The UCLA/NICADD Plasma Density Transition Trapping Experiment

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PBPL DoE Review - May 2004

Why Build Plasma Electron Beam Sources?

Better Emittance

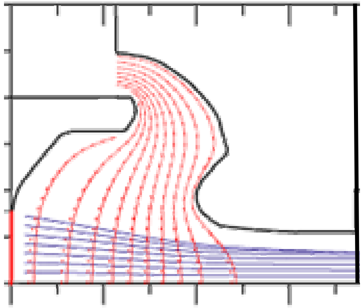
$$\varepsilon_{x,rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle} = \sigma_x \sigma_{x'}$$

Higher Brightness

$$B = \frac{I}{\varepsilon_{n,x}\varepsilon_{n,y}}$$

Larger Gradients

$$E_{wave\ breaking} = \frac{m_e c \omega_p}{e} \cong 96\sqrt{n_0[cm^{-3}]}\ \frac{V}{m}$$



Thermionic Gun:

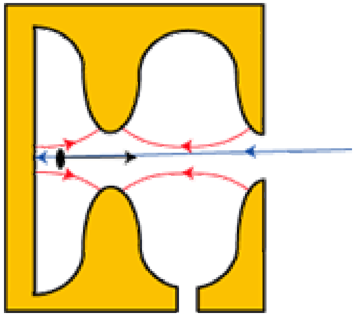
Cathode Size ~ 10^{-2} m

Emittance ~ 100 mm-mrad

Current ~ 10 A/cm^2

Brightness ~ 10^9 A/(m-rad)^2

Gradient ~ 1 MV/m



RF Photoinjector:

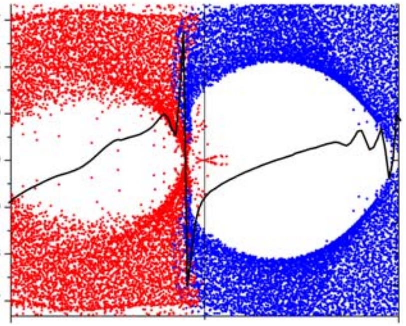
Cathode Size ~ 10^{-3} m

Emittance ~ 1 mm-mrad

Current Density ~ 10^3 A/cm^2

Brightness ~ 10^{12} A/(m-rad)^2

Gradient ~ 100 MV/m



10^{17} cm^{-3} Plasma :

"Cathode" Size ~ 10^{-5} m

Emittance ~ 0.1 mm-mrad

Current Density ~ 10^7 A/cm^2

Brightness ~ 10^{14} A/(m-rad)^2

Gradient ~ 10 GV/m

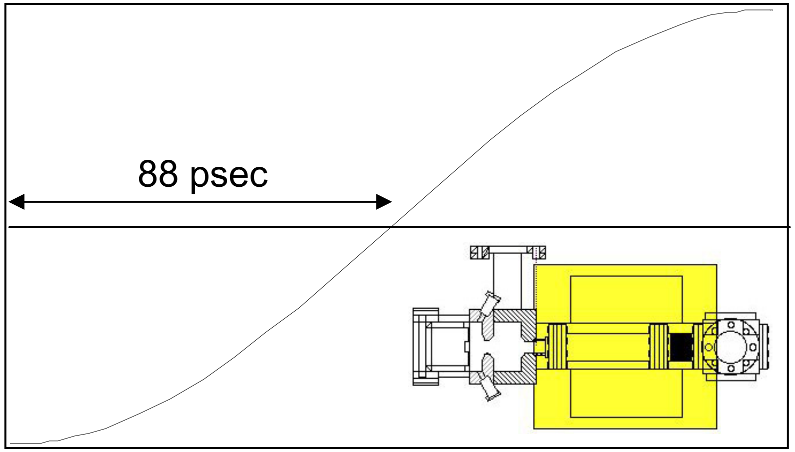
The Problem of Injection

All plasma accelerator schemes share two critical scalings:

$$E_{\max} \propto \sqrt{n}$$

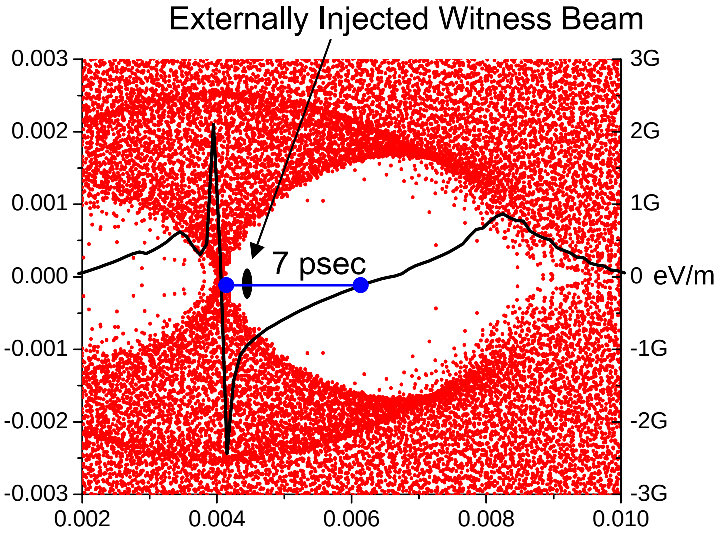
$$\text{Structure Size} \propto k_p^{-1} = \frac{c}{\omega_p} \propto \frac{1}{\sqrt{n}}$$

This scaling makes the injection of charge into plasma waves difficult because of the technical problems of pulse creation and timing at sub-ps levels.



High Gradient RF Structures:

Typical Frequency = 2856 MHz



Plasma Wake Field Accelerator Operated in the Non-Linear Regime at 5 x 10^{13} cm^{-3}

Trapping: The Injection of Plasma Electrons

The alternative to injecting external charge, e.g. from a cathode, is creating a situation in which the plasma wave can trap and accelerate electrons directly out of the plasma.

- Automatic Trapping:

  Gentle Convention Wave Breaking

  Disadvantage - High Energy Spread

  S. Bulanov, *et al.,* Phys. Rev. E 58, R5257 (1998)

- Stimulated Trapping:

  Multiple Colliding Laser Pulses

  Disadvantage - Complex Timing Requires

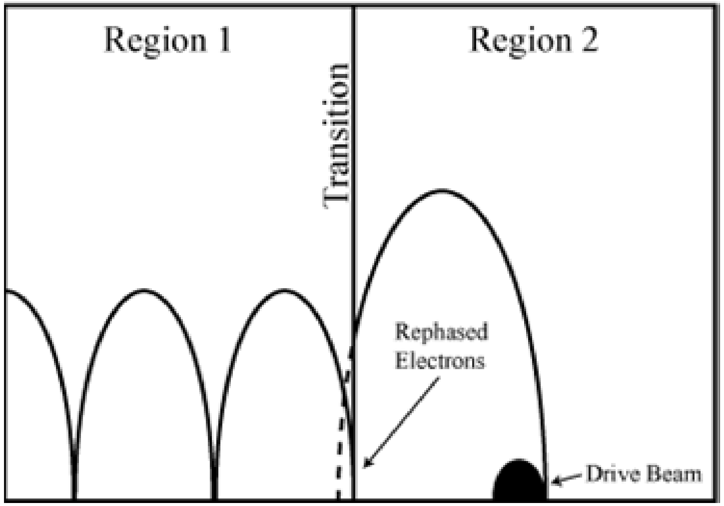
  E. Esarey, *et al.,* Phys. Rev. Lett. 79, 2682 (1997)
  D. Umstadter, *et al.,* Phys. Rev. Lett. 76, 2073 (1996)

Ideally we would like to combine the simplicity of “automatic” trapping with the beam quality of the stimulated methods . . .

Plasma Density Transition Trapping

Plasma Density Transition Trapping is a self-trapping scenario that uses the rapid change in the wake field wavelength at a steep drop in the plasma density to dephase plasma elections into an accelerating phase of the wake.

