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Simulations of Neutral Beam Ion Ripple Loss on EAST*

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Abstract Predictions on the ripple loss of neutral beam fast ions on EAST are investigated with a guiding center code, including both ripple and collisional effects. A 6% to 16% loss of neutral beam ions is predicted for typical EAST experiments, and a synergistic enhancement of fast ion loss is found for toroidal field (TF) ripples with collisions. The lost ions are strongly localized and will cause a maximum heat load of ~ 0.05 MW/m^2 on the first wall.

Keywords: ripple loss, neutral beam injection, EAST

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1 Introduction

Magnetic confinement of fast ions within a tokamak must be achieved with a finite number of toroidal field coils. This magnetic structure results in a non-axisymmetric component of the toroidal magnetic field, which is called a "ripple". The transport of fast ions in a rippled toroidal field is one of the most critical issues in magnetic confinement fusion research, and has been studied since the 1970s. Recent experimental and theoretical studies have focused on the ripple loss of fast ions in high-temperature tokamak plasmas [1~26]. The ripple loss of fast ions is an important issue for the design of future fusion reactors, mainly due to the fact that the ripple-induced excursion of fast ions can result in serious localized heat load on the first wall.

Despite the pioneering work by TANI [4,6], WHITE [5,7] and others over two decades ago, it is only with recent advances in computing technology that detailed simulations of ripple loss have become practical. Ripples have been shown to cause significant losses of fast ions on ISX-B [8], JET [16,18], JT-60U [10,19], Tore Supra [25] and TFTR [11,20,21]. To study the significance of ripple losses of neutral beam ions on EAST, we carry out detailed calculations of neutral beam ion ripple losses, including both the collisional and ripple effects. The present simulation study is performed with a Hamiltonian guiding center drift orbit Monte Carlo code, ORBIT, based on canonical Hamiltonian guiding center variables (see WHITE and CHANCE [5,7,9]).

In section 2 we briefly describe the physics of ripple loss and the EAST NBI system. In section 3 we discuss the details of the ORBIT code and the simulation procedure, with the results of the guiding center calculations presented in section 4, and a conclusion is given in section 5.

2 Ripple loss physics and the EAST NBI system

2.1 Ripple loss physics

The toroidal field (TF) ripple affects the transport of fast ions in different ways depending on the magnetic field structure, ripple trapping [2,4] and stochastic ripple diffusion [3,21,26]. The toroidal magnetic field is taken to be of the following form,

$$B=\frac{B_0R_0}{R}\left(1 \quad + \quad \delta\left(r,\theta\right)\sin N\phi\right), \tag{1}$$

where $\delta\left(r,\theta\right)=\frac{B_{\max}-B_{\min}}{B_{\max}+B_{\min}}$ ($B_{\max}$ and $B_{\min}$ are the maximum and minimum field magnitudes at constant major radius and elevation) is the TF ripple, N is the number of coils, R and r are the major and minor radius, and θ and ϕ are the poloidal and toroidal angles in a tokamak. For $Nq >> 1$, the ripple parameter α^* is obtained, which is defined by

$$\alpha^*=\varepsilon\left|\sin\theta\right|/Nq\delta. \tag{2}$$

Ripple wells are formed in the region where $\alpha^* < 1$. When the banana tip of an ion orbit is located in a ripple well, the ion is trapped in the local mirror of TF ripple and quickly drifts in the ∇B ion drift direction. Even for $\alpha^* > 1$, where local magnetic trapping has been eliminated, ripple-driven radial diffusion of fast ions still persists, due to the failure of fast-ion banana orbits to close precisely. GOLDSTON [3] et al. derived a threshold for stochastic ripple diffusion

$$\delta_{\rm s}=\left(\varepsilon/N\pi q\right)^{1.5}\left(1/\rho q'\right), \tag{3}$$

where ε is the inverse aspect ratio, q is the plasma safety factor, and $q'=\mathrm{d}q/\mathrm{d}r$ and ρ is the ion Larmor radius. Trapped ions, whose turning point lies in a region where

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δ exceeds the threshold δ_s, are subject to stochastic ripple diffusion. This formulation neglects the effects of collisions, banana width and up/down asymmetry. ORBIT includes both ripple trapping losses and stochastic ripple diffusion losses.

2.2 The EAST NBI system

The NBI system in EAST [27,28] proposed to have two deuterium beam lines, NBI-1 and NBI-2, with an adjustable beam energy between 50 keV and 80 keV, a pulse duration between 10 s and 100 s, and a beam power between 2 MW and 4 MW, which are movable with an injection angle varying from 0° to 19.5°. The angles between the two beam lines and the major radial direction are 66.15° and 74.85°, respectively. A schematic diagram of the EAST NBI is shown in Fig. 1. NBI-1, with tangential co-injected beams, and NBI-2, with tangential counter-injected beams, are located at the A and F window, respectively. The energy fraction of the EAST NBI is $E : E_{1/2} : E_{1/3}$ = 80%: 14%: 6%.

