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Disruption mitigation experiments carried out using the new shattered pellet injection on DIII-D

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1. Introduction

Prevention and mitigation of the harmful effects from disruptions are essential to reliable operation of ITER. One of the potentially most harmful effects from a disruption is the generation of runaway electrons (RE). These high energy (several 10 MeV) focused electron beams can damage elements of the first wall if they strike and penetrate the material surfaces. Thus new rapid shutdown strategies have been recently tested in the DIII-D tokamak to mitigate RE. Among the new techniques developed to mitigate RE, one of the most promising is the shattered pellet injection (SPI) [1]. The RE generation process in ITER is expected to be mainly from avalanche multiplication, which can be mitigated by collisionnal losses at high electron density levels, n_{crit} [2]. The SPI technique consists of the injection of a large cryogenic pellet (15 mm × 20 mm on DIII-D) in order to reach n_{crit}. Before entering the plasma, the pellet is shattered into sub-millimeter fragments by impacting on two metal plates. Shattering the pellet increases surface area for a more efficient ablation (according to preliminary 1D calculations) and protects the first wall from possible damage by impact from an intact pellet. This technique has been tested on DIII-D. The DIII-D SPI system injects enough particles into the plasma to reach an average electron density close to n_{crit}. Experiments were carried out using the SPI technique to terminate successfully 6 discharges. The plasma conditions in these discharges were a toroidal field of 2.1 T, plasma current of 1.5 MA and neutral beam injection power of 013.4 MW. The pellets injected in these discharges were deuterium pellets injected with a speed range of 500-600 m/s and containing $\sim 1.9\times10^{23}$ atoms. In this paper, the next section presents the density perturbation process during an SPI fast shutdown. A comparison between SPI and massive gas injection (MGI) (same gas and quantities) is described in the third section. The last section will present the conclusions for this new fast shutdown technique.

2. Density perturbation following a shattered pellet injection

The main purpose of SPI, as described in Sec. 1, is to increase the density of the plasma up to levels close to n_{crit}. This n_{crit} value is estimated using a 0D calculation of the toroidal electric field generated during the current quench (CQ) by the plasma current decay. In the fastest plasma current decay cases in DIII-D, this value is estimated at ~5×10^{22} m^{-3}. This value appears also to be rather constant for different tokamaks including ITER. The main goal of the experiments carried out on DIII-D was to study the density perturbation occurring from SPI in different plasma conditions and compare it with n_{crit}. These experiments enabled a study of this perturbation as a function of the thermal energy content of the plasma. The initial thermal plasma energy was changed using the neutral beam power injected in the discharge resulting in thermal energy contents varying from 170 kJ up to 1600 kJ. The local density at the injection location was measured using the visible bremsstrahlung emission of the plasma measured with several visible spectrometers. The results of this study are summarized in Fig. 1. In this set of experiments, the size of the deuterium pellet was kept constant at 1.9×10^{23} atoms. The local peak density appears to increase linearly with the thermal energy content. These measurements taken at different toroidal locations enabled also a lower bound estimate (because of signal saturation) of the total number of electrons N_{tot} in the discharge during the disruption. A typical example of the time evolution of N_{tot} during a SPI induced fast shutdown is shown in Fig. 2. This figure shows first that the maximum N_{tot} value is ~4.5×10^{22} electrons, which indicates a 24% assimilation efficiency during an SPI induced shutdown. This

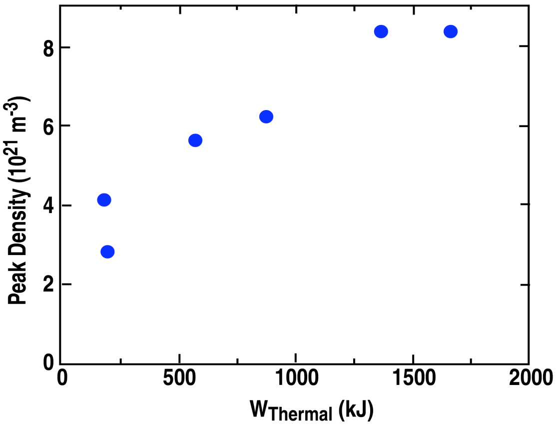

Fig. 1. Peak density observed after a shattered pellet injection as a function of the thermal energy content of the discharge.

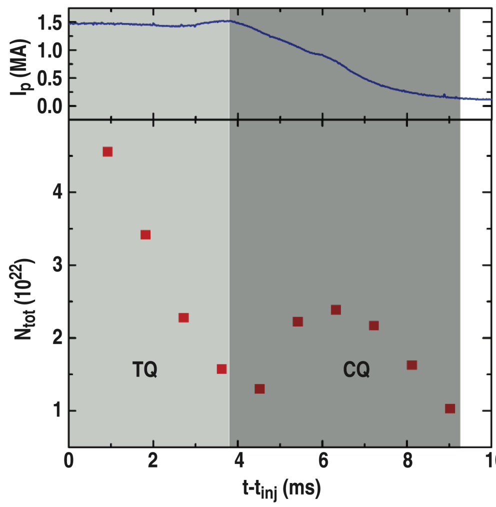

Fig. 2. Plasma current (upper) and N_{tot} (lower) during an SPI-induced shutdown with thermal energy content of 1600 kJ (t_{inj} being the injection time). The light shaded area shows the TQ phase and the dark shaded one the CQ phase.

