Experimental Observation of a Magnetic-Turbulence Threshold for Runaway-Electron Generation in the TEXTOR Tokamak

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Magnetic turbulence is observed at the beginning of the current quench in intended TEXTOR disruptions. Runaway electron (RE) suppression has been experimentally found at magnetic turbulence larger than a certain threshold. Below this threshold, the generated RE current is inversely proportional to the level of magnetic turbulence. The magnetic turbulence originates from the background plasma and the amplitude depends strongly on the toroidal magnetic field and plasma electron density. These results explain the previously found toroidal field threshold for RE generation and have to be considered in predictions for RE generation in ITER.

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Introduction.—Runaway electron (RE) currents of several mega ampere are expected to be generated in ITER disruptions due to avalanche multiplication [1]. An uncontrolled loss of these high energetic electrons to the plasma facing components might cause serious damage [2]. The occurrence of REs depends on various factors and no definite RE generation dependence on plasma parameters is given in theory or found in present experiments. In tokamak experiments it is observed that RE generation occurs only above a threshold for the toroidal magnetic field of about 2 T, as has been found, independent on machine size, on JET [3], JT-60U [4], Tore Supra [5], and TEXTOR [2]. As a possible explanation for this behavior the whistler wave instability has been proposed [6]; however, no clear experimental evidence has been found yet. Above the 2 T threshold, the RE generation shows an exponential dependence on the toroidal magnetic field [7].

Magnetic fluctuations cause strong RE losses and can even prevent RE generation [8]. A variety of analytical models and numerical simulations address the effect of magnetic fluctuations on RE generation and find that a magnetic turbulence level of $\delta B/B_t > 0.1\%$ suppresses the RE avalanche during disruptions [8–11]. The effect of externally applied magnetic perturbations (e.g., resonant magnetic perturbations) on RE generation has been studied in JT-60U [12] and TEXTOR [13]. Both publications conclude that RE production is completely suppressed above a certain amplitude of the applied perturbation field. The magnetic fluctuation level is correlated with the hard X-ray signal after the disruption in JET, showing that larger X-ray levels are obtained when magnetic fluctuations are lower [3]. The influence of intrinsic magnetic turbulence on the de-confinement of REs has recently been analyzed at TEXTOR during the flattop phase of low density discharges [14] where RE losses have been utilized to probe the spatial amplitude of magnetic fluctuations. In this letter, we will report evidence from the TEXTOR tokamak showing that intrinsic magnetic turbulence strongly correlates with the toroidal field threshold for RE generation during the disruption current quench.

Experimental setup and results.—Disruptions are deliberately triggered by injection of large amounts of Argon using a fast disruption mitigation valve (DMV) on TEXTOR [15]. Using the same experimental setup as in Ref. [13], the experiments were carried out with the following parameters: the toroidal magnetic field $B_t = 1.7$–2.5 T, the plasma current $I_P = 300$–350 kA, the edge safety factor $q_a = 2.9$–5, the line averaged central density $n_e = 2.0 \times 10^{19}$ m^{-3}, the major radius $R = 1.75$ m, the minor radius $a = 0.46$ m, and number of injected Argon particles N_{Ar} changing from 2.3×10^{21} to 1.9×10^{22}.

Figure 1 compares two discharges, one develops a RE current plateau during the current quench and the other does not. The DMV is triggered at $t = 2.0$ s. After 3–4 ms the thermal quench occurs. During the following current quench, the plasma current decreases as shown in Fig. 1(a). In some situations a RE current plateau forms (#117833) which has been observed to last up to 170 ms. Meanwhile, obvious magnetic turbulence is seen in signals from magnetic pick-up coils with the sampling rate of 1 MHz, shown in Fig. 1(b) and 1(c). The magnetic turbulence appears at the beginning of the current quench and lasts from 4 to

