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DUOPIGATRON ION SOURCES FOR PLT INJECTORS*

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Plasma heating requirements for the Princeton Large Torus (PLT) are set at about 1 MJ total beam energy or 5 MW beam power of energetic hydrogen (or deuterium) neutrals at 40 keV. To fulfill this design goal from four neutral beam injectors, the duoPIGatron ion source originally developed at ORNL has been modified, developed, and scaled-up to versions with 20-cm and/or 22-cm grid diameters. Utilizing the multipole line cusp magnetic field confinement for the ionizing electrons and created Philips Ionization Gauge (PIG) plasma, these sources generate a uniform (±5% density variation over 25-cm diam) and dense plasma (about 3×10^{12} cm^{-3} at the extraction surface). Such sources have been operated reliably to deliver a beam current exceeding 70 A of hydrogen ions at 40 keV. For such a beam condition the source is capable of running with an arc pulse of 0.5 sec. Moreover, the corresponding arc efficiency is very high, below 1.0 kW arc power per ampere of ion beam current. In this paper we describe the plasma generation, source characteristics and arc efficiency as functions of magnetic fields, gas pressure, and arc power (including the arc voltage and current). The other exciting feature, high proton yield (exceeding 80%), will be discussed.

Introduction

Energetic neutral beam injection has been successfully applied for heating the toroidal plasma in the Oak Ridge Tokamak (ORMAK).[1,2] This application has demonstrated that the injection of high power energetic neutral beams is one of the essential heating techniques for tokamaks. For future fusion devices,[3-5] multi-MW hydrogen and deuterium neutral beams are being planned. For the Princeton Large Torus (PLT) at Princeton Plasma Physics Laboratory (PPPL) 0.75 MW of energetic neutrals at 40 keV for each of four beam lines is planned and designed. To fulfill this goal, the heart of the neutral beam injectors, the ion source, should be capable of producing a hydrogen ion current well above 60 A.

Subsequently, we decided to form such an ion beam from thousands of elementary beamlets over an area of several hundreds of square centimeters. A designed ion source for the injector application should be able to create a quiescent, uniform, and dense plasma over the large area, as described in Table 1. Also listed are other desirable properties such as long pulse operation, high gas efficiency, high arc efficiency, good source reliability, and ion species selectivity. The efficient, reliable, and simple duoPIGatron ion source[2,5] developed for ORMAK injectors fulfills most of these desirable properties. By utilizing the multipole line cusp magnetic field for plasma confinement,[7] the duoPIGatron ion source has been successfully scaled-up to larger versions with 15-cm, 20-cm, and 22-cm grid diameters.

Two 15-cm neutral injectors have been developed. One is used for Laser Initiated Target Experiment (LITE) at UT (United Technologies Research Center) and the other is for ORMAK. For both PLT and ISX (Impurity Study Experiment at Oak Ridge) several 22 cm injectors have been developed. They deliver a beam current exceeding 70 A at an energy above 40 keV with a pulse length up to 500 msec.

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Table 1. Desirable Properties of a Good Plasma Source

High Plasma Density	$\geq 2 \times 10^{12}$ cm^{-3}
Low Nonuniformity	$\leq \pm 10\%$ over grid diam
Low Noise Level	$\leq \pm 10\%$
Long Pulse Operation	≥ 0.5 s
High Gas Efficiency	$\geq 50\%$

High Arc Efficiency
Good Source Reliability
Ion Species Selectivity

In the following the plasma generation and discharge model of these large duoPIGatrons will be briefly reviewed. Source characteristics as a function of the discharge parameters such as the magnetic fields, gas pressure, and arc power (including the arc voltage and current) will then be discussed. Finally, we will discuss the arc efficiency and proton yield.

