Influence of radiation on the energy spectrum of runaway electrons 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]. Impurity injection on RE plateau during disruptions, as a candidate method for ITER, is proposed for mitigating REs. Experimental results on DIII-D and Tore-Supra show large quantities of high-Z gas are injected into the RE plateau, resulting in decay of the RE current. We present here observations on the TEXTOR tokamak, which indicates influence of impurity injection on the energy spectrum of REs.

2. Experimental observations

Disruptions are deliberately triggered by injection of large amounts of Argon using a fast disruption mitigation valve (DMV) at 2.0s on TEXTOR. A RE current plateau forms during the following current quench phase. Then the second DMV was triggered on the RE plateau.

Figure 1 compares two discharges, #117528 with neon injection by the second DMV at 2.01s, 10ms after the first DMV, and #117533 without impurity injection during the RE plateau. The time evolution of plasma current shows that argon injection by the second DMV causes an enhanced decay rate of the RE current. For #117528, just several milliseconds after the second DMV triggering, the signals of Hα and SXR rise and then decrease slowly, which is clearly attributed to the increase of collisionnality. Meanwhile, no clear change is found in the ECE and synchrotron radiation.

Helium injection by the second DMV has also been tried on TEXTOR, shown in Fig. 2. Similar to #117993 which is without impurity injection during the RE plateau, no clear change of the RE current is found in #117999, in which helium is injected at 2.01s by the second DMV. The signals of Hα, ECE, and SXR raise after helium injection and then quickly decrease, even less than #117993.

Compared with these two cases, injection of amount of middle-Z (or high-Z) gas into RE plateau can cause enhanced current decay but no sufficient effect is observed with low-Z gas injection. The difference of radiation signals, such as Hα, ECE, and SXR, suggests that radiation caused by impurity injection may play an important role on the evolution of RE plateau.

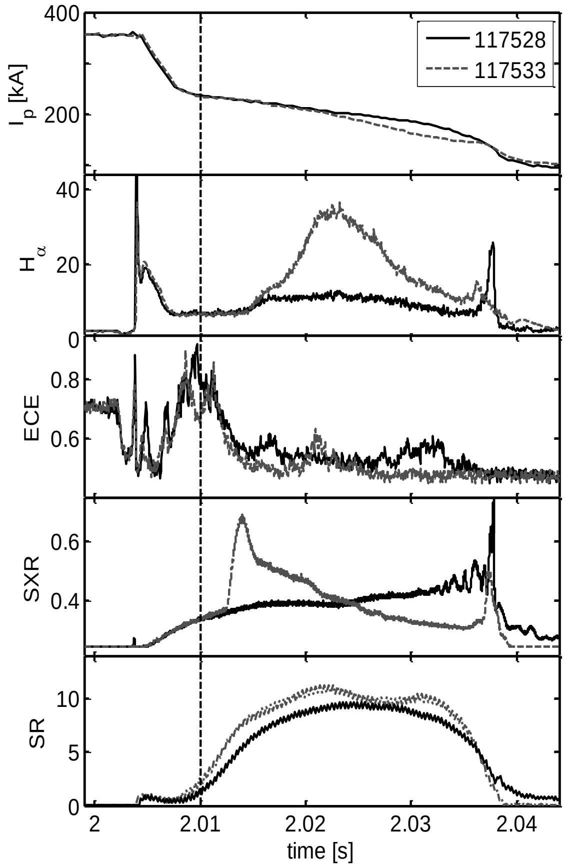

Fig. 1 Time traces from two discharges showing (a) plasma current, (b) Hα, (c) ECE, (d) SXR, and (e) synchrotron radiation shot 117849. The dashed line indicates the triggering moment of the second DMV.

