COLLECTIVE ACCELERATION OF INTENSE ION BEAMS IN VACUUM*

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Summary

We have developed a diode system with an insulated anode and rear target that operates in vacuum and produces 4×10^{10} neutrons per pulse. The system forms a pinch discharge that ejects a cluster of collectively accelerated ions that attain full energy in 7 cm. Target neutron data and activation analysis with multiple foils show that pulses of 10^{14} protons with energy up to 15 MeV have been achieved. Experiments with electrode materials and diode geometry have lead to large improvements in focusing and ion beams have been propagated 8 ft in vacuum.

The presence of high-energy carbon ions indicates that the pinch has the capability of forming and accelerating multiple ionized high-Z ions.

Introduction

Linear, collective field acceleration of positive ions by electrons appears to have been first reported by A. A. Plyutto[1] in 1961. Together with several co-workers, Plyutto has continued this research[2-5] up to the present time. These experiments are conducted with a plasma filled diode through which a nonrealitivistic electron beam is passed. Graybill[6-8] and his co-workers independently studied collective field acceleration due to a pinch discharge formed by a realitivistic electron beam in a gas-filled drift tube. Because particle accelerators must operate in vacuum, the gas-filled drift tube is isolated from the electron accelerator by a suitable vacuum-tight foil. The pressurized drift tube serves as the anode of the Graybill system. In 1971 E. O. Korop and A. A. Plyutto also reported on the conversion of cathode material to positive ions that are collectively accelerated in vacuum diodes. Thus, the pioneering work on linear collective field acceleration is divisable into three categories: plasma filled diodes, vacuum diodes, and drifting beams in pressurized gases. A number of other investigators are now doing linear collective effect acceleration experiments using these basic methods.

The system developed at the Lawrence Livermore Laboratory (LLL) does not fall logically into any of these three categories. Because the anode is highly insulated and its potential varies rapidly, it could be described as a pulsed anode accelerator that operates in vacuum. With this device protons and deuterons have been accelerated in pulses of 10^{14} ions with energies up to 15 MeV. A smaller number of carbon ions have been accelerated with sufficient energy to activate an Al target. The device also produces neutron pulses with high efficiency. Bursts of 4×10^{10} neutrons[9] have been produced with deuterated polyethelene electrodes. This neutron yield is surprising when compared to neutron data from other experiments[10-12] reported in the literature, particularly since the energy used in the LLL experiments is relatively small. To better understand these basic differences in performance we are now conducting, under identical accelerator conditions, comparative performance analysis between two of the grounded anode systems described earlier, (vacuum diodes and drifting beams in pressurized gases) and our insulated anode-target device.

Several different machines are used by our group for collective acceleration experiments, primarily to explore the effect of variation in ν/γ. However, because of its excellent operating conditions and fast turnaround time, the FX-75 machine at the Boeing Radiation Effects Laboratory is used for most of the LLL linear collective acceleration experiments. For these experiments the FX-75 is operated with a 4 MeV, 30,000 A pulse of approximately 30 nsec duration. This corresponds to a stored energy of about 5000 J, approximately half of which is delivered to our system at a measured voltage of 2.5 MeV. The ν/γ of this system is 0.3.

Description of Apparatus

Figure 1 shows the diode and target arrangement used in our system. With the low ν/γ beam provided by the FX-75, the length of the cathode assembly can be varied between 4 and 20 cm without significantly effecting yields. For the experiments described here a 6-mm diam nylon shank is imbedded in the 3.8-cm diam high voltage accelerator shank with 6 cm of nylon rod protruding. Nylon is used to reduce shank fire* and pointed cathode tips (15° taper)

