Non-linear simulations of disruption mitigation using massive gas injection on Tore Supra

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Disruptions are identified as a major threat to ITER and reactor-size tokamaks. They produce excessive heat loads on plasma facing components, induce electromagnetic (EM) forces in the vessel structures and generate multi-MeV runaway electrons. Therefore, disruption mitigation will be needed for next-generation devices. Massive Gas Injection (MGI) is one of the methods proposed to be installed on future machines [1]. Most of the tokamaks in the world have carried out MGI experiments and showed the method was efficient at reducing EM forces, heat loads and more marginally runaway generation. However, the magnitude of this efficiency still varies between machines, and results are not directly scalable to larger devices. The plasma energy density for such tokamaks is likely to be several orders of magnitude higher than in current ones, and it is unclear how the physical mechanisms involved in gas jet penetration scale with the machine size. Therefore, simulations are needed to assess the efficiency of the method on next generation devices. In this paper 3D MHD simulations of the pre-disruptive phase of massive gas injections on Tore Supra-like plasmas using the JOREK code are reported. First validation of the simulations with experimental observations are made, with the long term goal being to predict the plasma response to a massive gas injection in a larger tokamak like ITER.

Physical model and code setup

Experimental results obtained on Tore Supra [2], TEXTOR [3] and JET [4] showed that the penetration of a massive gas jet was linked to the rational surfaces in the plasma. The q=2 surface was found to play the main role in the behaviour of the neutral cold front. This observation led to use the MHD code JOREK to simulate the plasma response to a massive gas injection during the pre-disruptivas phase and the triggering of the disruption. JOREK is a non-linear 3D MHD code originally developped to simulate ELMs [5]. Massive Gas Injection has been integrated in the code by adding a neutral fluid density equation in addition to the ion density equation. It contains an ionization sink term, a volume recombination source term from ions and a diffusion term for neutrals (equation 1).

$$\frac{\partial \rho_n}{\partial t} = \nabla \cdot (D_n \nabla \rho_n) - \rho \rho_n S_i(T) + \rho^2 S_r(T) \quad (1)$$

Corresponding source/sink terms are included in the ion density equation. An energy sink term for ionization has also been added to the ion temperature equation and takes into account the cooling induced by the gas. Originally set for deuterium atoms (single ionization) this term can be increased to "emulate" heavier gases whose radiation processes and multiple ionization drain more energy from the plasma. Boundary conditions for the ions are reflective: ions that hit the domain boundary are reflected in the plasma as neutrals. The neutral source term for the neutral density equation is implemented as a fully 3D term, toroidally and poloidally localized. All simulations presented in this paper are based on Tore Supra-like plasma profiles, with a central ion temperature of 1.5 keV, a central density of 4.10^{19} m^{-3}, I_p = 850 kA and B_t = 3.85 T. The calculation domain is a circular flux surfaces-aligned grid with 60 radial steps and 45 poloidal steps, with the toroidal direction being treated with Fourier harmonics.

Low toroidal mode numbers simulations

First simulations were performed with only a limited number of toroidal mode harmonics (n=1 and n=2) to get the basic response of the plasma to an injection. The ion perpendicular diffusion coefficient is set at 1 $m^2.s^{-1}$, close to experimental values and the neutral diffusion coefficient is set at 50 $m^2.s^{-1}$ in order to take into account the gas jet speed. Without any gas, n=1 and n=2 modes are stable and no magnetic islands appear. When the gas is injected near the plasma edge, a high-density front appears, followed by the shrinking of the temperature profile due the ionization of the gas (figure 1). The case shown on this figure involves a low injection rate (1.22×10^{23}atomes.s^{-1}). The neutral front moves radially inwards with a speed around $20 m.s^{-1}$ which is in qualitative agreement with experimental observations.

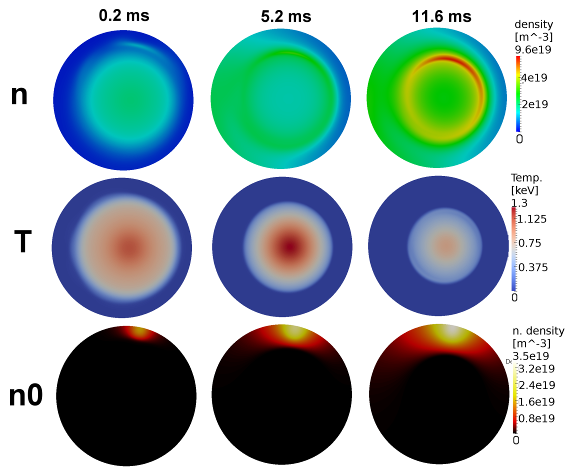

Figure 1: MGI simulation with n=0,n=1 only. Density, temperature and neutral density.

The injection triggers n=1 and n=2 instabilities on rational surfaces. The temperature is indeed lowered by the cold front when it reaches rational surfaces; resistivity increases, thus generating an instable current profile.

The most unstable mode is the m=2, n=1 tearing mode, which is linked to most of the disrutpions' onset. A magnetic island grows when the cold front reaches the q=2 surface. This growth is faster when large amounts of gas are injected in the plasma, as seen on figure 2. Two different amounts are injected, and the island growth is faster in the large injection case. This is consistent with experimental observations showing that disruptions are triggered more rapidly when large amount of gas are injected [2].

