 IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

IFA-2 COLLECTIVE ION ACCELERATOR EXPERIMENTS*

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Abstract

Ion acceleration has now been demonstrated with the IFA-2 collective ion accelerator system. The IFA-2 system is described, photoionization experiments are summarized, and ion results are presented. Using a 1 MeV electron beam and a 30 cm acceleration length, IFA-2 has produced 5 MeV H^+, 10 MeV D^+, and 20 MeV He^{++}. This means that accelerating fields of 33 MV/m over 30 cm have been achieved with a controlled collective accelerator for the first time.

I. Introduction

It is the goal of collective accelerators to produce high gradient particle acceleration using the collective fields of an ensemble of charged particles.[1] In conventional accelerators, the fields are produced by charges and currents in metallic structures, and the acceleration gradients are limited by electrical breakdown at the acceleration gaps. In contrast, very high fields are possible in collective accelerators. For example, using an intense relativistic electron beam (IREB), it should be possible to produce space charge fields of 1 GV/m or higher.[2] The challenge is to provide a method for controlling these large space charge fields over a sizeable distance to produce high gradient particle acceleration. In this paper, we present ion acceleration results for the IFA-2 collective accelerator system that demonstrate that accelerating fields of 33 MV/m over 30 cm have been achieved with a controlled collective accelerator for the first time.

The ionization front accelerator (IFA) concept uses a laser to accurately control the motion of the strong potential well at the head of an IREB.[1] As shown in Fig. 1, laser photoionization of a special working gas is used to create a charge neutralizing plasma through which the IREB will propagate. As the laser is swept, the potential well at the IREB head synchronously follows it. Ions trapped in the potential well experience high gradient particle acceleration as the laser sweep velocity is increased. It is important to note that the laser energy, the ion energy, and the IREB energy are, respectively,

$$\varepsilon_{laser} << \varepsilon_{ions} < \varepsilon_{IREB} \qquad (1)$$

This means that a very small amount of (expensive) laser photon energy is used to control a very large amount of (inexpensive) pulsed power IREB energy.

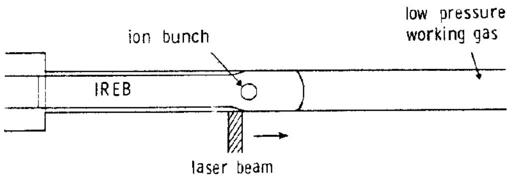

Fig. 1. Ionization Front Accelerator (IFA).

In the following, we will describe the IFA-2 system, summarize photoionization experiments, and then present the IFA-2 ion results.

II. The IFA-2 System

Two complete IFA systems have been built (IFA-1 and IFA-2). The first generation system (IFA-1) had a 10 cm acceleration length and used Cs as the working gas.[3] Two-step photoionization was employed with a dye laser exciter (852.1 nm) and a frequency-doubled ruby laser kicker (347 nm). The dye laser beam was accurately swept using a light pipe array. Controlled motion of the potential well was demonstrated with three different sweep rates, and limited ion data were obtained.[3] A second generation system (IFA-2) has a 30 cm acceleration length, and is shown in Fig. 2. In its final version, the IFA-2 system uses Cs as the working gas.[4] Two-step photoionization is again employed, but now with a dye laser exciter (852.1 nm) and an XeCl laser kicker (308 nm). The dye laser pre-excites the entire Cs volume, and the XeCl laser is swept in time with an electro-optic crystal deflector.

The IFA-2 IREB machine uses an oil-insulated Marx generator, an ethylene-glycol filled Blumlein, and a field emission diode with a carbon cathode. Laser-triggered gas switches are used to command fire the IREB with a 1 σ jitter as low as 1 ns. The beam emerges from the diode with a rise time of 18 ns, whereas a rise time of ≲ 5 ns is required. To steepen the rise time, the beam is injected into a gas conditioning cell (1.1 cm radius, 2 m long) filled with 1.5 Torr argon. The conditioning cell steepens the rise time to as low as 2.3 ns. The desired beam parameters at the Cs cell are 1 MeV, 30 kA, 1 cm radius, ≲ 5 ns rise time, ≳ 30 ns flat-top, and a ≲ 1 ns command fire jitter. The actual parameters are ~1 MeV, 12-42 kA, 3-8 ns rise time, 40 ns FWHM, and a command fire jitter of a few ns.