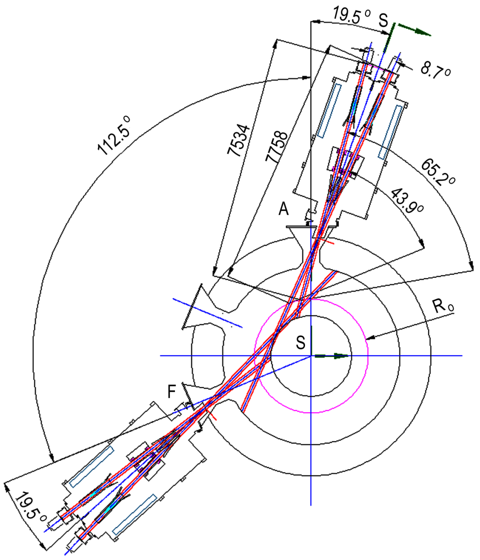

Fig.1 A schematic diagram of NBI-1 and NBI-2 in EAST

3 Guiding center code orbit simulations

A Monte Carlo Hamiltonian coordinate drift orbit guiding center code, ORBIT [7], was used to study the ripple losses of the neutral beam ions on EAST. The EAST plasma equilibrium flux surfaces were generated by the EFIT equilibrium reconstruction code, and the equilibrium flux surface coordinate was mapped into the Hamiltonian coordinates for the guiding center code. The earlier work from TFTR [21] was followed, simulating 1000 particles in a magnetic geometry given by

$$B = B(\Psi,\theta)\left[1+\delta(\Psi,\theta)\sin N\phi\right], \qquad (4)$$

where $B(\Psi,\theta)$ is from the EFIT equilibrium reconstruction after a transformation to the Boozer coordinates. Here, Ψ is the poloidal magnetic flux, and θ and ϕ are the poloidal and toroidal angles, respectively. There are 16 toroidal field coils on EAST, and the ripple on EAST increases to about δ =1.3% at the outer midplane wall. Fig. 2 shows the contours of the EAST toroidal field ripple strength. The analytic form for the TF ripple is given by [11]

$$\delta(R,Z) = \delta_0 \exp\left\{\left[(R-R_0)^2 + b_r Z^2\right]^{0.5} / w_r\right\}, \qquad (5)$$

where δ_0 is the minimum value of the ripple field, R_0 is the radius at which this minimum value occurs for Z=0, b_r is the ellipticity, and w_r is the scale length of the ripples. The coefficients δ_0, R_0, b_r and w_r were determined by fitting Eq. (5) to the calculated vacuum ripple. Fig. 3 shows the EAST ripple distribution. REDI [23] recently developed an analytic fitting for D-shaped ripple contours, which gives $R_0 = a + bZ^2$. The best approximation to EAST was found to be $R_0 = 1.7143 - 0.1811Z^2$. The minimum value of the ripple field δ_0, 1.2672×10^{-4}, occurs when $b_r = 0.2672$ and $w_r = 0.1492$ m, respectively. Comparisons between the data and the analytic fitting at the midplane, Z=0, and at R=2.3 m are shown versus the major radius and height in Fig. 4, respectively.

