

Helium Discharge Operation in TCV

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Introduction

There is presently considerable interest in the behaviour and physics occurring in helium discharges compared with deuterium operation. Many of the differences can be ascribed to the changes in impurity production resulting from He operation, where plasma-wall chemistry is virtually absent and atomic physics cross-sections differ markedly. In TCV, an all graphite machine, carbon is the dominant plasma impurity and the use of He is a particularly useful tool for investigating C production processes. Similar discharges in He and D have been performed with the aim of examining the impurity behaviour, the influence on the density limits, detachment and the L-H transition.

Operational conditions and diagnostics

To obtain He discharges on TCV, a standard deuterium prefill was required, followed by He gas fuelling. In this study, ohmically heated configurations, single null lower (SNL) configurations were performed, both with $I_p = 340$ kA, discharge duration ~ 1 s (flattop), typical electron densities of $7 \times 10^{19} \text{ m}^{-3}$. The ion $\nabla \times B$ drift direction was away from the X-point for the SNL configuration.

Visible spectroscopic diagnostics with one horizontal and two vertical views (see Fig. 1) combined with one vertical view of UV spectroscopy (SPRED) and soft-X ray cameras are used to observe the plasma impurities behaviour (C II -V, He I- II, D_α). In addition a neutral particle analyser (NPA) and a standard foil bolometer allow us to evaluate the neutral D flux and the total radiated power. For the profiles in the SOL plasma, target Langmuir probes were used.

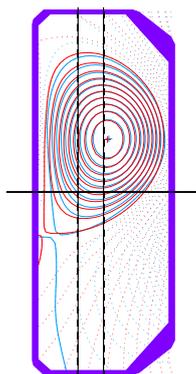


Fig. 1. Equilibria for two divertor configurations in D plasma: SDL (red) and LDL (blue) Also shown the two vertical views for visible spectroscopy (2, 3), SPRED (3) and horizontal view (4).

D-He and He-D changeover

Changeover from D to He was rapid, with He/(He+D) ratios already $\sim 60\%$ at the end of the first discharge with more than 80% after ~ 6 identical discharges (see Fig. 2). The He/(He+D) ratios are calculated using the HeI line at 728 nm and the D_α at 652 nm, corrected for the S/ XB assuming an edge temperature of 20 eV. The plasma D neutral flux observed with the NPA decreases to very low values within 0.25 s into the discharge showing that the walls have effectively pumped the D prefill. All carbon lines have lower intensity in He plasmas compared with equivalent D discharges, with Z_{eff} approaching 2 at the highest densities. Figure 3 shows the signal from SX, UV and visible spectrosc-

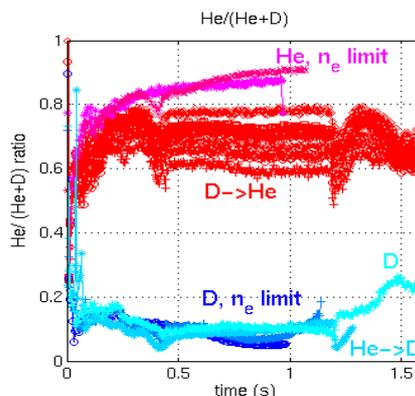


Fig. 2. Evolution of the He/(He+D) ratio during similar He and D shots.

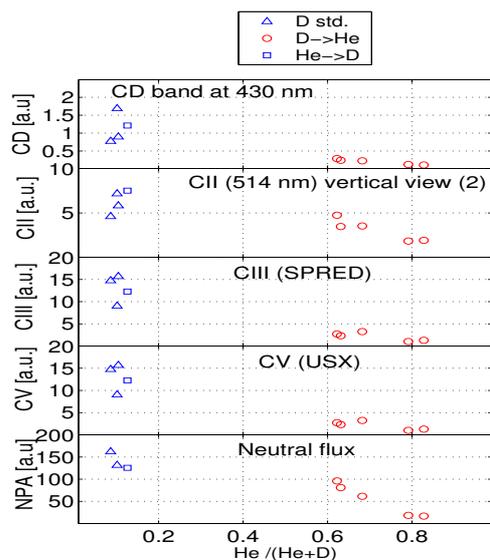


Fig. 3 CD band, carbon emission and neutrals behavior during the D-He changeover.

