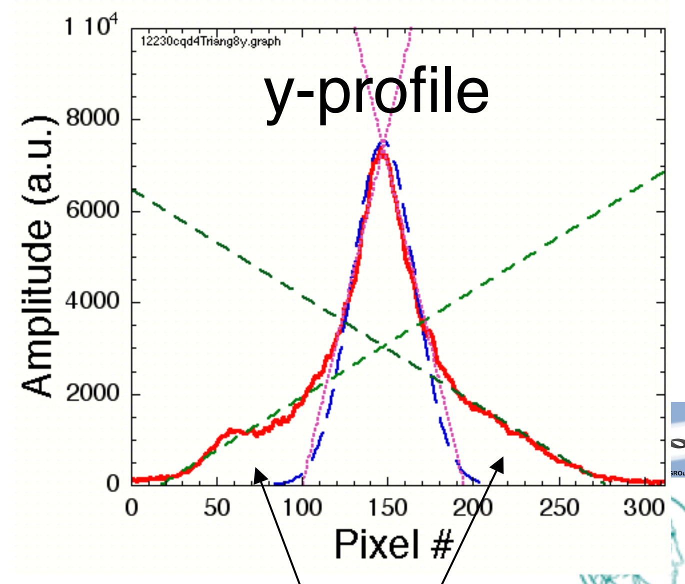
- Focusing of the beam well described by a simple model (n_b>n_e): Plasma = Ideal Thick Lens
- No emittance growth observed as n_e is increased
- Stable propagation over L=1.4 m up to as n_e =1.8×10^{14}cm^{-3}
- Channeling of the beam over 1.4 m or >12β_0

=> Matched Propagation over long distance!

FIT FOR BEAMS WITH HALO







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

Muggli, Proc. PAC'2003, 1915

HALO FORMATION

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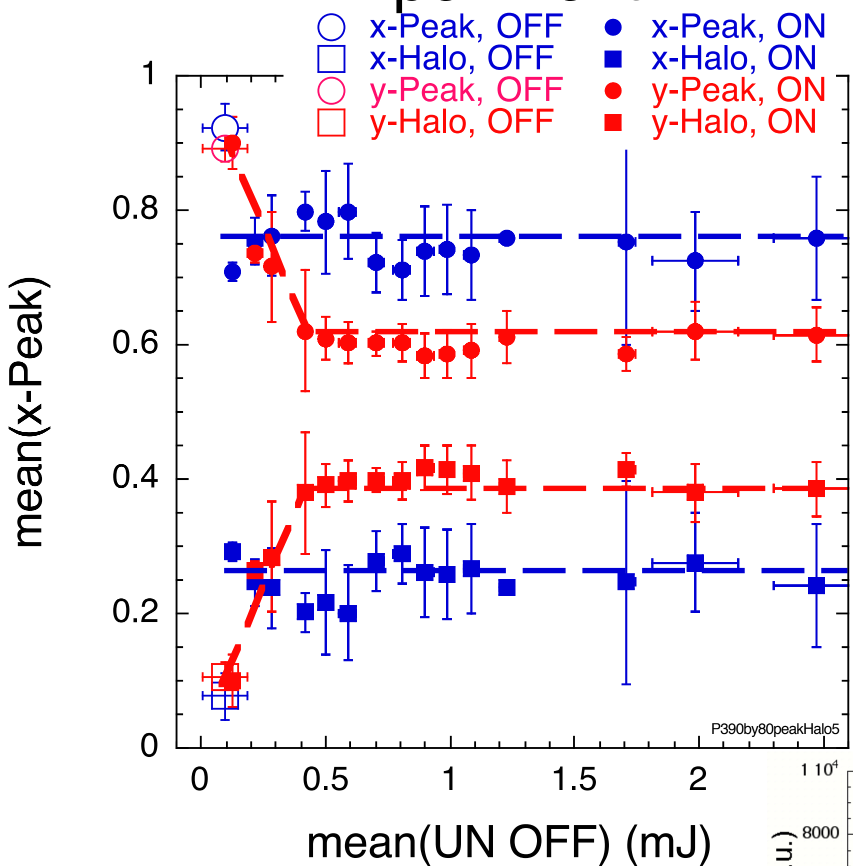
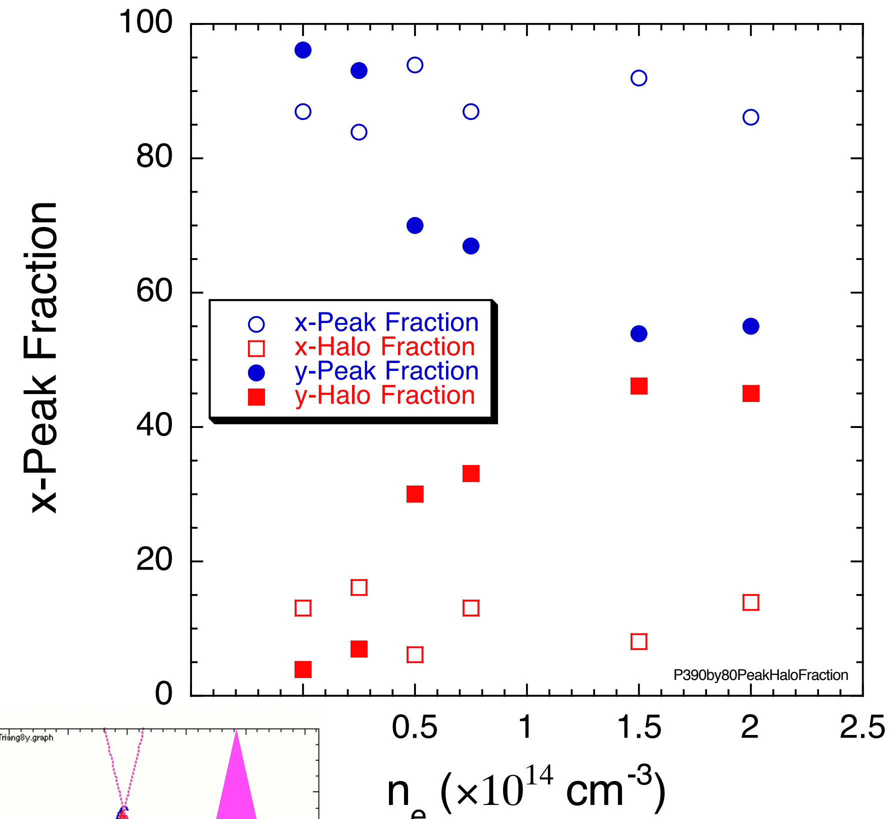
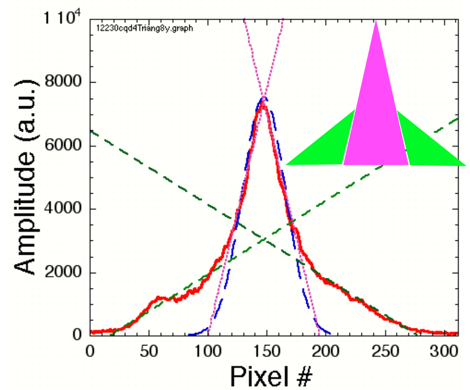
Experiment