Generation of Source Plasmas

Figure 1 shows the sketch of a duoPIGatron ion source with a 20-cm grid diam and a 30-cm diam of anode No. 2 chamber. As the conventional duoPIGatron does,[8] it consists of a hot cathode, intermediate electrode, anodes Nos. 1 and 2, and target cathode (also known as plasma or screen electrode). The hot cathode contains eight off-axis oxide-coated filaments, which emit sufficient electrons for running an arc current up to 1000 A. A solenoid wound on the intermediate electrode (which serves as a magnetic pole) provides an inhomogeneous axial magnetic field (hereafter called the source magnetic field) in the channel and snout region of the intermediate electrode and in the anode region. As described later, this magnetic field guides ionizing electrons from the cathode region to the anode region. Moreover, around the chamber of the anode No. 2 and just above the target cathode, 12-32 columns of permanent magnets are used to form a magnetic multipole line cusp field. The cusp field is used to confine these ionizing electrons and the plasma created. In this magnetic arrangement, each column is six or seven inches long formed of either six or seven permanent magnets (0.96 cm x 2.54 cm x 2.54 cm, magnetized along the 2.54-cm direction, maximum field 5 ~ 6 kG) and is arranged to produce a radial field with opposite polarity for the adjacent columns. The ends of columns must be located within 1 cm of the target cathode. Electrically, a pulsed arc voltage (~120 V) is applied between the anode and the hot cathode. But, both the intermediate electrode and the target cathode are floated by being connected to the positive terminal of the arc power supply through resistors of 1000 ohm and 250 ohm, respectively. For improving the source reliability, capacitor banks of

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3200 μF and 400 μF are respectively connected across the 1000 ohm and 250 ohm resistors.

Under normal operations sufficient gas (H_2) is fed into the source prior to the application of the pulsed arc voltage. During the arc pulse, primary electrons emitted from the hot cathode are accelerated towards the intermediate electrode and produce a cathode plasma. Some electrons from this plasma are guided by the source magnetic field and are accelerated towards the anode region. These electrons gain sufficient kinetic energy to create an intermediate plasma on the way through the channel and snout region of the intermediate electrode. In the anode region, they are constrained by the source magnetic field and are forced to oscillate between the intermediate electrode and target cathode. Because of their high energy and long path length, they produce a dense PIG plasma. Hence, the source plasma is composed of three plasmas: the cathode plasma, intermediate plasma, and the PIG plasma, which are separated by double layers. Such a discharge model is further supported by the experimental results of a Langmuir probe which is movable along the axis of the intermediate electrode chamber.

The intermediate plasma and its adjacent double layers form a plasma bridge. This plasma bridge not only sustains the potential difference between the PIG plasma and the cathode plasma but also maintains the arc conduction through them. Moreover, as an electron source, the cathode plasma supplies ionizing electrons to the PIG discharge. In fact, the cathode and intermediate plasmas are created by the low pressure and low potential hot cathode discharge within the intermediate electrode chamber. The assembly of the intermediate electrode chamber and the enclosed hot cathode works as a hollow cathode. As an ion source, the PIG plasma supplies ions to the ion beam formation electrodes (or the extraction electrodes). In the next section of the paper, the characteristics (including ion generation and ion loss) of the PIG discharge are discussed with regard to improving the source performance.

Source Characteristics

From the plasma generation described above, we see that the discharge in the duoPIGatron ion source is a kind of hot cathode discharge. The hot cathode, in fact, is a hollow cathode formed by the intermediate electrode chamber and its enclosed oxide filaments. This hollow cathode provides energetic ionizing electrons for the PIG discharge to form the uniform and dense PIG plasma. With a proper arrangement and suitable operating conditions, the source (Fig. 1) is capable of a long pulse operation. The waveforms of the arc voltage, arc current, and the ion saturation current of a Langmuir probe in the PIG plasma are shown in Fig. 2. In addition, this source is characterized with high gas and arc efficiency, good source reliability, and high proton yield (Table 2).

In practice, the PIG plasma works as an ion source. The characteristics of the PIG discharge can thus represent the source characteristics. In other words, the plasma properties and the ion generation and loss rates in the PIG region determine the source performance of the duoPIGatron.

In general, the generated ion current I_{ig} can be expressed as

$$I_{ig} = I_e n_o \sigma_i(E) L. \quad (1)$$

Here I_e is the current of ionizing electrons, n_o is the neutral gas density, $\sigma_i(E)$ is the ionization cross section of the ionizing electrons at an energy E, and L is the mean free path of the electrons. On the other hand, the ion loss rate to electrodes with a loss area A_w is denoted by $I_{i\ell}$ and is given by

$$I_{i\ell} = Ke\, n_i\, v_i\, A_w. \quad (2)$$

Here, K is a constant, e and n_i are respectively the charge and density of the ion in the plasma, and v_i is the ion sound velocity. For creating a steady state plasma, the ion generation rate should be sufficiently fast to make up the ion loss rate. That is, the ion current density J_i can be estimated from the last two equations as

