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* See annex of F. Romanelli et al, "Overview of JET Results",
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ABSTRACT.

Effectiveness of massive gas injection (MGI) for mitigation of disruptive wall damage has been investigated. Cross-reference analysis of the available JET experiments on MGI and their simulations with the TOKES code allow suggesting that in JET conditions one can convert into radiation the electron thermal energy and the plasma current energy, but the ion thermal energy does not converted into radiation because of very ineffective excitation of injected noble gas (NG) ions by D ions and long equipartition time between D ions and electrons. The model assumes rather high electron temperature during current quench (CQ), which contradicts with its time duration. Rough extrapolation of the result on ITER conditions shows that one can expect irradiation of total plasma energy if CQ duration in ITER is not shorter as in JET.

1. INTRODUCTION

Disruptions are abnormal events, which abruptly shut down some discharges in tokamak devices. They have been found in all tokamaks. In largest modern tokamaks like JET, DIII-D, ASDEX-Upgrade the disruptions can slightly melt and evaporate the first wall by direct plasma impact, when the separatrix touches it during disruption, and evaporate the divertor targets by drastic increase of the heat load. However, the wall and the divertor damage in existing tokamaks are not significant, even after thousands of disruptions. Nevertheless, simple estimations have shown that unmitigated disruption in ITER causes significant erosion to the first wall. This is why the disruptive damage for the first wall in ITER should be mitigated. Mitigation of the first wall heat load has been investigated in dedicated series of experiments in JET [1]. It has been proved that MGI is an effective technique for disruption mitigation, at least in JET. Massive injection of NG inside the confined plasma before it touches the wall leads to ionization of the gas and fast irradiation of the hot plasma energy due to high luminosity of high-Z noble gas plasma. Radiation heats the first wall, but this heat load redistributes plasma energy over all first wall area, thus decreasing the heat load comparing with the direct plasma impact, when the wetted area for energy deposition is thousands times smaller. Understanding the plasma energy conversion into radiation during the disruption in tokamaks, mitigated with MGI, is among the most important physics issues for estimation of the first wall damage and its lifetime in ITER.

However, extrapolation of the MGI efficiency on ITER conditions is not straightforward. For example, preliminary estimations have shown that to avoid any damage of the ITER first wall it is necessary to irradiate up to 90% of its thermal energy. Usually it was expected that the fraction of plasma energy, radiated by NG should increase with the amount of injected NG, so for ITER it is necessary to inject $\sim 10^{26}$ particles during few milliseconds.

However, a series experiments in JET, with injection of various amount of Ar in the discharges with the same plasma and magnetic field parameters has shown that radiated energy fraction $f_{rad}=E_{rad}/(E_{th}+E_{mag})$ is saturated at the level of 70-80% and then does not changed when the number of injected atoms increased ten times. These days discussed the possibilities that the mixing efficiency

is decreased with increasing of the amount of injected gas or radiation asymmetries may influence on determining the radiated energy.

2D simulations of the JET experiments have been performed using the TOKES code. Comparison of these results with available JET measurement allows supposition for the saturation mechanism at the measured level. Extrapolation of the f_{rad} saturation level measured at JET to ITER conditions has been performed.

2. COMBINED MGI ANALYSIS USING TOKES SIMULATIONS AND JET MEASUREMENTS

2.1 SIMULATIONS

Simulations of the thermal quench (TQ) stage of MGI performed in [2–4] and validated with JET experiments has revealed that TQ developed according to universal scenario, which is valid for both H- and L-mode discharges. According to the scenario at the first stage, so called pre-TQ, NG injected inside the separatrix is ionized and spread mainly along the magnetic field. Thermal energy of the main plasma contaminated with NG close to separatrix is spent for the NG ionization and line radiation from the ionized NG. The pre-TQ time duration in JET is 4–8ms for L- and H-mode discharges correspondingly. This time is so small, that the stationary cross-field thermoconductivity of the main plasma plays no role, so radial electron temperature profile evolves as cooling wave, propagating from separatrix inside the core, see first 5 curves in Fig.1. This figure represents the result of TOKES simulation for JET Pulse No: 77806 disrupted with Ar-D$_2$ mixture. Validation of TOKES simulations has been done for L-mode discharges [3] only. Electron temperature measurements are failed during MGI in H-mode discharges because of higher electron density, which cuts off ECE signal, used for T_e measurement, but understanding the physics allows conclusion that for both discharge types cooling wave propagates inside the core during pre-TQ. Electron temperature in the bulk is not affected because the edge cooling process is very fast.

