

Expression of Interest: NICADD/UCLA Collaboration on Plasma Density Transition Trapping

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Abstract. We propose a joint NICADD/UCLA collaboration to conduct a proof-of-principle plasma density transition trapping experiment. 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 electron in a plasma wake-field. The plasma source for this experiment is nearing completion at UCLA. The drive beam needed for this experiment falls within the parameters already achieved at Fermilab/NICADD Photoinjector Laboratory (FNPL).

INTRODUCTION

The current NICADD/UCLA collaboration to study plasma wake-field accelerator (PWFA) driver beam dynamics is unique. It is the only successful, low energy drive beam, compressor-based PWFA program in operation. The results of this program are important to the development of plasma acceleration science and a necessary compliment to the ongoing high energy drive beam experiments at SLAC such as E-157.

We would like to expand this successful collaboration to address the vital problem of injecting and phase-locking electron beams into short wavelength plasma accelerators. The problem of beam injection into plasma accelerators has not been solved experimentally. While significant strides have been made in solving the injection problem in laser based plasma accelerators, the problem has remained largely unaddressed in PWFAs. Plasma Density Transition Trapping is the first technique that promises to automatically inject a well defined beams into the accelerating phase of a PWFA.

THE PLASMA DENSITY TRANSITION TRAPPING CONCEPT

The difficulty of achieving the sub-picosecond timing required to inject an externally generated electron beam into a PWFA has lead many researchers to examine self-trapping scenarios. Most of these ideas have centered around inducing conventional wave breaking in the system. While conventional wave breaking does trap large amounts of charge in the plasma wave, this charge tends to fill large areas of phase space forming a poorly defined beam. Plasma density transition trapping replaces conventional wave breaking with a single, stimulated, wave breaking event.

In the plasma density transition trapping scenario a PWFA drive beam passes from a region of high plasma density into a region of lower plasma density. As the plasma wake crosses the sharp boundary between the two plasma density regions it must instantaneously increase in wavelength. The sudden growth in the plasma wavelength effectively dephases a significant volume of plasma electrons into an accelerating phase of the wake. A large portion of these electrons become trapped in a well defined beam. When this technique is scaled up to high plasma densities the trapped beams can exceed the parameters specified for the LCLS injector. An extensive explanation of transition trapping and its scaling behavior are provided in the attached paper.

EXPERIMENTAL OUTLOOK

The proposed proof-of-principle experiment, which is also detailed in the attached paper, is designed around a low energy 14 MeV drive beam of approximately 6 nC charge and $\sigma_t = 1.5$ psec. When this beam passes through a $2 \times 10^{13} \text{ cm}^{-3}$ plasma that has a sharp transition to $3.6 \times 10^{12} \text{ cm}^{-3}$ a 100 pC, 1.2 MeV beam with only 11% energy spread will be captured. The plasma density and drive beam parameter were chosen to make this initial transition trapping experiment as easy as possible.

The FNPL has already demonstrated the ability to produce beams that meet the requirements for this experiment. The plasma source for this experiment is nearing completion at UCLA. We have already produced plasma densities in excess of $2 \times 10^{13} \text{ cm}^{-3}$ and characterization of the plasma transition will begin in the near future. The apparatus will be complete and ready to perform the experiment in 4-6 months, soon after the completion of the current series of driver beam studies.

Plasma Density Transition Trapping as a Possible High-Brightness Electron Beam Source

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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 examines the quality of electron beams captured using this scheme in terms of emittance, energy spread, and brightness. Two-dimensional Particle-In-Cell (PIC) simulations show that these parameters can be optimized by manipulating the plasma density profile. We also develop, and support with simulations, a set of scaling laws that predict how the brightness of transition trapping beams scales with the plasma density of the system. These scaling laws indicate that transition trapping can produce beams with brightness $\geq 5 \times 10^{14}$ Amp/(m-rad)². A proof-of-principle transition trapping experiment is planned for the UCLA Neptune Laboratory in the near future. The proposed experiment and its status are described in detail.

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 $\omega_p = (4\pi n_o e^2 / m_e)^{1/2}$, where n_o is the plasma density, e is the electron charge, and m_e is the electron mass. It follows that high gradient PWFA's 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 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]. As a result the accelerated electrons had 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 its environment. Suk et al. [4] recently proposed a new self-trapping system for the use in the blow out regime of PWFA where $n_b > n_o$ (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 group 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

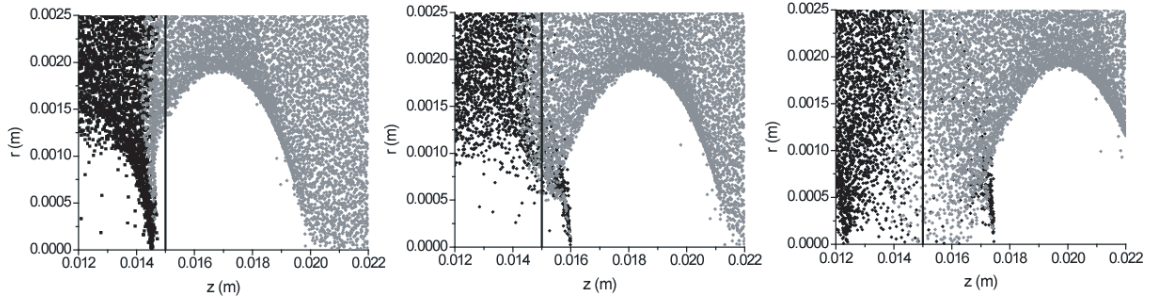


FIGURE 1. Illustration of particle trapping in the strong blowout case. The vertical black line indicates the original position of the density transition. Plasma electron particles originating in the high density region are colored black while particles originating in the low density region are colored grey.

