Non-linear MHD Simulation of ELM Energy Deposition

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Abstract. The mechanisms of the ELM energy deposition are studied by means of nonlinear MHD simulation of ELMs. The footprint of the ELM heat flux is found to increase linearly with the ELM size for JET-scale plasmas similar to the experimentally observed broadening of the ELM energy deposition. For these conductive ELMs the broadening is due to an increase in the magnetic perturbation of the ballooning mode. The resulting widening of the homoclinic tangles intersecting the target leads to the increase in ELM footprint. First results from ELM simulations in ITER Q=10 scenario indicate that at the ITER scale the broadening is similar for conductive and convective ELMs. For convective ELMs the ELM footprint is determined by the radial distance travelled by the expelled filaments. For conductive type ELMs the magnetic perturbation and its homoclinic tangles determine the pattern of the ELM heat flux at the divertor target.

1. Introduction

Measurements of the power deposition profile on the divertor target due to ELMs show that the wetted area increases significantly, compared to that between ELMs, with the amplitude of the ELM energy losses [1, 2]. Taking the broadening into account in the estimates for the allowable ELM size in ITER leads to a larger operating window in plasma current (up to ~ 8 MA) where natural ELMs can be tolerated [3]. On the other hand, due to the expected decrease of the power footprint between ELMs as \( I_p^{-1} \) and the increase of pedestal plasma parameters with \( I_p^2 \), the allowable ELM sizes for the high performance DT scenario at 15 MA are very small in comparison with the plasma thermal energy and thus no significant broadening is expected for tolerable ELMs in this scenario from this empirical extrapolation. On this basis, the allowable ELM size for the 15 MA \( Q_{DT}=10 \) scenario is \( \Delta W_{ELM} < 0.7 \text{MJ} \) [3].

Non-linear MHD simulations of ELMs have previously [4] shown good qualitative agreement on features like the formation of filaments and their propagation speed and the fine structure in the power deposition profile to the divertor during ELMs. The next step towards a quantitative validation of MHD simulations of ELMs, with the final aim to predict the ELM energy and density losses in ITER, is to compare observed trends in the experimental data with results from nonlinear MHD simulations. At this time, the amplitude of the ELM induced losses cannot yet be predicted by MHD simulations, due to challenging time scales involved in the onset and decay of the ELM. However, the consequences of ELMs at a given ELM size can be evaluated. Here, the non-linear MHD code JOREK is used to study the origin of the observed broadening of the wetted area as a function of the ELM size in present experiments, and to provide a physics basis for the expected ELM power losses in ITER.

2. The non-linear MHD code JOREK

The JOREK code [5] solves the MHD equations in toroidal geometry. The MHD model used here is a single fluid reduced visco/resistive MHD model with the poloidal flux, the electric potential, the parallel velocity, the density and temperature as variables. The temperature equation includes the parallel heat conduction with a Braginskii type temperature dependence of the parallel heat conductivity \( \kappa_p(T) = \kappa_{p0}(T / T_p)^{-5/2} \). The computational domain includes the complete central plasma on the closed field lines and the scrape-off layer on the open field lines. Both the poloidal plane \((R, Z)\) and the variables are discretised using \( C^1 \) (i.e. values and gradients) continuous Bezier finite elements. The finite elements are aligned to the
flux surfaces of the initial equilibrium. The variation in the toroidal direction is represented with a Fourier series.

The boundary conditions on the open field lines are the Bohm sheath boundary conditions on the parallel velocity and the parallel heat flux. The parallel velocity is set to the local sound speed \( |\mathbf{v}_p| = c_s = \sqrt{T/T_e} \). The condition on the parallel heat flux links the convective and conductive fluxes through the sheath transmission factor \( \gamma_{s\parallel} : \kappa_{\parallel} \mathbf{V}_e T = (\gamma_{s\parallel} - 1) n T v_h \). The perturbations to the flux, current, electric potential and vorticity are set to zero. On surfaces parallel to the equilibrium magnetic field, the boundary conditions set the perturbations of all variables to zero.