Simulation



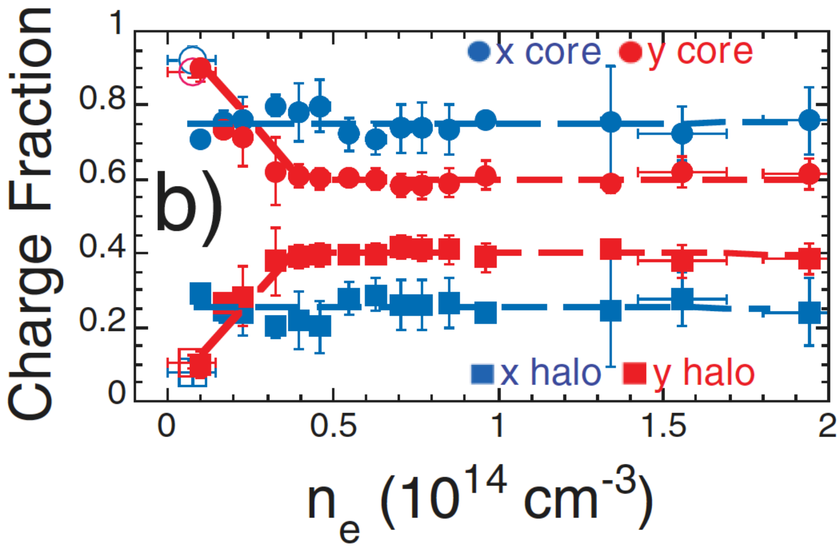


- Very nice agreement

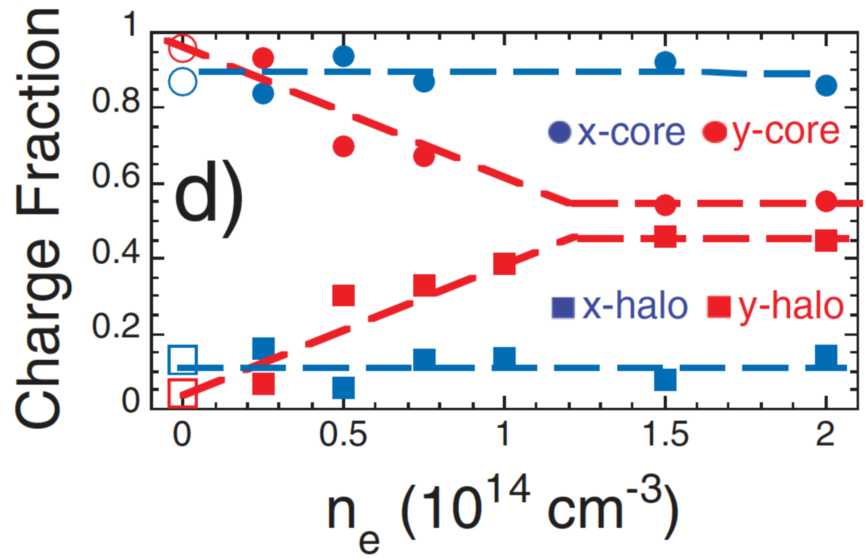
Halo Formation

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

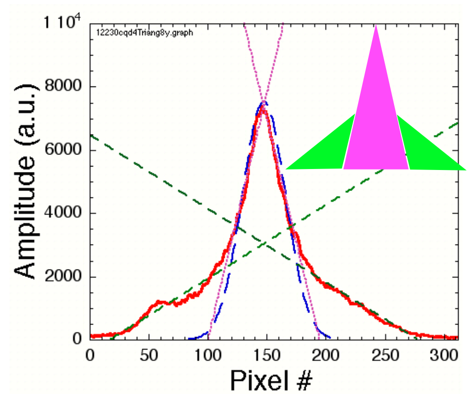
Experiment



Simulation



Muggli, Phys. Rev. Lett. 101, 055001 (2008)



