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COLLECTIVE ACCELERATION OF LIGHT AND HEAVY IONS*

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Abstract. The collective acceleration of ions (H, D, He, C, N, Ne, Al, Ar, Fe, Cu, Xe) from a well localized plasma immediately downstream of a relativistic electron beam diode is experimentally investigated. The ions are produced either by electron impact on a well confined gas cloud from a fast rise puff valve or by a high power (10J, 15ns), Q-switched ruby laser pulse incident on solid material. Peak ion energies up to 5 MeV/nucleon were observed using a 1.5 MeV, 35 kA, 30 ns electron beam pulse. Ion energy diagnostics include nuclear activation, range-energy/track etching, and time of flight measurements. The effect of a strong applied axial magnetic field (1-10 kilogauss) on the acceleration process has also been studied.

Introduction

During the past three years, a number of experiments have been conducted in our laboratory at the University of Maryland[1-4] to investigate the collective acceleration of ions from an independently controllable localized ion source using an intense linear electron beam. Such experiments have produced the highest peak ion energy and heaviest particle to be accelerated by collective means to date.[4] These studies were a natural outgrowth of experiments initially conducted by Graybill, et al.[5], who first reported the collective acceleration of ions when an intense electron beam is fired into a neutral gas background, and by Luce[6], who reported collectively accelerated ions when an intense electron beam is fired through a hole in a dielectric anode. This early work was followed by experimental and theoretical investigations of this phenomena at several other laboratories[7-11] as well as our own.

The use of independently controllable systems as the source of the ions collectively accelerated in our experiments has allowed an investigation of the acceleration process over a wider parameter range than has been achievable in Luce-type systems, and, more importantly, has allowed much greater control over the number and species of ions to be accelerated. In our experiments, gaseous elements are injected into a region immediately downstream of the anode-cathode gap by a fast rise puff valve, with ions produced by electron impact and subsequent ion-ion avalanche ionization processes. Ions from solid materials have been produced by the firing of a 10 J, 15 ns, Q-switched ruby laser at target materials located on the downstream side of the anode. The details of these experiments, and some indications of the relative advantages of the two systems, will be discussed in the next section.

Several experiments involving Luce-type systems have reported the suppression of effective ion acceleration in the presence of an applied axial magnetic field.[8] Experiments reported by our group previously[1] have indicated that when the puff valve ion source is used in place of the dielectric anode in a Luce diode, magnetic fields up to three kilogauss do not strongly affect the acceleration process. This question is important because the utility of such systems as high energy ion sources depends to some extent upon the beam emittance characteristics. Presumably, a strong applied magnetic field can limit the radial motion of the electrons, and therefore possibly improve the emittance of the collectively accelerated ions. In this paper, studies of the effects of applied magnetic fields of up to 10 kilogauss on the acceleration process will be reported.

Experiments

The general experimental configuration is shown in Figure 1. An intense, relativistic electron beam (1.5 MeV, 35 kA, 30 ns) is emitted from a 4 mm dia. tungsten cathode located 5 mm from a stainless steel anode. A 20 mm hole in the anode on axis allows almost all of the current in the beam to pass through the anode plane into the downstream region. The diameter of the drift tube is 25 cm. Ions to be accelerated are provided either by electron beam ionization of a well-confined neutral gas cloud injected on the downstream side of the anode, or from a plasma generated by firing a 10 J, 15 ns, Q-switched ruby laser at targets mounted on the downstream side of the anode. All experiments were performed in a background vacuum of less than 10^{-4} torr.

Accelerated ions were measured using three different diagnostic techniques. These are: 1) Time of flight of the ion current pulses between two charge collection probes after any accompanying electrons are swept away by a sweeping magnet (the probe separation distance was 30 cm), 2) range-energy/track etching techniques in which the ions penetrate through varying thickness foils of known stopping power before striking CR-39 track plates, which are etched to reveal individual ion tracks, and 3) nuclear activation of target materials by the accelerated ions (an especially useful diagnostic for the lighter ions, where several high cross section, low threshold energy reactions are available).

Gaseous Ion Sources

The collective acceleration of ions from a localized gas cloud has been studied extensively during the last two years and the results are available in the literature.[3,4] These results are summarized in Figure 2, which indicates that heavy ions (D, He, N, Ne, Ar, Kr, Xe) have been accelerated to peak energies of about

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5 MeV/nucleon independent of ion mass. The number of ions accelerated to these peak energies decreases as the mass of the accelerated ion increases, and in the case of Xe, about 10^7 ions have been accelerated to energies in excess of 638 MeV. In related experiments using a different experimental geometry, proton energies of up to 14 MeV have been obtained. Typical peak currents measured by the charge collection probes are about 30 A for protons decreasing to several amperes for the heavier ions. The charge state of the heavy ions has not been directly measured, but the number of particles counted on the CR-39 track plates for various ion energies can be reconciled with the currents observed on the time of flight probes only if the ions are assumed to be nearly fully stripped.

