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PROGRESS IN THE DEVELOPMENT OF HIGH-INTENSITY NEUTRAL BEAMS*

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The Controlled-Fusion Research Group at the Lawrence Berkeley Laboratory has taken a new approach to the development of neutral beams for injection into magnetic confinement systems. Our attack is twofold:

1. Close attention is paid to ion optics, i.e., we attempt to optimize the beam-forming process with the help of a sophisticated computer program.

2. A novel ion source is being perfected that evidently has the appropriate characteristics and seems to involve less complicated plasma physics than the duoplasmatron and reflex arc discharges that are customarily used.

The aim is to extend the ion current to tens of amperes at reasonable energies without sacrificing the quality of the beam. Clearly this requires large-area plasma sources of adequate density coupled with multiple-aperture extraction structures. The results of this effort so far have been very encouraging.

For instance, we have recently tested the performance of a 7 cm x 7 cm, 60% transparent ion extractor consisting of three electrodes in an accel-decel configuration. In each electrode is an array of 21 slots, the shapes of which have been computer-optimized for low-divergence beam production. The apparatus is designed to accelerate deuterium ions to 20 keV in 20 msec pulses and to convert them to an intense neutral beam is a closely coupled gas cell. No additional beam focusing is used. Operation with deuterium in the range 7.5 to 20 keV is about as predicted from calculations. At 20 keV, of the approximately 15 A of ion current extracted from the source, 12.4 A equivalent current (about 85% neutrals) were delivered to a 20 cm x 40 cm rectangular calorimeter 3.3 m from the source. The central 10 cm x 20 cm area of this calorimeter, which subtended an angle of ± 0.9 x ± 1.8 degrees from the center of the source, received 8.6 A equivalent current. Measurements of the various charged components remaining in the beam at the calorimeter indicated that the extracted ion beam consisted of about 75% D^+, 18% D_2^+, and 7% D_3^+. The source is also designed to permit rapid modulation of the energy and intensity of the beam.

The plasma which is used to illuminate the extractor structure is produced by a pulsed (30 msec) low-pressure high-current discharge between a ring of 20 half-millimeter diameter hot tungsten filaments and an annular anode. No externally applied magnetic fields are required. The elimination of magnetic fields results in a very stable and quiescent plasma with fluctuations less than 1%. When operating with an arc current near 1000 A this discharge can generate a deuterium ion current density in excess of 0.5 A/cm^2. Probe and extracted current measurements indicate that the plasma is uniform to better than 10% over a 10-cm diameter. The system is pulsed to avoid overheating of the extractor grid structure and to reduce the total gas load entering the confinement system through the beam line. Extension to even larger sources and to dc operation seems relatively straightforward. Some future improvement in efficiency and in the beam quality presently achieved seems also quite probable. The theoretical consideration underlying this source design will be discussed.

INTRODUCTION

Many controlled thermonuclear fusion experiments require the production of intense beams of neutral hydrogen or deuterium atoms to generate, maintain, or heat a confined plasma. For instance, in the 2X II Experiment at the Lawrence Livermore Laboratory, a flux of deuterium atoms equivalent to at least 10 A with 20 keV energy/particle is needed if an interesting plasma is to be maintained in a steady state. Similar figures apply to Tokamaks and Stellarators. It is clear that space-charge limitations restrict ion flows through single apertures at this energy to much lower currents, so that the design of such an injector must involve a large number of parallel beams. It is convenient to use an integrated extractor structure carrying many closely spaced apertures (i.e., a grid) backed by a single extended plasma source in which the ions are produced. Such "multiple-aperture" systems have been used before for ion-propulsion engines[1] and for other intense ion beams.[2] We describe here the large beam source, developed at

Berkeley, in which a special effort was made to minimize the beam divergence, eliminating the need for magnetic focusing and thus permitting the possibility of prompt neutralization. The system consists of two major components: the extractor and the plasma source.

THE EXTRACTOR

Design

The extractor was designed with the aid of a digital computer program[3,4] 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, described elsewhere,[5] 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 parallel, typically within ±1 degree. In the program, 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. This program has now been coupled with PISA, a general-purpose least-squares optimization program[6] which varies the shapes of the emitting surface and of the beam-forming electrode to achieve uniform ion current density at the emitting surface and parallel beams.

The extractor is a multiple-aperture accel-decel design employing slots; a cross section of a single slot, with calculated equipotentials and ion trajectories is shown in Fig. 1. 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 for the following reasons: (1) the transparency is higher, by about 50%, (2) the ion current density at the emitting surface is somewhat higher, by about 5%, and (3) an array of slots can be permitted to expand in one dimension under a heat load without buckling or destroying the symmetry. The extractor was 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 20 msec. The line feeds a vacuum tube which acts both as a voltage regulator and a series switch to remove the voltage quickly from the extractor and prevent damage if a spark is detected by a current monitor.

Beam Diagnostics

The accelerated ion beam undergoes charge exchange in a gas cell adjacent to the extractor; the gas from the source is sufficient for this purpose. No magnetic focusing is used. Immediately following the gas cell is a pulsed magnet to sweep out the charged fraction of the beam, if desired. The end wall of the vacuum vessel, 3.3 m from the extractor, is a plate of stainless steel 20 cm x 40 cm and 0.61 cm thick which serves as a calorimeter for the pulsed beam. The extractor slots are parallel to the short dimension of the calorimeter. There are 32 thermistors in a 4 by 8 array 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 of the calorimeter 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 converter 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 distribution of charged species in the beam.

