Tearing Modes during the current ramp-up of the hybrid scenario on JET

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1. Introduction

The hybrid scenario is characterized by a wide region of low magnetic shear in the plasma core, with a safety factor value $q \geq 1$ near the magnetic axis. The initial Ohmic current ramp phase is used on JET to optimize the current profile shape to achieve the target q-profile at the start of the main heating phase [1, 2]. To this purpose it is crucial to avoid any MHD instability, which can influence the evolution of the pulse or lead to a plasma disruption. The presence of 2/1 tearing modes, single or double [3, 4], has been observed during the current ramp-up phase of JET-ILW hybrid plasmas with most hollow electron temperature profiles. These modes can lock and trigger the disruption mitigation valve (DMV).

The analysis of a large JET hybrid dataset highlighted that disruptions correlate with T_e hollowness, defined as $(T_{e,max}-T_{e,on\text{-}axis})/T_{e,max}$. Indeed, all current ramp disruptions had a T_e hollowness greater than 12.5% at some point, whilst only 6% of all non-disruptive pulses had reached that threshold at any point. Furthermore, plasma that achieved highest fusion performance did not reach that threshold at any point, suggesting best performance with low T_e hollowness. Concerning the observed MHD activity in disruptive pulses (5.6% of dataset), the mode onset is observed when $q_{min} \leq 2$ (from q-profile reconstructions including polarimetry constraints), consistent with analysis indicating 2/1 tearing modes.

2. Low density and impurity contamination

Hollow Te profiles and locked modes (before the main heating phase) have been observed in pulses with reduced density and increased impurity contamination and radiation. It is worth noting that low density values are generally considered during the ohmic phase of hybrid pulses to increase the temperature and slow the current diffusion, allowing for broader current profiles and a flat q-profile.

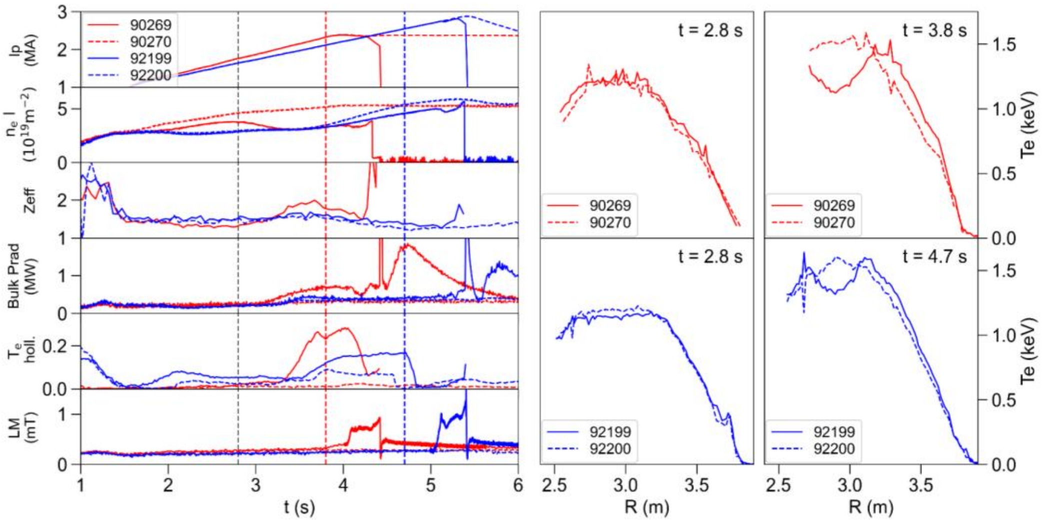

Fig. 1. (Left) From top to bottom: plasma current, line-integrated density, effective charge, bulk radiated power, temperature hollowness, locked mode detector. Solid (dashed) lines are utilized for disruptive (non-disruptive) pulses. (Right) Electron temperature profiles at the beginning of pulses and at the mode onset.

However, low density values can also affect the sputtering yield for metallic impurities and the impurity influx, leading to high-Z core impurity accumulation and central cooling. A combined effect of low density and impurity contamination can lead to hollow Te-profiles, so increasing the risk to develop locked modes [5]. Figure 1 shows a comparison between two pulses that develop locked modes because of impurity contamination at low density (solid lines) and two pulses in which no locked modes are present (dashed lines).

