



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

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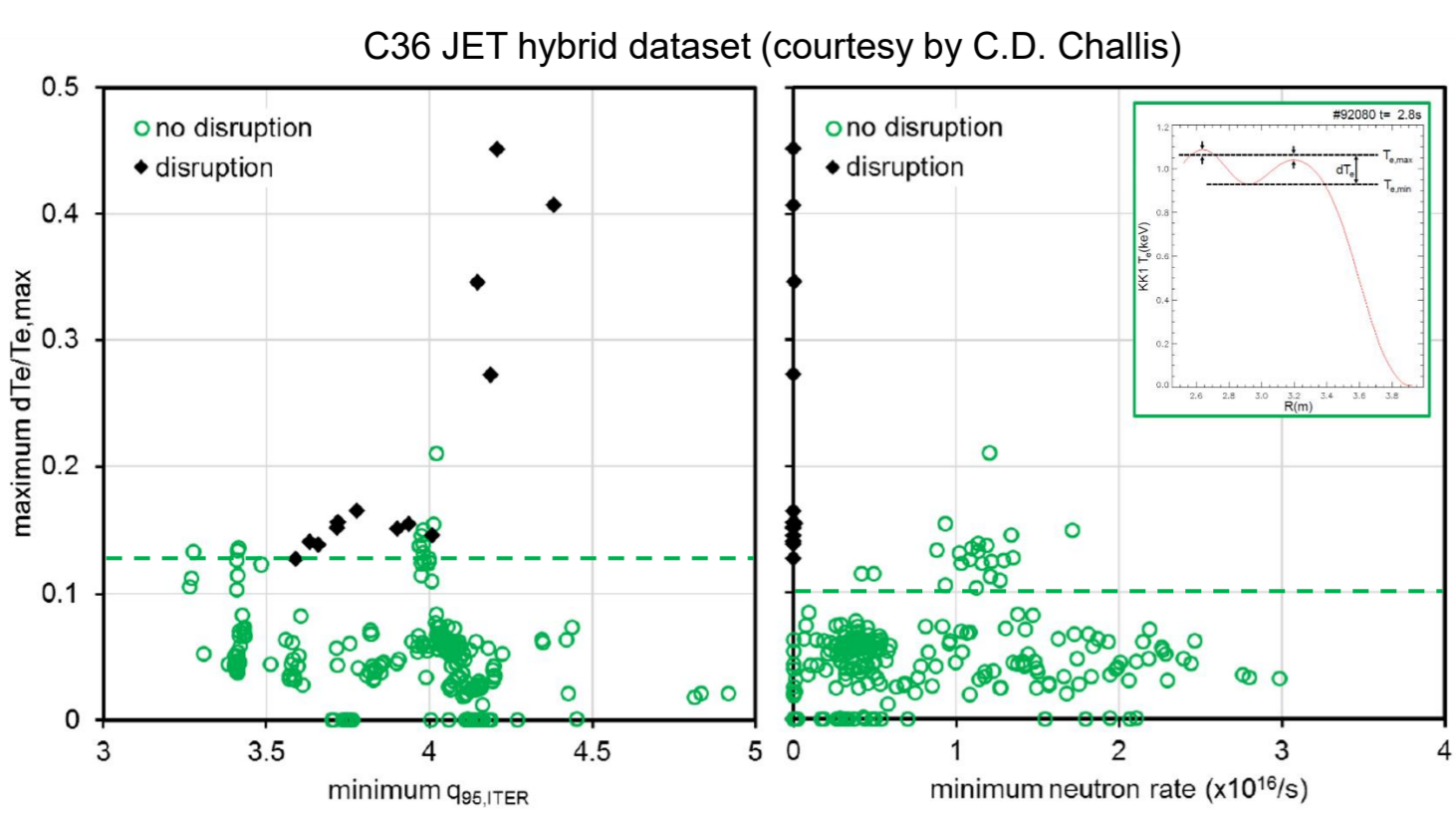
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Background