Performance

Figure 2 shows the performance of this extractor in producing deuterium beams in the energy range 10 to 20 keV. The figure shows for each extraction voltage (the voltage between the first and second electrodes) a range of extracted beam currents. The upper limit is the current measured leaving the high-voltage power supply. There is an uncertainty in the measurement of the extracted beam current, since some current appears on the second (accel) electrode, either from direct beam interception or from the collection of ions produced from charge-exchange in the extractor or by extraction from the downstream plasma. We show as a lower limit to the extracted beam current the high-voltage power-supply drain minus the current to the second electrode. In general, the extracted current is consistent with the calculated value for a reasonable assumption for the beam composition (we have measured the beam composition in some cases), and exhibits the expected $V^{3/2}$ dependence on extraction voltage. Also shown are the calorimetrically measured currents (total beam, ions plus neutrals) reaching the 20 cm x 40 cm calorimeter (x's) and the 10 cm x 20 cm central portion (circles). It is apparent that the beam divergence decreases with increasing beam energy. At 20 keV, the extracted current was 13 to 16 A, of which 12.4 A equivalent current reached the 20 cm x 40 cm calorimeter and 8.6 A reached the central 10 cm x 20 cm area. About 85% of the beam energy was in neutral particles. Measurements of the composition of this beam at the calorimeter indicated that the accelerated ion beam consisted of about 75% D^+, 18% D_2^+, and 7% D_3^+.

Measurements of the beam profiles with the 32-channel calorimeter showed that the beam divergence was less in the plane of the slots than perpendicular to the slots. This is to be expected, as the divergence in the plane of the slots should be limited by the initial transverse velocity spread of the ions, and not by 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 very well by a Gaussian folded with a rectangular source function. The 1/3 half-widths of these Gaussians (corrected for the contribution of the finite source) is shown in Fig. 3 for optimum operation with hydrogen and deuterium in the energy range 5 to 20 keV. The data are consistent with an initial transverse ion energy of 1 to 5 eV plus a contribution of about 2 degrees in the plane perpendi ular to the slots, presumably due to aberrations introduced by the extractor, and 0 degree in the plane parallel to the slots. The lines in the figure show the energy dependence for an initial transverse energy of 2.5 eV.

Energy Modulation

This extractor was also designed to permit rapid modulation of the beam energy. This can be done by keeping the extraction voltage and the plasma density constant, and decelerating the beam to the desired energy after extraction.[7] Computer calculations indicate that it should be possible to design an extractor to operate in this fashion at two energies separated by a factor of 5. If one starts at the maximum beam energy and begins to decelerate the beam, the beam starts to diverge. At still lower energies, however, the aperture in the third electrode acts as a converging lens, and production of a parallel beam should again be possible. Figure 4 shows the results of dc tests on a single-slot extractor of the same design as shown in Fig. 1; the width of the slot in the beam-forming electrode was again 2 mm, and the slot was 2 cm long. The figure shows the 1/e half-widths (corrected for the finite source size) of the Gaussian profiles parallel to and perpendicular to the slot, and also the extracted current, all plotted against the normalized beam energy (beam energy/11 keV). The plasma density was not changed during these measurements. The extracted current remained constant, as expected, while both divergences increased with increasing deceleration of the beam. While there was a tendency for the divergence perpendicular to the slot to decrease at low beam energies, as predicted, the design does not yet appear to be optimum for this type of operation.

We are planning further experimental optimization of this extractor for producing variable energy beams, and are beginning to test another slot design computer-optimized by PISA for operation at a single energy. Computer studies have been extremely useful in extractor design, but there remains room for further improvement. For instance, the computed perveances agree very well with the measured ones, but the measured beam divergences are consistently larger than those computed; more work will be required to understand and correct this discrepancy.

THE PLASMA SOURCE

Up to this point we have only discussed the design considerations for the extractor and the properties of the resulting beam, including the effect of charge-neutralization in the beam-line. It was tacitly assumed that the plasma source from which the ions were extracted was capable of supplying an ion current of sufficient density uniformly over the entire area of the large multiple-aperture structure, i.e., of the order of 0.5 A/cm^2 constant in space and time to better than 10% covering an area of at least 7 cm x 7 cm and involving a minimum of magnetic field. Conventional discharges were found to be inadequate so that a novel source had to be developed.

The plasma source which we describe here and which meets the above specifications will be recognized as an improved design of an earlier model reported on previously.[8] The basic principle is the same so that the underlying philosophy will only be summarized here: The plasma is produced by a diffuse low-pressure high-current discharge with a distributed, thermionically emitting cathode consisting of a ring of hot tungsten filaments. No magnetic field is added, so that the usual fluctuations associated with cross-field transport are avoided. In essence, we are dealing with a very powerful version of the so-called "electron-bombardment source", i.e., the ionization is produced entirely by the primary electrons originating at the cathode. The mean free path of these primaries is large compared to the dimensions of the discharge chamber. The efficiency of the source is therefore governed by the probability that such an electron produces an ion before it is either lost at a surface or reduced in energy by nonionizing collisions. A crude analysis of this situation, involving some simplifying assumptions, is presented in the Appendix which is reproduced from Ref. 8.

Design

A photograph of the present source, showing a front view without the extractor grid, is presented in Fig. 5. A block diagram of the source plus its associated electronics is shown in Fig. 6.

The unit described here contains 20 hairpin filaments, 0.5 mm in diameter, 10.5 cm in length, and thus the total cathode emission area is ~ 34 cm^2. They are electrically connected in parallel, and are inserted into molybdenum chucks. A total of 520 A (26 A/filament) at 12.5 V 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 source potentials.

Two filament-design considerations should be noted. First, the large radiant heat load from tungsten filaments not only aggravates general cooling requirements, but can warp the delicate and accurately machined extractor structures (No. 7 in Fig. 6). However, electron emission increases more rapidly with filament temperature than does radiant emission, thus small but very hot filaments are desired. In addition, as the heater current is pulsed, the temperature equilibration time for small filaments is less (~ 1 sec for this unit).