To study the ELM induced power loads to the ITER divertor and first wall, the computational domain has been extended to cover the whole interior inside the first wall with an accurate description of the ITER divertor and the first wall. In this case, the boundary conditions on the divertor and the first wall are those of the open field lines.

3. ELM energy broadening in JET-scale plasmas

To investigate the origin of the broadening of the ELM energy deposition, relative to the pre-ELM heat flux profile, ELMs with varying amplitudes have been simulated in JET-like equilibria. Non-linear MHD ELM simulations typically start from an MHD unstable equilibrium. The simulated ELM size can, for example, be varied by changing the pressure gradient in the H-mode edge. A larger pressure gradient, above the peeling-ballooning stability limit, will lead to an increased linear growth rate and a larger ELM size.

The initial JET-like equilibria are characterised by a major radius of 3.0m, a minor radius of 0.85m, plasma current and magnetic field of 3MA and 3T, the toroidal beta is 2.0%. The pedestal width is 4-5cm. The pedestal gradients are maintained by a suitable choice of the radial profile of the particle and energy diffusivities with a local minimum in the pedestal. The width of the Scrape-off layer (SOL) is determined by the ratio of the parallel and perpendicular transport. Using \( \kappa_{\parallel,0}/\kappa_{\perp,0} = 5 \times 10^4 \) yields a width of the heat deposition at the target of \(~2cm\). The magnetic Reynolds number on axis is \( S_o = 10^7 \), with the resistivity varying as \( \eta(T) = \eta_o (T/T_e)^{-3/2} \).

An example of the evolution of the magnetic and kinetic energies due to an \( n=8 \) ballooning mode from the non-linear MHD simulation of an ELM in a JET-like plasma is shown in FIG. 1. The duration of the ELM in the magnetic perturbation is about 150\( \mu \)s. Also shown is the evolution of the total energy and the energy inside the separatrix. In this case the ELM induced losses are \( \Delta W/W = 2\% \) (~0.17 MJ) of the total thermal energy and 1.4% of the total density. This is the largest ELM size obtained in the simulations. FIG. 2 shows the density

![FIG. 1a Magnetic and kinetic energy evolution of the \( n=0 \) and \( n=8 \) toroidal harmonics due to a ballooning instability. (ELM).](image1)

![FIG. 1b Evolution of the total plasma thermal energy and the thermal energy inside the separatrix.](image2)
and temperature at the time of the maximum magnetic perturbation. The density and temperature perturbations extend up to 2 cm radially at the outer mid-plane. Around the x-point, the perturbations are relatively symmetric and of large size, notably in the temperature on both the low and high field side.

The origin of these structures can related to the changes in the magnetic structure of the plasma edge during the ELM. The magnetic field perturbation of the ballooning mode instability is large enough to cause an ergodisation of the magnetic field [4, 7, 8]. FIG. 3 shows a Poincare plot of the magnetic field at the time of the maximum magnetic energy perturbation. To construct the Poincare plot, field lines starting from inside the original separatrix are followed for a 1000 toroidal turns or until the field line hits the target. The field lines are followed in both directions. The perturbed magnetic field forms characteristic so-called homoclinic tangles [9]. The field lines in the tangles start inside the main plasma and have a direct connection to the target. Due to the high parallel thermal conductivity, the temperature is relatively constant along the field lines yielding the structures (see FIG. 2) in the X-point and divertor region. The homoclinic tangles exist on both the low field side and the high field side, leading to a temperature perturbation on both sides, i.e. not only on the low field side as one could have expected for a ballooning mode. The tangles exist all along the inboard side mostly parallel to the separatrix, not reaching the wall but leading to a broadening of the power flux in the SOL during ELMs.