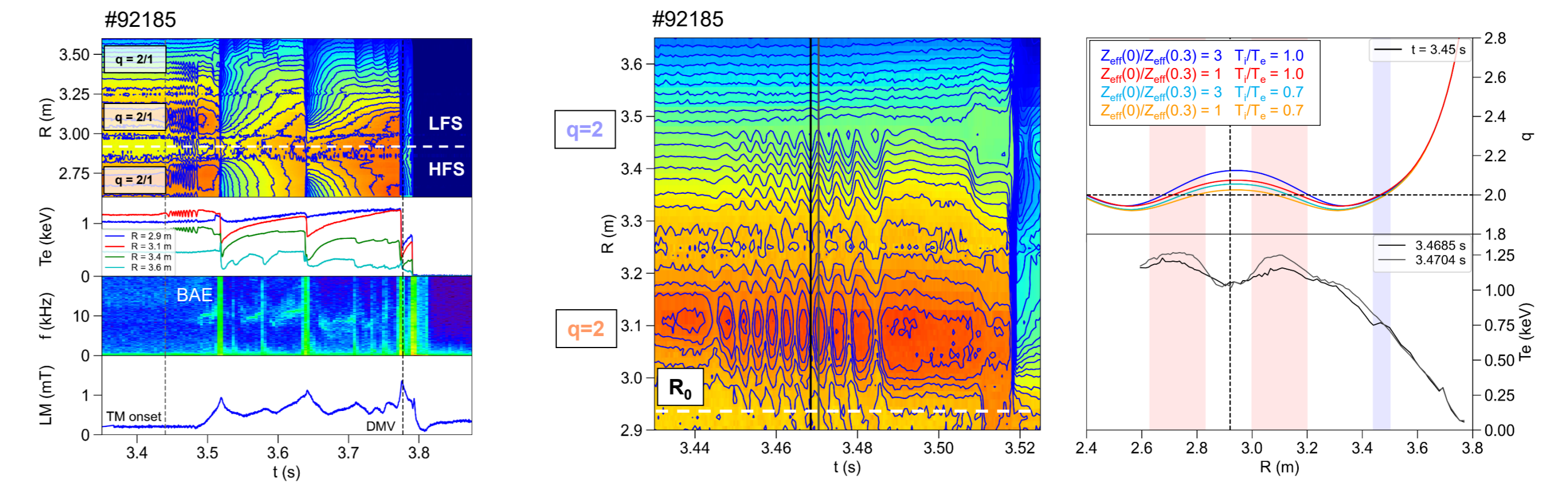
- The **hybrid scenario** is characterized by a wide region of low magnetic shear in the plasma core, with a safety factor value $q \geq 1$ near the magnetic axis. The initial Ohmic current ramp phase is used on JET to optimize the current profile shape to achieve the target q -profile at the start of 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 valve (DMV).



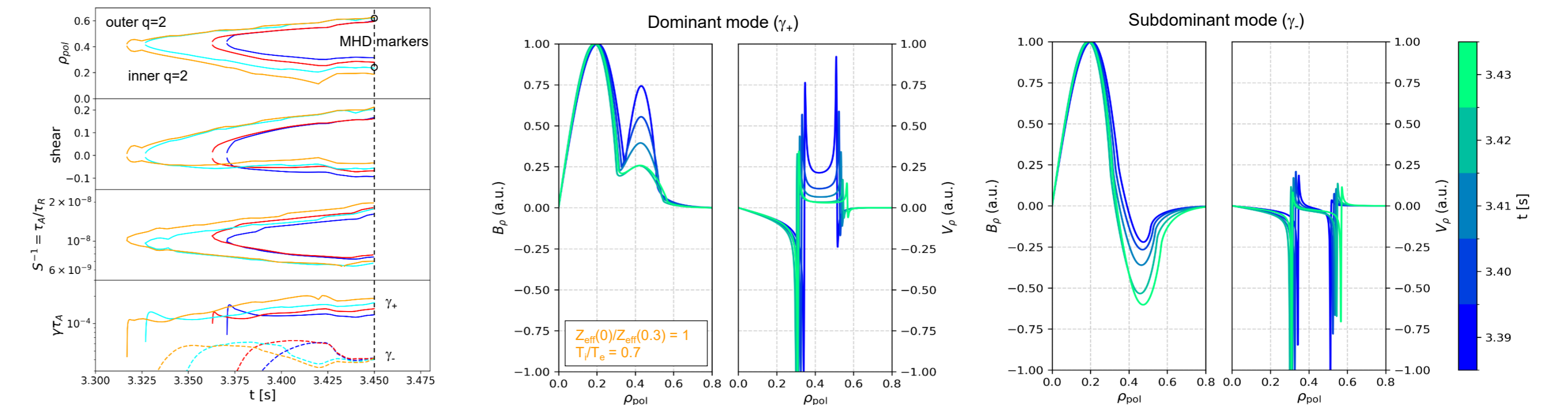
- Disruptions correlate with T_e hollowness (i_p proxy)**
All current ramp disruptions had $dT_e/dt_{e,max} > 12.5\%$ at some point. Only 6% of all non-disruptive pulses had reached $dT_e/dt_{e,max} > 12.5\%$ at any point.
- Best performance with low T_e hollowness**
Plasma that achieved highest fusion performance did not reach $dT_e/dt_{e,max} < 10\%$ at any point.
- MHD onset in disruptive pulses (5.6%)**
MHD onset when $q_{min} \leq 2$ (inc. polarity), consistent with analysis indicating 2/1 tearing modes.

