**Drift Tube Beam Blocking Experiments
Performed on the ORNL/PLT Neutral
Beam Line at the ORNL Medium
Energy Test Facility**

W. K. Dagenhart
C. W. Blue
H. H. Haselton
M. M. Menon
S. W. Schwenterly
W. L. Stirling
C. C. Tsai
J. H. Whealton

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FUSION ENERGY DIVISION

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ABSTRACT

The Fusion Energy Division of the Oak Ridge National Laboratory (ORNL) in cooperation with the Princeton Plasma Physics Laboratory (PPPL) designed, constructed, and tested four high power neutral beam injectors for application on the Princeton Large Torus (PLT). This system employs a modified duoPIGatron ion source which has produced ion beams with parameters up to 70 A, 45 keV, and 500 msec. Nominal extraction parameters were 60-A, 40-keV, and 300-msec pulses, simultaneously. Neutral power up to 750 kW for 100 msec was calorimetrically measured on a simulated PLT target behind a PLT-sized aperture of 20×25 cm located at 4.10 m. Initial performance of these beam lines on PLT was near these parameters. Calorimetric measurements of beam power delivered to the PLT torus with a 3.65-m beam line length and with 100-msec full power pulses indicate a 10-15% reionization loss when the beam line pulse is synchronized to the pulsed torus magnetic fields. Data taken at ORNL are presented to show that this power loss is approximately equal to that calculated on drift tube pressure measurements taken without drift tube magnetic fields.

A. INTRODUCTION

The Fusion Energy Division of ORNL in cooperation with PPPL has designed, constructed, and tested four high power neutral beam injectors (as shown in Figs. 1 and 2) for application on the PLT. This system employs a 22-cm modified duopIGatron ion source (as shown in Fig. 3) which has produced ion beams with parameters up to 70 A, 45 keV, and 500 msec. Nominal extraction parameters were 60 A at 40 keV and for 300-msec pulses simultaneously. Neutral power up to 750 kW for 100 msec was calorimetrically measured on a simulated PLT target behind a PLT-sized aperture of 20×25 cm located at 4.10 m. Initial performance of these beam lines on PLT was near these parameters. The injection solid angle simulated on the Medium Energy Test Facility (METF) is $\sim 20\%$ smaller than the injection solid angle on PLT.

B. EXPERIMENTAL SETUP

Figure 4 shows the location of the ion source main vacuum tank, drift tube, drift tube ionization gages, residual gas analyzer (RGA), and photomultiplier detector. Veeco RG-75 tube vacuum gages and a Varian nude gage were used. The RGA is a Veeco SPI-10 unit. A Baratron capacitance manometer gage was also used for absolute gage comparisons. Some difficulty was experienced in getting a good calibration for Varian nude gage, a fact that we still do not fully understand. With our best calibration effort we used gage factors of 2.5 for H_2 for the RG-75 and 1.0 for the Varian, which made both agree with the capacitance manometer. The ion gage controller and tube time constants are < 20 msec. The Baratron and tubing connection time constant was measured with a dc gas pulse to be < 100 msec.

An attempt was made to use the RGA to measure the gas spectrum during the beam pulse, but the resolution badly deteriorated when the scan speed was faster than 0.5 sec. This forced us to tune in on each gas peak in a nonscan mode and measure the RGA output of that peak as a function of time during and after the pulse. We have not had time to check the time response in this mode, but it has permitted us to eliminate certain gases from the desorption spectrum.

A photomultiplier tube with 6563-Å pass filter was mounted on the Pyrex window in the drift tube. The output was read on a scope assuming that the H_{α} light was proportional to $I \times n$, where I is the beam current and n is the H_2 gas density in the drift tube directly in front of the photomultiplier tube. All data were taken in a nonsaturating mode.

C. EXPERIMENTAL RESULTS

C.1 GAS VALVE SYSTEM AND GAGE TIME CONSTANTS

Gas is fed to the source with pulser controlled Veeco PV-10 piezo-electric gas valves whose specifications are 2 msec from full close to full open and vice versa. This gas is fed from a pressure regulated line through a 1-l surge tank on the source through 1.3-cm-diam lines into the source. Figure 5 shows the time response of the drift tube nude gage and vacuum system to a long gas pulse from the source with no arc.

