Disruption and Runaways Electron Mitigation Studies on Tore Supra

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Abstract. Disruptions are a major threat for future tokamaks, including ITER. The excessive heat loads, the huge electromagnetic forces and the runaway electrons (RE) production generated by the disruptions will not be tolerable for next-generation devices. Massive noble gas injection (MGI) is foreseen as a standard mitigation system for these tokamaks. Disruption mitigation experiments have been carried out on Tore Supra to investigate gas jet penetration and mixing. Comparisons of different noble gases (He, Ne, Ar, He/Ar mixture) and amounts (5 to 500 Pa.m3) were made, showing that light gases are more efficient regarding runaway electron suppression than heavier gases. Eddy currents in the limiter are moderately reduced by all the gases. Gas jet penetration in the cooling phase is observed to be shallow and independent on the gas nature and amount. The gas cold front is stopped along the q=2 surface where it triggers MHD instabilities, expelling thermal energy from the plasma core. Finally massive gas injection was triggered on an already developed RE plateau. Analysis of the toroidal asymmetry of photoneutron production indicates that the REs are slowing down on neutrals and/or background plasma. They experience also a larger transverse transport toward the wall.

1. Introduction

Disruptions are a major threat for future reactor-size tokamaks. Due to a sudden loss of plasma confinement and the associated plasma energy release, they produce excessive heat loads on plasma facing components, induce strong electromagnetic forces and currents in the structures, and can generate multi-MeV runaway electrons (RE). While these consequences are tolerable for nowadays tokamaks, they will overcome the mechanical and thermal limits of components for larger tokamaks. Disruption mitigation is therefore essential for next-generation tokamaks, including ITER [1].

Massive Gas Injection (MGI) is one of the techniques foreseen as a standard mitigation system for future devices. It aims at reducing the deleterious effects of the disruption. MGI experiments have been carried out on several tokamaks. A list of references can be found in ref [2]. Encouraging results have been obtained, with reductions of electromagnetic forces, halo currents, thermal loads and beneficial effects on runaway electrons generation. However, the injection scenario (gas species and amount) for larger devices is still an open question.

In this paper, disruption mitigation experiments performed on Tore Supra tokamak with a fast valve are reported. The experimental setup is described in Section 2 and the consequences of a MGI on RE production and disruption effects are presented in Sections 3 and 4. The gas jet dynamic and the gas penetration are analyzed in section 5. The effects of a MGI triggered on a RE plateau following a disruption are presented in section 6.

2. Experimental Setup

The experiments presented in this paper were performed using Tore Supra's massive gas injector [3]. This injector is a ferromagnetic valve, whose maximum gas capacity is 2×10^{23} atoms. It is located on the top of the machine, 1.6 meter away from the plasma edge. It opens in less than 1 ms, and delivers its gas load in 40 ms. Location of diagnostics used for the analysis is showed on figure 1. This includes a far-infrared (FIR) interferometer (16 μs time resolution), a fast-framing camera (visible light, 1 ms to 10 µs time resolution), Soft X-ray (SXR) tomography arrays (0 to 20 keV, 4 µs time resolution), bolometer cameras (0.2 – 200 nm, 2 ms time resolution), Mirnov coils for MHD analysis and neutron sensors [4].

