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Theory and Modelling activities in support of the ITER Disruption Mitigation System

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The ITER Disruption Mitigation System (DMS) should ensure that heat loads, ElectroMagnetic (EM) loads, and Runaway Electron (RE) impacts remain tolerable during ITER disruptions. The design of the Baseline ITER DMS, which shall be available from the beginning of ITER operation, relies on Shattered Pellet Injection (SPI). Up to 24 pellets may be injected from 3 equatorial ports, plus 3 pellets from upper ports. Several key parameters however remain to be defined, such as the injected species, the size of the pellets or the characteristics of the flight tube front end (which determine the shattering). An international DMS Task Force (TF) has been launched in 2018 in order to urgently inform the Baseline DMS design (which has to be fixed by 2022), as well as to consider options for a possible later DMS upgrade [M. Lehnen et al., 27th IAEA FEC, Gandhinagar, India, 2018]. The DMS TF comprises 3 divisions: Technology, Experiments and Theory & Modelling (T&M). The present contribution summarizes the T&M activities.

The most critical issue is the risk of large (multi-MA) RE beam generation [B. Breizman et al., Nucl. Fusion 59 (2019) 083001]. Open questions are the amount of hot tail generation and the amplification of RE seeds by the avalanche mechanism during the Current Quench (CQ). Concerning the hot tail issue, several actions are underway: 1) the modelling of hot tail generation in present experiments, in particular in DIII-D, using available numerical tools; 2) test particle studies in 3D non-linear MHD simulations to study electron transport (and in particular losses of hot tail electrons due to field line stochasticity) and electron parallel momentum dynamics during the Thermal Quench (TQ); 3) the development of more sophisticated numerical tools coupling 3D non-linear MHD and electron kinetics; and 4) a study on the possibility to reduce hot tail generation in ITER by diluting the plasma with a pre-TQ pure D2 or H2 SPI [A. Matsuyama et al., this conference].
Even if hot tail generation is negligible, large RE beams may still be produced during the nuclear phase of ITER operation, due to small but unavoidable RE seeds from tritium beta decay or Compton scattering of gamma rays emitted by the activated wall, combined with the very large avalanche gain expected in ITER, which may reach ~1016 [Hender et al., Nucl. Fusion 47 (2007) S128] or even more [L. Hesslow et al., Nucl. Fusion 59 (2019) 084004]. According to [J.R. Martín-Solís et al., Nucl. Fusion 57 (2017) 066025], this risk would be mitigated if the plasma could assimilate, in a uniform fashion, a large enough quantity (~20-40 times the plasma content) of H2 or D2 (in addition to a small quantity of Ne, which is necessary to radiate the thermal energy and mitigate EM loads by controlling the CQ duration). However, this work is currently being revisited [T. Fülöp et al., this conference] using more accurate models (e.g. in what concerns the effect of the partial screening of the nuclear charge for non-fully stripped ions [L. Hesslow et al., Nucl. Fusion 59 (2019) 084004] or finite aspect ratio effects [C. McDevitt et al., Plasma Phys. Control. Fusion 61 (2019) 054008]). Furthermore, the critical question of whether the plasma can assimilate the required amounts of material with sufficient spatial uniformity is being investigated by 1.5D transport [A. Matsuyama et al., this conference] as well as 3D MHD simulations.
An alternative scheme for RE beam avoidance, based on repeated SPI during the CQ in order to deplete small RE seed populations before they get amplified by the avalanche, is also considered. Simple estimates suggest that this scheme may work, motivating a more detailed investigation.
On the other hand, if a large RE beam forms, its mitigation appears difficult. This is due in particular to the fact that the beam will move up as its current decreases. T&M efforts regarding RE beams have thus shifted to understanding the beam termination and how impact damage may be minimized. In this respect, seemingly benign impacts observed recently at DIII-D and JET when performing a D2 SPI into a RE beam are the subject of particular attention [C. Paz-Soldan et al., this conference].
Thermal loads during the TQ are another important issue. Their mitigation requires radiating most of the thermal energy content of the plasma with minimal toroidal and poloidal peaking factors. Non-linear 3D MHD simulations with JOREK, M3D-C1 and NIMROD show that simultaneous dual SPI from toroidally opposite ports can substantially reduce radiation

asymmetries, as illustrated in Figure 1. Work is underway to assess the effect of imperfect synchronization between the different pellets.

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In parallel to the above-described efforts dedicated to providing urgently-needed input for the DMS design, actions are underway to 1) improve theories and models of disruptions and SPI; 2) benchmark and validate modelling tools; and 3) explore alternative solutions in case the Baseline SPI-based DMS turns out not to be fully effective.
Work on model improvements focuses in particular on pellet physics, involving a better description of electron kinetics and radiation in the ablation cloud, and the coupling of dedicated pellet codes to 3D non-linear MHD codes.
A detailed benchmark between non-linear MHD codes has been performed for axisymmetric impurity injection simulations [B. Lyons et al., Plasma Phys. Control. Fusion 61 (2019) 064001] and is being pursued in 3D. Non-linear MHD simulations of SPI are broadly consistent with experimental observations in DIII-D [C. Kim et al., Phys. Plasmas 26 (2019) 042510] and JET [D. Hu et al., APS-DPP 2018] and detailed comparison is in progress. RE generation models are also being compared to experimental data, showing promising agreement for JET massive gas injection cases [L. Hesslow et al., J. Plasma Phys. 85 (2019) 475850601].
In the present contribution, we will overview the progress in the above-mentioned topics and outline directions for future work.

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