Technical Progress Report

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The Study of the Acceleration, Focussing and Bunching of
Ions by Electronic Space Charge for Pellet Fusion

MASTER

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by

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Technical Progress Report:

[The following material summarizes the technical progress made on this contract during the past year. The material was being prepared for submission to a technical journal, but is in the format required by ERDA. We have concentrated on the planar diode problem and have observed ion acceleration and bunching. The following material describes the experiments and theory in detail].

ABSTRACT

A candidate for the initiation of a pellet fusion micro-explosion is ions, but the power level from existing sources is far below the calculated value ($10^{14} - 10^{15}$ watts for ~ 1 nsec). One can convert electron beam energy to ion motion with high efficiency ($\sim 40\%$), but even the largest E-beam in existence is still below the required power level by two orders of magnitude. If the ions are bunched in their arrival at the target, the instantaneous power delivered to the target can be much larger than the terminal value. Theoretical calculations show that the power, time scale, and energy requirements for pellet fusion can be met with modifications of existing E-beam sources.

This experimental work demonstrates that energy can be transferred from an electron beam to plasma ions and that resulting space charge neutralized ion pulse can be compressed in time. These experiments also demonstrate some unique transient interactions between the electron beam and the background plasma.

INTRODUCTION

Current estimates of the power required for pellet fusion lie in the range of 10^{14} to 10^{15} watts,¹ if either photons or electrons are used to deliver the energy to the target. This estimate can be reduced by about a factor of six² if suitable means are devised to accelerate and focus ions onto the pellet. Electron beam machines do not exist capable of providing the necessary power even if perfect conversion from electron to ion power could be performed, but machines with more than sufficient energy (≈ 100 KJ) are in operation.³ The problem is to devise a scheme that will convert electron energy to ion energy and, at the same time, shorten the time scale over which this energy is delivered to the target. This can be accomplished by accelerating the ions over a long period of time and bunching their arrival at the target within a short period of time.

One scheme has been described by Winterberg⁴ whereby all ions start at the same place and are accelerated to differing drift velocities. These ions run a "handicap" race, the slower ones starting first and the faster ones later. If the temporal shape of the acceleration field is correct, all contestants (ions) finish at the same time; thus, rise time bunching of the ions. Another way to run this race is through a spatial "handicap"; that is, to start the faster ions farther from the finish. Here the ions are created in their starting positions, and a field is generated (instantaneously) to accelerate them towards the target. The ideal potential shape for this acceleration is easily shown to be parabolic for optimum bunching.^{5,6} In practice,

this potential cannot be established instantaneously; therefore, any scheme of spatial bunching will be some combination of rise time and spatial bunching.

Lav'rentev and Kalmykov⁶ proposed generating the parabolic potential using spherically concentric meshes suspended in space and biased appropriately, but the angular scattering by the macroscopic structure of the grids would limit the minimum diameter of the focus. To alleviate this problem, it has been proposed to use electronic space charge to establish the accelerating fields.⁷ Support for this concept is derived from recent experimental work of Humphries, Lee, and Sudan,⁸ who have successfully used electronic space charge from a reflex triode to accelerate large ion currents (5K amps).⁹ The reported conversion of energy in the transmission line pulser to ion energy was efficient (~ 42%) even though only half the ions were accelerated in a usable direction. The source of ions in their experiment was a Nylon anode, a geometry which permitted ions to be accelerated in both directions. If ions were extracted from a plasma volume on the open side of the anode, the efficiency can be doubled.¹⁰ Another advantage of the volume source of ions is that it provides the different starting positions for spatial bunching.

