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Non-linear MHD simulations of ELMs in a high recycling divertor

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Introduction

In current-day tokamaks large amplitude ELMs are observed with low collisionality plasmas, or small ELMs when operating with high density/collisionality plasmas [1]. In ITER the plasma will have both a low collisionality and high density, therefore the expected ELM amplitude and associated power fluxes cannot be directly extrapolated from current experiments.

The ITER divertor will operate in a high density semi-detached state to reduce the heat flux to the plasma facing components. In experiments, a high density and high recycling divertor is created by gas injection. The gas injection rate determines, in most part, the detachment of the plasma from the divertor target. When the degree of detachment is high the heat load on the the divertor is generally lowered.

Given that the ITER conditions are not simultaneously available in current experiments, non-linear MHD simulations are required to predict the expected amplitude of ELM energy loss in ITER plasmas. The modelling of the high recycling divertor and detachment requires an extension of the conventional MHD model to include a description of the neutral particles.

This paper describes the implemented MHD-neutral model, boundary conditions and first application to the simulation of ELMs using the non-linear MHD code JOREK [2]. Previously, this model had been applied the simulations of disruption mitigation using massive gas injection [3]. The application of the MHD-neutral model is now expanded to plasma detachment and simulations of ELMs in a recycling divertor.

For this application a comparison is made between JOREK models. One ELM is simulated without the neutrals and one with a neutral gas with recycling boundary conditions. The comparison is made on the temperature, density and heat flux on the divertor targets.

MHD-neutral model

The non-linear MHD code JOREK includes a number of MHD models, including both reduced and full MHD models in toroidal geometry. In this paper, the extended reduced MHD model is used. This model include the mass density conservation law, perpendicular and parallel velocity and the poloidal flux. Recently, the JOREK code has been extended to include a neutral gas as a second fluid. This adds a diffusion equation (1) for the neutral fluid and terms that describe the ionisation of neutrals, recombinations of ions and radiation losses.

$$\frac{\partial n_0}{\partial t} = \nabla \cdot D_0 \nabla n_0 + S_0 - S_{ionisation} \tag{1}$$

New boundary conditions are implemented at the divertor targets for the modelling of a recycling divertor. This boundary condition states that the flux of the ions, convected with the sound speed at the target (Bohm criterion), are reflected back as diffusive neutrals. The amount of particles that is reflected is determined by the reflection coefficient C_R in equation 2.

$$\Gamma_0 = D_0 \nabla n_0 \cdot \vec{n} = C_R \rho \vec{v}_{||} \cdot \vec{n} \quad (2)$$

Here Γ_0 is the flux of particles into the wall, D_0 the neutral diffusion coefficient, n_0 the neutral density, ρ the plasma density and $\vec{v}_{||}$ the ion parallel velocity.

In this work the reflection is chosen to be 0.8. Some provisional results show that above $C_R = 0.8$ no big effects are visible because that walls other than the divertor target act as sink for particles. Further research is needed to determine in more detail the effect of this coefficient on the steady state solution.

The addition of the neutral fluid allows for new physics to be investigated with the JOREK code, notably the influence of divertor recycling and detachment on the amplitude of the ELM energy and density losses.

Stationary state, detachment

One of the actuators in controlling plasma detachment are the gas valves in the divertor region [4]. In this work a representation of a valve is placed in the outer leg at the height of the x-point in a JET-like geometry. By varying the gas injection rates the neutral density in the divertor changes with this also the plasma temperature and density. In all simulated cases the plasma had a H-mode configuration, with a I_p of 2.0 MA and toroidal magnetic field of 2.0 T. Simulation were run for a number of time steps equivalent of 500 ms. This long time scale is necessary to reach a true stationary state for the divertor solution. One of the main effects is visible in the temperature profile, plotted in figure 1, when following a flux surface with the peak temperature on the divertor target.

