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摘　要

提出了一个香蕉轨道损失模型用于解释托卡马克中逃逸电子损失的锯齿效应。由于锯齿崩塌过程中的磁场扰动，循环逃逸电子容易转换成俘获电子，经过一段时间延迟后由环向进动漂移到达孔栏。此模型也可解释与 $m=2$ 模式相关的硬 X 射线振荡和外破裂过程中的硬 X 射线尖峰。

Sawtooth-Induced Loss of Runaway Electrons in Tokamaks

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ABSTRACT

A model based on banana orbit loss has been proposed to explain the sawtooth effect on the loss of the runaway electrons in tokamaks. Circulating runaway electrons can be transferred into the trapped ones due to magnetic perturbation during sawtooth crashes, then they are repelled to the limiter via toroidal precession drift with a time delay. This model may also clarify the hard X-ray oscillations correlated with the m=2 mode and the hard X-ray bursts during outer disruptions.

INTRODUCTION

Sawtooth oscillations are routinely observed in tokamaks[1]. Sawtooth-like phenomena appear in many diagnostic signals, such as soft X-rays, hard X-rays, ECE and so on. Several models are proposed to explain sawtooth crash mechanisms and their perturbation propagation. Among other things, the sawtooth oscillations on the hard X-ray signals produced by the bombardment of the runaway electrons on a limiter have not been understood very well yet.

Three kinds of hard X-ray perturbations had been reported on Pulsator Tokamak[2]. These are the modulated perturbations due to internal sawtooth disruptions, Mirnov oscillations and outer disruptions. A peak of hard X-rays occurs typically about 0.2 ms after sawtooth crash. The hard X-ray modulations are almost consistent with Mirnov ones (m=2). A hard X-ray burst is often observed during outer disruption. Increased fluxes of runaway electrons at PLT limiter were observed following internal disruptions[3]. There is 1～5 ms time delay that increases with the plasma electron density. The time ratio of this delay time to the energy confinement time is about that of the electron thermal velocity to the parallel velocity of runaways. The hard X-ray bursts to occur at external disruptions are 5～10 times faster than those at sawtooth crashes.

Inverse sawteeth on hard X-rays with ～0.2 ms time delay had been observed in HL-1 tokamak[4]. A burst of hard X-rays or soft X-rays is often prior to minor disruptions caused by Mirnov oscillations (m/n=2/1) [5]. It had been observed that the ratio of the runaways diffusivity to the thermal one is about unity in TEXT [6]. This result shows that runaways are lost along stochastic magnetic field line and the thermal electron loss must be due to another mechanism, such as electrostatic fluctuation.

1 PHENOMENOLOGICAL MODEL AND ITS APPLICATION

Runaway electrons are often thought collisionless. A relativistic circulating runaway electron will be continuously accelerated by the toroidal electric field (E_ϕ):

$$\frac{\mathrm{d}}{\mathrm{d}t}(\gamma m_\mathrm{e} v_\phi)=e\left(\boldsymbol{E}+\boldsymbol{V}\times\boldsymbol{B}\right)\Big|_\phi \tag{1}$$

Here γ is the relativistic factor, the others have normal meaning. Considering a radial perturbed magnetic field $b_{\mathrm{r}}=b_{\mathrm{r}0}\cos(m\theta-n\phi-\omega t)$, the poloidal velocity (v_θ) of runaway electrons satisfies the equation

$$\frac{\mathrm{d}}{\mathrm{d}t}(\gamma m_{\mathrm{e}}v_\theta)=e(v_\phi b_{\mathrm{r}}-v_{\mathrm{r}}B_\phi) \tag{2}$$

Here v_{r} is radial velocity and b_{r} is related to the width of the magnetic island [7].

$$\frac{d_{\mathrm{m}}}{r_{\mathrm{s}}}\approx 4\left(\frac{|b_{\mathrm{r}}|q(r)}{B_\theta(r)mq'r_{\mathrm{s}}}\right)^{1/2}=4\left(\frac{|b_{\mathrm{r}}|}{B_\theta(r)s(r_{\mathrm{s}})m}\right)^{1/2} \tag{3}$$