Deeply hollow Te profiles and impulsive reconnections of magnetic field lines (sawtooth-like profile rearrangements) have been observed in pulses suffering from W events and high radiation or from legacy of poor breakdown, higher internal inductance and wall contact during early phase. It is worth noting that double tearing modes causing Te sawtooth-like crashes, linked to deeply reversed magnetic shear, have been observed in the past in JET-ILW plasmas with lowest ne and fastest Ip rise [6] and during the Ohmic ramp phase in metal wall tokamaks such as FTU [7]. The observation of Te crashes is consistent with the Kadomtsev reconnection model applied to reversed q-profiles with a pair of q=m/n resonant surfaces in the plasma around q_{min}. According to the Kadomtsev prescription, in the reconnection process plasma regions are mixed with the same value of the helical flux function and two cases can be distinguished, leading to “core crash” or “annular crash”, respectively.

3. Plasma current ramp rate

Pulses with different Ip ramp rates have been performed to investigate the effect on current diffusion and impurity influx. All pulses have hollow Te profiles from X-point formation.

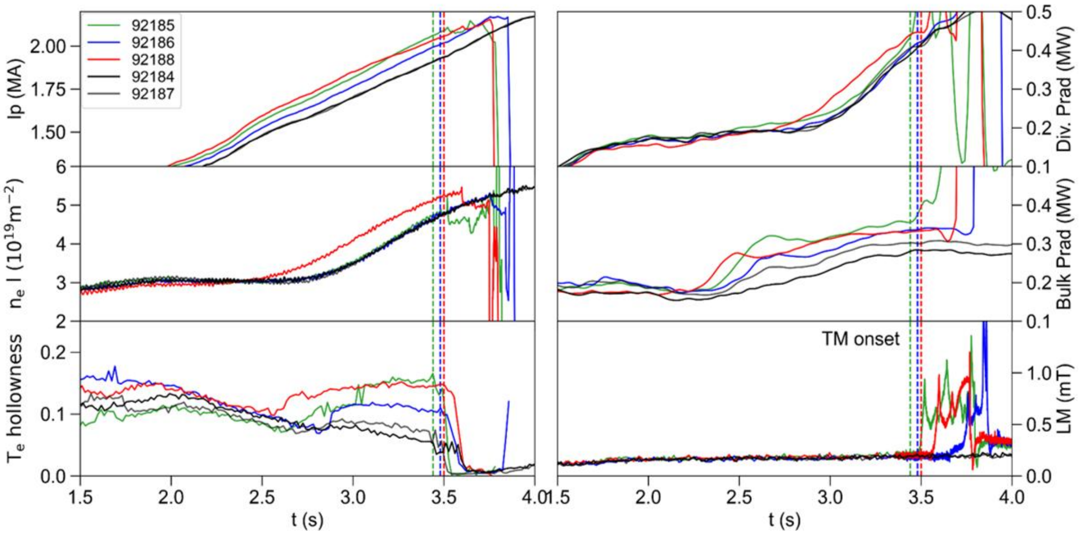

Fig. 2. (Left) From top to bottom: plasma current, line-integrated density, temperature hollowness. (Right) Divertor and bulk radiated power, locked mode detector. Black and grey lines for non-disruptive pulses.

Both plasmas with low current ramp rate have decreasing Te hollowness and no locked modes. All 3 plasmas with higher current ramp rate retain Te hollowness (with a further increase) and develop locked modes, triggering the DMV. A later decrease in the current ramp rate and an early increase in density (red line) tend to recover better conditions, but do not avoid a locked mode. The higher bulk radiation increase in disruptive pulses correlates with higher core W concentration and W radiated power from the XUV spectroscopy.

