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IMPACT OF PROFILE RESILIENCE ON ENERGY CONFINEMENT

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Multi-machine experimental observations indicate resilience in the temperature profiles at low pedestal temperatures, whereas at high pedestal temperatures the profile stiffness seems to disappear. The change of the profile behavior impacts the energy confinement, basically due to a strong non-linear dependence of the energy transport on the pedestal temperature together with different critical conditions for the onset of turbulence in the ions and electrons. This possible explanation for the different observations is based on the assumption that both ion and electron energy transport is governed by turbulence which sets in at a critical temperature gradient as well as on a significant energy equipartition between electrons and ions.

1. Introduction

One of the main signatures of the H-mode is a formation of knee (pedestal) on temperature and density profiles near the plasma edge. Recent results from ASDEX-UP and C-mod show linear dependence between energy confinement and the temperature on the top of the H-mode pedestal. This implies a strong dependence between the central temperature and the pedestal temperature (i.e. some stiffness of the temperature profiles) (see.Figs.1-2) [1,2].

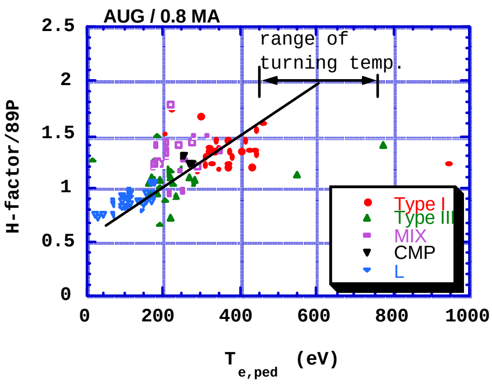

Fig. 1. H-factor vs. Tped for ASDEX UP for 0.3 MA and1MA regimes; predicted range of the turning temperature is shown; $H - factor = \tau_{E/H}/\tau_{E/L}^{89-P}$

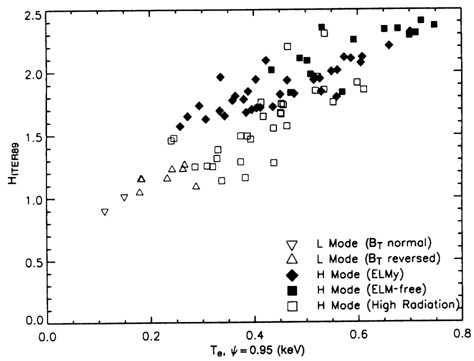

Fig. 2. H-factor vs. Tped for C-mod

Other machines such as JET, DIII-D and JT-60U also show such dependence in particular for higher density (low pedestal temperature) discharges (see Figs.3-4).

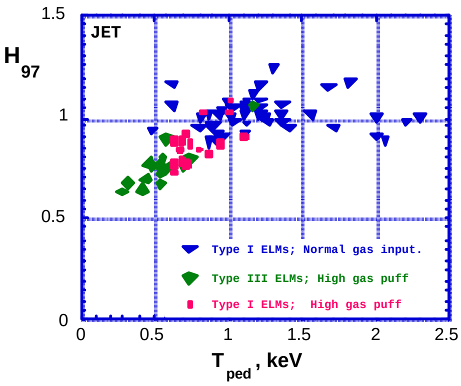

Fig. 3. H-factor vs. Tped for JET. $H = \tau_{E/H}/\tau_{E/H}^{97}$ *Shown are discharges with different gas puff scenarios and ELM types*

However at high temperatures the H-factor clearly saturates. In this case the H factor in discharges with low pedestal temperature is proportional to T_{ped} (characteristic for stiff temperature profiles) while it becomes independent of T_{ped} at high pedestal temperatures (non-stiff branch).

In this review paper we will discuss a possible explanation for these different observations, based on the assumption that both ion and electron thermal diffusivity are stro ngly non-linear and are governed by turbulence which sets in at a critical temperature gradient [3,4,5]. We will assume that ion transport is well described by an ion temperature gradient driven turbulence, which brings about profile stiffness. Therefore ion related energy transport should depend strongly on the temperature at top of the H-mode pedestal. Another reasonable suggestion is that electron energy transport also governed by a critical temperature gradient model, (e. g. such as Rebut-Lallia-Watkins model, which has no profile stiffness [5]). Then one would expect that above a certain pedestal temperature the improvement in energy confinement saturates and the stiffness in the temperature profiles disappear. The scaling of the turning temperatures (the pedestal temperature, where the H factor starts to saturate) can be

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identified by comparing the critical gradients defined by the two transport models, ITG and RLW.

