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SCALING STUDIES OF COLLECTIVE ION ACCELERATION WITH INTENSE RELATIVISTIC ELECTRON BEAMS

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Summary

Recent experimental observations[1] of collective ion acceleration produced when an intense relativistic electron beam was injected into a low pressure neutral gas have firmly established a threshold beam current for the process which was predicted by Olson[2]; for this geometry ion acceleration does not occur unless the electron beam current (I) exceeds the space-charge limiting current (I_ℓ). In this paper we report additional observations of ion acceleration obtained in two series of experiments. In the first series, the guide tube and diode were configured to provide a large ratio of injected beam current to space charge limiting current, and drift tube endplate effects were examined. When the separation between the anode and tube endplate become less than the drift tube diameter the efficiency of the collective acceleration process is strongly reduced. In the second series of experiments the scaling of accelerated ion energy with electron beam kinetic energy was investigated using two electron beam machines which differ in stored energy by a factor of approximately 20. Using the larger machine proton energies in excess of 16.5 MeV have been attained. In addition, we also present an expression for the optimum pressure for ion acceleration in the drifting beam neutral gas geometry.

Introduction

The electron beam machine used in the first series of experiments has been described earlier.[1] For a dc charge of 3MV, the mean electron beam kinetic energy is approximately 2.3 MeV, while the peak beam current entering the drift tube is typically 15-20 kA. The total pulsewidth is approximately 45 nsec, with fast voltage and current risetimes of 6-10 nsec. In the second series of experiments using the larger machine dc charged to 8 MV, two different diode configurations have provided typical beam parameters of 5 MeV electrons with a peak current of 40 kA, and 3 MeV electrons with a peak current of 55 kA. The pulse width (FWHM) is 125 nsec with a risetime of 20 nsec.

The electron beam radial profile, as determined from damage patterns which appear in the anode foil, is predominately that of a thin annulus. A convenient approximate expression for the space charge limiting current of a moderately relativistic annular electron beam is[3]

$$I_\ell = \frac{(\gamma^{2/3}-1)^{3/2}(mc^3/e)(1-f_e)^{-1}}{\{1-2[(r_1^2\ \ln(r_2/r_1))/(r_2^2-r_1^2)]+2\ \ln(R/r_2)\}} \quad (1)$$

where r_1 and r_2 are the inner and outer radii of the annulus, $(\gamma-1)$ is the electron kinetic energy in units of rest mass energy mc^2, e is the electron charge, R is the radius of the drift tube, and f_e denotes the fractional space charge neutralization. For a thin annulus and $r_2 \ll R$, Equation (1) reduces to

$$I_\ell \simeq \frac{(\gamma^{2/3}-1)^{3/2}\ mc^3/e}{2\ \ln\ (R/r_2)}\ (1-f_e)^{-1} \quad (2)$$

For a given machine and diode configuration, changes in I_ℓ were effected by varying (R/r_2). The ratio of the peak beam current to the initial space charge limiting current (f_e=0) is designated $I_o/I_{\ell o}$.

Both hydrogen and deuterium have been used as the drift tube fill gas. The detection and analysis of the accelerated deuterons were performed with thick carbon target foils which demonstrated the existence of energetic deuterons through the $C^{12}(d,n)N^{13}$ reaction (Q value of -0.28 MeV). Accelerated protons were detected with copper foil activation through the $Cu^{63}(p,n)Zn^{63}$ reaction, which has a Q value of -4.2 MeV, the $Be^9(p,n)B^9$ reaction with a Q value of -1.85 MeV, and the $Ti^{47}(p,n)V^{47}$ reaction with a Q value of -3.7 MeV. Thick target activity was measured for numbers of layers of absorber foils placed over the targets. With range-energy and stopping power relations[4] and total cross-section as a function of energy[5-7], it was possible to obtain accelerated ion yields and approximate ion energy spectra.