In our initial sources,[8] the gas was pulsed through a small cylindrical anode. Overall arc efficiency was fairly good for this style of anode. Unfortunately, the plasma density profile was peaked at r = 0, and this effect became more pronounced as the arc current was increased. By operating, instead, a portion of the cylindrical chamber wall as the anode (No. 5 in Fig. 6), a considerable improvement in radial profile was obtained, which in addition did not change as the arc current was increased. The enlarged anode area reduced our source efficiency somewhat, but the possible existence of anode sheaths as well as troublesome magnetic fields resulting from concentrated arc currents are eliminated.

The remaining parts of the wall, 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 needle valve or by altering the reservoir pressure.

Arc power is supplied from a pulse line composed of iron-core inductors and electrolytic condensers. The pulse line is crowbarred after 30 msec to remove the possibility of capacitor damage, which would result from voltage reversal. The arc current is controlled by a current-limiting resistor as well as by the pulse-line voltage charging level.

The pulse timing sequence is as follows: Filament on at -1 sec, gas pulsed on at t = -10 msec, arc power on at t = 0, extractor voltage pulsed on at t = +5 msec, and off at t = +25 msec; arc power, gas, and filament power off at t = +30 msec.

Arc voltages vary from about 25 to 70 V, depending largely on the level of arc current, the filament heat, and the gas flow.

RESULTS AND DISCUSSION

Figure 7 is a plot of the arc current, arc voltage, and the ion current density vs the level to which the arc pulse line is charged. In this case, in which the arc was operated with hydrogen, the source parameters of filament temperature and gas feed were adjusted at the 1000-A level and not changed as the charging voltage was reduced. At any one operating level the arc voltage can be increased by either the gas flow or the filament heat. In general the arc voltage is maintained at a maximum of 45 to 50 V, as the source is less apt to develop a cathode spot. Cathode spots, which seem to be caused by gas bursts resulting from sparking in the source or accelerating structure, appear when the arc current attempts to constrict to a spot on a single filament rather than coming uniformly from all filaments. A fault of this type produces extremely "hashy" operation and often results in the loss of a filament.

Figure 8 is a plot of the plasma density profile for two levels of operation, as indicated by the movable probes (No. 6 in Fig. 6). Although this source was designed for a square 7 x 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 locations of the filament ring and the anode wall are also indicated in Fig. 8, demonstrating that nearly the entire source diameter is available for extraction.

With large ion-extraction areas, good gas efficiency is required, as there is little structure separating the gas pressure required by the source from the high voltages on the extraction electrodes. Gas flow measurements compared with the extracted ion output indicate a gas efficiency of about 30%. In this case, gas not utilized by the source is used downstream in a charge neutralizer section, from which we get a neutralizing efficiency in excess of 80%.

A larger unit, with an 8-in.-diameter filament ring has been constructed. This will allow an extraction area approximately 2.5 times as large as the present unit. Preliminary indications are that it will require 2.5 times as much arc current to obtain equal density, but the ion current density profile will be similar to that in the present unit.

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. Aside from a small amount of 360-cycle filament ripple, the probe signals are essentially flat in time and completely free from noise.

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This development has been and still is a group effort, led and coordinated by R. V. Pyle. W. S. Cooper is responsible for the extractor design and participates in the testing. Beam diagnostics is primarily handled by K. H. Berkner aided by J. W. Stearns, and K. W. Ehlers is responsible for the plasma source development, aided by A. F. Lietzke, or lately by E. B. Hewitt. W. R. Baker is in charge of the design and testing of the various power supplies and electronic components and he is aided by V. J. Honey. The construction of most components is handled by L. A. Biagi and his excellent shop, and by H. A. Hughes.

APPENDIX

A precise statement about the importance of the primary electron's mean useful path length can be made in the following simple case. Consider a volume, defined by a simple closed surface, that contains a partially ionized, single-species gas. An electron source injects into the plasma monoenergetic electrons with an energy sufficient for one ionization or one excitation; the electrons are then contained by reflecting wall sheaths or collected by the anode. If p_1 denotes the average probability for anode collection between reflections, one can assign an approximate probability for anode collection survival after N reflections as $P_N \approx e^{-p_1 N}$, a good approximation for $p_1 \ll 1$. Likewise, if σ_i and σ_x denote the electron-bombardment ionization and excitation cross sections, the probabilities for surviving each effect for a distance s in a uniform gas are

$$P_i = e^{-n_0 \sigma_i s}$$

and

$$P_x = e^{-n_0 \sigma_x s} .$$

Hence, the probability for primary-electron survival of all three independent annihilations within a distance s is

$$P_p = P_N P_i P_x = e^{-[n_0(\sigma_i + \sigma_x)s + p_1 N(s)]} .$$

Assigning $N(s) = s/\bar{d}$ ($\bar{d}$ = average path length between reflections), one can define a mean useful path length λ_u

$$\lambda_u = \frac{1}{\frac{p_1}{\bar{d}} + n_0(\sigma_i + \sigma_x)} .$$

This parameter is also significant in the more general case of multiple ionizations per electron where, with the assumptions of constant σ_i, σ_x over the energy range of significance, one can obtain a probability for primary electron survival by a path length s of

$$P_p(s) = e^{-s/\lambda_u} [1 + \frac{s}{\lambda_{ie}} + \frac{1}{2} \frac{\quad}{\lambda_{ie}^{2}} + \cdots],$$

where

$$\lambda_{ie} = \frac{1}{n_0(\sigma_i + \sigma_x)} .$$

The effect that this parameter has upon source efficiency can be illustrated by the following estimation: the steady-state ion continuity equation requires that

$$\text{div } \vec{J}_i = e\ n_0 n_e' \langle \sigma_i v_e \rangle' .$$

where

$\vec{J}_i$ = ion current density,

n_0 = neutral density,

n_e' = primary electron density,

$\langle \sigma_i v_e \rangle'$ = appropriate average of the ionization rate coefficient over the primary electron velocity distribution.