Figure 5 shows that the gas feed is essentially constant after <100 msec and that pressure variations measured for longer pulses exist and are probably due to outgassing rather than the gas feed system.

Figure 6 shows the time response of the Baratron (from an earlier hookup) to an incremental increase in the gas flow. The inferred time constant of the Baratron and gas feed systems is ~ 300 msec. The time constant of the drift tube is ~ 5 msec and of the drift tube ionization gages is ~ 20 msec. A reconnection later reduced the Baratron system response to <100 msec.

C.2 ION SOURCE AND BEAM SIGNALS

Figure 7 shows typical arc plasma and extraction signals for the 22-cm modified ORNL duoPIGatron ion source being used on PLT for a 30-kV, 40-A, 300-msec pulse. These same shapes are obtained for 40-kV, 60-A operation. The top trace of Fig. 7a shows the arc voltage; the second shows the gas cell pressure; the third shows the arc plasma density, and the bottom trace shows the total arc current. Figure 7b shows the accel voltage on the top trace (0 at the bottom, 5 kV/cm or 30 kV) and the

total accel current on the bottom trace (10 A/cm or 40 A). The leading edge of the accel current trace can be squared up by a slight increase in the gas flow to the primary intermediate electrode gas discharge. The ~10-kV higher accel voltage on the leading edge results from the fact that the high voltage is currently turned on before the arc.

C.3 BEAM-OFF, BEAM-ON PRESSURE SIGNALS AT 30 kV, 40 A, and 300 msec

Figure 8a shows the ion gage and H_{α} light signals obtained with an arc pulse but no extraction. The top trace is the inverted pressure trace from the main ion source tank RG-75 ion gage (10^{-4} T/cm); the middle trace is the drift tube nude gage connected to the drift tube by a right angle bend and 15 cm of 3.5-cm-diam stainless steel tubing, and the bottom trace is the output from the photomultiplier tube, which is zero because the beam is off. Figure 8b shows these same transducer traces with the beam on. The magnitude of the ion source tank pressure is slightly decreased at the first due to beam pumping and the slope is slightly greater, indicating some outgassing from the ion beam dumps. The initial magnitude of the drift tube signal is the same as that from the ion source tank but with a greatly increased rate of rise, indicating substantial H_2 recycling from the drift tube walls. The photomultiplier signal shows a similar large ramp in the pressure because the beam current is approximately constant.

C.4 HYDROGEN LIGHT OUTPUT FOR DIFFERENT PRESSURE CONDITIONS

Figure 9 shows the inverted H_{α} light signals from the drift tube for 43-kV, 61-A, and 100-msec pulses. Figure 9a depicts a situation where the drift tube calorimeter is opened and Fig. 9b depicts the situation for closed calorimeter. Since the pumping speed from the light pickup area is approximately cut in half with the calorimeter closed, the initial signal is doubled. Also 100% of the beam is now recycling H_2 from the calorimeter so that the pressure slope is much larger. Unfortunately we have no long pulse pictures with the calorimeter closed to see where the pressure rise from recycling would saturate.

C.5 PLASMA PICKUP OF NUDE GAGE

Figure 10 shows a set of pressure signals similar to those in Fig. 8 except that the filament was turned off of the drift tube nude gage and all other nude gage voltages were left on. One notices a slight pickup from beam plasma penetration to the nude gage as shown by the middle trace and that it is rising linearly.

