Control of Runaway Electron Beam Heat Loads on Tore Supra

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1. Introduction. Disruptions and runaway electrons (RE) are identified as a major issue for ITER and reactor-size tokamaks. Disruption produces excessive heat loads on plasma facing components, induces strong electromagnetic forces in the vessel structures, and generates multi-MeV runaway electrons. First generation of RE is created in the plasma core during the thermal quench (TQ) of the disruption, when the plasma current profile flattens producing a huge toroidal electric field closed to the magnetic axis. Thus fast electrons experiencing low collisionnality can be freely accelerated. They initiate second RE generation during current quench (CQ) due to the avalanching process, leading to a multiplication of these relativistic electrons. The impact of RE on the first wall is well localized due to their very small pitch angle. Thus the energy deposition may be huge and plasma facing components (PFC) damages are often reported. The RE formation and their potential effect on the machine components have been identified as a major issue for ITER operation [1].

2. RE flat top characteristics. RE beams lasting several seconds are observed on Tore Supra for disruption occurring during the plasma current ramp-up (fig.1). A current of several hundred of kilo amps, corresponding to 20-60% of the pre-disruptive plasma current can be associated to these beams. The plasma scenario which leads to RE plateau has thus been investigated. Such a plateau formation is eased with circular plasma in limiter configuration. A good matching of the vertical field for equilibrium control during the CQ together with an adequate production of RE which finally sustain the toroidal current are mandatory. We found that long duration plateaux develop only when the CFC first wall is depleted of deuterium, like after a few hours of He glow discharges wall conditioning. Indeed, when the first wall is saturated with deuterium, the RE seed

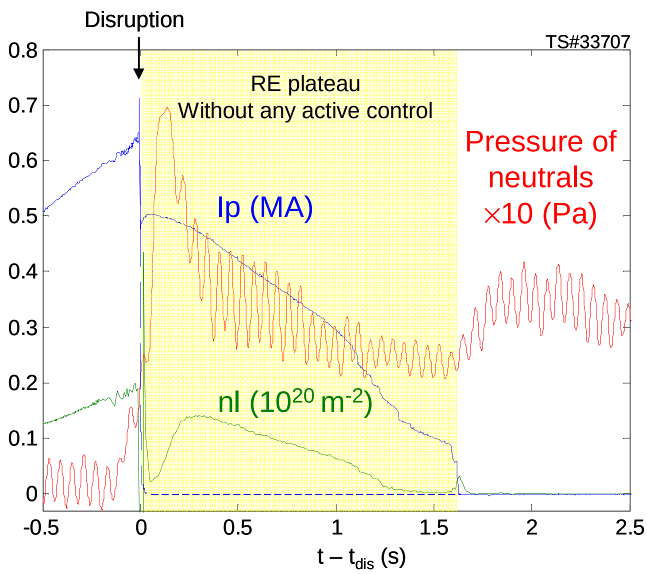

Figure 1: uncontrolled RE plateau generated after a disruption. 100 ms after the RE plasma regime establishment a free electron density recovers associated to a decrease of the pressure of neutrals.

formation seems to be strongly hindered by the large outgassing consecutive to the thermal quench, and sufficiently high runaway electron current cannot be generated to sustain the plateau due to the limited avalanching amplification at CQ on Tore Supra (Ip < 1.5 MA). Nevertheless, even the wall is saturated in deuterium, a shoulder attributed to RE with 10-100 ms duration and ≈ 100 kA current can be observed at the end of the CQ.

The capability to sustain long RE plateaus is a unique opportunity to study this unusual plasma regime. First results were presented in [2]. The RE plateau is characterized by the superposition of a relativistic electron beam that sustains the current ($3\ 10^{16}$ electrons per 100 kA of I_{RE} current on Tore Supra) together with a cold background plasma which gives rise of the free electron density (few 10^{19} m^{-1} line integrated electron density) (fig.1). The background plasma originated from the re-ionization of neutrals by RE collisions after the CQ, and also from the interaction of RE with carbon dusts suspended by mechanical forces generated at disruption. This interpretation is supported by the decrease of the neutrals pressure simultaneously to the increase of electron density (fig. 1). The RE plateau internal inductance is about twice the pre-disruptive value as expected when considering seed formation of RE at TQ closed to magnetic axis. Its value decreases along RE flat-top (fig.2). This current profile flattening might be due to RE collisions with background plasma. The parallel resistivity is larger by a factor of two than the one measured for well confined D2 ohmic plasma at the same current. The expected larger Zeff during RE plateau could explain this finding.

