Title
MULTIPLE-APERTURE EXTRACTOR DESIGN FOR PRODUCING INTENSE ION AND NEUTRAL BEAMS

Permalink
https://escholarship.org/uc/item/9w60w7hw

Authors
Cooper, William S.
Berkner, Klaus H.
Pyle, Robert V.

Publication Date
1971-06-01

Submitted to
Applied Physics Letters

W. Cooper

UCRL-20698
Preprint c.2

MULTIPLE-APERTURE EXTRACTOR DESIGN FOR PRODUCING INTENSE ION AND NEUTRAL BEAMS

William S. Cooper, Klaus H. Berkner,
Robert V. Pyle

June 8, 1971

AEC Contract No. W-7405-eng-48

20

MULTIPLE-APERTURE EXTRACTOR DESIGN FOR PRODUCING INTENSE ION AND NEUTRAL BEAMS

William S. Cooper, Klaus H. Berkner, and Robert V. Pyle

Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

8 June 1971

ABSTRACT

We describe an extractor design suitable for use in multiple-aperture ion sources. Tests with a 19-hole array, 1.4 cm in diameter, produced a 16-keV deuterium beam of 260 mA (equivalent current) with a Gaussian width of 1.31 deg, in good agreement with the computed performance.

The production and heating of plasmas in many controlled thermonuclear fusion experiments requires the development of sources of ion beams to create intense beams of neutral hydrogen atoms by charge exchange. The geometry of these experiments and the required equilibrium plasma densities place a high premium on beams with high current densities and low divergence--i.e., with high brightness. The development of suitable beams, usually involving magnetic focusing, is proceeding in several fusion laboratories around the world.[1] It may be advantageous from the point of view of plasma stability to accelerate beams of mixed composition (D^+ and D_2^+, for example) to broaden the velocity distribution in the plasma. To maximize the current of all species delivered into the experiment, one should avoid magnetic focusing if possible, and should try to achieve the required beam divergences by electrostatic fields only, since in that case the ion trajectories are independent of the charge-to-mass ratio.

In conjunction with the development of a 20-A 20-keV pulsed ion source for injection of a beam of neutral deuterium atoms into the 2X II experiment,[2] we have built and tested single- and multiple-aperture extractors based on computed designs that produce beams of high current density with divergences low enough that additional magnetic focusing is not required.

Since the ion species of interest in controlled fusion research cannot be produced by surface ionization, they must be extracted from a plasma, which is free to move under the influence of the electric fields used to extract the beam. The shapes of the electrodes of the extractor must therefore be determined so that they not only accelerate and focus the ion beam, but also optimally position and shape the emitting plasma surface. The extractor design consists of the usual three electrodes in an "accel-decel" configuration, with as close a spacing as is reasonable to avoid electrical breakdown. We based the design of the shapes of the apertures in the electrodes on the results of extensive numerical calculations of the ion trajectories through the extractor; for this purpose we used a computer code originally written by Kirstein and Hornsby[3] and modified by Bate.[4] This code uses as input data the boundaries and potentials of the accelerating electrodes and the shape of the emitting surface, and calculates the trajectories of ions originating at different points on the emitting surface. A charge density is assigned to each point on the trajectory and the procedure is iterated until the solutions are consistent with space-charge-limited flow; output consists of details of the trajectories and the ion current density at the emitter (j_+) as a function of position.

We assumed in the calculations, as have others,[4,5] that the emitting plasma surface positions itself in such a way that j_+ is simultaneously emission-limited and space-charge-limited at every point on the surface. In addition, we have assumed that j_+ is independent of position, an assumption which may or may not be satisfied in practice. We then modified the shapes of the electrodes and of the emitting surface and made new calculations repeatedly until solutions were found in which j_+ varied by less than ±5% over the emitting surface, and ion trajectories at the exit aperture were parallel to the axis to within ± 1 deg. As the electrode geometry was intended to be a unit of a multiple-aperture system, no effort was made to achieve high perveance by using large aperture dimensions (in a multiple-aperture system, the average current density depends only on the potentials applied and the separation and transparency of the electrodes). On the contrary, deliberate choice of the smallest aperture size consistent with acceptable machining tolerances greatly facilitated the design by minimizing the "anode-hole problem".[6]

A typical electrode geometry for a single-hole extractor is shown in Fig. 1; relative electrode potentials and equipotential contours are indicated. This design, a convenient one for use in a multiple-aperture array, consists of three flat plates, two with uniform-diameter circular holes in them, and a third (the beam-forming electrode) with a counterbored hole. The diameters and shapes of the apertures in the electrodes are the result of the computer-aided optimization procedure described above. The combination of the counterbored aperture in the beam-forming electrode and the spherical emitting plasma surface gives a beam which initially converges uniformly. The combined effects of the space charge of the beam and of the diverging-lens effect of the hole in the accelerating electrode

produce a nearly parallel beam at the exit aperture.

We constructed four single-aperture extractors of copper based on this computed design; they differed from one another only in the diameter of the counterbored hole in the beam-forming electrode, which ranged in diameter from 2.73 mm (the optimum of the computed design) to 2.09 mm (a straight-sided hole). We chose to vary this parameter because it affects the divergence and current density at the periphery of the beam; by a suitable choice one should be able to minimize the importance of nonuniformities at the edge of the emitting plasma surface. To evaluate the extractors we used them to extract ions from a deuterium plasma produced by a hollow-cathode arc discharge. We measured the power delivered to three concentric calorimeters subtending half-angles of 0.95, 1.90, and 3.45 deg, located 79 cm downstream. The beam line was filled with D_2 at a pressure of about 5 mtorr, so the beam at the calorimeter consisted largely of neutral particles. No magnetic focusing was used. Of the four extractors, the one which produced the best 20-keV beam (judged by the beam power in ±0.95 deg) was extremely close in shape to the computer-optimized design, differing by only 4% in the counterbore diameter.

