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15 cm DuoPIGatron Ion Source

W. L. Stirling
C. C. Tsai
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W. L. Stirling, C. C. Tsai, and P. M. Ryan
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

The 10 cm (grid diameter) duoPIGatron ion source[1] produces pulsed hydrogen ion beams of 10 to 15 A beam current in the 20 to 40 keV energy range for a duration of a few tenths of a second. To fulfill the requirements of the next generation of high-power neutral beam injectors for heating plasmas in CTR devices, this source has been enlarged to a version 15 cm in grid diameter. In addition, by utilizing a magnetic multipole line cusp field confinement method, the plasma created is characterized over the 15 cm grid diameter by a noise level within ± 10% and spatial density variations within ± 5% at a density on the order of 10^{12} cm^{-3}. This larger source has operated reliably and produced a beam current exceeding 30 A of hydrogen at 27 keV. Initial operation of a 20 cm version of this source employing line cusp confinement has produced an extraction current of 60 A at 33 keV.

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INTRODUCTION

Neutral beam injection heating experiments in ATC, ORMAK, and TFR have demonstrated that energetic neutral beams can heat the toroidal plasma significantly.[2,3] To heat the plasma in CTR devices to reactor temperatures requires high-power energetic neutral beams with tens of amperes of hydrogen (or deuterium) beam current of energy range 10 to 100 keV. For this application, the plasma source should be capable of producing a quiescent, uniform, and dense plasma in order to produce a well collimated, high current density beam; for example, the noise level and spatial density variations should be well below $\pm$ 10% over several hundreds of square centimeters at a density of a few times 10^{12} cm^{-3}. The other desired features are high gas and power efficiencies and source reliability. Plasma sources such as the multifilament source developed at Lawrence Berkeley Laboratory and the duoPIGatron ion source developed at Oak Ridge National Laboratory are able to fulfill some of these basic requirements. They are being seriously considered for use in the development of future high-power neutral beam injectors for PLT, PDX, and TFTR at PPPL, Doublet III at GA, and ORMAK Upgrade and TNS at Oak Ridge.

In the present state of technology, the plasma source requires at least 1 kW of arc power to produce 1 ampere of beam current. In order to raise the arc power efficiency, it is necessary to improve spatial uniformity and noise level of the source plasma. We have undertaken a study to improve the plasma properties of a duoPIGatron ion source modified with line cusp confinement, bearing in mind that the magnetic multipole line cusp containment device[4] developed at UCLA is capable of producing a desirable quiescent and uniform plasma in argon. The modified source has a magnetic multipole line cusp confining field around the arc chamber just above the target cathode. Preliminary results from a modified 15 cm duoPIGatron ion source indicate that it is capable of generating a desirable, quiescent, uniform, and dense plasma for producing 30 A of hydrogen ion current at 27 keV energy at a beam current density of above 300 mA cm^{-2}.

After a brief review of the source operation, we will describe recent progress and some envisaged future improvements.

SOURCE OPERATION

Figure 1 shows the sketch of a conventional duoPIGatron ion source[5,6] with a 15 cm grid diameter. Figure 2 shows the modified duoPIGatron with the line cusp added. (It should be acknowledged that our arc chamber is a variation of the magnetic multipole containment device[4] which was developed at UCLA by MacKenzie and associates.) The line cusp field arrangement is made of 12 columns of permanent magnets about 15 cm long, magnetized radially with opposite polarity for the adjacent columns. The columns lie on a circle having a diameter of 25 cm. The magnets (0.96 cm square by 2.54 cm long; maximum magnetic field $B \gtrsim 4$ kG) have been set in the slots on the walls of the arc chamber and just above the target cathode. The plasma generator consists of hot cathodes, intermediate electrode, anode 1, anode 2, and target cathode as in the standard duoPIGatron. The target cathode is sometimes referred to as the plasma electrode or screen electrode. The intermediate electrode serves as a magnetic pole to provide an axial magnetic field, the source field, in the anode region. A pulsed arc voltage is applied between the anodes and hot cathodes. The intermediate electrode and target cathode are returned to the arc supply positive terminal through resistances of 1 KΩ and 250 Ω respectively.

In conventional source operation, the source contains a cathode plasma and a PIG plasma separated by a double layer. The cathode plasma is produced within the intermediate electrode chamber by primary electrons emitted from the hot cathodes. In this region of zero magnetic field, the plasma density is determined essentially by the arc current and gas pressure because of the low electron kinetic energy (<30 eV).

