Experimental observation of magnetic turbulence causing runaway electron losses during tokamak disruptions

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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]. The Rosenbluth density is usually required to be achieved for RE suppression. Actually, REs are not observed even with lower density when the *E*-field is significantly higher than predicted by relativistic collisional theory. It suggests that additional RE loss mechanisms may play a significant role during the disruption. We present here observations of magnetic turbulence during the current quench both on the TEXTOR and J-TEXT tokamaks, which can cause strong RE losses and even prevent RE generation.

2. Experimental observations

Disruptions are deliberately triggered by injection of large amounts of Argon using a fast disruption mitigation valve (DMV) on TEXTOR and J-TEXT.

2.1 *Magnetic turbulence during current quench*

Figure 1 compares two discharges in TEXTOR, #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. 1 (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. 1 (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.

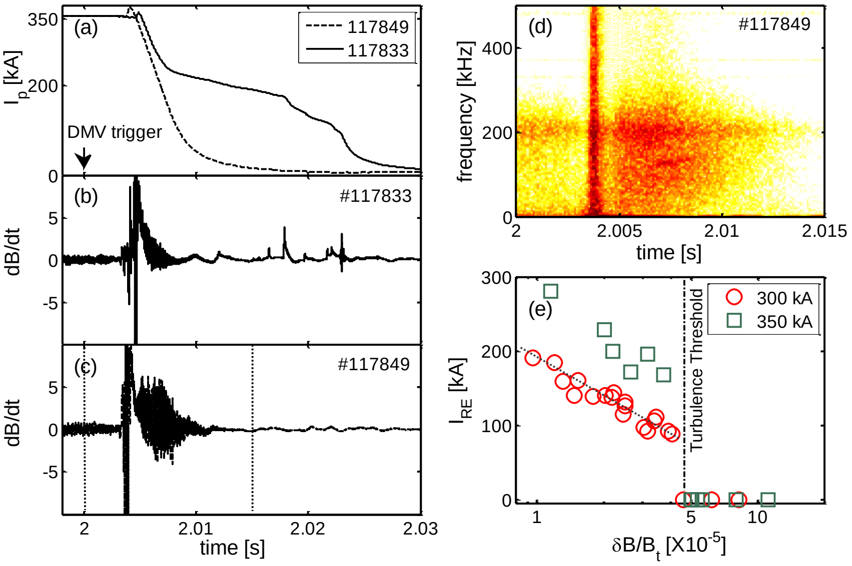

Fig. 1 Time traces showing (a) plasma current, (b) magnetic turbulence in shot 117833, (c) magnetic turbulence in shot 117849, and (d) spectrum of magnetic turbulence in shot 117849. (e) RE current in TEXTOR disruptions as a function of normalized magnetic turbulence level.

In Fig. 1 (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. 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. The results are confirmed in a series of disruption experiments on J-TEXT.

2.2 *Dependence of magnetic turbulence on plasma parameters*

A survey of disruption discharges both on TEXTOR and J-TEXT gives the relations between magnetic turbulence and plasma parameters, such as electron density, toroidal magnetic field, and plasma current. Clear evidence of the relation between the magnetic turbulence and plasma density can be drawn from Fig. 2 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 [4]. Figure 2 (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. 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. 2 (a)). As REs are only a small

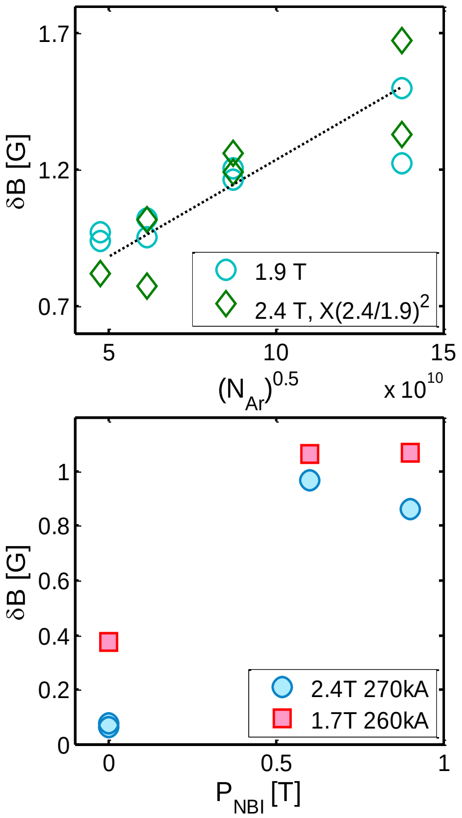

Fig. 2 Magnetic turbulence levels (a) for B_t =1.9T and B_t = 2.4T versus number of injected Argon atoms, (b) for Ohmic plasma and NBI plasma versus heating power in TEXTOR.

fraction of electron density, this supports that magnetic turbulence is mainly contributed from the background plasma. The effect of heating power on magnetic turbulence is indicated in Fig. 2(b). The level $\delta B < 0.4$ Gauss for the Ohmic plasma increases to about 1 Gauss for 0.6 and 0.8 MW NBI. This is well consistent with the results during the flattop in TEXTOR [5].