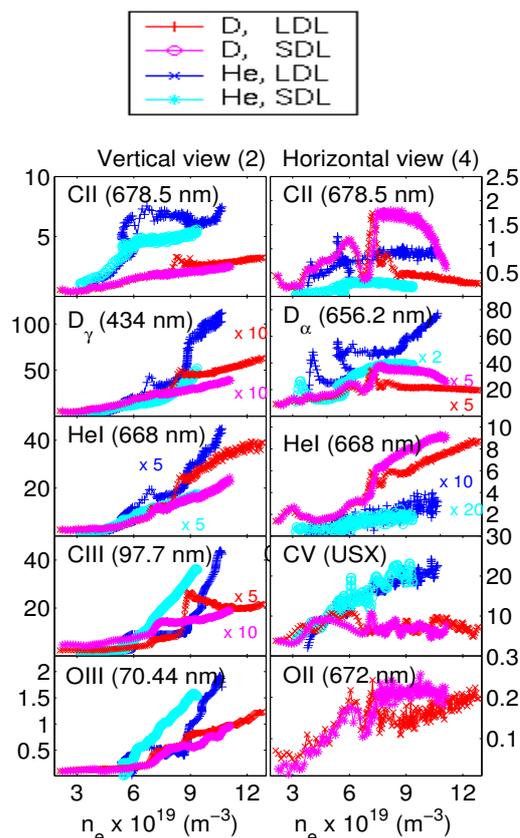


Fig. 4. Impurity dependence on electron density for both vertical and horizontal view. The CV dependence was inserted in the same graph to facilitate the comparison. Values are in [a.u.].

copy. The CII radiation, emitted at the plasma edge, is seen to decrease only by a factor ~ 2 while CIII- CV intensities show a stronger decrease (~ 4).

The backward He->D changeover was characterised by similar, or even higher, D neutral flux. The emission intensity of molecular bands of CD fell to low levels for all the He discharges and immediately returned to pre-He levels in the first return discharge.

Impurity behaviour

A set of four discharges ending in density limits were performed in D and He with two different divertor configurations, in order to compare the impurity production and behaviour and determine the density limit of He plasmas in TCV. One configuration has the last closed flux surface (LCFS) at ~ 2.5 cm from the inner wall and a small divertor leg (SDL) whereas the other has the LCFS at ~ 4.5 cm with a long divertor leg (LDL) connecting the bottom wall. The equilibria for the two configurations are shown in Fig. 1. The CII radiation, (see Fig. 4), is localised at the plasma edge with the vertical chord viewing the region of the outer divertor leg and the horizontal chord viewing the region of the inner wall. For the divertor view, there is $\sim 2x$ more carbon in D than in He with a slight intensity increase with n_e for both D and He. This would be the expected behaviour if chemical sputtering is the predominant production mechanism. For the inner wall view, CII shows a strong decrease with n_e (direct physical sputtering) and higher values in He SDL configuration than LDL one. The CV radiation, which is more characteristic of the plasma bulk, again increases with n_e in D but does not change with n_e in He, for both configurations.

Oxygen has similar behaviour in D and He for both configurations and its content does not decrease by more than $\sim 2x$ when passing from D to He. The presence of O could play a role in the production of C as the sputtering yield of O on C, Y_{O-C} is $\sim 10x$ higher than all the other sputtering yields (Y_{D-C}, Y_{C-C}) for these ion energies and could add to the chemical sputtering of D even in He plasmas. This could explain the higher values for the C levels than observed in other machines. The data show that chemical sputtering is dominating the D plasmas while He physical sputtering together with D (and O) chemical sputtering could be the C production mechanism in He plasmas.

