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CRYOSORPTION OF HELIUM ON ARGON FROST IN TFTR NEUTRAL
BEAMLINES

BY

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Cryosorption of Helium on Argon Frost in TFTR Neutral Beamlines

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ABSTRACT

Helium pumping on argon frost has been investigated on TFTR neutral beam injectors and shown to be viable for limited helium beam operation. Maximum pumping speeds are ~ 25% less than those measured for pumping of deuterium. Helium pumping efficiency is low, > 20 argon atoms are required to pump each helium atom. Adsorption isotherms are exponential and exhibit a two-fold increase in adsorption capacity as the cryopanel temperature is reduced from 4.3 K to 3.7 K. Pumping speed was found to be independent of cryopanel temperature over the temperature range studied. After pumping a total of 2000 torr-l of helium, the beamline base pressure rose to 2×10^{-5} torr from an initial value of 10^{-8} torr. Accompanying this three order of magnitude increase in pressure was a modest 40% decrease in pumping speed. The introduction of 168 torr-l of deuterium prior to helium injection reduced the pumping speed by a factor of two with no decrease in adsorption capacity.

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I. INTRODUCTION

Recently, helium neutral beam operation into tokamaks has been considered for TFTR at the Princeton Plasma Physics Laboratory, for DIII-D at General Atomics,¹ for JET at Culham,² and for JT-60 at JAERI.³ He³ beam operation can be used to simulate several of the properties of tritium operation presently planned for both TFTR and JET. Tritium magnet optics, neutralizer physics, ion source perveance, as well as calorimeter and ion dump power densities can be examined. He³ beam injection into low density deuterium plasmas could produce high values of energy gain, Q, and provide additional information relevant to understanding the TFTR high confinement regime.⁴ Low perveance, neutron-free beam conditioning has been achieved with helium beam operation at JET,² and the injection of helium beams into helium plasmas has been successfully carried out on DIII-D.

High speed pumping of helium is necessary for such operation since reionization of helium atoms beyond the charge-separation magnet is a loss mechanism, reducing system efficiency and providing a means for heating unprotected surfaces. In order to keep the loss to less than 5%, pressures less than 3×10^{-5} torr are necessary. TFTR beamlines operating with three helium ion sources, of ~ 15 torr-l/s each, would require pumping speeds comparable to those of present deuterium operation (i.e., $\sim 10^6$ l/s).⁵⁻⁷ Adsorption capacities capable of handling this throughput for up to six seconds are also required.

The neutral beam systems mentioned above all have condensation-based cryopumps operating at ~ 4.2 K. Helium is not condensed at these temperatures, but it can be cryosorbed on adsorbents such as charcoal,⁸⁻¹² molecular sieves,¹³⁻¹⁸ or condensed gases.^{12, 19-22} Since the beamline cryopanel is already installed

and operational, condensed gas adsorbents have been studied; argon has been used for TFTR, for DIII-D,¹ and for JET;² SF₆ was used for JT-60.³

Most earlier work^{12, 19-21} was carried out with the adsorbent continuously injected with the helium. The exception is ref. 22 in which argon was predeposited and saturated with helium in layers; recent experiments with helium pumping on argon (refs. 1 and 2, and this work) utilized the same technique. PPPL experiments were carried out with 10^4 torr-l of argon injected into the beamline followed by a series of helium pulses until the beamline pressure rose into the mid- 10^{-5} torr range. Following this near-saturation of the argon with helium, an additional argon layer was injected, bringing the base pressure nearly back to its value following the injection of the preceding argon layer. Helium pumping experiments were then carried out on this new argon layer. This process of covering up the saturated argon with fresh argon was continued to a maximum of six pumping layers.

It has been reported that small amounts of condensible gases on an adsorbent partially destroys its adsorption capacity.^{9, 12, 22, 23} Such an effect is important in developing a scenario for helium injection into deuterium plasmas. To determine the extent of the problem, an experiment was performed in which helium injection onto a fresh layer of argon was preceded by two deuterium pulses.

