# MHD studies in the hybrid scenario for D-T experiments at JET

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MHD studies were performed to support the development of the JET hybrid scenario [1] at moderate plasma current and high toroidal magnetic field ($I_p = 2.3$ MA, $B_T = 3.45$ T, $q_{95} \approx 4.7\text{-}5.0$) for the 2021 D-T experiments at JET with the ITER-like wall. To prepare for D-T experiments [2], the hybrid scenario was extensively developed in recent years using D fuel, selected plasmas were repeated using T fuel to investigate and mitigate isotope effects, and the experience gained in D and T experiments was translated into the final D-T plasma target. Different MHD instabilities were observed through the main phases of hybrid pulses illustrated in Fig. 1, with an impact on both disruption likelihood and plasma performance. In this paper, an analysis of the experimental observation of MHD instabilities in hybrid pulses is reported, together with the modelling activities carried out towards their interpretation and the strategies implemented for their avoidance and control.

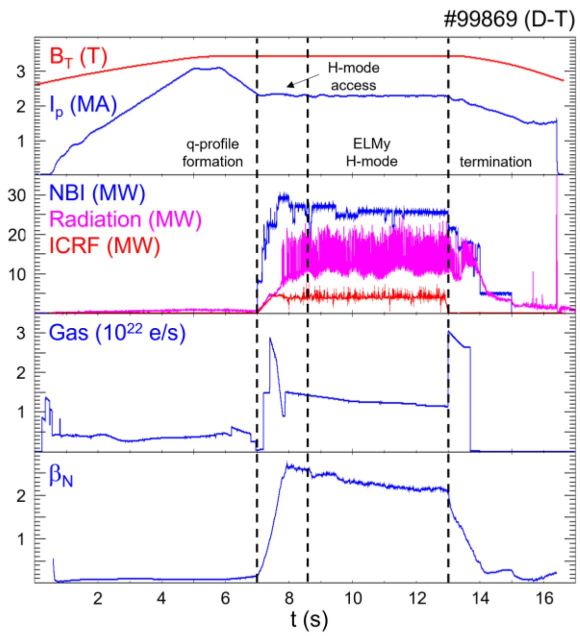


*Fig. 1. Waveforms for JET hybrid D-T reference plasma. From top to bottom: plasma current and magnetic field; NBI, ICRF and radiated power; requested gas-flow; and normalized beta.*

***(i)*** *q-profile formation*. 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. In the absence of flexible current drive mechanism on JET, a fast current ramp-up together with a current overshoot and a fine control of the plasma density were used to produce a broad q-profile with a target $q_0$ (q on-axis) around 1.1-1.2 at the start of the NBI heating, which finally allowed to slow down the q-profile relaxation for the time duration of the flat-top. The analysis of the current ramp-up of hybrid pulses with D fuel showed the occurrence of tearing or double tearing modes [3, 4] in pulses with hollow electron temperature profiles [5], mainly due to faster current ramp-up and core accumulation of heavy impurity at lower density values. Following these observations, an electron temperature profile peaking factor has been included in the JET real-time control system allowing an early pulse termination by rapidly ramping the plasma current down in case of strongly hollow profiles [6, 7]. An effect of the isotope mass on the q-profile shape was also highlighted, requiring an increase in plasma density during the current ramp-up phase to compensate the increase in core impurity radiation with main ion isotope mass and recover the desired q-profile, as indicated by previous H-D experiments [5] and predictive modelling [8] and confirmed by ohmic test pulses showing matched onset time of m/n = 1/1 MHD activity (m and n are the poloidal and toroidal mode numbers, respectively).

**(ii)** *H-mode access*. Detailed analyses were carried out in D plasmas to optimize the timing for the high external power switch-on, with a target $q_0$ at the start of the main heating phase finally set between 1.1 and 1.2 for D-T experiments. This range was determined by the risk of destabilizing early low-n neoclassical tearing modes (NTMs) if the plasma is “frozen” at too high a $q_0$ (anticipating the NBI power) and by the risk of developing sawteeth (possibly triggering NTMs) during the flat-top if “freezing” the plasma at too low a $q_0$ (delaying NBI power). However, the H-mode access phase (approximately the first second after the application of high external power), which is usually characterized by a higher performance, showed sometimes 3/2 and 4/3 NTMs in pulses with higher beta and relatively flat q-profile. These modes form magnetic islands that degrade confinement by short-circuiting radial transport [9], so that at high beta the presence of 3/2 NTMs can reduce confinement up to 20%. In addition, an effect of these islands on impurity transport has been sometimes highlighted in pulses with large 3/2 modes [10], causing or accelerating the core accumulation of high-Z impurity. As for the causes of these high-beta NTMs in sawtooth-free plasmas, an external triggering due to beam-driven fishbones or ELMs can be excluded as there is no time-coincidence, whilst a possible role of already existing ideal kink-like modes (visible in the spectrogram of magnetic pick-up coil, but at very low amplitude) in the onset of these modes in the high-beta regime cannot be excluded, through a kink-to-tearing topology transitions already observed in several other devices [11] and in high-beta JET advanced scenarios [12]. Considering the detrimental effect of 3/2 NTMs on plasma performances, an optimization of the H-mode access phase in D-T experiments has been implemented to avoid their destabilization, by adjustment of the waveforms of heating and fuelling.

