Experiments on helium enrichment and removal at JET

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Introduction

Helium ash removal is a critical issue for a fusion reactor requiring that the helium residence time $\tau_{\text{He}}^{*} \leq 14 \tau_{E}^{*}$ If impurities other than He are present in a fusion reactor, the ratio between $\tau_{\text{He}}^{*}$ and $\tau_{E}^{*}$ is further reduced; the pumping speed of ITER has been selected to allow for a steady state operation with respect to this requirement. In tokamaks with pump limiters or divertor pumping, this required helium removal rate can be fulfilled; the margin, however, becomes critical for enhanced confinement discharges as required for a reactor. A good compression of the helium in the divertor is therefore a key parameter for sufficient He ash removal.

In order to optimise the particle exhaust, the helium removal of different divertor strike point configurations in the gas box divertor MARK II GB has been investigated. The helium partial pressure in the subdivertor region is measured by a modified Penning discharge, and inside the plasma passive and active (CXRS) spectroscopic data are utilised although it must be pointed out the later is quite challenging. The experiments have been performed both with helium gas injection at the plasma edge and with the injection of energetic helium by neutral beams to deposit He in the core plasma region; for some discharges the divertor cryo pump was only pumping deuterium while for other runs an Ar frost layer was deposited in order to enable helium pumping.

Helium enrichment without pumping

The helium exhaust is characterised by the ratios of the helium concentration in the core and the SOL and by the compression within the divertor. The first part depends on the transverse transport in the core and the edge region and the latter on the parallel flow into the divertor and the recycling pattern. In order to simplify the analysis, at first a discharge without He pumping is analysed. Fig. 1 shows the Helium concentration from CXRS at three different radial positions as a function of time for an ELMy H-mode discharge (# 52842). In this discharge two puffs of helium gas have been injected namely at 19.5 s and at 26 s. In order to study the helium removal, the divertor strike point locations have been varied, namely the inner and outer strike points are located in the respective divertor corners from 15.5 s to 22.5 s and are raised to the side target plates from 22.5 s to 29 s; the D- NBI was operated from 18.6 s to 28.3 s.

Fig. 1 shows the sudden rise of the He concentration signal just after the injection of the helium gas (each He puff 6.9 mbarl). The initial helium concentration of about 3% is left over
from the previous discharge due to helium wall storage. The total number of He ions increases by $\Delta \text{He} \approx 3 \times 10^{19}$ ions per gas puff corresponding to a fuelling efficiency of close to 100%.

For the first divertor phase, the helium concentration for the three chords shown in Fig. 1 is roughly the same. There is, however, a tendency that the highest helium concentration is reached at the plasma edge while the core concentration increases steadily to the end of this phase, i.e. over 4 s. This inward transport of the helium requires further modelling.

During the second phase, where the strike points are raised to the side plates, the edge helium concentration decreases while the core concentration remains nearly constant during this movement. The behaviour following the second He-puff is similar to that following the first one. The channel at a normalised radius of $\rho=0.99$ shows a relatively small increase.

The radial distribution for two times, one after the first He-injection ($t=21$ s) and the other after the second ($t=27$ s), are shown in Fig. 2. At these two time slices one finds the maximum helium concentration at around $\rho=0.5$. Towards the core, the inward transport may not yet be completed. There is also a drop towards the edge which is more pronounced for the side-plate phase than for the corner one. The He concentration is reduced at the plasma edge by about a factor of two, or even more. This reduction of the helium concentration at the edge would be in agreement with the often-observed reduction of enrichment of the helium concentration in the divertor as compared to the core. This reduction is normally attributed to the compression properties of the SOL; these data may indicate that the radial transport near the edge barrier requires particular considerations.