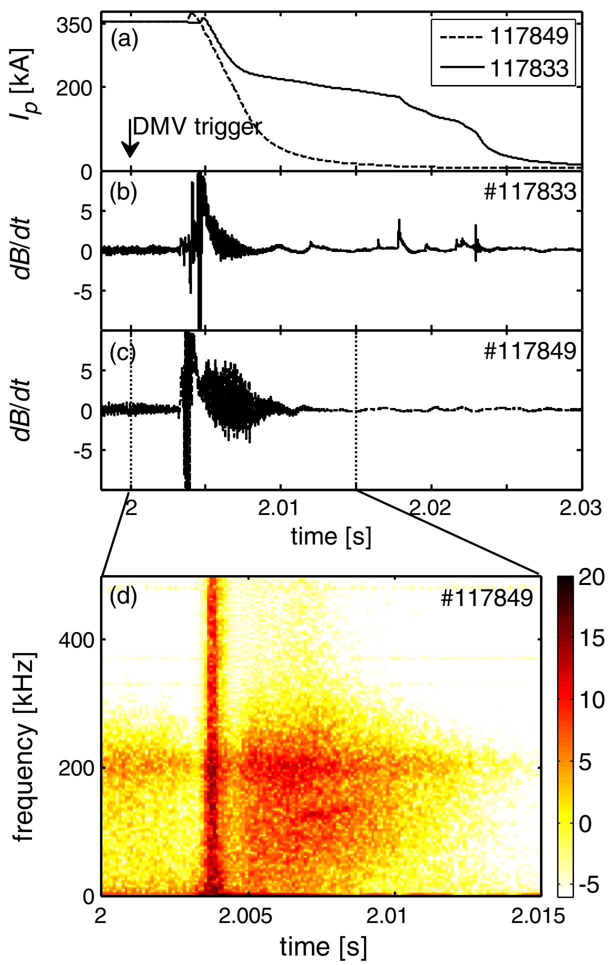

FIG. 1 (color online). Time traces from two discharges differing in the current quench phase showing (a) plasma current I_P, (b) magnetic turbulence dB/dt in shot 117833, (c) magnetic turbulence dB/dt in shot 117849, and (d) spectrum of magnetic turbulence in shot 117849. The current quench occurs at about 4.5 ms after triggering the DMV in shot 117849.

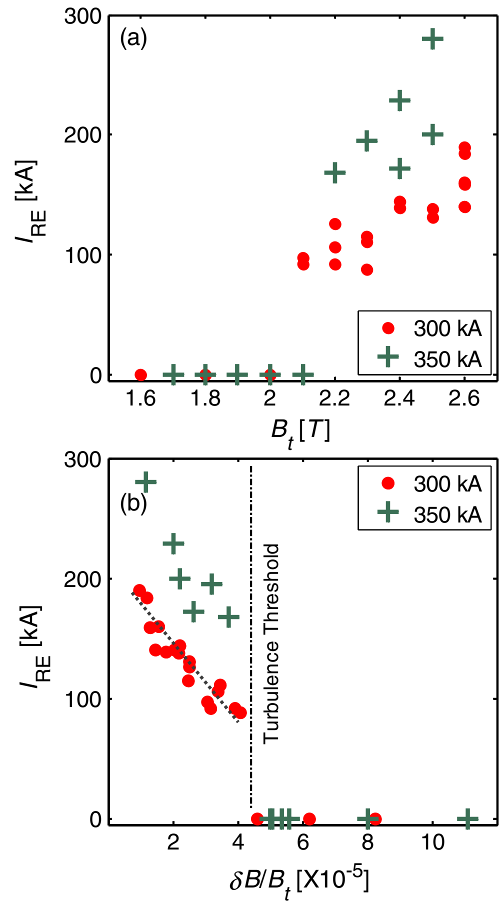

FIG. 2 (color online). RE current in TEXTOR disruptions as a function of (a) toroidal field (b) normalized magnetic turbulence level.

