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# COLLECTIVE ION ACCELERATION CONTROLLED BY A GAS GRADIENT

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## Abstract

Energetic alpha particles are observed when an intense relativistic electron beam is injected into a decreasing pressure profile of helium gas. In a 7 kG external magnetic field up to $10^{10}$ 9 MeV alpha particles are detected on cellulose nitrate. By viewing the electron beam as an expanding "gas" of reflecting electrons the corresponding ion distribution is calculated and compared to the measured distribution. Good agreement in these results supports the reflecting beam model of Ryutov.


## 1. Introduction

Graybill and Uglum[1] appear to have first studied collective field acceleration of positive ions due to a relativistic electron beam. The beam was injected into a drift chamber which was uniformly filled with a neutral gas.

Many other experiments[2-5] and theories[6,7,9] have followed and extended this initial investigation. We present experimental results for the case when the external magnetic field is large enough to radially confine the beam.[8] The results are compared with an extended version of the theory proposed by Ryutov.[9]

In this theory, a beam of electrons is confined radially by an external magnetic field. Axially the beam density is confined and allowed to multiply by reflecting alternatively off the cathode and virtual cathode as it passes through a dense plasma filled volume. Ions are accelerated out of the plasma front by the expanding electron "gas."

## 2. Apparatus

Figure 1 depicts the geometry and diagnostic locations used in the experiment. This figure represents a cross-sectional view of a cylindrical system.

In order to obtain a pressure gradient in the large vacuum chamber, where we require the pressure to be high enough to allow full beam propagation, a fast valve was developed.[10] The vacuum chamber is electrically grounded and made of stainless steel. The beam is formed from a graphite cathode (5 cm dia.) and is injected through a 1 mil thick titanium anode foil. The dashed lines represent the path of the beam.

In this experiment the diode injection conditions were 0.8 MV, 65-70 kA and 60 ns (FWHM). The beam is 5 cm in diameter. Cellulose nitrate film[11] was used to measure the ion energy and number.

## 3. Experimental Results

Figure 2 is a plot of the maximum helium ion energy against delay time. Delay time is defined to be the time that gas is allowed to enter the vacuum chamber before the beam is injected. Figure 3 translates delay time into pressure profile. The number of ions at each point is about $10^{10}$ (300-1350 μs). This number is measured at 1.7 meters from the anode over the entire cross-sectional area of the chamber (~300 cm$^2$).

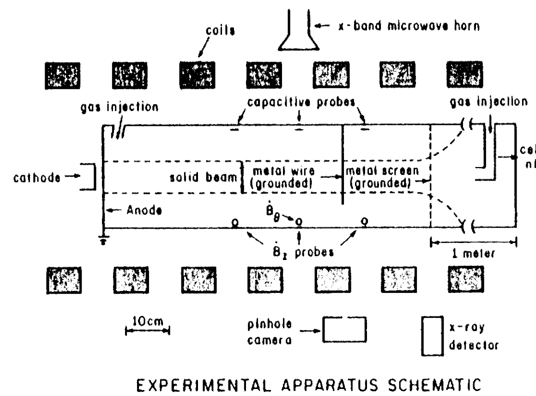


Figure 1. Schematic of experimental set-up.

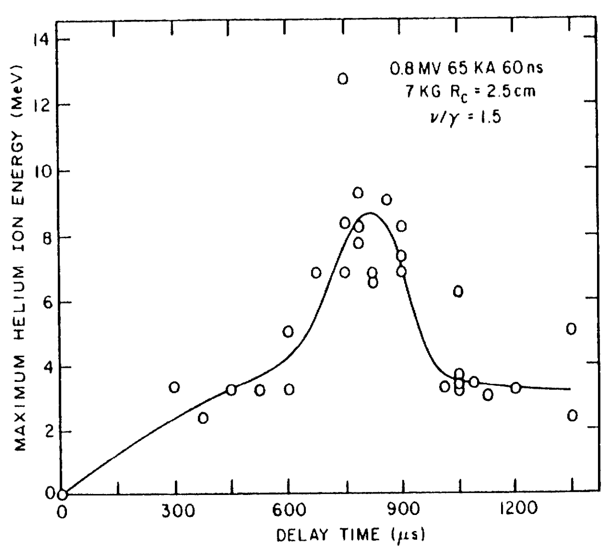


Figure 2. Maximum helium ion energy vs delay time. Each point above 300 μs contains about $10^{10}$ ions.

