Non-linear MHD Simulations of ELMs in a High Recycling Divertor

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ITER plasmas will be characterized by a high density plasma (i.e. Greenwald fraction) at low collisionality inside the separatrix, a high density in the scrape-off layer combined with a high recycling detached divertor. ELMs in ITER are expected to be tolerable at low plasma current but need to be controlled at the full 15MA current. Whether ELMs are tolerable depends in part on the interaction of the ELM energy and density losses with the detached divertor, i.e. do (very) small ELMs burn through the detached divertor plasma. Since the ITER regime cannot be obtained in current experiments, numerical simulations of ELMs are required for the extrapolation to ITER.

Presently in the nonlinear MHD code JOREK, a fluid model is used to describe the main plasma and the neutrals. The time evolution of the neutrals is described by a diffusion model combined with a boundary condition which reflects outgoing ions as incoming neutrals. This fluid model has been successfully used to simulate ELMs in the super-X divertor of MAST-U [1] and is applied below to ITER.

Kinetic neutrals and impurities

To improve the modelling of the divertor in the non-linear MHD code JOREK, a kinetic (i.e. particle) description of neutrals and impurities has been implemented [2,3]. The full orbits of the particles are followed using the well-known Boris method in toroidal geometry in the time varying electric and magnetic fields of the MHD fluid. Particles are followed in both (R,Z,φ) space and in the local (s,t,φ) space of the cubic Bezier finite elements. The ionization of the neutrals gives rise to a source of ions, momentum and energy in the fluid. To add these sources to the fluid equations the discrete particle distribution needs to be converted to the continuous, in space, description of the finite element basis. For example, the ion source $S_\rho(\vec{x}) = \int mf(\vec{x},\vec{v})\,d\vec{v}$ where f is the distribution of ionized neutrals is represented in the finite element $H_{ij}(s,t)$, Fourier basis: $\tilde{S}_\rho(\vec{x}) = \sum_{ijk} p_{\rho,ijk} H_{ij}(s,t) H_{\varphi,k}(\varphi)$, with p_{ijk} the expansion coefficients. In the weak form this yields a set of equations:

$$\int v^*(\vec{x})\tilde{S}_\rho(\vec{x})\,d\vec{x} = \int v^* S_\rho(\vec{x})\,d\vec{x}; \quad \int v^*(s,t,\varphi)\sum_{ijk} p_{\rho,ijk} H_{ij}(s,t) H_{\varphi,k}(\varphi)\,d\vec{x} = \sum_n v^* m w_n \delta(\vec{x}-\vec{x}_n) \quad (1)$$

As it depends only on the finite element geometry, the lhs of the system of equations needs be factorized only once. The system needs to be solved at every fluid time step. The time step of the neutrals is determined by the ionization and charge exchange time scales in order to get an accurate spatial distribution of the source. The particles are considered macro-particles with a certain weight w_n. At every ionization event this weight is reduced until it reaches a critical lower value at which it is removed. For the conservation properties of the combined fluid-particle system it has been found essential to collect the contributions to the right-hand side particle sums at every particle time step. To reduce the noise in the finite element representation (or as a regularization) the following equation is solved instead of Eq.1.

$$\int v^*(\vec{x})\left(1-\lambda\nabla^2-\varsigma\nabla^4\right)\tilde{S}_\rho(\vec{x})\,d\vec{x}=\int v^*(x)\,S_\rho(\vec{x})\,d\vec{x} \tag{2}$$

where λ and ς are the regularization coefficients. The atomic physics is taken from the OPENADAS database. The source of neutrals comes from reflected ions on the walls, recombination or from gas injection.

Radiation is included for both neutrals and impurities. Using the binary collision model for the impurities, the thermal force, leading to a flow of impurities up the temperature gradient, is taken into account. Multiple species of impurities, of arbitrary (time varying) charge state, can be included. The sputtering of impurities, by the main plasma, by self-sputtering or by other impurities has been implemented and verified. The sputtering model includes the prompt redeposition, particularly important for heavy impurities such as Tungsten. Fig. 1 shows an example of the calculation of the prompt redeposition rate of sputtered Tungsten as a function of temperature. It shows the strong influence of multiple ionizations at low temperatures, reducing the prompt redeposition rate from near 1 to 0.6.