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.

In this paper, we expand on the original proposed transition trapping system, examining in greater detail the issues of trapped beam quality and scaling of the system to higher plasma density. We also present a detailed plan for a plasma density transition trapping proof of principle experiment and report on substantial progress towards realizing this experiment.

TRAPPING SCENARIOS

The current development of the idea of plasma density transition trapping centers around the detailed study of two particular scenarios. The first case uses a high charge beam to create a very strong blowout of plasma electrons in a plasma with a simple step function longitudinal plasma density profile. This is the original case proposed for transition trapping [4]. The second case is optimized for a proof of principle trapping experiment. This case uses a beam of much more modest charge to create a weak blowout, in the high density region, and uses a sloped plasma density profile to enhance charge capture and reduce energy spread.

Strong Blowout Scenario

The strong blowout scenario uses the parameters presented in Table 1 and illustrated in Figure 1. The plasma density profile is a simple step function with a constant density of $n_{region1} = 5 \times 10^{13} \text{ cm}^{-3}$ in the high density region and a constant density of $n_{region2} = 3.5 \times 10^{13} \text{ cm}^{-3}$ in the low density region. The high charge driver produces a very strong blowout, which in turn results in a clear picture of the trapping process.

TABLE 1. Drive and Captured Beam Parameters in the Strong Blowout Case. Figures for the captured beam are for the core of the captured beam, which is about 20% of the captured particles, after 12 cm of acceleration.

Drive Beam		Captured Beam	
Beam Energy	50 MeV	Beam Energy	56 MeV
Beam Charge	63 nC	Beam Charge	5.9 nC
Beam Duration σ_t	3 psec	Beam Duration σ_t	161 fsec
Beam Radius σ_r	500 μm	Beam Radius σ_r	112 μm
Peak Beam Density	$1.2 \times 10^{14} \text{ cm}^{-3}$	Normalized Emittance ϵ_x	155 mm-mrad
		Total Energy Spread	13%

In order to increase our understanding of the trapping mechanism we performed a series of simulation with the 2D Particle-In-Cell code MAGIC [5] in which the high and low density plasma electron populations are tracked separately. The results show that the trapping process actually begins in the high density region, as can be seen in Figure 1. As electrons from the low density region are blown out and pushed backward they enter the high density plasma region. There the oscillation of the region 2 plasma electrons is accelerated by the higher ion density and these electrons return to the axis early and mix with electrons from the high density region. As this mixed concentration of plasma electrons crosses the boundary between the high and low density regions many of the electrons find themselves in an accelerating phase of the low density plasma wake and are trapped and accelerated.

The properties of the beam captured in this scenario are listed in the second column of Table 1. The captured beam is very short and has a small radius, both of which originate from the small accelerating volume of the accelerating plasma wave. The beam also has a high charge that results from the very high concentration of electrons in the oscillation density spike that are injected. Unfortunately, the captured beam has a significant energy spread that results from the fast variation in the plasma wake-field accelerating gradient where the particles are captured. The beam also has a poor transverse emittance. This is an unavoidable consequence of trapping background plasma particles in the strong blowout regime. The large transverse momenta imparted to the plasma electrons as the drive beam space charge blows them out to the side remains with the particles as they are trapped and accelerated to high energy.

In addition to the undesirable emittance and energy spread properties of the captured beam, this transition trapping scenario is also impractical from an experimental stand point. The drive beam parameters listed in the first column of Table 1 are not currently achievable. For this reason we began to look at what sort of trapping experiments could be done with the more modest driver beams that are available. During this development we also found ways to improve both the emittance and energy spread of the captured beams.

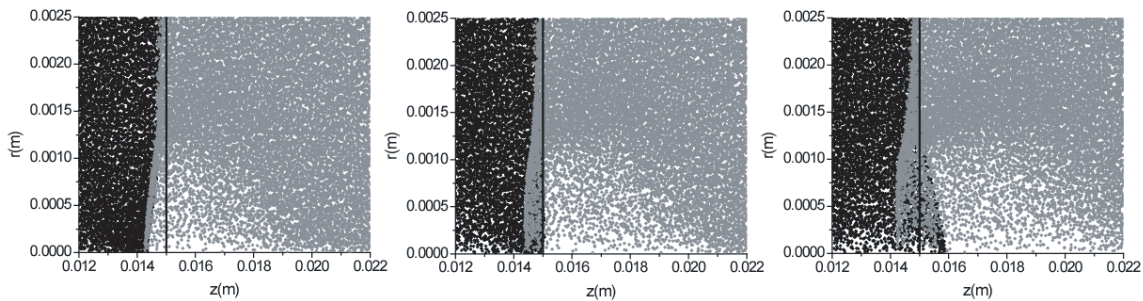


FIGURE 2. Illustration of particle trapping in the weak blowout case. This figure is directly comparable with Figure 1. The scale and particle coloring are identical. Note that the trapping mechanism is essentially the same except that it proceeds more slowly due to the low plasma density in the down stream region compared to strong blowout case. The weaker blowout also leads to much less transverse disturbance in the plasma, which in turn yields lower emittance.