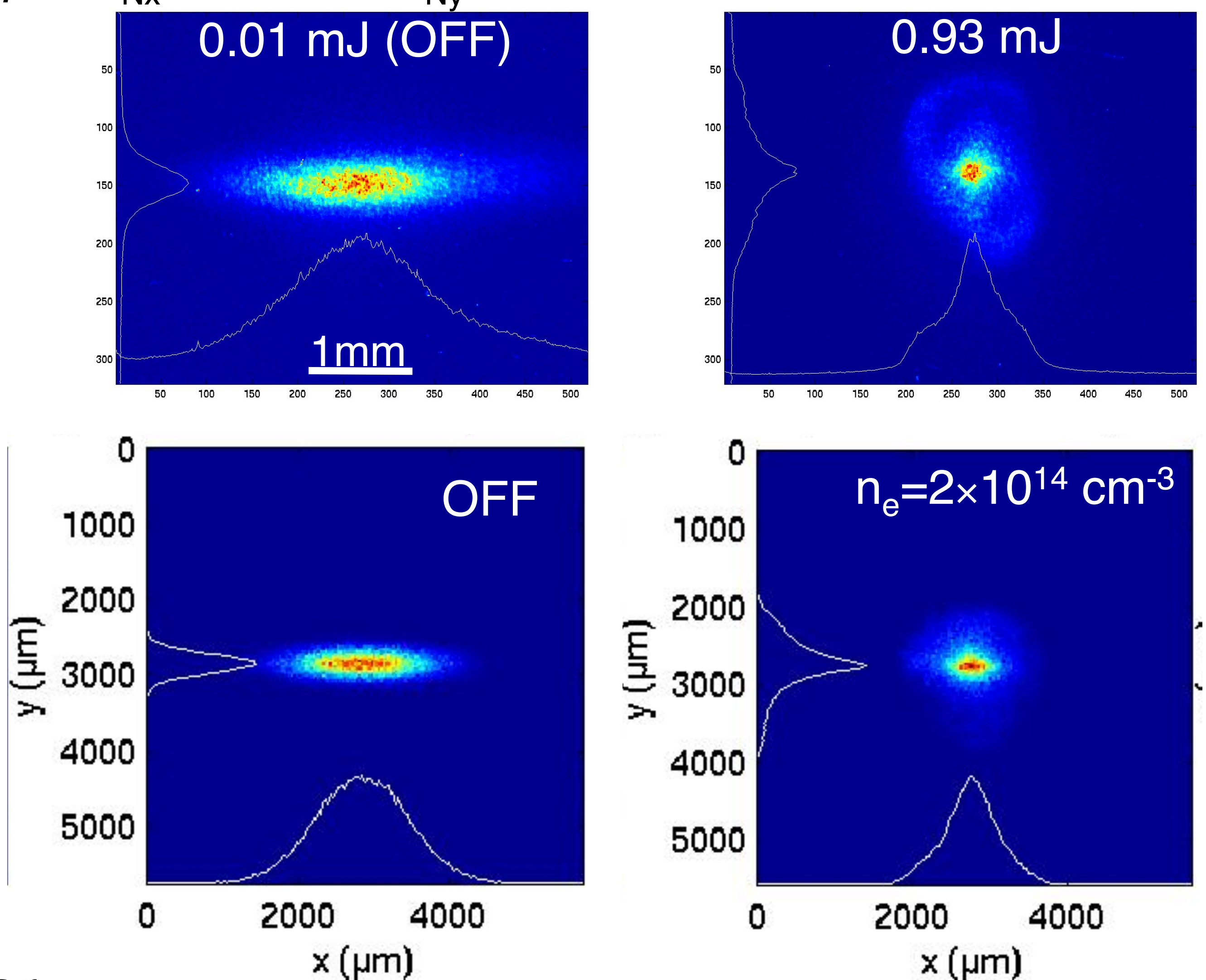
- Very nice agreement

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

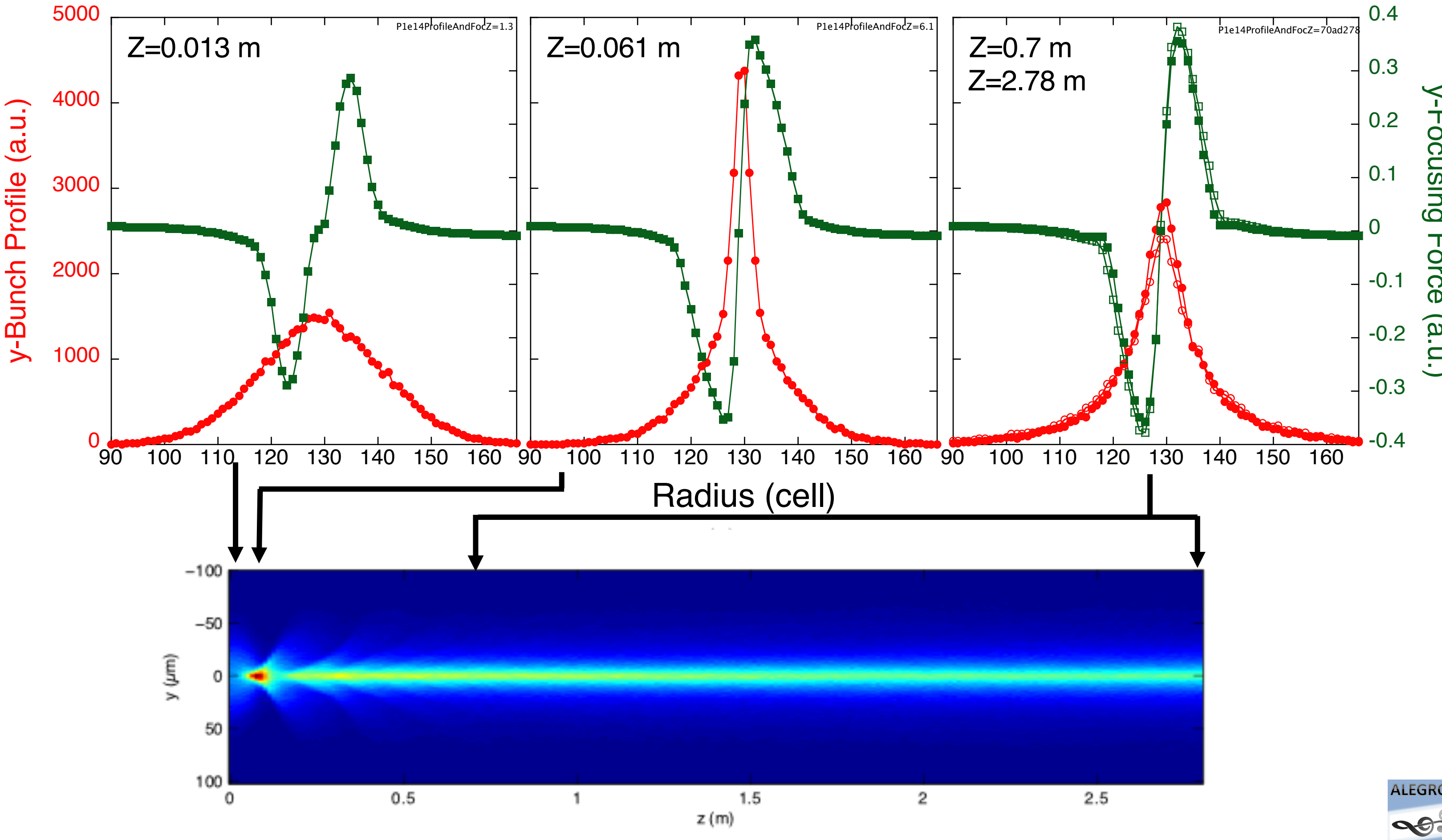
Simulation



- Very similar

BEAM/FIELD EVOLUTION

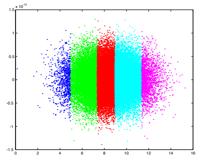
$\sigma_{x0}=\sigma_{y0}=25\mu m$, $\varepsilon_{Nx}=390\times10^{-6}$, $\varepsilon_{Ny}=80\times10^{-6}$ m-rad, $N=1.9\times10^{10}$