Transition Trapping Fundamentals:



Automatic Injection of Substantial Charge (~100 pC) Into accelerating Phase

Operates in PWFA Blow Out regime where $n_{beam} > n_{\text{plasma}}$ (underdense condition)

Trapping Condition: $k_p L_{Transition} < 1$ where k_p^{-1} is the plasma skin depth $k_p^{-1} = c/\omega_p$

UCLA Work On Transition Trapping:

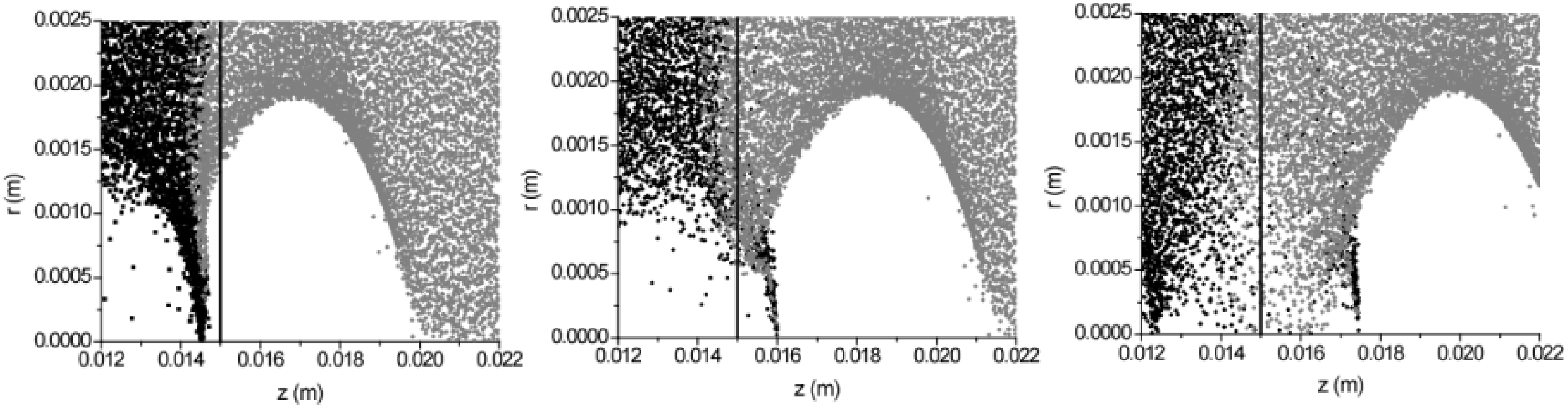
Concept Proposed - H. Suk, *et al.,* Phys. Rev. Lett. 86, 1011 (2001)

Trapping Experiment Proposed for the Neptune Lab at UCLA - M.C.Thompson, *et al.,* Proceedings PAC 2001, page 4014 (2001)

Improved analysis, Updated UCLA/NICADD Proposal - M.C. Thompson, *et al*., Proceedings PAC 2003, page 1870 (2003)

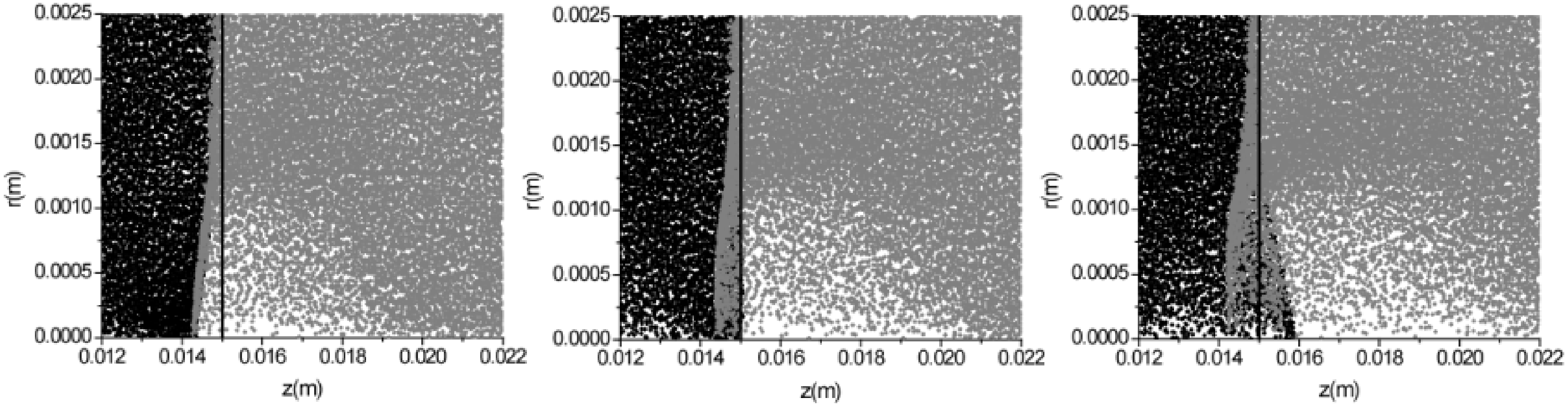
Analysis of Scaling and Merits as a High Brightness Source - M.C. Thompson, *et Al*., Phys. Rev. STAB 7, 011301(2004)

Trapping Regimes



Strong Blowout   Plasma: 5 x 10^{13} cm^{-3}/3.5 x 10^{13} cm^{-3}

Beam: 1.2 x 10^{14} cm^{-3} (63 nC)



Weak Blowout   Plasma: 2 x 10^{13} cm^{-3}/3.5 x 10^{12} cm^{-3}

Beam: 4 x 10^{13} cm^{-3} (5.9 nC)

Scaling of the Plasma Density

Scaling of the transition trapping system to higher Plasma Density (n_h) requires that all charge densities be increased by the ratio n_h / n and all lengths be decreased by the ratio:

$$\frac{\lambda_{ph}}{\lambda_p} = \frac{k_{ph}^{-1}}{k_p^{-1}} = \frac{1/\sqrt{n_h}}{1/\sqrt{n}} = \sqrt{\frac{n}{n_h}}$$

As the plasma density is increased, the captured beam parameters change according to the following scaling laws:

$$p \propto E_{\max}\lambda_p \propto \frac{\sqrt{n}}{\sqrt{n}} = \text{Constant} \qquad \varepsilon \propto \lambda_p p \propto \lambda_p$$

$$Q \propto n\lambda_p^{\ 3} \propto \lambda_p \qquad I \propto \frac{Qc}{\lambda_p} = \text{Constant}$$

$$B \propto \frac{I}{\varepsilon^2} \propto \frac{1}{\lambda_p^{\ 2}} \propto n$$

Transition Trapping as a High Brightness Source

Result of 2D PIC Simulations Examining the Scaling of a Weak Blowout Scenario

Peak Density	2×10^{13} cm^{-3}	2×10^{15} cm^{-3}	2×10^{17} cm^{-3}
$\sigma_{t,\text{ Diver}}$	1.5 psec	150 fsec	15 fsec
Q_{Driver}	10 nC	1 nC	100 pC
$\sigma_{t,\text{ Captured}}$	2.7psec	270 fsec	28 fsec
Q_{Captured}	1.2 nC	120 pC	12 pC
$I_{\text{Peak,Captured}}$	163 Amp	166 Amp	166 Amp
$\varepsilon_{x,\text{ normalized,Captured}}$	57 mm-mrad	5.9 mm-mrad	0.6 mm-mrad
$B_{\text{normalized,Captured}}$	5×10^{10}	5×10^{12}	5×10^{14}

LCLS Injector Spec:

$\varepsilon_{x,\text{ normalized}}$ = 0.6 mm-mmrad

I = 100 amp

$B_{\text{normalized}} = 2.8 \times 10^{14}$

Definitions:

$$\varepsilon^2_{x,normalized} = \langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2$$

$$p_x = \frac{\gamma v_x}{c}$$

$$B_{\perp,normalized} = \frac{I}{\varepsilon^2_{x,normalized}}$$

The Experimental Plan

Criteria for the first experiment:

Pre-Existing Drive Beam Parameters

Low Plasma Density

Easiest Possible Density Modification System

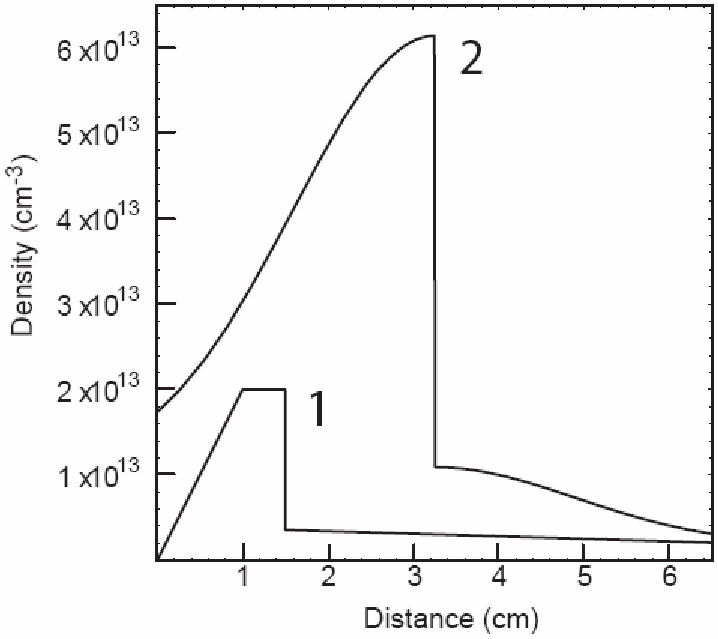


Table 1: Driving Beam Parameters

	Profile 1	Profile 2
Beam Energy	14 MeV	14 MeV
Beam Charge	5.9 nC	5.9 nC
Beam Duration σ_t	1.5 ps	1.5 ps
Beam Radius σ_r	362 μm	362 μm
Normalized Emittance	15 mm-mrad	15 mm-mrad
Peak Beam Density	4x10^{13} cm^{-3}	4x10^{13} cm^{-3}