Here d_{m}, r_{s}, q', $s(r_{\mathrm{s}})$, m is the island width, the radius at rational surface, the spatial derivative of the safety factor, the magnetic shear and the poloidal mode number, respectively. Using Eq. (3), we obtain

$$\frac{b_{r0}}{B_\phi}\approx\frac{1}{16}\frac{r_s}{R}\left(\frac{d}{r_s}\right)^2\frac{s(r_s)m}{q(r_s)} \tag{4}$$

According to Rogister's model[8], the radial speed can be calculated by formula

$$v_r=\left(\left(v_\varphi\frac{b_r}{B}\right)^2\pm\frac{2eU}{m_j}\right)^{1/2}=\frac{b_r}{B}v_{\mathrm{j}}\left(\frac{v_\phi^2}{v_{\mathrm{j}}^2}\pm X_{\mathrm{j}}\right)^{1/2} \tag{5}$$

Here $v_j=\sqrt{2T_{\mathrm{j}}/m_{\mathrm{j}}}$ is thermal speed, U is the radial ambipolar potential. The plus (minus) is for ions (electrons), j is the species label and

$$X_{\mathrm{j}}=eUB^2/(b_{\mathrm{r}}^2T_{\mathrm{j}}) \tag{6}$$

The value X_{e} can be estimated by plasma parameters

$$X_{\mathrm{e}}^2=\frac{0.36R(nZ_{\mathrm{eff}})}{T_{\mathrm{e}}^2(1/q(0)-1)}=\frac{0.2r(nZ_{\mathrm{eff}})}{T_{\mathrm{e}}^2(b_{\mathrm{r}0}/B_\phi)}$$

Here T_{e} is in keV, R is in meter, nZ_{eff} is in 10^{20} m^{-3}. Since the change of γ can be neglected during sawtooth crashes, Eq. (2) can be simplified by using Eq.(5)

$$\frac{\mathrm{d}v_\theta}{\mathrm{d}t}=\frac{ev_\varphi b_r X_{\mathrm{e}}}{2\gamma m_{\mathrm{e}}w^2} \tag{7}$$

Here $w=v_\varphi/v_{\mathrm{e}}$ is the ratio of velocities. If $\Delta v_\theta\sim v_\varphi$, the time scale for producing the trapped runaway electrons can be estimated as

$$\Delta t = \frac{2\gamma m_e w^2}{|e| c_r b_{r0} X_e} = 1.1\times10^{-11} \frac{\gamma w^2}{X_e c_r b_{r0}} \quad \text{(S)} \tag{8}$$

Here coupling coefficient c_r depends on the runaway electron energy and width of magnetic island [9].

Substituting the HL-1 parameters, m/n=1/1, $d_1=r_1$, r_1/a=0.25, $s(r_1)$=0.2, B_ϕ=2 T, a=20 cm, R=102 cm, the magnetic fluctuation is about $b_{r0} = 1.2\times10^{-3}\,\mathrm{T}$. By taking X_e=2, w=30, c_r=0.2, the minimum time scale for producing the trapped runaways is

$$\Delta t \approx 21\gamma \qquad (\mu\mathrm{s}) \tag{9}$$

Its typical time is 100 μs for 2 MeV runaway electron, which shows that the energetic circulating runaways are easily turned into the trapped ones due to magnetic perturbation during sawtooth crashes. If parameters q_a=3, r_2=0.6 a, d_2/a=0.2 and $s(r_2)$=1.0 were used, the magnetic field fluctuation of the 2/1 mode is about $b_{r0} = 6.0\times10^{-4}\,T$. By taking X_e=2, w=30, c_r=0.5, the time scale for producing the trapped runaways due to m/n=2/1 magnetic oscillations is