For delay times greater than 1050 μs the pressure is to high over most of the chamber. This results in



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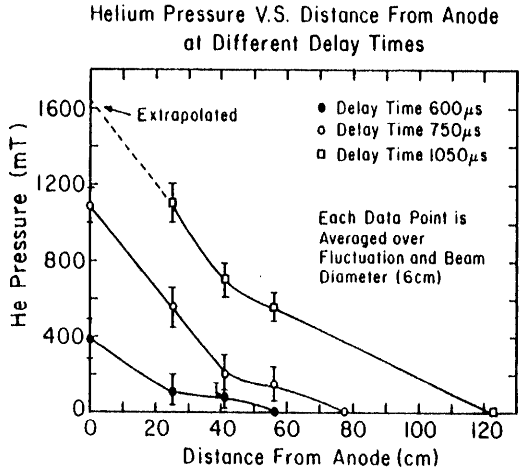



Figure 3. The helium pressure vs distance from anode at three different delay times.

full beam propagation. The forward acceleration of the beam front is too rapid to retain ions.

For delay times below 600 μs only the vacuum limit beam is allowed to propagate. In this region the potential well motion is inhibited by the lack of charge neutralization. Figure 4 illustrates these beam transmission properties.

Under the conditions of maximum ion energy which occurs near 800 μs, most of the transmitted beam is composed of electrons with an energy below 300 keV. A faraday cup covered with titanium foil is used for beam energy and transmission measurements. The foil is used as an energy filter.

The implication being that electrons are axially trapped between the cathode and virtual cathode. These electrons are forced to reflex many times through the anode foil and induced plasma which results in the loss of electron energy parallel to the magnetic field lines.

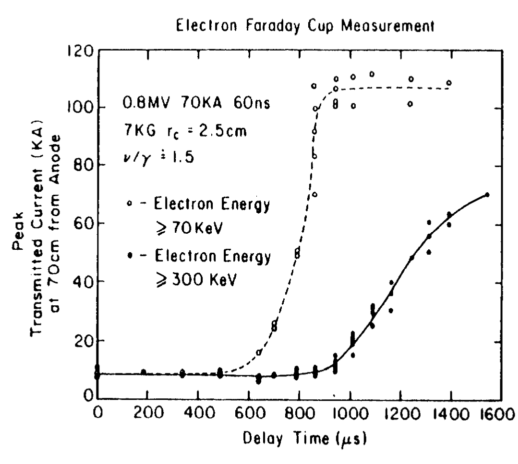



Figure 4. Transmitted beam current vs delay time at different energies.

A simple demonstration of the electrons reflecting is shown by increasing the anode thickness from 1 to 3 mil titanium. This reduces the transmitted low energy (~300 keV) electron current (Figure 5).

## 4. Theory

The present model extends that of Ryutov[9] by including a description of the potential-electron density relation based on measurements of the transmitted beam current. This model is applicable to the experiment at a delay time of 750-800 μs. Referring to Figure 3. This is so if we consider that the neutral gas from the anode out to 40 cm is a plasma during most of the beam plus length. And by also considering that very little ionization of the gas occurs after a distance of 40 cm from the anode.

We will use a fluid description for the ions:

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial z}(v_i n_i) = 0 \tag{1}$$

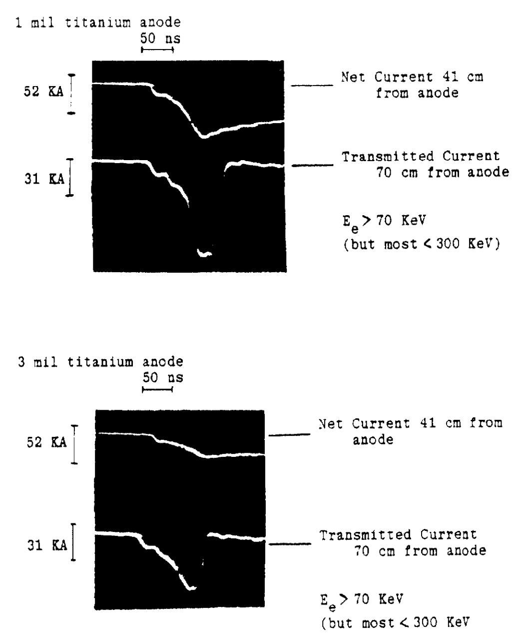
$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial z} = -\frac{q}{M}\frac{\partial \phi}{\partial z} \tag{2}$$

where $v_i$, $n_i$ are the ion velocity and density, respectively, $q$, $M$ are the ion charge and mass, respectively. $\phi$ is the electrostatic potential, $z$ is the axial position coordinate with its origin at the plasma front, $t$ is the time coordinate.

Equations (1) and (2) will be closed by the potential-electron density relation and the assumption of quasi-neutrality.

