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Citation: Chin. Phys. B, 2023, 32 (**7**): 075204. DOI: 10.1088/1674-1056/acc3f8
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SPECIAL TOPIC — Plasma disruption

Effect of tearing modes on the confinement of runaway electrons in Experimental Advanced Superconducting Tokamak

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(Received 29 December 2022; revised manuscript received 27 February 2023; accepted manuscript online 14 March 2023)

The effect of tearing modes on the confinement of runaway electrons is studied in Experimental Advanced Superconducting Tokamak (EAST). The general tendency of the radial diffusion coefficient of runaway electrons (REs) $D_{\rm r}$ is derived based on the time response relation between the tearing modes and runaway electrons. The results indicate that, the magnetic fluctuations of tearing modes will enhance the radial diffusion of runaway electrons when the magnetic island is small. Following the increasing of the magnetic fluctuations of the tearing modes, the formed large magnetic island may weaken the radial diffusion of runaway electrons. The results can be important to understand the confinement of runaway electrons when large magnetic islands exist in the plasma.

Keywords: runaway electrons, bremsstrahlung emission, tokamak

PACS: 52.38.Ph, 52.35.Py, 52.25.Fi **DOI:** 10.1088/1674-1056/acc3f8

1. Introduction

Major plasma disruptions are a well-known threat to the safety of magnetic confined nuclear fusion reactors of the tokamak type, and continue to be an important and unsolved scientific problem until now.[1,2] In particular, the generated high-energy runaway electrons (REs) is one of the serious issues during this phase.[3,4] It is important to reduce the energy and population of REs and mitigate their effects on the first-wall materials in tokamaks, especially for larger tokamak devices.[5,6]

REs are accelerated mainly by the toroidal electric field in plasma. Because of the weak Coulomb collision of REs with other plasma particles, the collisional radial transport of REs is much less than the thermal transport. It is widely recognized that the anomalous transport of REs in tokamak plasma is important. The transport induced by electrostatic fluctuations has an inverse dependence on the electron velocity. So, for REs, this transport is very small. Conversely, the transport of REs is very sensitive to the magnetic fluctuations.[7,8]

The tearing modes (TMs) instability is driven by the radial gradient of the toroidal current density, accompanied by the formation of magnetic islands, which can induce magnetic fluctuations with large amplitude. So, the study of the effect of TMs on the confinement of REs is of considerable interest and important. We report in this paper the results from EAST tokamak. It reveals that the magnetic fluctuations can enhance the radial diffusion of REs. In the same time, magnetic islands with large size can possibly confine the high energy RE beams inside the islands, preventing the REs from loss.

2. Experimental results

A typical discharge is shown in Fig. 1. The TMs with frequency $f \approx 4$ kHz are excited at 2 s. Its frequency decreases rapidly to $f \approx 2$ kHz following the growth of its amplitude. Its frequency remains roughly stable from approximately 2.08 s, although its amplitude is still evolving. The mode number of the TMs is $m/n = 2/1$, with m and n are the poloidal and toroidal mode numbers, respectively. It locates at the radial position of $\rho_{2/1}(r/a) \approx 0.38$. The second harmonic exists in the frequency spectrum of the TMs, which indicates possibly deformation of the magnetic island structure. The period of interest is divided into three phases. Phase I is the amplitude increasing phase after its frequency is stable. Phase II is the amplitude decreasing phase. Phase III is the phase when its amplitude has decreased to very low level.

In the same time, loss of REs is observed through the measurement of the high energy hard x-ray (HXR) signal. The HXR signal is from the thick-target bremsstrahlung emission when the REs are lost and then hit the limiter or first wall of the EAST device, with energy range from approximately 0.5 MeV to 10 MeV. As can be seen in the frequency spectrum of HXR signal, loss of REs can hardly be observed from 2 s to 2.06 s when the TMs amplitude is small. Then, loss of REs can be observed clearly in HXR signal with the same frequency response, except more harmonics exist probably owning to the response of its electric system.