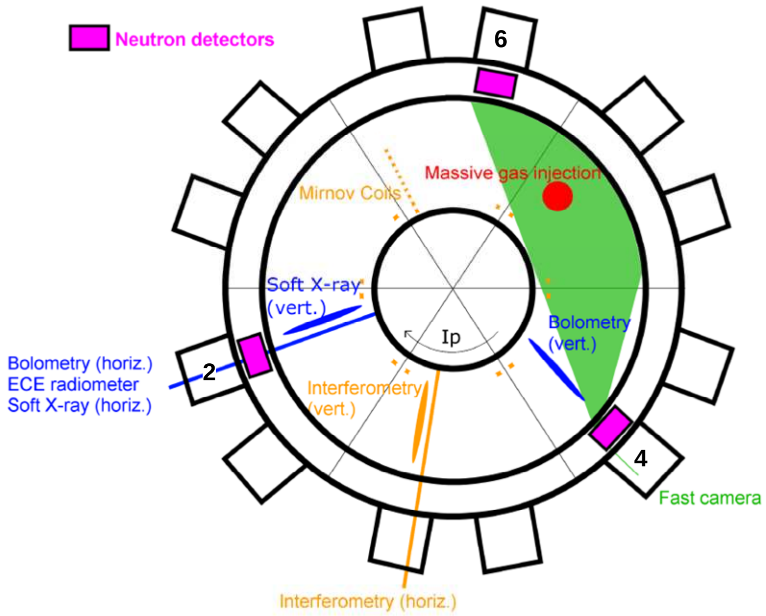

FIG. 1. Location of relevant diagnostics on Tore Supra - View from the top of the torus.

For disruption mitigation studies, several injection scenarios were performed using different gases in various amounts. The experiments were carried out with helium, neon, argon and a helium/argon mixture (95%-5%), from 5 to 500 Pa.m3. Helium was already successfully tested during previous experiments [3], and was found to suppress runaway electrons. The different gas sorts were mostly injected into the same target plasma: plasma current: 1.2 MA, central line-integrated density: 5×10^{19} m^{-2}, R = 2.37 m, a = 0.72 m. All tests were done on stable plasmas: disruption is induced by MGI. This guarantees that the results can be reproduced shot-to-shot

For MGI on RE plateau experiments, the disruption was triggered by Neon puffing using standard gas fuelling system during the plasma current ramp-up. Within these conditions it was found that a long RE plateau may develop [5]. Then, the disruption detection triggered the MGI after an adjustable delay.

3. Runaway Electron Production

The photoneutrons, produced when the multi-MeV electrons hit the first wall, are used to monitor the amount of RE. Helium-mitigated disruptions showed a reduction by 2 to 3 orders of magnitude in runaway production [3]. Present experiment shows that no dependence to the He injected amount (from 20 to 500 Pa.m^3) is observed. Using 10 Pa.m^3 Helium injections, REs are sometimes produced. Helium/Argon mixture is as efficient as pure Helium. Conversely Argon and Neon do not prevent RE generation. Moreover Argon generates even more RE with increasing amounts of gas. Such findings have also been observed on recent JET experiments [6].

Primary runaway electrons are created when the collisional drag force becomes weaker than the acceleration by the parallel electric field $E_{//}$ induced by the plasma current quench or the flattening of the current profile during the thermal quench. The primary RE production rate can be calculated using Dreicer model [7]. It strongly depends on the electron density and no production can occur when the density overcome the Dreicer limit.

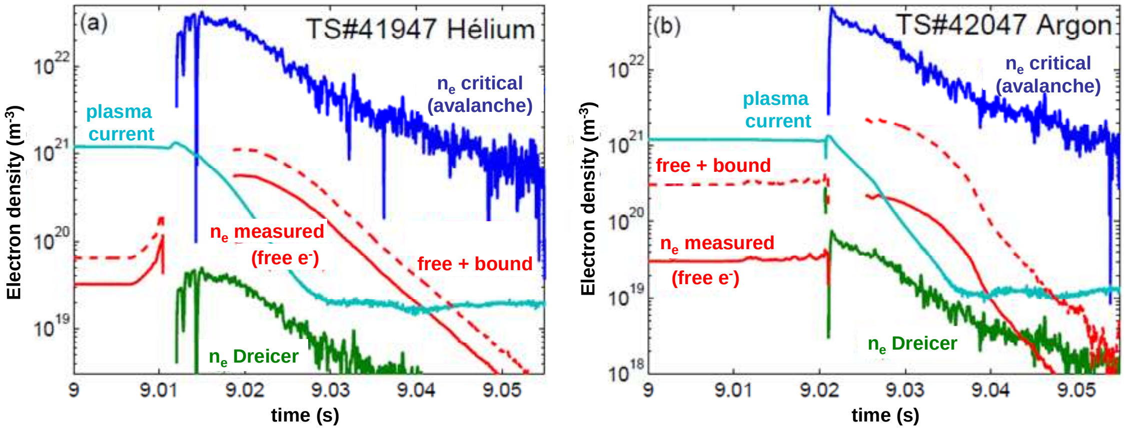

FIG. 2. Critical densities during MGI mitigated disruptions. Free electron density measurement (solid red curve) is not available at the beginning of current quench (fringe jump and laser refraction). Corrected electron density for bound electron is drawn (dashed red curve).

