EFDA–JET–CP(14)03/37

A. Fil, E. Nardon, P. Beyer, M. Becoulet, G. Dif-Pradalier, V. Grandgirard,
R. Guirlet, M. Hoelzl, G.T.A. Huijsmans, G. Latu, M. Lehnen, A. Loarte,
F. Orain, S. Pamela, C. Passeron, C. Reux, F. Saint-Laurent, P. Tamain
and JET EFDA contributors

Modelling of Disruption Mitigation by Massive Gas Injection

Modelling of Disruption Mitigation by Massive Gas Injection

A. Fil[1], E. Nardon[1], P. Beyer[5], M. Becoulet[1], G. Dif-Pradalier[1], V. Grandgirard[1],
R. Guirlet[1], M. Hoelzl[2], G.T.A. Huijsmans[3], G. Latu[1], M. Lehnen[3], A. Loarte[3],
F. Orain[1], S. Pamela[4], C. Passeron[1], C. Reux[1], F. Saint-Laurent[1], P. Tamain[1]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France
[2]Max-Planck-Institut fur Plasmaphysik, EURATOM Association, 85748 Garching, Germany
[3]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067, St Paul lez Durance
[4]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[5]International Institute for Fusion Science, CNRS Université de Provence, 13397 Marseille
** See annex of F. Romanelli et al, "Overview of JET Results",*
(24th IAEA Fusion Energy Conference, San Diego, USA (2012)).

Preprint of Paper to be submitted for publication in Proceedings of the
41st EPS Conference on Plasma Physics, Berlin, Germany
23rd June 2014 – 27th June 2014

1. INTRODUCTION

A disruption mitigation system is mandatory in ITER in order to reduce electromagnetic forces on the structures, mitigate heat loads and avoid the generation of runaway electrons which occurs during disruptions. Massive Gas Injection (MGI) is foreseen in ITER to trigger a “controlled” disruption in order to greatly reduce the potential damage on the tokamak compared to an unmitigated one [1]. However, mitigating all effects of a disruption at the same time is challenging. Modeling is therefore needed to provide insights into the physics involved and inputs to support the design of the MGI system in ITER. This article is divided as follows: the first part presents simulations of JET disruptions triggered by MGI with the 3D non-linear MHD code JOREK. The second part is devoted to simulations of the penetration of the neutral gas into the plasma with the 1D fluid code IMAGINE.

2. 3D NON-LINEAR MHD MODELING OF A JET DISRUPTION

JOREK is a 3D non-linear MHD code which accounts for realistic flows and diamagnetic effects [2].

2.1 MODEL.

The JOREK model we use includes an equation for neutral density with a source term for MGI injection, an ionization term and a transport of neutrals supposed diffusive. Ionization of neutrals also adds terms in the equations of ion density, energy and momentum.

2.2 SIMULATION PARAMETERS.

We simulate JET Pulse No: 77803 which is an Ohmic plasma with pure Argon MGI. The initial profiles of electron density and temperature are obtained from HRTS (High Resolution Thomson Scattering) measurements. The neutral source term is poloidally localized at the experimental position of the JET disruption mitigation valve [3]. The Lundquist number at the center in the simulation is $S_0 = 2.10^7$, a value allowing to account for the main physics effects within reasonable computational time. The resistivity is proportional to $T_e^{3/2}$.

The toroidal Fourier harmonics n=0,1,2 are included.

2.3 RESULTS.

With this model and these parameters, a Thermal Quench (TQ) is obtained after 50ms lasting less than 1ms. More precisely, the following sequence of events is observed. The MGI increases the electron density at the edge up to $10^{20}\,m^{-3}$ which is 3 times the initial central density and cools down the edge of the plasma with a cold front penetrating inward from the edge to the $q = 2$ surface at a speed of $10\ m.s^{-1}$. The increase of the plasma resistivity in the cooled region leads to a contraction of the current profile which destabilizes a $(m,n) = (2,1)$ tearing mode 40 ms after the beginning of the injection (when the cold front reach the $q = 2$ surface), giving rise to a clearly visible magnetic island chain (see figure 1a,b). About 10 ms later, a (3,2) mode grows rapidly, leading to fine structures on the current density distribution (figure 1c) and to the flattening of the whole temperature profile within 1ms (figure 1d). This seems to be the consequence of field line stochastization over the whole plasma (figure 2).

2.4 DISCUSSION

The simulated TQ duration is similar to the experiments on JET (1ms) and so is the number of electrons added to the plasma when the TQ occurs (5.10^{23}) [1]. On the other hand, the cooling phase duration (40ms) is too large compared to the experiments, which is likely to be a consequence of the simpified atomic physics in the current MGI model in JOREK. Present work is devoted to improving this part and the results of the 1D code presented in this paper will help defining the best MGI model for JOREK.

Another observation is that a temperature gradient remains at the edge, which prevents the temperature from decreasing to very small values. This could be due to a stabilization of the edge modes caused by the fixed ψ boundary conditions. Simulations with JOREK-STARWALL are currently on-going to account for resistive wall physics [4]. Finally, we note that the TQ is not associated to a (1,1) internal kink mode, which is in contrast with [5] and other disruption simulations.