Laser Produced Ion Sources

The collective acceleration of ions from a laser produced plasma has been reported previously[1,2], but a systematic study had not been attempted due to a lack of a laser of suitable power to provide the dense, high charge state plasmas desired. During the past year, however, a 10 J, 15 ns, Q-switched ruby laser has been acquired for this purpose, and studies of the collective acceleration of ions from various laser target materials have commenced. Preliminary results of these experiments are plotted in Figure 2 along with the results from the neutral gas injection experiments. Ions from Carbon, Aluminum, Iron and Copper targets were accelerated to energies of about 5 MeV/nucleon, as in the gaseous ion experiments. The optimum delay between the firing of the laser and the injection of the electron beam was about 500 ns. No accelerated ions were observed when the laser was not fired. An attempt was made to accelerate Tantalum ions using the laser system, but the results indicated that substantial numbers of impurity ions (including protons) were accelerated along with the Ta ions. Thus the time of flight and range-energy/track etching diagnostics did not yield the same peak energy (protons at 5 MeV penetrate almost an order of magnitude further into Aluminum stopping foils than do Ta ions of 5 MeV/nucleon). We therefore did not include Ta data in our results summarized in Figures 2 and 3.

Although the peak ion energies obtained using the laser ion source were similar to those obtained in the gas injection experiments, the use of the laser ion source does appear to increase the number of ions accelerated to high energy. In Figure 3, data allowing a comparison of the time of flight data for the two ion sources is given. In the gas injection experiments, the time of flight of the first rise of the ion current pulses is generally much faster than the time of flight of the first peaks in the current waveforms. In the laser ion source data, the two are comparable, as in the waveforms for Fe ions shown in the figure inset. Experiments to optimize target geometry are currently in progress.

Effect of an Applied Axial Magnetic Field

To study the effect of an applied axial magnetic field on the acceleration process, a new 15 cm dia. vacuum chamber was employed. Magnetic fields of up to 10 kilogauss were produced by a simple solenoid of length 75 cm and diameter 16 cm, with the field at the cathode about 80% of the value at the center of the solenoid. For comparison purposes, the new system was operated with both a dielectric "Luce" anode (CH_2 with a 10 mm hole on axis) and with the standard puff valve arrangement described previously. Figure 4(a) shows the neutrons produced when accelerated ions from both systems strike copper or mylar target foils located 90 cm downstream of the anode. The proton induced neutrons are predominantly from the reactions $Cu^{63}(p,n)Zn^{63}$ and $Cu^{65}(p,n)Zn^{65}$, and the deuteron induced neutrons are likely from the reaction $C^{12}(d,n)N^{13}$. As has been reported previously, the neutron counts observed when the dielectric anode is used as the ion source decrease rapidly as the applied magnetic field strength is increased, probably due to inhibition of the surface breakdown across the dielectric that produces most of the ions to be accelerated. When the puff valve ion source is employed, however, the decrease is much less, and significant neutron counts are observed even when magnetic fields of 8 kilogauss are applied. The peak deuteron energy (Figure 4(b), measured using stacked mylar foil activation techniques, remains almost constant up to magnetic field values of 9 kilogauss, above which experiments have not yet been attempted.

The reason for the slight decrease in the neutron counts and peak ion energy as the magnetic field is applied in the puff valve experiments is apparent from data shown in Figure 5(a), where the proton current reaching the charge collection probe 90 cm downstream of the anode is plotted as a function of applied field. The decline in the peak ion current observed may be due to the decreased volume of interaction of the electron beam (now confined by the magnetic field) with the gas cloud, and is consistent with the decline in neutron counts observed. The positive effect of the magnetic field on the ion beam emittance is evident in Figure 5(b), where the ratio of the peak currents measured at positions 120 cm and 90 cm downstream is plotted as a function of field strength. It is evident that confining the beam electrons to the system axis using the applied magnetic field also tends to inhibit radial spreading of the accelerated ion beam.

Conclusions

Light and heavy ions have been accelerated to peak energies of about 5 MeV/nucleon using a 1.5 MeV, 35 kA, 30 ns electron beam pulse. In the case where the puff valve was employed, the acceleration process is not strongly affected by an applied magnetic field up to 9 kilogauss, and the ion beam emittance appears to be improved. Preionization of the source of the accelerated ions by the laser-target interaction configuration appears to result in the acceleration of a larger fraction of the ions to the highest energies.