After start of TQ itself radial electron thermoconduc-tivity χ_e drastically increases due to ergodization of magnetic surfaces according to Rosenbluth mechanism, so the radial thermoconductivity became proportional to $T_e^{5/2}$, see [3] and references there. Radial temperature profile after TQ is very flat in the bulk and steeply drops almost to zero at the cooling wave front, see Fig.1. For JET Pulse No: 77806 the pre-TQ time is 8ms and TQ lasts 1 ms more. After TQ T_e at magnetic axis drops to 500–600 eV and remains almost constant during next ~3ms, which is usual for $\chi_e \sim T_e^{5/2}$. During all this time T_{imax} reduced from 5.3keV to 4keV only. This ion temperature drop is in accordance with ion-electron equipartition time $\tau_e^{i/e}$ ~10ms for electrons of $T_e = 500$ eV and $n_e = 5 \times 10^{13}$ cm^{-3}. Ion thermoconductivity also increased due to the same Rosenbluth mechanism, but it remains negligible on a few milliseconds timescale. Thereby, after finishing TQ only the main part of electron thermal energy is spent for Ar ionization and line radiation from Ar ions and main part of ion thermal energy remain inside the core, according to the TOKES simulations.

This feature of the plasma cooling during MGI can explain the measured saturation of the

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$f_{rad} \sim 0.75$ in the JET Pulse No's: 84838, 84839, 84841, 84846, 82731, 82826, 82731, 82826 despite the increase of injected Ar atom number from $6.5 \cdot 10^{20}$ to $5.3 \cdot 10^{21}$. All these experiments with MGI has been performed with the discharges of the same plasma parameters, namely, plasma thermal energy E_{th} is equal to the magnetic field energy of the plasma current E_{mag}. That means approximately ¼ of total energy is in electrons, ¼ in ions and ½ in magnetic field.

Measured in these experiments is only the total irradiated energy, integrated over TQ and CQ, so one can assume that irradiated are the electron thermal energy during TQ and the plasma current energy during CQ; the ion energy is not converted into the radiation. The energy of plasma current transferred to electrons by ohmic heating. The simplest way to test the validity of this assumption is to vary the ratio of the magnetic field energy to the plasma thermal energy. These measurements have already been done and the results are shown in Fig. 2. The line $f_{rad} = 1 - 0.5 \cdot E_{th}/(E_{th} + E_{mag})$ corresponding to assumption, that during MGI radiated is the total energy except of ion energy, fits the measurements quite good.

One can extract another indirect evidence of high ion temperature during TQ and main part of CQ from the diamagnetic signal $W_{dia}(t)$. Measurements of $W_{dia}(t)$ in JET is done with the sampling rate of 5kHz. In general this sampling rate is enough for measurements during TQ (~1 ms duration) and CQ (~10ms duration), but for fast processes the quasi-stationary model, used for W_{dia} calculation from magnetic probes signal is failed, because of too high time derivatives of the magnetic field, neglected in the model, contributes significantly to the equation, determining W_{dia}. This failure can be seen in the $W_{dia}(t)$ plots for the JET Pulse No's: 76806 (Fig.3), 76808, 76812, 76814, 76815, 76817 (Fig.4) and others: the $W_{dia}(t)$ drops to zero, or even to unphysical negative values during TQ of ~1 ms. Nevertheless, at pre-TQ stage the $W_{dia}(t)$ decrease is in agreement with the electron temperature decrease measured in JET and simulated using TOKES. One can suppose that the diagnostic fails for the plasma processes with characteristic time less than 1ms and gives still reasonable values for ten times slower processes: of 5–10ms. During CQ the diagnostics performs at the limit of its time resolution, so $W_{dia}(t)$ may indicate existence of plasma energy with approximately half of the value before TQ, because if the thermal plasma energy would be negligible, the signal should be zero. The oscillations seen at the $W_{dia}(t)$ are doubtful. The TOKES simulations and simple and robust estimations given above supports that after TQ the $W_{dia}(t)$ should drop approximately two times: electrons are cooled down and ions remain hot if $T_e \sim 500\text{eV}$.

