Influence of massive gas injection and resonant magnetic perturbations on the generation of runaway electrons during disruptions in TEXTOR

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A runaway electron (RE) beam with energies of several MeV carrying a large fraction of the plasma current can be generated during the current quench in major disruptions in tokamaks. Runaway electrons cause a threat to the integrity of the plasma facing components if they release their energy onto a small wall area and exceed the melt limit. The application of massive gas injection [1] and resonant magnetic perturbation fields [2] are presently under investigation as possible means to suppress the generation of runaway electrons.

The TEXTOR tokamak ($R = 1.75\,\text{m}$, $a = 0.46\,\text{m}$) is equipped with two fast eddy current driven disruption mitigation valves (DMV) [1]. The smaller system (DMV-10, 10 mm orifice) can deliver up to 0.6 bar l of gas and is mounted on top of the machine in a distance of 1.3 m from the last closed flux surface of the plasma. For most of the path the gas is guided through a tube with inner diameter of 40 mm. The larger DMV (DMV-30, 30 mm orifice) can deliver up to 11 bar l and is mounted at the horizontal mid plane of the plasma on the low field side in a distance of 10 cm from the last closed flux surface. In addition, TEXTOR is equipped with the so-called dynamic ergodic divertor [3], which allows to apply helical magnetic perturbations with mode numbers $m/n = 3/1, 6/2,$ or $12/4$.

Several dedicated experiments have been performed in order to investigate the effect of massive gas injection or magnetic perturbations on the generation, confinement, and loss of runaway electrons. Discharges with $I_p = 350\,\text{kA}$, $B_t = 2.4\,\text{T}$, and n_e in the range $1 \times 10^{19}\,\text{m}^{-3}$ to $2 \times 10^{19}\,\text{m}^{-3}$ were deliberately disrupted by injection of 0.02 bar l of argon using the smaller of two disruption mitigation valves. In these discharges runaway electron beams with current in the range 100 kA to 150 kA lasting up to 170 ms were reproducibly generated. A typical runaway discharge scenario is shown in figure 1. In this discharge the DMV has been triggered at 2 s, visible on the third trace which shows the output voltage of the power supply for the actuator coil. The electron cyclotron emission (ECE) traces at the bottom of the figure show that the cooling initiated by the gas reaches the edge plasma at $t = 2.0025\,\text{s}$, and the centre of the plasma about 1 ms later.

The current quench is initiated at $t = 2.004\,\text{s}$. The plasma current time trace shows clear indication that a runaway electron beam has been generated. The runaway phase in this discharge lasts for longer than 40 ms. A characteristic feature of runaway plasmas which are produced via massive gas injection is the slow decay of the runaway current. No plateau with constant runaway current is formed for those conditions. The decay is likely caused by collisional deconfinement due to the high gas pressure in the vessel.

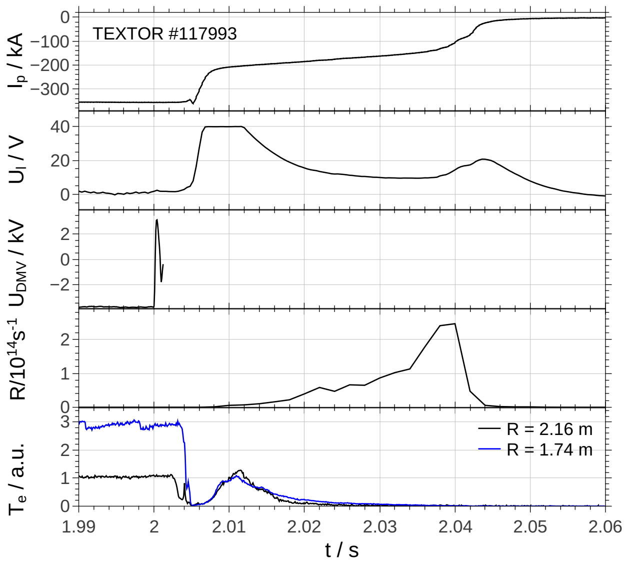

Figure 1: *Example of a discharge which shows runaway electron generation after injection of argon. Traces from top to bottom are: plasma current, loop voltage, voltage applied to the actuator coil of the valve, count rate of high energetic gammas, and ECE measurements in the plasma core and near the low field side edge of the plasma.*