8 ms. The level initially increases and then decreases. A typical frequency spectrum of magnetic turbulence is shown in Fig. 1(d).

The parameters of both shots 117833 and 117849 are the same except for the toroidal magnetic field, but the RE generation is totally different. The magnetic turbulence level with $B_t = 1.8$ T is at least twice of that with $B_t = 2.4$ T. Anomalous RE losses due to magnetic turbulence with $B_t = 1.8$ T are therefore much larger than with $B_t = 2.4$ T. This suggests that magnetic turbulence during the current quench plays the dominant role in this stage and is the cause of the different observed RE tails.

In Fig. 2(a), a survey of several discharges shows that REs occur after a disruption when the value of B_t exceeds the threshold and that the RE current increases at high toroidal magnetic field. However, the RE tail is not always reproducible, even with the same toroidal magnetic field. This could be due to the difference in the magnetic turbulence level (δB), as seen later in the spread of δB for the same value of B_t in Fig. 4(b). One possible reason for the difference in δB is the triggering of the disruptions at random phases of the sawtooth cycle, which locally changes the plasma parameters. The RE current is estimated by subtracting the current evolution of a disruption without any RE generation. RE current is given in Fig. 2(b) as a function of the maximum magnetic turbulence during the current quench. The amplitude of magnetic turbulence is calculated by filtering the signal with a high pass filter (> 2 kHz), integrating, and then determining the maximum of the envelope. In TEXTOR the RE plateau is always visible unless the normalized magnetic turbulence level exceeds the threshold of about $\delta B/B_t \sim 4.8 \times 10^{-5}$ for $I_p = 300, 350$ kA and the REs (which may be produced in the current quench) get quickly lost within the first 5 ms of the current quench. This value of the critical turbulence level is of the same order as JET result (Fig. 3 in Ref. [3]). The threshold dependence on different currents is not obvious from the measured data. For shots with lower magnetic turbulence level than the threshold it is found that the RE current ($I_{\rm RE}$) 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 only 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.

Figure 2(b) suggests that a good empirical relation for the RE current dependence on $\delta B/B_t$ below the threshold is given by

$$I_{\rm RE} \propto -\alpha \delta B/B_t.$$

Here α is a function of the plasma current decay rate or the electric field. It cannot be excluded at present that α depends on the pre-disruption plasma parameters. Magnetic turbulence appears after the thermal quench and it is only possible to cause RE losses but not the generation. The resultant RE current depends on both, electric field (RE generation) and magnetic turbulence (RE losses).

Magnetic turbulence.—In the following some basic aspects of magnetic turbulence are analyzed. The amplitude of the measured magnetic turbulence during the current quench is $\delta B/B_t \sim 10^{-5}$–$10^{-4}$, which is much weaker than that during the thermal quench [Fig. 1(d)]. The spectrum shows that the frequencies of the turbulence form a wide distribution and most of the power is in the range from 60 to 260 kHz. This excludes that it originates from macroscopic magnetohydrodynamics (MHD) activity though the origin of the magnetic turbulence is not yet clear and requires future investigations.

Comparing the signals of different Mirnov coils distributed along the poloidal circumference of the liner (= first wall) shows that the magnetic turbulence is poloidally asymmetric (Fig. 3). The level at the top of the inner wall is about 7 times larger than that at the low field side. Indeed, the magnetic fluctuations decay as $r^{-(m+1)}$ in the vacuum. Here, r is the minor radius and m is the poloidal mode number. Poloidal asymmetry during the current quench could be an indication that the plasma is shrinking and moving inward. If we assume $m = 10$ (here m is an average value because the poloidal mode number is a function of both time and frequency during the current quench) and the plasma movement to be inward by 8 cm, the simulated signals agree with the measured ones, as shown in Fig. 3. REs are always generated on the high field side as has been observed by measuring the synchrotron emission with an infrared camera in TEXTOR [16], which is also consistent with the assumptions for our simulations.

