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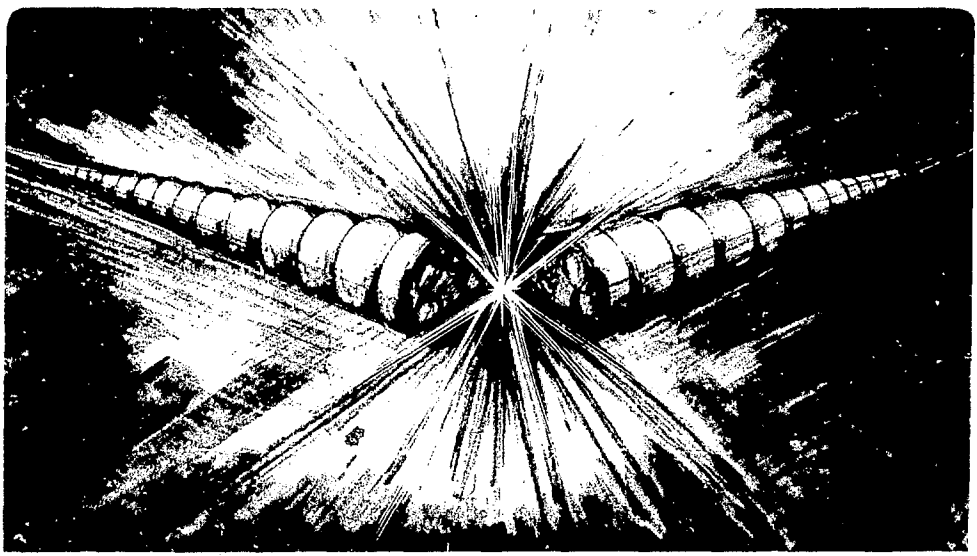

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LARGE AREA NEGATIVE ION SOURCE FOR HIGH VOLTAGE NEUTRAL BEAMS*

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Beams of high energy deuterium atoms are employed to energize and fuel the plasma in experimental fusion machines. When the energy required in these beams is extrapolated to reactor requirements, as in a tandem mirror reactor, it is typically in excess of 200 keV. Neutralization of positive ions is not efficient in this energy range; stripping of negative ions to produce neutral atoms is a relatively efficient process, however. We describe here a source of negative deuterium ions in the multi-ampere range that is readily extrapolated to the size, 10 amp or more of neutral beam, that is of interest in future experiments and reactors.

The negative ion source is based upon the double charge exchange process.[1] A beam of positive ions is created and accelerated to an energy at which the attachment process $D + M \rightarrow D^- + M^+$ proceeds effecient-ly. The positive ions are atomically neutralized either in D_2 or in the charge exchange medium M. Atomic species make a second charge exchange collision in the charge target to form D^-. For a sufficiently thick target, the beam reaches an equilibrium fraction of negative ions. For reasons of efficiency, the target is typically alkali metal vapor; this experiment uses sodium. The beam of negative ions can be accelerated to high (>200 keV) energy, the electrons "stripped" from the ions, and a high energy neutral beam formed.

The components of the beamline used in the experiment (Fig. 1) include the positive ion beam source, the charge exchange cell, and the diagnostic tank. The beam is not accelerated to high voltage in the present experiment.

The diagnostics employed with the experiment provide for measurement of the currents, voltages, and plasma density in the positive ion source; fast ion gauges to monitor the evolution of gas pressure along the beamline; a hot wire probe to measure the density of sodium in the charge exchange target; Langmuir probes to measure the electron density and plasma density along the beamline; a Faraday cup to measure the net current density distribution of the beam ions; a magnetic analyzer to measure the D^- current density; and a calorimeter that measures the power density of the beam and, in conjunction with a bending magnet, measures the power in the neutral fraction of the beam.

