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FUSION ENERGY DIVISION

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ON A PROTOTYPE BEAM LINE

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CONTENTS

ABSTRACT	1
1. INTRODUCTION	2
2. DESCRIPTION OF ION SOURCE AND PROTOTYPE BEAM LINE	3
3. EXPERIMENTAL TECHNIQUE	5
4. SUMMARY OF INJECTOR PERFORMANCE	8
5. BEAM OPTICS AND TRANSMISSION PROPERTIES	10
6. ION SPECIES YIELD	15
7. CONCLUSIONS	17
ACKNOWLEDGMENTS	19
REFERENCES	20

ABSTRACT

Two PLT-injector-type duoPIGatron sources, modified further by shaping the beam-forming apertures, have been tested and experimented on a prototype beam line similar to the ISX-B neutral beam injection system. The accelerator column modification has resulted in an increase of the beam power transmission efficiency from that of the straight-bore aperture by 50%. Maximum neutral beam powers achieved on a 28-cm-diam target simulating the ISX-B plasma, located 4.1 m downstream from the source, are ≈ 910 kW of H^0 at an accelerator power of 42 kV and 61 A and ≈ 1020 kW of D^0 at 43 kV and 55 A. Measurements have been made to investigate the following: the effects on beam optics of aperture shape, aspect ratio, and different ions (H^+ or D^+); the distribution of beam power deposition along the beam line; ion species compositions; and background pressure behavior due to scraped-off beam particles. The injectors have been shown to be characterized by an optimum perveance of $6 \times 10^{-6} \text{ AV}^{-3/2}$ for an effective extraction area of 142 cm^2 (1799 apertures), which is approximately invariant over the beam energies tried (viz., 25-45 keV).

1. INTRODUCTION

Neutral beam injection (NBI) heating of tokamak and mirror plasmas has been demonstrated to be the most promising means of heating fusion plasmas. The success of obtaining designed injection powers relies on satisfying two criteria, namely, (1) extracting enough ion beam current from an ion source and (2) converting the ions into the neutrals and transporting them along a beam line into a plasma device. The latter goal can only be tested in an actual beam line or in a prototype system. NBI heating experiments, for example, on Adiabatic Toroidal Compressor (ATC) and the Oak Ridge Tokamak (ORMAK) suffered from the lack of test stand operation to ascertain the beam transmission properties. The Princeton Large Torus (PLT) injectors, however, have been tested on a prototype beam line; the results were indeed proved credible except the effect of the stray tokamak magnetic fields [1]. The NBI heating experiments on PLT have achieved an ion temperature of ≈ 6 keV with a power of 2.1 MW of D^0 from four injectors [2]. Measurements of beam power flow along the PLT prototype beam line [3] with all four injectors [4] have been reported elsewhere.

Two hydrogen beam injectors to be used for NBI heating of the Impurity Study Experiment (ISX) tokamak [5] plasmas have been tested on a prototype beam line similar in geometry to the actual ISX-B beam line system. Requirements per injector of the first phase NBI experiment on ISX-B are similar to those for PLT, i.e., the beam energy of 40 keV and the nominal beam current of 60 A; the beam line structure is also similar. Although the ion sources are of identical design, the accelerator column has been improved by using shaped apertures on the plasma grid.

In this paper, we describe the techniques of injector operation and the performance results of the two ISX-B injectors in a prototype beam line. Experimental results are given for beam transmission properties along the beam line, beam optics properties, species compositions, and background pressure behavior in the drift duct region.