By making use of a generalized form for the definition of current density, which allows for currents of different energy,

$$n_e = \frac{-2}{e}\int \frac{(dJ/dE)\ dE}{v} \tag{3}$$




Note: Delay Time 863 μs Helium

Figure 5. Reduction of low energy reflexing electrons by increasing anode thickness.

the potential-density can then be determined.

Where e is the electron charge, E is the parallel (to the magnetic field lines) electron energy, v is parallel electron velocity, J(E) is the current density with electron energy E. The factor of 2 accounts for total reflection of the electron density.

From the two data points for the transmitted current at 800 μs (Figure 4), the shape of J(E) is strongly suggested. This data and assuming J(E) is monatonic is used to construct J(E).

We will assume that J(E) has the following form:

$$J(E) = J(0)\left[1 - \frac{E}{E_{max}}\right]^{\alpha} , \quad (4)$$

where $J = I/A$, I(E) is the transmitted current and A is the cross-sectional area of the beam. α is determined by picking I = 8 kA at 300 keV. This gives $\alpha \simeq 3.4$.

By using the non-relativistic energy conservation relation for electrons and substituting Eq. (4) in (3), the integration can be completed.

$$n_e = n_o(1 + \phi/\phi_o)^{5/2} , \quad (5)$$

where $n_o = \frac{16}{5} \frac{I(0)}{eA} \sqrt{\frac{2m}{E_{max}}}$

and $\phi_o$ is the cathode potential, m is the electron mass. To simplify the integration $\alpha = 3$ was used.

We will now determine the self-similar solution of Eqs. (1), (2), and (5) by making use of the definitions,

$$U \equiv v_i/v_o \quad , \quad N \equiv n_i/n_o \quad , \quad \psi \equiv \phi/\phi_o \quad , \quad v_o \equiv \sqrt{\frac{q\phi_o}{M}}$$

and $\zeta \equiv z/v_o t$,

The solution is completely determined when the conservation of energy at the plasma front is used. That is:

$$\frac{U^2}{2} + \psi = 0 \quad \text{at} \quad z = 0$$

Now the ion number-energy relation can be computed and is

$$N_i(E_i) = \frac{n_o A}{\beta}\left[\sqrt{\frac{6}{5}} - \sqrt{\frac{E_i}{5q\phi_o}}\right]^6 , \quad (6)$$

where $N_i(E_i)$ is the number of ions with energy $E_i$ and

$$\beta \equiv \sqrt{\frac{5}{2}} \frac{1}{v_o t} .$$

By picking the experimental numbers: t = 100 ns I(0) = 40 kA and $E_{max}$ = 800 keV for $He^{++}$, the natural logarithm of Eq. (6) can then be compared to the measured results. (See Figure 6.) The data has been corrected for the loss of ion energy ($q\phi_o$) at a grounded detector.

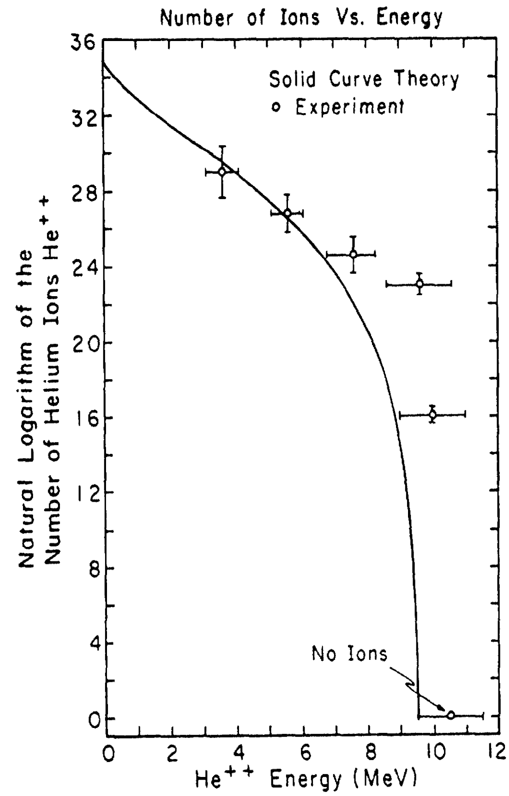



Figure 6. Comparison between theory and experiment of the natural logarithm of the number vs energy relation.

## 5. Summary and Conslusions

The reflecting beam model initially proposed by Ryutov[9] has been extended and used to predict the ion energy distribution subject to the constraints of the beam current-energy distribution. The predictions compare with the data quite favorably in a limited parameter regime.

The ion acceleration may be extendable to higher energies if thinner anode foils are used along with stronger external magnetic fields. These modifications would allow for more electron reflecting and a greater electron density.

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