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TURBOMOLECULAR PUMP VACUUM
SYSTEM FOR THE PRINCETON
LARGE TORUS

BY

H. F. DYLLA

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FOR THE PRINCETON LARGE TORUS

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Paper presented at the 24th National Vacuum Symposium
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TURBOMOLECULAR PUMP VACUUM SYSTEM
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ABSTRACT

A turbomolecular pump vacuum system has been designed and installed on the Princeton Large Torus (PLT). Four vertical shaft, oil-bearing, 1500 l/s turbomolecular pumps have been interfaced to the 6400 liter PLT Vacuum vessel to provide a net pumping speed of 3000 l/s for H_2 . The particular requirements and problems of tokamak vacuum systems are enumerated. A vacuum control system is described which protects the vacuum vessel from contamination, and protects the turbomolecular pumps from damage under a variety of possible failure modes. The performance of the vacuum system is presented in terms of pumping speed measurements and residual gas behavior.

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TURBOMOLECULAR PUMP VACUUM SYSTEM FOR
THE PRINCETON LARGE TORUS

INTRODUCTION

The vacuum system for a large tokamak presents a unique set of vacuum engineering design requirements. The vacuum system must: (1) cycle between high transient pressures (10^{-3} torr) of hydrogenic gases and UHV conditions for impurity gases (CH_4 , CO , H_2O , etc.) within the time-interval between high power discharges (100-300s); (2) pump at high pressures (10^{-4} torr) with high throughput for extended periods of time (8 hours) during discharge cleaning procedures; and (3) operate in an environment of high magnetic fields, repetitive mechanical shock, and possible high power ground faults. In addition the vacuum control system should protect the vacuum vessel from contamination, and protect the vacuum components from damage in the event of vacuum or utility failures or possible operator errors. This paper describes the design, operation and performance of a turbomolecular pump vacuum system recently installed on the Princeton Large Torus (PLT) which satisfactorily meets the above criteria.

I THE PRINCETON LARGE TORUS

The PLT device¹ is a 50cm minor radius, 130cm major radius, tokamak which began operation in December 1975 (see Fig. 1). The device was constructed to study the scaling of high temperature plasma transport properties as a function of magnetic field, plasma current, plasma dimensions and power input. The first phase of PLT operation, involving only ohmically heated plasmas, has recently been completed.² The second phase of PLT operation, involving high power neutral beam heating experiments is presently underway. Injections of up to 1MW of beam power from each of four 40keV, 25A neutral sources is planned.^{3,4} The difficult vacuum pump requirements of these neutral beam injectors (designed by Oak Ridge National Laboratories) will not be treated here as it involved an extensive cryopump development program that will be described elsewhere.

The construction details of PLT, with particular emphasis on the vacuum vessel design, have been given in a previous article in this journal.⁵ Briefly, the vacuum vessel was constructed of alternating sections of 6.3mm thick 305SS cylinders and .56mm thick bellows

(see Fig. 2). In addition, two ceramic sections (96% Al_2O_3 , 4% SiO_2), 7.6cm in length are brazed at diametric positions in the torus so that the ohmic heating current is not shunted through the vacuum vessel. Electron beam and TIG-welding or high temperature brazing⁶ was used to join the stainless steel sections of the torus and attach diagnostic and access ports. All removable flange seals employ either gold wire⁷ or copper gasket seals. Four of the largest ports on the vacuum vessel (30cm x 23cm), spaced 90° apart, are used for connection to the vacuum pumps. The addition of a pumping port extension elbow, which removes the vacuum pump positions from within the toroidal field coils, lowers the net conductance of each pump port to 1400 l/s for N_2 . The volume of the torus alone is 6400 liters and the addition of the pumping elbows yields a net volume of 6900 liters. The estimated geometrical surface area of the torus including the bellows convolutions is $5 \times 10^5 \text{ cm}^2$.

The PLT vacuum vessel is not bakeable in situ because of the complex ohmic heating and shaping field coil structures which are compactly nested between the toroidal field coils and the vacuum vessel. However,

separate components of the vacuum vessel were pre-baked at 400 C in a vacuum oven before assembly. We have relied primarily on discharge cleaning as an in situ method of cleaning (and modifying) the vacuum vessel surface. The results of various discharge cleaning efforts are summarized in Section V.