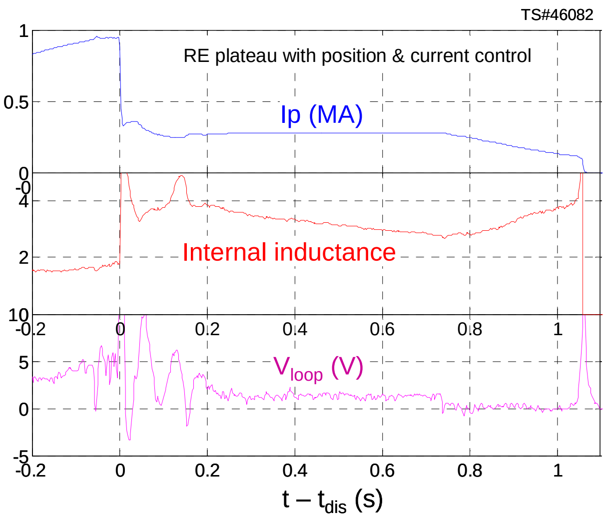

Figure 2: position and current controlled RE plateau generated after a disruption. On RE flat top a slow decrease of li might be attributed to current profile diffusion by collisions.

Transient events are observed during the RE plateau regime. Their signature is an increase of photoneutron flux together with MHD activity. Two types of events were identified:

- Very narrow photoneutron peaks (δt<2ms) associated to a RE current jump down, and no large variation of the total free electron density. This instability can be associated to a direct loss of RE onto the wall (fig.3a).
- Broad photoneutron bursts (δt>10ms) associated to large free electron density enhancement and no RE current variation. This type of instability is clearly associated

to radiating event which occurs inside the RE beam as recorded by fast camera (fig.3b). The interaction of RE with large size carbon dusts might by the seed of such events.

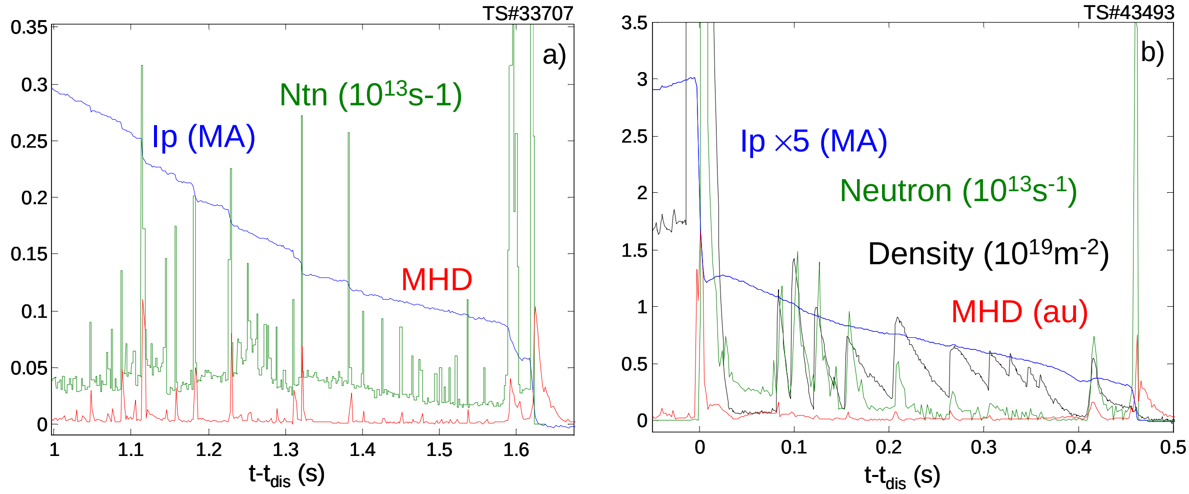

Figure 3: two types of transient events are observed during RE plasma dominated regime. Direct losses of RE on first wall (a), and radiating events due to RE collisions with large size carbon dusts (b).

This last type of event may be a key for RE heat loads mitigation as they produce a large increase of collisionnality together with a slowing down of RE before they reach PFC.

