IAEA-CN-69/THP2/26

SIMULATION STUDY ON AVOIDING RUNAWAY ELECTRON GENERATION BY MAGNETIC PERTURBATIONS

S. TOKUDA, R. YOSHINO, T. MATSUMOTO, S. R. HUDSON,
Y. KAWANO, T. TAKIZUKA

Naka Fusion Research Establishment,
Japan Atomic Energy Research Institute,
Naka-machi, Naka-gun, Ibaraki-ken, 311-0193,
JAPAN

Abstract

Simulations have demonstrated that magnetic islands having the widths expected on the major disruption cause the collisionless loss of the relativistic electrons, and that the resultant loss rate is high enough to avoid or to suppress the runaway generation. It is because, for the magnetic fluctuations in the disruption, the loss of the electron confinement due to the breakdown of the toroidal momentum conservation overwhelms the runaway electron confinement due to the phase-averaging effect of relativistic electrons. Simulation results agree closely with recent experiments on fast plasma shutdown, showing that it is possible to prevent the generation of runaway electrons.

1. INTRODUCTION

It is a crucial requirement that a fusion reactor be equipped with means to enable fast plasma shutdown in cases of emergency. Experiments on JT-60U have verified that the "killer pellet" injection (KPI) is an effective means of fast shutdown avoiding simultaneously high-energy heat flux on the divertor plate, halo current generation, and runaway electron generation[1]. In particular, it is found experimentally that magnetic fluctuations excited spontaneously or externally after the KPI can avoid the runaway generation[1,2,3]. However, theoretically, the confinement of the runaway electrons has been considered to be enhanced due to the phase averaging over the magnetic perturbations[4]. In this paper we demonstrate by direct 3-dimensional simulations on the orbits of electrons that the relativistic electrons are lost when the magnetic perturbations consist of the magnetic islands with the widths expected on the major disruption. The resultant loss rate of runaways becomes to be $10^3 \sim 10^4\ sec^{-1}$, sufficiently high to avoid and to suppress the runaway electron generation, and gives a confirmation for the JT-60U experiments on the fast plasma shutdown avoiding the runaway generation.

2. COLLISIONLESS LOSS MECHANISM

In the study of the relativistic electron motion, we adopt the canonical Hamilton theory for the relativistic guiding center drift motion[5]. We use the magnetic coordinate system (ψ_p, θ, ζ) on which the equilibrium magnetic field $\mathbf{B}_{\rm eq}$ can be written as

$$\mathbf{B}_{\rm eq} = \beta_*(\psi_p, \theta)\nabla\psi_p + J_t(\psi_p)\nabla\theta + J_p(\psi_p)\nabla\zeta, \qquad (1)$$

where ψ_p is the poloidal flux; θ the poloidal angle; ζ the toroidal angle. MHD perturbations producing magnetic islands are expressed by the vector potential $\tilde{\mathbf{A}}$:

$$\tilde{\mathbf{A}} = \epsilon\alpha(\psi_p, \theta, \zeta)\mathbf{B}_{\rm eq},\ \ \alpha(\psi_p, \theta, \zeta) = \sum_{m,n} \alpha_{mn}(\psi_p)\cos(m\theta - n\zeta + \phi_{mn}), \qquad (2)$$

where $\epsilon = c/(\omega_c R_0)$; R_0 is the major axis; ω_c the electron gyro-frequency at the axis; c the light speed. The canonical Hamilton form for the guiding center drift motion of a relativistic electron is given by

$$\omega = p_\theta d\theta + p_\zeta d\zeta - \epsilon h dt,\ p_\theta = -\psi + \epsilon\rho_c J_t,\ p_\zeta = \psi_p + \epsilon\rho_c J_p, \tag{3}$$

in the phase space $(\theta, p_\theta, \zeta, p_\zeta)$, where $h = \left[1 + (\rho_c + \alpha)^2 B_{\rm eq}^2 + 2\mu B_{\rm eq}\right]^{1/2}$; ψ is the toroidal flux; $\rho_c = \rho_{||} - \alpha$ and $\rho_{||}$ is the parallel world velocity normalized by $B_{\rm eq}$; μ the magnetic moment. Considering only passing electrons, we obtain the Hamilton form suitable for describing the orbits of passing electrons:

$$\omega = p_\zeta d\zeta + p_t dt - K d\theta,\ K(\zeta, p_\zeta, p_t, \theta) = -p_\theta,\ p_t = -\epsilon h, \tag{4}$$

where the canonical coordinates are comprised of (ζ, p_ζ, t, p_t) and the poloidal angle θ plays the role of time.