$$J_i = Ke\, n_i\, v_i$$

or (3)

$$J_i = I_e n_o \sigma_i(E)\, L\, A_w^{-1}.$$

Table 2. Source Performance of PLT Injectors

Neutral power	750 kW
Beam energy	45 keV
Beam current	70 A
Pulse duration	500 msec
Arc voltage	<150 V
Arc current	<900 A
Arc efficiency	~1 kW/A
Gas	Hydrogen
Gas efficiency	>50%
Proton yield	>80%
Beam divergence	$\theta_{HWHM} = 1.0^o$
Plasma density	$2\times10^{12}cm^{-3}$
Plasma uniformity	±5%
Noise level	~±10%

Since the ion current density adjacent to the target cathode can be utilized to estimate the beam current density, this equation could be used to study the effect of discharge parameters on the source performance. In the following, we will discuss the relationship between these quantities in the last equation and the essential discharge parameters such as the magnetic field, gas pressure, arc power including arc current and voltage. Particularly, we will emphasize the adjustment of the parameters to create a quiescent, uniform and dense plasma for large ion source application.

Magnetic Field

There are two applied magnetic fields superimposed in the PIG region of the modified duoPIGatrons. One is the source magnetic field and the other is the static line cusp magnetic field. Their effects are described below.

As discussed in the previous section, the source magnetic field is essentially utilized for guiding ionizing electrons from the cathode plasma through the channel and snout region of the intermediate electrode into the PIG region. This source field also controls the spatial distribution of these electrons in the radial plane. Because these electrons are the chief ionization agents in the PIG discharge, the source field influences the radial uniformity of the PIG plasma created. Figure 3 shows typical density profiles for various source magnetic fields, which are denoted by the coil exciting current I_{sm}. The ion saturation current J_i is measured by a Langmuir probe which is moved in the radial plane about 1.0 cm above the target cathode. It reveals that the peak plasma current density near the axis increases with the source field. That is, the spatial uniformity is gradually impaired as the source field is raised. This is understandable because the higher the magnetic field, the higher the concentration of ionizing electrons around the axis and therefore, the higher the peak plasma density near the axis.

For the conventional duoPIGatrons, raising the source field is one way to boost plasma density for increasing beam current. This is true provided that the radial uniformity is reasonably good — within $\pm 10\%$ over the grid diameter. However, in the large versions (15 cm, 20 cm, and 22 cm) this simple method of increasing source field strength is not applicable because the spatial density variations over the grid diameter can well exceed $\pm 20\%$. With these sources modified by adding the multipole line cusp field containment,[7] the problem of nonuniform plasma has been easily solved. Typical density profiles (Fig. 4) for a 15-cm source clearly show the advantage of the cusp field arrangement. In fact, the modified source with the cusp field can operate reliably to create a dense PIG plasma at relatively weak source fields. The associated uniform distribution of the ionizing electrons results in a uniform PIG plasma. Moreover, the static multipole line cusp field not only improves confinements of ionizing electrons but also the PIG plasma so created. Hence, the modified duoPIGatrons such as the 15-cm sources are able to deliver a beam current of 30 A of hydrogen ions.

In Eq. (3), the effects of the applied magnetic fields on the generated ion current density are related to the spatial uniformity through the term "I_e" by the radial distribution of ionizing electrons and to the density through the term "A_w^{-1}" by varying the loss area of electrodes. As noted from the study of a magnetic multiple confinement device,[9] the increase of number of the permanent magnetics columns will improve radial uniformity by increasing the volume of the field free region, but lower the plasma density by increasing the effective loss area. In the modified duoPIGatrons, the measured plasma uniformity is improved as the number of the magnetic columns is increased to an optimal number of 24 (Fig. 5). This is probably caused by extra-loss areas existing at both ends of magnetic columns (in addition to those under the pole face) described below. In the particular arrangement of the modified duoPIGatrons, the superimposition of the applied source field and the fringe fields of magnetic columns can form regions with zero axial magnetic field through with the ionizing electrons and created plasma leak to the electrodes. As a result with too many columns, the improved uniformity due to the increased field free region will be offset by the increased loss area.

