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Intense Ion Beam Production Below 40 KeV*

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ABSTRACT

An objective of the ORNL CTR ion source development program is to create a hydrogen ion source with an extracted current of 10 A at beam energies above 20 keV. This source and multiples thereof are used to heat and/or create hot ion plasmas for fusion research. A modified version of the four electrode duoplasmatron has been developed which is called a duoPIGatron. A 4-A current has been extracted for 0.1 sec at voltages between 20 kV and 40 kV from multi-aperture extraction grids. The grids are connected in accel-decel fashion and are 55% transparent. Optimum curvature of the first grid allows 68% of the current to be incident on a 9-cm diameter target 100 cm from the source. A 5-A current has been obtained from a scaled-up version of the source. Computer predicted current yields are in general agreement with the experimentally measured values. Studies of the ion source plasma show an m = 1 helical instability to be present which is responsible for illuminating the 5-cm diameter extraction surface. Instantaneous density variations from ± 10% to ± 50% are observed to be driven by the instability at 300 to 400 kHz. A stabilizer has been developed which reduces the oscillation amplitude by an order of magnitude. Initial studies at extraction voltages up to 10 kV show that use of the stabilizer yields a less divergent beam and higher current output through a single aperture either on axis or 1.75 cm from the source axis.

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Ion source development work at Oak Ridge has a twofold purpose: (1) heating plasmas in toroidal confinement devices in which case the objective is to transfer as much energy from the beam to the plasma as is possible on a 0.1 sec time scale; (2) filling mirror devices in which case the objective is to deliver a high density beam with high gas efficiency. To satisfy the first condition, one needs the neutral equivalent of multiampere beams in the 25 keV to 50 keV range; whereas the second condition requires 0.1 - 0.5 A equivalent neutral beams with energies in the 5 keV to 20 keV range. Because of the more difficult technological problems, this paper will be concerned with multiampere beam development.

The duoPIGatron [1] ion source concept is shown schematically in Fig. 1. Plasma is produced in the magnetic field free region above the zwischen aperture. The plasma streams into the magnetic field region exterior to the zwischen and inside the anode. Because of the electrostatic mirror action of the target cathode and zwischen, the plasma electrons are forced to oscillate (PIG) until collisions or anomalous diffusion permit their transit across the magnetic field to the anode. Previous publications [1] reported a total current drain of 4 amperes at beam energies above 30 keV for 50% transparent accel-decel grid structure, 5 cm in diameter, composed of 109 apertures, 3.75 mm in diameter with a grid spacing of 6 mm. About 60% of this beam power is delivered to a 9-cm diameter target 1 m from the extraction grid. A recently constructed 7-cm diameter grid structure containing 220 apertures of 3.75-mm diameter has been successfully operated. Figure 2 shows the total beam output and power on target as a function of beam energy. Also shown is the total energy delivered in a 0.2 sec pulse. It is significant to note that the arc power requirements are the same for the 5-cm diameter source operating at 4 A output as it is for the 7-cm diameter source operating at 8 A output. The gas flow for the 8 A output is twice as large as for the 4 A output.

Ion species analyses show the beam to be composed of ~ 45% H^+, ~ 45% H_2^+, and ~ 10% H_3^+. At 25 keV beam energy, about 65% of the 8 A is delivered to the target. Dissociation of the molecular components in the charge exchange cell brings the neutral beam of H_o back up to a current equivalent of 8 A but with three energy components: 25 keV, 12.5 keV, and 8.3 keV.

Impurity content of the beam as a function of beam off time, which is the time between source pulses, is shown in Fig. 3. In the ORMAK experiment,[2] the plasma pulses will be several minutes apart. To reduce the source off time and therefore the beam impurity content, the source will be operated between

ORMAK plasma pulses. The minimum source off time will be the time necessary to prepare the beam line, the pumping system, and the electronics for the heating pulse, and will be about 20 seconds. The impurity is of mass number $M \approx 18$. One can see there is a significant variation in the impurity content with the type of gas feed line. We feel there is no difficulty in achieving our design goal impurity level of $< 0.5\%$.

Numerical studies of ion optics are also being pursued using a computer code developed at CERN [3] and Culham [4]. This code is being used to find new electrode configurations for present beam sources and also to investigate the next generation of sources. Both slit electrodes and aperture electrodes are being studied to improve present sources. Two-stage acceleration configurations are being examined for the high energy (100 keV) ion sources which may be necessary for the next generation plasma containment devices.