The primary electron density can be estimated as

$$n_e' \approx \frac{I_e'}{eV} \tau',$$

where I_e' = primary electron current,

V = source volume,

τ' = $\lambda_u / \langle v_e \rangle'$ = average primary lifetime.

Integration of the continuity equation over the volume, assuming uniform densities, gives the ion current to the confining surface:

$$\oint \vec{J}_i \cdot d\vec{A} = n_0 I_e' \frac{\langle \sigma_i v_e \rangle'}{\langle v_e \rangle'} .$$

For any given electron velocity distribution, electron efficiency is therefore optimized by maximizing

$$n_0 \lambda_u = \frac{1}{\dfrac{p_1}{n_0 \bar{d}} + \sigma_i + \sigma_x} .$$

Likewise, gas efficiency is optimized by maximizing

$$I_e' \lambda_u = \frac{I_e'}{\dfrac{p_1}{\bar{d}} + n_0(\sigma_i + \sigma_x)} .$$

In the case of negligible magnetic fields, p_1 may be assigned the likely value

$$p_1 = \frac{\text{anode area}}{\text{total surface area}}$$

and $\bar{d}$ the likely value of the typical distance between reflections inside the ionization chamber. Conversely, in a reflex arc, one has $p_1 \approx 1$, while $\bar{d}$ is vastly increased by the application of a strong axial magnetic field.

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FIGURE LEGENDS

Fig. 1. Cross section of a single slot in the extractor, showing relative electrode potentials and calculated ion trajectories and equipotentials.

Fig. 2. Current (actual or calorimetric equivalent) vs 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. 3. 1/e Gaussian half-widths parallel and perpendicular to the slots (corrected for the contribution of the finite source) vs beam energy for operation with hydrogen and deuterium.

Fig. 4. Performance of a constant-current variable-energy extractor. The energy was normalized to the constant 11 kV extraction potential. The lines labeled D^+ and D_2^+ show the calculated current for those species.

Fig. 5. Photograph of plasma source. Front view with extractor structure removed.

Fig. 6. Sketch of source with block diagram of circuits. 1. Tungsten 0.20-in.-diameter filament (20 total). 2. Cathode mounting plates: one +, one -. 3. Floating plates. 4. Floating ring. 5. Anode. 6. Movable probes (4 total). 7. Floating grid support plate. 8. Floating back plate. 9. Pulsed gas valve.

Fig. 7. Plot of arc current, arc voltage, and ion current density vs pulse line voltage.

Fig. 8. Plasma density profile. Δ = D_2 gas arc current = 1000 A. $\square$ = H_2 gas arc current = 660 A.