With the above understanding, the modified duoPIGatrons always operate at relatively low source fields compared to that of the conventional duoPIGatrons. The 20-cm and 22-cm sources can operate reliably to create a desirable uniform and dense PIG plasma adjacent to the target cathode for delivering an ion beam current about 70 A.

Gas Pressure

Equation (3) indicates that the generated ion current or plasma density in the PIG region will increase with the gas pressure (or neutral density) there. As learned from the conventional duoPIGatrons, the easiest way to raise gas pressure is to increase the gas feed into the intermediate electrode chamber. In fact, the gas particles will subsequently enter the PIG region, pass through the apertures in the extraction electrodes and the gas cell, and finally reach the pumps. However, as a result of recent experiments on the 20-cm and 22-cm sources as described below, we declined this conventional way in favor of a modification.

Knowing the crucial effect of the double layer on the source realiability,[8] we scaled up the dimensions of the intermediate electrode and anode No. 1 with a smaller ratio compared to that of the anode No. 2. The resulting bottlenecks cause unusually high gas density in the snout region of the intermediate electrode and insufficient gas density in the PIG region. The associated high plasma density and low arc impedance in the snout region reduce the potential drop from the PIG plasma to the cathode plasma. The associated decrease in the kinetic energy of the ionizing electrons reduces the probability of ionization in the PIG region. Moreover, the dense plasma in the snout region will increase ion loss towards the intermediate electrode rather than towards the extraction electrodes. Consequently, the plasma density near the target cathode is insufficient for extracting a high beam current. To boost the plasma density by increasing the gas feed into the intermediate electrode chamber and hence boost the arc power often causes severe arc breakdowns in the snout region between the anode No. 1 and the intermediate electrode. This arc breakdown problem further jeopardizes the source reliability in addition to giving poor arc efficiency.

The above undesired properties related to conventional gas feed have been avoided substantially by providing extra gas feeds into the PIG region and/or the upstream section of the gas cell. With the proper combination of these gas feeds, the source performance (the arc efficiency, source reliability, and beam current capability) is greatly improved. For example, the beam current can be boosted to 50 A from 35 A simply by increasing the extra gas feed and keeping other arc parameters constant. Normally, the gas feed into the intermediate electrode chamber should be as low as possible but yet sufficient for a reliable source operation. The gas feed into the PIG region should be adjusted for the desired plasma density or ion beam current density. Under such conditions, the gas feed into the gas cell can be used for the desired equilibrium fraction of neutrals in the ion beam.

Arc Power

In general, the plasma density increases with the increasing arc power as shown in Fig. 6. This effect is further studied below. In fact, the arc power is the product of the arc voltage and arc current. As shown elsewhere[8] the potential drop between the PIG plasma and cathode plasma is about 80% of the arc voltage, and the electron current entering the PIG plasma from the cathode plasma constitutes above 90%

of arc current. Hence the arc current and voltage are closely related to the quantity and energy of the ionizing electrons in the PIG discharge. We see by Eq. (3), the plasma or ion density always increases with the arc power.

In general for a given arc power, the source can be operated with either a high arc current and a low arc voltage or with a low arc current and a high arc voltage, by adjusting the other source parameters. The former is the low impedance mode and the latter is the high impedance mode. For a given source, the favorable operating mode is determined by the source reliability and arc efficiency. Usually we prefer to run the reliable source with the high arc efficiency. From the distribution of ionizat on cross section with the electron energy, the high ionization efficiency of electrons requires their energy about 100 eV. Considering the usual 20 V drop between the intermediate electrode and the hot cathode, the arc voltage should be about 120 V. With this favorable arc voltage, the source should yield sufficient arc current for delivering the desired high beam current. As given in Eq. (3), the plasma density is expected to increase linearly with the arc current. Under such operation mode, the arc efficiency has been found to be higher. For example, for delivering a 60 A ion beam, the present sources can operate either at 900 A/90 V or at 600 A/110 V. Obviously, the high impedance mode has a better arc efficiency.

Arc Efficiency

As the required neutral beam power for heating future tokamaks increases to multi-MW, the injectors must deliver several hundred amperes of energetic positive ions. With the concern of the required high arc power at the high voltage terminals, the arc efficiency becomes increasingly important. Studies to improve the arc efficiency for the injectors have been conducted in both the design and the operating phases.