2. DESCRIPTION OF ION SOURCE AND PROTOTYPE BEAM LINE

The prototype beam line constructed for ISX-B injector development is shown in Fig. 1. The duoPIGatron ion source [4] with an effective extraction size of a 22-cm-diam circle is closely coupled with a cylindrical neutralizer cell of a 20-cm ID and a 108-cm length. A transverse deflection magnet separates the residual charged fraction of the beam onto a set of three beam dumps. The four movable plates define a square beam by blocking off the outside tail of the beam to reduce unnecessary particle loading on the drift duct wall. The opening is formed by four rectangular plates whose power loadings are separately monitored for the purpose of beam alignment. The drift duct consists of a rectangular duct and a round cylinder matched to a round ISX-B port (see Fig. 1). The round cylindrical duct joins to a large vacuum box which houses a target simulating the ISX-B plasma. In front of the beam target is a defining aperture simulating the torus opening. In the rectangular section of the drift duct, a retractable target is located, which in an actual ISX-B beam line is the neutral beam stop for use during the beam conditioning runs.

The main beam line tank is pumped by a pair of vertically suspended cryocondensation panels consisted of liquid-helium-cooled surfaces and liquid-nitrogen-cooled chevrons, providing a total pumping speed of $\approx 2 \times 10^5$ liter/sec or approximately 10 liter/sec/cm². Calorimetric power monitoring is made on the following: the accelerator grids, the neutralizing gas cell, the pole face of the deflection magnet, the four defining plates, the three ion dumps, the retractable calorimeter, the drift duct walls which are lined with water-cooled copper plates, the target defining plate, and the beam target. The calorimetry data are processed by a data acquisition system comprised of a CAMAC data acquisition system coupled to a PDP-11 computer.

A schematic of the duoPIGatron ion source with proper connection of power supplies is shown in Fig. 2. A glow discharge plasma is formed inside the intermediate electrode, which supplies ionizing electrons to the main plasma in the anode region through a double potential sheath. The plasma grid is typically tied to the positive side of the arc power supply through a 200- Ω resistor, effectively giving a "floating" potential. The relatively long cylindrical anode chamber has 20 alternating axial bar magnets producing a multiple-magnetic line cusp configuration for improved plasma confinement and spatial uniformity. There are 1799 round apertures within a 22-cm-diam circle on the plasma grid while the inner diameter of the magnetic cusp chamber (anode 2) is ≈ 32 cm, leaving a "relaxation" distance of $\Delta r \approx 5$ cm between the periphery of the extraction circle and the wall. A set of 18 parallel tubes of 1.57 mm O.D. is embedded in each grid to supply cooling water. There are three rows of apertures between two adjacent water lines.

The configuration of the accelerator column is illustrated for a single aperture in Fig. 3; the straight-bore aperture geometry of the PLT sources is illustrated in Fig. 3a, and the shaped aperture geometry of the ISX-B sources is illustrated in Fig. 3b. The accelerator is based on the accelerator-decelerator system; the first gap has the extraction/acceleration potential across it, and the second gap has an ~ 1 -kV voltage providing a suppressing potential hill for the electrons produced in the downstream. The shaped aperture of Fig. 3b is a closer approximation to the so-called Pierce geometry [6] than Fig. 3a; thus, it is expected to produce less aberrational effects. Summing up the aperture area over 1799 holes within a 22-cm-diam circle, the shaped aperture geometry has a geometric transparency of 37.5% (or $\approx 142 \text{ cm}^2$) in comparison with the transparency of 54% for the straight-bore geometry. A design current of 60 A/source means that the average ion extraction current densities to be achieved are 0.42 A/cm^2 from the geometry of Fig. 3b and 0.3 A/cm^2 from the geometry of Fig. 3a, respectively.

3. EXPERIMENTAL TECHNIQUE

A newly assembled injector requires initially a well-coordinated conditioning procedure for both the discharge plasma source and the high gradient accelerator column. The discharge plasma source is first conditioned to its full discharge current and voltage, typically 600 A and 110 V, respectively, by small incremental steps after a careful outgassing and conditioning of the oxide-coated cathode filaments. The discharge is pulsed with the arc voltage pulse applied between the cathode and the anode. Any sustained runaway condition of the discharge

(i.e., breakdown) is prevented by an arc inhibit circuit which cuts off the trigger pulse. Although the ion source geometry has been optimized and refined for the desired plasma density uniformity and maximum gas efficiency, the source magnet strength and gas flow rates (into both the cathode and the anode region) dictate the final fine tuning of the discharge condition.

