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Radiation Loads onto Plasma-Facing Components of JET

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ABSTRACT.

This contribution examines the impact of large type I ELMs with energies $0.25J\div1.3MJ$ in high current H-mode JET discharges on plasma radiation and on power load to the divertor. The ELMs provoke strong radiation losses, mostly confined to the inner divertor region. Large type I ELMs with $\Delta W_{ELM} \ge 0.72MJ$ show enhanced radiation losses which are associated with the ablation of carbon layers in the inner divertor. Such large ELMs are usually followed by a phase of type III ELMs with an increased radiation in the plasma core. The unmitigated disruptions exhibit small radiation fraction during the thermal quench with strong poloidal radiation asymmetry, which could cause Be melting by radiation in ITER. In dedicated experiments on massive gas injection more than 50% of the thermal energy and a significant part of the magnetic energy was converted in radiation and spread uniformly over the first walls.

1. INTRODUCTION

In ITER, the plasma-facing components (PFCs) will be subject to large power loads during intense transient events such as disruptions, Vertical Displacement Events (VDEs) and bursts of Edge Localised Modes (ELMs). The type I ELMy H-mode regime is the baseline scenario for operation of ITER in high fusion gain regimes ($Q_{DT} \ge 10$) with plasmas of high density ($\langle n_e \rangle \ge 10^{20} \text{m}^{-3}$) and high energy (~350MJ)[1]. The major drawback of this operating regime is the ELM-associated periodic power loading of plasma-facing components which can lead to high target erosion and a significant reduction of component lifetimes. To prevent an unacceptable erosion, cracks, melting etc. of divertor targets due to ELMs in ITER, the loss in plasma stored energy should be restricted to $\Delta W_{ELM} \sim 1$ MJ [2] for a single ELM, corresponding to ~3% of the plasma stored energy. In present tokamaks, the plasma energy drop normalised to the pedestal energy W_{ELM}/W_{ped} is typically 3-20% during a type I ELM. A recent analysis of the radiation losses shows that the significant part of this energy drop can be found in form of plasma radiation, located mostly in the divertor region. Systematic studies of the smallest type I ELMs will considerably exceed the maximum energies currently accessible in JET.

During JET plasma disruptions, the thermal energy (≤ 10 MJ) and magnetic energy (≤ 20 MJ) are lost in form of heat to the plasma-facing components on timescales of less than 1ms and 20ms, [3] respectively. Initially, the thermal energy stored in the plasma is dissipated in the thermal quench followed by the magnetic energy dissipation in the current quench. During the thermal quench phase of the unmitigated disruptions the main part of the thermal energy is lost by convection to the first wall and only a small part ($\leq 0.2 \times W_{th}$) by radiation. The energy deposition is distributed non-uniformly over the first wall surfaces and may significantly contribute to the local power loads onto PFCs. The heat loads during the thermal quench can be reduced by enhancing the radiation with Massive Gas Injection (MGI). Dedicated experiments on massive gas injection for disruption mitigation have been performed during the last JET campaigns and the results are summarized and discussed.

