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Non-linear Impact of Edge Localized Modes on Carbon Erosion in the Divertor of the JET Tokamak

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ABSTRACT
The impact of Edge Localized Modes (ELMs) carrying energies of up to 45kJ on carbon erosion in the JET inner divertor is assessed by means of time resolved measurements using an in-situ quartz microbalance diagnostic. The inner target erosion is strongly non-linearly dependent on the ELM energy: a single 400kJ ELM produces the same carbon erosion as ten 150kJ events. The ELM-induced enhanced erosion is attributed to the presence of co-deposited carbon-deuterium layers on the inner divertor target, which are thermally decomposed under the impact of ELMs.

MAIN SECTION
One of key issues for the success of the International Thermonuclear Experimental Reactor (ITER) project [1] will be the heat flux handling capability of the Plasma-Facing Components (PFCs). The ITER baseline operating scenario invokes the High confinement (H) mode [2] to achieve burning plasma conditions. One of the characteristic features of the H-mode with respect to the Low confinement (L) mode is the formation of a transport barrier at the plasma edge. The resulting high pressure gradient leads to quasi-periodic magnetohydrodynamic relaxations of the barrier known collectively as Edge Localized Modes (ELMs) [3]. The largest of these events (type I ELMs), usually associated with high quality H-modes, release substantial fractions $\Delta W_{ELM}$ of the plasma stored energy $W$ ($\Delta W_{ELM} / W$ of up to ~10%) across the magnetic separatrix into the Scrape-Off Layer (SOL). In the SOL, a major fraction of this energy is transported to the divertor, where magnetic field lines terminate on solid surfaces – the target plates. The induced target erosion is likely to be severe, leading to unacceptably short divertor target lifetime [4,5]. Even assuming that ELMs can be mitigated such that severe damage thresholds are avoided [6,7], some residual activity is always likely to remain. Due to the high stored energy of an ITER burning plasma (estimated at $W \sim 350$MJ), even small ELMs can be associated with high energy fluxes in comparison with today’s tokamaks.

Carbon based materials have outstanding thermal properties and can withstand extremely high heat loads. This is one reason why Carbon Fiber Composite (CFC) is currently being considered for ITER as material in the area of strongest plasma-surface interaction – the so-called Strike Point (SP) regions on the divertor targets [1]. One serious disadvantage of carbon for ITER is the re-deposition of eroded carbon in form of amorphous layers containing high quantities of hydrogenic isotopes (the deuterium and tritium constituting the plasma fuel in a fusion reactor). Particular attention must be paid to the co-deposited layers growing in areas shaded from the direct plasma impact. These remote locations may turn out to be inaccessible to cleaning techniques, providing a reservoir for tritium accumulation. This is a particularly serious concern for ITER, where the quantity of stored tritium will be limited to 1kg by nuclear safety restrictions [1].

The experimental program of JET as the worldwide largest operating tokamak is primarily focused on the development of ITER relevant scenarios in terms of confinement physics as well as plasma-wall interaction [8]. Large ELMs in JET can carry an energy of up to $\Delta W_{ELM} \sim 1$MJ over times of several 100ms leading to peak power fluxes to the divertor targets of up to ~1GW/m$^2$ [9,10]. JET is
equipped with an all-carbon first wall and operates mostly with deuterium as the plasma fuel, although it is currently the only tokamak in the world capable of fuelling with tritium. High levels of tritium retention were observed during the deuterium-tritium experiments of 1997, when H-mode discharges with large ELMs were used to produce record values of fusion power [11]. Of 35g tritium injected during these experiments, about 6g remained in-vessel despite an extensive program of discharge cleaning [12]. During the subsequent shutdown, the majority of tritium was found co-deposited in the remote region of the inner divertor leg on a series of water cooled louvres through which gas is exhausted to the cryopumps [13]. The deposition pattern of carbon at the inner louvre suggested that the carbon transport in the inner divertor is mainly line-of-sight [14]. However, both simple particle balance models [14] and sophisticated Monte-Carlo simulations [15,16] failed, by at least one order of magnitude, to reproduce the high amount of co-deposition in the inner louvre. Since this modeling was performed for plasma parameters averaged over both inter-ELM and ELM phases, it was speculated that ELMs could increase the amount of carbon eroded from the inner target and transported to the louvre region [14,15]. Until recently, however, no compelling evidence has been found for the additional ELM driven carbon transport. This letter provides that evidence.