The PIG plasma is produced in the region enclosed by the anodes, intermediate electrode, and target cathode. This plasma is created essentially by energetic electrons which originate from the cathode plasma and which are accelerated through the double layer. The electrons are then constrained by the applied magnetic field and oscillate between the intermediate electrode and the target cathode. They initiate a "Penning ion gauge" (PIG) discharge, which is the principal ionization mechanism. Because of their high energy and long path length, they create a dense PIG plasma; consequently, the density of the PIG plasma is mainly affected by the applied magnetic field, gas pressure, arc voltage, and arc current.

While the cathode plasma works as an electron source and supplies ionizing electrons to the PIG discharge, the PIG plasma works as an ion source and supplies ions to the extraction electrodes in order to form a high-current ion beam. The double layer works as a controlling mechanism which determines the PIG plasma uniformity and the source reliability.[5]

In the case of the modified duoPIGatron, the applied source field is much weaker and plasma confinement is accomplished by the line cusp magnetic field. The line cusp field also reduces the direct loss to the second anode of ionizing electrons in the PIG discharge. In this way the modified duoPIGatron provides magnetic field free containment over the extraction area and hence an easily achieved, uniform, dense PIG plasma.

SOURCE PERFORMANCE

Figure 3 shows a comparison of the density profiles for the conventional duoPIGatron, labeled NORMAL, and the modified duoPIGatron, labeled CUSP. Plasma density was determined from ion saturation current measured by a Langmuir probe located about 0.6 cm above the target cathode. In the conventional duoPIGatron, the noise level is below $\pm$ 10% and the plasma density variation over the 15 cm grid diameter is within $\pm$ 15% at a density of above 2×10^{12} cm^{-3}. The source has been operated reliably to produce a hydrogen ion beam of 20 A at 25 keV. Maximum density can be increased by increasing the source magnetic field, but the uniformity is impaired and high voltage spitting becomes severe. Uniformity can be improved by lowering the magnetic field, but the density is then too low to produce high-current ion beams because the weak magnetic field cannot effectively confine the energetic ionizing electrons within the PIG arc column. In addition, the weaker magnetic field increases the loss rate of charged particles from the PIG plasma to the anode walls.

The confinement and uniformity problems have both been alleviated in the modified duoPIGatron source. The line cusp magnetic field effectively confines both the energetic ionizing electrons and the charged particles within the PIG plasma. The modified 15 cm source has been operated reliably while producing a hydrogen ion beam with a current exceeding 30 A at 27 keV. Both the current and voltage of the ion beam were limited by the associated electrical supplies: high-voltage power supply, high-voltage modulator, and arc power supply.

Some characteristics of the conventional and the modified 15 cm sources are listed in Table 1. The column denoted by NORMAL is for the conventional source and that denoted by CUSP is for the modified source. For the modified source, the applied magnetic field represented by I_{sm} is weaker, and the potential difference between the anode and the target cathode, $V_A - V_{TC}$, is lower than that for the conventional source. The electron temperature, T_e, is higher and plasma uniformity, Δn, is improved over the grid diameter. The plasma density and uniformity appear more sensitive to the effect of pressure in the modified source; this increased sensitivity is probably caused by the lower applied magnetic field. The cusp field arrangement in the modified source plays a crucial role[4] in improving the plasma density and uniformity.

FUTURE IMPROVEMENTS

Preliminary values for plasma density and uniformity were reported in the previous section. On the basis of the discharge model for the duoPIGatron and the information given by Table 1, these values may be further improved by the following modifications:

1) Optimizing the arrangement of line cusp magnetic field. According to MacKenzie and associates,[4] the magnetic multipole confinement is a very effective way of confining a dense, uniform, large-volume, and quiescent plasma. This is because such an arrangement can effectively confine both the primary electrons and the charged particles in the plasma. However, as the number of magnetic multipoles is increased, the plasma density is lowered and the plasma uniformity is improved. A similar effect may exist in the source plasma in the modified duoPIGatron. By optimizing the length and number of columns in the line cusp magnetic field, and by adding a flux return path for the magnets, the source performance may eventually be improved.

2) Optimizing the source electrodes, particularly in dimension, configuration, and relative position. This will improve both the radial distribution of the ionizing electrons in the PIG discharge and their ionization efficiency. It may also reduce the loss rate of plasma to the electrodes and could lead to improvement in plasma density and uniformity. The source performance and reliability may also be improved.

3) Biasing the target cathode negative to the potential at which it floats when the source operates as a normal duoPIGatron. This should reduce the rate of PIG discharge ionizing electrons lost to the target cathode. The ionization efficiency of the ionizing electrons should thus be improved and the PIG discharge intensified. This modification may raise the plasma density without impairing the plasma uniformity.

