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Helium Transport and Pumping Measurements in Reactor-Relevant Plasma Configurations in JET

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1. Introduction

Control of helium (He) ash produced in deuterium-tritium (DT) fusion reactions is one of the key issues affecting the performance of a fusion reactor. The removal of He ash would be determined by a combination of: the intrinsic transport of helium in the plasma τ_p(He), where τ_p is the particle confinement time; enrichment and compression of helium in the divertor, η(He); and the pumping efficiency for helium S_p(He).

Thus the problem is one of system integration and is only partially determined by basic plasma physics. Several studies have identified target figures of merit for these quantities. The Wolf-Reiter-Kever condition [1] requires that τ_p^* (He)/$\tau_E \leq 15$, where $\tau_p^* = \tau_p/(1-R_{eff})$, with R_{eff} as the He recycling coefficient, and τ_E the energy confinement time. If this quantity is kept below the critical value then the build-up of He ash, and consequent reactor fuel dilution, can be avoided. The ITER design [2] requires $\eta \geq 0.2$ where

$$\eta = (P_{He}/2P_{D2})_{Divertor} / (n_{He}/n_D)_{core}$$

In the JET experiments, a realistic simulation of the ITER plasma shape was combined with a helium pumping capability of the JET Pumped Divertor (PD) cryopump using Argon frosting. The experiments were performed in the '*MkII GB*' divertor configuration [3].

2. Calibration of the Argon Frosting

The pumping speed of the PD cryopump for helium was first measured as a function of various Argon frost coatings using sequential He and D_2 gas pulses. The results are shown in Fig.1. The experiments established the systematic behaviour of the pumping as a function of the ratio of the deuterium + helium gas condensed on the Supercritical Helium (ScHe) cooled PD panels to the amount of argon frost condensed (N(D_2+He):N(Ar)).

The experiments showed that (see Fig.1):

- S_p(He) is a universal function of r(D_2,He:Ar) = N(D_2+He):N(Ar) where N(Ar) is the amount of Argon layed down in the *most recent* frosting;
- S_p(He) does not depend on the thickness of the Argon layer (for given r);
- a refresh layer restores the pumping to its original value;
- a maximum value of S_p(He) ~ 90m^3.s^{-1} could be achieved. This is about 75% of the PD pumping speed for deuterium ($S_p(D_2)$ ~ 120m^3.s^{-1}).

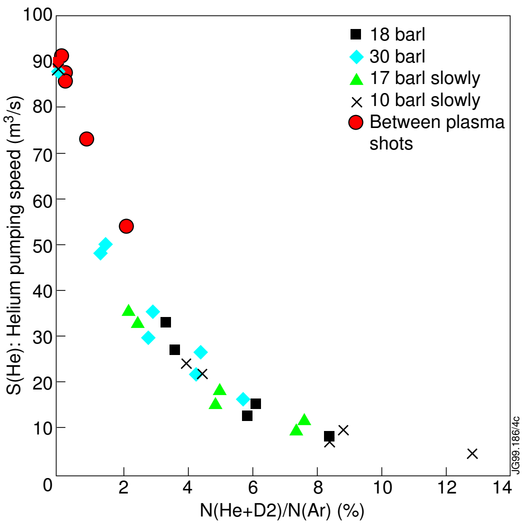

Fig.1: Pumping speed for the Argon frosted PD Cryopump as a function of He + D_2 loading

3. Overview of Experiments with Plasma

The experiments were performed in diverted plasma configurations as shown in Fig.2. Helium gas was puffed into plasmas heated by Neutral Beam Injection (NBI) at various power levels. The plasma helium concentration was measured using Charge Exchange Recombination Spectroscopy (CXRS) of the helium ions on the D^o NBI. The divertor helium content was measured using a Penning gauge fitted with a spectrometer to view the He light in the discharge [4]. Edge impurity spectrometers observed HeI and HeII lines. Spectroscopy was also used to examine any Argon contamination of the plasma.