3. 1D MODELING OF THE GAS PENETRATION INTO THE PLASMA EDGE

3.1 MOTIVATIONS

Mechanisms governing the gas penetration into the plasma and the cooling phase dynamics and duration are still unclear (compare e.g. [6] and [7]). In JOREK, neutrals transport has been assumed diffusive, which does not directly stem from first principles. In order to shed some light on these questions, a 1D first principles based fluid code, IMAGINE, has been developed.

3.2 MODEL

IMAGINE includes a complete model of atomic physics with ADAS coefficients. All ionization states are followed. Neutral transport is convective, in agreement with first principles. The equations are the following:

$$\frac{\partial n_e}{\partial t} = \sum_{k=0}^{Z-1} n_e n_k I_k - \sum_{k=1}^{Z} n_e n_k R_k \tag{1}$$

$$\frac{\partial T_e}{\partial t} = \frac{2}{3}\left(-\sum_{k=0}^{Z-1} n_k I_k \left(E_{ionk} + \frac{3}{2} T_e\right) - \sum_{k=0}^{Z} n_k L_k\right) \tag{2}$$

$$\frac{\partial n_0}{\partial t} = -\nabla.(n_0 V_0) + n_e(R_1 n_1 - I_0 n_0) + S_{n_0} \tag{3}$$

$$\frac{\partial n_k}{\partial t} = n_e(R_{k+1} n_{k+1} + I_{k-1} n_{k-1} - (I_k + R_k) n_k) \tag{4}$$

$$\frac{\partial P_0}{\partial t} = -V_0 \cdot \nabla(P_0) - \frac{5}{3} P_0 \nabla . V_0 \tag{5}$$

$$\frac{\partial V_0}{\partial t} = -V_0 \cdot \nabla V_0 - \frac{1}{m_0 n_0} \nabla(P_0) - \alpha_{fric} n_1 \sigma_{cx} V_{Th_{i+}} V_0 \tag{6}$$

Where n_e and T_e are the electron density and temperature, n_0 is the neutral density (currently Ar or D can be chosen), $n_k(k = 1; :::;Z)$ are the successive impurity ions, P_0 and V_0 are the neutral pressure and radial velocity. All other quantities are atomic physics parameters (ionization and recombinaison). Neutral transport is convective and a friction between neutrals and impurity ions is taken into account. An original aspect of this code is that the simulated domain comprises not only the plasma but also the gas reservoir and the vacuum tube. In terms of numerics, a MUSCL scheme is used to deal with shock waves [9].

3.3 RESULTS

Simulations of Argon and Deuterium MGI in JET have been carried out. In both cases, the gas propagation into the vacuum injection tube is similar to the experimental observations [5] with the formation of a rarefaction wave and a velocity of $3 \cdot c_s$ for the first particles (figure 3a), where cs is the sound velocity in the reservoir. Consequently, the neutral flux at the edge is realistic. Then, the neutral gas starts cooling down the plasma (figure 3b). A cold front velocity of a fraction of c_s is found, which is of the same order of magnitude as the experiment. This velocity depends weakly on the number of particles injected (figure 3c) and on the friction coefficient α_{fric} between neutrals and ions. Here, we assume that the friction is dominated by charge-exchange and that the ionized impurities are at rest (strong braking assumption).

3.4 DISCUSSION

It should be noted that ionized impurities are not necessarily at rest: they can progress radially due to the E×B drift but they undergo braking forces (see [7] for details). However, our strong braking assumption already leads to the right order of magnitude for the cold front velocity. The weak effect of friction may be due to the accumulation of neutrals behind the front. Future work will be devoted to comparing the simulations with experimental results from JET, ASDEX-U and Tore Supra for different gases.

CONCLUSION

First thermal quench simulations have been made with the 3D non-linear MHD code JOREK. The TQ is triggered by a massive gas injection and lasts less than 1 ms which is good agreement with experiments. Moreover, a 1D code, IMAGINE, has been developed to better understand the mechanisms that play a key role in the gas penetration into the plasma and the cooling phase. First results show that this model recovers the right order of magnitude for the gas and cold front velocities. Future studies will aim at an improvement of the JOREK MGI model and a detailed comparison with the experiment for both JOREK and IMAGINE.

