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Abstract

We describe two pulsed neutral-injection systems developed at the Lawrence Berkeley Laboratory. The first has a 7- X 7-cm extraction array of 21 slots. It produces a 20-keV 30-msec deuterium ion beam of ~ 16 A, which is converted to energetic neutrals in a close-coupled neutralizer; 13 A equivalent of ions and neutrals are delivered in ±1.8° X ±3.6°, and 9.5 A are within ±0.6° X ±1.8°. The second system is a scaled-up version with a 7- X 35-cm extraction array. With a 10-msec extracted ion beam of ~ 75 A (1.5 MW) at 20 keV, it delivers 67 A (1.34 MW) within ±2° X ± 4° of which 47 A (0.94 MW) are within ±1° ±2°.

I. Introduction

Many controlled-fusion experiments, present and proposed, rely on the injection of beams of energetic hydrogen or deuterium atoms for heating and refueling of the confined plasma. Multi-megawatt beams at tens to hundreds of keV are required, and since access apertures through the coils surrounding the confined plasmas are limited in size, there is a high premium on low beam divergence. We describe two pulsed neutral-injection systems developed at the Lawrence Berkeley Laboratory. The first, which will be called the "10-ampere" source, has a 7-cm by 7-cm extraction array of 21 slots. It produces a 20-keV, 20 m-sec deuterium ion beam of ~ 16 A. This beam is then converted to energetic neutrals (with about 90% efficiency) by electron-capture and dissociation in a close-coupled neutralizer containing 0.2 Torr-cm of D_2 gas. At 3.3 m, 13 A equivalent of ions and neutrals are delivered to a 20- by 40-cm calorimeter (±1.8° X ±3.6°) and 9.5 A of this are within the 7-by 20-cm central portion (±0.6° X ±1.8°). The second system, the "50-ampere" source, is a scaled-up version with a 70-cm by 35-cm extraction array. With a 10-msec (power supply limited) extracted ion beam of 75A at 20keV, it delivers 67A within ±2° X ±4° and 47A within ±1° X ±2°. The 50-A source is quite compact so that it can be used as a module for a larger system; 12 such modules are to be used on the 2XII-B mirror experiment at the Lawrence Livermore Laboratory to form a 600-A injection system.

Although the two sources differ in physical size and shape, they are functionally similar. A cross-section view of the 50-A source, Fig. 1, will be used to describe the general features. The plasma from which the ions are extracted is generated by a diffuse low-pressure high-current discharge with a distributed thermionically emitting cathode consisting of a ring of hot tungsten filaments. No external magentic field is employed, so the usual fluctuations associated with cross-field transport are avoided. The plasma source produces an extractable ion-current density of 0.5 A/cm² with spatial and temporal variations less than ±10% over the extractor array. The extractor design is based on the multiple-aperture concept which has long been used for large-area ion thrusters [1] and was adapted for neutral injection into plasmas by Hamilton et al. [2]. Three arrays of shaped electrode slots are used in an accel-decel configuration; the slots have been designed with the aid of a computer [3] to focus the beam electrostatically during extraction so that no additional focusing is required. Slots, rather than circular holes, were chosen for several reasons: higher transparency, better beam quality parallel to the slots, the possibility of expansion in one dimension under a heat load without buckling or destroying the symmetry, and ease of cooling in future electrodes (the present electrodes are not cooled).

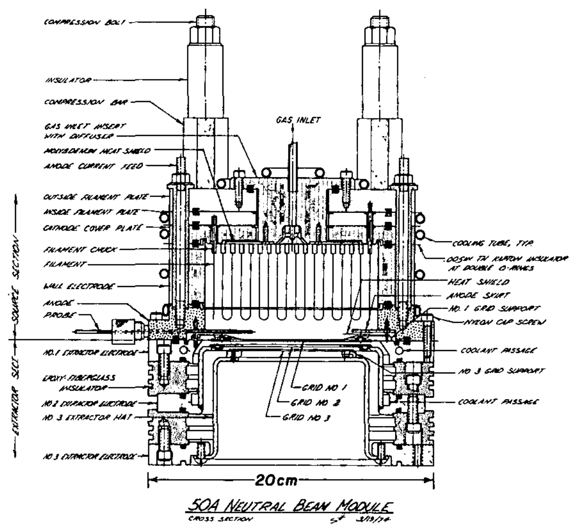

Fig. 1. Schematic cross section of the 50-A source. Plasma chamber on the top, extractor assembly on the bottom.

