Physics of the creation and mitigation of runaway electron beams in presence of their background plasma

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Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto,

Japan, 17-22 October 2016)

Introduction

Disruptions are a threat for the reliable operation of future tokamaks including ITER. Among other consequences, they can convert a significant fraction of the plasma current into Runaway Electrons (REs) in the MeV range. The possibility to suppress a runaway beam once it has been accelerated remains uncertain. Previous experiments at JET have shown that the suppression of a 750 kA runaway beam using massive gas injection was inefficient [1]. This situation contrasts with results of smaller tokamaks such as DIII-D[2], Asdex-Upgrade[3], TCV[4] and Tore Supra[5]. A number of explanations have been brought forward to explain the inefficiency: a gas plume geometry effect, a runaway current screening effect or the shielding by the cold background plasma coexisting with the runaway beam. This background plasma has already been observed on several machines[2, 5], but gaps remain in the understanding of its physics. The present paper reviews the three latter possible explanations and the interaction between REs, the background plasma and the mitigation gas.

Geometry effect and current screening

A typical runaway electron beam at JET is created using the first Disruption Mitigation Valve (DMV1) injecting a large amount of argon (6 to 300 Pa.m^3) in a limiter-configuration plasma. The second Disruption Mitigation Valve (DMV2) is used to try to suppress the runaway beam

which appears following the disruption. Since the runaway beam moves generally upwards in 50 to 100 ms, the gas plume coming from the midplane-located DMV2 might miss the beam. By firing with another disruption mitigation valve located on the top of the machine (DMV3 - 720 Pa.m3 of Krypton) no significant difference on the penetration of the gas plume was observed. The geometry effect was therefore ruled out.

In order to assess its impact on the penetration of the mitigation gas, the runaway current was varied by changing the pre-disruption current. This had no impact on the gas penetration efficiency: The density rise shown on figure 1(c) is similar in all three cases. However, Hard X-rays and neutron counts are much lower in the low current cases as shown on figure 1(d,e), indicating much lower runaway energies (below a few MeV for the 1.0 MA case). This may be partly due to the lower parallel electric field during the initial current quench. Surprisingly, the lower maximum energies do not facilitate the penetration of the mitigation injection hence pointing to the responsibility of the background plasma.
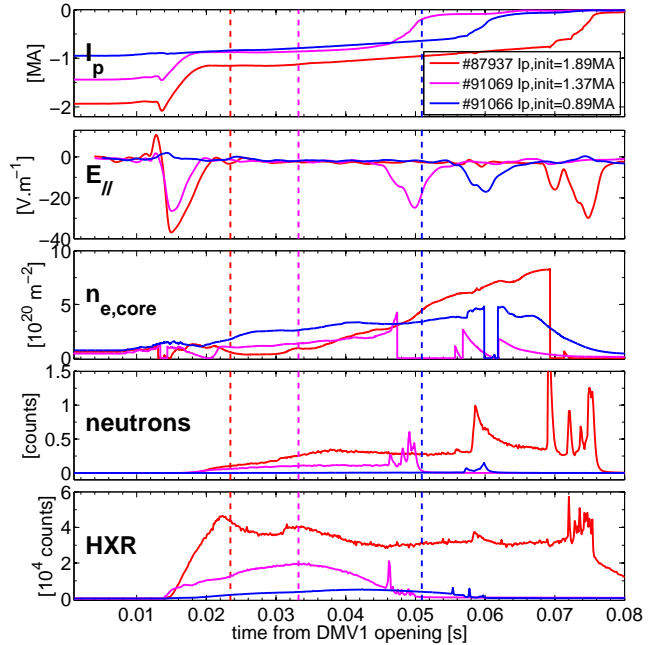

Figure 1: *Effect of the pre-disruption current on the runaway current and energy. Vertical dashed lines are the DMV opening times. (a) Plasma Current (b) Parallel electric field (c) relative density rise in the beam core (zero-value time windows indicate signal loss). (d) Neutron counts (e) Hard-X-ray counts.*

Background plasma characterization

The background plasma coexisting with the runaway electron beam typically shows a rising density in the core of the beam and a more constant density in the far scrape-off layer. Line-integrated densities of up to several 10^{19}m^{-2} may be observed 25 cm away from the beam supposed separatrix. These density features were found to be dependent on the way the disruption was triggered: the more gas is used to triggered the disruption, the denser the background plasma is, as shown on figure (a). The average line-integrated density rise in the core ranges from less than 1×10^{21}m^{-2}.s^{-1} for disruptions triggered by 6 Pa.m^3 of argon to 2×10^{22}m^{-2}.s^{-1} for disruptions triggered by 300 Pa.m^3 of argon. The background plasma is highly ionized, as a neutral density above 1×10^{20}m^{-3} would stop runaways by collisional braking according to ES-TAR stopping power calculations [1]. This is confirmed by the presence of Argon II, III and

