EFDA–JET–CP(09)06/36

M. Lehnen, A. Alonso, G. Arnoux, S.A. Bozhenkov, S. Brezinsek, T. Eich,
K.H. Finken, A. Huber, S. Jachmich, U. Kruezi, P.D. Morgan, V.V. Plyusnin,
C. Reux, V. Riccardo, G. Sergienko, M.F. Stamp and JET EFDA contributors

First Experiments on Massive Gas Injection at JET - Consequences for Disruption Mitigation in JET and ITER

First Experiments on Massive Gas Injection at JET - Consequences for Disruption Mitigation in JET and ITER

M. Lehnen[1], A. Alonso[2], G. Arnoux[3], S.A. Bozhenkov[1], S. Brezinsek[1], T. Eich[4], K.H. Finken[1], A. Huber[1], S. Jachmich[5], U. Kruezi[1], P.D. Morgan[3], V.V. Plyusnin[6], C. Reux[7], V. Riccardo[3], G. Sergienko[1], M.F. Stamp[3] and JET EFDA contributors*

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

[1]Institute for Energy Research - Plasma Physics, Forschungszentrum Jülich, Association EURATOM-FZJ, Trilateral Euregio Cluster, 52425 Jülich, Germany
[2]Laboratorio Nacional de Fusion, Asociacion EURATOM-CIEMAT, Madrid, Spain
[3]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[4]Max-Planck-Institut für Plasmaphysik, EURATOM-Assoziation, D-85748 Garching, Germany
[5]Laboratoire de Physique des Plasmas-Laboratorium voor Plasmafysica, Association EURATOM-Belgian State, ERM/KMS, B-1000 Brussels, Belgium
[6]Instituto de Plasmas e Fusão Nuclear/IST, Associacao EURATOM-IST, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
[7]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
** See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

Preprint of Paper to be submitted for publication in Proceedings of the
36th EPS Conference on Plasma Physics, Sofia, Bulgaria.
(29th June 2009 - 3rd July 2009)

1. INTRODUCTION

The mitigation of thermal and mechanical loads during disruptions is an urgent task to be solved for ITER to ensure the integrity of Plasma-Facing Components (PFC). However, extreme loads are already an issue for present day machines like JET and in particular for the new ITER-like wall implemented in JET which will have the material used in ITER for DT operation. Reduction of such loads to tolerable values is needed, thereby, the generation of high-energy electrons (RE) is of special concern. RE in JET can carry currents of up to 50% of plasma current before the disruption, leading to a fast and localised deposition of several MJ on plasma-facing components.

Disruption mitigation has to fulfil three aims: *mitigation of forces* by halo and eddy currents, *mitigation of convective heat loads* during the thermal quench, mitigation of heat *loads by runaway electrons*. ITER needs a reduction of the forces by a factor 3−5 and a reduction of the thermal loads on Be and W components by a factor 10 to ensure integrity and lifetime of PFC [2]. A fast valve (Disruption Mitigation Valve- DMV) has been recently installed at JET to study disruption mitigation by massive gas injection [1]. The valve is positioned on top of the machine and the gas is guided by a 4m long tube to the plasma. Gas species in-vestigated so far were neon, argon and mixtures of these with 90% of D_2. A maximum of 2.5×10^{23} particles can be injected.

Figure 1 shows the sequence of a typical induced JET disruption caused by injection of about 4×10^{22} Neon atoms, which is the lower bound in the experiments reported here. After the activation of the DMV, the gas flows through the tube and arrives after a delay of 4ms at the plasma edge. At that time the cooling of the plasma edge starts as indicated by the edge electron temperature. Eventually, the thermal quench is triggered when the cooling front arrives at a critical flux surface and the remaining thermal energy is released within less than 1ms. The thermal quench is followed by the decay of the plasma current caused by the generation of a low temperature plasma.

2. MITIGATION OF FORCES

Halo currents can generate strong forces on the vessel and on inner wall structures. Especially, the product of halo current fraction I_{halo}/I_P and toroidal peaking factor TPF has to be limited to ensure the integrity of ITER wall components. The product $I_{halo}/I_P \times TPF$ can be reduced by a factor of 4 down to 0.1 as shown in previous JET experiments, if the thermal quench is initiated before a significant vertical movement of the plasma has taken place [5].

Two timescales are of importance for successful mitigation of these forces: the delay from valve activation to thermal quench and the current decay time. The delay to thermal quench includes the flight time of the gas from the valve to the plasma edge and the duration of the edge cooling process prior to the initiation of the thermal quench. The flight time depends on the sound speed $c0$ of the injected species, and, thus on the mass: $\Delta t = L/2.5c_0$, where $L = 4.0$m and $c_0 \sim 1 = \sqrt{M}$. This minimum flight time has been found in the experiment by taking the decay of the electron temperature in the outer-most channel of the ECE diagnostic as indicator for the gas arrival. The flight time varies from 6.2ms for argon to 2.3ms for a mixture of 10% neon and 90% deuterium.

