NICADD / UCLA Collaboration on Plasma Density Transition Trapping

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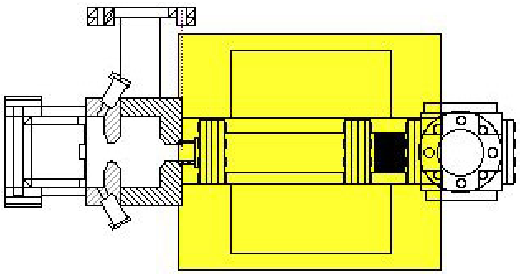
FNPL Advisory Committee Meeting

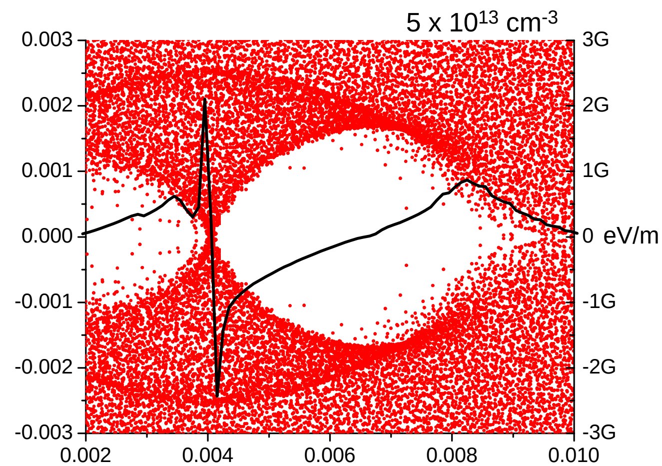
In Search of Higher Gradient

The study of high gradient PWFAs is the subject of a long standing collaboration that has grown between Argonne / Fermilab / NIU / UCLA. Currently represented by NICADD / UCLA collaboration on low energy driver beam energy loss experiments (N. Barov, *et al.,* PAC Proceedings (2001)).



High Gradient RF Structures:

Peak Gradient ~ 100 MeV / m



Plasma Based Structures:

Peak Gradient > 1 GeV / m

Plasma Structure Gradient Scaling:

$$E_{\max} \propto \omega_p = \sqrt{\frac{4\pi e^2}{m_e}}\sqrt{n_0}$$

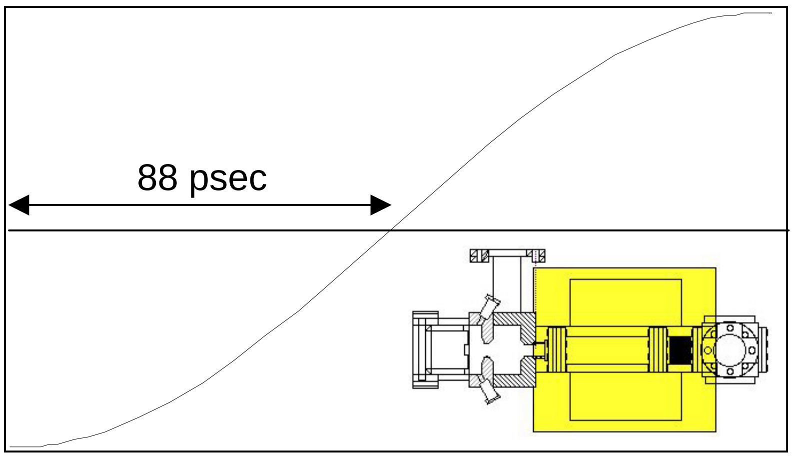
The Problem of Injection

All plasma accelerator schemes share two critical scalings:

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

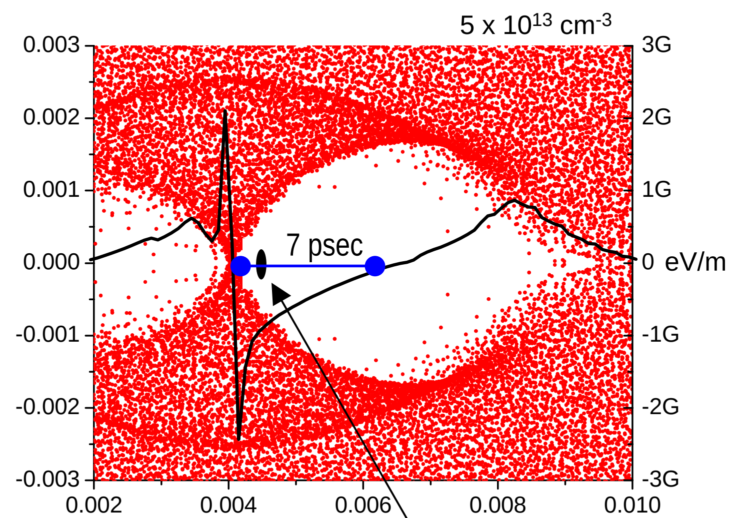
$$\text{Structure Size} \propto k_p^{-1} = \frac{c}{\omega_p} \propto \frac{1}{\sqrt{n}}$$

This scaling makes study and use of plasma accelerators difficult because of the technical problems of witness beam creation and timing at sub-psec levels.