A fundamental limitation of any multiampere ion source system is the ability to illuminate the extraction grid with a plasma having the desired properties. There are a number of important parameters to consider not all of which may be optimized simultaneously. In order to meet the objective for our source the following plasma parameters are very important: (a) plasma density uniformity over extraction surface, (b) plasma density fluctuations due to rf noise or instabilities, (c) plasma impurity content, (d) plasma ion specie concentrations, (e) plasma ion temperature, (f) gas and power efficiency of plasma production, and (g) simplicity and applicability of the system; that is, the plasma source must be operable over a time period sufficiently long to accomplish the desired experimental objective.

We have undertaken a study of the plasma properties for the 5-cm diameter ion source employing rf and Langmuir probe diagnostics. In addition, we have used a Faraday cup to examine the beam in conjunction with an aperture selector which permits extraction from a single aperture either on axis or 1.8 cm off axis. The rf and Langmuir probes are introduced into the source plasma about 5 cm above the target cathode or extraction grid. From a combination of probes separated both axially and azimuthally, we have established that an $m = 1$ helical instability is present in the plasma with an axial wavelength about equal to twice the discharge length. The instability is undoubtedly the means by which we achieve a density uniformity of $\pm$ 15% over the target cathode. Shorting out the target cathode bias resistor eliminated the instability but the plasma density gradient is so steep as to render more than half of the apertures useless. With the instability present, we find that there are

oscillations in the plasma density and on the extracted beam at a frequency between 300 kHz and 400 kHz. Oscillations on the beam through the center aperture are about ± 10% of the average value; whereas the beam through the aperture at 1.8 cm varies about ± 30%.

In a manner similar to Allen and coworkers,[5] we have developed a water-cooled stabilizing grid or electrode which effectively suppresses the oscillations in the plasma and on the beam without adversely affecting the plasma density gradient. The stabilizer is positioned about 0.5 cm from the anode and is electrically connected to the anode. Figure 4 shows the effect on the beam obtained from using two different stabilizer designs. The circular stabilizer is a simple, 1-in. O.D. circular loop of 1/6-in. copper water line; the cloverleaf is a configuration of 3 loops each 1/4-in. I.D., arranged symmetrically about a fourth, 1/4-in. loop. The first picture in each row shows that the total current extracted is about the same for all three examples. Radio-frequency comparisons are shown on the second picture and the last two pictures of each row show the Faraday cup signal with aperture selector passing a beam through the aperture at R = 1.8 cm.

We have made a number of studies of the plasma properties and single aperture beam profiles with and without the stabilizer. We measured the plasma potential as a function of radius at two axial positions separated by 4 cm. Both positions are in a region between anode and target cathode. The radial and axial electric fields are essentially zero with the stabilizer inserted in the plasma. There is a slight variation in the radial electric field when ions are being extracted from the plasma. When the stabilizer is removed and the instability is present, the plasma core becomes positive and produces a radial field of about 10 V/cm. The effect of ion extraction in this case is to reduce the positive potential on axis. The axial electric field without the stabilizer is a few volts/cm. We tabulate several observed properties of this plasma: (1) the radial electric field inside the plasma in the presence of the instability is in the wrong direction to account for the plasma rotation due to an E x B drift; (2) the axial electric field is sufficient to drive Kadomtsev's [6] positive column instability assuming a uniform magnetic field of about 50 gauss which is measured in the cicinity of our probes; (3) the measured frequency of about 350 kHz agrees with that calculated from positive column theory with 98% gas ionization. Thus we are inclined to identify the instability we observe as that present in a positive column or as the screw instability [7].

Faraday cup measurements of the beam profile show we can select the arc parameters to minimize beam noise and beam divergence for either the axial aperture or the aperture located 1.8 cm off axis separately but not for both at the same arc conditions. Figure 5 shows typical profiles obtained. Optimization of the arc for the center aperture produced a beam of about 2.4° half-angle with the stabilizer where half-angle is defined by a 1/e radial fall off in the beam intensity. Without the stabilizer, the angle increased to about 2.7°. Similar optimizations can be made for the aperture at 1.8 cm by increasing plasma density. In this case however, the half-angle through the center hole is 3.3° with or without the stabilizer. The increased plasma density has a twofold positive effect on the beam at 1.8 cm. The beam divergence is minimum and the radial separation between beam profiles from the R = 0 and R = 1.8 cm apertures is minimum when the plasma density is increased to that required for space charge limited emission through the outer aperture.

The effect of the stabilizer on the beam from the entire 109 hole source is tabulated in Fig. 6. For a 10% to 20% improvement in beam power on target, one must operate at a decrease in both gas and arc power efficiency.

