Presented at the 12th Symposium on
Electron, Ion, and Laser Beam Technology,
Cambridge, MA, May 21-23, 1973

LBL-1589
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May 1973

Prepared for the U.S. Atomic Energy Commission
under Contract W-7405-ENG-48

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DESIGN AND OPERATION OF AN INTENSE NEUTRAL BEAM SOURCE*

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ABSTRACT

We describe a neutral beam source capable of producing pulsed deuterium beams of up to 15 A equivalent current at 20 keV for heating and sustaining fusion plasmas. It consists of a large-area plasma source, multiple-aperture accel-decel extractor, and closely coupled charge-exchange cell. A larger source, to produce 80 A equivalent deuterium beams at 20 keV, is being constructed.

One of the more promising methods for producing and heating plasmas for a number of controlled fusion experiments is the injection of intense beams of energetic neutral deuterium. We have developed a neutral beam source for injecting such beams into the 2XII mirror-confinement experiment[1] at the Lawrence Livermore Laboratory (this source will also be used on the ATC tokamak experiment[2] at the Princeton Plasma Physics Laboratory). We describe a large-area plasma source and extractor which produces a pulsed deuterium ion beam of ~16 A with an energy of 20 keV. This beam is then converted to energetic neutrals by electron capture by passing through 0.2 Torr-cm of D_2 gas, resulting in ~ 10 A equivalent of fast neutrals entering the 2XII machine through a 10×20 cm aperture, 3.3 m from the source. Operation with 2XII requires beam pulses of about 30 msec with a low duty cycle. This allows the use of pulse lines for both the arc and extractor supplies and reduces source cooling requirements. Gas pulsing is also necessary, as the gas required for this beam current alone is very high. (Note that a 15 A beam of D^+ represents a D_2 gas flow rate of 1.4 Torr liters/sec.)

The source, shown schematically in Fig. 1, utilizes the multiple-aperture extractor concept which has long been used for large-area ion thrusters[3] and was adapted for neutral injection into plasmas by Hamilton et al.[4] The extractor consists of a 7×7 cm array of shaped slots in an accel-decel configuration designed to focus the beam electrostatically during extraction so that no additional focusing is required. This extractor requires that the plasma source have an extractable ion current density of 0.5 A/cm^2, with spatial and temporal variations less

than ± 10% over the extractor array (10 cm on the diagonal). These criteria led to the development of a source in which the plasma is generated by a diffuse, low-pressure, high-current discharge with a distributed, thermionically emitting cathode consisting of a ring of hot tungsten filaments.[5] No magnetic field is employed, so the usual fluctuations associated with cross-field transport are avoided. A photograph of the source without the extractor is shown in Fig. 2.

The cathode consists of 20 hairpin filaments, 0.5 mm in diameter, containing a total cathode emission area of ~ 34 cm^2. They are inserted into molybdenum chucks and are connected electrically in parallel. A total heater current of 500 A is used to bring the filaments to their operating temperature of ~ 3200°K. Pulsed dc heater power is used to avoid ac modulation of the plasma density.

Two filament-design considerations should be noted. First, the large radiant heat load from the filaments can warp the delicate and accurately machined extractor structures. However, electron emission increases more rapidly with temperature than does radiant emission; thus small but very hot filaments are used. In addition, as the filaments are pulsed, the temperature equilibration time for small filaments is less (~ 1 sec for this unit).

In our initial sources,[6] the wall opposite the grid (through which gas is introduced) was used as the anode; however, the plasma density profile was peaked on axis, and the effect was enhanced as the arc current was increased. By operating, instead, a portion of the cylindrical chamber wall as the anode, we obtained a considerable improvement in the uniformity of the radial density profile, which, in addition, did not

change with increasing arc current. This larger anode area eliminated the existence of anode sheaths as well as troublesome magnetic fields resulting from concentrated arc currents.

The remaining parts of the source, including the extractor grid, are allowed to float electrically. Gas flow is controlled by a solenoid valve in series with a needle valve connected to a regulated 15-psi deuterium reservoir. Gas flow changes are made either by varying the setting of the leak valve or by altering the reservoir pressure.

Arc power is supplied from a pulse line; and the arc current (up to 1000 A) is controlled by a current-limiting resistor, as well as by the pulse-line voltage charging level. Arc voltages vary from about 25 to 70 V, depending largely on the level of arc current, the filament heat, and the gas flow.