The Cs cell contains the main experimental drift tube which has a radius of 1.1 cm and a length of 30 cm. The Cs cell is inside an oven which is heated

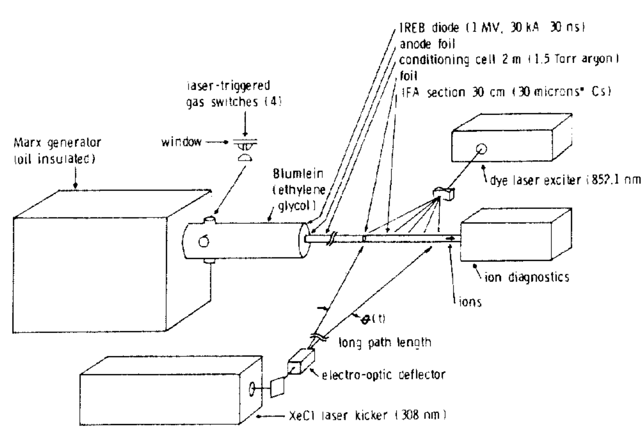

Fig. 2. The IFA-2 System.

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*Supported by Division of Advanced Energy Projects, DOE.

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to about 235° C. A Cs ampule held at a slightly lower temperature sets the Cs reduced pressure to about 30 microns, which provides a neutral Cs density of about 10^{15} cm^{-3}. The cell has windows through which the laser beams enter, and through which a streak camera can view the experiments. Lastly, the vacuum plumbing is arranged so that an ion source gas (e.g., hydrogen) can be mixed with the Cs inside the experimental cell.

A ruby-pumped dye laser tuned to the desired Cs line (852.1 nm) is used to pre-excite the entire Cs volume. The beam is spread with a diverging cylindrical lens and directed to enter the main Cs cell from the side as shown. The nominal dye laser parameters are 100 mJ with a 30 ns FWHM, although peak intensities up to 195 mJ have been obtained. The advantage of pre-exciting is that the cross-section for photoionization from the excited state is about 50 times higher than the cross section for photoionization from the ground state.

An excimer laser is used to photoionize the excited Cs. The excimer laser is an XeCl injection-locked amplifier system that has a very uniform, very low divergence beam. Nominal operating parameters are 1100 mJ, 30-40 ns FWHM, and with 75% of the energy in a four times diffraction limited spot (i.e., a half angle of 50 microradians). The main portion of this beam is injected into an electro-optic crystal deflector with a throughput aperture of 1.1 cm x 1.1 cm. The deflector contains 11 KD*P crystals and produces a maximum deflection angle of 2 mrad for a net 30 kV change in applied potential. In actual use, the deflector is biased at -15 kV and an electric driver circuit produces a rise to +15 kV with a quadratic temporal dependence. After traversing the optical equivalent of 150 m, the beam sweeps 30 cm along the Cs cell in 20 ns with a quadratic temporal dependence. The sweep time can be changed by changing an inductance in the driver circuit. A throughput threshold energy of 127 mJ with a spot diameter of $\lesssim$ 2.5 cm at the cell was needed for the IFA-2 experiments. The actual transmitted energy was 65-195 mJ with a spot diameter at the cell of about 2.5 cm.

An extensive number of diagnostics were used on the full IFA-2 experiments to monitor the IREB, the Cs, the dye laser, the XeCl laser, the deflector, and the timing. A streak camera and open shutter camera were used to monitor the IREB beam front. Ion diagnostics implemented included time-of-flight, nuclear activation, stopping foils with CR-39, and a magnetic spectrometer with CR-39. The last diagnostic was used to obtain the ion energy spectra we will present in Section IV.

III. Photoionization Experiments

Experiments were performed to verify that the Cs photoionization scheme was working as planned. In these experiments, the two lasers were used to excite and photo-ionize the Cs in the first 10 cm of the Cs cell. Then, by observing the IREB propagation behavior with a streak camera, we were able to observe the threshold for charge neutralization at which the IREB would propagate quickly through only the first 10 cm. From these experiments we found, in agreement with theory, that only 1 mJ/cm^2 of dye laser and 0.5 mJ/cm^2 of swept XeCl laser are needed for IFA control of the IREB (which has about 1 kJ of energy). These results demonstrate that the IFA-2 photoionization scheme works, and that the scaling relation (1) holds well for the IFA.

IV. IFA-2 Ion Results

A complete discussion of the IFA-2 experiments, including streak pictures, will be presented elsewhere. In the space available here, we will summarize our most interesting ion results. Ion energy spectra are produced by ion tracks in a solid state nuclear track detector (CR-39) placed inside a magnetic spectrometer. After etching in NaOH, the individual track pits are visible and can be counted with the aid of a microscope.