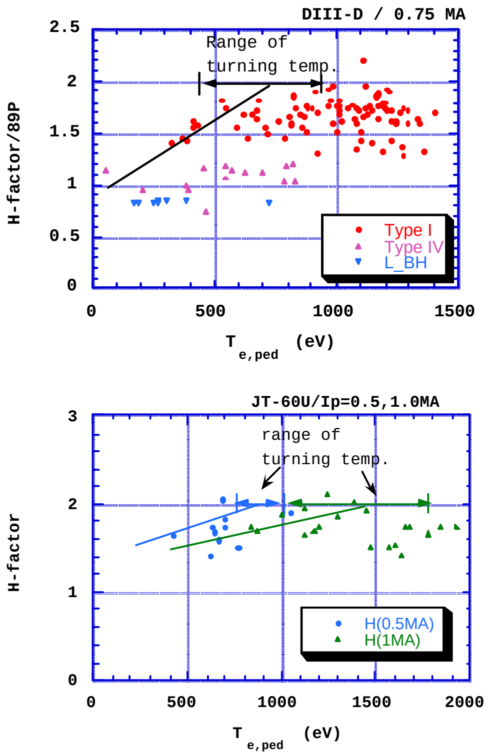

Fig. 4. H-factor vs. Tped for DIII-D for 0.75 MA and for JT-60 0.5 and 1MA; predicted range of the turning temperature is shown

The resulting turning temperatures are compared with the pedestal database from various tokamaks and the prediction for the ITER is made. Below the transport model, which explains the H-factor dependence on pedestal temperature will be describe [10]. The scaling for the turning pedestal temperature (at which confinement changes) will be derived. But first we will discuss what defines the size of pedestal width. Then we will mention the possible problems related with the Elm's at high confinement H-mode regimes.

2. Model of the pedestal width

During a well-developed H-mode the edge transport barrier is formed where the turbulence growth rate is balanced by a stabilizing ExB plasma-shearing rate (due to plasma rotation), which is predominantly supported by a steep pressure gradient. The magnetic shear, S, also plays an essential role through the fact that the critical pressure gradient for the ideal ballooning mode is increased and the turbulence growth rate is decreased with increasing the shear. The stabilizing condition can be written as $\gamma_{ExB} \geq \gamma_s$ where γ_s is the turbulence growth rate and γ_{ExB} is the stabilizing ExB shearing rate. Assuming that the dominant contribution to the radial electric field is the pressure gradient, which is determined by the ideal ballooning mode, γ_{ExB} is expressed as

$$\gamma_{ExB} \approx \frac{\rho_{tor} c_s}{\Delta^2} \qquad (1)$$

where, c_s and Δ are the sound velocity and the width scale length, respectively. For the turbulence growth rate, we will assume a general expression for the gyro-Bohm type transport including the stabilizing effect due to the magnetic shear:

$$\gamma_s \approx \chi_{GB} \kappa_\perp^2 \approx \rho_{tor} c_s \frac{\rho_{tor}}{\Delta} \kappa_\perp^2 \frac{1}{S} \approx \frac{c_s}{\Delta} \frac{1}{S} \qquad (2)$$

where $\kappa_\perp \rho_{tor} \approx 1$ is assumed. From Eqs. (1) and (2), the pedestal edge width $\boldsymbol{\Delta}$ scales as [11]

$$\Delta \propto \rho_{tor} S^2 \qquad (3)$$

Although this expression based on very simple assumptions, many experimental features seem qualitatively consistent with this assessment. For instance, with increasing plasma current I_p, the edge shear decreases, so that the width scales inversely with I_p (ion poloidal-Larmor-radius like dependence). The shear increases with δ, which increases the width as observed in C-mod [7]. The ion mass dependence can be retained through the toroidal Larmor radius. Examinations of this scaling with C-mod and JET data show that it can reproduce the data at least similarly well as the scaling based on ρ_{pol}. Fig. 5 shows T_{ped} with changing the pedestal density n_{ped} for fixed I_P (=2.5 MA) and B_T (=2.3 T) in JET [7] (closed squares). Dotted and dashed lines are expected T_{ped}, when the pedestal edge width is constant and poloidal Larmor radius like, respectively. Open circles show the expected T_{ped} when the width is evaluated by Eq. (3) using the experimental shear values. Although the evaluated points show some scatter due mainly to the scatter of shears calculated by EFIT code, they reproduce the experimental tendency reasonably well. This is realized by the decrease of shear with decreasing n_{ped} and increasing T_{ped}.

