Effect of fuel isotope mass on q-profile formation in JET hybrid plasmas

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The initial Ohmic current ramp phase of JET hybrid plasmas, including a current 'overshoot' before the main heating, is used to optimise the q-profile shape to allow access to high β and avoid MHD instabilities [1]. Such hybrid plasmas have never been operated using tritium (T) or mixed deuterium-tritium (D-T) fuel. However, experiments with internal transport barriers (ITBs), which are also sensitive to the q-profile shape, were carried out in the 1997 JET D-T campaign [2]. It was found that the q-profiles produced in D-T experiments were slightly different to reference deuterium (D) plasmas, and modifications were needed to the heating power timing and waveform to obtain similar ITBs. In recent mixed protium-deuterium (H-D) experiments, the q-profile evolution during the initial current ramp phase of hybrid plasmas varied systematically with average main ion atomic mass number (M_{eff}), as seen in Fig.1. The onset of 1,1 MHD indicates the arrival of a q=1 magnetic surface as current diffuses into the plasma core, which was delayed by increasing M_{eff}. It has also been found that the development of magnetic shear reversal during the Ohmic ramp phase can lead to 2/1 double tearing modes that can lock. When the locked mode is detected, the real-time protection system triggers the disruption mitigation valve to avoid an unmitigated disruption. Unfortunately, the resulting mitigated disruptions tend to coincide with the current 'overshoot', when the plasma current is high. Taken together these results suggest an increased risk of high current disruptions in future T and D-T experiments.

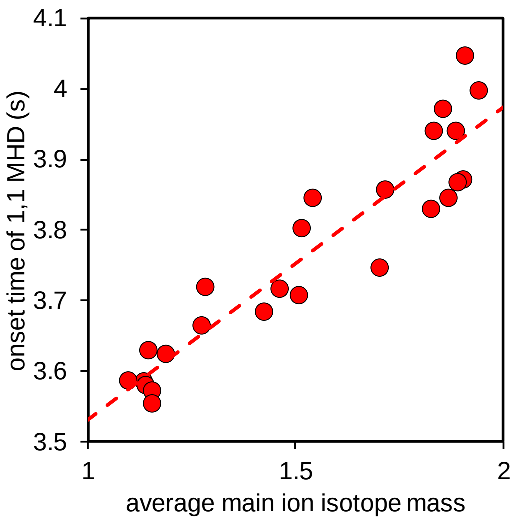

Fig.1 Delay in arrival time of q=1 surface as plasma main ion isotope mass is increased

* *See the author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018)*

JET experiments have been performed using mixed H-D plasmas to scan the main ion isotope mass at relatively low magnetic field (B≈1.7T) [3]. The plasmas were initiated at t≈0.5s and the Ohmic current ramp had the characteristic features of JET hybrid plasmas, including: (1) the rapid development of a large volume plasma and early transition from limiter to X-point configuration at t≈1.3s; (2) low plasma density; and (3) a current 'overshoot' before the start of the main heating pulse at t≈4s. This produces a wide region of low core magnetic shear with a high shear region near the plasma edge. For consistency, pulses were selected for analysis from a single week of plasma operation and with a similar density during the Ohmic X-point phase.

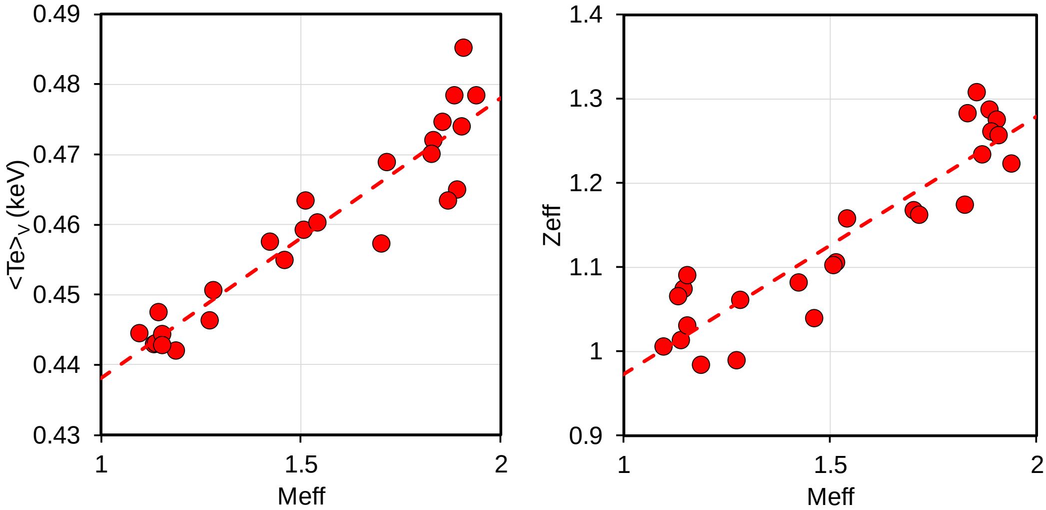

Fig.2. Volume averaged electron temperature (left) and Z_{eff} (right) plotted against the effective main ion isotope mass. All measurements averaged over t=1.5-3.5s.

