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ACCELERATION MECHANISMS IN SINGLE AND MULTIPLE STAGE COLLECTIVE VACUUM DIODES†

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SUMMARY

Experimental measurements and numerical simulations are presented for a single stage vacuum diode collective accelerator in the geometry developed by Luce.[1] The acceleration experiment and diagnostics are shown in figure 1. Experimental results include measurement of a 5-10KA, 7.5MeV proton pulse with a driving electron beam of 55KA and 3.2MeV. The ion beam energy distribution is bunched at the peak energy but extends down to the e beam energy level. A few percent of the ions reach very high energies ($\sim$10E_e, E_e is the REB energy).

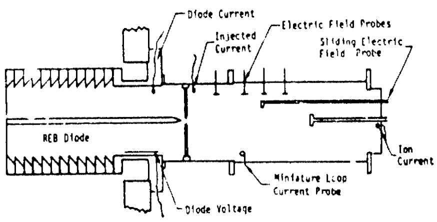

Figure 1. Collective acceleration experiment & diagnostics

One-dimensional particle simulation for both zero and finite risetime electron beams indicate that the ion velocity distributions quickly reach a saturated peak value equivalent to $\sim$2E_e. As the simulation continues ions are accelerated to fill the distribution between 1-2E_e. The space charge potential[2] decays to roughly the beam potential before the ions are accelerated to high energy indicating that the principle acceleration mechanism is a moving space charge well.

Progress in the design of a multiple stage collective accelerator[3] is reported. The operational concept of multistaging is shown in figure 2. A high current proton pulse formed at the first anode flows coaxially through each downstream REB diode. The staging pulsers are timed to fire sequentially, in phase with the ion bunch arrival. The critical issue of the phase stability of a drifting ion bunch with the REB space charge wave was examined with the simulation code. In the calculation the highest energy gain was $\sim$3-4E_e with the bulk of the distribution gaining $\sim$1E_e. Phase mixing tends to smooth oscillatory acceleration fields at the anode to produce a continuous proton density distribution.

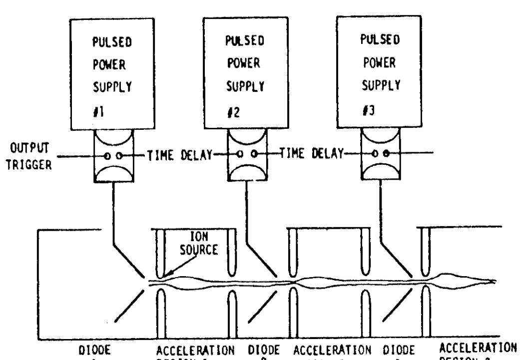

Figure 2. Multistage accelerator concept

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NUMERICAL SIMULATION

Using a finite-size one-dimensional, self-consistent, electrostatic, relativistic particle-in-cell code[4,5], we have performed computer simulations of ion acceleration using both zero and finite risetime electron beams. The configuration is a parallel plane geometry with the potential set to zero on both boundaries. The first two cells are filled with an ideal perfectly conducting anode plasma and enough ion charge is emitted at the plasma-vacuum interface to reduce the local electrostatic field to about zero. This method of ion emission has been used in electron beam diode simulations[6,7] and is useful for time-dependent simulations. The potential is obtained by solving Poisson's equation. Self-consistent fields are used to move the macroparticles and the full proton/electron mass ratio is used. The code parameters are: cell size = 0.1 relativistic electron Debye lengths, time step = 0.005 electron beam plasma periods, grid length = 192 cells, 2000 to 6000 particles. The injected electron density $n_0 = 1.62 \times 10^{13}$ cm^{-3}. The electron velocity $v_0 = \beta_0 c = .99c$. The one-dimensional approximation is valid only for beam displacement L less than $\sim$3cm. This follows from the restrictions that $r_b > c/\omega_b$ and $L << R/2$, where r_b is the beam radius, c is the speed of light, ω_b is the electron beam plasma frequency, and R is the cylindrical drift tube radius. In this region electron reflection lowers the net current so that inductive electric and self-magnetic fields are small.

First, we simulate a zero-risetime, 3.11MeV electron beam and emit the ions with zero velocity from the anode plasma. The potential well depth reaches 2.25 times the injected electron energy in 0.20nsec, then collapses. At this time, the peak proton energy is 1.45MeV. The virtual cathode quickly fills with ions until the ion emission is momentarily cut off due to the near charge neutrality condition. The ions at the beam head slow in the near-zero field while the trailing ions, in a stronger field, migrate upwards in phase space causing axial bunching. The increased ion space charge allows the well to move in front of the ion beam head. This early bunch moves away and another bunch is emitted.

The solid curve in figure 3 represents the zero-risetime results for the ion density and velocity distribution at 1.24nsec. The first two ion bunches are observed to coaslesce at Z = 1.75cm, while a third ion bunch is being accelerated out of the anode plasma forming a dense sheath. The ion velocity distribution (crosshatched) shows the bulk of the protons are 2.35MeV, $(E_i/E_e) = 0.76$, and the tail out to 7.57MeV $(E_i/E_e) = 2.43$.

