Results from the UCLA/FNPL Underdense Plasma Lens Experiment

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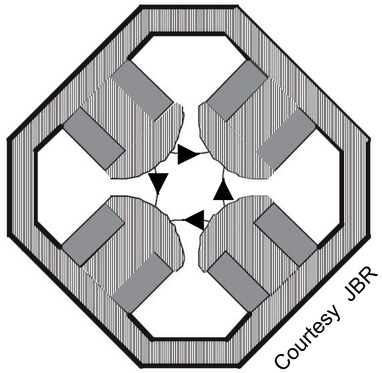
Advanced Electron Beam Lens

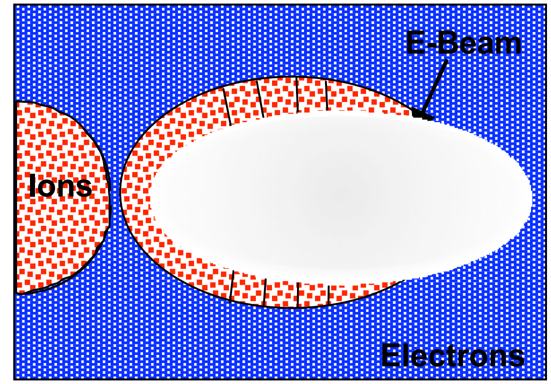
Magnetic Quadrupoles

Uses magnetic forces to focus electron beam in one dimension at a time.



Underdense Plasma Lens

Uses electrostatic forces to focus electron beam in both dimensions.



$$\vec{F}_\perp = q\vec{v}\times\vec{B}_{quad} = ecB'(y\hat{y} - x\hat{x})$$

$$\vec{F}_\perp = q\vec{E}_{ion} = 2\pi e^2 n_p(-y\hat{y} - x\hat{x})$$

$$B' \approx 250\ \mathrm{T}/\mathrm{m}$$

State-of-the-Art Superconducting Quad

$$B'_{equivalent} = 3\times10^{-11} n_p\ \mathrm{T}/\mathrm{m}$$

Adiabatic Focusing: Adiabatic increase in ***B'***

- Circumvents limits on focusing due to synchrotron radiation induced chromatic aberrations.
- Plasma lens are ideally suited for adiabatic focusing.

Even "weak" plasma lens are immensely strong:

150 T/m at $5\mathrm{x}10^{12}$ cm^{-3}

1500 T/m at $5\mathrm{x}10^{13}$ cm^{-3}

With appropriate parameters 70% - 80% of the beam is focused.

Plasma Lens Development

Overdense

$$n_b << n_p$$

Plasma cancels beam's space charge and remaining beam magnetic forces focus the beam

$$F_r \approx 2\pi n_b e^2 r$$

Since n_b is not generally uniform, overdense lens have significant aberrations.

Underdense

$$n_b \gtrsim \frac{n_p}{2}$$

Plasma electron ejected from beam entirely, uniform ion column focuses beam.

$$F_r = 2\pi n_p e^2 r$$

n_p can easily be both uniform and adjustable.

For a underdense gaussian plasma lens:

$$f = \frac{1}{KL} \qquad KL = \int \frac{2\pi r_e n_p(l)}{\gamma} dl$$

Overdense Channeling:
Rosenzweig et al. @ ANL (1989)
$n_p \sim 10^{13}\ cm^{-3}$ $n_b \sim 10^{12}\ cm^{-3}$
Plasma Length = 33 cm

Overdense Lens:
Nakanishi et al. @ U. Tokyo (1991)
$n_p \sim 10^{11}\ cm^{-3}$ $n_b \sim 10^{10}\ cm^{-3}$
Plasma Length = 15 cm
Focal Length ~ 1 m

Hairapetian et al. @ UCLA (1994)
$n_p \sim 10^{12}\ cm^{-3}$ $n_b \sim 10^{10}\ cm^{-3}$
Plasma Length = 7.5 cm
Focal Length ~ 30 cm

Govil et al. @ LBNL (1999)
$n_p \sim 10^{14}\ cm^{-3}$ $n_b \sim 10^{12}\ cm^{-3}$
Plasma Length = 2 cm
Focal Length ~ 15 cm

Bolton et al. @ SLAC (2001)
$n_p \sim 10^{17}\ cm^{-3}$ $n_b \sim 10^{16} cm^{-3}$
Plasma Length = 3 mm
Focal Length ~ 15 mm

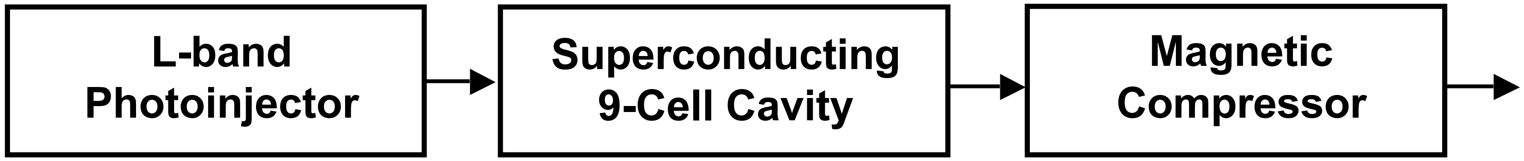
Underdense Channeling:
Barov et al. @ ANL (1998)
$n_p \sim 1\times10^{13}\ cm^{-3}$ $n_b \sim 2\times10^{13}\ cm^{-3}$
Plasma Length = 12 cm

