INTENSE-NEUTRAL-BEAM RESEARCH AND DEVELOPMENT[*]

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ABSTRACT

The LBL "10-ampere" source, which delivered 10-A, 20-keV, 20-msec
deuterium beams into the LLL 2XII mirror experiment, has been scaled up by
a factor of 5. This "50-ampere" source and its operation are discussed in
some detail in this paper. It produces a 10-msec, 20-keV deuterium ion beam
of approximately 75 A (1.5 MW), which is converted to energetic neutrals with
about 90% efficiency in a close coupled neutralizer; 67 equivalent amperes
(1.34 MW) of ions and neutrals are delivered in $\pm 2° \times \pm 4°$, of which 47 A (0.94
MW) are within $\pm 1° \times \pm 2°$.

We also discuss some of the modifications of the original 10-A source:
the use of curved grids to decrease beam divergence, the addition of vanes to
reduce gas flow from the source, and staging to higher energies by adding an-
other 7×7 cm electrode to give two accelerator gaps in series. Finally, we
briefly describe progress in the computational program on the optimization of
ion extractors.

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 the confined plasma. Multi-megawatt beams at tens to hundreds of keV are required, and since access apertures through the coils surrounding the confined plasma are limited in size, there is a high premium on low beam divergence. We describe the results of some of the research on pulsed neutral beam injection systems conducted at the Lawrence Berkeley Laboratory as part of the LLL/LBL neutral-beam program.

The LBL "10-ampere" source [1], which delivered 10-A, 20-keV, 20-msec deuterium beams into the LLL 2XII mirror experiment, has been scaled up by a factor of five. This "50-ampere" source and its operation are discussed in some detail in this paper. We also discuss some of the modifications of the original 10-A source: the use of curved grids to decrease beam divergence, the addition of vanes to reduce gas flow from the source, and staging to higher energies by adding another 7×7-cm electrode to give two accelerator gaps in series. Finally, we briefly describe progress in the computational program on the optimization of ion extractors.

II. THE "50-AMPERE" PLASMA SOURCE

A cross section view of the "50-A" system (plasma source and extractor) is shown in Fig. 1, and Fig. 2 is a photograph of the system. The rectangular shape of the source allows a number of similar units to be placed one above the other to inject into a common entrance port. Twelve such units have been built to inject 600 amperes into the 2XIIB experiment.

The plasma is produced by a diffuse low-pressure high-current discharge with a distributed thermionically emitting cathode which consists of a ring of hot tungsten filaments. Pulsed dc heater power is used (about 12 V, 25 A per filament) to avoid ac modulation of source potentials and plasma density. No externally applied magnetic fields are added, so the fluctuations usually associated with cross-field transport are avoided.

We have found empirically that for short-pulse operation (tens of milliseconds) the emission current drawn from each filament may be as great as, but must be no more than, twice the filament heater-current, otherwise the filaments will be destroyed by excessive heating. The "50-A" plasma source, designed to operate with arc currents up to 4000 A, has 86 hairpin filaments, 0.5-mm diameter and 10-cm long, inserted into molybdenum chucks and connected electrically in parallel. The filaments reach thermal equilibrium approximately 1.5 sec after the heater power is applied. The total filament power is 25 kW.

