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By

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ABSTRACT

Measurements of gas utilization in a test TFTR neutral beam injector have been performed to study the feasibility of running tritium neutral beams with existing ion sources. Gas consumption is limited by the restriction of 50,000 curies of T_2 allowed on site. It was found that the gas efficiency of the present long-pulse ion sources is higher than it was with previous short-pulse sources. Gas efficiencies were studied over the range of 35-55%. At the high end of this range the neutral fraction of the beam fell below that predicted by room temperature molecular gas flow. This is consistent with observations made on the JET injectors, where it has been attributed to beam heating of the neutralizer gas and a concomitant increase in conductance. It was found that a working gas isotope exchange from H_2 to D_2 could be accomplished on the first beam shot after changing the gas supply, without any intermediate preconditioning. The mechanism believed responsible for this phenomenon is heating of the plasma generator walls by the arc and a resulting thermal desorption of all previously adsorbed and implanted gas. Finally, it was observed that an ion source conditioned to 120 kV operation could produce a beam pulse after a waiting period of fourteen hours by preceding the beam extraction with several hi-pot/filament warm-up pulses, without any gas consumption. Operation of up to six ion sources on tritium gas should be compatible with the on-site inventory established for D-T, Q=1 experiments on TFTR.

I. INTRODUCTION

Within the past year, the injection of up to 20 MW of neutral beam power into low density TFTR discharges has led to the discovery of a regime of high plasma temperatures and significant thermonuclear neutron production.¹ This regime has been achieved by the injection of deuterium neutral beams of up to 120 keV into deuterium plasmas. Scaling these results to deuterium-tritium (D-T) operation yields an energy multiplication factor (defined as thermonuclear neutron power production/neutral beam power injected) of $Q_{dt} = 0.25$. Since a significant number of these neutrons arise from beam-beam and beam-target interactions, and central tritium fueling at low density is required, the likelihood of extending this regime to D-T operation depends upon the availability of tritium neutral beams.

For safety reasons the amount of tritium allowed on the TFTR site at any time is 50,000 curies (15,000 torr-l) of which only 25,000 curies is to be out of the tritium vault. When compared to a consumption rate of several hundred curies per pulse per ion source, and with the ion sources presently operating every two and one-half minutes for conditioning and/or filament temperature maintenance, the inventory is inadequate for present operating procedures. Issues of concern for tritium neutral beam injectors include: the gas consumption rate, gas pulse width, adsorption of gas within the neutral beam injector, and compatibility with the expected neutron fluences. Experimental results are presented, based on hydrogen and deuterium operation, that determine the gas consumption rate, beam neutralization, isotope exchange rate, and conditioning scenarios.

II. EXPERIMENTAL APPARATUS

Each TFTR neutral beam injector^{2,3} is designed to accommodate three ion sources (see Figs. 1 and 2). The injector has scrapers to define beam shape, a neutralizer to convert a fraction of the extracted ion beam to neutrals, a three-gap electromagnet to separate ions from neutrals, an ion dump to accept the unneutralized charged particle power, and a calorimeter assembly consisting of three "V"-shaped calorimeters to absorb the neutral beam when not injecting into TFTR and to measure the neutral particle power. To prevent reionization of neutral particles after the magnet, the beamline is differentially pumped in three sections with a total pumping speed for deuterium of 2.5×10^6 l/s.⁴ This pumping speed is attained by lining the entire left and right sides of the 48 m³ injector box with LHe cryopanel panels that are radiation shielded with LN₂ chevrons. The first pumping chamber extends up to the magnet, the second is from the magnet to the calorimeter scraper, and the third continues to the drift duct connecting the injector to the tokamak.

Recently, the ion sources were upgraded, from 0.5 s sources,⁵ to the US common long-pulse ion sources^{6,7} rated for 70 A at 120 kV for two seconds. As part of the upgrade program the scrapers in the optical diagnostic chamber (part of the neutralizer) in front of the magnet and in front of the calorimeter assembly were modified for long-pulse operation.

