Experimental observation of runaway electron related relaxation phenomena during disruptions in the TEXTOR tokamak

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1. Introduction

Runaway electron (RE) currents of several mega amperes are expected to be generated in ITER disruptions due to avalanche multiplication [1]. An uncontrolled loss of these high-energy electrons to the plasma facing components might cause serious damage [2]. However, the loss process has not yet been clarified. We present here observations of the RE related relaxation phenomena during disruptions in the TEXTOR tokamak.

2. Experimental observations

Figure 1 shows a typical discharge (#117991) with a RE plateau during a deliberated disruption in TEXTOR. Figures 1(a)-(d) illustrate the plasma current, toroidal loop voltage, soft X-ray emission, and magnetic turbulence, respectively. There are four phases during the disruption, (I) the thermal quench, (II) the current quench, (III) the RE plateau, and (IV) final termination. Magnetic activity in the latter three phases will be discussed in this paper.

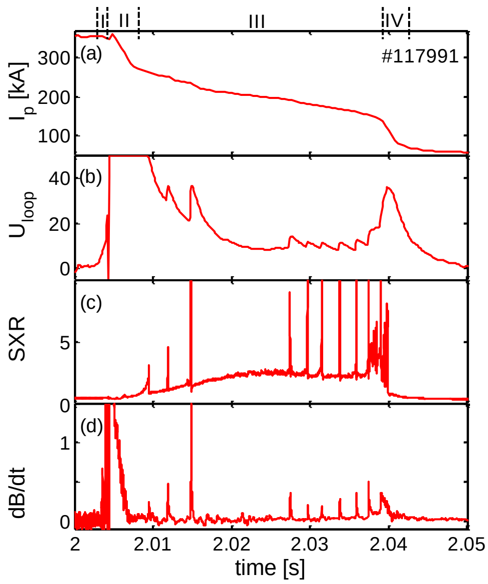

Fig. 1 Time traces in shot 117991showing (a) plasma current, (b) toroidal loop voltage, (c) soft X-ray emission, and (d) magnetic turbulence.

2.1 *Magnetic turbulence during current quench*

Figure 2 compares two discharges, #117833 develops a RE current plateau during the current quench while #117849 does not. The parameters of both shots are the same except for the toroidal magnetic field (B_t = 1.8 T for #117849 and B_t = 2.4 T for #117833). Obvious magnetic turbulence is seen during the current quench in the magnetic pick-up coil signals, shown in Fig. 2 (b) and (c). The magnetic turbulence lasts from 4 to 8 ms and the level initially increases and then decreases. A typical frequency spectrum of magnetic turbulence is shown in Fig. 2 (d). The turbulence frequency has a large distribution with most of the power in the range from 60 to 260 kHz. The magnetic turbulence level with B_t = 1.8 T is at least twice of that with B_t = 2.4 T. The RE tail is not always reproducible, even with the same toroidal magnetic field, in which the magnetic turbulence level (δB) is also different. These suggest that magnetic turbulence during the current quench plays the dominant role in this stage and is the cause of the different observed RE tails.

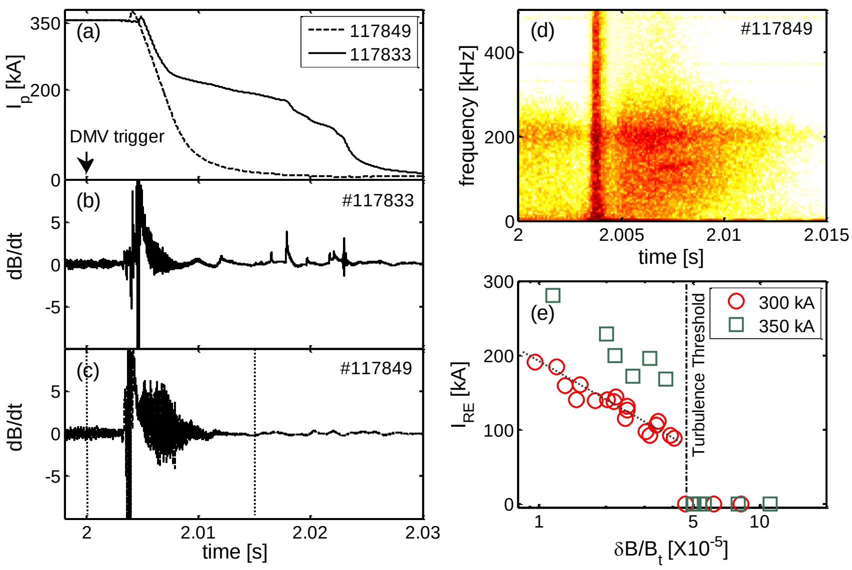

Fig. 2 Time traces showing (a) plasma current, (b) magnetic turbulence in shot 117833, (c) magnetic turbulence in shot 117849, and (d) spectrum of magnetic turbulence in shot 117849. (e) RE current in TEXTOR disruptions as a function of normalized magnetic turbulence level.