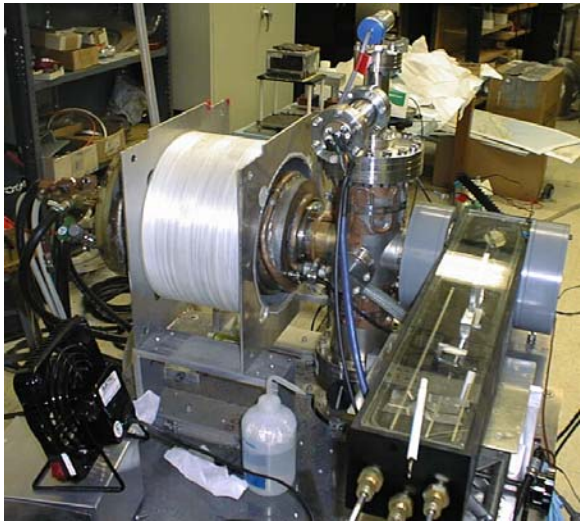
Table 2: Captured Plasma Electron Beam Parameters

	Profile 1	Profile 2
Beam Energy	1.2 MeV	1.5 MeV
Beam Charge	100 pC	470 pC
Beam Duration σ_t	1.7 ps	0.3 ps
Beam Radius σ_r	250 μm	100 μm
Normalized Emittance	24 mm-mrad	16 mm-mrad
Energy Spread (rms)	4%	4%

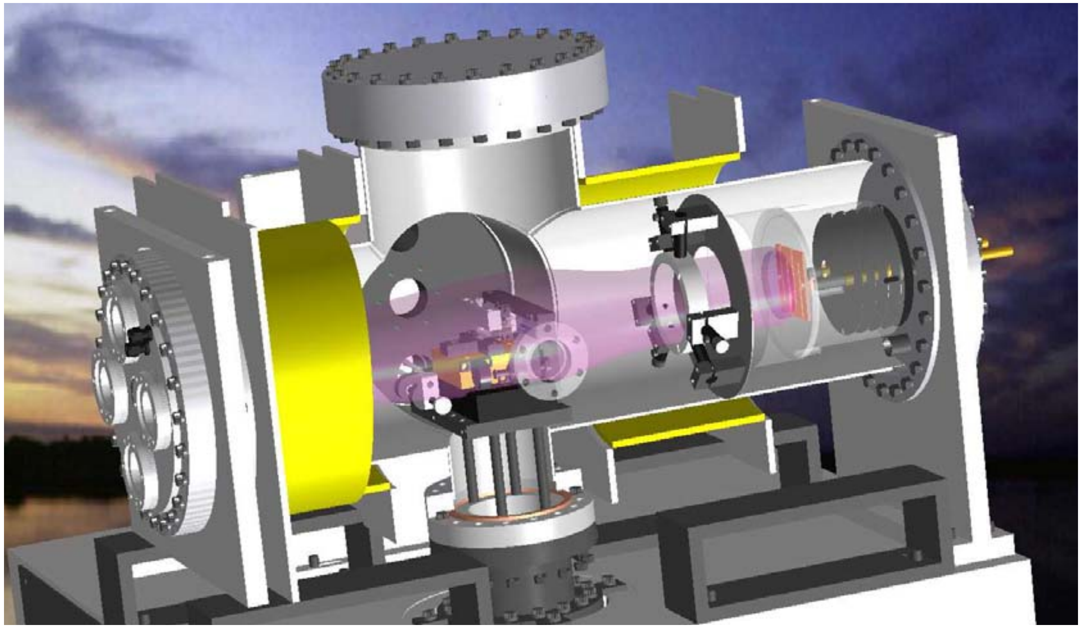
Argon Pulse Discharge Plasma Source

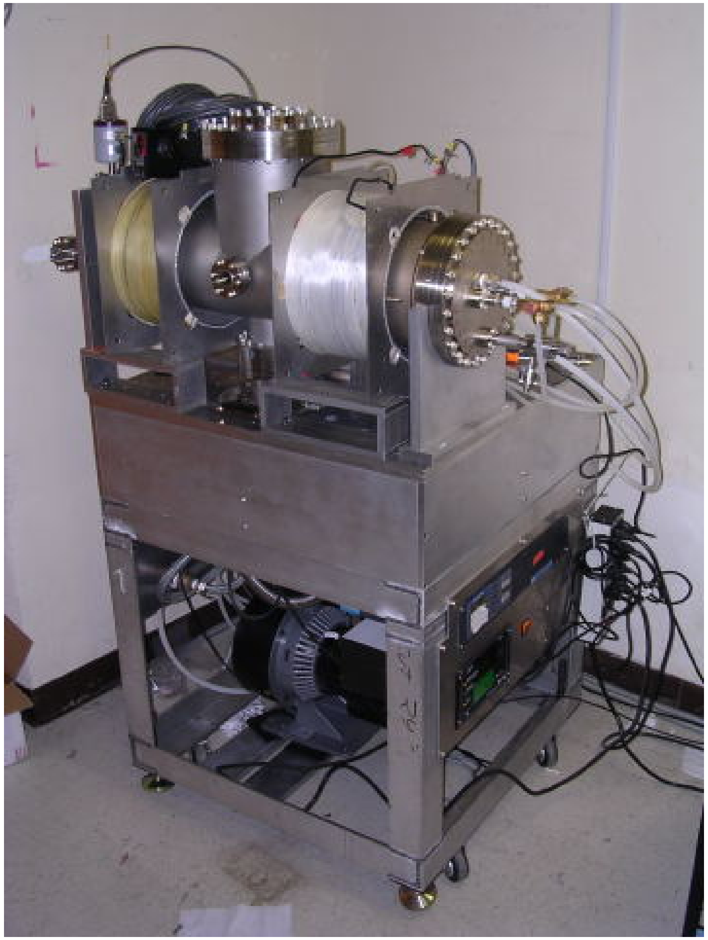
The Plasma Source was redesigned, rebuilt, and tested During 2002-2003.

Source shipped to Fermilab Nov 2003



Originally developed for a underdense plasma lens experiment at Neptune: H. Suk, C.E. Clayton, G. Hairapetian, *et al.,* PAC Proceedings (1999) p. 3708



