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REIONIZATION LOSSES

BY

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NEUTRAL BEAM SYSTEM REIONIZATION LOSSES

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ABSTRACT

A slow, linear pressure rise in the drift ducts of the PLT neutral beam systems, and the resulting reionization losses of neutral beam power, are reported and examined. A model is developed for the reionization losses, based on the observed test stand pressure rise and an additional pressure rise due to the reionized power.

Agreement between the model and the observed reionization losses is shown. Predictions are made of future reionization losses for the neutral beam injectors of PLT, PDX, Doublet III and TFTR. Finally, suggestions are made for research and development program directions and for machine design directions which could decrease neutral beam reionization losses.

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1. Introduction

Early in the testing phase of the PLT neutral beam injectors at ORNL, an unexpectedly high pressure was observed in the drift duct region during the beam-on time. This was recognized as a problem because in traversing the region of high pressure, a fraction of the neutral beam is reionized, and in the presence of the tokamak magnetic fields, this fraction is deflected and is lost power.

The possibility of high duct pressure and reionization losses in neutral beam systems had been predicted in an analysis by Riviere and Sheffield,¹ later modified by Hemsworth.² Their model is based on direct knock-off of gas from the wall by beam particles. This process, and the resulting duct pressure, reaches equilibrium with a time constant of about the duct-pumpout time, typically $\sim 10^{-3}$ sec.¹

In contrast, the duct-pressure observed during testing of the PLT beam systems increases linearly with time for at least 500 msec.³ This implies strongly that thermal desorption, as opposed to direct knock-off by the beam, is occurring. In the present analysis, a model for neutral beam reionization losses, based on the observed linear pressure rise, is developed. The model is shown to predict PLT beam reionization losses which agree, in magnitude and in time dependence, with the observed losses. It also predicts a gas flux to PLT which appears to correlate with observed plasma density increases during injection.

Section 5 of this report applies the model to predict beam

reionization losses for PDX, Doublet III, TFTR, and future operation of PLT. It is shown that these losses could be significant. Section 6 suggests research and development program directions and machine design directions which could significantly decrease such neutral beam system reionization losses.

2. Observations

2.1 Drift Duct Pressure Rise

Observations of the linear rise with time of pressure in the PLT beamline drift duct have been made at ORNL³ and PPPL.⁴ The geometry of the predominantly stainless steel duct is indicated in Fig. 1. The calculated conductance for gas coming from the main cryopump box to PLT is $\sim 4 \times 10^3$ l/sec, and for gas generated in the middle of the duct and escaping in either direction is 17×10^3 l/sec. The pressure rise as measured on the PPPL beam test stand is shown as the "Not Gettered" and "Accel On" data of Fig. 2.⁴ The "No Accel" data is acquired when the system is operated normally, including all gas inputs and arc plasma, except that no acceleration voltage is applied. It can be seen that the presence of the beam in the duct substantially affects the magnitude and time history of the duct pressure.

Besides the linear increase with time, it is found that the slope of the pressure increase varies linearly with beam power.³ Linearity with time and power can then be combined into one statement: linearity with energy (joules). The time constant of this "linearity" is at least seconds, longer than any system time constants except thermal time constants, so the conclusion is that the pressure increase is a thermal outgassing of the duct

walls by stray beam power.

In the present operation of the PLT beam systems without the tokamak magnetic fields, the drift duct walls are observed to intercept about 30% of the neutral power passing through. Combining this with pressure rise data from either ORNL or PPL and with the calculated duct conductance yields a value of 0.1 torr·l/sec/kJ for the observed pressure rise.

It is observed, somewhat surprisingly, that this value of 0.1 torr·l/sec/kJ, hereafter referred to as the gas evolution coefficient, C , is independent of the beam pulse repetition rate and the number of preceeding beam pulses. Physical mechanisms which might account for the linearity, for the long time constant, for the independence from repetition rate and history, and for the observed magnitude are being considered. For the purposes of the remainder of this report, 0.1 torr·l/sec/kJ can be considered an empirical fact.