M_{eff} was determined from visible spectroscopy measurements at the plasma edge, but is believed to be representative of the bulk plasma. Fig.2 shows that, during the Ohmic X-point phase, $\langle T_e \rangle$ increased with M_{eff}, consistent with improved Ohmic confinement and/or reduced electron-ion coupling [4]. But the effect on plasma resistivity was compensated by an increase in Z_{eff} with M_{eff} (see also Fig.2) due to increased metallic impurity contamination, consistent with increased sputtering by higher mass isotopes [5,6]. This is confirmed by current diffusion modelling using the TRANSP code [7], which is shown in Fig.3. Modelling of a D plasma (M_{eff}≈1.94) and an H plasma (M_{eff}≈1.10)

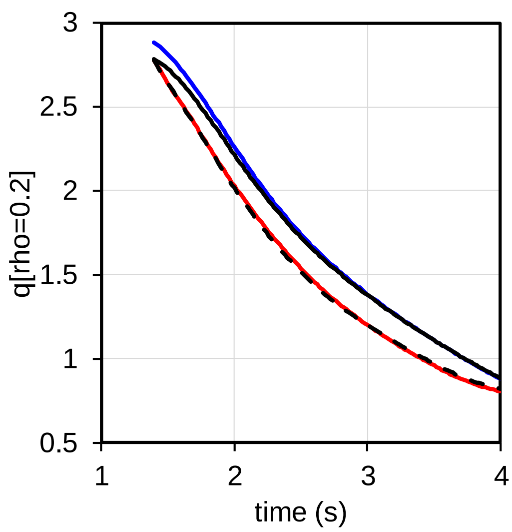

Fig.3 Modelled q[rho=0.2] evolution for: D plasma (blue); H plasma (red); H plasma with $\langle Z_{eff} \rangle_l$ & $\langle T_e \rangle_V$ scaled to match D plasma (dashed black); H plasma with $\langle Z_{eff} \rangle_l$ & $T_e(r)$ taken from D plasma (solid black)

qualitatively reproduces the observed delay in the arrival time of q=1 as M_{eff} is increased. The evolution of q at rho=0.2 is illustrated as this is roughly the inversion radius of the first sawtooth collapse. When the Z_{eff} and electron temperature of the H simulation are scaled to match the line average and volume average values, respectively, of the D simulation, there is no significant change in the q-profile evolution. But when, in addition, the electron temperature profile shape from the D simulation is used in the H simulation, the delay in the arrival time of q=1 seen in the D simulation is reproduced. This indicates that the change in the shape of the electron temperature profile and, therefore, the electrical conductivity profile, is a key factor responsible for the change in the q-profile evolution as the main ion isotope mass is varied.

Spectroscopic measurements show that the emission from spectral lines associated with many impurities increased with main ion isotope mass, including Be and Ni, where the increased source may include increased sputtering by change-exchange neutrals. There are also indications that tungsten contamination also increased with M_{eff} in this experiment, which is believed to be primarily due to sputtering by beryllium [6]. This variation in impurity contamination resulted in an increase in bulk plasma radiation and radiation peaking with main ion isotope mass, as shown in Fig.4. The increase in plasma radiation as the main ion isotope