It can be seen clearly in Fig. 2 the relation between the TMs and REs loss. The time evolving relation between the TMs and REs in a very narrow time window is shown in

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Fig. 2(a). Peaks in the $\tilde{b}$ and HXR signal are extracted, and the time evolving of those peaks is shown in Fig. 2(c). The general tendency is clear that the REs are lost with the same frequency comparing to the rotate frequency of the TMs, and the loss intensity of REs is approximately proportional to the amplitude of the TMs.

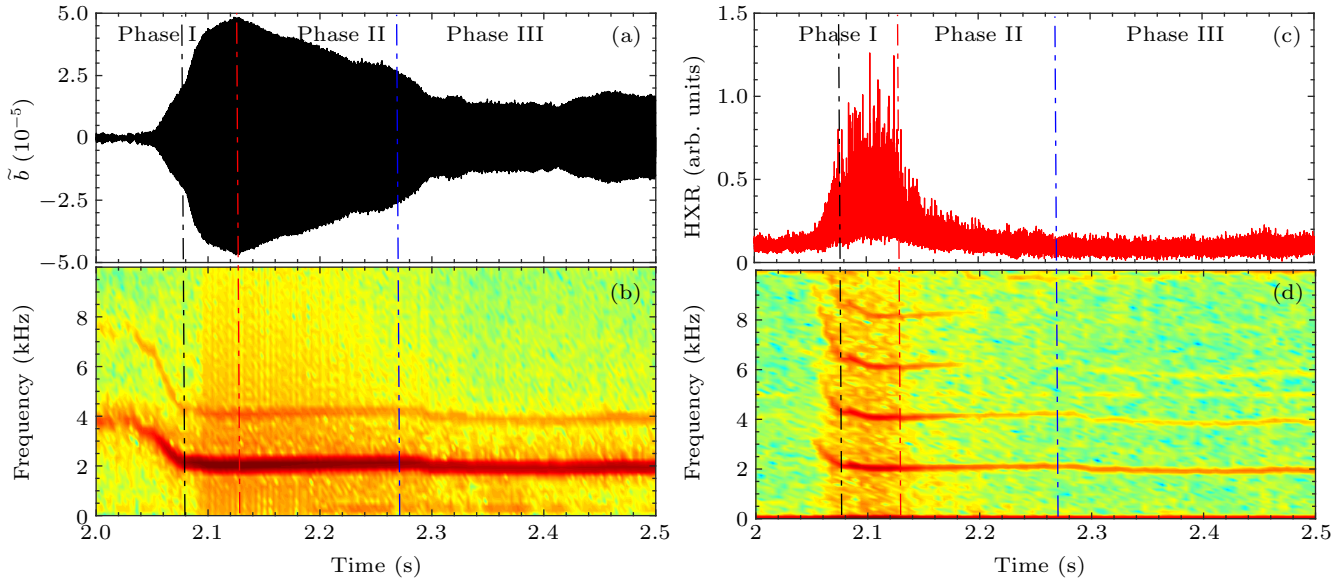


Fig. 1. (a) Time evolution of the normalized magnetic fluctuations $\tilde{b} = \tilde{B_\theta}/B_0$ deduced from Mirnov signal. (b) Time evolution of the frequency spectrum of $\tilde{b}$. Panels (c) and (d) are for the HXR signal.

3. Confinement characters

The lose of REs is used widely in tokamaks to derive its radial diffusion coefficients.[9–12] For REs, it has

$$\Delta t = \Delta r^2/12D_{\rm r}, \tag{1}$$

where Δt is the time delay between the peaks in $\tilde{b}$ signal and the corresponding peaks in HXR signal. Δr is the inversion radial position of the TMs. $D_{\rm r}$ is the radial diffusion coefficient of REs. So, for the case shown in Fig. 1, it can be modified to