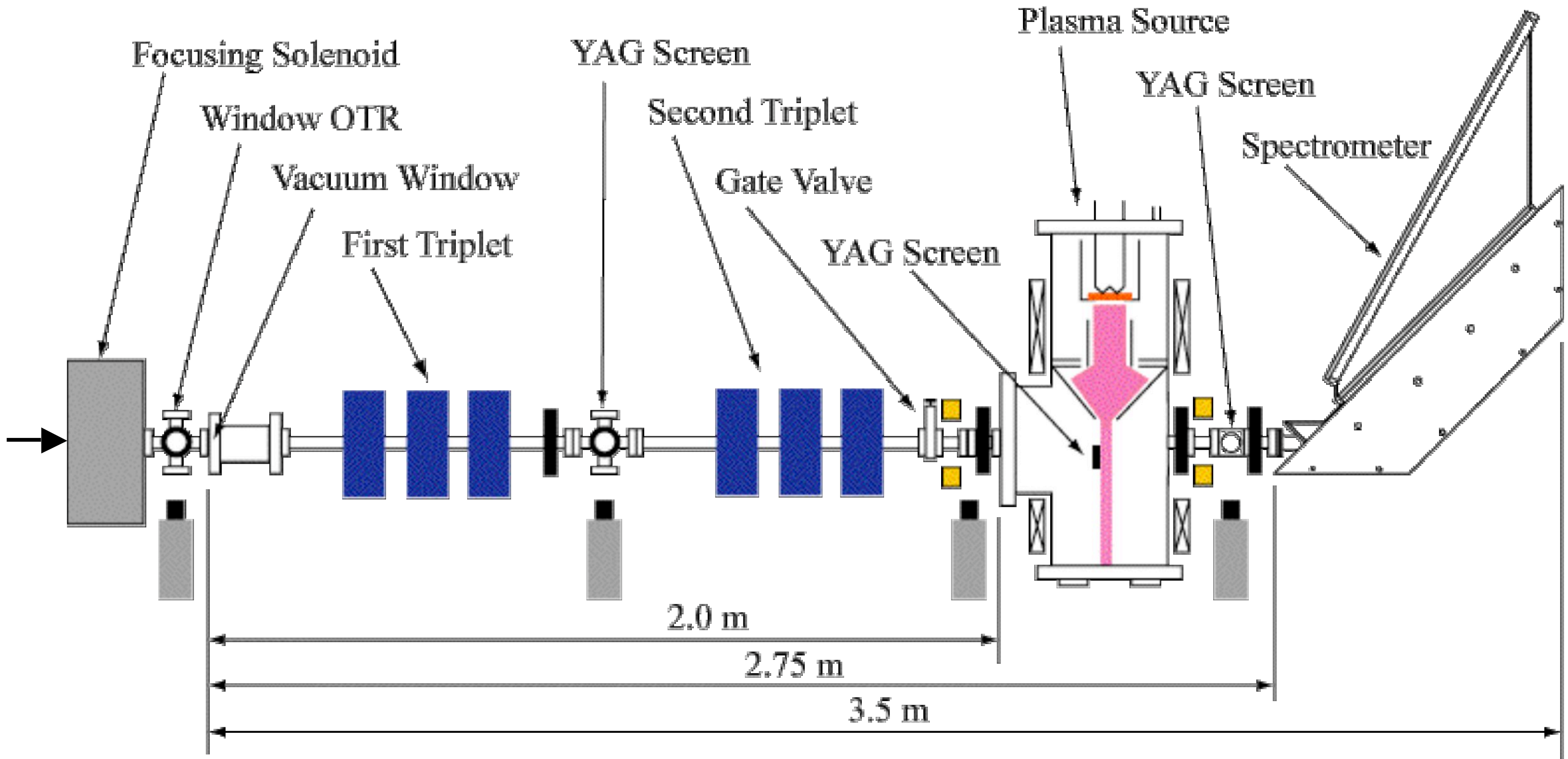
Clayton et al. @ SLAC (2002)
$n_p \sim 10^{14}\ cm^{-3}$ $n_b \sim 10^{15}\ cm^{-3}$
Plasma Length = 1.4 m

The Experimental Beam Line

The experiment took place at the Fermilab NICADD Photoinjector Laboratory (FNPL) in the spring and early summer of 2005.

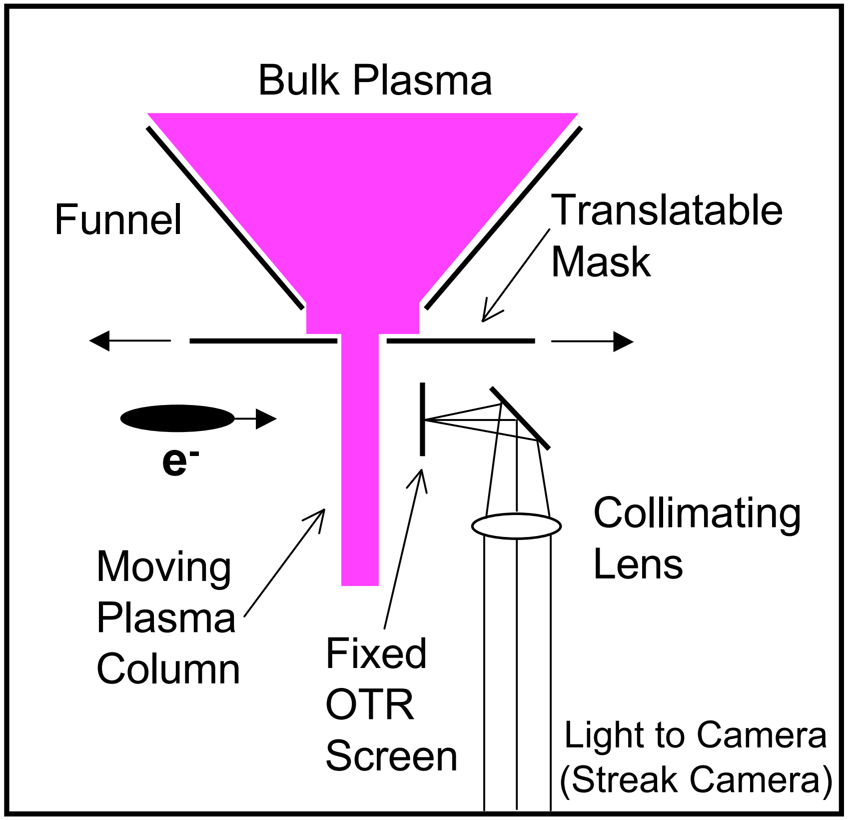
FNPL Beamline:



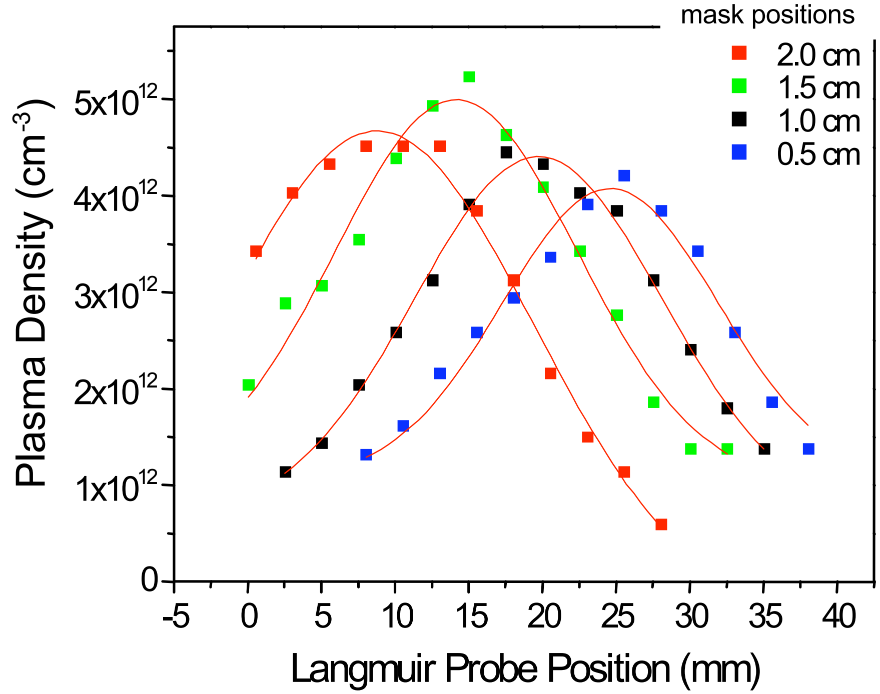


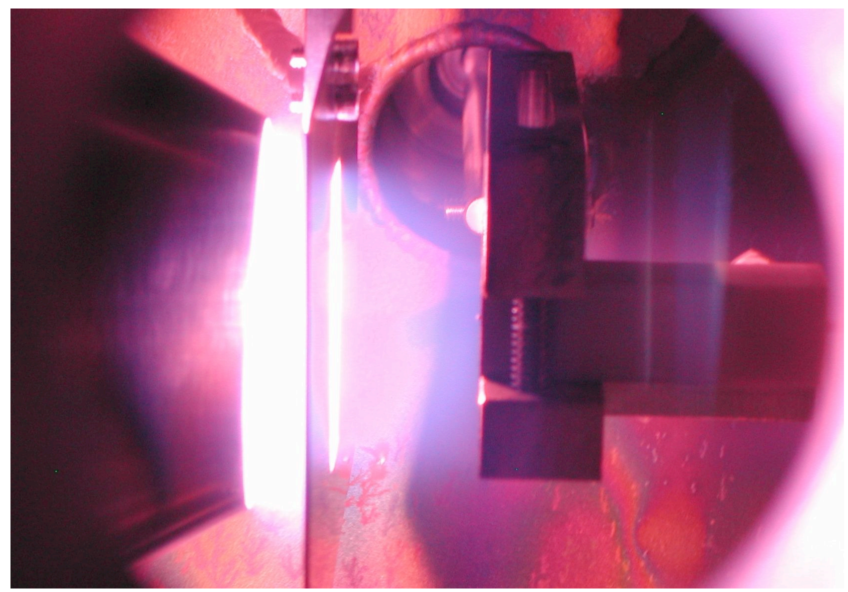
Plasma Lens Apparatus

A 1.25 cm wide moving window is placed in front of the fixed 5 cm plasma column. The resulting translatable plasma column is used to focus the beam onto a fixed OTR screen.