Weak Blowout Scenario

A great deal can be learned about the mechanism and dynamics of density transition trapping by comparing the strong blowout case previously described to a case in which a weak blowout is used. Our standard example of a weak blowout case is the proof of principle experimental case designed for the Neptune Advanced Accelerator Laboratory at UCLA [6]. This case was developed and optimized for parameters achievable at the Neptune Laboratory through extensive simulations with MAGIC. The driving beam parameters of the simulation are shown in Table 2. The driving beam has a ramped longitudinal profile as shown in Figure 3. Ramped profiles of this type maximize the transformer ratio of the wake field [7] and can be produced using a negative R_{56} magnet compressor system. We are developing such a compressor system for the Neptune Laboratory [8]. While the ramped beam profile improves performance, it is not critical to this trapping scenario.

The plasma density profile used in this case is illustrated in Figure 3. The plasma density profile is tailored to maximize the amount of charge captured while maintaining an acceptable amount of acceleration. The first cm of the profile reflects a realistic finite rise time from zero to the maximum plasma density. After 5 mm of maximum density the transition takes place and the density is reduced to 18% of the maximum.

TABLE 2. Drive and Captured Beam Parameters in the Weak Blowout Case

Drive Beam		Captured Beam	
Beam Energy	14 MeV	Beam Energy	1.2 MeV
Beam Charge	5.9 nC	Beam Charge	120 pC
Beam Duration	6 psec	Beam Duration σ_t	1 psec
Beam Radius σ_r	540 μm	Beam Radius σ_r	380 μm
Normalized Emittance ϵ_x	15 mm-mrad	Normalized Emittance ϵ_x	15 mm-mrad
Peak Beam Density	$4 \times 10^{13} cm^{-3}$	Total Energy Spread	11%

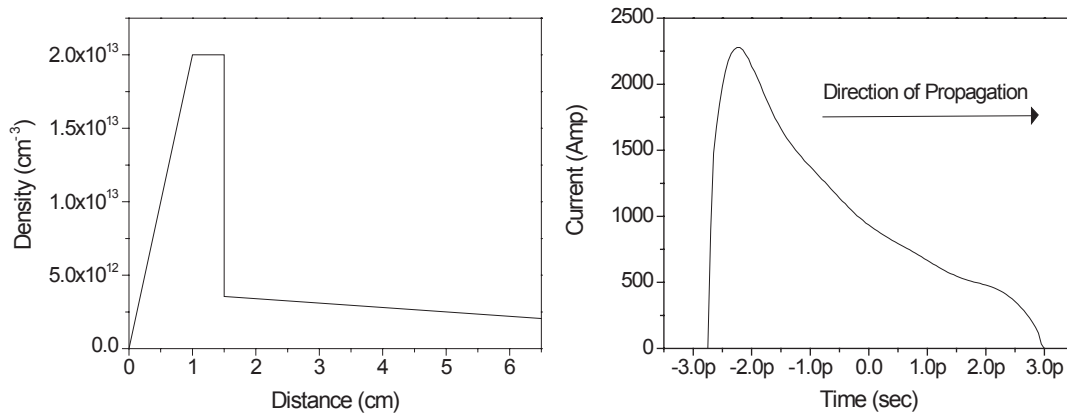


FIGURE 3. Plasma Density (left) and Drive Beam Current (right) Profiles.

This density drop is near the optimum to maximize charge capture. Decreasing the density of region 2 increase the wavelength of the accelerating plasma wave. This has the effect of enlarging the volume of the capture region and enhancing the amount of charge trapped. Lowering the plasma density also reduces the accelerating gradient, however, reducing the number of initially captured particles that ultimately achieve resonance with the accelerating wave. These two effects compete with the charge capture maximum occurring at $n_{region2} = 0.18n_{region1}$. This large drop is necessary to ensure adequate charge capture, which is achieved at the expense of reducing density and accelerating gradient in region 2. As can be seen from Table 2 and Figure 3 the electron beam density is 2 times larger than the peak plasma density of $2 \times 10^{13} \text{ cm}^{-3}$.

In the simulation the transition is approximated as a perfect step function, the validity of this assumption will be elaborated on later in this paper. Finally, the gradual decline in plasma density after the transition slowly increases the size of the accelerating wake field region, which reduces the peak gradient but rephases the captured charge toward the peak field of the wake. This rephasing both increases the amount of charge trapped and reduces energy spread.

The parameters of the bunch of captured plasma electrons are given in Table 2. The captured plasma electrons form a well defined beam of substantial charge that can be propagated and detected without major difficulty. The captured beam is also well separated from the drive beam in energy and should be easy to isolate. If a bi-gaussian beam with $\sigma_t = 1.5 \text{ pec}$ is substituted for the ramped profile shown in Figure 3 the captured beam parameters remain unchanged except for a 20% loss of captured charge.

EXPERIMENTAL PLANS

An experiment is planned for the Neptune laboratory at UCLA with the parameters presented in Table 2 and Figure 3. By modifying an existing pulse discharge plasma source [9] we have achieved a plasma density of $4.7 \times 10^{13} \text{ cm}^{-3}$. This density is well in excess of $2 \times 10^{13} \text{ cm}^{-3}$, the required peak density for the trapping experiment.