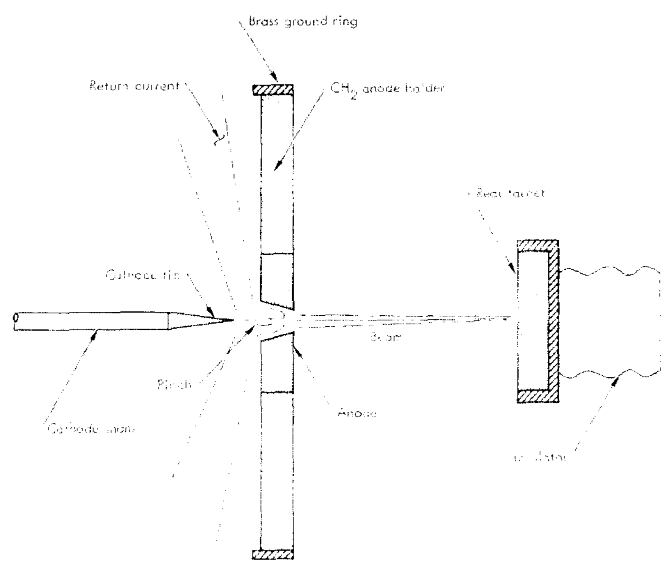

Figure 1. Relativistic pinch neutron geometry.

*No other operational differences have been noted with conducting shanks and dielectric shanks.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

are screwed into the end of the nylon shanks. Since the ions in our system are dominately produced by anode material, it is possible to use many different cathode tip materials. We have experimented with quartz, copper, stainless steel, carbon, natural polyethelene, deuterate polyethelene, and several molded composite materials. In the experiments described here, we have determined that tapered carbon tips with a slightly rounded 2 mm point produce a highly collimated electron beam which reduces radial angular divergence of the accelerated electrons and ions. The insulated anode is made from material that contains the proper elements to produce the desired ions. For example, natural polyethelene (CH_2) produces carbon and hydrogen ions, deuterated polyethelene (CD_2) produces carbon and deuterium ions, etc. The anode is mounted in another insulator which for the experiments described here is 11 cm in diam. The insulator assembly is pressed into a grounded brass cylinder that provides a path for the return current. A rear target is provided so that the number of ions and their energy can be determined by the neutron yield and activation analysis. Both insulated and grounded rear targets are used, with little noticeable difference in activation. When the accelerator is fired the electron beam is concentrated by the cathode assembly with most of the electrons emerging from the point. The electron beam appears to be space charged neutralized while it is on the cathode.[13] However, when it leaves the cathode tip it expands to a diameter that is determined by the geometry and the pressure in the diode region. Initially, most of the electrons strike the surface of the insulated anode assembly which then charges to a high potential.

The impinging electrons produce positive ions which reduce the electron space charge and cause the blown up beam to collapse toward the axial anode hole (8 mm diam). During this process the return current sheet forms and flows radially outward from the cathode side of the anode hole until it reaches ground potential at the periphery of the assembly. When the return current sheet reaches ground, an intense pinch forms that produces a neutron burst and ejects a cluster of high energy particles. These particles, together with the unused portion of the electron beam, impinge on the rear target. A burst of particles is also accelerated in the opposite direction, together with the radial return current sheet. Because of their wide divergence and the interference of the accelerator, these ions are of no practical value. Radial acceleration of ions from the cathode-anode gap of a vacuum diode system using a grounded anode was recently reported.[14]

The diagnostics used in our experiments include two silver activation counters that are calibrated in place using a Bureau of Standards PuBe source. We are also experimenting with silver detectors that can discriminate between D-D and D-T neutrons. The ratio of D-D and D-T neutrons produced in D-D plasmas is important in determining the origin of the neutrons. A time-of-flight neutron spectrometer is used to measure D-D and $^{12}C(D,n)^{13}N$ reactions. D-T neutrons have not been measured with this instrument because of interference by a strong gamma pulse. This neutron spectrometer uses a Pilot B plastic scintillator with two RCA 6342 photomultipliers amplified to give different sensitivities for varying neutron fluence levels. An integrating circuit is incorporated in each scintillator photomultiplier system so that an integrated signal proportional to the total yield can be produced in addition to the time-of-flight resolved signal. The energy of protons is determined by passing the beam through Cu foils 0.010 in. to 0.015 in. thick and measuring the activation of a second foil spaced 0.125 in. below the first.

The identification and quantification of radioactive isotopes produced by our collectively accelerated beams is accomplished by gamma pulse height analysis which can be carried out with either a NaI or Ge(Li) detector.

