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EXPERIMENTAL STUDIES OF HEAVY ION COLLECTIVE ACCELERATION AT THE UNIVERSITY OF MARYLAND*

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Abstract

The collective acceleration of ions (H, C, N) from a well-localized ion source immediately downstream of a relativistic electron beam diode is experimentally investigated. The ions are produced either in a well-confined gas cloud from a fast rise puff valve or from a solid material that is placed behind the anode and bombarded by a short, 1 joule ruby laser pulse. With a 1.2 MeV, 30 kA, 30 ns electron beam pulse, 11 MeV protons and 20 MeV nitrogen ions were observed (by foil activation diagnostics) when the electron beam was fired through the well-localized gas cloud, and 20 MeV carbon ions were observed when the beam was fired through a laser-produced carbon plasma.

1. Introduction and General Considerations

During the past three years, a number of collective ion acceleration experiments were conducted at our laboratory at the University of Maryland[1-5] with relativistic electron beams injected into a vacuum drift tube. Some experiments were also performed by members of our group at Kirtland Air Force Base, the most recent ones in collaboration with R. Hoeberling of Kirtland AFB.[4] Initially, all of these experiments were done with a Luce-type diode[6] where a dielectric insert is used in the anode and the accelerated ions originate in the plasma that is created by electron bombardment and surface breakdown of the dielectric material. The use of one or two insulated electrodes in the drift tube was also studied, and it was found that, under proper conditions, they increased the ion energy by a factor of two.[1,2] More recently, the floating electrodes were replaced by a helical slow-wave structure, suggested by H. Kim, and experiments at Kirtland Air Force Base resulted also in an energy enhancement by a factor or two with such structures.[4] The use of a magnetic guide field was found to be advantageous in the helix experiments. These studies were of an exploratory nature, and it should be possible to achieve even higher energy amplification and better control of the acceleration process than with the floating electrodes. However, before continuing this line of research, we decided to concentrate our efforts on a better understanding of the physics, modifications of the system, and investigation of collective acceleration of heavy ions. For these studies, we are using a simple drift tube geometry without any additional electrodes downstream of the anode plane.

Although the physics of a Luce-type diode is not yet well-understood, we believe that the main function of the dielectric insert is to serve as a source for the ions. The electrons in the leading part of the pulse charge up the dielectric very rapidly until the potential is high enough that surface breakdown occurs. This flashover, together with the electron bombardment, vaporizes parts of the dielectric and creates a plasma. The electrons in the peak and trailing part of the pulse pass through this plasma into the drift tube. When the electron current exceeds the limiting value, the beam does not propagate into the drift tube. It forms a deep potential well with high electric gradients (typically, several hundred MV/m) at the plasma surface. Positive ions are extracted from the plasma by this high electric field and accelerated into the space charge region of the beam. When a sufficient number of ions are present and partial neutralization is achieved, the electron beam, together with the ions, begins to propagate down the drift tube. Theoretical studies on the electron beam dynamics and a piston model of the ion acceleration mechanism, together with experimental data that are in good agreement with this general picture, were presented by members of our group in a paper being published in the Journal of Applied Physics.[5]

One of the major problems with the Luce diode is the fact that plasma formation by electron bombardment and surface breakdown of the dielectric is difficult to control and reproducibility is generally very poor. In addition, metallic ion plasmas cannot be efficiently formed in this manner. For these reasons, we have now abandoned the Luce geometry in favor of a stainless steel anode and a separate localized ion source plasma right behind the anode aperture through which the electron beam enters the drift tube. A puff valve has been developed, which produces a spatially well-defined gas cloud, which then is ionized by the beam electrons. To obtain ions from solids, we are using a high-power laser which strikes and ionizes a piece of solid material (mounted on the downstream surface of the stainless steel anode) prior to arrival of the electron beam. Preliminary results, both with the puff valve and with a laser-produced plasma, will be presented in the next section.

