35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-1.011 (2008)

A model for energy losses by type I ELMs

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Introduction

Observations on diverse tokamak devices demonstrate that energy losses from plasma provoked by type I Edge Localized Modes increase significantly with decreasing plasma collisionality [1]. Understanding of this behavior and firm predictions for losses are of very importance for the future International Thermonuclear Engineering Reactor (ITER) [2], by considering the large transient heat loads on material surfaces and constraints placed on the edge pedestal height due to ELMs. A model for particle and energy losses has been introduced recently in Ref.[3]. It is 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, perturbed field lines lean 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 have been examined. Presently the role of hot ions, escaping from deep plasma regions with an energy of the pedestal ion temperature, is considered. It is demonstrated that in collisionless ETB plasmas convection of such particles plays a very important role. With all channels accounted calculations reproduce well the found in experiments [1] absolute level and collisionality dependence of the energy losses per ELM crash and the width of the edge region where they are localized. Moreover, in agreement with observations [1], simulations predict that the maximum loss intensity is located at the barrier top and the averaged energy of escaping ions is close to the pedestal temperature.

Ion convection along perturbed magnetic field lines

Observations show that the energy of particles expelled from the plasma during ELMs is significantly higher than their thermal energy at separatrix and is close to the temperature at the ETB top [6]. These suprathermal particles, escaping from deeper plasma regions along field lines perturbed by MHD modes, may substantially contribute to the energy loss by ELMs. Due to increasing dissipation of particle energy by collisions with the background ones this loss channel is expected to be decreasing with increasing plasma collisionality, similar to the electron heat conduction and in accord with experimental observations [1].

Consider ions, which start to move at time $t = 0$, when the magnetic field lines begin to lean radially due to development of MHD-perturbations, from different initial positions r inside the separatrix, $0 \leq r \leq a$, with diverse initial values $0 \leq \xi \leq \xi_{\max}$ and $|U| \leq U_{\max}$ of the perpendicular energy ε and parallel velocity V, respectively. The variation of the particle radial position x in time is governed by the kinematic equation:

$$dx/dt = \alpha V \tag{1}$$

Here α is the inclination angle of perturbed field lines in the radial direction. In this study we neglect radial variation of α; its time dependence is described by the equation:

$$d\alpha/dt = \alpha(\gamma - 1/t_{ELM}) \tag{2}$$

where

$$\gamma \approx \frac{1}{Rq}\sqrt{\frac{B^2\beta_{cr}}{4\pi m_i n_b}\frac{n_b - n_{th}}{n_b}} \tag{3}$$

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 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 $n_{th} = B^2\alpha_{cr}\Delta_b/\left(16\pi Rq^2 T_b\right)$, with Δ_b and T_b being the ETB width and pedestal temperature, respectively. The time variation of pedestal density during ELM is governed by the particle balance in the edge region involved in ELM [3]:

$$\frac{\Delta_{ELM}}{2}\frac{dn_b}{dt} = \Gamma_i - \frac{(c_s\alpha)^2 n_b}{c_s\alpha\sqrt{n_b/n_s} + \gamma\Delta_{ELM}/2} \tag{4}$$

where Δ_{ELM} is the width of this region exceeding Δ_b by a factor $5-10$ [1] and $c_s = \sqrt{2T_b/m_i}$ the ion sound speed. As in Ref. [3] the characteristic ELM duration time τ_{ELM} is taken from the experiment.

The variation of the ion parallel velocity V and perpendicular energy ε of the ion in time is governed by the momentum and energy balance equations where coulomb collisions with thermal background particles are taken into account [7]:

$$\frac{dV}{dt} = \frac{e}{m_i}E - \frac{2\mu}{\tau_1}V,\ \frac{d\varepsilon}{dt} = \frac{2}{\tau_1}\left[\left(\mu + \mu'\right)\frac{m_i V^2}{2} - \left(\mu - \mu'\right)\varepsilon\right] \tag{5}$$

with e being the elementary electric charge, μ and τ_1 the Maxwell integral and elementary relaxation time, respectively, see Ref. [7], computed with the local plasma parameters at the instant particle position $x(t)$. The parallel electric field E is estimated from the balance of forces applied to electrons along field lines:

$$0 = -enE - \alpha d(nT)/dx \tag{6}$$

The radial profiles of the plasma density n and temperature T at the edge are assumed piecewise linear ones with sharp gradients in the ETB: plasma core, $0 \le r \le a - \Delta_b$:

$$n = n_b,\ T = T_c - (T_c - T_b)\,r/(a - \Delta_b),$$

edge transport barrier, $a - \Delta_b \le r \le a$:

$$n = n_s + (n_b - n_s)(a - r)/\Delta_b,\ T = T_s + (T_b - T_s)(a - r)/\Delta_b,$$

where the subscripts s, b and c indicate the parameters at the separatrix, the barrier top and in the plasma core, respectively.