2.2 Beam Power Attenuation

The anticipated neutral beam power attenuation, in the presence of the magnetic fields, is observed on PLT. Figure 1 shows the power transmitted to a calorimeter inside the tokamak as a function of the ion beam perveance. The transmitted power is normalized by dividing by the ion beam power and by the equilibrium neutralization fraction. Figure 3 is a compilation of all data, on the PLT east beamline, for 100 msec pulse length, H^0 beam, and the source running in the high-impedance mode. These conditions were chosen for this study because, although the optics

and hence beam transmission is not optimized, it is at present the only set of conditions for which there is sufficient data to provide a reliable data base.

The comparison in Figure 3, of the data in the absence of the magnetic field with the data in the presence of the field, clearly shows the power decrease. Ion source characteristics do not appear to change significantly in the two cases, so the power loss is attributed to the expected reionization losses.

An increase in losses with an increase in beam joules is indicated in Figure 4, which shows the normalized transmitted power as a function of the ion beam joules, IVt , times the equilibrium neutral fraction, f_0^m . $IVt f_0^m$ should be proportional to the neutral power going through the duct. The data as presented in Figure 4 have been normalized to the optimum performance value of Figure 3, in order that all of the Figure 3 data could be used and in order that longer pulse length data could be added. Each point accompanied by error bars in Figure 4 represents at least 10 observations, while the two points without error bars are individual observations.

If the pressure rises observed on the test stands are used to predict the reionization losses, the predicted losses are less than the losses shown in Figure 4, and this discrepancy increases with $IVt f_0^m$. The discrepancy is removed by considering an additional pressure rise, over that observed on the test stand, due to the additional wall heating and therefore the additional outgassing by the reionized power.

3. Model

Losses in the drift duct are assumed to be due to simple beam attenuation:

$$P = P_0 \exp(-\alpha n l) ,$$

where P_0 is the power which would have reached the plasma in the absence of reionization losses, α is the ionization cross section, and n is the line density in the duct. In accordance with the FLT observations, the line density must be calculated self-consistently as due in part to the reionized power, and is given by:

$$n l = \langle n l \rangle_0 + \langle n l \rangle_\theta + \langle n l \rangle_R ,$$

where $\langle n l \rangle_0$ is the line density in the absence of duct heating, $\langle n l \rangle_\theta$ is the line density due to direct interception of the beam power by the duct walls, and $\langle n l \rangle_R$ is the line density due to wall heating by the reionized power.

In the calculations, it is assumed that:

$$n l = (n_0 + n_\theta + n_R) l ,$$

where l is taken as the geometrical duct length and n_0 is the density in the absence of duct heating. n_θ is the density due to wall heating by directly intercepted power:

$$n_\theta = \frac{C}{F} \epsilon P_0 t ,$$

in accordance with test stand observations, where C is the gas

evolution coefficient of section 2.1, F is the pumping speed for gas generated within the duct, α is the fraction of the power passing through the duct which is directly intercepted by the duct walls, and t is the time the beam has been on. n_R is the density due to wall heating by the reionized power:

$$n_R = \frac{C}{F} (P_0 - P) t .$$

Design work and injected power predictions traditionally use the above model with $n_0 = n_R = 0$.

In the calculations for the PDX neutral beam system in Section 5.2, the effect of a final pumping stage was included in the above model by allowing reionization losses in this stage, with the pressure term including half of the time-dependent gas flux from the drift duct. The other half of the flux is assumed to go to the tokamak, and on most tokamaks such a flux should significantly perturb the plasma density.

4. PLT Fit

4.1 Reionization Losses

Figure 5 presents the data of Figure 4 (with the No Magnetic Field data replaced by a line at the mean value) along with the predictions of the model, using the PLT data base explained in Section 2.2. The predicted power has been time averaged to simulate calorimeter data. The gas evolution coefficient, C , was treated as a parameter. It can be seen that the value $C = 0.1 \text{ torr}\cdot\text{l/sec/kJ}$ inferred from the test stand pressure rise data provides for good agreement between the PLT power loss data

and the model.

4.2 Tokamak Plasma Density Increase

Figure 6 shows some data (the points with error bars) on the increase in the PLT plasma density during injection as a function of the injected neutral power.⁵ Also shown is the predicted density rise for a 450 kW, 35 keV neutral beam if the density increase was due to ionization of the beam neutrals only and the predicted rise if the density increase was due to ionization of both beam neutrals and half of the neutrals generated in the duct according to the above model (the remaining half of the neutrals are assumed to go to the beam cryopump). It is concluded that the model predicts a gas flux to PLT which appears to correlate with the observed plasma density increase.