High Gradient RF Structures:

Typical Frequency = 2856 MHz



Externally Injected Witness Beam

Trapping: A Witness From the Background

The alternative to injecting an external witness beam is creating a situation in which the plasma wave can trap and accelerate electrons directly out of the plasma.

This approach also raises the possibility of plasma e-beam sources.

• Automatic Trapping:

Many mechanisms (e.g. Conventional Wave Breaking) will "automatically" cause plasma electrons to become trapped in a large amplitude plasma waves. Unfortunately, these mechanisms do not naturally form beam-like distributions.

• Stimulated Trapping:

In order to trap beam-like particle distributions several researchers (e.g. Esarey and Umstadter) have proposed systems in which multiple high power laser pulses collide to stimulate particle trapping. These systems achieve quality beam injection at the expense of increased complexity.

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 new 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 an accelerating Phase

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

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

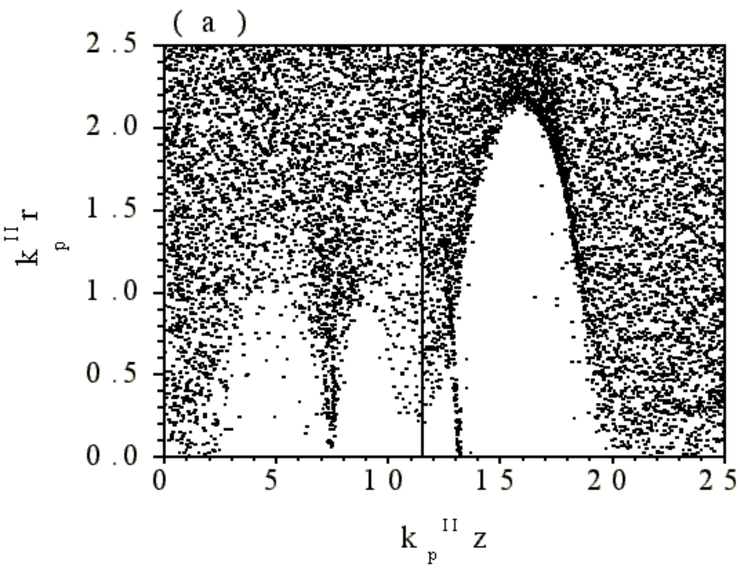


Illustration of Transition Trapping from H. Suk *et al.*

Brief History of Transition Trapping:

Concept Purposed by H. Suk While at UCLA
H. Suk, *et al.,* Phys. Rev. Lett. 86, 1011 (2001)

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

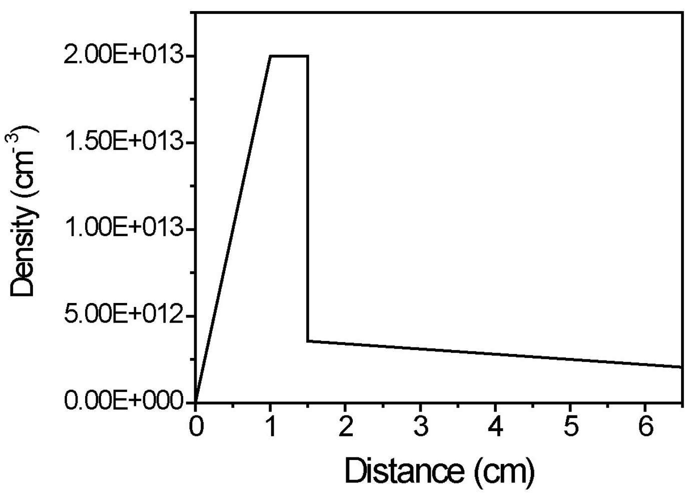
Study of the trapping process and experimental development continue.

Experimental Parameters

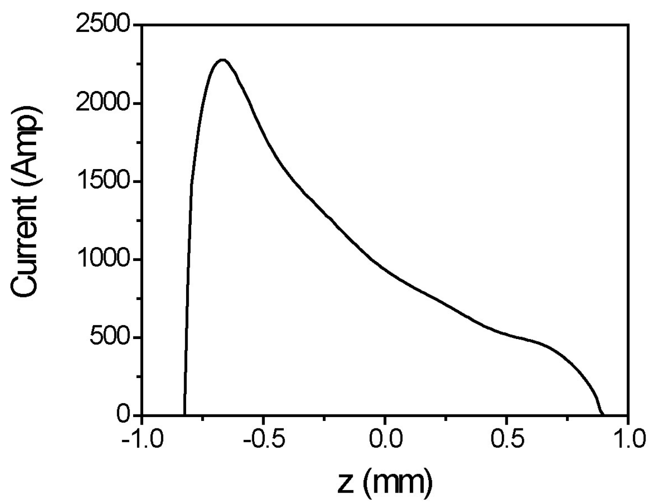
Driving Beam Parameters

Beam Energy	14 MeV
Beam Charge	5.9 nC
Peak Beam Density	4×10^{13} cm^{-3}
Beam Duration	6 psec
Beam Radius (σ_r)	540 µm
Normalized Emittance	30 mm-mrad

