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By

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PDX NEUTRAL-BEAM REIONIZATION LOSSES

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ABSTRACT

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Reionization losses for 1.5 MW H⁰ and 2 MW D⁰ neutral beams injected into the PDX tokamak were studied using pressure gauges, photo-transistors, thermocouples, surface shielding, and surface sample analysis. Considerable outgassing of conventionally prepared 304SS ducts occurred during initial injections and gradually decreased with the cumulative absorption of beam power. Reionization power losses are presently about 5% in the ducts and about 12% total for a beamline including the duct. Present duct pressures are attributed primarily to gas from the ion source and neutralizer with much smaller contributions from residual wall desorption. Physical mechanisms for the observed duct outgassing are discussed.

[†] On assignment from EXXON Nuclear Co.

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INTRODUCTION

Intense hydrogen and deuterium neutral beams have been used to heat magnetically confined plasmas to high temperatures. These beams are injected into fusion devices through transition ducts which contain stray magnetic fields. Neutral beam system power losses occur as neutral particles are reionized by gas in a transition duct and are then deflected out of the beam by stray magnetic fields. Previously discussed sources of duct gas include gas from the ion source and neutralizer cell, gas desorbed from the duct walls by incident beam particles, and gas desorbed thermally due to the absorption of beam power.¹ Little is known about the detailed surface physics and control of neutral beam induced outgassing effects. There are investigations in progress at several laboratories on these duct gas sources and others that may occur as neutral beam systems are increased in power and pulse length. The understanding and control of reionization losses is important for optimizing neutral beam system power efficiencies, determining future design concepts, and reducing system costs.¹ In this work, we report the results of duct reionization studies performed during the initial 8 megawatt neutral beam heating experiments on the PDX tokamak.

EXPERIMENTAL GEOMETRY

The PDX neutral beam injection system consists of four beamlines (identified as East, South, Southwest, and Northwest) which inject H⁰ beams of up to 50 keV, 300 msec, 1.5 MW (or 2 MW D⁰) into the PDX vacuum vessel at near-perpendicular angles (9°). The PDX neutral beam reionization losses were studied using pressure gauges, photo-transistors, thermocouples, surface shielding and surface sample analysis. Figure 1 gives a partial schematic

diagram, top view, of a PDX neutral beamline and shows its principal gas-handling features. The location of the ion gauges IG1, IG2, and IG3 is shown. Photo-transistors were used to view beam induced light at the location of IG3. The transition ducts were fabricated from 0.95 cm thick commercial type 304SS and were designed to maximize gas conductance and minimize beam power absorption within the constraints imposed by the proximity of the PDX toroidal field coils. Due to these requirements, the duct geometry is not simple. The ducts are 91 cm long and have a 31 cm x 34 cm rectangular cross section at the PDX vessel port. The stray magnetic fields are predominantly vertical in this region and typically about 300 g at the duct input and greater than 1 kg at the duct output. Prior to installation, the interior surface of the main duct assembly was degreased using 500 psi steam, followed by ultrasonic cleaning with Alconox detergent and demineralized water at 65° C, and finally ultrasonic rinsing in demineralized water and air drying. The calculated H₂ conductance from the duct midpoint to the PDX vessel and to the front box of the beamline is 48 kl/sec, and the conductance between the front box and the main box is 73 kl/sec. The main box contains a 1 kl/sec turbo pump and a 270 kl/sec cryopump consisting of two LHe panels shielded by LN₂ chevrons. A typical gas load into the main box from the end of the neutralizer cell is 45 Torr-liters/sec. The pumping speed in the PDX vessel during operation is typically in the range of 200-300 kl/sec. In the absence of stray magnetic fields, the beam power absorbed in the PDX ducts due to the finite geometrical spread of the beams is 10 to 15% of the input power, depending on the ion source optics. Due to the duct shape (Fig. 1), the small beam divergence and the water cooled aperture at the duct input, this stray neutral beam power in the absence of magnetic fields is incident on an estimated $5.6 \times 10^3 \text{ cm}^2$ of duct area with power densities of $\sim 30 \text{ W/cm}^2$

yielding peak surface temperature changes of 16°C for a 200 msec pulse. In the presence of stray magnetic fields, the additional reionized fraction is estimated to be incident on $2.6 \times 10^3 \text{ cm}^2$ of duct area with power densities of $\sim 50 \text{ W/cm}^2$ yielding peak surface temperature changes of 27°C for a 200 msec pulse. After a pulse, the surfaces cool to ambient temperature in a time shorter than the time between injections.