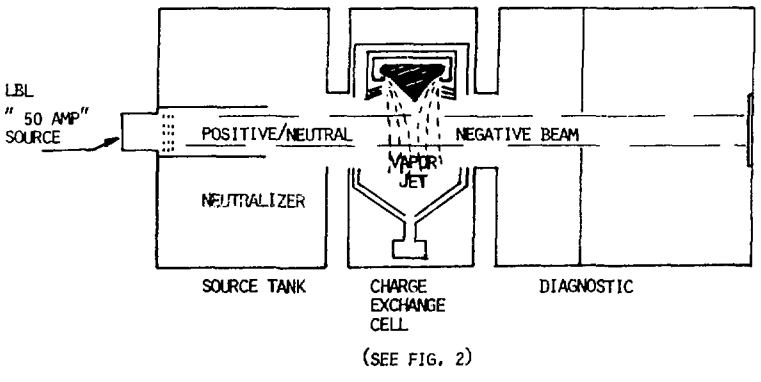
The Positive Ion Source

The beam of positive ions is generated by an LBL "50 amp" source.[2] The accelerated current density emitted from the 7 x 35 cm^2 extraction area is given by

$$j = 3.2 \times 10^{-3} V^{3/2}, \quad V \text{ in kV}.$$

The extracted beam consists of a mixture of D^+, D_2^+, and D_3^+. The ion beam passes through a neutralizer, consisting of a duct placed immediately downstream of the positive ion source. The neutralizer fills with D_2 gas streaming from the ion source, typically to a line density of 10^{15} cm^{-2}. A large fraction (85%) of the ions are neutralized, and the molecular species contribute particles at fractional (1/2, 1/3, and 2/3) energies by dissociation processes. The atomic species produced by the ion source/neutralizer are charge exchanged to D^- in the vapor jet.

The emitted beam has approximately a bi-Gaussian distribution in angle, measured to be 0.8° (along the grids) by 2.8° (across the grids). The source is focussed in both directions at a distance of 3 m.



(SEE FIG. 2)

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The Charge Exchange Cell

The charge exchange cell provides and contains the alkali metal vapor. It is of utmost importance that the metal vapor is contained within the charge exchange cell and does not migrate along the beamline to the positive ion source, the high voltage accelerator, if present, or to the target plasma.

The cell consists of three elements: The hot vapor circuit, the cold collector surfaces, and an enclosing box which contains the vapor during recovery of sodium. A schematic of the device is shown in Fig. 2. The metal is heated in the boiler (typically to 550°C) to generate the appropriate vapor pressure. The superheated section operates at a higher temperature than the boiler to minimize the fraction of sodium clusters.

A pulsed valve separates the nozzle from the superheated section. The valve can operate with variable aperture area up to 1 in^2.

The nozzle has been designed to minimize the flow of the metal vapor along the beamline. This is accomplished by forming a highly directed jet with low collisionality. The flow is directed across the ion beam by an external expansion nozzle[3] which consists of two slits on either side of a curved, wedge shaped centerbody. This type of nozzle was chosen because the boundary layers that are formed during the expansion of the flow and contain high temperature, poorly directed flow, are confined within the layers of supersonic ($M \geq 10$) directed flow. A density profile along the center of the beamline is shown in Fig. 3 and illustrates the effectiveness of the vapor confinement.

Experiments still in progress indicate an upper limit of the density of the vapor to be less than 5×10^8 cm^{-3} at a distance 120 cm from the nozzle. Both spectroscopic and activation diagnostics have been employed.[4,5]

During typical operation, the pulsed valve is opened for a 400 ms pulse of the vapor jet. The ion beam is pulsed for 10 ms during this time. The content of sodium in the boiler allows approximately 1000 pulses of vapor. Once the vapor from the boiler has been exhausted and collected on the cold surfaces, it is melted and flows back to the boiler by gravity. The vapor pressure during recovery reaches 10^{-6} Torr; the vapor is contained during this phase of the operation by the sealed surfaces of the charge-exchange cell.

The primary sources of difficulty in the operation of the charge exchange cell have been the pulsed valve and the boiler valve. With a vapor pressure of 4 - 10 Torr in the vapor circuit, the valve leakage is significant.