- **The ability to make high charge ramped beams is under development at the UCLA Neptune Lab.**
- **the ramped beam can be substituted with a 5.9 nC bi-gaussian beam of σ_t=1.5 psec. This change does not alter the experiment except for a small (~20%) loss of captured charge.**



Plasma Density Profile

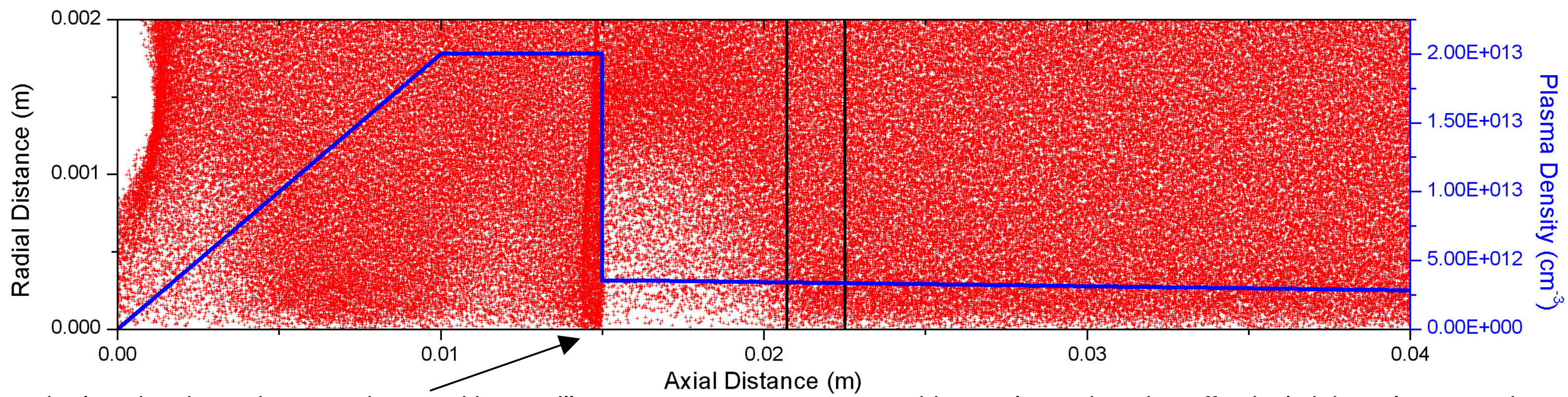


Drive Beam Longitudinal Current Profile

Illustration of the Trapping Process

The following time sequence of plots was generated from simulations of our planned "proof of principle" transition trapping experiment using the particle-in-cell code MAGIC. In all the plots the black vertical lines mark the head and tail of the drive beam.

