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ABSTRACT

Type-I Edge-Localized Modes (ELMs) are events associated with H-mode tokamak operations during which about 10% of plasma energy is released from the pedestal region. The largest fraction of this energy is deposited onto the divertor target tiles by parallel transport along magnetic field lines. At JET, the spatial and temporal resolution of a new infrared (IR) thermography system monitoring the outer divertor target (1.7mm and $35 - 86\mu s$, respectively) allows for an accurate study of the ELM induced non axisymmetric heat load patterns called here striations [1]. These striations can be linked to toroidal inhomogeneities at the outer midplane which has been observed on other devices such as ASDEX Upgrade, MAST or DIII-D. Here we report analysis of these striations and associated toroidal mode number carried out over Type-I ELMy H-Mode plasmas with B_T/I_P in the range 1.6T-3.3T/1.5MA-2.5MA and mainly NBI input power from 8 to 20 MW.

INTRODUCTION

Type-I ELMy H-mode plasmas are standard scenario for plasma operations in most of tokamaks and are forecasted as the ITER baseline operation scenario. These plasmas are associated with a high energy confinement but also with ELMs (Edge Localized Mode), quasi-periodic instabilities during which a significant part (10 to 20 $\%$) of the plasma stored energy is released from the pedestal region. Particles involved in ELMs radially cross the separatrix at the outer midplane and flow toward the first wall. Due to parallel transport along magnetic field lines, particles are driven toward the divertor where they strike the target tiles. At JET, heat fluxes associated with incoming particles can be studied thanks to the recent installation of an infrared (IR) camera monitoring these tiles. Its spatial resolution (down to 1.7mm on the outer target) allows resolving heat load patterns as single striations. The high acquisition frequency of the camera, 11600Hz (i.e. one snapshot every $86\mu s$) in its standard configuration, enables an accurate description of time and spatial evolution of these striations over the duration of ELMs (typically about $1000\mu s$). Thanks to pre-ELM equilibrium magnetic reconstruction, these striations can be linked to toroidal homogeneities at midplane, already observed in many devices such as ASDEX Upgrade, MAST or DIII-D. A quasi-toroidal mode number (QMN) can then be derived from position of striations. In this paper we report analysis carried out over 23 pulses ran in Type-I ELMy H-mode with a wide range of plasma parameters for I_P (1.5 to 3.5 MA), B_T (1.6 to 3 T) and input power. Dependence of the associated toroidal mode number with parameters such as the safety factor q_{95} has also been investigated, and results have been compared to a previous analysis carried out on ASDEX Upgrade.

TYPE-I ELM TYPICAL HEAT LOAD PATTERN

Heat loads on outer target associated with Type-I ELMs have been investigated for the different plasma configurations mentioned above. Despite the important ELM to ELM variability in patterns observed, a common set of characteristics can be established. The typical duration of one ELM is up to 10 ms and split into two stages. The first stage corresponds to a constant increase of the power deposited on outer target (see figure 1.a where power deposition on outer target is plotted against time for one Type-I ELM). The maximum of power deposition is typically reach after $300 - 400\mu s$ (called τ_{IR} in this paper); the maximum heat flux reached of $60MW.m^{-2}$ is 4 times higher than inter-ELM one. The second stage sees power decaying until it reaches inter-ELM value over a period at least ten times longer. On figure 1.b heat loads on target related previous ELM power deposition is shown; 1D heat profiles along target are given by figure 1.c. An inter-ELM heat profile is given as a reference: the outer strike point (OSP) is located at R=2.71m, the private flux region lies below this value and the Scrape-Off Layer (SOL) above. The maximum heat flux associated with inter-ELM is about $14.5MW.m^{-2}$ and the full width at half maximum (FWHM) of the profile is about 2.1cm, corresponding to 4.2mm at outer midplane, consistent with 4-5mm already reported at JET [4]. No substructures can be detected within the profile. During ELM, the heat flux spreads over the target in the outer direction, with FWHM of 7cm, 3.5 times larger than inter-ELM value. The intrinsic filamentary structure of ELMs is observed in heat fluxes as striations with a typical radial width at half maximum of about 1cm. The number of striations observed during ELMs rise (0 - τ_{IR}) has been investigated and result for one pulse is plotted on figure 2.a; the number provided there corresponds to an extrapolation to $360°$ (the IR view on the target corresponds to an insight of $280°$ along the toroidal direction, depending on the magnetic configuration). The rise is split into two stages; the first stage is characterized by the observation of new striations on the target. The second stage starts after a period typically around $0.4\tau_{IR}$, no new striations are observed and their number stays until τ_{IR}. As the power is constantly increasing during these two stages, it can be inferred that this increase is first due to new striations reaching the target and then, only due to the increase of energy carried by each single striation, as their number remains constant. This analysis is confirmed by heat profiles shown on figure 1.c where the number of visible striations is frozen after $200\mu s$ and where striations relative sizes is the only evolving parameter.

