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Disruption Mitigation Experiment on Tore Supra

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Disruptions can cause serious damages to tokamaks, and the threat they pose gets increasingly severe as the size of the machines increases towards fusion reactors. The plasma energy is lost on the first wall within a few milliseconds, resulting in forces of several hundred tons being applied to the structures. Furthermore, a significant fraction of the plasma current can be converted into runaway electrons that are accelerated up to energies in the region of 50 MeV. Mitigation techniques are thus required, and several possibilities are being studied on present day machines. In particular their applicability for ITER is being assessed. A promising method is massive gas injection (MGI), and encouraging tests have been carried out on Textor [1] and DIII-D [2]. Similar experiments, specially aimed at assessing the effect of MGI on runaway electrons, have been performed on Tore Supra where runaway electrons are observed in a majority of disruptions [3].

The gas injector can inject up to 2 10^{23} atoms in less than 4 ms [4]. An adjustable reservoir (10-100 cm^3) can be filled up to 10 bars. It is closed by a leak-free valve driven by an electro-magnet. The injected gas is accelerated through a Laval nozzle. In the experiments, up to 0.1 mole of helium was injected within 5 ms in ohmic plasmas, with currents up to 1.2 MA, either stable, or in a pre-disruptive phase (generated by argon puffing). The typical behaviour of MGI induced disruption is shown on figure 1.

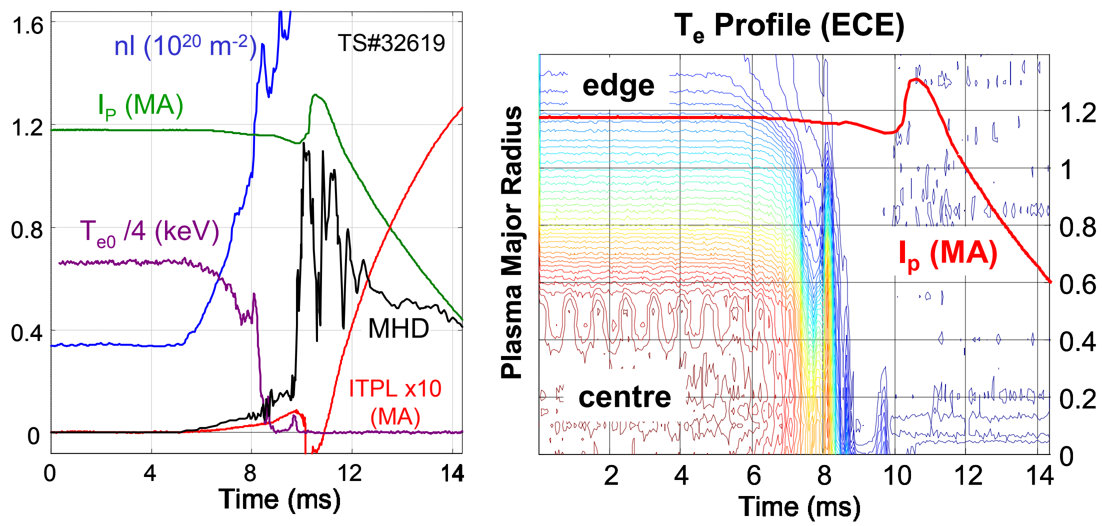

Figure 1 : Temporal evolution of plasma parameters after MGI disruption.

The time reference is the trigger of the electro-magnet. Opening of the valve takes roughly 3 ms, and 2 ms are necessary for the gas to flow from the nozzle to the plasma edge, 2 meters away (He speed of sound is 1000 m/s). After 5 ms, the density starts to rise sharply, and the electron temperature drops almost simultaneously on all chords (within 1 ms), suggesting transport towards the centre by neutral atoms.

This initial phase lasts 3 ms, and is followed by a fast temperature drop, comparable to the usual thermal quench observed during disruptions. A radiation flash is seen by infrared cameras looking at the first wall. MHD instabilities have not yet fully developed, and 2 ms are still needed for the current quench to start. This unusual phase, at full current and almost zero temperature has always been observed and still to be understood in details, but almost no diagnostics are available in these peculiar plasma conditions. One has to note that above 2 10^{20} m^{-2}, the interferometer used to measure the density cannot be used anymore, due to fringe jumps faster than the acquisition sampling time (50 µs). The current quench, starting 10 ms after the MGI trigger is rather classical, with strong eddy currents induced in particular in the toroidal pumped limiter (TPL).

