Disruption Mitigation on Tore Supra

G. Martin, F. Sourd, F. Saint-Laurent, J. Bucalossi, L.G. Eriksson

Association Euratom-CEA, DSM/DRFC/STEP, CEA/Cadarache
F-13108 SAINT PAUL LEZ DURANCE / FRANCE

e-mail contact : gmartin@cea.fr

Abstract : During disruptions, the plasma energy is lost on the first wall within 1 ms, forces up to hundred tons are applied to the structures and kA of electrons are accelerated up to 50 MeV (runaway electrons). Already sources of concern in present day tokamaks, extrapolation to ITER shows the necessity of mitigation procedures, to avoid serious damages to in-vessel components. Massive gas injection was proposed, and encouraging tests have been done on Textor and DIII-D. Similar experiments where performed on Tore Supra, with the goal to validate their effect on runaway electrons, observed during the majority of disruptions. 0.1 mole of helium was injected within 5 ms in ohmic plasmas, up to 1.2 MA, either stable, or in a pre-disruptive phase (argon puffing). Beneficial effects where obtained: reduction of the current fall rate and eddy currents, total disappearance of runaway electrons and easy recovery for the next pulse, without noticeable helium pollution of following plasmas. Analysis of the 4 ms period between injection and disruption indicates that to reach these goals, one need to inject enough helium to keep it only partially ionised. It correspond to 0.1 g for Tore Supra, and extrapolate to hundred's of grams for ITER.

1. Introduction

Disruptions are a threat to Tokamaks, getting worse and worse as their size increases towards fusion reactors. Mitigation techniques are required, and are developed in present day machines, in particular to be applied on ITER. Three axis of research are followed along this line, to reduce the burden on the in-vessel components caused by i) the sudden deposit of the plasma stored energy on the divertor plates; ii) the halo and eddy currents induced in all the structures; iii) the multi-MeV runaway electrons accelerated and lost on the first wall. Examples of such impacts are shown on figure 1.

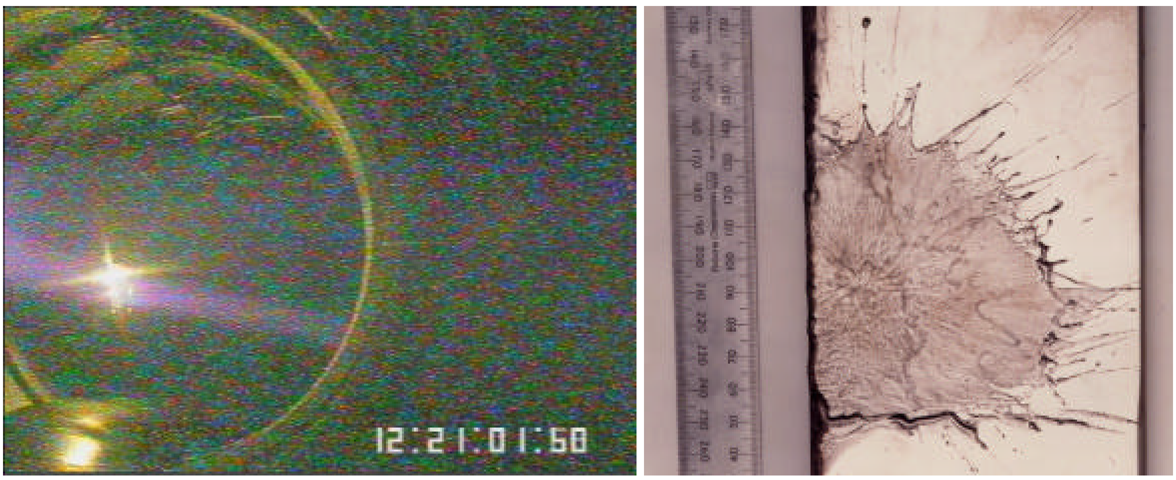

Fig. 1 : Left : Runaway Electron Impact on the Outboard Limiter of Tore Supra
Right - Melting of the Inner-side Bumper on JET

Massive Gas Injection (MGI) was proposed to mitigate disruptions effects, and encouraging tests have been performed on Textor [1] and DIII-D [2]. However, on these two machines, disruptions do not produce runaway electrons as a general rule, and the question of their avoidance remains an issue. On Tore Supra, runaway electrons are accelerated during most of major disruptions [3], and MGI was thus installed both to confirm results already obtained elsewhere, and to qualify its effects on runaway acceleration.

