Impact of the JET ITER-like wall on the current ramp up phase and q-profile optimisation for hybrid and advanced scenarios

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Introduction

The ITER-like wall (ILW) in JET is composed of B_e main wall and W divertor. As reported in [1], it has changed the wall conditioning and recycling behaviour, modified the plasma impurity content, and impacted on the plasma initiation, leading to lower radiation and higher electron density (n_e) at the end of the burn-through phase. This motivated experiments to assess the impact of the ILW on the plasma current (I_P) diffusion during the I_P rise, presented here. Also described is the work started to recover the q-profiles required for improved stability and confinement, i.e. with a broad region of weak magnetic shear in the plasma core with $q_0 \approx 1$ for hybrid plasmas and $1 < q_{min} \leq 2$ for advanced scenarios.

Impact of the ILW on the plasma during I_P rise

Plasmas with early X-point formation were performed and compared to shots in JET with the C wall. Fig.1 shows that in contrast to equivalent C wall plasmas (black triangles), hollow electron temperature (T_e) profiles are observed during the I_P rise with Ohmic heating (blue diamonds and red squares), which persists until the I_P flat-top is reached. Similar observations were made on other machines with metal walls, for example FTU [2]. Bolometer measurements show a peaked radiation profile, suggesting that impurity radiation in the core is cooling the plasma. The main impurity in the ILW plasmas during the I_P rise is W, with some Ni also present. W radiates most effectively at a T_e of a few KeV, as in the core of the plasma during the I_P rise. In C-wall plasmas, the main impurity was C.

TRANSP modelling of the q-profile evolution with the experimental n_e, T_e, and with neo-classical resistivity shows that a hollow T_e profile should result in magnetic shear reversal. Indeed, replacing the T_e of a C-wall plasma with a ILW T_e profile leads to shear reversal, even if the initial q-profile (imposed in this case) is not reversed (Fig. 2). Evidence for magnetic shear reversal in the ILW plasmas includes: EFIT equilibrium reconstruction constrained with polarimetry and kinetic pressure data; Alfvén cascades in shots where ICRH is added during the I_P flat-top; and double tearing modes causing T_e sawtooth-like crashes, linked to deeply reversed magnetic shear, in the ILW plasmas with lowest n_e and fastest I_P rise. The presence of double tearing modes during the I_P rise is also reported in other metal wall machines [2], but previously had only been seen in JET during I_P rise with LHCD and deeply reversed q-profiles [4].

The origin of the W in the plasma was investigated. Fig. 3 and 4 show I_P, n_e, internal inductance (l_i) and T_e (core and edge), Z_{eff} and the main impurities. The wavelengths used are 977.02 Å for C, 292.0 Å, for N_i, and ~180 Å for W. The intensity is normalised to n_e to make it proportional to the concentration. Fig.3 shows that a smaller n_e is obtained in the limiter phase (up to t=1.5s) of ILW plasmas, despite a slightly higher amount of gas puffed before 1.0s. This observation is consistent with low recycling, as is the fact that n_e during the limiter phase is proportional to the amount of gas injected (Fig.5-a). Enhanced electron cyclotron emission (ECE) is observed during the low n_e limiter phase of ILW plasmas, even when the plasma is optically thick to the radiation from the thermal T_e distribution. This indicates the presence of suprathermal electrons, which is confirmed by the gamma ray diagnostic. It is correlated with the largest amount of W and Ni (Fig.4), suggesting that the fast electrons are the cause of the influx. The last closed flux surface during the limiter phase is near the top of the divertor (where most of the W is located) possibly enough for the fast electrons to impinge on the divertor. In the plasma with the C-wall, the highest concentration of C is also observed during the limiter phase (Fig. 4). Suprathermal electrons have been observed in C-wall plasmas at very low n_e, or when Lower Hybrid (LH) waves are used. However, the influx of C does not affect the T_e profile as much as core radiating high Z materials such as W or N_i.