Modelling activity

- Interpretative **TRANSP simulations** were performed to compute pressure profile during the I_p 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.



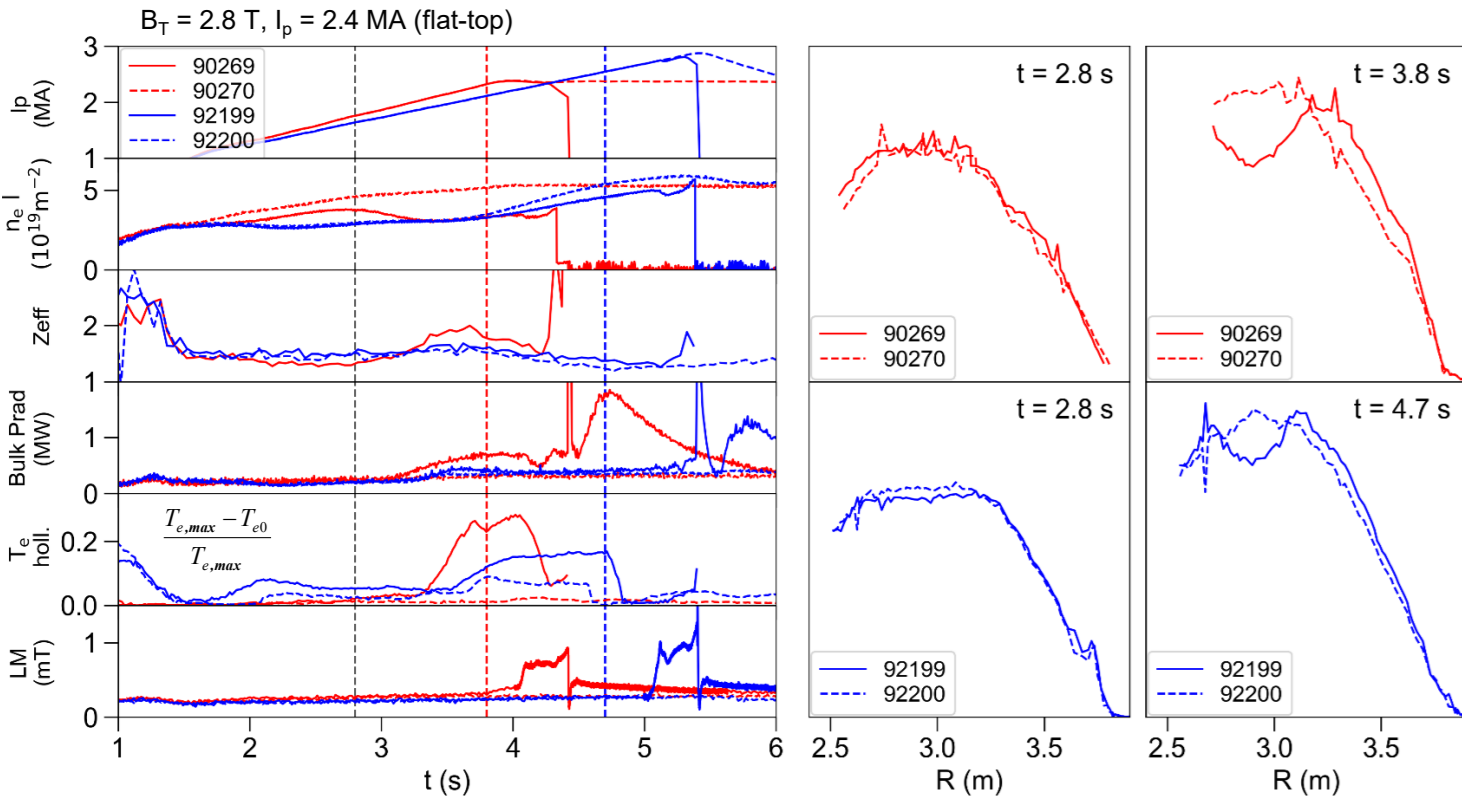
- Linear stability analysis** was performed by solving the equation for the perturbed radial magnetic field in the zero-pressure limit, to evaluate Δ' -matrix [8, 9], highlighting an **unstable double tearing mode**. Stability analysis was also performed using the linear, resistive, full MHD code **MARS** 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 T_e 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].