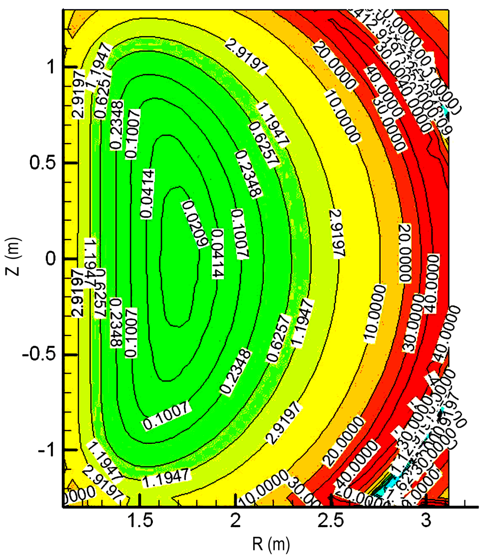

Fig.2 The ripple contours of EAST

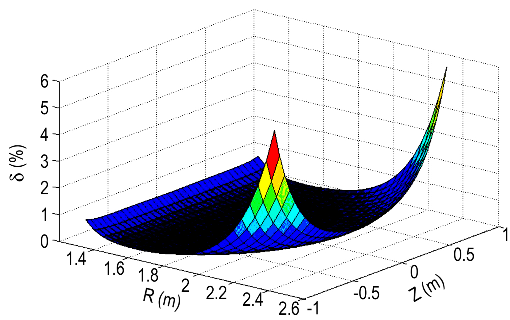

Fig.3 The EAST ripple data field

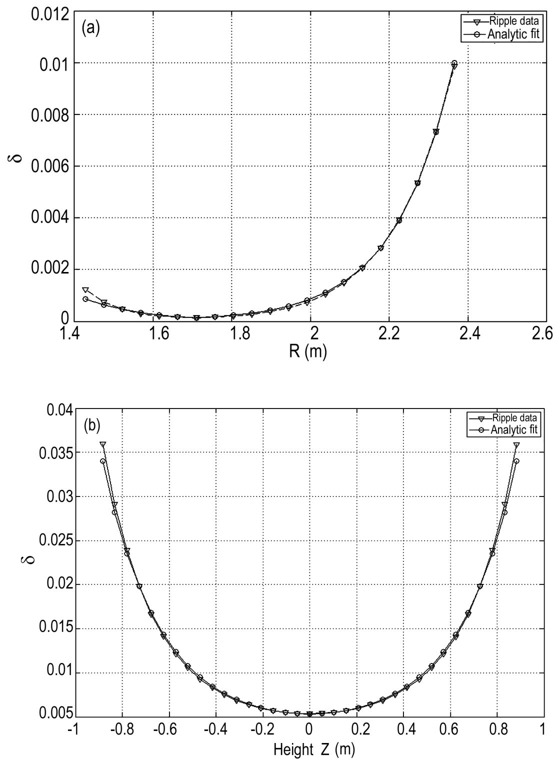

Fig.4 Ripple data and fitting at (a) Z=0 and (b) R=2.3 m

In our simulations, neutral beam ions were tracked with the pitch angle scattering and energy slowing down effects taken into account. Collision rates were evaluated near the magnetic axis, using the formulas for pitch angle scattering ($\nu_{\rm pa}$) and slowing down processes given in Ref. [29]. The neutral beam ion distributions were generated by the TRANSP code. Fast ions with full, half and one-third energies were simulated. ORBIT simulations follow each ion orbit in detail until it leaves the plasma. Particles reaching the last closed flux surface were defined as being lost. Plasma parameters for the two EAST discharges for which neutral beam ions were followed are shown in Table 1, where $E_{\rm nb}$ and $P_{\rm inj}$ are the injection beam energy and power for each discharge. The shots of 34128 and 34616 are L-mode plasma and H-mode plasma, respectively. The neutral beam ions for these experiments were injected along the first beam line, NBI-1, with tangentially co-injected beams at a tangency radius of $R_{\rm T}$=1.0005 m [28]. Table 2 shows the simulation parameters for the neutral beam ions, including both the pitch angle scattering collision rates, $\nu_{\rm pa'}$ and the energy slowing down time, $\tau_\varepsilon \cdot \tau_{\rm tran}$, is the toroidal transit time of a neutral beam ion at the magnetic axis with pitch $v_\parallel/v$=1. The source distribution in pitch is given by $v_\parallel/v = R_{\rm T}/R$ for neutral beam ions at the point of deposition. Total losses were integrated over half of an energy slowing down time for the neutral beam ions.

Table 1. The simulated EAST experiments

Shot	R(m)	a(m)	$I_{\rm p}$	$B_{\rm t}$(T)	$E_{\rm nb}$(keV)	$P_{\rm inj}$(MW)
34128^a	1.86	0.45	1	2.5	80	4
34128^b	1.86	0.45	1	2.5	50	2
34616^a	1.85	0.44	0.6	1.8	80	4
34616^b	1.85	0.44	0.6	1.8	50	2

4 Results and discussion

Table 3 shows the predicted losses of the neutral beam ions for EAST experiments simulated with ripple and collisional effects taken into account. Ripples and collisions, along with first orbit losses, cause total losses of 6%∼16% of the fast ions during $\tau_\varepsilon/2$ for typical EAST experiments. Fig. 5 shows the evolution of the loss fractions for each experiment, respectively. For all these experiments with tangentially co-injected beams, there were no first orbit losses of fast ions. The loss fraction of fast ions for each experiment is nearly linear in time within $\tau_\varepsilon/2$. Comparing the results of #34128^a and those of #34616^a, it was found that fast ion losses decreased as the energy decreased. This is because the pitch angle scattering rate is proportional to $E^{-3/2}$, meaning the less energetic fast ions are more strongly affected by pitch angle scattering.