Regarding the design phase, the study includes the optimization of the geometrical configuration, dimensions of the electrodes, and the arrangement of the magnetic fields. It is found that the intermediate electrode geometries and anode No. 1 are very crucial to the arc efficiency. As shown in Fig. 6, the smaller the size of the anode No. 1, the higher the plasma density for the same arc power. Relating to Eq. (3), this feature results from reducing the fraction of electrons which are directly lost to the anode without participating in ion generation and the ion loss area. Similarly, the dimensions of the axial button and insert in the intermediate electrode can influence these factors too. As a result, the geometry and dimensions of these electrodes are optimized to that shown in Fig. 1. Moreover, the distance from that of the intermediate electrode snout to the target cathode is also optimized for allowing the source field originating in the channel region of the intermediate electrode to be able to cover the grid area with a uniform axial field. As a result, a uniform PIG plasma can readily be created adjacent to the target cathode. In addition to the source magnetic field, the static multipole line cusp field is also optimized for the best uniform PIG plasma. As shown in Fig. 5, the optimum number of columns has been experimentally determined and is between 20 and 24. For the present PLT sources, 20 columns of permanent magnets are used for creating a uniform and dense plasma.

With a properly designed duoPIGatron, the arc efficiency can be further improved by adjusting the operating parameters. From the source characteristics described above, the arc parameters for the injector operation are listed below

a) Arc voltage should be above 100 V.
b) Arc current should be below 700 A.
c) Gas feed into the intermediate electrode chamber should be minimum but sufficient for a reliable source operation.
d) Gas feed into the PIG region should be sufficient for the desired plasma density.
e) Gas feed into the upstream section of the gas cell should be sufficient for the desired neutral equilibrium fraction of the ion beam.
f) Source magnetic field should be set to minimum for the above desired arc conditions.

With both the source elements and parameters optimized, the arc efficiency can be improved well below 1 kW per ampere of beam current. For example, the arc power for a beam of 65 A at 37 kV is about 59 kW (105 V arc voltage and 560 A arc current), i.e., 0.91 kW per ampere of ion beam current.

Proton Yield

In a hydrogen plasma, there are atomic ions and molecular ions. One of the requirements of the neutral beam injectors is to maximize the production of atomic ions. Our recent measurement on the ion beam by magnetic analysis indicates that the PLT-type ion source produces beam fractions $H_1^+ \sim 85\%$, $H_2^+ \sim 12\%$, and $H_3^+ \sim 3\%$. As described below, this outstanding feature results from high generation rate and low loss rate of H_1^+ ions in the plasma volume and low ion generation rate near the extraction surface. The high arc impedance mode of source operation for high arc efficiency mentioned above is just the right mode for the high proton yield. The ionizing electrons gain energy (∿100 eV) through the double layer between the cathode and PIG plasmas. They experience several collisions with gas particles for ion production and loss of kinetic energy. Approaching the extraction electrodes, the energy loss of these electrons results in a low production rate of molecular ions. Hence, the ions of the ion beam are those produced in the plasma volume. Due to the high density and low energy (∿5 eV) of the cold plasma electrons, the molecular ions created in the volume are almost completely converted to atomic ions through the dominant reactions of dissociative excitation, dissociative recombination and ionization, and charge exchange. Thus, the high proton yield in this source is the result of optimization of source elements and operating conditions.

Concluding Remarks

Table 2 shows the performance of a properly designed PLT 22-cm source. Compared to Table 1, this source fulfills the desired properties of the plasma source for neutral beam injectors.

It can deliver a beam current exceeding 70 A at 40 keV with a pulse duration exceeding 0.3 sec, the designed value. The gas efficiency is about 50%. Hence, it needs the extra gas feed into the gas cell for converting the fast ions into energetic neutrals. The arc efficiency is well below 1 kW per ampere of beam current. This high arc efficiency is essentially due to the source capability of effectively creating a uniform and dense plasma adjacent to the target cathode. The factors accounting for the high arc efficiency are also those that produce the high proton yield.

Such a desirable source performance is also due to the advanced technology in the design of the extraction electrodes and electronics for the arc and high voltage power supplies. The excellent performance of the modified duoPIGatrons indicates that larger versions for delivering a beam current of 150 A can be properly developed. Hence, it is possible to utilize one plasma source rather than three for each beam line for TFTR. At the moment, we are developing 100 A (ion current) sources for the plasma heating experiments on ISX and PDX at PPPL.