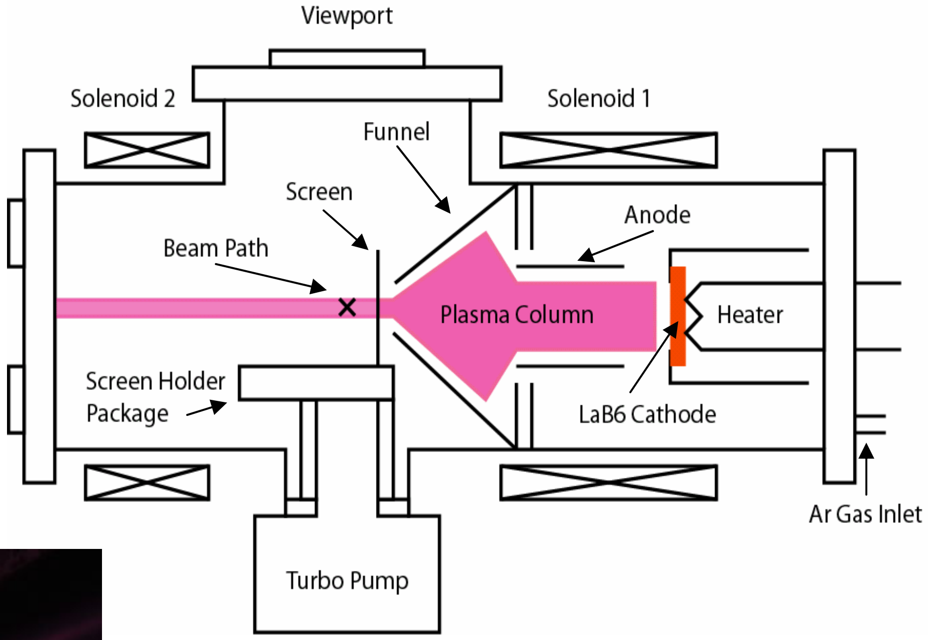


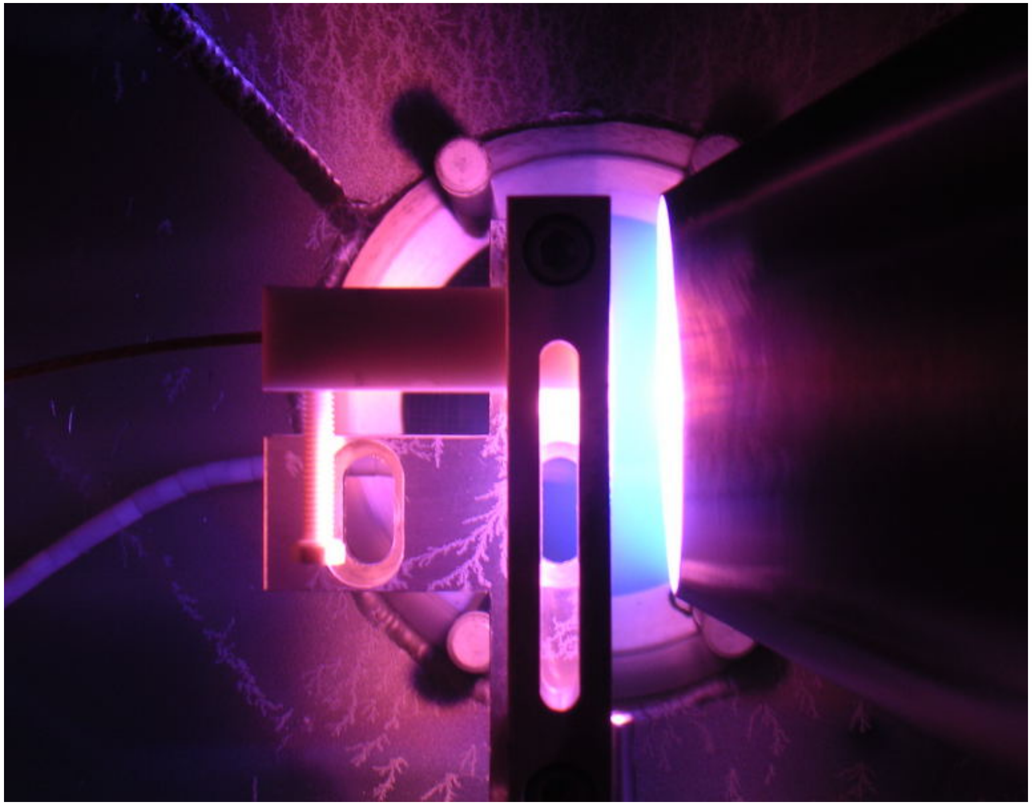
Source Testing

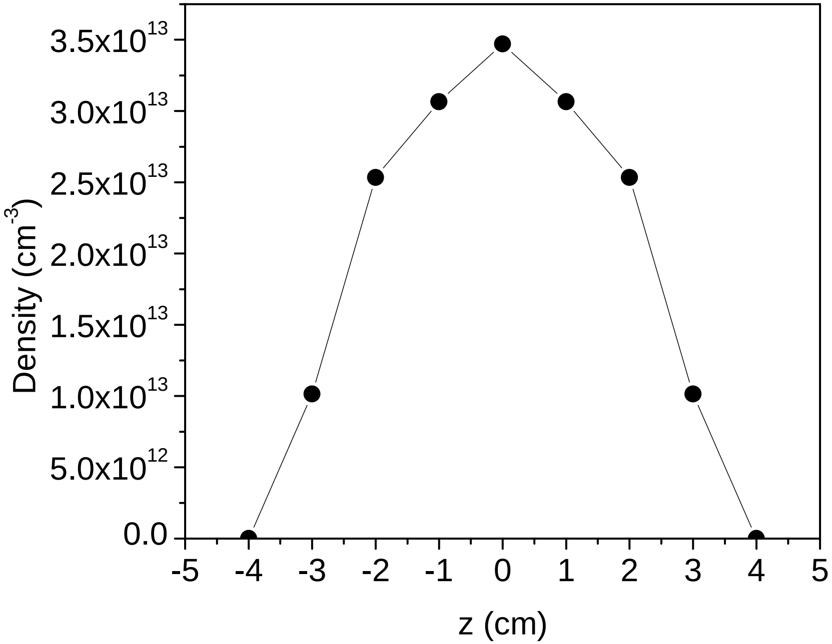
Highly Reliable Plasma Production

2 ms, 40 kW peak power pulses at 1 Hz

Peak Density > 3 x 10^{13} cm^{-3}

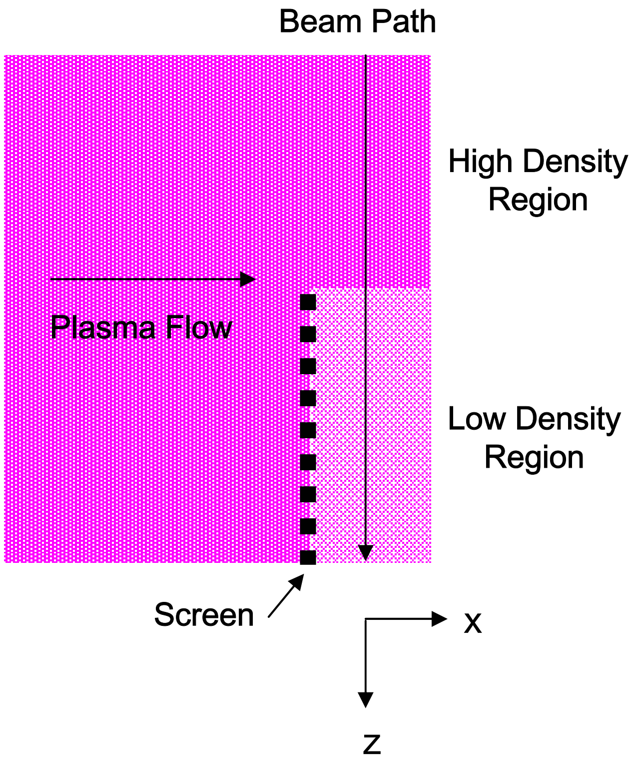


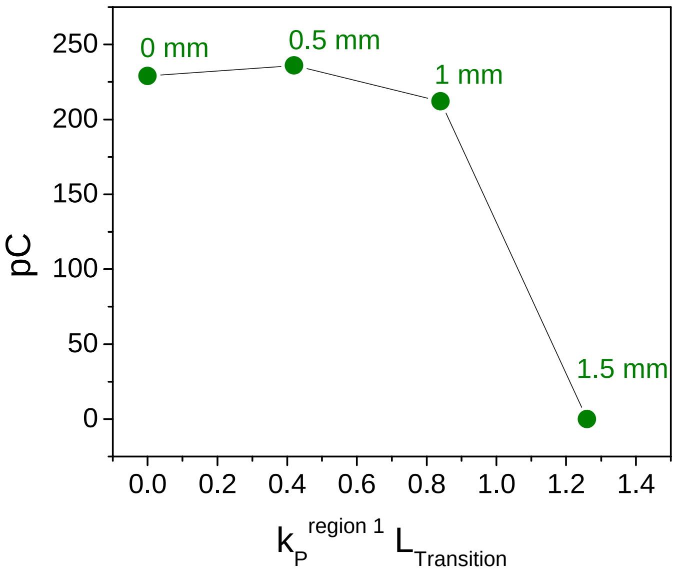




Tailoring Plasma Density Profiles

The directionality of the plasma flow in the pulsed discharge source allows the density to be manipulated by placing a perforated metal sheet between the source region and the interaction point. If the density modifying obstruction is placed very close the drive beam path the transition in density should be sharp enough to show trapping.





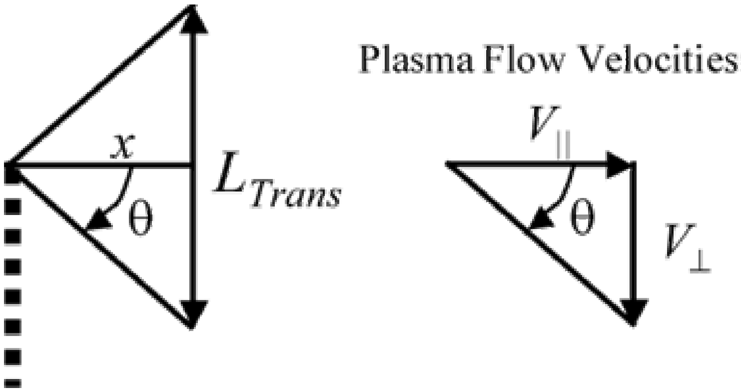
Dependence of the amount of charge captured on finite length of the plasma transition (MAGIC Simulation).

