ION ACCELERATION IN ELECTRON BEAMS*

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Introduction

Collective ion acceleration has been proposed and studied by investigators[1,2] in plasma and vacuum diodes and in low pressure neutral gases. It has only recently been noted that similar features exist for intense discharges across initially vacuum or plasma filled gaps and for intense electron beams drifting in initially neutral gases. In all these devices, energetic ions have been found to be radially and axially emitted, and rapid current changes often associated withradiation and particle emission have been seen. A more thorough understanding of the physics involved is certain to elucidate the processes responsible for neutron production in various pellet and wire heating experiments.[3-6] We point out some analogies between these experiments and investigations of linear pinches, exploding wires, and plasma focus devices. At the present level of understanding, the collective process of acceleration is not useful for producing a high quality accelerator, but as more is learned it may be possible to control the process.

Historical Review

We divide previous observations into three categories, plasma-filled diodes, vacuum diodes, and drifting beams in neutral gases. As shown in Table I plasma filled, ostensibly low-current-density diodes in the 1-2 kA range have yielded protons moving in the same direction as the electrons at energies up to 5 MV. Based on the gap length and the energies of protons, collective fields in excess of 0.2 - 0.6 MV/cm must exist. Further, the acceleration is associated with a rapid fall of electron current which occurs when a critical current is reached.

Table I also outlines vacuum diode results which are similar to the plasma filled diode observations. One or more current interruptions were again noted in connection with the acceleration process, but occurred later in the pulse, presumably because the threshold plasma density required for the interaction must build up as electrode material enters the gap. Korop and Plyutto reported a remarkable > 0.4 MV/cm collective field with a 100 amp diode.

The last section of Table I reviews observations made for beams drifting in neutral gas. Note that there is a trend toward higher ion energies at lower beam currents. We have attributed this seemingly paradoxical result to differences in divergence for various beam conditions.

Experimental Apparatus

For drifting beam acceleration in neutral gases the apparatus shown in Fig. 1 was used. The single parameter explored was diode geometry, i.e., beam current density and divergence. As a result of impedance change, the beam acceleration potential was also changed. The accelerator was an oil-filled Blumlein called Reba[7] and delivered a 70 ns pulse at 2 MeV into a 17 Ω load. Actual loads varied widely because anode-cathode gaps ranged from 1-10 mm and cathode diameters from 3-32 mm. A section of dielectric material 15-40 cm long in the cathode shank was used to reduce the machine's prepulse at the cathode so that slight early current flow would not cause the small gaps used to be shorted by plasma early in the main pulse. After surface breakdown, which takes only a few ns to occur, these dielectric rods become good conductors.[8] The anode was a 0.0025 cm sheet of aluminum foil which also separated the diode vacuum from the 5 cm diam. drift section filled to 150 μ with various gases, usually D_2 or H_2. The first 70 cm of the drift section contained closely spaced Rogowski coils to monitor net current. The Rogowski section was followed by an aperture leading to a differentially pumped chamber containing current collection screens for time-of-flight ion analysis. This section was followed by a Thomson parabola mass spectrometer. Targets of Al, C, Li were placed around the aperture on several different shots to verify the analyzed energies by means of neutron production threshold energies of incident deuterons or protons. The ions were detected by means of a Microchanneltron* electron multiplier plate coupled to a phosphor screen, and the recording medium was Polaroid film. The charge states, masses, and energies of all axially moving particles could be thus quickly determined on a single shot. For experiments on ions accelerated in the diode, the same apparatus was used as for drifting beams, but the neutral gas drift section was evacuated to examine axially accelerated ions. The targets located in the anode plane were provided with small pre-drilled holes. Radially accelerated ions were examined by mounting the energy analyzer on the side of the diode chamber at 90° to the anode-cathode gap. Different electrode geometries were used as described below, and silver activation counters were used to measure neutron yields and anisotropy.