2. The Massive Gas Injector of Tore Supra

The first objective of MGI is to increase the plasma density to level high enough to avoid the creation of runaway electrons, by a strong increase of their collisionality. Numerical simulations [4] as well as very high density operation in FTU [5] suggest that values of several 10^{20} m^{-3} are required. A value of 10^{21} $e\text{-}/m^3$ was chosen, i.e. 2. 10^{22} He for the 20 m^3 plasma of Tore Supra.

In addition, MGI might also prove able to stop a runaway population already accelerated, confined in the vacuum vessel, before its loss onto the wall (e.g. if injection occurs “too late”). The necessary amount of gas is higher in this case. To stop a 10 MeV electron, one require a linear density of 6 g/cm^2. This will be encountered in 10 ms at the speed of light in a gas density of 2 10^{-8} g/cm^3, i.e. 3 10^{21} He/m^3. As this gas must remain neutral to keep its stopping power, the full volume of the vacuum vessel has to be filled, i.e. 50 m^3. The amount of helium is then 1.5 10^{23}, i.e. ¼ of a mole or 1 g.

As such densities are much higher that known density limits (e.g. Greenwald limit), they can only be achieved in a disruptive plasma. It imply that MGI has to be performed within a very short time compared to the confinement time, i.e. within a few milliseconds. If the amount of helium entering the vessel is large enough to keep it only partially ionised, neutrals can reach the centre of the plasma, allowing its cooling down on such short time.

