The Runaway Electron Benign Termination Scenario: Physics Processes and Operational Limits

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Introduction

Runaway electrons (REs) are the most challenging consequence of tokamaks disruptions. Due to their potential of high and localized heat loads, they must be mitigated. Since avoidance may not be always possible, a scenario to suppress fully accelerated RE beams is needed. The *low-Z benign termination scenario* [1] is currently the most promising one. It consists in injecting large amounts of D_2 or H_2 into the RE beam, and leads to an almost complete suppression of heat loads at impact. The present contribution focuses on the limits and physics at play with this scenario, using recent JET experimental data.

Description of the scenario

The benign termination scenario uses low-Z material to mitigate the beam, because heavier gases were previously found not to be efficient [2]. The low-Z injection can be made through

Shattered Pellet Injection (SPI), Massive Gas Injection (MGI) or standard gas fuelling valves. Two ingredients are required to get a benign termination: a large MHD instability and a clean companion plasma (the cold plasma coexisting with the RE beam). Low-Z injections make the companion plasma recombine down to free electron density values below 10^{18} m^{-3}, which is favorable for both requirements. Recombination indeed dilutes impurities and partially flushes them out, while ensuring a high Alfvén speed leading to strong MHD.

Figure 1 shows that all recombined JET plasmas show non-measurable heat loads. Moving away from ideal conditions leads to the regeneration of small beams during the final collapse. This produces non-zero heat loads as shown on figure 1, blue triangles. Moving further away from the ideal conditions for benign termination generates incomplete collapses of the RE beam, leading to transient re-ionization of the companion plasma and larger heat loads (purple triangles). Once the limit of the operational domain of the benign termination scenario is crossed, the companion plasma stays reionized, leading to large heat loads (red squares).

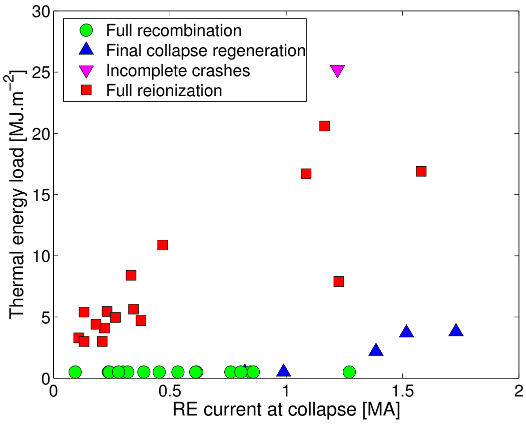

Figure 1: *Thermal energy load versus RE current at collapse. Marker types denote the status of the companion plasma at collapse onset.*

Influence of the impurity content

A sufficient amount of deuterium is needed to achieve recombination. Heat transport by neutrals cools the companion plasma down to recombination [3, 4]. Increasing the amount of high-Z impurities (argon in the present case, used to trigger the disruption) shows a transition through all types of companion plasmas: regeneration during final collapse, incomplete collapses, then finally reionization. The temperature reached at impact increases accordingly as shown on figure 2 left. An incompletely mitigated RE beam can however be salvaged by injecting more low-Z material. Figure 2 right shows two RE beams created with the same amount of argon, but mitigated by respectively 301 Pa.m^3 and 1540 Pa.m^3 of D_2. The former exibits intermediate crashes and 833 °C at impact while the latter stays recombined and leads to 350 °C at impact, which is essentially benign.

Upper D_2 limit

An arbitrarily high amount of high-Z material can unfortunately not be compensated by a equivalently large D_2 injection: an upper limit was observed on other machines [5]. In a benign termination scneario, the companion plasma stays recombined through the combined effect of

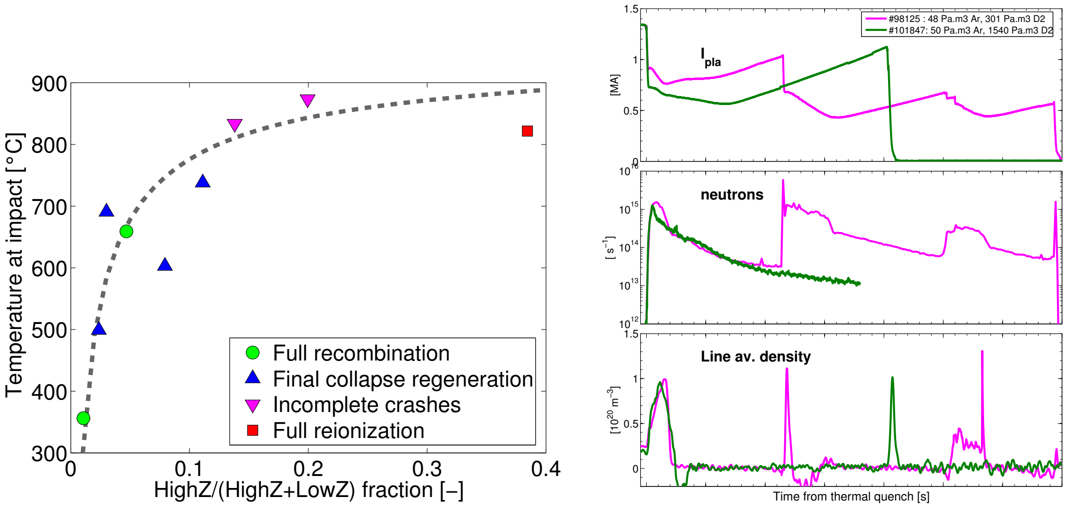

Figure 2: *Left: temperature at impact versus argon concentration, at fixed D_2 amount. The dashed line is only an eye guide. Right: comparison of an incomplete mitigation case (#98125, purple) and a benign case (#101847, green) thanks to a larger D_2 injection.*

