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Development of the Plasma Generator for Long Pulse 10 x 40 Neutral Beam*

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Abstract

Users of fusion devices have identified heating requirements for positive ion based neutral beams to include energies of 80 or 120 kV with pulse length up to 30 sec. Additional requirements are low beam divergence ($0.3^{\circ} \times 1.0^{\circ}$; 1/e half angles), low impurity (less than 1%), high species (over 80% atomic), and cathode lifetime exceeding 5 hours of beam operation. Accelerator design remains as an engineering problem whereas most of the performance goals have required development of the plasma generator. Problems of concern which relate to the performance goals are the heat dissipation, magnetic field configuration, and cathode placement.

The plasma generator was tested on TS IIA (the plasma generator testing facility) which does not have beam extraction capability but is used to evaluate efficiency, operating conditions, arc notching characteristics, species, plasma uniformity, and cathode conditioning. The source, consisting of the plasma generator mounted on the long pulse accelerator was mounted on NBETF (Neutral Beam Engineering Test Facility) for beam testing. During beam operation the back-streaming electrons add power to the source and affect the arc operation. Source durability and stability were studied at 80 kV and 40 Amps of accelerator current (deuterium). The arc efficiency was higher

than the value used for the design. Power loading from back-streaming electrons was much less than the design level. With feedback control plasma density and accel current were constant to $\pm 2\%$ during 30 sec shots. The beam atomic fraction of 84 - 88% (deuterium) was slightly higher than measured on TS IIA. Cathode durability was tested by operating over 500, 30 sec full shots at 80 kV and 40 Amps of Deuterium. Arc conditioning was found to be an important phase to avoid filament damage.

Introduction

Since 1976 the U.S. fusion neutral beam development program has focused on the advanced long pulse positive ion source (APIS). Originally, the source was intended for 150 kV reactor development but has been redirected to meet the program needs for 80 kV, 30 sec-beams for the Mirror Fusion Test Facility (MFTF-B) and 120 kV, 2 sec beams for the Tokamak Fusion Test Reactor (TFTR). Beam performance goals included atomic species ($>80\%$), divergence ($0.3^\circ \times 1.0^\circ$ for slot accelerator), impurities ($\sim 0.1\%$) and filament lifetime (~ 50 hours). Most of these requirements for the beam are ultimately determined by the plasma generator. This paper discusses the design and development testing of the plasma generator for the $10 \times 40 \text{ cm}^2$ extraction area long pulse accelerator (LPA). Plasma generator development includes testing with and without beam. After 500 shots at 80 kV, 30 sec, 40 A deuterium the LBL prototype met the requirements of the MFTF-B project.

Based on previous source/accelerator testing of other Lawrence Berkeley Laboratory plasma generators a design configuration was produced to accommodate the requirements of power loading, plasma uniformity, and species. Design modifications and additions were first evaluated on the plasma generator test stand and the results are discussed. Data from 80 kV,

30 sec beam testing on NBETF are analyzed to show the effects of the accelerator on the plasma generator operation, particularly on power loading and thermal time constants. Arc operational reliability and lifetime are also discussed.

I. Plasma Generator Evaluation

The plasma generator design was determined by the thermal power loading, the operational discharge stability, the need for plasma uniformity, and the desire for an high atomic fraction. The power loading caused by the back-streaming electrons, in particular affects the cooling requirements and filament placement. The anode area (1,2) which depends on the number and placement of the magnet line cusps and on the plasma generator size, determines the stability of operation. The number of magnet line cusps were chosen to provide sufficient anode area. They were placed to minimize magnetic field effects on the plasma uniformity at the extraction plane. The filament positions relative to the magnetic field affect both the uniformity and the atomic fraction. Structural and thermal calculations and the magnetic field geometry calculations aided the designers although many of the design decisions were based on past experience and a qualitative understanding of the plasma physics of the plasma generator.