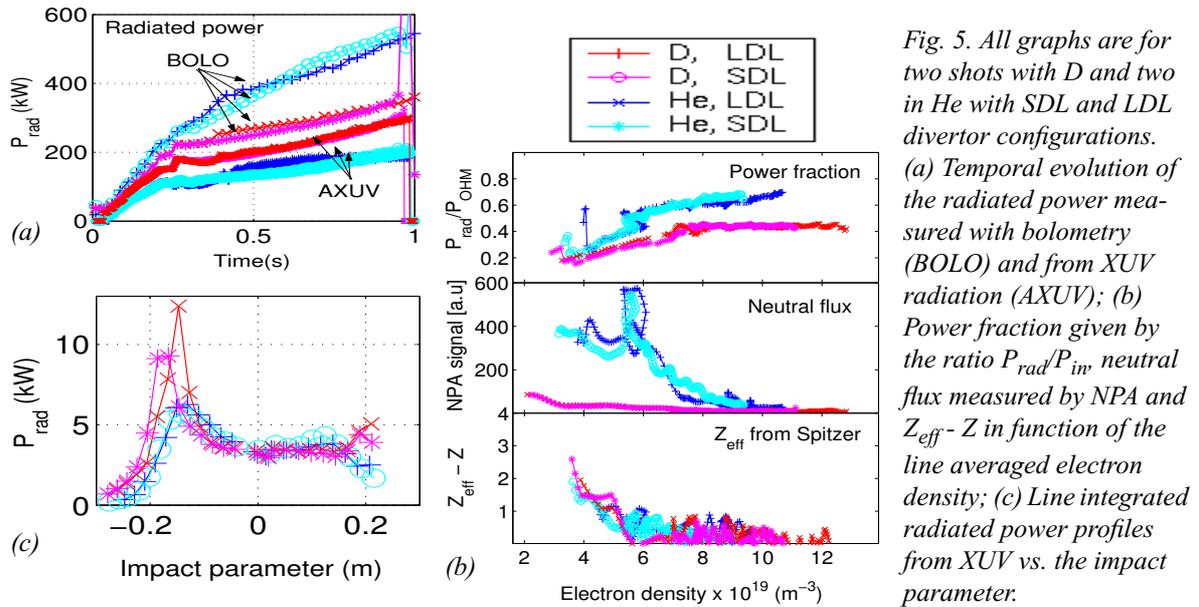


Fig. 5. All graphs are for two shots with D and two in He with SDL and LDL divertor configurations. (a) Temporal evolution of the radiated power measured with bolometry (BOLO) and from XUV radiation (AXUV); (b) Power fraction given by the ratio P_{rad}/P_{in} , neutral flux measured by NPA and $Z_{eff} - Z$ in function of the line averaged electron density; (c) Line integrated radiated power profiles from XUV vs. the impact parameter.

The bolometers measure higher total power in D than He by a factor of 1.5 [see Fig. 5 (a)]. The measured radiation power from the AXUV bolometers, which are not sensitive to the neutral flux, is higher in He, due to higher neutral content in D. The power fraction slightly increases with n_e in D and remains almost constant in He [see Fig. 5 (b)]. The peak emissivity is $\sim 2 - 3x$ higher at the edge and larger in He compared to D [Fig. 5(c)]. This, combined with the spectroscopic results, indicates that He becomes the main radiator for TCV in He plasmas. The electron density and temperature profiles are very similar with 15% higher electron temperature in the He plasmas. The $Z_{eff} - Z$ values from Spitzer calculation [see Fig. 5 (b)] are similar for both D and He plasmas approaching zero at the density limit. This is difficult to understand, since the Z_{eff} depends on $P_{in} * T_e^{3/2}$, so the lower input power in He (about 12%) and the 15% increase of the temperature cancel out. Intuitively, with bulk carbon reduced and almost no CX D outflux (from NPA) in He discharges, the plasma purity should be very high. Better Z_{eff} measurements are required to conclude on this point.

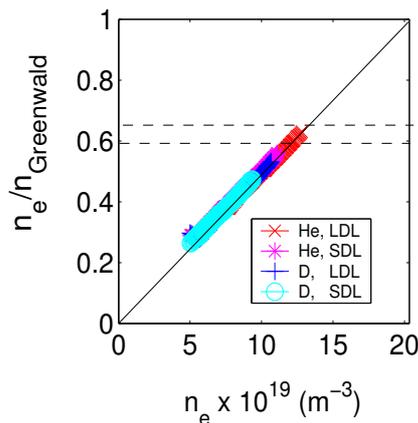


Fig. 6. Electron density normalised to the Greenwald limit ($2.03 \times 10^{20} \text{ m}^{-3}$) for TCV with $I_p = 340 \text{ kA}$ and $a = 0.25 \text{ m}$ vs. density. The dashed lines represent the range of density limits obtained in TCV in D plasmas.

