Scaling of ELM Crash Parameters

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Introduction

Edge localized modes (ELMs) are periodically occurring instabilities that cause fast relaxations of the strong edge pressure gradient in the high-confinement regime (H-mode) of tokamak fusion plasmas [1]. These crashes induce intense heat fluxes towards the divertor tiles. This is a major concern for future fusion devices like ITER [2].

To understand the nonlinear ELM dynamics, it is necessary to check the validity of the (potentially predictive) ELM models. This can be achieved by comparing modeling output to experimental results. One essential parameter for such a comparison is the structure of the ELM crash, i.e. the toroidal mode number n.

Recent quantitative comparisons of n and other parameters of the ELM crash between the nonlinear code JOREK and results obtained on the ASDEX Upgrade tokamak (AUG) demonstrated the progress in understanding the ELM crash by nonlinear modeling [3]. Consequently, the next question that is tackled here is how the ELM characteristics change with peeling-ballooning critical parameters. We therefore introduce a database of 30 shots containing more than 2500 type-I ELM crashes on AUG and investigate how the structure size changes with plasma parameters, which enables a more detailed testing of the codes in the future.

Results

Edge localized modes appear as strong bursts in magnetic pick-up coils and other plasma diagnostics. Spectra of magnetic pick-up coils during the ELM crash are dominated by low frequencies $f \leq 25\,\text{kHz}$. From toroidal arrays of pick-up coils the mode number n of the short lived low frequency fluctuations can be calculated also during this crash phase. However, as the ELM crash does not appear with single mode numbers but ensembles of several structures we introduce an average toroidal mode number $\langle n \rangle$ for the scaling studies.

The crash is typically dominated by low $n = 1$–8 structures on AUG. However, a detailed analysis reveals a strong variation of $\langle n \rangle$ with the edge safety factor q_{95} and its gradient ∇q. Furthermore, a strong scaling with pedestal top density n_e was detected. This might be explained by the fact that q_{95} is dependent on magnetic field and current. Increasing current on the other hand typically needs increased densities, which is the reason for a strong correlation of density and q_{95} in our database. Figure 1 shows the increase of $\langle n \rangle$ with pedestal top electron density and decrease with q_{95} with $\langle n \rangle$ color coded.
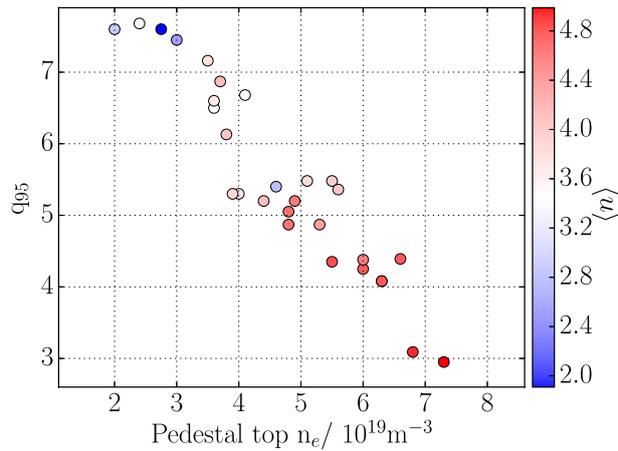
Figure 1: *Averaged toroidal mode number dependence on density and q_{95}, where the blue to red color range stands for low to high n.*