A. Description

The plasma generator (3) is a basic magnetic multipole bucket (Figure 1), using filament cathodes. The bucket side walls form a box 24 cm wide, 57 cm long, 30 cm deep and with 36 rows of samarium cobalt permanent magnets around the outside perimeter. Water cooling channels are set between magnet rows. The filament sandwich consists of two large adjoining plates on which the 34

filaments are mounted (60 diameter tungsten). The filament sandwich is made of gun drilled water cooled copper. Uncooled molybdenum sheets are mechanically attached to the filament-positive plate to shield the copper at cathode potential from the plasma. The filament sandwich has a floating spacer plate, 2 or 3 cm thick, between it and the bucket wall rear flange and a second floating spacer, 2 cm thick, between it and the back plate. The back plate is actively cooled to dissipate power loading by back-streaming electrons from the accelerator. On the back side of the back plate a central row of magnets is mounted, and combined with a loop around the border of the 10 cm x 40 cm region these form the multipole fields for the back plate. Between the front flange and the extraction grid, a 2 cm thick probe plate is mounted. This plate provides mounting space for six water cooled langmuir probes which monitor the plasma density and provide arc spot protection. Normally this plate floats electrically but it can be used to provide extra anode. The designers considered this desirable, in the event that the source be operated with hydrogen which requires more anode area than with deuterium. The bucket side walls and the back plate normally serve as anode for the source.

B. Testing

Source efficiency and stability were evaluated with testing. Also the effect of the back plate magnets on the plasma profile, species and efficiency could not be anticipated. Previous experiments (4,5) indicated that the magnetic flux bridging across to the side walls over the filament region might have a beneficial effect on the species and a detrimental effect on the plasma profile. Only after testing was a suitable back plate magnet configuration empirically determined.

The plasma generator was operated on a test stand set up specifically for plasma generator studies before testing on a neutral beam system. In addition to the usual operating monitors of arc current and voltage, grid potential, and ion saturation current density, this test stand has detailed probe profile and momentum analysis diagnostics.

A rake of eight langmuir probes, two rows of four, was pulled across half the distance of the 40 cm extraction length. One row was positioned at the mid-point and the other row began at one end so that the 20 cm of travel probed the full 40 cm length. The travel of the top row overlapped the initial position of the bottom row, providing scale factors for probe area differences. The probes at the ends of each row were positioned at plus or minus 3.8 cm from the extraction area centerline. At 4.8 cm three fixed probes were placed along one half the length.

A momentum analyzer was mounted in the test stand to measure the ion species near the center of the extraction plane. A 5 mil x 1 cm slit limits the gas flow into the analyzer box, which is pumped separately. The box is biased 40 to 50 volts negative of anode potential for ion extraction and the magnetic field is swept in time to analyze the species fractions and impurities. These diagnostics were used to evaluate plasma generator modifications. Some differences in plasma generator operating parameters of voltage and current and floating potentials were found during beam testing although without beam extraction operation was similar.

II. Plasma Generator Operation

A. Efficiency

The plasma generator efficiency affects filament lifetime and wall cooling requirements. The power efficiency is defined as the extractible current per

kilowatt of arc discharge power. Typically the plasma production increases linearly with the discharge power except at low gas pressure. In Figure 2 the efficiency is shown to be double-valued, which is due to two distinct modes of plasma generator operation. For beam, the source is always operated in the efficient mode. The data obtained on the plasma generator test stand (Figure 2) indicates that the efficiency decreases with arc power. This effect was due to having increased the arc voltage at higher power for this set of data. The data in Figure 3 taken with constant beam extraction current also shows a decrease with voltage. Operation with the probe plate at anode potential is less efficient because the extra anode increases the loss area for electrons.

Most of the testing on the beam line was with the probe plate floated and the back plate magnets mounted. The data in Figure 3 shows an efficiency at 52 volts which decreases by 40% at 102 volts. When the probe plate was biased toward anode potential the efficiency dropped by 15%. For this same probe plate bias the power efficiency in hydrogen was slightly higher than for deuterium.

The plasma generator was also operated without the back plate magnets (called "back anode"). In this configuration the efficiency increased even though the anode area was sufficiently larger. A possible explanation is that removing the back plate magnets also removes the magnetic flux linking the region around the filaments and thus the primary electrons can be more easily injected into the field the free volume of the source. Two measurements support this conjecture. When the back plate magnets were removed the floating potential of the extraction grid dropped from 15 volts to 28 volts below anode, suggesting more primaries in the generator volume, and the atomic fraction decreased.

Typical arc voltage and current waveforms for constant extractible current are shown in Figure 4. The arc voltage decrease from the first peak is due to filament heating caused by a net increase of heating power compared to the filament preheat. When the beam back streaming power arrives, the filaments are further heated as is indicated by the decreasing arc voltage (Figure 5). Concurrent with these voltage decreases are current increases consistent with the power supply load line. Because the plasma generator efficiency is arc voltage dependant the power decreased by 1.5%.

A typical operating point at 80 kV beam and with an arc voltage of 80 V the plasma generator requires 66 kW to produce 40 A of beam current or 170 mA/cm² of ion flux density. This translates to an efficiency of 0.6 A/kW.