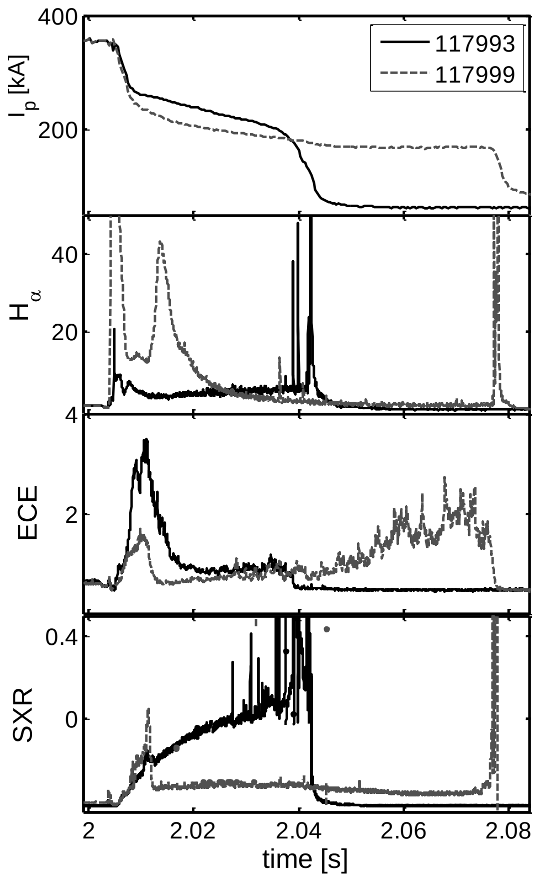

Fig. 2 Time traces from two discharges showing (a) plasma current, (b) Hα, (c) ECE, and (d) synchrotron radiation shot 117849.

3. Discussion

Experimental evidence from several tokamaks indicates that the electric field strength necessary for RE generation could in fact be several times larger than the critical electric field. Besides electric field and Coulomb collisions, many other potential mechanisms, such as bremsstrahlung [3] and synchrotron radiation [4, 5] have been considered as possible explanations for these observations.

The energy loss rate due to the collisions of a RE with the plasma particles is given by

$$P_{\mathrm{coll}} = (dW/dt)_{\mathrm{coll}} = n_e e^4 \ln\Lambda / (4\pi\varepsilon_0^2 m_e v), \qquad (1)$$

The energy gain in the electric field is $P_E = eE_{\parallel}v_{\parallel}$. The relativistic collisional theory of runaway electrons predict that the threshold electric field for runaway generation E_{th} is set by the condition that $P_E = eE_{\parallel}v_{\parallel}$ should be at least larger than such minimum value of P_{coll} when $v \rightarrow c$. Actually, runaway electrons not only lose energy due to collisions but they also lose energy in the form of bremsstrahlung and synchrotron radiation at high energy. The energy loss due to bremsstrahlung when they are deflected by the nuclei of atoms is given by

$$P_B = Z^2\, n_i T_e^{0.5} / (7.69\times10^{18})^2 * (1+k_B T_e/m_e c^2), \qquad (2)$$

The synchrotron radiation losses is

$$P_{SR} = 2/3\, r_e m_e c^3\, (v/c)^4 \gamma^4 \langle 1/R^2 \rangle. \qquad (3)$$

The total stopping power is obtained by adding the collision, bremsstrahlung and synchrotron radiation losses, $P_{loss} = P_{coll} + P_B + P_{SR}$. When P_E exceeds P_{loss}, REs are generated and the corresponding electric field is the new critical electric field E_{th}.

The new energy limit for REs is plotted in Fig. 3. The total stopping power and contribution of Collision, bremsstrahlung, and synchrotron radiation are also shown. For the curve of the total stopping power, the low energy region is dominated by collision while the bremsstrahlung and synchrotron radiation losses dominate at high energies. Fig. 3 indicates that including the bremsstrahlung and synchrotron radiation losses, the new threshold electric field for RE generation must be larger than prediction of the relativistic collisional theory of REs. As illustrated in Fig. 3, for a given electric field large than the threshold electric field, energy balance ($P_E = P_{loss}$) is found at two critical points, P_{th1} and P_{th2}. An electron with an energy large than P_{th1} will be accelerated by the electric field to run away until a balance is achieved due to the bremsstrahlung and synchrotron radiation losses.