C.6 DRIFT TUBE PRESSURE VS DEFINING PLATE OPENING AND DRIFT TUBE HEATING

Figures 11-14 show a series of pressure signal traces for the same condition as in Sect. C.3 except that the defining plate aperture opening at the entrance to the drift tube varied. Figure 11a shows arc pulse pressure signals with the beam off for the same conditions used for a 30-kV, 40-A, 300-msec beam and with a 17- x 17-cm aperture. Figure 11b is taken with the beam on. Figure 12a is taken with the aperture opened to 19 x 19 cm for the first shot after a 5-min cooldown, and 12b is ten shots later (one shot/20 sec). Figure 13a shows the first shot for these same conditions after a 3.5-min cooldown. One notices that there is a slight rise in the peak and initial pressures after ten shots, indicating a possible heating effect. Figure 13b shows the pressure pulse after three pulses for the aperture opened to 22 x 22 cm, and Fig. 14a shows 20 pulses later. Figure 14a shows a peak pressure which is very slightly lower than that of Fig. 13b. Again, Fig. 14b is with the beam off but with a 22- x 22-cm aperture opening. The pressure pulses of Fig. 14b are approximately the same as those of Fig. 11a even though the defining plates have been opened from 17 x 17 cm to 22 x 22 cm. The nude gage signal rise does not change very much with aperture opening, whereas the H_{α} light signal rise is four times as great. Wider openings move the beam driven gas recycling source much closer to the phototube pickup as the aperture is opened. Apparently the line density, $\langle nL \rangle$, is increasing with wider apertures.

C.7 PRESSURE SIGNALS VS BEAM CURRENT

Figures 15-17 are taken with the same conditions as in Sect. C.3 with a 30-kV, 40-A, 500-msec beam every 20 sec. Different beam currents are obtained by varying the arc current with no change in gas flows. Figure 15a depicts a situation where the beam is off, Fig. 15b represents a 15-A beam on, Fig. 16a represents a 20-A beam on, Fig. 16b represents a 30-A beam on, and Fig. 17a represents a 40-A beam. Figure 17b shows the pressure response with an accel voltage inhibit (turnoff) ~ 340 msec into the pulse with the arc (and gas) turning off at ~ 500 msec. We see first that the pressures measured by both the drift tube ion gage and H_{α} photopickup increased linearly with time during a pulse, and strongly increased with increasing current at constant voltage. Near the end of the 500-msec pulses the H_{α} signal shows some signs of leveling off, whereas the ion gage does not. One would expect larger pressure rises due to increased beam impingement on the drift tube walls as the beam perveance is varied away from optimum.

C.8 BARATRON CAPACITANCE MANOMETER MEASUREMENT OF DRIFT TUBE PRESSURE

A Baratron capacitance manometer was connected to the same point of the drift tube as the ion gages to provide an independent gage calibration and to determine the amount of plasma influence on the ion gage readings. Figure 18 shows the pressure response of the Baratron with the drift tube calorimeter closed. The source-on, beam-off case is indicated on the bottom trace, and the beam-on case is indicated on the top trace. Thus the beam is seen to cause a doubling of the drift tube pressure for this case where the Baratron responds to the 25-kV, 35-A, 500-msec pulse. The Baratron response to a gas incremental increase (ion gage response flattens out to this gas input in ~ 75 msec) is ~ 400 msec for this setup.

The Baratron was reconnected, resulting in a response of < 100 msec to equilibrium, as shown in Fig. 19a. Figure 19b shows the Baratron drift tube measurement of a 100-msec pulse (1×10^4 T/cm) on the bottom trace, the RG-75 Veeco tube response on the middle trace (1×10^4 T/cm),

and the nude gage response on the top trace (0.4×10^{-4} T/cm). These pictures show that the gages all roughly agree at this point and should have adequate response for >100-msec pulses.

C.9 EFFECT OF USING THE DRIFT TUBE CRYOPUMP

The drift tube cryocondensation pump has a speed of $\sim 20,000$ l/sec, and its effect on the drift tube pressure was measured earlier with ORNL/PLT beam line #1. Pressure measurements were made with the drift tube pump at ambient temperature. The drift tube pump was then cooled (while the same beam conditions were maintained) with the result that the peak drift tube pressures as measured by the ion gage were reduced to $\sim 70\%$ of their former value.

C.10 DRIFT TUBE GAS SPECIES

A Veeco SPI-10 residual gas analyzer was used to measure the drift tube gas species during beam pulsing. Scans made under static conditions indicate the major constituents are H_2 , OH, H_2O , N_2 , and O_2 . With the RGA tuned to a different one of these peaks on each successive shot, the only one which showed any substantial increase during a pulse was the H_2 peak.