Density limit and H mode

The ohmic density limit in TCV diverted He discharges obtained to date is only $\sim 15\%$ higher than that for a similar D discharge. The density limit on TCV is known to be lower than Greenwald limit, although the reasons for this are not understood. Figure 6 shows the dependence of the normalised density to the Greenwald limit against the density. One can see that the higher density limit obtained in the diverted He discharges is in the range of other TCV shots at $\sim 65\%$ of the Greenwald limit.

First attempts of obtaining an ohmic H-mode (see Fig. 7) in He indicate that the L-H transition power in pure He is significantly higher than in D. Inverted $\nabla \times B$ configuration, most favourable for H mode in D in TCV, a plasma current up to 450 kA with elongations varying

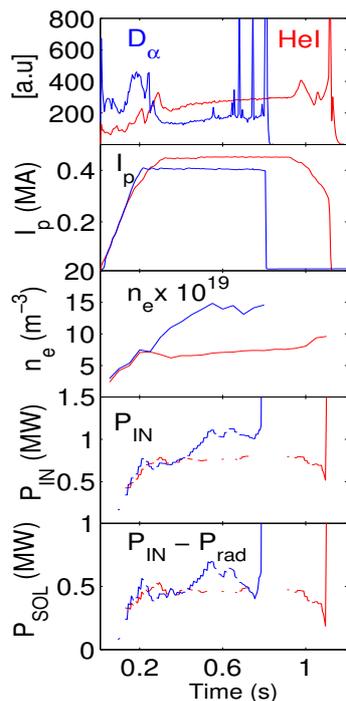


Fig. 7. Comparison between different plasma parameters in two similar shots in He (red line) and D (blue line). Temporal evolution of D_{α} , HeI, plasma current (I_p), averaged electron density (n_e), input power (P_{IN}) and power at the separatrix.

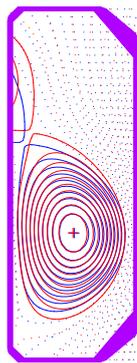


Fig. 8 Two equilibria for He (red line- #22672) and D (blue line- #22680) with inverted configuration at 0.5 s

from 1.6 to 1.75 were performed to locate the conditions for a possible H mode transition. In D, at a lower current than for the He H-mode attempts, with the same plasma configuration and similar values for the power crossing the separatrix, the L-H transition started very early in the discharge followed by an ELM-free phase and concluding with sporadic ELMs and disruption, [Figure 7]. This implies an input power limit exceeding 0.8 MW. In TCV, since ECRH is not efficient at these densities, higher power is not available. This result, which could be very important for the He initiation phase in ITER, is also observed in JET where the power threshold for He H modes is found to be 50% higher than in D H modes, contradicting the theory of the scaling of the power threshold with the mass.

Conclusions

He plasmas with ratios of He/(He + D) higher than 90% at high electron density were obtained in TCV using D prefll. Carbon is reduced to lower values than in D and is replaced by He as the main radiator in these discharges. The core C emission dependence on electron density (increasing with n_e for D and constant with n_e in He) shows that C is basically produced by chemical sputtering in D plasmas. The role of O in the C production must be clarified and comparisons with code simulations performed. The limited number of chords observing the divertor region does not allow us to conclude on the location of the source itself.

The L-H transition power in He is significantly higher than in D, an important conclusion that affects the considerations on the low activation phase in ITER. The density limit in TCV diverted He plasmas attempted thus far appears only to be ~15% higher than that in similar D, This is almost certainly linked to the divertor function and the distribution of edge radiation in TCV. Although not presented in this paper, divertor detachment in He is very different to that observed in D (as in JET). There is no observed rollover of target ion fluxes and both the inner and outer targets remain attached at the highest densities achieved. In similar D plasmas, the TCV outer target detaches easily at low density with the inner target following near the density limit.