Prior to operation of the long-pulse ion sources on the TFTR heating injectors, experiments were performed on the test stand in the neutral

beam test cell to qualify ion source, power system, and injector upgrades. For the test stand, a target chamber with a calorimeter is provided as a final beam stop at a point approximating the location of the plasma. This test system is better instrumented than the injectors in the TFTR test cell and operation of the long-pulse ion source here provided an opportunity to quantify source and injector operation. Diagnostics in operation on the test stand include: waterflow calorimetry on the neutralizer, scrapers, ion dumps, beamline calorimeter, and target calorimeter; beam composition measurements using Doppler-shift spectroscopy (OMA)⁸ at two locations, Rutherford backscattering, a charge exchange analyzer, and surface implantation;⁹ ion gauges were located at the rear of the main box in the first differential pumping chamber, in the drift duct, and in the target chamber. Data from these diagnostics are acquired through the TFTR CICADA system and presented to the operator, or alternatively stored for analysis at a later time.¹⁰

III. RESULTS

A. Gas Efficiency

As described above, the throughput of gas required to operate an ion source is important due to the limited supply of tritium. Gas efficiency is a parameter useful in quantifying the consumption of gas by an ion source. Here the working definition of gas efficiency is: the number of equivalent gas molecules per unit time that are transformed into beam particles divided by the throughput of gas molecules into the source. Two independent measurements of this quantity have been made. First, the equivalent throughput of gas transformed into beam particles

can be made from the extracted beam current and beam composition. The beam composition for this measurement comes from the OMA; we estimate a beam composition of 78% D^+ , 15% D_2^+ , 7% D_3^+ at the ion source, and it is relatively independent of beam voltage in the range of 90 to 100 kV.⁸ Approximately 61 A of the beam are extracted at 100 kV, implying 7.1 torr-l/s of gas in the beam. Gas throughput into the ion source is determined from calibrations of pressure rise in the beamline, with the cryopanels at room temperature, versus setting on the gas valve driver.

An independent estimate of the gas efficiency can also be obtained from the signal of the ion gauge located in the first chamber of the injector. Such a signal, corresponding to 61 A operation at 100 kV for 0.5 s, is shown in Fig. 3. The initial pressure rise occurs shortly after the gas valve is opened. Decreases in pressure are seen both when the arc is initiated in the plasma generator and when the beam is extracted. Gas efficiency can be estimated from the decrease when the beam is extracted. The pressure immediately before beam extraction is representative of the gas throughput into the source, and the pressure decrease due to extraction is representative of the rate at which incoming gas is transformed into beam particles. The latter is the case since the system is differentially pumped and the beam particles are transported to a different part of the injector and do not contribute, to first order, to the pressure in the first chamber. As the ion dump in the second differentially pumped chamber is heated by the beam, gas is desorbed and there is an increase in pressure in the first chamber. Gas is still being desorbed after the beam has turned off as can be seen by the overshoot in the pressure trace. The estimate of gas efficiency

from Fig. 3 is 64%. Table 1 shows the data from a gas scan, for 61 A, 100 kV operation over the range of 13 to 21 torr-l/s into the source.

It was found that the ion source is capable of operating over a wide range of gas efficiencies. Operation with gas efficiencies ranging from 35 to 60% have been realized with no limit found to prevent operation nearer to 100%, other than lack of gas for neutralization. This range is higher than that found for the short-pulse sources,^{5,11} which were less gas efficient and typically operated in the range of 30 to 40%.

B. Beam Neutralization

After the beam leaves the ion source it enters a close-coupled neutralizer utilizing the excess gas from the ion source as the charge exchange medium. While operation at high gas efficiency may appear desirable for tritium operation from a gas consumption point of view, if insufficient gas is provided to neutralize the beam, operation at high gas efficiency cannot be tolerated.

To study the effect of gas efficiency on beam neutralization, the ratio of neutral power to neutral plus charged particle power on the beamline calorimeter (= neutral power fraction) was measured during the gas scan shown in Table 1. Figure 4 presents the neutral power fraction versus line density for this scan. The data points are connected by a dashed line, and an estimate of the expected neutral fraction based on the measured beam composition is indicated by the solid line. Neutralizer line density, π (the integral of gas density over the length of the neutralizer), for the data points was calculated from the measured

throughput into the source and a computation of the room temperature molecular flow conductance of the neutralizer. Dimensions of the TFTR neutralizers are approximately 15 cm wide by 48 cm high by 264 cm long, with minor variations in cross section as the neutralizer is traversed. Estimates of the theoretical beam neutralization were made using the analysis of Berkner et. al.¹² Neutral power fractions were measured on successive pulses onto the beamline calorimeter with the magnet on and with the magnet off. Power deposited on the calorimeter was measured by integrating the product of the water temperature rise and waterflow rate.

As can be seen from the figure, enough gas should be present to neutralize the beam over the range of gas efficiencies scanned, but this is not observed; the difference between the expected and measured line densities is approximately a factor of three. Similar behavior was observed on the JET injectors¹³ and was modeled assuming beam heating of the neutralizer gas to temperatures of 1000 - 2000°C, such that the conductance increased significantly.¹⁴ Applying this model with reasonable parameters can account for approximately a factor of two in our line density difference.