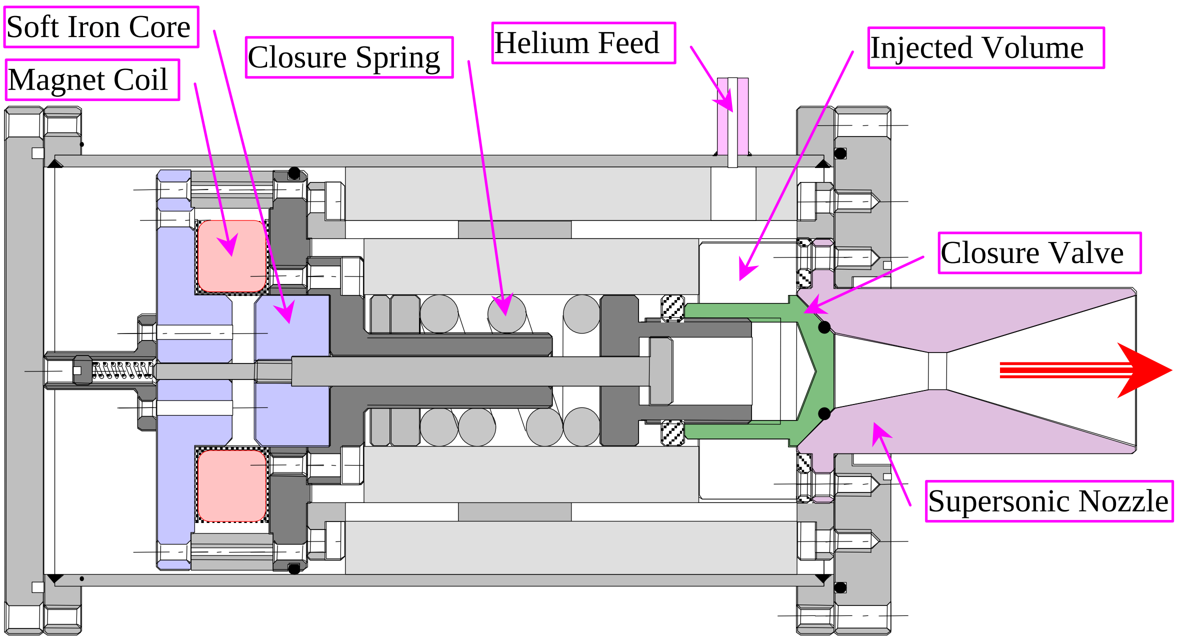

Fig 2. Tore Supra Massive Gas Injector

An injector was built, able to inject up to 2 10^{23} helium atoms in less than 4 ms. Its schematic is shown on figure 2. A adjustable reservoir of 10 to 100 cm^3 can be filled up to 10 bars. It is closed by a leak-free valve, connected to a Laval nozzle, located in a vertical port of the torus. The valve has a large aperture (4 cm^2) closed by a plastic o-ring. A strong spring keep it tightly closed (leak rate < 10^{-6} $Pa.m^3/s$). An electro-magnet, driven by a capacitor bank, can hit the valve, allowing its fast opening for a few milliseconds. This is enough to release a large part of the stored gas through the nozzle, towards the plasma.

3. Disruption Caused by MGI

To validate MGI, it was first used on stable ohmic plasmas. The typical behaviour is shown on figure 3. Time “0” correspond to the trigger of the electro-magnet. Opening of the valves takes roughly 3 ms, and 2 ms are necessary for the gas to flow from the nozzle to the plasma edge, 2 meter away (He speed of sound is 1000 m/s). After 5 ms, the density start to rise sharply, and the electron temperature drops almost simultaneously on all chords (within one ms), suggesting transport towards the centre by neutral atoms.