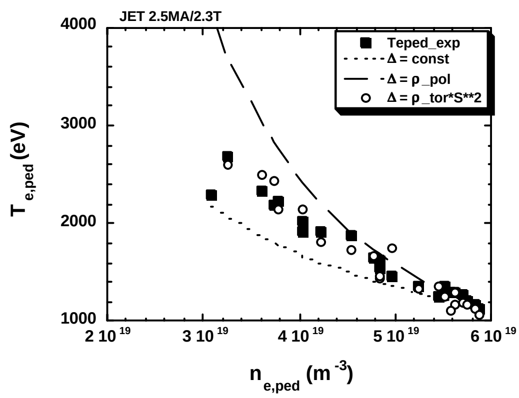

Fig.5. Experimental pedestal temperature (closed square) for fixed B_T and I_P discharge in JET. Open circles, dotted and dashed lines show expected pedestal temperature by the scaling of Eq. (3), constant width and poloidal Larmor dependent width, respectively

The most likely mechanism of this systematic decrease of shear is the effect of bootstrap current. Larger bootstrap current is expected to flow when n_{ped} decreases, since collisionality strongly decreases.

This larger bootstrap current decreases the edge shear, which makes the deviation of the pedestal pressure from Larmor radius dependence of the width.

This bootstrap current may not directly influence the shear value in the EFIT calculation. However, it can modify the equilibrium even for fixed B_T and I_P, which can as a result modify the shear value.

The DIII-D data in the database are not reproduced well by this scaling. The reason for this discrepancy is somewhat trivial when we consider that the pedestals are in the 2nd stability regime. Then, the relation between critical gradient and shear cannot be expressed as simply proportional to shear, which modifies the shear dependence of Eq. (1) greatly. In this model the machine size dependence appears through the spatial profile of the magnetic shear. The predicted pedestal temperature for ITER can be estimated then in the range of 3-4 keV depending on the magnetic shear profile.

3. Turbulent transport in the core plasma

According to the current understanding the ion transport in a core plasma driven by toroidal ITG mode turbulence mainly contributes to the total energy losses in the present large devices [5,6]. This anomalous transport exhibits a strong non-local feature and limits the attainable temperature profile by some critical value ∇T_i^{crit}[4]:

$$\nabla T_i^{crit} \approx T_i f(s, R, q, \nu_*, \tau, L_n) / R \qquad (4)$$

where f is some week function of shear, q, collisional frequency ν_* and major radius, R. It also can depend on the ion to electron temperature ratio, τ and the density gradient length, L_n. The thermal conductivity for pure plasma can be written as [4]:

$$\chi_i^{ITG} \propto \frac{\rho_i^2 v_{Ti}}{R} \left\{ \frac{R}{T} \left(\nabla T_i - \nabla T_i^{crit} \right) \right\}^{\alpha} H\left(\nabla T_i - \nabla T_i^{crit} \right), \qquad (5)$$

where α is 1 or 1/2, H is a Heaviside function, ρ_i is a toroidal ion gyroradius, v_{Ti} is an ion thermal velocity. When temperature rises, ∇T_i is forced to be close to ∇T_i^{crit} and the model leads to the temperature profile stiffness, e.g. $\nabla T_i \propto T_i$. The effective thermal conductivity can be assessed for given heat flux in ions q_i as $\chi_{i,eff}^{ITG} \propto q_i / \nabla T_i^{crit}$ and, assuming that $\chi_i >> \chi_e$, one has for $\tau_{E/H}^{i}$:

$$\tau_{E/H}^{i} \equiv H \tau_{E/L}^{89-P} \approx \frac{a^2}{\chi_i + \chi_e} \approx \frac{a^2}{\chi_{i,eff}^{ITG}} \propto \frac{a^2}{q_i} \left(\nabla T_i^{crit} \right) \propto T_{i,} ped, \qquad (6)$$

Here $\tau_{E/P}^{89-P}$ is the L-mode confinement scaling. Such a behavior of τ_E *vs.* *Tped* is seen on the H-Tped diagram at the low pedestal temperatures (and high densities) at the edge (see Fig. 1-4). On the other side, when the ion temperature gradient is lower than the marginal level due to a low input power or a strong equipartition with cold electrons, then as a subdominant ion transport the neoclassical value can be considered in agreement with experiment.