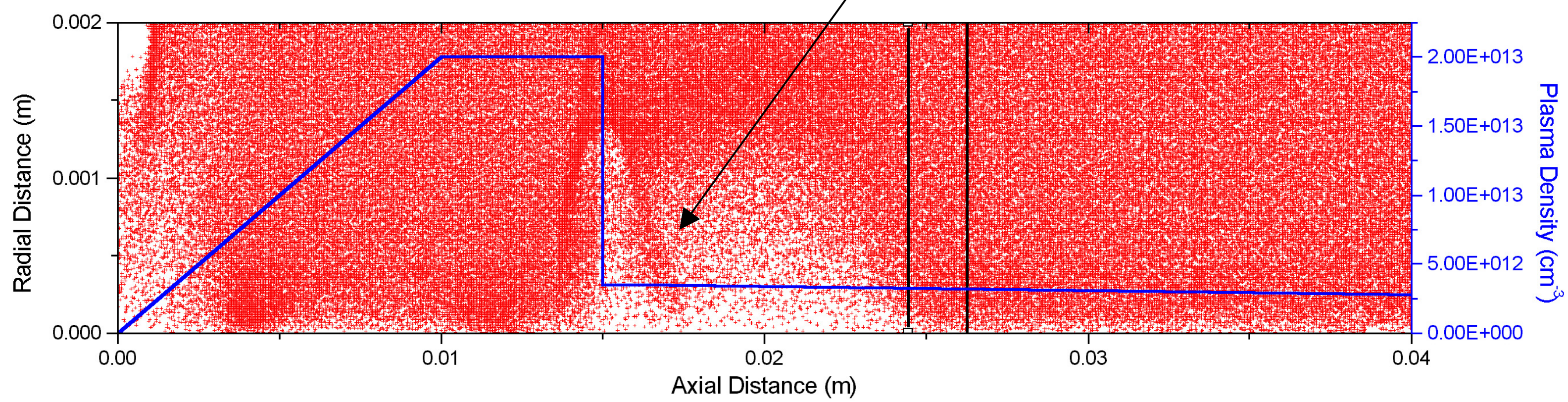
75 psec



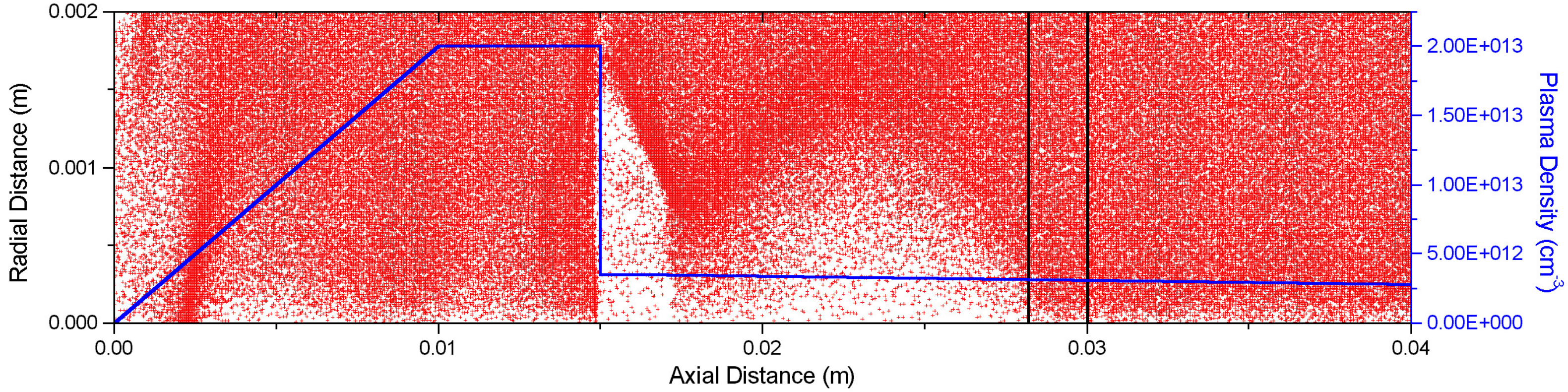
As electrons from the low density region near the transition oscillate backward, they enter the high density region where their oscillations are accelerated and they return to the axis early.

This accelerated motion effectively injects large numbers of these plasma electrons into accelerating phases of the wake field.