B. Stability

Two operational modes have been observed for this plasma generator: an inefficient and an efficient mode. Some care had to be taken to ensure stable operation in the efficient mode when the probe plate was a floating element. The discharge can be operated in the efficient production mode, but the dynamics of plasma density notching to facilitate the beam turn-on usually posed a stability problem because of the two operational modes. The stability of the filament temperature due to back-streaming beam power, affects plasma generator operation for long pulses.

1. Modes

One of the major difficulties with efficient bucket plasma generators is the occurrence of two operational modes, one of which (Figure 2) is inefficient for the production of plasma. Measurements indicate that the inefficient mode occurs as the net charge, or plasma potential becomes negative with respect to the anode. This may be interpreted as the net charge

adjusting itself so the net current entering the plasma at the cathode equals the net current to the anode. As the plasma potential becomes negative an electron-attracting sheath forms at the anode. This reduces the voltage drop across the sheath at the cathode and decreases the energy of the primary electrons. As a result, the power producing the plasma is reduced and the density falls. The remaining power is uselessly dissipated at the anode. The power supply response is to operate at higher voltage and lower current.

In the efficient mode the plasma potential is positive and the electrons are injected into the plasma with more than the full discharge voltage. The plasma generator can operate in one of the two impedance states (Figure 5) depending on how its impedance matches the power supply. If the impedance of the inefficient mode can match the power supply the coupling is unstable for the efficient mode. In Figure 5 the load line of the power supply is seen to intersect both the plasma generator impedance curves.

With the back plate magnets removed, the plasma generator operated emission or space charge limited without instability. This field free back plate provided sufficient anode area for electron loss, and the plasma potential remains positive. With the back plate magnets installed, the available electron collection area was reduced, and the higher impedance, inefficient mode prevailed for both hydrogen and deuterium operation. The plasma generator typically turned on in the inefficient mode because the initial low plasma density limits the extraction current to the space charge limit (low J_p signal illustrated in Figure 6a). The changing plasma conditions resulted in the transition to the efficient mode, provided the power supply load line did not cross an impedance characteristic of the inefficient mode at the equilibrated temperature of the filament. Since the

steady-state operating point was beyond the transition, the turn-on through the space charge limited, low efficiency mode was rapid (a few msec). Note that the grid potential (referenced to the cathode) is closer to cathode during the inefficient mode. The plasma density (probe signal) is low. The operating conditions for this example were; $V_{\text{arc}} = 65 \text{ V}$, $I_{\text{arc}} = 320 \text{ Amp}$, and $I_{\text{arc}} + \text{fil} = 112 \text{ Amps per filament}$. The efficiency variation with arc power for the two modes is shown in Figure 2. The data was obtained for steady state arc operation with $I_{\text{arc}} + \text{fil} = 106 \text{ Amps per filament}$. The efficiency of the inefficient mode is about half that of the efficient mode at the point of the transition. This difference depends on the operating voltage at which the mode change occurs and on the operating filament temperature.

For operation with hydrogen the plasma generator anode area was increased by connecting the probe plate to the anode. Without this extra anode the mode change voltage would be higher than the 50 to 60 volt level (Figure 5) found for operation with deuterium. Even with the probe plate at anode, the hydrogen mode transition was observed (less than 50 volts) during the space-charge limited operation. The probe plate was connected to the anode with a 80 mn resistor. A lower resistance caused a significant (> 10%) heat imbalance between the top and bottom half of the accelerator grids which indicated a profile non-uniformity. At full beam power (80 kV and 57 amps of beam) the arc power was 102 kW and the arc current was 1200 amps. The current to the probe plate during beam was 110 amps or 9% of the arc current. This suggests that an increase in effective anode area of 10% may be sufficient to maintain stable operation without encountering the inefficient mode.

2. Notching

For beam, the plasma density is briefly depressed (notched) to match accelerator perveance during turn-on. The inefficient mode can easily be

avoided if the notch is not too deep. For example, under the conditions shown in Figure 5 the arc power can only be reduced to 35 kW or about 500 amps at 70 V before the inefficient mode takes over. However reliable accelerator operation requires a deep notch and the plasma generator goes into the inefficient mode (Figure 6b). Coming out of the notch, the plasma density increase is very non-linear with discharge power (see Figure 7, probe plate floating) and the accelerator turn-on is impossible. During a notch, the transition into and out of the inefficient mode is rapid (less than 100 usec, Figure 6b). As the arc current rises from the bottom of the notch the ion saturation current density stays relatively low (inefficient mode). During the transition to the efficient mode, the probe signal rises from 20 mA/cm^2 to 70 mA/cm^2 , (i.e., close to the efficient level) in less than 50 usec. The other features of the inefficient mode are that the arc voltage is higher than normal and the grid potential is lower than would be normal (Figure 6c) in a notch without a mode transition. When the probe plate is biased to anode (probe plate anode), the plasma density coming out of the notch is close to linear with power (see Figure 7) and is compared to the case of a notch with a mode change (probe plate floating).