A photograph of the plasma source and the extractor for the 50-A source are shown in Fig. 2. The plasma source [4] and the extractor-design computations [5] are described in separate papers at this conference. In this paper we discuss the extractor and the system performance.

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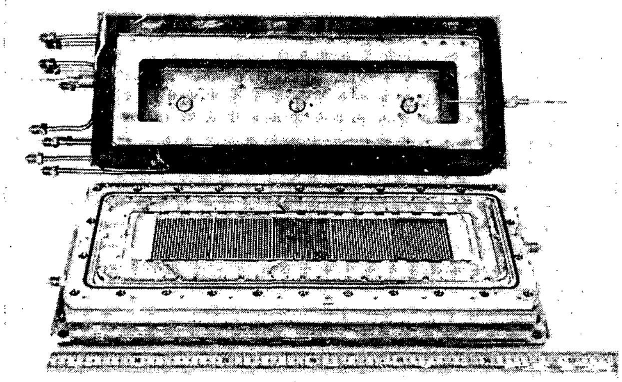

Fig. 2. Photograph of plasma chamber and extractor of the 50-A source.

II. The Extractor

The gross features of the extractor structure can be seen in Fig. 1. The 10-A extractor is fabricated entirely of OFHC copper; epoxy is used for the insulators. All metal parts in the 50-A extractor, with the exception of the grids, are stainless steel for mechanical rigidity; the insulators are made of epoxy-fiberglass material (NEMA G-10) with the inner surface coated with epoxy to make the structure vacuum-tight. Two different grid structures have been used: Flat copper grids and curved refractory-metal grids.

A. Flat Copper Grids

The slots are machined in flat copper sheet on a tape-controlled milling machine. For example, the beam-forming grid for the 10-A source is made from a sheet 7 × 10.8 × 0.075 cm which has 21 slots, each 2 mm wide and 7 cm long, spaced 3.3 mm center-to-center, filling a square array 7 cm on a side. One end is pinned securely to the supporting electrode, the other end is pinned loosely to allow for thermal expansion.

The shape of the slots and the calculated beam trajectories are shown in Fig. 5 of Ref. 5. The gap spacings are 2.25 mm for the accel gap and 1.75 mm for the decel gap. Mechanical imperfections and misalignments in the extractor assembly result in some broadening or steering of the beams. We find that a translation of the beam-forming electrode (next to the plasma) by 0.01 cm in a direction perpendicular to the slot will change the angle at which the beam emerges by 3.5°. This means that very careful construction and alignment of the electrodes are mandatory, but it does allow us to construct a large-area plane extractor from which the beams can be made to converge toward the plasma target. We have used this effect in the 50-A source in which five of these grids are placed side-by-side to form a 7- × 35-cm extraction array: The outer two grids of the beam-forming electrode are dispaced 0.065 mm toward the center of the array, and the intermediate grids are displaced 0.03 mm toward the center, so that the beams from each 7- × 7-cm grid section are steered toward a common center at 3 m.

We have used this type of grid successfully for several years, but there were several disadvantages: The frame-like structure was well suited to uniform heating of the grid, since the entire frame was free to expand; however, if one grid-rail received more heat than the others, e.g., from a violent spark, that rail would buckle and the entire grid had to be replaced. Furthermore, to take advantage of the small beam divergence along the slots (see Sect. IV), it was desirable to curve the grid rails; although we fabricated and used curved grids made of carbon, this fabrication technique was not amenable to the mass production of curved copper grids. It also seemed desirable to use refractory metals which would not be damaged as readily as the copper. Because of this we adopted the curved refractory-metal grids designed by T. J. Duffy of the Lawrence Livermore Laboratory [6].