Schematic of the Experiment





Photograph of Measurement in Progress

Gaussian Underdense Plasma Lens

This is the first experiment to examine underdense plasma focusing in a well diagnosed true lens configuration with:

- **High Demagnification**
- **Beam Focus Outside Plasma**
- **Variable Lens Position**

Achieved Experimental Parameters

Peak Plasma Density	4.7 x 10^{12} cm^{-3}
Plasma Skin Depth (c/ω_p)	3.6 mm
Plasma Thickness (_$_p$)	9.9 mm
Beam Energy	15 MeV
Beam Charge	16 nC (10^{10} e^-)
Beam Duration (σ_t)	22 ps
Initial Beam Radius (σ_r)	950 μm
Beam Emittance (_$_n$)	90 mm-mrad
Peak Beam Density	2.2 x 10^{12} cm^{-3}

$$f = \frac{1}{KL} = \sqrt{\frac{2}{\pi}} \frac{\gamma c^2}{\sigma_p \omega_p^2 \big|_{peak}}$$

$$f_{predicted} = 1.5\text{cm}$$

$$f_{observed} \cong 1.9\text{cm}$$

Threshold Operation:

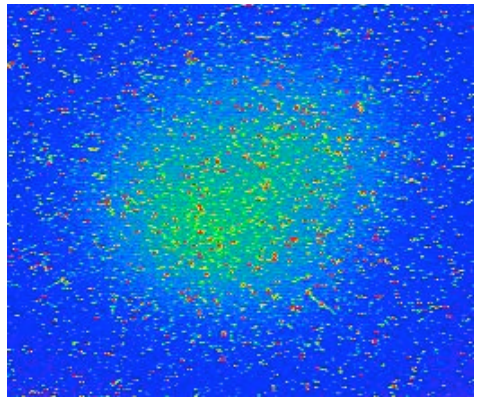
$$n_{beam} \approx \frac{n_p}{2}$$

Analysis of Round Beam Focusing Results

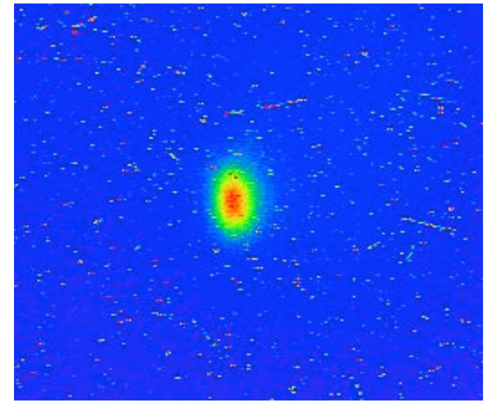
Beam Spot Before:
x FWHM = 1630 μm
y FWHM = 1540 μm
$n_b = 2.2 \times 10^{12}\ cm^{-3}$

Beam Spot After (Ave.):
x FWHM = 260 μm
y FWHM = 420 μm
$n_b = 5 \times 10^{13}\ cm^{-3}$

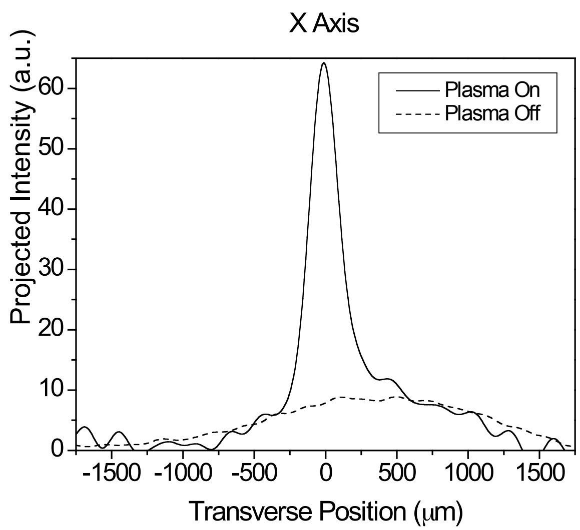
The average transverse area of the beam is reduced by a factor of 23.