Drift Tube Endplate Effects

For the first series of experiments Table 1 presents a summary of the new results and a comparison with previous results using deuterium as the fill gas. Although the previously observed scaling laws[1] were apparently violated, the discrepancy is readily understood. For each of the previous cases, the ratio of the drift tube length to drift tube radius (L/R) was always greater than or equal to 5. For the new series, however, (L/R) was only 1.6. To test the effect of having an anode to endplate separation less than 2R, the system was reconfigured to the $I_o/I_{\ell o}$ = 2.2 geometry, but with a movable drift tube endplate. The observed activity of carbon targets centered on

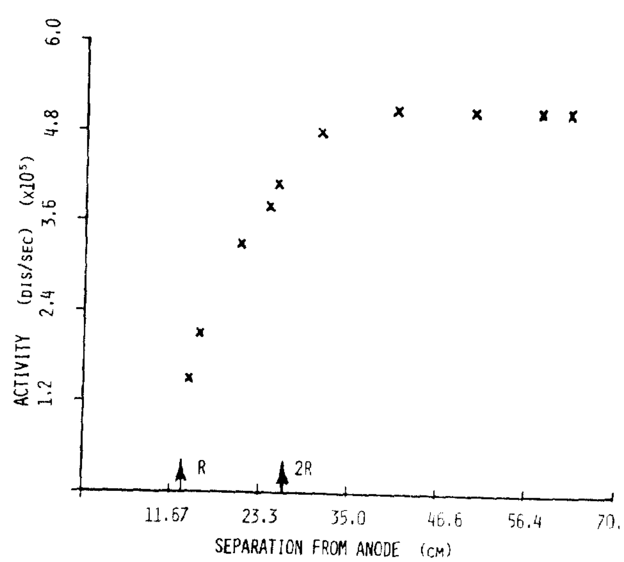

Figure 1. Carbon target activity as a function of anode-endplate separation for E_e = 2.3 MeV, $I_o/I_{\ell o}$ = 2.2 The deuterium pressure was 260 mTorr.

Table 1. Summary of Experimental Results (Deuterium)

Ratio of Drift Tube and e^- Beam Radii R/r_b	Ratio of Injected Current to Limiting Current $I_o/I_{\ell o}$	Maximum Ion Beam Energy on Target (joules)	Average Ion Energy at Maximum Beam Energy (MeV)
2	0.54	---	<0.3
4	0.86	---	<0.3
8	1.2	$\sim 2\times10^{-3}$	~ 1
10	1.3	3×10^{-2}	1.6
20	1.6	~0.2	~2.3
42	2.2	2.9	3.1
*167	2.8	1.9	2.8

*New data.

the conducting endplate is plotted as a function of endplate separation from the anode in Figure 1. Assuming that target activity is an approximate measure of the efficiency of the acceleration process, we interpret the rapid decrease in target activity for separation distances less than 2R to be due to a decrease in both the axial extent and depth of the initial, stationary well.

The effect of reduced anode-endplate separation on the axial shape of the potential well can be predicted qualitatively.* In the context of the Olson model, if the injected current exceeds the space charge limiting current, the beam stops axially and blows up radially forming an initial deep stationary well. When $L/R \gg 1$, in front of the stopped beam the well depth on axis decreases in an approximately exponential fashion with characteristic decay length[2] of R/λ_1 (λ_1 is the first zero of the J_o Bessel function). When $L \simeq R$, however, the potential well depth on axis decreases approximately as

$$e\phi(0,Z) \propto \exp(-\lambda_1 Z/R)[1-\exp(-2\lambda_1(L-Z)/R] \qquad (3)$$

The well length (L_1) of interest is the minimum axial distance for which ions accelerated in the well can still cause appreciable ionization, and is given approximately by the well depth which corresponds to the ion energy at which charge exchange collisions predominate[2]. The approximate dependence of the well length is displayed in Figure 2 as a function of the anode-endplate separation. For ($L/R > 2$, L_1 is approximately 2R, while for $(L/R) < 2$, L_1 is approximately equal to L.

Autoradiographs taken by placing an activated carbon target directly over a piece of Type 57 Polaroid film are presented for several values of L/R in Figure 3. The radial diffusion of the ion bunch is probably due to ion scattering events in addition to a radial ion velocity component imparted by the two-dimensional stationary potential well.

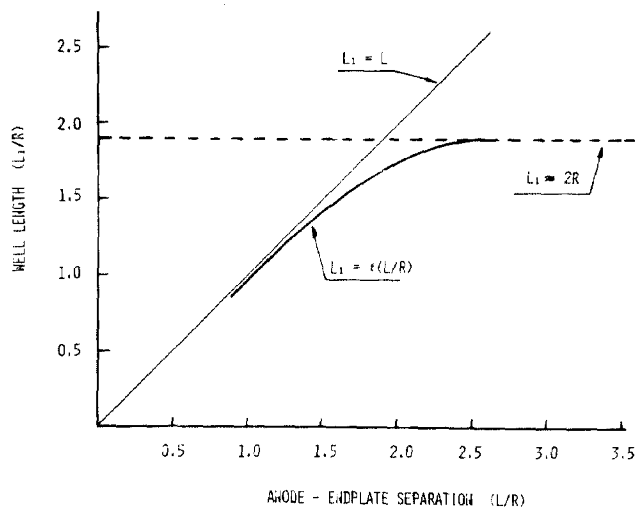

Figure 2. Potential well length, L_1/R, as a function of anode-endplate separation, L/R.

