Numerical simulations of edge localised modes in MAST-U plasmas

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Introduction

Edge localised modes (ELMs) are magneto-hydrodynamic (MHD) instabilities that drive filamentary plasma eruptions in high confinement tokamak discharges [1]. In future fusion reactors ELM heat fluxes will be reduced to ensure durability of divertor materials [2]; peak heat fluxes from uncontrolled type-I ELMs are predicted to significantly damage the ITER Tungsten divertor plates so gaining an improved understanding of ELMs is important. The MAST-U tokamak will test a new divertor configuration, the Super-X, as a possible solution to lower the target heat fluxes. Additional PF coils in the divertor region will control the strike point radius length (R), at larger R the contact area of the plasma increases, which decreases the target heat flux. Flux expansion in the chamber is also possible, increasing the neutral interaction volume [3]. The closed divertor design of the Super-X allows for retention of neutrals [3], this is important for attaining detachment whilst keeping impurities low in the core plasma. Plasma detachment can occur as the ion temperature is reduced due to the ion-neutral interaction. The characteristics of ELM divertor heat fluxes in the Super-X are unknown, particularly it is not known if the ELMs will burn through the detachment front. The following presents simulation results of ELM dynamics in MAST-U plasmas using the nonlinear MHD code JOREK [4]. A brief overview of the model is given, including fluid neutrals. Initial results on the impact of neutrals are described.

JOREK and simulation set-up

The nonlinear MHD code JOREK is being developed to establish quantitative validation against current experiments [5]. JOREK contains a reduced MHD model, the equations are given in [5] where physical variables of perpendicular and parallel velocity, poloidal flux, density and temperature are evolved in time. The JOREK model has been extended for neutral fluid simulations, previously used for massive gas injection and disruption simulations [6]. An extra equation for the neutral density is introduced in addition to terms describing ionisation and recombination rates. In this model the neutrals are only diffusive; equations given in [6].

The MAST-U equilibria are generated using pressure profiles taken from typical H-mode type-I ELM MAST plasmas, these are input to JOREK where a 2-D grid of finite elements is generated. This grid has a higher resolution in the plasma edge where ELMs occur and includes the entire vacuum domain extending to the MAST-U wall, where wall boundary conditions are applied. A Fourier decomposition is applied in the toroidal direction within JOREK. The boundary conditions set during the simulations are Neumann for density and temperature, Bohm for parallel velocity and Dirichlet for all other variables. The neutrals have reflective boundary conditions set by a coefficient (C = 0.5). This boundary condition is defined by the ion flux to the boundary, which is convected with the sound speed, and is reflected back as diffusive neutrals. The MHD parameters used are resistivity ($\eta = 4.0\times10^{-6}$ Ωm a factor 100 above the Spitzer value), viscosity ($\mu_\perp = 4.0\times10^{-6}$ and $\mu_{||} = 4.0\times10^{-5}$ kg m s^{-1}), particle diffusivity ($D_\perp = 4.0$ m^2 s^{-1}) and thermal diffusivity ($\kappa_{||} = 8.0\times10^2$ m^{-1}s^{-1} a factor 1.5 larger than the Braginskii value for ions and $\kappa_\perp = 5.0\times10^{-8}$ m^{-1}s^{-1}). In the simulations where the neutrals model is used $\kappa_\perp = 2.0\times10^{-7}$ m^{-1}s^{-1} and the neutral diffusivity is $D_n = 2.0\times10^2$ m^2 s^{-1}, a range of values of D_n will be tested as a realistic value is unknown [6].

ELM simulations for MAST-U plasmas

Starting with the equilibrium generated in JOREK the simulation is run with equilibrium flows only (n=0) until a quasi-steady state is reached; then a perturbation is introduced. In these results a single toroidal mode number of n=20 has been used; if it is an unstable scenario a linear growth in energy of the system occurs, eventually reaching a nonlinear phase where the ELM crash occurs. During the nonlinear phase the energy and particle losses are determined and the heat flux to the boundary is calculated, these values can be used for future comparisons to experimental data. The aim is to investigate the significance of the Super-X on heat fluxes during an ELM. A scan in R (see fig. 1a)) for both the Super-X and conventional divertor is performed with R at 1.5 m and 0.7 m respectively.

The steep pressure profile (fig. 1b)), used as an input for the H-mode plasma, collapses as expected during the Super-X ELM simulation; as this occurs filamentary structures of high density erupt from the plasma edge (fig. 1c)). Particles are lost as the pedestal collapses, the loss is $\sim 17\%$ calculated from volume integrals of the density in the pedestal. The temperature in the divertor increases during the ELM crash as energy is lost, the pedestal energy loss is calculated to be $\sim 24\%$. The heat flux to the lower divertor targets is calculated and the evolution of this is in fig. 2c) and d) for the inner and outer targets respectively. The peak heat flux is 3 MW/m^2 on