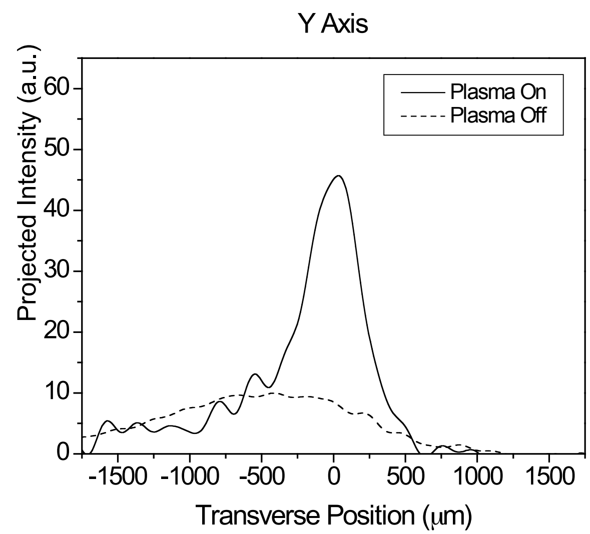


Unfocused – 5 electron pulses



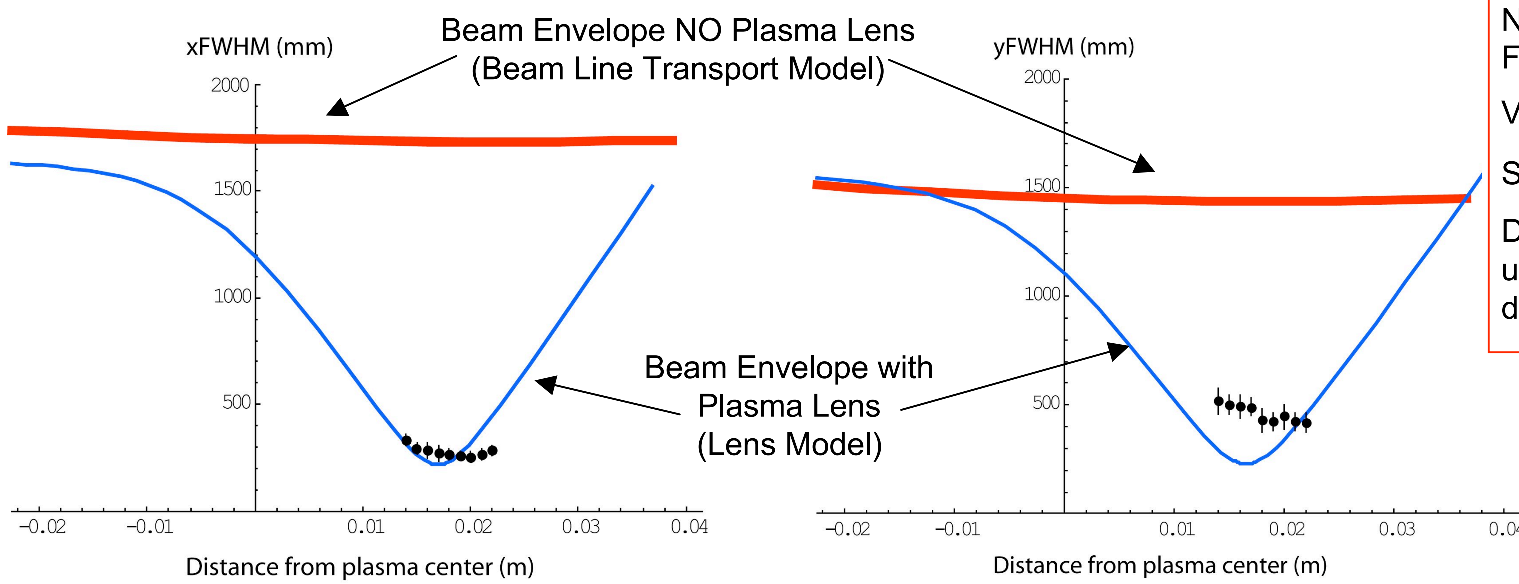
Focused – 1 electron pulse





Plots of the image intensity of the above photographs (normalized to 1 electron pulse).

Evolution of the Beam Envelope



Model Ignores:

Non-Gaussian Beam Features,

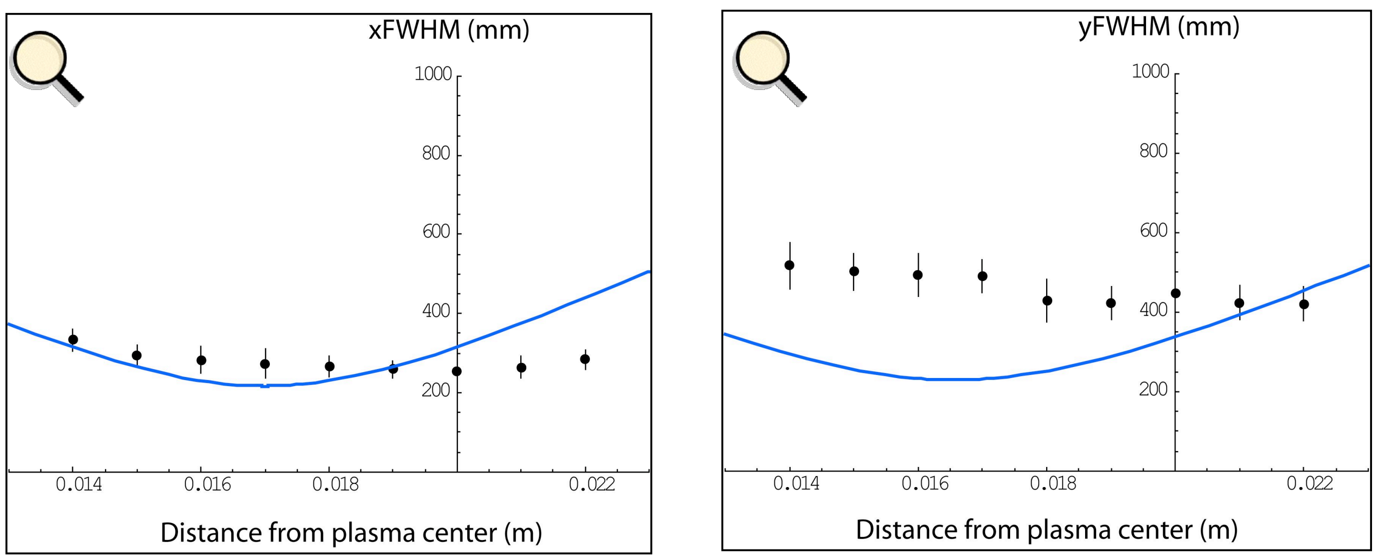
Variation in n_p and σ_p

Space charge

Deviation from perfect underdense lens dynamics

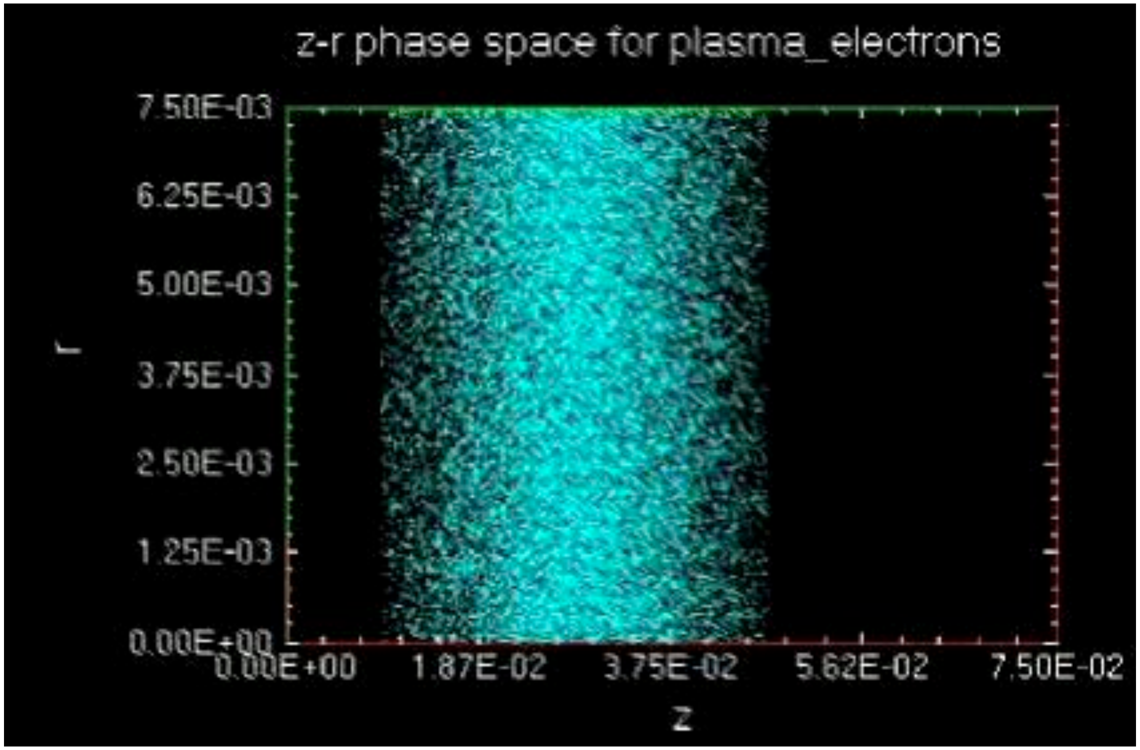
Region Near Focal Point with Data:

Line is the evolution of the beam core.



Simulations: Plasma response

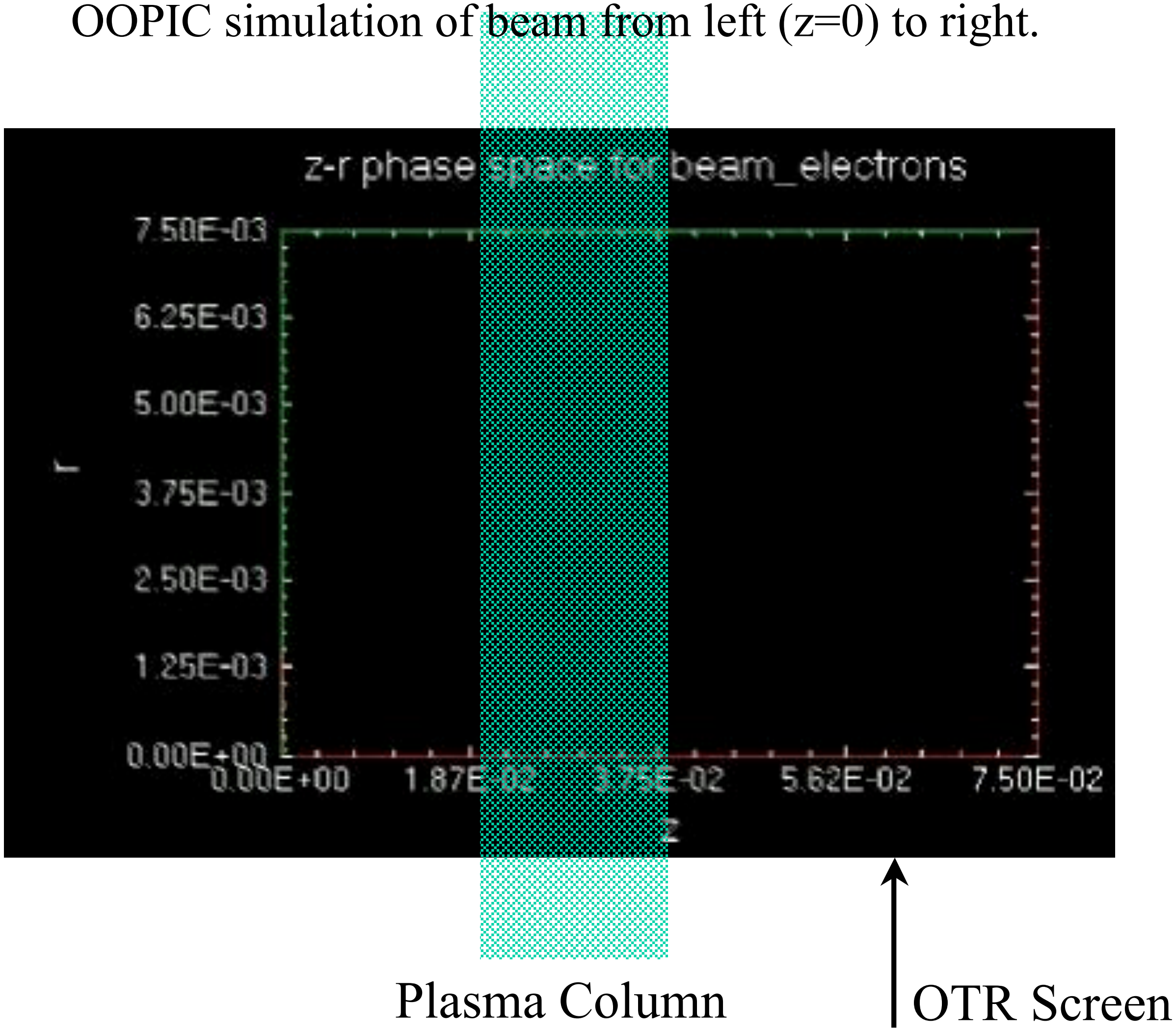
OOPIC simulation of plasma electrons as the electron bunch traverses from left (z=0) to right.



