Demonstration of rapid shutdown using large shattered deuterium pellet injection in DIII-D

2010 Nucl. Fusion 50 112001

(http://iopscience.iop.org/0029-5515/50/11/112001)

IOP Publishing and International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion **50** (2010) 112001 (4pp) doi:10.1088/0029-5515/50/11/112001

LETTER

Demonstration of rapid shutdown using large shattered deuterium pellet injection in DIII-D

N. Commaux[1], L.R. Baylor[1], T.C. Jernigan[1], E.M. Hollmann[2], P.B. Parks[3], D.A. Humphreys[3], J.C. Wesley[3] and J.H. Yu[2]

[1] Oak Ridge National Laboratory, Oak Ridge, TN, USA
[2] University of California San Diego, San Diego, CA, USA
[3] General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA

Received 7 May 2010, accepted for publication 18 August 2010
Published 8 September 2010
Online at stacks.iop.org/NF/50/112001

Abstract

A severe consequence of a disruption on large tokamaks such as ITER could be the generation of multi-megaelectronvolt electron beams that could damage the vacuum vessel and the structures of the machine if they hit the wall unmitigated. The mitigation of runaway electron beams is thus a key requirement for reliable operation of ITER. In order to achieve reliable disruption mitigation, a new fast shutdown technique has been developed: the injection of a large shattered cryogenic pellet in the plasma, which is expected to increase the electron density up to levels where the beam generation processes are mitigated by collisional losses. This technique has been implemented and tested for the first time ever on DIII-D. The first tests show evidence of an almost instantaneous deposition of more than 260 Pa m^3 of deuterium deep in the core. Record local densities during the thermal quench were observed for each injection with a very high reliability. Pellet mass and plasma energy content scans show an improvement of the assimilation of the particles for higher plasma energy and larger pellet mass.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Prevention and mitigation of the damages due to disruptions are essential to reliable operation of the ITER tokamak. Because of the high thermal and poloidal magnetic energy content of the plasma (1.3 GJ total stored energy during the 500 MW inductive scenario), three different kinds of deleterious effects from disruptions have the potential to induce damages to the machine: convective heat loads to the plasma facing components, poloidal halo currents in the vacuum vessel which generate mechanical stress and the generation of multi-megaelectronvolt electron beams called runaway electrons that can damage the vacuum vessel or the supporting structures if they hit the wall. This necessitates that ITER will strongly rely on active disruption avoidance and, if the disruption cannot be prevented, on disruption mitigation through rapid shutdown strategies. Currently, the most promising rapid shutdown technique that has been tested on present day tokamaks is the injection of massive amounts of gas (several 100 Pa m^3 in DIII-D for example) in the plasma. This massive gas injection (MGI) technique has been proven to mitigate both heat loads on the first wall and halo currents on the vacuum vessel [1] when compared with natural disruptions.

In ITER, the runaway electrons are expected to be mainly generated through an avalanche process [2, 3]. Theory predicts that the avalanche generation process can be compensated (thus mitigated) by collisional losses at high density levels. It is necessary to reach an electron density, known as the Rosenbluth density (n_{eRos}), in order to mitigate the avalanche process such that the toroidal electric field generated during a disruption by possible magnetic reconnections and/or by the plasma current fast decay is lower than a critical value E_{c}:

$$E_{\mathrm{c}} = \frac{q_{\mathrm{e}}^3(2n_{\mathrm{e}} + n_{\mathrm{bound}})}{4\pi\varepsilon_0 m_{\mathrm{e}} c^2} \ln\Lambda. \qquad (1)$$

In this equation, n_{e} is the free electron density and n_{bound} is the bound electron density. Thus for typical tokamak plasma parameters and assuming that the toroidal electric field is generated mainly by the plasma current decay, n_{eRos} is expected to be $\sim 5 \times 10^{22}$ m^{-3}. This value appears to be rather constant for different tokamaks including DIII-D and ITER. Thus injecting a large number of particles in order to reach the

Rosenbluth density could potentially be an efficient method to mitigate runaway electrons.

