MGI in plasmas with locked modes

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Introduction. Massive gas injection (MGI) is foreseen as a mitigation technique for ITER disruptions. Typically, MGI experiments have been carried out by injecting impurity gas in a H-mode plasma, in order to test the capability of the contaminated plasma in radiating a large amount of thermal energy and to have a target plasma with predefined parameters. Nevertheless MGI will be used in ITER in discharges with a high probability of disrupting and therefore likely with large non-rotating modes.

A series of plasmas with locked modes (LMs) were terminated by MGI on ASDEX Upgrade (AUG) in order to study the influence of these modes on the fuelling efficiency and radiation asymmetry. This paper reports on the experimental findings and discusses their implications for ITER.

Experimental conditions. Two types of plasma scenarios with LMs were first created and then terminated by MGI. A series of ohmic-heated plasmas with a toroidal current (I_p) of 1 MA, low plasma thermal energy at the time of valve triggering ($E_{th}(t_{trig}) < 0.1$ MJ) and a safety factor $q_{95} \sim 4.1$ were driven to the density limit, by means of strong feed-forward gas puffing. These discharges developed a MARFE and a slowly rotating (m,n) = (2,1) or (3,1) mode. The second scenario was a repeat of a high-beta discharge, previously developed on AUG for experiments on disruption avoidance and known to generate a (2,1) NTM, which grows and disrupts the plasma. In this case $E_{th}(t_{trig}) \sim 0.32$ MJ, $q_{95} \sim 3.8$ and the plasma core is still rotating at some tens of km/s at the time of MGI.

In both scenarios, the tearing modes were artificially slowed down and locked by applying an n=1 radial magnetic field with the RMP coils turned on well before mode development. In this way, the position of the LM could be controlled by the choice of the coil configuration. The amplitude of the n=1 radial magnetic field, measured by a pair of saddle coils, located on the high field side (HFS) of the torus (routinely employed to detect a LM), was then used to trigger the MGI valves. In addition, two recently-installed pairs of saddle coils - with each coil covering a 90 degree toroidal angle - permit the localization of the n=1 and n=2 modes.

AUG is equipped with two fast valves, located circa 10 cm from the plasma edge, one on the HFS and the other on the low field side (LFS) of the plasma. In this experiment, only one valve at a time was triggered to inject 4×10^{22} atoms of neon (corresponding to a pressure of 20 bar in the gas reservoir volume of 80 cm^3). This quantity, divided by the AUG plasma volume (14 m^3), corresponds to the number of neon atoms per m^3, planned to be injected by the ITER thermal quench (TQ) mitigation system (plasma volume of 830 m^3, gas quantity of 10 kPa$\times m^3$ [1]).

Pre- thermal quench (pre-TQ) time and fuelling efficiency. The pre-TQ time

(Δt_{preTQ}) is defined as the time interval between the appearance of the injected impurity gas at the plasma edge and the start of the TQ. This time is an important design parameter for a mitigation system since it is the amount of gas, which is assimilated by the plasma in this time interval, that radiates a fraction of E_{th} before and during the TQ, and therefore prevents this fraction from being conducted into the divertor. Therefore, the longer is the pre-TQ time, the larger is the amount of gas delivered to and assimilated by the plasma.

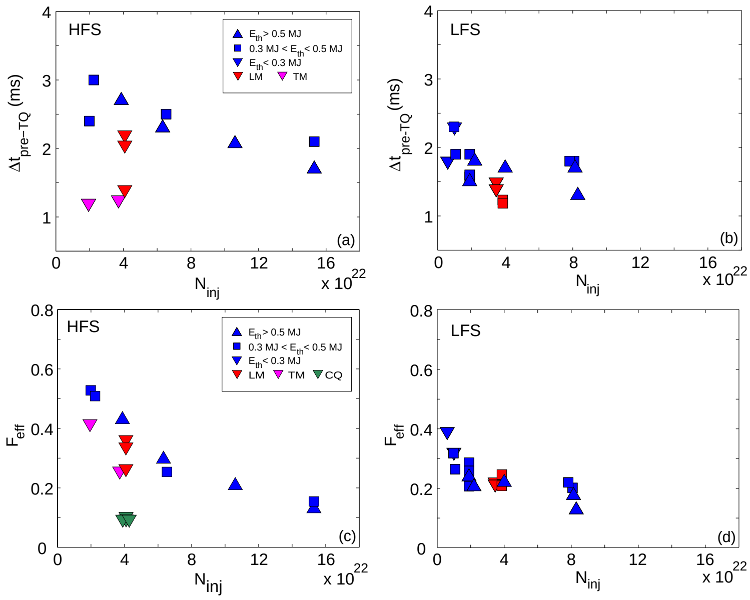

Figure 1 . *Duration of the pre-TQ phase versus the number of injected neon atoms for (a) HFS and (b) LFS MGI. Fuelling efficiency versus the number of injected neon atoms for (c) HFS and (d) LFS MGI.*

