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EXPERIMENTAL INVESTIGATION OF LINEAR-BEAM COLLECTIVE ION ACCELERATION IN VACUUM*

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Summary

Preliminary experimental results of collective ion acceleration using a linear beam from the University of Maryland Electron Ring Accelerator injector are presented. Neutron yield of 10^9 neutrons/pulse from Cu(p,n)Zn reactions are observed. From the Q value of the reaction, the energy of the proton must be above 4 MeV. The number of protons per pulse is estimated to exceed 10^{13}.

1. Introduction

The two principal methods of collective ion acceleration embed ions either in an electron ring or in a linear collective field. In the electron ring accelerator, the positive ions are trapped and accelerated by the moving space charge potential of the electrons, and the individual electrons also move coherently with the space charge potential. The theory of electron ring accelerator is well-advanced, and the experimental investigation of the method is being performed at several laboratories, including our laboratory at the University of Maryland.[1-4] In linear collective ion acceleration, the motion of individual electrons is not coherent with the positive ions, and theoretical interpretations are difficult. Experiments have been performed with plasma filled diodes, with vacuum diodes, and with drifting beams in pressurized gasses.[5]

In these experiments, the highest energy positive ions observed were reported by the Livermore group[6] that used a vacuum diode with an insulator anode. A possible mechanism for positive ion acceleration in a vacuum diode can be visualized as a process of ambipolar diffusion. The high energy electrons make a virtual cathode just outside the plasma boundary, and a large electric field is created near the surface of the plasma. This large electric field accelerates positive ions towards the virtual cathode, and the virtual cathode moves coherently with the positive ions. Based on a one-dimensional model, the maximum electric field at the surface of the plasma due to the virtual cathode is given by[7]

$$E = \left[\frac{4m_o c}{e\varepsilon_o} J_o(\gamma_o{}^2 - 1)\right]^{1/2} \qquad (1)$$

where e and m_o are the electron charge and mass, c is the velocity of light, γ_o is the ratio of the total electron energy to its rest mass, and J_o is the current density. As can be seen from Eq. (1), the maximum electric field, E, is approximately proportional to the square root of the product of the electron current and the voltage, and therefore directly related to the beam power.

The Electron Ring Accelerator Group at the University of Maryland has studied the problem of heavy ion acceleration with linear beams, not only because of its general interest but also as a means of producing ions for instrument calibration purposes.

In this initial experiment, we have drawn heavily on the methods of the Livermore group.[6] The results reported are preliminary; however, they do substantiate the production of a relatively large flux of multi-MeV protons by the use of a simple arrangement operating at a pressure of 10^{-4} torr.

2. Experimental Apparatus

This experiment used the electron injector of the Maryland Electron Ring Accelerator Laboratory. Briefly, it is a 12-stage Marx generator (0.5 μf per stage) charged to <100 kV and discharged into a ~4 ohm water Blumlein. When the Blumlein is triggered, it creates a pulse whose amplitude is increased by impedance mismatches as it passes through an oil transformer section to a field-emission diode. See reference 8 for a detailed description.

A recent modification to the injector, which is of some importance in this experiment, was the insertion of a high-voltage spark-gap switch between the Blumlein and oil-transformer lines. This switch has been instrumental in reducing the pulse rise time to ≲3 ns at the diode and in reducing the so-called prepulse which appears at the diode when the Blumlein is being charged.

Under normal ERA operation (60 kV charging), the injector produces an output pulse which has a rise time of ~2 ns and a width of 30 ns. It has a peak voltage of 2.2 MV with a peak current of ~10 kA. In the present experiment, the peak current is 35 kA. The output voltage has not been measured but it is less than 2 MV.

Figure 1 shows the experimental arrangement used. The Faraday cup, neutron activation counter, voltage probe and camera are seen. Signals are observed and recorded inside an r.f. enclosure (not shown). The outline of the anode plate and cathode stalk are drawn in dashed lines. The anode plate (as well as the plasma lens of Figure 2) may be adjusted in position without breaking vacuum by the use of the three rods that protrude from the end plate. The whole system operated at a pressure of 10^{-4} torr.

A scaled section drawing of the central region between the cathode tip and the Faraday cup is shown in Figure 2. Dashed lines give the shape and position of a plastic plasma lens which was used in some of the experiments. The Faraday cup has a rise time of less than 2 ns. The camera was a standard laboratory camera.