Results were taken on the decay of He in L mode plasma (Ip=2.35MA, B_T=2.5T with 2.5MW NBI) with strike zones on the divertor Vertical Targets (V) - see Fig.2. More extensive data on He removal were taken in ELMy H-mode plasmas with I_p=1.9MA, B_T=2.0T (similar q values to the ITER reference design [2]). Parameter scans in the ELMy H-mode compared He removal for:

- corner (C) strike zone position vs vertical target (V) strike zone position (see Fig.2);
- low triangularity ($\delta \sim 0.22$) vs high triangularity ($\delta \sim 0.35$);
- medium NBI power (10MW) vs high NBI power (14.5MW);
- no added D_2 gas puffing vs D_2 gas puffing ($\phi_D \sim 10^{22}\ s^{-1}$).

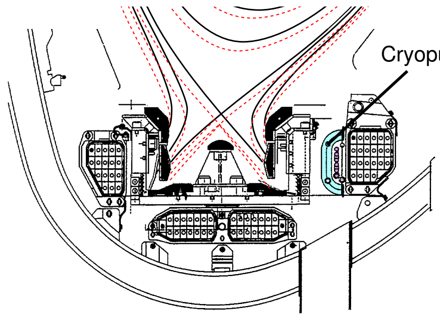

Fig.2: Divertor configurations for ELMy H-modes Solid (Black) Vertical Target: Dashed (Red) Corner Target. The vertical target configuration was also used for L-mode

Between plasma shots, the He pumping speed of the PD Argon frost layer was calibrated with puffs of He gas into the Torus. It was found that a similar dependence on r(D_2, He;Ar) held as in the gas-only calibration runs (see Fig.1) showing that the effect of D_2 loading of the Argon layer was independent of the origin of the D_2. It was also found that the Argon layer provided adequate pumping for two or three plasma shots.

4. Results: (I) L-mode

A value of τ_p^*(He)/$\tau_E \sim 10$ was obtained for L-mode discharges. No L-mode parameter scans were performed, as experiments concentrated on the more reactor-relevant ELMy H-mode.

5. Results: (II) ELMy H-mode

A comparison of a low triangularity/Corner strike zone (LT/C) discharge with a low triangularity/vertical target strike zone discharge (LT/V) is shown in Fig.3. In general, the ELMy H-modes had good quality with high confinement (H97 factors of 1.25-1.4) and low Z_{eff} with little sign of Argon contamination.

Figure 3 shows that τ_p^*(He) is much lower in the LT/C configuration, due to the enhanced pumping of He arising from the higher pressure at the pump throat (Fig.3(d)) in this configuration. At these elevated pump speeds, a value of τ_p^*(He)/$\tau_E \sim 7.6$ was achieved, well within the range required by a reactor and similar to values achieved in DIIID [5], JT-60U [6] and ASDEX-U [7]. The decay time of the He concentration was similar at all radii within the plasma being about 25% higher towards the plasma edge. The He profile thus relaxed in a self-similar manner with ∇n(He)/n(He) remaining approximately constant.

Other results which were achieved in the ELMy H-mode are:

- τ_p^*(He) is essentially independent of triangularity;
- τ_p^*(He)/τ_E is essentially independent NBI power input;
- η (He) enrichment values of were in the range ~ 0.5-1.0.

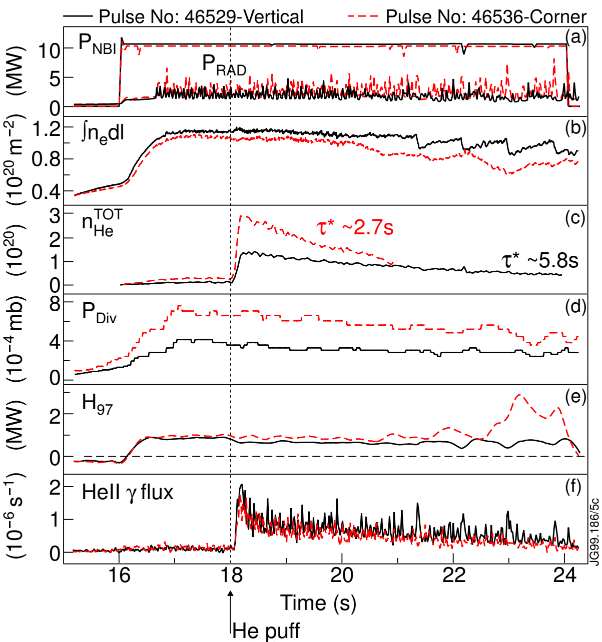

Fig.3: Comparison of helium concentration decay (c) and (f) for two ELMy H-modes (1.9MA/2.0T) at constant input power