Figure 3 is a plot of the extractable ion current density profile for two levels of operation as indicated by movable probes. Although the source was designed for a square 7 × 7 cm grid, it can be seen that a larger extraction area could be utilized, as the profile here is flat to ± 6% to a diameter of 12 cm. The position of the filament ring and anode wall is also indicated to demonstrate that nearly the entire source diameter is available for extraction.

Gas flow measurements compared with the extracted current output indicate that about 25% of the gas nuclei fed into the source leave as energetic beam nuclei. Gas from the source is used downstream in the neutralizer section, in which we get a neutralizing efficiency of about 90%.

Shot-to-shot reproducibility is excellent. Scope traces of numerous successive shots are routinely photographed while taking profile and

ion extraction data; and these appear coincident, even in fine detail. The probe signals are essentially flat in time and completely free from noise.

The extractor was designed with the aid of a digital computer program[7,8] which determines the trajectories of particles from an emitting surface through a set of electrodes, taking into account the space charge of the beam. The iterative design procedure[9] was carried out until the current density over the emitting plasma surface was constant to better than ± 5% and the ion trajectories at the exit of the extractor were almost parallel, typically within ± 1 deg. In the calculations only the beam's space charge is considered; the downstream plasma surface has been assumed to be flat, and the ions are assumed to start from rest.

The extractor is a multiple-aperture accel-decel design employing slots; the cross section of one of these slots is shown in Fig. 4. There are 21 slots in the beam-forming electrode, each 2 mm wide and 7 cm long, spaced 3.3 mm center-to-center, filling a square array 7 cm on a side. Slots, rather than circular holes, were chosen because the transparency is higher by about 50% and because an array of slots can be permitted to expand in one dimension under a heat load without buckling or destorying the symmetry. The extractor is constructed of copper with epoxy insulators.

The high-voltage for ion extraction and acceleration is provided by a pulse line with a pulse length of 30 msec. The line feeds a vacuum tube which acts both as a voltage regulator and series switch to remove the voltage quickly to prevent damage if a spark is detected by a current monitor.

Figure 5 shows the performance of the system in producing deuterium beams in the energy region of 10 to 20 keV. For each extraction voltage the figure shows a range of extracted beam currents. For the upper limit, we show the actual high-voltage power supply drain; and, as a lower limit, that current minus the current to the second electrode. The extracted current exhibits the expected $V^{3/2}$ dependence on extraction voltage. Also shown are the calorimetrically measured currents (ions plus neutrals) reaching a 10×20 cm target at 330 cm, and similar measurements for a 20×40 cm target. It is apparent that the beam divergence decreases with increasing beam energy.

The latest model of this source has an extracted current of about 16 A at 20 kV, with a total equivalent current of 9.6 A to the 10×20 cm target; about 90% of the beam energy is in neutral particles. Measurements of the composition of the beam at the calorimeter indicated that the accelerated ion beam consisted of about 75% D^+, 18% D_2^+, and 7% D_3^+.

Measurements of beam profiles with a 32-channel calorimeter show that the beam divergence is less in the plane of the slots than perpendicular to the slots, as expected.[10] 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 folded with a rectangular source function. The 1/e half-widths of these Gaussians (corrected for the contribution of the finite source) are shown in Fig. 6.

Mechanical imperfections and misalignments in the extractor assembly result in 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 long axis of the slot, will change the angle at which the beam emerges by 3.5 deg. This effect 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 are using this effect in the design and construction of a much larger source (extraction grid 7×35 cm) from which we hope to obtain a converging neutral beam of 80 A equivalent current. The unit will incorporate a compact design so that a number of these modules can be employed to obtain even higher currents.

ACKNOWLEDGMENTS

The authors would like to thank L. A. Biagi and H. A. Hughes and members of their groups for the skillful construction and assembly of the source and associated parts, and E. B. Hewitt for assistance in experimentation.

FOOTNOTE AND REFERENCES

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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FIGURE CAPTIONS

Fig. 1. Assembled plasma source and extractor.

Fig. 2. Two views of ion source without accelerating structure.

Fig. 3. Plasma density profile.