RESULTS AND DISCUSSION

PDX neutral beam operations were initiated in 1980 using the East beamline. Considerable outgassing of the transition duct occurred initially but gradually decreased during several months of operation as the cumulative power absorbed in the duct walls increased. Typically, from 1 to 4 duct "clean-up" injections were performed, without magnetic fields present, prior to the first heating injections of a standard 10 hr run. This was done in order to minimize the introduction of duct outgassing impurities into the PDX plasma, and it was convenient to do so without the application of the PDX magnetic fields. During the initial runs with the East beamline, the increases in duct pressure during "clean-up" injections were so large as to immediately shut off the duct ion gauge ($P > 10^{-3} \text{ Torr}$). This also happened in early runs during some heating injections of sufficient power and pulse length. However, eventually the duct conditioning progressed sufficiently to allow the observation of duct pressure rises using an ion gauge. During relatively high outgassing conditions, when several "clean-up" injections were followed by a heating injection, the pressure rise during the heating injection was usually larger as reionized power was deflected onto the duct surface. In general, during runs, the pressure rises during heating injections were observed to slowly decrease as the cumulative power absorbed

in the duct increased. Under duct conditions which exhibited low outgassing, little or no distinguishable change was observed between injections with or without stray magnetic fields present, which is similar to results reported previously.¹

Figure 2 shows several oscillograms of the ion source arc current and IG1, IG2, IG3 pressure traces versus time for the East beamline. The initial duct pressure behavior (e.g. shot no. 19549, Fig. 2a, lower trace) exhibited a slow, almost linear rise with time for a 200 msec heating injection. This is similar to previously reported results for both stray field and no-field conditions which suggested a time dependent pressure contribution due to thermal desorption.¹ Figure 2b (lower trace) was recorded 29 shots later and illustrates how the duct pressure rise slowly decreased during the same run as the cumulative energy deposition in the duct increased. The duty cycle was about one shot every 300 seconds. Figure 2c, (lower trace) shows the pressure level in the duct due to the ion source and neutralizer cell when the ion source was pulsed without acceleration voltage. This pressure is about the same as the pressure levels at the beginning of the pulses shown in figures 2a and 2b prior to the turn-on of the acceleration voltage. Figure 2d (lower trace) shows how duct pressures rises during cleaner duct conditions (shot no. 25049) were relatively low and that the duct gas was primarily from the ion source and neutralizer cell, i.e., the gas pressure during the pulse was comparable to its value at the start of the pulse. Figure 2e (lower trace) shows duct pressures with relatively low outgassing for an injection (shot no. 24805) with the PDX magnetic fields in their normal operating direction, and reionized beam power impacting on the duct right wall as for the above injections. Figure 2f (lower trace) shows the substantial increases in outgassing that occurred when the PDX magnetic fields were operated in the

opposite direction on the following day (shot no. 24936) and reionized beam power was absorbed on the duct left wall. Figure 2g (lower trace) shows the duct outgassing that occurred during injections later that day (shot no. 24981) after the pulse length was increased from 100 to 200 msec. Note the change in the outgassing rate at about midpulse which suggests that a significant outgassing source was being depleted and was unable to maintain the initial fast rise in duct pressure. Figure 2h (lower trace) shows results from an injection on the following day (shot no. 25012) when the PDX magnetic fields were operated in their normal direction and reionized beam power impacted once again on the duct right wall and the duct outgassing returned to relatively low levels. Thus, as noted above, changes in duct pressure due to the presence, direction or absence of stray magnetic fields can be large or negligible depending on the duct surface conditions at the time of the measurement.

Duct pressure rises were also studied using fast photo-transistors. At fixed beam voltage and current, the visible light signal from these detectors is proportional to the duct pressure. Phenomena similar to those shown in Fig. 2 were observed. Figure 3a, upper trace, (no. 20772) shows how the South duct pressure varied for a 200 msec pulse during a run with moderately high duct outgassing conditions. The slow linear pressure rise is characteristic of a linearized exponential temperature dependence associated with thermal desorption as discussed previously.¹ There is also an indication of a small inflection point at ~ 150 msec. As the run continued, the decrease in pressure toward the end of the pulse became more pronounced (Fig. 3b, no. 20782; Fig. 3c, no. 20796) and for the next and last injection of the run (Fig. 3d, no. 20797) the pressure peaked earlier and actually increased by about 25% for about the same power, indicating an abrupt change in surface

desorption. A decrease in pressure during a pulse is characteristic of thermal desorption when the surface temperature is monotonically increasing while the concentration of absorbed gas is being depleted.²

The total duct outgassing per injection induced by the absorbed beam power was obtained from the pressure measurements (e.g., see Fig. 2) by first integrating the pressure over the injection time and multiplying by the conductance from the duct midpoint to give the total Torr-liters in the duct during the injection. The outgassing induced by the absorbed beam power was obtained from these results by subtracting the gas contribution due to the ion source and neutralizer cell. Figure 4a shows these results presented as Torr-liters of desorbed gas per kilojoule of beam power absorbed in the duct walls during each injection versus the cumulative total kilojoules absorbed over many runs. It is seen that the initially high outgassing decreased during each run and then rebounded to a high level at the beginning of the next run, but with a slow long term decrease that eventually caused the outgassing to reach relatively low levels after the cumulative absorption of about 5 megajoules in the duct surfaces. Duct pressure rises of 0.1 Torr-liters/sec/kJ were reported for PLT from results obtained both at PPPL and ORNL.¹ In the case of a 200 msec. pulse, this rate of pressure rise would produce a total gas output of 0.02 Torr-liters/kJ. Figure 4a shows that this corresponds to about the midrange of PDX East duct outgassing behavior. The outgassing shown in Fig. 4a for the runs of 25-April-80 and 5-June-80 exhibit an almost exponential decay with an average decay rate of about a factor of 2 per 500 kilojoules of absorbed energy.

