PRODUCTION OF INTENSE ION AND NEUTRAL BEAMS WITH A MULTIPLE-SLOT, LARGE-AREA EXTRACTOR*

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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. A high premium is placed on extractors capable of making high-current, low-divergence ion beams from which neutral beams for this purpose can be produced by charge-exchange. In this paper we describe the performance of such an extractor.

The extractor was designed with the aid of a digital computer program^{1,2} 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,³ was carried out until the current density over the emitting plasma surface was constant to better than $\pm 5\%$ and the ion trajectories at the exit of the extractor were 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. This program has now been coupled with PISA, a general-purpose least-squares optimization program⁴ 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 24 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

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

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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 plasma source from which ions are extracted consists of a hot cathode discharge between a circular row of 20 hairpin-shaped tungsten filaments and a concentric outer anode.⁵ This source operates with an arc voltage of 40-70 volts and a current of up to 1000 A, with pulse lengths up to 30 msec, and produces a deuterium plasma from which ion current densities of 0.5 A/cm^2 can be extracted, uniform to better than $\pm 10\%$ over a diameter of 10 cm. Figure 2 shows a drawing of the assembled extractor and plasma source. 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.

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

Fig. 2. Assembled plasma source and extractor.

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.

Figure 3 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. 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 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 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 only 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

Fig. 3. 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.

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 $1/e$ half-widths of these Gaussians (corrected for the contribution of the finite source) is shown in Fig. 4 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 deg in the plane perpendicular to the slots, presumably due to aberrations introduced by the extractor, and 0 deg 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.

This extractor was also designed to permit rapid modulation of the beam energy at constant plasma density by keeping the extraction voltage constant and decelerating the beam to the desired energy after extraction.⁶ If one starts with a well-focused beam at the maximum beam energy for a given accelerating voltage 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. Guided by computer calculations, we de-

signed our extractor to operate in this fashion over an energy range of 5.

We have not yet operated the 7 cm×7 cm extractor in this mode; however, a single-slot extractor has been tested. Figure 5 shows preliminary results of d. c. tests on the single-slot extractor of the same design as shown in Fig. 1; the width of the slot in the beam-forming

Fig. 4. $1/e$ Gaussian half-widths parallel and perpendicular to the slots (corrected for the contribution of the finite source) versus beam energy for operation with hydrogen and deuterium.

Fig. 5. 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.

electrode was again 2 mm, but 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 measure-

ments. The extracted current remained constant with increasing deceleration of the beam. The divergence perpendicular to the slot initially increased and then did decrease at lower beam energies, as predicted, but the design does not yet appear to be optimum for this type of operation. The maximum in both the perpendicular and parallel divergences at a normalized beam energy of 0.65 is a repeatable phenomenon as yet not understood.

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 the PISA code for operation at a single ratio of beam energy to extraction voltage. 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.

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