UCLA/FNPL Underdense Plasma Lens Experiment: Results and Analysis

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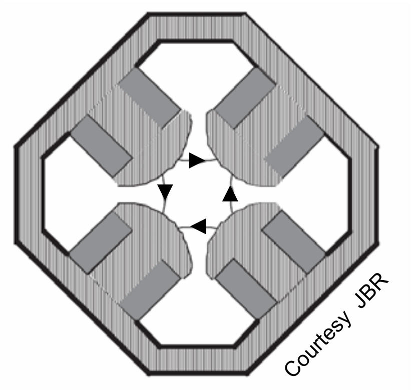
Advanced Electron Beam Lens

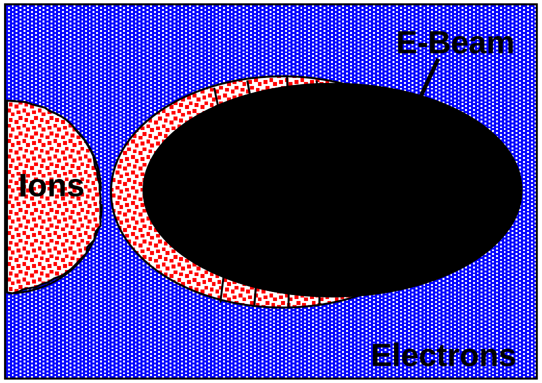
Magnetic Quadrupoles

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.



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

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

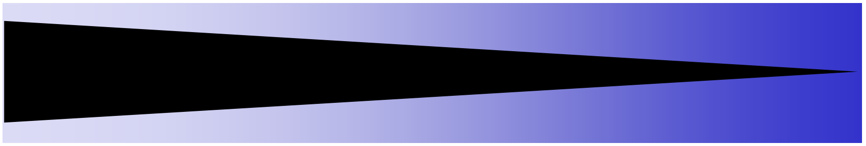
$$B' \approx 250\ \mathrm{T/m}$$

State-of-the-Art Superconducting Quad

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

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 5x10^{12} cm^{-3}

1500 T/m at 5x10^{13} cm^{-3}

Head of the beam is not focused.

Plasma Lens Regimes

Previous Experiments

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.

Spherical Aberrations:

(Gaussian Beam)

$$\frac{\Delta K}{K} \geq 0.22$$

Our New Results

Underdense

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

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

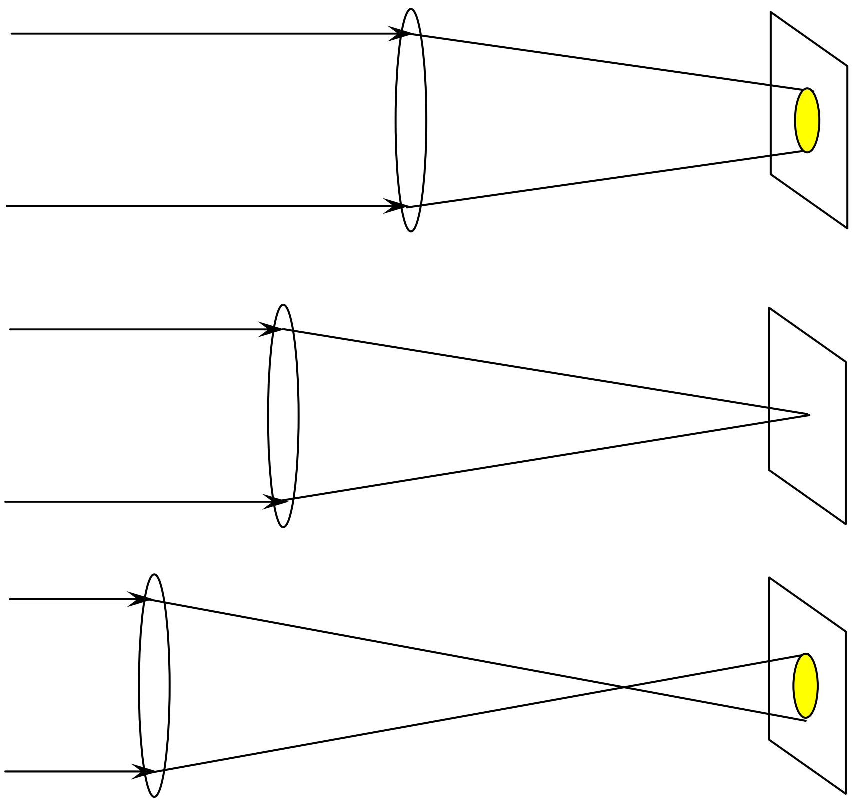
$$F_r = 2\pi n_p e^2 r$$

n_p can easily be both uniform and adjustable.