B. Curved Refractory-Metal Grids

These grids are made of individual gridrails which are supported at each end in dove-tail grooves machined into a support structure made of tellurium-copper. The grooves are machined such that the rails they support are curved to a predetermined radius. Each rail is free to slide in its support grooves.

The rails of the beam-forming grid are made of molybdenum wire which has been cold-rolled to the desired cross-sectional shape. The rails of the accel grid are 1.5-mm-diam tungsten rods. The third (decel) grid is made of 0.25-mm-diam tantalum wire.

Trajectory calculations for this structure show that the beam divergence transverse to the slots should be similar to that for the copper grids.

III. The Neutralizer

Since these sources are designed for the production of neutral beams, it is desirable to close-couple the charge-exchange cell to the extractor so as to minimize the transport of the high-current-density ion beam with its inherent space-charge fields. This is accomplished by coupling the extractor to the pumping system with a conductance-limiting pipe. The gas streaming from the source through the extraction grids is used in this region to provide a charge-exchange neutralizer for the beam. On both sources the neutralizers are ~ 80 cm long and have a target line-density of $\sim 8 \times 10^{15}$ D_2 molecules/cm^2.

Microwave-interferometer measurements on the neutralizer for the 10-A source show that ionization of the neutralizer by the beam produces an ion density of $\sim 5 \times 10^{11}$ cm^{-3} in the neutralizer.

IV. System Performance

We find that the grids must be conditioned to hold voltage under extraction conditions. This is done by starting at low currents (arc density) and low extraction voltages and gradually increasing both of these parameters. Neither of these parameters is increased until sparking has dimished for a given set of conditions. The sources are operated at a rate of one pulse per minute to allow the capacitor banks to recharge and the grid structures to cool. The low duty cycle makes conditioning tedious; however, once a set of grids has been conditioned, the maximum voltage and extracted current can be achieved routinely.

For a given extraction potential the source is "tuned" by varying the voltage on the arc pulse line. This varies the discharge current and, in turn, the plasma density. The extracted current increases with plasma density; the beam divergence decreases with plasma density to an optimum value, then increases again. It is difficult to avoid sparking at densities exceeding the optimum condition. The results presented below are those obtained under conditions of optimum beam focus.

The principal diagnostic tool is a 20- by 40-cm calorimeter plate which forms the end wall of the vacuum system. The extractor slots are parallel to the short dimension of the calorimeter. There are 32 thermistors, uniformly spaced in a 4 by 8 array on 5-cm centers attached to the plate on the atmospheric-pressure side, which are used to determine the temperature rise of the plate due to the beam pulse; from that information we can determine 32 points on the profile of the beam energy density. A small hole in the center permits a sample of the beam to exit to an external gas cell, bending magnet, and set of Faraday cups to measure the molecular composition of the beam. Both these signals and the signals from the thermistor bridges are read by an analog-to-digital convertor controlled by a small digital computer used for data acquisition and analysis. This system permits rapid determination of the equivalent beam current reaching the calorimeter, its spatial distribution, and the charged-species composition of the beam.

For some of the measurements the thermistor spacing was too coarse to obtain good profile measurements in the direction parallel to the slots. We then scanned the beam with a small rectangular calorimeter block which intercepted a 1- X 10-cm portion of the beam.