II THE USE OF TURBOMOLECULAR PUMPS ON TOKAMAKS

During the first 14 months of PLT operation a Hg-diffusion pump vacuum system was in use that was similar to the vacuum system designed for the C-Stellarator⁷ and subsequently used on the ST Tokamak. The performance and reliability of the C-Stellarator Hg-pump system was excellent over its 16 year history. However, the particular PLT Hg-pump system suffered from numerous technical problems which led us to consider other pumping schemes in the redesign of the system. Recently, several manufacturers have marketed larger-sized (>1500 l/s) vertical shaft, oil bearing turbomolecular pumps (The Airco-Temescal 1514 and the Leybold-Heraeus TMP-1500 are examples). The vertical turbo design provides UHV pumping without the use of intervening cryogenic baffles between the pump and the vacuum chamber.^{8,9} Blank-off pressures are in the 10^{-9} torr range for unbaked pumps, and in the 10^{-10} - 10^{-11} torr

range for baked (120 C) pumps. The large compression ratio for hydrocarbons (typically greater than 10^8 for masses greater than 16amu) prevents backstreaming of oil vapor from the rotor-bearing or fore-pump while the pump is running at design speed. However, the system must be protected from possible contamination when the turbo-pump is shut off, (see Section IV).

An important feature of turbo-pumps with regard to their use in tokamaks is the high throughput which is available over the entire operating pressure range,⁸ from blank-off pressures through the transition region. This feature is particularly useful during discharge cleaning operations which require operation of the vacuum system at pressures of 10^{-4} torr for extended periods of time. For comparison, if cryopumps or diffusion pumps were used under such circumstances, the cryogenic surfaces would have to be regenerated after each cleaning cycle to maintain optimum performance. The use of sputter-ion pumps or getter pumps for such purposes is impractical due to the rapid saturation rate of the getter surfaces at such pressures.

Possible disadvantages of the use of turbopumps on tokamak devices include the following: (1) Susceptibility to damage by mechanical shock, excessive

vibrations, ingestion of large particulates, or atmospheric implosions; (2) the need to be shielded from high magnetic fields; and (3) the low compression ratio for H_2 as compared to heavier gases. None of the above problems has caused any observable deleterious effects on the performance of the PLT vacuum system; however, definite concessions were made in the design of the system to minimize the possible influence of these problems. These design concessions will become more complicated as turbo-pump systems are applied to future devices which are larger than PLT.¹⁰

In a pulsed device such as PLT, expanding and collapsing magnetic fields can induce eddy-current strains in the vacuum vessel. Net displacements of the PLT vacuum vessel of ~1mm have been measured during a typical high power discharge. Under normal discharge conditions this net displacement occurs over a time interval of 50-100ms, however, occasional major MHD disturbances can lead to a disruption of the plasma current, whereby the total plasma current (presently in the range of ~500kA) can vanish on a millisecond time scale. The maximum accelerations and displacements that can be tolerated by a vertical-shaft turbo-pump

are not known, therefore to minimize any possible problems the PLT turbo pumps were supported independent of any of the PLT structural components, and the connection to the vacuum vessel was made through a double set of bellows.

In addition to mechanical problems caused by the pulsed magnetic fields, any direct effects of operating a turbo-pump in high ambient magnetic fields must be considered. There is little data presently available on this subject. Leybold-Heraeus recommends maximum allowable dc magnetic fields of 150 gauss axially and 35 gauss radially.¹¹ The tolerance to slowly-varying pulsed magnetic fields is apparently much higher. The Institute of Plasma Physics at Garching (West Germany) has tested a vertical turbo in a 600-800 gauss inhomogeneous field for a pulse length of 5s. A 10% decrease in pump frequency, possibly due to eddy-current heating, was the only deleterious effect noted.¹² More extensive testing of the effects of magnetic fields on turbo performance is being done at KFA, Jülich (West Germany).¹³

The maximum magnetic fields¹⁴ at the position of the PLT turbo pumps is shown in Figure 3. Port extensions (1.6m long) to the pumping ducts remove the pumps sufficiently to render the stray toroidal field (TF) negligible (~10 gauss). Of the remaining stray fields, the worst

case is presented during a disruption when the plasma current field which normally subtracts from the ohmic heating (OH) field disappears. The maximum value of the sum of the remaining OH and shaping (SF) fields is estimated to be 330 gauss for the present PLT operating conditions.