In AUG, Δt_{preTQ} was found to be 50 % longer during the HFS MGI into H-mode plasmas, with respect to the LFS MGI [2]. This is probably due to the larger distance between the plasma edge and the low q (2 and 3) surfaces, on which the MHD modes rapidly grow and initiate the TQ. In addition, an increasing amount of injected gas (N_{inj}) accelerates the destabilization of the plasma and decreases Δt_{preTQ}. The plasma E_{th} does not seem to influence this time interval; this observation is counter-intuitive and implies that Δt_{preTQ} is not simply proportional to the amount of energy which has to be radiated outside of a critical low q flux surface. The presence of LMs and also large tearing modes is now found to reduce the pre-TQ time by a factor up to two when the gas is injected from the HFS, as one would expect for a plasma which is more unstable (see fig.s 1(a) and 1(b)). In the case of LFS injection, the pre-TQ time is already relatively short, even at small N_{inj}, and the presence of rotating or locked modes decreases this time by a smaller factor.

The fuelling efficiency, F_{eff}, is defined in this and previous MGI-related AUG publications as the increase of the total number of electrons per number of injected impurity atoms, averaged over the plasma volume and the current quench duration. F_{eff} is a fundamental figure of merit and is a complex function of plasma and gas parameters. The detailed physics, determining its magnitude, has not yet been formulated but some of the mechanisms and parameters influencing it are known. For example, F_{eff} decreases with N_{inj} - in both LFS and HFS MGI - because Δt_{preTQ} and therefore the amount of gas assimilated up to the TQ decrease. The presence of tearing modes is seen to have a significant influence on the HFS MGI F_{eff} (up to a factor of 1.8). No influence of tearing modes is observed on the LFS MGI F_{eff}, probably because of their small influence on the already small Δt_{preTQ} and F_{eff}.

Fig. 1(c) also shows four discharges with MGI starting during the TQ (therefore with Δt_{preTQ}=0) and exhibiting a $F_{eff} \sim 0.1$. These data points prove that a density increase by MGI into TQ and CQ is possible and, therefore, that MGI can be used for runaway electron suppression.

Radiation asymmetry. During the pre-TQ, both the impurity density and the radiated power are strongly poloidally and toroidally asymmetric, and larger in the vicinity of the valve. It was calculated in [3] that an increase of a factor of two in the energy deposited on the wall with respect to the energy *assumed* uniformly radiated during an ITER pre-TQ (E_{th} = 350 kJ within 1 ms) would melt the Be wall.

AUG is equipped with several AXUV diode arrays in sector 5 and 13, and foil bolometers in sector 5, which allow the reconstruction of the power radiated at these toroidal locations. In order to quantify the degree of asymmetry of the energy radiated in the sector of (or close to) the valve, $\phi = 0$, and in the sector $\Delta\phi = \pi$ away from the injection location, the ratio

$$AF(\Delta t) \equiv E_{rad}(\phi = 0, \Delta t)/E_{rad}(\phi = \pi, \Delta t), \qquad E_{rad}(\phi, \Delta t) = \int_{\Delta t} P_{rad}(\phi)dt \quad (1)$$

is defined and calculated during the pre-TQ and TQ phases. In this definition, $E_{rad}(\phi, \Delta t)$ is the energy radiated during the time interval Δt, measured in a given sector and extrapolated to the whole torus. As shown in fig.s 2 (a) and (b), the $AF(\Delta t_{preTQ})$ spans a wide range of values (up to 5) and the presence of LMs at low E_{th} clearly tends to increase this ratio. The inspection of the P_{rad} time traces reveals that the degree of toroidal asymmetry of the radiated power can be of the same order of magnitude in both LM and no-LM cases.