To obtain bunching, the shape of the electrostatic potential well must resemble a parabolic shape with its positive curvature; thus almost any electron space charge dominated well will accelerate and bunch the ions. Experimental measurements of the potential shapes inside spherical diodes have demonstrated that spherically parabolic-like wells are easily attainable for wide ranges of perveance ($1/V_a^{3/2}$) and angular energy spreads of the injected electron beam.¹¹

Furthermore, these potential shapes can be established in a time interval (a few electron transit times) which is fast in comparison with ion transit time scales. Thus, it is possible to generate deep potential wells for which bunching is predicted in spherical geometry. Other work on the inertial electrostatic confinement device (IEPC) indicates that the ions accelerated in these potential wells should have angular energy spreads $\leq 0.1\%$; thus, focusing should be feasible.¹²

The theoretical work to date on this scheme has concentrated on spherical geometry because of the obvious advantages of focusing, radial compression, and low electron loss. None of the theoretical developments has taken into account the effect of plasma space charge in calculating the movement of ions in the electrostatic potential wells. Although particle codes exist to approximate this situation, such a computation would be costly, prone to accumulated computational errors, and, at best, just a theory.

Described in this paper is a planar experiment that studies the electrostatic wells generated in a finite, plasma filled planar device with particular attention given to the acceleration and bunching properties of these wells. The essential concepts of this planar experiment are displayed in Fig. 1 for an infinite device in the steady state condition. Without a plasma, electrons are injected into space through the highly transparent anode and set up a space charge limited potential as described by the familiar Child-Langmuir law. This law predicts a potential minimum to the right of the anode screen at a distance $X = X_c$.

$$X_c^2 = \frac{2}{9} \epsilon_0 \left(\frac{2e}{m} \right)^{1/2} \frac{V_a^{3/2}}{J_{eb}^+} \quad (1)$$

where J_{eb}^+ is the positively directed beam current as defined in Fig. 1. Most of the electrons miss the transparent anode and circulate to make many transits in the potential well. Hence, the part of the anode current due to the injected beam is

$$J_{Ab} = \frac{\eta}{1 - \eta^2} J_{eb}^+ \quad (2)$$

where η is the transmission factor (openess) of the anode.

The addition of plasma ions neutralizes some of the electronic charge, thus altering the potential shape and allowing a neutralized beam to be transmitted through the potential minimum. The ion current emitted to the region beyond X_c is limited by bipolar space charge limitations to be¹³

$$J_i \approx 2 \left(\frac{m}{M} \right)^{1/2} J_{eb}^+ = \frac{\eta}{1 - \eta^2} 2 \left(\frac{m}{M} \right)^{1/2} J_{Ab} \quad (3)$$

where the plasma electrons merely circulate through the anode until captured. If these plasma electrons are captured before the ions are transmitted through the potential minimum; the plasma contributes a net positive charge to the region of well formation, thus requiring additional electronic charge to establish the accelerating field when a plasma is present. Losses of beam electrons by capture or lateral spread to the walls aggravate the problem further. Therefore, an excessive plasma density or high electron losses will preclude the formation of the potential well.

Because of these problems, it was not at all clear that the experiments would bear any relation to the 1-D analysis. Thus, the first task was to confirm the existence of a potential well in a finite device even with its associated three dimensional losses. Next it was necessary to show that a space charge well could be formed in the presence of sufficient ionization to provide the ions needed for acceleration. The velocities of the ions ejected by the space charge field were inferred from time of flight measurements. Finally, we show that the pulse width of the accelerated ions does indeed narrow; i.e., bunch, as predicted by simple theory.

EXPERIMENTAL RESULTS

Although it is clear that a spherical geometry would be optimum for pellet fusion, diagnostics on such a diode are difficult, as probes inside the diode affect the quantities to be measured. For this reason, a planar geometry was chosen in which to conduct the experiment. The first experiment was to determine how seriously well formation would be affected by electron losses due to edge effects in the finite planar geometry and by the plasma space charge. As shown in Fig. 2a, the 5 cm diameter oxide coated cathode is placed close ($< 1/4$ cm) to a 70% transmitting anode screen. The emission from the cathode is temperature limited to facilitate varying the injected current independent of the cathode to anode spacing; thus, the potential well beyond the anode screen is more or less independent of the real A-K gap conditions.

