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Experimental study of gas jet dynamics during disruption mitigation using massive noble gases injections on Tore Supra

C. Reux, J. Bucalossi, F. Saint-Laurent, C. Gil, J.-L. Ségui

CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

Disruptions are a potential threat to reactor-size tokamaks. They produce excessive heat loads on plasma facing components, induce strong electromagnetic forces in the vessel structures, and generate multi-MeV runaway electrons. Therefore, disruption mitigation is essential for next-generation tokamaks. Massive gas injection is one of the methods which are proposed to be installed as a mitigation system on future devices [1]. In this paper, disruption mitigation experiments performed on Tore Supra tokamak with a fast valve are reported. Effects of several gases are compared regarding disruption consequences. Gas jet dynamics are analyzed and mechanisms which could explain experimental observations of the gas penetration are proposed.

1. Gas comparisons

The massive gas injector installed on Tore Supra can be used to inject a wide range of gases and mixtures. Helium was initially successfully tested during previous experiments [2]. 2 other gases and 1 mixture were more recently tested: Neon, Argon and a 95%/5% He/Ar mixture. The injection amounts ranged from 5 Pa.m^3 (low pressure Argon injections) to 500 Pa.m^3 (high pressure Helium injections).

Electromagnetic (EM) loads: EM loads reduction was analyzed using the maximum plasma current derivative (max. dIp/dt) which is linked to the duration of the current quench, and the eddy currents in the toroidal limiter. All gases slowed down the current quench, decreasing the maximum dIp/dt by a factor 2 to 3. The efficiency is independent of the injected amount of gas: 12 Pa.m^3 Helium injections have nearly the same effect as 500 Pa.m^3 injections. Plasma scenario ($Ip/n_e/P_{add}$) was changed for during additional Helium injections, but without any change in the efficiency.

Runaway electrons: The amount of runaway electrons produced during the disruption is proportional to the neutron production measurement. (fig. 1). Photoneutrons are indeed produced when the runaway electrons hit the wall. Helium and He/Ar mixture strongly reduce the amount of neutrons to the plasma background noise level (2 to 3 orders of magnitude less). No dependence to the amount injected was observed, except for very low He amounts (<10 Pa.m^3), which are sometimes prone to a small runaway production (albeit nonreproducible shot-to-shot). Conversely to Helium, Neon and Argon do not prevent runaway generation. Argon mitigation may generate marginally more runaway than an unmitigated disruption.

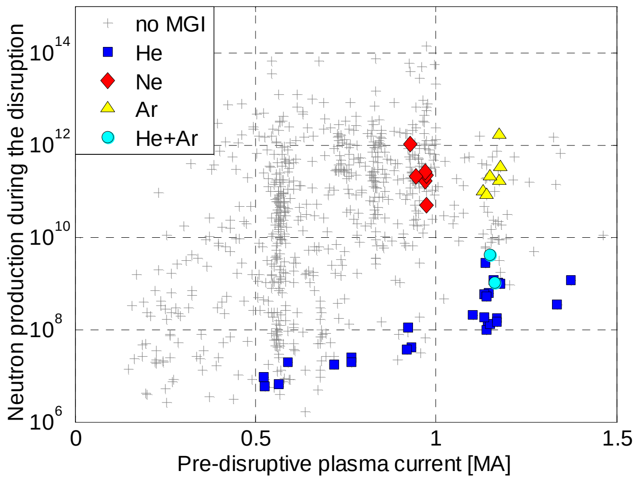

Fig. 1. Neutron production showing runaway amounts during Tore Supra disruptions. Background level is between 10^6 and 10^8.

2. Gas jet dynamics

Gas jet penetration mechanisms still remain to be thoroughly explained. Latest experiments tend to show that the penetration is quite superficial, and may be linked to some particular flux surfaces [3, 4].

Mixing efficiency: Overall gas mixing is measured by the density rise triggered by the arrival of the massive amount of neutrals in the plasma. A fast FIR interferometer was thus used to estimate the mixing efficiency. Unfortunately, density gradients induce laser refraction, and the signal is lost 1-2 ms before the thermal quench. The total number of electrons added to the plasma was calculated using the sum of density measured by several chords. Major differences were observed between Argon and Helium (fig. 2). Helium adds at least 2 times more electrons to the plasma (up to 2.10^{21} electrons, last valid measurement 1 ms before the thermal quench) than Argon. In addition, the density rise is respectively faster with Helium than Argon, and with high amounts of gas. Besides, thermal quench is triggered at much lower density for Argon. These observations may explain the better runaway suppression (collisionnal) induced by Helium injections. Overall pre-disruptive mixing efficiency is quite low, especially for high injected amounts: <15% of the gas is mixed, assuming single ionization. This may be explained by the relatively small fraction of neutrals which reach the plasma before the thermal quench.

