

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. Two and three dimensional Particle-In-Cell (PIC) simulations show that electron beams of substantial charge can be captured using this technique, and that the beam parameters such as emittance, energy spread, and brightness can be optimized by manipulating the plasma density profile. These simulations also predict that transition trapping can produce beams with brightness $> 5 \times 10^{14}$ Amp/(m-rad)² when scaled to high plasma density regimes. A proof-of-principle plasma density transition trapping experiment is planned for the near future. This experiment is a collaboration between UCLA and Northern Illinois University (NICADD). The goal of the experiment is to capture a ~ 100 pC, 1.2 MeV beam with $\sim 4\%$ rms energy spread out of a 2×10^{13} cm⁻³ peak density plasma using a ~ 6 nC, 14 MeV drive beam. Status and progress on the experiment are reported.

1 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]. As a result the accelerated electrons had an 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 automati-

cally loaded into the accelerating portion of the wake by the drive beam's interaction with the static plasma environment. This approach allows timing concerns to be eliminated entirely. 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 [6]. Suk et al. [7] recently proposed a new self-trapping system for the use in the blow out regime of PWFAs where $n_b > n_0$ (underdense condition). In this 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. 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.

The plasma density transition trapping scheme originally proposed by Suk et al., like the one presented by Bulanov et al., provides very short injection pulses that are phase locked to the plasma wave, but suffers from a lack of beam quality, as defined by energy spread and transverse emittance. These beam quality issues are shared to a significant extent by the optically stimulated injection systems [8, 9], which also have challenging timing requirements due to the multiple interacting laser pulses. We have found, however, that beam quality, as measured by beam brightness, can be greatly enhanced in the plasma density transition trapping system by tailoring the density profile of the plasma and scaling to higher plasma density. The beam brightness benefits of scaling to higher plasma density are quantified by a set of scaling laws that we have developed following similar work concerning rf acceleration in photoinjector sources [10]. From this work we conclude that the beam brightness B obeys the relation

$$B \propto \frac{I}{\varepsilon^2} \propto n_0, \quad (1)$$

where I is the beam current, ε is the beam emittance, and n_0 is the plasma density [11]. This scaling law has been verified through simulation.

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We have planned and constructed a proof-of-principle transition trapping experiment that will use an order 10^{13}cm^{-3} peak density plasma with a density profile optimized to maximize charge capture and minimize energy spread. The predicted brightness of the beam produced in this experiment is about $5 \times 10^{10} \text{ Amp}/(\text{m-rad})^2$. Scaling laws and simulations predict that the same system scaled up to 10^{17}cm^{-3} will produce a beam of brightness $5 \times 10^{14} \text{ Amp}/(\text{m-rad})^2$, which rivals the brightness specified for the LCLS photoinjector [12].

2 PARTICLE-IN-CELL CODE SIMULATIONS

The development of an experimental plan for the transition trapping experiment has evolved through extensive PIC code simulations, primarily with the two dimensional PIC code MAGIC [13]. The majority of this work has centered on the original experimental case model [14] which uses the plasma density profile labelled number 1 in Fig. 1 and has the parameters listed in Tables 1 and 2 under Profile 1. The two dimensional simulation results for this case have been verified using the three dimensional PIC code OSIRIS [15]. Our recent efforts have focused on substantially improving the simulations to reflect the real experimental conditions as accurately as possible.

Profile 1, as seen in the lower trace in Fig. 1, is an idealized plasma density profile composed of linear segments and a step function transition. This idealization, especially the perfect step function transition, is clearly not realistic. Simulations have shown that a finite length density transition is acceptable as long as it is shorter than the plasma skin depth $k_p^{-1} = v_b/w_p$ of the high density region [14]. We produce plasma density transitions by using a perforated metal foil to partially block the flow of a plasma column. An electron beam passing through the column on the far side of the obstruction sees a sharp transition in the plasma density as it passes the foil edge. This process has been studied extensively in simulation [11]. The results of these studies, as well as preliminary experiments, indicate that metal screen barriers can be used successfully to produce transition trapping at our target density in the mid 10^{13}cm^{-3} .

It is exceedingly difficult to produce a plasma density profile with the smooth linear dependencies shown in the

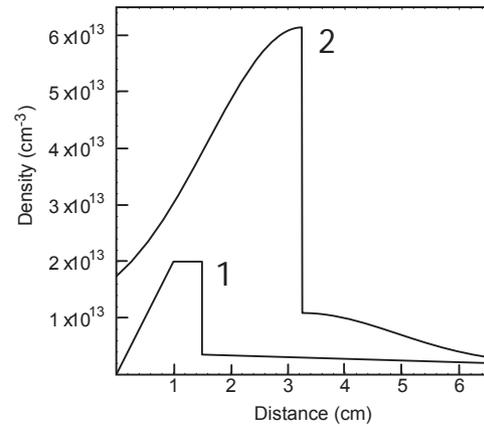


Figure 1: Plasma Density Profiles

lower curve in Fig. 1. A more realistic option is to alter the natural profile of the plasma column as little as possible. As can be seen from Fig. 2, the raw plasma column produced in our plasma source has a gaussian profile with a higher peak density than we originally anticipated. If we use a simple screen of uniform open area to reduce the amplitude of half the gaussian distribution we produce the profile labelled number 2 in Fig. 1. The gaussian based profile is qualitatively similar to the linear profile and preserves most of its features including the gradual decline in density after the transition. This gradual density decline is critical for enhancement of charge capture and the reduction of energy spread [11]. Simulations using this new cut-off gaussian profile indicate that its performance is superior, especially in terms of captured charge, to that of the original linear density profile. This is primarily do the higher peak plasma density. The drive and captured beam parameters from these simulations are presented in Tables 1 and 2, respectively, under Profile 2.