Experimental Observations

We first report observations made on acceleration in neutral gases. Figure 2 shows the net currents recorded by the series of Rogowski coils for the case of a 1 cm diam. cathode spaced 3 mm from the anode and peak injected current of 75 kA. This diode will self pinch as the current exceeds the critical 8500 $\beta\gamma \frac{r}{d}$ amperes (less when space charge begins to be neutralized in the gap). The resulting beam is divergent and much current will hit the walls of the drift region; this is reflected by the 40 kA current registered by the first Rogowski coil 2 cm from the anode in comparison with 75 kA measured by the diode monitor. The most important feature of this data is the oscillation observed in coils 3, 5 and 6. Only oscillations seen near the anode were reproducible. We interpret these to be related to localized pinches, the most intense occurring close to the anode and weaker ones at other locations. At the time of pinch, part of the current is lost to the chamber walls or reflected back to the diode before reaching a given loop. Farther downstream the beam is sufficiently diffuse due to erosion of the beam front that the current interruption which occurs near the diode is not seen. We have noted deuteron-induced radioactivity on the walls of the chamber near the loop 1 in excess of 100 mR/h with several minute half-life. Silver activation counters showed that ~ 10^{8-9} neutrons were produced in the same region near the anode. From typical thick-target yield curves in the MeV incident deuteron range we calculate that 10^{11} - 10^{14} deuterons were accelerated into the tube walls. Time-of-flight neutron detectors placed at 1 and 10 meters from the source indicated a neutron burst of ~ 2.5 MeV. Other neutron energies were present but complete characterization was not possible because the large x-ray signal preceeding the neutrons partially saturated the detectors.

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The effect of current density (and therefore, beam divergence) on the beam front velocity is shown in Fig. 3; the currents were varied by changing the anode-cathode gap from 3 to 6 mm. In general, when the beam conditions allowed self-inching, the front velocity determined by the Rogowski coil signals was ~ 0.04 c and the net current was less in comparison with injected current. For lower current, and less divergent beams, the net current was relatively greater and the electron beam front velocities were ~ 0.07 - 0.08 c, which has the same velocity as 2-3 MeV protons. We observed that an increase in the beam-front velocity occurs at 5-7 cm from the anode, which is close to the tube diameter. These results agree with those reported earlier by Rander et al., as noted on Fig. 3. We have taken time-integrated photographs which show an apparent pinch in this location. Further, results reported by Graybill,[10,11] who used a 15 cm diam. chamber and a movable Faraday cup on axis to detect ion time of arrival, indicated that the acceleration region was about 15 cm from the anode.

Some typical energy spectra obtained on axis during a single shot using the Thomson parabola spectrometer are shown in Fig. 4. The spots in the lower left hand corners are caused by x-rays on the axis of the spectrometer and the parabolic traces are produced by magnetic deflection in the vertical direction and electrostatic deflection horizontally. These deflections are proportional, respectively, to Z/E and Z/MV, where Z is the charge, E is the energy, and MV is momentum. A wide range of energies is present for each species (in this case the gas admitted to the drift tube included some air). Previous reports[10,11] showed much narrower energy spreads.

We next examine data obtained for diode experiments. The geometry used to obtain the data shown on Fig. 4 consisted of a pointed 6 mm diameter cathode with a powdered TiD surface. The anode, 3 mm away had a prebored 1 mm diam. hole in a CD_2 disc. The hydrogen trace which is the most intense was caused by pump oil contamination. The multiple line structure of the parabola is due to a series of ion bursts occurring at different times during the pulse so that variations in magnetic field change the trajectories of the ions slightly. A parabola due to deuterium is visible, and below lie fainter parabolae representing various ionized states of carbon and impurities. Evidence of a negative macromolecular component is seen near the center spot. A continuum in energy of ions was present for a single shot; previous reports showed several widely spaced, but narrow, groups of ions.[7,12]