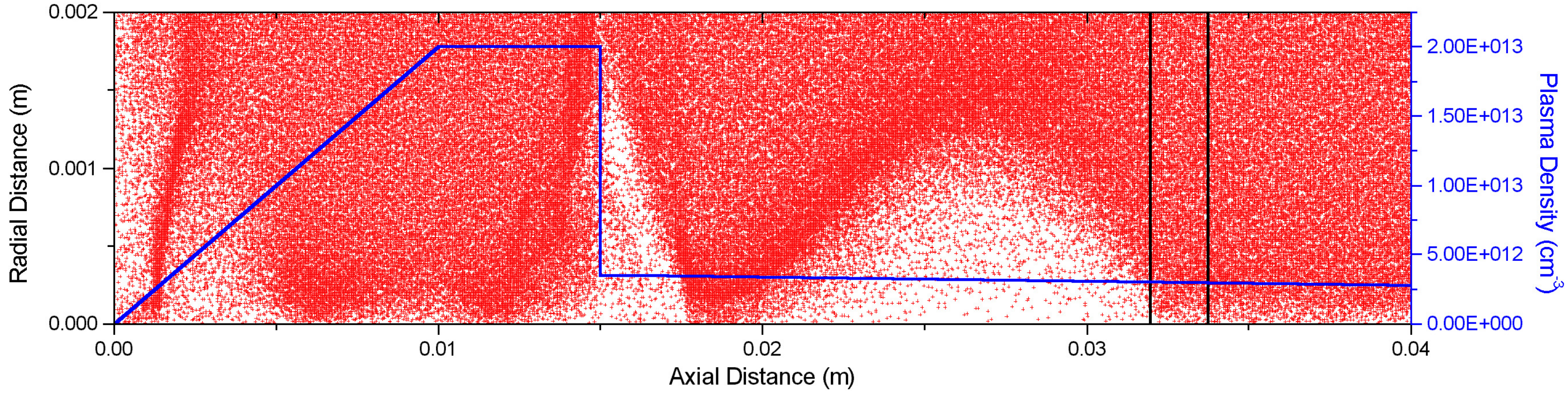
87.5 psec



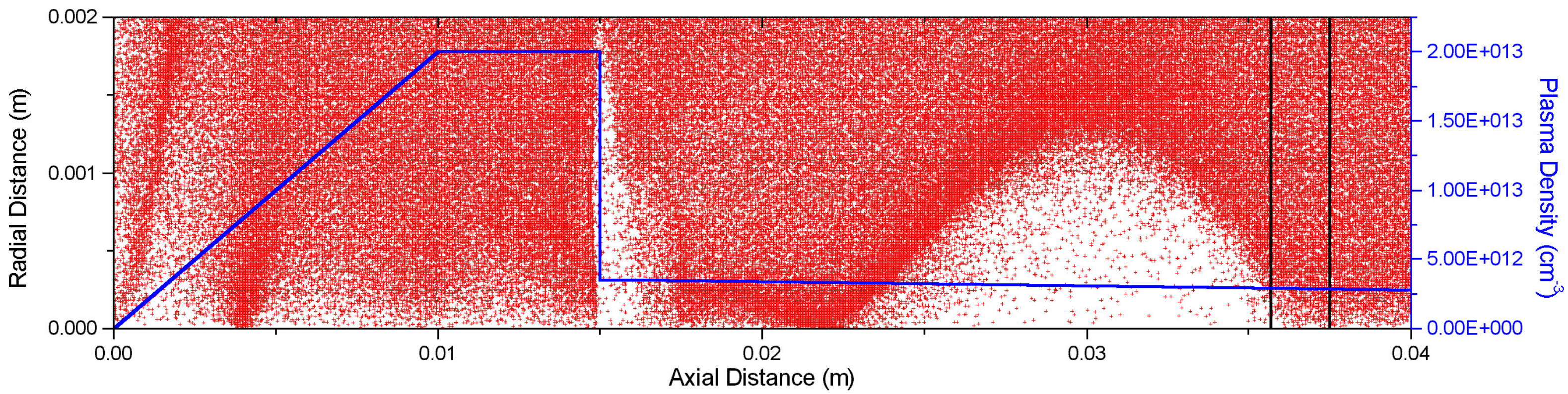
100 psec



112.5 psec

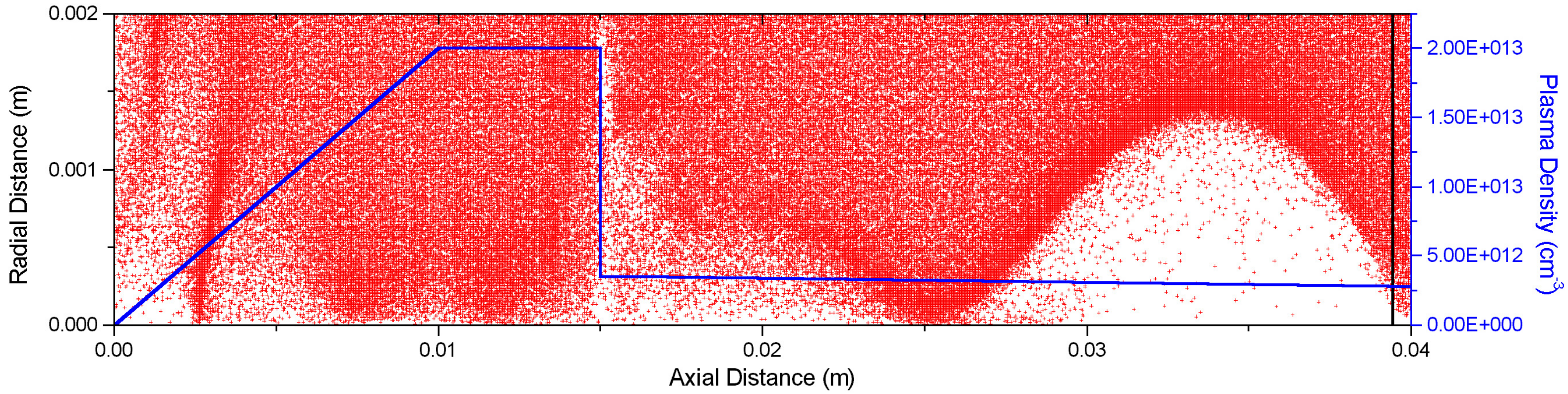


125 psec

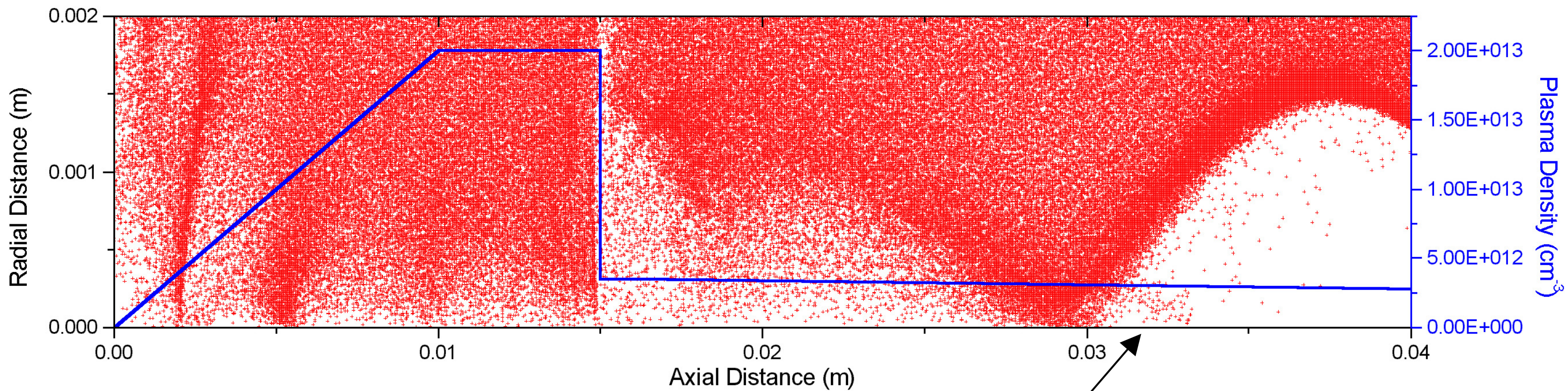


As the drive beam and its wake move on most of these injected plasma electrons are lost.

