Disruption mitigation at JET using massive gas injection

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1. Introduction

ITER is planning to install four injectors suitable for massive impurity injection and located at three different toroidal and two different poloidal positions [1]. This disruption mitigation system is designed to tackle the potentially high electromagnetic loads (EM) and high heat loads following the disruption of a 15MA pulse. Disruption mitigation studies, carried out at a number of tokamak experiments , have demonstrated the viability of massive gas injection (MGI) to reduce the loads. However, uncertainties in the disruption mitigation efficiency exist due to toroidal and poloidal asymmetries in the radiation [2]. In order to address these issues, JET has installed three MGI-valves at poloidal and toroidal positions similar to ITER (see Figure 1). The three valves differ slightly in their total throughput and distance to the plasma. The latter affects the gas delivery time, which should be as short as possible for active mitigation. The results reported here are not affected by the gas delivery time, as the disruptions have been initiated feed-forward by the massive gas injection. The parameters of the valves are summarised in table 1. Typically gas mixtures of D_2 with either Ar or Ne in the range of 5 up to 40% have been used.

Location	Vol [ltr]	p_{inj} [MPa]	Gas (D_2) [barL]	Dist. to plasma [m]	ToF [ms] (D_2+10%Ar)
Top,L	0.65	3.6	~10	4.1	~1.8
Midpl	0.975	5.0	~45	2.4	~1.0
Top,S	0.35	5.0	~17	1.9	~0.8

Table 1: Parameters of the three MGI-valves at the locations as in Fig. 1.

2. Electromagnetic load mitigation

EM-loads are the result of halo and eddy currents induced into the vessel structures. The first ones can be reduced by accelerating the current quench, whereas the latter ones increase with decreasing current quench time. The dynamic vertical vessel forces following a MGI have been measured over a plasma range up to 3.5MA for all three injection locations separately. The results are summarised in Figure 2. The amount of injected Argon has been kept constant with increasing plasma current. For a given plasma current the unmitigated disruption force, which has been determined by deliberate test-VDEs (c.f. black line), could be reduced by 33%-40%. The three data sets (diamonds) and the derived vessel force scalings indicate that the choice of the injection location has no influence on the vessel force reduction. Over the explored plasma current range no change in the mitigation efficiency has been observed. It is worth noting that even at the highest tested plasma current of 3.5MA no runaway electron generation was observed. At two plasma currents the gas amount from the midplane injector has been varied to determine the optimum injection (figure 3). By increasing the impurity-fraction of the gas mixture more impurity particles can be injected before the start of the current quench. At about $4\text{x}10^{22}$ impurity particles the current quench time could not be further reduced below ~10ms. In fact at very low amounts a minimum for the disruption vessel force can be found, which is probably due to a balance of the **j**x**B** forces resulting from the halo- and eddy-currents.

3. Heat load mitigation

ITER is aiming at radiating at least 90% of the stored thermal energy for mitigating disruptions at high energy. Initial experiments at JET carried out with the Top,L injector have resulted in a saturation of the radiated energy fraction with increasing impurity injection. The radiated energy fraction is defined as $f_{rad} = W_{rad}/\left(W_{mag} + W_{thermal} - W_{coupled}\right)$, with W_{rad} as radiated energy, W_{mag} as magnetic energy of the plasma, $W_{thermal}$ as thermal plasma energy and $W_{coupled}$ as energy, which is dissipated into the vessel and poloidal field coils [3]. Similar saturation levels have been observed when using the Midplane or Top,S injectors, which are significantly closer to the plasma, having a throughput at least twice the Top,L valve and hence are capable of injecting a higher amount of impurities before the start of the current quench [4]. Our data indicate this saturation to be about 85% of the total minus the coupled energy. Presently, further analysis is ongoing to disentangle whether this level is due to measurement errors or are a result of poloidal and toroidal asymmetries in the radiation during the disruption.

4. Toroidal radiation asymmetries

The uneven distribution of the radiative power following a single massive gas injection can lead to large localised radiation and hence to significant local thermal loads to the first wall. In addition, the presence of the n=1 mode can produce toroidal and poloidal radiation asymmetries as it has been shown by NIMROD calculations for DIII-D [5]. Depending on the phase relationship between the n=1 mode and the MGI-location, this effect can be enhanced or diminished. In order to characterise the radiation distribution toroidal and poloidal peaking factors, have been introduced. The determination of poloidal radiation peaking factors would require tomographic reconstruction of bolometer data, which is not possible at JET due to the toroidal separation of the viewing channels by 132^{o}. The toroidal peaking factor *TPF* can be estimated by assuming a cosinus-like radiation distribution $p_{\text{dis}}(\phi)$ [2] and a Gaussian-type toroidal distribution of the impurity density $n_{\text{i}}(\phi)$:

$$p_{dis}(\phi) = 1 + \Delta p\cos(\phi_{n=1} - \Delta\phi_{n=1} - \phi) \qquad (1)$$

$$n_i(\phi) = n_{i0}\exp\left(-\left(\phi - \phi_{inj}\right)/\lambda_{\phi}^2\right) \qquad (2)$$