The Thomson parabola mass spectrometer was mounted to accept ions emitted radially from the anode-cathode gap. For this preliminary work, the analyzer was not arranged to give resolution comparable to that obtained in measuring axial ions. However, the spectrum obtained establishes the existence of radially accelerated ions with a spectrum qualitatively similar to those obtained on the axis. The relative ion fluences and more exact energy distributions must yet be obtained. This observation causes us to question the interpretation placed on neutron yields from H and D-bearing filaments in diodes, which have been shown to produce neutrons claimed to be predominately of thermonuclear, rather than beam-target origin.[13] In these experiments the existence of some high energy deuterons or protons accelerated into the anode was recognized, but the interpretation of the data was predicated upon purely axial motion of the high energy component, which may not be true. The proof of radial ion emission also causes one to question interpretations that partial or total yields of neutrons from deuterated targets are thermonuclear.[3,5] McCann, et al.[3] based their conclusions of purely thermonuclear reactions on experiments showing a nearly isotropic neutron distribution. Freeman, et al., used several target configurations and resulting changes in anisotropy to conclude that some of the yield was attributable to thermonuclear reactions and some was from beam-target interactions by axially accelerated ions; the possibility of ions widely distributed in angle was apparently not considered. Bradley and Kuswa[5] suggested on the basis of on-axis ion energy spectra and neutron anisotropy that neutrons arose from a beam target interaction of collectively accelerated ions impinging on the anode with a wide angular distribution. The present data strongly supports the latter model.

Since various investigators[3-6] have measured different neutron anisotropies between unity and 1.4, several geometries were investigated on the Reba diode. Neutron counters[9] were positioned 76 cm on either side of the axis laterally from the gap, and at 76 cm in the forward direction. The two side counters were used to show any errors introduced by possible azimuthal asymmetry of the discharge. Isotropy values measured by the ratios of the foreward count to the two side counts differed for a given electrode geometry by as much as 20% on some shots, but usually were within 5%. For a configuration employing a 6 mm diam. glass-rod cathode with a 45° half-angle tip coated with TiD_2 powder and spaced 6 mm from a 1 cm diam. deuterated polyethylene (CD_2) pellet 1-3 mm thick, the anisotropy was foreward-directed with a value of 1.9 ± 0.5. Neutron yields were in the range $2\text{-}5 \times 10^8$. Another configuration employed a cathode identical to the one just described and a pointed 1 cm diam. glass anode located 6 mm from the cathode and also covered with TiD_2 dust. Foreward/lateral yields for this configuration averaged near unity with values falling within the limits 0.7 to 1.3 on individual shots. Between 3 and 12×10^8 neutrons/shot were produced. For both configurations some tendency toward foreward enhancement was noted for higher yields. We conclude from these measurements that ion trajectories in the diode can be altered by the electrode configuration, and are not reproducible.

Theoretical Models

Theories advanced for collective ion acceleration which appear to be relevant to this paper fall into three catagories. During the initial stages of beam propagation, before space charge neutralization occurs, a strong field of electrostatic origin exists at the beam front.[14] While this model can explain acceleration of ions at the head of the beam to modest energies, it cannot explain processes which appear to be operative within the beam as suggested by some of the experiments. In particular, it cannot explain ion bursts obtained from the diode late in the pulse.

The model which best fits the observations appears to be that of a moving pinch which begins when space charge neutralization becomes sufficient for the beam's self-magnetic forces to overcome space charge repulsion.[15] At this time, an electrostatic potential well is created by the slowed or reflected electrons entering the vicinity of the pinch. The field of electrostatic origin is augmented by the field arising from magnetic induction associated with the pinch dynamics. The position of the well will change as the ion bunch is accelerated and as the concentration of background ionization changes. The depth of the well for singly charged ions can be no greater than the energy of individual beam electrons, but since the well moves, the energy of particles moving in phase with the pinch may be many times the well depth. Electrons entering the negative charge concentration near the pinch region will be decelerated and then either returned to the diode or reaccelerated as they move downstream over the potential hump. If the pinch is moving, nonadiabaticity introduced by the velocity of the potential hump can increase or decrease the energy of particles which pass through or near the pinch. This model predicts that many electrons give a fraction of their energy to the moving potential well which is responsible for accelerating a much smaller number of ions to very high energies. The wide divergence in direction of the accelerated particles can be attributed to the large magnetic fields of the pinch region and the moving radial electric fields from the potential well in analogy to calculations relating to a plasma focus.[18]