The persistent observation of strongly asymmetric carbon deposition in the JET divertor has triggered the recent development of *in-situ* plasma-wall interaction diagnostics capable of providing time resolved data [17]. This is in sharp contrast to that of *post-mortem* analysis which delivers an averaged footprint of material erosion and deposition covering a complete experimental campaign totaling, in the case of JET, several thousand discharges of different types and divertor magnetic geometries (notably SP positions). The diagnostic upgrade includes the installation of Quartz MicroBalance (QMB) systems capable of measuring the amount of deposited material at the QMB location from shot to shot [18,19]. A distinctive feature of the JET QMBs is the electromagnetically driven protective shutter allowing a time window, typically of a few seconds duration, to be defined in any given discharge. This feature permits the isolation of specific temporal regions, for example the ELMing H-mode phases of interest to this letter. A QMB measures the net amount of deposited material, namely the gross deposition on the detector less erosion due to the incident particle flux (mostly deuterium neutrals in the case described here). In this letter, the amount of deposition on the QMB located at the inner divertor louvre (Fig.1) is expressed as areal densities of carbon atoms $D_C$. The lowest detection limit of the system is $D_C \approx 1 \cdot 110^{15} \text{C/cm}^2$, corresponding to about one monolayer of co-deposited film.

Among the many aspects of carbon transport in the divertor that can be studied with the new QMB system, the effect of ELMs has turned out to be one of the most significant. A striking example of the ELM effect was observed in a pair of discharges with similar plasma conditions but different ELM behavior, as illustrated in Fig.2. Both discharges had an input power of 21MW and employed a magnetic field geometry such that the inner SP was positioned on the vertical tile 3 (Fig.1). The only discharge actuator modified between the two pulses was the external gas fuelling, with a deuterium rate of $1.2 \cdot 10^{22} \text{atoms/s}$ in the first and zero fuelling in the second. Gas fuelling is known to strongly influence the ELM energy $\Delta W_{ELM}$ and frequency $f_{ELM}$ on JET, with unfuelled discharges producing the largest
ELMs [4]. In the first pulse, ELMs with $\Delta W_{ELM} \approx 300\text{kJ}$ at $f_{ELM} \approx 10\text{Hz}$ produced a net-deposition on the QMB in the inner louvre of $D_C = 4 \cdot 10^{15} \text{C/cm}^2$ during its 0.8s exposure. Switching off the gas fuelling in the second pulse resulted in large but infrequent ELMs ($\Delta W_{ELM} \approx 700\text{kJ}, f_{ELM} \approx 3\text{Hz}$). In this pulse, the QMB exposure time window captured the time period between two large ELMs. The deposition and erosion of the QMB were balanced ($D_C \approx 0$) within the accuracy of the system, thus showing that the carbon erosion from the target in the inner divertor decreases dramatically in the absence of large ELMs.

During the recent JET experimental campaign covering the period 2005-2007, the QMB has been used to assess carbon erosion in the divertor as function of ELM energy by collecting data over as many different discharges as possible. To extract a meaningful ELM scaling, only pulses meeting the following criteria are considered for analysis: (i) exposures occurring only during the phase of stationary plasma conditions (discharge flat-top); (ii) constant magnetic geometry in the divertor, choosing a configuration with inner SP on horizontal target tile 4 – see Fig.1. This latter condition ensures line-of-sight to the position of the inner divertor louvre, corresponding to magnetic field configurations employed during the deuterium-tritium experiments of 1997. Of the total number of about 900 discharges in the database, 69 pulses fulfill these selection rules, with 51 in H-mode and 18 in L-mode.