$$\Delta t = 16\gamma \qquad (\mu\mathrm{s}) \tag{10}$$

Therefore, the m/n=2/1 magnetic perturbation can also make runaway electron trapped. The banana width of the trapped runaway electron can be estimated as [10]

$$\Delta_b = 2\rho_p (2r/R)^{1/2} \tag{11}$$

Here $\rho_p = \frac{\gamma m_e v_\perp}{e B_\theta}$ is the poloidal Larmor radius. Its typical order is 8.5 cm at q=1 surface for E=2 MeV. A more precise calculation of the width needs using the conservation of canonical angular momentum[7]. Although the trapped runaway electron cannot close move along poloidal direction, they can still circulate via toroidal precession drift. The drift speed is[10].

$$u_\phi = \frac{(\gamma-1) m_e c^2}{e B_\theta R} \tag{12}$$

It can reach the order of 10^7 m/s for runaways instead of 10^4 m/s for thermal electrons, which is the same order as the thermal electron's velocity. The radial velocity caused by toroidal precession drift is

$$u_r = \frac{c_r b_{r0} u_\phi}{B_\phi} \tag{13}$$

A condition for the trapped runaways to arrive at the limiter from q=1 surface is

$$r_{\mathrm{ci}}+d_{\mathrm{r}}+d_{\mathrm{p}}+\Delta_{\mathrm{b}}/2=a \tag{14}$$

Here r_{ci} is the maximum radius, $d_{\mathrm{r}}=(a/R)\rho_{\mathrm{p}}$ is the displacement between the runaway orbit and the magnetic center, d_{p} is the shift of current distribution with respect to the geometrical center. Compared with Δ_{b}, the d_{p} and d_{r} can be neglected. The toroidal precession velocity for E = 2 MeV in the HL-1 tokamak is about

$$u_{\phi}=5.1\times10^{5}(\gamma-1)/B_{\theta}(r)\approx1.2\times10^{7}\ \text{(m/s)}$$

If the normalized perturbed magnetic field is assumed to be $c_r b_{r0}/B_{\phi}=5\times10^{-5}$ after sawtooth crashes [11], the radial velocity of the trapped runaway is u_r=600 m/s. The delay time to arrive at a limiter is

$$\tau_{\mathrm{d}}=\Delta r/u_r\approx(a-\Delta_{\mathrm{b}}/2-r_1)/u_r\approx200 \qquad (\mu\text{s})$$

Therefore, the typical delay time is about 200 μs in small tokamaks, which is consistent with experimental results with sawtooth crashes as above. If the perturbed magnetic field is assumed to be $c_r b_{r0}/B_{\phi}=1.5\times10^{-4}$ for m/n=2/1 mode, the delay time is $\tau_{\mathrm{d}}\approx28$ μs. This result indicates that the hard X-ray oscillations correlated with Mirnov ones may propagate much faster than those due to sawtooth crashes. The produced runaway electrons would collide with the limiter at once. The hard X-ray bursts during outer disruptions can also be explained by the model as above.

It should be emphasized that the above analysis is valid only when $\omega\tau_{\mathrm{d}}<1$. A condition states that the trapped runaway electrons can bombard at the limiter during a period of the slowly varying perturbed magnetic field. In our example with sawtooth crashes, this corresponds to $\omega<5\times10^{3}\ \mathrm{s}^{-1}$, which is comparable to the sawtooth frequencies in the HL-1 tokamak.

2 CONCLUSION

A model for the banana orbit loss of runaway electrons has been considered to explain the sawtooth oscillations on the hard X-rays in tokamaks. The energetic runaway electrons can be transferred into the trapped ones due to the magnetic perturbation during sawtooth crashes. Then they would be repelled to the limiter via toroidal precession drift of banana orbit, which has about 200 μs delay in the HL-1 tokamak. Trapped runaway electrons due to Mirnov oscillations would collide with a limiter, which is much faster than those due to sawtooth crashes. Because runaway electrons are sensitive to plasma magnetic perturbation, hard X-rays at the limiter are important in observing magnetic fluctuation and predicating the outer disruptions.

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