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SIXTY keV D⁻ BEAMS USING DOUBLE CHARGE-EXCHANGE SYSTEM*

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Abstract

A D⁻ beam with current greater than 100 ma was accelerated to 60 kV. The beam, with pulse length 10 ms, was generated by charge-exchange in cesium vapor. The physics of generation, propagation at low energy, and acceleration is discussed.

Introduction

More than 100 mA of negative deuterium ions have been produced by double charge-exchange in cesium, transported to an accelerator, and accelerated to 60 keV. The beam with pulse length 10 ms originates as a 1 keV D⁺ beam which is passed through a cesium jet. The transport distance of 1.4 meters for the low energy beam prevents significant cesium deposition in the accelerator and is used to control the electron density in the beam at the entrance to the accelerator. The accelerator has been designed to yield good beam optics, and this paper presents first results of its operation.

The use of double charge-exchange for producing intense D⁻ beams by Osher et al.¹ demonstrated the feasibility of obtaining large area

beams at kilovolt energies. Recent measurements² indicate that the equilibrium fraction of D⁻ at a few hundred eV is greater than 30%. With demonstration of acceleration, it follows that systems based on double charge-exchange in cesium have the potential of being scaled to tens of amperes or more at very high energies. Combined with a stripper, intense neutral beams could thus be produced at the high efficiencies required for controlled fusion experiments and reactors.

The experiments and calculations described here have the purpose of determining the physics needed to construct much larger beams. After a brief description of the overall system, the design and operation of the major components are described. Analysis is made of beam acceleration, charge-exchange, beam propagation, and control of the electron component of the beam. The latter is necessary to prevent loading of the negative ion accelerator and resulting power inefficiencies.

Negative Ion System

Figure 1 shows a schematic of the overall system. The excess gas from the positive ion source is handled by expansion into a large volume, so the beam duration is 10-25 ms. The useful

Fig. 1 Schematic of the D⁻ experiment.

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positive ion current is limited to about 1A by system apertures and by the angular divergence of the present beam, as discussed below. The beam passes through the cesium cell and a drift space to the accelerator. The diagnostic tank floats to the accelerator voltage, and data is telemetered to the diagnostic area at ground. A stripping cell, needed to convert the beam to neutrals, has not been added to the system in the present experiments.

The drift space between the cesium cell and the high voltage accelerator has the double purpose of providing the proper environment at the accelerator entrance and of permitting access for analyzing the low energy negative ion beam.

Not shown in the schematic are the high voltage power supplies to accelerate the beams, control electronics, and diagnostic gear.³

Positive Ion Source

The positive ion beam is generated using a "1QA" LBL arc chamber.⁴ The accelerator, which uses a strong accel-decel system, was designed using the *Wolf* code.⁵ At the design current of $0.5A/cm^2$, the R.H.S. angular divergence of the

Fig. 2. Calculations of electric potential and particle trajectories in low voltage sources. The plasma emitter is to the left, the downstream electrode is at ground, and the emitter electrode is at 1 kV. (a) $V_{center} = 12.5$ kV, $j = 0.5A/cm^2$; (b) $V_{center} = 11.0$ kV, $j = 0.37A/cm^2$; (c) $V_{center} = 15$ kV, $j = 0.5A/cm^2$.

1 keV was predicted to be 3.5° perpendicular to the grids, as shown in Fig. 2a. At this current density, however, the accelerator was unable to hold voltage. As a result, the source is operated at a current density of $0.37A/cm^2$ with a predicted width of 8° ; c.f. Fig. 2b.

The maximum obtainable current density scaled according to a Child-Langmuir equation:

$$j = 1.22 \times 10^{-3} V_2^{3/2} / d^2$$

where the distance d is measured from the middle of the center electrode to the surface of the emitting plasma (as calculated by the Wolf code), and V_2 is the voltage across the gap. The result is illustrated in Fig. 3. Electrical breakdown thus occurs under conditions for which particle

Fig. 3. Current vs center voltage in the 1 kV source. Electrical breakdown occurred for larger currents.

trajectories are identical. The lack of dependence on current density, per se, indicates that the mechanism is not secondary particles generated in the intergrid gas or from downstream, but rather collisions between beam particles and the exit grid.

As a result of this problem, a new grid, Fig. 2c, has been designed and constructed. The change can be considered a decrease in the focal length of the electrical lens formed by the center and exit grid. The result is predicted to be a RMS divergence of 3.5° , but with a narrower output beam than in the original design. The grid will be tested in the near future.