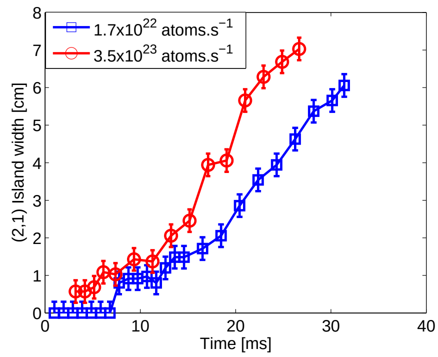

Figure 2: (2,1) island growth for two different amounts of gas

Simulations with a larger number of toroidal harmonics

A large number of toroidal harmonics allows a better toroidal resolution, and shows that neither poloidal nor toroidal homogenization in density or temperature is obtained on the disruption timescale (20 ms). High densities are transported along field lines passing near the injection point and following the edge safety factor. The toroidal peaking factor for density can exceed 1.5 in the lowest injection rate cases. Poloidal asymmetries are also observed. This stresses the importance of taking into account 3D effects when simulating massive gas injection, as some physical effects linked to the density ans temperature peaking (e.g. radiation) may be locally very intense, and could lead to damages on the main chamber.

The MHD response of the plasma during the injection was also investigated. The energy of the various MHD modes is given on figure 3 (left). Injection starts at t= 0 ms. Islands slowly grow from to time steps (a) to (b). Just before time step (b), the mode energy rapidly increases, and ergodization occurs around q=4 and q=3. Filamentary structures of density and temeprature appear in the stochastic region. These structures show a poloidal rotation, presumably because of the localization of the density source. This however, remains to be fully understood.

After a second rise in the mode energy just before time step (c), q=2 is ergodized. A decrease in the mode energy then occurs at time step (d), followed by the reappearance of magnetic islands inside the ergodic zone and by a minor flattening of the temperature profile. This may be a event similar to an internal disruption expelling energy from the core and healing rational surfaces, although it is less clear than in the experiments. The cold front then resumes its inward movement, leading eventually to the ergodization of nearly all the field lines, which means that the disruption is fully triggered. The temperature, density and Poincaré sections at time step (e) can be found on figure 3 (right). The duration of the whole process is of the same order of magnitude as the time needed to trigger a disruption with this amount of gas during experiments.

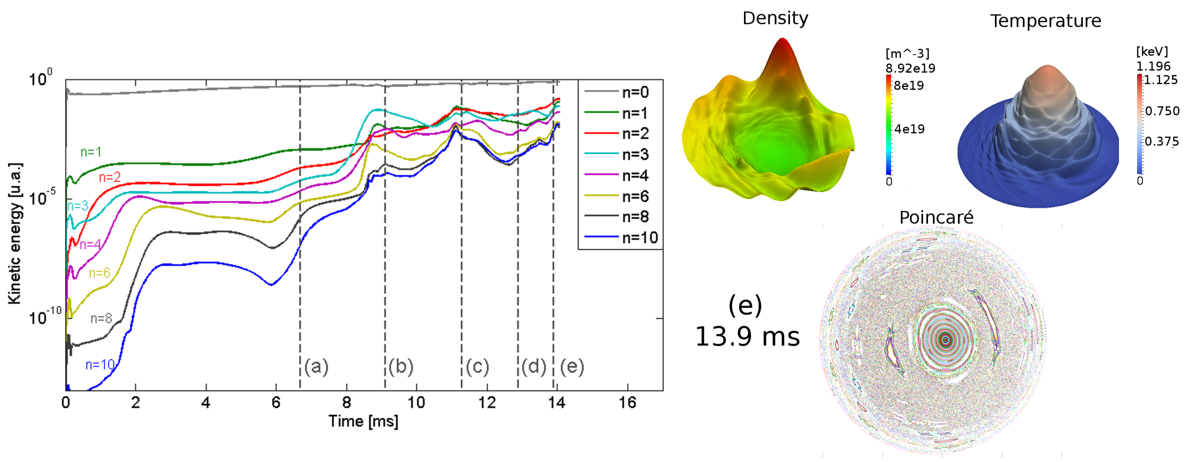

Figure 3: Left: kinetic energy of modes. Right: temperature, density and Poincaré section at time step (e)

Although the thermal behaviour of the plasma is not yet fully in quantitative agreement with the experiment, this simulation shows that JOREK is able to reproduce most of the aspects of the triggering of a disruption. This confirms also the importance of MHD in the interaction between the gas and the plasma even at the early stage of the disruption.

Conclusion and perspectives

Simulations of disruptions triggered by massive gas injections on Tore Supra were performed using the code JOREK. A neutral fluid model was implemented in the code to handle the interaction between the gas and the plasma. Results show that a cold dense front propagates inwards in the plasma, at around 20 $m.s^{-1}$, in qualitative agreement with observations. A (2,1) tearing modes is destabilized by the gas, and islands grow faster with high amounts of gas. Strong toroidal and poloidal asymmetries are also observed, with rotating density and temperature filements. Successive magnetic surfaces are stochastized by the gas injection, eventually leading to the disruption. This shows that JOREK is able to reproduce most of the aspects of a disruption triggered by massive gas injection. Perspectives for this work are to improve the neutral fluid model and the boundary conditions to be able to simulate a realistic thermal quench. Validation against experiment on X-point plasmas, full disruption simulations including the current quench and on the long term, predictive simulations for next-generation tokamaks are also planned.

References

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