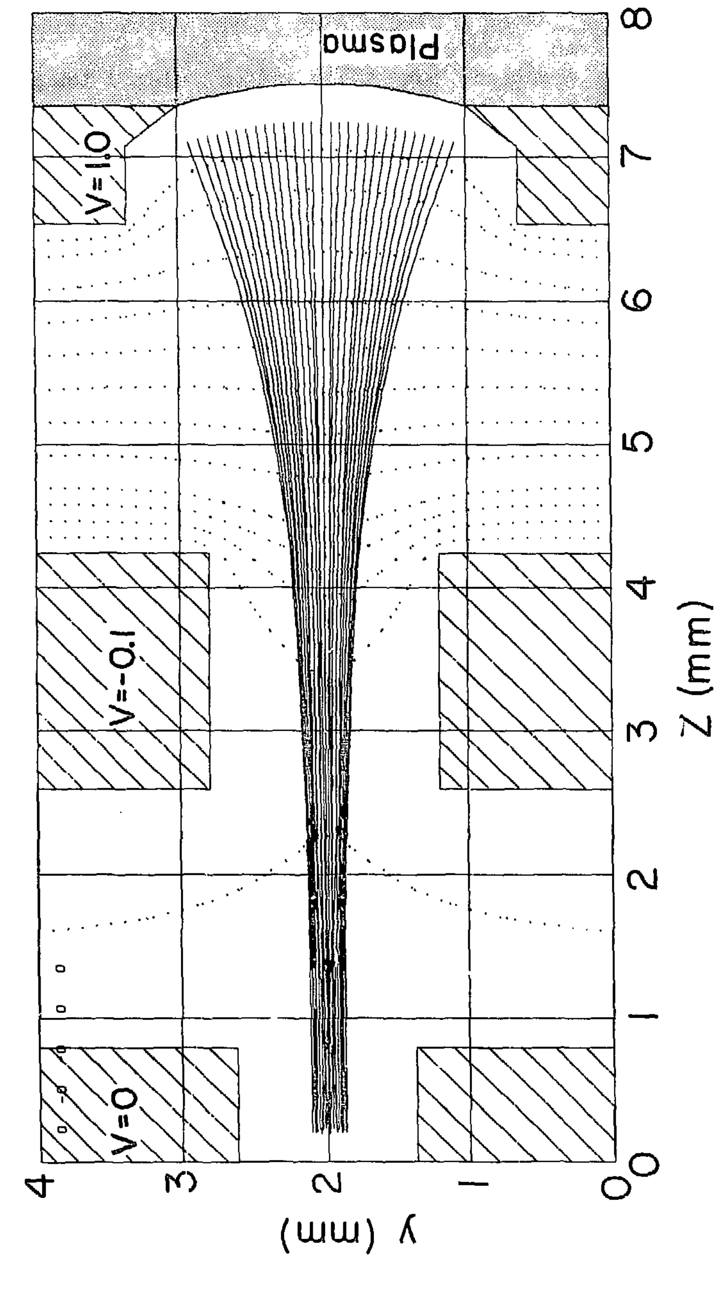

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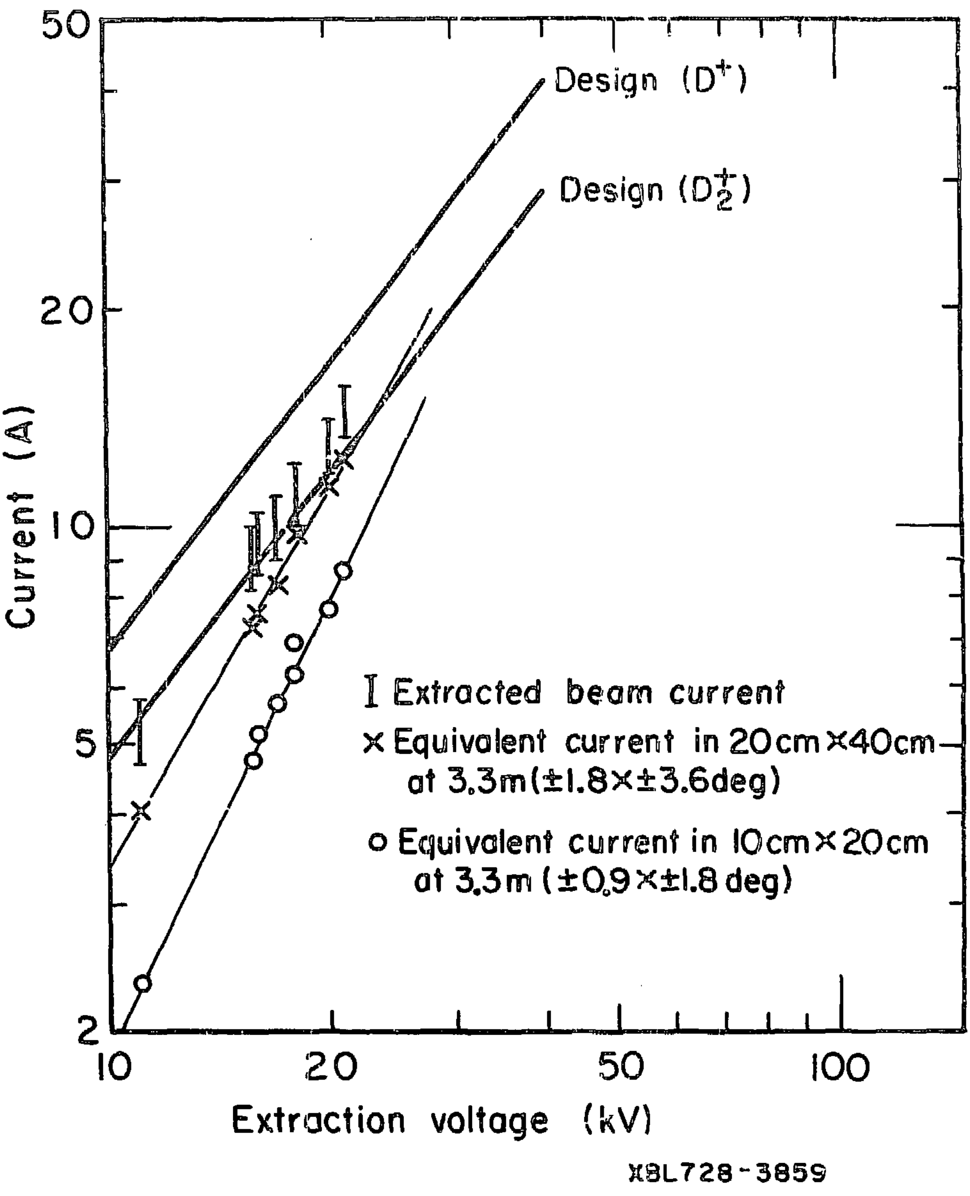
Fig. 1



Design (D+)
Design (D2+)
50
20
10
5
2
Current (A)
10
20
50
100
Extraction voltage (kV)
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. 2

