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Ablation and assimilation of massively injected cryogenic pellets into tokamak plasmas

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Introduction – Cryogenic pellet injection is the most promising technique for fueling of magnetically confined plasmas under the condition of high temperature relevant to fusion reactors. The ablation and assimilation process of injected pellets is complicated, being an interesting topic not only for its practical aspect of the control of tokamak plasmas but on the physics aspect of plasma-matter interaction. In the past decade, the pellet injection was applied to a new research area – mitigation of thermal and electromagnetic loads during major disruptions in tokamak fusion reactors like ITER. The injected quantities are larger by up to many orders of the magnitude than those of fueling pellets. Such massive material injection significantly perturbs the target plasma and dissipates a large part of stored thermal and magnetic energies of the tokamak plasmas. The baseline strategy presently envisaged for the ITER Disruption Mitigation System (DMS) relies on Shattered Pellet Injection (SPI) technology [1], which injects multiple cryogenic pellets shattered into small fragments (mm or sub-mm) by impacting on the metal tube. This paper will address key questions relevant to optimization of such pellet injection scheme for disruption mitigation.

What quantities need to be injected? – It is considered that the ITER DMS offers the capability of injecting up to 24 pellets from the equatorial port plugs at three different toroidal locations. These significant material injection capabilities have been chosen from the requirements of Runaway Electron (RE) avoidance and mitigation, including redundancy and the possibility to provide pellets with different composition for the different phases of an ITER pulse. The required quantities for given target plasma are determined from the analysis of plasma parameters after Thermal Quench (TQ) via the power balance between ohmic heating and radiation losses. Possible RE generation can be estimated once the post-TQ parameters are determined. It is focused here that massive low-Z injection results in that the cooled plasma becomes opaque to line radiation at the post-TQ stage.

How much quantities are assimilated in a plasma? – Very large pellets are needed to inject the required mass but have the potential to cause first-wall damage if they are not fully ablated by the plasma. The SPI scheme then protects the first wall by shattering the pellets into small fragments before penetrating into the plasma. Shattering into small fragments also improve the assimilation efficiency. The dependences of penetration depth of fueling pellets have been shown to lead a close scaling obtained from the neutral gas shielding (NGS) model. Up to present, the ablation of a shattered pellet has been analyzed using similar models to those used in the study of fueling pellets, assuming that the ablation of individual fragments is of independent with each other. We analyze SPI triggered disruptions using the 1.5D disruption simulator INDEX [2]. It has been shown that the amount of material that can be assimilated strongly depends on the thermal energy of the target plasma. A comparison has been made between the injection of pure hydrogen pellets and that of neon mixed hydrogen pellets, which identifies an efficient pre-thermal quench (TQ) SPI scheme that maximizes the electron density, depending on the pellet composition, the injection velocity, and the fragment sizes.

Mechanisms limiting the efficacy of disruption mitigation by SPI – RE avoidance in the fusion reactor is challenging because steady sources of high energy electrons are present via the tritium decay and the Compton scattering. Many factors are still uncertain but a positive aspect for RE avoidance in the fusion plasma is that a plasma with high stored energy is favorable regarding density assimilation and is resilient to line radiation. Nevertheless, a possible mechanism limiting the density assimilation is the ExB drift displacement of ablated materials. This effect is expected to be pronounced at high electron temperature for which the ablated material is significantly over-pressured and drifts down the magnetic field gradient. Here we implement an improved ablation model [3] in the INDEX code, demonstrating the impact of the ExB drift displacement on the particle deposition profiles due to SPI. We will discuss the possibility to mitigate particle losses due to ExB drift displacement by controlling the composition of neon mixed hydrogen pellets.

References

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