The existence of current bursts is fully consistent with a moving pinch model, for as a pinch forms the impedance will rise as some electrons are reflected back to the cathode, or back to the diode in the case of drifting beams. When the pinch reaches the anode or is driven unstable, current can again freely pass. Under certain conditions, several pinches may be formed at the same time or in sequence; in this case, the time resolved electron energy spectra would consist of a number of bursts with energy spread which reflects diode voltage changes caused by the effect of pinching on impedance. This type of electron spectrum has been observed on a small experimental diode.[8]

The third possible mechanism for collective ion acceleration is that during the evolution of the beam and plasma densities, favorable conditions are reached for an instability to grow. According to Karchevskii et al.,[24] conditions which permit a two-stream interaction to grow can cause sudden impedance rises and strong plasma heating to occur even in low current discharges. Certainly as the beam pinches and plasma moves into the gap or neutral gas becomes ionized, critical conditions for electron runaway would be momentarily met in the experiments we described. However, it is presently not known exactly how this interaction can lead to rapid and intense ion heating.

When ions are accelerated by any of the above models, very high energies can be attained only if a self-synchronization of a moving potential well and an ion group exists. In the high energy e-beam regime investigated this synchronization is apparently not as efficient as in the low-energy experiments of Korop.[2] One can use as a figure of merit the maximum proton energy divided by electron beam energy.

Conclusion

If more can be learned about the processes at work, it may be possible to design a configuration which prolongs the coherence length of acceleration. The most important new feature we have reported, that of radially accelerated ions, may have been anticipated on the basis of earlier work on exploding wires[22] and pinches.[23] The detection of these radially moving particles in our experiment emphasizes the importance of using great care in the interpretation of experimental neutron data in pulsed discharge experiments.

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TABLE I

SUMMARY OF COLLECTIVE ION ACCELERATION IN VACUUM AND PLASMA FILLED DIODES AND DRIFTING BEAMS

	Ref.	Peak Voltage kV	Peak Current kA	Current Rise Time Pulse Duration ns	Burst Pulse Duration	Burst Current Density kA/cm^2	Proton Yield	Proton Energy MeV	Acceleration Length cm	Average Collective Field MV/cm
PLASMA FILLED	12,17	100	1-0	---	---	$\gtrsim$ 1.0	10^{11}	2.0	10	0.2
	17	200-300	---	---	---	---	10^{11}-10^{12}	4.0-5.0	---	---
	18,19	30	2-0	100/500	10.0	10.0	10^{11}-10^{12}	>1.2	1.0	0.3-0.6
INITIALLY VACUUM	2	300	5	700/1400	10-15	> 10.0	---	2.0	2.0	1.0
	20	60-120	0.1	10/40	15	---	---	0.4	1.0	0.4
	8	100	10	2/150	10	~100.0	$>10^{10}$	0.1	0.1	0.1
	5	2000	50	70/90	10	>100.0	10^{10}-10^{12}	<2.0	0.6	<4.0
DRIFTING BEAMS	10,11	1500	40	25/50	---	< 10.0	10^{13}	5.0	30	0.1
		1700	30	25/50	---	< 10.0	10^{12}	5.0-10.0	30	<0.4
	21,25	200-1000	200-100	35/80	---	< 10.0	10^{12}	2.0	10	0.3
	*	1500-2000	50-100	70/90	---	~100.0	10^{11}-10^{14}	1.0-5.0	< 6.0	<1.0

* Present Work

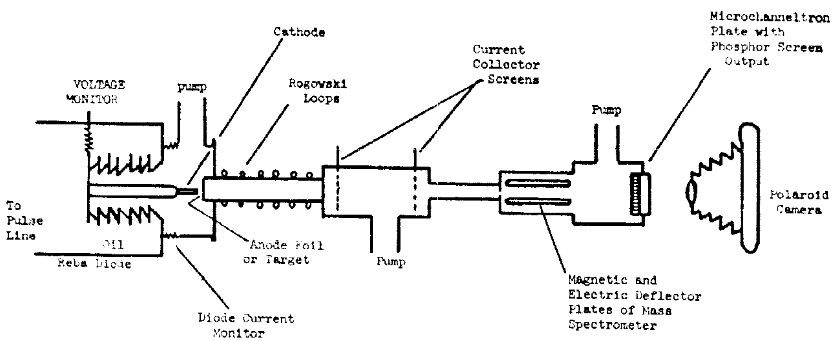

Figure 1. Apparatus for Ion Acceleration in Diodes and Drifting Beams.