The maximum of $E_{//}$ which occurs at the beginning of the current quench has been estimated using a 0D model [2]. Selecting a threshold at $E_{//} < 0.01 \times E_{Dreicer}$ for suppressing primary generation, the density needed to suppress the primary mechanism is around 5×10^{19} m^{-3}. The average free electron density during the current quench, measured by FIR interferometer, is shown in figure 2 for helium and argon gases. After correction for bound electrons we found that both gases can increase the density beyond the minimum Dreicer value ("n_e Dreicer" in FIG.2). These findings remain valid when considering the non thermal electron production in cooling plasma. The model of reference [8] was thus applied given a RE suppression for He MGI [5].
Secondary runaway electrons are produced by collisions between already accelerated electrons and electrons from the background plasma. If given enough energy due to the toroidal electric field generated by the current quench, these cold electrons may run away. This avalanching process, driven by an amplification factor, is foreseen to be dominant for ITER (amplification factor up to 2×10^{16}). It can be suppressed by increasing the electron density above the critical density given by Rosenbluth [9]. This higher limit "n_e critical" is never reached in the present MGIs (FIG.2) but the amplification factor remains low (≈ 20) on Tore Supra.
According to the free electron density measurement, primary mechanism should be suppressed by all the massive gas injections. However, runaway electrons are observed during neon and argon mitigations. The electric field calculation performed here is indeed 0-D: peaking of the electric field profile is not taken into account. When the thermal quench occurs, the flattening of the current profile responsible for the current spike at the beginning of the disruption generates a localized parallel electric field in the plasma core. This huge electric field (up to 50 V/m) [5] generates REs which are driven towards the wall by MHD activity. For heavy gases a small population might survive when MHD activity reduces even more the initial population is expected to be enlarged for argon injections.

4. Electromagnetic effects

Due to the circular shape of Tore Supra plasmas, electromagnetic effects during the disruption involve mainly eddy currents and electromagnetic forces. Halo currents are not measured but are expected of minor importance for a circular plasma configuration.

The current quench duration is slowed down by MGI, associated to a reduction of $|dI_p/dt|_{max}$ (30% to 50% slightly depending on the gas). The larger density either modifies the internal inductance leading to a peaking of current profile or reduces the plasma resistivity. Both will enlarge the current quench characteristic time.
The eddy currents in the toroidal pumped limiter are only moderately reduced by all the gases. The reduction is independent of the amount of gas: 5 Pa.m^3 are as efficient as 500 Pa.m^3. This suggests that the eddy current reduction may be more dependants on the time constants of the machine structure rather than on the gas species. This is supported by a simple model describing the electrical circuits [2].

5. Gas Jet Penetration and Dynamic

Following the time evolution of the free electron density measured by the FIR interferometer, the fuelling efficiency has been investigated. Due to its higher speed velocity light gas penetrates more rapidly, and the density rise is steeper. Helium adds at least 2 times more free electrons to the plasma than Argon. Finally the thermal quench (TQ) is triggered at much higher density with Helium. These findings could explain the observed RE suppression when using light gases.
The gas penetration was studied using a fast framing visible camera equipped with interference filters [10]. The emissive front is thus supposed to be the region where the ionization of neutrals takes place. The analysis of camera pictures allows localizing objects (like a flux surface) at given time stamp (FIG.3.).