Diagnostics and Results

The Positive/Neutral Beam

The beam current is measured in two ways; By the power supply current drain, and by the power incident upon the target calorimeter. The current derived from the calorimeter measurements is less than the measured power supply drain due to charge exchange and ionization events in the accelerator structure (a 9% effect at a gas flow of 18 TL/s), back scattered power from the calorimeter (a 5% effect),[6] the finite area of the calorimeter, and possible calibration errors. At 10.5 kV accelerator voltage, the power supply drain corrected by gas flow yields an accelerated, well directed current of 23.6 amp. The beam current that is derived from corrected calorimeter measurements is 20.0 amps.

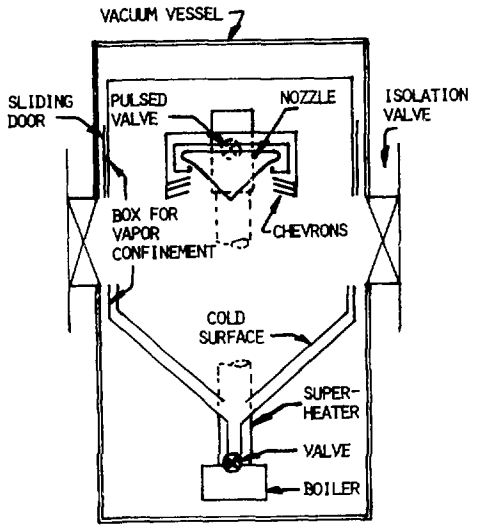

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Fig. 2. Schematic of the charge exchange cell.

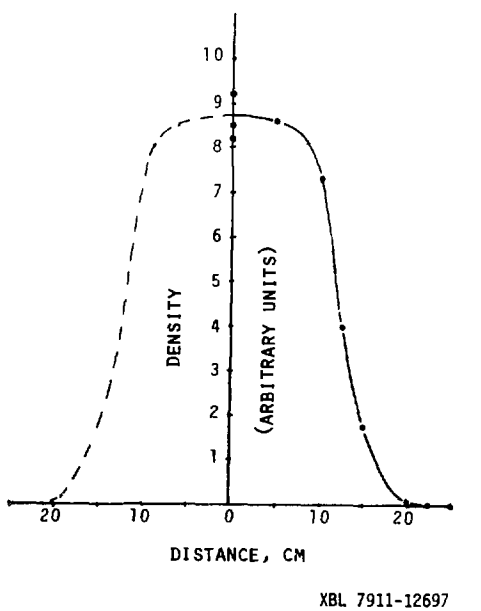

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Fig. 3. Density profile of vapor jet along beamline center.

The optimum beam divergence at this current is 0.8° by 2.8°. The divergence is confirmed by Faraday cup measurements of the net ion current density. The beam consists primarily of neutral particles, having passed through a neutralizer with a line density of 5 x 10^{15} cm^{-2}. The species fraction for the present operation is estimated to be 60-70% D^+, 20-30% D_2^+, and approximately 10% D_3^+.

Gas Evolution

The flow of gas in the beamline is due to gas flowing from the positive ion source and to gas evolved from the surfaces exposed to beam or plasma. It is necessary to maintain a pressure below 3 x 10^{-4} Torr downstream of the charge exchange cell. At higher pressure, a significant fraction of the negative ion beam would be lost by stripping ($D^- + D_2 \rightarrow D + e^- + D_2$). The gas flow from the positive ion source is controlled by expanding the gas into a large volume, the source tank, and operating in a pulsed mode.

Surfaces in the beamline contribute to the gas load if they are exposed to the beam or the plasma generated by the beam. The primary contribution to the gas load is gas evolved from the calorimeter at a rate of ~ 10 Tℓ/s for a 23 amp incident beam. During initial operation of the experiment, a large quantity of gas was evolved in the region of the charge exchange cell and the diagnostics tank. Placing copper surfaces near the edges of the beam reduced the gas evolution to a low level. Gas is also evolved from instrumentation that is inserted into the beam. The surfaces exposed to the beam are made as small as possible in order to minimize the loss of beam due to stripping.