assimilation efficiency appears to increase weakly with the thermal energy content of the discharge for the NBI heated discharges (the efficiency varying between 18% and 24% for thermal energy content varying between 172 and 1660 kJ). The ohmic case (lowest energy cases in Fig. 1) seems to be an exception: the assimilation process appears to be longer thus improving the assimilation when compared to a weakly heated discharge. Figure 2 shows also that N_{tot} varies significantly during the fast shutdown: it decays very fast during the thermal quench (TQ), but starts to increase again after the onset of the CQ. The fast decrease during the TQ can be explained by the cooling of the plasma lowering the ionization rate. But not why it increases at the beginning of the CQ. Since the heating power is rather constant during this phase, the fact that N_{tot} increases could indicate an improvement of the particle confinement at the beginning of the CQ possibly due to a re-healing of the magnetic surfaces destroyed during the TQ MHD activity. These measurements show that the moment at which n_{crit} can be achieved during a fast shutdown is also an important parameter since N_{tot} can vary significantly.

3. Comparison between SPI and MGI

The experiments carried out recently on DIII-D provided for the first time a direct comparison between the MGI and SPI techniques using the same plasma target, the same injected species (deuterium) and the same amount of particles injected (~1.9×10^{23} electrons). These experiments showed that the SPI allows a comparable mitigation of heat loads and vessel forces to the MGI. The other important measurements that are compared are the maximum assimilation fraction and the time delay between the injection and the assimilation: the particles have to be in the discharge before the avalanche process has occurred in order to mitigate it. The only available data for a direct comparison of the density perturbation between MGI and SPI is the

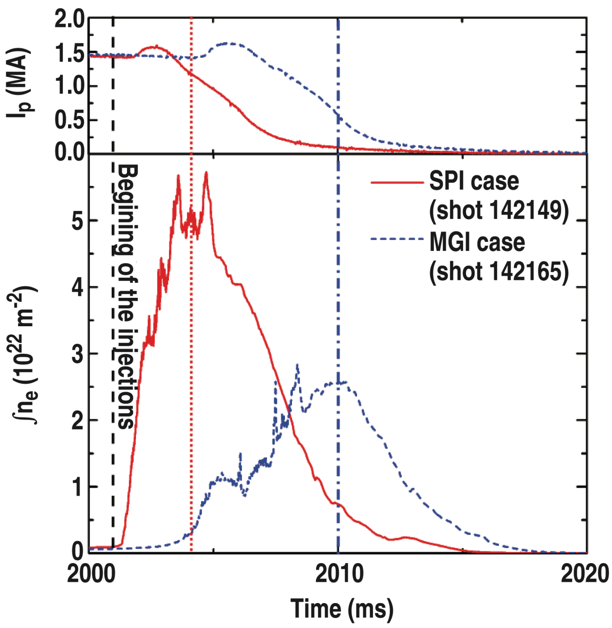

Fig. 3. Line-integrated density during a SPI (solid) and MGI (dashed) rapid shutdown of an ohmic plasma. The dotted and dash-dotted lines show the time when the density starts to roll over for respectively the SPI and MGI cases.

interferometry data during the ohmic cases (the interferometry data during NBI heated discharges are impossible to analyze because of laser refraction by the plasma). Figure 3 shows the line-integrated density during an ohmic plasma rapid shutdown using comparable MGI and SPI. Since the central interferometry chord is located at a toroidal location 150 degrees apart from the injection location, this density measurement shows the particles that have already been transported and homogenized in the plasma. This figure shows that the maximum line integral density in the SPI case is twice as high as the maximum MGI density. This results in an assimilation efficiency of ~10%–15% for MGI compared to the 20%–25% for the SPI (as described in Sec. 2). The other important point in this figure is the timing of the homogenization process. Despite a faster CQ onset (the MGI and SPI both hit the plasma at t = 2001 ms), the SPI reaches the maximum density when the plasma current is still at 1.2 MA (80% of the initial current). The MGI case reaches its maximum density when the plasma current is down to 0.6 MA (40% of the initial current). This faster rise of the density for the SPI all around the torus can have a significant effect on the efficiency of the collisional mitigation since the avalanche process depends on the absolute value of the plasma current as well as on the toroidal electric field (dI_p/dt). This faster rise of the density could indicate different transport mechanisms. The SPI would rely on parallel transport in the core plasma since it appears to penetrate much deeper than MGI. Particles from MGI would propagate initially at the edge as colder and slower neutrals then mix with the plasma due to major MHD events during the CQ [3].

4. Conclusion

The SPI technique using deuterium reached higher densities when the avalanche process is at its highest efficiency in DIII-D than with deuterium MGI. It appears to be a possible RE mitigation system for major tokamaks because of the high assimilation fraction and the fast delivery of the particles. The homogenization process appears to play an important role in reaching high densities when the avalanche multiplication process is taking place.

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[1] S.K. Combs, et al., IEEE Transactions on Plasma Science **38** (2010) 400

[2] M.N. Rosenbluth, et al., Nuclear Fusion **37** (1997) 1355

[3] E.M. Hollmann, et al., Nuclear Fusion **48** (2008) 115007