From this plot it is not clear whether it is q_{95} or density and thereby the current that is influencing $\langle n \rangle$. There are discharge pairs with similar q_{95} but varying $\langle n \rangle$ as well as with similar density n_e and varying $\langle n \rangle$. Dedicated experiments would therefore be necessary in order to scan q_{95} with the magnetic field B_t and not via the current. This might disentangle the influence of q_{95} and n_e and thereby current on the crash structure. However, a similar investigation on the structure of the ELM crash with fast camera i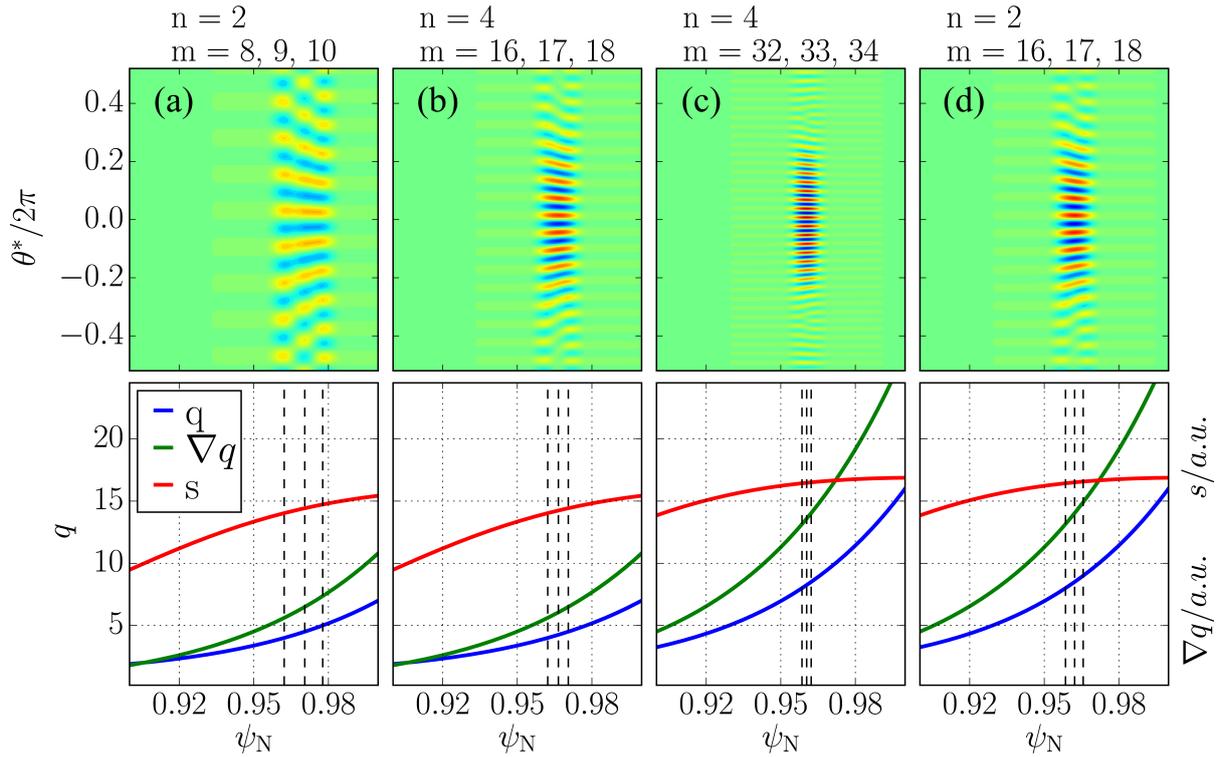maging on DIII-D also found an increase of n with pedestal density [4]. The effect of the edge safety factor was not investigated there.

The only other parameter showing a week tendency of decreasing $\langle n \rangle$ in our database is the bootstrap current j_{BS}. Other parameters that are thought to influence the $\langle n \rangle$ values according to basic peeling-ballooning theory seem to play either a minor role or influence the crash either nonlinearly or in a multifaceted way. For example the experimental data did not show any clear trend of crash $\langle n \rangle$ with the normalized pressure gradient α, triangularity δ or magnetic shear s.

Interpretation

Summarizing the obtained results for the structure of the ELM crash yields that the peeling-ballooning relevant parameters such as α, s, δ or j_{BS} barely influence the structure of the ELM crash. However, the result that $\langle n \rangle$ varies strongly with edge safety factor is very robust. An intuitive geometrical explanation for this behavior is given in the following. The basic idea of the model is that the ELM crash as a mixture of peeling and ballooning modes is driven nonlinearly in the whole region of the pedestal gradients trying to maximize structure size (minimize n), but a low ∇q hampers the existence of low n structures due to larger separation of interfering modes on rational surfaces.

Figure 2 visualizes the effect of edge safety factor and magnetic shear on mode structures. The bottom plots show realistic artificial q profiles and corresponding ∇q and s profiles in arbitrary units. The two types of profiles visualized here have (a), (b) low $q_{95} = 3.2$ and (d), (e) high $q_{95} = 7.0$. The top plots show compositions of artificial mode structures in the θ^*/ψ_{N} plane of the edge region with the straight field line coordinate θ^* and the normalized poloidal flux ψ_{N}. Each composition consists of three modes on rational surfaces $q(\psi_{\text{N}}) = m/n$ with one n but different m values, given at the top of the plots. The different central positions of the mode compositions are sketched with black dashed lines in the profile plots.