Interpretative TRANSP simulations were performed to compute pressure profile during the Ip ramp-up of pulse #92185, where two 2/1 magnetic islands rotate at different radii with the same toroidal velocity and a relative phase locked at π These pressure profiles were then provided to EFIT++ to compute the plasma equilibrium self-consistently. The effect of W core accumulation on Z_{eff} profile and of the $T_i < T_e$ condition on p-profile were also considered. The results are shown in Figure 3. Linear stability analysis was performed by solving the equation for the perturbed radial magnetic field in the zero-pressure limit to evaluate Δ'-matrix [8, 9], highlighting an unstable double tearing mode. Stability analysis was also performed using the linear, resistive, full MHD code MARS to estimate the growth rate of both dominant and subdominant modes. While the early, slow growth of the coupled magnetic islands can be captured via quasi-linear Rutherford theory [10], full non-linear simulations are essential to model the subsequent explosive reconnection phase triggered by island overlap, which is a signature of structure-driven double tearing modes [11]. The remaining hot structure in Te profile is consistent with incomplete reconnection: the crash terminates during the mutual exchange of islands through their X-points, driving a clear off axis plasma expulsion [12].

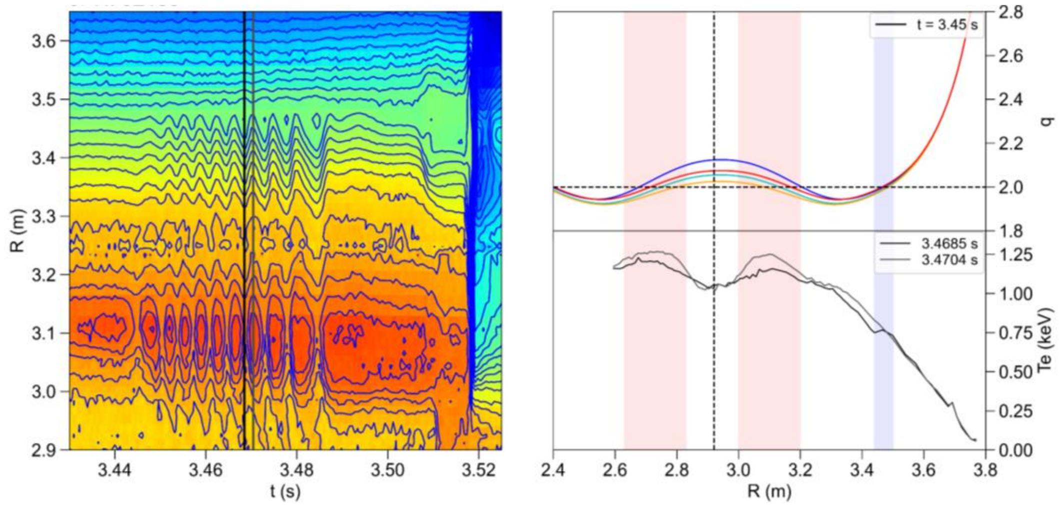

Fig. 3. (Left) From top to bottom: plasma current, line-integrated density, temperature hollowness. (Right) Divertor and bulk radiated power, locked mode detector. Black and grey lines for non-disruptive pulses. where the q-profiles at the top right refer to different choices of Zeff(0)/Zeff(0.3) and Ti/Te (blue: 3/1.0, red: 1/1.0, cyan: 3/0.7, orange: 1/0.7).

4. Conclusions.

Disruptions of hybrid plasmas during the current ramp up on JET correlate with a hollow Te profile, suggesting a link to magnetic shear reversal, as confirmed by the observation of 2/1 double tearing modes (characterized by electron temperature oscillations on different radial positions or sawtooth-like reconnection processes), although single modes can also occur. In all the analyzed pulses, a locked mode is finally observed, triggering DMV intervention. The strong link between hollow Te profiles and locked modes has led to inclusion of a Te profile peaking factor in the JET real-time control system [13], allowing an early pulse termination by rapidly ramping the plasma current down in the case where the Te profile becomes excessively hollow in the early current ramp phase. The comparative analysis of both disruptive and non-disruptive pulses has shown that hollow Te profile and magnetic shear reversal could be result of low electron density, core impurity radiation, fast current ramp, high current overshoot (i.e., low minimum q_{95}) or combination of them, thus providing a reference to describe a key piece of underlying physics crucial for the optimization of the q-profile for high performance hybrid plasmas on JET [14].

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