One of the most important future applications of collective accelerators would be the generation of high-energy heavy ions where conventional methods are rather limited and very expensive. So far, only protons and light ions (below mass 20) have been accelerated by collective methods at various laboratories. The problems and prospects of acceleration of heavy ions above mass number 20 were discussed in a paper by one of us (M.R.) at the Third International Conference on Collective Methods of Acceleration.[7] As was pointed out there, it is necessary to produce a clean plasma with high charge state ions to prevent "runaway" of the electron beam with light mass impurity ions. With laser-produced high density plasmas, one should get highly stripped ions with large charge-to-mass ratios and efficient energy gain in the collective field of the electron beam. The experiments reported in this paper are, we believe, a first step in this direction, and the results so far have confirmed our expectations.

2. Experiments

In previous experimental work at our laboratory, the collective acceleration of protons to energies of 16 MeV and of carbon, nitrogen, and fluorine ions to energies of about 50 MeV was reported using electron beams of 1.5 MeV, 35 kA, 30 ns and a system of floating electrodes downstream of the anode.[1,2] The experiments reported here were performed with lower electron beam power, and, as stated above, the system of floating electrodes was eliminated in favor of a simpler configuration that more readily allows study of the acceleration process.

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A 1.2 MeV, 30 kA electron beam emitted from a 2 mm diameter carbon or tungsten cathode was used for the collective acceleration of protons and heavier ions. The stainless steel anode, located 6 mm from the cathode tip, has a 1 cm hole on axis to allow most of the electron beam to pass into a drift region downstream of the anode-cathode gap, where ions are provided by either a fast rise gas puff valve or by laser vaporization and ionization of a target material. Magnetic fields of up to three kilogauss may be provided by external dc-powered field coils. Diagnostics include Faraday cups for measuring the electron and ion current reaching a given location in the downstream drift region, B-field-swept Faraday cups for measuring ion currents, neutron detectors for measuring neutrons produced by accelerated ions striking target materials, foil activation for determining accelerated ion energy, and diode voltage and current monitors. An $E\|B$ Thomson spectrometer is currently being tested to provide better information on ion energy and charge state.

A. Gaseous Ion Sources

The collective acceleration of gaseous ions (p, N, Ne) is being investigated using the experimental configuration shown in Fig. 1. A well-localized gas cloud is injected into the region immediately downstream of the anode by a fast rise gas puff valve. A fast ionization gauge has been used to measure the pressure distribution of the injected gas in the region of the anode, and a plot of the injected gas pressure on axis as a function of axial position downstream of the anode is shown in Fig. 2. Peak gas pressures in excess of 10 microns may be injected in this manner, and it is easily seen that the gas cloud represents a source of ions that is well-confined to the anode region at the time of electron beam injection. Ionization of the gas is provided by the electron beam.

Theoretical work by several groups[5,8] has indicated that electron beam propagation in such systems in excess of the limiting current cannot be expected in the region downstream of the anode unless ions are provided at the anode plane to allow some charge neutralization. Figure 3 shows the results of experimental measurements of the current reaching a position 31 cm downstream of the anode as a function of the injected H_2 gas pressure. Also plotted in the figure as a function of injected gas pressure are the relative number of neutrons produced by accelerated protons striking copper target foils. Neutron production is usually a good indication of the effectiveness of acceleration in such systems. It is easily seen that significant acceleration is observed only when enough ions are present that sufficient electron beam propagation can take place. At very high injected gas pressures, the diode voltage probe shows diode shorting, and effective acceleration is not observed.

The activation of stacked copper foils has been used to obtain a crude proton energy spectrum in this configuration, and a typical result is shown in Fig. 4. Proton energies 8-10 times the electron energy have been routinely observed in these experiments.

Measurements of the effect of an applied magnetic field (up to three kilogauss) on the acceleration process are shown in Fig. 5. It is evident that, at least for fields of these magnitudes, an applied magnetic field has little or no effect on the ion acceleration process in contrast to results reported previously[3,4] where the ions were produced by a dielectric anode and magnetic fields above two kilogauss effectively quenched the acceleration. It is presumed in that case that the magnetic field inhibits the surface breakdown of the dielectric anode that produces most of the ions.