The associated electrical supplies limitation mentioned earlier has been removed by installing a 60 kV/60 A high-voltage power supply, a 60 kV/60 A modulator, and a 100 VDC/800 A arc power supply.

In addition to developing the modified 15 cm source we have enlarged the duoPIGatron to a 20 cm diameter utilizing the line cusp confinement geometry. Initial operation has produced a 60 A beam of hydrogen at 33 keV. Optimization of the source parameters is proceeding with a goal of 60 A at 40 keV. We also have 22 cm and 25 cm ion source components in fabrication. It seems certain, therefore, that the duoPIGatron ion source, suitably modified and upgraded, is capable of development for use in future high-power beam injectors.

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FIGURE CAPTIONS

1. 15 cm Prototype DuoPIGatron Ion Source
2. Modified 15 cm DuoPIGatron Ion Source with Magnetic Multipole Line Cusp Confining Field
3. Typical Density Profiles of Conventional and Modified 15 cm Ion Source

TABLE CAPTION

1. Source Characteristics of Conventional and Modified 15 cm DuoPIGatron Ion Source

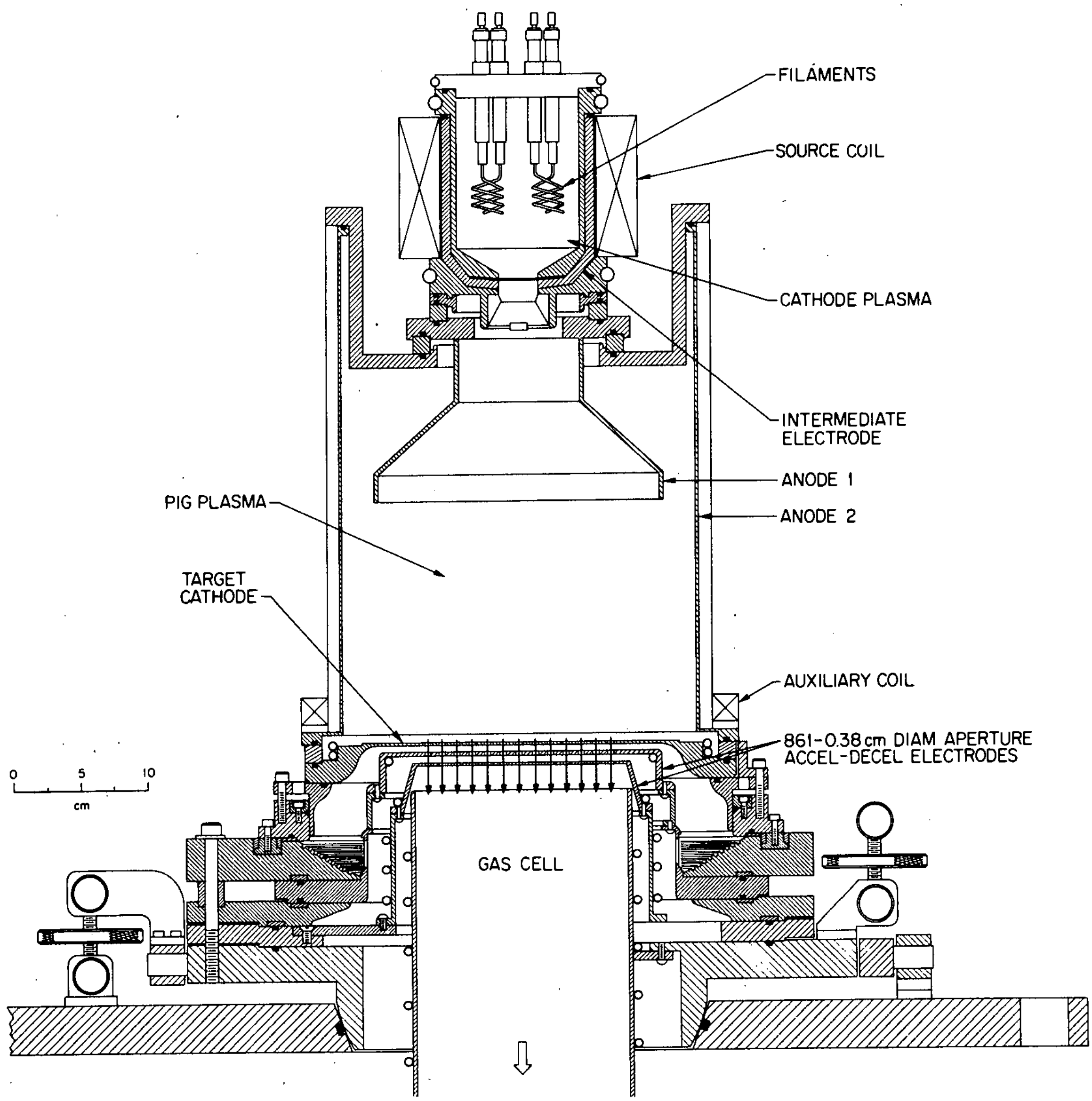

Fig. 1. 15 cm Prototype DuoPIGatron Ion Source.