From these studies it is evident that we can further reduce the divergence of our beam by using a more uniform quiescent plasma source and there are some indications that the 7-cm diameter plasma source may have already improved these parameters. We will examine other plasma sources and contrast potential improvements in plasma uniformity and stability with the ability of the source to satisfy the other essential parameters listed previously. The ultimate aim of our work is to build the steady-state, 10-A or greater ion source modules that seem essential for future thermonuclear research. We are optimistic that our present ion sources can be developed to satisfy these stringent demands, but we will continue to examine other alternatives.

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FIGURE CAPTIONS

Fig. 1. DuoPIGatron Ion Source.

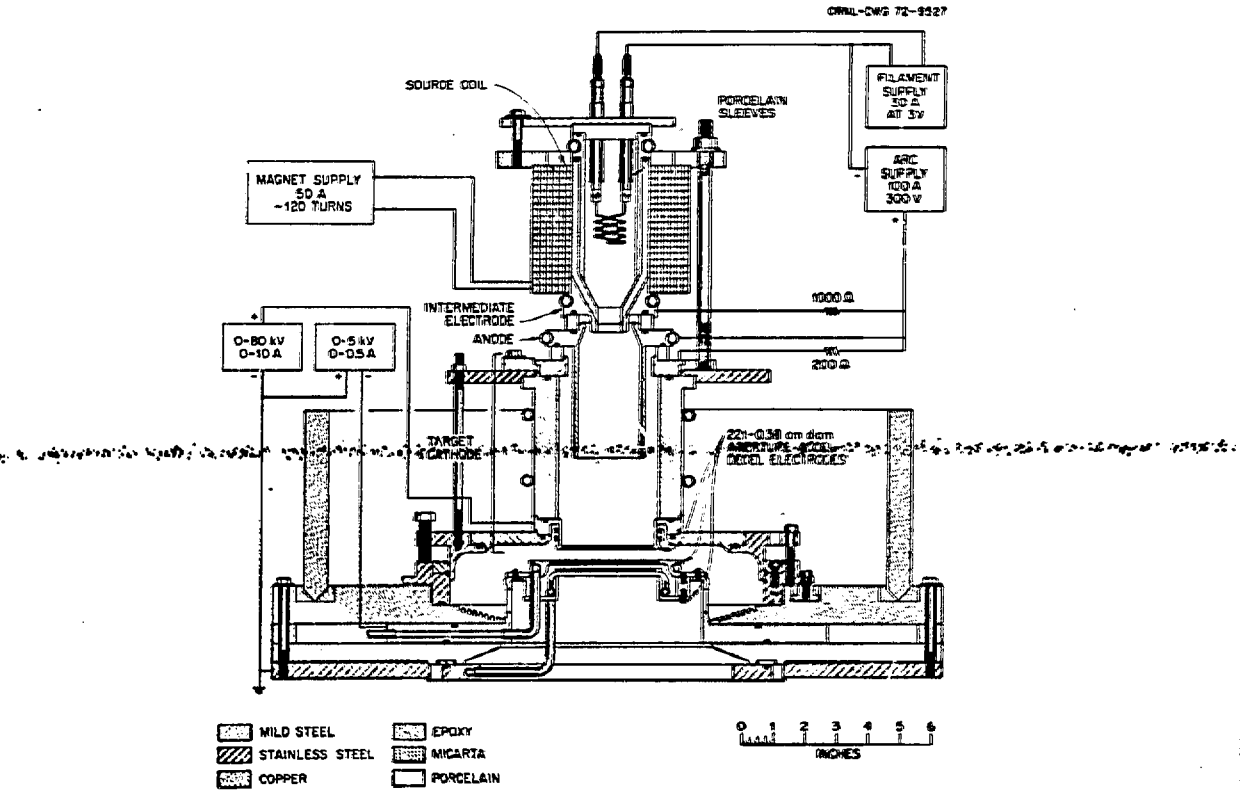
Fig. 2. 7-Cm Diameter DuoPIGatron Ion Source 25-kV Beam.

Fig. 3. Beam Impurity Content as a Function of Source Off Time.

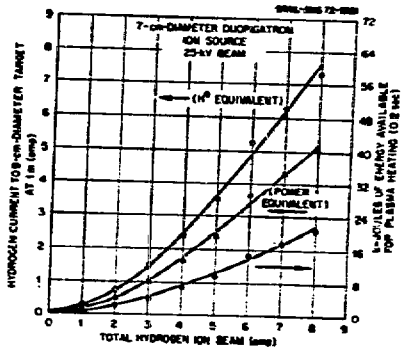
Fig. 4. Modulation of Beam Through Hole at R = 1.8 Cm.