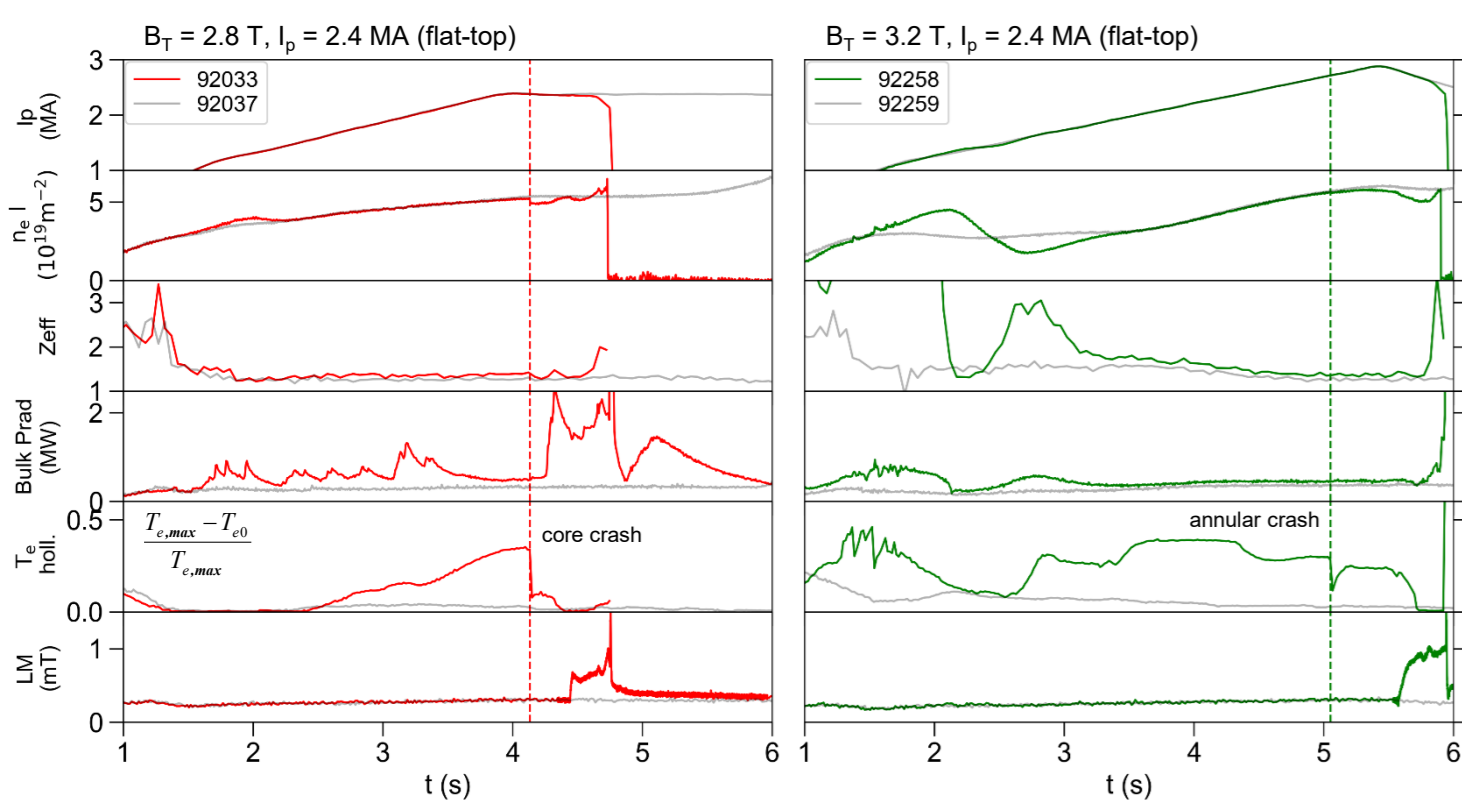
Low density & impurity contamination

- Hollow T_e profiles and locked modes (before the main heating phase) have been observed in pulses with **reduced density** and **increased impurity contamination** and radiation.