To avoid the formation of an anode sheath, which tends to make the discharge noisy and wastes arc power, the anode should have enough area so that the arc current can be supplied entirely by the random-electron flux striking the anode. The anode area required for this source is 350 cm^2. An extracted deuterium ion-current density of up to 0.5 A/cm^2 has been obtained. There is excellent repeatability and complete freedom from discharge noise. Despite its rectangular shape the plasma density variations can be held to less than ± 10%, as required for the extractor.
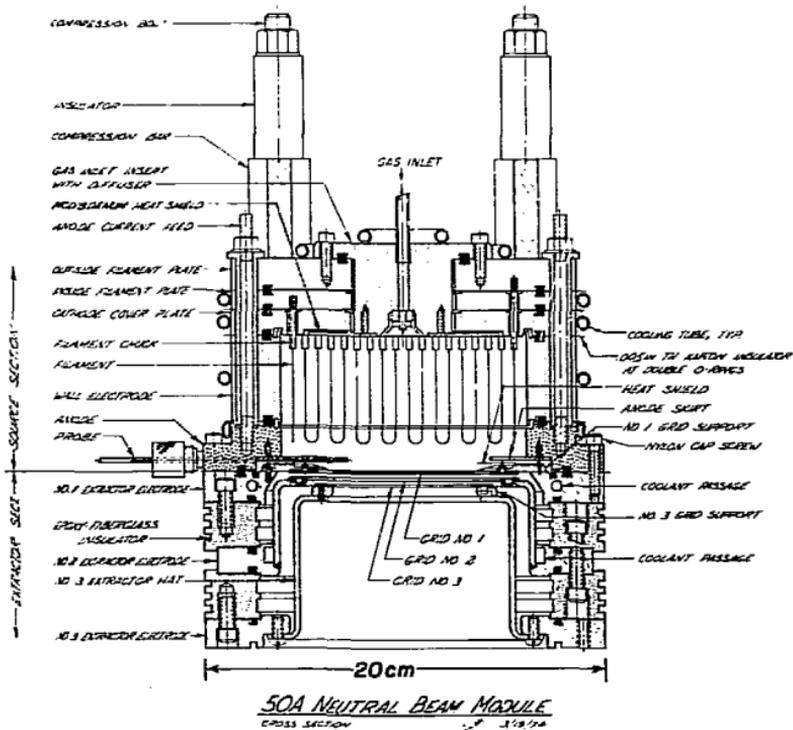
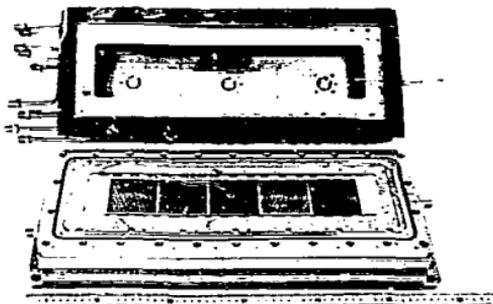Fig. 1. Schematic cross section of the "50-A" source. Plasma chamber on the top, extractor assembly on the bottom.

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

III. THE "50-AMPERE" EXTRACTOR ASSEMBLY

The extractor is a multiple-aperture design employing 105 slots. The shapes of the slots were designed with the aid of a digital computer program and the calculated beam trajectories are shown in Fig. 3. Each slot in the beam-forming electrode is 2 mm wide and 7 cm long. 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 beam. 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.
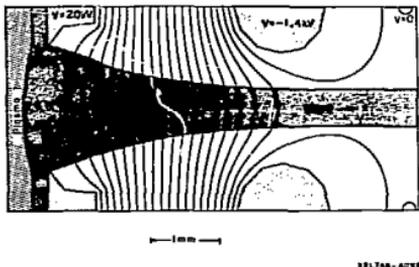

Fig. 3. Electrode geometry and computed equipotentials and extracted ion beam of a curved electrode 50-A ion source. The final D^+ beam energy is 20 keV, the current density extracted from the plasma is $j^+ \approx 0.61$ A/cm^2, and the ion temperature in the plasma is $kT_i = 1.3$ eV.

Two different grid structures have been used: flat copper grids and curved refractory-metal grids. The slots for the copper grids are machined in a flat copper sheet by a tape-controlled milling machine. In the case of the "50-A" source the beam forming grid is made from five separate sheets 7 cm $\times$ 10.8 cm $\times$ 0.075 cm, each of 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 five sheets are placed side-by-side to form a 7$\times$35-cm extraction array. The outer two grids of the beam-forming electrode are displaced 0.065 mm toward the center of the array, and the intermediate grids are displaced 0.03 mm toward the center, so that the beams from each 7$\times$7-cm grid section are steered toward a common center 3 m from the source.

Curved refractory-metal grids are made of individual W and Mo grid rails 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 [2]. This electrode structure has several advantages over the flat copper grids: it is easier to manufacture, individual rails can be replaced if damaged, and curvature of the electrodes to concentrate the beam at the target (see later section) is more easily achieved.

IV. 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. This neutralizer is ~ 80 cm long and has an effective target line-density of ~ 5×10^{15} D_2/cm^2. In the energy range covered by this source about 90% of the power in the extracted ion beam is converted to neutral beam power.

