AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

HELIUM EXHAUST STUDIES IN THE DIII-D TOKAMAK

by

M.R. WADE,* J.T. HOGAN,* D.L. HILLIS,* M.A. MAHDAVI, R. MAINGI,*
W.P. WEST, N.H. BROOKS, K.H. BURRELL, D.F. FINKENTHAL,[†]
R.J. GROEBNER, G.L. JACKSON, C.C. KLEPPER,* G.L. LAUGHON,
M.M. MENON,* P.K. MIODUSZEWSKI,* AND THE DIII-D TEAM

This is a preprint of a paper to be presented at the
Eleventh International Conference on Plasma
Surface Interactions in Fusion Devices, May 23-27,
1994, Ibaraki-ken, Japan, and to be printed in the
Proceedings.

Work supported by
U.S. Department of Energy
Contract Nos. DE-AC03-89ER51114 and DE-AC05-84OR21400

*Oak Ridge National Laboratory

[†]University of California, Berkeley

GENERAL ATOMICS PROJECT 3466
JULY 1994

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

Significant exhaust of thermal helium in a diverted, H-mode deuterium plasma has been demonstrated for the first time on the DIII-D tokamak using an in-vessel cryopump conditioned with an argon frost. The helium, introduced via gas puffing, is observed to reach the plasma core and then is readily removed from the plasma with a time constant of ~ 8 – 15 energy confinement times. Detailed analysis of the helium profile evolution indicates that the exhaust rate is limited by the exhaust efficiency of the pump ($\sim 5\%$) and not by the intrinsic helium transport properties of the plasma. Additional studies focusing on the recycling properties of helium relative to deuterium in the divertor region indicate some dependence of the helium concentration in the divertor pumping plenum on the divertor outer strike-point (OSP) position in Ohmic discharges. However, the helium concentration in the plenum appears to have little dependence on OSP position in beam-heated, ELMing H-mode discharges.

1. INTRODUCTION

The continuous and efficient removal of helium (He) is essential for the success of future burning devices based on the deuterium-tritium (D-T) reaction. The overall performance of such devices is critically dependent on the ability to remove this He ash from the plasma core to prevent dilution of the D-T fuel while maintaining good plasma energy confinement. Previous studies on several tokamak devices have demonstrated adequate He exhaust during L-mode plasma operation (Hillis [1]; Hillis [2]; Synakowski [3]; Nakamura [4]; Synakowski [5]). However, there are significant engineering and economical benefits if next-generation tokamaks, such as the International Thermonuclear Experiment Reactor (ITER) could operate in an enhanced confinement regime, such as H-mode, and still achieve adequate helium exhaust. A long-standing objection to such regimes has been the possibility that particle (and hence ash) removal would be insufficient. To date, helium exhaust measurements in H-mode have been limited to polarization-induced, quiescent H-mode plasmas in TEXTOR, a limiter device. These experiments have produced unfavorable results in terms of He exhaust (Hillis [6]). The results reported herein therefore represent the first He exhaust experiments in diverted, ELMing H-mode plasmas with active helium pumping.

In judging He exhaust capabilities, the figure of merit generally used is the ratio of the global residence time of the He ash within the plasma chamber, τ_{He}^* , to the plasma energy confinement time, τ_E . Studies have shown that successful reactor operation can be maintained only if the He ash is removed from the system within 7–15 energy confinement times (*i.e.*, $\tau_{He}^*/\tau_E \leq 7-15$), depending on the impurity content of the plasma (Reiter [7]). In the experiments discussed here, $\tau_{He}^*/\tau_E \sim 10$ with a helium exhaust efficiency of ~5% has been achieved in an ELMing H-mode plasma simultaneously with good energy confinement. The exhaust efficiency of helium is defined as $\epsilon_{He} = Q_{Exh}/(\Gamma_{He}A_{pl})$ where Q_{Exh} is the exhaust

rate for helium and $\Gamma_{He}A_{pl}$ is the core helium efflux. These results are discussed in more detail in Section 2.

This exhaust efficiency is strongly dependent on the mechanisms governing the flow of helium within the scrape-off layer (SOL) and divertor region. For example, studies using two-dimensional SOL codes predict that in the presence of a strong deuterium flux to the divertor plate, the resulting frictional drag will cause the He to be preferentially segregated at the cooler, outer part of the divertor plate. Such segregation could possibly provide a mechanism for preferential removal of helium. To date, little experimental data is available to validate these modeling results. In this regard, preliminary experiments on DIII-D have been conducted. From the data obtained thus far, there is little evidence that this predicted separation exists although some dependence of helium concentration in the pumping plenum on the location of divertor strike point has been observed in Ohmic-heated discharges. The results of these studies along with modeling efforts in this area are presented in Section 3.