Figure 3 compiles the carbon deposition rates on the inner QMB as a function of $\Delta W_{ELM}$ for the selected pulses. Although quasi-periodic, ELMs typically comprise a range of energies and frequencies even in an otherwise stable discharge [4]. As illustrated in Fig.2, there will often be a mixture of different ELM sizes during a single QMB exposure. The abscissa value in Fig.3 is therefore defined as the mean energy of all events which occurred during the respective QMB exposure with energies >80% of the largest $\Delta W_{ELM}$. Deposition rates at the inner louvre for ELMs with $\Delta W_{ELM} > 30 – 40\text{kJ}$ are considerably higher in comparison to discharges with smaller events or L-mode discharges without ELMs (data points with $\Delta W_{ELM} = 0$). For $\Delta W_{ELM} > 100\text{kJ}$ the dependence of deposition rates at the QMB on ELM energy becomes rather flat, largely due to the compensating effect of the lower frequencies associated with larger ELMs.

A further step in the analysis can be obtained by estimating the deposition on the inner louvre QMB due to single ELMs and deriving a fit function providing an analytic scaling for the deposition per ELM. For all data points in Fig.3, the deposition rates were divided by $f_{ELM}$ to obtain the deposition per ELM $\Delta_{ELM}$ (open squares in Fig.4). The abscissa in Fig.4 has the same definition as in Fig.3, namely the mean energy of the largest events occurring during the given QMB exposure. Consequently, $f_{ELM}$ is determined as the number of these events within the exposure window divided by the duration of the exposure. Each of the derived data points, however, includes a contribution due to additional, smaller ELMs within the exposure period. These contributions are quantified and subtracted from the original data points by fitting the following equation to the data set:

$$D_C^{ELM} = D_S^{C} \cdot \Delta W_{ELM} + D_a^{C} \cdot \exp \left( -\frac{W_a}{\Delta_{ELM}} \right),$$
where $D_a^C$ and $W_a$ are fit coefficients and $D_S^C$ is fixed to $5 \cdot 10^{11} \text{C/cm}^2 \text{kJ}$ according to the argument given below. Using an iterative fitting procedure a self-consistent function with fit coefficients $D_a^C = 1.97 \cdot 10^{16} \text{C/cm}^2$ and $W_a = 680 \text{kJ}$ is obtained: The correction of the original data with this fit function delivers the data set, which, in turn, yields the same fit function. Both the original and the corrected data are shown along with the fit function in Fig.4.

The fit formula is the sum of two terms containing $\Delta W_{ELM}$. The first, $D_S \cdot \Delta W_{ELM}$, represents physical sputtering of carbon by deuterium ions during ELMs (assuming a linear relationship between the impinging ion flux and the ELM energy). Coefficient $D_S^C$ is estimated for plasma parameters in the divertor target vicinity typical for an ELM of a few 100kJ [10], a sputtering yield of 1.5% [20] and the QMB geometry with respect to the inner SP position. QMB deposition induced by small ELMs with $\Delta W_{ELM} < 50 \text{kJ}$ is reasonably well reproduced by physical sputtering. However, for larger ELMs deposition reveals a clear non-linear behavior with significantly higher values, which cannot be assigned to physical sputtering. Chemical erosion of carbon can be neglected on the basis that at the elevated target surface temperatures (~1000°C) and high fluxes (>10^{20} \text{cm}^{-2}\text{s}^{-1}), characteristic for the large ELMs, the erosion yield is <0.1% [21].

The non-linear behavior of QMB deposition for $\Delta W_{ELM} > \sim 100 \text{kJ}$ is well described by the second term in the fit formula, the ubiquitous Arrhenius function. The fact that the process obeys an Arrhenius-like scaling implies a thermal origin and suggests that the strong increase in observed QMB carbon deposition rate beyond a given $\Delta W_{ELM}$ is due to thermal decomposition of carbon in the ELM impact regions. In this case, $W_a$ is identified as the activation energy of the process. Fast infrared thermography of the JET divertor target has demonstrated that, even for the largest ELMs, the induced surface temperature rise rarely exceeds 1000°C [22]. Combining this with the inter-ELM power flux, the maximum tile temperature never approaches the sublimation temperature of graphite of about 3700°C. However, the ELM energies characteristic of JET appear to be sufficient to trigger thermal decomposition of co-deposited carbon-deuterium layers in the inner divertor.

