A model for particle and energy loss during type I ELMs

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Understanding of ELMs behavior and firm predictions for losses are important for the future International Thermonuclear Engineering Reactor (ITER) [1], by considering the large transient heat loads on material surfaces and constraints placed on the edge pedestal height due to ELMs [2]. A model for particle and energy losses was introduced in Ref.[3]. It was based on the idea that type I ELMs are generated by ballooning-peeling ideal MHD modes, developing when the pressure gradient in the edge transport barrier (ETB) surmounts a critical level [4, 5]. These modes produce a radial component of the magnetic field and, therefore, perturb field lines by leaning them in the radial direction. The radial inhomogeneity of the plasma parameters in the ETB results in flows along such field lines increasing the particle and energy transport during ELM crash. In Ref. [3] energy loss contributions with thermal particles and electron heat conduction along perturbed field lines were examined. The role of hot ions, escaping from plasma with an energy of the pedestal ion temperature, was considered in Ref. [6]. In present work the influence of time evolution of the field line inclination angle on the losses is considered.

Time evolution of magnetic field perturbation

In Refs. [3] and [6] the losses of particles and energy have been calculated with a characteristic time independent radial component of the magnetic field perturbation and the field line inclination angle α. Here the time dependence of α is taken into account. By neglecting radial variation of α this is described by the equation:

$$d\alpha/dt = \alpha\left(\gamma - 1/t_{elm}\right) \tag{1}$$

where

$$\gamma \approx \frac{B}{Rq}\sqrt{\frac{\beta_{cr}}{4\pi m_i n_b}\frac{n_b - n_{th}}{n_b}} \tag{2}$$

is the the linear growth rate of the ballooning mode [5] with R being the major radius, q safety factor, B magnetic field, m_i ion mass, and the dimensionless factor β_{cr} depends on the magnetic shear, elongation and triangularity of magnetic surfaces. The mode starts to grow when the density at the pedestal n_b, increasing between ELM crashes due to ionization of neutral particles released from the machine walls, exceeds a threshold value $n_{th} = B^2\alpha_{cr}\Delta_b/\left(16\pi R q^2 T_b\right)$, with Δ_b and T_b being the ETB width and pedestal temperature, respectively. As in Ref. [3] the characteristic ELM duration time τ_{elm} is taken from the experiment.

The time variation of pedestal density during ELM is governed by the particle balance in the edge region involved in ELM [3]:

$$\frac{\Delta_{elm}}{2}\frac{dn_b}{dt} = \Gamma_i - \Gamma_s \tag{3}$$

where Δ_{elm} is the width of this region exceeding Δ_b by a factor $5-10$ [2] and Γ_s the particle flux through the separatrix induced during the ELM due to radial component of the flow along pertubed field lines estimated according to Ref.[3]:

$$\Gamma_s = \frac{\left(c_s\alpha\right)^2 n_b}{c_s\alpha\sqrt{n_b/n_s} + \gamma\Delta_{elm}/2} \tag{4}$$

with $c_s = \sqrt{2T_b/m_i}$ being the ion sound speed and n_s the density at the separatrix.

Energy and Particle loss by ELM crash

The energy loss due to convection of superthermal ions is calculated according to the approach elaborated in Ref. [6]. Kinematic, momentum and energy balance equations for ions, where ambipolar parallel electric field and coulomb collisions with thermal background are taken into account, are integrated numerically with different initial conditions for the radial position r, parallel velocity U and perpendicular energy ξ of ions at time $t = 0$, when $n_b = n_{th}$, $\gamma = 0$ and the ballooning mode starts to grow up, till the moment t_s when the ions escape through the separatrix. The final ion energy at the escape moment is added to the convection energy loss ΔW_{elm}^{conv}. For a maxwellian distribution over the initial parameters U and ξ one gets:

$$\Delta W_{elm}^{conv} \approx S_{sep} \int dr \int dU \int \frac{2n(r)}{\sqrt{\pi} M V_T^3(r)} \times \exp\left[-\frac{U^2}{V_T^2(r)} - \frac{\xi}{T(r)}\right] \left(\frac{MV_s^2}{2} + \varepsilon_s\right) d\xi \tag{5}$$

where S_{sep} is the separatrix area, $V_T = \sqrt{2T/M}$ the ion thermal velocity, V_s and ε_s are the parallel velocity and perpendicular energy attained by the particle at the separatrix.