2. HELIUM EXHAUST

This set of studies was made possible by the recent installation of a cryocondensation pump as part of an advanced divertor configuration on DIII-D (Menon [8]; Smith [9]; Schaubel [10]). Figure 1 shows a cross-section of the lower divertor of DIII-D and the associated hardware. The divertor cryopump is located inside a pumping plenum, which is closely coupled to the divertor plasma when the outer strike-point (OSP) is located near the baffle entrance. Helium pumping via this pump is accomplished by condensing an argon (Ar) frost layer on the liquid helium surface of the cryopump between successive plasma discharges by isolating the vacuum chamber from the external turbomolecular pumps and injecting a known amount of Ar into the main vacuum chamber. In this manner, a layer of ~ 1500 Torr-l (~ 1.5 μm thick layer) is condensed on the pump, providing a measured pumping speed for He of approximately 18,000 l/s when the layer is fresh. It should be noted that deuterium is also pumped via the Ar frost and that the pumping speed for He decreases substantially as the amount of deuterium adsorbed on the pump increases.

To simulate the presence of He ash in these experiments, a short (50 ms) puff of He gas was injected and allowed to diffuse into the plasma core. Sufficient He was introduced to bring the He concentration to $\sim 15\%$ of the electron density n_e . Because the He was introduced at the plasma edge, active control of the helium exhaust rate is essential in this experiment to allow the He to fully diffuse into the core before strong pumping is applied. This was accomplished here by actively controlling the position of the OSP, thereby controlling the buildup of pressure in the pumping plenum. From the initiation of the discharge until well after the He gas puff, the OSP is maintained well away from the baffle entrance ($\Delta_{OSP} \sim 15$ cm). The magnetic separatrix of an equilibrium reconstructed from external magnetic measurements by the EFITD code (Lao [11]) is shown as the dashed lines in Fig. 1. After the He density profile has come to steady-state subsequent to the He gas puff, strong He exhaust is initiated by rapidly moving the OSP to the

throat of the baffle entrance ($\Delta_{OSP} = 1.5$ cm). The OSP is then maintained in this location for the remainder of the discharge so as to provide maximum exhaust efficiency. A representative magnetic equilibrium for times subsequent to the OSP sweep is shown as the solid lines in Fig. 1.

Fig. 1. (a) Schematic of the lower divertor of DIII-D showing the location of the baffle plate, bias ring, and cryocondensation pump. Also shown are magnetic equilibria with the outer strike point (OSP) close to the pumping plenum entrance (solid lines) and with the OSP far away from the entrance (dashed lines). (b) Enlarged view of divertor floor and bias ring. The OSP position is parameterized in terms of the minimum distance from the separatrix to the front face of the bias ring (denoted as Δ_{OSP}).

A set of spectroscopic diagnostics is used to follow the evolution of He in the plasma core, divertor, and pumping plenum. The evolution of the He density profile is inferred from

measurements of the intensities of the He II $n = 4-3$ transition at 4685.68 Å induced by charge-exchange excitation by energetic deuterium neutrals injected via neutral beam injection using a high resolution spectroscopy system. The DIII-D charge-exchange recombination (CER) system has 32 channels that span the entire cross section, with spatial resolution of over 3 cm in the core and 3 mm at the edge (Gohil [12]). A modified Penning gauge, located in an appendage to the pumping plenum, is used to measure the He and deuterium partial pressure (Finken [13]). The time response of this gauge is vacuum conductance limited and is approximately 50 ms.

For the experiments discussed here, a lower, single-null, divertor configuration was used with a plasma current of 1.0 MA and a major radius of ~ 1.67 m. The neutral beam injection (NBI) power, ranging from 4.2 MW to 10 MW, was held steady throughout each discharge. At these power levels, the transition to H-mode occurs almost immediately after application of NBI. The He gas puff (~ 6.0 Torr-l total, 50 ms duration) was introduced shortly after this transition and the OSP was swept to the baffle entrance approximately 500 ms after the gas puff, allowing the injected helium enough time to diffuse into the plasma core. Deuterium gas puffing was disabled during the H-mode portion of this discharge; hence, the line-averaged n_e decreases slightly due to pumping, and there is a corresponding increase of the electron and ion temperature. No evidence of Ar evolving from the pump to the plasma core was observed by either VUV spectroscopy or soft X-ray emission in any of these discharges.

