Modeling of disruption mitigation by massive gas injection in JET with JOREK and IMAGINE

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Introduction

A Disruption Mitigation System (DMS) is mandatory in ITER in order to reduce electromagnetic forces, mitigate heat loads and avoid Runaway Electrons (RE) [1]. These combined objectives make the design of the DMS a complex and challenging task, for which substantial input from both experiments and modeling is needed. We present here modeling results on disruption mitigation by Massive Gas Injection (MGI), which is one of the main methods considered for the DMS of ITER.

This article is divided as follows: the first part is devoted to the study of the gas penetration into the plasma with the first-principle based 1D code IMAGINE. The second part presents simulations of MGI-triggered disruptions in JET with the 3D non-linear MHD code JOREK.

First principle modeling of neutral gas penetration during massive gas injection

IMAGINE is a 1D code in the radial direction which includes a complete model of atomic physics with ADAS coefficients. Neutral transport is convective, in agreement with first principles. The equations for a deuterium MGI derive from the mass, momentum and energy conservation, with sources taking atomic processes into account:

$$\partial_t n_e = n_e n_0 I - n_e^2 R + \partial_x (D \partial_x n_e) \tag{1}$$

$$\frac{3}{2}n_e\partial_t T_e = -n_e n_0 I(E_{ion}+\frac{3}{2}T_e) - n_e n_0 L + \partial_x(\chi n_e \partial_x T_e) - \frac{3}{2}T_e\partial_x(D\partial_x n_e) \tag{2}$$

$$\frac{3}{2}n_e\partial_t T_i = -\frac{3}{2}n_e(I+<\sigma v>_{cx})(n_0 T_i - P_0/e) + \partial_x(\chi n_e\partial_x T_i) - \frac{3}{2}T_i\partial_x(D\partial_x n_e) \tag{3}$$

$$\partial_t n_0 = -\partial_x(n_0 V_0) - n_e n_0 I + n_e^2 R \tag{4}$$

$$m_0 n_0 \partial_t V_0 = -m_0 n_0 V_0 \partial_x V_0 - \partial_x P_0 - m_0(n_0 n_e <\sigma v>_{cx} + n_e^2 R)V_0 \tag{5}$$

$$\partial_t P_0 = -V_0\partial_x P_0 - \gamma P_0 \partial_x V_0 + n_e <\sigma v>_{cx} (e n_0 T_i - P_0) - n_e I P_0 + n_e^2 R e T_i \tag{6}$$

n_e and T_e are the electron density and temperature (in eV) of the plasma, T_i is the ion temperature (in eV) of the plasma, n_0 is the neutral density, P_0 and V_0 are the pressure and radial velocity of the neutrals. We simulate the JET shot 86887, starting from experimental (n_e, T_e) plasma profiles and a realistic initial number of particles in the gas reservoir. In the simulation domain, the vacuum injection tube which links the gas reservoir and the plasma edge is also included. First, a rarefaction wave is propagating in the injection tube and we obtain the same gas flow as in laboratory experiments [2]. After 0.9 ms, the neutral gas reaches the plasma edge and starts penetrating into the plasma. Figure 1 presents the evolution of the electron temperature profile without (left) and with (right) the inclusion of charge-exchange. The slower gas penetration in the latter case is attributed to the very fast charge-exchange heating of the neutrals, which creates a shock wave slowing down the gas (see Figure 2 which presents the evolution of the neutral density profile). It is thus found that the energy transfer by charge-exchange plays a major role in the gas penetration into the plasma and is a key ingredient to recover a realistic pre-TQ time as well as a realistic increase of the plasma density.

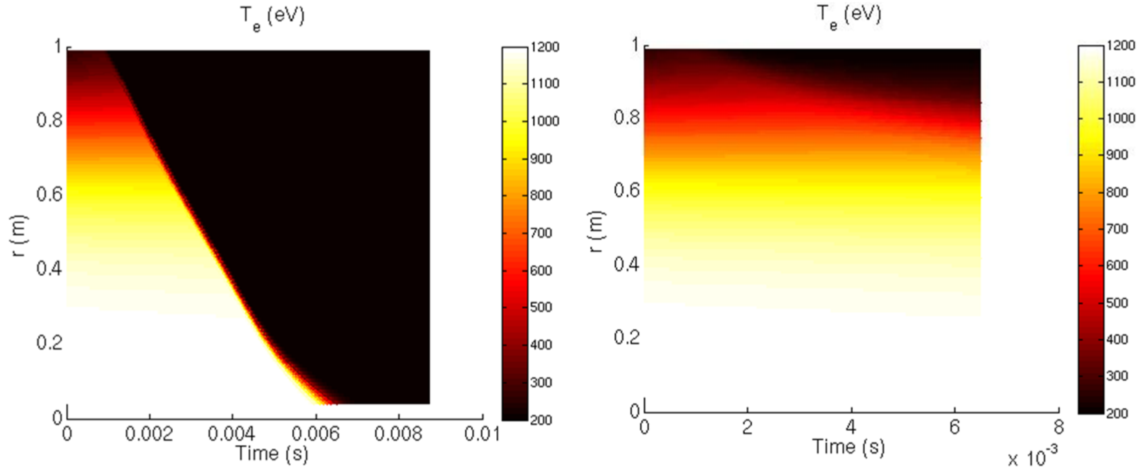

Figure 1: *Electron temperature evolution, left/right: without/with energy transfer by charge-exchange*