increased heat transport by light neutrals and a reduced RE-plasma collisions and line radiation through the partial purge of argon. Injecting more deuterium increases the RE-plasma collision rate, but transport does not increase as quickly [4]. It was confirmed at JET that it is more difficult to drive the RE current at high density, and that recombination is more difficult. However, even with a vessel pressure 16 times larger than for DIII-D (4350 Pa.m^3 D_2 injected), the termination is still benign at JET, which shows that the pressure threshold is not universal.

Influence of the plasma current

Pre-disruption current at RE current during the plateau phase are two other key parameters for RE generation, since the RE avalanche rate depends exponentially on the current. High pre-disruption currents produce higher current beams. They are also more vertically unstable possibly due to the combined effect of larger initial current drop after the thermal quench, thus challenging vertical position control and a lower edge safety factor leading to an earlier termination by a low-safety factor instability. The duration needed to recombine the companion plasma also gets longer with increasing current, as shown on figure 3 left. The maximum fraction of high-Z impurities allowed in the plasma to reach recombination or to avoid reionization also decreases with current as shown on figure 3 right. None of the six cases attempted at 3.0 MA were able to reach full recombination, although it is not clear whether this is due to insufficient D_2, to excessive D_2 (upper limit), or to insufficient time to let recombination happen: the longest beams at 3.0 MA pre-disruption current are 120 ms long. Note also that large injections ($\geq$3000 Pa.m^3 D_2) were benign at 1.5 MA, but not benign at 3.0 MA, which may be the sign that the

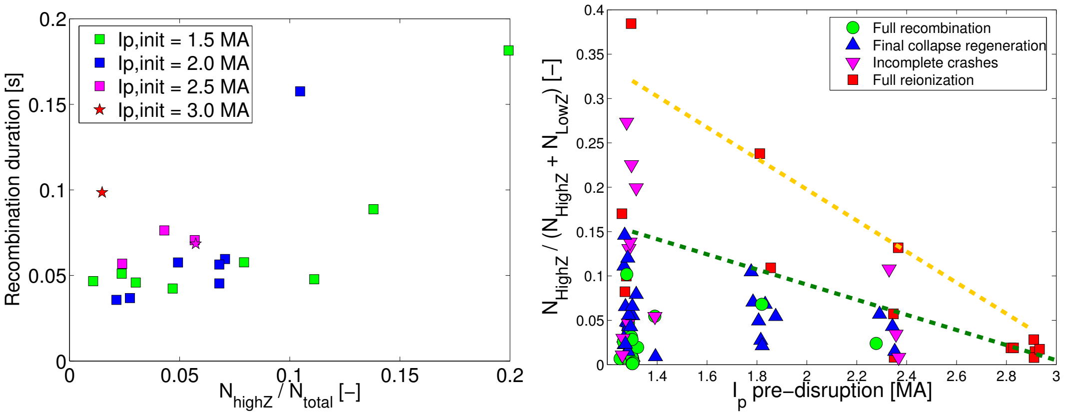

Figure 3: *Left: Recombination duration versus high-Z fraction. Star symbols denote an absence of complete recombination at the time of the collapse, hence representing a lower estimate. Right: Operational space for benign termination scenario as a function of the high-Z concentration and the pre-disruption* I_p*. The yellow dashed line marks the maximum high-Z concentration allowed to avoid reionization, and the green dashed line the maximum high-Z concentration allowed to ensure recombination.*

upper D_2 limit decreases with I_p, further restricting the operational space.

Incomplete mitigation vs. absence of mitigation

Surprisingly, incomplete mitigations such as the high argon fractions from figure 2 left were found to be more harmful than unmitigated cases. No definitive explanation has been found yet, but the fact that deuterium makes beams longer may give more times to electrons to accelerate. If the observation is confirmed by simulation, it means that if the low-Z benign termination scheme is attempted, one needs to be reasonably sure it will succeed.

Conclusion

The boundary of the operational space for the low-Z RE benign termination scenario has been explored. It shows that the high-Z concentration is a critical parameter. Too large amounts of low-Z material may be harmful, although not as badly as on other tokamaks. High pre-disruption currents make recombination more difficult by simultaneously decreasing the maximum allowed impurity concentration, the RE beam duration, and possibly the maximum allowed low-Z amount. Modelling has started to extrapolate the scenario to future machines.

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