- 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.
- 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 T_e -profiles, so increasing the risk to develop locked modes [5].

- Deeply hollow T_e profiles and impulsive reconnections of magnetic field lines (sawtooth-like profile rearrangements) have been observed in pulses suffering from **W events & high radiation** or from legacy of **poor breakdown, higher I_p & wall contact** during early phase.

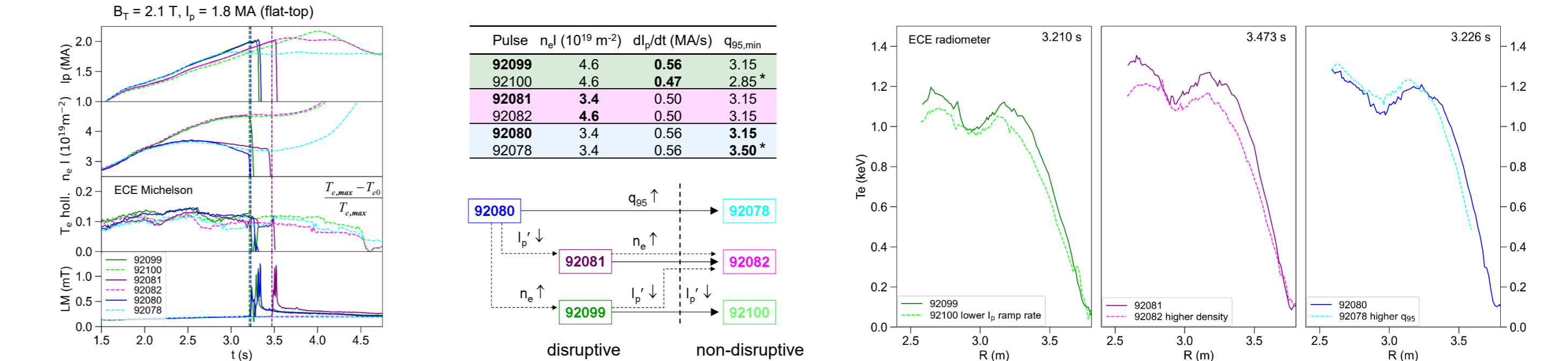


- Double tearing modes causing T_e sawtooth-like crashes, linked to deeply reversed magnetic shear, have been observed in the past in JET-ILW plasmas with lowest n_e and fastest I_p rise [6] and during the Ohmic ramp phase in metal wall tokamaks such as FTU [7].
- The observation of T_e crashes is consistent 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 different reconnection regions:

$$\psi_m = \frac{B_z}{R_0} \int \frac{1}{q(r')} \frac{n}{m} r' dr' \rightarrow \begin{cases} (a) \psi_m(0) < \psi_m(r_2) & \text{core crash} \\ (b) \psi_m(0) > \psi_m(r_2) & \text{annular crash} \end{cases}$$

