

Status of the UCLA/NICADD Plasma Density Transition Trapping Experiment

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Abstract. Plasma density transition trapping is a recently proposed self-injection scheme for plasma wake-field accelerators. This technique uses a sharp downward plasma density transition to trap and accelerate background plasma electrons in a plasma wake-field. This paper recounts the first attempt to demonstrate density transition trapping experimentally. The goal of the experiment is to capture a ~ 100 pC, 1.5 MeV beam with 4% rms energy spread out of a $2.5 \times 10^{13} \text{ cm}^{-3}$ peak density plasma using a 6nC, 14 MeV drive beam. The first experimental run occurred at the Fermilab NICADD Photoinjector Laboratory (FNPL) between January and May 2004. While several key objectives were achieved, we were unable to achieve the drive beam parameters necessary for the experiment due to technical problems. We are in the process of resolving these problems in preparation for a second experimental run.

INTRODUCTION

In a plasma wake field accelerator (PWFA) a short, high density electron beam is used to drive large amplitude plasma waves. Accelerating gradients in these systems scale with the non-relativistic plasma frequency $\omega_p = (4\pi n_0 e^2 / m_e)^{1/2}$, where n_0 is the plasma density, e is the electron charge, and m_e is the electron mass. It follows that high gradient PWFAs have very short period waves. Accelerating a second beam in such a system and maintaining its energy spread and emittance requires injecting a sub-picosecond beam into the drive beam's wake with well sub-picosecond timing accuracy. This is often referred to as witness beam injection, which has never been fully achieved experimentally. All experiments to date that have injected external electrons into accelerating plasma waves have used either continuous electron beams or beam pulses that were long compared to the plasma wave [1, 2, 3, 4, 5, 6]. As a result the accelerated electrons had induced energy spread equivalent to the acceleration, which would eventually result in 100% energy spread.

The difficulty of witness beam injection makes it desirable to develop a system in which charge is automatically loaded into the accelerating portion of the wake by the drive beam's interaction with the static plasma environment. Bulanov *et al.* have suggested such a scheme for laser wake-field accelerators (LWFA) in which a region of gradually declining plasma density is used to produce plasma electron trapping through gentle conventional wave breaking [7]. Suk *et al.* [8] recently proposed a new self-

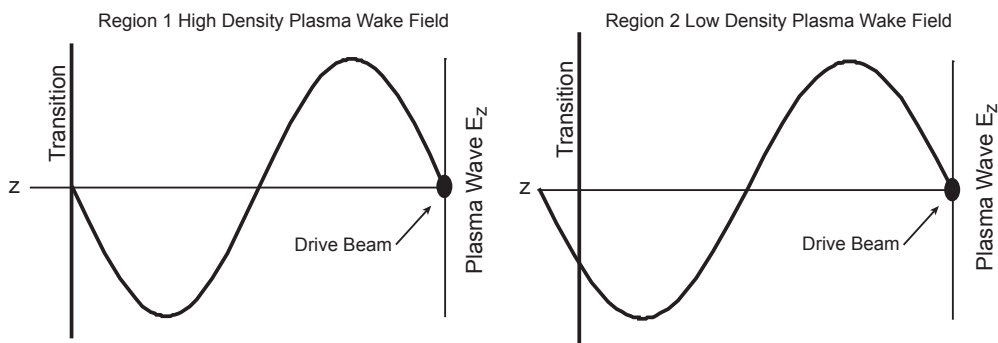


FIGURE 1. Diagram of the plasma electron rephasing caused by the plasma density transition. Note that the longitudinal electric field oscillations in the blowout regime are not actually sinusoidal, but have been represented that way for clarity.

trapping system for the use in the blowout regime of PWFAs [9] that uses a sharp density drop. Interestingly, trapping and acceleration of a few nC of plasma electrons has recently been observed in a PWEA during the E-164X experiment at SLAC [10]. The origin of the trapped charge is unknown, but it is theorized that second ionization of the lithium plasma ions by the extremely high electric fields within the wake may be the source. Once it is understood, this mechanism could prove to be a useful trapping technique.

In the Suk *et al.* scheme the beam passes through a sharp drop in plasma density where the length of the transition between the high density in region one (1) and the lower density in region two (2) is smaller than the plasma skin depth $k_p^{-1} = v_b/\omega_p$, where $v_b \cong c$ the driving pulse's velocity. As the drive beam's wake passes the sudden transition there is a period of time in which it spans both regions. The portion of the wake in region 2 has lower fields and a longer wavelength than the portion in region 1. This means that a certain population of the plasma electrons at the boundary will suddenly find themselves rephased into an accelerating portion of the region 2 wake, see Fig. 1. When the parameters are correctly set, these rephased electrons are inserted far enough into the accelerating region to be trapped and subsequently accelerated to high energy. It has been shown that the transition trapping can generate high quality beams, especially when operated at high plasma density [11, 12].