Conditioning of the accelerator column usually requires more pulses than conditioning of the discharge plasma source, typically about 2000 shots of 0.1-sec pulse; however, the variation from one source to another is very wide. A fast-switching high voltage modulator system [7] has been an essential element for the successful operation of the accelerator by virtue of the protection against high voltage breakdown damage and the fast conditioning rate. The accelerator gap conditioning is best achieved by a gradual increase of the gap voltage along with the beam current roughly scaling according to the Child-Langmuir relation [8], $I \propto V^{3/2}$, where I and V are the accelerator supply current and voltage, respectively. A more detailed procedure for injector conditioning was reported elsewhere [9].

The timing logic of the various pulses is as follows. The gas supply valves (piezoelectric Veeco Model PV10) are opened first, 40-100 msec in advance of the arc voltage pulse. The cathode filaments are maintained at operating temperatures in steady state. The accelerator voltage and the decelerator voltage are simultaneously pulsed on about 10-30 msec before the arc voltage pulse. However, the accelerator voltage pulses are normally turned off before the arc pulse ends. Therefore, the beam pulse length and shape are determined by the discharge turnon at the beginning and by the accelerator pulse turnoff at

the end. Oscillographs of the discharge voltage, the discharge current, the accelerator voltage, and the accelerator current are shown in Fig. 4. The gas valves are opened at the beginning of the traces and closed when the discharge pulse ends. The accelerator current pulse shows the initial turnon characteristic which is somewhat different from the discharge current pulse shape. On the accelerator voltage pulse, the initial unloaded voltage lasting about 10 msec is shown to drop with the initiation of the ion source discharge and to exhibit a cycle or so of ringing before settling at a flat voltage of 40 keV with a beam current of 60 A. The initial pulse shape of the accelerator current can be changed by varying the gas flow rates as shown in Fig. 5. Excessive gas flow into the source results in a high initial spike followed by drooping, while too little gas flow yields a slow rise of the ion current. The sharp turnoff of the beam pulse is made possible by turning off the accelerator voltage while the discharge pulse is still on.

The beam power measurement consists of temperature measurement and flow rate monitoring of the cooling water, signal amplifiers, and a computerized processor [10]. Although the result is for a single pulse, the correct measurement requires about ten good successive beam pulses to ensure a steady state in a pulse-to-pulse basis. Other beam diagnostics include a thermocouple array on the back side of the beam target, a pinhole at the center of the target for pinhole camera exposure, light measurements from the beam column using photodiodes or an interferometer, and fast ion gages for pressure measurements. Charged particle species measurements have been made by scanning the beam onto a water-cooled tube by the deflection magnetic field strength. Alignment of the ion

source, and thus the beam direction, is achieved by steering the entire source and gas cell in both a horizontal and a vertical direction against a spherically curved O-ring seal surface. Three techniques have been employed for alignment: (1) equalizing the beam power loadings on the respective defining plates, (2) maximizing the beam power on the target, and (3) measuring the intensity profiles on the target. Methods (1) and (2) were found to be in very good agreement and more reliable than method (3).

4. SUMMARY OF INJECTOR PERFORMANCE

Two identical injectors have exhibited somewhat different performances, likely due to small inevitable variation in the assembled accelerator geometry. In particular, it is observed that the values of the optimum current or the optimum perveance ($I/V^{3/2}$) to yield the maximum transmission efficiency differ from one another: $5.7 \times 10^{-6} AV^{-3/2}$ for source I and $6.4 \times 10^{-6} AV^{-3/2}$ for source II. However, the maximum transmission efficiencies at their respective optimum perveances are about the same. As discussed more in detail in the following section, the beam optics property of an injector is characterized by the beam perveance. It should be noted that in this paper, we will use the accelerator current as a main parameter rather than the actual extracted beam current. The accelerator current is the sum of the beam current and the backstream electron current which is typically small (a few percent).