- Beam becomes non-Gaussian
- Beam size and focusing field "stop" at z≈0.7 m

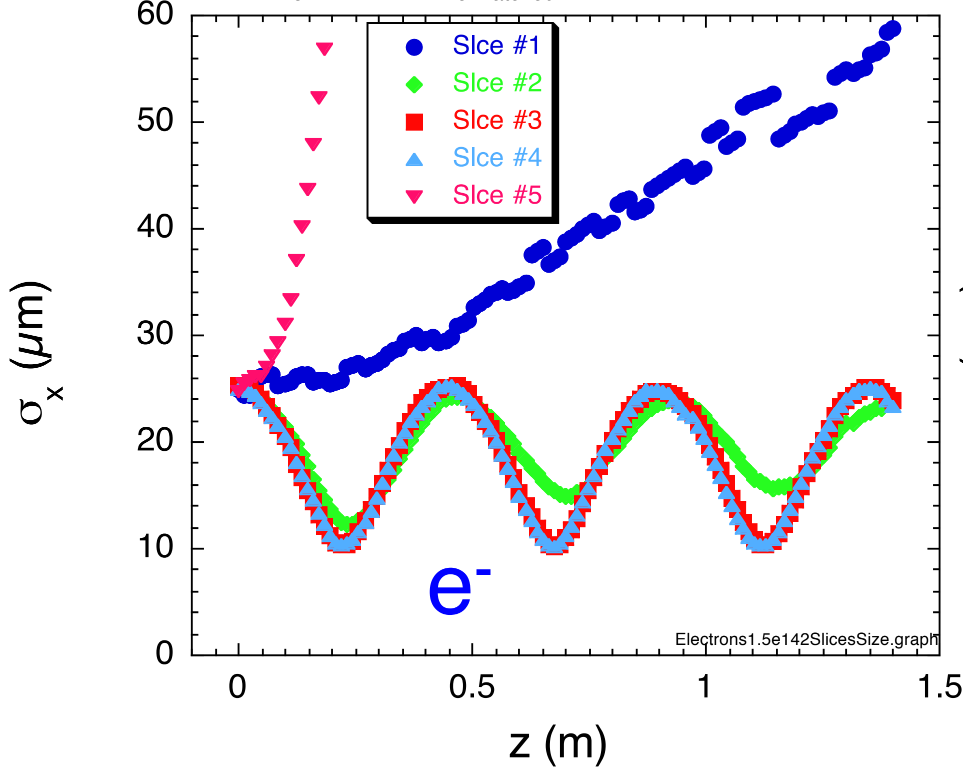
e^-/e^+: Slices Size in the Plasma

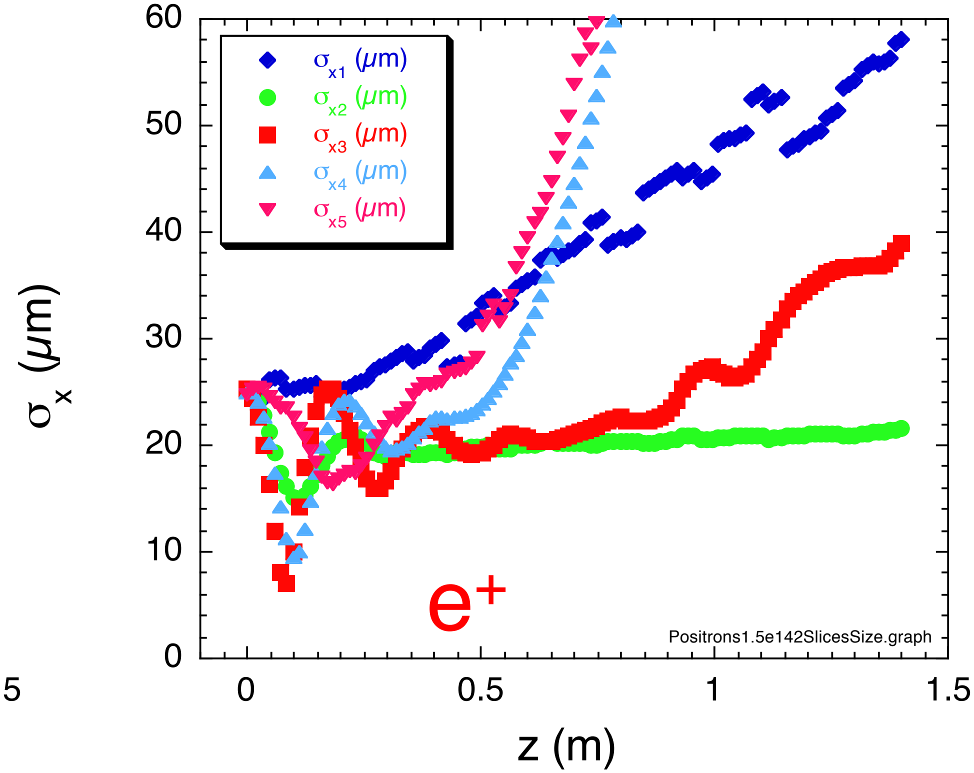
Front



Back

β_o=0.34 m, $n_{e\ matched}$=1.6×10^{13} cm^{-3}

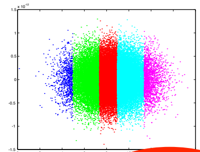


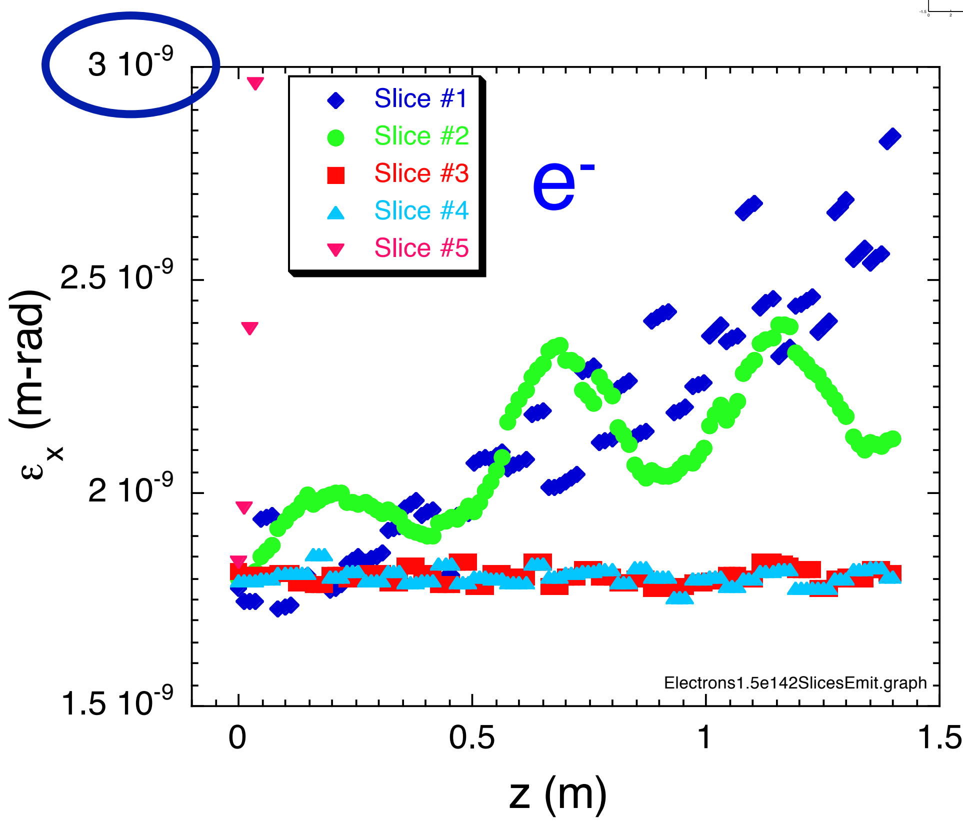


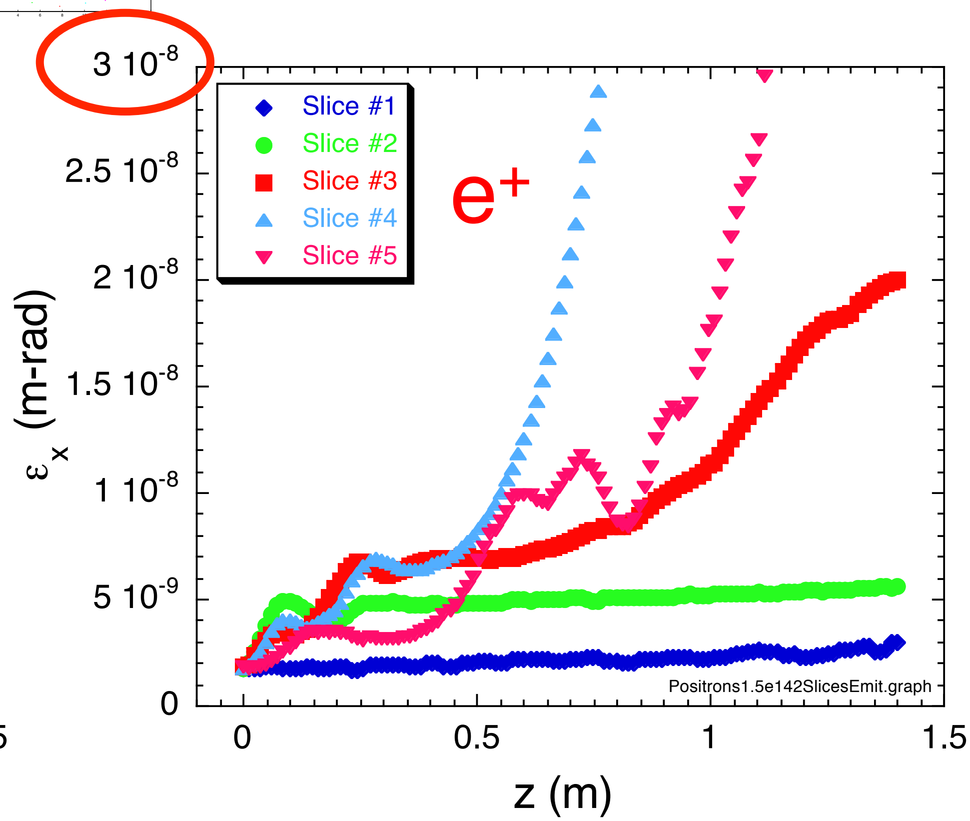
- Head diverges ≈β_0
- Coherent betatron motion of the core