The transport model for electrons remains rather uncertain. However, the model, which can meet the experimental requirements, must also be strongly non-local and governed by turbulence, which sets in at some critical temperature gradient. The upper limit in temperature gradient can be taken, for example, from the Rebut-Lallia-Wotkins (RLW) model [5]:

$$\chi_e^{RLW} \propto \rho_i^2 c_s \left(\nabla T_e - \nabla T_e^{crit} \right) H \left(\nabla T_e - \nabla T_e^{crit} \right), \qquad (7)$$

where the critical gradient

$$\left(\nabla T_e^{crit} \right) \approx \left(\frac{JB^3}{pT_e} \right)^{1/2}, \qquad (8)$$

drops with temperature. Here p is an electron pressure, J is a current and B is a magnetic field. Note, that this model, in contrary to the ITG model, does not produce profile stiffness because ∇T_e^{crit} drops with pedestal temperature. This weakens the core temperature dependence on the pedestal temperature. The electrons remain well below the critical gradient at low Tped, depending on what species are primary heated and the equipartition value. The subdominant electron transport even in case when the ions are mainly heated and the species are decoupled remains anomalous ("superclassical" [7]) exceeding the neoclassical transport by two orders of magnitude.

4. Turning point temperature

Let us consider now the possible scenario of how degrades the confinement in the ELMy H mode with increasing the input power. When heating ions, ∇T_i reaches its upper limit ∇T_i^{crit} and is controlled by the ITG. The electron transport is superclassical and due to a strong equipartition ∇T_e follows close to ∇T_i. In this range of the pedestal temperature variation the temperature profile is stiff and τ_E increases with Tped. With increasing the input power Te increases and electrons start to be controlled by RLW turbulence. Its critical gradient drops with temperature, remaining lower than the limiting gradient for the ITG, ∇T_i^{crit}, which, in contrary, increases with temperature so that $\nabla T_i^{crit} > \nabla T_e^{crit}$. This keeps electron temperature far below the ion temperature. Due to equipartition electrons are pulling down the ions to neoclassical transport. In this case $\chi_e^{RLW} > \chi_i^{ITG}$, , $\nabla T_e^{crit} < \nabla T_i^{crit}$ and

$$H \tau_{E/L} \propto \frac{a^2}{\chi_i^{SC} + \chi_e^{RLW}} \approx \frac{a^2}{\chi_e^{RLW}} \propto \nabla T_e^{crit} \approx \left(\frac{JB^3}{nT_e^2} \right)^{1/2}, \qquad (9)$$

In this range of the pedestal temperature the profile stiffness is broken, since the ion temperature is pooled down to the electron temperature value, which is limited by RLW transport. The profile stiffness breaks at a point where the heat transport in electrons overcomes that in ions. Roughly it happens when H factor approaches two. Keeping in mind that the density profile in H mode typically is rather flat, the scaling for the turning point for the ion temperature, T_i^* can be estimated from $\nabla T_e^{crit} \approx \nabla T_i^{crit}$ averaged radialy [11]:

$$T^* \propto \sqrt{L_{Ti}} \cdot \left(\frac{I_p B^3}{ka^4 n} \right)^{1/4} \sqrt{\frac{R}{a}} \qquad (10)$$

where k is an elongation, L_{Ti} is the ion temperature dragnet length, which is a rather week function of the plasma parameters [4]. Excluding pressure via input power, P, $nTa^2Rk/\tau_{E/H} \approx P$, one can find from (9), that the H-mode energy confinement time, relevant to RLW model is $\tau_{E/H} \propto RI^{0.75}B^{0.25}n^{0.25}k^{0.25}P^{-0.5}$. This value is close to the L mode confinement scaling $\tau_{E/L}^{89-P}$, except the density dependence, which is somewhat stronger. Nevertheless, this similarity in scalings ensures the saturation of the H factor at the value close to two. The turning temperature values for different tokamaks were estimated (for details see [3]) and are presented in Figs. 1-4. The ridged lines show the predicted range of the pedestal turning temperatures. The comparison provides a reasonable agreement with experimental data.