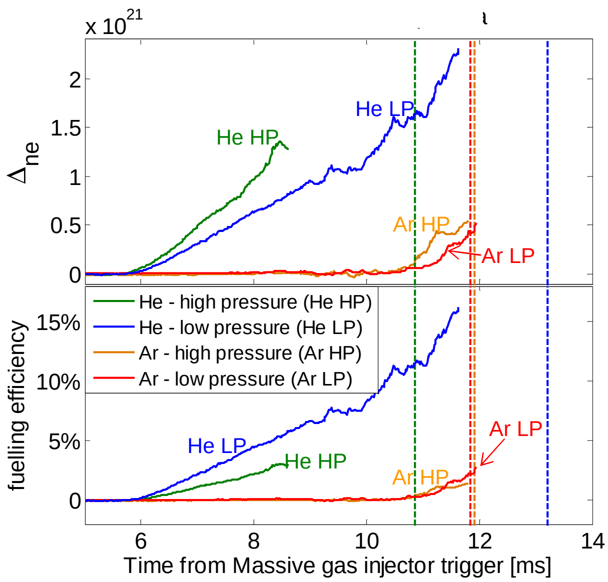

Fig 2. total amount of electrons added to the plasma by massive gas injections. (a): absolute value. (b): amount normalized to the number of particles injected. Vertical dashed lines are the thermal quench times. Helium reaches plasma edge at ~5.5 ms, Argon at 7 ms

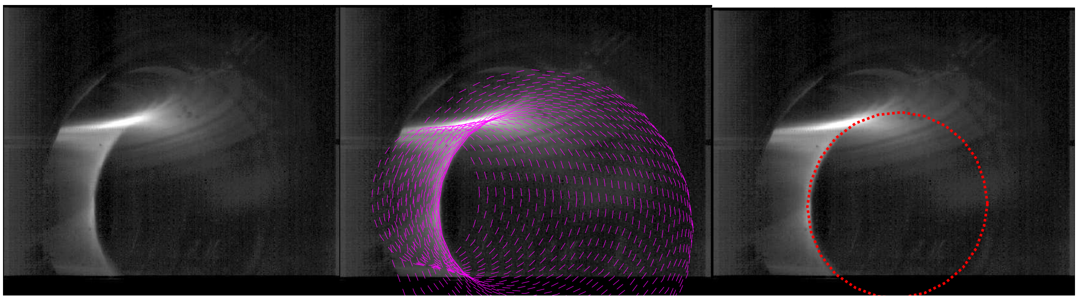

Fig 3. Shot 42047 - Position of the gas cold front (a) fast camera picture – (b) reconstructed flux surface (r = 55cm) – (c) poloidal plane parallel to the endoscope lens

Gas penetration: Gas jet penetration was estimated using the newly-installed fast-framing camera [5]. Line emissions of low-ionized species were considered using interference filters (Ar I 476 nm, He II 468.5 nm, He I 706.5 nm). Emissive front is thus supposed to be the region where the ionization of neutrals takes place. The cold front speed inside the plasma ranges from 20 m/s for low Argon injections to 120 m/s for high Helium injections, to be compared with the sound velocity of Helium and Argon (1000 m/s and 320 m/s respectively). These speed differences are consistent with what is observed on density measurements. On the contrary to the gas front speed, the maximum depth of penetration seems to be independent of the nature or the amount of the injected gas. The cold front is thus stopped at the same depth for Helium and Argon, whatever the amount considered.

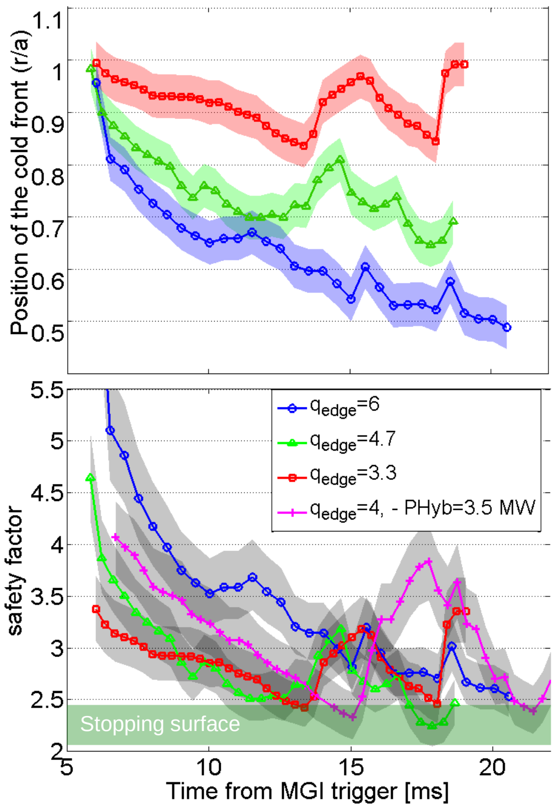

Fig. 4. Penetration of the cold front for different q profiles. 25 Pa.m^3 Helium injections. (a) penetration in normalized radius. (b) penetration in safety factor. Green zone on (b) shows the gas stopping area (between q=2 and q=2.5)