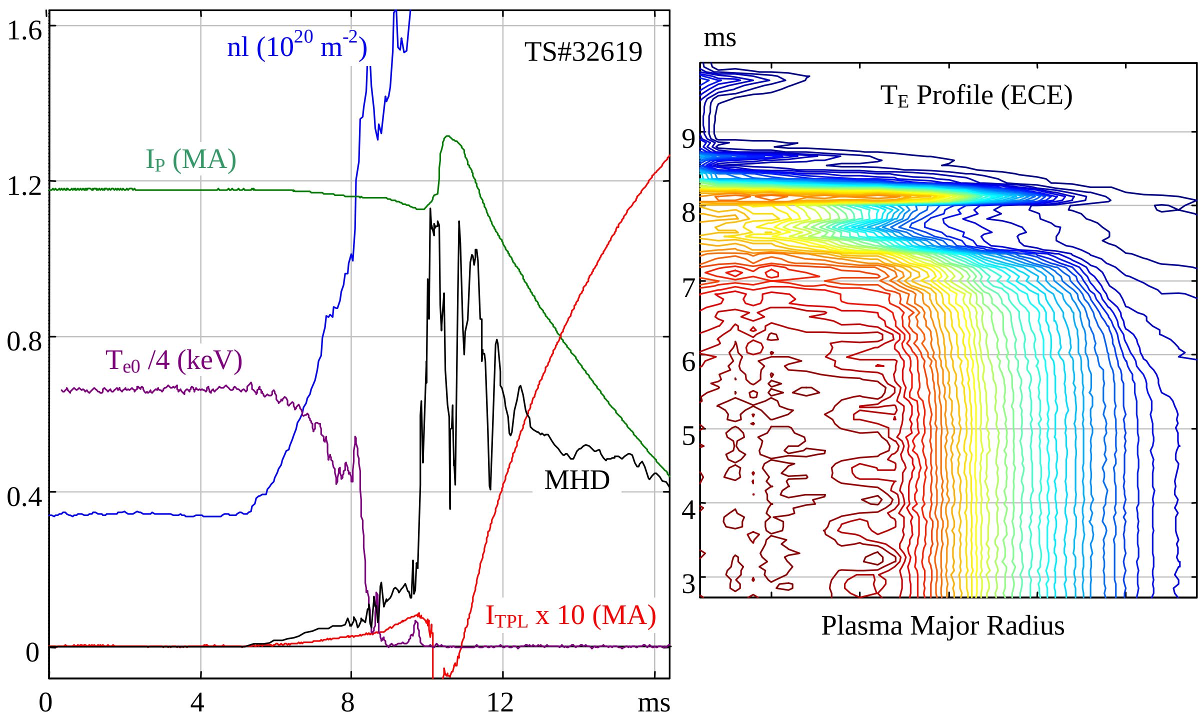

Fig.3: Temporal Evolution of Plasma Parameters after MGI

This initial phase last 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 still to be understood in detail, 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 time (50 µs).

The current quench, starting 10 ms after the MGI trigger is rather classical, with strong eddy current, induced in particular in the toroidal pumped limiter (TPL). However, comparison between 2 disruptions, triggered, one by MGI, and the second by argon puffing (on similar plasma targets), shows a milder I_P falling rate in the case of MGI (figure 4). This effect is confirmed by a statistical analysis of several disruptions (figures 5), either spontaneous or induced by MGI. It shows a reduction of a factor 2 in the maximum dI_P/dt, and 10 to 30% less eddy currents in the limiter.

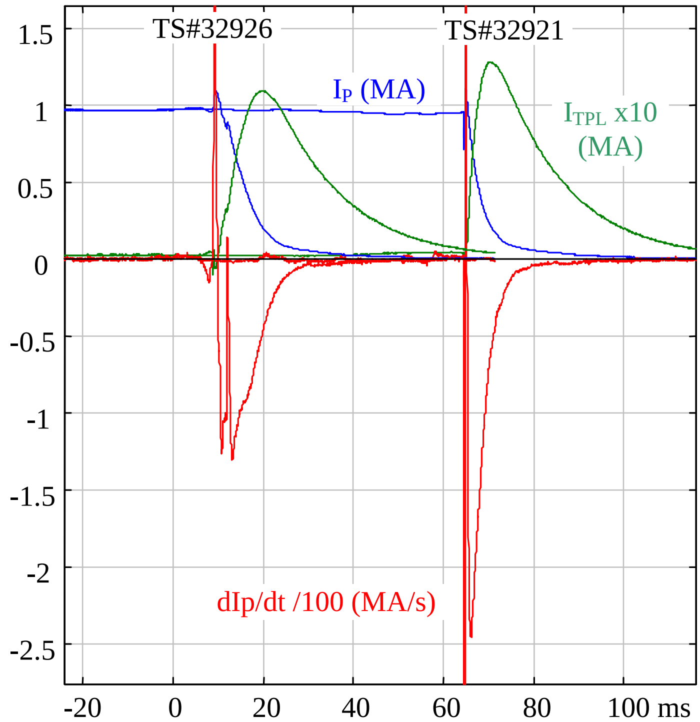

Fig.4 : Comparison of a Disruption by MGI [32926] and by Argon Puffing [32921]