- Head diverges ≈β_0
- Phase mixing of the following slices

e^-/e^+: SLICE EMITTANCE

Front  Back

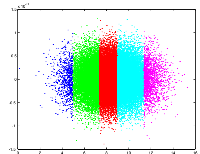


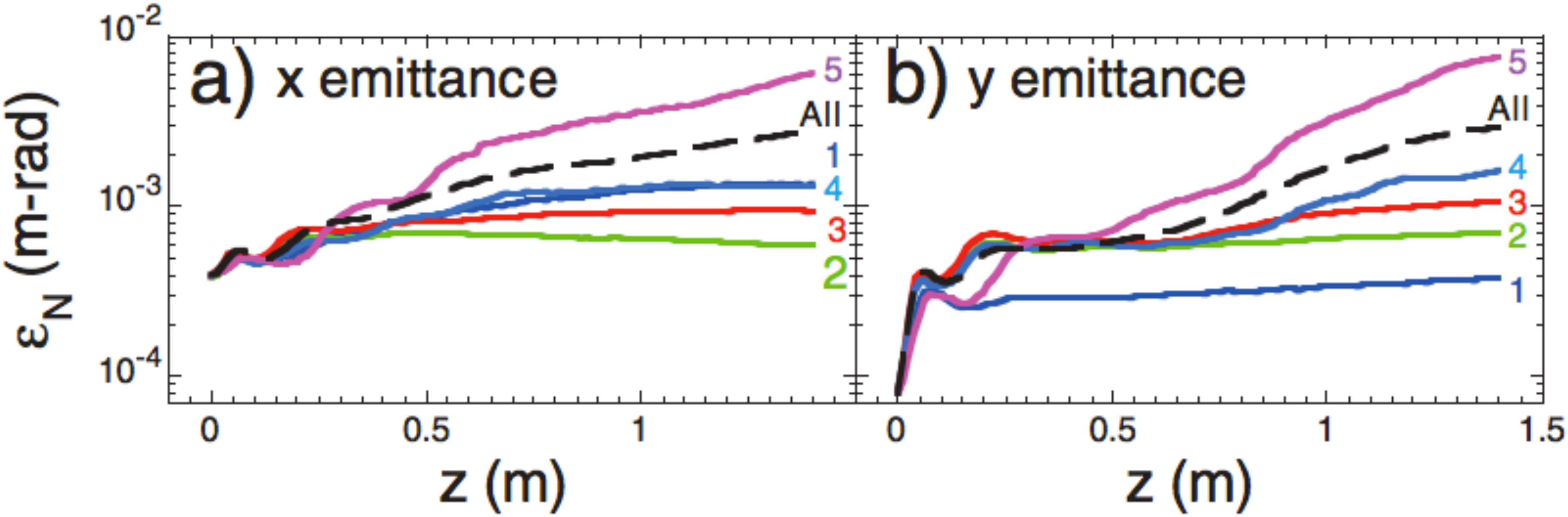


- Increase in the head ...
- Blow-out, pure ion column preserves beam emittance

- Increase in the head ...
- Phase mixing of the following slices

e^+: SLICE EMITTANCE

Front  Back



✧Less emittance growth in large (initial) emittance plane
✧Large growth over first few cm in low emittance plane
✧For z>0.5m the bunch is “round”

Muggli, Phys. Rev. Lett. 101, 055001 (2008)

OUTLINE

✧e^+ bunches in plasmas/wakefields driven by a e^+ bunch

✧Experiments with long e^+ bunch (700μm) and low plasma density (<10^{13}cm^{-3})

✧Experiments with long e^+ bunch (700μm) and high plasma density (<5×10^{14}cm^{-3})