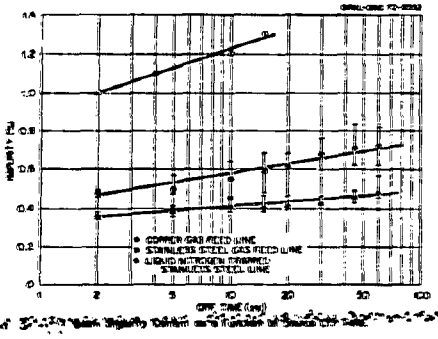
Fig. 5. Beam Profiles at 10 kV, Arc Current = 20 A.

Fig. 6. Effect of Stabilization on 109 Aperture (3.75 mm diam) Source at 6-mm Grid Spacing.



DUOPIGATRON ION SOURCE





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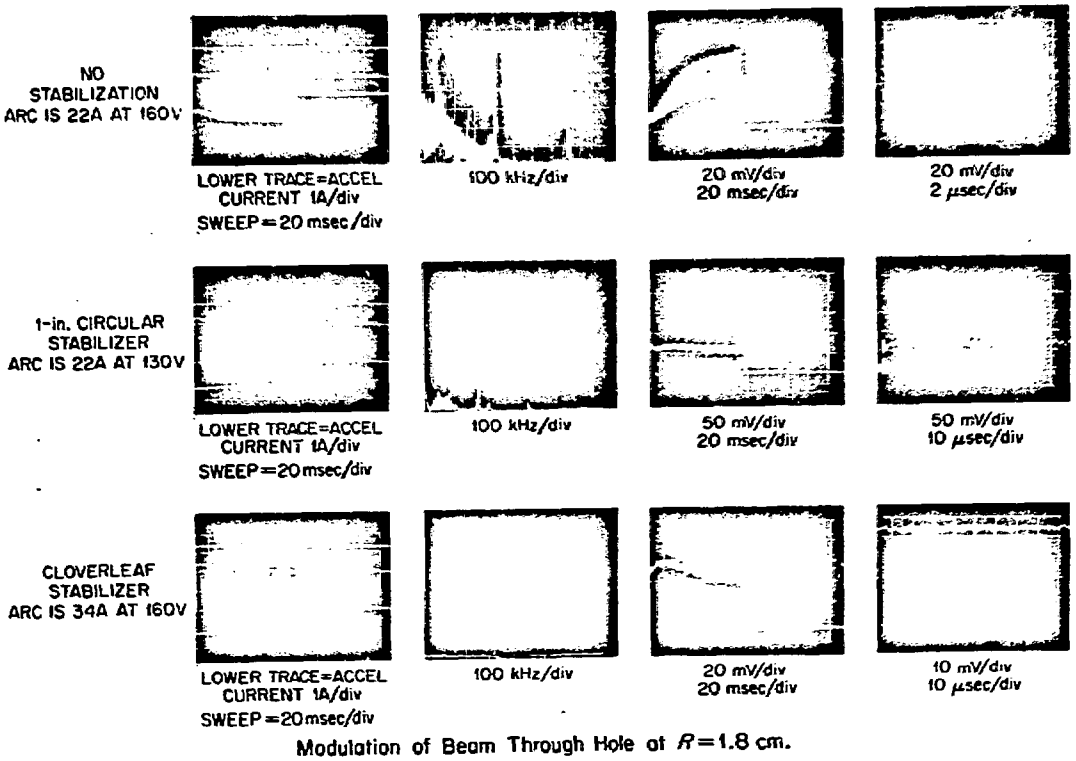
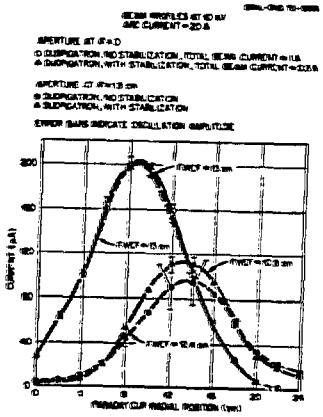


Modulation of Beam Through Hole at $R = 1.8$ cm.



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BEAM	WITHOUT STABILIZATION	WITH STABILIZATION
10 kV	P_T = 10% OF 0.7A	P_T = 14% OF 0.7A
15 kV	P_T = 11% OF 1.3A	P_T = 15% OF 1.2A
20 kV	P_T = 14% OF 2.2A (7.9 kW ARC)	P_T = 21% OF 1.6A (9.7 kW ARC)

P_T = POWER ON TARGET LOCATED 1.8 m FROM EXTRACTION GRIDS

Effect of Stabilization on 109 Aperture (3.75 mm diam) Source at 6-mm Grid Spacing.