The magnetic tangles lead to multiple strike points at the targets and to a fine structure with multiple peaks in the heat deposition profile. These peaks form spirals in the toroidal direction (see FIG. 3). The number of peaks is linear in the toroidal mode number $n$, their width is inversely proportional to $n$. The additional peaks in the heat deposition profile are fewer and wider at the inner target compared to the outer target. This is a direct consequence of the difference in the structure of the stable (outer target) and unstable homoclinic tangles (inner target). The multiple strike points lead to an effective broadening of the divertor heat deposition profile. FIG. 4 shows the evolution of the wetted length during the ELM together with the heat flux at the divertor target. The wetted length $\lambda_w$ is defined as $\lambda_w(t) = \int Q(t) dA/(2\pi R Q_{\text{max}}(t))$ with $Q$ and $Q_{\text{max}}$ the local and maximum heat flux onto the target. The maximum broadening is a factor of two in this case. The maximum broadening does not necessarily coincide with the time of the maximum heat flux. In the case shown in FIG. 4 the broadening is 1.6 at the time of maximum heat flux.
To investigate the dependence of the broadening of the ELM footprints, ELM simulations have been run for a series of equilibria. To obtain different ELM sizes the width and height of the pedestal have been varied as well as the toroidal mode number and the ratio of the parallel to perpendicular heat conduction. The resulting broadening as a function of ELM size is shown in FIG. 5. It shows a dependence on the ELM size very similar to the experimentally observed trend [1, 2]. There is also a good correlation between the broadening and the maximum of the amplitude of the magnetic perturbation of the ELM. The wetted area can vary rapidly in time depending on how the power is distributed over the tangles. Note that the broadening can also become smaller than one, i.e. the wetted area can decrease during the ELM. In this case, most of the power goes to the first tangle which is generally smaller in width compared to the pre-ELM wetted area.

4. ELM energy deposition in ITER Q=10 H-mode scenario

At present, the estimates of the heat loads due to ELMs on the ITER divertor and the first wall are based on an extrapolation from current experiments and a 1D model describing the radial expulsion of filaments and the parallel losses in these filaments [10]. This section describes the first results of the calculation of the ELM heat loads from 3D non-linear MHD simulations of ELMs in ITER plasmas.

In principle, there are two mechanisms that contribute to the broadening of the ELM footprint on the divertor and first wall. As described in the previous section, the magnetic perturbation of the ballooning instability can create an ergodic field at the plasma edge. The parallel heat conduction on the perturbed magnetic field (homoclinic tangles) leads to a broadening of the ELM footprints compared to the pre-ELM footprint. This effect will be more pronounced for large ELMs in the conductive ELM regime at low density and large parallel heat conduction. The second mechanism is due to the formation of filaments related to the convective motion across the separatrix of the ballooning mode. The energy and density expelled with the filament are then lost in the parallel direction on mostly unperturbed open magnetic field lines. The broadening of the ELM footprint and the fraction of energy arriving at the first wall is thus determined by the radial distance travelled by the filament compared to the parallel energy loss time, which is determined by the sheath boundary conditions [10]. In this section, the simulation results from ELMs in the convective and the conductive regime are discussed.
The initial equilibria for the ELM simulations in the ITER Q=10 H-mode scenario are reproduced from the ITER scenario modelling using the CORSICA code [11]. The case presented below is characterised by a temperature and density at the top of the pedestal of 5.1keV and $0.85 \times 10^{20} \text{m}^{-3}$, the pedestal width is 4.5cm. The total plasma energy is 378 MJ at a plasma current of 15MA and a normalised beta of 1.9%. This initial static equilibrium is evolved in time to allow the poloidal and parallel flows to develop into a new stationary equilibrium. The magnetic Reynolds number in the simulation is $S=5 \times 10^6$.