II. EXPERIMENTAL APPARATUS

Experiments were performed in a TFTR neutral beam injector, shown schematically in Fig. 1. An ion beam, created by the electrostatic acceleration of ions to high energy in the ion source, is subsequently converted into a mixed ion and neutral beam in the neutralizer. Charged particles are removed from the

beam by the deflection magnet. Due to the tokamak's magnetic fields, neutral particles reionized after this point are lost. The reionization cross section of 10^{-16} cm² over a 5 m path length from the magnet to the plasma sets an upper limit on acceptable pressure (5% loss) during a beam pulse of 3×10^{-5} torr.

The pumping system was designed to meet similar reionization constraints for pumping hydrogenic isotopes. A differential pumping scheme, shown in Fig. 1, was devised to handle a deuterium gas load of 30 torr-l/s per ion source.⁵ With only the cryopanel installed in the beamline, a deuterium pumping speed of 2.5×10^6 l/s was measured. With all components installed, the total deuterium pumping speed was reduced to 7×10^5 l/s.^{6, 7} Due to the difficulty of quantifying the pumping speed in such a differentially pumped system, the helium pumping speed was only measured relative to the pumping speed of deuterium.

Helium was injected through a piezoelectric valve located on the 138° port in the OMA box noted in Fig. 1. To ensure that the argon distribution in the differentially pumped system was similar to that of the helium, argon was injected nearby, through a manual valve into ports located between the source isolation valve and the beamline enclosure. Deuterium was injected through the same port as the helium. Gas throughputs were measured from pressure rises, during timed gas pulses, into the known beamline volume when the cryopanel was at room temperature.

During normal operation the local beamline LHe dewar pressure slightly exceeds one atmosphere, corresponding to cryopanel temperatures of ~ 4.3 K.²⁴ Subatmospheric operation at 3.7 K was achieved by isolating the dewars of all four beamlines from the refrigerator and using an array of four compressors originally installed for operation of a neutral beam test stand²⁵ to provide suction. Cryopanel temperatures were inferred from the helium vapor pressure in the

dewar, the latter being monitored by a diaphragm pressure gauge; temperature accuracy was ± 0.1 K. At the conclusion of each day's operation the dewars were refilled and the beamline on which the experiments were performed was regenerated. Experiments were performed with the beamline isolated from the external pumping system; the valve between the beamline and turbomolecular pump was closed prior to initial argon injection and not opened until the day's experiments were concluded.

Three Bayard-Alpert ionization gauges are located on each beamline as indicated in Fig. 1. The "input" and "rear duct" ion gauges were used in these experiments. Typical gauge correction factors, relative to nitrogen, of 2 and 5.6 were used to compute the deuterium and helium pressures, respectively. Pressures were further corrected by a factor of 1.56 (for both helium and deuterium) for thermal transpiration. This factor was derived by injecting gas when the cryopanel was at room temperature and later injecting the same quantity of gas when the cryopanel was cooled with liquid nitrogen. Error estimates, based on calibration statistics for many gauges, are $\pm 10\%$ for pressure ratios and $\pm 20\%$ on absolute pressures. A mass spectrometer, located near the "input" ionization gauge, was used to monitor helium and argon partial pressures. Data from the ion gauges and mass spectrometer were recorded on chart recorders, and pressure waveforms during pumpout, after the helium pulse was terminated, were recorded on an oscilloscope.

III. RESULTS

Each argon layer consisted of 10^4 torr-l manually injected over a period of 6 to 12 minutes. If uniformly distributed over the 30 m^2 LHe cryopanel area, the argon thickness would slightly exceed 1000 monolayers. Due to the differential

pumping geometry, the thickness decreases with distance from the ion source. The structure of the argon frost is believed to be quite porous,²⁶ presenting a large surface area for pumping. Helium injection was at rates of 14 torr-l/s for pulses of 2-s, 4-s, or 6-s duration; only the 6-s data will be presented. Helium pulses were repeated approximately every two minutes and proceeded until the uncorrected beamline base pressure rose into the mid- 10^{-5} torr range.