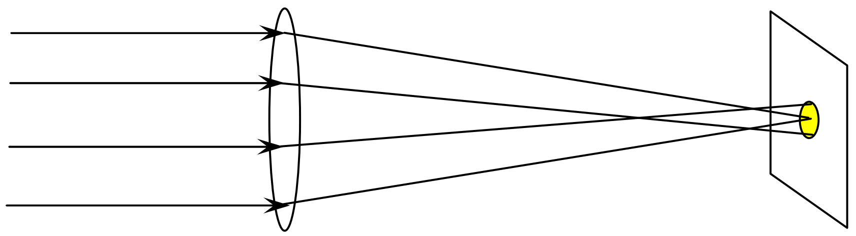
Spherical Aberrations:

$$\frac{\Delta K}{K} \approx 0$$

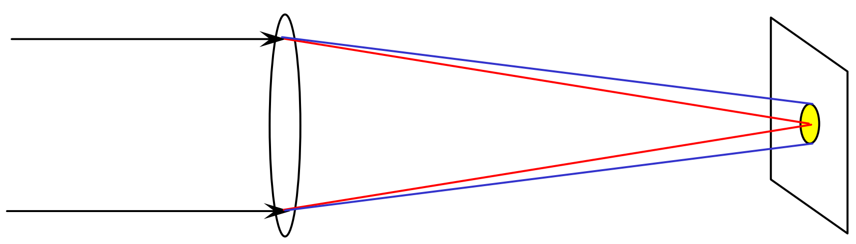
A Simple Lens Experiment



Focusing a Perfect Beam Through
a Waist with a Perfect Lens



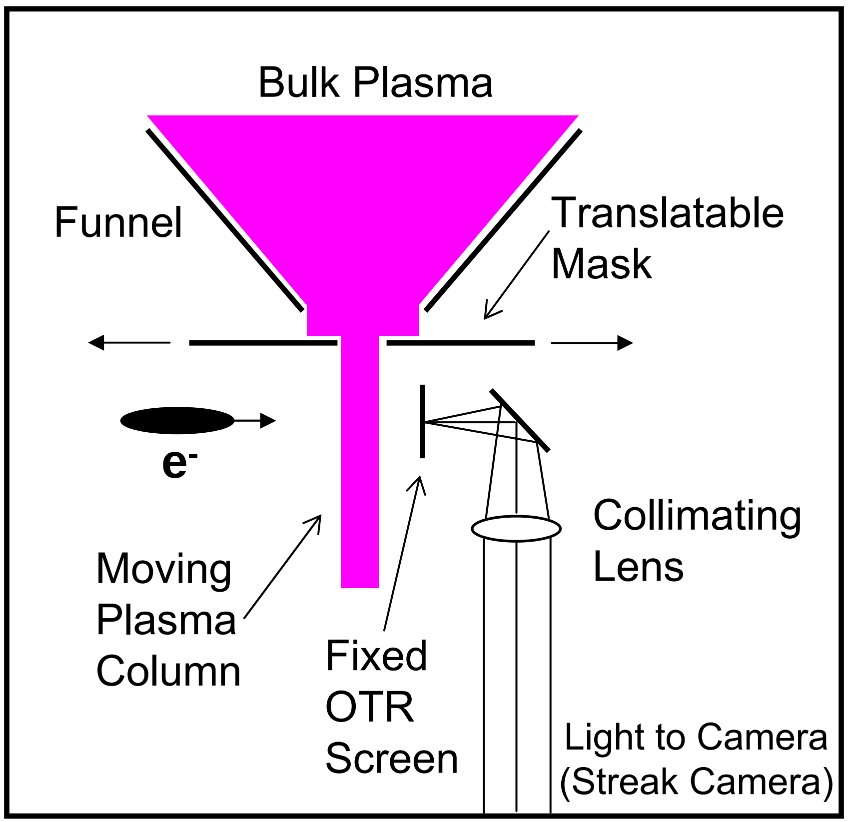
The Waist with Spherical Aberration



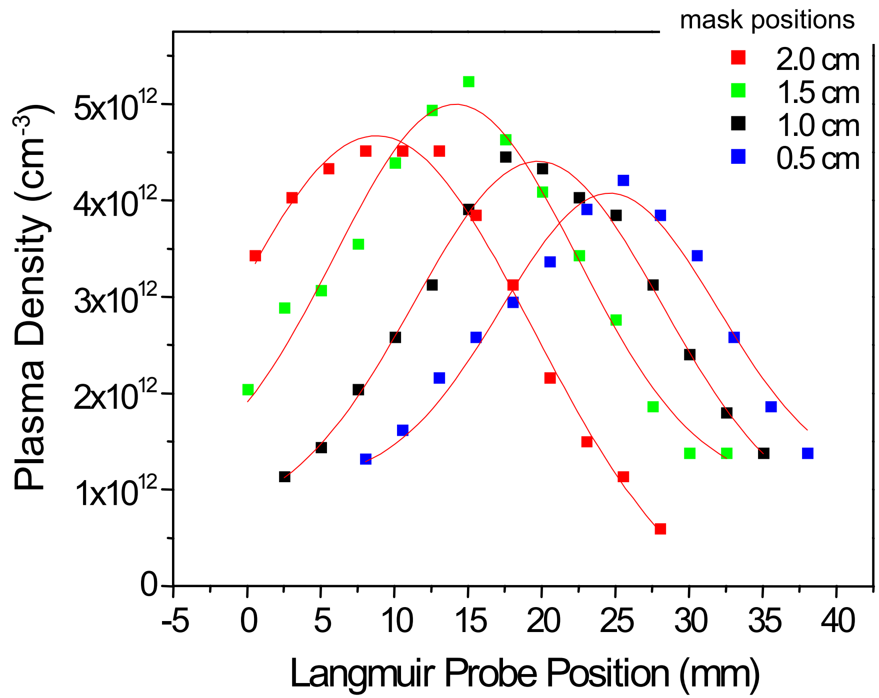