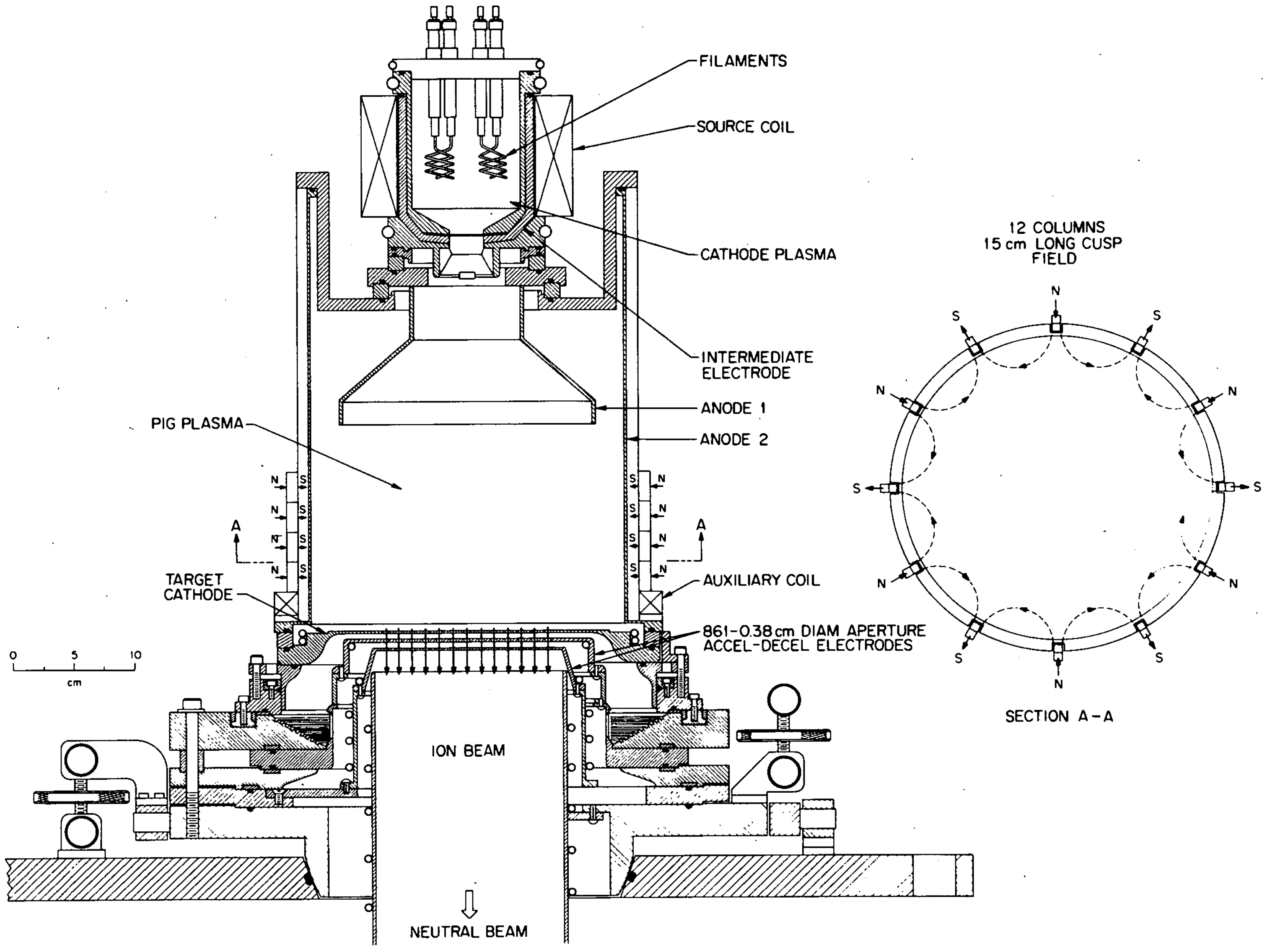

Fig. 2. Modified 15 cm DuoPIGatron Ion Source with Magnetic Multipole Line Cusp Confining Field.

