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Test of the Eich model for ELM energy densities in DIII-D

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Introduction

The standard H-mode is subject to edge-localized-modes (ELMs) leading to the collapse of the edge pressure gradient and bootstrap current in a repetitive cycle. The ELMs provide impurity transport out of the plasma, but also produce pulsed heat loads on plasma facing components. While the loads are benign on present day devices, they will likely cause erosion, melting and recrystallization in the divertor of ITER and future power plants[1,2]. Recent tungsten tests simulating pulsed loads revealed material tolerance limits below expected ITER loads, making uncontrolled ELMs a major operational constraint. To define mitigation requirements, it is necessary to understand the scaling of ELM heat loads and their dependence on plasma parameters. Based on experimental findings on ASDEX Upgrade (AUG) and JET a model was put forward proposing that parallel ELM energy densities $\varepsilon_{\|}$ scale with pedestal electron pressure $p_{e,ped}$ as

$$\varepsilon_{\|,Eich} = 6\pi \cdot p_{e,ped} \cdot a_{pol} \cdot \frac{B_T}{B_p}, \qquad (1)$$

from here on referred to as the Eich model [3]. $\varepsilon_{\|}$ is the maximum of the time-integrated heat flux during ELMs mapped onto the divertor, a_{pol} the minor radius weighted by the elongation and $\frac{B_T}{B_p}$ the ratio of the magnetic fields at the outer midplane. As the model scales favourably towards ITER's active phase compared to previous considerations [2], the work presented here is dedicated to testing the Eich model on DIII-D. Additionally, the origin of the large 1x-3x scatter typically observed about the scaling, and the role of plasma parameters (in particular pedestal pressure and collisionality) on ELM energy densities are investigated.

Experimental Setup

To facilitate ITER relevance, the DIII-D experiment (R=1.7 m, a=0.6 m) was setup in a low collisionality H-mode plasma in lower single null shape (near the ITER similar shape ISS: lower triangularity of 0.74-0.78, upper triangularity of 0.33-0.39, elongation 1.77-1.80). The NBI power ranged between P_{NB}=2 – 5 MW, β_N =1.5- 2.2, and the edge safety factor q95 was 4.0 – 4.4. Additional density pump-out and pedestal temperature increase was provided by using edge electron cyclotron heating (ECH). Up to 3.5 MW of ECH power was deposited near the pedestal top at $\rho = 0.70$-0.92, so that pedestal electron temperatures in excess of $T_{e,ped}$=2 keV were measured. Both the inner and outer strike points were monitored with the fast infrared television camera (IRTV) to determine ELM heat loads. Operationally, a non-dimensional collisionality scan was executed [4], i.e. the magnetic field was varied on a discharge by discharge case over a range Bt=1.6 T – 2.15 T, while keeping the dimensionless parameters q95 and β_N constant by adjusting the plasma current accordingly from 1.0 MA – 1.5 MA. In this setup, collisionality scales with $\nu^{*}\sim\frac{1}{B^4}$ and a $\nu_e{}^{*}$ range at the pedestal top from 0.05 to 2.17 could be covered during the experiment through additional variation of heating power. To increase the covered parameter space (especially with regards to $\nu_e{}^{*}$ and triangularity), selected discharges from previous type-I ELM studies with IR coverage were added to the analysis.

Results

The measured ELM energy densities on DIII-D are generally consistent with the Eich model. Figure 1 shows the comparison of model prediction and experimental values, computed by averaging the IR measurements over the five largest ELMs in the respective time-interval. The intervals span stationary plasma conditions (constant heating power, similar pedestal conditions before ELM crash) between 0.5 s and 1.5 s. The values of the peak parallel ELM energy density $\varepsilon_{\|}$ are found to be within 0.5 - 2 x the prediction of the Eich model. The peak parallel ELM energy density is slightly higher on the inner divertor, mostly due to a higher target heat flux on the inner divertor. As plasma shape and the field ratio $\frac{B_T}{B_p}$ were kept approximately constant during the experiment, a linear relation between $p_{e,ped}$ and $\varepsilon_{\|}$ is implied by the Eich model. Such a relation is not observed experimentally, and neither is there indication of $\varepsilon_{\|}$ increasing for lower collisionality values. Moreover, large ELM energy densities in the 0.4 $\frac{MJ}{m^2}$ range are measured in the high collisionality