FIG. 6 shows the evolution of the magnetic and kinetic energy perturbations of an $n=10$ ballooning mode (only the $n=0$ and $n=10$ toroidal harmonics are used in this simulation). The large initial perturbation, with a dominant magnetic component, lasts $\sim 100 \mu$s, followed by smaller bursts. This leads to a thermal energy loss of 4MJ, i.e. $\Delta W/W=1\%$ and a relative density loss of 2% in $\sim 300 \mu$s. Note that this ELM size is well above the estimated allowable ELM size in ITER of 0.7MJ [3].

The structure of the magnetic field is shown in FIG.7 as a Poincare plot at the time of the maximum magnetic perturbation. It shows large homoclinic tangles, both on the low and high field side. The maximum extent of the tangles at the midplane is 4-6 cm beyond the separatrix on the high field side and up to 4 cm on the low field side. For this equilibrium, the minimum distance from the separatrix to the wall is 11cm at the high field side and, thus, the tangles do not reach the first wall. The tangles on the high field side lead to a broadening of the heat flux scrape-off layer on this side due to the parallel conduction. The width of the broadened layer agrees well with the radial extend of the tangles. The high field side tangles extend well into the main plasma (~6cm). Their short connection length leads to the loss channel on the high field side. On the low field side, the temperature perturbation has the typical ballooning mode perturbation structure and the density shows the formation of filaments due to the convective $E \times B$ ballooning mode flow. The combined convective and conductive losses lead to an ELM affected depth in the main plasma of $\sim 12$cm at the outboard midplane (i.e. 6% of the minor radius). In the divertor region, the tangles do reach the inner and outer targets and lead to fine structures of the temperature, density and heat flux at the targets (see FIG. 10). The heat flux to the inner and outer divertor and to the first wall for an ITER ELM simulation is shown in FIG.8. For this simulated 4MJ ELM, the highest peak ELM power flow of $\sim 20$ GW is to the outer divertor. Most of the energy is deposited on the outer target, i.e. 2.8MJ versus 1.1 MJ on the inner target. The power to the first wall is very small at a level of $\sim 0.12$ MJ or 3% of the total ELM energy loss. For this conductive ELM, the delay between the arrival of the power to the inner target compared to the outer target is only $\sim 20 \mu$s.
FIG. 9 Peak heat flux and ELM wetted length on the ITER outer target during the simulated 4 MJ ELM.

For convective ELMs (see below) this delay is about 150 µs, which is of the order of the ion transit time from the outboard side to the inner target at the local sound speed. For conductive ELMs there is no significant delay due to the losses being conductive and occurring also on the high field side.

One important question concerns the wetted area over which the ELM energy is distributed as this will have a direct influence on the maximum allowable ELM size in ITER. FIG. 9 plots the time evolution of the peak heat flux and the wetted length during the 4 MJ ELM. In this case, the wetted length varies between 12 and 25 cm depending on the dynamics of the distribution of the heat flux over the magnetic structures at the target. Fig. 10 shows the heat flux at the target and the first wall at the time of maximum loss power. On the outer target the power is distributed over an average profile with a half width of about 20 cm on top of which there are sharp peaks width a width varying from 1-2 cm close to the separatrix to 5-8 cm further outwards. The structure of the heat flux is determined by the structure of the homoclinic tangles of the perturbed magnetic field as discussed above (see FIG.7). On the inboard target there is no target or at most one additional peak in the heat flux profile, the ELM wetted length at the inner target is 10-15 cm.