The temporal evolution of the He density near the plasma center (normalized radius $\rho = 0.3$) with and without Ar frost applied to the cryopump is shown in Fig. 2 for a discharge with 4.2 MW NBI. The helium gas puff occurs at 1.5 s in this discharge with the OSP sweep at 2.0 s. From this figure, it is evident that the evolution of the He density is roughly the same in both cases until the OSP is swept to the baffle entrance at 2.0 s. The core He density rises sharply just after the He gas puff and reaches steady-state in the plasma core after ~ 200 ms. In the case without helium pumping, the core He density remains approximately constant after the initial rise although a small decrease in the He density is observed at the time of the OSP sweep. The magnitude of this decrease is consistent with a simultaneous increase of He partial pressure in

the pumping plenum, suggesting that the observed decrease is due to a “baffling” effect in which a significant amount of He is being retained within the pumping plenum volume without actually being exhausted from the system.

Fig. 2. Comparison of the evolution of the helium density near the plasma center measured with CER spectroscopy during discharges with and without Ar frost applied to the divertor cryopump. Helium was puffed at 1.5 s and the divertor OSP was swept to the baffle entrance at 2.0 s to initiate active pumping. The dashed curves represent MIST transport calculations using different recycling models after the OSP sweep: constant $R_{He} = 0.98$ (upper dashed curve); steadily increasing R_{He} with $R_{He} = 0.95$ at the time of the OSP sweep (solid curve); and constant $R_{He} = 0.95$ (lower dashed curve). R_{He} is assumed to be unity before the OSP.

With Ar frost applied to the pump, the He density decreases rapidly starting at 2.0 s with approximately 65% of the He being exhausted within 2.0 s. From measurements of the helium density profile via CER, the time dependence of the total plasma inventory of He ions can be determined directly. The characteristic helium residence time in the system τ_{He}^* can then be determined from the He global particle balance equation: $dN_{He}/dt = -N_{He}/\tau_{He}^* + \int S_{He} dV$ where N_{He} is the total number of He ions in the plasma and $\int S_{He} dV$ is the external He particle source

rate. Note that in this experiment, $\int S_{He} dV = 0$ after the initial He gas puff. Such analysis indicates that τ_{He}^* increases steadily with time in all of the helium exhaust discharges studied to date. This increase in τ_{He}^* is believed to be due to a decrease in the effective He pumping speed of the pump due to contamination of deuterium within the Ar frost. Tests conducted with Ar frost on the pump have shown that the pumping speed for He decreases roughly exponentially with deuterium loading from $\sim 18,000$ l/s when the Ar frost is fresh (*i.e.*, no deuterium loading) to ~ 7000 l/s with ~ 100 Torr-l deuterium adsorbed on the Ar frost layer. In the discharge of interest, this translates into a decrease in pumping speed from $\sim 14,000$ l/s (~ 25 Torr-l D₂ adsorbed on pump) at the initiation of active pumping to ~ 8100 l/s (~ 80 Torr-l adsorbed on pump) at the end of the pump-out phase ($t = 4.0$ s). Taking this decrease in pumping speed into account in the discharge of Fig. 2, τ_{He}^* is found to be ~ 1.1 s for this discharge. From measurements of the magnetic and kinetic stored energy, $\tau_E = 137$ ms and therefore $\tau_{He}^*/\tau_E \approx 8$, well within the range generally considered necessary for successful operation of future fusion reactors, such as ITER.