However, a statistical comparison of several disruptions either spontaneous or triggered by MGI shows a reduction by a factor 2 in the maximum dI_p/dt fall rate, and 10 to 30 % less eddy currents in the TPL (fig.2).

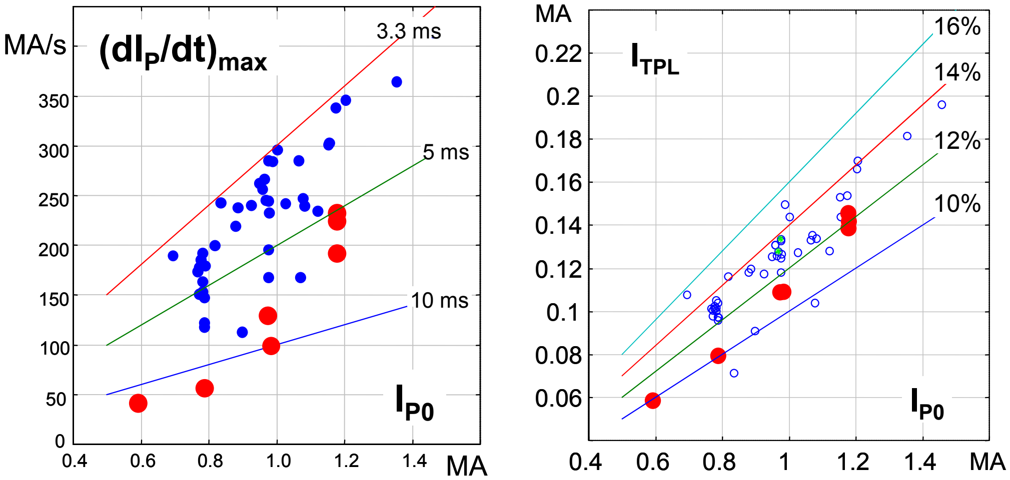

Figure 2 : Statistical analysis of standard (blue) and MGI disruptions (red).

This indicates that MGI disruptions are less violent, with a good benefit for the machine structure. Compared to a standard disruption, a MGI disruption enables an easy plasma recovery for the next pulse, without noticeable helium pollution of following plasmas [4]. This was firstly reported in Textor [1], and confirmed on Tore Supra.

The runaway electrons are accelerated (up to the MeV range) in the high toroidal electric field (up to 20 V/m) induced by the plasma current fall and can carry up to 60 % of the initial plasma current. Their signature when impinging the first wall is a large neutron flux produced by the hard X-rays emitted by the electrons slowing down in the wall material. The most important effect of MGI disruptions is the total disappearance of the runaway electron production. This is observed in the reduction by more than 3 orders of magnitude in the neutron fluxes (fig.3).

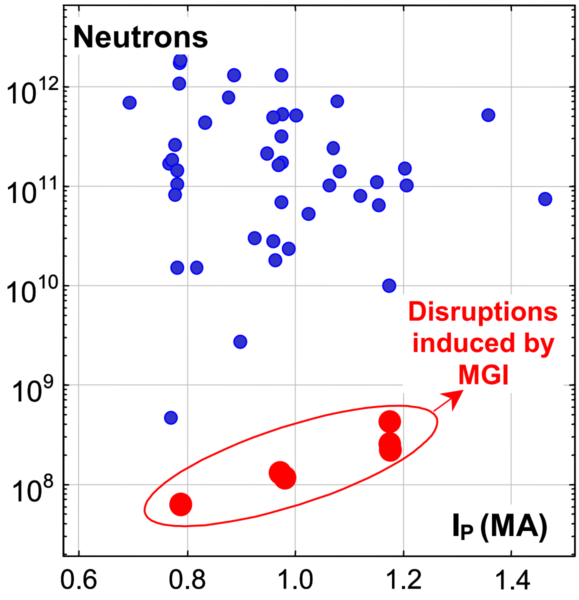

Figure 3 : Statistical analysis of neutron production during Tore Supra disruptions.