Microwave-interferometer measurements on the neutralizer for the 10-A source show that ionization of the neutralizer by the beam produces a density of ~ 5×10^{11} cm^{-3} in the neutralizer. No plasma density measurements have been made in the "50-A" neutralizer.

V. THE "50-AMPERE" POWER SUPPLIES

Power supplies and control circuits are designed so that each "50-A" unit can be operated and protected separately against damaging electrical break-downs. We find that small, but non-negligible amounts of damage are caused by sparks that deposit tens of joules in a localized spot; consequently, we require that power be removed in about 10 μsec if a fault is detected.

The filament supply is a 12-phase rectifier supplying 2000 A at 0-15 V. The arc supply is a 0-150 V, 4000 A, 0.035 Ω Z_0, electrolytic-capacitor pulse line. The 90 μF, 35 kV accel energy storage module is made of 1000 μF, 450 V electrolytic capacitors and has an internal impedance of 6 Ω. The accelerating voltage regulator and interrupt circuit uses an Eimac 4CX35000 screen grid tube, and provides 0-20 kV, 80 A for 0-10 msec. Decelerator power from a 125 μF, 6.5 kV capacitor bank is controlled by a 0-5 kV, 20 A circuit using an Eimac 4CX15000 tube. This supply is slaved to the accelerator supply.

VI. "50-AMPERE" SYSTEM OPERATION

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 is increased until sparking has diminished 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 volt-age and extracted current can be achieved routinely.

For a given extraction potential the source is optimized by varying the voltage on the arc pulse line which 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 system performance for the 10-msec 50-A source with flat copper grids using deuterium is summarized in Fig. 4. Of the ~ 75 A (1.5 MW) extracted at 20 keV, the calorimetrically measured current (ion and neutral) to the 20×40-cm calorimeter at 2.9 m ($\pm 2° \times \pm 4°$) is 67 A (1.34 MW), and that to the 10×20-cm section ($\pm 1° \times \pm 2°$) is 47 A (0.94 MW). The beam delivered to the calorimeter is five times greater than that of the 10-A source but the spatial power distribution is the same reflecting the effectiveness of the grid displacement in steering the beam from the 7×35-cm extraction area.
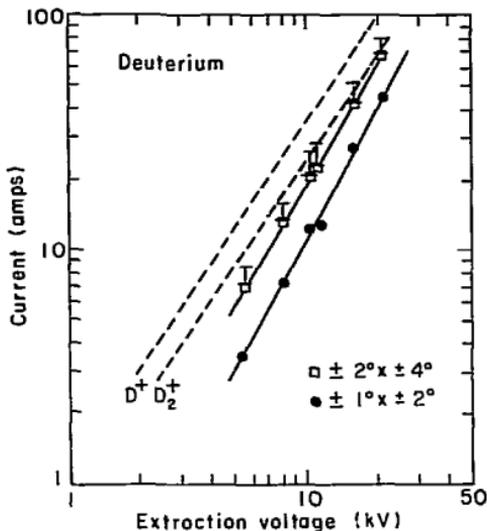
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Fig. 4. System performance for the "50-A" source with flat copper grids, operated on deuterium. The bars indicate the extracted ion current; the $\square$ indicate the equivalent current (ions and neutrals) to a 20- $\times$ 40-cm calorimeter ($\pm 2° \times \pm 4°$); the o indicate the current to the 10- $\times$ 20-cm central portion ($\pm 1° \times \pm 2°$). 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.

The 20-keV results were obtained with: gas flow, 20-msec pulse of 21 Torr-l/sec; filament power, 25 kW; arc power, 160 kW (45V, 3500A); accelerator power, 1.6 MW; and decelerator power, 13 kW.

The molecular mixture of ion species extracted from the 50-A source has been measured to be about 76% D^+, 22% D_2^+, and 2% D_3^+ when the system is optimized at 20 kV. This is similar to the results previously obtained with a 10-A source.

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.

VII. "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 for a deuterium beam at 15 kV are illustrated in Fig. 5 for a grid curved with a 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 1×10-cm calorimeter block was 2.3 A at 2.05 m; i.e., with curved grids we have been able to achieve an average current density of 0.23 A/cm^2 on the calorimeter (an average power density of 4.6 kW/cm^2) at 2.05 m. With curved grids 9.5 A are delivered within ±0.6° × ± 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.