Combining equations (1) and (2) one obtains for the toroidal distribution of the radiated power

$$P_{rad}(\phi) = n_i(\phi) p_{dis}(\phi) \langle P_{rad} \rangle \quad . \tag{3}$$

The toroidal peaking factor is defined as

$$TPF = \max\big(P_{rad}(\phi)\big) / \langle P_{rad}(\phi) \rangle \quad . \tag{4}$$

Using the horizontal and vertical bolometer the total radiated power, labelled $P_{\mathrm{rad,H}}$ and $P_{\mathrm{rad,V}}$ respectively, can be measured at two toroidal locations. In order to impose a phase for a n=1 mode, external magnetic field coils were used to induce a toroidal magnetic perturbation field with mainly an n=1 component. By reducing the density in ohmic discharges, error field modes were seeded and a MGI was triggered once the locked mode amplitude has exceeded a certain threshold. By varying the coil phasing, the imposed locked mode phase could be varied on a pulse-to-pulse basis. Figure 4 shows the radiation asymmetry factor, defined as $(P_{\mathrm{rad,V}} - P_{\mathrm{rad,H}})/(P_{\mathrm{rad,V}} + P_{\mathrm{rad,H}})$ for two series of MGIs one using 10% Argon and one using 10% Neon mix as a function of the resulting O-point location of the n=1 mode at the outer midplane. The radiation asymmetry for the Argon pulses is higher than for Neon, probably due to the smaller toroidal distribution of the impurities. The corresponding solid lines represent the radiation asymmetry by applying equations (1)-(3) with Δp, n_{i0}, $\phi_{n=1}$ and λ_ϕ as free parameters. The estimated TPF is approximately 1.2 and 1.1 for Ar and Ne respectively, when the gas is injected opposite to the O-point of the n=1-mode. However, the TPF could reach ~1.8 and ~1.5 if the injection would occur close to the O-point. This could lead to local heat loads beyond acceptable limits [6]. Using the two Top-injectors the radiation can be distributed more toroidally equal as shown in figure 5. With increasing gas amount from Top,S while the injection from Top,L is kept the same, the radiated power asymmetry factor reduces. Remarkably, in a very small range around $1.0\ 10^{22}$ Argon particles from Top,S, the asymmetry almost vanishes. Depending on the phase of the n=1 mode the toroidal peaking factor varies between 1.2 and 1.3.

5. Conclusions

MGI-experiments at JET have shown that the mitigation efficiency of electromagnetic and heat loads is not influenced by the location of the injection (midplane or top). Single injection can lead to toroidal peaking factors of the radiated power up to 1.8, which can be reduced by dual massive gas injection from the top. These findings support the choice of injection locations for the ITER-disruption mitigation system.

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References

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Figures

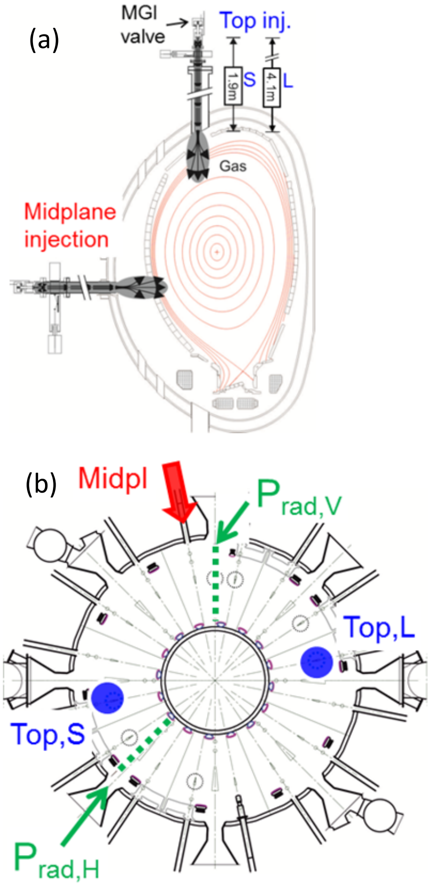

Fig 1: (a) Toroidal and poloidal (b) cross-section of the JET-tokamak indicating the locations of the three massive gas injection valves and the horizontal ($P_{rad,H}$) and vertical ($P_{rad,V}$) bolometers.