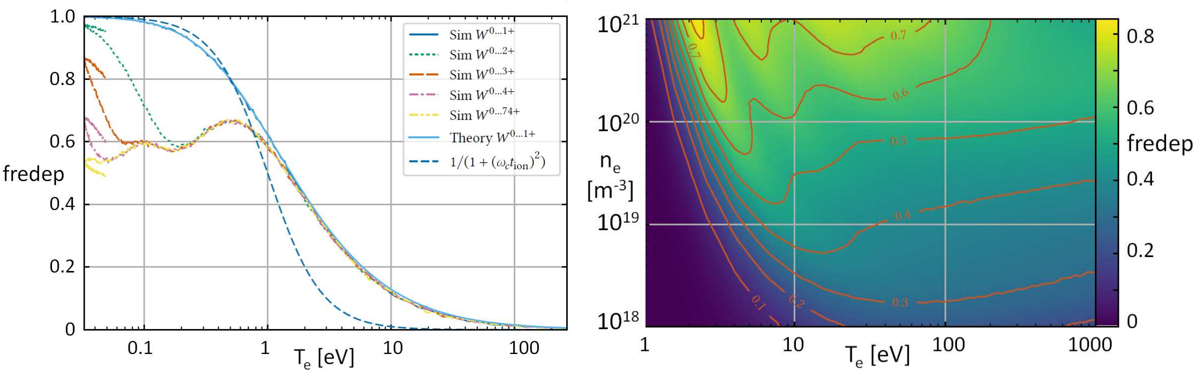

Fig 1. Prompt redeposition from full orbit Tungsten sputtering: the effect of multiple ionisations (left) and the prompt redeposition as function of density and temperature (right) [3]

ELM simulations in the high recycling divertor in ITER

The first simulations of ELMs in ITER including the effects of neutrals have been performed using the neutral fluid model, not yet taking into account the recent kinetic extensions described above. The neutrals are described with a diffusive model, including ionization, recombination and radiation. The model also includes a constant background impurity distribution, radiating at the local temperature, assuming a coronal distribution of charge states. The boundary condition on the neutrals reflects the outgoing ion flux with a reflection coefficient (chosen to be 0.9 here). A second source of neutrals comes from two gas injection points, one at the top of the machine and one on the low field side just above the divertor. The finite element grid, in the poloidal plane, is extended from a flux surface aligned grid up to a close match of the ITER first wall and divertor.

The ITER H-mode equilibrium at 5.3T/15MA is characterized by a pedestal pressure of 126 kPa and a separatrix density of $0.32 \times 10^{20} m^{-3}$ (from IMAS #131025, [4]). A set of quasi-stationary states have been created with a varying gas injection rate. Fig.2 compares the ion and neutral density profiles and temperature profiles along the separatrix at the outer divertor. Included is a low recycling case with a zero reflection coefficient. With increasing gas injection, the density (and neutral density) at the divertor strongly increases, forming a thin layer with a width of about 3 cm. At the highest gas injection (C), the target temperature reduces to 6 eV compared to a temperature of 220 eV in the case (0) without recycling neutrals. In the high recycling cases (A-C) a constant background density of Neon at 5×10^{17} m^{-3} is included. At the highest gas injection, Neon radiates 42 MW, the total radiation amounts to 70 MW with a total heating power of 110MW. In this case (C), the peak heat flux to the outer target is ~6 MW/m^2.

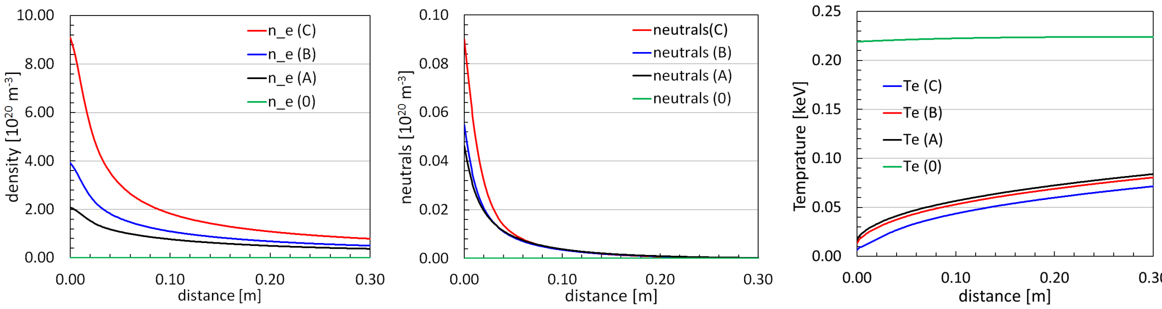

Fig.2 Profiles of plasma density, neutral density and temperature along the outer separatrix as a function of the distance from the outer divertor for different neutral gas injection rates ($A=1.1 \times 10^{23}$, $B=2.2 \times 10^{23}$, $C=4.4 \times 10^{23}$). The case (0) is a low recycling case with zero reflection of ions into neutrals.