137.5 psec



150 psec



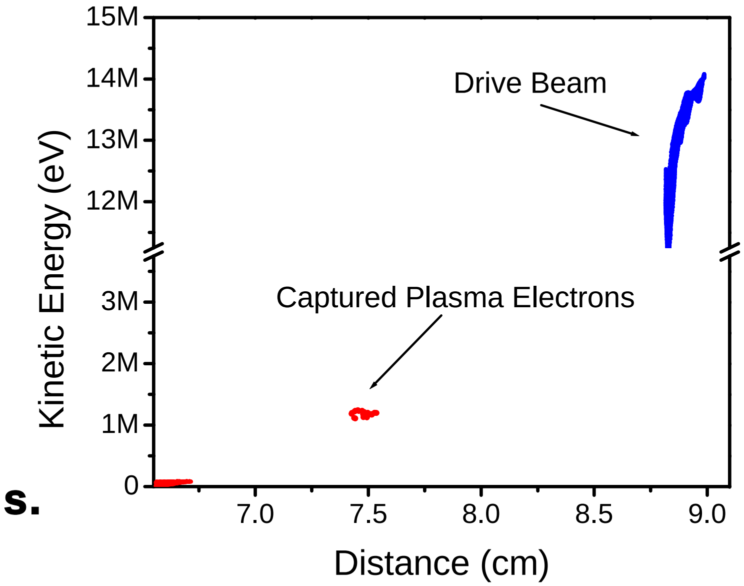
A small fraction these of plasma electrons are accelerated quickly enough to become trapped in an accelerating phase and form a well defined beam.

Simulated Experimental Results

The captured beam is well defined, has substantial charge, and is isolated in energy from the drive beam.

Beam Energy	1.2 MeV
Total Energy Spread	11%
Beam Charge	120 pC
Beam Duration (σ_t)	1 psec
Beam Radius (σ_r)	380 μm
Normalized Emittance (ε_x)	15 mm-mrad

Captured plasma electron beam parameters.
Beam is collimated using a 1mm radius aperture



Kinetic energy versus longitudinal position for both plasma and drive beam electrons after they have emerged from the plasma.

Transition Trapping Scaling:

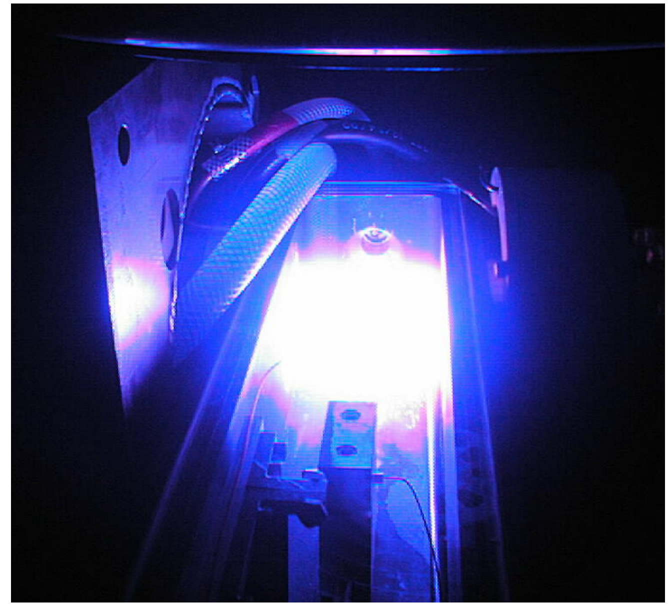
$$n = 2x10^{13}\,cm^{-3} \Rightarrow n = 2x10^{17}\,cm^{-3}$$

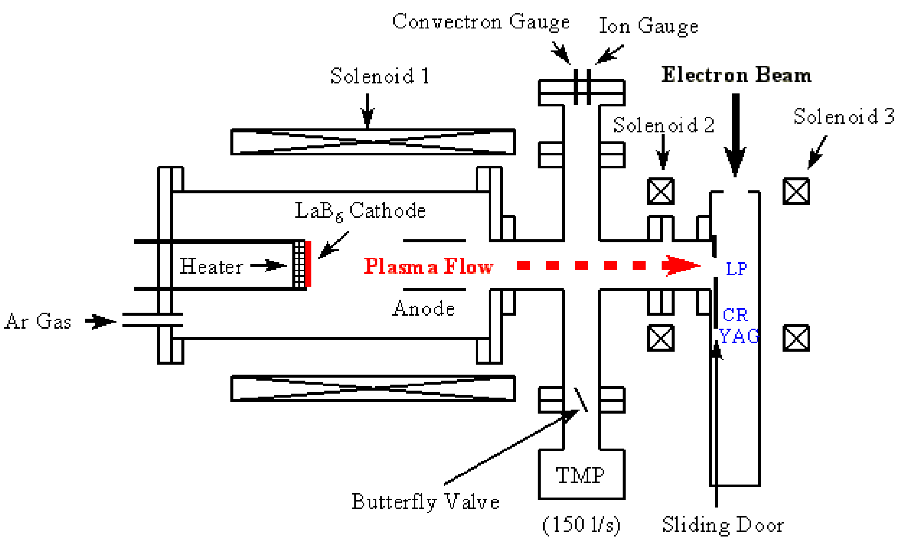
$$B = 5x10^{10}\,\frac{Amp}{(m-rad)^2} \Rightarrow B = 5x10^{14}\,\frac{Amp}{(m-rad)^2}$$