Clear evidence of the relation between the magnetic turbulence and plasma density can be drawn from Fig. 4 in which measured magnetic turbulence is plotted versus the amount of injected gas. In a series of experiments the number of injected Argon atoms has been varied from 2.3×10^{21} to 1.9×10^{22}. The impurity ion density in MGI disruptions on TEXTOR is proportional to the number of injected atoms [17]. Figure 4(a) shows that, the relative level of magnetic turbulence is proportional to the square root of post-MGI plasma density both for $B_t =$ 1.9 T and $B_t = 2.4$ T. This result is in agreement with a scaling law obtained in the Tore Supra tokamak [18]. In order to compare the fluctuation level with $B_t = 2.4$ T to the one with $B_t = 1.9$ T, the first value is multiplied by a factor $(2.4/1.9)^2$ yielding a good agreement of both data sets [Fig. 4(a)]. The level of magnetic turbulence is a decreasing function of the toroidal magnetic field as can be seen from Fig. 4(b). The influence of the plasma current is again not clear. Both parameter scans can be summarized as

$$\delta B/B_t \propto \sqrt{n_e} \quad \text{and} \quad \delta B \propto B_t^{-2}.$$

The level of magnetic turbulence does strongly dependent on the toroidal magnetic field. The lower the magnetic field, the larger is the level of the magnetic turbulence and more RE losses occur. The turbulence also depends on the plasma density of which REs are only a small fraction. This supports that magnetic turbulence is mainly contributed from the background plasma.

Discussion.—The magnetic turbulence can cause RE losses due to increased radial transport and the characteristic diffusion time associated with magnetic turbulence can be written as $\tau_{\delta B} = (a^2/\nu_{\parallel} D_M)\gamma^5$, where $\nu_{\parallel}$ is the parallel electron velocity, γ is the relativistic scaling factor (γ^5 represents the phase-averaging effect of electron orbits deviating from flux surfaces), and D_M is the magnetic diffusion coefficient, given by $D_M \approx \pi q R(\delta B/B_t)^2$, where q is the safety factor [8–10]. Since the RE diffusion

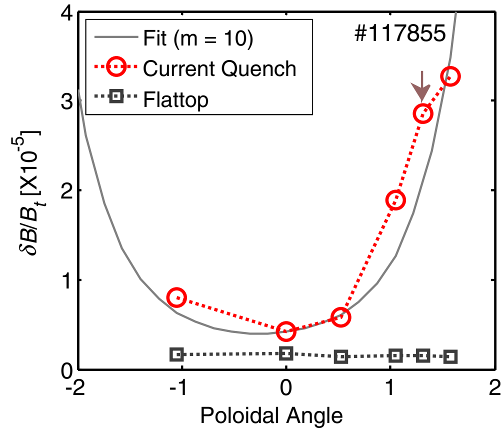

FIG. 3 (color online). Comparison of magnetic turbulence level at different poloidal angles: Circles correspond to measured values during the current quench ($t = 2.0065$ s) and squares correspond to the values before the disruption ($t = 2.0$ s). The fitting line is simulated assuming the plasma moves inwards by 8 cm. Poloidal angle "0" is at the low field side and the magnetic turbulence value used in this Letter is from the coil in the poloidal angel of 1.3, marked by the arrow in the figure.