III DESCRIPTION OF THE PLT VACUUM SYSTEM

A schematic flow diagram of the turbomolecular pump (TMP) vacuum system installed on PLT is shown in Figure 4. The system consists of four independent and identical high vacuum lines except for the addition of a separate torus roughing line on the southwest quadrant. Each high vacuum line consists of a TMP pumping stack interfaced to the torus through a 36 cm diameter, 1.6 meter long elbow. Each TMP pumping stack consists of a 30 cm ID, 8 cm long bellows, a 30 cm ID, viton-sealed, high vacuum gate-valve, a 1.27 mm mesh, 33% transparent inlet screen, a 1500 l/s TMP ¹⁵, an 8 cm ID fore-line gate-valve, and a venting-valve for venting the pump-stack with argon. The nominal (N₂) pumping speed of the TMP was chosen to approximately match the conductance of the pumping elbows. The viton gate seals

on the high vacuum valves were baked at 150C before installation so that the net viton outgassing¹⁶ was negligible in comparison to the torus outgassing.

Below the fore-line valve each TMP pump-stack is backed by a $90\text{m}^3\text{h}^{-1}$ mechanical pump¹⁷, which is trapped by a Freon-cooled baffle. The backing lines are 8 cm OD stainless steel piping approximately 30 m in length. A manual butterfly-valve is mounted directly above the baffle for use in the start-up of the system. In addition, an automatic gate-valve is mounted directly above the mechanical pump which is interlocked to close when power is removed from the fore-pump.

Also shown in Figure 4 are the instrumentation and vacuum hardware for measuring the performance of the vacuum system. Two quadrupole mass spectrometers (Q_1 , Q_2) are installed on the SW pumping duct. Directly interfaced to the pumping duct, Q_1 is used primarily for residual gas analysis.¹⁸ The other, Q_2 , is a more sensitive, higher resolution quadrupole mass spectrometer¹⁹ which is differentially pumped and magnetically shielded. Q_2 is used to study the composition and time-behavior of residual gas components produced by tokamak discharges. Two Bayard-Alpert ionization gauges²⁰ are

located on each pumping duct. The ion gauges and the quadrupole mass spectrometers are calibrated against capacitance manometers which span the range 10^3 - 10^{-5} torr, and are located on the torus and the Q_2 assembly. A modified, high conductance capacitance manometer ²¹ is mounted directly on the vacuum vessel for pressure measurements requiring fast time (<5ms) response. Various gases can be introduced into the torus vacuum system either through a calibrated leak-valve located on the Q_2 assembly or through a manifold of piezoelectric pulse-valves connected to the torus.

IV DESCRIPTION OF THE CONTROL SYSTEM

The control system for the TMP vacuum system was designed for protecting against (1) vacuum failures, (2) loss of cooling water for the TMP's, (3) failure of the TMP power supply, (4) power failure, (5) loss of air pressure needed for valve operation, and (6) possible operator error in opening valves. A schematic diagram of the control system logic is shown in Figure 5.

A failure in the high vacuum (torus) side of the TMP is sensed by a capacitance manometer (Baratron M/N 221M) located between the TMP and high vacuum valve

seal. At sensed pressures greater than 2×10^{-2} torr, the high vacuum valve will shut and latch closed, requiring a manual reset. [The Baratron was chosen for the high vacuum control sensor because of its UHV compatibility and lack of a hot filament which would require special care for operations in the 100 - 300 gauss magnetic fields. Standard Bayard-Alpert ion gauges have been mounted on each pump-stack to check the pump base pressure; however, they do not serve any control function.] During a failure in torus vacuum which is sufficient to cause a high vacuum valve closure (Baratron pressure greater than 2×10^{-2} torr), it may not be necessary to completely shut down the affected TMP line. If a frequency sensing circuit within the power converter detects a rotor frequency smaller than the normal run frequency of 300Hz (due to a possible high gas level), the converter will shift to an "acceleration" mode which is a timed operation. If the converter is able to reaccelerate the TMP rotor to 300Hz in less than 8 minutes, the TMP will return to normal operating condition, the "run" mode. If acceleration requires longer than 8 minutes, the converter will shut off ("overload" mode), initiating the complete shutdown of the pump-line.²²