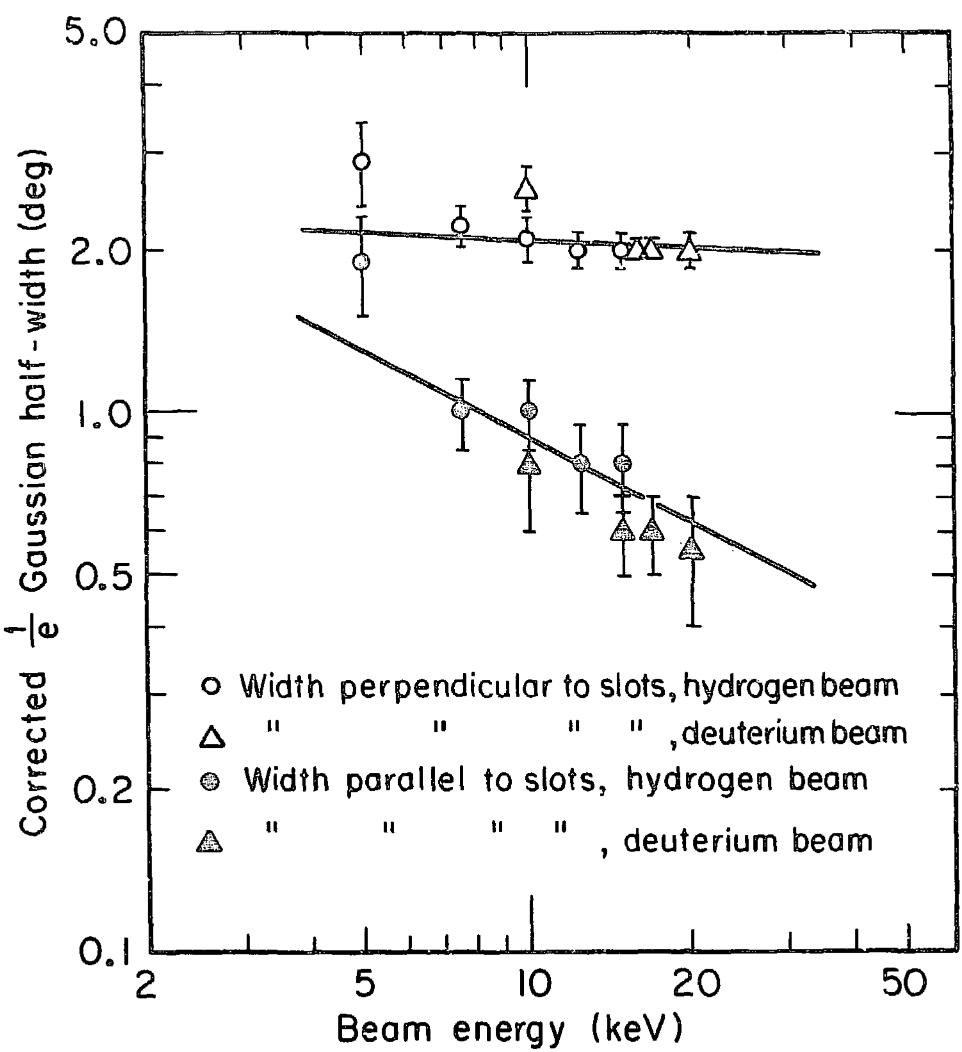


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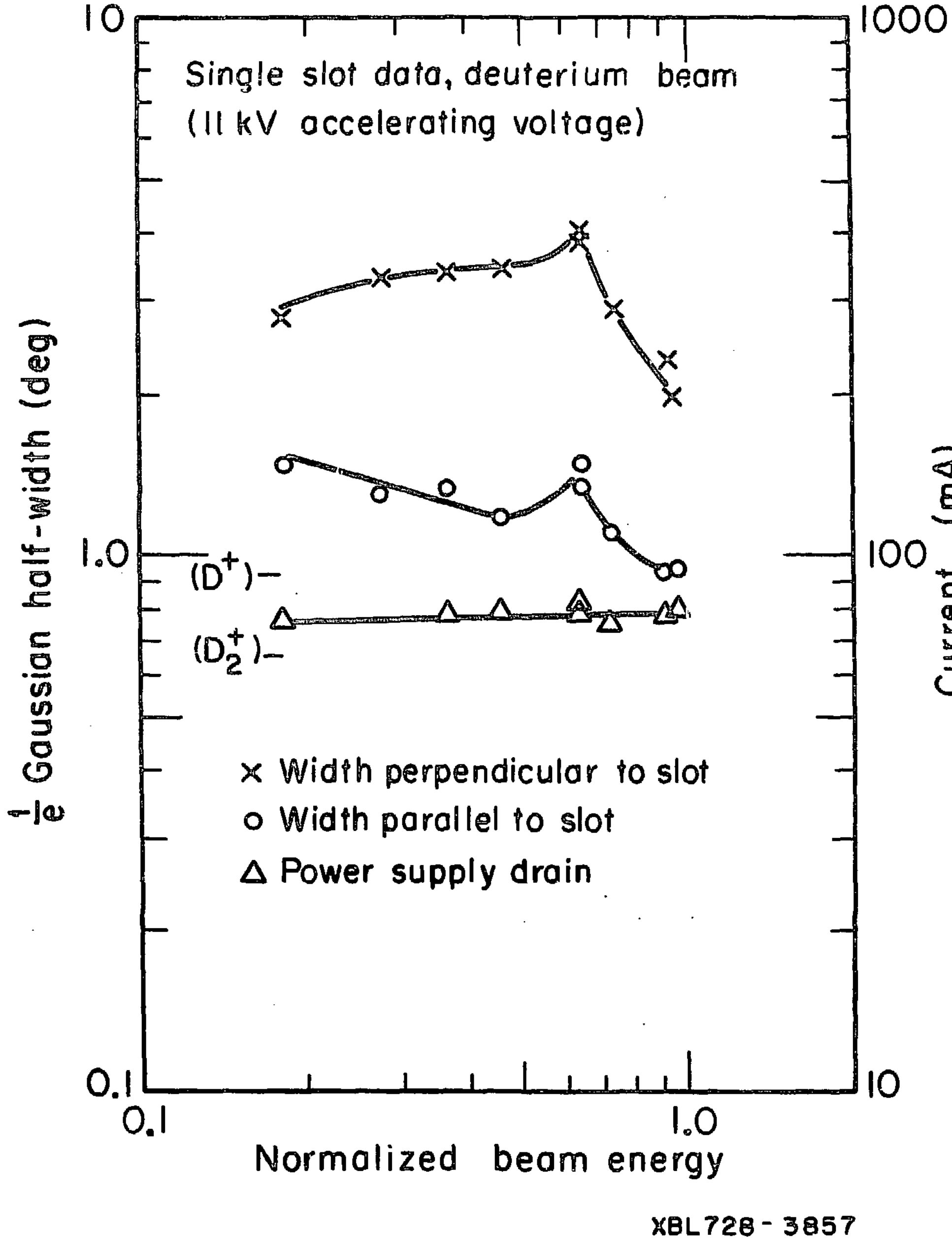
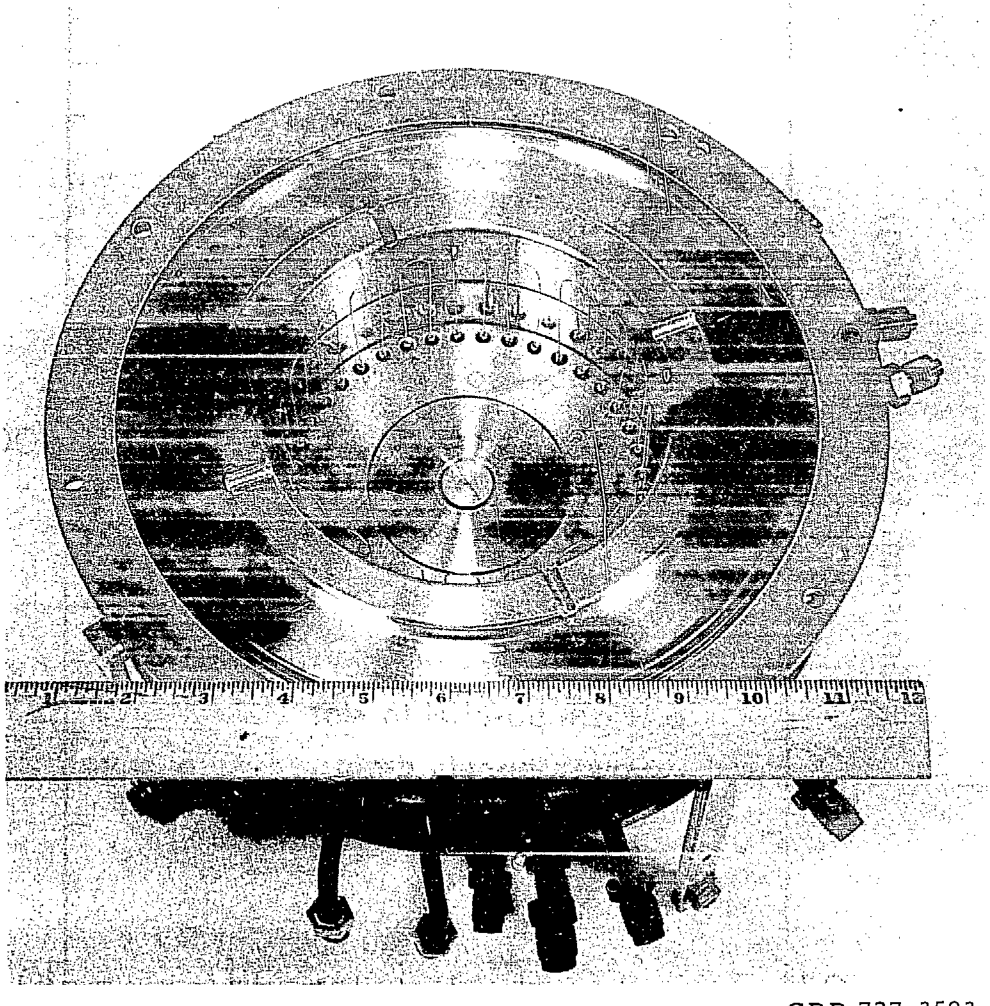
Fig. 3