Figure 6 shows the neutral beam power delivered to a 28-cm-diam target as a function of the total accelerator current at a fixed energy

of 40 keV for both injectors. The target power reaches a maximum at ~ 57 A and actually decreases as the accelerator current is increased further. This behavior is illustrated in another manner in the top figure where the transmission efficiency, as defined by the ratio of the target power to the accelerator power (IV), is shown also as a function of the accelerator current. A maximum transmission efficiency occurs at an accelerator current of about 50 A, and the transmission efficiency drops in either way from the optimum current value, which is an intrinsic beam optics property of the multiaperture accelerator geometry of these injectors. Consequently, these injectors perform to their maximum efficiency at an optimum combination of the current and the voltage given by an optimum value of perveance, which is $\cong 6 \times 10^{-6} \text{ AV}^{-3/2}$ on the average.

Highest reliable neutral beam powers on the target were obtained from source II and were only limited by the power supply capability: 910-kW hydrogen neutrals at 42 kV and 61 A and 1020-kW deuterium neutrals at 43 kV and 55 A. The ion-to-neutral conversion efficiency of the 1-m long, 20-cm-diam gas cell was very close to the theoretical equilibrium efficiency [11,12]. An extra gas feed into the gas cell was necessary in order to provide the equilibrium line densities. Each injector has been operated up to 50,000 shots with a pulse length of ~ 100 msec and a duty cycle of 1%.

A gas efficiency of $>50\%$ was measured during the beam pulse as defined by the particle flux ratio of the extracted beam to the input gas to the source. A discharge power of 1.1 kW was consumed on the average per ampere of extracted beam current.

5. BEAM OPTICS AND TRANSMISSION PROPERTIES

Large-area, high-current beams in use for the NBI application consist of a number of small beamlets (e.g., 1799 beamlets for the present source) focused at the end of a beam line. The combined beam profile evolving along the beam line downstream is determined by the combined effects of the single beamlet divergence and the beamlet focusing. If the beamlet focusing is perfect and all the individual beamlets have the same divergence characteristics, the total combined beam profile can be uniquely defined. An analysis has been made for such an ideal case with a Gaussian single beamlet distribution [13]. Figure 7 illustrates a downstream evolution of the combined beam profile, given beam conditions of a single beamlet divergence, $\theta_e = \pm 1.5^\circ$ and a source diameter of 22 cm. The calculation of Fig. 7 does not include a beam scrape-off along the beam line, nor the separation of residual charged particles. In Fig. 8, the beam transmission efficiencies are calculated as a function of the single beamlet divergence angle and the beamlet focal length for three apertures of interest along the ISX-B beam line: the gas cell aperture, the square defining aperture, and the beam target. In reality, the individual beamlet divergence angle varies and the beamlet focusing is imperfect, which results in a lower beam transmission than predicted by the calculation. The experimental investigation of the properties of combined beams is based only on the total beam power transmission data, because the properties of the beamlet focusing and the single beamlet divergence of an injector are difficult to resolve.

As a result of the geometry effect on single beamlet optics, different beam transmission efficiencies of the multibeamlet beams are observed from the two accelerator systems of Fig. 3. The total target power normalized to the accelerator power (IV) is compared in Fig. 9a as a function of the beam perveance ($IV^{-3/2}$). The maximum beam transmission efficiency increases from 0.4 for the straight-bore aperture system to 0.6 for the shaped aperture system; the optimum extraction current density increases from 0.23 A/cm² to 0.31 A/cm² at a fixed accelerator voltage of 40 kV. The optimum value of the perveance is less for the shaped aperture system than the straight-bore aperture system because of the reduced geometric transparency in making the apertures shaped with the identical beamlet pattern. It is a well-known fact that a shaped beam-forming aperture yields less divergent beams due to more uniform formation of the beam-plasma interface. Effects of various beam-forming aperture shapes on the beam divergence have been investigated using a single aperture on a 7-cm-diam duoPIGatron [14].