Models for runaway acceleration predict such a disappearance when the density at the current quench stays above a few 10^{20} m^{-3} [5]. In Tore Supra MGI experiments, the density reaches 10^{21} m^{-3} (estimated from a partial ionisation of the injected helium amount). We can estimate the number electrons in the runaway regime after the cooling phase in an MGI plasma. First we need the toroidal electric field. Its evolution is deduced from the poloidal magnetic flux evolution keeping the toroidal flux constant with the help of an equilibrium code reconstruction [6]. This analysis shows that the electric field typically reaches values up to around 100 V/m in MGI terminated plasmas. As an averaged value in the post MGI phase and over the central part of the plasma, a value of 20 V/m is reasonable. The number of non-thermal electrons generated during the rapid cooling phase of the plasma can be estimated from the analytical theory presented in Ref. [7]. We have applied this theory to typical parameters for a plasma with MGI, n_{e0} $=4\times10^{19}$ m^{-3}, T_{e0}=3keV (electron density and temperature before injection), n_{ef} $=5\times10^{20}$, T_{ef} =50eV (electron density and temperature in the final stage), t_{cool}=2ms (cooling time). The calculated non-Maxwellian distribution in the post-cooling phase then has a non-thermal population of the order $n_{tail}/n_{e0} \sim 0.4\%$. In the calculation we assumed an averaged density in the cooling phase of 0.5 ($n_{e0} + n_{ef}$). On the other hand, the number of electrons in the runaway regime, i.e. the number of electrons for which the accelerating force due to the electric field exceeds the collisional friction force is much smaller, for 20 V/m one finds around $n_{tail}/n_{e0} \sim 3\cdot 10^{-19}$. This can be compared to a normal disruption where the density increases typically by a factor of two in the quench phase. A similar analysis then gives a fraction of runaway electrons of the order $n_{tail}/n_{e0} \sim 1\cdot 10^{-5}$. Thus, these theoretical estimates are consistent with the observed absence of runaway electrons after an MGI.

The capability of MGI to stop already accelerated runaway electrons have also been investigated. Disruptions (induced by 1 Pa.m^3/s Ar puffing) in the current ramp-up lead always to self-sustained runaway beams. A MGI is triggered 200 ms after the disruption. One observes a 5 fold increase of the neutron flux and a termination of the plasma in less than 150 ms (fig.4). The total number of neutrons is conserved, indicating that neutrals accelerate the runaway electron drift towards the wall. The MGI is not able to stop already accelerated runaways. This point to the absolute necessity to develop disruption precursor techniques to identity disruption sufficiently in advance (6-10 ms) to allow for the MGI to penetrate the plasma core before the current quench.

The minimum gas quantity required to mitigate disruption and avoid runaway formation is not known yet. The 0.1g of He gas injected in Tore Supra MGI experiments were sufficient but extrapolate to hundreds of grams for ITER. Experiments are scheduled in Tore Supra to explore this issue. The nature of the injected gas which also be investigated.

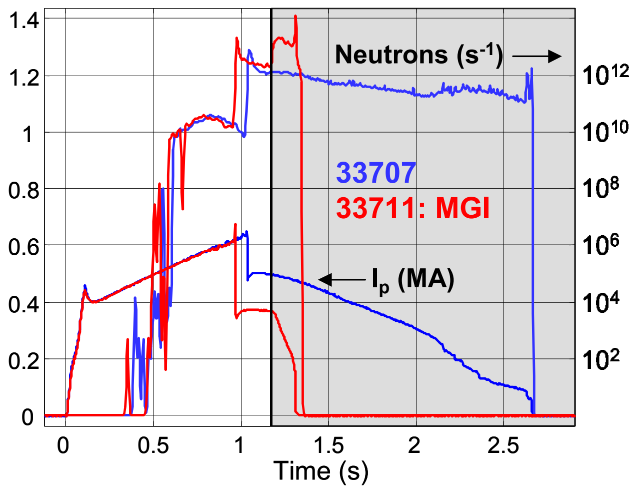

Figure 4 : MGI on already accelerated runaway electrons as compared to standard runaways.

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