✧Thin passive plasma lens

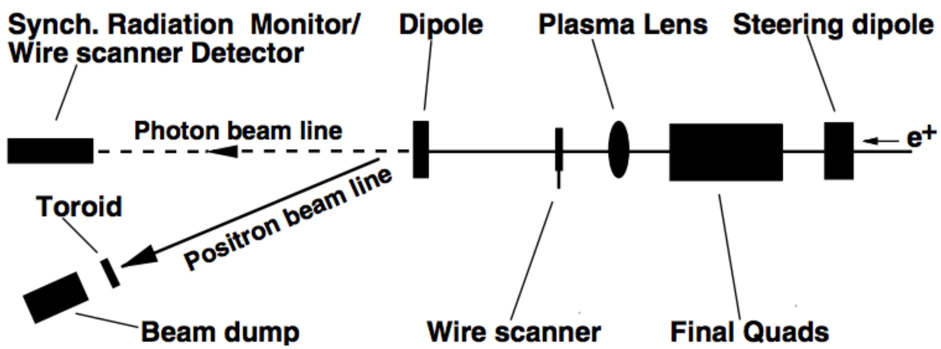
✧ Acceleration

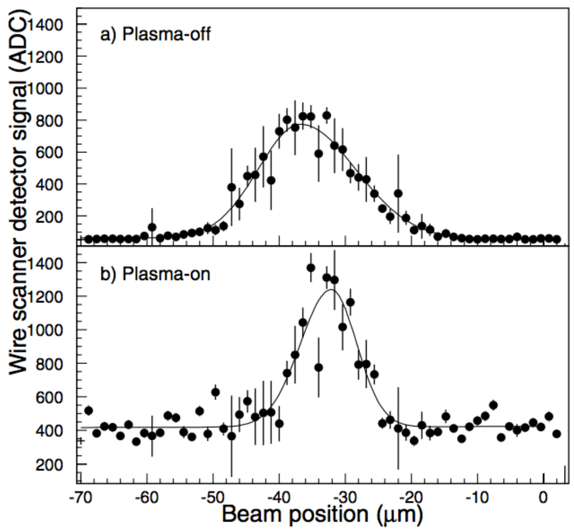
✧Conclusions

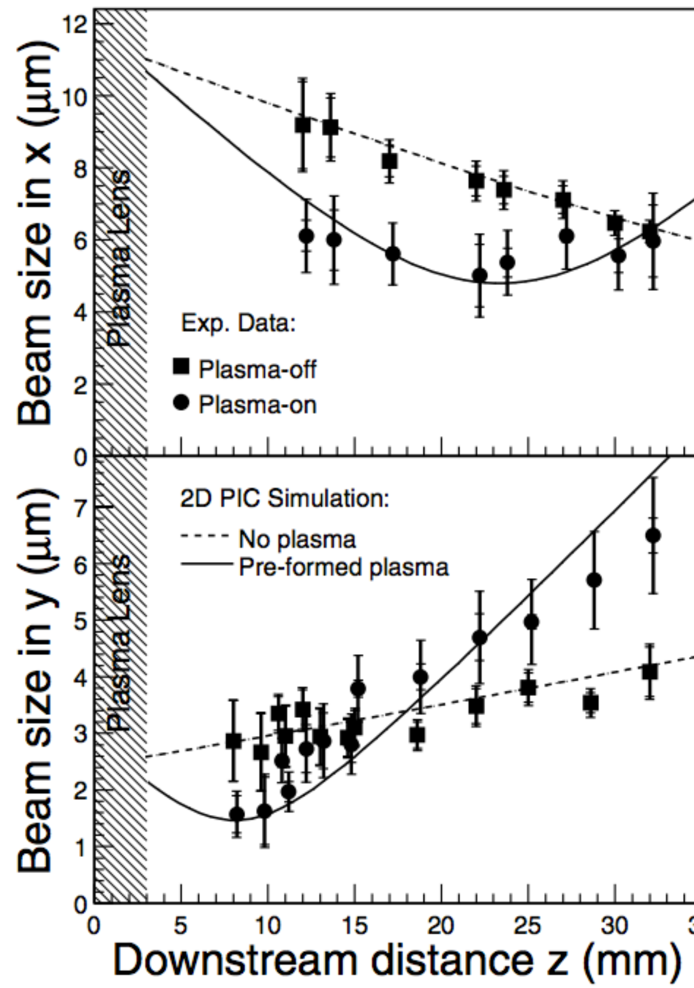
Comparisons/analogies with e^- bunch results

PASSIVE PLASMA LENS FOR e^+ BUNCH

Ng, Phys. Rev. Lett. 87, 244801 (2001)







- ✧Ionization N_2 jet, 3 mm thick, n_{N2}~$7x10^{18}cm^{-3}$
- ✧Laser ionization
- ✧Reduction of the transverse size area by factor 2.0±0.3
- ✧x: 0.7T/μm, f=34mm, y: 4T/μm, f=1.6mm
- ✧Thin lens, no evolution in the lens, “single kick”

OUTLINE

✧e^+ bunches in plasmas/wakefields driven by a e^+ bunch

✧Experiments with long e^+ bunch (700μm) and low plasma density ($<10^{13}$cm^{-3})

✧Experiments with long e^+ bunch (700μm) and high plasma density ($<5\times10^{14}$cm^{-3})

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Comparisons/analogies with e^- bunch results

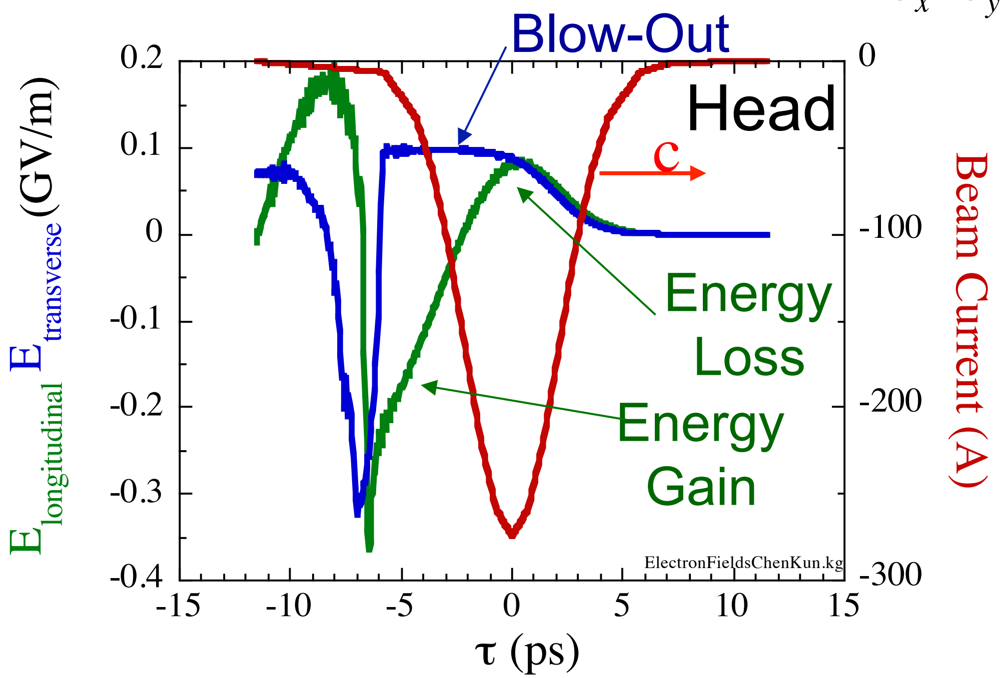
PLASMA WAKEFIELD FIELDS (e^-)

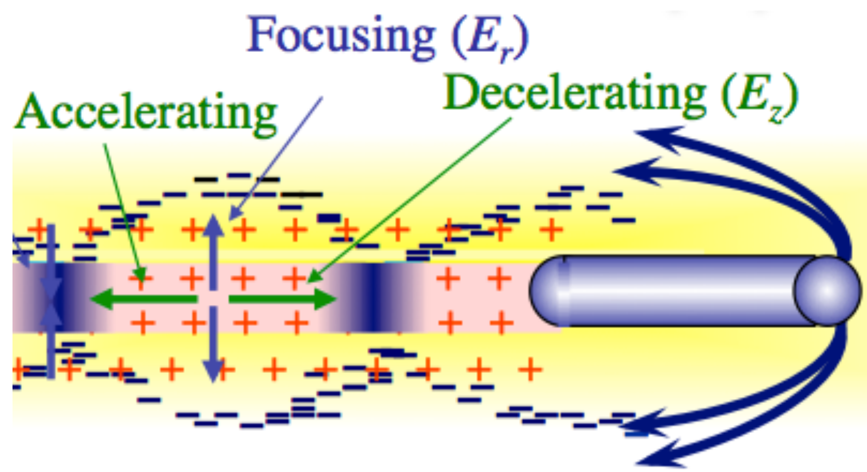
Muggli, Phys. Rev. Lett. 93, 014802 (2004).