An experiment in which the extraction gap was reduced on source I was tried in an effort to enhance the value of the optimum perveance. Figure 9b illustrates the effect of the extraction gap on the resulting beam power transmission efficiency. The reduced gap, however, produces less transmission efficiency, although the optimum perveance appears to be higher, which is apparently due to a dominant increase of the aperture aberration with the greater aspect ratio (i.e., the ratio of the aperture radius to the gap). A numerical simulation study [15] of ion beam optics under the similar geometry also confirms this observation.

In Fig. 10 the effect of the source plasma uniformity on the beam transmission efficiency is studied with source II for two situations: (1) the nonuniformity caused by two "missing" magnet cusps (out of a total of twenty cusps), which occurred rather accidentally due to adjacent magnet columns having the same polarity at two azimuthal positions 180° apart and (2) substitution of a larger diameter cusp-field chamber than the standard one. A substantial decrease of the beam transmission (Fig. 10a) is due to a poor optics condition for the beamlets in the vicinity of the two "openings" on the "magnetic picket fence." To ensure a uniform plasma density across the beam extraction area, a certain "relaxation" distance (Δr) between the periphery of the extraction circle and the magnetic cusp cylinder is needed. The beam transmission efficiency improved noticeably when this "relaxation" distance was increased (Fig. 10b). With the regular-size cusp cylinder, the discharge plasma is to some extent affected by the cusp fields. This effect has also been illustrated by a technique of pinhole camera imaging of all the beamlets, which exhibits ten conspicuous "scallop" along the boundary of the beamlet pattern [16].

Beam transmission properties between the hydrogen and the deuterium beams are compared in Fig. 11. Deuterium beams were tried on source II after it had been operated with hydrogen beams (about 20,000 shots). The optimum perveance of the deuterium beam is lower than that of the hydrogen beams as expected from the Child-Langmuir scaling [8]. Taking an average mass weighted for the beam composition of each case (see Sect. 6), the ratio of the square root of the average masses is estimated as ~ 1.4 , which is close to the ratio of the optimum currents. It is

also noticed that around the optimum currents, the deuterium beam seems to yield a higher transmission than the hydrogen beam. It may be due to the deuterium beam experiencing less space-charge spreading along the downstream because the beam perveance is less and the ion-to-neutral conversion efficiency is greater at the same accelerated energy.

A calorimetrically measured distribution of beam power deposition, normalized to the accelerator power (IV), along the beam line system with no separation of charged fraction is illustrated in Fig. 12 as a function of the total beam perveance ($IV^{-3/2}$) for varied beam energy (30-45 keV) and beam current (25-65 A). The error bars indicate the scattered data points from both ion sources rather than the rms deviation. It was observed that the beam power distributions under varied conditions are much the same irrespective of the accelerator voltage if plotted against the beam perveance. It is rather subtle that multi-beamlet beams can be well characterized by the total beam perveance alone. Power loadings to the other two grids (plasma grid and extraction grid) are not plotted in Fig. 12. These grids have no more power loading than the exit (or the ground) grid ($\sim 2\%$). The power drain to the exit grid is fairly insensitive to the beam condition as shown. The gas cell power loading as a function of the beam perveance is peculiar in that, starting from $\sim 18\%$ at a low perveance, it decreases monotonically with the perveance and has a flat minimum before increasing at very high perveances. This behavior is partially due to the characteristic of beamlet focusing of multiaperture beams. On the other hand, the beam power deposition in the region between the end of the gas cell and the target exhibits a clear minimum ($\sim 20\%$) at a perveance a little lower

than the optimum perveance for the target power. The sum of this power loading and the gas cell power loading, however, exhibits a consistent behavior to that of the target power. The maximum efficiency of beam power transmission to the target is about 60% at an optimum perveance of $\cong 6 \times 10^{-6} \text{ AV}^{-3/2}$. It is noted that the data of Fig. 12 show a near 100% power accountability by the calorimetric measurements including the other two grids' contribution (3-4%).