Reduction of W in the plasma

This magnetic shear reversal is undesirable in the hybrid scenario because it can lead to instabilities detrimental to the plasma performance. Ways of (1) reducing the influx of W and (2) recovering a peaked Te profile during the I_P rise were investigated. Increasing the D_2 gas dosing, hence n_e, during the limiter phase, leads to a reduction of the fast electron energy (Fig. 5-c). The maximum energy of the suprathermal electrons was calculated using the additional information provided by oblique ECE views as in [5] for shot 82078, and the result applied to the other shots, assuming a T_e distribution function with a tail of fast electrons. The W influx also decreases when n_e increases (Fig.5-b) (and when the suprathermal energy decreases). The

T_e profile in shots with highest limiter phase n_e is less hollow. But n_e required for reducing significantly the influx of W is higher than that typically used in C-wall plasmas.

Increasing n_e later during the current rise can also lead to less hollow T_e profiles. However, a consequence of operating at higher n_e is that the overall T_e is lower (Fig. 1, blue points compared to red), and l_i is higher (Fig.3). Also, it does not eliminate completely the effect of the core radiation cooling. Adding Ion Cyclotron Resonance Heating (ICRH) with central resonance (1MW, H minority heating, 47MHz) results in a peaked T_e profile (Fig. 1, green and purple points). The total radiation increases during ICRH (Fig.4), but the fraction of radiated to input power does not change and the radiation profile does not become more peaked. On that shot, a high influx of W is observed before ICRH is applied, making it impossible to conclude on its effect on W.

q-profile assessment following initial optimisation

Higher l_i is obtained as a result of increasing n_e during the limiter phase, indicating that the I_P profile at that time is more peaked. A lower l_i (matching that of C-wall plasmas) can be recovered at the end of the I_P rise by adjusting n_e at that time. However, systematically, the sawteeth linked to the presence of the q=1 surface are seen earlier in the ILW discharges compared to equivalent C-wall plasmas. This indicates that the core q goes down faster in the ILW plasmas. This is supported by q-profiles for shots with MSE data and taking into account the kinetic profiles. The flux consumption during the I_P rise is up to 10% higher in the ILW shot, with the difference occurring during the limiter phase. Further optimisation is needed to recover the q-profiles required for advanced scenarios and for reducing the flux consumption.

Summary

The main impact of the ILW on the plasma during the I_P rise is due to the presence of W in the plasma leading to hollow T_e profiles, and to the need to operate at higher n_e to reduce the W influx. The work to diagnose and optimise the q-profile is not completed and will include investigating the effect of adding core electron heating during the I_P rise. The fact that l_i at the end of the I_P rise remains low is a positive indication for ITER but a more detailed comparison using ITER relevant parameters is required for a better prediction.

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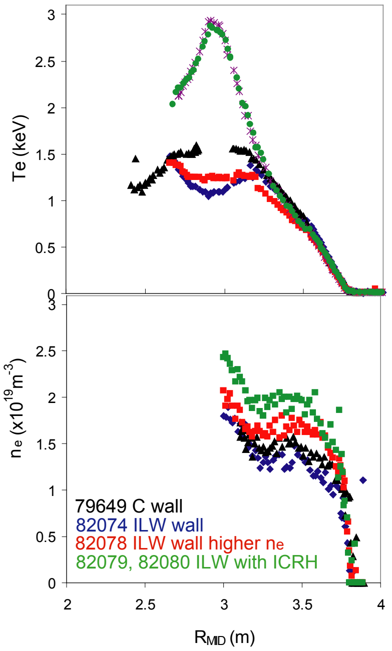

Figure 1. Te and ne near end of I_P rise (3.8s), C-wall (black), ILW (red), ILW, higher n_e (blue), ILW + ICRH+ higher n_e (green and purple)

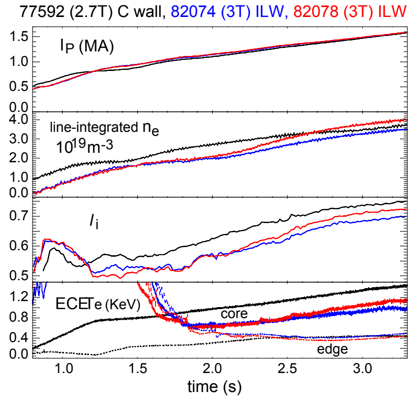

Fig. 3. evolution during I_P rise, C-wall (black) and ILW (red and blue).