The anode is pulsed positive (600-2500v) and currents (0.05-2.5 amperes) are injected to establish the desired potential well (height and length). A simple moveable probe samples the current to the probe as a function of bias voltage at various distances to the right of the anode screen. The electrode labeled HC is biased slightly negative with respect to the cathode to reduce electron losses due to the three-dimensional fringing fields.

Figure 2b illustrates the two possible electrostatic solutions when the probe is biased to V_p . Case A represents the situation where there is insufficient net negative charge to produce a potential minimum. In this case, all of the injected current is transmitted to the probe, thus the electron densities are low and little ionic charge can be accelerated before the

net charge in the well is neutralized. In case B, virtually none of the injected electrons are transmitted to the probe and high net electronic space charge exists if: (1) the probe does not physically interrupt the electron orbits for $X \leq X_c$ or, (2) the probe does not draw sufficient current from the virtual cathode to become a predominant electron loss process.

To determine which potential shape exists, the probe is biased to draw a small amount of current from the virtual cathode. The current is held constant by adjusting the bias as the probe is moved toward the potential minimum. As exhibited in Fig. 3 in the hard vacuum case labeled $P = 4 \times 10^{-7}$ torr, the potential can be extrapolated to a distinct potential minimum which exists for X slightly less than 3 cm. In fact, at $X = 3$ cm, a probe potential of only two volts is required to draw the indicated current, thus showing that the probe is indeed close to the potential minimum and that the minimum is quite small. When the probe is moved inside the virtual cathode, the current to it increases sharply; therefore, measuring the potential well itself is impossible since condition 1 is violated. But the existence of a potential minimum is sufficient to show that a deep potential well is being generated. For the case studied here, the potential minimum should occur at $X_c = 2.45$ cm by the simple Langmuir law. This is in excellent agreement with the measured value and indicates that the losses of beam electrons are indeed low enough to approximate the 1-D analysis.

Beam ionization of the background pressure of helium gas generates ions which modify to the space charge of the original potential well. Notice that even with the ionization associated with pressures of 2×10^{-4} torr, the data in Fig. 3 indicate that a distinct

potential minimum exists. Thus the accelerating potential can be successfully generated in the finite device even with electron losses and a small amount of plasma space charge. Obviously, if the ionization is too high, the plasma short-circuits the space-charge field.

The energy deliverable to the ions by an electrostatic well is ultimately limited by the constraint that the well shape is altered so drastically that bunching cannot occur. Having shown the existence of a steady state potential well, it remains to study the dynamic properties of the well and the effect of excess plasma density on the acceleration properties. Figure 4 shows the schematic used to study the acceleration properties of the well by detecting the ion pulse. The probe was replaced with a moveable Faraday cage which was carefully constructed to insure sufficient high frequency response (< 3 ns rise time) to the pulse of charged particles. The area of this cage was small enough (~ 2 cm diameter) to sample the center of the ion flux accelerated by the potential well where edge effects should play little role. The anode was biased positive (~ 100 V) to provide a low energy, low current density beam of electrons which partially ionized the background gas and thus supplied the initial source of ions. The anode was pulsed positive (0.8 to 2 kV) for 300 ns (at 60 pps) to provide the electron current (~ 1 -2 amps) which establish the accelerating potential well. Two screens were placed just past the potential minimum to act as an electron mirror for the low energy electrons. The first screen was biased positive to that of the preionization anode, whereas the second screen was held at cathode potential. As indicated in Fig. 4, only the anode screen was pulsed

to the high potential. This system allowed a controlled and nearly uniform preionization region between the anode and the first screen. These screens also isolated the detection system from the pulsed electrode, thus reducing noise and the possibility of some plasma interaction of the probe with the diode region. Data taken with and without these screens indicate that the only difference is the range of initial plasma densities obtainable.