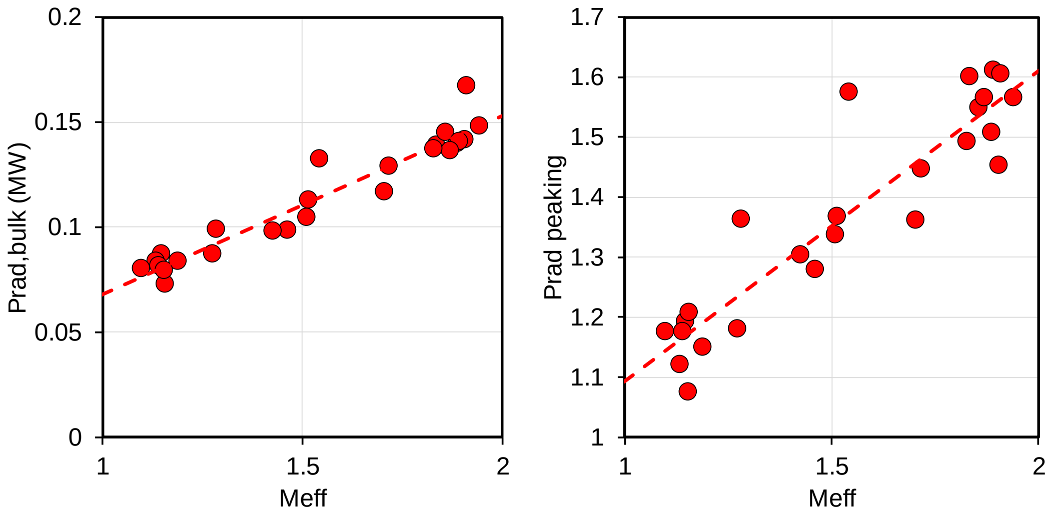

Fig.4. Bulk plasma radiation and central radiation peaking plotted against the effective main ion isotope mass. The radiation peaking is defined as the ratio of on-axis and off-axis horizontal channel signals from the bolometer camera. All measurements averaged over t=1.5-3.5s.

mass was increased correlates with a reduction in electron temperature peaking, consistent with radiation cooling in the plasma core. This appears to be the primary cause of the change in q-profile evolution as M_{eff} is varied. However, the radiation peaking may be accompanied by some peaking to the Z_{eff} profile, which would further broaden the electrical conductivity profile and slow the rate of current diffusion to the plasma centre.

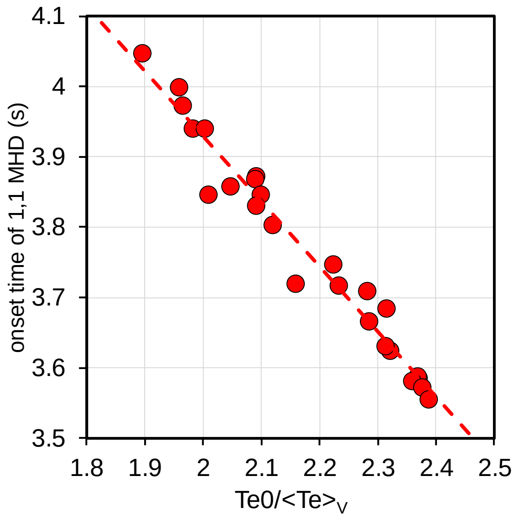

Fig.5 Delay in arrival time of q=1 surface plotted against electron temperature peaking averaged over t=1.5-3.5s.

The electron temperature profile is strongly coupled with the plasma current density profile in Ohmic plasmas through both electrical conductivity and plasma heating effects. This is illustrated in Fig.5, which shows the strong correlation between the electron temperature peaking and the arrival time of q=1. This is further supported by the observed correlation between hollow electron temperature and the occurrence of 2/1 double tearing modes, which indicate the presence of magnetic shear reversal. Given the difficulties in providing accurate real-time q-profile measurements, this allows electron temperature profile peaking to be used as a proxy for current density peaking for the purpose of real-time control and, in particular, for the avoidance of high current disruptions during the hybrid Ohmic current ramp phase. Consequently, ECE electron temperature profile measurements are being included in the JET real-time control system to allow control actions, such as central heating, density control or early pulse termination, in cases where the electron temperature profile becomes hollow. These control schemes will first be tested using D plasmas with the aim to apply them in T and D-T experiments to mitigate the increased risk of disruptions during the current ramp, and to allow rapid development of plasmas with high fusion power. These studies are also relevant to other plasma scenarios aimed at generating elevated q_0, such as 'advanced tokamak' scenarios for steady-state operation, and the experience being gained at JET will help to guide the safe transition to D and D-T in ITER.

[1] Hobirk J. *et al* 2012 *Plasma Phys. Control. Fusion* **54** 095001

[2] Gormezano C. *et al* 1999 *Nucl. Fusion* **39** 1875

[3] King D.B. *et al* 2017 *Proc 44th EPS Conference on Plasma Physics (Belfast, Northern Ireland, UK)* O3.112

[4] Delabie E. *et al* 2017 *Proc 44th EPS Conference on Plasma Physics (Belfast, Northern Ireland, UK)* P4.159

[5] Borodin D. *et al* 2018 *Proc 27th IAEA Fusion Energy Conference (Ahmedabad, India)* EX/P1-14

[6] Brezinsek B. *at al* 2018 *Proc 27th IAEA Fusion Energy Conference (Ahmedabad, India)* EX/9-4

[7] Goldston R.J. *et al* 1981 *J. Comput. Phys.* **43** 61

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