The neutron counter used was a silver activation counter of rather standard design.[9] A Geiger-Müller counter was wrapped with 0.25 mm thick silver foil and surrounded by a 4.1 cm thick polyethelene moderator followed by a 1 mm thick cadmium slow-neutron shield. The calibration for neutron pulse detection was made with a brief exposure (10 sec.) to a PuBe source. Based on this calibration and the background rate in the counter, it has been estimated that the minimum number of neutrons from the Cu target region that could be detected above the background was ~10^7 per pulse.

3. Experimental Results

Following a number of trials, neutrons were detected and the Cu target plate was activated. The necessary conditions were: an open spark-gap switch to decrease the pre-pulse and pre-plasma formation at cathode, and a "proper" size of the hole in the anode. Less important conditions seemed to be the cathode-anode gap, and the presence or not of the plasma lens.

The neutron activation counter response after one pulse is shown in Figure 3. The curve shown in this figure is the response curve for an ideal detector. It was normalized to roughly coincide with the measured values of the counting rate, R, for times less than ~50 sec.

Figure 4 shows a photograph of the currents registered during a pulse. The upper trace is the Faraday cup current which shows a rapid variation with a period of ~2 ns and positive excursions. The lower trace is the shunt current of the injector and has a peak value of 35 kA. For proper relative timing of these signals, the apparent time difference between these pulses should be reduced by 5 ns.

An open shutter photograph of the region between the anode and the plasma lens when neutrons were observed is presented in Figure 5. Large variations in the characteristics of these photographs were observed and no salient characteristics have been found which correlate with neutron production.

In order to study the radioactivity produced, the machine was opened immediately following a pulse and Cu foils mounted on the Cu target plate were removed and their activity measured. The result of a measurement of the delay curve for the activity produced is seen in Figure 6, where the count rate is plotted as a function of time. The half lifetime determined from these data is 39.9 ± 1.0 min. Measurements were made in parallel of the γ-ray spectrum and an analysis of this data identified the isotope produced as Zn^{63}, which has a half lifetime of 38.6 min. in agreement with the measured value. A continued study of the γ-ray spectrum revealed also the presence of Zn^{65}, having half lifetime of 244 days as would be expected.

The evidence presented above indicates that two nuclear reactions have been observed:

$$Cu^{63}(p,n)Zn^{63}, \quad Q \text{ value} = 4.21 \text{ MeV}$$

$$Cu^{65}(p,n)Zn^{65}, \quad Q \text{ value} = 2.16 \text{ MeV}$$

This requires protons to have been accelerated to an energy greater than 4 MeV.

Based on the calibration of the activation counter, the number of neutrons produced per beam burst is in the range $10^8 - 10^9$. From a knowledge of the range-energy relation for protons in Cu and the reaction cross section, the number of protons that are commonly being accelerated per pulse is $\sim 10^{13}$. The number of participating electrons is $\sim 10^{15}$.

The large number of protons accelerated in such a simple device would suggest further investigations of this mechanism as a useful source of multi-MeV protons and heavy ions.

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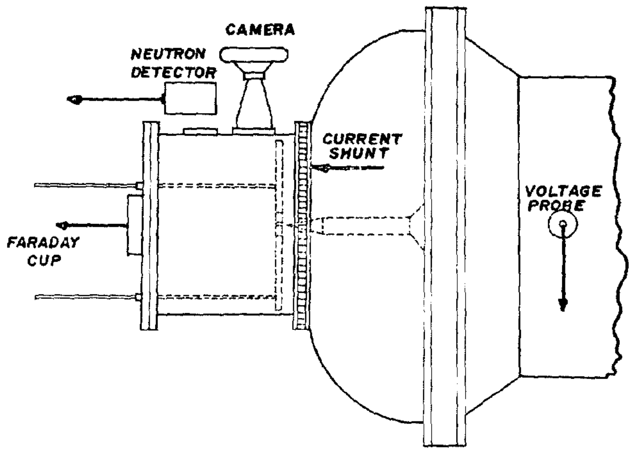

Fig. 1. Experimental setup at end of ERA injector.