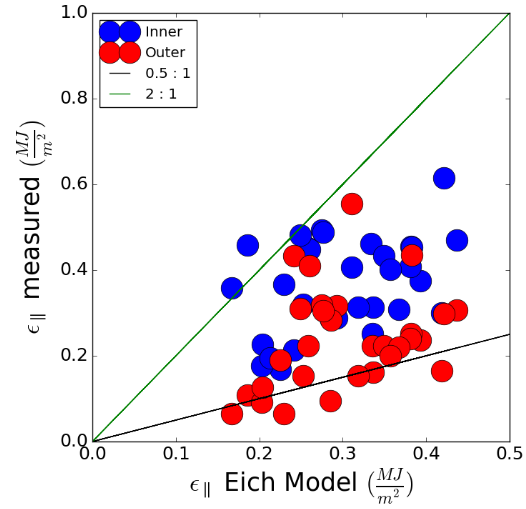

Figure 1 Comparison of experimental ELM energy densities on DIII-D to Eich model prediction

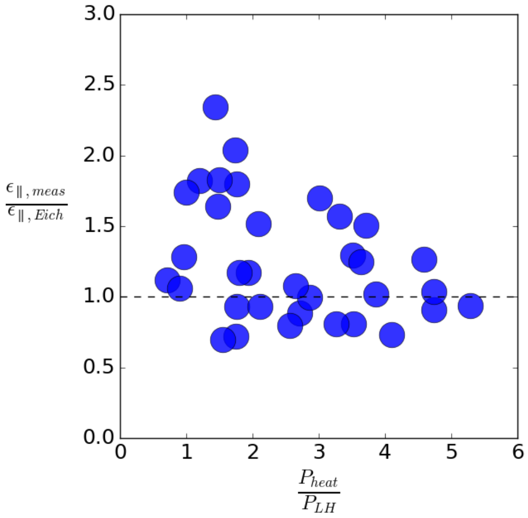

Figure 2 ratio of ELM energy density measured on the inner divertor and Eich model prediction in dependence of ratio of heating to LH-threshold power

region ($\upsilon_e^* \geq 0.8$) over a wide pressure range. These values were achieved in phases of the discharges with lower heating power, when the plasma was kept marginally above the L-H-threshold. As illustrated in figure 2, , the ratio of heating power to the power required to overcome the L-H-threshold is identified as a parameter determining the accuracy of the model, with discharges marginally above the threshold exceeding the prediction by up to a factor of two and showing the largest scatter in the database. Operation close to the L-H-threshold comes with low ELM frequency and large ELM heat loads. Aside from the L-H-threshold proximity, no single parameter or combination of parameters (widths, rotation and current quantities) was found to significantly reduce the scatter of data. Hence, linear stability analysis is employed to investigate the relationship between ELM sizes and mode structure. Based on the generation of kinetic equilibria from measured edge pressure with computed neoclassical edge bootstrap current, the ELITE code was employed [5] to find the most unstable linear mode for the experimental point. The analysis reveals, that ELM energy densities are inversely proportional to the most unstable linear mode number n_{max} before the ELM crash (figure 3). These results

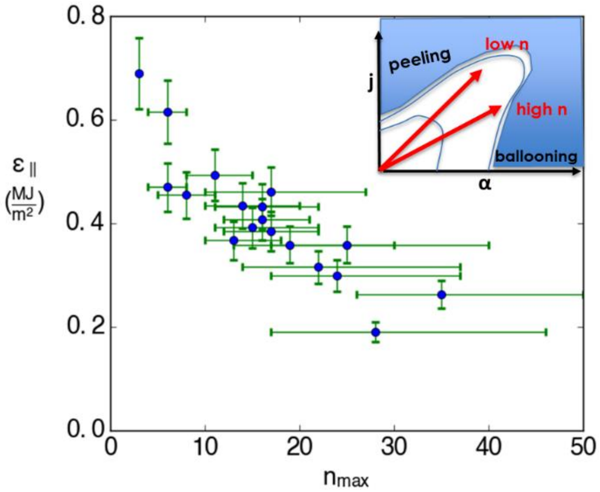

Figure 3 Inverse proportionality between linear mode number with the highest growth rate and peak parallel ELM energy density for type-I ELMy plasmas.

indicate that low n peeling-ballooning modes in the linear phase come with large ELM sizes, especially if close to the L-H-threshold, the ITER operational space.

Conclusions

As all experimental data remained below the threefold limit, our studies have shown consistency of DIII-D data with the Eich model. Beyond the parameters used in the model, the proximity to the L-H-threshold and the most unstable linear mode number n_{max} are found to be drivers for ELM heat loads and as such are potential explanations for the spread of experimental data observed with the model. The results encourage further machine comparisons regarding low heating scenarios and influence of mode numbers on ELM energy densities. A good non-dimensional normalization factor for the ELM energy densities to compare with the most unstable linear mode number has not been found yet; hence a multi-machine analysis is advisable to support this search.

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