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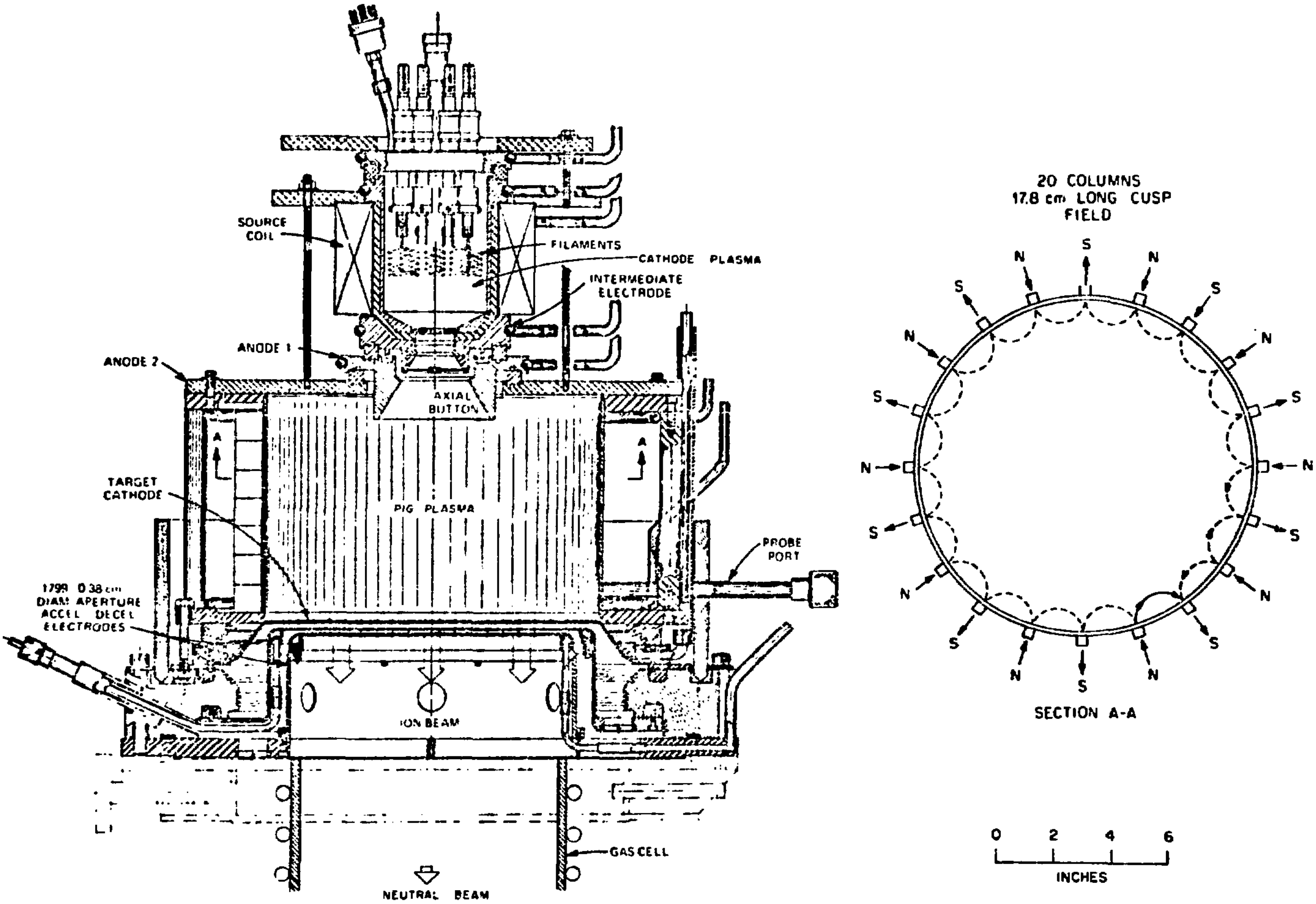

