

Intrinsic Oxygen and Iron Sources in Tore Supra Long Discharges

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Since the installation of actively cooled plasma facing components over 97% of the Tore Supra vessel in 2001, several experimental campaigns have been dedicated to long discharge operation. Injected energy records have been performed in two situations: **1)** fully non-inductive discharge sustained by means of lower hybrid (LH) current drive (LHCD) alone (best discharge: 1.02 GJ, 6 mn 25 s) [1], **2)** $V_{loop} \approx 0.1$ V discharge sustained by LHCD with ion cyclotron resonance heating (ICRH) in H minority heating scheme throughout the discharge (best discharge: 0.45 GJ, 75 s) [2]. Such long durations are thought to be longer than all time constants playing a role in the particle production (main ion as well as intrinsic impurity species). However,

edge oxygen and iron spectral line emission is often seen to increase during a long discharge (carbon has not evidenced any sign of non stationarity). In the present study, two possible mechanisms of impurity production are studied and the effectiveness of a common conditioning technique, boronisation, is assessed.

Plasma characterisation: in order to evaluate the behaviour in the long duration plasmas of these 'crucial' intrinsic species (O and Fe) several diagnostics are used. The electron density is measured by Thomson scattering and interferometry in the core and reflectometry at the edge. The radial ranges of these diagnostics overlap partly, allowing to check the measurement consistency. The central impurity content behaviour is deduced from the visible bremsstrahlung emission (from which the effective charge, Z_{eff} , is calculated) and soft-X ray emission. A VUV spectrometer line of sight views a plasma diameter, providing the spectral line brightnesses of peripheral ions such as Fe^{14+} (28.41 nm) and O^{4+} (62.97 nm). The ratio of these brightnesses to the local density (here the volume averaged density is used, since the scenario, and hence the density profile shape, is always the same), is roughly proportional to the corresponding emitter density:

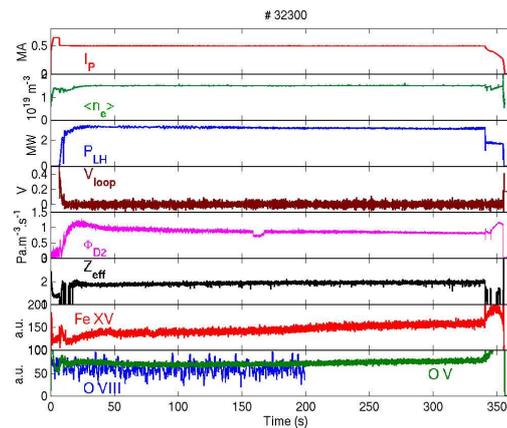


Fig. 1: (top to bottom) plasma current, volume averaged density, LH power, loop voltage, injected D2 flow, radiated power fraction, effective charge, Fe XV, OV and O VIII line brightnesses. Typical LH-only long pulse (32300)

$$n_z = B_{FeXV,OV} / (n_e \times PEC)$$

The photon emissivity coefficient PEC ($\text{m}^3 \text{s}^{-1}$) is considered to be constant over the long pulse database because of the scenario similarity of all pulses. From the preceding equation we obtain also the peripheral impurity density growth rate which will be used to characterise the impurity time evolution:

$$d(\ln n_{Fe^{14+}, O^{4+}}) / dt = d(\ln B_{FeXV,OV}) / dt - d(\ln n_e) / dt$$

General description of impurity behaviour: both scenarios, with LH only and with LH and ICRH, have been described elsewhere [1,2]. A database has been built with about 50 pulses for the first scenario and 15 for the second scenario. For all pulses, the plasma leans on the actively cooled toroidal pump limiter (TPL) made of CFC tiles, which leads to carbon being the dominant plasma impurity (typically 3%). At the typical level of available power (3 MW first scenario, 5-7 MW 2d scenario), the TPL temperature never reaches the 'carbon bloom temperature'. Far SOL interaction with the vessel components made of stainless steel is a potential source of Fe and Ni. Finally, observation of the LH launchers and of the ICRH antennae in the visible and IR domains shows that these can also be a source of impurities (Cu and Ni). They are not studied here. The long discharge impurity content varies along the campaign depending on the vessel conditioning status, of the long discharge scenario and of the scenario of the preceding discharges. Towards the end of a campaign Z_{eff} tends to be constant during a discharge and is typically around 2-2.5, the main contribution being from carbon. The edge O and Fe densities evaluated as above increase (sometimes irregularly) during most discharges, thus questioning the behaviour of the sources in the long discharge scenarios.

Effect of ripple losses: The trajectories of ions and electrons trapped in the magnetic field ripple (large in Tore Supra due to the 20° toroidal angle between neighbouring superconducting coils) have been calculated. Specific plasma facing components (PFC) have been designed and implemented accordingly. Because of the calculation uncertainties and possibly local electric field modifications due to these PFCs, small PFC areas were damaged by the ripple trajectories. To protect these areas additional tiles had to be added along the first experimental campaigns. It seems that the peripheral iron growth rate has lowered since then. However, on the same time scale the scenario has evolved (density and current lowered, geometry slightly changed,...) so that the database does not provide the unbiased information needed. No obvious effect is observed on the Z_{eff} , indicating that the metallic sources were anyway not large enough to contaminate the plasma core. Direct inspection of the vessel at the last opening has not shown any evidence of persisting damage to the PFCs due to the ripple trajectories.