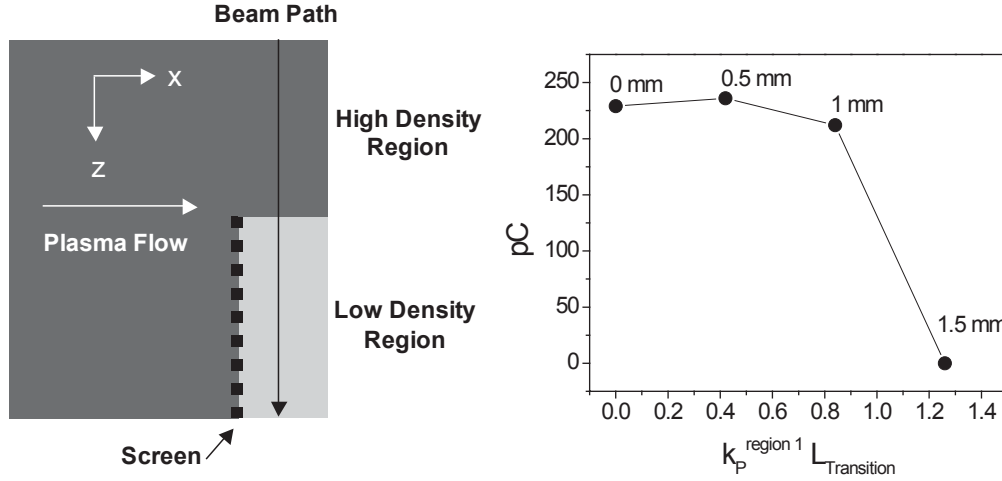


FIGURE 4. Left: Simplified diagram of a plasma density transition produced by an obstructing screen. Right: Simulated dependence of captured charge on transition length in the proposed experimental case. Each point is marked with the length of the transition.

Experimental realization of plasma density transition trapping depends on the creation of sharp density transitions. The limit on the sharpness of the transition necessary to produce trapping is set by the trapping condition

$$k_p^{region 1} L_{Transition} < 1. \quad (1)$$

As can be seen from Figure 4, this is a very strict condition. The turn on of the capture in this regime is nearly a step function.

The creation of a density transition that satisfies this criteria is an interesting experimental challenge. At high plasma densities, $n \geq 10^{14} cm^{-3}$, it will probably be necessary to directly create the plasma with the required density profile already built in. This might be accomplished through photo-ionization using a laser with an intensity profile that matches the desired plasma density profile or using a uniform laser to ionize a dual density gas jet. At lower densities such as $10^{13} cm^{-3}$, which can be easily produced using discharges, it is possible to consider a simpler method using a masking screen to generate the density transition. The basic concept of operation for the masking screen is illustrated on the left of Figure 4. Consider a system in which the plasma discharge is separated from the path of the driver beam. Once the plasma is created in the discharge apparatus it will diffuse and flow towards the beam path. If a perforated metal foil or grid of wires is placed in the path of the plasma flow it will block a portion of the flow creating a low density region. Unfortunately, the plasma density transition will not remain sharp as the distance from the screen grows as portrayed in the simple picture of Figure 4. In reality the two plasma regions will diffuse into one another on the far side of the screen so that the plasma density transition will lengthen and blur as the distance from the screen edge increases. This process can be quantified using a simple model based on

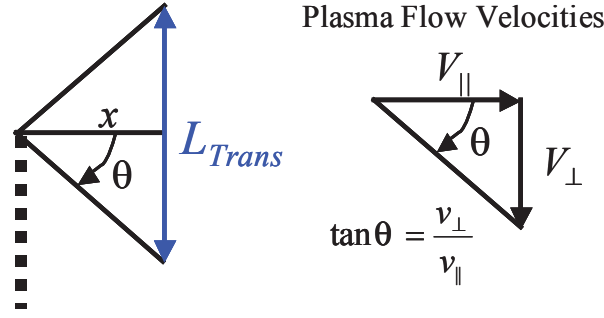


FIGURE 5. Illustration of the transition geometry.

the velocities with which the plasma diffuses as shown in Figure 5. On the far side of the screen from the plasma source the high density plasma will continue to flow past the screen in the direction of the bulk plasma flow with a velocity V_{\parallel} and will begin flowing into the low density region with a velocity V_{\perp} . The sum of these two vectors defines the line which marks the end of the transition into the low density plasma region. Symmetry dictates that the start of the transition in the high density region can be defined in the same way so that the total transition length is given by

$$L_{Trans} = 2x \tan \theta = 2x \frac{V_{\perp}}{V_{\parallel}}. \quad (2)$$

Since our plasma is weakly magnetized it is reasonable to assume that the parallel and perpendicular plasma flow velocities are approximately equal. This assumption leads to the conclusion

$$V_{\perp} \approx V_{\parallel} \rightarrow L_{Trans} = 2x, \quad (3)$$

which in turn leads to the new trapping condition

$$x < \frac{k_p^{-1}}{2}. \quad (4)$$

This new trapping condition for obstructing screens requires that the drive beam passes within half a plasma skin depth of the boundary. For a $2 \times 10^{13} \text{ cm}^{-3}$ plasma the drive beam will have to pass within $600 \mu\text{m}$ of the screen. This level of pointing accuracy and stability is not difficult to achieve.

We have explored the validity of this model through simulations. We began by looking at MAGIC PIC simulations in which a neutral plasma was initialized in half the simulation volume and allowed to diffuse through a periodic series of conduction obstructions into the rest of the volume. This is essentially the situation that we wish to create in our discharge plasma source. By plotting histograms of the simulation particles contained in small bands of Δx at various distances from the edge of the obstructions we were able to make predictions of the transition length at various positions. The results of this study match the prediction of Eq. (3) almost exactly.