CER measurements throughout the active exhaust phase of this discharge indicate that the He density profile shape remains essentially unchanged. This observation coupled with the fact that the He density at $\rho = 0.3$ responds within ~ 20 ms to the initiation of active pumping suggests that the exhaust of He is limited by the effective exhaust efficiency of the pumping configuration and not by transport of He within the plasma core. This also implies that the He particle confinement time in the core τ_{He} is much less than the residence time of He within the system τ_{He}^* . Modeling results using the MIST impurity transport code (Hulse [14]) confirm this result. This code computes the He density profiles as a function of time given a spatially dependent anomalous diffusivity D_{He} , a pinch velocity [$n_e V_{He} = C_v D_{He} dn_e/dr$], and a global He recycling coefficient R_{He} . For the discharge of interest, the model is very sensitive to the recycling model chosen with the best fit being obtained with a time-dependent recycling model. The sensitivity to the recycling model used in the simulation is demonstrated in Fig. 2 where the simulated data is plotted for a fixed $R_{He} = 0.95$, a fixed $R_{He} = 0.98$, and a steadily increasing

R_{He} with the initial $R_{He} = 0.95$. In all cases, R_{He} is assumed to be unity before the OSP at 2.0 s. The best fit to the measured data is obtained with a steadily increasing R_{He} with $R_{He} = 0.95$ just after the initiation of active He exhaust at 2.0 s. This result implies that $\tau_{He} \approx 0.05 \tau_{He}^*$, providing further confirmation that the helium exhaust in this case is not limited by He transport within the core plasma. Also, this implies that the global particle confinement time τ_{He} is actually less than the energy confinement time τ_E .

Within the limited data set obtained to date, the only systematic variation of major plasma parameters is that of injected beam power. From this data, the ratio τ_{He}^*/τ_E appears to be fairly insensitive to the level of injected power, consistently falling in the range $8 \leq \tau_{He}^*/\tau_E \leq 15$ and is clearly within the range generally considered necessary for successful reactor operation. It should be pointed out that the plasma conditions in the discharges from which the data for this figure were taken were not individually optimized for maximum helium exhaust.

3. PREFERENTIAL PUMPING OF HELIUM

Another important issue in the area of helium exhaust is whether or not it is possible to remove helium preferentially (relative to the hydrogen isotopes) in a highly recycling divertor configuration. Such a scheme would reduce the required on-site tritium inventory while still maintaining sufficient helium throughput to prevent significant fuel dilution. Various two-dimensional SOL codes have predicted that this may be possible in a highly recycling divertor in the presence of a strong deuterium flux to the the divertor plate (Cohen [16]). To address this issue, preliminary studies on DIII-D have been conducted to determine if such a separation exists. These experiments are conducted in discharge conditions similar to the helium exhaust measurements described in Section 2 except that the OSP is swept from the initial (dash curve) to final (solid curve) positions in Fig. 1 at a slow rate (2 cm per 100 ms). The aforementioned penning gauge is used to measure the helium concentration in the baffle region and a capacitance monitor is used to measure the total pressure. Note that because of non-linearities in the penning gauge for pressures above ~2 mTorr, the helium fraction cannot be obtained above this pressure. These experiments were performed without Ar frosting of the cryopump.

In Ohmic discharges [Fig. 3(a)], there is a clear increase in both the He partial pressure and He atomic fraction $n_{He} / (n_{He} + n_D)$ in the pumping plenum as the OSP is swept outward and then a subsequent decrease as the OSP is moved up on the bias ring (Fig. 1). Conversely, in beam-heated discharges, the helium fraction in the pumping plenum appears to be insensitive to OSP location [Fig. 3(b)]. Unfortunately, because of the aforementioned non-linearities in the penning gauge for pressures above ~2 mTorr, the helium fraction cannot be obtained in the beam-heated case for OSP locations closer than 2 cm to the baffle entrance. In the beam-heated case, the core helium atomic fraction as measured by CER is approximately constant throughout the discharge at ~0.14. This suggests a fairly strong dilution of helium as it flows from the plasma core to the

pumping plenum. Core concentration measurements via CER are not possible in the Ohmic discharge.

Fig. 3. Measured helium fraction (solid circles) and pressure (open triangles) in the pumping plenum of DIII-D during an OSP sweep as a function of the minimum distance from the bias ring to the separatrix (see Fig. 1) in an (a) Ohmic discharge and (b) 10 MW NBI-heated discharge. Negative distance results when the OSP is swept onto the bias ring.