5. Implications

5.1 PLT

Figure 7 shows the predicted neutral kW to PLT, per beamline, as a function of the time the beam has been on. The curve labeled "Initial Operation of East Beamline" is obtained using data from the initial operation of the PLT east beamline (see Section 2.2) applied to a 60 kV, 40 A extracted ion beam. It can be seen that severe attenuation of the beam can be expected with 0.3 sec pulses.

Some improvement is expected due to optimization of the existing systems. More significantly, optics work at ORNL⁶ will be applied to the PLT injectors to increase beam transmission, with the predicted power given in the Figure 7 curve labeled "Add ORNL Precel Optics." The improved transmission is apparent

at beam turnon. Even though the averaged power will increase significantly, the instantaneous power at 300 msec is lower because of the increased duct wall heating occurring as more power is forced through the duct.

A partial coating of titanium decreased the pressure rise as shown in Figure 2.⁴ The effect of the partial coating on the predicted neutral power is illustrated by the curve labeled "Precel + 18% Reduction in Outgassing." This coating procedure is to be applied to the PLT systems and is expected to be more effective because more of the outgassing surface will be coated. The predicted power for a 50% effective coating and a 90% effective coating is shown in Figure 2. The curve for a 50% coating can also be interpreted as due to the addition of 17×10^3 l/sec of duct pumping with no wall coating. The duct has been designed to accept a 20×10^3 l/sec cryopump.⁷

5.2 PDX

The PDX neutral beam units⁸ will be modified PLT designs with an additional pumping stage added between the drift duct and the primary beam cryopump. Figures 8 and 9 show the predicted neutral power per beamline as a function of t , using as a data base the data from the PLT units and the ORNL precel optics⁶ data. The drift duct design has a length of 79 cm and a calculated conductance of 70×10^3 l/sec for gas generated within. Figure 8 assumes 5% of the power going through the duct is directly intercepted ($f = 0.05$) and shows as a parameter the speed of the additional pump. The design goal for the pump is

$\sim 2 \times 10^5$ l/sec, which is assumed in Figure 9. The parameter of Figure 9 is the fractional direct interception, β . Extrapolating the PLT beam system data indicates an $\beta \approx 0.05$ for PDX.

5.3 Doublet III

In early designs of the Doublet III beam system,⁹ tangential injection was attempted. The resulting duct had a length of ~ 105 cm and a conductance of $\sim 28 \times 10^3$ l/sec for gas generated within the duct. Figure 10 shows the predicted neutral power to Doublet III per beamline, assuming the desired 3.6 MW of neutral power entered the duct and assuming the gas evolution constant obtained from PLT beam system operation. It can be seen that the model predicts choking at ~ 0.1 sec, and almost no power transmitted by the end of the desired 0.5 sec pulse. The point on the curve indicated by "Maximum Observed Linear Buildup" is approximately the point where the model predicts that the total amount of gas evolved per unit surface area of duct is equal to the maximum observed during PLT beam system operation. So although there has been no indication that the gas will not continue to come off with a rate given by the evolution coefficient, C , no observations at larger values of atoms/cm² of duct surface have yet been made.

The present Doublet III beam system design¹⁰ is for near-perpendicular injection and has a substantially improved duct. The effective length has been halved while the conductance has been increased by a factor of four. Figure 11 shows the predicted neutral power transmitted for this design, out to one

second, a pulse length considered desirable, but twice the design specification. The fractional directly intercepted power, ϵ , is shown as a parameter; the design value is $\epsilon = 0$.

5.4 TFTR

The TFTR duct will have an effective length of ~ 2.5 m and a conductance of ~ 150 kl/sec¹¹ for deuterium leaving the duct. The predicted neutral power to TFTR per beamline is shown in Figures 12 and 13, in which it is assumed that the desired 8 MW enters the duct and that the evolved gas is hydrogen. In Figure 12, the neutral power transmitted is displayed for the evolution coefficient determined on the PLT units, with the directly intercepted beam fraction shown as a parameter. The directly intercepted fraction is expected to be ~ 0.01 , and this value is used in Figure 13, where the gas evolution coefficient is shown as a parameter. In Figure 13, the neutral power transmitted is shown out to 1 sec, which, although a desirable pulse length, is twice the present design specification. The extent of maximum observed linear buildup, as described in Section 5.3, is indicated in both of the figures. It can be seen that the TFTR system must be considered at best marginal, especially in view of the uncertainties in the model and in the experimentally derived coefficients.