VIII. "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 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.

IX. "10-A" SOURCE WITH TWO ACCELERATOR STAGES

One method of raising the energy of a beam without reducing the current density is to accelerate in several stages. As the first step in this direction,
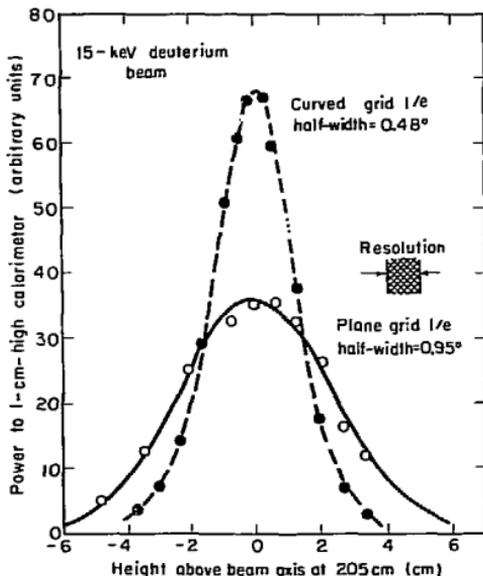
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Fig. 5. Improvement in divergence parallel to the slots by curving the grids. The solid line shows the beam profile measured at 2.05 m for flat grids for a 15-keV deuterium beam. The broken line shows the beam profile under the same conditions for refractory-metal grids curved to a 2.05-m radius. No change was observed in the divergence of the beam perpendicular to the slots.

we have added another accelerator electrode to one of the LBL three-grid single-stage extractors, which delivered 10 A of 20-keV deuterium beam into $\pm 0.6° \times \pm 2°$. The two accelerator electrodes each consist of 22 1.5-mm diam W rods, and the gap for each stage is 2.25 mm. Preliminary results for 20-msec, 34-keV deuterium beams are as follows: with accelerator-accelerator-decelerator gap voltages of 15.5, 20.1, and -1.6 kV, the extracted current was approximately 10 A; of this 8.1 A (equivalent current, about 85% neutrals) were delivered to a 20-cm $\times$ 40-cm calorimeter at 3.3 m ($\pm 1.7° \times \pm 3.5$) and 4.9 A were delivered to the central 10-cm $\times$ 20-cm ($\pm 0.9° \times \pm 1.7°$) part of this calorimeter. The change in beam optics for different voltage combinations applied to the accelerator electrodes is being studied.

X. COMPUTATIONAL ION EXTRACTOR OPTIMIZATION

A new program, WOLF, has been written for calculating and optimizing ion extraction with more realistic input data and physics. The program treats

symmetric or asymmetric two-dimensional extractors (slots), with no magnetic field. Ion flow with space charge is calculated by solving the equations of motion and Poisson's equation iteratively on a flexible triangular mesh attached to the boundaries. The emitting surface is assumed to be a flexible surface at the position of the plasma sheath edge. Ions are assumed to arrive at this surface with a distribution in directed velocities to simulate an ion wind; a non-zero ion temperature and the effects of electrons in the sheath are included. The magnitude of the electric field E_0 on the surface must also be specified. The ion velocity distribution and E_0 must be calculated, assumed, or derived from measurements of the plasma properties. The ion current density j^+ can be specified or treated as a variable. WOLF then varies the shape of the emitting surface until the electric field at each mesh interval on the emitter equals E_0 in a least-squares sense; this is equivalent to specifying j^+ = constant on the surface, and determines the shape that the plasma sheath edge will assume in the vicinity of the extractor electrode. In addition, the program can vary the shape and potential of selected electrodes to minimize the beam divergence. This program is the first step toward a model containing enough physics of the plasma and of the extraction process to accurately predict the performance of a given extractor, and then to optimize the extractor design for a given task[3].

So far WOLF correctly calculates all measured beam properties if the ion temperature in the source is assumed to be slightly over 1 eV, in agreement with the value required to explain the beam divergence parallel to the slots.

XI. ACKNOWLEDGEMENTS

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