Accelerated Proton Energy Spectra

By unfolding absorber foil activation data we have been able to determine approximate accelerated ion energy spectra. In Figure 4 the accelerated proton spectrum obtained with the larger electron beam machine in the higher diode impedance configuration is compared with the proton specturm obtained using the smaller machine with the $I_o/I_{\ell o} = 2.2$ geometry. Both spectra were taken at the experimentally determined optimum pressure for total target activation. The spectra are normalized such that the area enclosed is

*The argument presented is strictly valid for $R/r_b \leq 6$, but should be qualitatively correct for larger values of R/r_b.

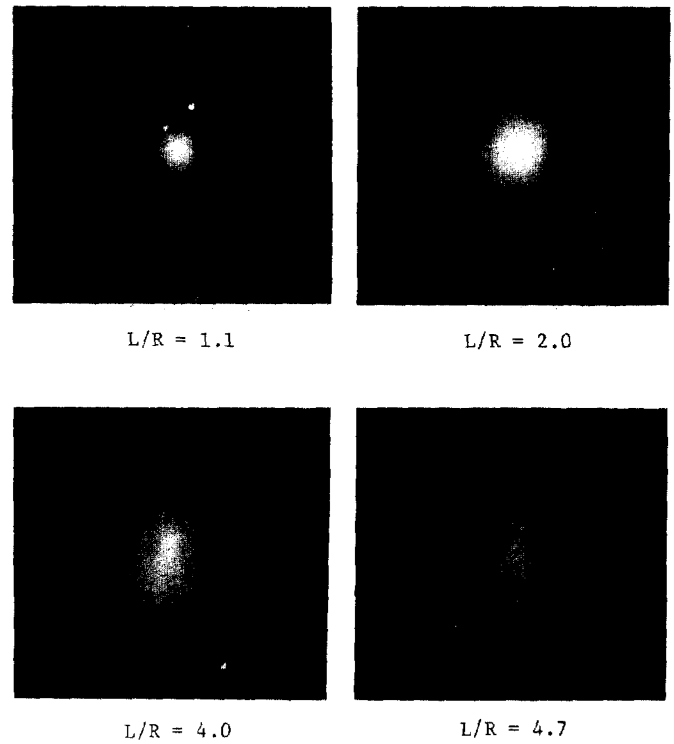

Figure 3. Four "autoradiographs" for increasing L/R ratios for the same beam parameters stated in Figure 1. The exposure time was one hour.

unity. When the abscissa of the graph is the ratio of the proton energy to the average electron beam kinetic energy E_e, we note good correspondence between the two spectra.

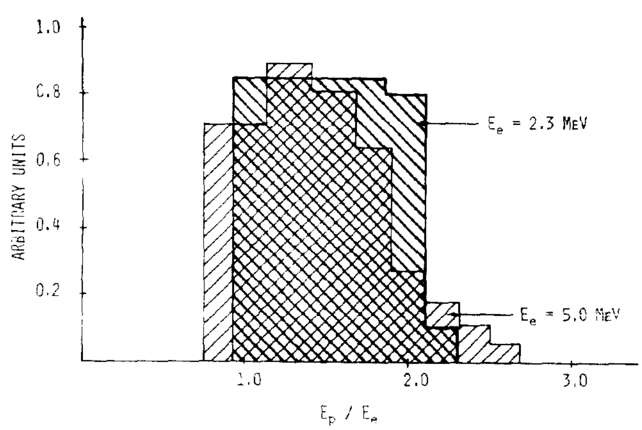

Figure 4. Normalized proton energy spectra for two electron beam mean kinetic energies.

The maximum proton energies in these experiments were obtained from the 8 MV electron beam machine with the 5 MeV, 40 kA beam. A minimum of 2×10^8 protons with energy in excess of 16.5 MeV exists in the ion pulse based on the detection of ~1 - 2 x 10^5 atoms of Zn^{63} in copper foils placed behind 0.020 in (5.1 x 10^{-2} cm) of copper absorber foils.