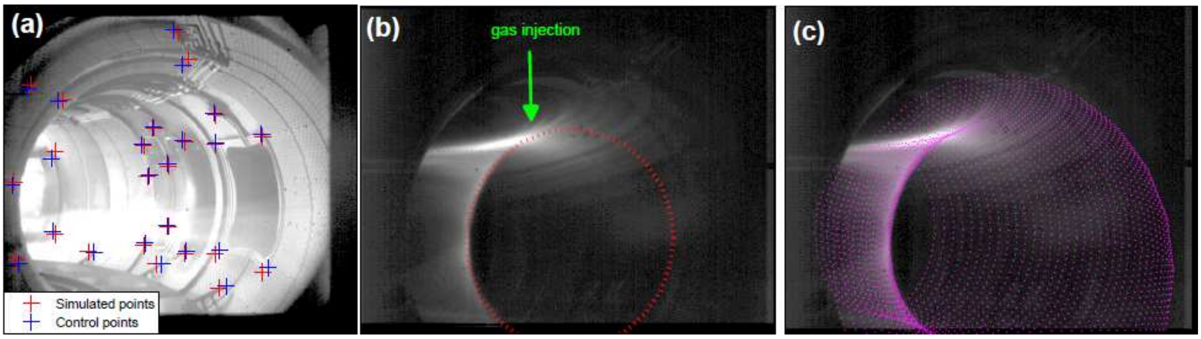

FIG. 3. Fast camera pictures reconstruction - (a) control points vs. simulated points. (b) Gas front during MGI shot. (c) Corresponding flux tube.

The cold front speed inside the plasma ranges from 20 m/s for weak Argon injection to 120 m/s for large helium injections.
On the contrary the penetration depth seems to be independent of the nature and amount of gas. The gas jet is seen to be blocked along or near the q=2 flux surface, whatever the plasma current is. This finding remains valid when modifying the plasma electron temperature and/or current profile using Lower Hybrid (LH) additional heating (from 1 MW to 3.5 MW) [2].
The role of q=2 surface is supported by Soft X-ray (SXR) observations. During the mixing phase of a MGI shot, edge SXR chords drop slowly as the gas moves inwards, indicating a temperature drop (FIG.4, time 1). When the gas front reaches q=2 a sudden drop is recorded on central SXR chord (FIG.4, time 2). It is associated to a “bounce” seen on the fast visible camera, as if the radiating front moved backwards (FIG.4, time 3). This bounce may be understood as a sudden burst of energy from the core which ionizes all the neutral gas near the rational surface, hence making it disappear in visible light. This explanation is confirmed by the temperature drop seen by the SXR central chord: a part of the energy is expelled towards the plasma edge. This phenomenon could explain the shallow penetration of the neutrals and

its dependence to the position of the rational surfaces. As the gas approaches q=2 surface, it triggers an MHD instability (tearing mode ?) enhancing the radial energy transport, ionizing all the gas in the vicinity, and thus preventing neutrals from penetrating further into the plasma. Analysis of Mirnov coils measurements shows that this mode has a n=1 structure and its frequency lies between 1 and 5 kHz (FIG.4c.). Depending on the amount of energy stored in the core and the amount of gas injected, the plasma stability can be sustained during a few of those internal disruptions until it eventually undergo a major disruption (FIG.4, time 4). If enough gas is injected, no bounce is observed, and the major disruption immediately develops as the cold front reaches q=2.