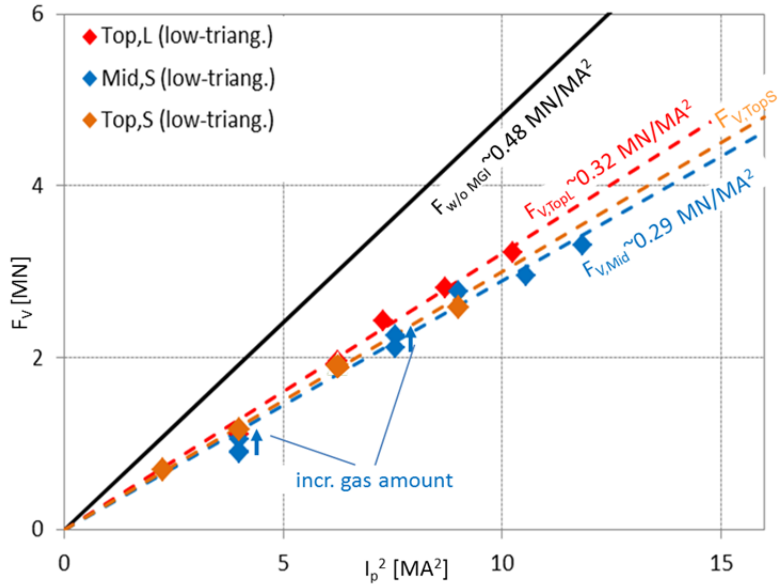

Fig 2: Vertical vessel force F_V as a function of plasma current squared. The black line represents the expected F_V without MGI. The dashed lines are the scaling derived from the corresponding data set for each injector.

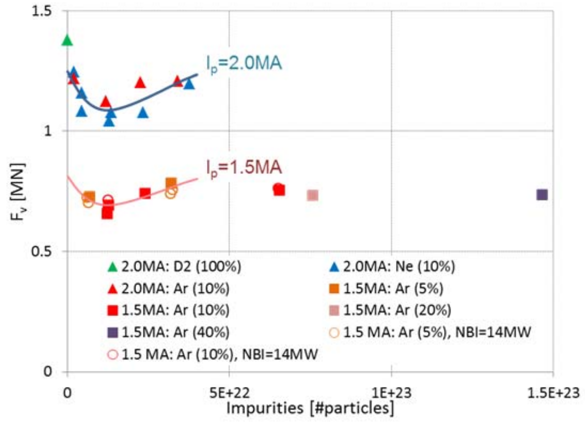

Fig 3: Vertical vessel force, F_V, as a function of impurities (Ar,Ne) injected by the midplane injector. For the two sets of data at two plasma currents a minimum has been found at similar injected amount of impurities.

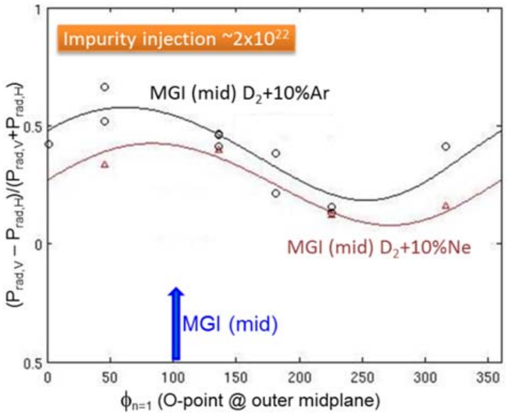

Fig 4: Radiation asymmetry factor as a function of the resulting O-point position of seeded n=1 modes for single midplane injection. The solid lines are fits according to Eq. (1)-(3) for the two data sets of Ar (black) and Ne (red) injections.

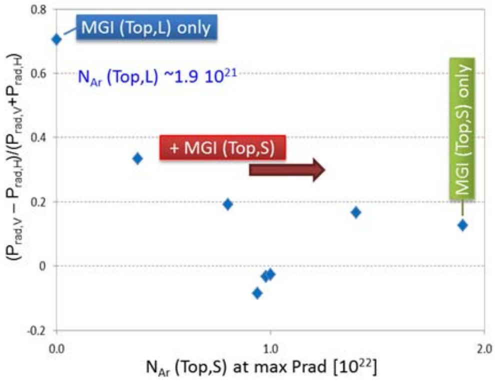

Fig 5: Rad. asym. fact. for dual injections as a function of Ar-amount from Top,S while the Ar injected from Top,L was kept constant.