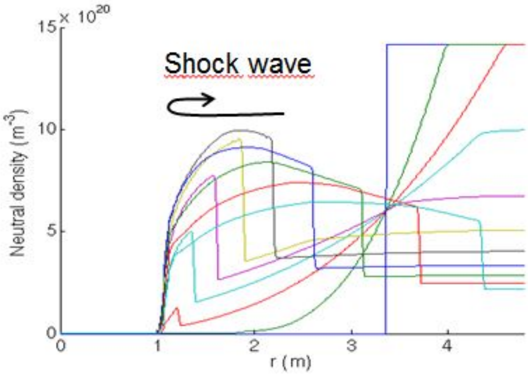

Figure 2: *Neutral density at different time steps for the simulation including energy transfer by charge-exchange*

3D non-linear MHD modeling of MGI-triggered disruptions

We now present simulations with the 3D non-linear MHD code JOREK. The code calculates the evolution of the neutral and plasma densities, plasma temperature, plasma velocity and electromagnetic field, giving access to key quantities which are not directly measurable, e.g. the toroidal electric field responsible for the creation of REs. The aim at present is to validate the code, for which purpose we simulate a relatively simple case: MGI of pure D_2 during the same recent JET shot (86887) as simulated with IMAGINE. The appropriate atomic physics for a D_2 MGI (see equations below) is included but the modeling of the gas injection and the transport of neutrals is simplified compared to IMAGINE. The MGI is treated as a volumetric source term S_n which is calibrated so as to match the experimental density measurements using synthetic interferometers.

$$\frac{\partial \rho}{\partial t} = -\boldsymbol{\nabla}\cdot(\rho \boldsymbol{v}) + \boldsymbol{\nabla}\cdot(D_\perp \boldsymbol{\nabla}_\perp \rho + D_\parallel \boldsymbol{\nabla}_\parallel \rho) + \rho\rho_n S_{ion}(T) - \rho^2 \alpha_{rec}(T) \tag{7}$$

$$\begin{aligned}\frac{\partial(\rho T)}{\partial t} = -\boldsymbol{v}\cdot\boldsymbol{\nabla}(\rho T) - \gamma\rho T \boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{\nabla}\cdot(\kappa_\perp \boldsymbol{\nabla}_\perp T + \kappa_\parallel \boldsymbol{\nabla}_\parallel T) + \frac{2}{3R^2}\eta_{\text{Spitzer}}(T) j^2 \\ -\xi_{ion}\rho\rho_n S_{ion}(T) - \rho\rho_n L_{lines}(T) - \rho^2 L_{brem}(T)\end{aligned} \tag{8}$$

$$\frac{\partial \rho_n}{\partial t} = \boldsymbol{\nabla}\cdot(\boldsymbol{D}_n : \boldsymbol{\nabla}\rho_n) - \rho\rho_n S_{ion}(T) + \rho^2 \alpha_{rec}(T) + S_n \tag{9}$$

Other synthetic diagnostics have been implemented in JOREK and the results of the simulations are compared to the experiment in [4]. The MHD activity is dominated by internal kink modes and tearing modes ($m/n = 2/1$ and $3/2$) and is qualitatively similar to the experiment. Compared to the results presented in [4], a much higher MHD activity is now observed due to the reduction of the hyperresistivity used in the simulations. In Figure 3, magnetic fluctuations are plotted and an important burst of MHD is observed. At the peak of MHD activity, small scale structures of toroidal current density are observed (middle) and the Poincare plot (right) shows that the magnetic field is stochastic across the whole plasma (weakly stochastic in the core). The evolution of the electron temperature at the center is also plotted and shows that the temperature is still high (few hundreds of eV) after the MHD burst, even including a background of impurities, indicating that the simulations do not reproduce a complete thermal quench. This may come from a too low parallel heat conductivity in these simulations. This hypothesis is currently being tested.

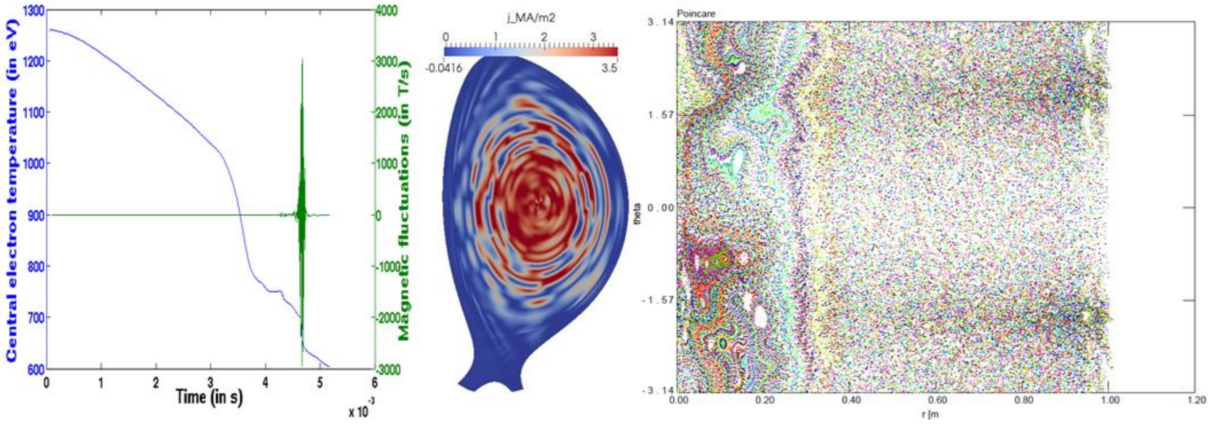

Figure 3: *Central electron temperature and magnetic fluctuations evolution (left). Poloidal cross-section of the toroidal current density (middle) and Poincare plot (right) at the peak of MHD activity.*

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