Role of plasma edge conditions: The role of the plasma edge is studied by comparing 3 pairs (at 3 different densities) of similar discharges with or without pumping [3].

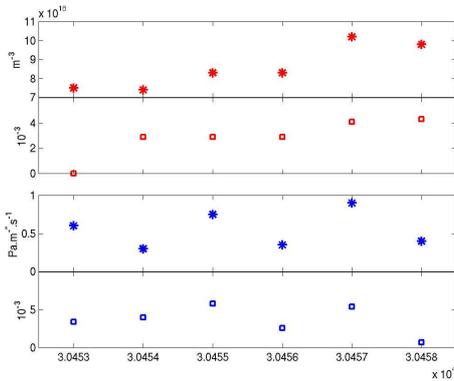


Fig. 2: (top to bottom) electron density on LCFS, edge oxygen growth rate, injected D_2 flow, edge iron growth rate.

The gas injection is fed back on a target density, which leads to quantities of injected D_2 a factor of 2-3 higher in pumped out discharges. Fig. 2 shows, as a function of the pulse number in the series, the density at the last closed magnetic surface, the oxygen growth rate, the injected D_2 flow and the iron growth rate. There is a clear similarity between the first two quantities on the one hand, and between the last two on the other hand.

This indicates that the dominant contribution to the oxygen source variation is oxygen released by charged particle impact on surfaces close to the plasma. Conversely, the dominant mechanism for iron can be inferred to be the interaction between charge exchange neutrals with 'remote' vessel areas (first wall stainless steel panels). Note that the correlation using the whole long pulse database is unclear, which means that parameters other than the above two play a significant role in the iron and oxygen production.

Conditioning by boronisation: Vessel conditioning is particularly important in the

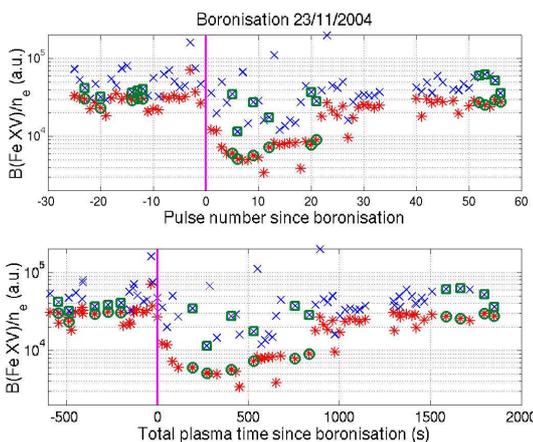


Fig. 3: Fe XV brightness normalised to n_e (\propto edge n_{Fe14+}) as a function of (top) pulse number, (bottom) plasma time. *: flat top average, \times : maximum, \square and \circ : long pulses. Vertical magenta line indicates boronisation.

long discharge scenarios, part of which is a trade-off between the density (not too high, in order to be able to sustain as much as possible of the plasma current with the available LH power) and the Z_{eff} (not too high, in order to have the best possible current drive efficiency). Vessel conditioning is routinely performed on Tore Supra with boronisation [4]. Boronisation has been shown to reduce the oxygen and iron sources [5] by a

factor 2-6 and 3-8 respectively, as illustrated for iron on Fig. 3. A database of 11 boronisations performed between 2002 and 2004 has been analysed. Two of them

were performed at too low a vessel temperature ($< 150^{\circ}\text{C}$) and have been excluded from the study. For the others, the boronisation effect reduces the Z_{eff} at the beginning of a campaign but never enough to enhance the LHCD efficiency. It becomes weaker as the vessel conditioning by the plasma itself improves. A question specifically related to long pulse operation is that of the effect duration. The database indicates that in the LH-only scenario, the boronisation effect attenuation depends more on the number of pulses than on the total plasma integrated time elapsed after the boronisation, thus evidencing the role of the plasma current ramp-up and ramp-down phases. Fig. 3 illustrates this result by showing the edge iron content evolution as a function of the pulse number (top, the origin is the first pulse after boronisation) and of the total plasma time (bottom, the origin is the last pulse before boronisation). Note that for this boronisation, the maximum-to-average ratio of iron edge density is higher, meaning that metallic bursts ('UFOs') are more frequent when the boronisation effect is present. When the LH+ICRH scenario is used, the iron and oxygen sources recover faster their pre-boronisation values and the total plasma time seems to play the dominant role.

Conclusions: A database of long pulses (flat top $> 60\text{s}$) performed on Tore Supra has been analysed in order to assess the main impurity (C, O, Fe) behaviour on long plasma time scales. Carbon is found to be constant during pulses along the campaign. Oxygen and iron edge densities are commonly observed to increase during pulses. Among the possible reasons the effect of ripple losses damaging small areas of the vessel wall or PFCs may contribute to the impurity sources. It is anyway not large enough to pollute the plasma core and degrade the LHCD efficiency. The correlation between the injected D_2 flow and the iron edge density is interpreted as the effect of the interaction between the charge exchange neutrals and the stainless steel parts of the vessel. A mechanism responsible for part of the oxygen source is thought to be oxygen released by the charged particle flux on surfaces close to the plasma. Boronisation reduces both the oxygen and the iron sources. The boronisation effect duration depends more on the number of pulses (i.e. plasma start and end play the major role) than on the total plasma time after a boronisation. This makes us confident that boronisation is a relevant conditioning technique for the LH-only long pulse scenario. In an LH+ICRH long pulse campaign, the boronisation effect fades away more rapidly and depends mostly on the integrated plasma time.

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