2. IMPACT OF LARGE TYPE I ELMS ON PLASMA RADIATION IN JET 2.1 EXPERIMENT

A series of dedicated discharges with both strike points symmetrically on the lower vertical targets and with identical plasma shape ($\delta = 0.25$, $\kappa = 1.74$) was performed in the JET Mark II HD divertor configuration. The parameters were the following: $I_p = 3$ MA, $B_T = 3T$, $q_{95} = 3.15$, stored plasma energy W_{plasma}~8MJ and a total injected energy of ~195MJ. The purpose was to study the impact of large ELMs on plasma radiation in JET. The gas fuelling is progressively reduced from pulse to pulse, producing type I ELMs with ELM losses ΔW_{ELM} in the range 0.25–01.30MJ, where ΔW_{FLM} is defined as the drop of energy stored within the pedestal on the time scale of 4ms as measured by diamagnetic loops. The time resolution of diamagnetic loops located behind the vacuum vessel is defined by the characteristic time for the magnetic flux to penetrate the vacuum vessel and is ~3÷4ms. Fig. 1 shows typical time traces of the parameters of an ELMy H-mode discharge in JET with strike points on the vertical tiles - comparable to the standard ITER configuration. The gas fuelling was switched off after 14s, what leads to a transition from a moderate regime of ELMs with ΔW_{ELM} \approx 0.3÷0.6MJ to the regime with large (giant) ELMs ($\Delta W_{ELM} \approx$ 1.3MJ). Such ELMs are often followed by a phase of type III ELMs (so-called "compound" phase) or even a back-transition to L-mode confinement is possible. The "global energy balance" for this discharge (energy balance integrated over the entire discharge) reads: total injected energy of E_{in} =195MJ, radiated energy E_{rad} =73MJ, E_{rad} / $E_{in} = 0.47$ and deposited energies onto inner and outer divertor targets measured by thermocouples of 24.6MJ and 70.9MJ respectively.

The radiation distribution has been studied by means of the improved JET bolometer camera system [5]. This allows a tomographic reconstruction of the radiation pattern on a timescale of the order of the typical duration of a type I ELM cycle (~1ms). The tomographic reconstruction model which is used (anisotropic diffusion model) [6] has been coupled with a Monte-Carlo technique to calculate the poloidal radiation distribution and the corresponding "Radiation Peaking Factor" (RPF) (the local radiation power load onto the wall normalised to its value averaged over the entire surface), hence the radiation load onto the vessel during these transient events. The toroidal symmetry has been assumed.

2.2 ELM-INDUCED RADIATION

A significant part of the total ELM energy loss is in the form of plasma radiation, located mostly in the divertor region. Please note that the radiation is integrated over ~2ms, which is considerably longer than the ELM target power deposition peak of several 100µs [7]. Fig.2 shows the radiation distribution for type I ELMs with medium ($1\% \le \Delta W_{ELM}/W \le 5\%$), large ($5\% \le D\Delta_{ELM}/W < 9\%$) and giant ($\Delta W_{ELM}/W \ge 9\%$ corresponding to ELM energy losses above ΔW_{tr}^{ELM} (see the description below)) sizes. In all cases, the radiation distribution is strongly weighted to the inner divertor region (in-out asymmetries of ~factor 3). The total radiated energies during the type I ELM normalised to the ELM energy losses, evaluated by an algorithm similar to that described in [8], are 44\%, 53\% and 85% for medium, large and giant ELM sizes, respectively. For ELMs with $\Delta W_{ELM} \ge_0 0.6MJ$ the radiation "spills over" in the outboard X-point region.

2.2.1 Threshold in the radiation energy loss

Figure 3 presents the dependence on the ELM energy drop ΔW_{ELM} of the radiated plasma energy which follows the ELM crash. In this case the radiated energy includes only the radiated losses integrated over the first main peak of the ELM. For ELM energies below $\Delta W_{tr}^{ELM} \approx 0.72 MJ$, the radiated plasma energy is proportional to the ELM energy. In this range, ~50% of the ELM energy drop radiates with the ELM. For a ΔW_{ELM} larger than the threshold of ~0.72MJ, an enhanced increase of the divertor radiation occurs which is interpreted as an indication of additional carbon ejection from the target tiles made of carbon-fibre composites and covered with substantial carbon deposits. The carbon ejection may be due to the thermal decomposition and ablation of these layers which are known to exist on the inner divertor target. The target surface temperature during the transient loads as measured with infra-red thermography reaches peak values significantly below ~2000°C at the inner divertor. Even the maximum value of 2000°C is too low for bulk carbon ablation which would correspond to a carbon sublimation of about 10^{19} C-at./m² s at this temperature, yielding a total release of 2×10^{19} C-at./s for a 0.5m² loaded surface during the ELM. This quantity of carbon is much smaller than the known intrinsic carbon sources ($\sim 10^{21}$ C/s from the main wall and $\sim 7 \times 10^{21}$ C/s from the divertor [9]). The re-deposited layers in the inner divertor contain a large amount of Be (up to 50%). Interestingly, the fast signals in BeII- and CIII-emission react at the same time (~300µs after fall in plasma energy) during the transient events, confirming the assumption of ablation of deposited layers in the inner divertor.