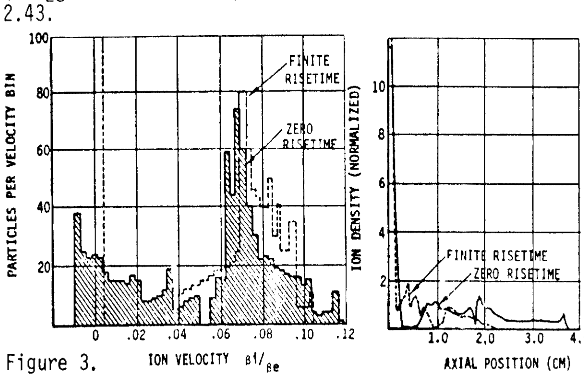

Figure 3.

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The second case considered a beam with a finite risetime equivalent to several beam plasma periods. A 0.75nsec linear risetime, 3.11MeV electron beam was used. Here, the peak well depth is only 2.00 times the injected electron energy, then collapses to about the beam energy. The dashed curves of figure 3 show ion density and velocity at 1.24nsec. The first ion bunch has a linear density increase followed by a second bunch with an oscillatory profile. The ion velocity distribution shows a bulk with energy at 2.49MeV, $(E_i/\varepsilon_e) = 0.80$, with a tail out to 4.85MeV, $(E_i/\varepsilon_e) = 1.88$. The distribution is noticeably more filled in towards the high energy end than the zero risetime case.

Figure 4 shows the time history of the potential minimum for the finite-risetime case. Notice the quick well collapse followed by beam electron plasma oscillations. The low frequency modulation beginning at 0.5nsec is coincident with ion beam moving out and the modulation frequency appears to be between the electron beam and ion plasma frequencies.

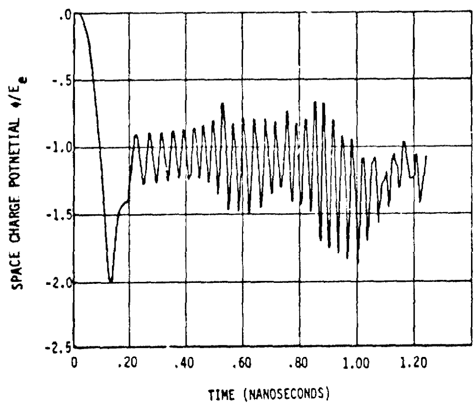

Figure 4. Potential for finite risetime e-beam

In the third case, a mono-energetic zero-risetime 5.84MeV proton beam is injected along with a zero-risetime 3.11MeV electron beam to simulate a second accelerator stage. Early in time, the ion beam head causes virtual anode formation, resulting in a break of the ion phase space. The beam ions continue to accelerate and propagate but the ion density profile is very oscillatory. Phase mixing tends to smooth out this effect. Figure 5 shows the ion velocity distribution at 0.329nsec (cross-hatched) and at 0.458nsec. As can be observed, the bulk proton energy gain increases from 6.4 to 8.2MeV while the tail of the distribution stays peaked at 17.8MeV. This represents a proton energy gain for the bulk of about E_e while the tail gains 3-4 E_e.

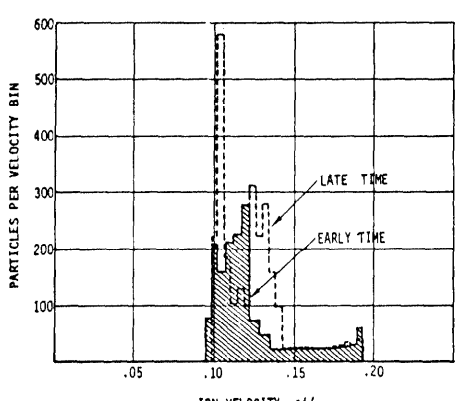

Figure 5. Ion velocity distribution, staging diode

EXPERIMENT

The collective acceleration experiment was performed on the Boeing FX-75 accelerator, a 12KJ coaxial line pulser. The electron and ion beam parameters are given in the table below:

CHARGE VOLTAGE	CATHODE VOLTAGE (MV)	REB CURRENT (kA)	PROTON ENERGY (MeV)	E_p/V_c
3 MV	1.42	29.2	4.3	3.0
4 MV	1.96	38.6	5.5	2.8
5 MV	2.78	47.7	7.0	2.5
6 MV	3.24	55.4	7.5	2.3

The proton energies here are the peak energy of the propagating high current ion pulse and are determined by time of flight. The typical proton pulse waveform is shown in figure 6. Pulse spreading in propagation

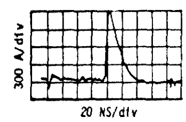

Figure 6. Proton current pulse, collimated detector, 1 meter

is approximately 10nsec/m indicating an energy spread up to 50% for some of the ions. The pulse retains the characteristic sharp risetime and high current in the first 10 nanoseconds indicating a bunched distribution at the high energy. The beam current measurements are made with Faraday cup that employs a magnetic separator and collimator that admits ∿20% of the full proton beam as measured by nuclear activation. The Faraday cup net currents are 1-2kA indicating a full ion current of 5-10kA. This current is in agreement with a formulation for equilibrium ion current for full charge neutrality in the region between the anode and the space charge head.

$$I_i = \frac{\beta i}{\beta e} I_e$$

I_i, I_e are the ion and electron currents $\beta_i c$, $\beta_e c$ are ion and electron velocities.