Figure 5 displays the variety of ion current pulse shapes detected as the plasma density is increased with the trace labeled 1, using the lowest preionization current and 4 using the highest value. The difference between Traces 1 and 2 implies an increased ion current associated with a higher plasma density, thus indicating almost identical potential wells which decrease smoothly and monotonically from the anode to the potential minimum. This is sketched in the insert of Fig. 5. As the ionization is increased, the plasma will not support the space charge fields; thus more electrons must be injected to the region to generate the accelerating potential. The effect of increased ionization on the well is to short circuit the initial portion of the well; therefore, the acceleration region moves to the right. Since the screens constrain the potential at a fixed value, only the top of the well is allowed to move as indicated by the curve labeled 3. The net effect is that the acceleration region moves toward the probe, shortening the effective drift distance to the probe, and thus the peak of the ion pulse shifts to earlier times as demonstrated in Trace 3. The potential well length is also being altered which decreases the volume or actual number of ions

available to be accelerated as evidenced by the lower pulse amplitude. Trace 4 shows much the same but more exaggerated behavior, but now the long tail on the current pulse is clearly evident. This behavior can be explained by allowing the acceleration region to move toward the anode after it has depleted the ions in its volume. It is clear from this experiment that although an excess ion density prevents optimum acceleration of the ions, a range does exist where the space charge can accelerate and preserve the potential shape necessary for bunching.

Having shown that ions can be accelerated by the space charge fields, let us now characterize the energy of the ejected ion beam. Figure 6 illustrates the timing relation between the injected electron beam current and the peak of the ion current pulse arriving at the probe. As the probe to anode distance is increased, the time of flight increases. Figure 7 shows the time of arrival of the peak of the ion current for a 1 KV pulse applied to the anode screen and indicates 735 volts ions. To determine the functional form of the ion energy dependence on injected electron energy, data was taken over the range of 600 v to 1500 v where it was found that ion energy was approximately 0.7 of the applied anode potential. This is close to the mean energy of $0.71 e V_a$ found in the approximate analysis of a planar well.

It is also evident from Fig. 6 that the ion pulse shape also changes with drift distance. This observation is consistent with the ions comprising the pulse having a distribution of velocities; a necessary requirement for bunching. Figure 8 is a graph of the width of the ion pulse as a function of the probe position. The ion pulse first narrows with distance and then becomes wider, thus demonstrating bunching of the ion pulse.

Other evidence for bunching can be found in the amplitudes of the detected ion current. In the steady state, the maximum ion current that can be emitted by the anode region is limited by Eq. (3).

$$\frac{J_i}{J_{eb}^+} \leq 2 \left(\frac{m}{M}\right)^{1/2} = .023 \text{ for He}^+ \text{ ions}$$

where J_{eb}^+ is defined in Fig. 1 as the one way injected electron current measured to the right of the anode screen. This equation differs from the classic Langmuir¹³ result $(m/M)^{1/2}$ because of the circulating electronic charge and the energy spread of the electrons. Further confirmation of bunching is obtained by experimental measurement of ion currents that exceed this ratio by a factor of five, thus bunching is occurring in the finite device in spite of the exceedingly large electron losses.

SUMMARY AND CONCLUSIONS

This series of experiments has shown that electronic space charge dominated potential wells could be formed in a finite planar experiment and in the presence of appreciable plasma density. Furthermore, we have shown that space charge field can accelerate the plasma ions to a significant fraction of the anode potential.

Most important is the observation that the ions can be bunched. With the proper geometry, bunching will increase the instantaneous power delivered by the neutralized beam to the target. Even though ion bunching has been demonstrated in this experiment, the power "amplification" is less than one.

We attribute this failure to the three dimensional characters of the experiment. Even though transverse electron losses were held to a minimum, ions are accelerated into roughly 2π steradians, and thus only a fraction is detected by the Faraday cage. This difficulty could be avoided by applying a strong longitudinal magnetic field,^{8,9} or by using the optimum geometry (spherical) for the experiment. This will be attempted in the near future.