The radiation fraction in the divertor region, defined as ratio of the radiation power below Z \leq -1.0m (radiated power in the divertor) to the total radiation power, is significant over the entire range of the observed ELM sizes: $P_{rad}^{div}/P_{rad}^{tot} \geq 0.6$. The Radiation Peaking Factor (RPF) at inner strike point (ISP) reaches the maximal value of 2.8. For the largest observed ELM, with $\Delta W_{ELM} \approx 1.3$ MJ and $\Delta E_{rad}^{ELM} = 1.1$ MJ, the radiation load on the inner target at the ISP is about 20MW/m² using RPF = 3 and assuming a radiation heat load time of 2ms. This additional radiation heat load leads to the maximum excursions of ~100°C at the inner strike point and is not a critical issue.

2.2.2 Compound phase

Along with the crucial question of the radiated energy during the type I phase, the radiated energy during the compound phase is an important parameter. The variation of some plasma parameters during the different phases (ELM crashes, compound phase and recovery) of the type I giant ELM is depicted in Fig. 4 on the right hand side. The figure shows the stored and radiated energy. It illustrates the strong degradation of the plasma energy (drop of ≈ 2.2 MJ) during the compound phase; analysis of the radiation occurring during this phase shows that it accounts for a significant fraction (up to 90% at this ELM) of this energy loss. The Abel inversion indicates an **increased**

radiation in the plasma core and correspondingly points to plasma contamination. Z_{eff} increases by about ΔZ_{eff} »0.4-0.5 in the compound phase. No significant energy deposition on main chamber plasma-facing sides was observed in compound phases [10]. The electron temperature T_e and electron density n_e profiles at the outer midplane around the edge barrier during the different phases were measured by the High Resolution Thomson Scattering (HRTS) system [11]. The collapse of T_e at the pedestal by 50% and a reduction of max. 25% of n_e in the edge region follow directly the ELM crash. The degradation of the confinement during the compound phase is accompanied by a large density reduction right across the plasma profile and a loss or reduction of the edge transport barrier associated with density pump-out.

As already mentioned above, the large and giant ELMs are followed by a "compound" phase (type III ELMY H-mode phase) with strong degradation of the plasma energy. The understanding of the mechanism responsible for compound phases is required to avoid the energy degradation as well compound ELMs in the ITER. The time evolution of different plasma parameters for an ELM with medium and large energy drop is depicted in Fig.4. It shows the stored energy, radiated energy, D_{β}/D_{α} ratio as well as the pedestal parameters. In the case of a large ELM, the D_{β}/D_{α} ratio increases by a factor of 1.8 in the inner divertor region, which is attributed to the onset of recombination and is correlated with detachment [12]. The inner divertor remains detached over the entire compound phase and returns to the attached status in the recovery phase. Short detachment phases have been observed also directly after medium size ELMs. Thus the impurity influxes, which are much larger in the case of large ELMs lead to a strong divertor cooling and trigger the temporary transition to type III ELMs. The similar picture has been observed in the ELM mitigation experiments by nitrogen seeding in JET [13]. At approximately 55% radiative power fraction, the ELM characteristic changes from type I to type III, resulting in a loss of confinement of about 25% due to degradation of the edge pedestal. The observed frequency of the type III ELMs during the compound phase lies around ~400Hz and the estimated transient energy heat load during the single type III ELM onto divertor targets is ~3kJ ($\Delta W_{ELM}/W_{ped} \approx 0.3\%$). The ITER divertor load would be ~0.3MJ and is below the limit of 1MJ. The same statement was done in [13]. If the compound ELMs are to be avoided, the ELM energy loss must be below the threshold for ablation of deposited layers $\Delta W^{ELM}_{tr}.$ In ITER in the case of both CFC and W targets, the codeposits are expected to be dominated by Be out of the main chamber and the likely behaviour under ELM loads cannot be directly extrapolated from the JET results.