Instead of biasing the probe plate to anode, anode area is added by removing the back plate magnets. This means of increasing the anode area (e.g. by removing the back plate magnets) works well for stability but the atomic fraction was reduced by 15% and the profile was not as good. Whereas adding the probe plate as anode decreased the atomic fraction by only a few percent.

Since retaining the good species was desirable, an acceptably controlled notch was found by adding capacitance between the probe plate and the

cathode. The capacitors charge up to the floating potential of the probe plate under normal source operation, about 15 volts below anode potential. During the notch, the plasma generator is shunted, lowering the total impedance seen by the power supply circuit. A series inductance limits the rate of increase in total current, and drops the voltage across the plasma generator to about 40 volts. Since the probe plate capacitors hold the voltage of the probe plate at or above the notched anode potential, there is a temporary increase in anode area and the plasma generator charge balance remains positive. As long as capacitors keep the potential of the probe plate high enough to collect a net electron current, the source discharge remains in the efficient mode. The arc voltage and the probe signal rise smoothly and with a similar wave shape (Figure 6c) as the shunt is turned off. The grid potential also rises with the arc voltage in contrast to the grid potential of Figure 6b where it stays low in the inefficient mode and the arc voltage is higher than normal. The total capacitance required to keep the source in this mode depends upon the source plasma impedance and the duration of the requested notch. The probe plate potential stays low at the end of the notch and increases slowly according to the capacitor recharge time.

When the capacitors were active during a notch a similar smooth relationship (comparable to operation with the probe plate biased at anode) was observed between ion flux density and the discharge power (Figure 8, dynamic anode). Again this is compared to the floating probe plate operation without the capacitors. The measured circuit currents indicate that the capacitor circuit absorbs 250 Amps of peak electron current, compared to 300 Amps in the power supply circuit at the bottom of the notch (Figure 9). This method was successful for beam turn-on, unless too many notches were required

for repeated interrupts. For the eight (1500uf) capacitors used, the recharge time after the notch was about 25 ms as the probe plate rises to its floating potential (Figure 6c). The plasma production efficiency is very slightly reduced during the recharge, but without significant effect upon the accelerator operation or beam current.

With hydrogen, the "dynamic anode" technique was not used because the probe plate was biased to anode. This was required because the mode change voltage was considerably higher (> 60 V), making operation difficult. Even with the extra probe plate anode the notching could still result in the inefficient mode, but only at low arc power where the ion current density was about 25% of the operating level. The effects on the plasma density were minor so that no operational difficulties occurred for notching and beam extraction.

3. Long Pulse

Since it is important that the accelerator remain "on perveance" for the best beam optics, the plasma generator must hold the extractible current density constant in time. Long thermal time constants affect the arc operation. Other thermal times which don't appear to effect source operation are the molybdenum shields (3 to 5 seconds), and the bucket walls (10 seconds). There is an equilibration time of about 3 seconds probably due to the filaments. Depending on how far from the equilibrium temperature the filament pre-heat condition is, the plasma production may typically vary by 5 to 10% after the arc is initiated during a 3 second time constant. A similar variation occurred after the beam turned on probably due to filament heating by back-streaming electrons.

A feedback control system was used to maintain a constant beam current during long pulse beam shots. The feedback phase controls the arc power supply's SCR elements to maintain a constant probe signal. For example, with regulation the measured voltage changed from 75 V before beam to 72.5 V with beam as the filament temperature increased (Figure 4). The arc current increased by the same percentage, while the probe current density remained constant. Hydrogen operation resulted in a larger plasma generator impedance decrease with beam probably due to a 25% higher beam power and thus more back-streaming electron power (48 kW compared to 27 kW for deuterium). Because of the large impedance change the efficiency increased in concurrence with a larger decrease in arc voltage. This efficiency change makes regulation using the probe signal mandatory for constant extracted current. Otherwise regulation on the arc power might be accurate enough.