Charge-exchange within the grids generates neutral atoms to 10 keV and residual secondary ions which are trapped in the potential until they reach the center grid. The ion flow at the highest energy is highly directed, as can be seen

from Fig. 2, so that these energetic neutrals are directed in the forward direction. Analysis of this energetic component requires knowing the particle trajectories, the gas composition and pressure in the grid region, and the energy dependence of the charge-exchange cross section. Details given elsewhere⁶ result in the excellent agreement between theory and measurements shown in Fig. 4. This charge-exchange has consequences

Fig. 4. Energy spectrum of neutrals formed by charge-exchange in the 1 kV accelerator.

which are tolerable in the present experiment, but which must be mitigated for d.c. systems. The energetic current is only 5% of the total, but because of the high energy, represents about a 40% power drain. In addition, the secondary ions cause an additional drain which heats the center grid. Consequently, the use of a strong accel-decel accelerator in an eventual device will require that the gas pressure in the grids be reduced by an order of magnitude, e.g., by pumping on the arc side of the grids. Alternatively, the fact that the equilibrium fraction is so large at energies of order of 100 eV may permit the use of plasma acceleration techniques which do not require grids.^{7,8}

A deuteron beam in D_2 rapidly reaches an equilibrium in which 90% is D^0 . The mean free path for neutralization $\lambda = [n(D_2)]^{-1} \approx 0.1/p$ cm at 1 keV, with p in Torr. The pressure at the exit to the grids is estimated to be 5×10^{-3} Torr, so neutralization occurs in about 20 cm, and the beam at the entrance to the charge-exchange cell is predominantly D^0 .

Cesium Charge-Exchange Cell

The charge-exchange cell is illustrated in Fig. 5. The cesium passes from an oven through a pulsed valve, open ~ 1 second, and forms the jet. After crossing the beam, the used cesium is frozen on a cold surface. It is periodically recycled into the oven. The beam passes through a

Fig. 5. Cesium charge-exchange system

a set of cold apertures which limit the flow of cesium from the cell. Operation has been highly reliable, with many recyclings before additional cesium is required.

The jet consists of a simple slot, as illustrated in Fig. 6. The resulting cesium density

Fig. 6. Detail of the cesium jet

was measured along the beam axis by a hot tungsten wire probe, with the results shown in Fig. 7. The fit to the data was obtained by assuming cosine emission from a virtual surface a distance 2 cm below the jet, a distance which gave the best fit to the data. The cesium is thus distributed along the beam axis as

$$n(Cs) = n_0 h^3 / (z^2 + h^2)^{3/2}$$

with h the vertical distance from the virtual surface and n_0 the density extrapolated to that point. The density thus drops as z^{-3} for $z \gg h$.

The intensity of the beam downstream from the cell is a function not only of the efficiency of

Fig. 7. Measured cesium density profile, with $\int n d\Omega = 2.5 \times 10^{15} \text{ cm}^{-2}$. The solid line follows the model described in the text.

production, but also of the angular spread introduced to the beam, in the cell. Analysis of scattering during the charge-exchange collisions⁹ shows that scattering is small at the cesium line density required to produce a full equilibrium fraction (relative to the initial beam) of D^- in the forward direction. This result is confirmed by measurements of the production efficiency in the present experiment. A result of 20% is obtained at 1 keV which can be compared to 24% equilibrium fraction.² In this measurement, correction factors arise from molecular components and the high energy component in the beam and from effects of space charge and beam temperature, so the accuracy is probably no better than 25%.

The maximum in D^- current in the forward direction occurs at a cesium line density low enough that the molecular component of the original beam is only partly dissociated.¹⁰ The use of D_2^+ or D_3^+ thus faces considerable difficulties, as the beam will be spread considerably in angle at the cesium line densities required.

Plasma generated in the cesium cell will have several effects.¹¹ It provides the ions necessary for space charge neutralization. Indeed, the transverse ambipolar electrical field will slightly focus the beam. The field is of order T_e/R_b , with R_b the beam radius and $T_e \sim 0.5 \text{ eV}$. As the cell length is comparable to the radius, the beam is bent through an angle of about $T_e/E_b = 10^{-3}$ radian, so the effect is not significant.

A possible detrimental effect is the charge-exchange process

The cross section is not known accurately, but has been calculated¹² to be $\sigma_1 \approx 1.5 \times 10^{-14} \text{ cm}^2$. The process will be important at a degree of cesium ionization:

$$n_i/n_e \sim 10^{-1} (\sigma_0/\sigma_1) \approx 3 \times 10^{-3}$$

Balance of ionization and loss¹¹ indicate that at 1 keV this will occur at a total beam current of 0.1 A/cm². At lower energies, larger currents would be possible. Electron temperatures much above 0.5 eV could also cause significant ionization, but energy loss to excitation and ionization of the cesium will probably prevent this.

Beam Propagation and Electron Control

The plasma generated in the cesium cell can have considerable density. If a significant current of plasma electrons enter the accelerator, they will cause a considerable power drain and may cause voltage-holding problems if they strike surfaces. Calculations^{13,14} show, however, that when the ionization rate drops rapidly, e.g., due to a decrease in background neutral density, the plasma also drops with a scale length on the order of the beam radius.

The physics is discussed elsewhere in this conference¹⁵; here we wish to emphasize the consequences for negative ion beams. Because of the decrease in density, the accelerator can be effectively isolated from the charge exchange cell.