△ = D_2 gas arc current = 1000 A, arc voltage = 48V

□ = H_2 gas arc current = 660 A, arc voltage = 40V

Fig. 4. Cross section of a single slot in the extractor, showing relative electrode potentials and calculated ion trajectories and equipotentials.

Fig. 5. Current (actual or calorimetric equivalent) versus extraction voltage for operation with deuterium. The decelerating voltage was 1.1 kV. The two lines labeled "Design" were obtained from the calculated perveance; the thin lines connect data points.

Fig. 6. 1/e Gaussian half-widths parallel and perpendicular to the slots.

0 0 0 0 3 9 0 0 8 9 9

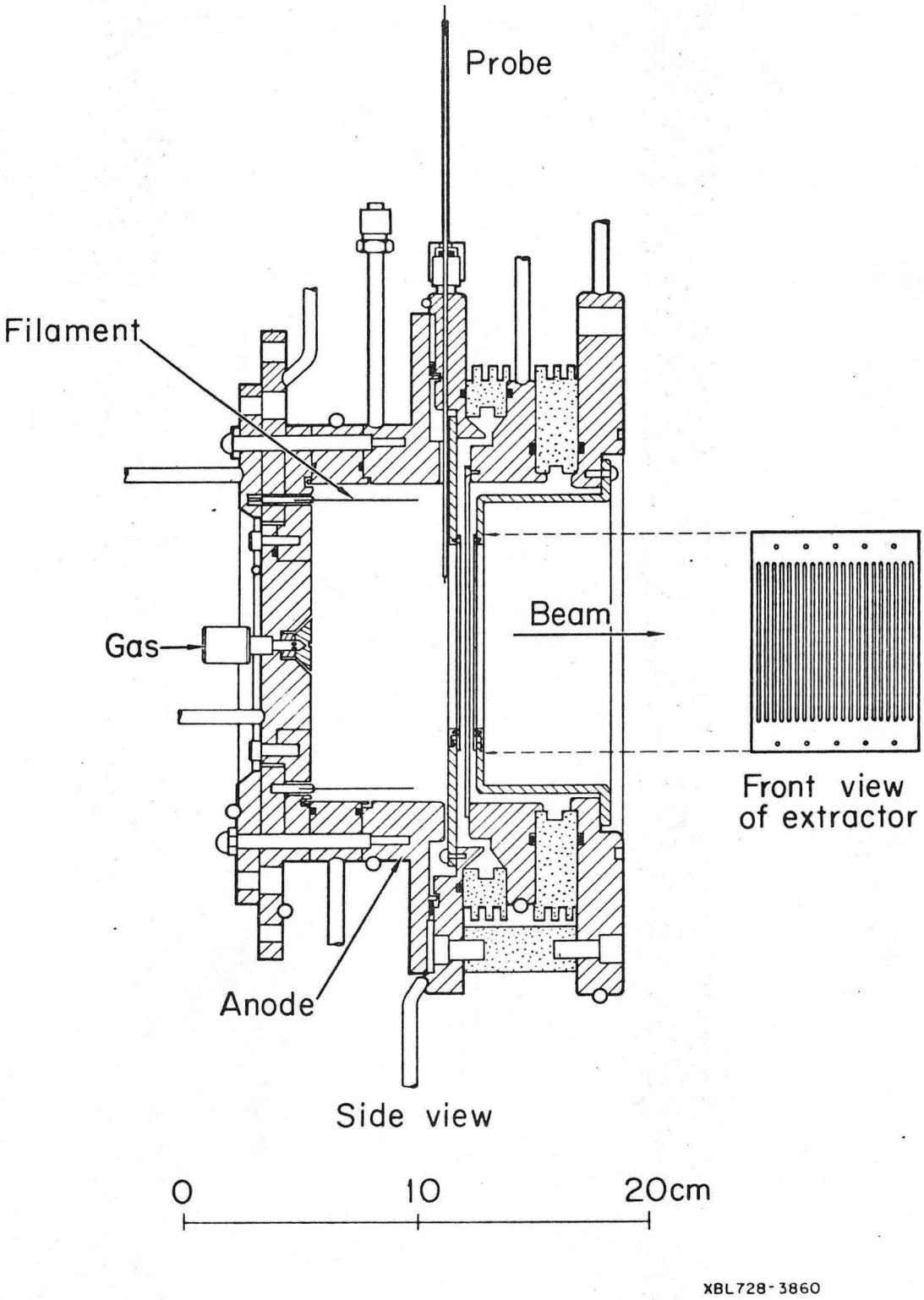
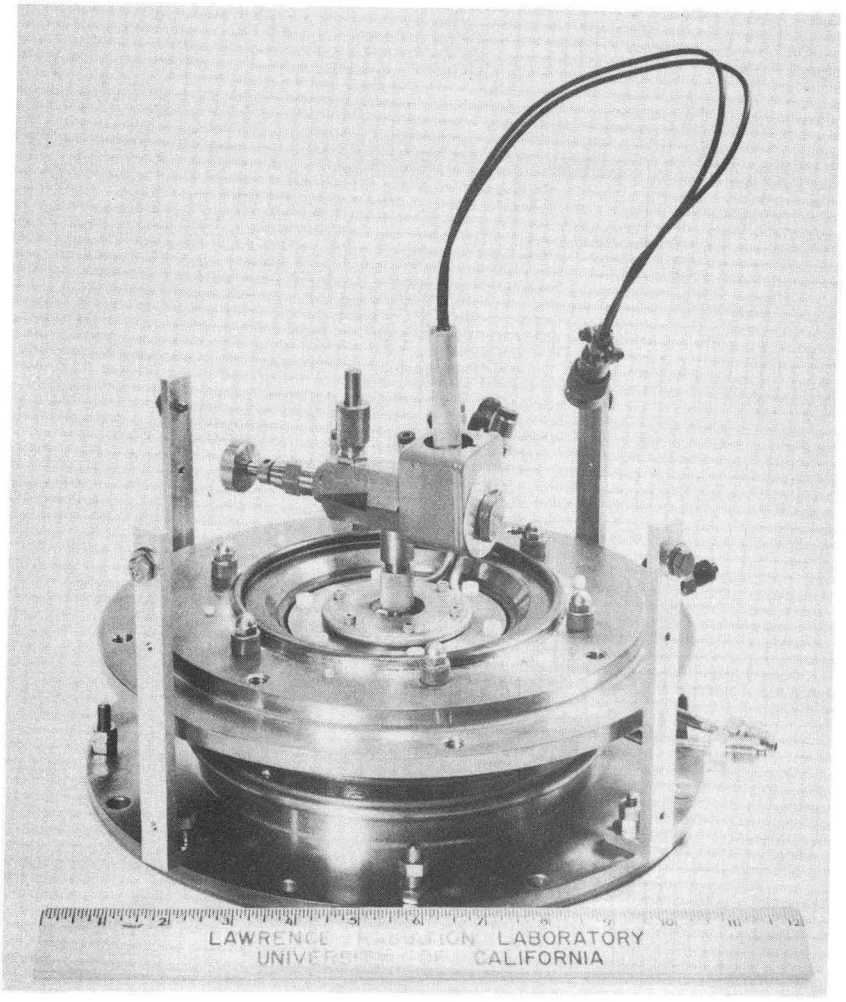
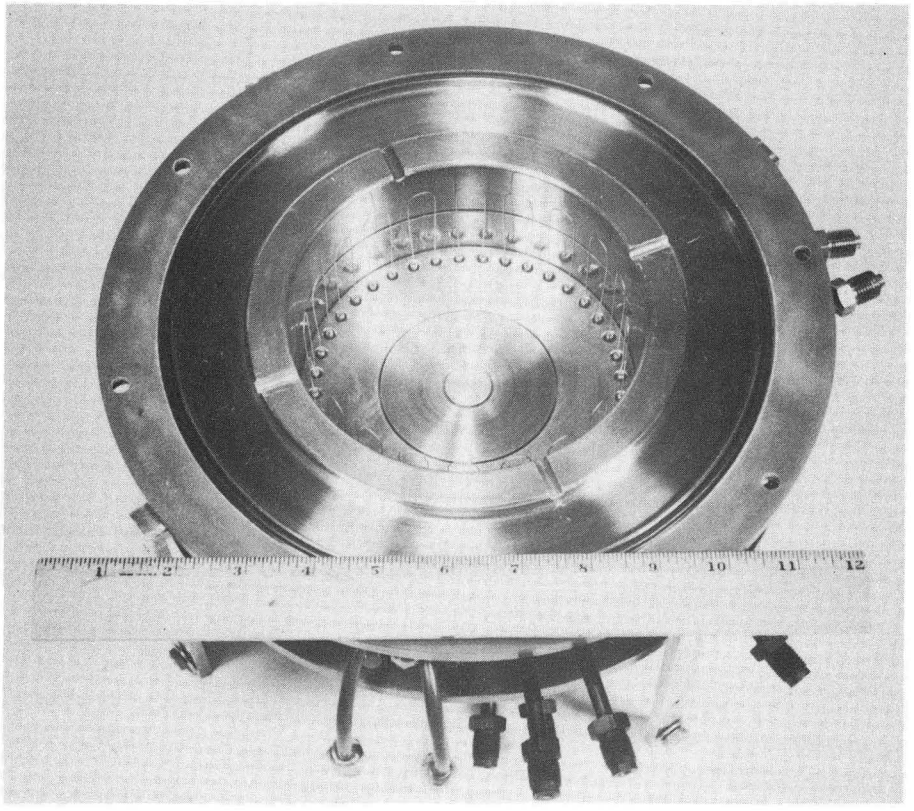