Energy loss by ELM crash

Equations (1) and (5) are integrated numerically with the initial conditions for the radial position $x = r$, parallel velocity $V = U$ and perpendicular energy $\varepsilon = \xi$ 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_a when the particle escapes through the separatrix, i.e., $x(t_a) = a$. The final particle 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:

$$\Delta W_{ELM}^{conv} \approx S_{sep} \int_0^a dr \int_{-U_{max}}^{U_{max}} dU \int_0^{\xi_{max}} \frac{2n(r)}{\sqrt{\pi} M V_T^3(r)} \times \exp\left[-\frac{U^2}{V_T^2(r)} - \frac{\xi}{T(r)}\right] \left(\frac{MV_a^2}{2} + \varepsilon_a\right) d\xi \quad (7)$$

where S_{sep} is the separatrix area, $V_T = \sqrt{2T/M}$ the ion thermal velocity, V_a and ε_a are the parallel velocity and perpendicular energy attained by the particle at the separatrix. Typically $U_{max} = 6V_T(T_b)$ and $\xi_{max} = 11T_b$ provide ΔW_{ELM}^{conv} with a high enough accuracy. It is worth indicating that the computational effort required for the calculation of ΔW_{ELM}^{conv} was minimized eminently by use of some numerical techniques, which permitted to operate with larger steps of t, U, ξ and r. In particular, the parametric dependence of the integrand in Eq.(7) has been interpolated by a cubic spline determined by its values for four consecutive parameter values.

Electron parallel heat conduction is another important channel for the energy losses by ELM crashes. An approach to estimate this has been developed in Ref.[3] and in the case of inclination angle varying in time we have:

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

here $t_{\max}$ 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 ξ_{FS} the heat flux limit factor. One can see that in collisionless plasmas where $\Delta_{ELM}\xi_{FS}/\alpha \ll \lambda_b$ the conductive contribution to the energy loss scales proportionally to ξ_{FS}. With $\xi_{FS} \approx 0.2$ adopted in Ref. [3], this contribution alone was enough to explain well the experimentally found magnitude and collisionality dependence of ΔW_{ELM}. However a recent interpretation [8] of magnetic island heating experiments has provided ξ_{FS} values by a factor of 5-10 lower, i.e., on the same level as in laser plasmas [9] and the maximum level of the conduction loss has to be reduced by this factor.

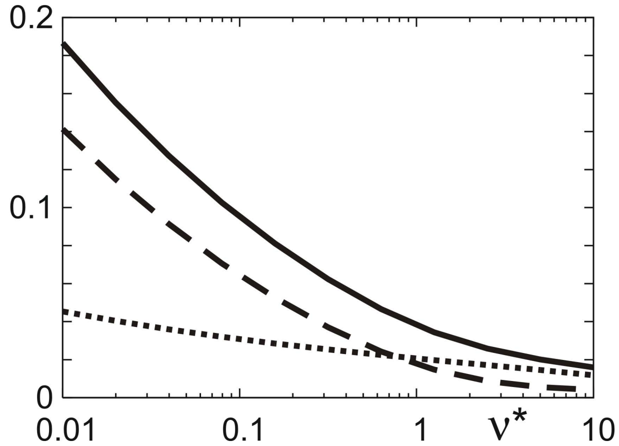

Figure 1: Collisionality dependence of normalized convective (dashed curve), conductive (dotted curve) and net energy loss (solid curve) by ELM crash.