The experiments to study RE suppression with massive gas injection (MGI) have been conducted in the following way: The smaller DMV has been used to deliberately disrupt the discharge by injecting 0.02 mbr l argon resulting in a reliable generation of runaway electrons. The second DMV injecting 1.1 bar l of helium has been triggered with varying delay times and the influence on the runaway beam has been studied. Figure 2 summarises three discharges with various delay times between the triggering of both fast valves. The upper panel shows the plasma current decay after massive gas injection. Two discharges show no sign of runaway current (#118005 and #118007), whereas the third discharge (#118009) exhibits a short lasting, decaying runaway *plateau*. The lower three panels show two ECE traces, measured near the centre of the plasma at $R = 1.74\,\mathrm{m}$ and close to the low field midplane plasma edge at $R = 2.16\,\mathrm{m}$. The fast drop in the edge ECE channel shows the time when the gas arrives in the plasma. The collapse of the central temperature is delayed by about 1 ms, with the exception of discharge #118005. The earlier drop of the central temperature in this discharge is caused by the second gas injection from the larger DMV-30 with a small time delay of 2 ms. Due to the much closer distance to the plasma the gas arrives earlier. DMV-30 is triggered at $t = 2.002\,\mathrm{s}$ and the core temperature starts to collapse at $t = 2.0028\,\mathrm{s}$, i.e. the time from triggering the valve until the first gas reaches the plasma centre is only $800\,\mu\mathrm{s}$.

Discharge #118005 with a time delay of several $100\,\mu\mathrm{s}$ between the initiation of the thermal quench and start of injection from DMV-30 shows no runaway electrons.

Discharge #118009 with a much larger delay (injection from DMV-30 after $t = 2.009\,\mathrm{s}$) has runaway electron generation.

The third discharge #118007 with a delay of 5 ms, i.e. the DMV-30 injects early during the current quench, shows no indication of runaway electrons on the plasma current signal. However, the gamma radiation measurement within the TEXTOR bunker reads $0.48\,\mu\mathrm{Sv}$ for this discharge, what is about 10% to 20% of the radiation dose of a fully developed runaway plasma. Therefore, for massive gas injection to be effective in suppressing the generation of runaway electrons the injection has to be before the current quench. This observation confirms previous measurements on Tore Supra where it has been found that massive gas injection into the developed runaway beam phase was not successful [4]. However, the injected high-Z atoms increase RE losses and help to dissipate the RE current [5].

Recent work on TEXTOR has reported on the successful suppression of runaway electrons with an $m/n = 3/1$ resonant magnetic perturbation [6]. In this experiment the perturbation field has been switched on already prior to disruption. Unfortunately, the determined field threshold for runaway electron suppression coincides with the threshold for locked mode generation in similar plasmas [7]. In order to resolve this ambiguity a series of experiments has been conducted where the magnetic perturbation field has been either operated at levels below mode excitation threshold, or switched on late during the current quench and runaway beam phase. Three discharges are compared in figure 3. The main plasma parameters are: $B_t = 2.4\,\mathrm{T}, I_p = 350\,\mathrm{kA}, n_e = 1.5\times10^{19}\,\mathrm{m}^{-3}$. The disruptions are triggered by injection of $0.02\,\mathrm{mbar\,l}$ of argon at $t = 2\,\mathrm{s}$ using the DMV-10. The perturbation field is applied by the dynamic ergodic divertor in $m/n = 3/1$ configuration.