The observation in J-TEXTshows that, the level of magnetic turbulence is a decreasing function of the toroidal magnetic field both for I_P = 160 kA and I_P = 180 kA and an increasing function of plasma current as can be seen from Fig. 3 (a) and (b), although δB is spread for the same B_t and I_P. The level of magnetic turbulence does strongly dependent on the toroidal magnetic field and plasma current. The lower the magnetic field or the large the plasma current, the larger is the level of the magnetic turbulence and more RE losses occur. The relation between the magnetic turbulence and plasma density before the disruption (Fig.3 (c)) is not yet clear from J-TEXT results.

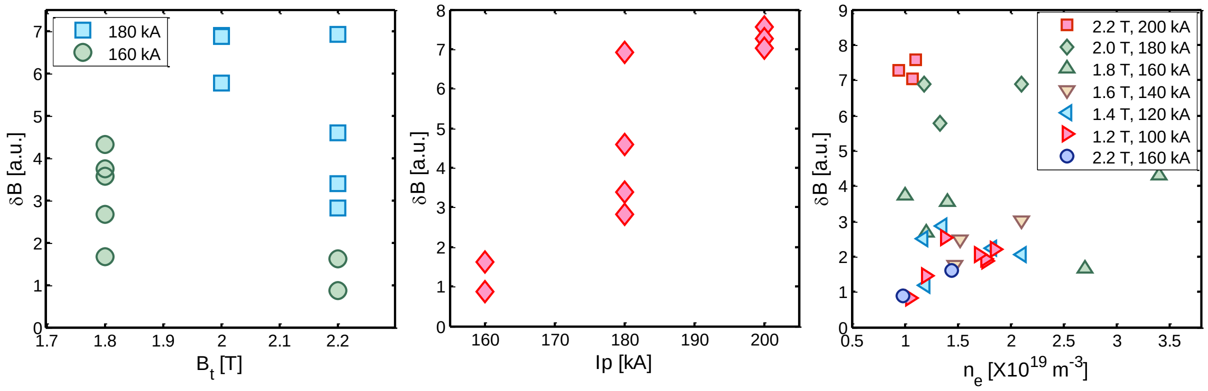

Fig. 3 The relation between magnetic turbulence levels and (a) toroidal magnetic field for Ip=160 kA and Ip = 180 kA, (b) plasma current, and (c) electron density before the disruptions in J-TEXT.

3. 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

$\tau_{\delta B} = \dfrac{a^2}{v_{\|} D_M}\gamma^5$, where D_M is the magnetic diffusion coefficient, given by $D_M \approx \pi q R(\delta B / B_t)^2$.

Since the RE diffusion is dominated by the magnetic turbulence, the RE diffusion time τ_{loss} can be approximately regarded as the magnetic turbulence induced diffusion time $\tau_{\text{loss}} \approx \tau_{\delta B}$. A 0D model of the current quench including RE generation n_{RE} and magnetic turbulence loss is applied in [4]:

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

With high magnetic turbulence the RE diffusion time should be shorter than the avalanche growth time and thus suppress avalanche generation of REs. Typical results of the simulations for the effect of diffusion time on RE currents are shown in Fig. 4. All the parameters are fixed except that only $1/\tau_{\text{loss}}$ (γ) is varied from 35 to 3000 s^{-1}. Increasing the loss rate clearly reduces the runaway current and consequently the plateau amplitude. There are clearly two regions: a linear decay for $\gamma < 350\ s^{-1}$ and for $\gamma > 350\ s^{-1}$: (I) the linear fit to the first region is consistent with experiments; (II) The second linear decay appears because of the Dreicer mechanism, which is very powerful but short in time, at this point the avalanche is suppressed. The REs mainly generate and get lost both during the current quench, so no RE plateau are observed and then the RE current is evaluated as zero in the survey shown in Fig. 1(e). The simulation results support the experimental observation in TEXTOR and J-TEXT.

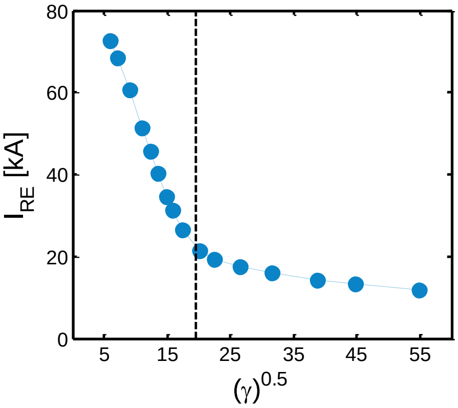

Fig. 4 RE currents versus magnetic turbulence levels.RE plateau is only obtained with the loss rate lower than a threshold

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