Optimum Neutral Gas Pressure For Collective Acceleration

Both in previous experiments[1] and in the present series, we have noted an increase associated with the optimum number of accelerated ions with an increase in the parameter $I_o/I_{\ell o}$ for a given machine. Qualitatively, the optimum pressure p_o should be somewhat less than the maximum pressure at which the maximum number of ions are created before the deep stationary potential well begins to move.

The criterion for beam stopping and deep well formation is $I(t) \geq I_\ell(t)$. Writing Eq. (1) as $I_\ell(t) = I_{\ell o}[1 - f_e(t)]^{-1}$ we have

$$I(t) \geq I_{\ell o}[1 - f_e(t)]^{-1} \tag{4}$$

For times before the beam stops the most important ionization process is electron impact ionization, and the background ion density $n_i(t)$ is simply described by[8]

$$\frac{dn_i(t)}{dt} = \frac{n_b(t)}{\tau_e} \tag{5}$$

where $n_b(t)$ represents the electron beam density and τ_e is the electron impact ionization time. For H_2[8]

$$\tau \simeq 5.0[p(\text{torr})]^{-1}\text{ns} \tag{6}$$

Assuming that both $n_b(t)$ and $I(t)$ increase linearly according to

$$n_b(t) = n_b t/t_r \qquad I(t) = I_o t/t_r \qquad (\text{for } t \leq t_r) \tag{7}$$

then $f_e(t) = t/2\tau_e$, and Eq. (4) becomes

$$I_o t/t_r \geq I_{\ell o}[1 - t/2\tau_e]^{-1} \tag{8}$$

Assuming equality, Eq. (8) has two roots given by

$$t_\pm = \tau_e[1 \pm \sqrt{1 - 2(t_r I_{\ell o}/\tau_e I_o)}] \tag{9}$$

t_- corresponds to the onset on beam stopping and well formation. If electron impact were the only important ionization process during the time of existence of the deep well, t_+ would correspond to the beam propagation time; however, when the beam is in its stopped state, ionization of the background gas may occur by an effective ion avalanche process[8], and Eq. (5) is incorrect. Consequently, for $t > t_-$, $f_e(t) \neq t/2\tau_e$.

If the stopped beam condition is to be reached, we must have $t_r > t_-$, which implies

$$t_r < \tau_e (1 - I_{\ell o}/I_o) \tag{10}$$

or, from Eq. (6) for H_2 (and D_2), $p(\text{torr}) < [5.0(1 - I_{\ell o}/I_o)/t_r]$, and the optimum pressure is then given by

$$p_o(\text{torr}) \leq 5.0(1 - I_{\ell o}/I_o)/t_r \tag{11}$$

where the units of t_r are nanoseconds. A comparison of the experimentally determined optimum pressure and the optimum pressure given by Eq. (11) is presented in Table 2. The agreement is very good.

Acknowledgments

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Table 2. Optimum Pressure for Collective Acceleration

Ratio of Injected Current to Limiting Current $I_o/I_{\ell o}$	Electron Beam Current Risetime t_r (nsec)	Fill Gas	Calculated Optimum Pressure p_o (mTorr)	Experimentally Determined Optimum Pressure (mTorr)
1.2	10	D_2	83	60
1.3	10	D_2	115	100
1.6	10	D_2	188	200
2.2	10	D_2	272	250
2.2	10	H_2	272	250
1.7	20	D_2	103	120
4.1	20	D_2	189	200

References

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1. D. C. Straw and R. B. Miller, Appl. Phys. Lett., 25, 379 (1974).

2. C. L. Olson, Sandia Laboratory Report No. SLA-74-0235, (1974). (To be published in Physics of Fluids.)

3. R. B. Miller, Air Force Weapons Laboratory Report No. AFWL-DYS-TN-74-108, (1974) (unpublished).

4. M. Rich and R. Madey, Lawrence Berkeley Laboratory Report No. UCRL-2301, (1954) (unpublished).

5. Von K. Wohlleben and E. Schuster, Radiochim. Acta 8, 78 (1967).

6. J. Wing and J. R. Huizenga, Phys. Rev. 128, 280 (1962).

7. H. Taketani and W. P. Alford, Phys. Rev. 125, 291 (1962)

8. C. L. Olson, Sandia Laboratory Report No. SLA-74-0327, (1974). (To be published in Physics of Fluids.)