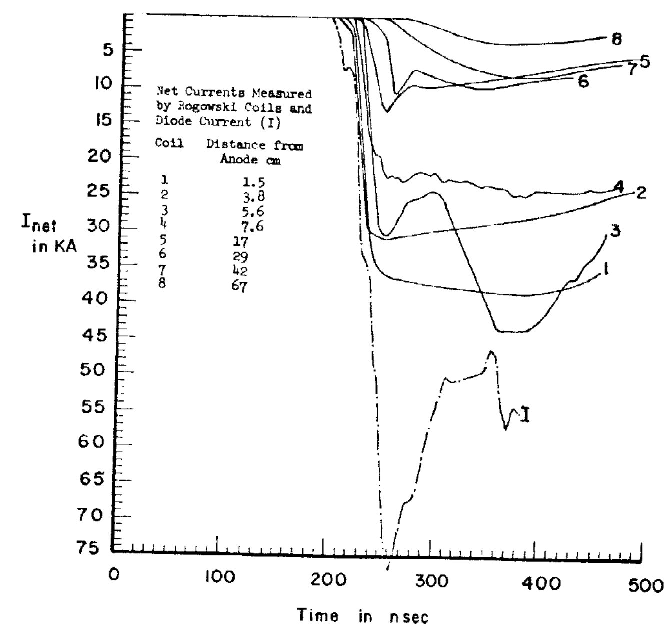

Figure 2.

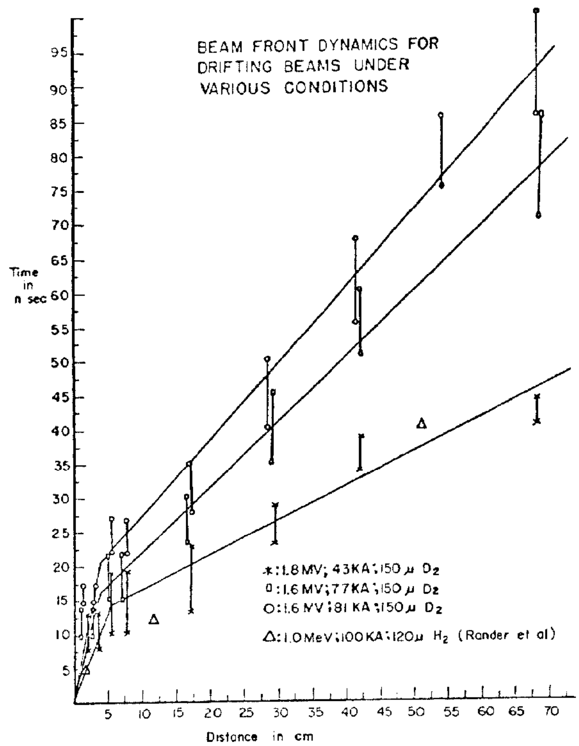

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Figure 3.

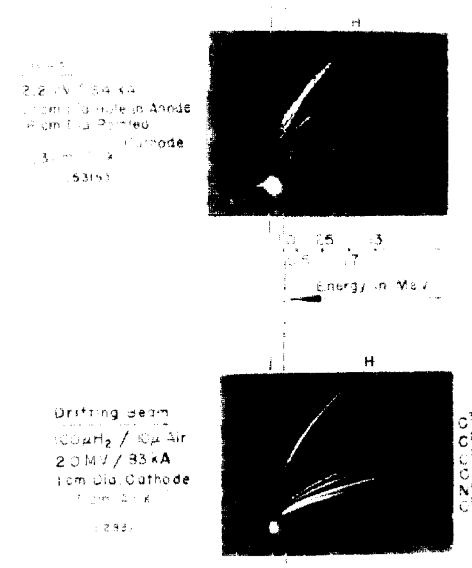

Figure 4. Energy Analyzer Data for Diode and Drifting Beam Accelerated Ions.