2.3 PREDICTED ELM SIZE IN ITER

2.3.1 Need for a reduction of the ELM size

The early experiments show that the collisionality of the pedestal plasma seems to play a major role in determining the type I ELM energy loss across various experiments: ASDEX Upgrade, DIII-D, JT-60 and JET. The observed ELM energy normalised to the pedestal energy increases with the decrease of the neoclassical pedestal collisionality (v_{ped}^*). The Fig.5 shows the normalised ELM

energy loss ($\Delta W_{ELM}/W_{ped}$) versus pedestal plasma collisionality for large range of type I ELMs achieved during the fuelling gas scan in JET confirming the result reported in [14]. If we assume, similarly to [14], that the observed ELM behaviour can be used to extrapolate this result to ITER with $v_{ped}^*(neo) = 0.062$, the expected W_{ELM} would be 22MJ (for W_{ped} ITER = 112MJ). Recent material research has shown that in order to prevent unacceptable divertor target erosion due to ELM heat loads, the energy flux at divertor of first wall components should not exceed ~0.5MJm⁻² [15]. Assuming a wetted area of the inner divertor of $\approx 1.2m^2$ and asymmetrical ELM loads $P_{out}/P_{in}=0.5$, the material limit will correspond to a loss in plasma-stored energy at the ELM of WELM~1MJ. This requires a decrease in the 'natural' ELM size by a factor of ~20.

2.3.2 Correction to the required reduction factor

Note that the above estimation was made under assumption that the entire energy drop is conducted to the divertor plates. Due to the limited time resolution of the diamagnetic loops, the drop of plasma energy W_{ELM} in the figure has been evaluated on the time scale of $\tau = 4$ ms. A significant part of this energy loss during the time window τ is exhausted by radiation (E_{rad}). Also the energy ($E_{in}^{\tau} = P_{in} \times \tau$) introduced during this time into the plasma has not be neglected. Thus the energy load into the divertor or wall surfaces would be $E_{target} = W_{ELM} - E_{rad} + E_{in}^{\tau}$ and is shown in the Figure. For $v_{ped}^* > 0.1$ the energy load E_{target} shows linear increase with decreasing of the v_{ped}^* . For lower collisionalities $n_{ped}^* < 0.1$ the E_{target} shows saturation. One, of the possible explanations for the saturation is the shielding of the heat load during the ablation of deposited layers, the linear behaviour of E_{target} could be extrapolated for smaller v_{ped}^* . Then the expected E_{target} at v_{ped}^* (neo) = 0.062 would be 11MJ (for $W_{ped}^{\text{ITER}} = 112$ MJ). A proper account of the energy reduction by radiation thus brings a decrease in the ELM size by a factor of ~2 with respect to the old scaling, and the necessary reduction in the ITER ELM size decreases to a factor of ~10.

3. RADIATION LOADS DURING DISRUPTIONS

3.1 RADIATION DURING THE UNMITIGATED PLASMA DISRUPTIONS

A disruption is an abrupt termination of a plasma discharge in which the magnetic and the thermal energy stored in the plasma are rapidly lost. Typically, tokamak disruption can be described by two main stages as shown in the Fig.6: a Thermal Quench (TQ), where the plasma thermal energy is lost, followed by the loss of the energy stored in the poloidal magnetic field in the Current Quench (CQ). The thermal quench is preceded by precursor, where the stored plasma energy is deteriorated on the time scale of several tens of millisecond. The figure shows the stored energy, radiated energy and power and plasma current for a typical upwards VDE disruption in a JET pulse with I_p = 1.5MA, B_T = 1.5T, W_{th} ≈ 2.7MJ, q₉₅ = 3.2. The energy content is reduced by $\Delta W_{th} \sim 0.78MJ$ just before reaching the thermal quench. Only a small part ($E_{rad} \sim 0.26MJ$, corresponding to Erad/ $\Delta W_{th} \approx 0.34$) of this energy loss was found in radiation. The same picture was observed during the thermal