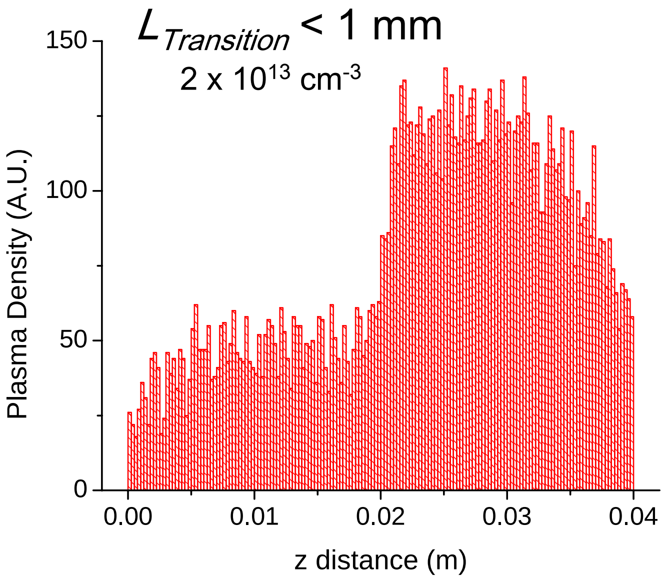
Density Screening

- Density Behind the Screen is Determined by the Open Area of the screen.
- PIC Simulations and experiments are consistent with the equation expected to govern the transition size:

$$L_{Trans} = 2x$$

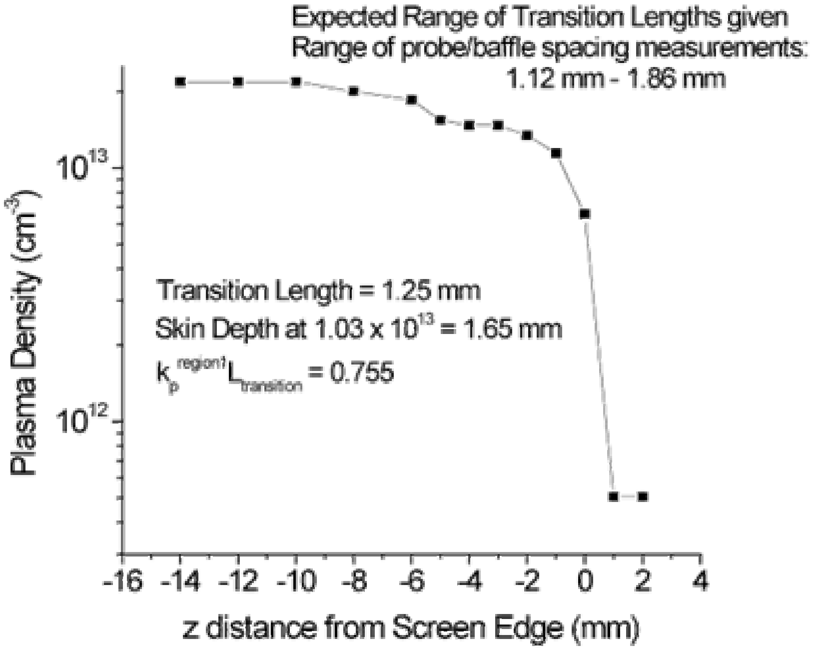
- Transitions short enough to exhibit trapping have been produced.
- Pre-transition density roll off not yet fully understood.





Simulation of a Screen with 500 μm holes and 50% open area. Density is Integrated over a 400 μm band from 100 – 500 μm away from the foil.

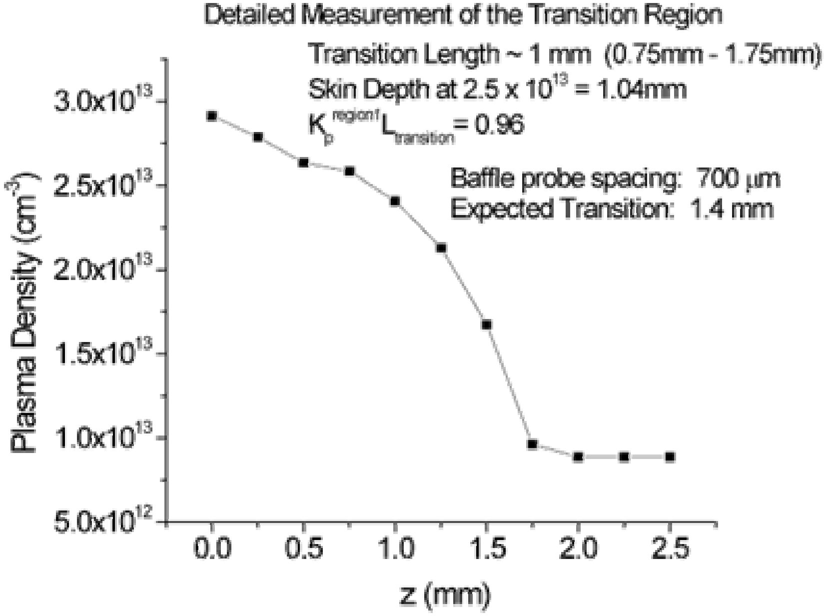
Transition Measurements


Expected Range of Transition Lengths given Range of probe/baffle spacing measurements: 1.12 mm - 1.86 mm

Transition Length = 1.25 mm

Skin Depth at 1.03 x 10^{13} = 1.65 mm

$k_p^{region1} L_{transition}$ = 0.755


Detailed Measurement of the Transition Region

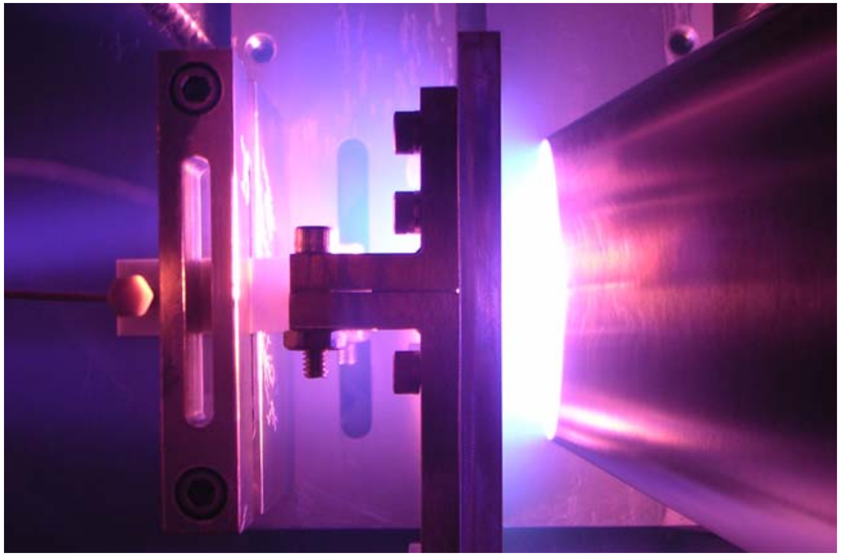
Transition Length ~ 1 mm (0.75mm - 1.75mm)

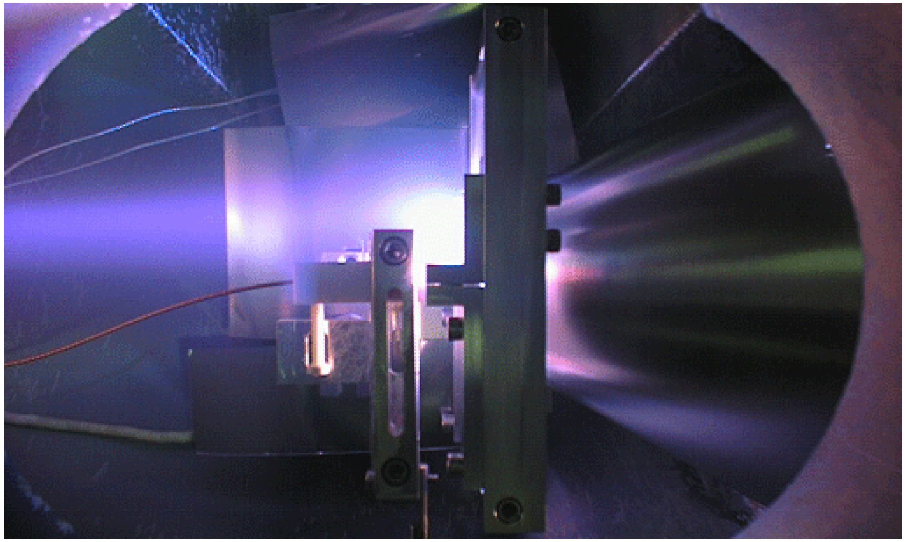
Skin Depth at 2.5 x 10^{13} = 1.04mm

$K_p^{region1} L_{transition}$ = 0.96

Baffle probe spacing: 700 µm

Expected Transition: 1.4 mm

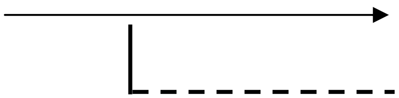




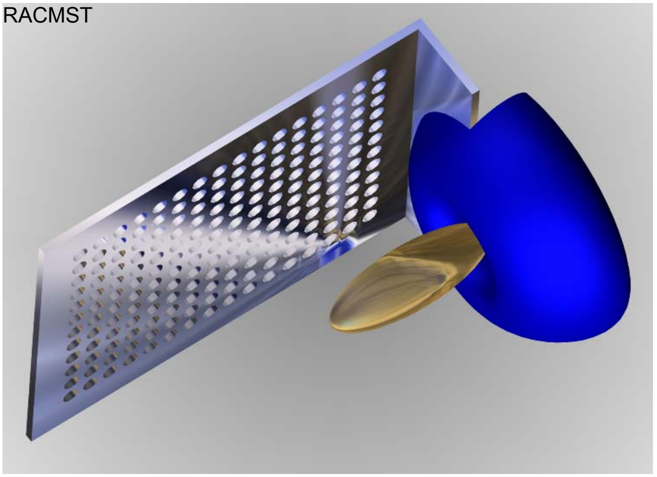
Screens in 3-D

In order to satisfy the trapping condition the beam must pass within $k_p^{-1}/2$ of the screen.