As a figure of merit we consider the energy loss per ELM crash, ΔW_{ELM}, related to the pedestal energy content W_{ped} defined as the thermal energy in the whole plasma volume calculated at the pedestal density and temperature , $W_{ped} = S_{sep}a/2 \times 3n_bT_b$ [1]. With ion convection and electron parallel heat conduction accounted in ΔW_{ELM} one has:

$$\Delta W_{ELM}/W_{ped} = \left(\Delta W_{ELM}^{conv} + \Delta W_{ELM}^{cond}\right)/W_{ped} \quad (8)$$

Parameters characteristic for the ELMy H-mode discharges in JET [1, 10] have been assumed in calculations: $R = 3m$, $a = 0.9m$, $\kappa = 1.6$, $q = 4$, $\Delta_b = 0.05m$, $n_b/n_s = 2$, $Z_{eff} = 2$; the reference pedestal density $n_b = 3\times10^{19}\ m^{-3}$ and temperature $T_b = 2\ keV$ [10] correspond to the plasma collisionality $\nu^* \equiv (\lambda_b/qR)(R/r)^{3/2}$ of 0.062. By taking into account that before ELM crash n_b and T_b satisfy the threshold condition for ballooning-peeling MHD modes [4, 5], it can be shown [3] that $n_b \sim (\nu^*)^{1/3}$ and $T_b = (\nu^*)^{-1/3}$ for a constant Δ_b. For the characteristic ELM duration time τ_{ELM} we use the experimental value of $200\mu s$, being, according to observations [1], nearly independent of ν^*. In agreement with rough estimates in Ref.[3] present calculation show weak sensitivity of results to the initial inclination angle $\alpha_0 = \alpha(t=0)$. Dependences obtained with $\alpha_0 = 10^{-5}$ are presented henceforce. Figure 1 demonstrates the collisionality dependences of $\Delta W_{ELM}/W_{ped}$ and contributions $\Delta W^{conv}_{ELM}/W_{ped}$ and $\Delta W^{cond}_{ELM}/W_{ped}$. It illustrates the decline of $\Delta W_{ELM}/W_{ped}$ with increasing ν^* as observed experimentally [1]. Also in agreement with the recent observations [6] is the fact that in collisionless plasma with $\nu^* < 1$ the energy loss is dominated by ions rather than by electron conduction. This loss sharing changes, however, for ν^* larger than 1. The decline of $\Delta W_{ELM}/W_{ped}$ with increasing ν^* is due to collisions of hot ions with thermal ones: (i) the friction force reduces V and fewer ions have enough time to escape the plasma during the ELM burst and (ii) ion kinetic energy is dissipated more strongly in the background plasma. Figure 2 illustrates the radial profile of the normalized density of the ion kinetic energy loss, $w_E = \Delta_b \mid dW^{conv}_{ELM}/dr \mid /W_{ELM}$. This value has its maximum at the ETB top and the region where the losses are localized becomes narrower with increasing collisionality as it is observed experimentally [1]. On the one hand, steep gradients of density and temperature imply a powerful electric force in the ETB driving ions out of the plasma. This force is much smaller deeper inside the plasma where the parameter profiles are relatively flat. On the other hand, near the separatrix in the ETB the initial energy and number of escaping particles decrease since by approaching to the separatrix T and n drop, and the same happens to the loss contribution. Also in agreement with observations [1, 6] the present calculations provide the average energy of escaping ions close to the ion thermal energy at the barrier top.

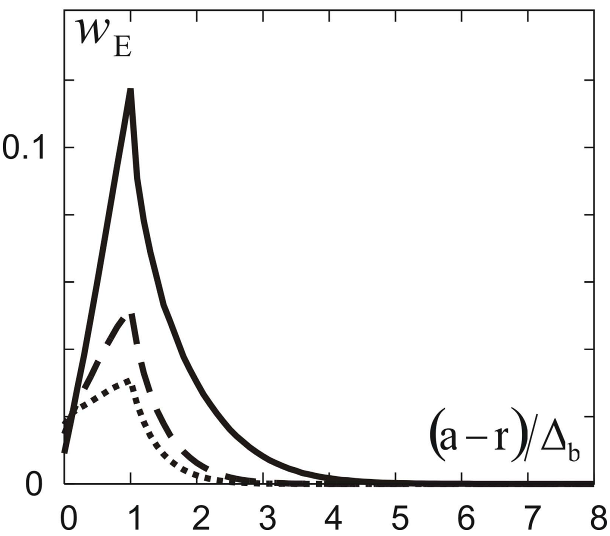

Figure 2: The radial profile of the normalized ELM energy loss density calculated for different pedestal collisionality: $\nu^* = 0.062$ (solid curve), 0.5 (dashed curve) and 0.1 (dotted curve).

This study has been partly performed within GRK1203 of German Research Society.

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