5. Physics based confinement scaling

Based on the transport model described above one can readily derive a physic based energy confinement scaling. The total stored energy in the plasma, W, consists of the energy in the core, W_{core}, and the part stored in pedestal area, W_{ped}: $W = W_{core} + W_{ped}$. The energy stored in the core (more than 70%) can be written as: $W_{core} \approx 3\left(4\pi^2 Rk\right)\bar{n}_{av}\bar{T}_{av}$, where $\bar{n}_{av}$ and $\bar{T}_{av}$ are the averaged radial density and temperature profiles, k is the elongation. The radial temperature profiles can be derived from the Eqs 4 and 8, and are different for stiff and non-stiff cases. Which branch dominates the scaling depends on the ratio $\eta = T_{ped}/T^*$ so that the core confinement scaling can be written, for example, as:

$$\tau_E(\eta) = W_{core}/P \propto a^2Rk\bar{n}_{av}\frac{T_{av}^{ITG} + \eta^4 T_{av}^{RLW}}{1+\eta^2} \quad (11)$$

Here $T_{av}^{ITG/RLW} \approx \int_{T_{ped}} T(r)rdr$ and $T_{ped} \approx \left(\frac{\partial p}{\partial r}\right)_{crit}\Delta;$.

Using (3) for the pedestal width, Δ, and assuming the ballooning limit for the pressure gradient, one can find an assessment for T_{ped} : $T_{ped} \approx \frac{s^{3/2}B^{1/2}}{\sqrt{8\pi q^2 R\bar{n}_{av}}}$

6. Confinement and ELMs

The operation with good confinement at high density is only possible for high pedestal pressures (thus with high triangularity) resulting in a high pedestal energy content. Due to a large pedestal energy content in high triangularity larger energy losses during ELMs can be expected and are in fact observed [9]. There is a serious concern for reactor-scale devices that divertor erosion due to ELMs could be unacceptably high.

Based on these considerations, it is reasonable to assume that the above defined turning point temperature is an optimized operation point for good H-mode confinement (optimized for minimum ELM size and good energy). It was found that the energy loss per ELM is about ~ 31% ± 5 % of the pedestal electron energy content. Assuming that the loss fraction will be the same in ITER, the energy loss per ELM can be evaluated as ~ 14 to 19 MJ which is 4% to 5.5% of the total stored energy. This result is in principle in line with observations on present machines, for low gas puff good energy confinement H-modes at < 0.5 of the Greenwald density. Increasing the gas puffing rate can reduce the energy loss per ELM. However, increasing the gas puffing rate and / or the density of a discharge significantly causes in many cases not only a reduction of the ELM sizes but also of energy confinement. This loss of energy confinement can be understood from a reduction of the average pedestal pressure (ELMs are triggered early before maximum possible pressure is achieved) or by reducing the pedestal temperature below the TPT. The short deposition times of ELMs energy to the divertor plates reported by the larger machines suggest that there might be a collisionless transport of energy and particles in the SOL. The energy stored in ions cannot be lost faster than that with ion sound speed, which gives for a typical JET ELM a characteristic time of ~ 150 to 180 μs. However, in high density low pedestal temperature discharges can become collisional also during an ELM resulting in even longer energy deposition times (can be up to 1 ms). If one assumes that an ELM occurs because a pressure gradient limit (e.g. ballooning) is exceeded and if the transport of energy and particles across field lines is due to turbulence similar to an avalanche effect, as reported for the core plasma in heat pulse experiments, the driving term (pressure gradient) and thus the turbulence should last only a few 10^{th} of μs, i.e. only in the order of the time period where the critical gradient is exceeded (due to transport limit along field lines density and temperature in the SOL are similar to pedestal parameters in very short time scale, i.e. gradient disappears on this fast time scale) Thus it becomes most likely shorter than the energy transport time along field lines when assuming ion convection is dominating there. This means that the total energy, which can be lost during an ELM, is determined by the characteristic loss time in the SOL and not by the pedestal physics. This loss time is in turn dependent on the temperature which exists in the SOL during an ELM and thus on the pedestal temperature. This model predicts the observed energy loss fractions (compared to total stored energy) and explains the confusing observations with different deposition times and different energy loss fractions.