We have also begun to experiment with metal screens in our plasma source. By moving a Langmuir probe through the transition region behind the screen we have

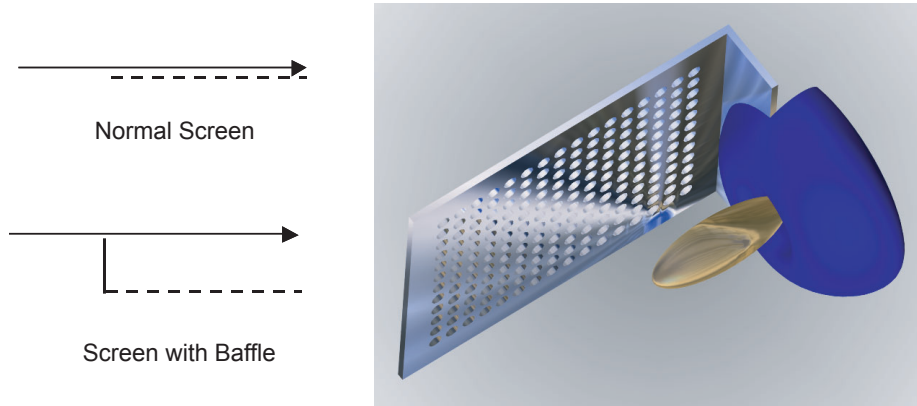


FIGURE 6. Artist's conception of partial blocking of wake particles by the baffle. The prolate spheroid represents the electron beam and the toroid that partially intersects the screen baffle is the plasma wake.

made rudimentary measurements of the plasma transition. Unfortunately, our existing equipment does not allow a precise distance to be set and maintained between the probe tip and the metal screen. This makes a direct comparison between the data and Eq. (3) impossible. The data do, however, appear to be in approximate agreement with Eq. (3) and we are upgrading our equipment to make more precise measurements. While giving inconclusive measurements of the plasma transition, these early screen experiments did confirm our ability to reliably set the plasma density behind the screen. In the limit of thin sheaths, the density of the plasma in the low density region behind the screen should be related to high density plasma by the relation

$$\frac{n_{low}}{n_{high}} \approx \frac{A_{ScreenOpenArea}}{A_{ScreenTotalArea}}. \quad (5)$$

The screen experiments were conducted using a micro-etch perforated stainless steel screen with $152\mu m$ diameter holes and an open area of 21%. The observed plasma density behind the screen was 19.5% of the unfiltered plasma density, which agrees well with Eq. (5). This means that we should be able to produce the gradual density decline shown in Figure 3 by tapering the open area of the screen.

Propagating a beam so close to a metallic screen leads to other difficulties. Interactions with the screen over the entire length of the low density plasma region will completely disrupt the processes of trapping and acceleration. To circumvent this problem we examined many alternative geometries and arrived at a solution based on a screen with a solid metal baffle attached to its edge. As shown in Figure 6 this baffle moves the sharp portion of the density transition away from the screen so that the beam and plasma wake will no longer interact with it. During the trapping process at the transition, however, the beam and wake still interacts with the baffle. The primary effect of the baffle is to block a portion of the particles participating in the plasma wake oscillation, as illustrated on the right in Figure 6. Simulating the effects of the baffle on particle trapping is a complex problem. The baffle breaks the cylindrical symmetry of the problem requiring that any simulations of its effects must be done in three dimensions.

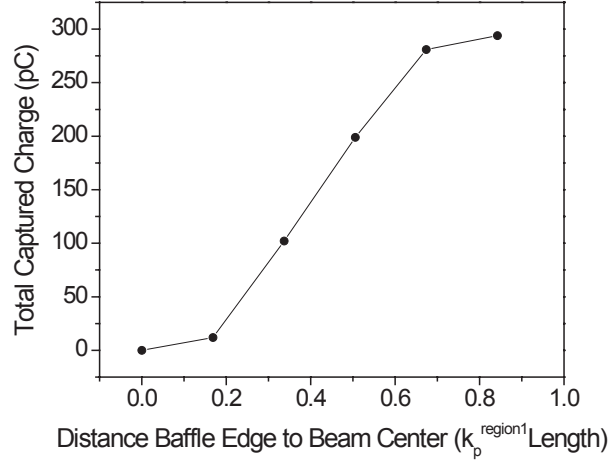


FIGURE 7. Effect of the Beam-Baffle Distance on Trapping

We used the three dimensional version of the PIC code MAGIC to simulate this problem. Unfortunately, MAGIC 3D is not a parallel code, which ultimately limited the accuracy we could obtain in our simulation, but it was the only three dimensional code available to us that would allow a conducting boundary to be placed near the beam path in the plasma. We were able to reproduce the results of our 2D simulations almost exactly with the 3D version of the code. We then modelled the same system with a metallic baffle at various distances from the beam center. The results of these simulations are summarized in Figure 7. The points in the graph are taken from simulations in which the simulation cells are $0.17k_p^{-1}$ on a side, which is the maximum resolution we could obtain with our computing hardware. Since Eq. (4) indicates that the beam must pass within $k_p^{-1}/2$ of the baffle edge, the results shown in Figure 7 predict an approximate 50% loss of total captured charge. This may not translate into a 50% loss of particles in the beam core, however, since the large amplitude particles blocked by the baffle are not necessarily the ones that form the beam core. The 3D simulations lacked the resolution to resolve this question.