In an attempt to understand the above observations, extensive modeling of these cases has been carried out with the b2.5 SOL transport code (Braams [17]). A survey consisting of approximately 450 different cases has been done in which each of the main parameters

determining the physics in the SOL are systematically varied over a fairly large range. These parameters include the particle diffusivity, thermal conductivity for electrons and ions, pinch velocity, recycling coefficients for helium and hydrogen, power entering the SOL from the main plasma, and the electron density and temperature at the separatrix. The model includes a proper representation of the the DIII-D divertor geometry. The main result of this survey is that there are only a few cases that exhibit enrichment of the helium concentration in the baffle relative to the concentration in the plasma core (see Fig. 4). Furthermore, all of the cases that exhibit enrichment are at low input power. Further b2.5 modeling has also been done in which it is assumed that the particle diffusivity in the SOL increases as the injected beam power increases. Such an assumption is based on the fact that previous measurements of particle diffusivity in the plasma core have shown such an increase with increasing beam power. Using these assumptions, b2.5 predicts that at low injected power (and low particle diffusivity), the helium concentration profile at the divertor plate peaks approximately 4 cm outside the OSP location whereas in higher injection (and higher particle diffusivity) the helium concentration peaks at the OSP location. Presently, more work is in progress to compare the model's predicted density, temperature and heat flux at the divertor target with Langmuir probe and infrared camera measurements.

Fig. 4. Results from a survey of ~450 cases using the b2.5 SOL code to predict the helium fraction in the pumping plenum given a wide range of SOL parameters. The table indicates the range of variation in each of these parameters.

4. CONCLUSIONS

The successful exhaust of helium demonstrated in these experiments is very encouraging, especially considering that the calculated exhaust efficiency in this experiment was only ~5%. An equally encouraging result from this study is that the global helium confinement time τ_{He} is actually less than the energy confinement time τ_E . Further optimization of these results should be possible, considering the small number of discharges in which helium exhaust has been performed thus far on DIII-D. These results should eliminate some of the concern about He ash removal in ITER if such a device is operated in an ELMing H-mode regime.

In the area of preferential pumping of helium, there are few strong conclusions that can be drawn at this point from the limited data set on DIII-D. However, it does appear that some effect related to higher heating power strongly limits the degree of separation of helium from the main ion flux at the divertor target and therefore limits the obtainable helium fraction in the divertor pumping plenum.

REFERENCES

- [1] D.L. Hillis, *et al.*, Phys. Rev. Lett. **65**, 2382 (1990).
- [2] D.L. Hillis, *et al.*, in *Proceedings of the Thirteenth International Conference on Plasma Physics and Nuclear Fusion Research, Washington, 1990* (International Atomic Energy Agency, Vienna 1991), Vol. 3, p. 597.
- [3] E.J. Synakowski, *et al.*, Phys. Rev. Lett. **65**, 2255 (1990).
- [4] H. Nakamura, *et al.*, Phys. Rev. Lett. **67**, 2658 (1991).
- [5] E.J. Synakowski, *et al.*, Phys. Fluids B **5**, 2215 (1993).
- [6] D.L. Hillis, *et al.*, J. Nucl. Mater. **196-198**, 35 (1992).
- [7] D. Reiter, *et al.*, Nucl. Fusion **30**, 2141 (1990).
- [8] M.M. Menon, *et al.*, Fusion Technol. **22**, 356 (1992).
- [9] J.P. Smith, *et al.*, in *Proceedings of the 15th IEEE/NPSS Symposium on Fusion Engineering, Hyannis, 1993* (IEEE, to be published, 1994),
- [10] K. Schaubel, *et al.*, Advances in Cryogenic Engineering **39**, (1994).
- [11] L.L. Lao, *et al.*, Nucl. Fusion **30**, 1035 (1990).
- [12] P. Gohil, *et al.*, in *Proceedings of the 14th Symposium on Fusion Engineering, San Diego, 1992* (IEEE, New York, 1992), Vol. 2, p. 1199.
- [13] K.H. Finken, *et al.*, Rev. Sci. Instrum. **63**, 1 (1992).
- [14] R.H. Hulse, Nucl. Technol. Fusion **3**, 259 (1983).
- [15] C.C. Klepper *et al.*, Nucl. Fusion **33**, 533 (1993).
- [16] S.A. Cohen *et al.*, in *Proceedings of the Thirteenth International Conference on Plasma Physics and Nuclear Fusion Research, Washington, 1990* (International Atomic Energy Agency, Vienna 1991), Vol. 3, p. 321.
- [17] B.J. Braams and D.K. Rayevski, Bull. Am. Phys. Soc. **38**, 1919 (1993).

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of the DIII-D operations staff. This research was sponsored by the U.S. Department of Energy, under Contracts DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. and DE-AC03-89ER51114 with General Atomics.

DATE

FILMED

9/22/94

END