Although each detector-analyzer-shield configuration is unique, the International Atomic Energy Agency has available standard sets of radionuclides for calibration purposes. Identification of the radioisotope is made by comparing the gamma energy peak to standard source decay schemes and matching their half-lives to published tables.[15]

Experimental Results

Initial efforts to detect collective acceleration of positive ions were made using the Febatron which is a 5000 A, 2.1 MeV device that delivers approximately 200 of its 600 J of stored energy. This energy is delivered in roughly 50 nsec and the beam has a ν/γ of 0.1. Using the configuration shown in Fig. 1, neutron bursts of 2×10^8 were observed on a silver counter placed at 90°. This exceptionally high efficiency for producing neutrons naturally raised the possibility of neutrons being produced by processes other than D-D reactions. Neutron time-of-flight measurements, using the LLL diode system shown in Fig. 1, indicate that the neutron yield is due primarily to the D-D reaction as shown in the first oscilloscope trace in Fig. 2. The first pulse (seen at the left) is due to gamma rays, while the second pulse is due to D-D neutrons. The diode system was then modified by the addition of grounded surfaces as shown in Fig. 3, and 0.5 MeV neutrons were then observed. An oscilloscope trace showing the 0.5 MeV neutron peak due to the $^{12}C(D,n)^{13}N$ reaction produced with the new geometry is shown at the right in Fig. 2. Experiments were then conducted using natural polyethelene (CH_2) anodes which produce protons and Cu rear targets with the objective of producing $^{65}Cu(p,n)^{65}Zn$ and $^{63}Cu(p,n)^{63}Zn$ reactions. The thresholds for these reactions are 2.16 MeV and 4.21 MeV, respectively. Neither of these reactions was produced; therefore, collective

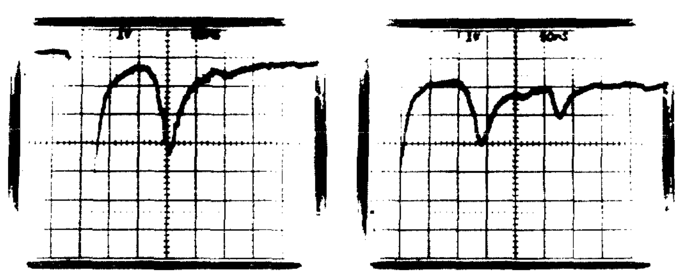

Figure 2. Time-of-flight traces.

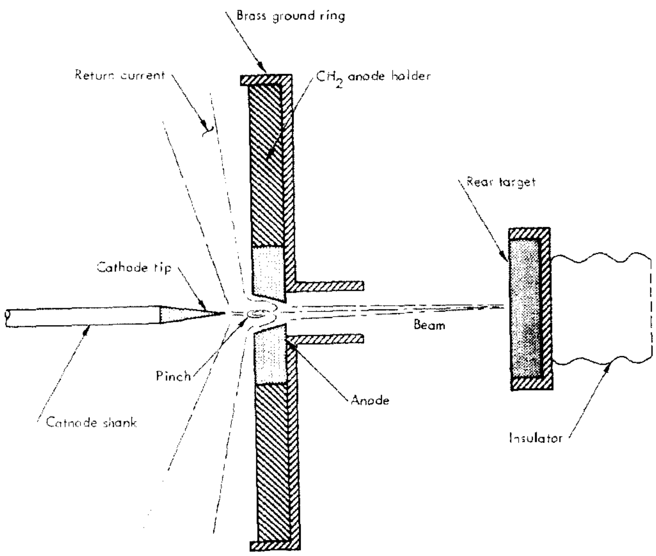

Figure 3. Relativistic pinch gun geometry.

acceleration research was discontinued on the Febatron.

Research was continued on the BREL machine described previously, using the geometry shown in Fig. 3. Another series of cathode experiments was conducted and the tapered carbon cathode tip with a 2 mm point was adopted as standard for collective acceleration experiments. Anode materials used in these experiments include CD_2, CH_2, C and rear target materials include CD_2, CH_2, C, Cu and natural U. Deuterons, protons, and carbon ions were collectively accelerated in our system, producing the following reactions in the rear targets: $^{12}C(D,n)^{13}N$, $^{65}Cu(p,n)^{65}Zn$, $^{63}Cu(p,n)^{63}Zn$ and $^{27}Al(^{12}C,n)^{38}K$. Examples of these data are shown in Table I. When a natural U rear target was bombarded with a beam of protons and carbon ions a 4×10^9 burst of neutrons was observed. The reaction causing these neutrons has not been identified as yet. The $^{27}Al(^{12}C,n)^{38}K$ reaction however suggests that the device has the potential for producing high energy multiply ionized high-Z ions.