The Waist with Chromatic Aberration

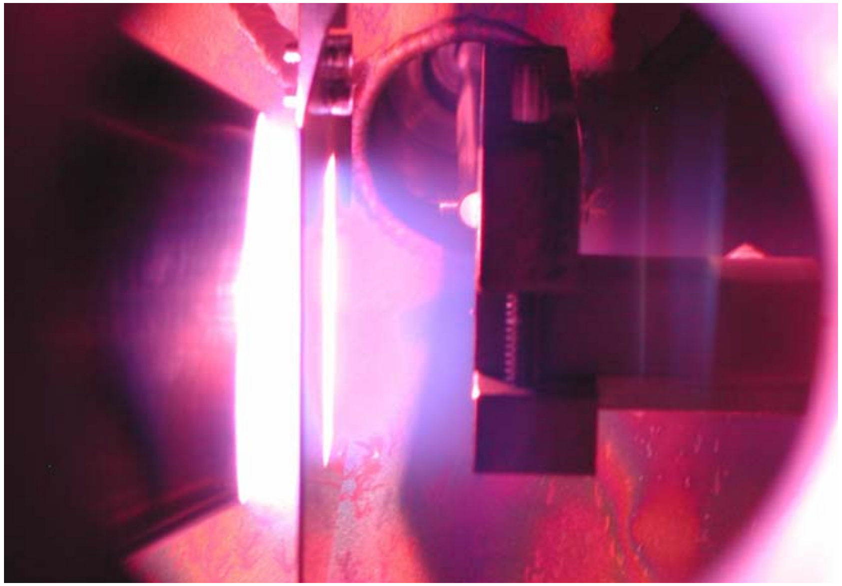
Plasma Lens Apparatus

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

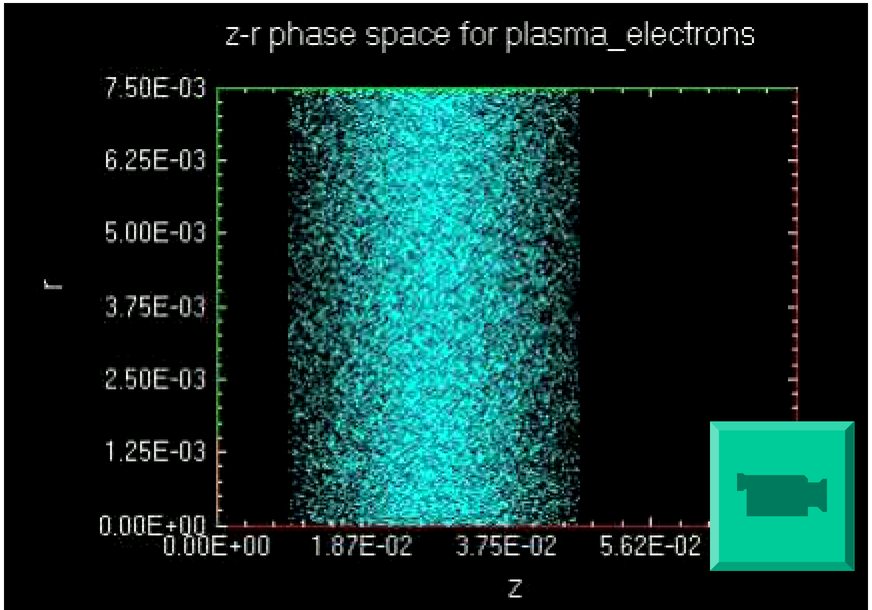
OOPIC Simulations

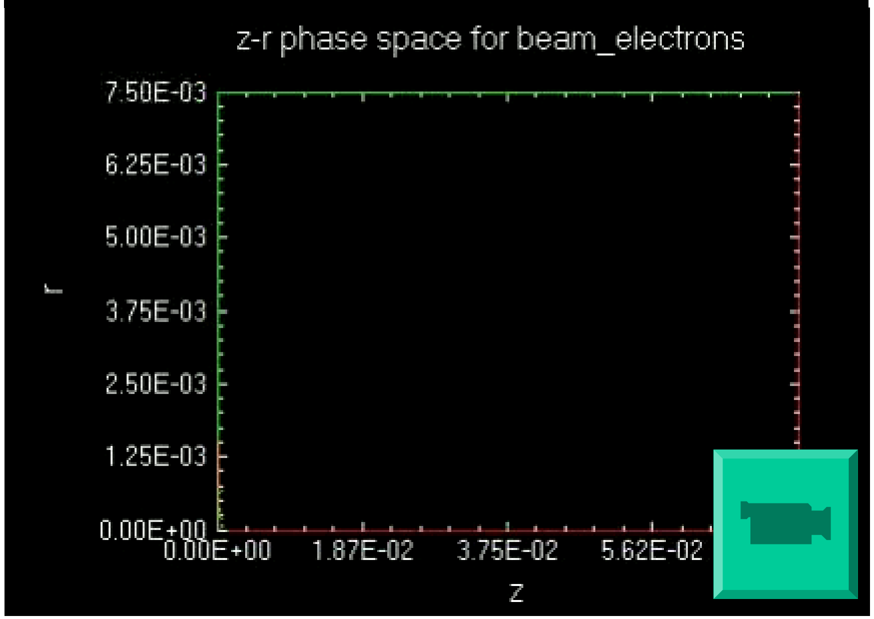
Experimental Parameters

Peak Plasma Density	4.9×10^{12} cm^{-3}
Plasma Width (FWHM)	19.3 mm
Beam Energy	14.8 MeV
Beam Charge	16 nC (10^{11} e^-)
Beam Duration (σ_t)	22 psec
Initial Beam Radius (σ_r)	900 μm
Beam Emittance (ε_n)	87 mm-mrad
Peak Beam Density	2.2×10^{12} cm^{-3}
Focal Length $f = 1/Kl$	1.9 cm

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

Just on the boundary of the underdense regime.