In order to achieve such large injection of particles, a new technique has been employed on DIII-D: large shattered pellet injection. This technique consists of using a pipe gun cryogenic pellet injector called the shotgun pellet injector (SPI) [4, 5], which injects a large cryogenic pellet (15 mm diameter and 20 mm length) into the plasma. Just before the pellet enters the plasma it is shattered into small fragments by impacting on two metal plates. The pellet is shattered to protect the inner wall which could be damaged by the intact pellet. Shattering the pellet also increases the pellet surface area and generates a gas and liquid spray in order to increase the ablation rate, thus increasing the assimilation efficiency (fraction of the particles injected that effectively enter the plasma) of the material by the plasma.

This system has been tested recently on DIII-D in order to characterize the fast shutdown triggered by the shattered pellet injection. Seven discharges were successfully terminated by the injection of a deuterium shattered pellet. The typical plasma parameters during these experiments were a toroidal field of 2.1 T, plasma current of 1.3 MA and neutral beam injection power range 2.3–6.5 MW. The pellets injected in these plasmas were deuterium pellets injected with a speed range 500–600 m s^{-1} and mass range (1.6–2.6) × 10^{23} atoms (measured with a microwave cavity at the exit of the barrel). In this paper, the next section presents the general results of these first tests. The density levels achieved and particle assimilation are more specifically described in the third section. The penetration of the particles is studied in the fourth section. To conclude, the possible improvements of this technique are discussed.

2. Characteristics of an SPI induced shutdown

A typical fast shutdown triggered by a shattered pellet injection is shown in figure 1. This figure shows the main phases of the fast shutdown: the thermal quench (TQ) and the current quench (CQ). The shattered pellet induces a rapid (typically 2–3 ms) increase in the electron density, which triggers a TQ: the plasma almost completely loses its thermal energy (through radiation and convection). This cooling of the plasma is followed by strong MHD activity that triggers the CQ: a rapid decay of the plasma current (usually less than 15 ms on DIII-D). The different characteristics of the fast shutdowns triggered by a shattered pellet appear similar to shutdowns with deuterium MGI using comparable amounts of gas (∼400 Pa m^3). The plasma current decay timescale is ∼4.7 ms, which is consistent with the values observed during equivalent quantity low Z (H_2, D_2 or He) gas injection. This fast current decay (when compared with an unmitigated current decay timescale which can be 15 ms or more) produces an efficient reduction in the poloidal current generated during the CQ thus reducing the mechanical stress on the vacuum vessel as shown on figure 2: the poloidal halo currents and the vessel vertical displacement during a SPI shutdown are comparable to the typical values observed during a MGI shutdown and are approximately two times lower than the values during an unmitigated disruption.

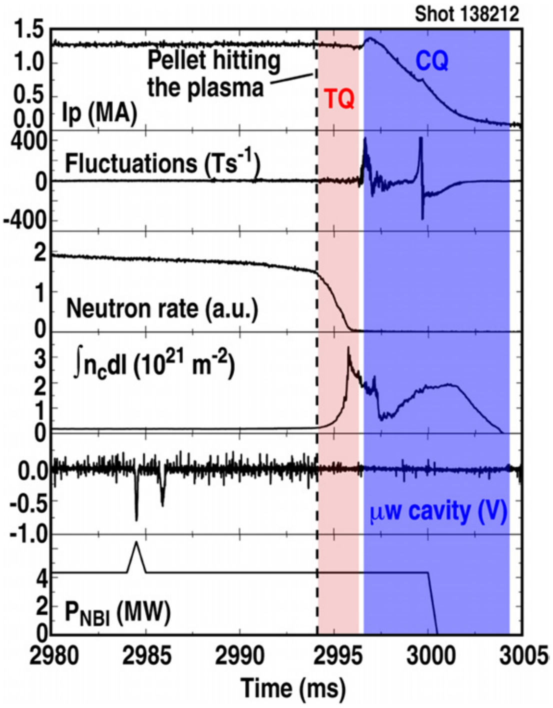

Figure 1. Typical plasma parameters during a shattered pellet fast shutdown. From top to bottom: the plasma current, magnetic fluctuations, neutron rate, line integrated density; pellet mass detector signal and neutral beam power.