$$D_{\rm r} = (a^2 - (0.38a)^2)/12\Delta t \approx a^2/14\Delta t. \tag{2}$$

The value of Δt can be deduced easily during sawteeth-like situations when the oscillation period is large. The time interval is about several ms in that case. However, for TMs case, the time interval is about 0.5 ms, and the particle confinement time of REs is about the order of several ms in this case. This means there will have several peak delays between the magnetic peaks and the corresponding HXR peaks. So, it is hard to identify which $\tilde{b}$ peak should responsible for one specific HXR peak in TMs case. In this case, dedicated procedure is performed. Firstly, the correspondence between the peaks of $\tilde{b}$ and HXR is aligned when their amplitudes are reached their maximum around 2.12 s, as shown in Fig. 2(c). Also, it can be confirmed by the cross-correlation relation between the peaks of $\tilde{b}$ and HXR signal, as shown in Fig. 2(b). It indicates there is an 8 peaks delay. As shown in Fig. 2(a), the 8 peaks delay corresponding to a time delay of approximately $\Delta t \sim 4$ ms, and a diffusion coefficient of approximately $D_{\rm r} \sim 3.1$ m$^2\cdot$s^{-1}. Then, matrix of the $\tilde{b}$ and HXR peaks is build in which they have the corresponding relations. On the other hand, the frequency response of the two signals should correspond with each other. The inverse of the time interval between two adjacent peaks will represent the main frequency character of the signal. As shown in Fig. 2(d), the main frequency characters of $\tilde{b}$ and HXR can well represent the frequency spectrum in Figs. 1(b) and 1(d), and the two signals are aligned with each other. Moreover, the time delay Δt deduced in this way is reasonable in physics. However, considering the phase shift of the magnetic fluctuations of TMs from plasma center to edge region, correction of the Δt is still needed. It will be quite complicated to perform this correction properly. So, the diffusion coefficient derived from Eq. (2) in this paper will have large errors, and it is used only to study the tendency of the response of the REs diffusion to the TMs amplitude.

In theory, the diffusion coefficient of REs $D_{\rm r}$ is proportional to $\tilde{b}^2$. The well-known Rechester–Rosenbluth coefficient $D_{\rm RR} = \pi q v_\parallel R\tilde{b}^2$ holds when the magnetic field is assumed to be fully stochastic.[13] A shielding factor Υ should be included considering the correction of $D_{\rm r}$ due to the displacement of the runaway electron orbits from the magnetic surfaces (orbit-averaging) and their large gyroradii (gyro-averaging) $D_{\rm RR} = \Upsilon\pi q v_\parallel R\tilde{b}^2$.[14,15] So, it is important to analyze the relation between the diffusion coefficient of REs $D_{\rm r}$ and the magnetic fluctuation amplitude of TMs $\tilde{b}^2$. This is also why we choose only the time window when the frequency of TMs is stable. It is suitable to analyze only the effect of $\tilde{b}^2$

on D_r without affected by other parameters. The results are shown in Fig. 3.

It can be seen in Fig. 3(a), D_r is decreasing following the increasing of $\tilde{b}^2$ during phase I, D_r increasing following the decreasing of $\tilde{b}^2$ during phase II, and D_r is decreasing following the decreasing of $\tilde{b}^2$ during phase III. A clear separation exists around $\tilde{b}^2 \approx 0.8 \times 10^{-9}$, which is corresponding to a magnetic island width of approximately $\omega_{crit} \sim 1$ cm based on the semi-empirical formula $\omega\,(\mathrm{cm}) = a_m\sqrt{\tilde{B}_\theta\,(\mathrm{Gauss})}$.[16] It has to point out the analyze from ECE signals indicates this critical width is larger than 1 cm. The exact value of this island width is hard to be derived accurately from the experimental data. Nevertheless, it indicates that, the magnetic fluctuations of TMs will enhance the radial diffusion of REs when the magnetic island is small. However, when the magnetic island is larger, it can possibly confine the RE beams inside the islands, preventing the REs from loss. A critical magnetic island width exists which can separate this two situations.