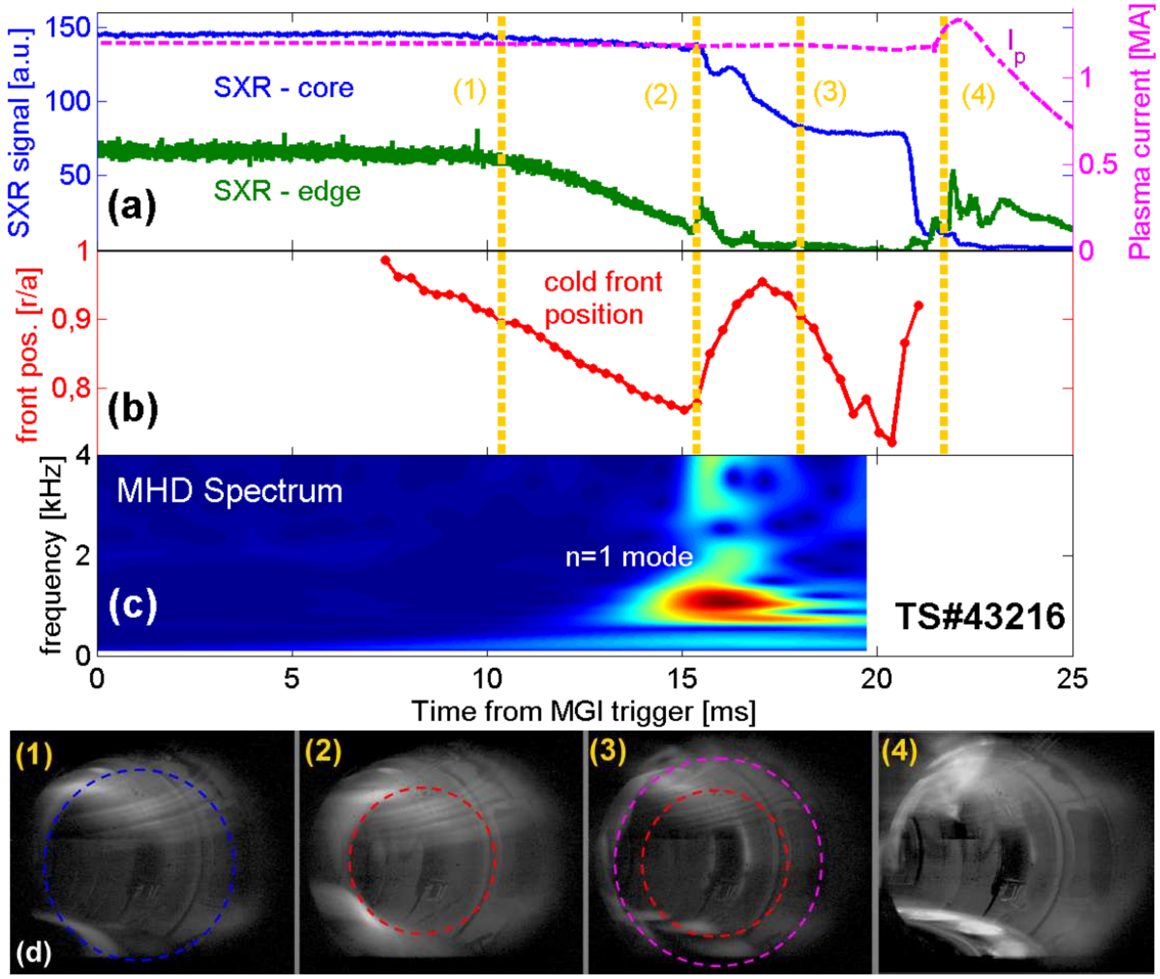

FIG. 4. Time evolution for a MGI shot (a) SXR and plasma current. (b) Position of the cold front (c) MHD spectrogram. (d) Corresponding fast camera pictures.

6. Runaway Electron Characterization and Mitigation

On Tore Supra, after unmitigated disruption occurring during the current ramp-up, a long RE tail (up to several seconds) may develop. These REs carry a current of several hundred of kiloAmps, corresponding to 20-60 % of the pre-disruptive current. This provides a unique opportunity to characterize plasma mainly sustained by relativistic electrons.

During the RE regime the line integrated electron density shows a decrease below 10^{18} m^{-2} at the end of the current quench, and then recovers to 1-1.5×10^{19} m^{-2} after 50 ms, without any gas puffing. This density is well above the RE density (few 10^{17} m^{-2}). It could originate from the re-ionization by the RE of the neutralized gas at disruption. Ionization is the dominant process

process in the RE energy range 10-20 MeV. Free electrons are also generated by the RE-wall interaction.
Due to their very small pitch angle, RE-wall surface interaction is localized on a small area, mainly governed by the misalignment of the components. Huge density power deposition is thus observed leading to already reported damages on many devices (see references in [1]). To reduce first wall loads generated by REs several mitigation techniques are under evaluation:
- Control of the RE beam position such as driving the RE on dedicated PFC,
- Time spreading of the energy loss associated to a decelerating electric field,
- Use of massive gas injection (He and Ar) for slowing-down the RE.