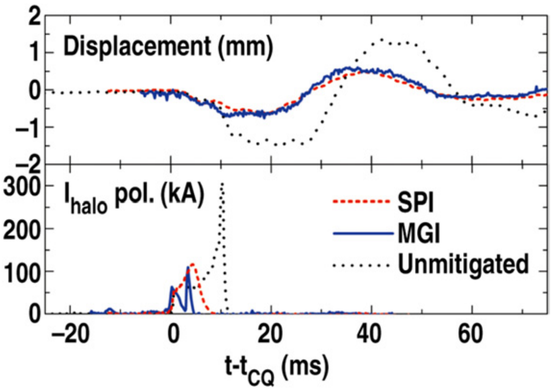

Figure 2. Comparison of the typical values of the measured poloidal halo current (bottom) and vertical vessel displacement (top) during a SPI (dashed lines), a MGI (solid line) and an unmitigated disruption (dotted line).

3. Density perturbation

The most important part of these experiments is to characterize the density perturbation induced by the SPI. As mentioned in the introduction, the mitigation of the runaway generation process in ITER is theoretically achievable by reaching very high density levels close to n_{Ros}. In order to examine the density perturbation, several SPI shutdowns in different plasma conditions have been performed. A pellet mass scan was performed in order to test if the amount of particles injected has an effect on the density perturbation. An energy scan was performed to test if increasing the thermal energy available to ablate the pellet fragments injected in the plasma has an

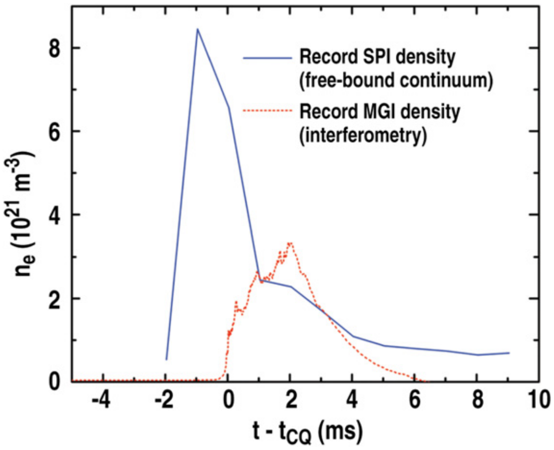

Figure 3. Comparison of the electron density measured during the DIII-D record SPI and the DIII-D record MGI.

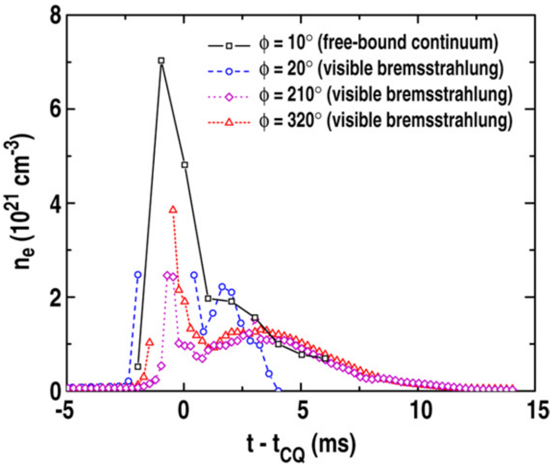

Figure 4. Electron density measurements (using interferometry and spectral analysis) at different toroidal angles during a SPI shutdown on DIII-D.