A. <u>10-A Source with Flat Copper Grids</u>

The performance [7] of the system in producing deuterium beams in the energy region of 3 to 20 keV is shown in Fig. 3. The abscissa is the extraction voltage (the voltage between the first and second electrodes) which is the sum of the accel and decel voltages. (The decel boltage was usually adjusted to be 6% of the accel voltage; at least 5% was required to block electrons from the downstream plasma.) For each extraction voltage we indicate a range for the extracted beam current. Some of the high-voltage power supply drain may be due to electron collection, and some of the current appearing on the second (accel) electrode may be due to direct beam interception, the collection of ions produced from ionization or charge-exchange in the extractor, or ion extraction from the downstream plasma. For these reasons we show as an upper limit to the extracted beam current the high-voltage power supply drain and, as a lower limit, that current minus the durrent to the second electrode. Also shown are the calorimetrically measured currents (total beam ions plus neutrals) reaching the 20- X 40-cm calorimeter (□) and the 10- X 20-cm central portion (o). The dashed lines indicate the currents calculated for a pure D^+ or $D_2{}^+$ beam. The fact that the extracted current increases more rapidly than

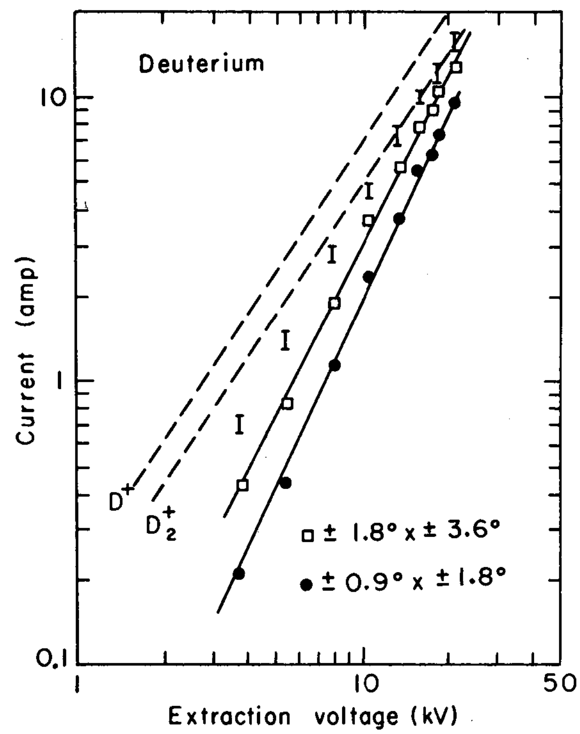

Fig. 3. System performance for the 10-A source with flat copper grids, operated on deuterium. The bars indicate the extracted ion current; the □ indicate the equivalent current (ions and neutrals) to a 20- X 40-cm calorimeter (±1.8° X ±3.6°); the o indicate the current to the 10- X 20-cm central portion (±0.9° X ±1.8°). The two dashed lines were obtained from the calculated perveance, assuming either a pure D^+ or $D_2{}^+$ beam. The solid lines connect data points.

$V^{3/2}$ may be due to a change in the molecular ion composition in the source as the arc power is increased.

At 20 keV the extracted current was 14 to 16 A, of which 13 A equivalent current reached the 20-X 40-cm calorimeter and 9.5 A reached the central 10-X 20-cm area. The pulse-length was 30 msec. The arc parameters for 20-keV operation were: gas flow, 8 Torr-l/sec; filament power, 8 kW; arc power, 48 kV (60 V, 800 A).

Measurements of beam profiles with the 32-channel calorimeter show that the beam divergence is less in the direction parallel to the slots than perpendicular to the slots. This is to be expected, since the divergence in the parallel direction should be limited by the initial transverse velocity spread of the ions and not be aberrations introduced by the extractor. In all cases, when the current to the central portion of the calorimeter was maximized by varying the plasma density, the beam profile in either plane could be fitted by a Gaussian function folded with a rectangular source function. At 20 keV the 1/e half-widths of these Gaussian distributions (corrected for the distribution of the finite source) were ±2° in the direction perpendicular to the slots and ±0.8° in the parallel direction.

This system has also been used to produce hydrogen beams. In this case we could only achieve optimized beams up to 15 keV because of limitations in our arc power supply. The system performance for hydrogen beams is shown in Fig. 4. For 15-keV operation the arc parameters were: gas flow, 9 Torr-l/sec; filament power, 7 kW; arc power, 40 kW (65 V, 600 A).

The neutral fraction of the beam was determined by sweeping out the charged beam at the exit of the neutralizer section with a pulsed magnet. With this we determined that about 90% of the beam energy was in neutral particles.