An example of a non-linear MHD simulation of a ‘convective’ ELM is now described for comparison with the ‘conductive’ ELM described above. The equilibrium profiles of this ITER Q=10 H-mode scenario have a pedestal width of 6 cm with a pedestal temperature and density of 5.2 keV and 6x10¹⁹ m⁻³. In this case the kinetic and magnetic perturbations of the n=10 ballooning mode are of comparable amplitude (see FIG.11). In some ELM simulations there is a clear indication that the magnetic amplitude is limited by the interaction with the ELM induced n=0 flow. The ELM causes a thermal energy loss of 1.6 MJ (ΔW/W=0.4%) and a relative density loss of 2% (i.e. similar to that of the conductive 4 MJ ELM) on a timescale of 500 µs. The amplitude of the magnetic perturbation is too small to cause a significant perturbation of the magnetic field (see FIG.12) and no sizeable homoclinic tangles are formed in this case. The convective ELM is thus characterised by the formation of filaments, expelled from the plasma by the convection cells of the ballooning mode instability.
The filaments accelerate within \( \sim 30 \, \mu s \) to a maximum speed of 4-6 km/s, slowing down to a speed of 1-2 km/s on a similar time scale. The width of the filaments is 1-2 cm at the midplane. The maximum radial displacement of the filaments at the midplane is about 4 cm, i.e. they do not reach the first wall at this location. Closer to the x-point the filaments travel up to the flux surface corresponding to the 4 cm at the midplane. Most of the filaments do reach the outer divertor target not directly but through parallel transport on the open field lines over a distance of \( \sim 40 \) cm along the vertical target consistent with the flux expansion of 4 cm in the midplane. Indeed most of the power reaching the first wall arrives in the area located immediately above the divertor baffle (see FIG.14) which is closest to the plasma (in magnetic surfaces) than the midplane.

The parallel heat flux to the divertor and first wall are plotted in FIG.13. In this convective 1.6 MJ ELM simulation most of the power goes to the outer divertor at a ratio of almost 4:1. The power to the first wall is less than 10% of the total energy loss. The 2D distribution (FIG.14) of the heat flux shows a qualitatively similar structure to that of the conductive ELM, although here the structure is due to energy propagating along the ejected filaments on mostly unperturbed magnetic field lines outside the separatrix and not to electron conduction along homoclinic tangles in conductive ELMs. A clear difference can be seen in this respect because the filaments of convective ELMs do cause larger amplitude perturbations of the power flux further away from the separatrix at the outer target than the conductive flux along homoclinic tangles in conductive ELMs. As a result, the width of the ELM wetted length is in the range of 10-15 cm, similar to that of the conductive ELM of about twice the ELM energy loss.
5. Conclusions

Non-linear MHD simulations of ELMs indicate that the footprint of the ELM energy deposition is influenced by two different mechanisms: ejection of filaments and energy conduction along homoclinic tangles. The magnetic perturbation of the ballooning mode underlying the ELM can be large enough to create a magnetic structure (homoclinic tangles) at the target. This creates multiple strike points and a broadened ELM footprint. The ELM simulations for conductive ELMs in JET-scale plasmas show a linear increase of the broadening with the ELM size in reasonable agreement with experimental observations. The homoclinic tangles also exist on the high field side creating a loss channel on the stable (good curvature) side of the ballooning mode. This mechanism is dominant in the conductive ELM regime. The second mechanism is the expulsion of filaments from the plasma due to the convective cells of the ballooning mode. In this case, the width of the ELM footprint is determined by the distance travelled by the filaments as energy is lost in the parallel direction along the filament. Strictly speaking it is not appropriate to interpret the wide ELM heat flux patterns observed when this mechanism is dominant as a broadening of the pre-ELM footprint as the underlying physics is different. This second mechanism is likely to be dominant in the convective ELM regime. Quantitative validation of the ELM simulations on current experiments is required and in progress to improve the confidence of the predictions for ITER. It is important to note that the in/out asymmetry of the ELM energy deposition obtained in the ITER simulations does not agree with experimental findings and it is not yet clear what causes this difference. Similarly, most experimental measurements concentrate on the outer divertor, while the divertor that leads to the limitation for ELM size in ITER is the inner divertor (due to the ELM in/out power deposition asymmetry). The JOREK simulations presented in this paper show that the processes that lead to the ELM footprint broadening could be very different at the two divertors, particularly for convective ELMs. These are likely to be the type of ELM occurring at the levels of ELM energy loss acceptable for controlled ELMs in ITER and thus analysis of the power fluxes at the inner divertor for this type of ELMs is urgently required.

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References