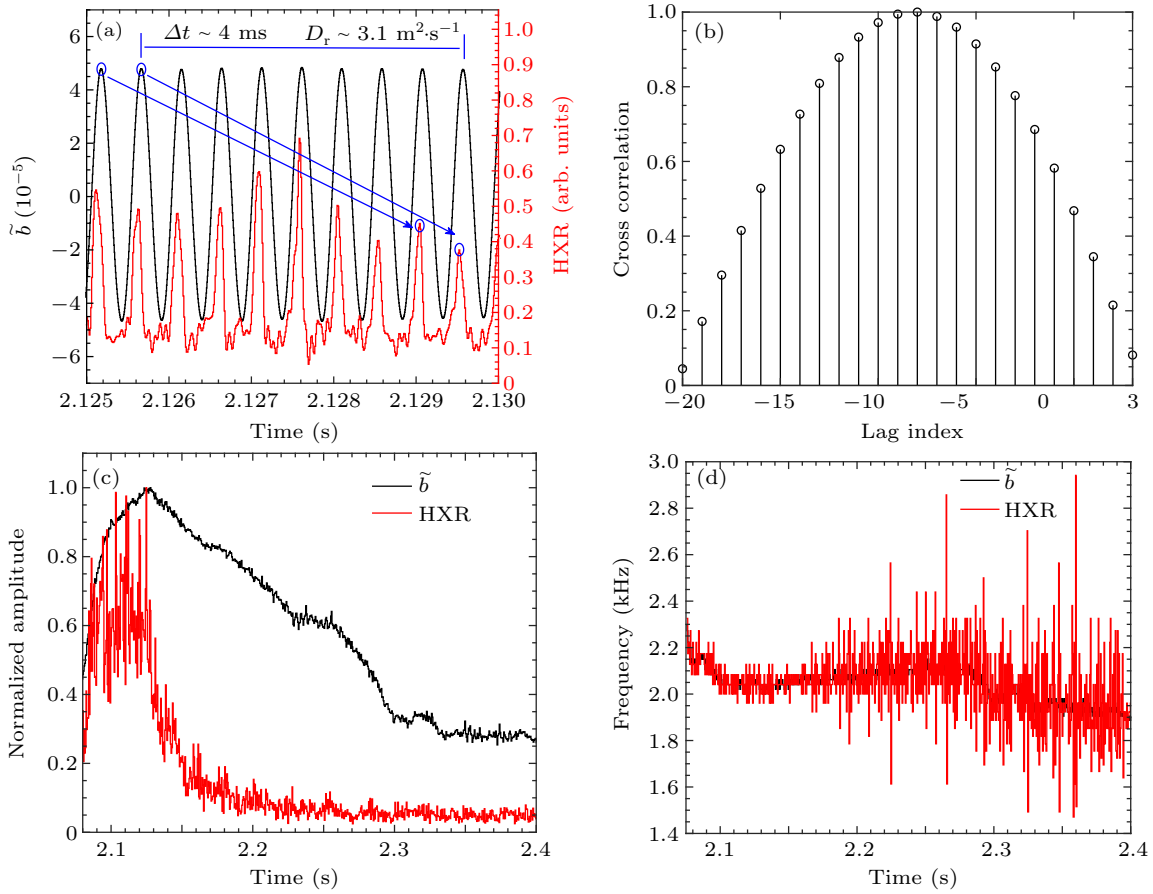


Fig. 2. (a) The time evolving relation between the TMs and REs, in a very narrow time window. (b) The cross-correlation relation between the peaks of normalized amplitudes of magnetic fluctuations $\tilde{b}$ and the HXR signal. (c) The time evolving relation between the $\tilde{b}$ and HXR signal. (d) The inverse of the time interval between two adjacent peaks for the $\tilde{b}$ and HXR signal.