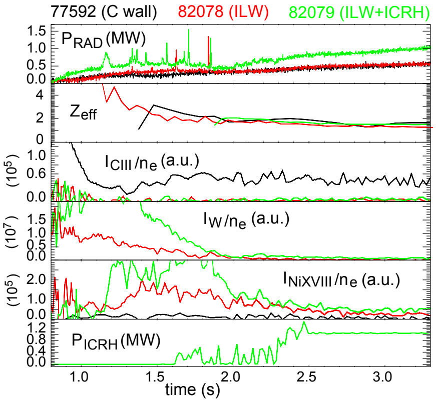

Figure 4. evolution of impurities during I_P rise, C-wall (black), ILW (red) and ILW + ICRH and higher n_e (green).

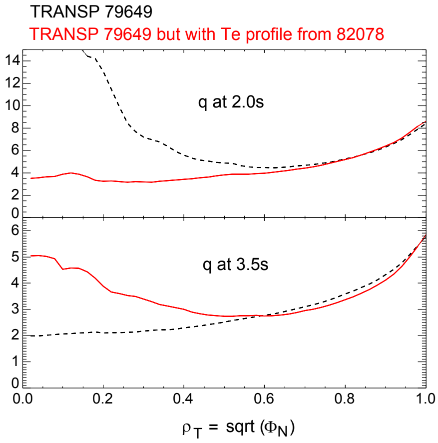

Figure 2. top: initial q-profiles, bottom: resulting q-profiles from TRANSP after 1.5s

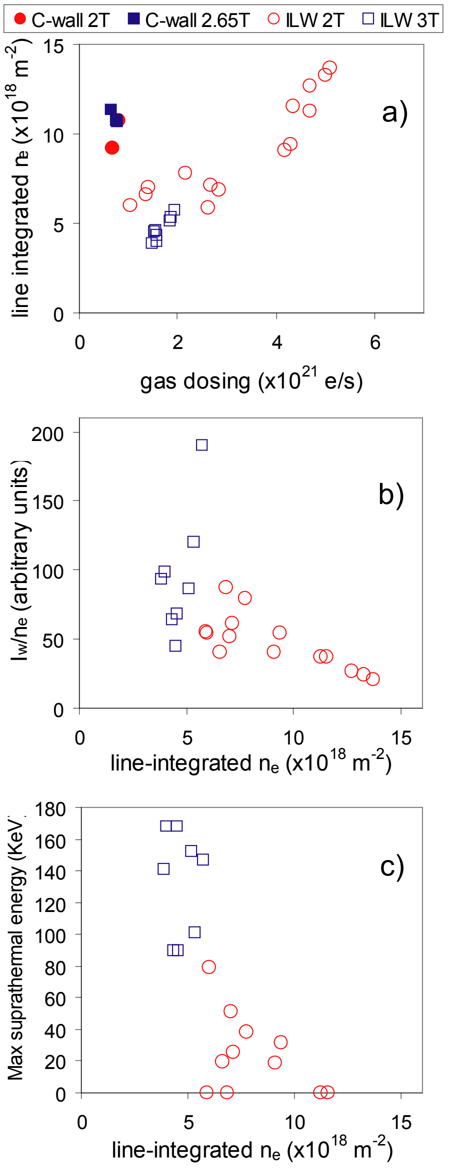

Figure 5. all data averaged over limiter phase, but for suprathermal E which is at time of peak