Fig. 1





XBB 735-3019

Fig. 2

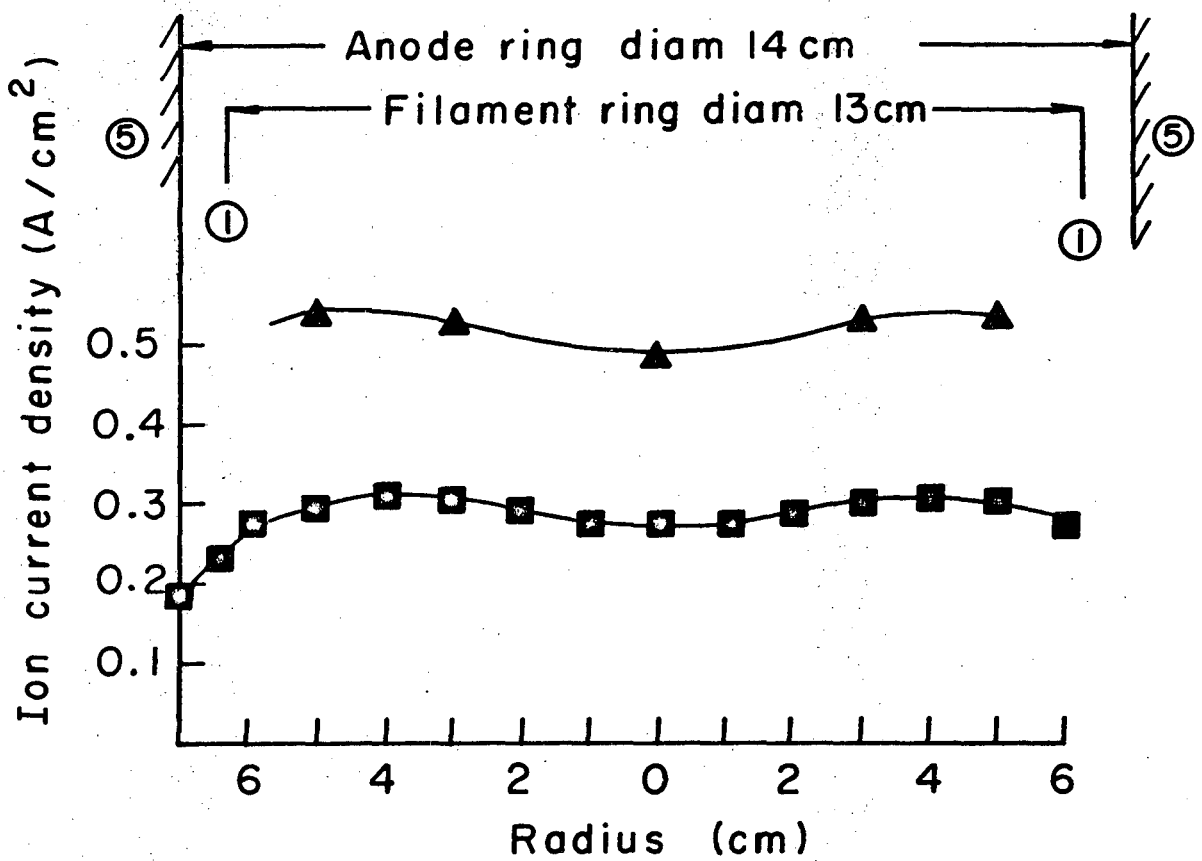


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Fig. 3

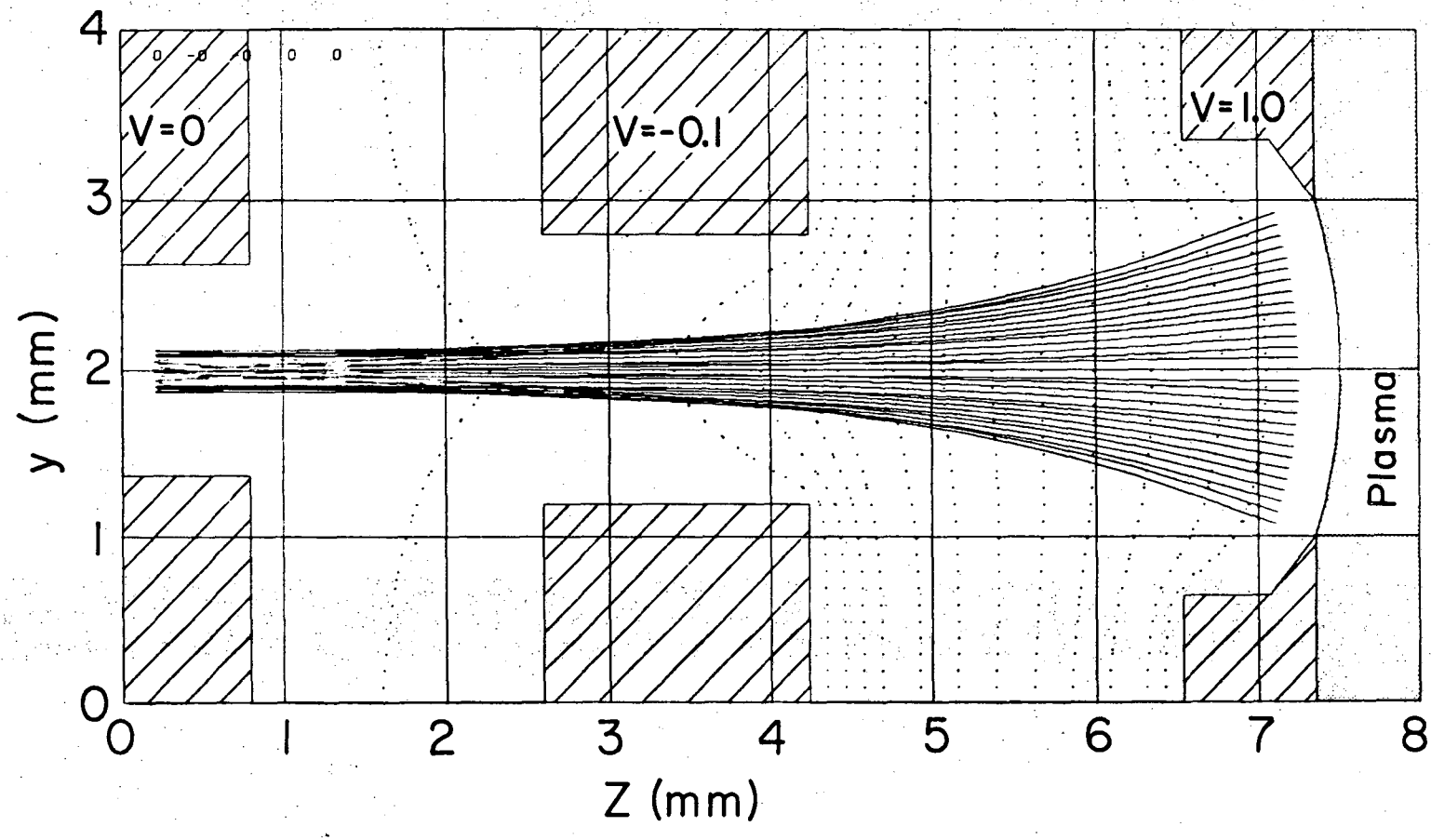