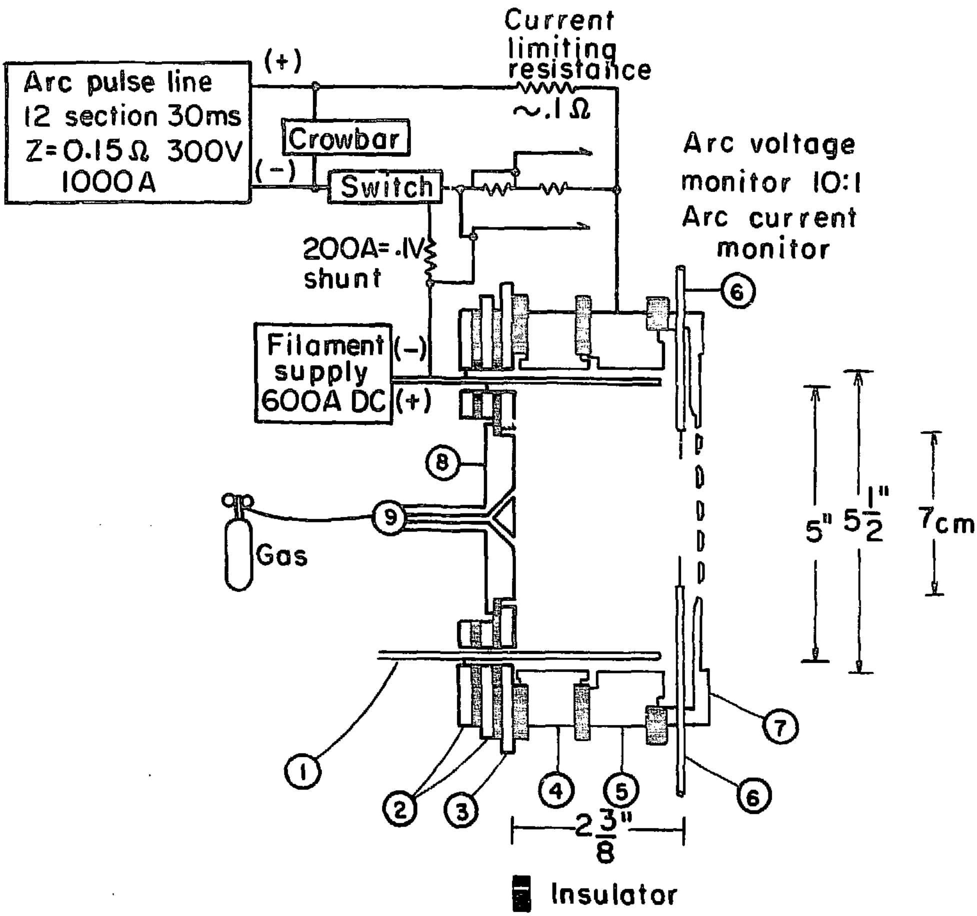
Single slot data, deuterium beam
(11 kV accelerating voltage)
10
1.0
0.1
1000
100
10
(D+)–
(D2+)–
× Width perpendicular to slot
o Width parallel to slot
Δ Power supply drain
1/e Gaussian half-width (deg)
Current (mA)
0.1
1.0
Normalized beam energy
XBL728-3857