However, it remains unclear where the ion energy of the discharge has disappeared? For answering this question one should analyze the current density distribution during the TQ of MGI. It is evident that during pre-TQ, when the core outskirts are cooled down, the current channel is shrinking, so the current density is increased, because the total plasma current remains almost constant or even slightly increases (current spike). With increase of the current density the safety factor q decreases and may became less then unity. Plasma equilibrium is violated when $q < 1$, starting well known sawtooth instability [5], which expels the plasma with hot ions from the core centre to the separatrix and substitutes it with cold plasma contaminated with NG. Analysis of experimental data

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from JET has revealed evidences for this assumption despite large difficulties originated from the fact that JET diagnostics operates at the margins of its validity during TQ and CQ. Nevertheless, scrutinizing various diagnostics and comparing the measurements with TOKES simulations one can find the evidences for sawtooth instability at CQ stage of MGI. For example, let us consider the measurements and the reconstructions done for JET Pulse No: 77806 shown in Fig.3. Time dependence of the diamagnetic energy and the total plasma current, shown in the central panel of Fig.3 are determined the timing of the disruption caused by MGI: the pre-TQ stage lasts from 61.7505 s to 61.7585s, then TQ starts and W_{dia} drops drastically during next 1.5 ms. CQ duration for this pulse is ~15ms; after this the total plasma current drops to zero. According to the scenario revealed, the sequence of events is as follows: during pre-TQ the core outskirts are cooled down and W_{dia} drops from 3.3MJ to 2.3MJ. The plasma is stable at this stage: the safety factor at the magnetic axis is larger than one, for example, q_0 (61.7534)≈1.5 as shown in the upper left panel of Fig.3. Then, during TQ, W_{dia} drops approximately twice; the diagnostic failed at this time, but later the $W_{dia}(t)$ signal is recovered at approximately half of the value before the failure, $W_{dia} \approx 1.3$MJ, then it gradually decreased to zero during ~8ms after TQ. This $W_{dia}(t)$ signal recovery following with gradual decrease to zero during the same characteristic time ~8 ms is a systematic event, Fig.4 shows this behavior for the JET Pulse No's: 76812, 76814, 76815, 76817. The plasma became unstable after TQ: during pre-TQ and TQ q_0 is monotonically decreased, so q_0(61.7598)=1. q_0 became less then unity just before or just after this time, starting the sawtooth instability, which redistributes current and restores the stable q-profile: q_0(61.7618)>2 in the upper right panel.

These measurements are at the very limit of time resolution for EFIT diagnostics, but the measured results are rather robust: if the iterative process of magnetic reconstruction converges, the probability of convergence to wrong solution is rather low, if something wrong in the raw data, the reconstruction process most probably diverges.

Basing on the $W_{dia}(t)$ measurement one can suppose that the plasma of hot ions and cold electrons exist ~8 ms gradually diffusing across the separatrix. Nevertheless, this gradual diffusion does not mean that the ion energy is deposited to the divertor plates: measurements performed in [6] indicate that only 3-7% of total discharge energy is deposited to the divertor. During CQ the magnetic configuration of the core is significantly distorted because of the plasma current decay, so the hot ion thermal energy is deposited onto considerable part of the first wall following movement of separatrix strike position (SSP).

CONCLUSIONS

Massive injection of noble gas into the hot core of tokamak before the disruption induces sequence of physical processes, which lead to the core cooling down by radiation, thus mitigating plasma impact to the first wall and to the divertor. The wall damage by disruptions in JET is tolerable, but to investigate mitigation of the disruptive damage in ITER conditions a series of dedicated experiments on MGI has been performed in JET. Unfortunately, the JET diagnostics is not fitted for such short

event as MGI with characteristic time duration of 1–10ms. During the disruption caused by MGI the JET diagnostics is performing at the limit of its time resolution and even beyond the limit, but cross-reference analysis of the available measurements combined with analysis of TOKES simulations allowed suggesting the sequence of physical processes – the MGI scenario – universal for all JET pulses analyzed and providing basis for the MGI scenario extrapolation to ITER.

Successful mitigation of ITER disruption requires irradiation of up to 90% of the discharge energy. However, the results of dedicated series of experiments in JET have revealed unexpected saturation of the radiated energy fraction at ~70–80% when the amount of injected Ar increased almost on one order of the magnitude, from $6.5 \cdot 10^{20}$ to $5.3 \cdot 10^{21}$ atoms. Analysis of the MGI physics performed in this paper has revealed that the amount of NG in the saturation range is always enough to irradiate thermal energy of electrons and plasma current energy. Cross-reference analysis of experiments and simulations allows supposing that the thermal energy of ions cannot be converted into radiation because of very ineffective excitation of Ar ions by D ions and long equipartition time between D ions and electrons. The thermal energy of ions deposited not only onto divertor targets, but mainly on the first wall due to SSP roaming during CQ stage of MGI.