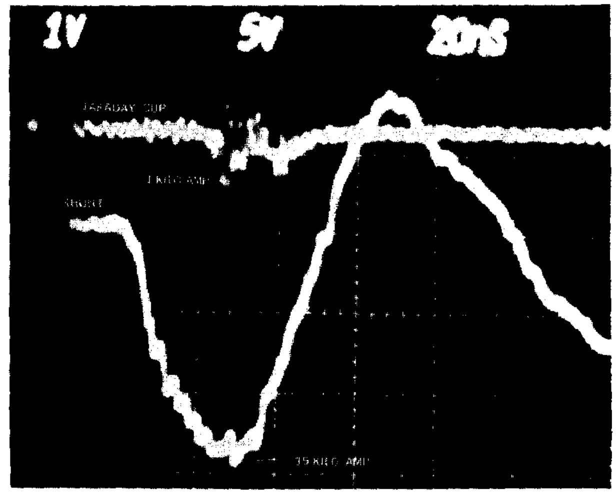

Fig. 4. Oscilloscope traces of Faraday cup current (top trace) and return shunt current (bottom trace). Top trace is delayed by 5 ns relative to bottom trace.

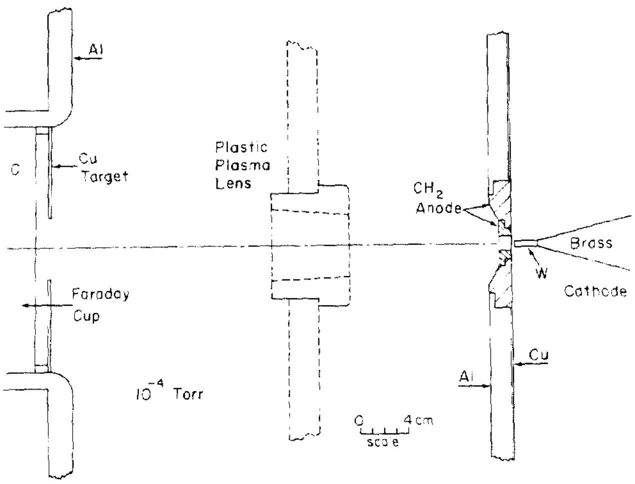

Fig. 2. Scale drawing of experimental arrangement.

Fig. 5. Photograph of plasma between anode and plasma lens.

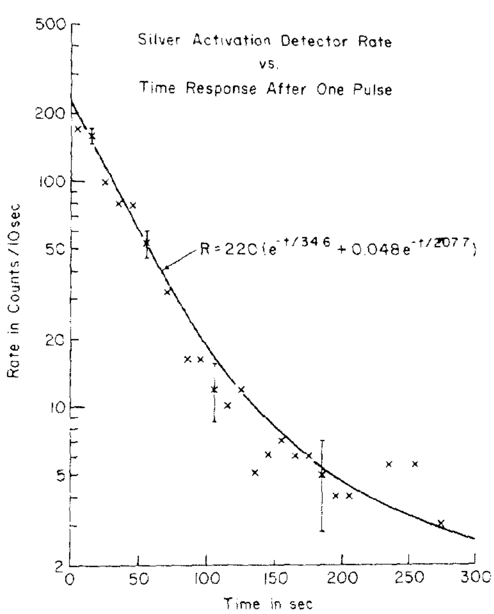

Fig. 3. Silver activation counter response after one beam pulse.

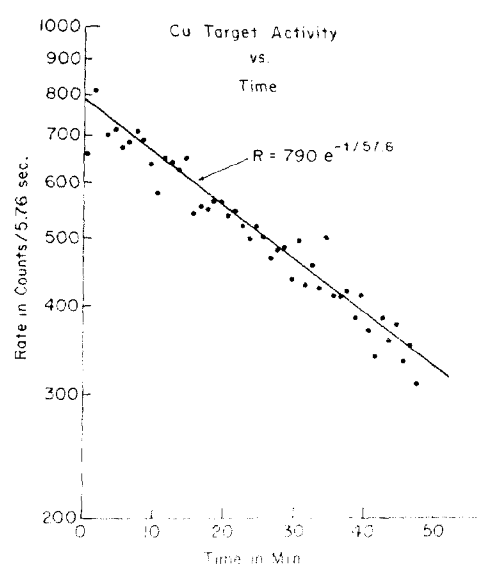

Fig. 6. Activity of Cu target plotted versus time.