However, we feel that the observed bunching has established the principle that the instantaneous power delivered by the ions to a target can be larger than the power delivered to the terminals of the device. Given this principle, one can do some elementary calculations to estimate the bunching required to utilize existing technology for ion pellet fusion.

If one ignores the anode dissipation due to the collection of low energy plasma electrons, and the energy carried by the neutralizing electrons beyond X_c , then the energy supplied to the A-K terminal of Fig. 1 is given by:

$$W_{IN} = \left(\frac{1-\eta^2}{\eta} \right) J_{eb}^+ V_A \tau_p + J_i \langle V_i \rangle \tau_p \quad (4)$$

The first term of Eq. (5) represents the useless dissipation of the electron beam energy at the anode; the last term is the useful energy carried by the ions accelerated to the region beyond X_c with a mean energy $\langle V_i \rangle \sim 0.7 V_A$ for the time of the anode pumping pulse τ_p . If we assumed that $J_i/J_{eb}^+ = 2 (m/M)^{1/2}$ for bipolar flow, and that the ions arrive at the target within a time Δt centered around the mean arrival time, then the power amplification is:

$$\frac{P_{(ions)}}{P_{INPUT}} = \frac{2(m/M)^{1/2}}{(1-\eta^2)/\eta + 2(m/M)^{1/2}\langle V_i \rangle/V_A} \cdot \frac{\langle V_i \rangle}{V_A} \cdot \frac{\tau_p}{\Delta t} \quad (5)$$

Equation (6) emphasizes the importance of keeping the electron losses low by making the anode as transparent as possible ($\eta \rightarrow 1$). The equation also points out the importance of making the bunch time Δt very short compared to the time the energy is supplied to the system.

Although our experiments were performed at low energies, the bunching results imply that power amplification is possible in the regime envisioned for ion-pellet fusion. Such an extra-

polarization requires considerable faith, but space charge laws are well established, justifying such a belief. Operation at higher voltages should enhance the trends indicated here, as higher beam densities will allow higher, more easily attainable and controllable plasma densities and real gas effects such as charge exchange¹⁴ will be unimportant in scaled devices.

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- Fig. 1. Conceptual representation of the planar model. (a) Plasma location with respect to real cathode and transparent anode; (b) Potential variation with plasma fixed in space; (c) Spatial electron current distribution; (d) Spatial ion current distribution; (e) Plasma electron orbits through the transparent anode.
- Fig. 2. (a) Apparatus for the planar experiment. The grounded 5 cm diameter cathode emits electrons through the positively pulsed screen into the cylindrical electrode (HC). A moveable probe collects the transmitted electrons; (b) Potential shapes of system. The state A transmits the injected electrons while state B reflects most of the injected electrons from the virtual cathode.
- Fig. 3. Spatial variation of probe bias required to draw 5 ma from virtual cathode. Beam ionization of the Helium gas changes the transmission properties of the potential minimum.
- Fig. 4. Experimental setup for ion acceleration. The double screen assembly reflects the low current DC beam to improve ionization in the acceleration region. The moveable Faraday cage detects the pulse of ions accelerated when the anode is pulsed positive $\sim 1-2$ KV.
- Fig. 5. Variation of the ion pulse shape with initial plasma density in acceleration region. Trace 1 results from lowest preionization and trace 4 from highest. The insets qualitatively describe the effect of plasma density on the accelerating potential shape.

Fig. 6. Variation of ion current pulse with probe position.

The arrival time of the pulse peak and width of the probe both vary with drift distance.

Fig. 7. Time of arrival at ion pulse vs drift distance. Data shown for 1 KV anode pulse and represents 735 volt ions. Ion energy found to be ~ 0.75 of the applied potential over the range of 600-1500v anode voltage.

Fig. 8. Ion pulse width variation with drift distance. The pulse width changes indicate that the ions have a distribution of energies as predicted by the simple theory of bunching.⁽⁷⁾

REAL CATHODE TRANSPARENT ANODE

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