effect on the density. Three values of pellet mass have been tested: 1.6×10^{23}, 2.1×10^{23} and 2.6×10^{23} atoms. By changing the amount of neutral beam power injected in the plasma, two different thermal energy content levels were used: 610 and 840 kJ. Normally, a CO_2 interferometer is used to measure the plasma electron density in DIII-D. Unfortunately the interferometer could not provide reliable data during these experiments because of a large refraction of the CO_2 beam in the plasma at high density. The electron density was thus evaluated using various spectral analysis techniques: Stark broadening, free-bound continuum brightness and visible bremsstrahlung brightness. The main technique that was used to evaluate the free electron density close to the injection port during the whole disruption was the brightness of the deuterium Lyman free-bound continuum. It provided the evaluation of the density (with a 30% error bar mainly due to the accuracy of the diagnostic) even during the TQ since it uses features of the base continuum instead of line emissions which usually saturate the detectors during this highly radiative phase. Figure 3 shows a comparison of the density measurement during the DIII-D record SPI (free-bound continuum measurement) with the density measured (CO_2 interferometer) during the DIII-D record MGI. This comparison shows that the local densities achieved during a SPI rapid shutdown are higher than the densities observed during the record MGI case. The fact that these two measurements were not performed with the same technique is because the interferometer data were not reliable during the SPI experiment and the free-bound continuum brightness was impossible to measure in the MGI experiment due to impurity lines 'polluting' the spectrum. But in lower density cases, when both techniques are available, they agree within 10% indicating that the comparison should be pretty accurate. But this comparison has to take into account the possible toroidal density asymmetries that can occur on such short timescales. To study these asymmetries, several diagnostics were used to acquire visible or UV spectra around the DIII-D torus. Through spectral analysis, it was possible to evaluate the density and the temperature at several toroidal locations (even though these diagnostics were saturated during the TQ). Figure 4 shows the different density values measured at several toroidal angles. During the TQ, the measurements at $\phi = 10°$ (almost at the injection port) and at 210° show very different results. This yields a very strong density asymmetry. Figure 4 shows that this asymmetry begins to relax at the beginning of the CQ: the different measurements become consistent with each other. This results in a toroidally symmetric average density of $\sim 1 - 2 \times 10^{21}\,\mathrm{m}^{-3}$, very close to the record density achieved using similar quantities of hydrogen during a MGI (as shown in figure 3). The temperature measurements show that during the fast shutdown the electron temperature was 1–5 eV. This would indicate that the ionization fraction of the gas was close to 1 so n_{bound} in equation (1) is in this case much lower than n_e: the free electrons are the only significant one contributing to the mitigation in these injections. The preliminary pellet size and plasma energy scans tend to show that the maximum density perturbation increases linearly with the size of the pellet and the plasma energy content (from $1.8 \times 10^{21}\,\mathrm{m}^{-3}$ to $8.4 \times 10^{21}\,\mathrm{m}^{-3}$).

4. Penetration

One difference between the SPI and MGI shutdowns that could change the efficiency of runaway mitigation is the depth of the deposited mass inside the plasma. Several experiments have shown that the MGI deposition (during the TQ) is at the edge of the plasma [6, 7]. The SPI deposition is significantly different. A fast framing camera was used to image the plasma in the vicinity of the injection port. The images show penetration of the pellet fragments almost to the centre of the plasma. The deeper penetration can also be observed by bolometric tomography achieved using a poloidal bolometer array implemented on DIII-D [6, 8]. Figure 5 shows a comparison between the radiated power contours obtained by tomography of bolometry signals during the TQ for a typical MGI case and a typical SPI case. This figure shows that the poloidal radiation pattern is somewhat different in the two cases. In the MGI case, the radiation is localized in the scrape-off layer and in the vicinity of the injection port (upper port on DIII-D). In the SPI case, the radiation appears to be localized deeper in the plasma and is not localized close to the injection port (same port as MGI), which indicates that there is a strong mixing of the injected particles deep into the