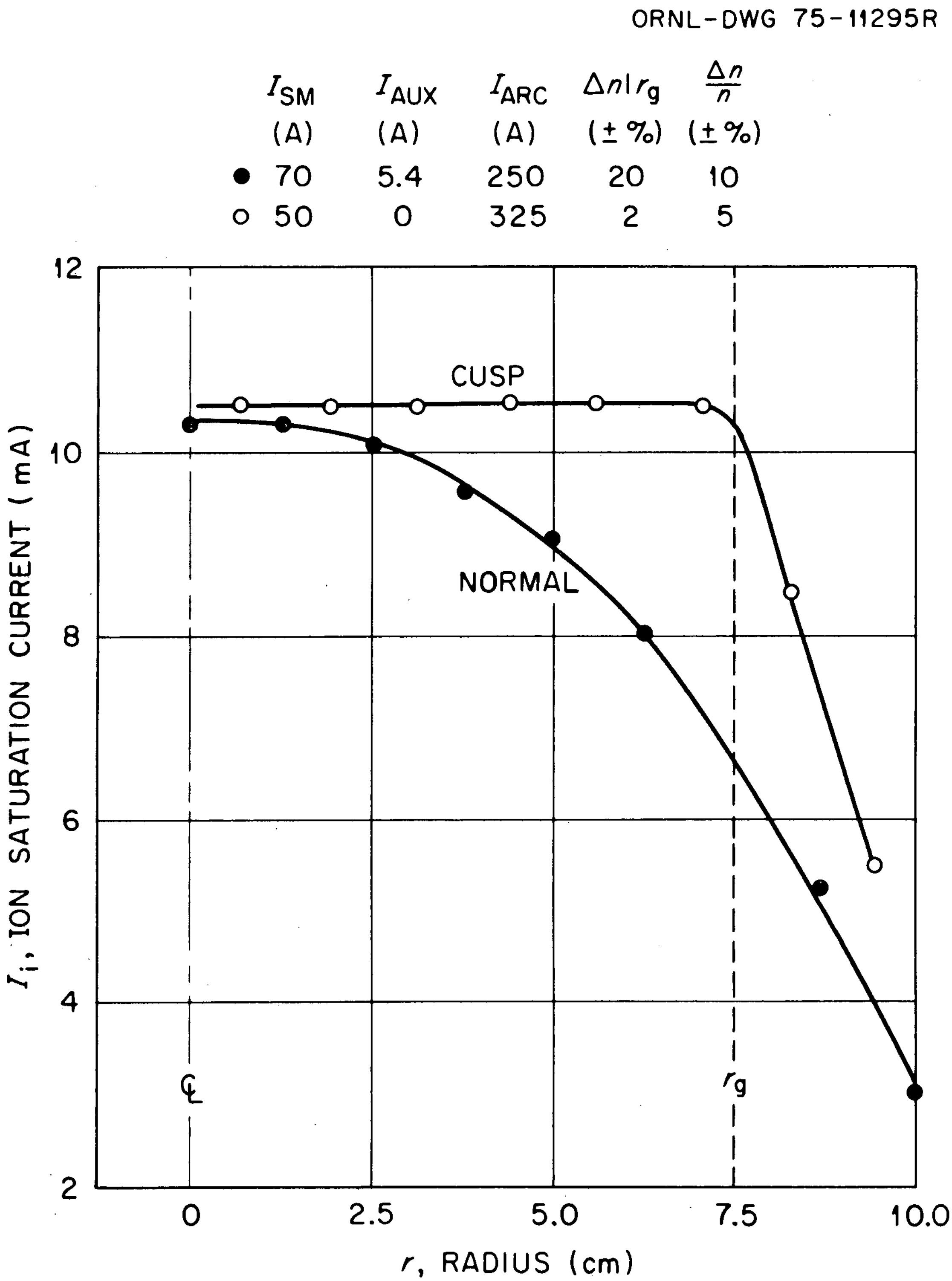

Fig. 3. Typical Density Profiles of Conventional and Modified 15 cm Ion Source.

TABLE I

SOURCE CHARACTERISTICS

	NORMAL	CUSP
I_{SM}	70 TO 80 A	20 TO 40 A
I_{ARC}	UP TO 400 A	UP TO 450 A
V_{ARC}	UP TO 150 V	UP TO 150 V
$V_A - V_{TC}$	$\gtrsim$ 50 V	$\leq$ 30 V
kT_E	$\sim$ 6 eV	$\sim$ 12 eV
Δn/15 CM DIAM	$\geq$ 15%	$\leq \pm$ 5%
P_{TC}	$\sim$10 mTORR	$\sim$10 mTORR

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