A trial-and-error matching of the theoretical calculations of the transmission efficiencies through three well-defined apertures along the beam line (Fig. 8) to a set of measured power transmission efficiencies (e.g., Fig. 12) has been attempted to resolve information on the single beamlet divergence and the beamlet focal length. From this very crude analysis, we obtained a result on "effective" beamlet divergences and focal lengths for varying beam currents at a fixed beam energy as shown in Fig. 13. The beamlet focal length is shown to decrease with the increase of the beam current, while the radius of the grid curvature was about 4 m when first assembled. The single beamlet divergence angle thus determined appears to vary consistently with the measured transmission efficiency to the target, but deviate much from e-folding half angles of around 1.5° that were inferred from a beam intensity profile measured by an array of thermocouples embedded on the target. What possibly happens in reality may be one or all of the following:

- (1) individual beamlets have varying divergences due to the nonuniform extraction gap, (2) the beamlet focusing is imperfect and also time-varying in a pulse, (3) the spatial spreading is enhanced by the removal of outermost particles by finite apertures along the downstream, and (4) the single beamlet profile deviates from a Gaussian distribution.

The background pressure rise during a beam pulse in the drift duct region was of great concern in PLT neutral beam systems because of an appreciable reionization loss of neutral beam particles resulting from a substantial pressure rise [17]. The present ISX-B prototype beam line employs water-cooled copper liners in the drift duct in contrast to the uncooled stainless steel wall with the prototype PLT beam line [18]. A time variation of the drift duct pressure is compared in Fig. 14 with and without beam extraction under the same gas feed. The pressure signal with a beam pulse shows an apparent decrease from the one without a beam pulse during a pulse, but rises after the pulse and remains higher than the one without a beam pulse for a long time. This is a remarkable contrast to the results from the prototype PLT beam line experiment, in which a pressure rise of 60% would typically be observed for a beam of 35 keV and 37 A (linearly extrapolated from a pressure rise of 120% measured at 40 kV and 60 A by the beam power) [19]. A drift-duct power loading of 6% of IV is measured for the case of Fig. 14, which is lower by a factor of 2 than the case of Ref. [19]. In addition to the effect of less wall loading, a change in the gas desorption rate due to wall materials (copper vs stainless steel) and due to the surface temperature (cooled vs uncooled) appears to be the reason for the difference between the present and the earlier result [19].

6. ION SPECIES YIELD

Three species of hydrogen ions (H_1^+ , H_2^+ , and H_3^+) are generally produced from discharge ion sources, and in passing through a gas cell, diatomic (H_2^+) and triatomic (H_3^+) ions are mostly dissociated into

multiplespecies of ions and neutrals with different energies. At the end of a gas cell, there exist the following species (denoting the total accelerated energy as E): $H_1^0(E)$, $H_1^+(E)$, and $H_1^-(E)$ from atomic ions; $H_1^0(E/2)$, $H_1^+(E/2)$, $H_1^-(E/2)$, $H_2^0(E)$, and $H_2^+(E)$ from diatomic ions; $H_1^0(E/3)$, $H_1^+(E/3)$, $H_1^-(E/3)$, $H_2^0(2E/3)$, $H_2^+(2E/3)$, and $H_3^+(E)$ from triatomic ions. In general, molecular species and negative ions are a small fraction. Energetic neutrals originating from diatomic and triatomic ions do not penetrate deep enough into a plasma due to their lower velocities, and thus fewer fractions of those are desired. A separation magnet then deflects all the charged particles into a set of ion dumps.