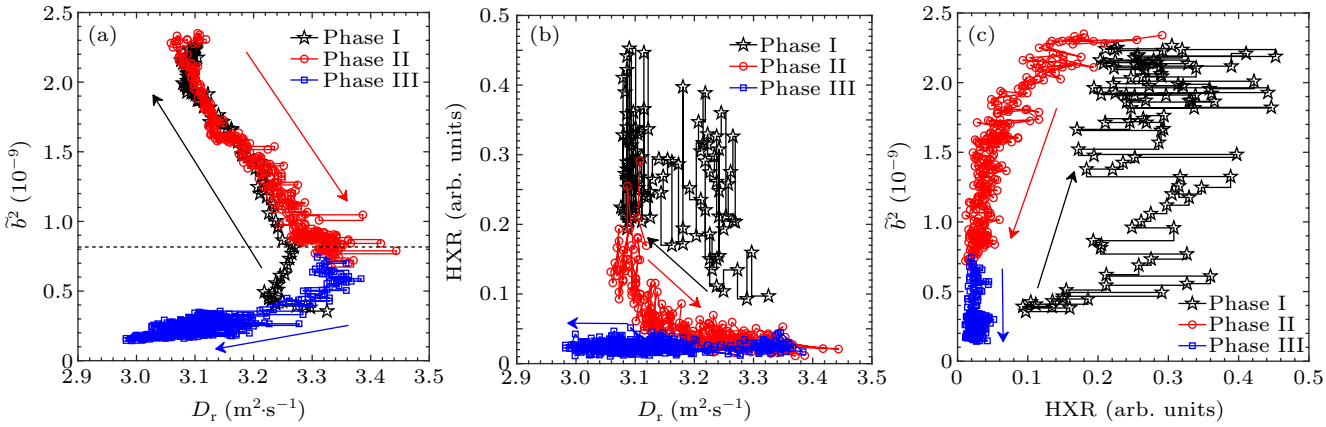


Fig. 3. (a) The relation between the diffusion coefficient of REs D_r and magnetic amplitude of TMs $\tilde{b}^2$ during phases I, II, and III. The arrows indicate the direction of the time evolution. (b) The relation between the diffusion coefficient D_r and the HXR intensity that originated from the REs loss. (c) The relation between the HXR intensity and magnetic amplitude $\tilde{b}^2$.

Figure 3(b) is the relation between the diffusion coefficient D_r and the HXR intensity that originated from the REs loss. The REs loss is governed by $dN/dt = S - N/\tau_p$, in which N is the number of the REs, S is the source term related with the plasma region where REs are lost, and τ_p is the particle confinement time of REs related with the diffusion coefficient D_r. So, HXR intensity is related with both the source term S and the diffusion coefficient D_r. Considering phase III, when D_r is decreasing, HXR is almost constant. It indicates that the plasma region where REs are lost is decreasing, related with the decreasing of the $\tilde{b}^2$ during this phase. The HXR intensity can be very sensitive to the plasma region affected by TMs.

Figure 3(c) is the relation between the HXR intensity and the magnetic fluctuation amplitude of TMs $\tilde{b}^2$. It indicates that the REs loss is enhanced firstly during phase I following the increase of $\tilde{b}^2$. Then, the REs loss is stable and decreases when $\tilde{b}^2$ is large. At last, REs loss is very weak during phase III. With the same amplitude of $\tilde{b}^2$, REs loss is weaker in phases II and III, comparing to the phase I.

4. Confinement of RE beams

The energy spectrum of the thick-target bremsstrahlung emission produced by REs when they are lost from plasma is continuous. The spectrum has a maximum energy $E_{HXR}^{max} \leq E_{RE}^{max}$, in which E_{HXR}^{max} is the maximum energy of the generated HXR, and E_{RE}^{max} is the maximum energy of REs. Besides this bremsstrahlung emission, high energy REs that confined inside plasma can also produce synchrotron radiation in the infrared or visible light range.[17,18] When REs with energy high enough to generate synchrotron radiation lost from plasma and then hit the limiter or first wall, they will also generate thick-target bremsstrahlung emission in the low energy hard x-ray range which can be measured by the HXR system.

Figure 4(a) is the synchrotron radiation image from the RE beams around 2.1 s. The intensity of the synchrotron radiation is higher in the high field side, which is related with the large orbit shift of RE beams.[19–21] The pixel marked by circle A is located around the location of the TMs $\rho_{2/1}(r/a) \approx 0.38$. Clearly, it indicates the RE beams are trapped by the magnetic islands, and then confined inside the islands. There is also another location near $\rho_{3/2}(r/a) \approx 0.19$ marked by circle B where RE beams exist, which is still being analyzed. The pixel marked by circle C is located near the plasma center.

Time evolution of the pixel intensity for those three pixels is shown in Fig. 4(b). The intensity of pixel A is at its maximum around 2.1 s when the magnetic amplitude $\tilde{b}$ is also at its maximum. It is coincident with the results that RE beams are confined by the magnetic island when the island grows to large size. The intensity of pixel B and C grows to stable after 2.1 s. RE beams are confined stably inside the location $\rho_{2/1}(r/a) \approx 0.38$. This is coincident with the results that REs loss is weaker in phases II and III comparing to phase I.