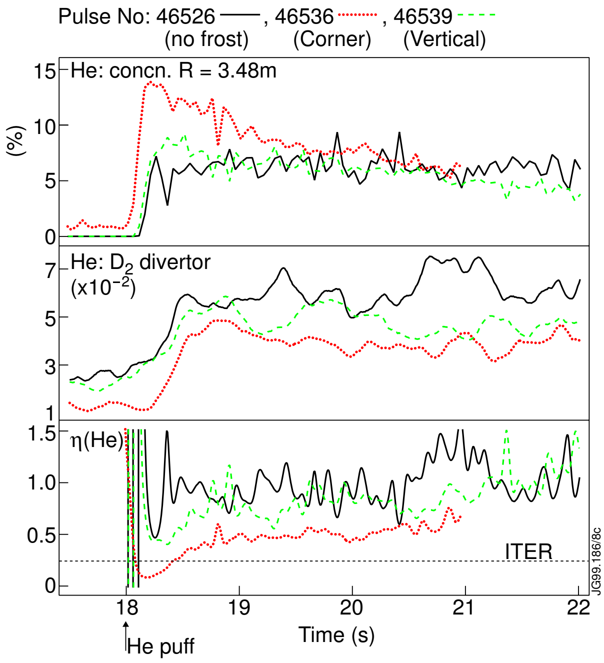

Fig.4: Comparison of bulk plasma He concentration and divertor He ratios for three identically heated 1.9MA/2.0T ELMy H-modes at constant q

The He enrichment in the divertor is thus sufficient for a reactor such as ITER. There is a tendency for η to decline as the efficiency of the pumping is raised (Fig.4) but the ITER criterion is always satisfied.

The *mean* He removal rate in the LT/C configuration in Fig.4 is $S_p(He).p_{div}(He)$ ~ $(50m^3.s^{-1}).(3.5\ 10^{-5}mbar)$ ~ $1.8\ 10^{-3}mbar.m^3.s^{-1}$. The ratio of removal rate to the plasma volume (V_p ~ $80m^3$) is similar to the design basis ratio for ITER [2]: $S_p(He).p_{div}(He)/V_p$ ~ $2.3.10^{-5}$ $mbar.s^{-1}$ for JET compared to ~ $1.8\ 10^{-5}mbar.s^{-1}$ for ITER.

Strong gas puffing tends to cause $\tau_p^*(He)/\tau_E$ to increase by ~ 40%, but this is mainly because τ_E declines as the electron density increases in the gas puff discharges, where the electron density reaches ~ 70% of the Greenwald Limit.

Since successive plasma shots are performed on the same Argon frost layer, because of the shot to shot variation in $r(D_2$, He:Ar), identical shots with different $S_p(He)$ can be compared. Using this method the value of He particle confinement time ($\tau_p(He)$) can be established. By definition:

$$\tau_p^*(He) = \tau_p(He)/(1-R_{eff}) \qquad (1)$$

where $R_{eff} = (1- \varepsilon_{scr})R_{ret}$; R_{ret} being the 'return coefficient' and ε_{scr} the 'screening efficiency' of the plasma for a particular species. R_{eff} can also be expressed in terms of R_{ret} using the fuelling efficiency (γ) for a returning species:

$$R_{eff} = \gamma R_{ret}/(1-(1-\gamma)R_{ret}) \qquad (2)$$

The return coefficient relates to pump efficiency (ε_p) and wall pumping efficiency (ε_w) as:

$$R_{ret} = (1-\varepsilon_p)(1-\varepsilon_w) \qquad (3)$$

Thus, using the absence of wall pumping of helium ($\varepsilon_w = 0$) and expressing ε_p as $S_p.p_{div}/\Phi_{out}$, where Φ_{out} is the He outflux one can rewrite (1), using (2) and (3) as:

$$\tau_p^*(He) = \tau_p(He) \left[1 + \gamma \left(\frac{\Phi_{out}}{S_p.p_{div}} -1 \right) \right] \qquad (4)$$

Hence τ_p^*(He) is plotted against $^1/S_p.p_{div}$ for constant plasma configuration and conditions (Φ_{out} and γ constant), *extrapolation to infinite pumping speed* gives (since γ <<1) a value for τ_p(He). This is shown for two (LT/C) configuration plasmas in Fig.5, where the rudimentary method gives a value of τ_p(He) ~ 1.3s for a 1.9MA/2.0T ELMy H-mode with 10MW NBI ie: $\tau_p(He)/\tau_E = 4$.