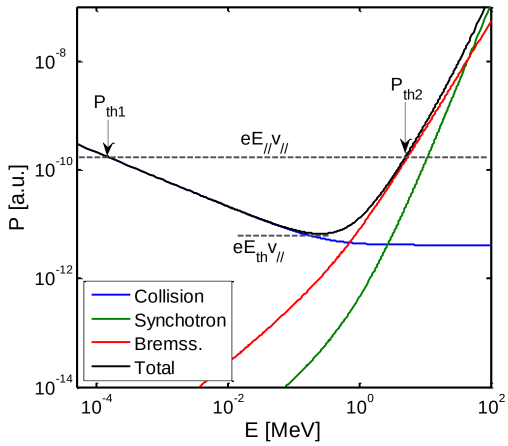

Fig. 3 Collision, bremsstrahlung, synchrotron radiation, and total stopping powers for an electron. . The energy gain in the electric field crosses the curve of the total stopping power in two points P_{th1} and P_{th2}.

Basing on the method, the effect of impurity injection on RE plateau can be discussed here. The electron density will increase due to impurity injection will increase the electron density (n_Z) and Z_{eff}. The energy losses caused by the collision and synchrotron radiation are both not sensitive to the noble gas species too much, so the difference of radiation in the experiments could be caused by the bremsstrahlung.

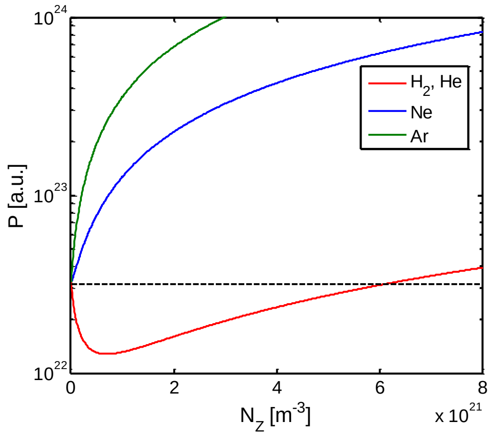

Fig. 4 bremsstrahlung due to impurity injection by the second DMV. Both low-Z (H_2, He) and middle-Z (Ne, Ar) are considered here.

Assume $n_Z = 10^{20}$ m^{-3} and Z_{eff} = 18 for the background plasma after disruptions triggers by DMV. Simulation results including impurity injection by the second DMV are shown in Fig. 4. It is clear that for H_2 and He, the bremsstrahlung decreases when the injection amount is less than a value but for Ne and Ar, the bremsstrahlung increases continually. The effective charge number of H_2 and He is less than the background plasma and mixture of them together will decrease the final Z_{eff} if the injection amount is limited. Impurity injection by the second DMV changes the bremsstrahlung and then the total energy balance. Simulation results (Fig. 5) show that when helium is injected to the RE beams and the bremsstrahlung will decrease, the new P_{th2} (P_{th2}') is large than before, which means that REs with the previous energy P_{th2} will be accelerated to P_{th2}'. When argon is injected and the bremsstrahlung will increase, the new P_{th2} (P_{th2}') is less than before, which means that REs with the previous energy P_{th2} will be reduced to P_{th2}'. These results are consistent with the results in TEXTOR and support the experimental observations that middle-Z (or high-Z) gas injection by the second valve is more effective at reducing RE current in DIII-D and Tore Supra disruptions.

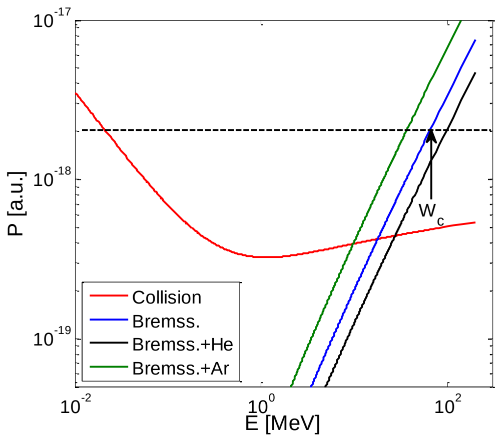

Fig. 4 the energy balance changed due to impurity injection by the second DMV. Both low-Z (He) and middle-Z (Ar) are considered here.

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