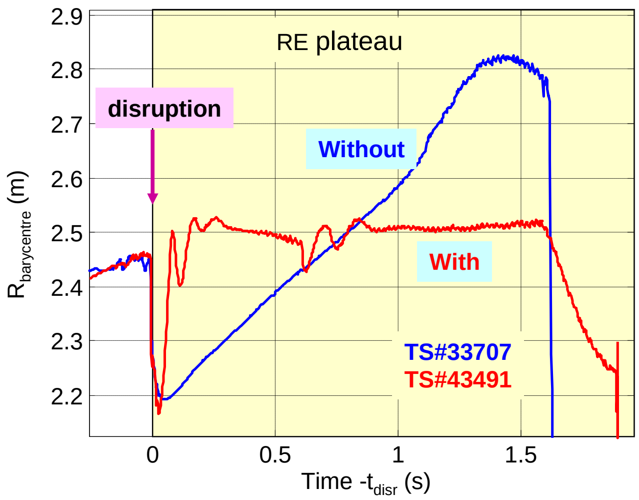

FIG.5. Plasma current barycentre with and without active control. The control is switch on/off 30 ms after the disruption. No current control was set in and the gas fuelling was switch off.

Using a feedback on poloidal coil voltage an active position control of the RE current barycentre has been successfully tested [11]. Figure 5 compares the RE current barycentre of two shots, with and without the active position control. Without any control the RE beam is found to move horizontally toward low or high field side depending on the shot. When a control of the current barycentre is switched on (30 ms after the disruption) the radial position stays under control even if transient events are still visible on the RE beam position. It demonstrates that the location of the RE impact on the first wall components might be freely chosen. Such a control enable us to save time for spreading the RE energy density deposit and for triggering mitigation systems.
The effect of a toroidal decelerating electric field was investigated by varying the central solenoid voltage ($E_{//}$ = 0, 17 and 35 mV/m were applied) while controlling the RE beams position. The increase of $E_{//}$ reduces the RE plateau duration and the nearly exponential RE current tail evolves with a characteristic time constant of 1.3 s, 0.7 s and 0.3 s respectively. Nevertheless the neutron flux toward the wall increases with the applied electric field and the total amount of neutrons remains roughly constant, indicating that the expected slowing-down is not effective. The current variation associated with the applied electric field indicates that the major part of the RE current is carried by non relativistic electrons.
A high neutral density has been used for slowing-down already accelerated RE. First results show that Helium enlarges the photoneutron flux without wall damages [5]. The use of a heavier slowing-down gas (Ar) is assessed in the present experiment. Whatever the injected gas is, the behaviours are comparable (FIG. 6). The MGI is triggered 200 ms (He) and 300 ms (Ar) after the disruption. In both case a faster decrease of the RE current, larger for the Ar case, is observed leading to a shorter RE plateau duration. At the same time the photoneutron flux is enlarged by a factor 10 for He and a factor 50 for Ar. Using pure Argon gas injection no

no huge photoneutron peak is observed at the RE plateau end as commonly observed for unmitigated RE tail ending and when using He gas. Despite the large enhancement of photoneutron flux, no localized impacts are observed by the fast framing visible camera. Such impacts are commonly observed during the current quench of standard disruptions.