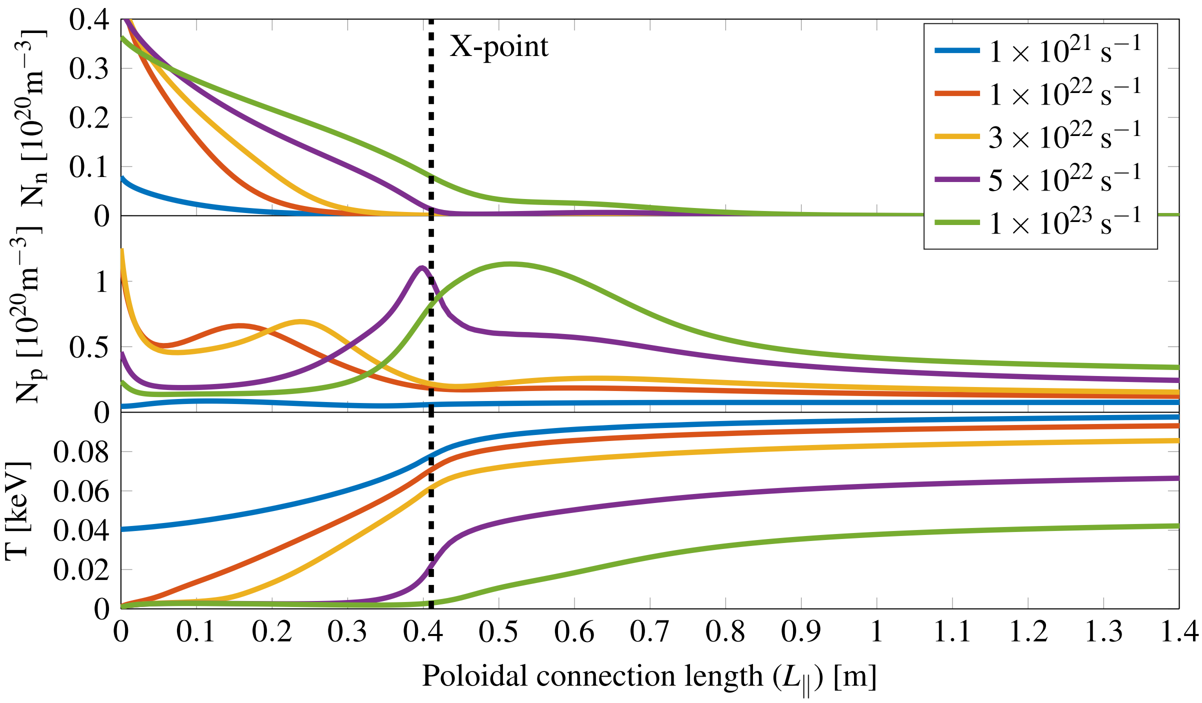

Figure 1: *The temperature, neutral and plasma density profiles on the flux surface of maximum temperature at the target, from the outer target to the mid-plane, for different gas injections rates. Observable is the drop of the temperature on the divertor plate as soon a significant amount of gas is injected with a transition to a detached divertor for a gas injection of* 1×10^{22} s^{-1} *to* 3×10^{22} s^{-1}.

Also visible in figure 1 are the neutral and plasma densities on the same positions as the temperature profile. The neutral density shows a steady increase of neutrals present in the divertor region eventually reaching even towards the X-point. The plasma density starts to develop a