Measurements of the composition of the extracted ion beam have been described elsewhere [8]. For deuterium operation at 20 kV, the accelerated ion beam is about 75% D^+, 15% $D_2{}^+$, and 10% $D_3{}^+$; for hydrogen, the mix is 60% H^+, 20% $H_2{}^+$, and 20% $H_3{}^+$. In the range 15 to 20 keV, where these measurements were made, we have not been able to change the ion composition significantly. We have not yet measured the composition at lower energies for which the arc operates at lower power levels.

B. 10-A Source with Curved Refractory Metal Grids

The divergence in the direction parallel to the slots is so small that the 7-cm length of the slots contributes significantly to the beam size when flat grids are used. To take advantage of this small divergence we have curved the first two grids to a radius equal to the target distance; the third grid, which only serves to block electrons, is not curved. The improvements in the beam focus are illustrated in Fig. 5 for a grid radius of 205 cm. The solid line is the measured beam profile for flat grids, the dashed line for curved grids. From the width of the beam profile obtained for the curved grids, we obtain an upper limit of 1.25 eV for the ion temperature in the source. For deuterium beams at 20 keV, the measured current to the 1-X 10-cm calorimeter block was 2.3 A at 2.05 m; i.e., with curved grids we have been able to achieve a current density of 0.23 A/cm² (at power density of 4.6 kW/cm²) at 2.05 m. With curved grids 9.5 A are delivered within ±0.6°X ±1.8°.

Curved-grid 10-A sources have been constructed and operated both for 2- and 3-m focus. The beam divergence perpendicular to the slots is the same for the refractory-metal grids as for the flat copper grids.

C. 10-A Source with Vanes

One way to increase the gas efficiency of the source is to add pumping impedance between the arc chamber and the neutralizer cell, thereby allowing the required pressure in the plasma source to be maintained with a lower gas flow. We have raised the pumping impedance and reduced the gas flow about a factor of 2 by placing 0.25-mm-thick molybdenum sheets, 5 cm long (in the beam direction) between the beams emerging from the individual slots in the third electrode. In fact, this array of vanes has been used as the third electrode for both types of grids. The vanes intercepted some of the beam and decreased the current to

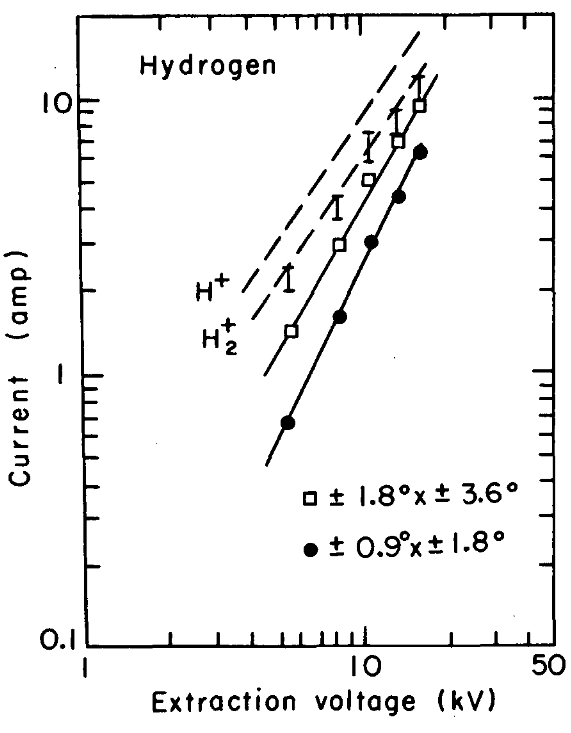

Fig. 4. System performance for the 10-A source with flat copper grids, operated with hydrogen. For symbol identification see legend to Fig. 3.

