Divertor detachment in ITER during application of resonant magnetic perturbations for ELM suppression

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Recent improvements of the EMC3-EIRENE code have allowed to assess for the first time the detached divertor scenario foreseen for ITER during ELM suppression by resonant magnetic perturbation (RMP) fields. This is a major breakthrough because ELM suppression is required for ITER to maintain the integrity of the plasma wall interface. The ITER divertor has been designed based on extensive 2D (axisymmetric) simulations, but whether the 3D (non-axisymmetric) boundary from RMP application remains compatible with divertor operation in a dissipative, partially detached state remains unknown. New EMC3-EIRENE results show that detachment transition with RMPs occurs at lower upstream density within the traditional strike zone of the symmetric configuration (see figure 1). At the same time, however, non-axisymmetric strike locations with a magnetic connection into the bulk plasma appear further outside, and those remain attached - even at higher upstream densities when the symmetric configuration is already (partially) detached. Neon seeding can mitigate those non-axisymmetric heat loads by about 30% for an average impurity concentration of 1% at the separatrix.

Fundamental for the extended application range of EMC3-EIRENE has been the numerical stabilization of the iterative solver by linearization of the electron energy loss term [1]. Furthermore, volumetric electron-ion recombination is now activated in EMC3-EIRENE along with neutral-neutral collisions (in BGK approximation) and molecular assisted recombination. Simulations for the ITER Pre-Fusion Plasma Operation (30 MW) show that detachment transition occurs at lower upstream density within the traditional strike zone of the symmetric configuration while non-axisymmetric strike locations further outwards remain attached [2].

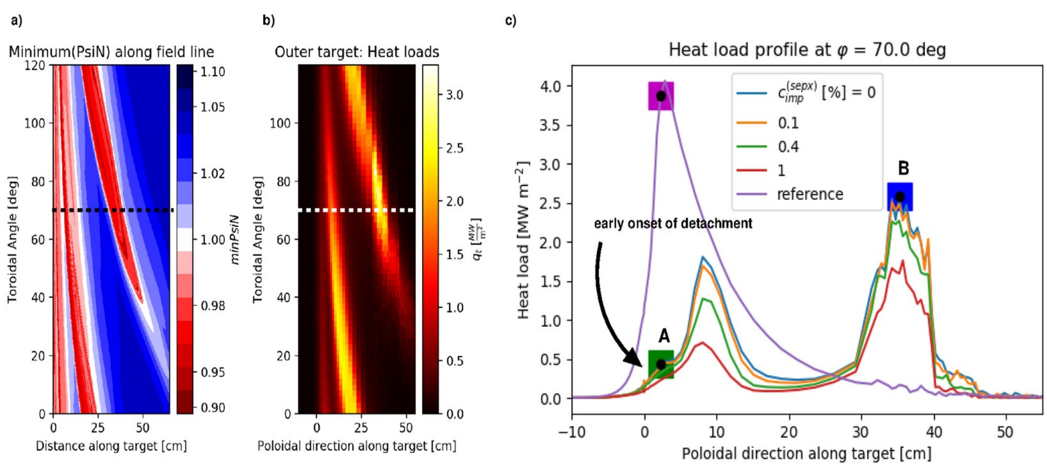

Figure 1: (a) Magnetic footprint at the outer target, (b) corresponding heat loads, (c) heat load profiles at φ = 70 deg for different Ne concentrations in comparison to the axisymmetric reference (without Ne).

Figure 1 shows the correlation between the magnetic footprint (a) and the heat load pattern (b) on the outer divertor target. A reference simulation with comparable upstream density of $n_{up} \approx 1.7 \cdot 10^{19}$ m^{-3} (evaluated at the midplane position of the separatrix of the symmetric configuration) is included in 1 (c). The same amount of power as in the symmetric reference configuration is now distributed over perturbed field lines connecting the bulk plasma to the target (red areas in figure 1(a)). Not only is the upstream heat flux at strike point A reduced (green box in Fig. 1.c), more energy is lost to neutral gas and dissipated through cross-field diffusion here compared to the reference (magenta box). Evaluation of the upstream-downstream pressure balance confirms the earlier onset of detachment here.

On the other hand, no pressure and power losses are found at strike point B (blue box) which remains attached at temperatures well above 10 eV. Simulations with Ne seeding have been performed to explore a possible mitigation strategy in anticipation of the Fusion Plasma Operation phase at 100 MW. It can be seen in figure 1 (c) that Ne seeding can indeed mitigate the non-axisymmetric heat loads, but it is more efficient within the traditional strike zone (approximately 0 – 15 cm from the separatrix of the symmetric configuration). Nevertheless, a heat load reduction of about 30 % can still be achieved at strike point B with impurity concentrations of 1 % averaged along the former separatrix.

Plasma response is key for reliable predictions of divertor heat and particle fluxes. The present simulations are based on MARS-F results [3] within a single fluid, linearized resistive magneto-hydrodynamic model. The relative phasing between coil rows of the externally applied perturbation field can be optimized for ELM control based on the X-point displacement caused by the edge-peeling component of the plasma response, but this is found to be correlated with a relatively large magnetic footprint on the divertor targets. Despite screening of resonances in the bulk plasma, field amplification near the separatrix is found and this determines the magnetic footprint size. It is possible for the magnetic footprint to extend beyond its size in the vacuum perturbation field approximation, and it can be seen in figure 2 that it can even extend beyond the dedicated high heat flux region on the divertor targets (dashed line) under certain assumptions related to plasma rotation. This can bring high heat loads to those locations, and it is found that Neon seeding is significantly less effective under these conditions.

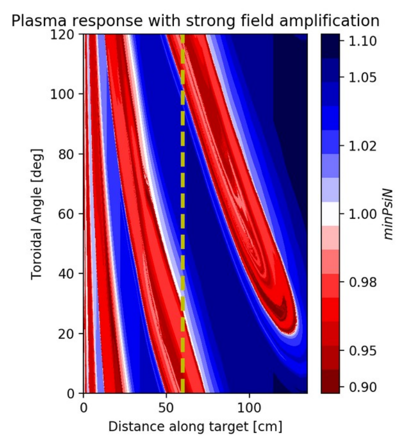

Figure 2: Magnetic footprint for MARS-F plasma response based on a ratio of momentum to thermal confinement time of 2 instead of 0.65 as in figure 1.a.

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[1] H. Frerichs *et al.*, Nuclear Materials and Energy **18** (2019) 62–66
[2] H. Frerichs *et al.*, accepted in Physical Review Letters (2020)
[3] L. Li *et al.*, Nuclear Fusion **59** (2019) 096038