The cooling duration, given in figure 2, decreases with the injected amount of gas. A dependence on thermal energy was found only for small injections of about 5×10^{22} particles. The dependence vanishes at maximum injection rates due to the fact that an ELM event is triggered in the cooling phase, which leads to a sudden loss of energy in the plasma edge and a fast cooling towards the critical flux surface. The existence of this critical flux surface was confirmed by a variation of the safety factor q_{95}; the cooling phase duration increases with higher q_{95}. The shortest delay from DMV activation to thermal quench of about 7ms has been achieved with the N_e/D_2 mixture at q_{95} = 5.1. Lower q_{95} for the deuterium mixtures have not yet been addressed in the experiment. The growth time of VDEs in JET varies between 2 and 10ms. Thus, a reduction of the halo current fraction could be achieved marginally. This could be improved, if the VDE is detected not by the displacement itself, but by a failure detection in, for example, coil currents.

The linear current decay time normalised to the plasma cross-section area before the disruption is given in figure 3. This decay time has been extrapolated from the decay time from 100% to 70% of the plasma current to avoid any influence from the runaway current plateau in the case of pure Ar and N_e injection. The fastest current decay is found for pure argon injection, which lies even below the minimum value of 1.7ms/m^2 allowed for ITER. A faster current decay has to be avoided in ITER to keep forces from eddy currents below the design value.

3. MITIGATION OF HEAT LOADS

A reduction of convective heat flux can be obtained by increasing the impurity concentration in the edge plasma before the thermal quench. This is in contrast to non-MGI disruptions, where the impurities (in JET carbon) are released during the thermal quench by the high heat fluxes to the divertor or other plasma-facing components. Direct measurements of the reduction of heat °flux in the divertor is difficult, because of strong background radiation caused by the injected impurities. Moreover, the energy is not only distributed to the observed divertor targets, but due to the broadening of the SOL during the thermal quench to structures further away from the separatrix. IR thermography measurements in the divertor show a broadening of the footprint by about a factor of 5, comparable to natural disruptions. A full energy balance is thus challenging.

Because of the above mentioned difficulties an energy balance is done by comparing the radiated energy during the disruption measured by bolometry with the thermal and magnetic energy stored in the plasma before the disruption. The radiated energy is

$$W_{rad} = f_{mag} \times (W_{mag} - W_{mag}^{structure} - \mathrm{W}_{mag}^{RE} + f_{th} \times W_{th} ,$$

with $f_{mag} \approx 1$; it was shown for JET that almost 100% of the ohmic power during the current quench is dissipated by radiation [4]. In the following, we analyse disruptions with Ne/D_2 and Ar/D_2 injection, which show no generation of runaways (W_{mag}^{RE} = 0). In figure 4 the radiated energy is shown as function of the thermal energy. The plasma current is 2MA, the magnetic energy $W_{mag} = 6.9 \pm 0.3$MJ, accordingly.

With the assumption that the dissipation of magnetic energy in the structure $W_{mag}^{structure}$ is constant for these disruptions, we find that about 50% of the stored thermal energy is radiated during the thermal quench. For comparison disruptions with slow gas injection (10^{22} atoms/s), a $q = 2$ disruption, caused by deliberate ramp-down of the toroidal magnetic field, and natural disruptions from a broader JET database with the same magnetic energy are shown. The reference disruptions without gas injection show no dependence on *Wth* and a higher *Wstructure mag* as seen from the extrapolated offset in W_{rad} at $W_{th} = 0$.

Because of runaway generation, such an analysis for pure argon and neon injection is challenging.

4. GENERATION AND MITIGATION OF RUNAWAY ELECTRONS

Runaway generation is observed with injection of pure neon and argon in JET. Argon injection leads for all possible gas amounts to a current plateau with up to 1MA of runaway current for these 2MA pulses. Runaway generation during Neon injection is much weaker and occurs in most cases in the tail of the current quench phase.

The primary generation of runaway electrons during disruptions is in present-day tokamaks caused by the Dreicer mechanism. In ITER other sources of runaway electrons will exist. The primary runaways are then multiplied by the avalanche process. Suppression of the Dreicer mechanism happens at densities of the order of $10^{20}\ m^{-3}$ in JET, whereas the suppression of the avalanche requires a total electron density (free and bound) of $n_e^{tot} = 5\times10^{22}\ m^{-3}$ at $E = 50V/m$. To reach these high densities, a high fuelling efficiency is required.