Figure 2 shows data from both ion gauges for a six-pulse helium sequence onto a layer of argon. P_{duct} is the signal from the "rear duct" ion gauge, and the inverted signal, P_{input} , is that of the "input" ion gauge. Pulses are six seconds long with the chart recorder stopped between pulses. The base pressure rises as a result of each pulse, with P_{duct} showing a slight pressure recovery over the time between pulses. The increase in base pressure is slightly less than the pressure rise that occurs during the helium pulse. Both the base pressure rise and the pressure rise during the pulse increase with the amount of adsorbed helium, the former at a considerably faster rate. The beamline pressure differential, $P_{\text{input}}/P_{\text{duct}}$, is four. This is slightly less than the factor of five measured with deuterium.

Adsorption isotherms at 3.7 K are presented in Fig. 3. With the exception of the first pulses on the first two layers (where helium is not the dominant partial pressure), the isotherms are exponential. If the base pressure immediately following creation of a fresh argon layer is subtracted from the data for that layer, the adsorption capacity increases monotonically with the number of argon layers. Increasing adsorption capacity with the number of argon layers is contradictory to the observed base pressure increase, but consistent with that observed by others.²² Isotherms at 3.7 K and 4.3 K are compared in Fig. 4. Adsorption capacity is 50% higher at the lower temperature. An estimate of the isotheric heat

of adsorption based on this data, 145 (+70, -40) cal/mole, is in reasonable agreement with published data for helium adsorbed on nitrogen.²⁷

Figure 5 shows the pressure rise during the pulse as a function of adsorbed helium for a series of five sequential argon layers at 3.7 K. Pressure rise was measured as the difference between the peak pressure at the end of the pulse and the following base pressure. This value is proportional to the pumping speed since the gas throughput was invariant. On any argon layer the pumping speed decreases linearly with the amount of adsorbed helium, e. g., decreasing by ~25% for layer #6. A decrease in pumping speed is also apparent as each argon layer is created. It is not known whether the decrease in pumping speed at the last point on the first two layers is real or an artifact in measuring the base pressure under near-saturation conditions. Pumping speed was independent of temperature over the temperature range investigated.

Helium partial pressure was monitored with the mass spectrometer during argon injection. Helium pumpout during six argon injections is shown in Fig. 6. Each curve corresponds to the creation of a fresh argon layer (all with the injection of 10^4 torr-l) following one of the isotherms measured in Fig. 3. Data points in Fig. 6 represent the height of the helium peak each time it is scanned by the mass spectrometer. The helium base pressure increase with successive layers of argon is apparent. Pumpout is exponential, with deviations due to the inability to manually maintain constant pressure. As layers accumulate, more argon is required (but not necessarily provided) to bring the base pressure back to previous levels.

A final experiment studied the effect of deuterium on helium adsorption. Two deuterium pulses, each 14 torr-l/s for two seconds, were injected onto the fourth argon layer following three layers of normal helium pumping. The helium

adsorption capacity of the deuterium-coated argon layer was the same as for an uncontaminated argon layer. The pumping speed, however, was considerably reduced, as indicated in Fig 7.

IV. DISCUSSION

It has been demonstrated that helium can be cryosorbed on ~ 0.4 micron thick argon frost. Satisfactory pumping has been attained on stacks of argon frost up to six layers thick (~ 2.5 micron). Pumping speeds are similar to those for condensation of deuterium. The primary difficulty in the implementation of a helium neutral beam operating scenario is that the process is gas inefficient; 20 to 30 argon atoms are necessary to pump each helium atom.

It is speculated that the increase in adsorption capacity of the argon with the number of argon layers is due to the fact that the argon layers are not completely saturated before being covered over by the next layer, and that the argon surface temperature increases with the number of layers, enhancing diffusion into the bulk of the argon.^{16, 17} For the first few argon layers, the base pressure data indicate that a fresh layer of argon effectively seals in the adsorbed helium. Helium mobility is low for the colder first few layers and the argon is not uniformly saturated in depth; the argon layers are too thick. As layers accumulate, the argon surface temperature increases due to poor conduction with the cryopanel surface. This temperature increase enhances helium mobility within the argon. As a result, 1) more helium is near the surface, 2) this helium can desorb more easily due to the increased temperature, and 3) it can migrate into the previous partially saturated argon layers faster. The first two conditions cause the pressure to rise, while the third implies that a larger argon volume is

available to the helium as more layers are created, increasing adsorption capacity. At high enough temperature it is expected that the helium distribution in the argon would become uniform and the increase in adsorption capacity with argon layers would cease. This is what is observed. At 3.7 K the adsorption capacity increased with each layer as in Fig. 3; whereas at 4.3 K the increase became small after the second layer.

