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Interpretative modeling of disruption mitigation via deuterium shattered pellet injection on JET

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Shattered pellet injection (SPI) is the chosen method for mitigating plasma disruptions on ITER. Injection of large quantities of deuterium prior to an impurity injection can be beneficial as it may significantly increase plasma density before thermal quench (TQ) and avoid the generation of runaway electron (RE) beams [1,2]. However, the drifts of ablation plasmoids towards the tokamak low field side (LFS) [3,4] and the existence of background impurities [2] could put pure deuterium (D_2) SPI into question. In this talk, we will present detailed 3D non-linear MHD modelling of a JET D_2 SPI discharge with the JOREK code [5], focusing on effects of ablation plasmoid drifts and background impurities.

The JET discharge considered here (JET #96874) [6,7] is a H-mode plasma with pre-SPI plasma current (I_p) of 3MA, thermal energy 7MJ and central electron density $8.5\times10^{19}m^{-3}$. A D_2 pellet with about 1.6×10^{23} atoms in total was launched and broke into two pieces before shattering, leading to two groups of shards arriving at the plasma about 3.5ms apart. The pre-TQ duration, defined here as the time elapsed from the time when the 1st group of shards reach the plasma edge (denoted as t=0) to the onset of strong MHD activity and I_p spike, is about 9.5ms.

The basic numerical model used consists of reduced MHD equations, diffusive neutrals and an extension for SPI [1]. The ablation rate (N') is estimated by $N'\propto r_s^{1.33}n_e^{0.33}T_e^{1.64}$, where r_s is the shard radius, n_e the electron density and T_e the electron temperature. The ablated neutrals are deposited around each shard with a Gaussian shape [1,2]. Radiative cooling rates of background impurities are estimated using open ADAS data [8] and assuming coronal equilibrium.

In JET #96874, outward motion of SPI shards was observed by a fast camera, possibly due to a rocket effect associated with the drifts of high-β plasmoids formed by ablated material [9]. In fact, as shown by the red curve in Fig. 1, the JOREK simulation without plasmoid drifts clearly overestimates the central line-integrated electron density (n_{el}) measured by the JET polarimeter [10]. This motivates the inclusion of ablation plasmoid drifts in the simulations.

Given the limitation on spatial resolution of 3D MHD simulations to realistically resolve high-β plasmoids and thus their drifts, we propose a "teleportation" model instead to account for the particle and energy transfers caused by drifts. The ablated neutrals, used as a source term for the neutral equation, are shifted from the shard's location by a certain distance (Δ_{drift}) along the outward R direction; meanwhile energies are transferred from the shard location to the shifted neutral location. As depicted in Fig. 1, the simulation with $\Delta_{\text{drift}}=30$cm (assuming the same for all ablation plasmoids) matches better the measured n_{el}, highlighting the crucial role of plasmoid drifts in D_2 SPI. These drifts also increase the ablation rate (due to higher T_e with weaker dilution cooling) and limit the penetration of LFS D_2 shards into the plasma.

Background impurities could dominate radiative cooling in D_2 SPI due to their ability to radiate more strongly. For JET #96874, simulations scanning background impurity densities (neon, carbon and tungsten) highlight the role of neon in matching the measured radiated power during SPI. Effects of background impurities and ablation plasmoid drifts on radiative cooling and density rise emphasized by this interpretative modelling could affect the effectiveness of D_2 SPI in RE avoidance and need to be considered in ITER predictions.

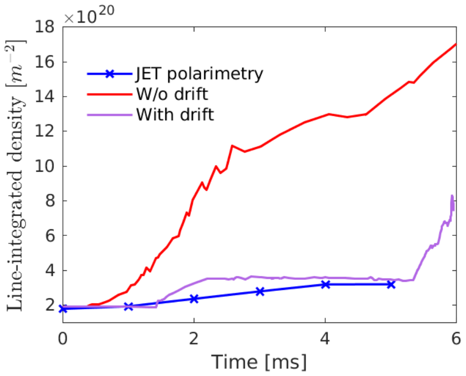

Fig.1 Central line-integrated density for JOREK simulations without (red) or with plasmoid drifts (purple, $\Delta_{\text{drift}}=30$cm)

[1] D. Hu et al, NF 58, 126025 (2018) [2] E. Nardon et al, NF 60, 126025 (2020) [3] B. Pégourié, PPCF 49, R87 (2007) [4] A. Matsuyama, POP 29, 042501 (2022) [5] M. Hoelzl et al, NF 61, 065001 (2021) [6] S. Jachmich et al, NF 62, 026012 (2022) [7] U.A. Sheikh et al, NF 61, 126043 (2021) [8] http://adas.ac.uk [9] H.W. Müller et al, NF 42, 301 (2002) [10] A. Boboc et al, RSI 86, 091301 (2015)