There are several factors which will be present in the actual experiment, but which we cannot simulate simultaneously, that will lead to reductions in the captured charge. The value for the captured charge give in Table 2 should therefore be taken as an upper bound. The first of these factors are the finite transition length and effects due to the transition creation mechanism. As indicated above, the first two of the factors have been simulated extensively and should only lead to minor loss of captured charge. An-

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	$4 \times 10^{13} \text{ cm}^{-3}$	$4 \times 10^{13} \text{ cm}^{-3}$

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%

other important factor is the three dimensional effects associated with the drive beam interacting with the plasma confinement field. A magnetic field on the order of 100 gauss is necessary to confine the plasma in the region where the drive beam will encounter the density transition. This field must be oriented perpendicular to the drive beam path so that the drive beam will actually be steered by the plasma confinement field during the trapping process. This steering is a disruption to the trapping process that may lead to loss of captured charge. In order to investigate this effect we have started a series of simulations with the three dimensional PIC code OSIRIS. Initial indications are that bending during the trapping process may have a significant detrimental effect, but further study is needed.

3 PLANNED EXPERIMENT

This experiment will be performed at the Fermilab NICADD Photoinjector Laboratory (FNPL) as part of an ongoing collaboration with UCLA. This collaboration has centered on PWFAs and has recently yielded interesting new results in the field of witness beam injection [16].

3.1 Photoinjector and Linac

The FNPL accelerator is a 18 MeV electron linac [17]. The system consists of a normal conducting L-band RF gun 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 durations of 1.6 ps rms using magnetic compression. All the beam parameters necessary for the plasma density transition trapping experiment have already been demonstrated at FNPL.

3.2 Plasma Source

By modifying an existing pulse discharge plasma source [18] we have created a plasma column with a peak density of $6 \times 10^{13} \text{ cm}^{-3}$. As shown in Figure 2 the raw plasma column has a gaussian transverse density profile and over 6 cm of the plasma has density greater than $2 \times 10^{13} \text{ cm}^{-3}$, ensuring that we have sufficient plasma to form either of the density profiles in Fig 1.

We have made preliminary measurements of plasma density transitions produced using obstructing screens. These initial measurements lack fine resolution, but were consistent with our understanding of the density transition production mechanism. High resolution measurements of the density transition are planned for the near future.

4 PRESENT STATUS AND CONCLUSIONS

Preparations for the transition trapping experiment are near completion. The plasma source and associated diagnostics are assembled and in the final stages of testing at UCLA. Once testing is complete the apparatus will be moved to FNPL and integrated into the existing beamline.

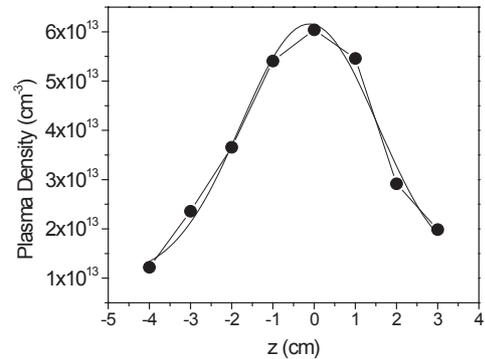


Figure 2: Measured Transverse Density Profile of the Plasma Column

We expect to perform the plasma density transition trapping experiment during the summer of 2003.

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REFERENCES

- [1] J. B. Rosenzweig, *et al.*, *Phys. Rev. Lett.*, **61**, 98 (1988).
- [2] C. E. Clayton, *et al.*, *Phys. Rev. Lett.*, **70**, 37 (1993).
- [3] F. Amiranoff, *et al.*, *Phys. Rev. Lett.*, **81**, 995 (1998).
- [4] N. Barov, *et al.*, *Phys. Rev. Special Topics - Accel. Beams*, **3**, 011301 (2000).
- [5] M. J. Hogan, *et al.*, *Physics of Plasmas*, **7**, 2241 (2000).
- [6] S. Bulanov, *et al.*, *Phys. Rev. E*, **58**, R5257 (1998).
- [7] H. Suk, *et al.*, *Phys. Rev. Lett.*, **86**, 1011 (2001).
- [8] D. Umstadter, *et al.*, *Phys. Rev. Lett.*, **76**, 2073 (1996).
- [9] E. Esarey, *et al.*, *Phys. Rev. Lett.*, **79**, 2682 (1997).
- [10] J. B. Rosenzweig and E. Colby, in *Advanced Accelerator Concepts*, 1995, vol. 335 of *AIP Conf. Proc.*, p. 724.
- [11] M. C. Thompson and J. B. Rosenzweig, in *Advanced Accelerator Concepts*, 2002, vol. 647 of *AIP Conf. Proc.*, p. 600.
- [12] M. Ferrario, *et al.*, in *Proc. EPAC 2000*, Austrain Acad. Sci. Press, 2000, p. 1642.
- [13] B. Goplen, *et al.*, *Computer Physics Communications*, **87**, 54–86 (1995).
- [14] M. C. Thompson, *et al.*, in *Proc. PAC 2001*, IEEE, 2001, p. 4014.
- [15] R. A. Fonseca, *et al.*, in *Computational Science - ICCS 2002*, Springer, 2002, LNCS 2331, pp. 342–351.
- [16] N. Barov, *et al.*, "High-Gradient Plasma Wakefield Acceleration of a Witness Beam," in *Proc. PAC 2003*.
- [17] J.-P. Carneiro, *et al.*, in *Proc. PAC 1999*, IEEE, 1999, p. 2027.
- [18] H. Suk, *et al.*, in *Proc. PAC 1999*, IEEE, 1999, p. 3708.