Unregulated beam operation could be held to a minimum variation of 10% over 30 seconds. With feedback on the arc power, the beam current variation was held to 2.3% during the first 3 seconds and the change thereafter was a further 0.7% up to 30 seconds of beam time. When the plasma generator was regulated on a water cooled probe the beam current variation was held to about 1%. For hydrogen operation the larger beam power produced a greater heating effect on the filaments and resulted in a larger (2.5%) variation of extractible current. Regulation was a benefit for operation because a desired power or probe level could be chosen so that repetitive shots were available with unchanging values of beam current limited to about a 1% change during a shot.

C. Plasma Uniformity:

The uniformity of ion flux density over the area of extraction is a major

concern for good optics. The plasma profiles of various plasma generator configurations were measured in the long dimension on the plasma generator test facility using the eight rake probes.

Profiles with the thin (2 cm) forward spacer (Figure 1) were not as good as those for the thick (3 cm) forward spacer. There was a profile tilt in the long dimension from the plasma generator top as placed on the test stand. A rotation by 180 degrees of the back plate magnets had some effect on the degree of tilt. The best profile had a 15% overall variation ($\text{max/min} = 1.15$). Without the back plate magnets, the profile was similar.

Profiles with the thicker spacer were better, with a slight tilt only on the bottom half. Rotating the back plate magnets made about a 5% improvement, so that the final accepted profile had a max/min of 1.10. The maximum over the minimum ratios for the four traces (see Figure 10) with the arc power at 85 kW and gas flow at 10 Tl/s, were 1.09, 1.10, 1.03, 1.09. At 15 Tl/s the maximum variation was the same although the details were different. Also, the plasma profile was relatively invariant to the discharge power. When the probe plate was connected to the anode the profile variation increased to 12%. Without back plate magnets, the profile variation was 11%. These variations were acceptable for beam operation.

No profile measurements were made for hydrogen operation. The divergence of the hydrogen beam was 0.45 parallel to the rails compared to 0.3 for deuterium. The inference is that the hydrogen profile was not as good as with deuterium.

D. Species

A principal development goal was to produce at least 80% atomic species. The momentum analyzer on the plasma generator test stand was used as a

relative measurement for purposes of optimization because it only measured the species at the center of the extraction area. Operationally, two parameters had minor correlations to the species. Most of the testing was done at 10 Tl/s of flow on the plasma generator test stand, at the desired ion current density of 200 mA/cm^2 . The atomic fraction decreased by 2% at 16 Tl/s and decreased by 3% at 6 Tl/s. Above 10 Tl/s the D_3^+ fraction increased and the D_2^+ fraction decreased. Below 10 Tl/s the D_2^+ fraction increased and the D_3^+ fraction remained constant. The species with beam (Figure 11) shows a higher atomic fraction for the 17 Tl/s flow than for 12 Tl/s with a corresponding decrease in the half energy (D_2^+) species. The plasma generator test stand does not have the same conductance as the long pulse accelerator. The pressure, not the flow, is the important parameter for species. The conclusion is that 17 Tl/s with the accelerator gives about the same plasma generator pressure as the test stand at 10 Tl/s.

The other parameter which correlates with the species fractions is the discharge voltage. Increasing the voltage from 60 to 90 volts, decreased the atomic fraction by 3 or 4%, and both the D_2^+ and D_3^+ fractions increased.

Removal of the back plate magnets removed the bridging magnetic flux and the result was a 15% decrease in the atomic species (Figure 12).

A less significant change in the atomic fraction was observed on changing the thickness of the forward spacer. The spacer thickness also affects the magnetic flux bridging from the back plate to the side walls. The atomic fraction was increased by 2 to 3% upon decreasing the spacer from 3 cm to 2 cm. Connecting the probe plate to anode rather than allowing it to float caused a decrease of about 2 or 3%. On the plasma generator test stand the best atomic species was between 80 and 85%, with the D_2^+ and D_3^+ being about 7 and 10% respectively.

For deuterium beam tests on NBETF, the source used back plate magnets and a capacitively coupled probe plate ("dynamic anode"). The species were measured using OMA (optical multi-channel analyzer) doppler shift spectroscopy. At the operating current density of 175 mA/cm^2 for 80 keV beam, the comparison of species results to the momentum analyzed data were within measurement accuracy (see Figure 13), with the atomic percentage obtained by momentum analysis 3 to 5% lower. However, the spectroscopy data shows a much higher atomic fraction at lower extractible current densities. It is interesting to note that this higher atomic fraction corresponds to an equivalent decrease in the third energy component. For other types of plasma sources, spectroscopy species data have varied with extractible ion current density like the momentum analyzed data (6).