QUASI-TOROIDAL MODE NUMBER

It has already been demonstrated in a previous work on ASDEX Upgrade that patterns observed on target during ELMs can be mapped with intersections of open magnetic field lines on the target. Here we assume that during one ELM, particles collected on the outer target have been expelled from the outer midplane and have then followed open magnetic field lines until they reach tiles. From this assumption and pre-ELM equilibrium magnetic reconstruction, a toroidal angle $\Delta\phi$ can be computed from the radial distance Δr between two striations on the target. From angles between consecutive striations, a quasi-toroidal mode number (QMN) can be derived as follow :

$$QMN = \frac{1}{s}\sum_{i=1}^{s}\frac{2\pi}{\phi_{i+1}-\phi_i}, \tag{1}$$

where ϕ_i stands for the toroidal angle of striation i and where the summation is performed over striations seen on the target. In order to perform a quantitative analysis of striations observed on the target during ELMs, one has to deal with acquisition rate of the camera. The acquisition frequency of the IR camera is not high enough to provide an accurate coverage of the rising phase of ELMs (before τ_{IR}) : one frame every $86\mu s$ only provides 4 or 5 profiles during this lap of time, not enough to accurately describe filaments evolution. To tackle this issue, a statistic has to be derived from the study of similar ELMs from a JET pulse. Figure 2.b shows the result of such an analysis, where QMN is plotted against time during the rise phase of ELMs. The two stages spotted from the number of filaments on the target are again observed: qmn starts at an initial value of 3 to 5 and increases until $0.4\tau_{IR}$ when its maximum value is reached and is about 25. This increase as well as the values taken is similar to what has been observed in ASDEX Upgrade and reported in [xx]. As defined above, QMN only provides a relevant number for toroidal mode number when the mode analyzed is fully consistent, meaning that filaments are equally spaced in the toroidal direction. In order to determine if modes observed are consistent or not, QMN and the number of filaments extrapolated to $360°$ has been compared for 23 JET Type-I ELMy H-Mode discharges. These two independent methods (the former is based on an average over consecutive striations and latter on the total number of striations seen on the target) only agree for equally spaced filaments. From figure 3 one can see that this agreement is achieved, within error bars, for pulses investigated so far. As toroidal modes have been found to be consistent, the last analysis presented in this paper is focused on QMN; maximum value reached at τ_{IR} and its evolution according to plasma parameters. In order to investigate the influence of some of these different parameters, two subsets of pulses has been selected from the database. The 3 pulses designated by violet crosses on figure 4 have been ran with $I_P/B_T = 2.0MA/2.0T$ but different levels of input power (7.5MW/13.5MW/15MW). QMN does not show any dependence with input power, its variation staying within error bars. Other data points on this plot corresponds to pair of pulses where the plasma current I_P has been kept constant at 1.5MA, 2.0MA and 2.5MA and B_T increased so that q_{95} varies from 3.5 to 5.5. The trend is now clearly noticeable and shows a net reduction of QMN when q_{95} increases (QMN decreases from 20 down to 10 when q_{95} increases from 3 to 5). At this point, a multilinear regression would be usefull to sort out importance of the different parameters, but a largest database is required to achieve this analysis.

CONCLUSION

The filamentary structure of Type-I ELM has been observed on many tokamaks as filaments of plasma observed on visible pictures. At JET, the recent installation of a high resolution IR camera allowed for an extended analysis of footprints of these structures on the divertor target tiles. The resulting patterns on heat loads during Type-I ELM has been resolved as striations with a typical extent of about centimeters. The analysis has shown that the increase of power deposition during one ELM is first due to an increasing number of striations reaching the tiles, and then only due to the increase of energy carried out by each single striation, as their number stays constant $0.4\tau_{IR}$, time corresponding of the maximum of the power deposition. Thanks to pre-ELM magnetic equilibrium reconstruction, a toroidal mode number has been derived from the position of striations on the target. Comparison of this number with extrapolation to $360°$ of the number of striations seen on the target has demonstrated that modes observed are quasi-coherent, i.e. that the filaments are roughly equally spaced in the toroidal direction. Finally, the dependence of this mode number with input power and q_{95} has been investigated. The input power does not seem to have any influence on QMN but the safety factor seems to be a key parameter as QMN strongly decreases when q_{95} increases. Further investigations will focus on the impact of ELM absolute (energy carried by one ELM) and relative sizes (energy carried normalized to plasma stored energy) on the number of filaments observed on the target and on the associated QMN.