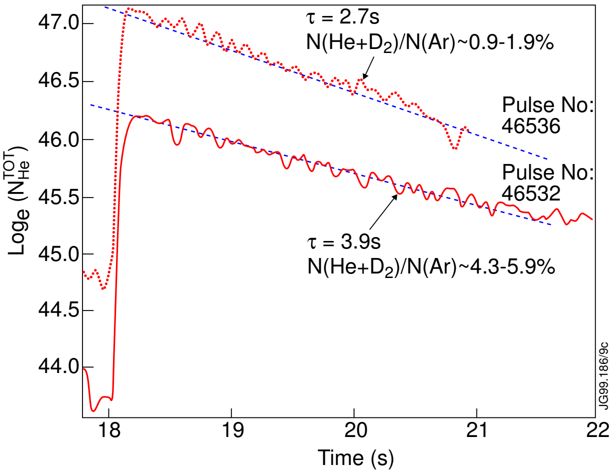

Fig.5(a): Central He decay rates for identical 1.9MA/2.0T ELMy H-modes as a function of PD pump loading.

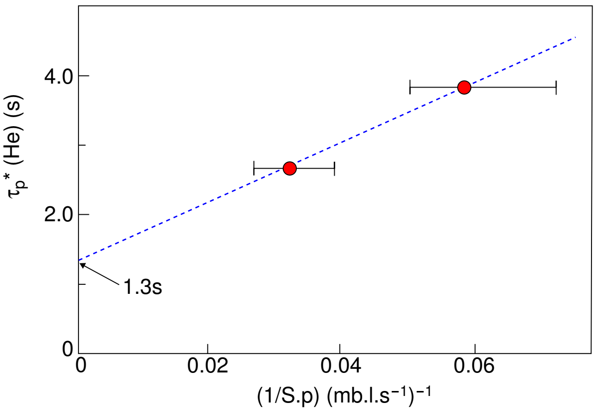

Fig.5(b): Extrapolation of data on τ_p^*(He) to obtain τ_p(He) at infinite pumping

6. Discussion and Conclusions

The experiments show that He pumping conditions which are relevant to the ITER pumping regime (S_p(He).p_{div}(He)/V_p) can be achieved in JET using the Argon frosted PD cryopump. Also, using the variable, but calibrated, pumping speed for the Argon layer one can infer the helium particle confinement time (τ_p(He)). For a JET ELMy H-mode at 1.9MA/2.0T which has similar properties to the ITER reference design (q_{95} ~3.1; $\beta_N^{thermal}$ ~1.8) a value of τ_p(He) ~ 1.3s has been established.

In JET ELMy H-modes and with optimum pumping without strong gas puffing, the ratio $\tau_p^*(He)/\tau_E$ ~ 7.6 is measured. In configurations with poorer pumping this worsens to ~15. The ratio is independent of plasma triangularity and, over the limited range tested, of NBI power. The ratio also worsens with strong gas puffing principally because τ_E declines as the Greenwald Limit is approached. For a typical L-mode discharge a value of $\tau_p^*(He)/\tau_E$ ~ 10 has been measured. Results on particle transport parameters (D(He) and v_r(He)) are still being evaluated.

The 'enrichment' parameter for helium in the divertor is in the range $0.5 \le \eta(He) \le 1.0$ in ELMy H modes. This value exceeds the requirements for an ITER type reactor ($\eta \ge 0.2$) by a considerable margin. The values of $\tau_p^*(He)/\tau_E$ show that *helium transport per se will not be a limiting factor in reactor performance* and that accumulation of He ash should not be a problem in a reactor.

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