Electron parallel heat conduction, another important channel for the energy losses by ELMs, is estimated as in Ref.[3], and in the case of inclination angle varying in time we have:

$$\Delta W_{elm}^{cond} \approx \int_0^{t_{\max}} \frac{S_{sep} n_b T_b \sqrt{T_b/m_e}\,\alpha}{\Delta_{elm}/(1.9\alpha\lambda_b) + 1/\xi_{FS}} dt \tag{6}$$

where $t_{\max}$ is the maximum calculation time equal to several t_{elm}, λ_b the mean free path length calculated for the plasma parameters at the barrier top and $\xi_{FS} \approx 0.03$ the heat flux limit factor, assessed recently from an interpretation [7] of magnetic island heating experiments.

The total energy loss per ELM crash, ΔW_{elm}, computed by taking into account both channels, due to the ion convection and electron parallel heat conduction, is characterized normally by its ratio to the pedestal energy content $W_{ped} = 3n_b T_b V_{pl}$ [2], where V_{pl} is the plasma volume, $\Delta W_{elm}/W_{ped} = (\Delta W_{elm}^{cond} + \Delta W_{elm}^{conv})/W_{ped}$. The loss of particles per ELM crash, normalized to pedestal particle content is given by:

$$\frac{\Delta N_{elm}}{N_{ped}} = \frac{S_{sep}}{n_b V_{pl}} \int_0^{t_{\max}} \Gamma_s dt \tag{7}$$

Results

Parameters characteristic for the ELMy H-mode discharges in JET have been assumed in calculations [2, 8]: $R = 3m$, $a = 0.9m$, $\kappa = 1.6$, $q = 4$, $\Delta_b = 0.05m$, $n_b/n_s = 2$, and $Z_{eff} = 2$. By taking into account that the time averaged plasma parameters at the barrier top have to satisfy the threshold condition for ballooning-peeling MHD modes [4, 5], it can be shown, see, e.g., Ref.[3], that they scale with the collisionality parameter ν^* at the ETB top as $n_b = n_{b0}(\nu^*/\nu_0^*)^{1/3}$, $T_b = T_{b0}(\nu_0^*/\nu^*)^{1/3}$, where n_{b0}, T_{b0} and ν_0^* are the reference parameters taken henceforth equal to $3 \times 10^{19}\ m^{-3}$, $2\ keV$ and 0.06, respectively [8]. According to experimental observations [2] the characteristic ELM duration time $\tau_{elm} \approx 200\mu s$ and is nearly independent of ν^*.

Equations 1 and 3 are integrated numerically up to time $t_{\max} = 10\tau_{elm}$. In contrast to [6] where α was considered constant in time, some new physics can be distinguished with the present model.