D. ANALYSIS OF THE DATA

A drift tube reionization loss calculation was made from pressure measurements made at ORNL of the drift tube reionization losses to be expected. The calculation assumed no H_2 recycling caused by reionized particles hitting the drift tube walls, a 39-kV, 60-A, 100-msec beam pulse, beam defining plates all the way in (15- x 15-cm opening), and an $\sim 95\%$ equilibrium gas cell. These are similar to the actual beam conditions used during PLT injection. The integrated reionization loss for the whole beam pulse is calculated to be 10% for 100-msec pulses. The calorimetrically measured value on PLT with the torus fields on is 10-15%.

A similar calculation made for a 300-msec pulse, again using ORNL measured pressures, predicted 15-20% reionization losses on PLT. The drift tube pump should reduce this peak pressure to about 70% of its former value, resulting in a predicted loss of ~16%. Thus the drift pump would reduce the 300-msec full power predicted reionization loss from 20% to 16%.

Experimental observations at ORNL indicate that the stainless steel drift tube walls could adsorb up to $3.5 \pm 1.5 \times 10^{16}$ molecules/cm² and so would provide a bountiful supply of gas. This could be reduced to 1×10^{15} molecules/cm² by gold plating, but the plating would soon be covered again by sputtered copper or other beam line materials. It appears that a significant fraction of the recycled H₂ gas is caused by direct beam impingement on the walls from beamlet ion distribution tails because about two-thirds of the beam line is directly in line of beamlet tails even with the defining plates closed. With them open (25 × 25 cm) the entire drift tube is within line of sight of the outermost beamlet tails. Further measurements are needed to ascertain how much recycling can be ascribed to beam plasma and photo desorption.

A more detailed analysis was made by Riviere and Sheffield¹ and amended by Hemsworth,² in which the steady-state solution was found to the nonlinear transcendental equation for the evolution of ambient neutral gas in the drift tube. In addition, a solution was found to a linearized differential equation for the time evolution of the ambient neutral gas (linearized by assuming small reionization). The nonlinear steady-state analysis was extended to include a source term due to direct beam interception on the drift tube wall.³ This analysis was put in terms of the properties of the beamlets by previous analysis for Gaussian⁴ or Lorentzian⁵ beamlet distributions accounting for steering.^{6,7} The beamlet distribution appears to lie somewhere between Gaussian and Lorentzian.⁸⁻¹⁰

A principal difference between this analysis¹⁻³ and that in the previous paragraphs is that it attempts to explain the buildup of gas due to desorption from the walls. A parameter, called the desorption coefficient, γ , is defined to be the number of neutral gas molecules

desorbed per incident ion. The specification of numerical values of this parameter is outside of the domain of the analysis,¹⁻³ and the experimental results are consistent with the analysis only for suitably chosen values and functional dependence.

An illustrative computation of the dependence of the steady-state transmission efficiency through the drift tube is shown in Fig. 20 for Gaussian beamlets perfectly focused to the downstream end of the drift tube. All of the beam not transmitted due to finite divergence is assumed to hit the drift tube wall. The effect of various values of the desorption coefficient is also shown. An illustration of the sensitivity of the results in Fig. 20 to perfect focusing (at $z = z_p$) and beamlet distribution is shown in Fig. 21, where the fraction of beam not transmitted due to finite divergence is plotted vs $1/e$ beamlet divergence angle.

Many mechanisms of desorption are possible besides a reionized beam bent by a magnetic field^{1,2} or direct beam interception.³ Among these are: 1) photon induced desorption; 2) slow ion collision with the drift tube wall, where the slow ions are generated in the plasma formed in the drift tube and accelerate to the wall through a sheath; 3) multiple desorption, where a fast neutral desorbed by a high energy ion collides again with another part of the drift tube wall and desorbs yet more gas. This could be expressed mathematically by making γ geometry dependent.

An experimental finding which at first sight appears at variance with the analysis of Ref. 1 is the slow rise of the gas pressure. The transient analysis of Ref. 1 shows that for constant γ , a steady state should be reached on a time scale of the order of milliseconds. However, the observations suggest a time scale whose lower bound is on the order of seconds. A reasonable explanation for these findings in terms of the analysis is to suppose that γ is a sharply varying function of the wall temperature. The wall temperature is the only quantity whose time scale is so long.

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Fig. 2. ORNL/PLT Beam Line and ORNL Test Facility target box.

Fig. 3. ORNL 22-cm modified duoPIGatron ion source.