We have used the deflection magnetic field to scan the residual charged particles on a water-cooled tubing extended normal to the beam direction just above the ion dumps. Calorimetric monitoring of the charged particle intensity as a function of the magnetic field strength gives energy and mass spectra as shown in Fig. 13a. Three distinct energy peaks [$H_1^+(E)$, $H_1^+(E/2)$, and $H_1^+(E/3)$] and a small $H_2^+(E)$ peak at high fields are visible, while the $H_2^+(2E/3)$ peak, which would be comparable to $H_2^+(E)$, is hidden on the right side of the $H_1^+(E)$ peak. In some other species scans, the $H_2^+(E)$ peak is almost invisible. The finite tail at high fields is the contribution from stray particles produced through charge exchange collisions in the magnet pole region, which spread out between the ion dump and the target at a normal setting of the deflection magnet [20]. The gas cell line density is fine-controlled by an extra gas feed to ensure a near equilibrium for $H^0(E)$ while comparing the target powers with (P_T^0) and without (P_T^t) the deflection magnet energized. The value of the line density is determined from the calculated conversion efficiencies and the measured P_T^0/P_T^t .

The relative abundance for $H_1^+(E)$, $H_1^+(E/2)$, and $H_1^+(E/3)$ peaks is obtained from the areas under these peaks after fitting each profile shape to be symmetric. Figure 15a yields areas under these peaks as 93, 5, and 2, respectively. Unfolding these relative intensities through the surviving probabilities [11] (0.39, 0.17, and 0.12, respectively, for $E = 40$ keV and a line density of 10^{16} cm $^{-2}$), we obtain a species composition for the extracted ions of 84% H_1^+ , 10% H_2^+ , and 6% H_3^+ . The resulting neutral beam composition is then estimated as 79.4% $H_1^0(E)$, 11.8% $H_1^0(E/2)$, 7.2% $H_1^0(E/3)$, 0.8% $H_2^0(E)$, and 0.8% $H_2^0(2E/3)$. An example of a similar species scan for deuterium beams is shown in Fig. 15b, showing a composition of 79% D_1^+ , 15% D_2^+ , and 6% D_3^+ . It is expected, however, that the deuterium beams (run after a long time of hydrogen operation) contained hydrogen ion impurities. The $D_1^+(E/2)$ peak would be mostly affected by the full energy atomic hydrogen ions. It has been observed that the species distribution remains roughly unchanged over a range of the beam current (correspondingly the discharge current) from 40 A to 65 A. The atomic ion fraction tends to decrease with the decreasing beam current below 40 A.

7. CONCLUSIONS

Performance of the two ISX-B injectors was shown to be characterized by an optimum (in the sense of the beam transmission efficiency to the target) perveance in terms of the total accelerator current and voltage. Both the optimum perveance ($\sim 6 \times 10^{-6}$ AV $^{-3/2}$) and the corresponding total (ions and neutrals) beam transmission to the target ($\sim 60\%$) are approximately invariant over the range of accelerator voltages tried

(25-45 kV). The average extraction current density under optimum conditions is 0.34 A/cm^2 at 40 kV for an effective extraction area of $\sim 142 \text{ cm}^2$ with 1799 round apertures over a 22-cm-diam circle, while the highest average extraction current density operated at 40 kV is about 0.45 A/cm^2 . An attempt made to increase the optimum current density by reducing the extraction gap was not successful because the field aberrations became more dominant for the present accelerator geometry when the gap was shortened. Shaping of the plasma grid apertures has improved the beam transmission efficiency by $\sim 50\%$ over the straight-bore aperture geometry. The distribution of power deposition along the beam line was also shown to be characterized by the beam perveance regardless of the beam energy and thus to be dictated by beam optical properties.

The extracted hydrogen ion beams typically have an atomic fraction of 85%, but in the limited runs of operation, the deuterium beams exhibit lower atomic fractions — probably due to hydrogen ion impurities still present. The arc power efficiency is $\sim 1.1 \text{ kW/A}$ of extracted beam current, and the gas utilization efficiency is typically $>50\%$ when computed in terms of the ratio of the beam current to the equivalent current of input gas flow rate. No pressure rise related to scrap-off beam particles was observed in the drift duct region where the walls are water-cooled copper plates. Hydrogen neutral beam powers as high as 910 kW with an overall electrical efficiency of 36% have been achieved on the target which simulates the ISX-B plasma.