In ITER the characteristic transport time in the SOL is ~ 310 μs when considering a pedestal temperature of 3.5 keV and a pedestal density of 8.0 $x10^{19}m^{-3}$ and thus twice as long as the one in JET and JT60U. This result in not quite a factor of 2 lower pedestal energy loss fraction than the one observed in JET and JT60U.

This has motivated the search for H-mode regimes with good confinement but much smaller ELMs. Such regimes have been found on several experiments, including the ‘Low Particle Confinement’ H-mode on JET, the Enhanced D-alpha (EDA) H-mode on observed that the pressure gradient in the pedestal is close to the stability limit for the ideal ballooning mode. Access is favored by high triangularity, $\delta_{\alpha\varpi}$ > ~0.4, and high safety factor q_{95} (> ~4 on C-Mod and AUG, > ~5 on JT60U). Relatively high edge density and/or neutral pressure also appear to play a role, although this condition is more difficult to quantify. Small ELMs have been observed with ohmic, ICRF and NB heating and there does not seem to be a clear power threshold, as long as P_{loss} is sufficient to avoid Type III ELMs, which are associated with low edge temperatures and often lower confinement. However, the regimes with small ELMs existing only at low plasma current, which makes them irrelevant to reactor parameters.

7. Conclusion

The influence of a high H-mode pedestal pressure on global energy confinement was found experimentally and can be understood by assuming stiff temperature profiles, which are related to ITG driven turbulence. In fact several machines observe such profile stiffness in their H-mode discharges albeit in some cases only at medium to high densities (e.g. JET JT60U) while other machines are almost always in a stiff temperature regime (e.g. C-mod, ASDEX-UP, DIII-D). In cases where the stiffness of the temperature profiles disappears (above a certain edge – pedestal temperature) an energy transport behavior very different from ITG turbulence takes over and it is suspected that this transport behavior is dominated by the electrons (assumed is strong energy equipartion, i.e. higher densities). Based on these considerations a minimum temperature at the top of the pedestal, i.e. the temperature at which the confinement behavior changes (Turning Point Temperature), is required in order to achieve good H-mode confinement.

In cases where energy equipartition between electrons and ions is weak, the ions and the electrons follow their critical gradients. If at the same time the external sources would heat predominantly the ions energy confinement should improve also significantly above 2 times L-mode. This is in fact the case in Hot-ion-H-modes where ion heating dominates, a very high pedestal temperature is achieved and a decoupling of electrons and ions in the core plasma as well as a confinement above the standard H-mode can be observed. It must also be noted that the gas puffing decreases the pedestal temperature, which can drop below a certain threshold value and degrade the confinement. Scaling of energy confinement time should consider these dependencies and should take the two regimes of energy transport into account, namely the stiff temperature profile region and the region where electron transport dominates and thus the confinement improvement with the pedestal temperature saturates.

Finally we can summarize the main points. Experimental observations indicate clear dependence of H-mode confinement on the pedestal temperature. The temperature profiles are stiff at low pedestal temperatures, whereas at high pedestal temperatures the profile resilience seems to disappear.

The change of the profile behavior impacts the energy confinement, basically due to a strong non-linear dependence of the energy transport on the pedestal temperature. The possible explanation is that both ion and electron transport are governed by turbulence, which sets in at a critical temperature gradient as well as a significant energy equipartition between electrons and ions.

The Turning Point Temperature is the minimum temperature at the top of the pedestal at which the confinement changes. This temperature is an optimized operational point for good confinement and minimum size ELMs.

The scaling of the pedestal width can be determined by assuming that the plasma turbulence at the edge is suppressed by ExB shear flow. This point is dependent on the magnetic shear because the turbulence weakens with increasing shear.

The Type I ELMs are negatively affecting confinement. The different deposition time and loss fraction seen in different machines can be explained by different collisionality of the SOL plasmas. The total energy loss fraction per ELM could be determined by the transition time in the SOL (“plugging” effect) and not by pedestal physics. In dense SOL plasma the fraction of loss energy can drop without affecting the pedestal energy, and thus degrading the confinement.

The expression for energy confinement based on a physical model (developed above) becomes now available and can be checked statistically by comparing with experimental database. It will take account of the different profile behavior depending on pedestal temperature.

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