quench: $\Delta W_{th} \sim 1.92 MJ$, $E_{rad} \sim 0.29 MJ$, $E_{rad} / \Delta W_{th} \approx 0.15$. Thus, in the precursor and thermal quench of unmitigated disruptions, most of the thermal energy is deposited by convection to the first wall. It has been observed that the TQ-phase started in the pure VDE disruptions when the q = 2 surface touches the vessel structures. The radiation distribution is strongly poloidally asymmetric and most of, the radiation is located in the vicinity of the upper dump limiter. This strongly localised radiation is most likely the result of an increased local impurity influx to the main chamber plasma which can, in addition to the convective heat loads, lead to significant local radiation loads. Fig.7 shows the evaluated radiation peaking factors as function of the poloidal distance along the wall for three types of disruptions: density limit disruption, disruption driven by Neoclassical Tearing Mode (NTM) and VDE disruption. It was observed that VDE disruptions generate the largest radiative heat loads, with a maximum of the observed radiation peaking factor for the VDE-disruption thermal quench of about RPF=3.5. These "peaking factors" have been used to extrapolate to ITER reference conditions. The 'ablation/melting parameter', which determines the surface temperature rise caused by VDE, can reach in ITER values up to $8.5 MWm^{-2}s^{1/2}$ (assuming $W_{th} = 350MJ$, duration of the thermal quench $t_{tq} \approx 1$ ms, RPF = 3.5, $E_{rad} / \Delta W_{th} \approx 0.15$) due to the radiation load alone. It will increase the Be temperature to values around 1/3 of the melting point. Carbon released from the wall during the thermal quench is ionised and transported toward the plasma core, radiating strongly and cooling the surrounding electrons. The radiation travels inwards and fills the entire plasma cross-section at the beginning of the current quench. During the current quench about half of the magnetic energy is radiated ($W_{mag} \sim 4.6 MJ$, $E_{rad} \sim 2.04 MJ$, $E_{rad} / W_{mag} \approx 0.44$) with nearly poloidal radiation distribution $(RPF \approx 2).$

3.2 Radiation behaviour during the massive gass injection experiment

The heat loads during the thermal quench can be reduced by enhancing the radiation with Massive Gas Injection (MGI). A fast valve (Disruption Mitigation Valve- DMV) has been recently installed at JET to study disruption mitigation by massive gas injection [16]. The valve is positioned on top of the machine and the gas is guided by a 4m long tube to the plasma. Different gas species have been investigated: Ne, Ar, He, mixtures of Ne and Ar with, 90% of D₂ and pure D₂. Fig.8 shows the selection of key plasma parameters of a typical induced JET disruption caused by injection of a mixture of Ar with 90%D₂. About 5×10^{21} Argon atoms have been injected into the main chamber. After the activation of the DMV, the gas flows through the tube and arrives after a delay of 4ms the plasma edge. At that time the cooling of the plasma edge starts triggering the reduction of the plasma thermal energy. In the precursor phase up to 80% ($\Delta W_{th} \approx 1.0MJ$, $E_{rad} \approx 0.80MJ$) of the thermal energy stored in the plasma (before DMV activation) is lost predominantly by radiation before the TQ. About 45- 55% ($\Delta W_{th} \approx 2.2MJ$, $E_{rad} \approx 1.0-1.25MJ$) of the remaining energy is radiated during the TQ. Thus, only 30% of the initial energy is lost by convection during the TQ to the first wall. This is a factor of ~2 smaller than during the pure VDE disruption. Fig.8 shows the tomographic reconstruction of the radiation at four different times: at the beginning of the cooling phase, in the