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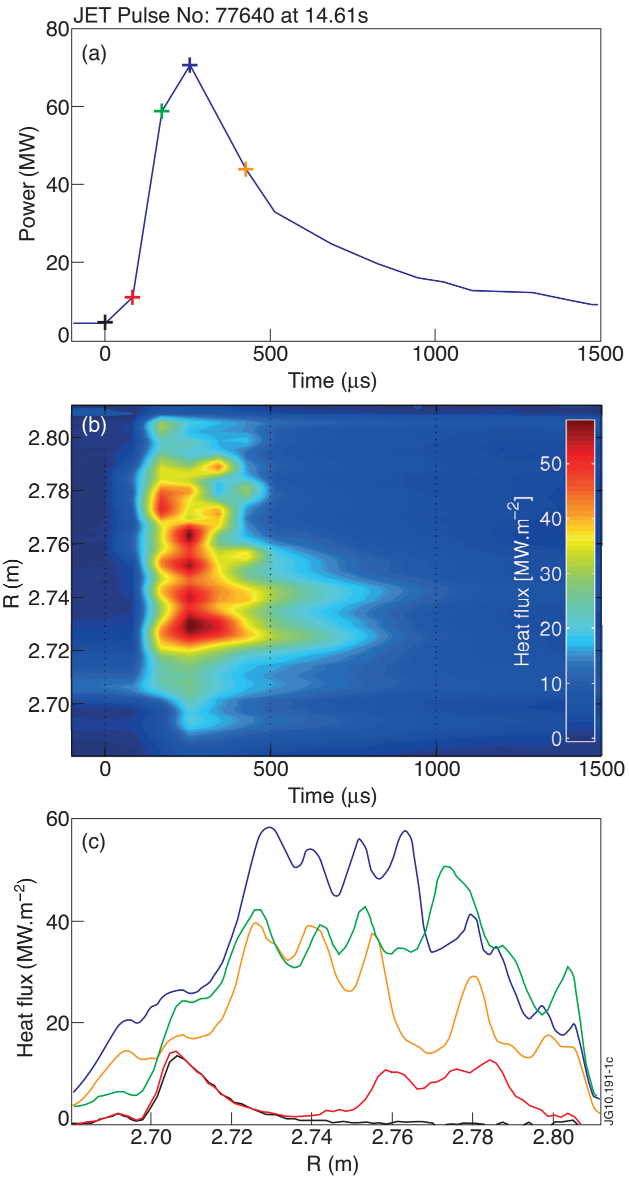

Figure 1: Power load and heat fluxes profile on outer target during one Type-I ELM. (a) shows power deposition on target, which maximum is reached for $\tau_{IR} = 300 - 400\mu s$. (b) and (c) plots provide the corresponding 2D and 1D heat profiles on the target for the corresponding ELM, respectively; colors correspond to time step on top plot. One centimeter wide striations appear along the target only during ELM (pre ELM profile, black curve, is given as a reference).