A vacuum failure which is capable of raising the TMP fore-line pressure above 6×10^{-1} torr (as sensed by a fore-line thermocouple gauge) is sufficiently large to warrant a complete shut-down of the pump line. Under such conditions, the following actions are initiated:

(1) the high vacuum valve will shut (if not already shut by the Baratron); (2) the fore-line valve will shut; (3) the converter will be shut off, and (4) the TMP will be vented with clean argon at a rate of 5 torr-liter/sec after the TMP rotor speed has dropped below 100 Hz.

As noted in the control system logic diagram in Figure 5, the TMP is vented with argon under any failure mode that requires the TMP to be shut off. Such a venting procedure protects both the high vacuum stages of the TMP and the torus from possible contamination from TMP bearing oil (Apiezon B). If the TMP rotor speed drops below 10-15% of the run speed (18,000 rpm) while under vacuum (i.e. under molecular flow conditions), the bearing oil could diffuse through the rotor to the high vacuum region. With greater TMP speeds, the rotor acts as an effective mechanical trap. To effectively impede the diffusion of the oil when the TMP is shut

off, the control system vents the TMP with clean argon to pressures near atmospheric levels. Overpressures are prevented by 2 - 4 psi relief valves in the argon feed lines. The argon venting rate is sufficient to slow the TMP down in approximately 5 minutes, compared to the typical spin down time of 15 minutes under vacuum. The advantage, in terms of pump cleanliness and subsequent pump-down performance, of venting a TMP with a clean, dry inert gas rather than a direct vent to atmosphere has been demonstrated in a study by Frank and Usselman.²³

A failure in the TMP cooling water, as sensed by a water-flow sensor²⁴ reading less than .1 gal/min., will initiate the same shut-down procedure as outlined above for a fore-line vacuum failure. The water supply for the PLT TMP vacuum system is a filtered, closed-loop, refrigerated system operated at a temperature of 25 C.

During a power failure, (1) the high vacuum valve closes; (2) the fore-line valve closes; (3) the TMP converter, baffle refrigerator and mechanical pump will latch off and (4) the safety-valve above the mechanical pump closes. (5) When the TMP rotor speed drops below 100 Hz the argon vent valve will open. The power

for both the TMP speed-sensing circuit and the argon vent valves is taken from a battery supply which is constantly being charged during powered operation. The approximate 10 minute time-delay before argon venting during this failure mode allows the system to be carried over short power outages or over the transition to an emergency power bus.

The mechanical pump refrigerator and both the high-vacuum and fore-line valves require manual resets after a power failure. If air pressure for valve operation is lost, an alarm of this condition (pressure less than 70 psi) is given on a vacuum alarm panel. If the air compressor is lost (due to a power failure for instance), a check-valve closes between the compressor and a ballast tank which supplies sufficient air for at least two valve closures.

Finally, to prevent operator error in the manual use of the valves, the high vacuum valve has been interlocked with a torus Baratron to prevent an opening when the torus pressure is high, and the fore-line valve has been interlocked with a thermocouple gauge above the baffle to prevent opening when the fore-line pressure is high.

V. SYSTEM PERFORMANCE

The performance of the TMP vacuum system in terms of the resulting pumping speeds and residual gas behavior is summarized in this section.

The high vacuum pump-out time constant (τ) and resulting net pumping speed (V/τ) were measured for the gases H_2 , D_2 , Ne and N_2 (see Figure 6). The use of pump-out time-constants for measuring pumping speeds is not as accurate as a measurement based on calibrated flow rates²⁵ because of possible variations in pumping speed with pressure and competing wall-pumping effects. However, the pump-out time constant is the parameter of interest for tokamak systems because of the pulsed characteristics of the gas-loading. In addition, the chosen gases for the speed measurements interact with the vacuum vessel walls relatively weakly in their molecular forms. The measurements given in Figure 6 were made by filling the torus to a pressure in the range of 10^{-5} - 10^{-4} torr with a pulse-valve, then following the decay of the pressure after the pulse-valve closure with both the quadrupole mass spectrometer (Q_2) and a torus capacitance manometer.