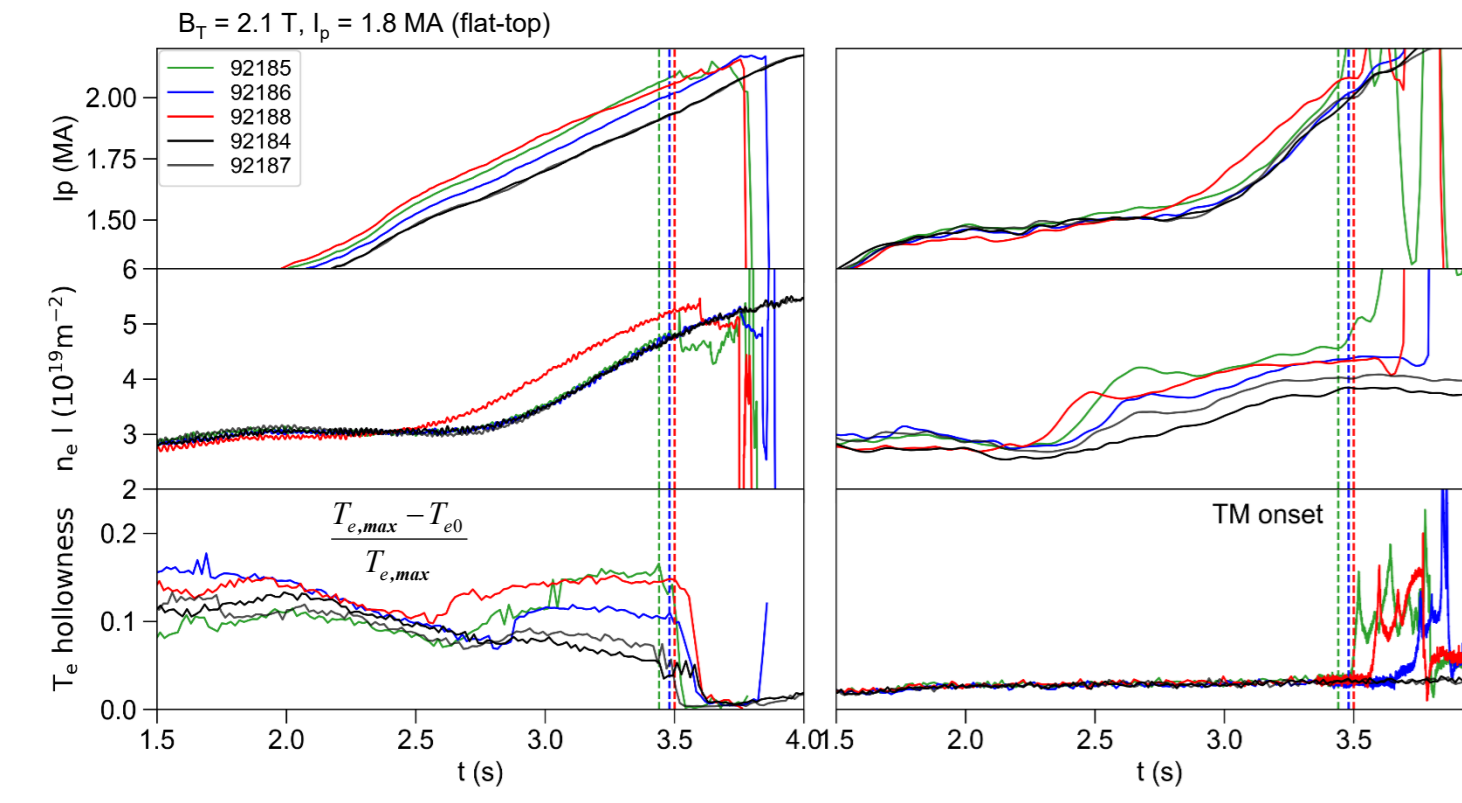
From disruptive to non-disruptive pulses

- The transition from disruptive to non-disruptive pulses can be achieved by making one or some of the following choices: **increase the electron density**, **reduce the current ramp rate**, **reduce the current overshoot** (i.e., increase the minimum q_{95}).



Plasma current ramp rate

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



- Both plasmas with low current ramp rate have decreasing T_e hollowness and no locked modes.
- All 3 plasmas with higher current ramp rate retain T_e 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 Prad increase in disruptive pulses correlates with higher core W concentration and W radiated power from the XUV spectroscopy.

Conclusions

- Disruptions of hybrid plasmas during the current ramp up on JET correlate with a hollow T_e 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 T_e profiles and locked modes has led to inclusion of a T_e 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 T_e profile becomes excessively hollow in the early current ramp phase.
- The comparative analysis of both disruptive and non-disruptive pulses has shown that hollow T_e profile and magnetic shear reversal could be result of low electron density, core impurity radiation, fast current ramp, high current overshoot 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].
- The avoidance of too low densities during current ramp, also through real-time density control by gas puffing, seems to be essential to prevent negative magnetic shear due to slow current diffusion into the core or to core impurity accumulation and the use of additional radiofrequency heating during current ramp should be investigated to mitigate hollow T_e profile due to central impurity radiation.

References

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