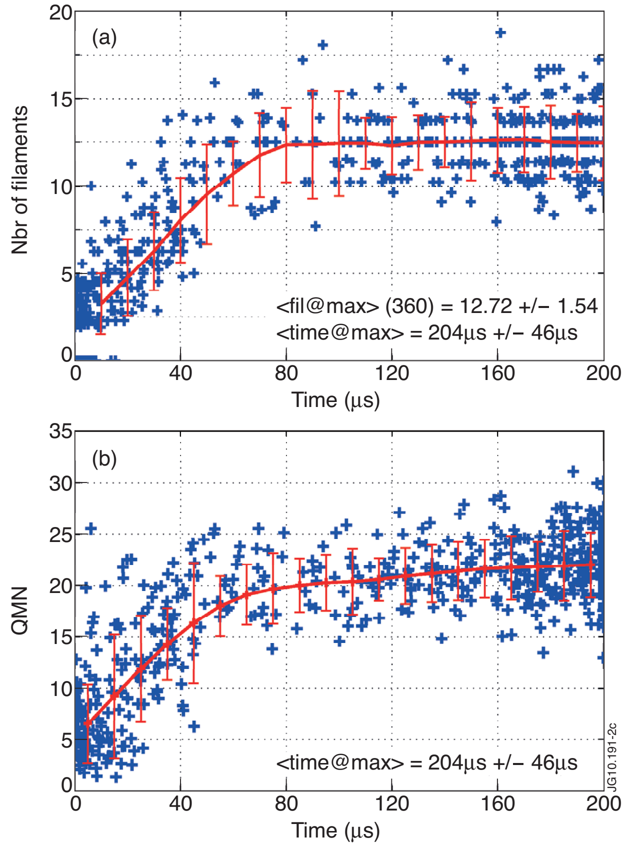

Figure 2: (a) Number of filaments observed on the target, extrapolated to 360^o, during the rise phase of one Type-I ELM. New striations are only observed during the first stage, lasting from $t = 0$ to $t = \tau_{IR}$, time corresponding to the maximum of power deposition on target. (b): quasi toroidal mode number derived from the position of consecutive striations on the target. QMN exhibits a behavior similar to one observed for the number of filaments on the target. This increase from 5 to 20 is comparable with results obtained on ASDEX Upgrade.

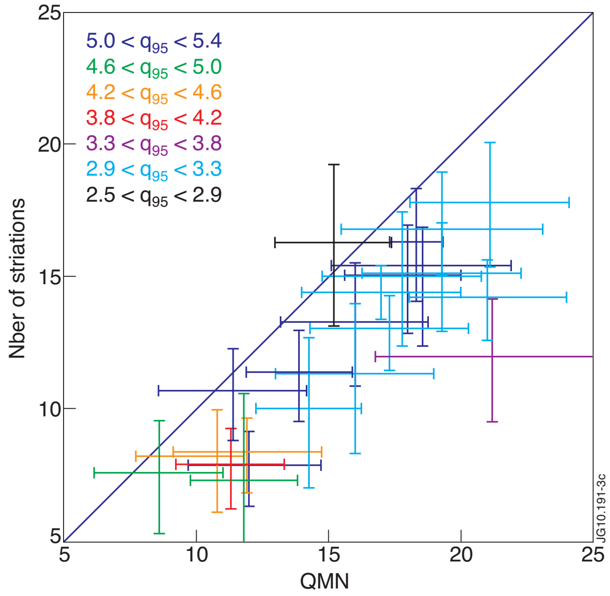

Figure 3: Number of filaments versus Quasi Toroidal Mode Number (QMN) for Type-I ELMy HMode plasmas with various q_{95}. The equivalence of both numbers, which give an estimation of the toroidal mode number using two independent ways, shows that modes are fully consistent, meaning that striations are equally spaced in the toroidal direction.

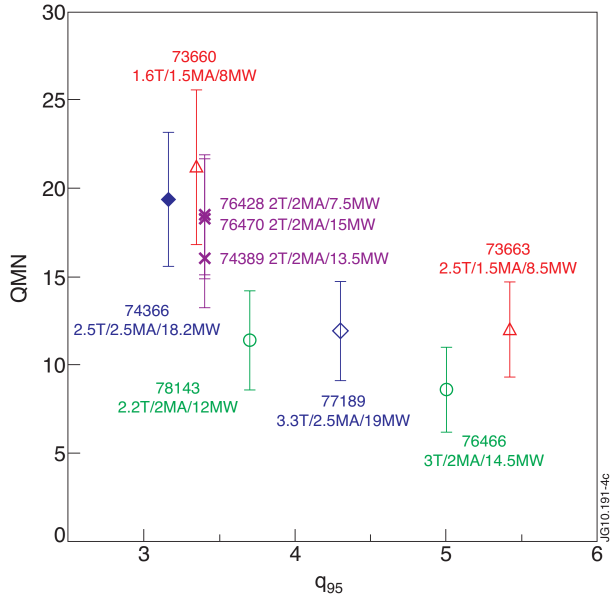

Figure 4: Quasi Toroidal Mode Number (QMN) associated to ELMs decreases when q_{95} increases. QMN has been derived for pair of pulses (see markers) where plasma current has been kept constant but toroidal field increased. Crosses correspond to plasma with same I_p/B_T but different input power; QMN variations are within error bars and do not show any dependence with input power.