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Fig. 4. Location drawing for pressure transducers, residual gas analyzer, and H_{α} light photomultiplier tube on drift tube.

Fig. 5. Time response of the drift tube nude gage and beam line to a 700-msec long gas pulse from the source (1×10^{-4} T).

Fig. 6. Time response of the Baratron capacitance manometer and beam line to a step increase in the source gas flow (tailoff due to a slow reference pressure rise).

Fig. 7a. Ion source signals for a 30-kV, 40-A, 300-msec pulse used for all the drift tube pressure measurements.

Fig. 7b. Extracted beam signals for a 30-kV, 40-A, 300-msec pulse used for all the drift tube pressure measurements.

Fig. 8a. Beam off drift tube pressure signals for the 30-kV, 40-A, 300-msec pulse.

Tank pressure 1×10^{-4}
T/cm

Drift tube pressure
 1×10^{-4} T/cm

Photomultiplier signal
from drift tube
light

Fig. 8b. Beam on drift tube pressure signals for the 30-kV, 40-A, 300-msec pulse.

Fig. 9a. Hydrogen light signal (6563 Å) for a 43-kV, 61-A, 100-msec pulse with the drift tube calorimeter opened.

Fig. 9b. Hydrogen light signal (6563 Å) for a 43-kV, 61-A, 100-msec pulse with the drift tube calorimeter closed.

Fig. 10. Drift tube nude gage plasma pickup nude gage filament off (all electrode voltage on) for a 30-kV, 40-A, 500-msec beam as shown in the middle trace.

Fig. 11a. Drift tube pressure rise for a 17- × 17-cm defining plate opening, beam off.

Fig. 11b. Drift tube pressure rise for a 17- × 17-cm defining plate opening, 30-kV, 40-A, 300-msec beam on.

Fig. 12a. Drift tube pressure rise for a 19- x 19-cm defining plate opening, first 30-kV, 40-A, 300-msec beam shot after >5-min cooldown.

Fig. 12b. Drift tube pressure rise for a 19- x 19-cm defining plate opening, first 30-kV, 40-A, 300-msec beam shot after 10 successive beam shots.

Fig. 13a. Drift tube pressure rise for a 19- x 19-cm defining plate opening, for the first shot after a 3-1/2-min cooldown.

Fig. 13b. Drift tube pressure rise for a 22- x 22-cm defining plate opening, third pulse after >5-min cooldown.

Fig. 14a. Drift tube pressure rise for a 22- x 22-cm defining plate opening, 20 consecutive shots.

Fig. 14b. Drift tube pressure rise for a 22- x 22-cm defining plate opening, where the beam is off, source on.

Fig. 15a. Drift tube pressure rise for a 19- x 19-cm defining plate opening, for an arc pulse to supply a 30-kV, 40-A, 500-msec beam pulse, beam off.

Fig. 15b. Same conditions as 15a except arc lowered to supply a 15-A beam, no gas supply change, beam on.

Fig. 16a. Same conditions as 15b except arc changed to supply a 20-A beam.

Fig. 16b. Same conditions as 15b except arc changed to supply a 30-A beam.

Fig. 17a. Same conditions as 15b except arc changed to supply a 40-A beam.

Fig. 17b. Same as 17a except that a high voltage inhibit occurred 340-msec into the pulse with the arc and gas turning off at 500 msec.

Pressure signal with and
without beam, calorimeter
closed, 25-kV, 35-A, 500-
msec pulse.

Fig. 18. Baratron capacitance manometer measurement of the drift tube pressure rise for an earlier hookup with a time response < 400 msec. Beam off lower trace, beam on upper trace.

Fig. 19a. Time response of the drift tube Baratron capacitance manometer and vacuum system to a step increase in gas flow with new connections, $\tau < 100$ msec.

Fig. 19b. Drift tube pressure signals from the nude gage (top trace, 0.4×10^{-4} T/cm), Veeco RG-75 ion gage (middle trace, 1.0×10^{-4} T/cm), and Baratron capacitance manometer (1×10^{-4} T/cm).

Fig. 20. Steady-state transmission efficiency through the gas cell vs the effective angular divergence (1/e width at half maximum).

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Fig. 21. Fraction of the beam not transmitted to the target vs the beamlet divergence angle.

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