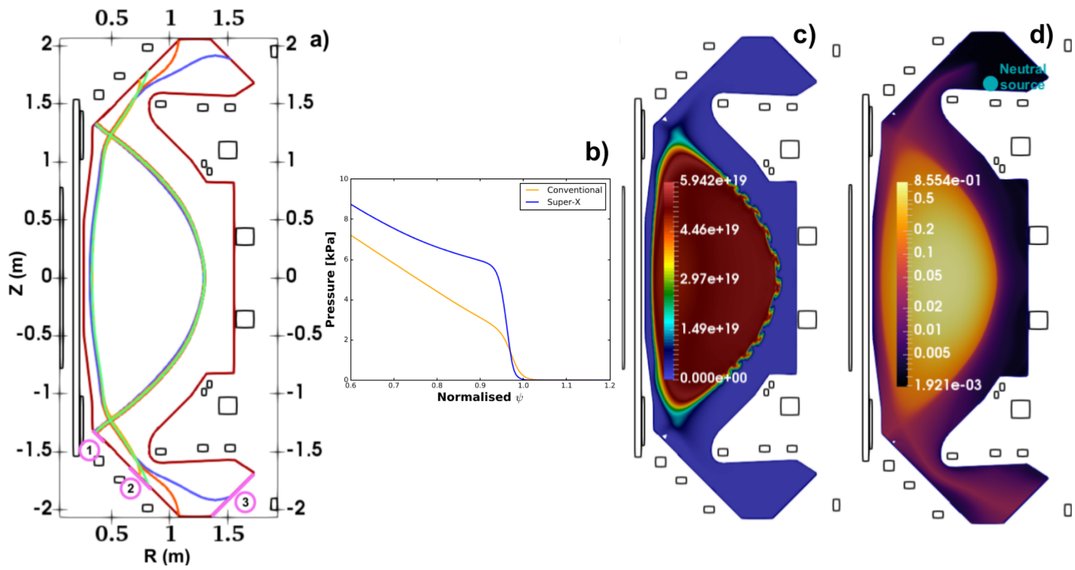

Figure 1: *a) The separatrix for the conventional divertor configuration (yellow) to the super-X (blue). b) Pressure profiles for the Super-X and conventional divertor configurations. Poloidal slice of c) density* (m^{-3}) *during an ELM and d) temperature (keV) during a simulation with neutrals.*

the inner target (labeled 1 in fig. 1a)) and 0.1 MW/m^2 on the outer extended leg target (labeled 3 in fig. 1a)). The peak heat flux to the outer target is an order of magnitude less than the typical peak heat flux obtained from previous MAST experiments with a conventional divertor [7].

Simulations of a MAST-U equilibrium with a conventional divertor leg are performed; the equilibrium is not the same at the Super-X case, future work will include a comparison with the same initial equilibria. The pressure profiles for each case are given in fig.1b); the core pressure and pressure profile are lower with a shallower pedestal for the conventional case indicating a smaller ballooning mode. As expected a smaller ELM crash is observed with a pedestal energy loss of $\sim 18\%$ and a similar particle loss to the Super-X case. The heat flux pattern is shown in fig.2a) and b) for the inner and outer divertor targets respectively. The peak heat flux to the inner target is similar to the Super-X case and to the outer target (labeled 2 in fig. 1a)) is $\sim$ 5 MW/m^2. The heat flux results to the outer target are an order of magnitude larger for the conventional divertor compared to the Super-X, even though the assumed pressure pedestal is lower.

The neutral fluid model allows a more thorough investigation of the effect of ELMs in the MAST-U tokamak, including the effect on detachment. The simulation is run with equilibrium flows for $\sim$ 6 ms, allowing for the neutrals to diffuse. Fig.1d) is an example of the results from the neutrals model; a source of neutrals is injected into the upper divertor. Fig. 1d) indicates detachment is achieved in the upper divertor where the temperature is below 5 eV, whilst the lower divertor remains attached. This first test indicates the JOREK fluid neutrals model is

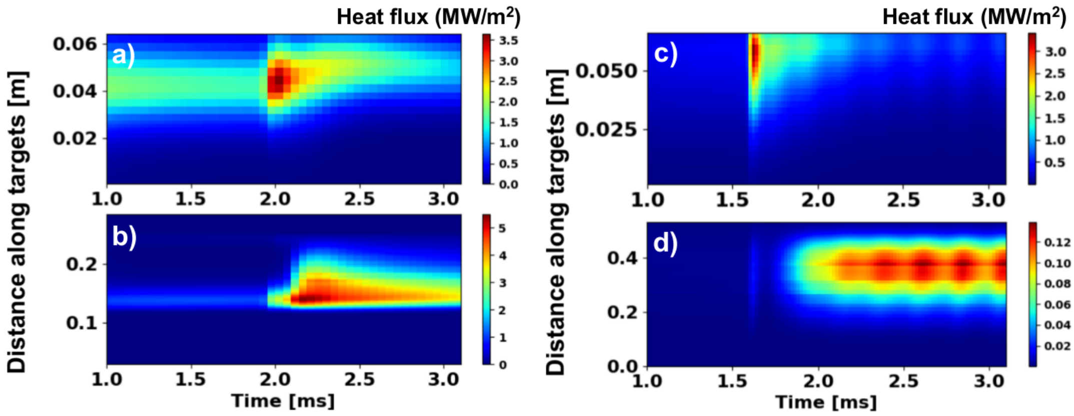

Figure 2: *Heat flux on the lower divertor during the evolution of an ELM a) inner and b) outer targets for the conventional divertor configuration, c) inner and d) outer targets for the Super-X configuration.*

capable of achieving detachment when a neutral source is included. Further work will include a full ELM simulation using the neutrals model with both outer divertors detached, to investigate if the plasma stays detached during the higher parallel flux of energy when an ELM occurs.

Conclusion

Simulations are presented to investigate the effect of ELMs in the MAST-U Super-X divertor. Initial results show reduced heat fluxes to the extended leg target, even where the ELM crash is larger, but with a similar size to previous MAST experiments. Further simulations will use the same initial equilibria for the two scenarios where the only difference will be R and the flux expansion. Initial simulations with the neutrals model in JOREK show detachment of the plasma in the divertor when neutrals are being injected into the chamber and future work will include full ELM simulations with the neutrals model to study the impact of ELMs on detachment.

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