Figure 5 shows the amount of impurities in the current quench plasma as function of the total injected amount of impurities. The plasma impurity concentration was estimated from a simple 0-d model for the current quench [3]. The calculated plasma current was fitted from 100% to 50% of the initial current. This procedure was chosen, because a direct measurement of the density by the JET interferometer is only possible up to the time of thermal quench and again at the very end of the current quench. The dotted green line indicates an estimate of the maximum amount of carbon atoms released during non-MGI disruptions [6]. A low fuelling efficiency of about 2.5% is found for argon, whereas 5% is found for neon. The low fuelling efficiency is caused by the fact, that only a fraction of the gas arrives in the plasma before the thermal quench, as can be seen from lab measurements and gas flow models [7]. Higher fuelling efficiencies can be achieved by using deuterium as carrier: 10% and 25% for Ar/D_2 and Ne/D_2, respectively. Because of the higher electron densities for the mixtures, runaway generation was completely suppressed.

CONCLUSIONS

Reduction of halo currents during VDE by MGI in JET has not been directly studied yet. However, a comparison of timescales shows that mitigation could be feasible for JET, if other precursors than directly the vertical displacement can be exploited. In ITER, the mitigation of forces is much easier, because of the slowly developing VDE. The eddy current limit has to be considered, when increasing the amount of injected gas to values necessary for avalanche suppression. A reduction of heat loads by 50% is expected in JET from radiation measurements. Suppression of runaway electrons has been achieved by injection of Ar/D_2 and Ne/D_2 mixtures. This is important for the protection of the new ITER-like wall in JET, especially to prevent the beryllium PFC from melting. The maximum amount of injected electrons during MGI in JET is about a factor 50 below the amount needed for avalanche suppression, which will become essential in ITER. The timescale on which the gas is to be injected is given by the cooling duration. This parameter needs to be extrapolated towards ITER. A short distance between valve and plasma in JET and later in ITER is expected to be essential for a fast reaction time and a high fuelling efficiency.

ACKNOWLEDGEMENTS

This work, supported by the European Communities under the contract of Association between EURATOM/FZJ, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1]. U. Kruezi *et al.*, this conference.

[2]. M. Sugihara, ITPA-MDC meeting Daejeon, Korea, April 2009.

[3]. S.A. Bozhenkov *et al.*, Plasma Physics Controlled Fusion **50** (2008) 105007.

[4]. J.I. Paley *et al.*, Journal Nuclear Materials **337-339** (2005) 702.

[5]. V. Riccardo, private communication.

[6]. M. Lehnen *et al.*, Journal Nuclear Materials **390-391** (2009) 740.

[7]. S.A. Bozhenkov *et al.*, this conference.

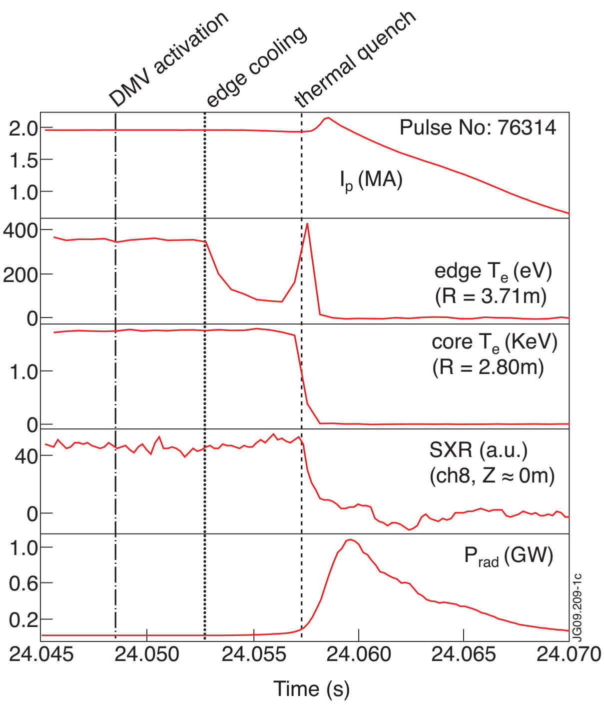

Figure 1: Disruption sequence. Neon injection, N = 4×10^{22}.