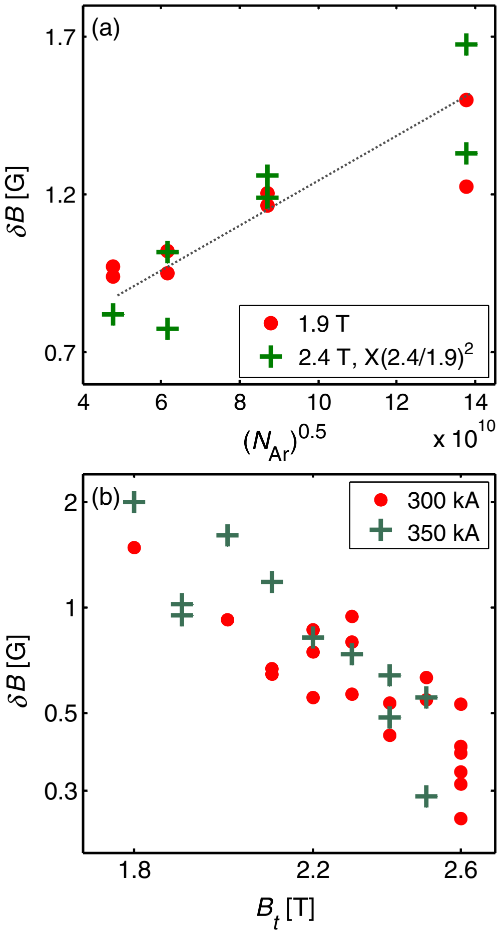

FIG. 4 (color online). (a) Magnetic turbulence levels for $B_t = 1.9$ T and $B_t = 2.4$ T versus number of injected Argon atoms. In order to compare both data sets the amplitudes measured at $B_t = 2.4$ T are multiplied by a factor $(2.4/1.9)^2$. (b) Magnetic turbulence level for $I_P = 300$ kA and $I_P = 350$ kA versus toroidal field.

is dominated by the magnetic turbulence, the RE diffusion time $\tau_{\rm loss}$ can be approximately regarded as the magnetic turbulence induced diffusion time $\tau_{\rm loss} \approx \tau_{\delta B}$. A 0D model of the current quench including RE generation $n_{\rm RE}$ and magnetic turbulence loss is applied in [17]:

$$\frac{dn_{\rm RE}}{dt} = f_{\rm prim} + (1/\tau_{\rm RE} - 1/\tau_{\rm loss})n_{\rm RE}.$$

Here, $f_{\rm prim}$ is Dreicer generation and $\tau_{\rm RE}$ is the avalanche growth time. With high magnetic turbulence the RE diffusion time should be shorter than the avalanche growth time and thus suppress avalanche generation of REs. In fact, $1/\tau_{\rm RE} \sim 260\ {\rm s}^{-1}$ for typical TEXTOR parameters ($B_t = 2.4$ T, $N_{\rm Ar} = 3.8 \times 10^{21}$, $R = 1.67$ m, $a = 0.35$ m, $q = 2$, $\nu_{\parallel} \approx c = 3 \times 10^8$ m/s, and $\gamma = 3$ at the beginning of the current quench). The corresponding threshold of magnetic turbulence is $\sim 2.2 \times 10^{-3}$. Previous modeling studies also find that $dB/B_t > 10^{-3}$ suppresses the RE avalanche [8–11]. This value is much larger than the measured magnetic turbulence amplitude $\sim 4.8 \times 10^{-5}$ using the Mirnov coils. This can be explained by the inward movement of the plasma and a shrinking of the minor radius during the current quench. Assuming an average poloidal mode number $m \sim 10$, a movement of 8 cm and a reduction of the minor radius to 0.35 m, the estimated level of magnetic turbulence at the plasma edge amounts $\delta B/B_t \approx 2.4 \times 10^{-3}$. This value is in good agreement with calculated value needed to explain the experimentally observed increase in RE transport.

Conclusions.—Magnetic turbulence (broadband frequency) is observed at the beginning of the current quench in deliberate TEXTOR disruptions. The analysis carried out in this Letter shows that RE suppression has been experimentally found only when the magnetic turbulence exceeds a certain threshold. Below this threshold, the RE current is inversely proportional to the level of magnetic turbulence. Magnetic turbulence is mainly contributed from the background plasma and the level does strongly dependent on the toroidal magnetic field and plasma density. The results reported in this Letter support evidence for a new threshold for RE suppression due to magnetic turbulence and should be considered when making predictions on RE generation in devices such as ITER.

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