Proton results are given in Fig. 3. In Fig. 3a, we show the proton spectrum produced for the IFA-2 system at room temperature, filled with 100 microns H_2, and the lasers blocked. This result gives the natural collective acceleration result for our system and shows a peak at ~1 MeV. In Fig. 3b, we show the proton spectrum for the full IFA-2 system, heated, with 50 microns Cs and 50 microns H_2, and lasers fully operational. Here the sweep length was 10 cm and the final laser sweep speed βc had $\beta = 0.058$, which corresponds to a 1.7 MeV proton. The proton spectrum is peaked very close to 1.7 MeV indicating that ion trapping and ion acceleration occurred as programmed. In Fig. 3c, we show the proton spectrum for the full 30 cm IFA-2 system. Here the final sweep speed had $\beta = 0.1$ which corresponds to a 5 MeV proton. Note that a shift in the main ion energy from Fig. 3a to Fig. 3b to Fig. 3c is clearly demonstrated.

Helium ion results are given in Fig. 4. In Fig. 4a, we show the natural collective acceleration result for 100 microns He at room temperature. In Fig. 4b, we show the He^{++} spectrum for the full 30 cm IFA-2 system. Here the final sweep speed had $\beta = 0.1$ which corresponds to a 20 MeV He^{++} ion. The ion number is low which is why the noise level of the CR-39 is visible. Nonetheless a clear ion peak is shown at the programmed ion energy.

Deuterium ion results are as follows. For the full 30 cm IFA-2 system, the final sweep speed had $\beta = 0.1$ which corresponds to a 10 MeV D^+ ion. A narrow ion peak at 10 MeV is clearly visible in the D^+ energy spectrum.

The helium and deuterium results demonstrate that fields of 33 MV/m over 30 cm have been controlled by IFA-2.

The number of ions that can be trapped under optimum conditions should be about $NZ = n_b r_b^3$, where Z is the ion charge, n_b is the IREB density, and r_b is the IREB radius. For IFA-2 parameters, this is $NZ \approx 2.0 \times 10^{12}$. Based on the estimated phase space distribution of the final ion bunch, and assuming that the bunch is charge neutral and drifts ballistically, then it is possible to estimate N based on the small number of ions in the phase space accepted by the magnetic spectrometer. The rough estimates for N corresponding to the data in Figs. 3a, 3b, 3c, 4a, and 4b are, respectively, 5×10^{12}, 1×10^{12}, 2×10^{10}, 1×10^{11}, and 3×10^{7}. The last number is low presumably because the swept XeCl laser intensity was just marginal for this case. Also, there was no opportunity to optimize the laser timing and ion source gas pressure to maximize N. For the 10 cm IFA case of Fig. 3b, the laser intensity was ample, and we