The final issue with the use of screen produced plasma density transitions is the rapid growth of the transition length with distance from the screen. The growth rate is large enough that there will be a significant transition length gradient over distance spanned by the plasma wake field. The effect of this transition length gradient is unknown, but will soon be examined in simulation. We expect this effect to produce another minor but acceptable degradation of the trapping performance.

DRIVER CHARGE SCALING

While the captured beam parameters presented in Table 2 are adequate for a first step, proof-of-principle type experiment they are far inferior to the state of the art beams produced in modern photoinjectors. In order to find a systematic way to improve the

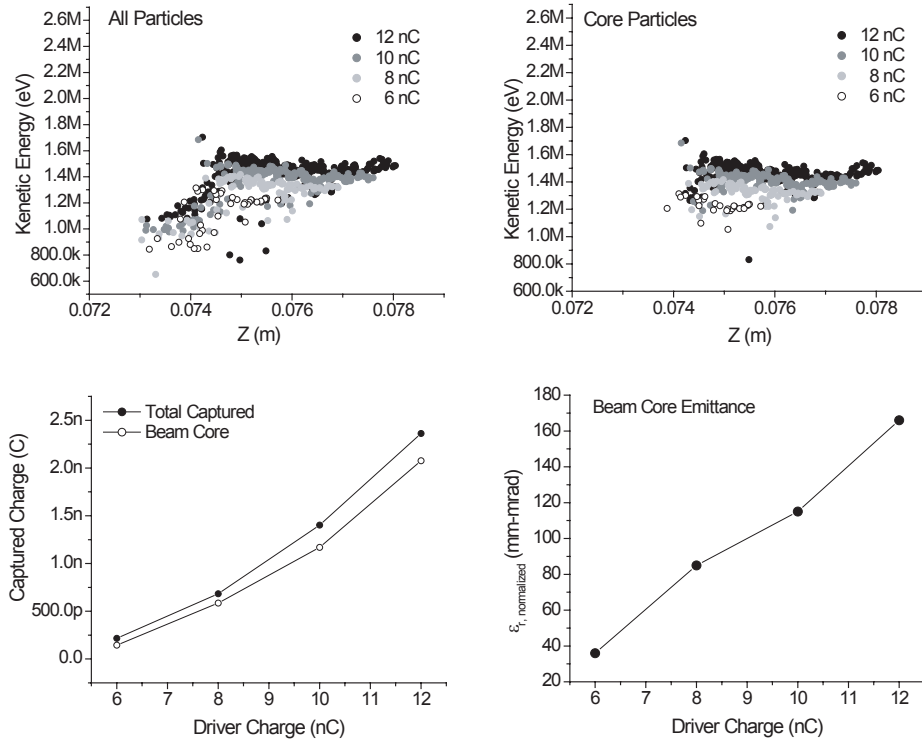


FIGURE 8. Variation of the captured beam parameters with scaling of the driver beam charge in the weak blowout case.

captured beam parameters we began to simulate the effects of scaling up the drive beam charge without altering the rest of the experiment. The results of these simulation are shown in Figure 8. Increasing the driver charge increases the strength of the blowout forming a larger amplitude more non-linear plasma wave. It follows that all the accelerating fields in the problem are increased as is the size of the accelerating wave. The impact on the captured beam is clearly shown in Figure 8. The amount of charge captured, the length of the beam, and the emittance all grow as the driver charge is increased. Although it deserves more detailed study, simple scaling of the driver charge appears to lead to bigger captured beams but not higher quality ones.

WAVELENGTH SCALED SOURCES

We have seen the performance of density transition trapping in densities $n_0 \sim 10^{13} \text{ cm}^{-3}$ in the preceding sections, as well as how the performance changes with driver charge scaling. It is also interesting to examine how the captured beams performance scales with plasma density or, equivalently, the plasma wavelength. In order to scale the transition trapping system to a higher plasma density n_{high} all the charge densities in the system must be increased by the ratio,

$$n_{high}/n_0, \tag{6}$$

and all the lengths in the system are decreased by the ratio,

$$\frac{\lambda_{p \text{ high}}}{\lambda_{p 0}} = \frac{k_{p \text{ high}}^{-1}}{k_{p 0}^{-1}} = \frac{1/\sqrt{n_{\text{high}}}}{1/\sqrt{n_0}} = \sqrt{\frac{n_0}{n_{\text{high}}}}, \quad (7)$$

where λ_p represents the typical wavelength of oscillations in the plasma and is equal to the plasma skin depth $\lambda_p = k_p^{-1} = c/\omega_{pe}$.

If the transition trapping system is scaled in accordance with these ratios, several simple rules can be deduced to describe the corresponding changes in the captured beam. Since the accelerating gradient E_{max} in a plasma accelerator grows as $\sqrt{n_0}$ and momenta p of the captured particles goes as the product of the force acting on them and the distance through which it is applied, we can immediately write,

$$p \propto E_{\text{max}}\lambda_p \propto \sqrt{n_0} \frac{1}{\sqrt{n_0}} = \text{Constant}. \quad (8)$$

This scaling law applies to both the longitudinal and transverse particle momenta. Consequently, the emittance ε , which is proportional to the product of momenta and the beam size, goes like

$$\varepsilon \propto \lambda_p p \propto \lambda_p. \quad (9)$$

The emittance of the captured beam improves as the system is scaled to higher density as a result of the reduction in the transverse beam size.

