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Transport Study on the W7-AS Island Divertor: Physics, Modelling and Comparison to Experiment

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Introduction

A realistic prediction of the detachment physics in island divertors has become possible after implementation of the impurity transport and radiation into the EMC3-EIRENE code [1-3]. Up to now, the code has employed an island divertor model of W7-AS consisting of the true geometry of plates, baffles and walls but an approximate geometry of the magnetic configuration with closed islands [3,4]. This approach is sufficiently realistic to describe the global plasma behaviour as long as the key geometric parameters of the island divertor, namely the connection length, the island size and the field-line pitch are correct and the magnetic structures are weakly ergodic. However, it poses a restriction for a comparison with local experimental data. This restriction has been overcome recently by implementing a new reversible field-line mapping technique in the EMC3 code, which extends the code applicability to general configurations with open islands and arbitrary ergodicity [5]. First simulations with the new code version addressing the physics of the particle and power depositions on the target plates are presented in this paper.

EMC3-EIRENE predictions

Previous EMC3-EIRENE simulations for pure hydrogen plasmas showed strong differences in transport between island divertors and standard tokamak divertors [6]. Compared to tokamaks, the downstream density n_{ed} typically exhibits a roughly linear scaling with the upstream density n_{es} indicating no high recycling and never exceeding n_{es}. The upstream temperature T_{es} drops significantly with n_{es} even in the case of $T_{ed} << T_{es}$. The particle fluxes to the targets are smaller than in the two-point model even at low densities, high temperatures, indicating a significant momentum loss of the plasma ions flowing in the main channel. All these effects, which do not appear in tokamaks, are related to the prominent role of the cross-field transport arising from the combined effects of the small field-line pitch [5] (≈ 0.001 for W7-AS compared to ≈ 0.1 for tokamaks) and the small distance of the X-point from the target plate.

After implementation of the impurity transport model into the EMC3-EIRENE code [3], a dedicated numerical transport study including intrinsic carbon impurities was carried out, aiming at the exploration of the detachment physics in the W7-AS island divertor. One basic result of these calculations was that higher upstream densities are needed to achieve detachment as compared to tokamaks, because of the additional momentum losses associated with the island divertor geometry, which have to be balanced by higher upstream pressures. Concerning the physics of detachment, major predictions of the code calculations were a jump of the radiation level and a jump of the radial position of the radiation zone at detachment transition. The first effect is due to a thermal instability associated with the two-branch characteristic of the carbon cooling rate function [5]. The second effect reflects an unbalance between the impurity radiation and the radial heat transport [5]. As soon as the radiation capability of the impurity at the target exceeds the power entering the SOL, the radiation zone becomes unstable and detaches form the target. It will stop only if it finds a radial position where the local radiation capability equals the input power. No such stable position of the radiation zone has been found inside the SOL so far from both the code calculations and the bolometric measurements.

Comparison to the experiment

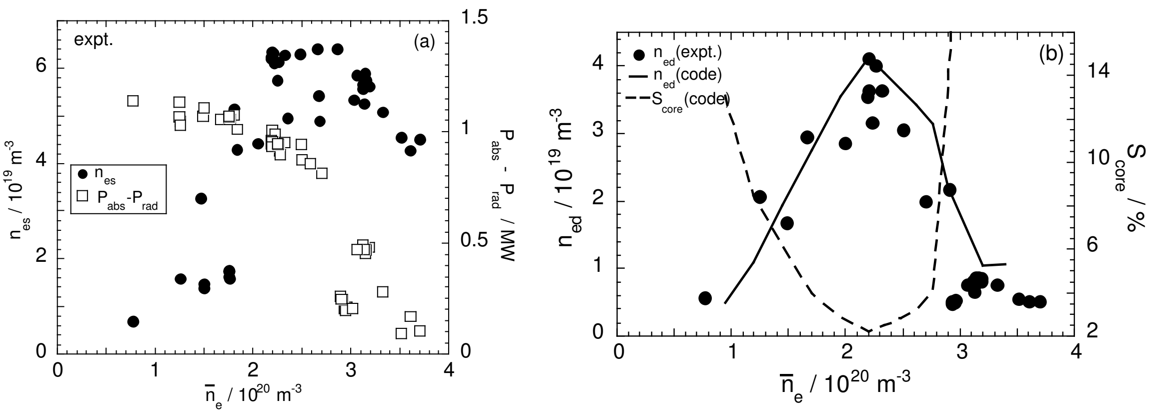

Fig. 1: Comparison of modelling and experiment for high-density 2 MW NBI-heated discharges:

(a): Experimental data set taken as input for EMC3-EIRENE simulations.

(b): Downstream densities from experimental data and code simulations and ionisation fraction in the core from code. Drop of n_{ed} and rise of S_{core} indicate shifting of the ionisation front towards the separatrix and subsequent detachment.