The partial pressures for deuterium and helium are shown in Fig. 3. In the first divertor configuration, the D$_2$ and He pressures reach values of $3 \times 10^{-3}$ mbar and $3 \times 10^{-4}$ mbar. With the strike points on the side target, both the D$_2$ and He pressures are strongly reduced. The enrichment factor, $\eta_{\text{He}} = C_{\text{He}}^\text{edge}/C_{\text{He}}^\text{core}$, where $C_{\text{He}}^\text{edge}$ is the He concentration in the edge/divertor as measured by the Penning gauge and $C_{\text{He}}^\text{core}$ is the core He concentration as measured by CER Spectroscopy. For the case with the strike points located in the corner position ($15.5$ s to $22.5$ s) $\eta_{\text{He}} \approx 1.0$, while for the case with

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Helium concentration as a function of time at three radial positions ($\rho=0$: blue, $\rho=0.2$: pink, $\rho=0.99$: green).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Radial helium distribution at two different times in the discharge}
\end{figure}
the strike points placed on the vertical target $\eta_{\text{He}} \approx 0.6$, very similar as observed earlier. Typical enrichment values found on JET for the Mk2 divertor configuration were $\eta_{\text{He}} \approx 0.8 - 1.1$ for the corner configuration. For DIII-D, recent measurements found $\eta_{\text{He}} \approx 0.9$.

Experiments with different strike point locations show that the highest pressure contribution comes from the inner divertor leg, even though this strike point is usually detached.

**Helium removal studies**

In order to study helium removal on JET, Ar has been deposited on to the panels of the divertor cryo pumps. The Ar deposited prior to the discharge was 30 barl at the beginning of the campaign and additionally 10 barl after every shot. This procedure provided an initial He pumping speed of 100 m$^3$/s after the activation which was further reduced during the shot down to 40 m$^3$/s. The reduction of the pumping speed results from the competition of D and He for the traps on the pump such that during discharges the deuterium is mainly responsible for the reduction of the pumping speed. During the discharge, an average helium pumping speed of 70 m$^3$/s may be used. The Ar frosting can be repeated until 60 barl of Ar has been deposited on the pumps; at higher deposition values Ar may be released with the attendant risk of provoking disruptions.

An example of a He pumped discharge is shown in Fig. 4. With the exception of the pumping, the discharge is similar to the previous one. As in Fig. 1, the helium gas puffs (each 12.4 mbarl) lead to a rapid increase of the helium concentration of about 7.5 %. Due to the activated pump, the helium is removed from the plasma with a residence time inside the plasma of about $\tau_{\text{He}}^{*} = 2.5$ s (green fitted curve). When the divertor strike points start to move upwards, the helium exhaust ceases and the concentration remains at about 3.8 %.

The figure of merit for the helium removal is the ratio of the helium residence time to the energy confinement time. For the given discharge, the value of $\tau_{\text{He}} = 0.5$ s yielding a figure of
merit ratio of 5. This number is probably sufficient for a burning reactor at a moderate impurity level.

The partial pressures of deuterium (blue curve) and the helium (pink curve) in the divertor are shown in Fig. 5. Following the first He gas puff, the He enrichment \( n_{\text{He}} \approx 0.5 \) in the corner configuration (15.5 s to 22.5 s); however, when the strike points are moved onto the vertical target then \( n_{\text{He}} \) is further reduced to a value of 0.3.

If the injected amount of He (12.4 mbarl) is equated to pumped helium \( Q_{\text{pump}} = S_{\text{He}} \cdot P_{\text{He}} \cdot \tau_{\text{He}} \), the effective pumping speed for helium at the location of the Penning gauge entrance is found to be \( S_{\text{He}} = 94 \, \text{m}^3/\text{s} \); this value sounds rather plausible. Finally, a quantity of interest is the reduction of the helium partial pressure in the divertor chamber due to the pumping. The ratio of the divertor helium partial pressure (with and without pumping) normalised to the input helium puff is:

\[
\frac{P_{\text{div}}/Q_{\text{He}} \mid \text{with pumping}}{P_{\text{div}}/Q_{\text{He}} \mid \text{no pumping}} = 0.1
\]

This shows that the helium partial pressure is strongly reduced by the pumping. Modelling may reveal whether this strong reduction is due to the high recycling.

References


Fig. 5: Sub-divertor helium and deuterium pressures and helium concentration for a actively pumped discharge.