The amount of charge captured Q depends on both the available plasma electron density n_0 and the volume of the accelerating portion of the wave, which is proportional to λ_p^3 . This scaling can be written as

$$Q \propto n_0 \lambda_p^3 \propto n_0 \left(\frac{1}{\sqrt{n_0}}\right)^2 \lambda_p \propto \lambda_p. \quad (10)$$

While the captured charge goes down as the plasma wavelength is reduced, the current I remains constant since the length of the beam also goes down with the plasma wavelength,

$$I \propto \frac{Q}{\lambda_p/c} = \text{Constant}. \quad (11)$$

Finally we can combine the scaling laws for emittance and current to deduce the scaling of the beam brightness B

$$B \propto \frac{I}{\varepsilon^2} \propto \frac{1}{\lambda_p^2} \propto n_0. \quad (12)$$

Thus the brightness of electron beams produced using density transition trapping increases linearly with the density of the plasma.

These scaling laws were tested using the 2D PIC code MAGIC. The cases examined are scaled versions of the proof-of-principle experimental case with a slightly larger driver charge. The results are summarized in Table 3. The simulation results follow the scaling laws precisely in the range studied. At $2 \times 10^{17} \text{ cm}^{-3}$ transition trapping can

TABLE 3. Simulations of Wavelength Scaling using MAGIC 2D

Peak Density	$\sigma_{t,Driver}$	Q_{Driver}	$\sigma_{t,Trap}$	Q_{Trap}	$I_{Peak,Trap}$	$\epsilon_{x,norm,Trap}$	$B_{norm,Trap}$
$2 \times 10^{13} \text{cm}^{-3}$	1.5 psec	10 nC	2.7 psec	1.2 nC	163 Amp	57 mm-mrad	5×10^{10}
$2 \times 10^{15} \text{cm}^{-3}$	150 fsec	1 nC	270 fsec	120 pC	166 Amp	5.9 mm-mrad	5×10^{12}
$2 \times 10^{17} \text{cm}^{-3}$	15 fsec	100 pC	28 fsec	12 pC	166 Amp	0.6 mm-mrad	5×10^{14}
LCLS Photoinjector Specification					100 Amp	0.6 mm-mrad	2.8×10^{14}

produce an extremely short beam with excellent emittance and a brightness that exceeds state of the art photo-injectors. The drive beams needed at all densities must be of similar length and approximately one order of magnitude greater charge than the beams they capture. The emittance of the driver, however, is irrelevant as long as the driving beam can be focused sufficiently to match into the plasma. This means that plasma density transition trapping might be used as an emittance transformer to produce short, low emittance beam from short beams with high emittances that were produced using extreme magnetic compression or other techniques that produce significant emittance growth. The feasibility of this idea is still under study and may be enhanced by our effort to find new scenarios that produce low emittance trapped beams.

As described previously, plasma density transition trapping, at least in the regimes examine so far, produces beams of large emittance do to the sizeable transverse momenta the plasma particles have at capture. Scaling to higher density improves the emittance by reducing the beam size rather than reducing the transverse momentum. We are continuing to explore alternative transition trapping scenarios in an effort to reduce the transverse momentum of the beam further. Two possibilities under study are wide beam drivers and foil trapping.

FUTURE DIRECTIONS

In order to proceed beyond a proof-of-principle transition trapping experiment will necessarily require scaling to higher plasma densities. This will require improvements to both the driver beam and higher density plasma sources with sharp transitions. The production of very short, high current electron drive beams is a matter discussed at great length elsewhere. Ideas for producing plasmas with transition that satisfy Eq. (1) at high densities $n \geq 10^{14} \text{cm}^{-3}$ are still in the conceptual phase. H. Suk plans to pursue development of a laser ionized dual density gas jet for use in transition trapping. We have tentative plans at UCLA to pursue development of a high density source based on photo-ionization of Lithium using a laser with step function intensity profile.

In the extreme limit, one can imagine creating an ultra-sharp transition into a plasma by simply replacing the high density plasma region in a transition trapping scenario with a solid metal foil. Electrons would be provided for trapping from the foil via Fowler-Nordheim field emission [10]. Since this situation is much easier to produce experimentally than sharp plasma density drops, we have begun to look at the idea closely.

The field values necessary for significant Fowler-Nordeim emission are easy to

TABLE 4. Comparison of α parameters

	E_{max}	frequency	v_ϕ	α
1.6 Cell Photoinjector	$80MeV/m$	$2.856Ghz$	c	2.6
Barov et al. Wake Field Experiment (7 nC)	$300MeV/m$	$90Ghz$	c	0.3
Experiment with High Charge Driver (70 nC)	$1.5GeV/m$	$90Ghz$	c	1.6

achieve in current plasma wake-field experiments. N. Barov et al. have produced wake fields $\geq 140MeV/m$ in a $10^{14}cm^{-3}$ plasma at Fermilab [11]. In this experiment the drive beam enters the plasma through a metal foil, one side of which is immersed in the plasma and experiences the large plasma fields. Taking a reasonable value of $\beta \geq 50$ for the microscope surface field enhancement factor of the foil, Fowler-Nordheim theory predicts a large emission $J \geq 100Amp/mm^2$ under these conditions. Unfortunately, the emission of charge does not guarantee that the emitted charge will be trapped and accelerated. The charges emitted from the foil due to the plasma wake fields start essentially at rest and must be accelerated to resonance with the wave within the same period of the plasma wake. This situation is analogous to that in RF photoinjectors and the same dimensionless parameter can be used to evaluate the plasma wake's potential to capture foil electrons. This parameter, α , is the ratio of the maximum normalized energy gain per unit length and the wave number of the accelerating wave.