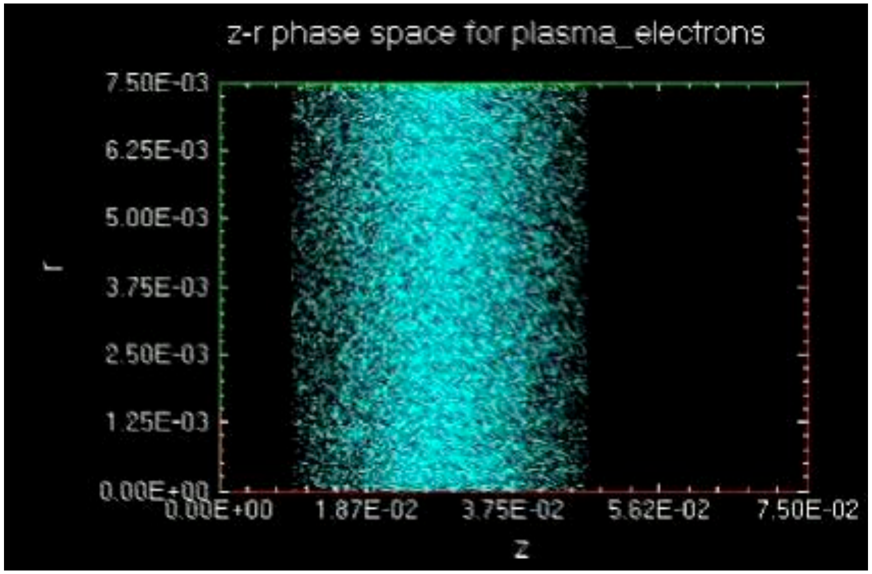
Beam Direction

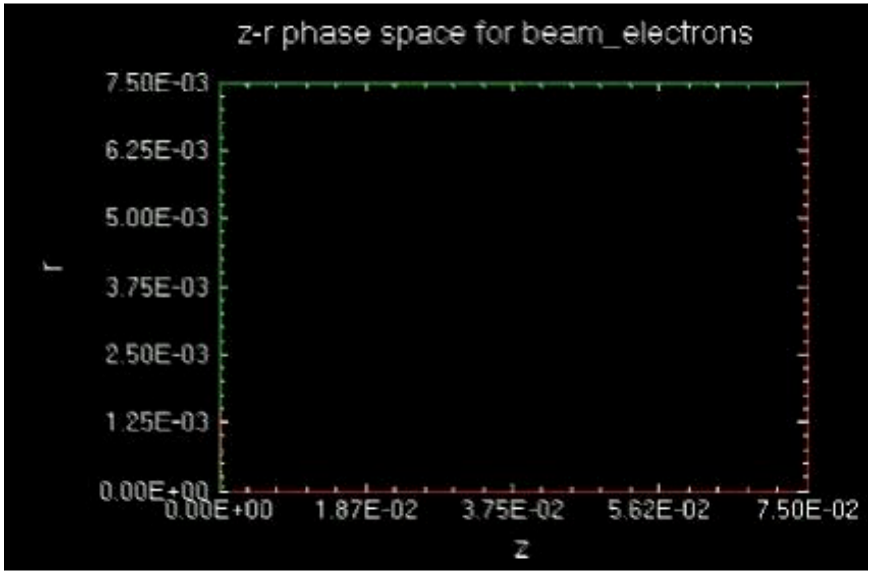
Simulations: Beam response

OOPIC simulation of beam from left (z=0) to right.