The mechanism of carbon layer thermal decomposition in the JET divertor is still a matter of discussion. Laboratory investigations have demonstrated that co-deposited layers are more sensitive to thermal loads than bare graphite due to different structural properties [23]. The high sensitivity of the layers is also reflected in spectroscopic observations of carbon emission lines in the JET divertor [24]. However, the thermal release of single atoms or molecules is unlikely to be the main contributor to the decomposition of layers on the inner target. For high plasma densities and temperatures at the target during large ELMs, the ionization length of carbon atoms is < ~1mm, so that the majority of particles released will be promptly re-deposited and will not find their way to the QMB location. A more likely scenario is the ELM driven formation of carbon particle clusters from the target surface layers. These dust particles can easily overcome the distance between the inner SP and QMB of ~10cm [25], in agreement with the observed line-of-sight character of the carbon transport to the inner louvre.
CONCLUSION
The data derived from the QMB diagnostic are the first direct evidence of ELM-induced enhanced carbon erosion in the JET inner divertor. Even when divertor target conditions are far from the threshold for carbon sublimation, ELMs enhance erosion of co-deposited carbon-deuterium layers in a non-linear manner, provoking much faster material re-dislocation. The observed Arrhenius behavior of this erosion points to a thermally assisted process, strongly suggesting that large ELMs induce thermal decomposition of deposited layers on the inner divertor target surfaces. The result explains the large amount of carbon and hydrogenic isotopes typically observed in the remote areas of the inner divertor of JET, in particular after the 1997 deuterium-tritium campaign. It underlines the necessity for the development of efficient wall cleaning methods applicable in the remote areas of ITER if carbon is used as target material.

REFERENCES
Figure 2: A pair of discharges with similar main plasma parameters (see text) but different ELMs. Spikes on signals of the radiated power and the divertor D$_{\alpha}$ light emission are signatures of ELMs, each associated with a sudden drop of the plasma stored energy. The first event in (b) illustrates the definition of the ELM energy drop $\Delta W_{\text{ELM}}$. The time window of the QMB exposure is indicated by shaded region. (a) Discharge with deuterium gas fuelling rate of 1.2 $\times$ 10$^{22}$ atoms/s and a typical ELM energy of $\Delta W_{\text{ELM}} \approx 300$kJ. Several of these ELMs occurred during the QMB exposure between 20.9– 21.7s; (b) Pulse without fuelling resulting in large ELMs of $\Delta W_{\text{ELM}} \approx 700$kJ followed by a phase with a number of small events where $\Delta W_{\text{ELM}} \lesssim 10$kJ. Here, the QMB was exposed during small ELMs and in the ELM-free phase (20.6– 21.4s).

Figure 1: Poloidal cross-section of the MarkII-HD divertor deployed during the JET campaigns of 2005-2007 with numbers as used in the text to denote the CFC divertor target tiles. The dashed line is the separatrix of the magnetic field configuration common to the pulses in which the QMB data of Fig.2 are obtained. The full line indicates the configuration chosen for the QMB database used in Fig.3 and Fig.4. The intersection points of each separatrix with the tiles are the respective strike points.
Figure 3: Carbon deposition rate of the QMB in the inner louvre as function of ELM stored energy drop.

Figure 4: Amount of carbon deposited on the inner louvre QMB per single ELM as function of ELM stored energy drop. (□) Original uncorrected data; (●) Data corrected for the influence of smaller ELMs; (—) Self-consistent fit function comprising (----) linear term for physical sputtering and (——) Arrhenius term for thermal decomposition.