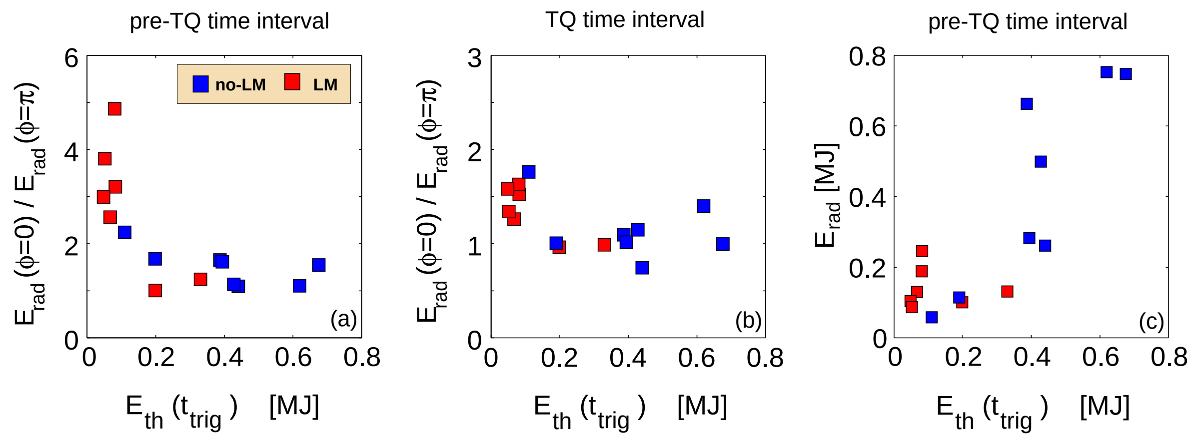

Figure 2. *(a) Values of the toroidal asymmetry factor, AF, versus thermal energy of the target plasma during the (a) pre-TQ and (b) TQ phase. (c) Energy radiated during the pre-TQ as measured by the foil bolometers versus thermal energy of the target plasma.*

Nevertheless, in the rotating plasmas the asymmetry can reverse sign in the presence of a rotating short lived n=1 mode structure seen in SXRs and magnetic measurements. Therefore the presence of rotating modes - or just plasma rotation - can decrease $AF(\Delta t_{preTQ})$. The foil bolometers indicate that the overall energy radiated during the pre-TQ phase is of the order of $E_{th}(t_{trig})$(fig. 2(c)).

The TQ phase is defined here as the interval of +/- 0.3 ms about the maximum of the toroidally averaged (between two sectors) radiated power, as measured by the AXUV vertical arrays. AF(Δt_{TQ}) is typically of order unity and reaches the value of 2 in fig. 2(b). The LM cases exhibit a larger radiation asymmetry also in this phase, with the exception of the higher beta discharges which have AF(Δt_{TQ}) $\sim$ 1. How the radiated power can become toroidally symmetric in these last discharges is not clear.

The tendency of AF(Δt_{TQ}) to be smaller than AF(Δt_{preTQ}) is understood in terms of an enhanced mixing of impurities and target plasma during the TQ, due to the heating of the impurities, caused by the out-flowing thermal energy, and to the MHD activity, causing large convective flows. Nevertheless, recent calculations carried out with the NIMROD code, suggest that the radiation asymmetry can be very large, with factors of AF(Δt_{TQ}) down to 1/6 and toroidal peaking factors down to 1/3.5 reported in [4] for LFS MGI. However, the current AUG experimental results do not confirm such large radiation asymmetry during the TQ. These simulations have also pointed out a possible dependence of the gas assimilation efficiency and radiation asymmetries on the relative location of the gas injection footprint and tearing mode phase. The values of AF presented here seem to vary independently of this relative phase, which has been artificially varied by choosing different RMP n=1 configurations. Additional work is necessary to clarify the origin of the discrepancy between modelling and experimental findings. Moreover, a consistent numerical model of the whole gas-plasma interaction dynamics need to be developed in order to extrapolate these experimental observations to ITER.

The ITER disruption mitigation system (DMS) foresees several gas injectors at different toroidal locations, which potentially can distribute the radiated power more evenly around the torus. Only few attempts have been made up to now on AUG to synchronize the different valves and to study the effect of multiple injection on the radiation asymmetry.

Summary. Experiments of MGI in plasmas with LM have been performed in AUG with neon quantities per plasma volume comparable to ITER. A reduction of the pre-TQ phase is observed when large rotating or locked modes are present. These effects decrease the amount of gas assimilated by the plasma up to the TQ (up to a factor of 2) and up to the middle of the CQ and should be taken into account when dimensioning the ITER DMS. Large radiation asymmetries are observed during the pre-TQ phase when the plasma is locked; nevertheless, in these cases the plasma thermal energy is small (order of 10 % of the maximum E_{th}) and would not cause the melting of the ITER wall. Years of disruption mitigation studies have contributed to a conceptual picture of the physics processes determining MGI dynamics but a quantifiable physical model, which allows to extrapolate present experimental observations to ITER, is still missing.

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