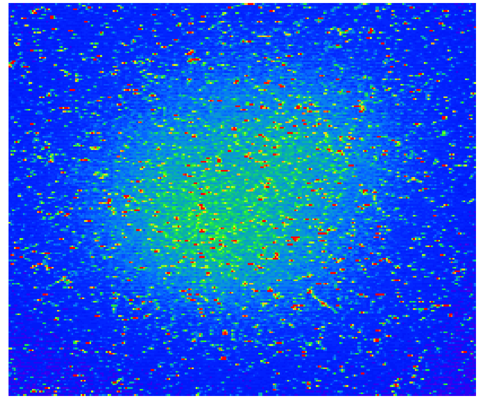


Plasma Focusing Results

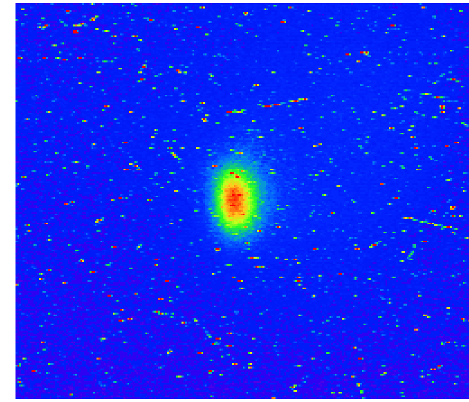
Beam Spot Before:
x FWHM = 1630 μm
y FWHM = 1540 μm
$n_b = 2.2 \times 10^{12}\ \mathrm{cm}^{-3}$

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

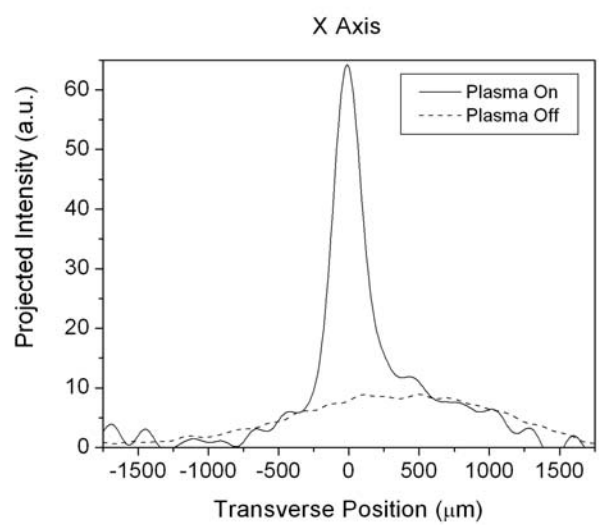
The transverse area of the beam core is reduced by a factor of 23.