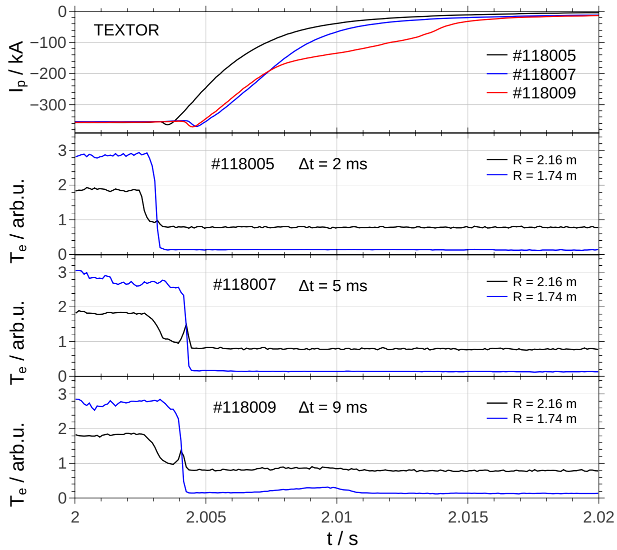

Figure 2: *Runaway electron suppression with massive gas injection. In all discharges runaway electrons are generated with the small DMV (triggered at $t = 2\,\mathrm{s}$). The larger DMV is triggered with various delays as indicated in the figure. The ECE traces in the lower panels show temperature in the centre ($R = 1.74\,\mathrm{m}$) and close to the plasma edge ($R = 2.16\,\mathrm{m}$).*

The first discharge (#119868) has no magnetic perturbation applied and develops a runaway beam phase of almost 80 ms.

In the second discharge (#119876) a perturbation coil current of 2 kA is applied and the waveform reaches flat-top 100 ms before the disruption. There is no runaway current observed. However, the signal of the central electron temperature shows the stabilisation of sawtooth oscillations and a drop during ramp-up of the field. These observations are well known from many experiments using the dynamic ergodic divertor and indicate that an $m/n = 2/1$ locked mode has been excited in the plasma. A strong influence of internal MHD modes on the runaway confinement has been reported previously and could explain the lack of runaways in this discharge [8].

The third discharge (#119878) uses a similar waveform for the perturbation coil current, but the ramp-up is delayed in order to prevent excitation of a locked mode before the current quench. This discharge shows runaway electrons, although the maximum runaway current seems to be less. According to [2] the required perturbation level $\tilde{B}/B$ is about 10^{-3}, what is larger than the perturbation field generated in this experiment. It is worth to note that these field amplitudes are about one order of magnitude larger than the perturbation fields required for mode excitation.

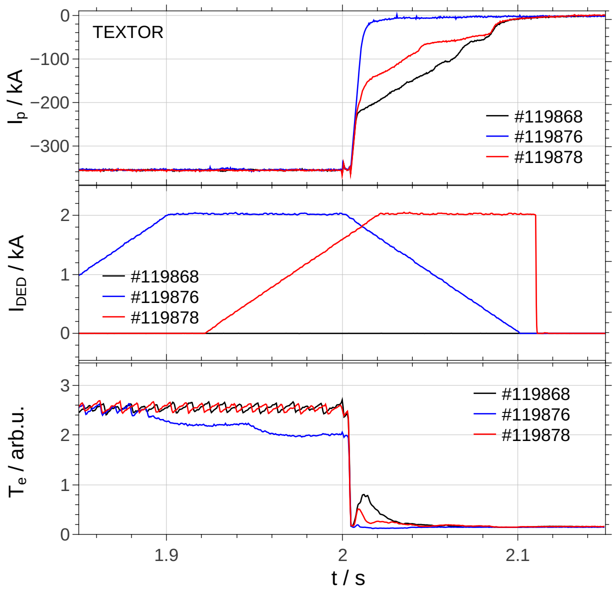

Figure 3: *Influence of a resonant magnetic* 3/1 *perturbation field on the suppression of runaway electrons. Top: plasma current; Middle: current in the perturbation field coils; Bottom: electron temperature in the plasma centre.*

No clear effect of magnetic perturbation field on the runaway electron generation has been found. Only the discharge where a locked mode has been deliberately excited prior to current quench showed no runaway electron production. In this case it could be either the amplification of the perturbation field by the locked mode which increases the radial diffusion and de-confines energetic electrons, or the associated drop in electron temperature suppresses the runaway electron generation via the hot tail mechanism [9, 10]. Conversely, the previous experiment [6] reports on a reference shot with locked mode and trimmed down perturbation field which developed REs. It seems that there is still something missing for a consistent picture, e.g. the horizontal position of the RE beam with respect to the perturbation coils, or an effect of the vertical field may play a role.

Summary and Conclusion. Massive gas injection prior or at the current quench was able to suppress the generation of runaway electrons. Resonant magnetic perturbations showed no clear effect on the suppression of runaway electrons, but internal MHD modes seem to hinder the runaway generation.

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