Activation analysis using layered foils and rear target neutron yields shows that ions are accelerated in the multi-MeV range and that some ions achieve an energy as high as 15 MeV. For deuterons with an average energy of 1 MeV, the thick target yield is known to be about 10^{-5} neutrons per incident deuteron. For a deuteron of 4-5 MeV the thick target neutron yield would be 10^{-4}. The production of 10^{10} neutrons due to the interaction of a high-energy deutron burst with a CD_2 rear target, and a yield of 2.5×10^9 neutrons due to protons striking a Cu rear target, indicate that pulses of at least 10^{14} ions with a total energy of about 100 J per pulse are produced. The number of activated atoms produced in the rear targets is determined by activation analysis which serves as a method of confirming the acceleration of high energy ions. A large number of the activated atoms are lost due to sputtering of the rear targets. Thus it is

Table 1. Examples of activation analysis.

Experiment components	Activation product	Activity (10^6 atoms)	Machine voltage (MeV)	Rear target spacing (in.)
Cathode tip - C Anode - CH_2 Rear target - Cu	^{63}Zn	7.9	5.0	9
Cathode tip - C Anode - CH_2 Rear target - Cu	^{13}N ^{63}Zn	3.7 3.0	4.0	11
Cathode tip - C Anode - CH_2 Rear target - Cu	^{63}Zn	3.7	5.4	11
Cathode tip - C Anode - CH_2 Rear target - Cu	^{63}Zn	3.1	4.0	20
Cathode tip - C Anode - CH_2 Rear target - Cu	^{63}Zn ^{65}Zn	15 39	4.0	20.5
Cathode tip - C Anode - CH_2 Rear target - Cu	^{63}Zn	23	4.0 4.8 4.8 (3 shots)	96 20 16
Cathode tip - C Anode - CH_2 Rear target - Cu	^{63}Zn	0.5	3.8	96
Cathode tip - C Anode - CH_2 Rear target - Al	^{38}K	0.66	3.5	2.5

not possible to correlate rear target neutron yield with the number of activated atoms.

In contrast to drifting beam experiments reported in the literature, we find that the electron beam emerging from our diode system is well collimated and can be brought to a sharp focus at a target placed 7 cm from the anode. The ions, because of their greater mass, are not as well focused as the electrons. However, we have found by activation analysis that the greatest activity is at the center of 5-cm diam circular targets centered on the axis of the system 50 cm from the back of the anode. The ions in the beam tend to be stopped in a short distance when they penetrate a conducting target. The electrons will, however, penetrate to a greater distance.

Figure 4 shows the damage done by these electrons after penetrating most of the distance through Cu slabs. In the upper left hand corner is shown a blister formed on the back of a thick Cu target. In the upper right hand corner of the figure are two pieces of copper that have been "cold welded" by mass transfer. The lower part of the figure shows two similar pieces of welded Cu that have been pried apart to show the mass transfer weld. All the Cu pieces shown in this figure have a thickness of 6 mm.

Damage to these Cu targets indicates the beam has a diameter of 6 mm with a dense center core of 3 mm. At a distance of 50 cm the beam diameters are twice as large. These collective accelerated beams can be focused so that the dense center core is less than 1 mm in diameter by the use of pointed Cu targets. Figure 5 shows both a side view and a direct view of a hole made by the beam in such a target. The hole is 4 mm in depth and tapers from 1 mm at the entrance to a fraction of a millimeter at the bottom of the hole.