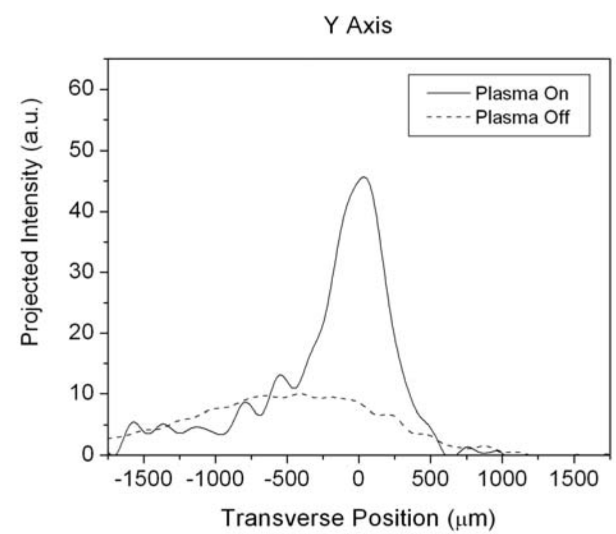


Unfocused – 5 electron pulses



Focused – 1 electron pulse

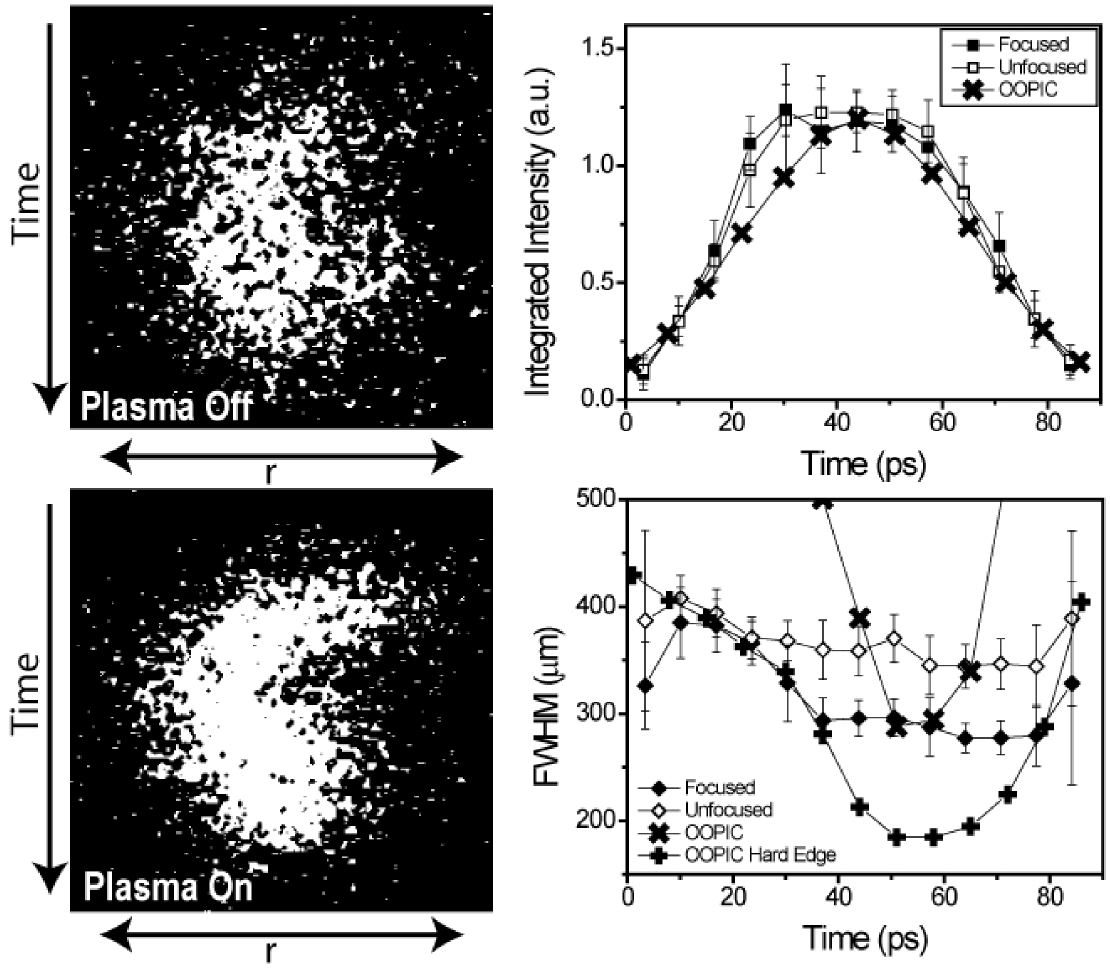




Plots of the image intensity of the above photographs (normalized to 1 electron pulse).

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 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.
- While the focused beam diameter observed on the steak images matches the value measured using the OTR screen CCD camera, there is clearly clipping of the signal in the transverse direction.



Analysis of the Aberrations

The transverse evolution of an electron beam can be described by (neglecting space charge effects) the beam envelope equation:

$$\frac{d^2\sigma_x}{dz^2} + K\sigma_x = \frac{\varepsilon_x^2}{\sigma_x^3}$$

For our gaussian plasma lens the focusing strength K is a function of z:

$$K = \frac{2\pi r_e n_p(z)}{\gamma}$$

Aberrations can be included in the model by defining an effective emittance that contains both the original beam emittance and the extra angular spread resulting from the lens aberrations:

$$\varepsilon_{eff} = \sqrt{\varepsilon_0^2 + \beta_0\varepsilon_0\delta\theta^2}$$

$$\delta\theta = \frac{\sqrt{\beta_0\varepsilon_0}}{f}\frac{\Delta K}{K}$$

$$\beta_0 = \frac{\sigma_0^2}{\varepsilon_0}$$

$$\frac{d^2\sigma_x}{dz^2} + K\sigma_x = \frac{\varepsilon_{eff}^2}{\sigma_x^3}$$