At the entrance to the accelerator, plasma ions are repelled by the applied field, so that there are no ion losses along the axis. We can model the problem by a cylinder, with continuity equation for the ions

$$\frac{1}{r} \frac{d}{dr} (r n v) = S$$

with S the creation rate for background positive ions. The dominant mechanism in this experiment is ionization by the 10 keV component, with $\sigma = 10^{-16} \text{ cm}^2$ and density = the beam density as the 10 keV particles are directed in the forward direction. Thus $S \approx \sigma n_b n_g$, with n_g the deuterium gas density. Ionization by electrons, ionization by the 1 keV beam, charge exchange processes, and effects in cesium are estimated to be weaker.

Assuming, for estimating purposes, that the right side is constant, and setting $v = \sqrt{kT_e/M_i}$ at the beam edge R_b , the gas density for which $n_e = n_b$ is $n_c = (2/R_b \sigma) / (\sqrt{kT_e/M_i} v)$. Thus, with $R_b = 5 \text{ cm}$ and $T_e = 1 \text{ eV}$, $n_c \approx 2 \times 10^{13} \text{ cm}^{-3}$ ($p \approx 6 \times 10^{-4} \text{ torr}$). The experiment operates at more than an order of magnitude below this pressure; stripping of the D^- ($\sigma = 10^{-15} \text{ cm}^2$) is measured to reduce the D^- beam density by 20%.

It is thus found experimentally to be relatively easy to keep the electron density below the beam density. Measurements by Langmuir probes verify this conclusion. Because the electron thermal velocity is comparable to the beam velocity, the electron current into the accelerator is less than the beam current.

At gas pressures below about $4 \times 10^{-5} \text{ Torr}$, the beam is observed to be unstable. An example

Fig. 8. Measurements by Faraday cup of the 1 keV D^- current. (a) $p = 4 \times 10^{-5}$ Torr of D_2 , $j = 2.3 \text{ mA/cm}^2$, $t_{\text{pulse}} = 10 \text{ ns}$; (b) $p = 3 \times 10^{-6}$ Torr, $j = 0.75 \text{ mA/cm}^2$, $t_{\text{pulse}} = 10 \text{ ns}$; (c) Case b, 5 $\mu\text{s/div.}$; (d) Case b, 0.2 $\mu\text{s/div.}$

is shown in Fig. 8, in which a small increase in D_2 pressure stabilizes the beam. Analysis¹⁵ of the infinite medium beam-plasma dispersion relation indicates stability for $n_0/n_b > m_0/M_1$, certainly true here. Preliminary analysis for a finite beam¹⁶, however, indicates a possible instability.

D^- Acceleration

Approximately 100 mA of D^- is injected into the accelerator shown in Fig. 9. The trajectories have been calculated by the Wolf code.

Fig. 9. High voltage accelerator, $j = 3 \text{ mA/cm}^2$. Electrode potentials are (from the left) 0 kV, 2.5 kV, 10 kV, 35 kV, 60 kV, and 60 kV.

although the accelerator aperture, 6 cm x 12 cm, is not a good approximation to the assumed two-dimensional geometry. For these results, the beam has been assumed to have zero temperature.

The detailed design takes into account the actual particle trajectories, of course, but the electrodes have specific purposes. The first (entrance) electrode defines the beam size. The third (focusing) electrode is used to concentrate the beam to optimize the beam optics in the main accelerating gap. To the first approximation, the resulting space charge in this gap satisfies the Child-Langmuir law. The second (control) electrode is biased to minimize over-focussing of the particles at the beam edge; in essence, it plays the same role as the Pierce angle in standard charged particle accelerators. The last pair of electrodes can be biased to prevent backstreaming ions, although in the present experiments they were set to the same voltage. The shapes of electrodes near the walls prevent a direct line of sight between the beam and insulators.

Initial measurements of the accelerated beam indicate that the electron current is significantly less than the negative ion density. These measurements were made using a weak magnetic field at the exit to the accelerator, and confirm the measurements made in the 1 keV beam upstream from the accelerator.

Faraday cup measurements 1 meter from the accelerator, Fig. 10, yield a beam divergence of $\pm 2.4^\circ$ both along and across the aperture, which compared with $\pm 1.6^\circ$ calculated by the Wolf code.

Neutrons produced in a titanium disk saturated with deuterium give a qualitative confirmation that a high energy deuteron beam is produced.

Although these results are preliminary in nature, they are very encouraging for the accelerator techniques used in the experiment. Work will continue to compare experimental and theoretical results.

Conclusion

The successful acceleration of a D^- beam produced by double charge exchange is an important step toward obtaining intense D^0 beams at high energy. The present experiment will continue to examine the fundamental physics of the processes involved in producing these beams. Modifications will be made to increase the current density and total current to more interesting levels in order to examine intensity-related effects. Within the next year or two, a large beam system will be designed and constructed to operate on the HVTS (200 kV) test stand at LLL.

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Fig. 10. Beam profiles at end of diagnostic tank, as measured by a Faraday cup. Solid dots: D⁻ current. Open dots: D⁻ plus electron current.

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