The acceleration of nigrogen ions to energies in excess of 20 MeV has also been observed using the same configuration. In this case, aluminum target foils were used and the production of Cl^{34m}, Al^{28}, and N^{13} was observed from both the gamma spectra and the halflives of these products. The acceleration of neon ions was not observed, probably due both to the difficulty in achieving high charge states using electron beam ionization of the gas and to the high threshold energies for the expected nuclear reactions.

B. Laser-Produced Ion Sources

A most promising method for the production of high charge state heavy ions appears to be laser-target interaction. In experiments reported in detail elsewhere,[5] a 1 joule Q-switched ruby laser was used to create a dense carbon plasma in the region immediately downstream of the anode, and a 1.2 MeV, 30 kA electron beam was injected through the plasma in a manner similar to the gas valve configuration. Aluminum target foils were used, and the production of C^{11}, Al^{28}, and Cl^{34m} was observed from both the gamma spectra and the product halflives. From considerations of the known cross sections for the production of these isotopes, the estimated carbon ion energy is greater than 20 MeV.

III. Conclusions

The acceleration of heavy ions to high energies using intense linear electron beams requires the preparation of high purity, high charge state ion clouds in advance of the electron beam injection. Relying upon the electron beam to provide the ionization of a neutral gas cloud would require a very long electron beam pulse length to achieve the desired high charge states. For this reason, laser-produced plasmas appear to be preferable. A new experimental facility is under construction at our laboratory that will allow the careful preparation of such heavy ion plasmas using a 10 joule Q-switched ruby laser irradiating various solid target materials. Impurities will be reduced by separating the pumping of the downstream region from the diode and injecting the electron beam through a thin foil. Such a system should allow careful parameter surveys of the optimum beam/plasma parameters for the collective acceleration of heavy ions. In addition, a higher current, longer pulse length electron beam generator is also under construction and will be available for these studies within the next year.

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References

1. C. N. Boyer, H. Kim, and G. T. Zorn, Proc. Int. Topical Conf. on Electron Beam Res. & Tech., Vol. II (Albuquerque, N.M., 1975).
2. C. N. Boyer, W. W. Destler, and H. Kim, IEEE Trans. Nucl. Sci. 24 (June 1977).
3. W. W. Destler and H. Kim, Proc. 2nd Int. Topical Conf. on High Power Electron and Ion Beam Res. & Tech. (Ithaca, N.Y., Oct. 1977).
4. W. W. Destler, H. Kim, G. T. Zorn, and R. F. Hoeberling, Proc. 3rd Int. Conf. on Collective

Methods of Acceleration, Laguna Beach, Calif., May 1977 (to be published).

5. W. W. Destler, H. S. Uhm, H. Kim, and M. Reiser, Journal Appl. Phys., Mar. 1979 (in press).
6. J. S. Luce, Annals of N.Y. Acad. of Sci. 25, 2171 (1975).
7. M. Reiser, Proc. 3rd Int. Topical Conf. on Collective Methods of Acceleration, Laguna Beach, Calif., May 1978 (to be published).
8. J. W. Poukey and N. Rostoker, Plasma Phys. 13, 897 (1971).

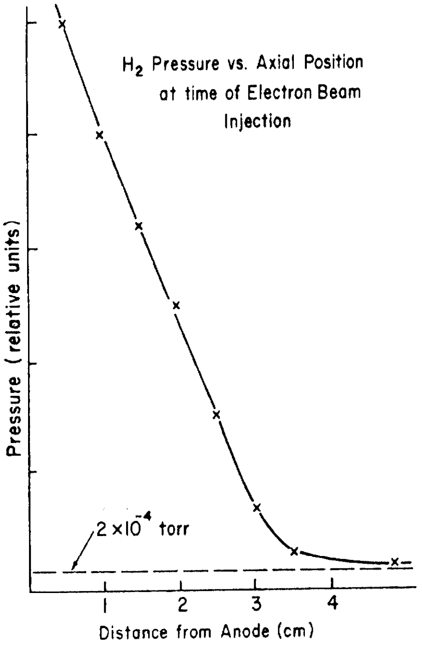

Fig. 2 Hydrogen gas pressure on axis as a function of axial position downstream of the anode.