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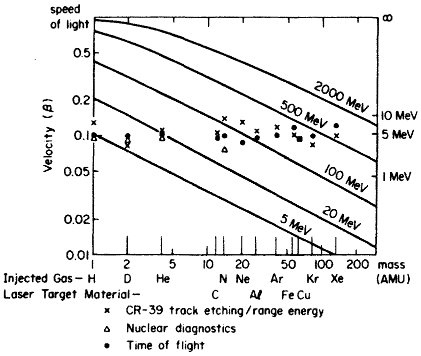

Figure 2. Peak ion energy for different ion species using various diagnostics.

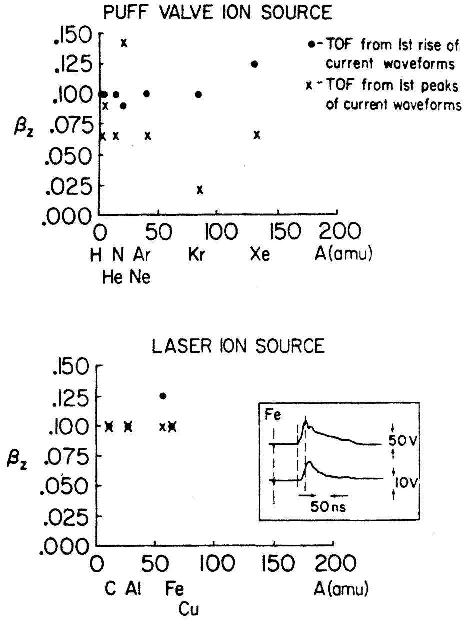

Figure 3. Measured ion velocities using time of flight diagnostics for the gaseous ion source and laser ion source.

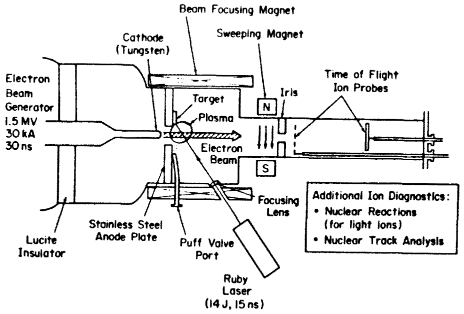

Figure 1. General experimental configurations.

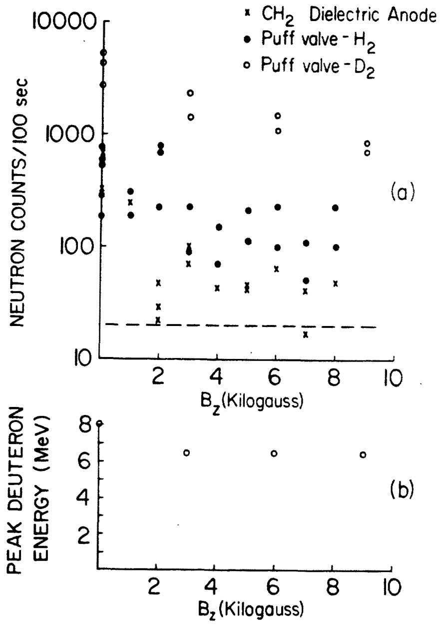

Figure 4. (a) Neutron counts for the Luce diode and the diode with the puff valve for hydrogen and deuterium versus magnetic field intensity. The dashed line indicates the background level. (b) Peak deuteron energy versus magnetic field.

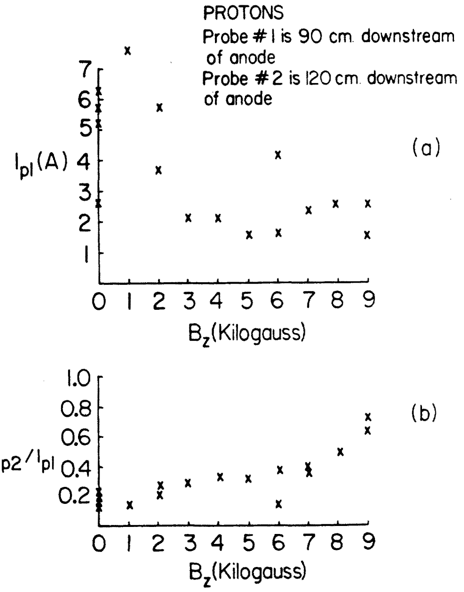

Figure 5. (a) Front probe current versus magnetic field. (b) Ratio of rear probe current to front probe current versus magnetic field.