Ballooning modes can be interpreted as an overlap of several close-by mode structures that

Figure 2: *(Top) Artificial mode structures in the θ^*/ψ_N plane for (bottom) two different q, ∇q and s profiles: (a, b) weak shear with $q_{95} = 3.2$ and (c, d) stronger shear with $q_{95} = 7.0$.*

interfere such that they have an increased amplitude in the bad curvature region ($\theta^* = 0$). Figure 2 (a) shows a composition of such modes with $n = 2$ at the $q = 4, 4.5$ and 5 surface. Due to the low q shear they are too far apart to be able to interact properly. Therefore, it is unlikely that such a low n composition causes the crash in this region for a low q profile as it cannot sufficiently incorporate the ballooning drive. The first idea of the geometrical model is therefore that the modes need to be close enough to interfere. Figure 2 (b) shows $n = 4$ modes, which lead to a ballooned structure in the LFS region. The interaction of modes is now enabled because the rational surfaces are close enough together at $q = 4, 4.25$ and 4.5. Figure 2 (c) also shows $n = 4$ modes but in the steeper q profile. The modes in the same plasma region now have higher q values of $q = 8, 8.25$ and 8.5 and are closer together because ∇q is also higher, which leads to narrower ballooning modes. However, with the steeper q profile, $n = 2$ modes, figure 2 (d), can also be close enough to interfere at $q = 8, 8.5$ and 9.0. From which it is clear that there are two possibilities for obtaining ballooned modes, namely that either n or ∇q is high enough. However, the experiments showed that no high $n \geq 10$ appeared at all during the ELM crash. Similarly, also nonlinear modeling showed that modes couple to form low $n = 1$–5 structures [3]. From this observation it seems that the ELM crash modes are most unstable with minimized n, meaning larger structures. In the frame of MHD this effect of a transition to larger structure sizes is explained by the mode minimizing the energy of the system by influencing the broadest possible region of the pedestal gradients. Assuming now that the crash modes minimize n, the mode in figure 2 (d) would not exist, because also the $n = 2$ components are close enough to

interact within the steep q profile, but have lower n. This is exactly what is seen in the experiment. If q_{95} and thereby ∇q is high, lower n are observed, whereas higher n are found at low q_{95}.

In addition to the simple geometric model, simulations of ELM crashes were performed with the JOREK code based on the case described in [5], in which q_{95} was modified by changing the toroidal magnetic field strength while leaving all other parameters unchanged. A clear trend is observed of lower dominant mode numbers at larger q_{95} values, which qualitatively agrees very well with the experimental observations: The dominant mode numbers are $n_{q_{95}=4} = 6 \pm 1$, $n_{q_{95}=5} = 5.5 \pm 1$, $n_{q_{95}=6} = 4 \pm 1$, $n_{q_{95}=8} = 2 \pm 1$. The simulation with $q_{95} = 6$ corresponds to the experimental discharge and the simulations reported in [5]. While the absolute mode number distribution at $q_{95} = 4$ and 5 might be shifted to slightly higher or lower values, because the toroidal resolution used ($n = 0$–8) might be insufficient for these cases, the trend of lower mode numbers for higher q_{95} is very reliable from the JOREK simulations.

In summary we can state the following. The influence of plasma parameters on toroidal structure of the ELM crash was investigated with a database of 30 discharges with more than 2500 ELMs. The toroidal structure of the ELM crash is strongly influenced by the edge safety factor q_{95}, i.e. higher average toroidal mode numbers $\langle n \rangle$ appear during the crash for lower q and thereby lower ∇q cases. This effect can, however, not be separated from the influence of the pedestal top density which increases $\langle n \rangle$ accordingly. To disentangle both effects, future experiments which vary the toroidal magnetic field would be necessary. Nevertheless, nonlinear modeling with JOREK shows the same $\langle n \rangle$ trend with a pure variation of the magnetic field supporting the dominant role of q_{95}. Furthermore, an intuitive qualitative geometrical model was proposed that shows that lower ∇q values need higher toroidal mode numbers in order to have close enough structures for interaction. This sets a lower boundary for the n numbers that are in general found to be minimized during the crash, thereby influencing a broader region. Other parameters such as normalized pressure gradient, bootstrap current density or triangularity have a weaker influence on the toroidal geometry of the ELM crash.

Acknowledgement

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