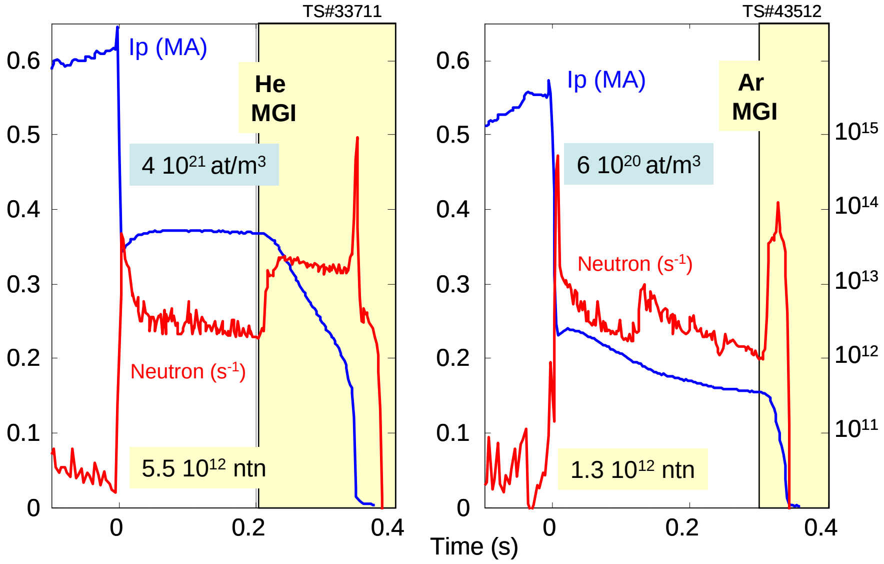

FIG. 6. Effect of He (left) and Ar (right) massive gas injection on RE plateau. The RE flat-top is reduced and the photoneutron flux is enhanced. The amount of injected gas and the total number of neutrons detected after the MGI trigger are indicated.

The total amount of photoneutrons scaled by the RE current when the MGI is triggered is found to be roughly the double for He gas case. But large fluctuation on neutron production is observed (factor 2 to 4) and a statistical analysis on a larger set of shots must be performed. Nevertheless the photoneutron production is not strongly reduced using MGI mitigation, indicating that the slowing-down by neutrals is not as much effective as expected. The decelerating effect is partially compensated by the larger avalanche factor associated with a faster decrease of the RE current.

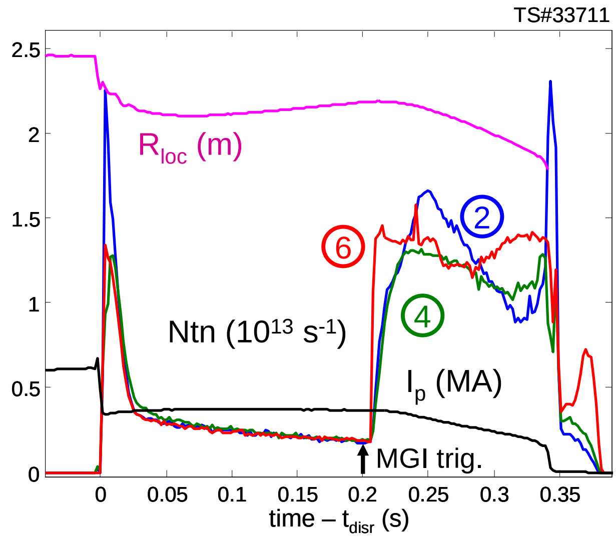

FIG. 7. Toroidal distribution of photoneutron flux during a He MGI.

The toroidal distribution of photoneutron flux is displayed in figure 7. Before the MGI is triggered photoneutron flux is well axisymmetric. The REs mainly interact with the existing background density originating from the initial plasma density. The fast camera movie shows that RE interaction occurs also on dusts (mainly carbon) filling the vacuum chamber after the disruption. At the MGI a faster increase of neutron flux is recorded by the detector # 6 the closer to the massive gas injector. The increase of collisionnality can then be followed while the gas propagates inside the vacuum chamber. This effect minimizes the amount of energy density deposit on the wall.

After about 50 ms the gas density is equilibrated, but some toroidal anisotropy remains in the neutron flux. This anisotropy can be explained by the increase of RE transverse transport towards the first wall. The neutron flux becomes thus sensitive to the wall misalignment. The variation of the RE beam position might lead to the observed toroidal anisotropy variation of the neutron flux. Multiple Coulomb scattering is responsible for the deflection. Following the Molière theory the deflection angle scales as the square root of the path length expressed in radiation length unit [12]. The radiation lengths are 94.3 g/cm^{-2} and 19.5 g/cm^{-2} for He and Ar respectively, and the path length scales as the pressure times density factor, assuming the same initial energy spectrum for RE. Thus the deflection angle is found to be 3 times larger for Ar injection than for the He case, in qualitative agreement with the neutron flux measurements. Because the deflection is stochastic the RE are spread over a very large wall area, leading to a huge reduction of the heat load, despite the total number of REs does not significantly decrease.

Such MGI on already accelerated RE beam might be a useful tool to reduce the loads on the first wall provided the amount of gas will not be too large. Indeed a gentle slowing-down seems to be preferable to a fast and possibly uncontrolled reduction. This mitigation technique must thus be associated to an active control of the beam position. Of course the RE current variation must be kept as low as possible especially at the RE plateau termination.

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