EXPERIMENTAL ANALYSES AND NUMERICAL MODELLING OF TRACE NEON SHATTERED PELLET INJECTION DISCHARGES ON JET

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Shattered pellet injection (SPI) is the current strategy for the disruption mitigation system (DMS) in future large tokamaks including ITER to mitigate three critical consequences arising from disruptive events: excessive heat loads, intense electromagnetic forces and the generation of runaway electrons (REs) [1]. A good series of well-diagnosed trace neon SPI discharges were recently achieved in the final campaigns on JET, where a small percentage (less than 2%) of neon is added to hydrogen-isotope such as deuterium (D2) SPI. These were carried out to explore the feasibility of the so-called trace neon SPI scheme in substituting pure D2 SPI as a solution for RE avoidance, which is crucial for developing injection schemes for the ITER DMS.

D2 SPI, originally envisaged to contribute to RE avoidance in ITER via a strong dilution cooling before the thermal quench (TQ) [2], was shown to suffer from the $\boldsymbol{E} \times \boldsymbol{B}$ drift of the ablation plasmoid toward the tokamak low field side (LFS) [3], where $\boldsymbol{E}$ and $\boldsymbol{B}$ refer to the electric and magnetic field, respectively. This was based on three-dimensional (3D) interpretative modelling of a JET D2 SPI discharge with the non-linear MHD code JOREK. The $\boldsymbol{E} \times \boldsymbol{B}$ drift originates from the vertical polarization induced inside the plasmoid by the ∇B drift [4] and has been studied further via 3D JOREK modelling, exhibiting a quantitative agreement with existing theory [5]. This drift could substantially limit the core density rise needed for RE avoidance and restrain the effectiveness of the LFS D2 SPI strategy. Trace neon SPI, on the other hand, is envisaged to reduce the pressure imbalance of the plasmoid via stronger local radiation, thus suppressing plasmoid drift and facilitating RE avoidance [6]. In this contribution, we will present in-depth analyses of this new series of trace neon SPI discharges on JET based on available diagnostics and numerical modelling with JOREK and the 1.5D transport code INDEX [7]. This will provide important inputs for the DMS strategy in large tokamaks including ITER.

The series of JET discharges considered are H-mode plasmas with a nominal plasma current of 2.5 MA, on-axis toroidal magnetic field of 2.5 T and thermal energy of 4 MJ before SPI. A cylindrical pellet with a diameter of 10 mm and a nominal velocity of 350 m/s was shattered and injected into the plasma, with a neon mixture ratio (based on the number of neon and deuterium atoms contained) of 0.016%, 0.04%, 0.33%, 0.5%, 1% and 2%, respectively. Discharges with pure D2 SPI but otherwise the same setup were also performed to provide a clean reference. A newly upgraded High Resolution Thomson Scattering (HRTS) system including low temperature spectrometers [8] was applied in these discharges. This allows the measurement of electron temperature as low as 1 eV. Repetitions of discharges were performed wherever needed to ensure obtaining at least one electron density and temperature profile measurement during the ablation of the SPI fragments, given the relatively low temporal resolution of HRTS (50 ms). This provides valuable inputs for further modelling. Fast visible cameras were used in the experiments, facilitating the detection of possible outward motion of SPI fragments due to the "rocket effect" originating from the drifts of the ablation plasmoids [9].

Two key observations can be drawn from this series of trace neon SPI discharges: 1) evident outward movement of the fragments, especially towards the end of fragment ablation, was observed in the case of D2 SPI, but not in

trace neon SPI even with a neon mixture ratio as low as 0.016% (containing about 1.26×10^{19} neon atoms); 2) the cooling time, defined as the duration between the arrival of SPI fragments at the plasma edge (t=0) and the peak of the plasma current spike (as a result of a global reconnection event), drops from about 70 ms in the pure D2 SPI case (#101918) to about 7 ms with 0.016% neon (Fig. 1). Cases with higher neon concentrations show similar cooling time, e.g., with 0.5% neon in #102487. These have important implications for the effectiveness of the trace neon SPI scheme in RE avoidance: while 1) implies possible suppression of plasmoid drifts with trace neon SPI, 2) may cause a prompt global reconnection event, hindering the benefits of the staggered injection scheme, where a second neon pellet is launched to radiate out the thermal energy before the TQ.

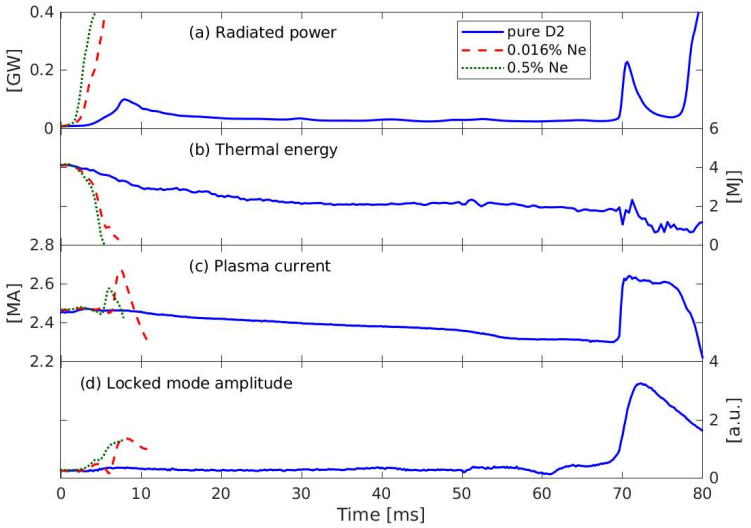

Fig. 1 Time-evolution of the (a) radiated power from bolometry, (b) plasma thermal energy from diamagnetic loops, (c) plasma current and (d) locked mode amplitude of JET SPI discharges with different neon concentrations: pure D2 in #101918 (solid blue), 0.016% neon in #101917 (dashed red) and 0.5% neon in #102487 (dotted green).

Note that the less evident rocket effect in the trace neon SPI cases does not provide a decisive answer on the existence of plasmoid drifts. JOREK and INDEX modelling is on-going to examine this based on various synthetic diagnostics. The sharp drop of the cooling time with a neon mixture ratio as low as 0.016%, is also being investigated with JOREK to clarify the fundamental mechanisms. For instance, 2D JOREK simulations with a coronal equilibrium assumption for the charge state distribution have been performed. As shown in Fig. 2, while the case with 0.5% neon exhibits a much shorter cooling time than that of the D2 SPI, the 0.016% case does not reach an as short cooling time as that observed in the experiment. This is expected to be due to the absence of MHD instabilities in these 2D simulations, as well as the oversized ablation plasmoid and the coronal equilibrium assumption that limit the localized cooling by impurities. JOREK simulations with a collisional-radiative non-equilibrium impurity treatment and 3D geometry are being carried out to clarify this.

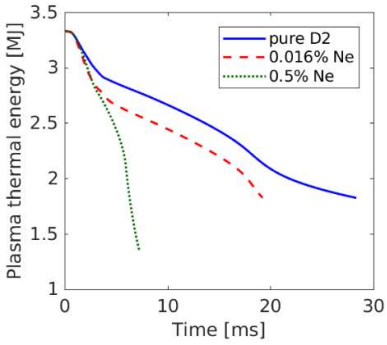

Fig. 2 Plasma thermal energy evolution in 2D JOREK simulations with different neon mixture ratios in the SPI.

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