middle of the precursor and TQ phases as well as during the CQ-phase. The radiated power shows a very homogenous poloidal distribution with a peaking factor below 1.5 as shown in Fig.9 during the thermal and current quench. In contrast, a peaking factor of 3.5 is found during the thermal quench in an unmitigated VDE, which could increase the Be temperature to values around 1/3 of the melting point. In MGI disruptions, stronger poloidal peaking of up to 2.5 is observed only during the short time window (1-2ms) caused by the local gas injection at the beginning of the cooling phase. In this experiment, it was demonstrated that 5×10^{22} of injected Ar atoms are sufficient to cause the edge temperature to collapse, initiating the inward propagation of a cold front. When the cold front reaches the q \approx surface, the MHD modes are destabilised leading to the abrupt mixing of the hot core plasma with edge impurities. To radiate away 1MJ stored outside 1MJ stored outside the $q \approx 2$ surface, about 5×10^{20} Ar particles (assuming $T_e = 0.5$ keV, $n_e = 4 \times 10^{19}$ m⁻³ and cooling rate function for Argon $L_{rad}(T_e = 0.5 \text{keV}) \approx 10^{-26} \text{ W cm}^3[17])$ are required. This is about 10% of the injected Ar particles and is consistent with prediction of the non-stationary flow modelling presented in [18]. Fig.10 shows the radiation distribution during the TQ- (upper row) and CQ (lower row) phases for 3 discharges with different plasma stored energy. The radiation distribution is close to poloidally symmetric during the thermal and current quenches in the entire range of the observed W_{th} .

The result of the energy balance analysis for MGI disruptions in discharges with different W_{th} has been reported recently in [19] and is shown in Fig.11. Here the radiated energy is shown as function of the thermal energy. The plasma current is 2MA, the magnetic energy W \approx 11MJ, accordingly. With the assumption that the dissipation of magnetic energy in the vessel structure is constant for these disruptions, it was found that more than 50% of the stored thermal energy is radiated during the thermal quench. This is consistent with earlier founding reported above. It can be see that significantly more energy is radiated during MGI than in reference disruptions with D2 injection.

3.3 Combined MGI+VDE Experiment

A combined VDE-MGI experiment was performed to demonstrate the efficiency of the MGI technique after loss of control of the vertical plasma position. In this experiment the upward VDE was triggered by the vertical stabilisation system of JET. After about of 10ms of the VDE triggering, the cooling phase with MGI has been started. With the injection of Ar atoms proceeding (a mixture of Ar with 90%D₂), the radiation poloidal symmetry increased (maximal RPF=2.14), but it is lower than in pure MGI experiment (RPF=1.5). Despite this reduction of the radiation homogeneity, the combined experiment demonstrates that the RPF = 2.14 is much smaller than the peaking factor during the precursor and TQ in a pure VDE, disruption (RPF~3.33). During the CQ, like in pure MGI experiment, the significant part of the W_{mag} was converted in radiation and spread nearly uniformly over the walls.

CONCLUSIONS

To prevent an unacceptable erosion of divertor targets due to ELMs in ITER, the target energy

density should be restricted to 0.5MJm^{-2} . Large type I ELMs with energy size up to $\Delta W_{\text{ELM}} \approx 1.3 \text{MJ} (\Delta W_{\text{ELM}} / W_{\text{th}} \approx 0.14)$ and with energy densities similar to those of the material limit can be already approached in JET at high current, high input power and with low or zero gas fuelling. The production of large type I ELMs with ΔW_{ELM} in the range 0.25-1.3MJ was demonstrated. The ELMs induce strong radiation losses, mostly confined to the inner divertor region.

Taking into account the radiation loss in the energy load calculation onto divertor target, the expected target load at an ITER-like collisionality of $v^*_{ped}(neo) = 0.062$ would be 11MJ (for $W_{ped}^{ITER} = 112$ MJ). This energy load requires a decrease in the 'natural' ELM size by a factor of ~10, assuming a wetted area of the inner divertor of ≈ 1.2 m². Large type I ELMs with $\Delta W_{ELM} \ge 0.72$ MJ show enhanced radiation losses and indicating enhanced impurity release. The peak surface temperatures do not exceed ~2000°C at the inner target and are thus significantly below the values for carbon bulk ablation, but it is enough to provoke an ablation of the deposited layers in the inner divertor.