This sharp focus appears to be due to an interesting effect predicted by Linhardt[16] which is enhanced by pointed targets. Relativistic electrons can penetrate into a conducting target but the magnetic field due to the current in the beam is excluded from the conductor. The exclusion of the magnetic field occurs because a nonrelativistic return current is induced by the incident beam in the conductor and this current cancels the relativistic current everywhere inside the conductor as shown in Fig. 6. When the return current reaches the face of the conductor it diverges radially. The accumulation of magnetic field outside the conductor results in a growing electric field that accelerates electrons toward the conductor and decelerates ions. The growing magnetic field outside the target also tends to further compress the beam. It is our belief that the acceleration processes described above takes place, in a modified form, if the conducting target has an axial hole, since a portion of the magnetic field is excluded due to a change in diameter of the return current path. Thus, the possibility exists that a portion of a beam can be accelerated to very high energy by converting some of its energy into magnetic and electric forces that focus and accelerate the remaining beam. We are now conducting experiments with a series of foils with axial holes to test this concept.

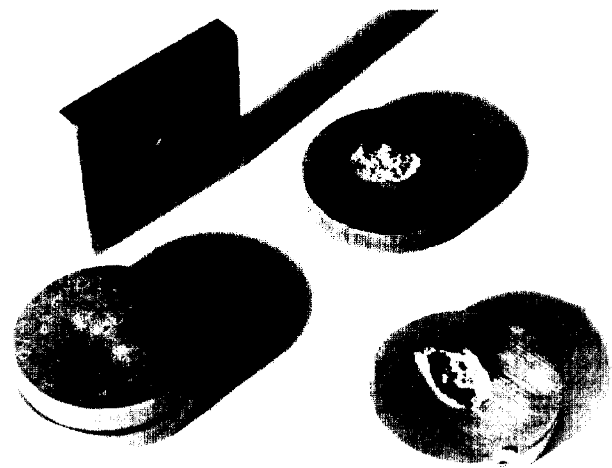

Figure 4. Blistered and cold welded targets.

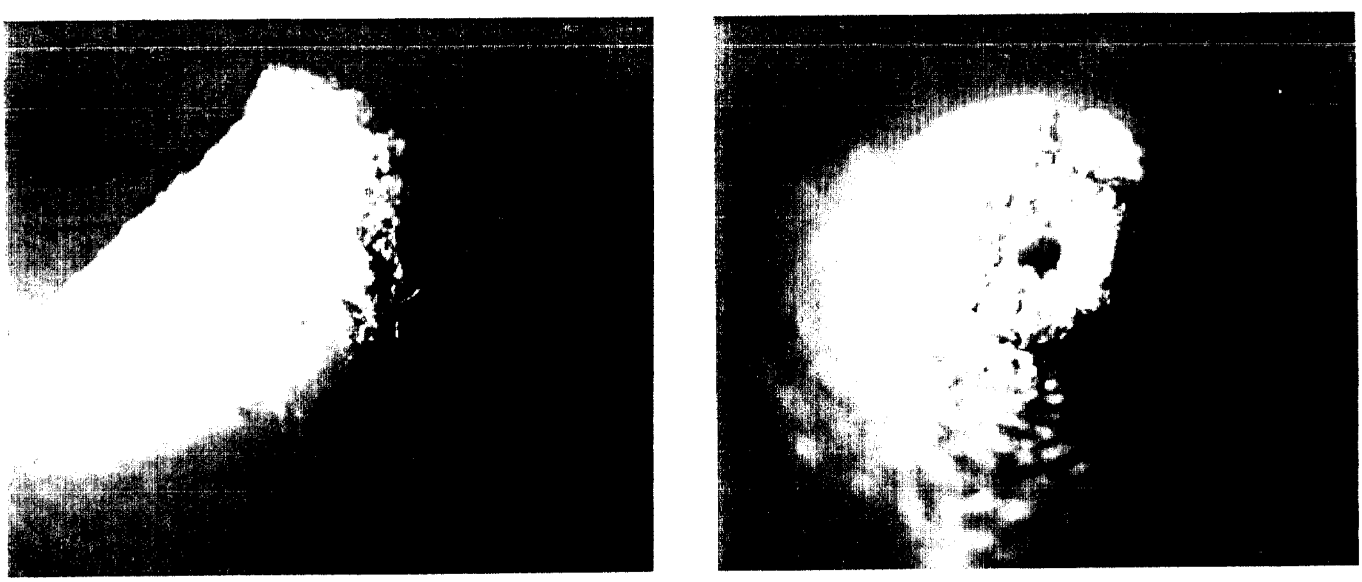

Figure 5. Microphotographs of damage sustained by pointed rear targets.

