Influence of resonant magnetic perturbations on transient heat load deposition – a short review

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Introduction

Over the last decade, the macroscopic effects of resonant magnetic perturbations (RMPs) on edge localized modes (ELMs) have been studied in detail [1–4] and theories to explain their effects have been developed [5–8]. However, a full understanding has not yet been achieved. Especially, the study of the actual influence on the target energy deposition was restricted due to mechanical issues in the past. After a significant improvement of the infra-red viewing systems [9, 10] of the world's largest tokamak Joint European Torus (JET), this important aspect can now be studied.

Dynamic structures prior to an edge localized mode crash

Applying RMP fields above a certain strength (at JET: $I_{\text{EFCC}} > 2.5\,\text{kA}$ ($\times 16$ turns), in $n = 2$ configuration) leads to a significant modification of the heat deposition on the outer divertor target: several ms before the major energy deposition of an ELM appears, heat flux structures propagating radially outward are seen. These structures form either near the original strike-line or at a distance of up to several cm away from it, depending on the plasma configuration. The distance depends on the magnetic topology, experimentally controlled by the edge safety-factor. Additionally, the propagation speed of the structures is found to be altered at different edge safety-factors. A relatively slow propagation between $7\,\text{m}\,\text{s}^{-1}$ to $20\,\text{m}\,\text{s}^{-1}$ is observed.

These structures appear as several parallel lines in the heat flux profile and propagate until the major energy deposition of the ELM reaches the target, see fig. 1 (a). The ELM energy

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[*] See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

deposition profile shows increased heat fluxes at the locations of the structures, which indicate that these pre-ELM structures directly affect the final ELM heat deposition. In some cases, a few of the structures even seem to continue to propagate during the major ELM energy deposition on the target, causing large heat fluxes.

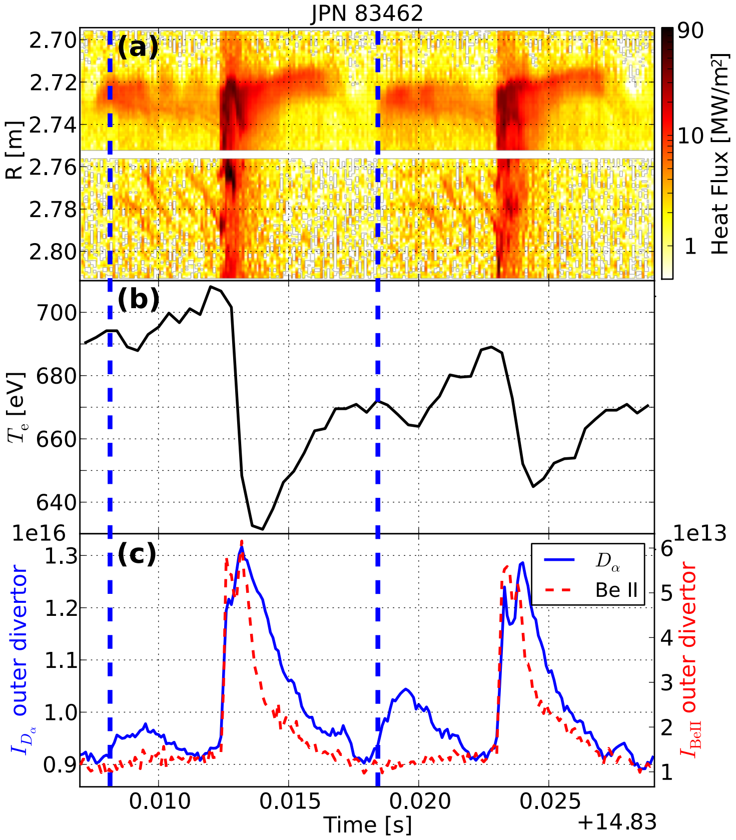

Figure 1: Two ELMs during the application of RMPs are shown: time-traces of the heat flux profile on the outer target (a), electron temperature at the plasma edge (b), and intensity of the D_α and Be II emission (c). Reprinted with permission from [11]. Copyright 2014, Euratom.

A statistical analysis of the creation time of the pre-ELM structures with respect to the major energy deposition of the ELM gives a time delay of about 3 ms. This is much longer than any ELM timescale known before. Due to this long delay it appears impossible to understand the pre-ELM structures as rotating ELM filaments, which are reported to have a fast radial motion from 0.5 km s^{-1} to 2 km s^{-1} [12] and therefore much shorter lifetimes.