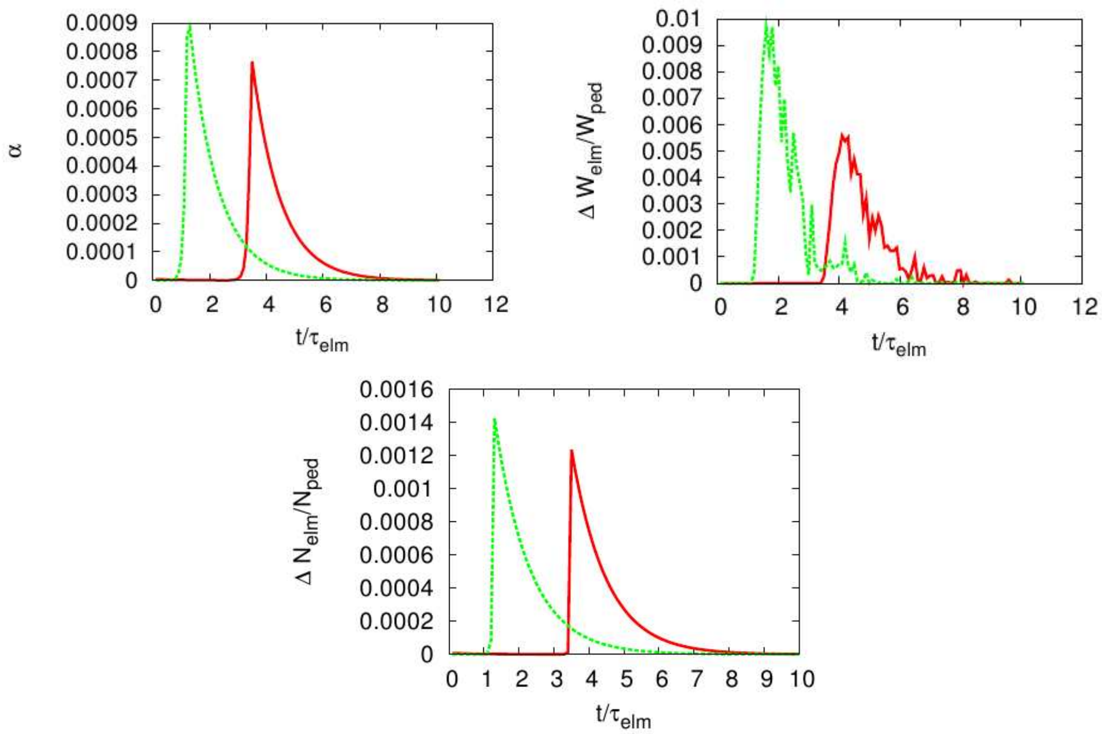

Figure 1: Time variation of α (left), $\Delta W_{elm}/W_{ped}$ (right) and $\Delta N_{elm}/N_{ped}$ (bottom) for $\alpha_0 = 5\times10^{-8}$ (dashed lines) and $\alpha_0 = 5\times10^{-6}$ (solid lines). α grows faster for smaller α_0 and appears to have a higher magnitude during the ELM. The energy loss $\Delta W_{elm}/W_{ped}$ and particle loss $\Delta N_{elm}/N_{ped}$ follow similar time evolution as α, energy and particle loss is higher for smaller α_0

Figure 1 shows the time evolution of α, energy and particle losses vs t/τ_{elm} for different initial values $\alpha_0 = \alpha(t=0)$ before the onset of an ELM. We see that for smaller α_0 the perturbation grows quicker and has higher peak than in the case for higher α_0. This can be explained looking at the coupling between equations 1 and 3. In the case where α_0 has lower value, the particle influx greatly exceeds the particle outflux which is proportional to α, and thus the density at the edge increases very rapidly. The rate of change of α in time is proportional to the square root of the density overshoot over the instability threshold level and as a result also grows quickly. Although in this case α does reach a level whereon it enhances the particle outflux over the source and relaxes the density, it already achieves a much higher peak than the case beginning with higher α_0. The behavior is in line with analytical estimates in Ref.[3].

The α averaged over time is also greater as can be seen more explictly from fig. 2, which shows the variation of α_{avg} for cases beginning with different α_0. Fig. 2 shows the collisionality dependence of energy and particle loss during ELMs for cases beginning with different α_0. As expected from the behavior of α_{avg} with ν^*, these losses are also higher for lower α_0. The interesting result obtained above can actually explain certain important physics of the ELM phenomenology. First of all, the effective time during which the most of the losses by ELMs takes place, would correspond to the time where α lies above a certain threshold level and as seen from figure 1 this corresponds roughly to τ_{elm}. Secondly, α_0 at the onset of ELM, determines to a great extent the α_{avg}, $\Delta W_{elm}/W_{ped}$ and $\Delta N_{elm}/N_{ped}$, which appear to be higher for lower α_0. This can explain the mitigation of ELMs by resonant magnetic field perturbations where the magnetic field lines are perturbed by means of an external source to a level above their normal values. The transport between ELM crashes increased due to higher α_0 hinders the growth of α and consequently α_{avg}, $\Delta W_{elm}/W_{ped}$ and $\Delta N_{elm}/N_{ped}$ are reduced.