C. Isotope Exchange

Since tritium will be in short supply, its consumption in performing an isotope exchange on up to six ion sources, whether only once or during periodic conditioning phases with deuterium, must be minimized. An experiment was performed to determine how many pulses, and of what type, are necessary to ensure repeatable operation of the source with a new

gas. The experiment was performed by switching the working gas from hydrogen to deuterium after operating with hydrogen for approximately 100 two-second pulses of up to 71 A at 105 kV. The changeover was monitored with the OMA, which is capable of resolving the unshifted H_{α} and D_{α} from the arc discharge as well as the Doppler-shifted lines from the accelerated beam particles.

Figure 5 shows the spectroscopic data integrated over the two-second beam of the first D_2 pulse. Shown are the unshifted D_{α} line, due to excitation of thermal deuterons in the neutralizer by the beam and due to excitation in the arc, as well as the Doppler-shifted lines of the three beam components. Resolution of the spectroscopic data is 0.148 Å/channel, linear to within 5% over the 500 channels of the detector. Beam extraction on the 58 A, 105 kV deuterium pulse was preceded by two filament warm-up pulses. No H_{α} light was observed on the real-time scan monitor during the time when the arc was on by itself. The small unshifted H_{α} line was observed at the time the beam was extracted. No evidence of any significant accelerated hydrogen was observed as can be seen from the expanded view of the Doppler-shifted lines in Fig. 6.

While the isotope changeover in the ion source was immediate, the changeover in the pumping system took considerably longer. This is seen in Fig. 7 where the initial base pressure corresponds to the vapor pressure of H_2 at 4.2 K, and the final pressure is a partial changeover to the vapor pressure of D_2 . Tens of pulses are necessary to build a monolayer of D_2 over the H_2 .

D. Source Conditioning

How much gas is used during neutral beam injection experiments depends greatly on the operating scenario chosen. For example, the present standard operating procedure for injecting into TFTR consists of a 150 s repetitive clock cycle, pulsing only arc and filament between injection shots. Such a mode allows the filaments, which are run emission limited, to always start a pulse at the same temperature; a necessary condition for reliable operation.

An experiment was performed on the test stand with a well-conditioned ion source that had operated up to 120 kV. The purpose of the experiment was to determine whether pulses with filament only were sufficient to maintain the filament temperature, and if so, how long could the time between extractions be stretched while maintaining reliable operation. The results of this experiment, performed in deuterium at 105 kV, 58 A, are summarized in Table 2. Reliable operation with delays of up to fourteen hours between pulses was observed with this ion source.

IV. DISCUSSION

These experiments indicate that the US common long-pulse ion source can be operated at high gas efficiency, so high that there is insufficient gas to provide nearly equilibrium neutral fractions. The reason for the under-neutralization appears to be the fact that the gas in the neutralizer is not at room temperature. A model to fit similar data on JET has been developed by Pamela.¹⁴ Other evidence of an enhanced neutralizer gas temperature is evident in our data. Hot gas exiting the

neutralizer is pumped at an increased speed due to its higher molecular velocity. Evidence for an increased pumping speed exists in the data of Table 1 where the gas efficiency as measured from the ion gauge signals is greater than that measured from the extracted beam current and measured gas throughput into the source. That is, the pressure decrease in the first chamber when beam is extracted is larger than expected from the other gas efficiency measurement. This can be explained by hot gas coming from the neutralizer. Unfortunately, the temperature of the gas exiting the neutralizer cannot be obtained from this measurement since gas molecules must make several collisions with the internal injector components before reaching the ion gauge. These accommodating collisions are known to reduce the effective temperature of the gas within an injector to less than 150°K.^{15,16} By adding more gas to the ion source and forcing it to operate at reduced gas efficiency, the gas heating effect can be overcome as seen in Fig. 4.

Short-pulse ion sources operated on TFTR never exhibited reduced neutralization. Measured neutral fractions were always in agreement with the measured beam composition and equilibrium neutral fractions. Experiments at JET show an increase in pressure in the neutralizer when beam is extracted, and this has been attributed to the rise in pressure due to heating of the neutralizer gas.¹³ Experiments at the Lawrence Berkeley Laboratory on a prototype TFTR injector with a short-pulse ion source showed a decrease in pressure in the neutralizer when beam was extracted;¹¹ consistent with observations of the pressure in the first differential pumping chamber; inconsistent with the JET results. The difference between the long- (TFTR and JET) and short-pulse ion sources

causing the onset of gas heating is deduced to be differences in gas efficiency.