Simulations: Beam and Plasma

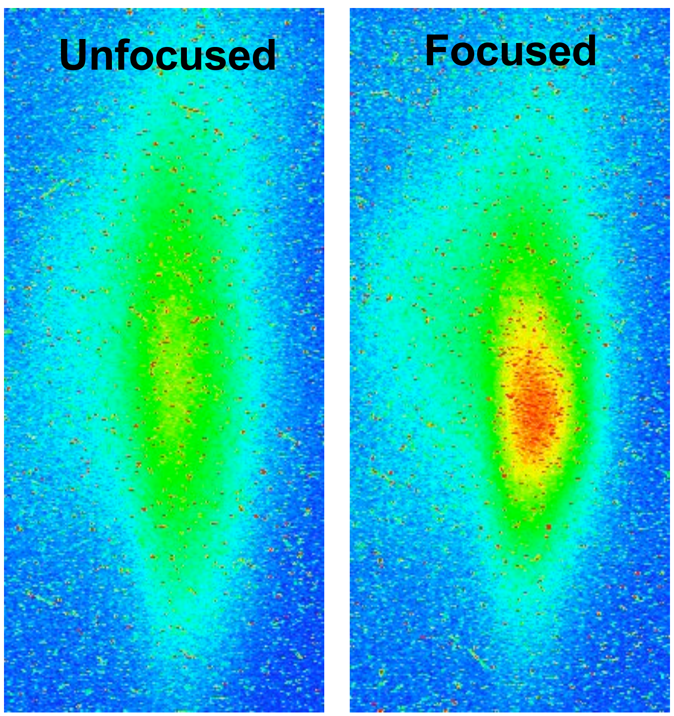




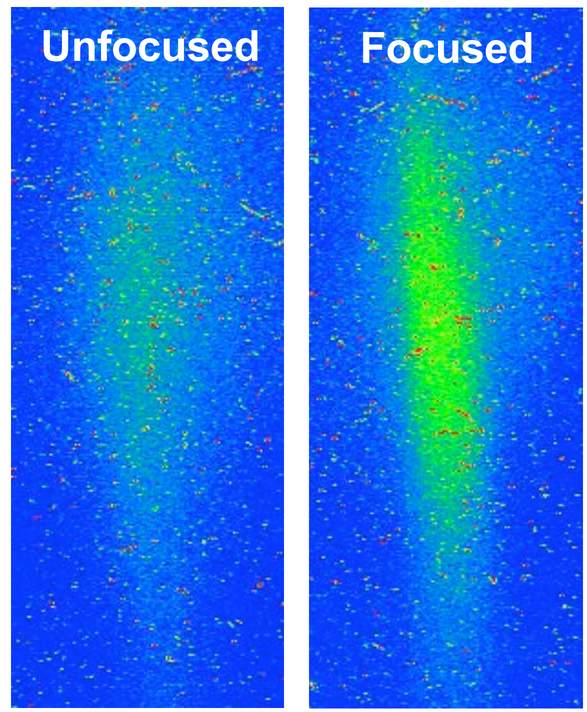
Plasma Focusing of High Aspect Ratio Beams

• The International Liner Collider will use a 100:1 aspect ratio beam in order to mitigate detrimental beam/beam affects.

• We measured plasma focusing of beams with transverse aspect ratios up to about 1:5. Note that the emittance remained equal in x and y.



1:3.4 Beam Aspect Ratio
Equal Number of Beam Pulses

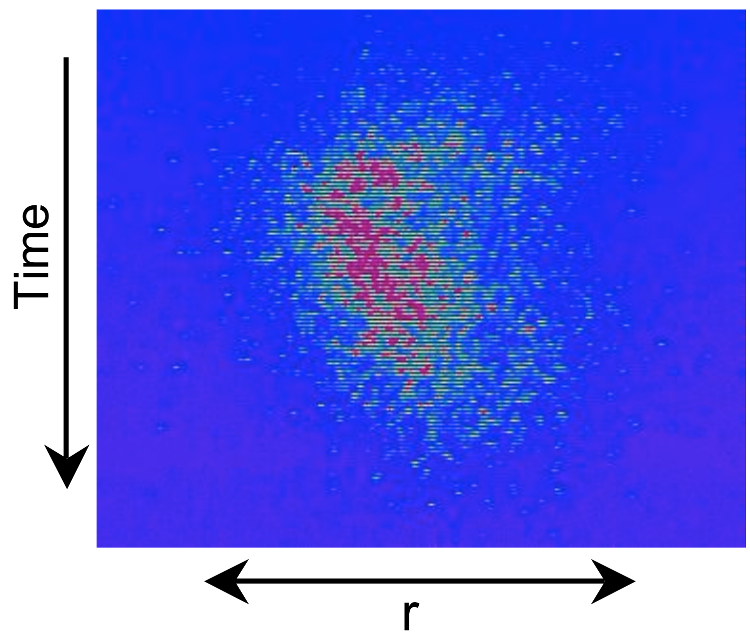


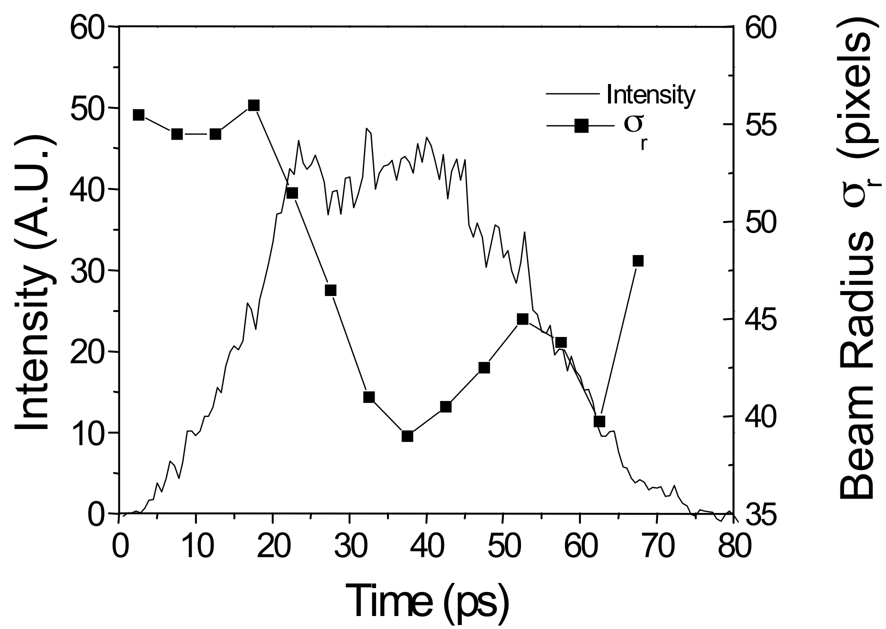
1:4.5 Beam Aspect Ratio
Equal Number of Beam Pulses

Time Resolved Measurements

A series of time resolved measurements of the plasma focusing were made by imaging the beam OTR light onto the slit of a streak camera.

As expected, the intensity profile (~charge) of the focused beam in the time domain remains roughly gaussian while the beam is radially larger at the head than in the middle or tail.





Conclusions

- We have demonstrated a compact, high demagnification plasma lens for relativistic electron beam operating at the threshold of the underdense regime.
- Time integrated measurements of the plasma focusing of both round and elliptical beams were made.
- Time resolved measurements of the round beam focusing were also obtained.
- Our analysis of this data is ongoing.

Future Directions

- Recent work pointing out the problem of ion collapse in the ILC afterburner scenario also has implications for final focus plasma lens, especially those of the adiabatic variety. More work is need to explore ion collapse in this context.