The Negative Ion Beam

The current of D^- ions that is produced as the positive/neutral beam passes through the charge exchange target is a function of the line density $\int n\, d\ell$ of the target, as illustrated in Fig. 4. The Faraday cup (0.081 cm diameter aperture) measures the net current density of the positive and negative ions in the sampled part of the beam. The magnetic analyzer, with an equal aperture size, measures the D^- current only. The difference between the two signals is the current contribution from the positive deuterium ions and any, positive and negative, impurity ions. The net current from these species is seen to be small at high sodium line density. The possible presence of low levels of negative impurities in the beam is currently under investigation.

The total current of negative ions in the beam is computed by integrating a fitted bi-Gaussian to the measured beam profile. For operation at 10 kV, the negative ion beam current is 1.8 amp for a 22 ± 2 amp extracted beam. Extraction of 26 ± 2 amp at 10 kV yields a negative ion beam of 2.0 amp.

The electrical efficiency, i.e., the negative ion beam current relative to the actual extracted beam current, is 7.5 to 9.0% for operation at 10 kV. The currents and efficiencies obtained when operating at other extraction voltages are being measured.

Discussion

One objective of this experiment is to demonstrate that a negative ion beam based upon double charge exchange can be scaled to beam currents that are within

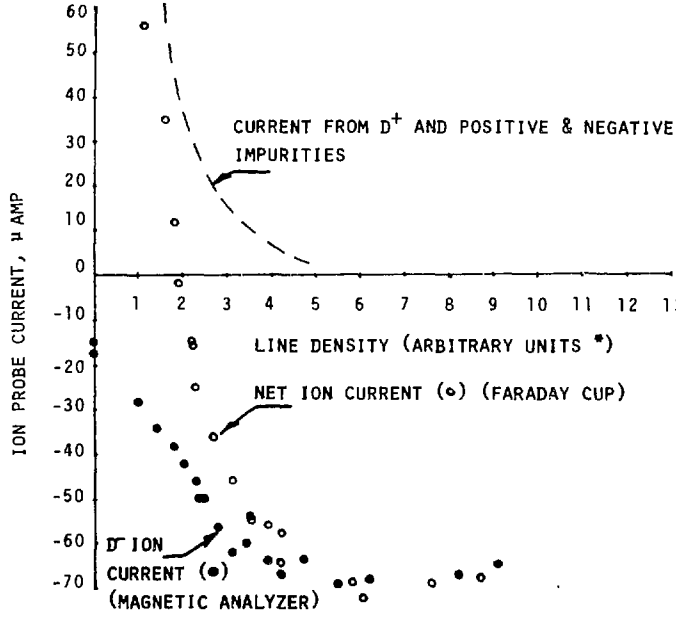

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Fig. 4. Ion probe current on beamline center vs sodium line density (*preliminary results indicate 1 arb. unit = 1.4 x 10^{14} cm^{-2}).

the range required by large fusion experiments and reactors. Scaling to a higher current from a previous experiment requires a larger and more intense beam. The beamline apertures are larger, with more stringent requirements on control of the flow of gas, alkali metal vapor, and plasma.

This experiment has shown that the pressure in the critical beam transport region downstream of the charge exchange cell can be held below 3×10^{-5} Torr for a 10 ms pulsed experiment. In a steady state experiment, the corresponding required pumping rate is 40,000 ℓ/s, well within the capability of cryopumps.

The external expansion nozzle produces a jet which is highly directed and effective in maintaining sodium confinement. The density of sodium downstream of the charge exchange cell has been measured to be in the 10^8 cm^{-3} range; hence the negative ion flux density exceeds that of sodium by a factor of 10^4 in the region where acceleration of D^- to high energy takes place.

The beam of plasma density and temperature was measured by a shielded Langmuir probe in the charge exchange cell. The electron temperature was below 1 eV, and the density scaled linearly with sodium density in agreement with a model by Hooper, et. al.(7) Both the measurements and the model indicate that the beam is space charged neutralized and that charge-exchange of D^- on positive ions is not important.

The observed conversion efficiency to negative ions is 7.5% to 9.0%. This production efficiency is consistent with charge exchange of the atomic species that are formed by neutralization and dissociation during the passage of the beam through the neutralizer. Significant further dissociation with subsequent formation of negative ions is not observed to take place in the sodium target for the range of line densities investigated.

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