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UCRL 76020
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An Intense Steady-State 20 KV Multiple Aperture Ion Source
"MATS III"

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MASTER

Sources and Formation of Beams
Berkeley, California Oct. 22-24, 1974

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AN INTENSE STEADY-STATE 20 KV MULTIPLE APERTURE ION SOURCE* "MATS III"

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Abstract

A multiple aperture ion source MATS III has been developed for 5 to 20 Mev steady-state H^0 beam injection into the Baseball II controlled fusion experiment. The source utilizes a magnetically shaped reflex arc for plasma production over a large area. For steady-state operation each of the accelerator-decelerator set of three electrodes is designed with internal water cooling. Typical operation for a 6.4 cm diameter array of 63.4 mm diameter shaped apertures is 1.5 amp drain at 20 kv yielding a total of .9 amp calorimetric on a 100 cm² target located 250 cm from the ion source.

1. Introduction

Neutral beam injection for plasma buildup in the Baseball II controlled fusion experiment requires intense ion beams from 1 to at least 20 keV. For "vacuum buildup" using plasma trapping in a magnetic well (through Lorentz ionization of excited states and plasma cascaded Lorentz ionization) a series of low-voltage steady-state ion sources was developed. Each of these ion sources LVTs-12 and MATS 13 for .2 to 2 kv and MATS 14 for 1-5 kv, and MATS III for 5 to 20 kv utilizes a large area reflex arc plasma source mapped into an array of multiple apertures. The apertures and gaps of each are scaled appropriately to achieve the desired operating voltage range and output current consistent with space charge limitations and practical mechanical constraints.

The accelerator-decelerator set of three electrodes is essential to act as an electron gate to prevent loss of electron space charge neutralization in the subsequent drift space region. For reliable steady-state operation each of these three electrodes were designed of copper to

include internal water cooling channels. Semi-Pierce (computer optimized L.J.L. design)⁵ circular and slot aperture arrays were tested in comparison with simple⁶ but higher transpency circular apertures.

11. Ion Source Design

The MATS III geometry is shown in the cross-section drawing of Fig. 1. For discussion purposes the ion source features will be divided into (a) the plasma source, (b) the extraction electrodes, and (c) the output beam and optics.

(a) The Plasma Source.

The arc plasma used in this source is described in some detail in the 1977 BNL Symposium report.³ Briefly here it consists of a hot cathode reflex arc magnetically expanded through a 1.9 cm i.d. anode from 300-700 gauss in the arc chamber to ~10 gauss at the plane of the extraction electrodes. Typical power consumption is 3.5 - 4 kw (e.g. 35 amp - 100 v arc). The plasma can be made uniform $\pm 10\%$ over the 6.4 cm diameter at lower densities, but at higher current densities more typically includes up to $\pm 40\%$ m = 1 flute like modulation at ~300 - 400 kHz off axis at $r \sim 2$ cm. Electron diffusion due to collisions and instabilities complete the electrical current for the reflex arc. Action of the rotating flute evidently aids in a time averaged spreading out the plasma radially, but limits instantaneous uniformity and ultimately the current by reducing the useful duty cycle of apertures at higher radii.

The gas efficiency of this source is typically 30 - 50% with ~27 cm³/min STP required for 1.5 amp drain with a typical composition of 70% H^+ , 25% H_2^+ , 5% H_3^+ and including $\leq .2\%$ impurities.

(b) Extraction Electrodes

For steady-state operation each of the three copper electrodes in the accelerator-decelerator set are internally water-cooled. A cross-section view of a typical electrode is shown in Fig. 2. Selection of the brazing foil and accurate control of the brazing furnace temperature are critical to a

*Work supported by the U. S. Atomic Energy Commission.

Fig. 1. MATS III assembly drawing.

successful sandwich bond between the milled electrode and the cover plate-vacuum tight, but without the brazing material wetting over and blocking the fine coolant channels. Final machining of the apertures is done after brazing.

Fig. 2. Typical water-cooled electrode--a laminated, brazed sandwich with milled cooling channels and headers.