For these first ELM simulations in a high-recycling ITER divertor, a single toroidal harmonic n=6 is selected to obtain a relatively small ELM. Fig.3 shows the snapshots of 3 time slices of the temperature and the density, at the first maximum of the n=6 magnetic energy perturbation (=0.36 ms), at the first maximum of the thermal energy losses (t=0.45ms) and towards the end of the ELM at t=0.65 ms). The time scale for the growth of the n=6 magnetic energy is ~300 μs, the maximum of the thermal energy loss follows ~100μs later. On this time scale, the outer divertor “burns through” the high density region at the target. The temperature profile becomes constant along the separatrix, rising to from 6 eV to 450 keV in less than a 100 μs rising further to 650 eV in a second burst of the ELM. In this time only 0.12 MJ of thermal energy has been lost due to the ELM instability. The density is depleted along the separatrix on a comparable time scale. A high density region remains just below the separatrix in the private region. In the initial ELM rise, the temperature rises in three stripes, following the homoclinic tangles of the magnetic field perturbation. However, at the time of max energy loss, only one dominant peak (in both temperature and heat flux) remains at the separatrix. Fig.4 shows the profiles along the outer ITER divertor for several time slices. The width of the power deposition on the outer divertor is comparable to the width of the pre-ELM profile at ~3 cm at full-width half maximum. There is no broadening of the ELM footprint due to the high recycling divertor.

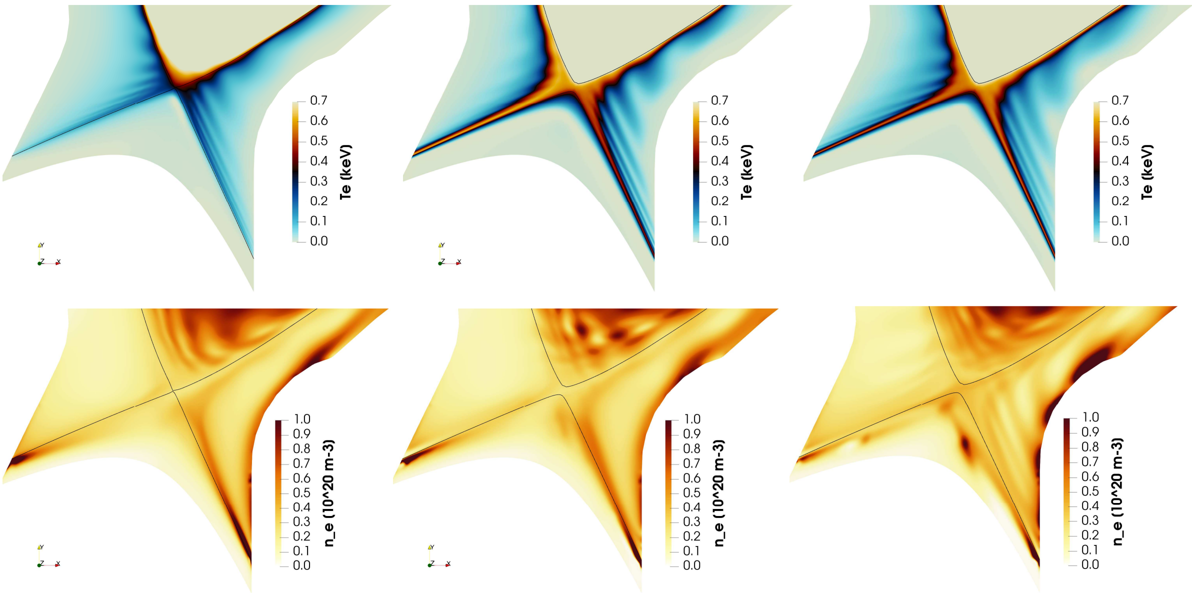

Fig.3 Snapshots of the temperature and density during the ELM at t=0.36ms, t=0.45ms and t=0.66 ms.

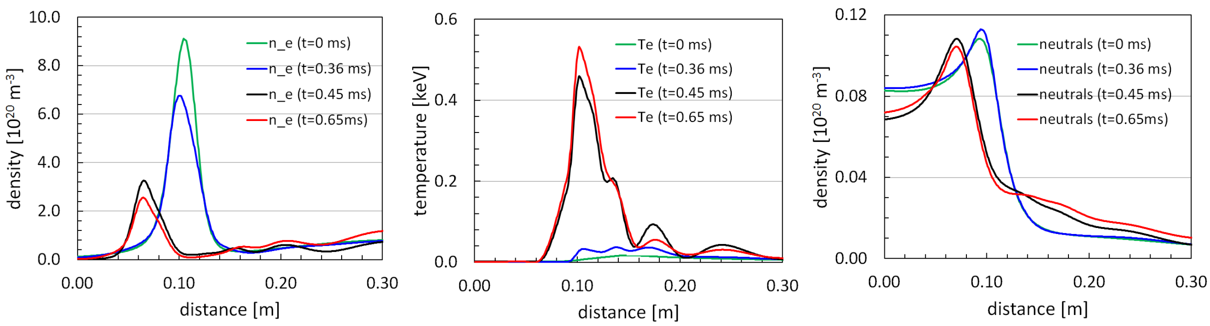

Fig.4 Density, temperature and neutral density profiles along the ITER outer divertor (-4.5<Z<-4.2)

Conclusion

The first ELM simulations in the ITER high recycling divertor show that even a small ELM burns through the high density layer leading to a low recycling, high temperature ELM energy exhaust. The next step, the kinetic extensions for neutrals and impurities, described above, will be applied to improve the description of detached plasmas.

Acknowledgements

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