The H_2 and N_2 pumping speeds of the TMP pump-stacks,

exclusive of the PLT port-extension elbows, (but including the isolation bellows, high vacuum valve and inlet screen), were measured using a 100 liter test dome. The results $S_p=840$ l/s for H_2 and $S_p=770$ l/s for N_2 , are in the same ratio but considerably below the manufacturer's ratings of 1500 l/s for N_2 and 1650 l/s for H_2 . However, the rated speeds are measured at the pump inlet without an inlet screen. Our values are close in value to more extensive measurements conducted at CERN²⁶ which yielded H_2 speeds of 600-750 l/s over the range 10^{-7} - 10^{-4} torr.

Since the pumping speed at the TMP inlet is expected to be relatively constant as a function of mass⁹ (at least for $M \geq 4\text{amu}$), and since the calculated conductance of the pumping port elbow ($C_p \approx 1430$ l/s for N_2) is of the same order as the measured pump speed ($S_p=770$ l/s for N_2) the net speed for the entire system should slowly decrease with increasing molecular mass:

$$S_{\text{NET}} = \frac{4S_p}{\left(\frac{S_p}{C_p}\right)\sqrt{\frac{M}{28}} + 1} \quad (1)$$

The above function is plotted in Figure 6. The measured net speeds for the three lighter gases (H_2 , D_2 , and Ne) agree reasonably with the predicted curve, however, the

measured net speed for N_2 is much lower (30%) than predicted, and lies outside the margins of error in the calculation of C_p and the measurement of V/τ .

The pump-out behavior immediately after a high power discharge is quite different from the situation shown in Figure 6 because of the diffusion of gases implanted in the near-surface region of the vacuum vessel wall by the discharge, and because of the increased reactivity of residual gas components due to ionization and excitation in the discharge. Figure 7 shows the time behavior of the major residual gas components after a high power discharge in H_2 . The pump-out time for H_2 increases from 2.3s in the case of gas-injection only, to 3.7s after a high power discharge due to outgassing of the implanted H_2 . The predominant residual gas components produced by the discharge are CH_4 and CO. A possible production mechanism for CH_4 is the reaction of out-diffusing atomic hydrogen with absorbed hydrocarbons on the vessel wall. Examples of possible reactions which yield CH_4 as the primary product have been given by Rye²⁷.

The rapid disappearance of CO ($\tau = .35s$) indicates that significant wall-pumping of this component occurs. From the observed time behavior, the effective sticking

coefficient of CO on the vacuum vessel wall is estimated to be greater than 10^{-2} , whereas the sticking coefficients of H_2 and CH_4 must be less than 10^{-4} . The mechanism of production and the small sticking coefficient of CH_4 allows the molecule to remain within the vacuum system for several pump-out time constants, and provides a means of carbon removal from the vessel. This is the basis of most discharge cleaning schemes which involve running an extended series of low-level tokamak discharges at an increased repetition rate. The removal of oxygen from the vacuum vessel wall has proved to be a more complex problem. The only oxygen containing molecule evident in significant quantities during high power discharges is CO, which is rapidly pumped by the wall. The transient behavior of H_2O usually shows a decrease in the background H_2O partial pressure during and immediately following a high power discharge (See Figure 8). This indicates that H_2O is rapidly getterred on the wall by such discharges. By drastically lowering the temperature of the discharge so that only a partially-ionized plasma is produced, the H_2O partial pressure will increase and the transient behavior is such that a significant fraction can be removed by the vacuum pumps, (see Figure 8). This is the basis for a low-

temperature discharge cleaning technique developed by Taylor on the MIT and UCLA tokamaks²⁸, and subsequently used on PLT since February, 1977²⁹.