$$B_{LCLS,Injector} = 2.8x10^{14}\,\frac{Amp}{(m-rad)^2}$$

Argon Pulse Discharge Plasma Source

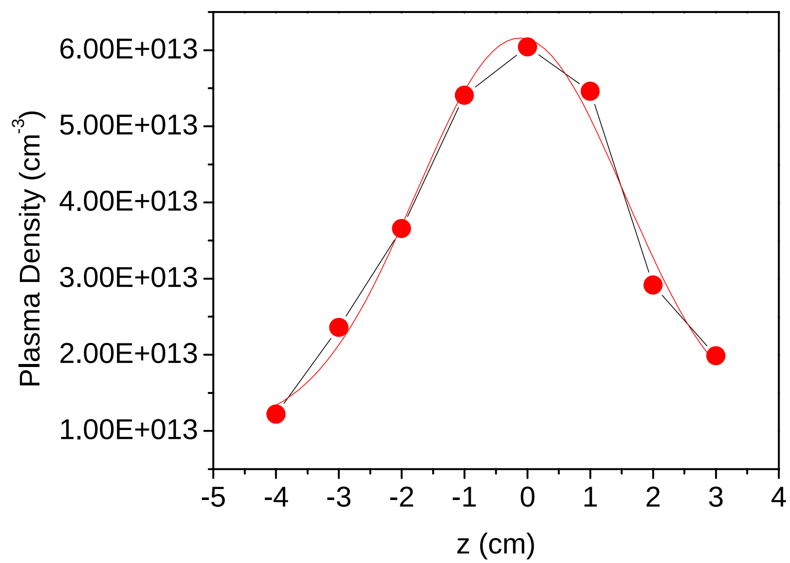
- **6 cm of plasma with density > 2 x 10^{13} cm^{-3} is reliably produced.**
- **The plasma is magnetically confined and allowed to drift from the production region into the electron beam path.**





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

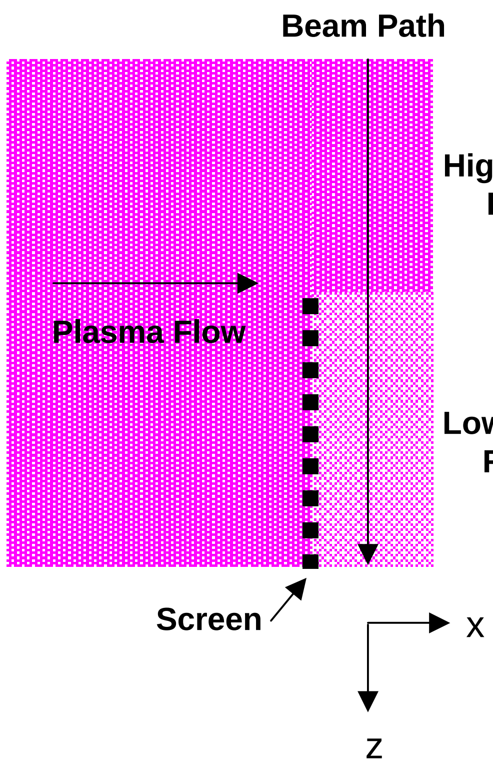
LP : Langmuir Probe
CR : Cherenkov Radiator
YAG : YAG Crystal



Raw Plasma Density Profile at Beam Interaction Point

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.



From Geometric Considerations:

$$L_{Trans} = 2x$$

Recalling the Trapping Condition:

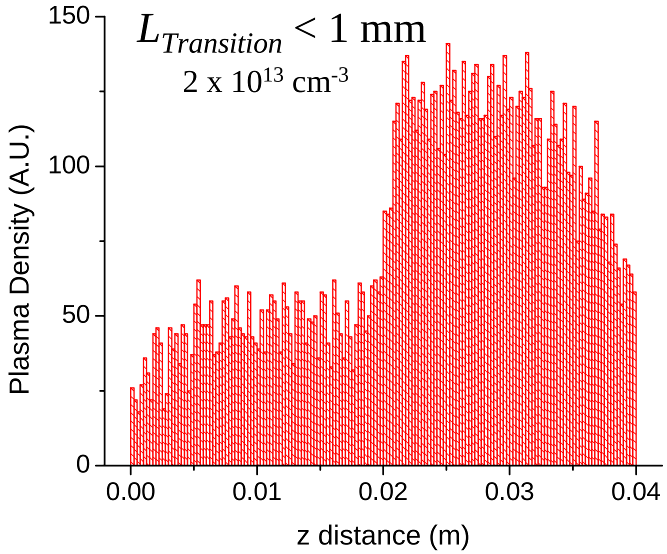
$$k_p L_{Trans} < 1 \quad \rightarrow \quad x < \frac{k_p^{-1}}{2}$$

For Plasma Density $2x10^{13}cm^{-3}$:

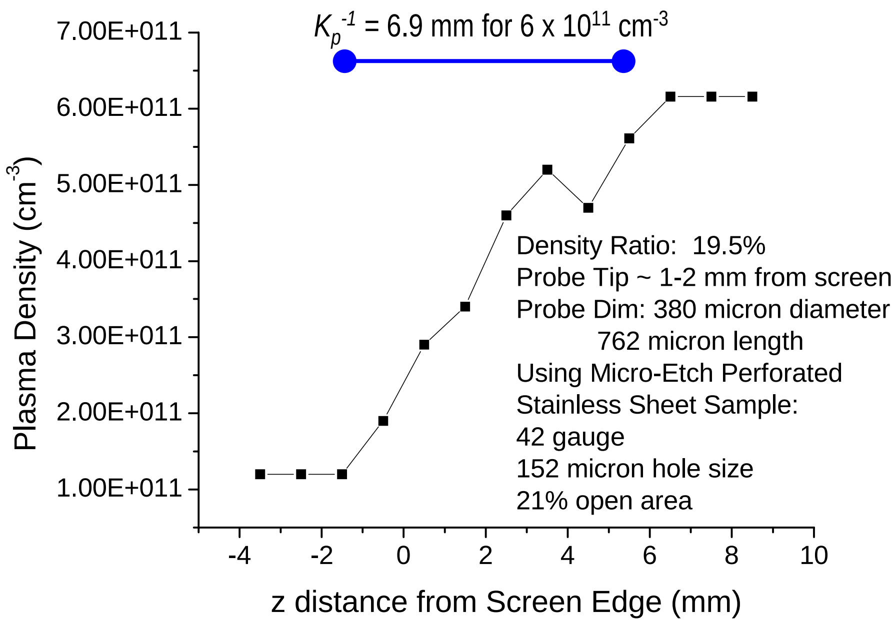
$$x < 600\mu m$$

Screen Development

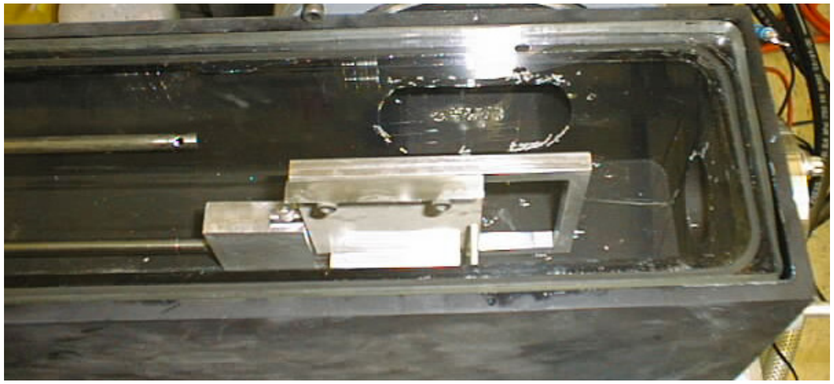
- **Density Behind the Screen is Determined by the Open Area of the screen.**
- **Simulations and early experiments are consistent with the equation** $L_{Trans} = 2x$.



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.

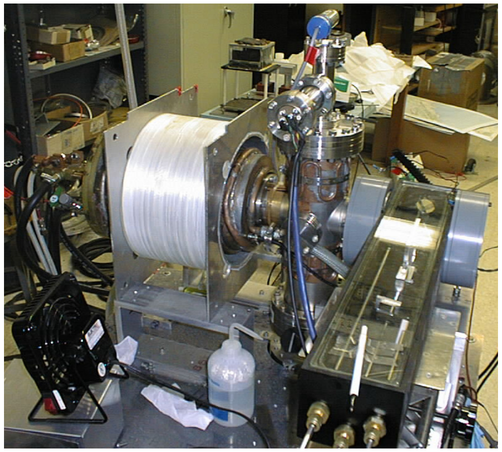


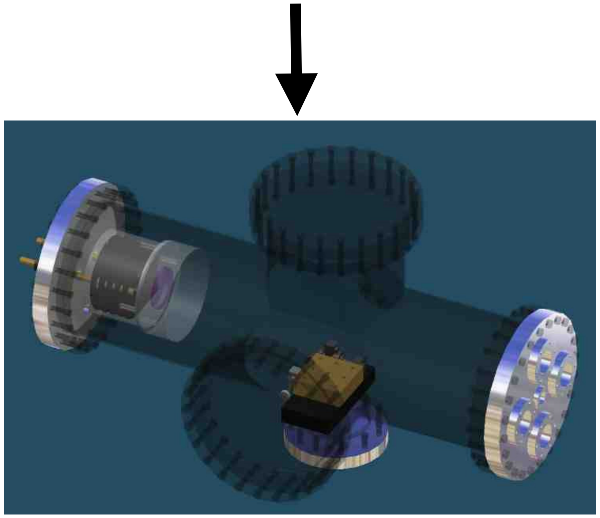
Data from the first screen test.



Screen Apparatus

NICADD / UCLA Collaboration:





UCLA - Winter 2003:

The upgrade of the plasma source vacuum chamber complete.

Detailed measurements of the density transition complete.

Broad range spectrometer complete.

Experiment ready for drive beam.

NICADD:

FNPL has already produced beams suitable for this experiment.

Preliminary NICADD / UCLA discussions on the technical issues of the proposed collaboration are very promising.