ACKNOWLEDGEMENTS

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

REFERENCES

[1]. Lehnen M., et al., Nuclear Fusion **51** (12), 123010 (2011)

[2]. Huysmans G.T.A, et al., Plasma Physics and Controlled Fusion **51**, 124012 (2009)

[3]. Finken K.H., et al., Nuclear Fusion **51**, 033007 (2011)

[4]. Hölz M. Journal of Physics: Conference Series **401**, 012010 (2012)

[5]. Izzo V.A. Nuclear Fusion **46**, 541 (2006)

[6]. Bozhenkov S.A., et al., Nuclear Fusion **51**, 083033 (2011)

[7]. Rozhansky V., et al., Nuclear Fusion **46**, 367 (2006)

[8]. Parks P.B., et al., Nuclear Fusion **54**, 023002 (2014)

[9]. Van Leer B., Journal of Computational Physics **32**, 101-136 (1979)

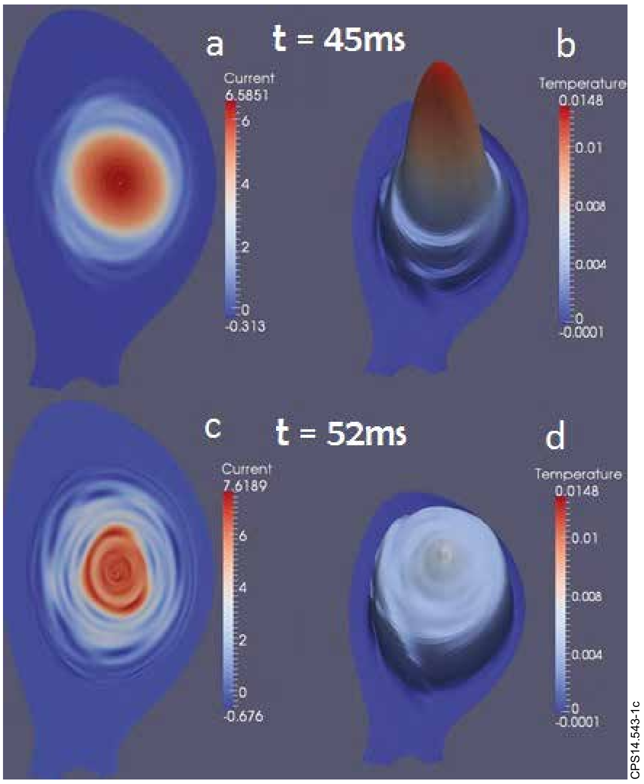

Figure 1: Toroidal current density (a and c) and temperature (b and d) before (top) and after (bottom) the thermal quench.

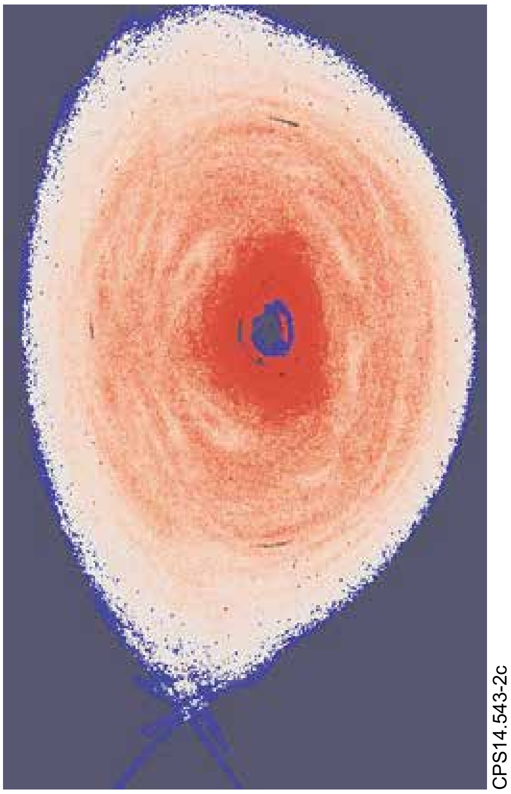

Figure 2: Poincare plot during the TQ.

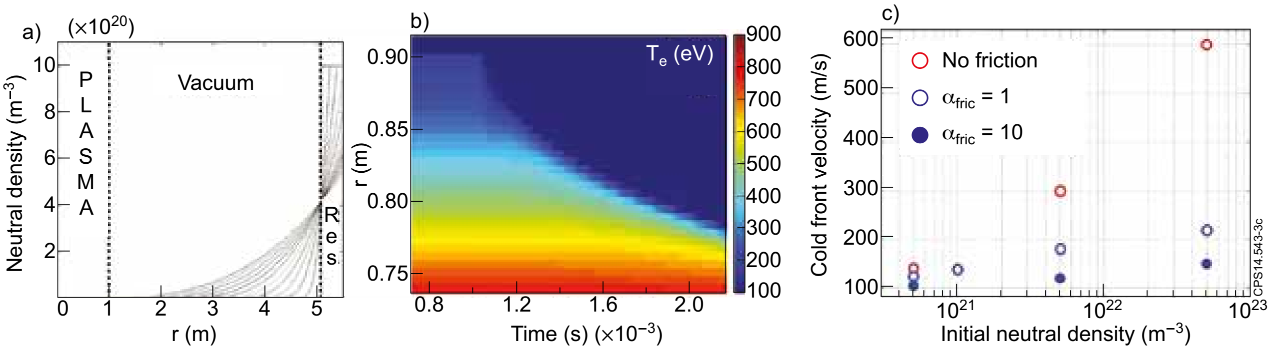

Figure 3: IMAGINE simulation results for a MGI of deuterium in JET: (a). Successive neutral density profiles, (b). Evolution of electron temperature, (c). Influence of friction parameter and number of particles injected on the cold front velocity.