In Fig. 2 (e), a survey of several discharges shows that in TEXTOR the RE plateau is always visible unless the normalized magnetic turbulence level exceeds the threshold of $\delta B/B_t \sim 4.8 \times 10^{-5}$ for both the I_p = 300 and 350 kA cases [3]. The REs (which may be produced in the current quench) are quickly lost within the first 5 ms of the current quench. For shots with lower magnetic turbulence levels than the threshold, it is found that the RE current (I_{RE}) decreases linearly with $\delta B/B_t$ for I_p = 300 kA and also for I_p = 350 kA, but in the latter case the RE current is larger. The value of the critical fluctuation amplitude seems to depend mainly on the toroidal field and not on the plasma current. From the analysis above it follows that there is clear evidence that the development of a RE beam depends strongly on the level of magnetic turbulence during the current quench.

2.2 *Magnetic activities during RE plateau*

Burst-like relaxations during the RE plateau cause large RE losses, seen by spikes in the signals of soft X-ray arrays, shown in Fig. 1(a) and 1(c). RE losses will reduce the current and, as a consequence, induce a positive voltage spike (Fig. 1(b)). A series of bursting activities are also observed on the Mirnov coils, consistent with the spikes on the SXR arrays, shown in Fig. 1(d). The physical mechanisms for the magnetic bursts are complex and at least two distinct types are found: i) RE beam interaction with the inner wall and ii) RE beam interaction with the outer wall.

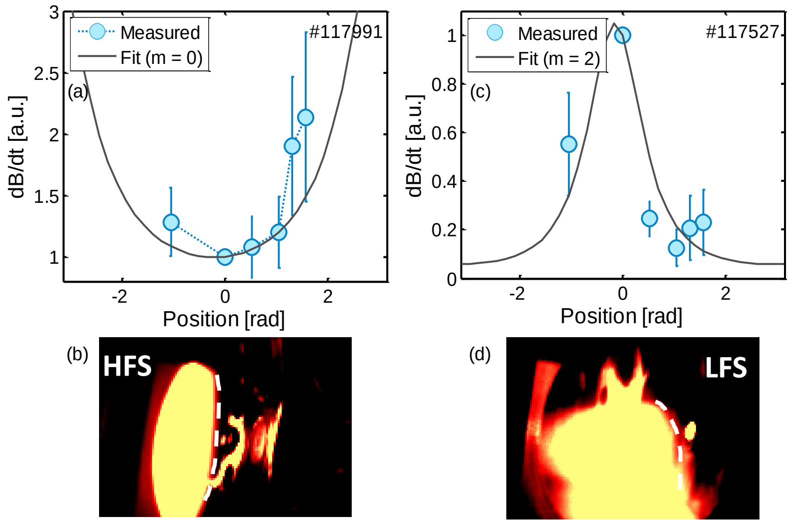

Fig. 3 (a) and (c) Comparison of magnetic turbulence level at different poloidal angles in shots 117991 and 117527. (b) and (d) IR radiation observed by the camera in shots 117993 and 117434.

i) RE beam interaction with the inner wall. — For the interaction with the inner wall, the magnetic spikes can be found at every phases of the RE beam lifetime, i.e., the whole RE, plateau and final termination. The poloidal and toroidal mode numbers are both 0. The time periods for the duration and the intervals between the spikes are ~100 μs and ~2 ms, respectively. Moreover, high frequency fluctuations (~200 kHz) followed by the spikes are often observed by the coils, at the end of the RE plateau and final termination, and the toroidal mode number is 1. Similar to the signal distributions of the Mirnov coils during the current quench (Fig. 3 in Ref. [3]), the magnetic spikes are poloidally asymmetric. The level at the top of the inner wall is about 2 times larger than at the low field side. This can be explained by the inward movement of the plasma. Indeed, the magnetic fluctuations decay as $r^{-(m+1)}$ in the vacuum. Assuming an inward movement of 25 cm, a reduction of the minor radius from 0.45 m to 0.25 m and m = 0, the simulated signals agree with the measured one, shown in Fig. 3(a). The RE beam is located on the high field side as has been observed by measuring the synchrotron emission with an infrared camera in TEXTOR, which is also consistent with the assumptions for our simulations (Fig. 3(b)).