6. Summary and Conclusions

An examination of the equation for reionization losses and of the experimentally-based equations for drift duct pressure rise (see Section 3), and a small argument expansion of the

exponential, yields a "trouble parameter," $\ell t P_0 / F$, by which neutral beam systems can be classified with respect to potential reionization loss problems. In the trouble parameter, ℓ is the duct length, t is the beam pulse length, P_0 is the desired transmitted neutral power, and F is the conductance for gas escaping the duct after being generated inside. Table I presents this parameter, in units of joule-sec/cm², for various beam systems. Initial performance of the PLT systems indicate that they are at best marginal with respect to reionization losses, so one should worry about the TFTR beam system. It is more-than-coincidence that the two safest systems, present Doublet III and present PDX, are also the two systems which were designed after the difficulties on the PLT systems were encountered.

As the trouble parameter indicates, potential reionization loss problems can be significantly reduced by redesigning ducts to be shorter and to have a higher conductance. This has been done for Doublet III and PDX, as indicated by Table I. Unfortunately, redesign of the TFTR drift ducts would be very painful at this point in the program. Another and probably more effective way of decreasing reionization losses is to decrease the gas evolution rate by using wall materials other than untreated stainless steel or by using wall coatings. An initial attempt and some initial success with a titanium coating is indicated in Figure 2 and described in Reference 4. Tests of a water-cooled copper duct liner are being done on the ISX beamline mockup at ORNL.

As a final point, it should be stressed that neutral beam development and test facilities should be equipped with the capability to simulate the tokamak magnetic fields in the drift duct region, so that the extent of the reionization losses and the effectiveness of countermeasures can be determined. PDX, Doublet III, and TFTR designs have small, directly intercepted power fractions, so on the test facilities there will be essentially no duct heating, therefore no duct pressure rise, and therefore no experimental confirmation of the success of the design, unless the tokamak stray fields are simulated.

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TABLE 1

Neutral Beam Injector	Trouble Parameter, $t_{\text{F}0}/F$, joule.sec/cm ²
Present Doublet III	0.7
Present PDX	0.8
Initial PDX	1.5
PLT	2.7
TFTR	4.8
Initial Doublet III	6.8

FIGURE CAPTIONS

Figure 1. PLT Neutral Beam Drift Duct Schematic. Dimensions are in cm.

Figure 2. PLT Beamline Drift Duct Pressure.

Figure 3. PLT Beam Transmission as a function of Perveance.

Figure 4. PLT Beam Transmission as a function of IVt_0^2 .

Figure 5. Measured PLT Beam Transmission Compared with Transmission Predicted by Reionization Loss Model.

Figure 6. Measured and Predicted PLT Plasma Electron Density Increase as a function of Injected Neutral Beam Power.

Figure 7. Predicted PLT Injected Neutral Power.

Figure 8. Predicted PDX Injected Neutral Power with Final Stage Pumping Speed as a Parameter.

Figure 9. Predicted PDX Injected Neutral Power with Directly Intercepted Power as a Parameter.

Figure 10. Predicted Doublet III Injected Neutral Power for the Early Duct Design.

Figure 11. Predicted Doublet III Injected Neutral Power for the Present Duct Design.

Figure 12. Predicted TFTR Injected Neutral Power with Directly Intercepted Power as a Parameter.

Figure 13. Predicted TFTR Injected Neutral Power with Gas Evolution Coefficient as a Parameter.

Fig. 1. 783632

Fig. 2. 783320

Fig. 3. 783441

Fig. 4. 783638

Fig. 5. 783639

Fig. 6. 783633

Fig. 7. 783631

Fig. 8. 783634

Fig. 9. 783635

Fig. 10. 783630

Fig. 11. 783629

Fig. 12. 783636

Fig. 13. 783637