The species measurement on the plasma generator test stand showed a significant fraction of impurities (about 8 or 10% compared to less than 1% on NBETF). An operational difference between the plasma generator test stand and NBETF may affect the impurities. NBETF is cryo-pumped, with a much better vacuum quality than the oil diffusion pump on the plasma generator test stand. The atomic fraction difference raises the question of what beam interaction can affect the species production.

The floating potential of the extraction grid relative to the anode is considered to be a rough indicator of the atomic fraction (4). This potential is related to the flux of primary electrons arriving at the grid which in turn depends on the gas density, the arc discharge current, and the magnetic flux configuration. For example, as gas density increases, the mean-free path length for energy degrading collisions decreases, degrading the primary energy at the grid and allowing the floating potential to approach the value expected for the maxwellian distribution.

$$V_f = -kT_e/2 \ln (2.718 M/(2m))$$

The presence of magnetic flux influences the floating potential because the primary electrons are confined by the magnetic field. For example, the removal of the back plate magnets lowered the floating potential from 15 to 28 volts below anode and the atomic fraction decreased by 15%.

Operation with beam also influences the grid potential. With 80 kV beam and 17 Tl/s of gas flow, the source arc operated at about 65 V and 65 kW. On the same shot the floating potential was 15.5 V below anode just before the accelerator was turned on and 17.5 V after. For a gas flow of 12 Tl/s, with an arc voltage of 72 V, the grid potential changed from 21 to 26 V below anode when the beam turned on. A possible explanation is that the electrons which normally free-stream out the accelerator grids are turned back into the source lowering the plasma potential and thus the grid potential. It is not known whether this effect relates to the observed species differences between the plasma generator test stand and those on NBETF.

For hydrogen operation at 25 Tl/s of flow, the arc voltage changed from 75 to 68 V when the beam was turned on. The grid potential increased from 28 V below anode to 36 V below anode. The effect of gas flow was observed by changing from 20 Tl/s to 30 Tl/s which changed the pre-beam floating potential from 31 V below anode to 16 V. The atomic fraction of hydrogen was about 15% lower than deuterium at the same ion flux density and was not significantly changed by the flow change. It should be noted, however, that the grid potentials are lower than for deuterium.

III. Source Power Loading

A. Arc and Beam Power Loading

Power loading of the plasma generator is important for long pulses. Water flow calorimetry was done on three plasma generator elements; the electron dump or the back plate, the bucket side walls, and the filament sandwich plus the probe plate. The electron dump is actively cooled and has a short time constant (50 msec). The equilibration time constant for the bucket walls is about 10 seconds, and the equilibration time for the filament sandwich is longer than the 30 second discharge time. The peak temperatures of the source elements are of principal concern. The design limit for the bucket wall is 30 C at an arc power loading of 100 kW and 80 kV operation. An estimated 3% of back streaming power was assumed for the design. The accelerator grids also have calorimetry, and the time constant is short. Calorimetry was done at the optimum accelerator operating conditions for 60, 70 and 80 keV beam. Accelerator grid calorimetry is included because of the interaction between the plasma generator and the accelerator.

Water flow calorimetry can be done by integrating the temperature history to get an average power loading or by using the temperature change once steady state has been attained to get the active power loading. For the plasma generator elements which have a long time constant the integration method is the best estimate of the average power loading. The power loading on the plasma generator elements due to arc and filament operation, is measured first. Using the measured water flow, the integral of the temperature history gives the absorbed energy. The integral for the filament assembly, which has a long time constant (comparable to the measurement time), is estimated by extrapolating the exponential part of the measured decay. This leaves the

measurement in doubt depending on how well the exponential decay can be evaluated.

The data points of integrated energy are fit to a least squares straight line with the slope being the power deposited and the intercept being the energy absorbed from the filament pre-heat. From this information the deposited beam power can be obtained by subtracting the arc and filament power from the total power measured during a beam pulse.

The tests with 62 kW arc power at 17 Tl/s of deuterium flow, showed a 15 C equilibrated temperature rise of the wall (Table I) during 80 kV operation. This was half the considered design limit of 30 C. Calorimetry on the plasma generator and accelerator elements account for 93% of the injected arc plus filament power (86 kW total), of which 72% was measured in the plasma generator. Part (8%) of the arc power was deposited on the accelerator grids. Thirteen percent, or 11 kW, are estimated to be deposited on the first grid hat or to pass downstream through the accelerator slots, the remaining 7% of the injected power is not accounted for and may be lost out the filament and arc electrical connections.