When there exist no perturbations, $\alpha \equiv 0$, the toroidal momentum p_ζ is conserved and an electron returns to the initial radial position after one poloidal turn. The width of radial excursion of this *unperturbed* electron during one poloidal turn, δx, is determined by the variation in K in Eq.(4). For an ultra relativistic electron, $\gamma >> 1$, we have $\delta x \sim \gamma J_p \delta(1/B)$, where $\delta(1/B)$ is the variation of $1/B$ the electron sees. Thus the radial excursion of a relativistic electron is greater by the factor γ than that of a non-relativistic electron. When $\alpha \not\equiv 0$, there are two scales characterizing the loss mechanisms; δx and w_{mn}, the width of the (m, n) magnetic island. The perturbation α affects the radial motion of the electron in two different ways. When $w_{mn} >> \delta x$, which is satisfied by a low energy electron, the breakdown of p_ζ conservation due to the perturbations causes wandering motion of the electron, which works as a collisionless loss mechanism when the magnetic islands overlap each other to the plasma edge.

On the other hand, a higher energy electron with $\delta x >> w_{mn}$ does not exhibit the wandering motion since p_ζ is almost conserved when the electron is far from the island. However, the p_ζ conservation breaks when the electron passes the island, and the electron cannot return to the initial radial position, which regards as *scattering* (see Fig.1, $s = \sqrt{\psi_p}$). Such scattering yields another collisionless loss mechanism. This mechanism becomes weaker for higher energy electrons and for a smaller island width since the time of stay in the island becomes shorter. This would give another physical ground found by Ref.[4] that the runaway electrons are not affected by magnetic islands. However, it should be noticed that, at the disruption or the fast shutdown in a large tokamak such as JT-60U, there exist many islands and each island is expected to have "macro-scale" width of several *cm*. It is the fundamental difference from Ref.[4] where "micro turbulence" is considered. When there exist many islands with "macro-scale" widths, accumulation of the scattering can work as a loss mechanism for the relativistic electrons. Furthermore, for such electrons, island overlapping is *unnecessary* as the loss mechanism. In the next section, we verify the both loss mechanisms for the low- and high- energy electrons by the direct simulation.

3. SIMULATION RESULTS

Magnetic perturbations used in the present study consist of 20 modes with

$$\begin{aligned}(m,n) \ = \ & (2,1),\ (19,9),\ (11,5),\ (9,4),\ (25,11),\\ & (7,3),\ (19,8),\ (12,5),\ (22,9),\ (5,2),\end{aligned}$$

$$(13,5),\ (8,3),\ (11,4),\ (20,7),\ (3,1),$$
$$(25,8),\ (10,3),\ (7,2),\ (15,4),\ (4,1). \qquad (5)$$

The degree of stochasticity of the magnetic field configuration is controlled by giving the widths of the modes. In such magnetic field configuration, the orbits of 1,000 electrons with the same, given energy are traced. Electrons are initially loaded around $q = 5/2$ in the radial direction and uniformly random in $\theta-$ and $\zeta-$ directions. The magnetic moment μ is set to zero for all electrons since we assume passing electrons. The number of electrons which reach the plasma edge is counted and the average loss rate is evaluated.

Figure 2 illustrates the energy dependence of the loss rate for $w_{21} = 0.02$ and $w_{21} = 0.03$, where w_{21} represents the width of the $(2,1)$ island. We see that ultra relativistic electrons, as well as low energy electrons, are lost. The loss rate for ultra relativistic electrons with $\gamma \geq 40$ saturates or decreases, which accords with the phase averaging mechanism. The magnitude of the loss rate is $2\times10^3\ sec^{-1}$ to $1\times10^4\ sec^{-1}$ for $w_{mn} = 0.02$. Such values are sufficient as the loss mechanism in the experiments to avoid and to suppress runaway electron generation. The loss rates strongly increase for $w_{mn} = 0.03$ to more than $3 \times 10^4\ sec^{-1}$. We can confirm from Fig.3 such drastic increase in the loss rates. For the case of $w_{21} = 0.018$, weak overlapping, no loss occurs ($\nu = 0$) for the low energy electron, while the loss rate for the ultra relativistic electron has the finite value of $\nu = 2 \times 10^3\ sec^{-1}$, since overlapping of the islands is unnecessary. This high loss rate even without the overlapping suggests the termination of the runaway current tail observed in JT-60U[6]. As shown in Fig.3, island overlapping strongly increases the loss rate from $\nu \sim 10^3\ sec^{-1}$ to $\nu \sim 5 \times 10^4\ sec^{-1}$ for both the low energy and the ultra relativistic electrons. These results verify that the two loss mechanisms, wandering motion of the low energy electron and the accumulation of the scattering of the ultra relativistic electron, are effectively enhanced by island overlapping.