2-D PIC Simulation QUICPICK

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

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		





- Simulations - cartoon
- Experiment: measure energy gain/loss not wakefield amplitudes

PLASMA WAKEFIELD FIELDS (e^-)

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

2-D PIC Simulation QUICPICK

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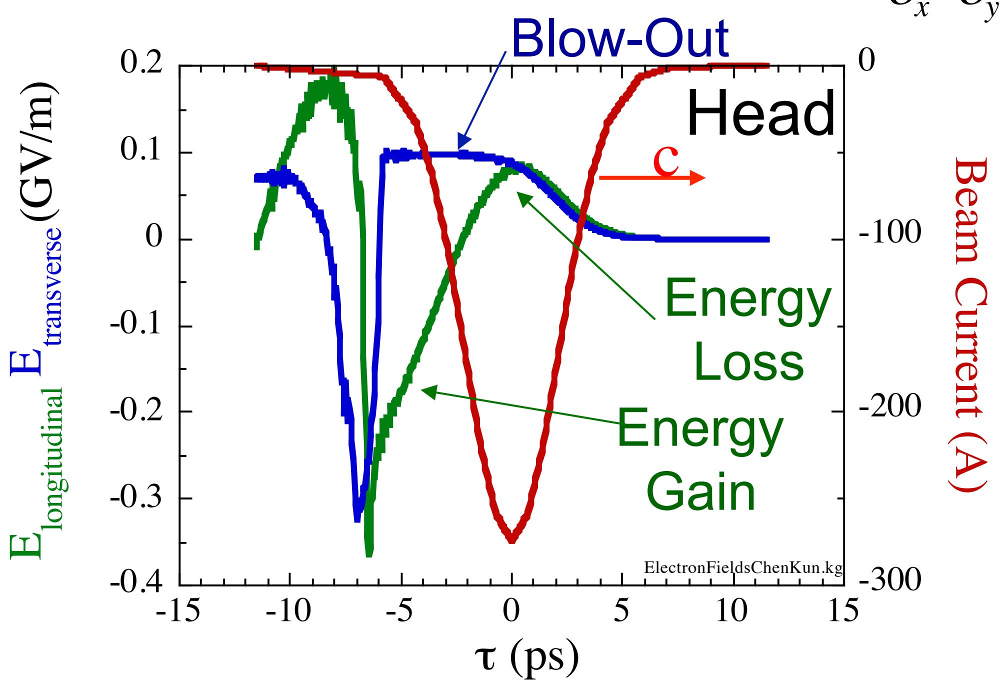
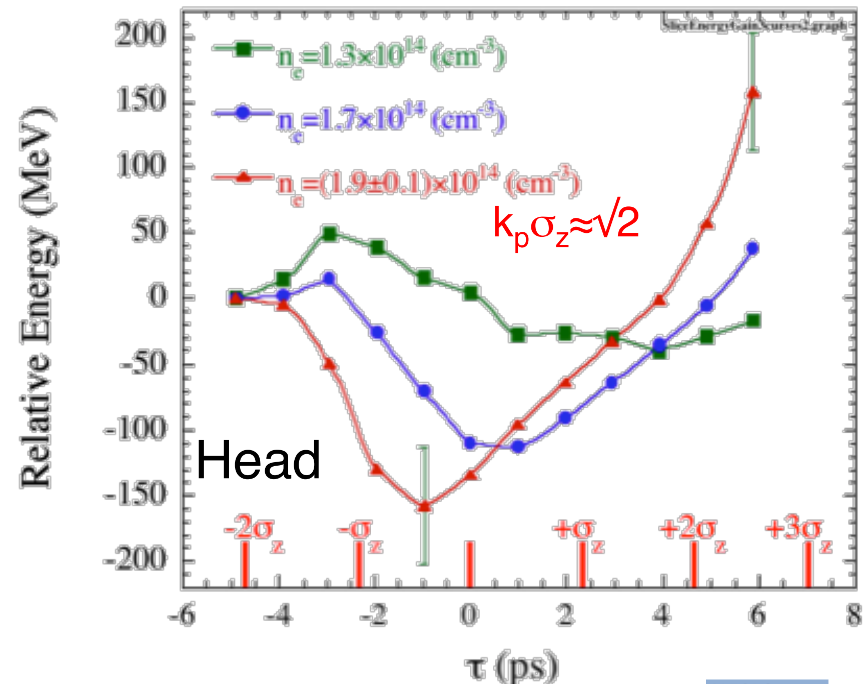
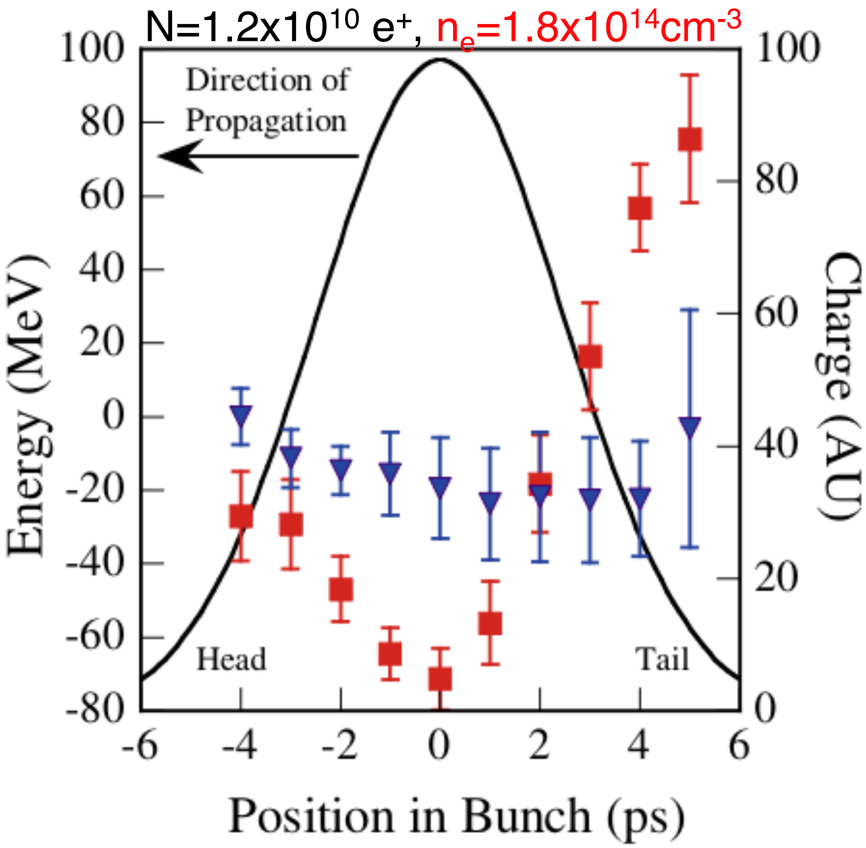
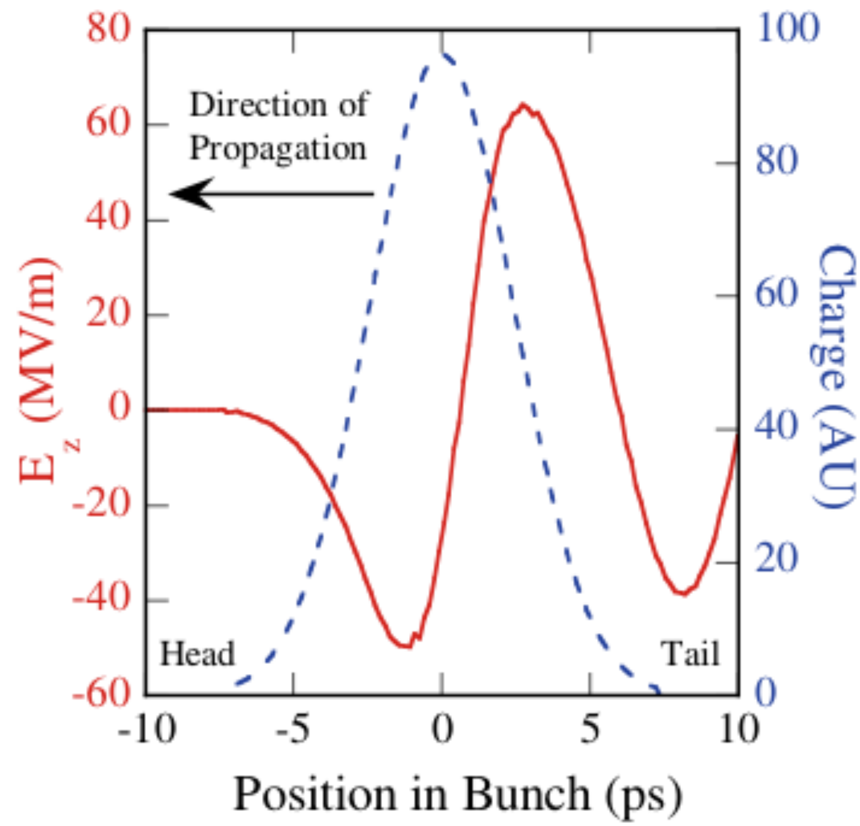