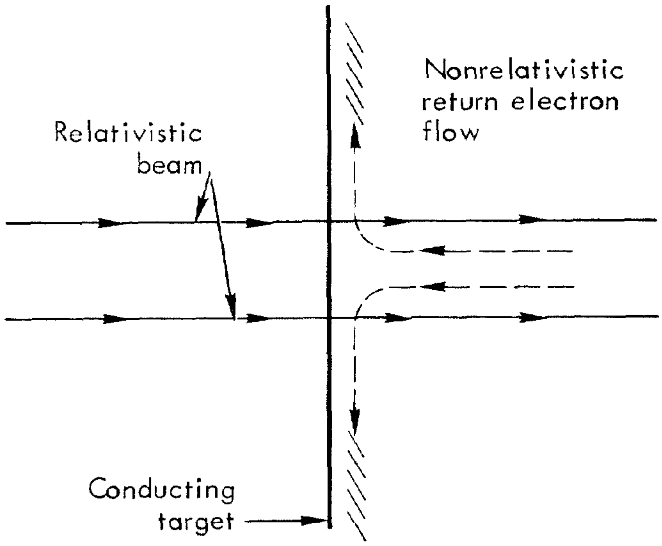

Figure 6. Acceleration of electrons by magnetic compression and axial electric field.

Initial experiments with copper rear targets have produced 2.5×10^9 neutrons from the p,n reaction, and have revealed a $^{65}Zn/^{63}Zn$ ratio of $\leq 2/1$.* This implies that a substantial fraction of the protons must have an energy well above the 4.21 MeV threshold and confirms the presence of ion bursts with up to 10^{14} protons and with a total energy of about 100 J. The thick target yield for 6 MeV protons is 1.8×10^{-5} neutrons per incident proton.

In order to study the propagation of collectively accelerated ions, a drift space was provided by extending the vacuum chamber with a 2.1 m brass tube which permitted activation studies of either insulated or grounded rear targets spaced up to 2.45 m behind the insulated anode. The majority of the experiments conducted with this long drift tube facility were performed with 38 mm diam copper discs with a thickness of 0.39 mm. The presence of ^{63}Zn was detected in all experiments, showing the acceleration of large bursts of protons with energy in excess of the applied voltage. In these experiments 10^6 - 10^7 ^{63}Zn atoms were detected on the first Cu disc in a multi-disc target. In several experiments, a few thousand atoms of ^{63}Zn were found on the second Cu foil. Since protons of about 15 MeV are required to pass through a 0.015 in. copper foil and activate the second foil, the ion burst contains some protons with an energy of at least 15 MeV.

When the spacing from the anode to the Cu foil target was increased from 48 cm to 51 or 52 cm, there was no visible evidence that the rear target had sustained any damage, but substantial ^{63}Zn was detected on these undamaged rear targets. We also found that the neutron yield, due to collectively accelerated protons, was larger in those cases where the rear target spacing was large enough so that the target did not sustain damage.

For rear target spacings of less than 48 cm the target is struck by a relatively well-collimated electron beam and an associated ion burst. As the rear target spacing is increased beyond this point, a narrow transition region exists over which the electron beam suddenly disperses, striking the wall and probably carrying a portion of the ions with it. A sufficient number of ions are well directed along the tube axis so that they survive the electron beam dispersal and travel the entire length of the drift tube to produce ^{63}Zn activation of the rear target at that point.

At present it is unclear why the electron beam suddenly disperses and why such dispersal leads to higher neutron yields, although the reduction in sputtering of activated Cu when the electron beam has been dispersed must play a role in increasing activation of the target. This does not, however, explain the increase in neutron yield with undamaged targets. One possibility under consideration is that the electric field produced when a relativistic electron beam enters a solid is no longer present. Since this field decelerates ions, its absence may account for an increase in neutrons because of higher ion energy.

*^{65}Zn is always present when an effort is made to count the $^{65}Cu(p,n)^{65}Zn$ reaction. Because of its long half life, this measurement is inconvenient and is usually eliminated.

Acknowledgments

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