Examining the Beam Envelope Near the Waist

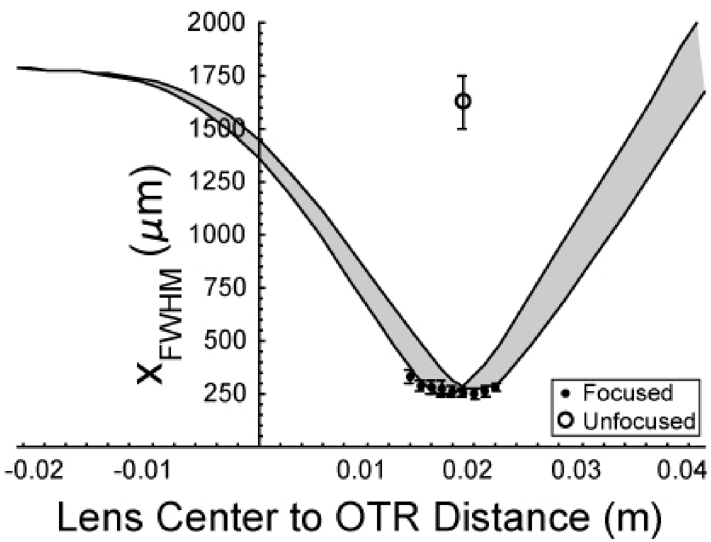
The focused electron beam spot was measured at several different lens/screen spacing near the waist.

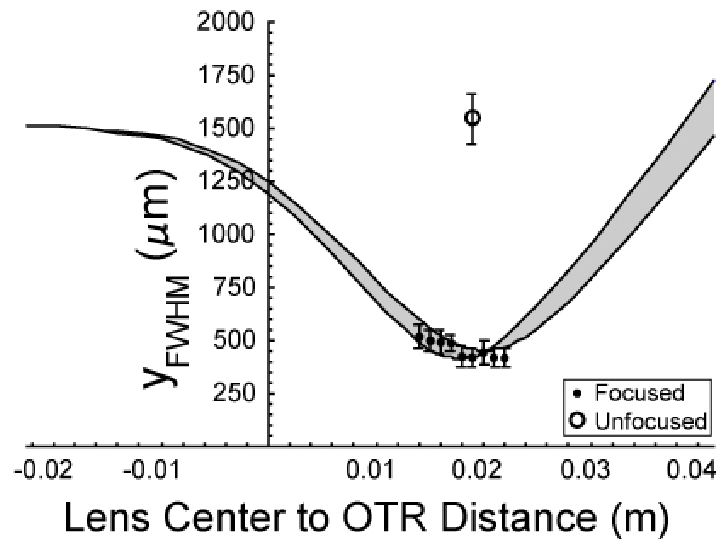
Using the know plasma lens parameters, and leaving the effective emittance as the free parameter, the beam envelop equation was fit to the data.

Effective Emittance Values:

$$\varepsilon_{eff,x,n} = 110 \text{ mm-mrad}$$

$$\varepsilon_{eff,y,n} = 155 \text{ mm-mrad}$$





Behavior of the Beam Spot Size Near the Waist

Calculation of the Aberrations

From the envelope data:

$$\varepsilon_{eff,x,n} = 110 \text{ mm-mrad}$$

From quadrupole scans:

$$\varepsilon_{x,n} = 87 \text{ mm-mrad}$$

$$\varepsilon_{eff}^2 = \varepsilon_0^2 + \frac{\sigma_0^4}{f^2}\left(\frac{\Delta K}{K}\right)^2$$

Total Lens Aberrations: $\frac{\Delta K}{K} = 0.076 \pm 0.006$

Overdense Minimum: < 0.22

Chromatic Contribution: $\left(\Delta K/K\right)_{chromatic} \leq 0.025$

Which demonstrates that we have low aberration underdense behavior even at the regime threshold.

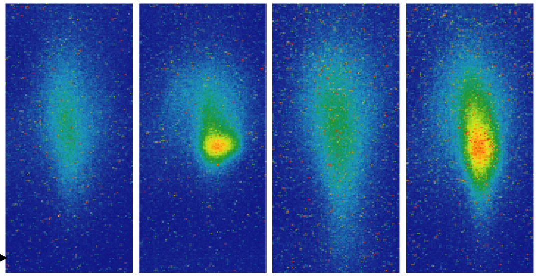
Conclusions

- We have demonstrated a compact, high demagnification plasma lens for relativistic electron beams operating at the threshold of the underdense regime.
- The aberrations of the underdense lens are much lower than in the overdense case, as predicted by theory, even near the threshold.

Future Directions

- Studies of plasma lenses in general must begin to examine the focusing of strongly asymmetric beams.

Modestly asymmetric beam focusing near the underdense threshold.



- 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. The near threshold underdense regime my prove optimal.