A dedicated numerical study has been carried out with the input data n_{es} and P_{SOL} taken from the experiment [7] and the measured $\overline{n}_e$ as independent parameter (Fig. 1a). At high $\overline{n}_e$ values, P_{SOL} strongly drops due to enhanced impurity radiation in the core. The calculated n_{ed} values (Fig. 1b) reproduce correctly the measured upward/downward dependency on $\overline{n}_e$ including a rollover value of about $4x10^{19}$ m^{-3} at $\overline{n}_e \approx 2\text{-}2.5x10^{20}$ m^{-3}. Here the calculated core ionisation fraction, S_{core}, has a minimum, which reflects the improved neutral screening and the attached ionisation front at maximum n_{ed}. If $\overline{n}_e$ is increased further, P_{SOL} and hence the downstream temperature drop, leading to a detachment of the ionisation front, which moves towards the separatrix, hereby reducing n_{ed}. The sharp rise of S_{core} from 4% to 14% indicates a jump of the ionisation zone to the separatrix. A jump of the radiation zone to the separatrix (not shown here) follows as soon

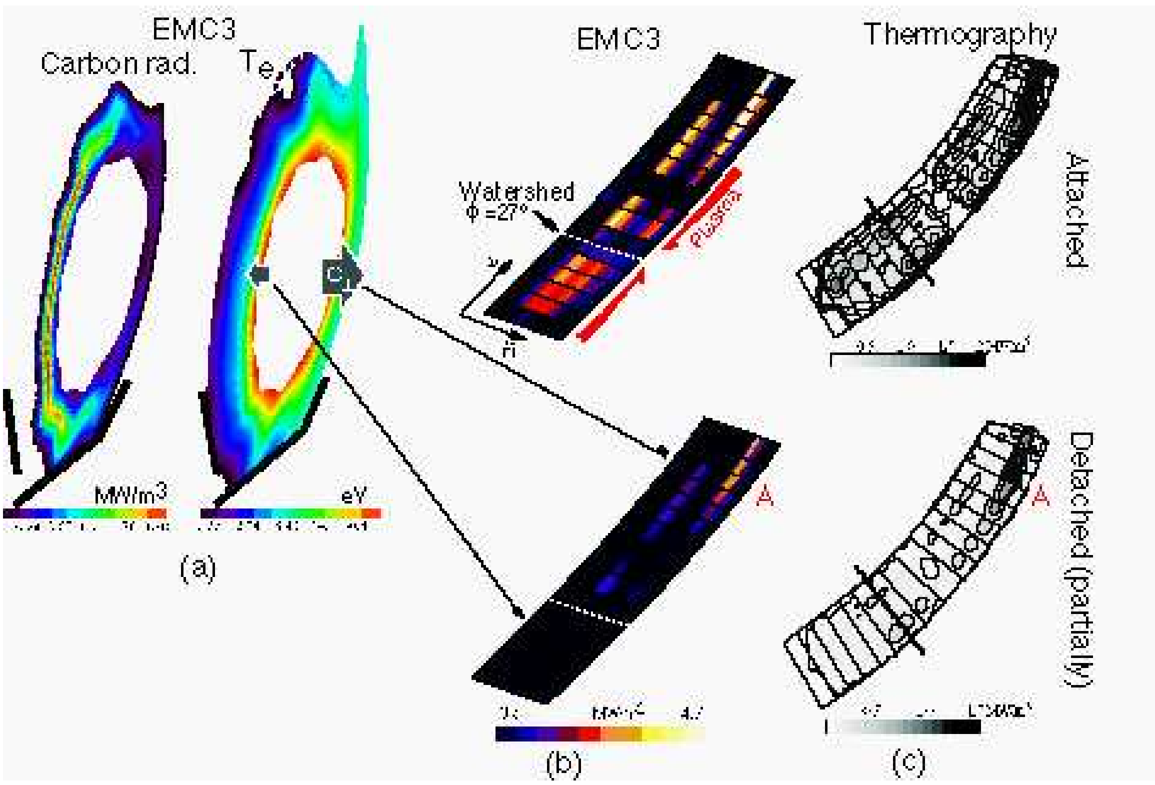

Fig. 2: Asymmetric power unloading of the divertor plates at detachment transition:

(a): Distribution of carbon radiation and electron temperature from EMC3-EIRENE simulations.

(b): Simulated power load distributions for attached and detached conditions. The watershed separates the island fans striking the plates from the positive and negative toroidal directions, respectively. The strike zone A remains attached.

(c): Measured power load distribution from IR thermography for attached and detached conditions.

as the radiation capability at the target exceeds the SOL input power, in agreement with the detachment physics discussed in [5]. This jump is supported by bolometric measurements in the island divertor edge [8].

Additionally, the EMC3-EIRENE code has predicted a jump of the carbon radiation at detachment transition [9], in agreement with bolometric measurements for a large number of quasi-stationary discharges.

After implementing the real open-island geometry of W7-AS in the EMC3 code, a realistic interpretation of local experimental data has become possible. In particular, unexpected patterns of the target particle deposition could be reproduced by taking into account classical ExB drift effects [10]. Furthermore, an asymmetric power unloading of the target at transition to detachment has been observed [11]. Typically the plasma does not detach at the strike zone A in the $\phi > 27°$ section of the plates (Fig. 2c). This behaviour is reproduced by the simulations (Fig. 2b) and can be explained as follows. The $\phi > 27°$ strike zones are magnetically connected to the outboard side of the torus. Here, the temperature is higher due to the radial field line compression which favours the radial heat transport. On the other hand, the carbon radiation is localised at the poloidal zone with lowest temperatures, i.e. at the inboard side (Fig. 2a), which is supported by bolometric measurements [8]. These two effects strongly reduce the drop of the parallel power flux to the plates in the strike zone A.

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