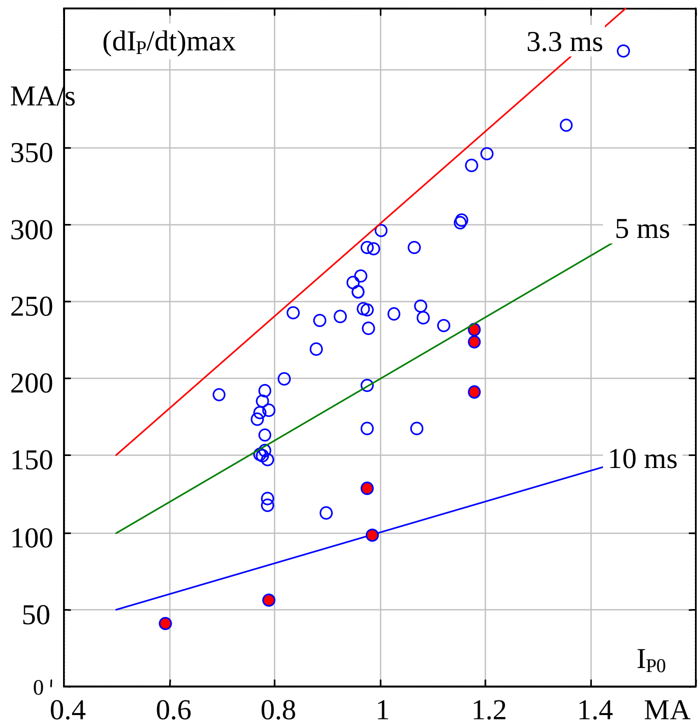

Fig. 5: Statistical Analysis of I_P Ramp down Rates. Closed Circles for MGI Disruptions.

Although the density after the quench is much higher in the MGI case, the residual temperature stays higher, probably due to the lower Z_{eff} (no measurements are available at this stage of the plasma).

4. Runaway Electron Suppression by MGI

The high toroidal electric field induced by the fall of the current (up to 20 V/m) accelerates electrons up to the MeV range. Electron beams, carrying up to 60% of the initial plasma current, with a mean energy of 12 MeV, impinge the wall very locally, inducing severe damages to water cooled components (e.g. figure 1). The signature of these electrons is seen on neutron detectors (figure 6). Neutrons are produced by the hard X-rays emitted when the electrons are lost in the wall. A rough correspondence of 3.10^{12} neutrons for 100 kA of electrons has been determined [6], on disruptions where a runaway electron plateau can be clearly seen, as TS#30133.

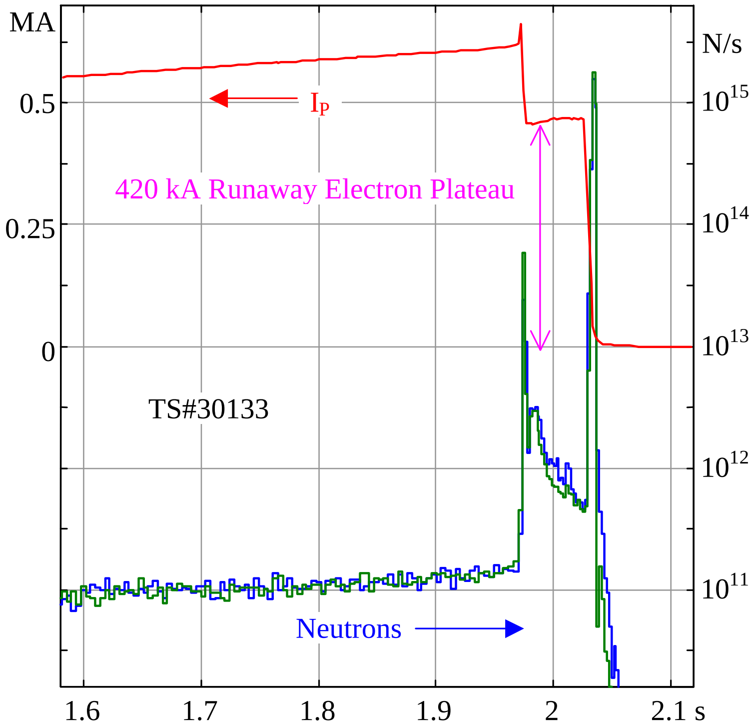

Fig.6: Photo-neutrons produced by disruptions

A statistical analysis is shown on figure 7. Disappearance of the runaway electrons is observed when disruptions are induced by MGI (reduction by more than 3 orders of magnitude in neutron fluxes). Models for runaway acceleration predict such a disappearance when the density at the current quench stays above a few 10^{20} m^{-3} [7]. In Tore Supra MGI experiments, the density reached 10^{21} m^{-3} (estimated from a partial ionisation of the injected helium amount).