The pre-ELM structures are also accompanied by additional effects shown through different plasma parameters. A probable explanation for the observations is a reconnection process which triggers the formation of the observed structures. The stochastization of the plasma edge, caused by a reconnection process, would lead to the loss of fast electrons, seen by the drop in electron temperature when the pre-ELM structures are created (fig. 1 (b)) and the increased ion influx (seen via the D_α signal) with no effect on the Be II light emission (fig. 1 (c)). Furthermore, the loss of electrons can start a self-amplification process of thermoelectric currents as suggested by Evans [13], which finally results in the ELM crash. For testing this hypothesis, the thermoelectric current model [14,15] has been applied and compared to the experimental data. A good qualitative agreement was found, which further supports the hypothesis. In the next step, measurements of the thermoelectric currents are required; but those are beyond the capabilities of JET and need to be performed elsewhere, such as at

ASDEX Upgrade (AUG). The reader is referred to [11] for further details on the experimental measurements, its analysis and modelling.

Heat load splitting during the major energy deposition

The latest experiments with RMPs on JET enabled the further study of the previously found heat load splitting, during the ELM crash, on the DIII-D tokamak [16]. It is observed that theoretical predictions made, based on the DIII-D results, do not hold for the findings on JET and need further refinement.

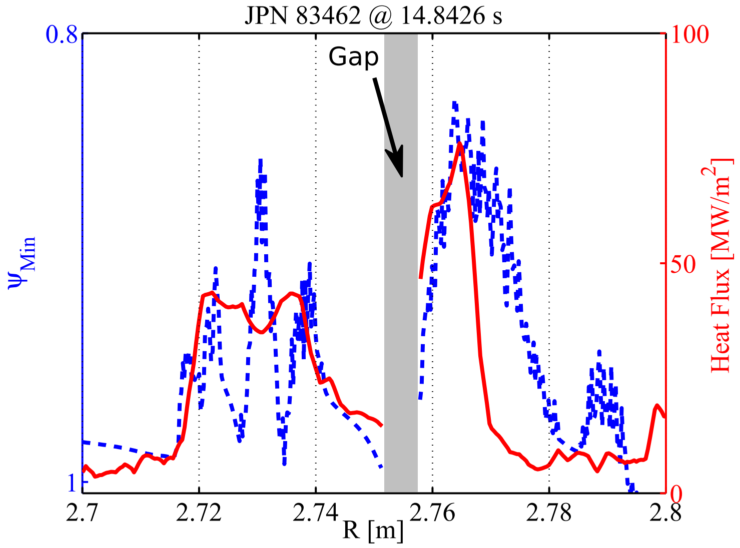

Figure 2: Comparison of the experimental heat flux profile (solid) with the predicted field line penetration depth, $1-\psi_{\mathrm{Min}}$, of the thermoelectric current model (dashed) during the peak heat deposition of one ELM. Reprinted with permission from [17]. Copyright 2014, Euratom.

Uncontrolled type-I ELMs show a random heat deposition on the divertor target during their crash [18]. Taking an average over a large number of these ELMs results in a smooth radial decay of the heat load along the target. In contrast, ELMs in the presence of RMPs appear to have radially predefined locations for the heat deposition. If RMPs are applied, the averaged heat deposition profiles, under the same conditions, show preferred heat deposition at distinct radial positions. This distinct heat deposition can be described as splitting during the ELM crash in reference to strike-line splitting during low-confinement mode (L-mode) operation. The structure of the splitting changes when the magnetic topology varies, for instance by a difference in the applied perturbation field or a changed edge safety-factor of the plasma.

For a better understanding, the magnetic topology for two ELM crashes at different perturbation strengths has been modelled based on the vacuum approach and compared to experimental observations. The predictions indicate the correct trend, but a precise comparison at the measurement location shows a strong discrepancy between measurement and prediction: a much stronger splitting is measured than predicted. Previous publications [14, 15] have demonstrated that consideration of additional thermoelectric currents explains the heat deposition of standard type-I ELM. This provides motivation for also applying the thermoelectric current model to controlled ELMs in the presence of RMP fields. Application of this extended model results in a good qualitative agreement between the experiment and predictions, see fig. 2. The reader is referred to [17] for further details on the experimental results and its modelling.

Conclusions

The new finding of pre-ELM structures extends the understanding of ELM control by RMPs: although RMPs lead to an increased ELM frequency, dynamic heat flux structures occur which are very slow compared to typical ELM time-scales. It appears that due to the RMPs, this dynamic process decouples from the major energy ejection. This may contributes to the further development of theories for the understanding of RMP ELM control.

Studying the strike-line splitting during ELM crashes lead to the discovery of an important aspect: due to the fact that a much larger splitting is observed than initially predicted by the simple vacuum approach, severe damage can occur if regions which are not prepared for such heat loads come into contact with the plasma. Therefore, it is crucial to consider an improved model – including thermoelectric edge currents – to predict the expected strike-line splitting.

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