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Fig. 4

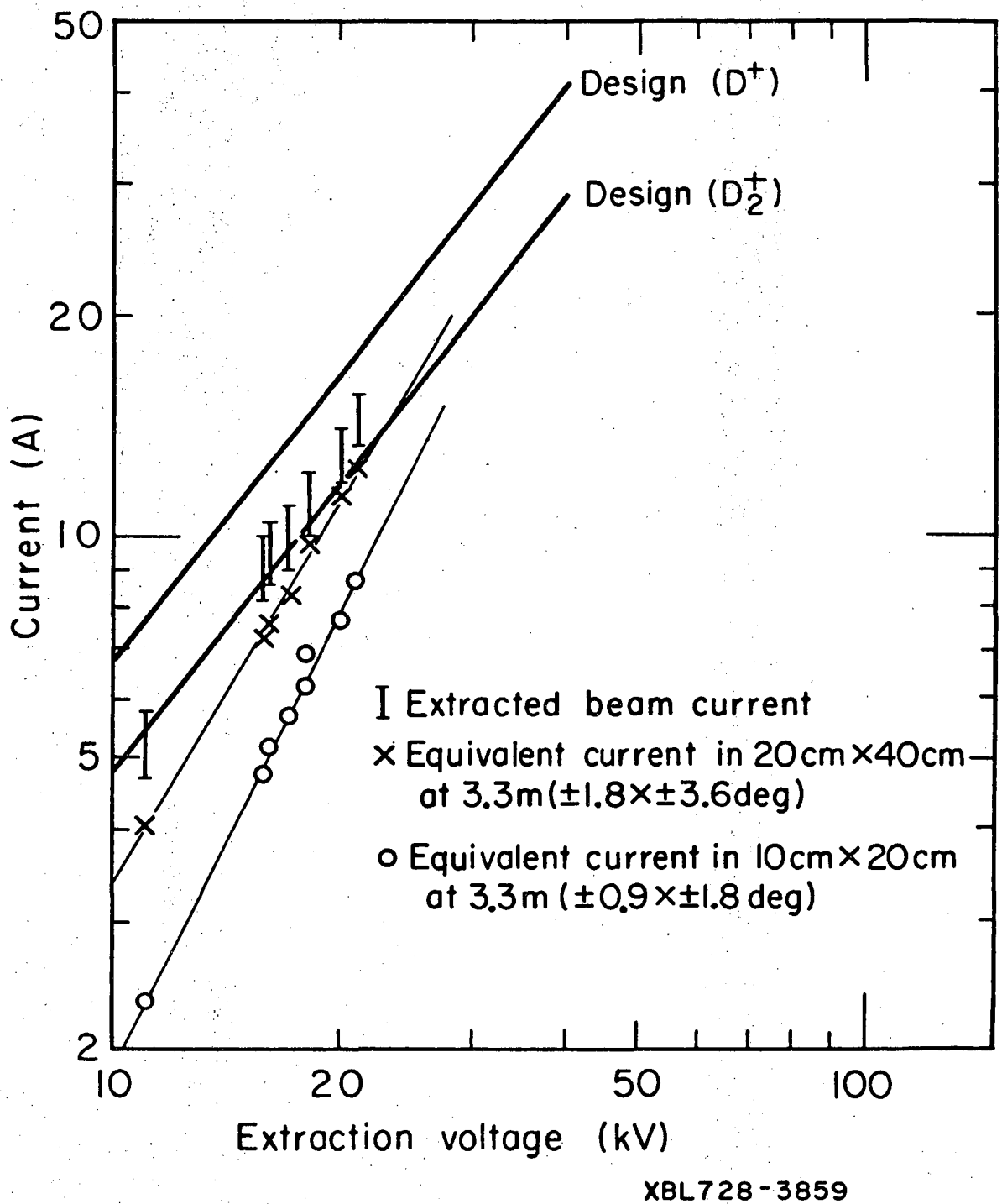
50
20
10
5
2
Current (A)
10
20
50
100
Extraction voltage (kV)
Design (D^+)
Design (D_2^+)
I Extracted beam current
× Equivalent current in 20cm×40cm at 3.3m(±1.8×±3.6deg)
o Equivalent current in 10cm×20cm at 3.3m (±0.9×±1.8 deg)
XBL728-3859