A runaway plateau is rarely observed (less than 5% of the disruptions), due to the loss of the plasma equilibrium after the disruption. However, when disruptions occur in an early stage of the plasma, this equilibrium can be kept for up to 2 seconds, even without active feed-back (the feed-back controller is "stopped" after a disruption, to "spare" the power supplies). MGI was tested on such post-disruptive plasmas, where the current is carried by electrons of a mean energy of 12 MeV, as shown on figure 8. MGI was triggered 200 ms after the disruption. One see a 5 fold increases in the neutron signal, and a termination of the plasma in less than 100 ms. However, some of the electrons are still lost in the wall, due to the drift of the plasma column toward the inner wall, when the plasma current start to ramp down after MGI.

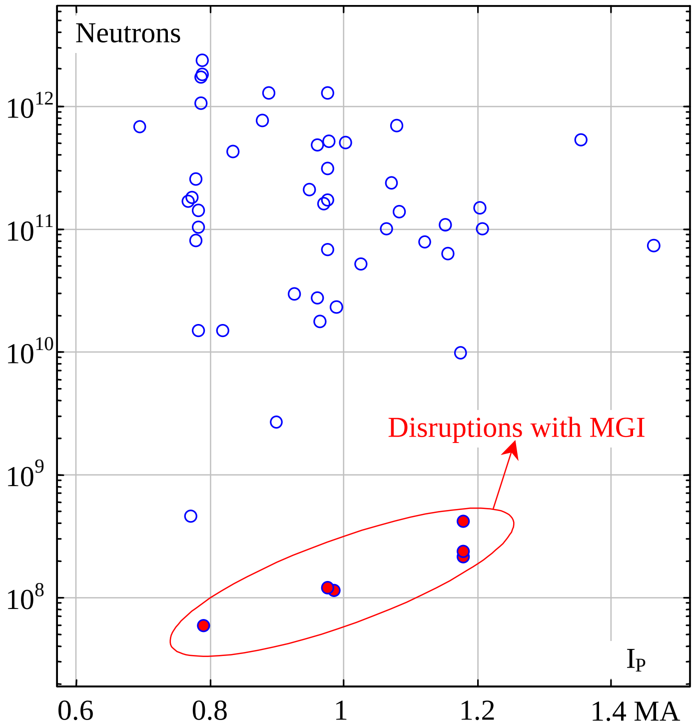

Fig. 7 : Number of Photo-neutrons produced by Tore Supra Disruptions

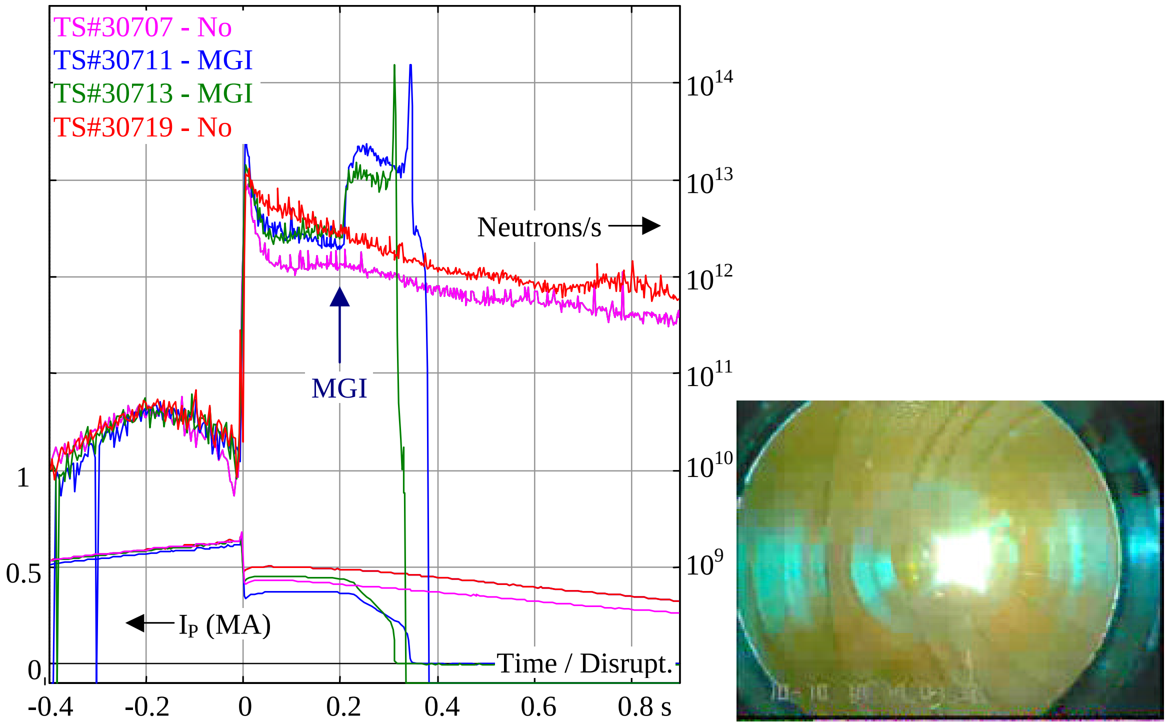

Fig. 8: MGI on an already developed runaway electron population

The total number of neutrons does not change between cases with MGI and without, suggesting that the electrons are still lost in majority to the wall. Electron impact can be seen on the CCD camera (fig. 8). Estimation of electron acceleration by the electric field due to the ramp down of I_P, and their deceleration by the helium gas indicates that the plasma equilibrium has to be kept to insure the stopping of the electrons in the gas. More experiments will be performed with the active feed-back on the plasma position turn “on”, but these preliminary results are encouraging.

5. Plasma Recovery after MGI

Injecting up to 10^{23} helium atoms in the vessel, where plasmas usually contain less than 10^{21} electrons could lead to serious pollution of the discharges following helium MGI. To quantify this effect, a comparison between two plasmas, a standard one and one just following a MGI has been plotted on figure 9. After a transitory phase of 4 seconds, both plasma parameters are exactly the same. The helium content in the second plasma was negligible, as suggested by the superposition of the two neutron signals, very sensitive to deuterium dilution. In addition, it was possible to restart the next plasma without any cleaning discharge, which are required as a general rule after spontaneous disruptions, for first wall recovery. This was already reported by Textor [1], and is confirmed by Tore Supra.