Maximum helium pumping speeds on argon frost, as determined from the pressure rises during the gas pulses, are approximately 25% less than that for pumping of deuterium. Confirming information was obtained from the time constants associated with the pumpout following gas turn-off. Error bars for this latter measurement are $\pm 25\%$. The helium and deuterium pumping speeds could not be distinguished with this technique. Equivalent hydrogen/helium pumping speed ratios were measured on argon frost by Dawbarn and Haygood.²²

Helium pumping speed decreases with the quantity of helium adsorbed on any given argon layer and with the number of argon layers. The dependence appears to be with the helium pressure and is presumably due to helium on the argon surface occupying adsorption sites. Pumping speed decrease with the number of argon layers is believed due to increased surface temperature.

Temperature reduction is known to increase the adsorption capacity of cryo-deposits pumping helium.^{22, 27} In our case a 50% increase in adsorption capacity was measured as the temperature was reduced from 4.3 K to 3.7 K. Further improvement is expected at lower temperatures than those studied here. Pumping speed, however, was found to be independent of temperature over the temperature range studied. This may be due to the fact that the sticking coefficient is near unity.²²

Adsorption of deuterium reduces the pumping speed with little or no effect on the sorption capacity. Deuterium, which condenses at higher temperatures than helium, is relatively immobile at ~ 4 K and is trapped on the surface;²⁸ either helium does not stick to the sorbed deuterium,²³ or deuterium decreases the argon's porosity by icing over the surface. Potential adsorption sites are taken up, and/or the pathways into the bulk of the argon are blocked, thereby slowing adsorption and reducing the pumping speed. Once adsorbed, helium diffuses through the bulk argon unaffected by the deuterium on the surface; deuterium has no effect on the adsorption capacity.

Due to the deleterious effect of deuterium on the pumping speed of helium, the proposed operating scenario for helium beams calls for the application of a fresh layer of argon prior to each beam pulse. Assuming a helium gas throughput of 15 torr-l/s (equivalent to present deuterium operating conditions), three helium ion sources per beamline, 6-s gas pulses, 50% ion source gas efficiency, and the return of injected helium from the tokamak at the end of the plasma discharge, 270 torr-l of helium must be pumped per pulse. From Fig. 4, at least six such pulses can be adsorbed at 3.7 K, if 10^4 torr-l of argon is injected prior to each pulse. Argon injection is possible with the isolation valve between the beamline and torus open. Based on the measured torus argon pumping speed of 6000 l/s,²⁹ the torus will pump the expected ~ 0.1 torr-l/s throughput of argon for the duration of the argon injection, and return to an acceptable partial pressure in approximately two minutes.

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FIGURE CAPTIONS

Figure 1. Schematic elevation view of a TFTR neutral beam injector.

Figure 2. Chart recorder data for six helium pulses. Duct ion gauge is on the bottom and the input ion gauge signal is inverted and on top. Pulses are six seconds long, separated by approximately two minutes.

Figure 3. Adsorption isotherms at 3.7 K for each of six argon layers; a) through f) are for argon layers 1 through 6, respectively.

Figure 4. Second argon layer adsorption isotherms at 3.7 K and 4.3 K.

Figure 5. Pressure rise during helium pulses, as a function of adsorbed helium at 3.7 K, for five sequential pulses; a) through e) are for argon layers 2 through 6, respectively.

Figure 6. Decay of helium partial pressure during the addition of argon; a) through f) are for argon layers 2 through 7, respectively.

Figure 7. Pressure rise during helium pulse, as a function of adsorbed helium at 3.7 K, for: a) following the injection of deuterium, and b) for the first three argon layers preceding deuterium injection.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

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