Large ELMs are often followed by a phase of type III ELMs with an increased radiation in the plasma core indicating an increased plasma contamination, which otherwise does not lead to a radiative collapse of the plasma. A significant part (up to 90%) of the plasma energy degradation during the compound phase is exhausted by radiation. It was found that the reason for the compound phase is the strong impurity influxes cased by large ELMs, which lead to a strong divertor cooling and therefore trigger the temporary transition to type III ELMs. Due to strong divertor cooling, large ELMs drive the divertor into detachment after the ELM crash and the divertor detachment remains during the entire compound phase.

The transient events such as density limit, NTM- driven and VDE disruptions exhibit small radiation fraction during the precursor and strong radiation asymmetry during the thermal quenches. It was observed that VDE disruptions generate the largest radiative heat loads, with a maximum of the observed radiation peaking factor for the VDE-disruption thermal quench of about RPF = 3.5. The 'ablation/melting parameter', which determines the surface temperature rise caused by VDE, can reach in ITER values up to 8.5MW $m^{-2}s^{1/2}$. It will increase the Be temperature to values around 1/3 of the melting point. It was demonstrated in the dedicated experiments on massive gas injection for disruption mitigation that more than 50% of the thermal energy and the significant part of the magnetic energy was converted in radiation and spread uniformly over the walls. Nearly symmetric poloidal distributions of the radiation during precursor, thermal and current quenches have been observed (RPFs \leq 81.5) Analysis shows large radiation fraction ($\Delta E_{rad}/\Delta W_{dia}$) during the precursor (83%) and thermal quenches (40%-56%). MGI-triggered disruptions are thus much less critical for ITER than the NTM-driven or VDE disruptions: lower RPFs and a factor of ~2 lower convective load during the thermal quench. The plasma radiation analysis during the combined VDE+MGI experiments shows a slight reduction of the radiation poloidal symmetry (the maximum of RPF increased from 1.5 to 2.14) in comparison with pure MGI experiment. In contrast to JET the VDEs in ITER will take place on the longer timescale of ~1s and we expect that the radiation

behaves like in the pure MGI experiment. Even if we consider the worst case with RPF = 2.14, the 'ablation/melting parameter' in ITER would be ~17MWm⁻²s^{1/2} assuming that the thermal energy before thermal quench (1/2×W_{th} = 175MJ) is completely lost by radiation during $t_{tq} \approx 1$ ms. This load increases the Be temperature to values that remain below the melting point.

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Figure 1: Selected plasma signals for a 3.0MA H-mode discharge.



Figure 2: Radiation distribution between ELMs, radiation distributions integrated over the ELM crashes during the middle size and large size ELMs as well during the giant ELM.



Figure 3: Radiated plasma energy (a), and divertor radiation fraction (b).



Figure 4: Comparison of ELM with medium and large sizes.



Figure 5: Normalized ELM energy loss $(\Delta W_{ELM}/W_{ped})$ and the target load versus pedestal plasma collisionality for large range of type I ELMs in JET.



Figure 6: Some characteristic time traces of the VDE disruption including (a) plasma stored and radiated energy (b) radiated power and (c) plasma current. Also shown on the right hand side: the radiation distribution during the TQ of the disruption.



Figure 7: Radiation peaking factors during the TQ in JET for three types of disruptions: density limit disruption, disruption driven by NTM and VDE disruption.



Figure 8: Time traces during a typical induced disruption caused by injection of a mixture of Ar and 90% D_2 . Also shown are the radiation distributions during different time phases of the disruption.



Figure 9: Radiation peaking factors during the different phases of the MGI experiment discussed in Fig.8.



Figure 10: The radiation distribution during the TQ- (upper row) and CQ (lower row) phases for 3 discharges with different W_{th} .



Figure 11: Radiated energy versus plasma thermal energy