$$\alpha \equiv \frac{qE_{max}}{k_z m_0 c^2} = \frac{d\gamma_{max}}{k_z dz}, \quad (13)$$

where $k_z = \omega/v_\phi$. The capture of electrons starting from rest typically requires $\alpha \geq 1$. If we compare the α parameters of the Barav et al. experiment and a standard 1.6 cell photoinjector, see Table 4, we see that a plasma wake is not capable of capturing charge from a foil in this regime since its α is only 0.3. The frequency of the accelerating wave is too high in comparison to the accelerating field and the emitted particles can not achieve resonance with the wave.

The peak accelerating field can be increased by increasing the driver beam charge. If this is done while holding the plasma density constant, the plasma frequency will remain essentially unchanged and α will increase. The driver charge can be increased to the point where $\alpha > 1$ and charge is captured from the foil in the plasma wake. If the driver charge in the Barov et al. experiment is increased by a factor of ten the α of the system reaches 1.6 and charge is captured. The trapping behavior predicted by the α parameter has been verified by initial MAGIC 2D simulations. Further work needs to be done to explore the parameter space of foil trapping and characterize the captured beams.

CONCLUSIONS

The theoretical understanding of the basic plasma density transition trapping mechanisms are well developed. The quality of the beams produced by transition trapping is

also well understood, as are a number of methods for optimizing the beam quality. We have shown, through the development of the wavelength scaling laws, that at high densities transition trapping can produce beams with brightness $\geq 5 \times 10^{14}$ Amp/(m-rad)². This exceeds the state of the art brightness of modern photoinjectors. Many variations on the idea of transition trapping, such as foil trapping and the use of wide beam drivers, remain to be studied.

A detailed plan is in place for a proof-of-principle plasma density transition trapping experiment. This experiment will be conducted at low density using density modifying screens, a technique which we have made substantial progress in developing. The rest of the hardware necessary for the experiment is either already in place, or being constructed at this time. We plan to conduct this experiment in late 2002 or early 2003.

With further research and refinement plasma density transition trapping holds promise as a future high brightness beam source. This source may take several forms such as an automatically timed PWFA injector or an "emittance transformer" used to convert short beams with poor emittance into short beams with a much lower transverse emittance.

ACKNOWLEDGMENTS

The authors would like to thank T.C. Katsouleas and L. Ludeking for their assistance with the MAGIC PIC simulations. The authors also thank Mike Schneider, Chris Muller, Soren Telfer, and Ronald Agustsson for their technical assistance. This work was supported by the U.S. Dept. of Energy grant number DE-FG03-92ER40693.

REFERENCES

1. Rosenzweig, J. B., Cline, D. B., Cole, B., Figueroa, H., Gai, W., Konecny, R., Norem, J., Schoessow, P., and Simpson, J., *Phys. Rev. Lett.*, **61**, 98 (1988).
2. Amiranoff, F., Baton, S., Bernard, D., Cros, B., Descamps, D., Dorchie, F., Jacquet, F., Malka, V., Marques, J. R., Matthieussent, G., Mine, P., Modena, A., Mora, P., Morillo, J., and Najmudin, Z., *Phys. Rev. Lett.*, **81**, 995 (1998).
3. Clayton, C. E., Marsh, K. A., Dyson, A., Everett, M., Lal, A., Leemans, W. P., Williams, R., and Joshi, C., *Phys. Rev. Lett.*, **70**, 37 (1993).
4. Suk, H., Barov, N., Rosenzweig, J. B., and Esarey, E., *Phys. Rev. Lett.*, **86**, 1011 (2001).
5. Goplen, B., Ludeking, L., Smithe, D., and Warren, G., *Computer Physics Communications*, **87**, 54–86 (1995).
6. Thompson, M. C., Clayton, C. E., England, J., Rosenzweig, J. B., and Suk, H., *Proceedings of the 2001 Particle Accelerator Conference, Chicago*, p. 4014 (2001).
7. Chen, P., Su, J. J., Dawson, J. M., Bane, K. L., and Wilson, P. B., *Phys. Rev. Lett.*, **56**, 1252–1255 (1986).
8. England, R. J., and Rosenzweig, J. B., *these proceedings* (2002).
9. Suk, H., Clayton, C. E., Hairapetian, G., Joshi, C., Loh, M., Muggli, P., Narang, R., Pellegrini, C., Rosenzweig, J. B., and Katsouleas, T. C., *Proceedings of the 1999 Particle Accelerator Conference, New York*, p. 3708 (1999).
10. Fowler, R. H., and Nordheim, L., *Proceedings of the Royal Society of London*, **A119**, 173–181 (1928).
11. Barov, N., Bishofberger, K., Rosenzweig, J. B., Carneiro, J. P., Colestock, P., Edwards, H., Fitch, M. J., Hartung, W., and Santucci, J., *Proceedings of the 2001 Particle Accelerator Conference, Chicago*, p. 126 (2001).