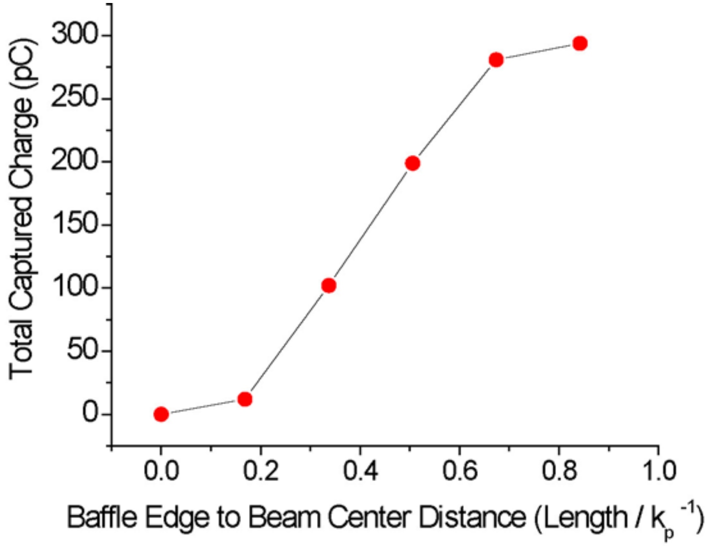
For a simple screen this means the beam must be within one $k_p^{-1}/2$ of the screen for the entire trapping and acceleration process. Wakefield interactions with the screen can destroy the trapping.



By adding a solid metal baffle to the screen, transition sharpness can be preserved while limiting the beam interaction with the screen.



Artist's conception of partial blocking of wake particles by the baffle.



Preliminary simulations of baffle loses using MAGIC 3D.

Other Problems & Solutions

Loss Mechanisms

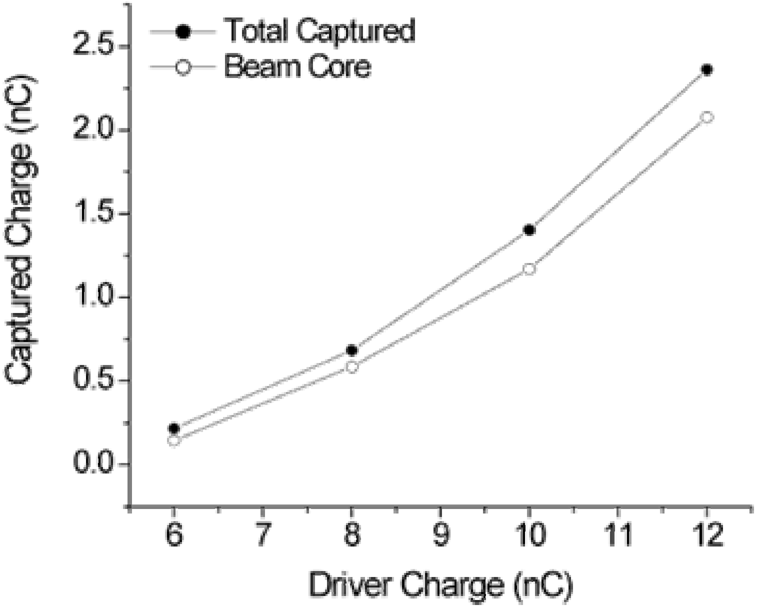
Other effects that may lead to trapped charge loss:

- Beam path bending during trapping.
- Growth of the transition length across the wake.
- Longer than expected driver bunches.

None of these effects should kill the trapping entirely, but simulating their effects correctly is difficult.

Charge Scaling

A relatively small increase in driver beam charge can compensate for significant losses.

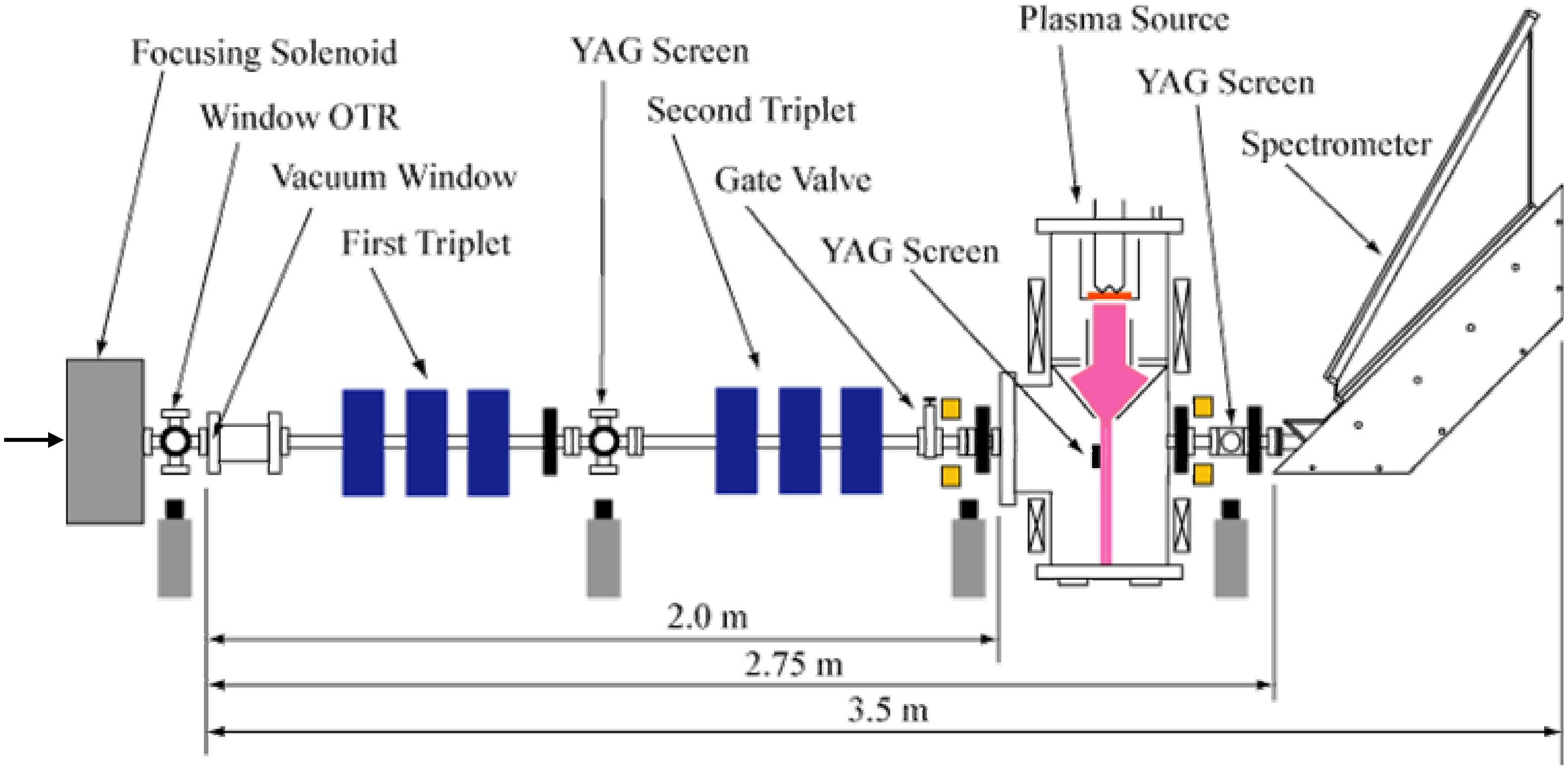


The First Experimental Run

Took place at the Fermilab NICADD Photoinjector Laboratory (FNPL) from Jan 2004 to May 2004

FNPL Beamline:

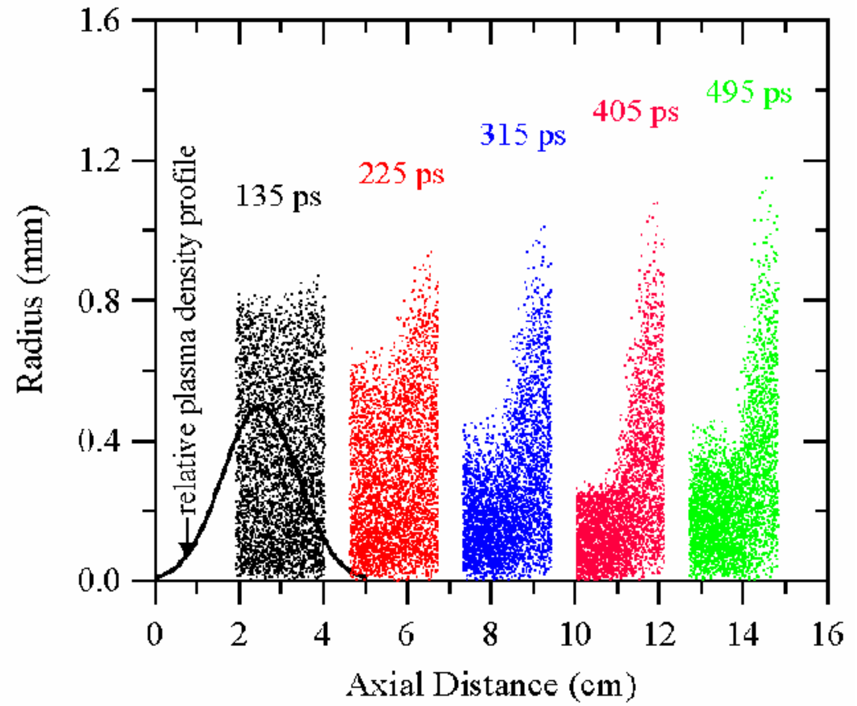
L-band Photoinjector → Superconducting 9-Cell Cavity → Magnetic Compressor →



Underdense Plasma Lens

Plasma Density	1.3 x 10^{12} cm^{-3}
Plasma Thickness	2 cm
Beam Charge	4 nC
Beam Duration (FWHM)	30 psec
Initial Beam Radius (σ_r)	400 μm
Beam Density	2.6 x 10^{12} cm^{-3}

Neptune Exp. – H. Suk Proc. PAC 99, p. 3708



Rudimentary Plasma Focusing Observed at FNPL Feb 2003:

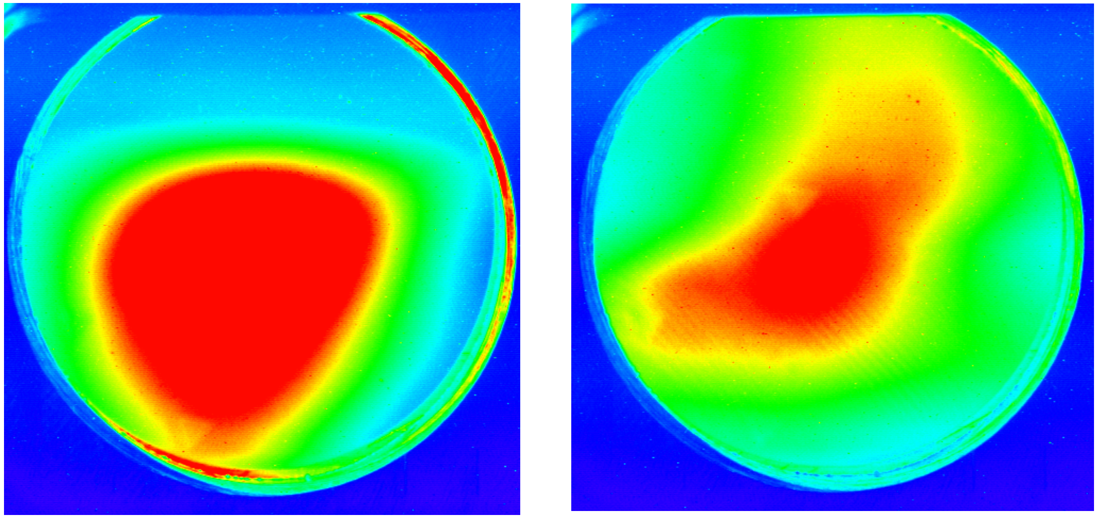
Beam Charge ~ 8 nC

Beam Density ~ 2 x 10^{13} cm^{-3}

Beam Radius (σ_r) ~ 400 μm

Beam Length (FWHM) ~ 15 ps

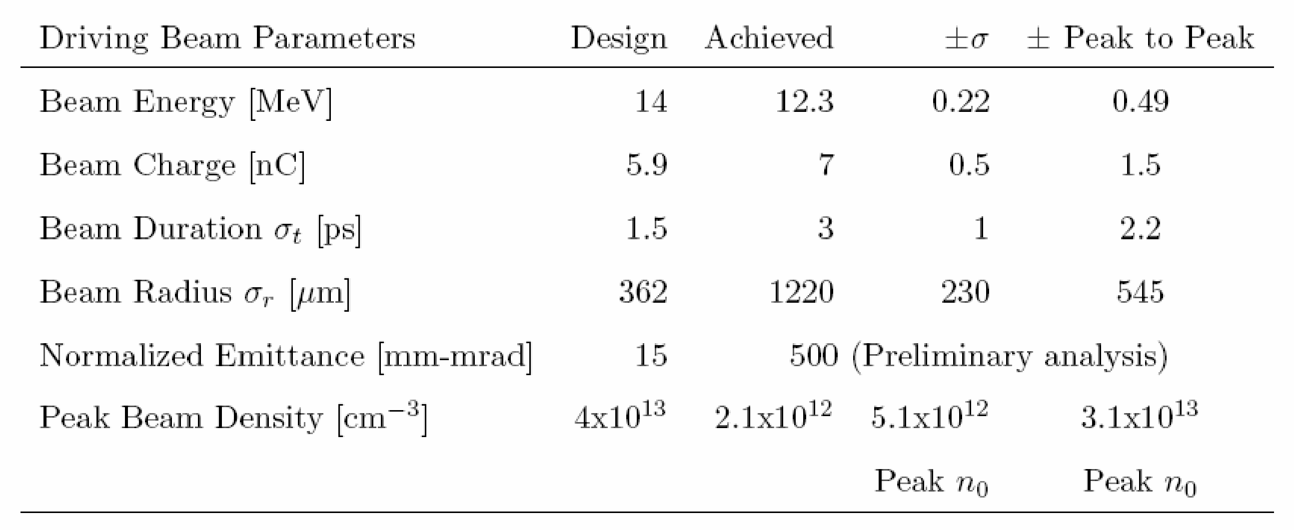
Screen ~ 30 cm from plasma



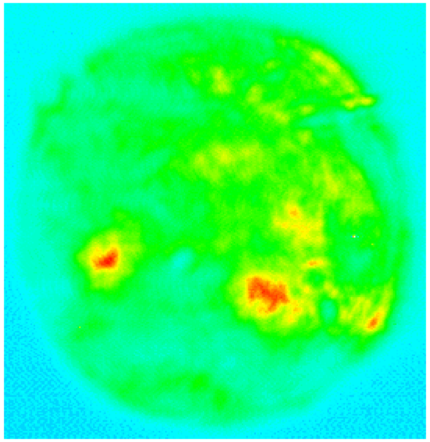
Plasma Off

Plasma On

Achieved Beam Parameters



Driving Beam Parameters	Design	Achieved	$\pm\sigma$	$\pm$ Peak to Peak
Beam Energy [MeV]	14	12.3	0.22	0.49
Beam Charge [nC]	5.9	7	0.5	1.5
Beam Duration σ_t [ps]	1.5	3	1	2.2
Beam Radius σ_r [μm]	362	1220	230	545
Normalized Emittance [mm-mrad]	15	500 (Preliminary analysis)		
Peak Beam Density [cm^{-3}]	4x10^{13}	2.1x10^{12}	5.1x10^{12}	3.1x10^{13}
			Peak n_0	Peak n_0



FNPL Drive Laser
Virtual Cathode

Problem Origins:

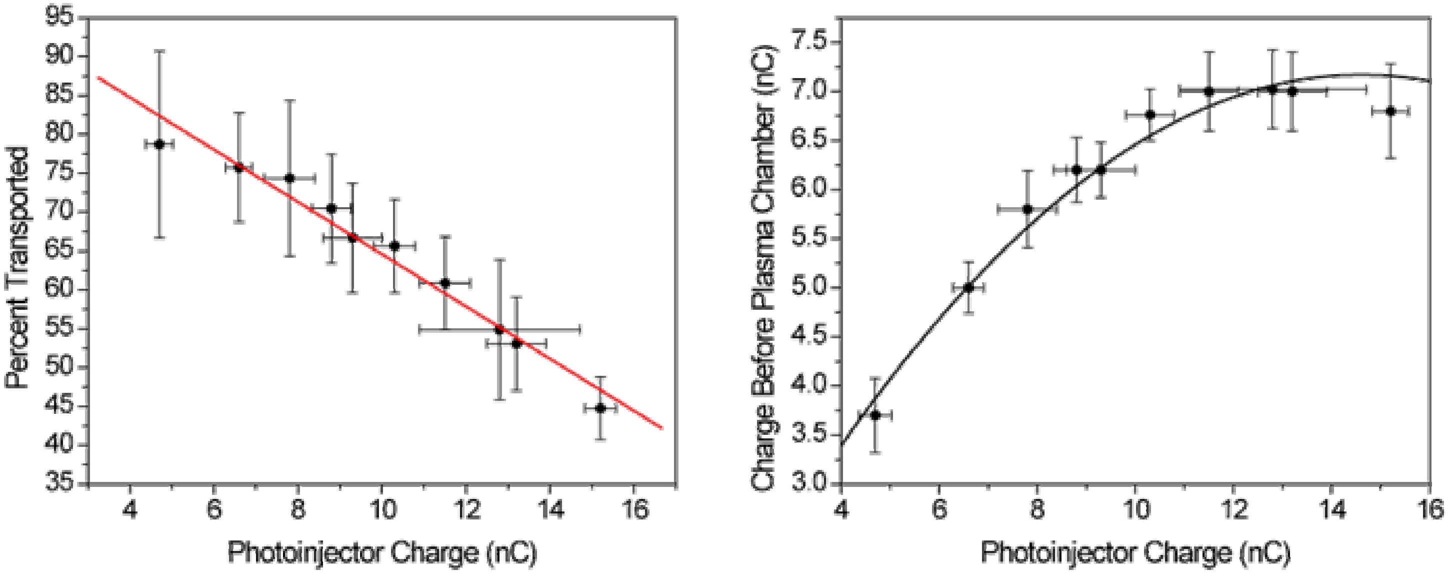
UV Laser

Compressor

Energy Spread

Isolation Foil

Charge Transport

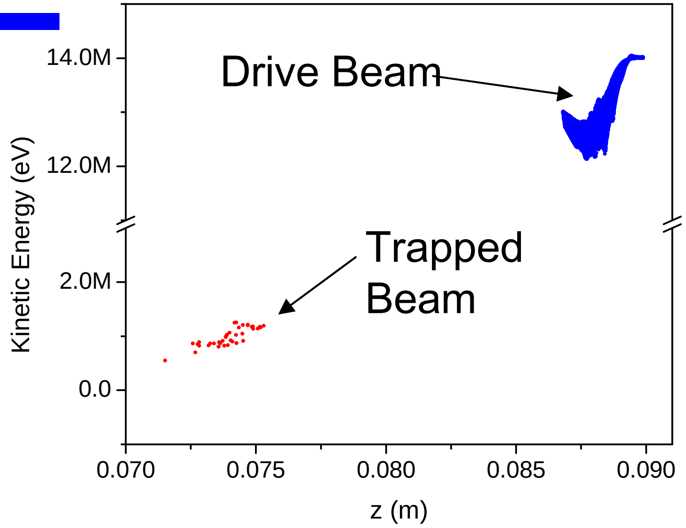


Drive Beam Deceleration

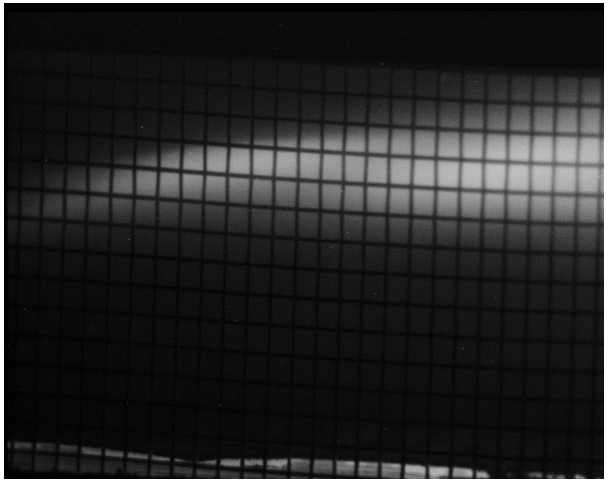
Deceleration of the drive beam is direct evidence of presence of wake fields.

Simulations indicate that passing through the trapping experiment plasma should produce 2 – 3 MeV of drive beam deceleration.

Max Deceleration of ~ 1 MeV observed.



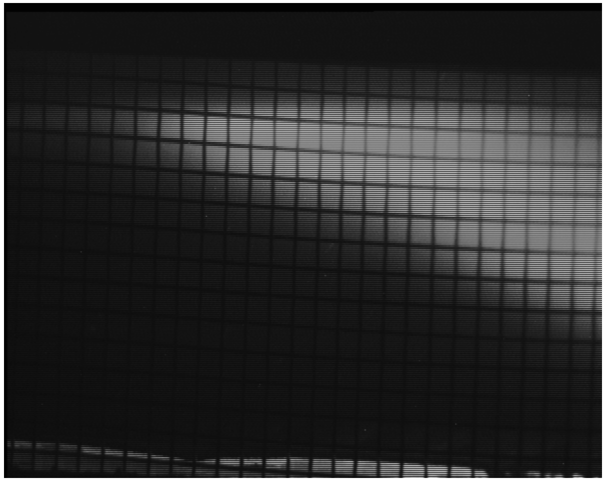
Drive Beam Deceleration Expected from Simulations of The Design Case



11.58 MeV

With Plasma

12.4 MeV



12.4 MeV

Just Driver

13.3 MeV

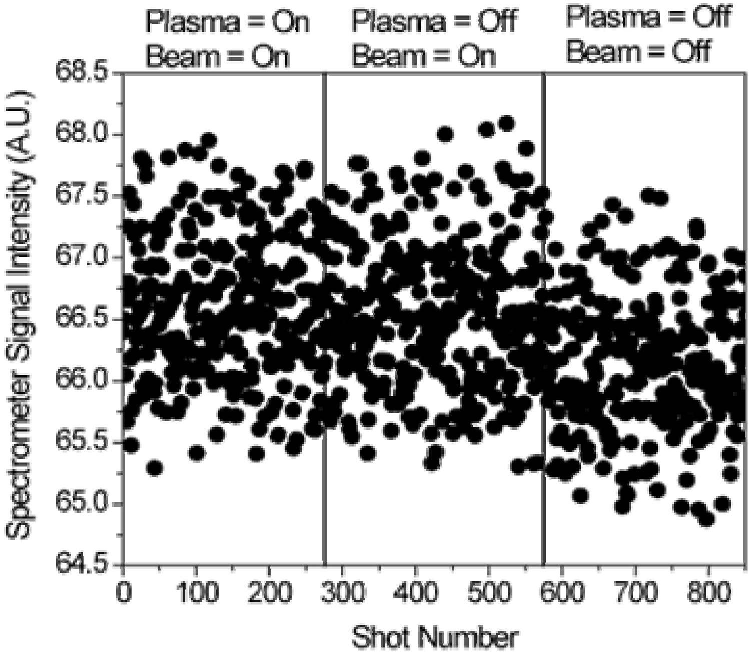
The Search For Trapped Electrons

Possibility of small quantities of trapped during good shots.

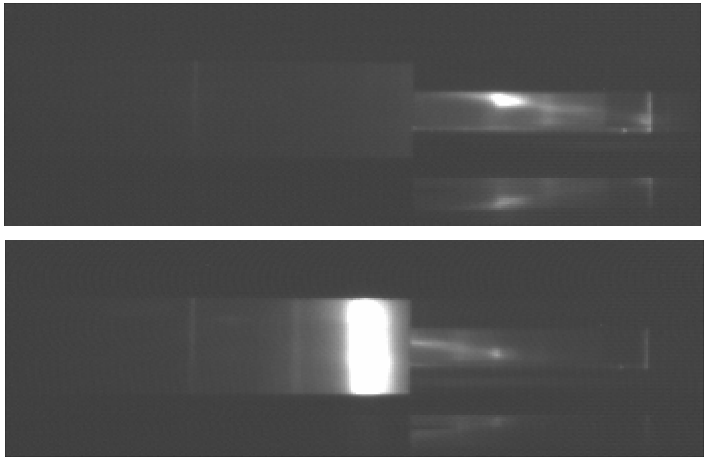
Cylindrical lens added to the spectrometer light collection optics.

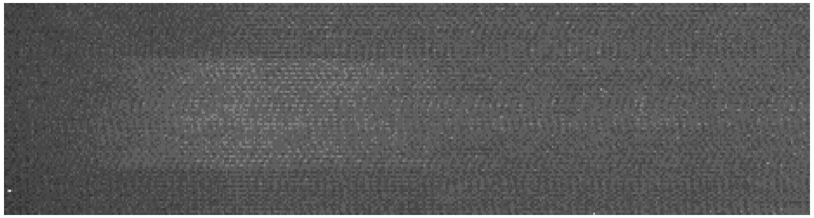
Demonstrated sensitivity to < 100 pC using the drive beam.

Low energy signal observed, but it did not correlate to the presence of the plasma.



Cylindrical lens added for enhanced light collection





0.87 MeV 1.4 MeV 2.2 MeV

Weak Low Energy Signal

Future Plans

Improved Trapping Experiment:

Requirements:

Understanding and improvement of the beam quality and charge transport.

Construction of a new spectrometer exit port.

Sharper Transitions.

Improved plasma and beam diagnostics.

Underdense Plasma Lens Experiment:

Requirements:

Simulation studies to update the experiment to FNPL parameters

Minor modifications to the plasma source.

The 2nd experimental run is scheduled to begin late September 2004. The time allocation for these two activities has yet to be determined.