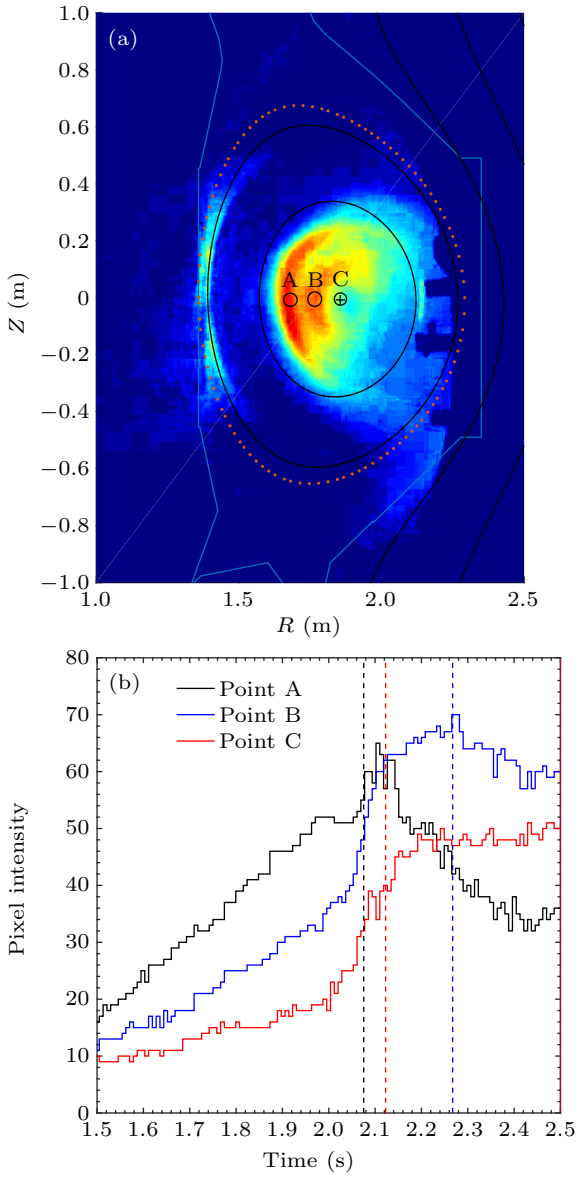


Fig. 4. (a) The synchrotron radiation image from the RE beams around 2.1 s, measured by a visible light camera. (b) The time evolution of the pixel intensity for the three pixels that marked in panel (a).

5. Summary

The effect of TMs on the confinement of REs is studied in EAST tokamak. The loss of REs is observed with the same frequency response comparing to the rotate frequency of the TMs when the magnetic fluctuation amplitude grows to a certain level. The HXR intensity can be very sensitive to the plasma region that affected by the TMs and the diffusion coefficient D_r. Based on the time response relation between TMs and REs, the general tendency of the radial diffusion coefficient of REs D_r can be derived. The results indicate that, the magnetic fluctuations of TMs will enhance the radial diffusion of REs when the magnetic island is small. Following the increasing of the magnetic fluctuations of TMs, the formed large

magnetic island may weaken the radial diffusion of REs. Combining with the synchrotron radiation originated from the high energy REs that confined inside plasma, it indicates that large magnetic island may confine the RE beams inside the islands or inside the plasma center, and weaken the radial diffusion of REs.

At last, it is possible that the critical magnetic island width may related with the large displacement size of REs orbits from the magnetic surfaces. Also, with energy substantially higher than the thermal electrons, REs can carry current effectively in plasma. So, the discrete spatial location of the confined RE beams inside the plasma is possible to change the monotone current distribution of the plasma, which in turn can potentially affect the evolution of the TMs. This two topics are worthy to be studied further, and they will be studied in our future works.

Acknowledgments

Project partly supported by the Youth Innovation Promotion Association of Chinese Academy of Sciences (Grant No. 2021445), the Science Foundation of Institute of Plasma Physics of Chinese Academy of Sciences (Grant No. DSJJ-2022-05), and partly supported by the Comprehensive Research Facility for Fusion Technology Program of China (Grant No. 2018-000052-73-01-001228).

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