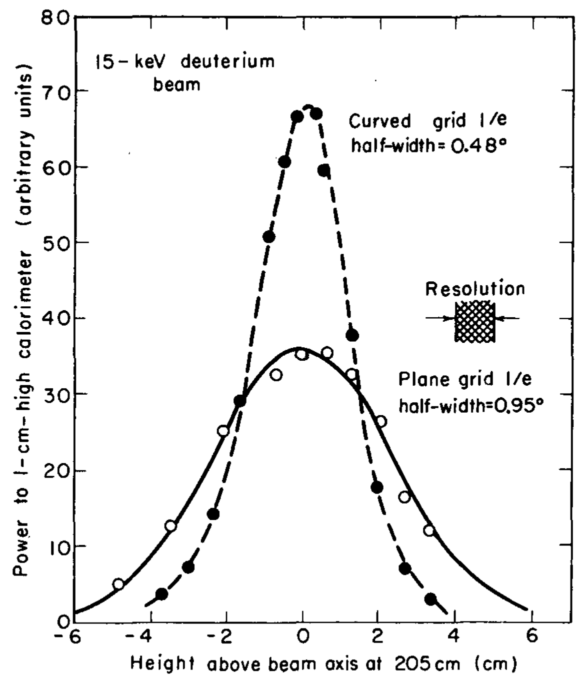

Fig. 5. Improvement in divergence parallel to the slots by curving the grids. The solid line shows the beam profile measured at 2.05 m for flat grids for a 15-keV deuterium beam. The broken line shows the beam profile under the same conditions for refractory-metal grids curved to a 2.05 m radius. No change was observed in the divergence of the beam perpendicular to the slots.

the calorimeter by about 30%. Because of this interception, we do not routinely use vanes in our sources; however, we plan to incorporate this into our source designs when we learn to improve the beam divergence perpendicular to the slots and can hold the required mechanical tolerances in manufacture.

D. 50-A Source with Flat Copper Grids

The system performance for the 10-msec 50-A source using deuterium is summarized in Fig. 6. Of the ~ 75 A Extracted at 20 keV, the current (ion and neutral) to the 20- by 40-cm calorimeter at 2.9 m ($\pm 2° \times \pm 4°$) is 67 A, and that to the 10- × 20-cm section ($\pm 1° \times \pm 2°$) is 47 A. The beam delivered to the calorimeter is five times greater than

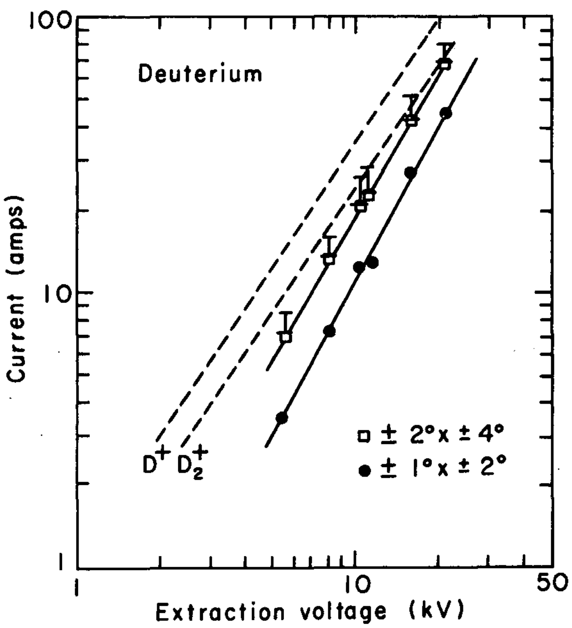

Fig. 6. System performance for the 50-A source with flat copper grids operated with deuterium. For symbol identification see legend to Fig. 3.

that of the 10-A source, reflecting the effectiveness of the grid displacement in steering the beam from the 7- × 35-cm extraction area.

The 20-keV results were obtained with: gas flow, 21 Torr-l/sec; filament power, 25 kW; arc power, 165 kW; accel power, 1.6 MW; and decel power, 13 kW.

Several of the 50-A sources have been constructed with the curved refractory-metal grids, but as yet we have not had enough operating experience to present performance characteristics.

V. Acknowledgments

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