With the promise of plasma density transition trapping as a useful beam source established theoretically, we set out to demonstrate the concept experimentally. To facilitate this goal we chose to develop an experiment using a relatively low density plasma in the 10^{13} cm^{-3} range. Performing the experiment at low plasma density greatly reduces the technical difficulty of the experiment by relaxing the drive beam and plasma source requirements.

THE EXPERIMENTAL PLAN

The plasma density transition trapping experiment utilizes a plasma source designed and built at UCLA. This source has successfully produced density transitions sharp enough

TABLE 1. Planned driving and captured beam parameters [12].

Driving Beam Parameters		Captured Beam Parameters	
Beam Energy	14 MeV	Beam Energy	1.5 MeV
Beam Charge	5.9 nC	Beam Charge	100 pC
Beam Duration σ_t	1.5 ps	Beam Duration σ_t	~ 1 ps
Beam Radius σ_r	362 μm	Beam Radius σ_r	~ 200 μm
Peak Beam Density	$4 \times 10^{13} \text{ cm}^{-3}$	Energy Spread (rms)	4%

to exhibit trapping [12, 13]. The transverse density profile of the plasma column is shown in Fig. 2. The electron beam for the experiment is provided by the FNPL accelerator. The FNPL accelerator is a 18 MeV electron linac [14]. The system consists of a normal conducting L-band RF photoinjector with a cesium telluride photo-cathode and a 9-cell superconducting accelerating cavity. Bunches with charge in excess of 8 nC can be produced and compressed to $\sigma_t = 1.6$ ps using magnetic compression. The drive beam parameters for this experiment, along with the trapped beam parameters expected from simulation, are shown in Table 1.

As shown in Fig. 3, the beamline for the trapping experiment consists of a strong focusing solenoid, a vacuum isolation window, two quadrupole magnet triples that first capture the beam and then focus it into the plasma, the plasma chamber, and the spectrometer [12]. Several steering magnets are provided for correcting the beam trajectory. A host of diagnostics are also included, as marked in Fig. 3.

EXPERIMENTAL PROGRESS

The first run of the plasma density transition trapping experiment took place at the FNPL between January and May 2004. This was the first time that the plasma apparatus had seen an electron beam. During this five month period, two types of beam-plasma interactions were directly observed, the drive beam parameters were extensively characterized, and a thorough search for trapped plasma electrons was conducted.

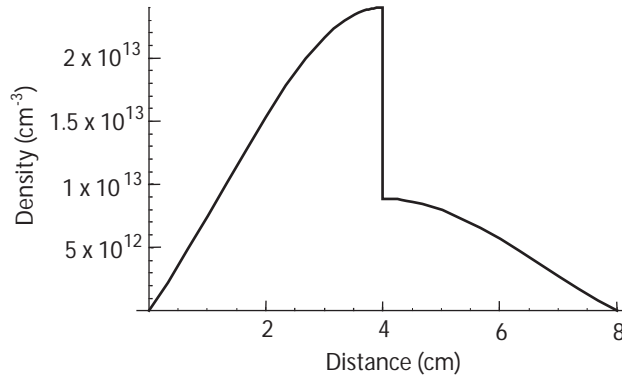


FIGURE 2. The transverse density profile of the plasma column.

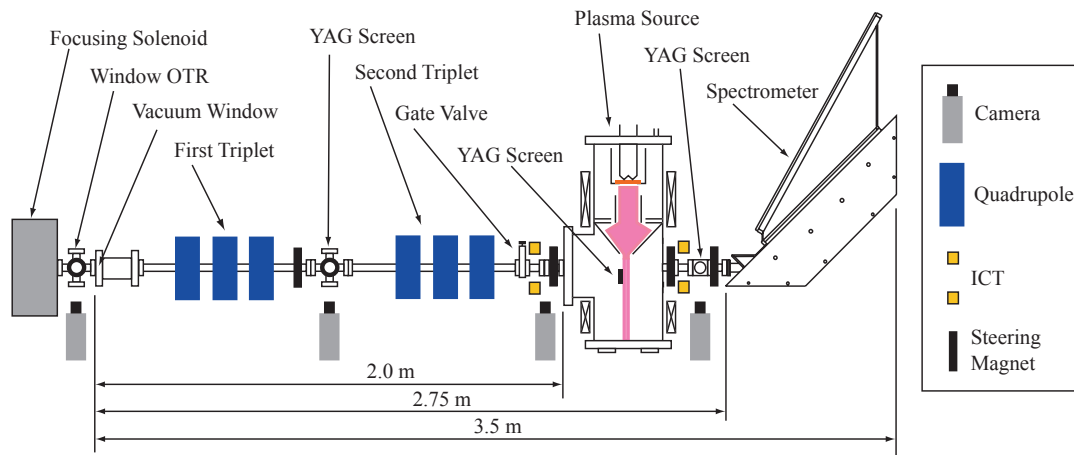


FIGURE 3. The plasma density transition trapping beamline.