Fig. 4



CBB 727-3593

Fig. 5



XBL727-3607

Fig. 6

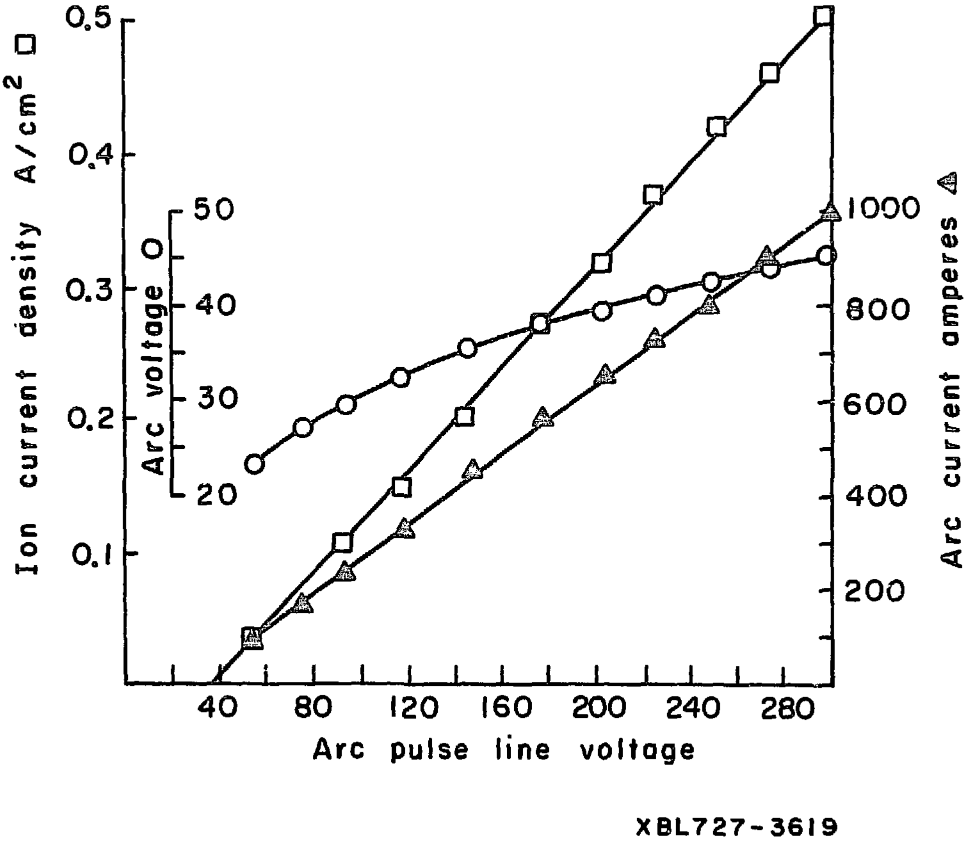

0.5
0.4
0.3
0.2
0.1
Ion current density A/cm² □
50
40
30
20
Arc voltage ○
1000
800
600
400
200
Arc current amperes △
40
80
120
160
200
240
280
Arc pulse line voltage
XBL727-3619

Fig. 7

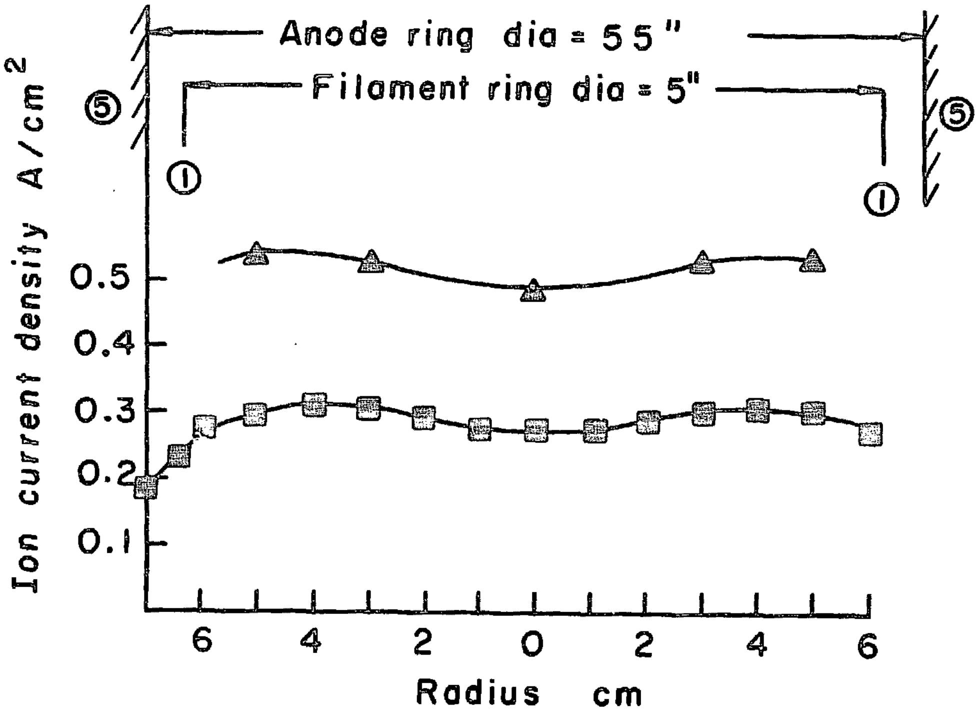


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Fig. 8