At a lower flow (12 Tl/s), the total arc power deposited on the various elements changes slightly. The electron dump received 4 kW less power, and the filament/probe plate group received 3 kW more power. Also, grid 1 received 1 kW more power from the arc.

For hydrogen, operated at 25 Tl/s, the arc and filament power is much larger on the filament/probe plate group, due to the use of the probe plate as anode. The bucket wall load is larger because the injected power was larger, although the percentage of total arc and filament power is smaller.

The back-streaming electron power deposited (32 kW) into the plasma generator (Table II: the arc power has been subtracted) for the 17 Tl/s flow

is 1% of the beam power; only one third of this is deposited on the back plate. For 12 Tl/s flow, the back-streaming power into the plasma generator is decreased to 0.8%. About one percent of the beam power is deposited on the grids by ions or electrons. Some of the first grid power may have come from back-streaming electrons which have reflected off the plasma generator back plate. The grid 4 loading is almost entirely due to beam effects. The accelerator grids received 0.5% of the beam power at 12 Tl/s flow. For the increased flow of 17 Tl/s, 1.1% of the power falls on the grids. Interestingly, only 0.75% is deposited on the grids for hydrogen operation at 25 Tl/s.

The total power loading is well below design limits due to good arc efficiency and low back-streaming electron power. Some components, such as the electron dump, were over designed and could have relaxed cooling requirements.

B. Durability

The durability of the plasma generator elements has been evaluated qualitatively. The power loading on the wall, the filament sandwich, and the back plate was observed to be less than the design estimates and introduced no operational limitation. Two particular operational difficulties were observed; filament and/or cathode spotting and thermal cycling of the molybdenum shields.

Spotting can damage the tungsten filaments, shortening their lifetime. Almost all the spotting occurred during the initial conditioning phase of the plasma generator. In nine months of long pulse beam testing, arc spots were rare (approximately one per thousand shot seconds) during periods of good

vacuum. Spots were common during operation with water leaks in the beam target.

Since the discharge conditioning phase is of utmost importance for the sake of filament integrity, a procedure was established for conditioning. Best conditioning was done at the lowest discharge voltage with tight control on spot duration by rapidly diverting the arc current. The inefficient mode was avoided by connecting the probe plate to the anode during the conditioning phase, or by removing the back plate magnets. Without the inefficient mode, a smooth plasma density transition can be made from low (50 to 60 V) to high arc voltage (80 to 90 V). Conditioning with careful attention to these concerns resulted in a very clean undamaged set of filaments.

The prototype molybdenum shields covering the anode-cathode interface regions and the cathode plates were 10 mils thick and suffered some curling and a few cracks during operation, probably due to thermal cycling. Although this caused no adverse effects on the source performance, a thicker shield (20 mil thick) was considered desirable. Testing with the 20 mil shield for over 200 shots of 30 sec beam at 80 kV and 40 amps also caused warping so significant that the source impedance changed slightly. However, compared to previous source operation without the shields, cathode spotting to the copper filament plates had been effectively eliminated. Two solutions are now being tried. The first is to fabricate thick (0.125 inch) stress relieved molybdenum shields. The second may be to plate the filament sandwich with plasma sprayed tungsten.

Summary

Long pulse characteristics of the $10 \times 40 \text{ cm}^2$ magnetic bucket plasma generator have been measured on the plasma generator test stand and on the

NBETF beam line. The performance goals of good plasma profile, low impurity, high species, and cathode lifetime exceeding 5 hours have been met. Testing has shown the need for arc regulation, particularly for long pulses. Regulation of the probe ion saturation current density appears to be better than regulating the arc power. Control of the beam current was within 1% during a 30 sec shot.

Plasma uniformity was measured to be within $\pm 5\%$ over $10 \times 40 \text{ cm}^2$ for deuterium operation. With hydrogen the plasma uniformity was not measured on the plasma generator test stand, but seems to have been inadequate, as suggested by the poor beam divergence. Further work will be needed to evaluate the reason for this difference.

The atomic species fraction on the beam line, as measured by OMA doppler shift spectroscopy was a few percent higher than on the plasma generator test stand with a momentum analyzer. On the beam line the atomic fraction was as high as 87%. Experience with filter bucket sources suggest that this plasma generator has some bridging flux across the filament region which produces a higher atomic fraction than other bucket plasma generators. This was demonstrated when the back plate magnets were removed and the atomic fraction decreased by 10%. Further testing with back plate magnet position changes may improve the understanding of how to ensure the high species for any scaled plasma generator, and for hydrogen operation.