IV spectroscopy lines and the almost complete absence of Argon I (neutral Argon) lines in the background plasma emissions as shown on figure (b). Assuming collisional radiative equilibrium, a temperature between 5 and 15 eV can be inferred. Note that the most dense background plasma seem to be colder (closer to 5 eV) than the less dense ones but still hotter than on other machines such as DIII-D [2].
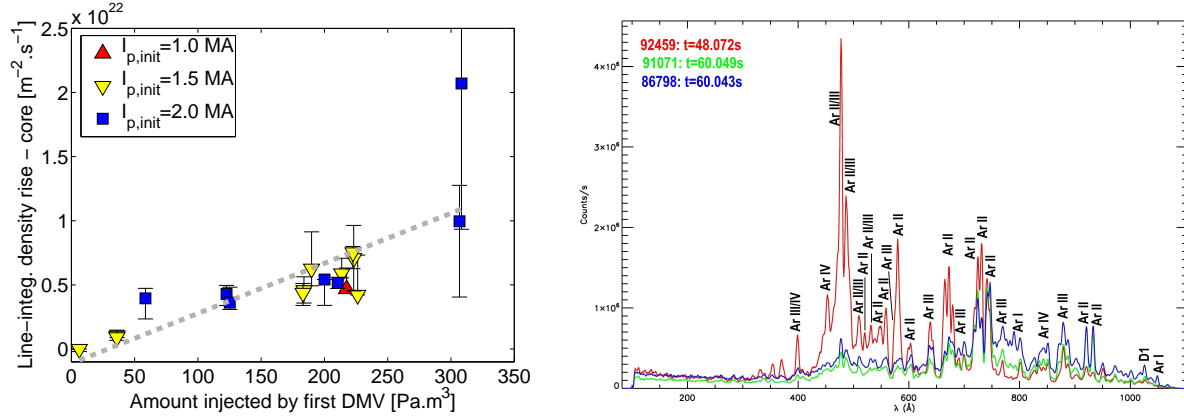

Figure 2: *(a-left) Average line-integrated electron density rise of the background plasma during the runaway beam phase. (b-right) VUV spectrum with argon lines for 3 background plasmas. Red: low density background plasma. Green and blue: high density background plasma*

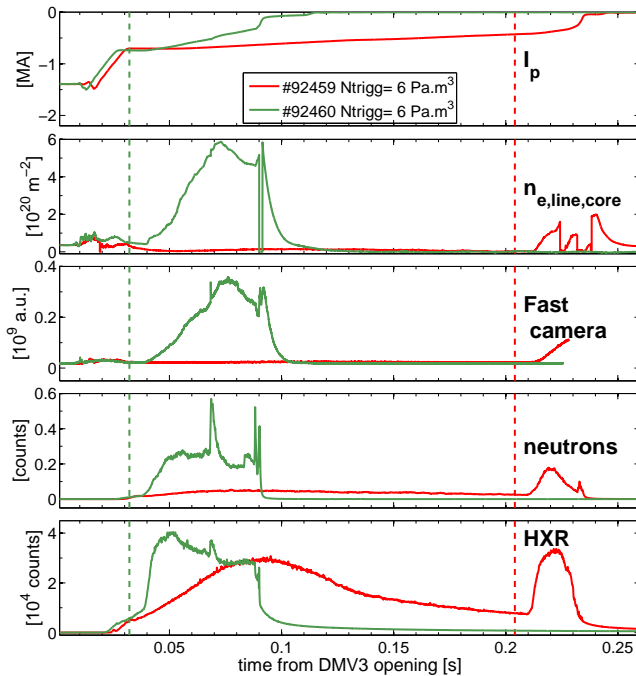## Consequences on mitigation

Figure 3: *Example of an effective mitigation for two low density cases. Vertical dashed lines indicate the DMV times.*

The characteristics of the background plasma have consequences on the effect of the second injection as shown on figure 3 for krypton massive injections in a low-density background plasma. The electron density, neutron and Hard-X-ray rate increase significantly following the second injection. This is not the case in a high density background plasma for which the neutron or HXR count rates do not change much after the second injection (see figure 1, pulse #91069). The better penetration of the second injection is confirmed by the intensity of krypton II line as shown on figure 4. The less gas is used to trigger the disruption (i.e. the less dense the back-

ground plasma is), the more intense the krypton line is. It is to be noted though that the density rise due to the second injection is only moderately higher than the natural density rise of a high density background plasma in spite of a 10 times larger injection. This can be interpreted as a self-limiting effect: as the density increases thanks to the mitigation injection, the penetration of the gas front is more and more difficult. The background plasma also has an influence on the vertical stability of the beam. The more dense it is, the more vertically unstable. The fact that the vertical movement is also accelerated by a second injection means it is likely that the vertical stability is partly influenced by the characteristics of the background plasma. In addition, the initial plasma current drop during the early phase of the current quench (before the runaway plateau appears) may also determine the ability of the shape controller to catch the runaway beam in position.

Conclusion

For the first time at JET, a post-disruption runaway beam was altered by a massive gas injection. The electron density and temperature of the background plasma coexisting with the runaway beam are determined by the disruption-triggering injection. The penetration of the mitigation gas is only possible in a low density background plasma leading to increased runaway losses but tends to be self-limited when the background density rises. A shattered pellet injector such as the one to be installed at JET for the next experimental campaigns might alleviate this effect as it should be able to
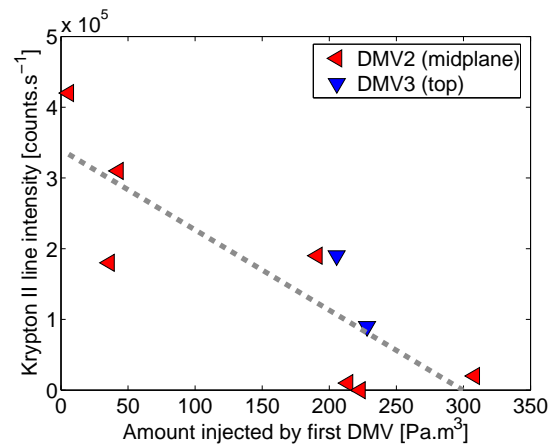

Figure 4: *Kr II line intensity following the mitigation injection versus the amount of gas injected to trigger the disruption*

break through the background density barrier. The vertical stability is worse when the background plasma is more dense, possibly linked to a higher current decay rate. Efficient mitigations also make the beam more vertically unstable, calling for a better vertical control to ensure good runaway beam suppression.

References

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