4. SUMMARY

Simulations verify that magnetic perturbations consisting of magnetic islands of several cm, overlapping each other, yield efficient collisionless loss of runaway electrons. These results agree closely with experiments on the avoidance and the suppression of runaway electron generation in JT-60U. Analytical and numerical analyses also confirm the two different loss mechanisms originating from the breakdown of the toroidal momentum conservation due to the toroidal asymmetry of magnetic perturbations: wandering motion in the overlapping islands and accumulation of the scattering when an electron passes the island. The former is effective for low energy electrons. The latter is effective for ultra relativistic electrons, and overwhelms the phase averaging effect found for micro-scale magnetic perturbations. Such perturbations will be also enough to suppress the avalanching effects investigated in Ref.[7].

ACKNOWLEDGMENTS

The authors thank Prof. M. N. Rosenbluth for useful suggestions. They are also grateful to Dirs. H. Kishimoto, M. Azumi and A. Funahashi at JAERI for their encouragement.

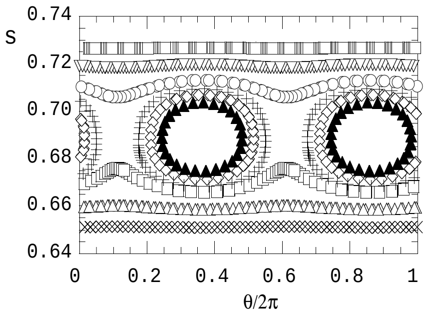

Fig.1(a) (2,1) magnetic island with w =

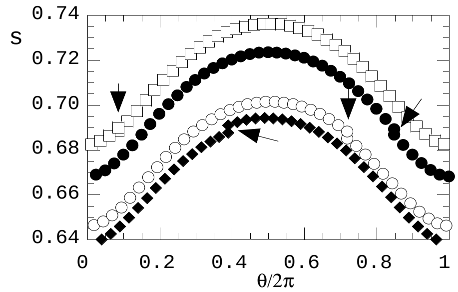

Fig. 1(b) Trajectories of electrons
the (2,1) magnetic is (γ=40)

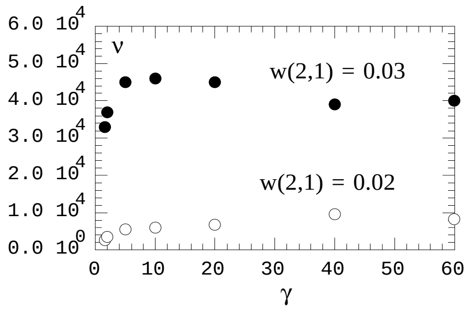

Fig.2 Energy dependence of the los

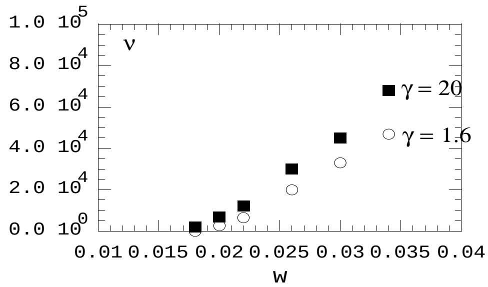

Fig.3 Dependence of the loss rat
the island width w

REFERENCES

[1] YOSHINO, R., KONDOH, T., NEYATANI, Y., ITAMI, K., KAWANO, Y., ISEI, N., Plasma Phys. Control. Fusion **39** (1997) 313.

[2] KAWANO, Y., et al., in Fusion Energy 1996 (Proc. 16th Int. Conf. Montreal, 1996), Vol. 2, IAEA, Vienna (1997) 345.

[3] KAWANO, Y., et al., 24th EPS Conf. on Control. Fusion and Plasma Phys., Berchtesgaden, Vol. **21A**, Part **II** (1997) 501.

[4] MYNICK, H.E., STRACHAN, J.D., Phys. Fluids **24** (1981) 695.

[5] TOKUDA, S. YOSHINO, R., *Simulation Study on Collisionless Loss of Runaway Electrons by Magnetic Perturbations in a Tokamak*, submitted to Nucl. Fusion (1998).

[6] YOSHINO, R., TOKUDA, S., KAWANO, Y., *Generation and Termination of Runaway Electrons at Major Disruptions in JT-60U*, submitted to Nucl. Fusion (1998).

[7] ROSENBLUTH, M.N., PUTVINSKI, S.V., Nucl Fusion **37** (1997) 1355.