One should mention that JET diagnostics is not suited for measurements during MGI, so all the models, proposed for explanation of the MGI physics are based on indirect evidences or on the measurements performed at the limit of diagnostics validity. This refer to E_{rad}, $W_{dia}(t)$, bolometry reconstructions, plasma shape and position, energy deposition to the wall and to the divertor. Unfortunately, there is no possibility to improve JET diagnostics to the level, which allows direct measurements for a final decision of this issue. The E_{rad} saturation at 75% could be a result of radiation asymmetries, which can influence E_{rad} measurement. The proposed model explains all above mentioned experimental results: f_{rad} saturation at ~70–80%, the dependence $f_{rad}(E_{th}/(E_{th}+E_{mag}))$, the $W_{dia}(t)$ dependence measured in JET, but high electron temperature, suggested by this model contradicts with CQ time duration of 10 ms. Resolution of this contradiction is necessary for acceptance of the model. An attempt to resolve this contradiction will be done in the next paper. Rough extrapolation of the result to ITER is straightforward: the minor radius of ITER is twice larger than that of JET, but very weak radial dependence of T_e profile after TQ leads to small increase of T_e in ITER core after TQ, so the equipartition time there ~6 ms due to higher density, so ion thermal energy can be radiated during $\tau_{CQ} > 15$ms.