Plasma induced focusing of the electron beam was the first evidence of interaction between the electron beam and plasma. The development of the plasma density transition trapping source began with a thin underdense plasma lens experiment in mind [15]. The more sophisticated source that evolved from those beginnings still retains the capability to operate as a thin underdense plasma lens. During the commissioning of the trapping experiment at the FNPL, a high charge, but uncompressed, beam was sent through the plasma and strong focusing of the beam was observed [12]. The electron beam being focused had a charge of 8 nC, a radius σ_r of about 400 μm , and a FWHM length of 15 - 30 ps. These parameters yield a peak beam density of $1 - 2 \times 10^{13} \text{ cm}^{-3}$. Given this range of beam density, which is somewhere in between the densities of the high and low density regions of the trapping experiment plasma column, see Fig. 2, the beam probably experienced a mixture of overdense and underdense lens focusing. Su *et al.* [16] provides a detailed review of these two types of plasma focusing.

When magnetic compression was used to shorten the beam for the trapping experiment the electron beam quality degraded significantly. The extent of the beam quality degradation was first noticed because of problems with the beam transport. Despite the availability of high charge electron bunches of up to 16 nC at the photoinjector, it proved exceedingly difficult to transport even 6 nC of this charge to the experiment even after extensive work to optimize the beamline. Systematic studies, see Fig. 4, indicated a linear decline in transport efficiency with increasing photoinjector charge. This decrease in transport efficiency effectively limits the charge that can be delivered to the experiment to 7-8 nC. This result hints that the beam emittance was very high.

Initial measurements of the beam emittance after the vacuum window were made during the beamline commissioning using quadrupole scans. The normalized emittance of a 5 nC uncompressed beam was measured to be as low as 60 mm-mrad after the vacuum isolation foil. This value is consistent with the nominal FNPL emittance of 15 mm-mrad [14] and the estimate of 40 mm-mrad for the expected emittance growth caused by the foil [12]. While it was known that compression and running at high charge would increase the emittance somewhat, estimates indicated that the dominate

TABLE 2. Comparison of the design beam parameters with the best drive beam parameters that were achieved simultaneously. Values given in the achieved column are the mean.

Driving Beam Parameters	Design	Achieved	$\pm\sigma$	\pm Peak to Peak
Beam Energy [MeV]	14	12.5	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]	~ 60	347 (statistics unavailable)		
Peak Beam Density [cm^{-3}]	4×10^{13}	2.1×10^{12}	$5.1 \times 10^{12\dagger}$	$3.1 \times 10^{13\dagger}$

\dagger Calculated using the most favorable combination of parameters

contribution to emittance growth would always come from the foil. When the charge transport problems suggested that the emittance might be much higher than what was believed, more measurements were taken after the foil. A normalized emittance of 347 mm-mrad was measured for a $\sigma_t = 3$ ps compressed beam after the foil. This beam had exited the photoinjector with 14 nC, of which, only 7 nC arrived at the trapping experiment. This emittance was much larger than expected and was the likely cause of the charge transport losses, as well as the large beam spot sizes at the plasma chamber. Scattering in the vacuum isolation foil cannot account for emittance values this large by itself. The average beam spot size at foil was $\sigma_x = 700 \mu\text{m}$ under the compressed beam conditions for which the 347 mm-mrad emittance was measured. Multiple Coulomb scattering calculations predict that the foil induced emittance growth for a beam of this size passing through the $10 \mu\text{m}$ aluminum foil is $\epsilon_{n,foil} = 132$ mm-mrad [12, 17]. Since the predicted foil emittance growth is only about a third of the observed emittance, there must be significant emittance growth occurring upstream of the foil. This upstream emittance growth is also a factor in the larger than expected beam spot size at the foil.