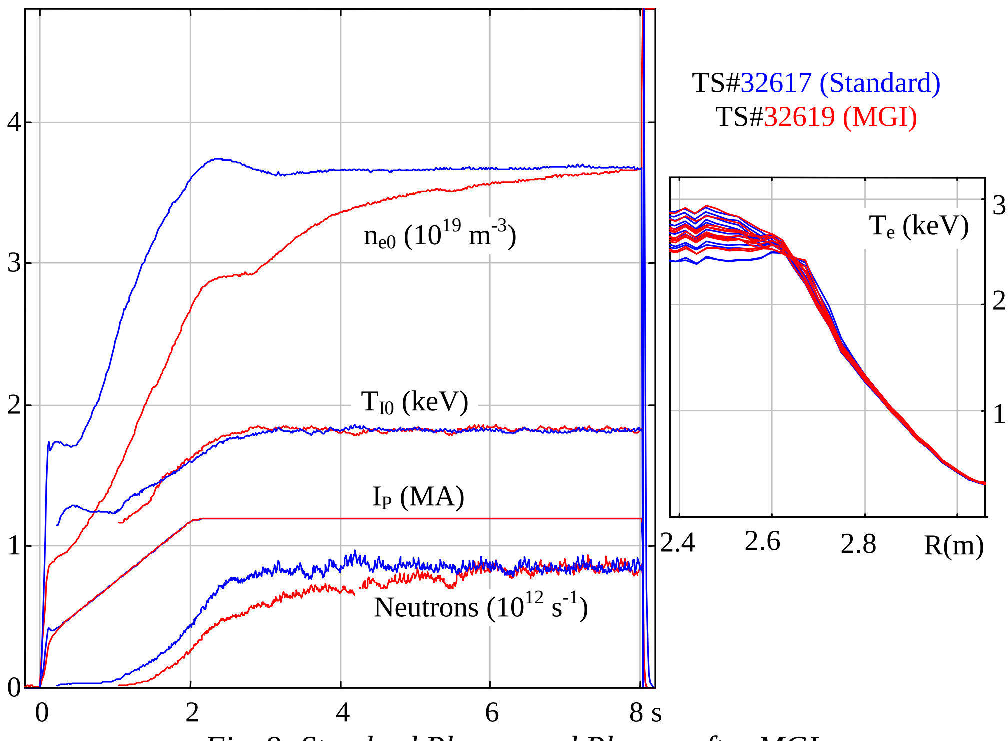

Fig. 9: Standard Plasma and Plasma after MGI

6. Discussion

Analysis of several MGI disruptions suggest that a minimum amount of helium is required to get all the beneficial effects: the neutral gas influx must be large enough to insure that helium transport up to the centre is done by neutrals. At usual plasma temperature (keV) and density (10^{19} m^{-3}), the penetration depth of an helium atom is lower than a centimetre (first ionisation). However, this ionisation length increases rapidly below 100 eV, and neutrals are able to go deeply in the plasma when it has been cooled down below this temperature. Thus, if one injects roughly 1 atom for each 100 eV of stored energy, the plasma will become more or less “transparent” to the neutrals, which will be able to reach the centre. Its translates to 1 g of Helium for 2.5 MJ of stored energy, i.e. 0.1 g for a Tore Supra typical ohmic plasma, and 200 g for a full performance ITER plasma (450 MJ). When such a large amount of Helium will have recombined around 30000 K, a pressure of more than 1 bar will suddenly appear in the vacuum vessel. The impact of such a sudden pressure rise has to be evaluated to validate the opportunity of MGI on ITER, but runaway electrons might prove such a threat to the PFC integrity, that mitigation seems unavoidable.

7. Conclusion

Massive gas injection (MGI) has been proposed as a way to mitigate the deleterious effects of the disruptions, especially in the large Tokamaks like ITER. Experiments performed on Tore Supra have confirmed results obtained elsewhere, and add new information, in particular for the creation and acceleration of runaway electron. The main results are: i) disruptions caused by MGI are milder in term of dI_P/dt and eddy currents; ii) first wall recovery for plasma break-down is easier after MGI; iii) MGI with helium does not pollutes the following plasmas; iv) runaway electron are reduced by more than 3 orders of magnitude.

More experiments are still needed, to assess the technical consequences of the pressure peak on the in-vessel components, and to validate the stopping “in-flight” of a runaway population already accelerated by the gas, rather than by the wall.

8. References

[1] K.H. Finken, G. Mank & al., Nuclear Fusion 41 (2001) 1651
[2] D.G. Whyte, T.C. Jernigan & al., 19th IAEA FEC, Lyon (2002)
[3] [2] G. Martin, Proc. 25th EPS Conf. on Controlled Fusion, Praha, (1998) 651
[4] M.N Rosenbluth, S.V. Putvinski, Nuclear Fusion 37 (1997) 1355
[5] B. Esposito, J.R. Martin-Solis, & al., Physics of Plasma 10 (2003) 2350
[6] G. Martin, F. Sourd, 7th IAEA TCM on Energetic Particles, Göteborg, (2001)
[7] L.G Eriksson, P.Helander, Computer Physics Communications 154 (2003) 175