Figure 1 Sketch of a 22-cm DuoPIGatron

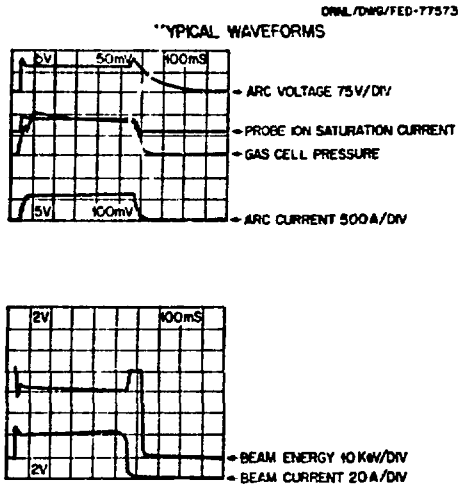

Figure 2 Waveforms of arc voltage, arc current, ion saturation current, beam energy, and beam current.

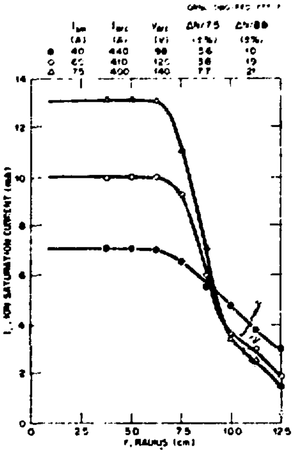

Figure 3 Typical density profiles for various magnetic fields.

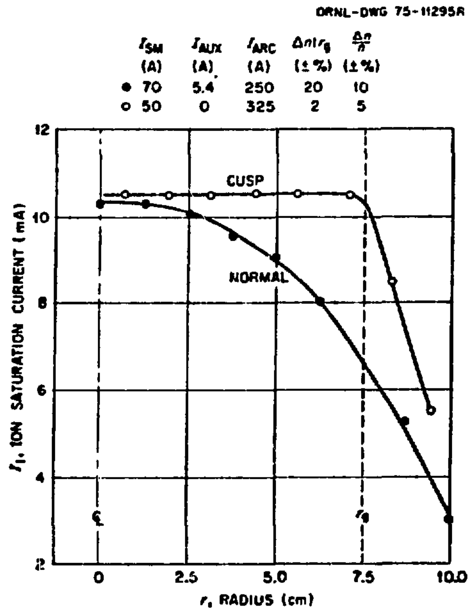

Figure 4 Typical density profiles of conventional and modified 15 cm duoPIGatron ion sources.
Chamber diam: 25 cm
Grid diam: 15 cm

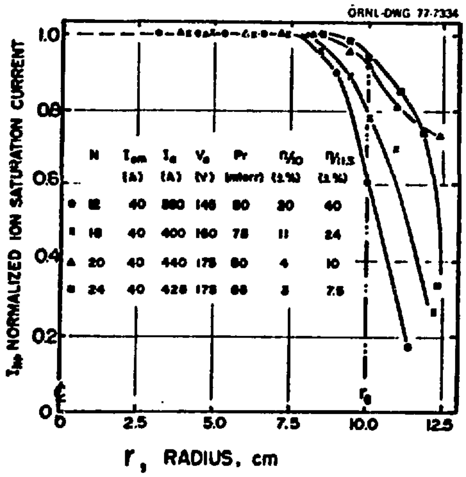

Figure 5 Variations of plasma uniformity with number of magnet columns.
Chamber diam: 30 cm
Grid diam: 20 cm

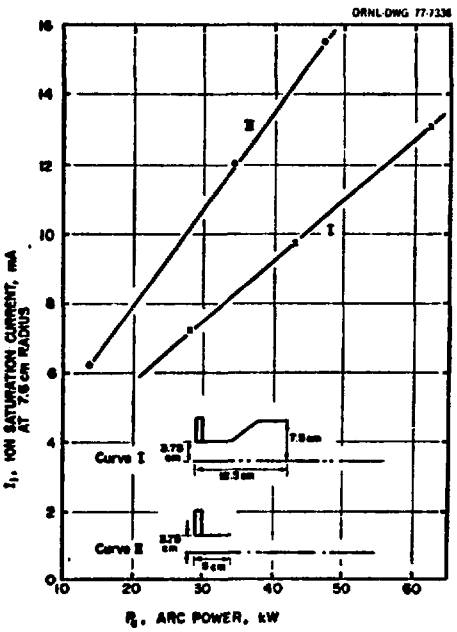

Figure 6 Variations of ion saturation current with arc power for two types of anode 1.