The combination of the charge transport limitations and the enormous compressed beam emittances after the foil prevented us from attaining all the parameters originally

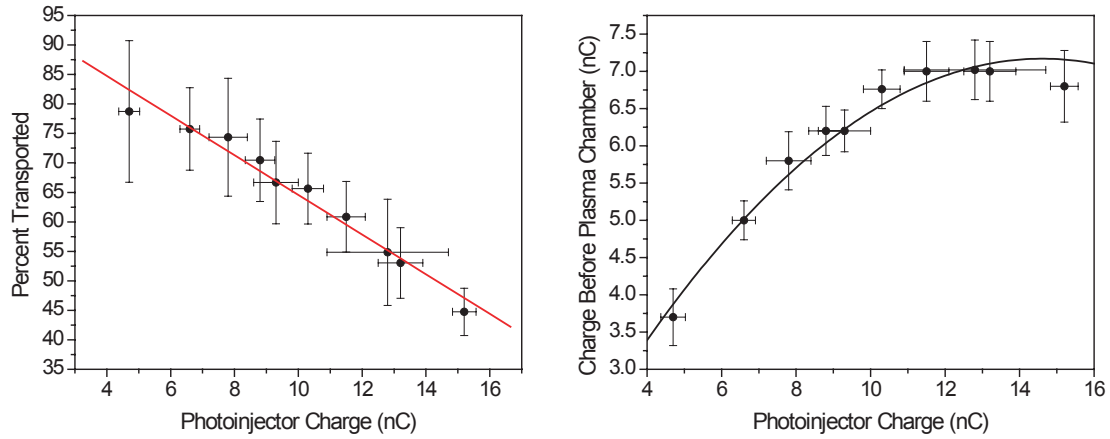


FIGURE 4. Variation in charge transport with photoinjector charge. The error bars in both plots are the one σ fluctuation in the average value.

specified for the drive beam. Table 2 lists the design drive beam parameters along with the best, simultaneously optimized, beam parameters that were achieved near the end of the experimental run. The shot to shot fluctuation of the parameters are also listed. The combination of a longer and wider than expected beam, along with the inability to compensate by adding more charge, meant that the average peak beam density achieved is over an order of magnitude lower than design.

The pointing jitter of the electron beam at the plasma is also important due to critical dependance of the trapping performance on the position of the beam in the plasma column [11, 12]. The transverse pointing jitter of the beam centroid within the plasma source was measured to be $\pm 134 \mu\text{m}$ ($\pm 0.13 k_p^{-1}$) σ and $\pm 392 \mu\text{m}$ ($\pm 0.4 k_p^{-1}$) peak to peak. This much variation in the beam position will lead to significant fluctuation in trapped charge.

Despite the problems with the drive beam, wake fields were still observed when it was interacting with the plasma. The presence of wake fields was indicated by deceleration of the drive beam. The lowest energy drive beam electrons observed were at about 11.6 MeV when the plasma was on, and about 12.6 MeV when the plasma was off. This equates to a maximum bunch deceleration of 1 MeV and an average deceleration gradient of about 12 MV/m. 1 MeV is about half to one third of the amount of deceleration that simulations indicate should occur in cases with significant trapping.

The presence of wake fields, even if they were substantially weaker than anticipated, raised the possibility that some small amount of trapped charge might be detectable. A weak signal was observed on spectrometer that originally seemed to be correlated to the presence of the plasma. More detailed measurements showed that this weak signal was independent of the presence of the plasma but did correlated to the presence of the electron beam [12]. The exact origin of this weak low energy spectrometer signal is unknown but it is believed to be caused by some combination of beam generated x-rays and low energy secondary electrons.

DISCUSSION

Simulations were run with the PIC code MAGIC [18] using the achieved beam parameters shown in Table 2 and the plasma profile used during the experiment, Fig. 2, in order to ascertain whether any plasma electron trapping could be expected. The simulations predict no trapped charge and about 1 MeV of drive beam deceleration in the mean case, which agrees with observation. The best beam that can be expected within the one σ fluctuation of all the parameters is likewise insufficient to excite trapping. This best beam is the one that would exist if the parameters fluctuated to the maximum charge, minimum length, and smallest spot size simultaneously. Note also that the resolution limit of the simulations is about 1 pC of trapped charge. Simulations of the analogous best beam derivable from the peak to peak fluctuations shows $> 100\text{pC}$ of trapped charge and 4 MeV of drive beam deceleration. Unfortunately, it is very unlikely that shots with these best peak to peak parameters occurred, especially since 4 MeV deceleration was never observed.

Progress on understanding the drive beam emittance blowup is ongoing. Improvements to the UV cathode drive laser spot have been made and a faulty power supply was repaired which had been slightly energizing one of the skew quads [19] even when it was ostensibly off. A reasonable emittance of 54 mm-mrad was measured before the foil for a 13 nC, 15 MeV, uncompressed electron beam after these improvements were made. It remains to be seen how the emittance of the improved beam will change with magnetic compression. A second run of the density transition trapping experiment will begin as soon as the specified drive beam parameters can be reliably achieved. While preparations are being made for that experiment, we intend to perform a rigorous underdense plasma lens experiment with parameters similar to those originally proposed for a lensing experiment at the UCLA Neptune Lab [15].

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