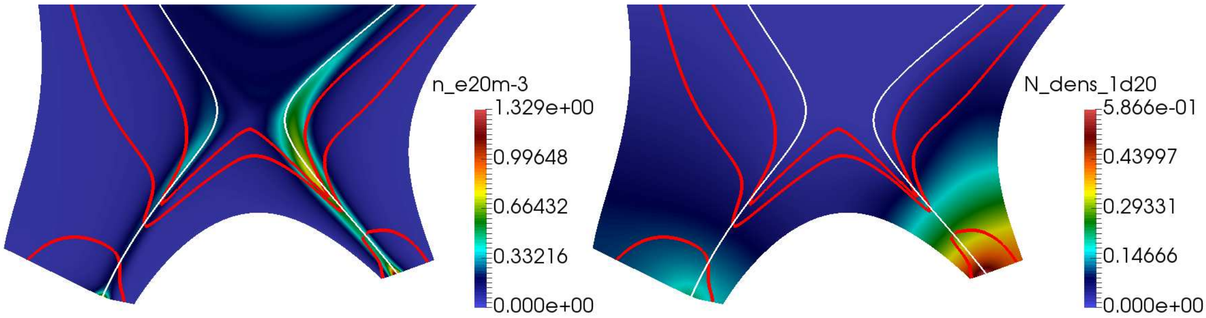

Figure 2: *2D overview of the steady state solution of the case with a gas injection of* $3\times10^{22}\,\mathrm{s}^{-1}$*, cropped to the divertor region. On the left the plasma density and on the right the neutral density. The red contours are isothermal's:* 10 eV, 5 eV *and* 3 eV *(From in to out). The while line indicates where the profiles in figure 1 are plotted.*

peak that moves toward the position of the X-points when the gas injection rate is increased. Combining these features it is estimated that the plasma passes from an attached state to a detached state at the gas rate of $1\times10^{22}\,\mathrm{s}^{-1}$ to $3\times10^{22}\,\mathrm{s}^{-1}$.

Figure 2 illustrates the 2D profiles of the density and neutral densities of the detached solution in the divertor region. In the outer leg there is a build-up of neutral particles because the neutral gas is injected in this leg.

Simulations of ELMs with a recycling divertor

As a first application, a comparison is made between ELM simulations using two JOREK models: one including only plasma particles and one with the additional neutral particle fluid and a recycling divertor. Both models use the same input parameters and made the same amount of time steps to get in stationary equilibrium before starting the ELM simulation. In the case with the model including the neutral particles, the plasma was not in a detached state. Since the gas injection rate was of the order $1\times10^{21}\,\mathrm{s}^{-1}$, well below the $1\times10^{22}\,\mathrm{s}^{-1}$ to $3\times10^{22}\,\mathrm{s}^{-1}$ transition discussed above. Results show that for the same initial conditions both models produce a different ELM size. The ELM energy loss in the model excluding the neutrals is 167 kJ in 1 ms, which is around 5 % of the total plasma energy. The ELM energy loss including neutrals is about 20 % higher at 205 kJ.

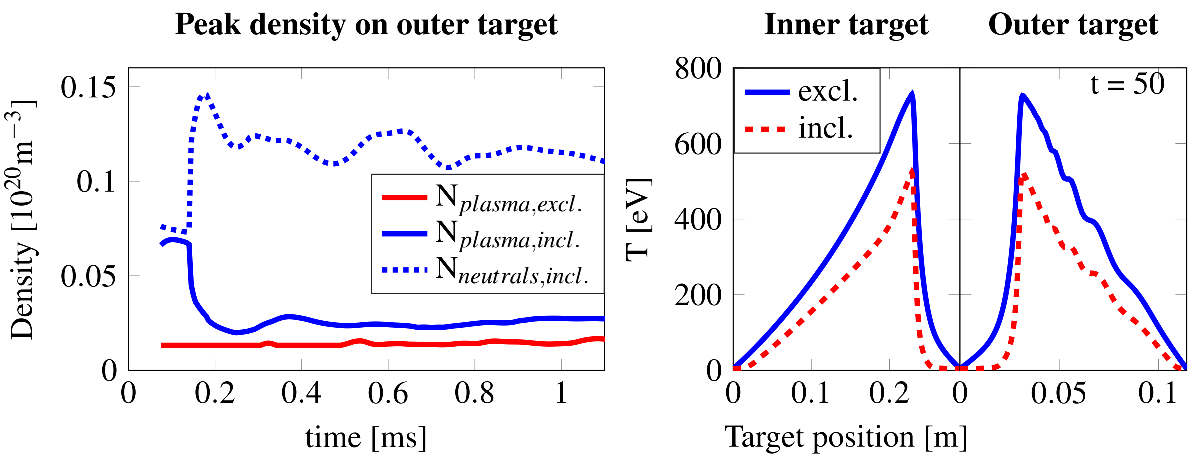

Figure 3: *On the left: the density and neutral density at the outer divertor target. On the right: the temperature profiles on the inner and outer target for the two different models. The model including the neutrals shows for the most part a colder divertor target.*