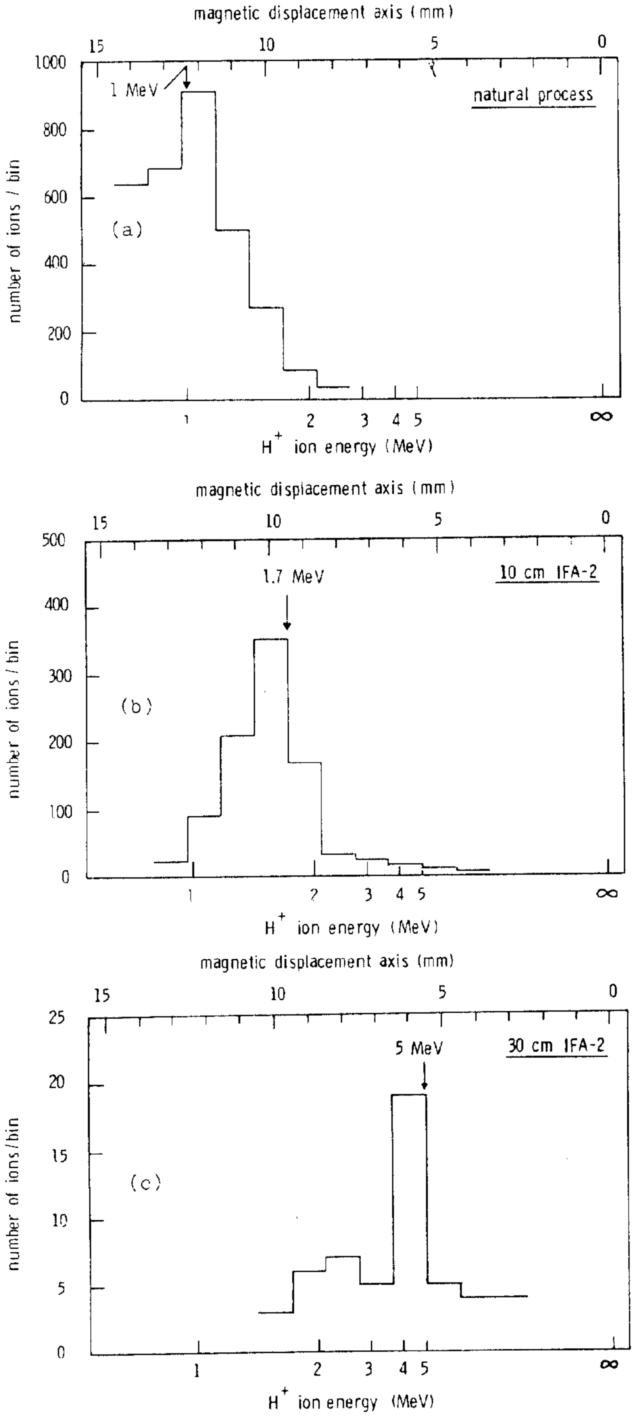

Fig. 3. Proton acceleration. (a) Natural process, (b) Full IFA-2 system with 10 cm sweep, (c) Full IFA-2 system with 30 cm sweep (bin size: 0.1 mm x 0.1 mm).

have $N \approx 1 \times 10^{12}$ without any optimization of laser timing or ion source gas pressure. Thus with proper laser intensity and ion source optimization, we expect that $N \gtrsim 10^{12}$ should be routinely attainable.

We would like to note that with the appropriate laser intensity, the same experiment should control fields of 100 MV/m over $\gtrsim$ 1 meter.

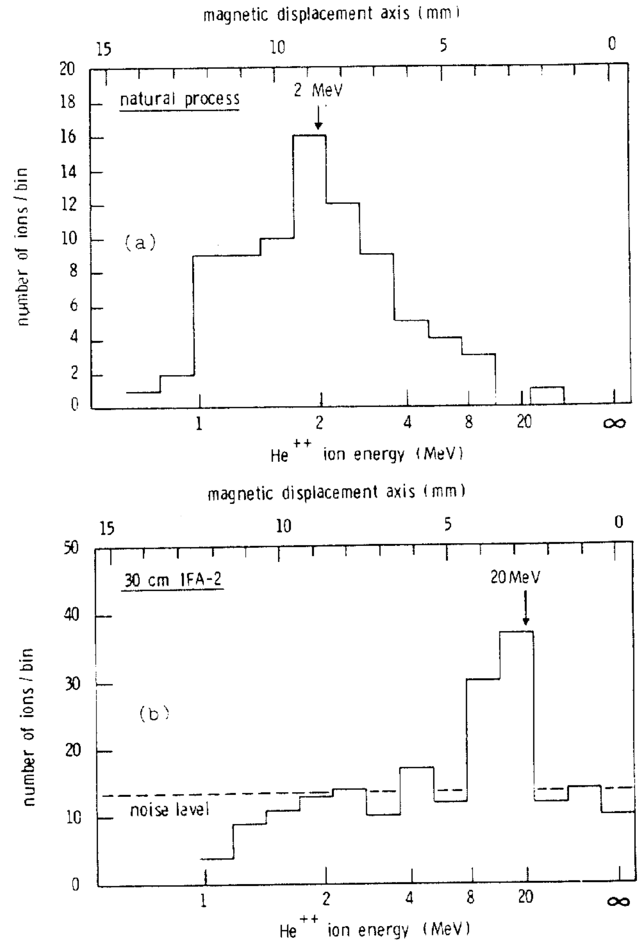

Fig. 4. Helium ion acceleration. (a) Natural process (bin size: 0.1 mm x 0.1 mm). (b) Full IFA-2 system with 30 cm sweep (bin size: 1.0 mm x 4.0 mm).

V. Conclusions

IFA-2 ion results have been presented showing that 5 MeV H^+, 10 MeV D^+, and 20 MeV He^{++} have been achieved with an acceleration length of 30 cm. The last results demonstrate controlled collective acceleration with fields of 33 MV/m over 30 cm.

Acknowledgments

The assistance of Willie Jaramillo and Gary Samlin with the experiments is gratefully acknowledged.

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