The use of water-cooled channels has the effect of setting a limit on the minimum practical thickness and hence a scaling factor which must be considered with the aperture diameter. Similarly the use of straight cooling channels with an array of circular apertures tends to limit designs to relatively low 10-25% transparency. High transparency slot designs can be accommodated as shown in Fig. 3; however, performance of slots with the reflex arc plasma has tended to be poor to unsatisfactory as discussed below.

Shaped semi-Pierce circular and slot aperture designs were both tested on this source, as were a set of somewhat higher transparency simple circular apertures. The design features of these three electrode types are described in Table I below.

Table I
"Electrode Design Features"

	Number	Geometry Diameter	Trans- parency	First Gap mm
Shaped	63	4 mm	25%	4.7
Simple	63	5.1 mm	40%	4.7 (also 3.7)
Shaped slot	14	2 mm wide	46%	2.3

The shaped circular apertures are of LBL design scaled x2 for our thicker electrodes. The performance is in general accord with expectations considering the low transparency and the large gap spacing; the beam optics was quite good with the mean 1/e divergence $\theta \approx 1.10^\circ$ at 20 keV. Decelerator drain was typically 20 - 50 ma for 1.5 amp beam.

The simple aperture was designed on the identical array to shaped circular set, but allowed a higher first electrode transparency without the constriction of the shaped electrode lips. Operation was quite satisfactory with higher currents in accord with the higher transparency, but with slightly higher divergences ($\theta \approx 1.30^\circ$ at 20 keV). Decelerator drain typically < 10 ma for 1.5 amp beam.

Fig. 3. Detail of water-cooled slotted electrode, shaped in accordance with LBL design. (a) intended position of plasma surface, (b) water channel between slots formed by brazed sandwich, (c) beveled surface as in LBL design, and (d) extracted beam.

The shaped slot set with high transparency were a sharp disappointment. Operation was stable only over a narrow range of arc parameters and total extraction voltage. Possible explanations include the rotating plasma source flute generally giving poor quality meniscus shapes in the slot apertures.

(c) Output Beam and Optics

The typical total (charged plus neutral) calorimetric beam yield for the simple circular array (b of Table I) on a 100 cm² target located in a test stand 250 cm from the source is shown in Fig. 4. The shaped circular beam yield follows $V^{3/2}$ through essentially the same yield at 18 - 20 keV. These data include use of a lens magnet for focusing, though the gain due to the lens is only ~ 20% for extraction over 12 kv because of the large source area and fairly good electrostatic focusing. The performance indicated by Fig. 4 is consistent within 25% with the performance of high-intensity pulsed beams³ under $V^{3/2}/d^2$ scaling law. We consider this agreement to be satisfactory in view of the non-uniformity of our plasma source.

Fig. 4. MATS III beam output compared with beams from MATS I, MATS II, and Calutron, measured in the same geometry ($\pm 1.3^\circ$).

The intended application to Baseball II is shown in Fig. 5 as the vertical beam line employing directed jets of potassium vapor for charge exchange. The vertical beam line was not installed as intended because of a beam-driven plasma instability that limited "vacuum plasma buildup" in Baseball II. However, MATS III was briefly tested on the horizontal Baseball beam line. In these tests the beam performance was degraded 20% to 50% below expectations because of stray magnetic fields, less than equilibrium charge-exchange gas, apparent magnetic-field effects on electrons and perturbation by the iron shielding surrounding the plasma source magnets.

Summary

In summary MATS III is a steady-state multi-aperture source of moderate beam density yielding a total beam of 1.5 amp with a mean $1/e$ $\theta \sim 1.1^\circ$ at 20 kev. This implies a normalized emittance $\epsilon \approx 6 \mu\text{A}/\text{m}$ of 4 cm mrad and a brightness $B \approx 21 \times 10^{10}/\text{m}^2\text{e}^2$ of 1.9×10^{10} ma/cm² rad². The low transparency and thickness of the electrodes tends to limit performance in terms of extraction current density, but because the sources met experimental specifications this was not further optimized or enlarged in area for higher output.

Acknowledgment

The authors would like to particularly thank A. F. Waugh and B. S. Denhoy for their engineering support, and J. Fabyan and W. Strohm for their assistance in experimental operations. The continued support and encouragement of C. C. Gamm is also appreciated.

Fig. 5. The vertical beam line (5 to 15 kev) for Baseball II.

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