The base pressures achieved by the PLT vacuum system are in the range of $1-2 \times 10^{-8}$ torr. Figure 9 shows the residual gas spectrum after six weeks of tokamak operation with the TMP vacuum system. The predominate background species are H_2 , H_2O and CO . The predominate outgassing species are H_2 (or D_2) and CO . Figure 10 shows the outgassing spectrum of the torus, taken 30 minutes after the high vacuum valves were closed following the termination of a series of high power discharges. Within this time interval outgassing rates are typically of the order of 10^{-9} torr-l/s-cm². Outgassing rates under base pressure conditions are typically in the range of $0.6-6 \times 10^{-10}$ torr l/s-cm². There is generally little correlation of base pressures and outgassing rates with the subsequent low-Z impurity (C,O) level in high power discharges. More relevant measurements are the partial pressure levels during discharge conditions (such as shown in Figure 7), and direct measurements of the changes in surface conditions from plasma exposure.^{30,31}

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FIGURE CAPTIONS

Figure 1   View of the Princeton Large Torus (PLT) taken during July 1977 after the installation of the two 40keV neutral beam injectors visible in the lower left and upper right corners of the photograph.

Figure 2   View of the PLT vacuum vessel after fabrication and during initial vacuum testing.

Figure 3   Maximum magnitudes of the stray magnetic fields in the vicinity of the PLT turbo-pumps.

Figure 4   Schematic flow diagram of the PLT turbomolecular pump (TMP) vacuum system. The system consists of four identical high vacuum lines (only one is shown for clarity), consisting of a high vacuum valve (HVV), 1500 l/s TMP, fore-line valve (FLV), manual butterfly valve, Freon-cooled baffle (FB), fore-pump safety valve (SV), fore-pump atmospheric vent (V), and a $90 \text{ m}^3 \text{ h}^{-1}$ mechanical fore-pump (FP). Each TMP can be vented in a controlled manner with filtered argon through a piezoelectric leak-valve. Capacitance manometers (CM) and thermocouple gauges (TC) are used in high vacuum and low vacuum control circuits

respectively. There is a separate roughing-line on the southwest quadrant of the torus. Vacuum conditions are monitored by two quadrupole mass spectrometers (Q_1 , Q_2), capacitance manometers (CM) and ion gauges (IG). Controlled amounts of various gases can be introduced through either of two gas manifolds (GM).

Figure 5   Schematic diagram of the vacuum control system logic.

Figure 6   Measured high vacuum pump-out times (left ordinate) and pumping speeds (right ordinate) for various gases. The predicted net speed (Eq.1) using the calculated pumping port conductance and measured TMP speed for N_2 is also plotted.

Figure 7   Time behavior of the major residual gas components (CH_4 , CO) within the torus after a typical high power discharge in H_2 , (discharge duration $\approx .5s$). For comparison, the time behavior of H_2 in the case of gas-injection only is also plotted. The indicated partial pressures were measured with a calibrated mass spectrometer, however considerable variation

in the absolute quantities of CH_4 and CO are noted with variations of plasma and wall conditions.

Figure 8 Time behavior of the partial pressure of H_2O observed during low-temperature (Taylor-type) discharge cleaning pulses (TDC) and high power discharge cleaning pulses (PDC). The pulse repetition period is indicated by the dotted lines. Note the net increase in the H_2O pressure over the ambient level in the case of TDC, whereas the PDC pulses induce gettering of H_2O onto the vacuum vessel wall.

Figure 9 PLT Residual gas spectrum after six weeks of operation with the TMP vacuum system. There are mixed H-D species in the spectrum because normal PLT operation includes discharge cleaning in H_2 and high power discharges in D_2 .

Figure 10 PLT outgassing spectrum 30 minutes after the cessation of high power discharges and closure of the high vacuum valves. The mass spectrum of both this figure and figure 9 have been uncorrected for the fall-off in transmission with mass for the quadrupole mass spectrometer, (Q_1).

Fig. 1. 773585

Fig. 2. 744752

Fig. 3. 773883

Fig. 5. 773882

Fig. 6. 773887

Fig. 7. 773884

Fig. 3. 773881

PLT RESIDUAL GAS SPECTRUM

Fig. 9. 773769

PLT OUTGASSING SPECTRUM

Fig. 10. 773696