With deuterium the arc stability, especially during a notch, was achieved by the use of capacitors between the probe plate and the anode or by resistive biasing of the probe plate to anode. With hydrogen the additional required anode area could only be obtained by biasing the probe plate toward anode potential in which case no capacitors were used. An equivalent method for helping to achieve stability would be to reduce the ion loss areas.

Because the back-streaming beam power was smaller than expected (about 1% compared to the design value of 6%), and because the source was efficient, the bucket wall power loading was half the design limit. Since the back plate power loading was considerably less than expected, the cooling requirements could be relaxed. The mechanical design was sufficient, or over-designed. The only area of concern is the cathode area shields which are under development.

List of Tables

Table I	Arc and filament power accountability
Table II	Back-streaming beam power accountability

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Source/ Accel Element	Deuterium/12 Tl/s	Deuterium/17 Tl/s	Hydrogen/ 25 Tl/s
SOURCE ELEMENTS			
Bucket Wall	29.4 kW (50% B.T.)	30.6 kW (50% B.T.)	35.0 kW (45% B.T.)
Electron Dump	9.3 kW (16% B.T.)	13.6 kW (22% B.T.)	11.2 kW (14% B.T.)
Filament/Probe Plate Group	20.5 kW (34% B.T.)	17.6 kW (28% B.T.)	31.7 kW (41% B.T.)
Bucket Totals ; (B.T.)	59.2 kW	61.8 kW	77.9 kW
ACCELERATOR ELEMENTS			
Grid 1	4.0 kW	2.9 kW	5.5 kW
Grid 2	2.2 kW	1.9 kW	2.7 kW
Grid 3	1.8 kW	1.7 kW	1.9 kW
Grid 4	0.7 kW	0.8 kW	0.5 kW
Accelerator Totals	8.7 kW	7.3 kW	10.6 kW
<u>TOTAL MEASURED POWER</u>	67.9 kW	69.1 kW	88.5 kW
UNMEASURED COMPONENTS			
Grid Hat (estimated)	9.7 kW	7.0 kW	13.2 kW
Accelerator Gaps (estimate)	6.0 kW	4.3 kW	8.2 kW
<u>TOTAL POWER ACCOUNTED</u>	83.6 kW	80.4 kW	109.9 kW
Total Electrical Power	90.5 kW	86.2 kW	118.8 kW

Table I

Source/ Accel Element	Deuterium/12 Tl/s	Deuterium/17 Tl/s	Hydrogen/ 25 Tl/s
SOURCE ELEMENTS			
Bucket Wall	6.9 kW	11.0 kW	17.8 kW
Electron Dump	8.4 kW	9.0 kW	16.8 kW
Filament/Probe Plate Group	11.2 kW	11.6 kW	13.3 kW
Bucket Totals ; (B.T.)	26.5 kW (0.8% B.P.)	31.6 kW (1.0% B.P.)	47.9 kW (1.1% B.P.)
ACCELERATOR ELEMENTS			
Grid 1	4.2kW	8.2 kW	9.7 kW
Grid 2	3.5 kW	7.9 kW	7.8 kW
Grid 3	2.8 kW	7.5 kW	4.6 kW
Grid 4	7.1 kW	12.0 kW	10.5 kW
Accelerator Totals	17.6 kW (0.5% B.P.)	35.6 kW (1.1% B.P.)	32.6 kW (0.75% B.P.)
<u>TOTAL MEASURED POWER</u>	43.1kW	67.2 kW	80.5 kW
Total Beam Power; (B.P.)	3.3 MW	3.3 MW	4.3 MW

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Figure 11. Beam species as measured the optical mass analyzer: Deuterium

□ 12 Tl/s

▲ 17 Tl/s

Figure 12. Plasma generator species as measured by momentum analyzer

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▲ No back plate magnets

◆ Biased probe plate

Figure 13. Comparison of momentum analyzed species from the plasma generator to the optical mass analyzed species of the beam

□ Beam species on NBETF

▲ Species on the plasma generator test stand

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XBL 852-9741

Figure 2

XBL 852-9745

Figure 3

XBL 855-2521

Figure 4

XBL 852-9749

Figure 5

Figure 6

XBB 851-502

XBL 852-9733

Figure 7

XBL 852-9742

Figure 8

XBL 852-9743

Figure 9

XBL 852-9734

Figure 10

XBL 852-9750

Figure 11

XBL 852-9735

Figure 12

XBL 852-9746

Figure 13

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