It has been our experience that while the range of gas efficiencies over which the long-pulse ion sources operate includes values as low as 35%, the arcs of some sources will not operate at this level, preferring a more gas efficient mode. Experiments are planned with a separate gas feed into the center of the neutralizer, to ensure operation close to equilibrium conditions even at high gas efficiency.

Results from the isotope exchange experiment indicate that little if any working gas is retained in the plasma generator at the completion of a pulse. A similar phenomenon has been observed on the calorimeter in the target chamber.¹⁷ During the early part of a pulse, gas is implanted into a surface exposed to the plasma or beam. As the surface is heated, gas in the near-surface region is thermally desorbed. In the case of the calorimeter, the amount of gas desorbed was equal to the amount implanted, once equilibrium conditions were attained. At the end of the pulse the near-surface layer is depleted of hydrogenic gas.

This same mechanism appears to be at work in the plasma generator. A decrease in injector pressure is observed when the arc is struck; see the initial pressure drop illustrated in Fig. 3. Such behavior has been observed elsewhere.^{11,15,18} As the arc ignites, ions are implanted into the arc chamber wall driven by the plasma potential. This represents a gas sink to the system and the pressure decreases. Over the next several hundred milliseconds the plasma generator walls heat up, the

surface ceases to be a sink of energetic particles, and eventually, as the temperature rises, the gas is returned to the system. The temperature of the walls are maintained at this as yet unknown equilibrium temperature during the remainder of the arc pulse and the surface is depleted at the end of the pulse. Since no gas remains, the working gas can be changed without reconditioning the source to eliminate the former working gas.

Implications of these experiments for a tritium neutral beam on TFTR during Q_{dt} experiments is that no insurmountable obstacles are present. To minimize the gas consumption rate the source will be operated in the most gas efficient manner possible. Gas will be fed into the neutralizer to provide the necessary line density to neutralize the tritium beam. This gas will be either hydrogen or deuterium. The ion sources will be conditioned to 120 kV with deuterium working gas. Once conditioned to this level, reliable operation, on demand, should be attained by preceding each injection pulse by one or more filament-only pulses to bring the filaments to temperature. Prior to commencing injection experiments, the working gas will be changed to tritium. With such a scenario the injection of up to 18 MW of neutral tritium power should be available from two tritium injectors, within the overall experimental tritium inventory constraints.

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TABLE 1. Gas efficiency scan at fixed beam parameters of 61 A, 100 kV.

THROUGHPUT INTO SOURCE	GAS EFFICIENCY MEASURED FROM THROUGHPUT	GAS EFFICIENCY MEASURED FROM ION GAUGE
13 torr-l/s	54%	64%
15 torr-l/s	48%	59%
17 torr-l/s	42%	50%
19 torr-l/s	39%	47%
21 torr-l/s	35%	41%

TABLE 2. Sequence of beam pulses, at 105 kV, 58A, to determine if reliable operation can be achieved even with long delays between beam extractions.

- 1) Twenty two-beam shots preceded by a number of filament pulses. The number of filament pulses preceding each extraction are

1, 1, 1, 2, 2, 2, 3, 3, 3, 4, 4, 4, 4, 5, 5, 6, 6, 7, 7, 8, 9, 10

- 2) Three-beam shots, each preceded by one filament pulse only.

30-minute wait, then filament pulse and a beam pulse

one-hour wait, then a filament pulse, and a beam pulse; this shot failed after one second

150 s later this pulse was followed by a good beam pulse

- 3) After this last pulse the wait was overnight.

fourteen hours later, there were four hi-pot/filament pulses followed by a beam pulse.

FIGURE CAPTIONS

- Figure 1. Schematic plan view of the TFTR neutral beam injector test stand.
- Figure 2. Schematic elevation view of the TFTR neutral beam injector test stand.
- Figure 3. Ion gauge signal in the first differential pumping chamber for operation at 13 torr-l/s, 61 A at 100 kV for 0.5 s. Gas efficiency is 64%.
- Figure 4. Neutral power fraction versus neutralizer line density. Data points are for throughputs of 13, 15, 17, 19, and 21 torr-l/s. Solid line is a prediction based on room temperature molecular gas flow.
- Figure 5. Spectroscopic data of the first pulse with D_2 working gas following H_2 operation. Shown are the stationary D_α and H_α lines, and the Doppler-shifted D_α lines of beam components at full, half, and third energy.
- Figure 6. Expanded view of the Doppler-shifted lines of Fig. 5, indicating the absence of any accelerated hydrogen components.
- Figure 7. Ion gauge signal in the first differential pumping chamber on the first pulse with D_2 working gas following H_2 operation.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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