- Energy gain measured with ps-resolution streak camera
- Time resolution needed, but shows the physics
- Peak energy gain: 279 MeV, L=1.4 m, ≈200 MeV/m

e^+ ACCELERATION PRE-IONIZED, LONG BUNCH

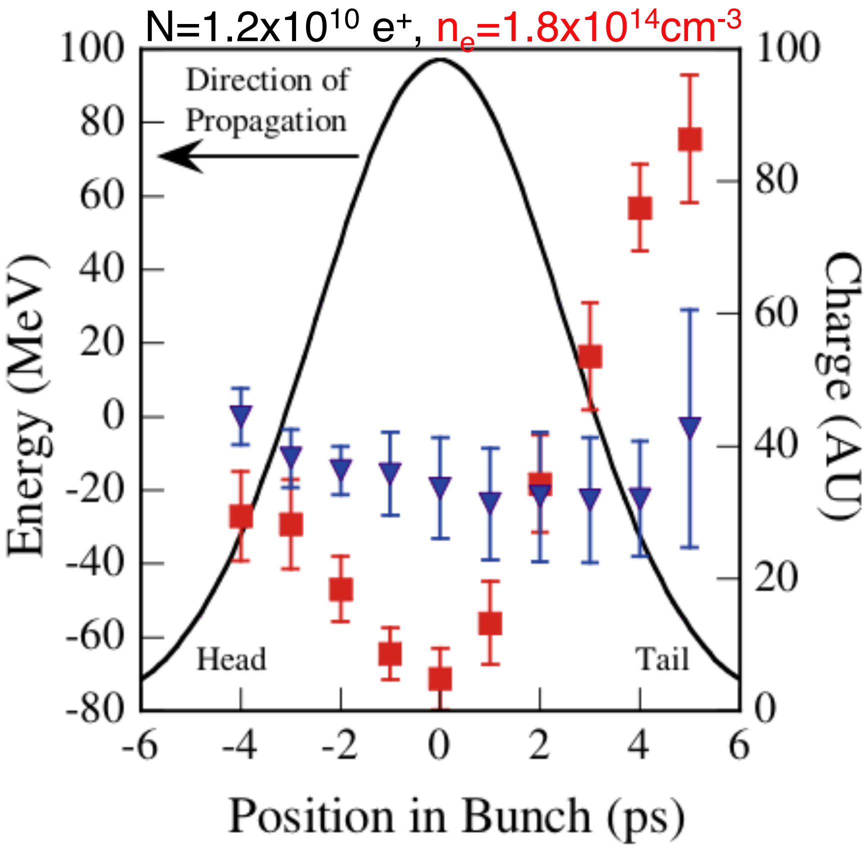




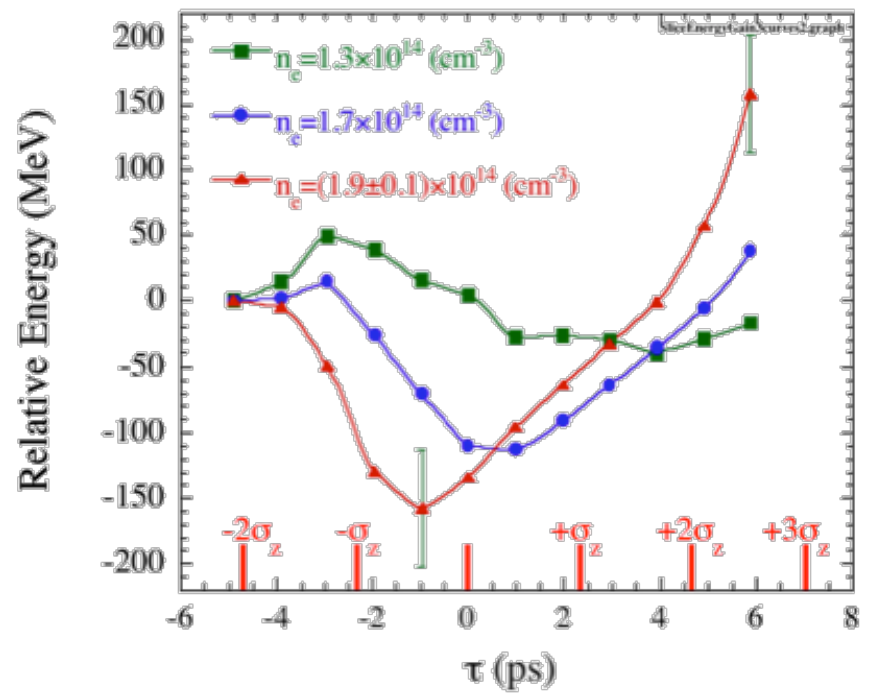
Blue, Phys. Rev. Lett. 90, 214801 (2003).

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

e^+/e^- ACCELERATION



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



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

➡ Similar … of course …

OUTLINE

✧e⁺ bunches in plasmas/wakefields driven by a e⁺ bunch

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✧Experiments with long e⁺ bunch (700μm) and high plasma density (<$5\text{x}10^{14}$cm^{-3})

✧Thin passive plasma lens

✧ Acceleration

✧Conclusions

Comparisons/analogies with e⁻ bunch results

CONCLUSIONS

- Focusing of e^+ bunches by a (thick, passive) plasma is qualitatively different from that of e^- bunches ($n_b \sim> n_e$)
  - e^-: uniform density, heavy plasma ions ($n_i \sim< n_{b0}$)
  - e^+: non-uniform density, light plasma e^- ($n_e >> n_{b0}$)
- e^+ and plasma are a fully self-consistent state
- A thin passive plasma lens may be interesting for a collider
- Acceleration of e^+ by plasma wakefields is (of course) possible
- Challenge: combining transverse dynamics (emittance preservation) and longitudinal dynamics (energy gain and energy spread) over long propagation distances
- See next talks …

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