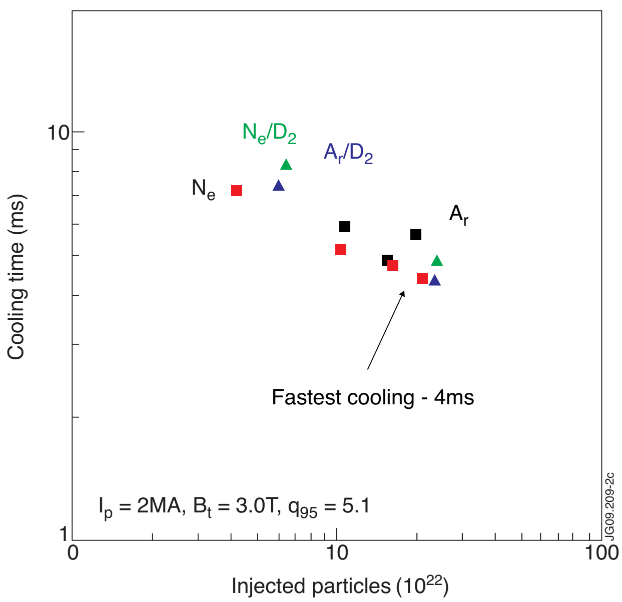

Figure 2: Duration of the cooling phase.

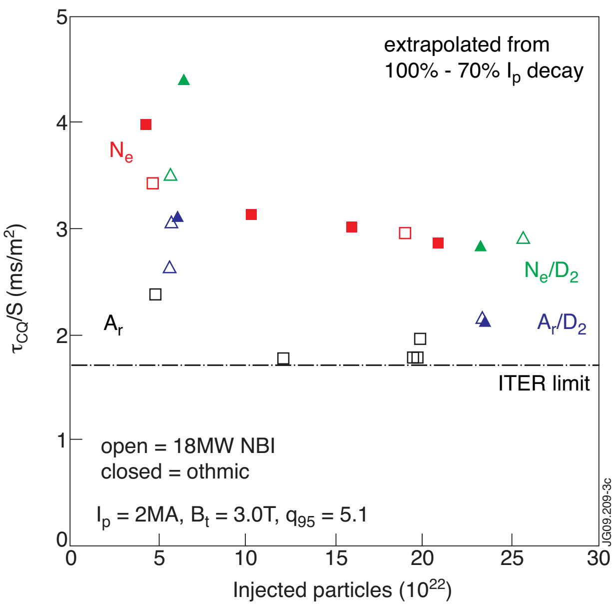

Figure 3: Current decay time.

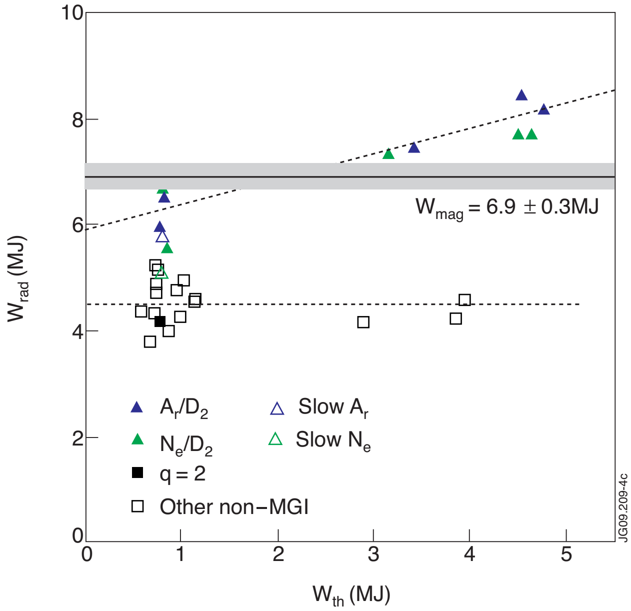

Figure 4: Radiated energy.

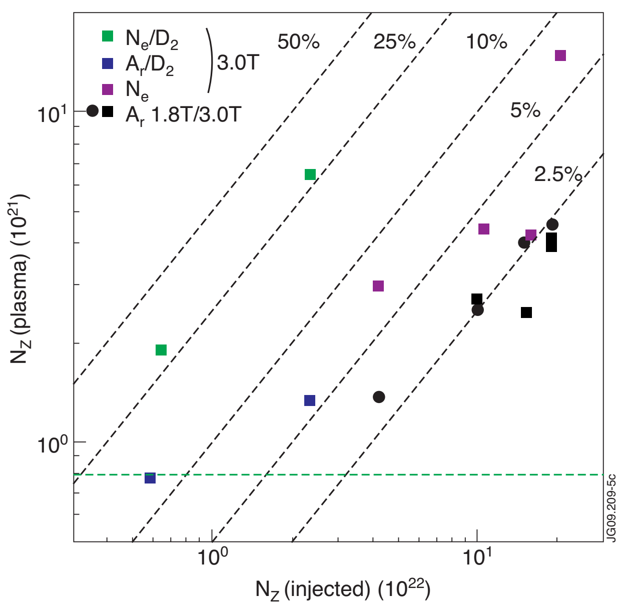

Figure 5: Fuelling efficiency. NZ represents only Ne or Ar for the deuterium mixtures.