Figure 4b was obtained from the same data shown in Fig. 4a but normalized to the number of desorbed particles per incident beam particle (γ). It is seen that during the time at which the measurements were made, the number of

desorbed particles per incident beam particle decreased from more than 4 to less than 1, which indicates that much of the implanted beam is absorbed. Yields for ion-desorbed gas are typically in the range of 1-10.² Kulygin and Panasenkov³ have proposed a model for reionization losses which gives the time dependence of the duct pressure rise in terms of an increasing rate of ion-desorbed particles causing an increasing rate of reionization as ionized beam is deflected onto the duct surface. Results were given for γ ranging from 1 to 4. This model cannot explain pressure rises observed in the absence of stray fields and gives pressure rises that are faster than the present and previous results.¹ However, the ion-desorption yields available in the literature² are comparable to the γ yields observed in this work, and although this model alone cannot entirely explain the observed pressure rises, the available measurements do not have sufficient sensitivity to resolve the respective contributions of thermal and particle desorption.

Experimental studies of the surface chemistry of commercial stainless steel have shown that surface cleaning for high vacuum application using suitable solvents results in a surface with a homogeneous hydrocarbon layer covering metal oxides.⁴ In a hydrogen environment, this hydrocarbon and oxide structure is gradually reduced by removal of easily desorbable components (e.g., H_2O , CH_4) leaving a stable Cr enriched oxide layer.⁴ This surface chemistry is relevant to the study of reionization losses since the physical processes of desorption, trapping, and sputtering are very dependent on surface conditions.⁴ In order to study the effect of surface conditions on duct pressure rises, the inner walls of the Northwest duct were covered with a 0.05 cm thick liner of specially processed stainless steel which was spot-welded to the duct surface every 2.5 cm. The special commercial processing⁵ consisted of mechanical polishing, followed by electropolishing,

glow discharge cleaning, and finally vacuum baking for 3 days at 600°C. The vendor⁵ found that samples prepared in this way resulted in a surface depleted in Fe and enriched in elemental Cr, with outgassing rates of less than 200 femtotorr-liters/sec/cm² after 48 hours pumping without baking. Measurements at our laboratory using sputter-Auger analysis on samples of this material (having some exposure and handling), found an oxide layer at least a factor of 5 thinner than is found on standard stainless steel surfaces, and a chromium enriched surface. Final state elemental atomic percentages were achieved at ~ 100Å. At ~ 300Å no trace amounts of O, C, or Ar (the sputter gas) were observed. Although the installation procedure probably degraded small areas of the liner surface, the duct pressure rises observed from the very first injections were negligible and comparable to those observed for the East duct during the lowest outgassing conditions (Fig. 2). There was little difference between "clean-up" and heating injections, and the gas in the duct was mostly due to the ion source and neutralizer. Although, this liner would not have sufficient thermal mass to be suitable for high power, longer pulse operation due to undesirable heating, subsequent cyclic stresses, and outgassing of the underlying original wall, these results, even with the present powers (the highest in tokamak research at this time) and pulse lengths, clearly show the importance of surface condition and chemistry in reducing reionization power losses due to duct wall desorption. The understanding and control of duct wall desorption would be aided by definitive multi-keV, hydrogen beam-surface interaction studies of surface desorption, chemistry, and structural changes at near tangential angles of incidence.

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FIGURE CAPTIONS

1. Schematic top view of a PDX neutral beamline.
2. Ion gauge pressure measurements. In all of the figures, the horizontal scale is 100 msec/division (dv), with the ion source arc current given as a time reference. The second trace is IG1, 1.7×10^{-4} T/dv, the third trace is IG2, 1.7×10^{-4} T/dv, the bottom trace is IG3, as follows: (a) and (b) 1.8×10^{-4} T/dv, (c) through (h) 9.1×10^{-5} T/dv. Horizontal scale 100 msec/dv.
3. Phototransistor signal (top trace) and ion source acceleration current (lower trace) for a 200 msec pulse width. Ignore tokamak electrical interference after pulse.
4. (a) East duct outgassing per kJ of absorbed power per injection versus the cumulative power absorbed, (b) East duct outgassing normalized to the number of desorbed particles per incident beam particle versus cumulative number of particles absorbed.

Fig. 1

81X1063

Fig. 2

81X0984

Fig. 3

Fig. 4