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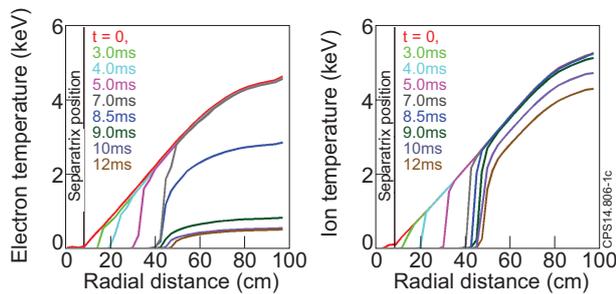
Figure 1: TOKES simulation of temperature profile evolution during MGI. During pre-TQ (first 5 curves) the profile is cooled from separatrix and the cooling wave propagates inside the core, but the temperature in the bulk is not changed. After start of TQ itself (last 3 curves) the electron thermoconductivity drastically increases and the bulk T_e drops. Ion temperature in the core bulk is slightly decreased due to eln-ion equipartition.
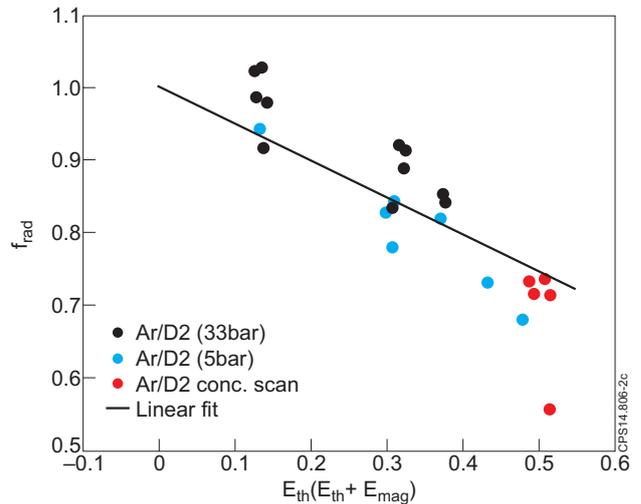
Figure 2: f_{rad} dependence of the $E_{th}/(E_{th}+E_{mag})$ ratio measured in the dedicated series of experiments in JET. The measured dependence is perfectly fit with assumption that radiated are the electron thermal energy and the plasma current energy, but the ion thermal energy did not (black line).
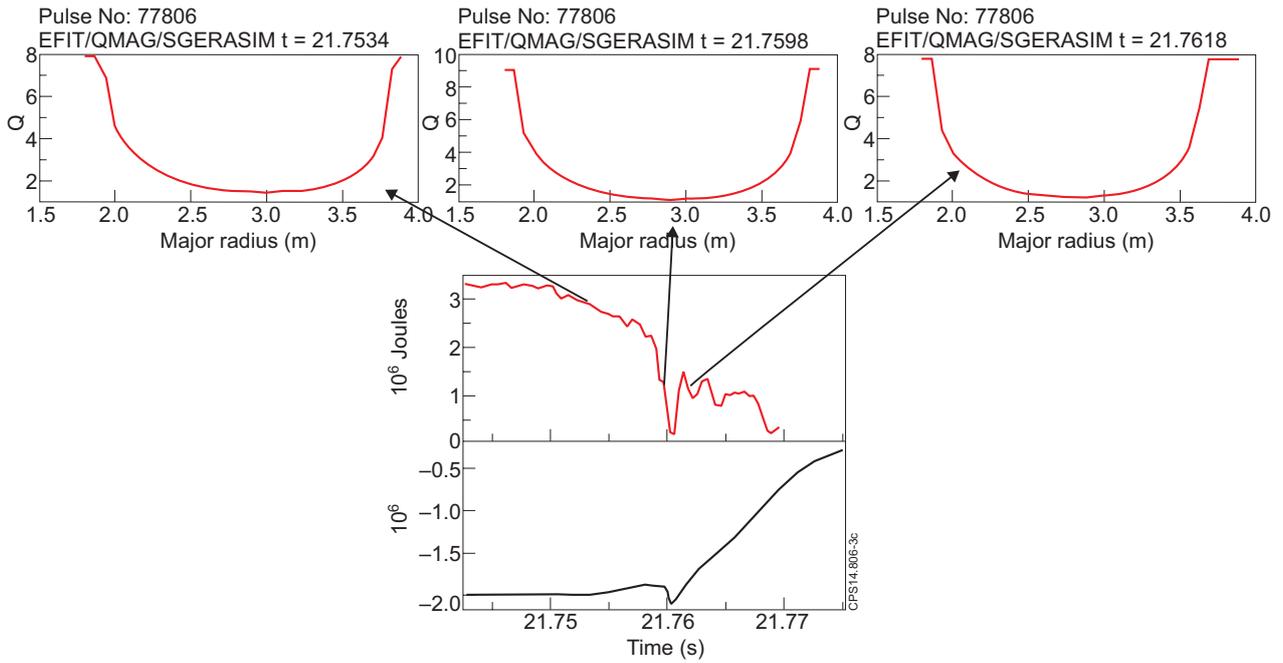
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Figure 3: Evidences for sawtooth instability expelling hot plasma from the core center and substituting it with cold Ar plasma at the end of TQ in JET Pulse No: 76806. q-profile at pre-TQ, just before TQ and after TQ.
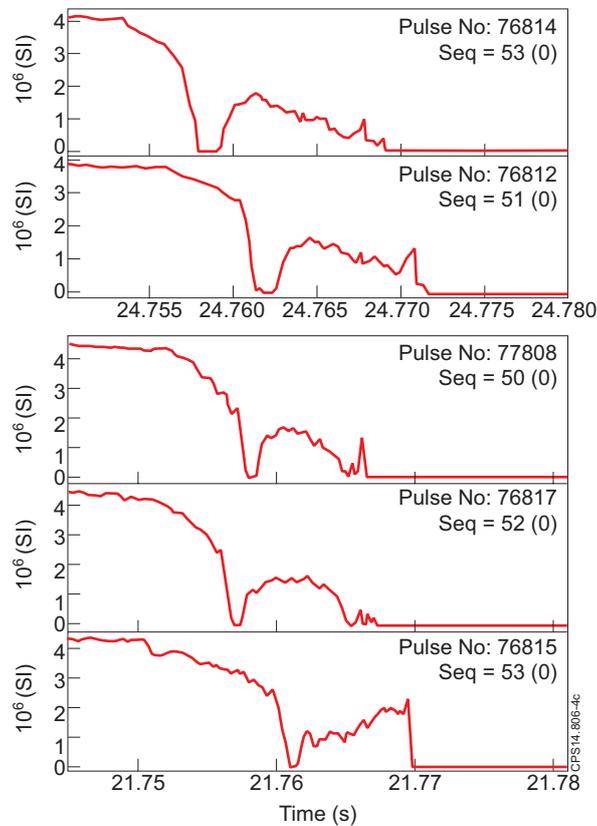

Figure 4: Measured time dependence for diamagnetic energy in JET. The diagnostics fails at thermal quench lasting < 1ms. Then it recovers at CQ, $W_{dia}(t)$ drops 2 times after TQ and gradually decreases during CQ.