Fig. 5

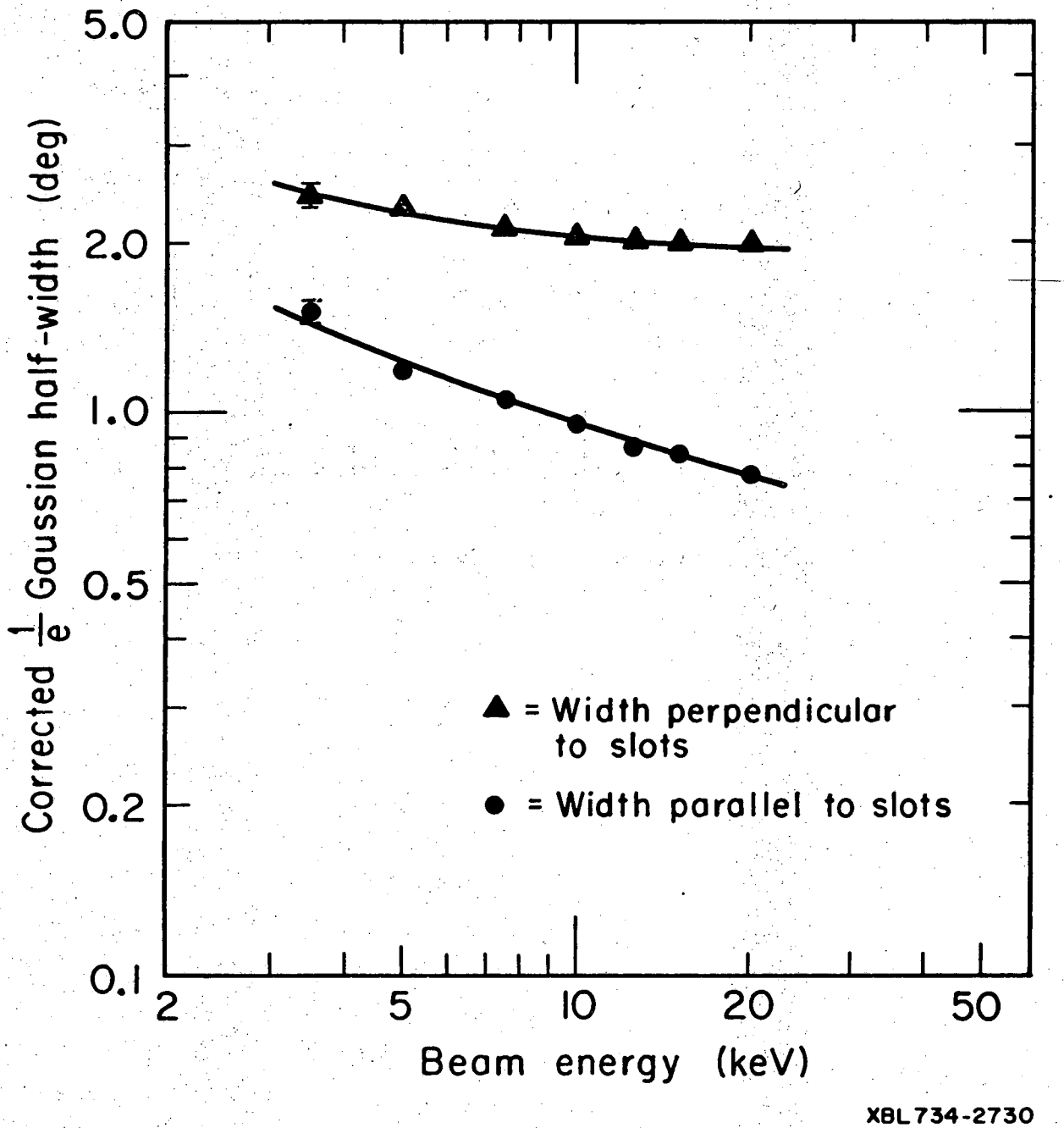
5.0
2.0
1.0
0.5
0.2
0.1
Corrected $\frac{1}{e}$ Gaussian half-width (deg)
2
5
10
20
50
Beam energy (keV)
▲ = Width perpendicular to slots
● = Width parallel to slots
XBL 734-2730

Fig. 6

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