Before the ELM onset, the divertor solution with neutrals and recycling is characterised by a high density at the target. The effect of the ELM leads to a large increase in the neutral density and a strong reduction of the plasma density (see figure 3b). This is due to the increased ionisation from the ELM heat pulse. The ions are then lost with the parallel flow and reflected as neutrals. During the ELM, the density and neutral density at the target remain constant. Because the density with neutrals is higher than the case without neutrals, the temperature at the target is lower. The temperature profile at the target for the two cases is plotted in figure 3a.

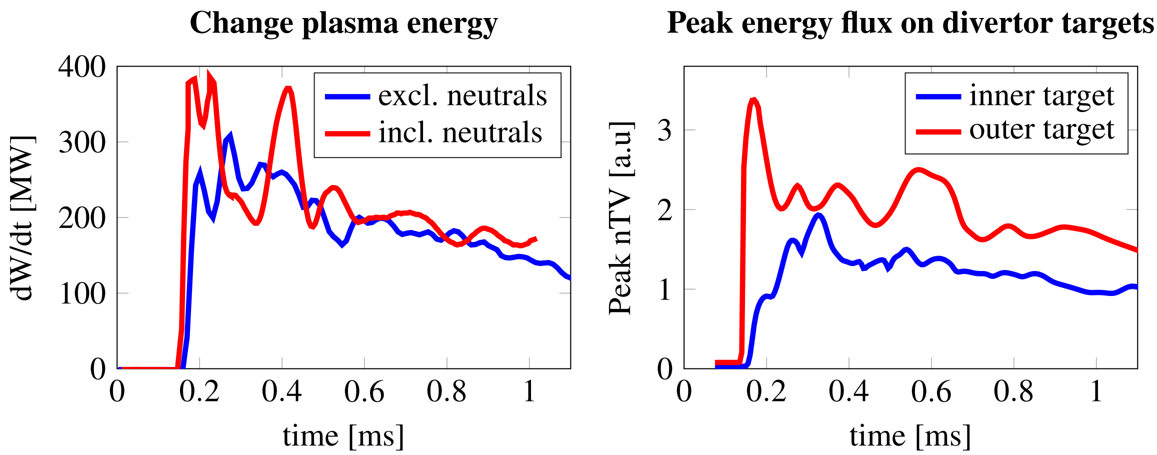

Figure 4: *On the left: Time trace of the derivative in time of the total thermal energy in the plasma for the two different models. The models show a similar ELM energy loss. On the right the peak energy loss to inner and outer divertor targets. A clear asymmetry is visible between the two.*

The ELM induced peak power loss (dW/dt) shows a clear increase when neutrals are included (see Fig 4a). The dynamics and the asymmetry between inner and outer divertor (see Fig. 4b) does not change significantly between the two models. The power first arrives at the outer target, with a delay and smaller amplitude at the inner target.

Conclusion

Results have shown that the addition of a neutral fluid model to JOREK made it possible to simulate detached plasmas. Effects such as the drop in temperature on the divertor target are observed when gas is injected. For increasing gas injection this lower temperature is also observed to expand toward the x-point.

ELMs were simulated with the new JOREK model using the MHD model including a neutral fluid. The addition of neutrals and a recycling divertor yields a small increase in the ELM size and a significant increase in the peak heat flux to the target.

Ongoing work is the simulation of ELMs with a high density divertor. These simulations have the plasma in a (semi)-detached state and the same plasma parameters as the ELM cases discussed above. Aspects like the reflection coefficient, wall effects and valve position also remain subjects for investigation.

References

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