ii) RE beam interaction with the outer wall. — For the interaction with the outer wall, the spikes can usually be found at the end of the RE plateau and final termination. The poloidal mode number is 2 or 3 and the toroidal mode number is still 0. The magnetic spikes are usually observed initially and then these develop to continuous fluctuations, with a frequency up to ~10 kHz. The magnetic spike is also poloidally asymmetric but the peak is found at the low field side. Assuming an outward movement of 20 cm and m = 2, the simulated signals agree with the measured one (Fig. 3(c)). This suggests RE beam is located on the low field side. The results can also be confirmed by measuring the synchrotron emission with an infrared camera (Fig. 3(d)).

During the RE current plateau, most of the current are carried by REs. RE drift orbits, shifted outward from the magnetic flux surfaces, depend on the electron energy. This is illustrated in

Fig. 4 where poloidal sections of the drift surfaces of the REs with different energies are plotted. For the HFS case, background plasma and low energy electrons do firstly interact with the inner wall. Another possibility is that closed magnetic surfaces are firstly broken, due to the interaction with the inner wall, and then the REs confined on these surfaces are lost immediately. For the LFS case, high energy electrons interact with the outer wall and the whole plasma with the RE beam is still well-confined. But the phase difference seen in the poloidal Mirnov coil signals could not be understood by this.

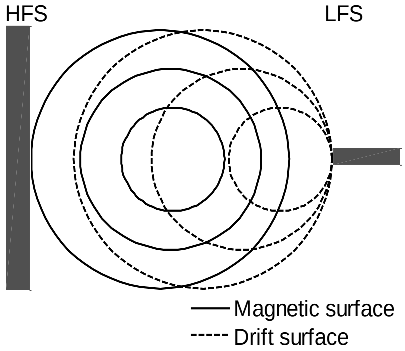

Fig. 4 Drift orbits of runaway electrons on different magnetic flux surfaces.

2.3 *Magnetic turbulence during final termination*

During final termination, several kinds of magnetic turbulence are also observed on the Mirnov coils. Some of them are similar to the magnetic turbulence during current quench. In some other cases, regular fluctuations are observed both on the Mirnov coils and SXR signals, shown in Fig. 5(a)-(b). The frequency spectrum of magnetic turbulence (#115208) is shown in Fig. 5(c) and the turbulence frequency changes from ~100 kHz to ~60 kHz in 0.8 ms. The toroidal mode number is 1. Similar behavior is also found during the current quench in some discharges without a RE plateau. These suggest the modes are likely to be from the interaction between the high-energetic REs and the background plasma.

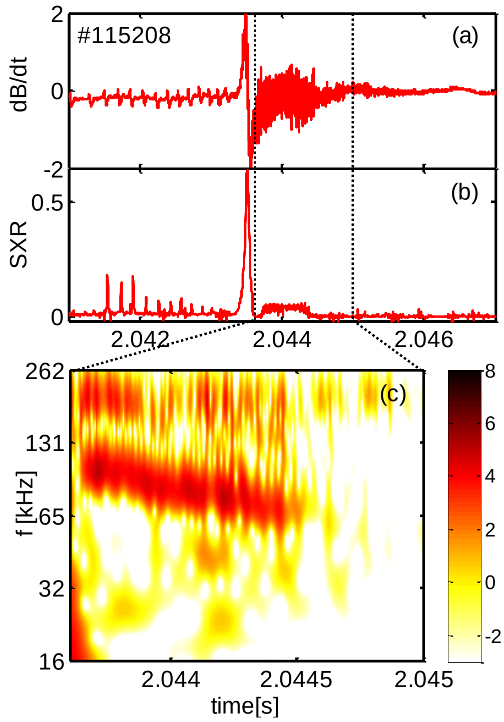

Fig. 5 Time traces showing (a) magnetic turbulence, (b) SXR emission, and (c) spectrum of magnetic turbulence in shot 115208.

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