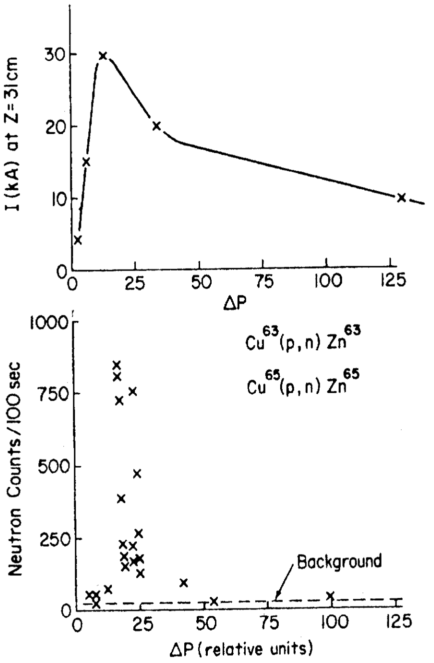

Fig. 3 Electron beam current reaching z = 31 cm and relative neutron production from copper target foils as a function of injected hydrogen gas pressure.

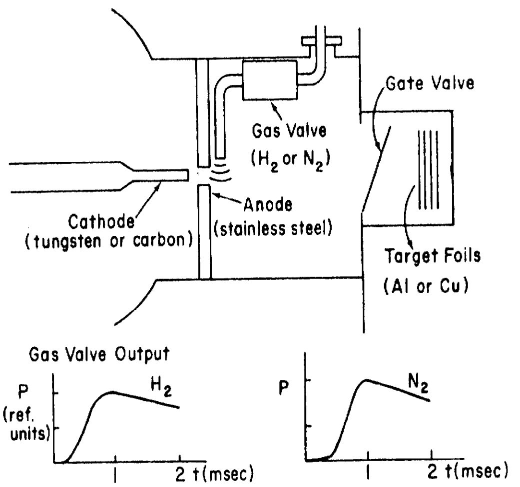

Fig. 1 Experimental configuration used for the collective acceleration of gaseous ions.

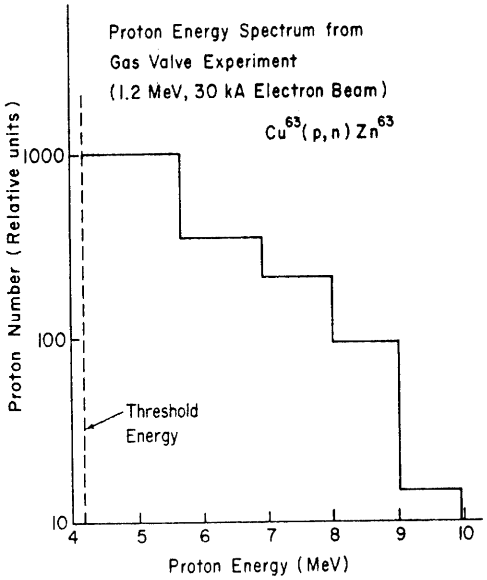

Fig. 4 Typical proton energy spectrum from stacked copper target foils.

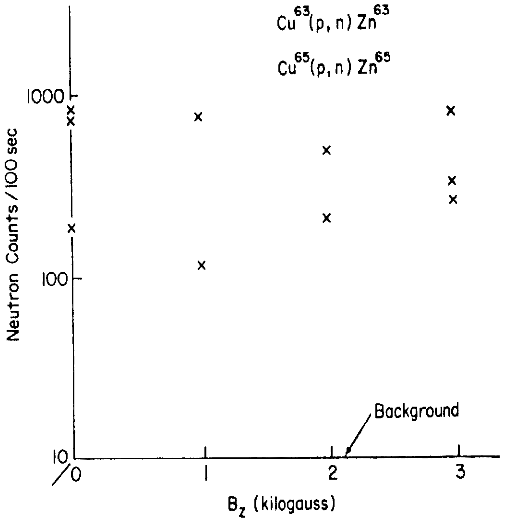

Fig. 5 Relative neutron production from copper target foils vs applied axial magnetic field.