3. RE beam control and mitigation. Mastering the RE plateau regime is a key to deploy mitigation techniques. The increase of collisionnality by massive gas injection (MGI) is a promising technique for mitigation [2]. Collisions drive the RE towards the wall and enhance the RE slowing down. The first effect spreads the REs over the entire first wall, the second reduces their energy. Both are beneficial to reduce the heat loads. Nevertheless the thermalization of multi MeV relativistic electron takes time. Thermalization of 1 MeV electron into 1.7 10^{20} m^{-3} electron densities requires 30 ms [3]. This value extrapolates to half a second for 15 MeV electrons. Thus an active control of RE regime is required. Together with a beam position control, the RE current must also be sustained to maintain its value inside the operational domain of the plasma control system. A control of the RE beam position has already been demonstrated on Tore Supra [2].

Associated to a position control, the RE current control was recently demonstrated on Tore Supra. Considering the strong current profile peaking, the standard real time plasma controller was modified to feedback on the current barycentre localization rather than the plasma boundary. Reproducible several seconds controlled RE plateaus were achieved.

Massive gas injection (MGI) was triggered on a controlled RE plateau. The gas penetration leads to a fast increase of the free electron density associated to a larger light emission (fig. 4). Just after the MGI triggering, the flux of photoneutron rises. A toroidal asymmetry of photoneutron flux correlated to the MGI valve location is also observed [4].

This increase of photoneutron flux is thus clearly attributed to the increase of collisionnality. MGI initiates also a slowing-down of relativistic electrons and a subsequent progressive reduction of the photoneutron flux is seen. At constant I_{RE} the high energy population of RE reduces and a partial thermalization is observed.

4. Conclusion. We have demonstrated that a MGI associated to a RE active control might be a good strategy to mitigate RE effects. Nevertheless more experiments are needed to demonstrate that a full thermalization of RE is feasible. In present work the RE plateau terminates often abruptly before thermal equilibrium achievement. Future plan are to master RE plateau termination towards a full thermalization.

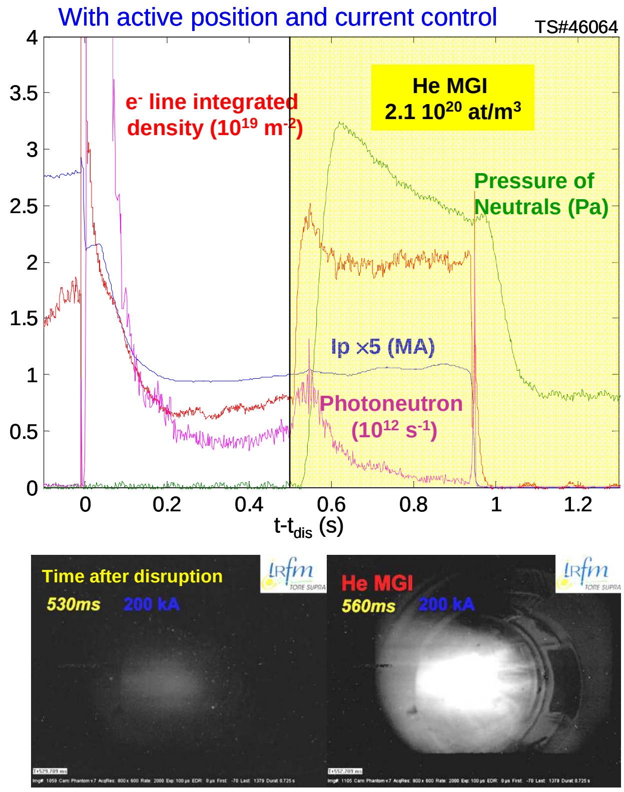

Figure 4: Top: MGI on position and current controlled RE plateau generated after a disruption. Increase of collisionnality is effective and partial thermalization of RE beam is deduced from the photoneutron flux evolution. Bottom: pictures from fast framing camera before (left) and after (right) MGI.

More generally the defence in depth concept can be used to describe the overall strategy of disruption mitigation for ITER. Thermalization of RE is thus the fourth and ultimate barrier interposed to mitigate disruption effects. The previous successive barriers can be summarized as:

- Detection of disruption precursor as earlier as possible and deployment of actions to avoid the disruption. Plasma performance could be temporarily loss.
- When disruption is unavoidable, trigger a controlled/mitigated disruption by MGI or shattered pellets to reduce heat loads and electromagnetic forces.
- Prevent exponential amplification of seed RE at CQ using resonant magnetic perturbations or multiple ultra fast gas injections (UFGI).

The demonstration of UFGI capability to destabilize RE at CQ is undertaken at Tore Supra.

References:

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