Temperature or density profiles do not change the depth of penetration neither, as shown by a density scan and an auxiliary heating scan. Indeed, the depth remained the same for 0 to 3.5 MW of lower hybrid wave heating, despite the fact that the thermal energy available in the plasma layers crossed by the gas is 50% to 100% higher. This tends to show that the gas is not stopped only by a lack of neutrals or a pressure balance. The safety factor profile was indeed found to be the relevant parameter. A plasma current scan from 0.6 MA to 1.4 MA and a toroidal field scan showed dramatic changes in the position of the cold front (fig. 4a). Whereas the gas penetrates deeply into the plasma when q_{edge} is high (Ip = 0.6

MA, B_t = 3.85 T - q_{edge} = 6), it seems to be stopped at the very edge when q_{edge} is low (Ip = 1.2 MA, B_t = 2.5 T – q_{edge} = 2.7). Fast camera pictures reconstructions show that the stopping front may be located near rational surfaces (q=2 or q=5/2) (fig. 4b).

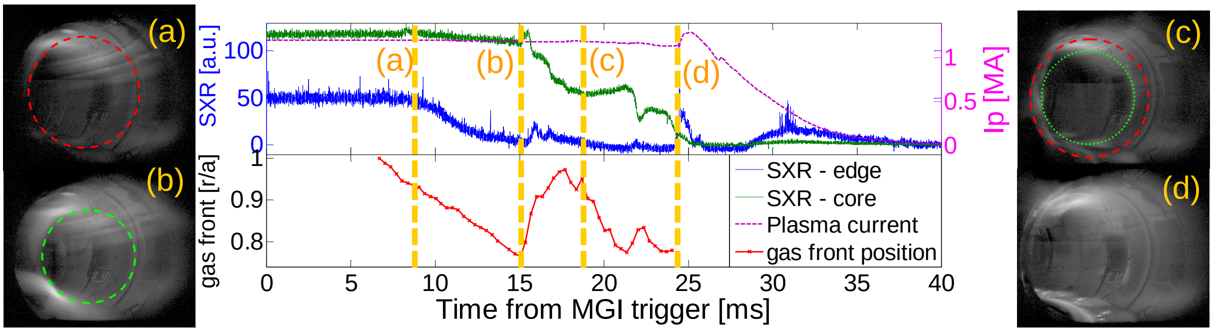

Fig 5. Disruption timeline : soft X-ray signal, plasma current and fast camera pictures at 4 times

This assumption is supported by some additional observations of the gas cold front movement. After the gas reached its maximum penetration depth, the cold front sometimes moves backwards as seen on figure 4. This “bounce” is correlated with small spikes on the plasma current, and drops on the soft X-ray signal (fig. 5). Soft X-ray emission depends on density, temperature and impurity content. Whereas edge chords slowly drop at the beginning of the cooling phase, central chords remain almost unchanged until the gas reaches a critical surface. The chord intensity then suddenly drops, which implies a fast radial transport of the energy from the core to the edge. This may explain the apparent backward movement of the gas front as seen on the fast camera: all the gas located near the critical surface is rapidly ionized by the energy burst. This “internal disruption” preventing the gas from penetrating further could be triggered by the perturbation induced by the gas around rational surfaces.

Conclusion and prospects

Massive gas injection was studied on Tore Supra, using a fast gas valve. Gas comparisons were performed, showing that the current quench is slowed down by all the gases tested (He, Ne, Ar and He/Ar mixture). Runaway electrons are suppressed only by light gases. Gas jet dynamics is analyzed using a fast interferometer, fast camera imaging and soft X-ray analysis. This shows that the penetration of the gas is linked to the safety factor profile. The gas cold front is stopped along rational surfaces, by the triggering of large radial energy transport that prevents the neutrals from penetrating deeper until the disruption occurs. Those results bring important insights to the mechanisms allowing massive gas mixing and valuable input for further simulations and extrapolations to larger devices.

References :

[1] ITER Physics Basis 2007, Nucl. Fusion 47 S192
[2] Martin G. et al, 2004, Proc. 20th Int. Conf. on Fusion Energy (Vilamoura, Portugal)
[3] Bozhenkov et al, 2007, 34th EPS Conference on Plasma Phys. (Warsaw)
[4] E.M. Hollmann et al, 2005, Nuclear Fusion 45 1046–1055
[5] Géraud et al., Rev. of Scientific Instruments 80 033504 (2009)