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FIGURE CAPTIONS

FIG. 1. A schematic of the prototype beam line for ISX-B injector development.

FIG. 2. A schematic of a 22-cm-diam duoPIGatron ion source.

FIG. 3. Accelerator geometries of (a) a straight-bore aperture for PLT injectors and (b) the shaped aperture for ISX-B injectors.

FIG. 4. Oscillographs of the arc discharge voltage and current and the accelerator voltage and current of a typical beam pulse (pulse length is 100 msec).

FIG. 5. Variation of pulse shapes due to different gas feed rates. Oscillographs shown are, from the top, the accelerator voltage, the accelerator current, the arc current, and the arc voltage.

FIG. 6. Neutral beam power delivered on a 28-cm-diam target as a function of accelerator current at a fixed beam energy of 40 keV.

FIG. 7. A downstream evolution of beam intensity profile of a 22-cm-diam multibeamlet beam.

FIG. 8. Beam transmission efficiency through (a) a 21-cm-diam opening at 108 cm downstream, (b) an 18×18 cm opening at 211 cm downstream, (c) a 28-cm-diam opening at 406 cm downstream, as a function of beamlet focal length and single beamlet divergence.

FIG. 9. Total beam power transmission efficiencies (a) for accelerator geometries of Fig. 3 and (b) for different extraction gaps as a function of beam perveance.

FIG. 10. Effects of source plasma uniformity on beam transmission efficiency: (a) effect of perturbed magnetic cusp fields and (b) effect of the "relaxation" distance between the emission circle and the wall.

FIG. 11. Comparison of beam transmission characteristics between hydrogen and deuterium beams.

FIG. 12. Distribution of beam power deposition along the beam line as a function of beam perveance.

FIG. 13. Single beamlet divergences and beamlet focal lengths deduced by matching the measured transmission data and the calculations of Fig. 8.

FIG. 14. Background pressure behavior in the drift duct with and without beam extraction.

FIG. 15. Beam species scanning by the deflection magnetic field (a) for the residual hydrogen ion beams and (b) for the residual deuterium ion beams.

Fig. 1

Fig. 2

ORNL-DWG 79-2032 FED

STRAIGHT - BORE APERTURE
(PLT SOURCE)1799 HOLES
22 cm - DIA SHAPED APERTURE
(ISX SOURCE)1799 HOLES
22 cm - DIA

DIMENSIONS IN (mm)

TRANSPARANCY ~ 54 %

(a)

TRANSPARANCY ~ 37 %

(b)

Fig. 3

ORNL/DWG/FED-78-920R

ARC VOLTAGE
(75 V/DIV)
ARC CURRENT
(200 A/DIV)

BEAM CURRENT
(10 A/DIV)
BEAM ENERGY
(10 kV/DIV)

Fig. 4

ORNL/DWG/FED 78-919

$V_{ACC} = 43 \text{ kV}$ $I_{ACC} \approx 50 \text{ A}$ $I_A \approx 620 \text{ A}$ $V_A = 97 \text{ V}$

(a) EXCESSIVE GAS FLOW

$V_{ACC} = 43 \text{ kV}$ $I_{ACC} \approx 50 \text{ A}$ $V_A = 135 \text{ V}$ $I_A \approx 420 \text{ A}$

(b) DEFICIENT GAS FLOW

Fig. 5

Fig. 6

ORNL/DWG/FED-78-907

Fig. 7

Fig. 8

Fig. 9

ORNL-DWG 79-2496 FED

Fig. 10

Fig. 11

Fig. 12

Fig. 13

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Fig. 14

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Fig. 15

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