**(iii)** *ELMy H-mode*. The main ELMy H-mode phase was usually sawtooth-free, but core $n = 1$ MHD activity, either in the form of fishbone cycles or in the form of continuous oscillations, was commonly observed along the pulse evolution, as shown in Fig. 2, suggesting that the q-profile was slowly evolving with $q_0$ decreasing to a value close to unity. The possibility of fishbones alternating with a continuous mode was also highlighted, which seems to correlate with the shape of the electron temperature profile in the core region and with the dynamics of the core impurity content, which is in turn influenced by the core $n = 1$ MHD activity. In addition, it was found in D-T experiments that α-particles losses related to MHD instabilities are correlated with fishbones and continuous modes.

The central main heating phase also presented a variety of NTMs, as shown in Fig. 2, with different effects on plasma performance that can be ordered according to the toroidal mode number n. Modes with $n \geq 5$, generally not affecting the confinement, were observed in the first half of the current flat-top of pulses with low radiated power and good confinement, whilst some evidence of a correlation between the amplitude of modes with $n = 4, 3$ and the impurity influx and transport have been observed. A chain of modes with decreasing toroidal mode number, up to $n = 2, 1$, was instead observed in pulses with an increased radiated power due to core accumulation of high-Z impurities, finally leading to q-profile modification.

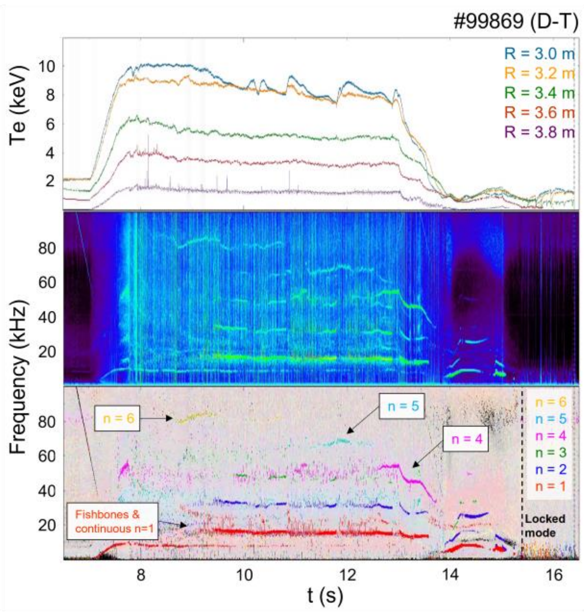


*Fig. 2. MHD analysis of hybrid pulse #99869. From top to bottom: electron temperature at different radii; spectrogram; and toroidal mode number analysis from magnetic pick-up coils (plasma current flat-top from 7 to 13 s).*

**(iv)** *Termination*. The capability to terminate plasma pulses safely is an important goal towards the optimization of an operational scenario in a tokamak. The development of a 2/1 TM inside the plasma is a major cause of disruptions [13]. In the absence of external triggers, two main paths leading to the destabilization of a 2/1 TM have been highlighted during the plasma termination on JET, connected to the problem of impurity control [14]: 1) the core accumulation of high-Z impurities, leading to a temperature hollowing (TH) and to a broadening of the current density profile, and 2) the influx of low-Z impurities, which are mainly radiating at the edge, leading to an edge cooling (EC) and to a shrinking of the current density profile. Their percentage incidence strongly depends on the operational scenario. Lower density and a flatter safety factor profile are prone to develop TM because of a TH, whilst for peaked safety factor profile and higher density the TM are mainly caused by an EC. The termination phase of the JET hybrid plasmas with D fuel was often characterized by core impurity accumulation, with the destabilization of chains of classical tearing modes, from the inner ones to the outer ones. To evaluate the impact of the isotope mass on the incidence of disruptions, the complete set of D-T pulses has been compared with the set of T and D pulses performed with the same values of $I_p$ and $B_T$, highlighting an increasing percentage of disruptions, due to the occurrence of 2/1 locked modes, with increasing isotope mass. The analysis of the disruptive patterns showed that in most of the cases disruptions follow a TH or an EC pattern, with the TH becoming the dominant pattern as the isotope mass increases, which suggests providing more central additional heating in the termination to counteract the inward transport of high-Z impurities [15].

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