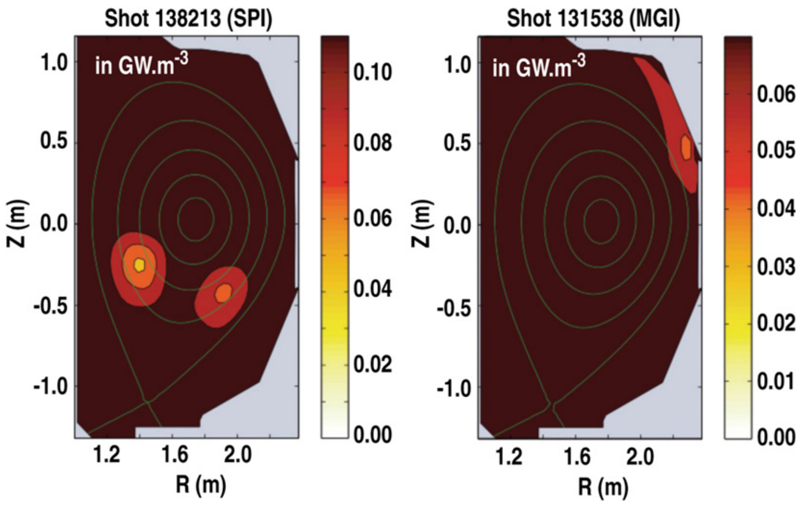

Figure 5. Contours of radiated power from bolometer tomography at the beginning of the TQ for a typical SPI shutdown (on the left) and a typical MGI shutdown (on the right).

background plasma. This could be significant for runaway electron mitigation since the runaways are expected to be generated mainly at the centre of the plasma and not at the edge.

5. Conclusion

The SPI technique has been successfully tested on DIII-D and showed for the first time that large shattered pellet injection could be used as a fast shutdown technique to mitigate the consequences of a disruption. The mitigation of the halo currents and vessel forces appears comparable to that observed using strong MGI on DIII-D. These experiments have also shown a very strong density perturbation of the order of the maximum MGI case on DIII-D during the first attempt despite the fact that the system is still to be optimized. The assimilation efficiency appears to be close to the highest values for MGI but is difficult to measure. These preliminary results appear very promising and show that the shattered pellet injection could be a useful fast shutdown technique for ITER. In the future, different higher Z gases, in particular neon, should be tested providing more electrons per pellet volume for injection into the discharge. The trade-off between a higher number of electrons and the higher radiation losses due to line emissions should be tested. The timing of the density perturbation has also to be studied in future experiments since the electron density appears to drop rapidly after the onset of the CQ which could lower the efficiency of the runaway mitigation. The other main improvement that should be studied is the way the pellet is shattered. Some measurements show that the mass of the fragments is ~30% of the total mass after being shattered (the rest is gas or very small droplets). These solid fragments are the part of the mass that is expected to inject particles deep in the core of the plasma. Therefore maximizing the fraction of solid surviving the shattering process could be beneficial.

Acknowledgments

This work was supported in part by the Oak Ridge National Laboratory managed by UT-Battelle, LLC for the US Department of Energy under DE-AC05-00OR22725 and partially supported by the US Department of Energy under DE-FG02-07ER54917, DE-FG02-95ER54309 and DE-FC02-04ER54698.

References

[1] Taylor P.L. *et al* 1999 *Phys. Plasmas* **6** 1872
[2] Rosenbluth M.N. and Putvinski S.V. 1997 *Nucl. Fusion* **37** 1355
[3] Connor J.W. and Hastie R.J. 1975 *Nucl. Fusion* **15** 415
[4] Baylor L.R. *et al* 2009 *Nucl. Fusion* **49** 085013
[5] Combs S.K. *et al* 2010 *IEEE Trans. Plasma Sci.* **38** 400
[6] Hollmann E.M. *et al* 2008 *Nucl. Fusion* **48** 115007
[7] Bozhenkov S.A. *et al* 2008 *Plasma Phys. Control. Fusion* **50** 105007
[8] Gray D.S. *et al* 2004 *Rev. Sci. Instrum.* **75** 4133