We also constructed and tested a multiple-aperture extractor which used this same shape for the apertures in the beam-forming electrode; there were 19 holes, 3 mm center to center, in a hexagonal array. The beam-forming electrode was 40% transparent; the transparency of the other two was 23%. Probe measurements in the plasma indicated that the plasma density across the 19-hole array varied by less than ±10%.

The performance of this extractor and of the single-aperture version in producing 16-keV deuterium beams is summarized in Table I and is compared, when possible, with the results of the computer calculations; we have used Kelley's definition of effective brightness.[7] Since we have not yet measured the molecular composition of the beam, we show results evaluated for both D and D_2, the most probable species.

It is clear from the table that there is generally good agreement between the measured and calculated beam properties, than an array of 19 apertures performs as well as 19 isolated apertures without adverse interactions among the beams, and that these extractors are capable of producing beams of very high effective brightness.[7] These results, plus the close agreement between the computer-optimized shape of the beam-forming electrode and the experimentally optimized one, indicate the validity and usefulness of the computer-aided design procedure.

We thank Vincent J. Honey and George M. ("Greg") Wheeler for their help with the experiment.

Table I. Calculated and measured extractor performance of a 16-keV deuterium beam.

Quantity	Calculated value	Measured value for single-aperture extractor	Measured value for 19-aperture extractor
Current to calorimeter (mA equivalent)		11.9 ± 0.4	260 ± 7
Maximum beam loss in a "halo" or by electrode interception	0	9 ± 4%	8 ± 4%
Beam width	100% power in ≈ ± 1 deg	Gaussian; 1/e width = 1.23 ± 0.04 deg	Gaussian; 1/e width = 1.31 ± 0.04 deg
Perveance ($A/V^{3/2}$)	6.5×10^{-9} (D^+) 4.6×10^{-9} (D_2^+)	5.1×10^{-9} (a)	1.1×10^{-7} (a), or 5.9×10^{-9} per hole
J_+ at emitting plasma surface (mA/cm^2)		≈390	≈450
Effective brightness(b) (for $\theta = \pm 0.95$ deg) ($mA/MeV\ cm^2\ rad^2$)		2.4×10^{10} (D) 4.8×10^{10} (D_2)	5.6×10^{9} (D) 1.1×10^{10} (D_2)

TABLE I FOOTNOTES

(a) The calorimetrically measured current was used in calculating the perveance.

(b) In evaluating the expression for the effective brightness (Ref. 7), we used for d_1 for the single-aperture extractor the diameter of the hole in the decel electrode; for the multiple-aperture extractor, the diameter of a circle enclosing all 19 holes.

FOOTNOTES AND REFERENCES

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

1. The status of these efforts is reported in laboratory progress reports. See, for example, Culham Laboratory Eighth Annual Report, 1969-1970, Lawrence Radiation Laboratory report UCRL-50002-70, 1970, and Oak Ridge National Laboratory report ORNL-4545, 1970 (unpublished).
2. F. H. Coensgen, W. F. Cummins, V. A. Finlayson, W. F. Nexsen, Jr., and T. C. Simonen, in Proceedings of the Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 17-23 June, 1971 (to be published).
3. P. T. Kirstein and J. S. Hornsby, IEEE Trans. Electron Devices ED-11, 196 (1964).
4. D. G. Bate, A Computer Program for the Design of High Perveance Ion sources, Culham Laboratory report CLM-R53, 1966 (unpublished).
5. J. Hyman, Jr., W. O. Eckhardt, R. C. Knechtli, and C. R. Buckey, AIAA Journal 2, 1739 (1964).
6. P. T. Kirstein, G. S. Kino, and W. E. Waters, Space-Charge Flow (McGraw-Hill Book Co., 1967), p. 407.
7. G. C. Kelley, IEEE Trans. Nucl. Sci. NS-14, 29 (1967).

FIGURE LEGEND

Fig. 1. Electrode geometry for a single-hole extractor, showing relative electrode potentials, equipotential contours, and ion trajectories.

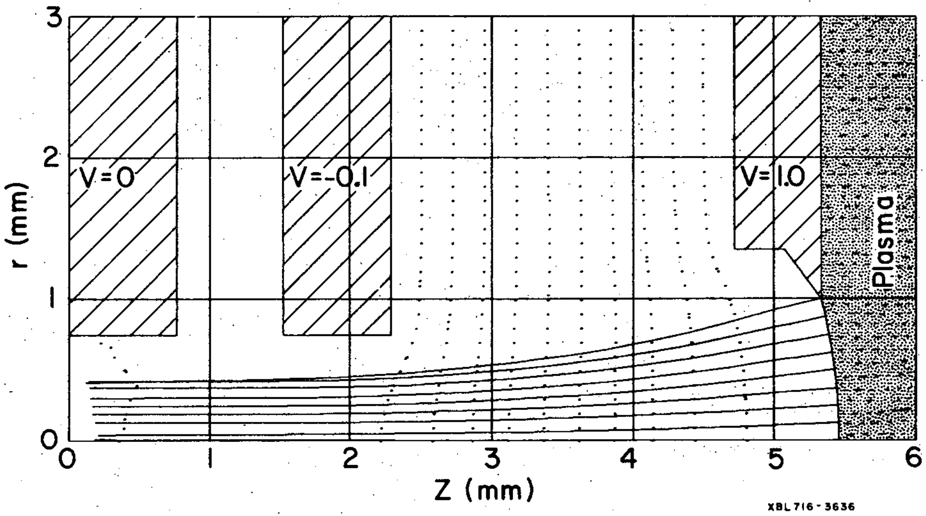

Fig. 1

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720