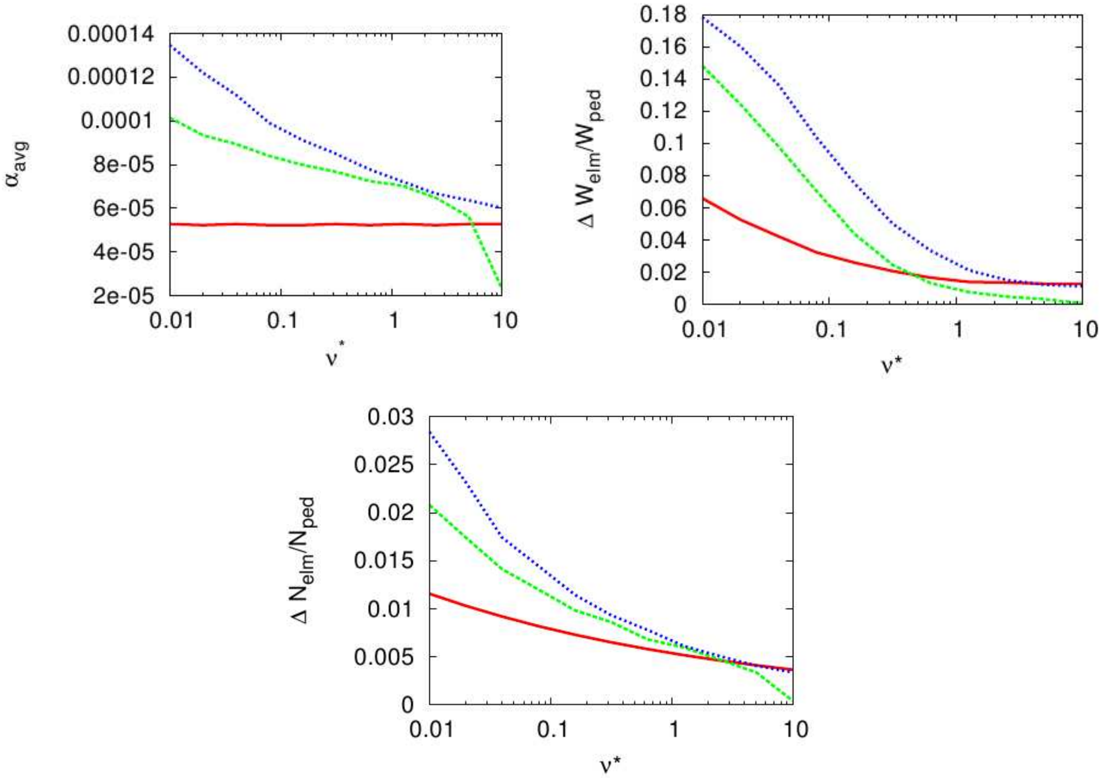

Figure 2: Variation of α_{avg} (left), $\Delta W_{elm}/W_{ped}$ (right) and $\Delta N_{elm}/N_{ped}$ (bottom) with ν^*, for different values of α_0, $\alpha_0 = 5\times10^{-8}$ (dotted lines), $\alpha_0 = 5\times10^{-6}$ (dashed lines) and $\alpha_0 = 5\times10^{-4}$ (solid lines). α_{avg}, $\Delta W_{elm}/W_{ped}$ and $\Delta N_{elm}/N_{ped}$ decrease with ν^*, and with increasing α_0

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