The charge neutral equilibrium synchronizes the beamfront to the ion speed. Figure 7 shows the motion of the leading edge of the propagating electron beam as the REB pulse turns on. The data indicate that free propagation of the electron beam was cut off and front motion continued to accelerate for the full risetime of the REB pulse, 10nsec.

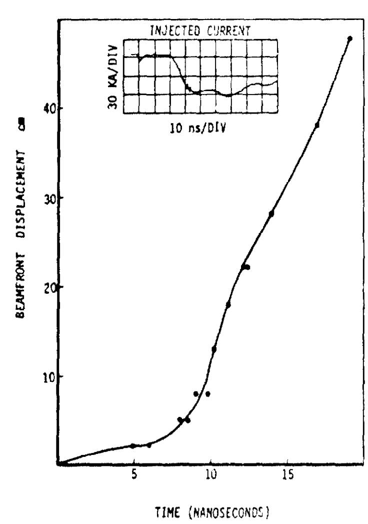

Figure 7. Beamfront displacement

The total beam energy spectral distribution contains a few ions at very high energy. These are evident in a spectrum mathematically unfolded from nuclear activation stack data, figure 8. The high energy ions are evident only at distances of tens of centimeters from the anode. At these distances a low current fraction of the electron beamfront is observed to propagate away from the bulk at times after the REB pulse has flattened out. This low current breakaway is observed in the current density data in figure 8. The number of high energy ions is roughly that required for force neutral propagation of this fraction of the electron beam. The ion current, then, is reduced by $1/\gamma_e^2$, making this high energy mechanism very inefficient.

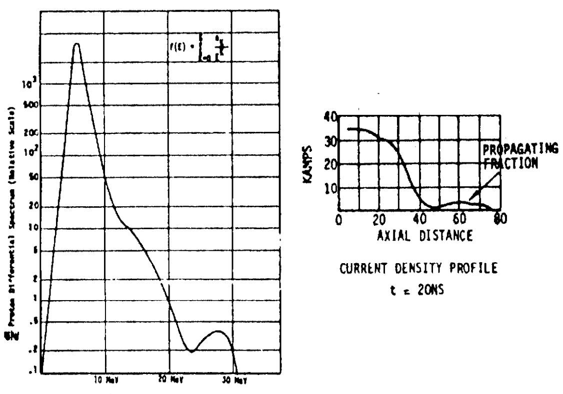

Figure 8. Proton spectral distribution

MULTISTAGE DIODE PERFORMANCE

An electrode design for the radial power entry staging diode has been fabricated and tested on the FX-75.

The efficiency of energy delivered to the anode was 43% of the FX-75 stored energy. In figure 9 these data are compared with an efficiency of 70% for the conventional cathode. The impedance remained constant within 20% throughout the power pulse. The collectively accelerated proton fluence has been mapped. A beam profile taken at 60cm axial displacement, figure 9, was obtained by autoradiographic imaging of an activated copper target. The total flux is estimated to be 10^{13} particles with an average energy of 5-8MeV.

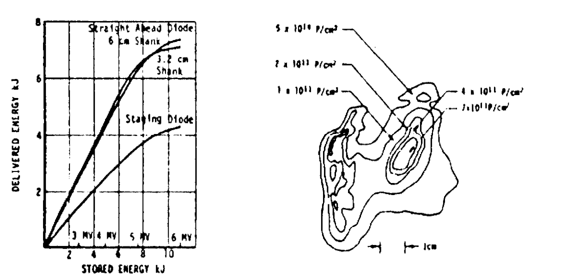

Figure 9. Staging cathode performance test data

CONCLUSIONS

Acceleration in collective diodes is apparently due to a traveling space charge potential with phase stability provided by the requirement for nearly full charge neutrality in the region between the source and beamhead. The code and experiment both show the ion spectral spread from 1-2 E_0. The measured distribution is more concentrated at the high end and this may be due to the much longer acceleration time (10ns vs. 1.5ns) in the physical experiment. Measured ion currents are consistent with the ion density required for a near neutral acceleration column.

The code results for the interaction between a drifting beam entering a pulsed diode show strong energy gain mechanism. Oscillations at the anode are damped by phase mixing as charge densities equilibrate to provide a continuous ion current.

The observation of a full cut off of electron propagation during the REB risetime and the strong coupling of well motion to ion speed may enable a phase stable interaction in multiple stages.

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