Table 3. The fraction of neutral beam ions lost in simulations of EAST experiments during $\tau_\varepsilon/2$

Shot	Fraction lost(%)
34128^a	16
34128^b	9
34616^a	10
34616^b	6

Table 4 shows the relative roles of ripples and collisions on the losses of fast ions for shot 34128^a. Compared with the total losses, the individual roles of ripples and collisions are relatively small. The effect of collisions is not strong on the increase in total losses, and the ripple effect is even weaker than collisions when they are considered individually. Compared with the "no ripple and no collisions" case, when ripples and collisions are added separately and together, we can see a strong synergistic enhancement of fast ion losses in this EAST experiment. This is not a linear effect, and the total losses are calculated to be roughly three times the sum of the ripple and collisional losses calculated individually. This synergism is similar to the results predicted on TFTR [21] and can be understood

Table 2. The simulation parameters

Shot	$\nu_{\rm pa}$(s^{-1})	τ_ε(s)	$n_{\rm e0}$($\times10^{13}$ cm^{-3})	$T_{\rm e0}$ (keV)	$\langle n_{\rm e}\rangle$($\times10^{13}$ cm^{-3})	$\langle T_{\rm e}\rangle$ (keV)	$Z_{\rm eff}$	$\tau_{\rm tran}$(μs)
34128^a	1.8	0.49	2.0	1.2	1.5	1.0	2.5	4.3
34128^b	3.8	0.24	2.0	1.2	1.5	1.0	2.5	5.4
34616^a	4.5	0.18	5.5	0.9	4.0	0.75	2.2	4.2
34616^b	9.0	0.09	5.5	0.9	4.0	0.75	2.2	5.3

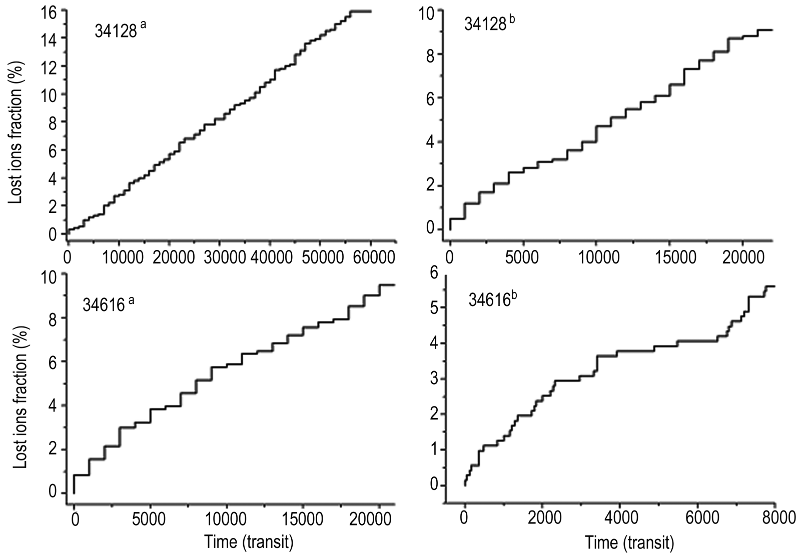

Fig.5 The evolution of the loss fractions of neutral beam ions during $\tau_\varepsilon/2$ for the EAST experiments

Table 4. The effect of ripples and collisions on neutral beam loss for shot 34128^a during $\tau_\varepsilon/2$

Ripple	Collisions	Loss(%)
No	No	0
Yes	No	2
No	Yes	4
Yes	Yes	16

as follows: collisional pitch angle scattering makes fast ions scatter into the first orbit loss and ripple loss domains, when the TF ripple opens both the ripple trapping and stochastic ripple diffusion domains. In addition, the accumulation of fast ion losses during the slowing down time is also the reason for the strong synergistic enhancement of fast ion losses.

It is interesting to see what our simulations predict for the poloidal distributions of fast ion losses. Fig. 6 shows the predicted poloidal distribution of fast ions for EAST experiments. It was found that losses peaked just below the mid-plane in all cases and lost ions were strongly localized. We also estimated the heat load for maximum neutral beam ion ripple losses of 16% in shot 34128^a, with a poloidal extent of about 21°, and the footprint of the neutral beam ion ripple losses of 2π (2.3 m) (0.84 m) $\sim$12 m^2, while the power loss will be 16% of the 4 MW injection beam power. Thus, the maximum heat load caused by the ripple losses of the neutral beam ions is the maximum power loss per unit impact area, which is $\sim$0.05 MW/m^2 on the first wall in our simulations. The effects of toroidal Alfvén eigenmodes (TAE) and magnetohydrodynamics (MHD) were not included in our calculation. REDI[23] predicted that the effects of TAE and MHD increased alpha losses and the wall heat load by a factor of two.

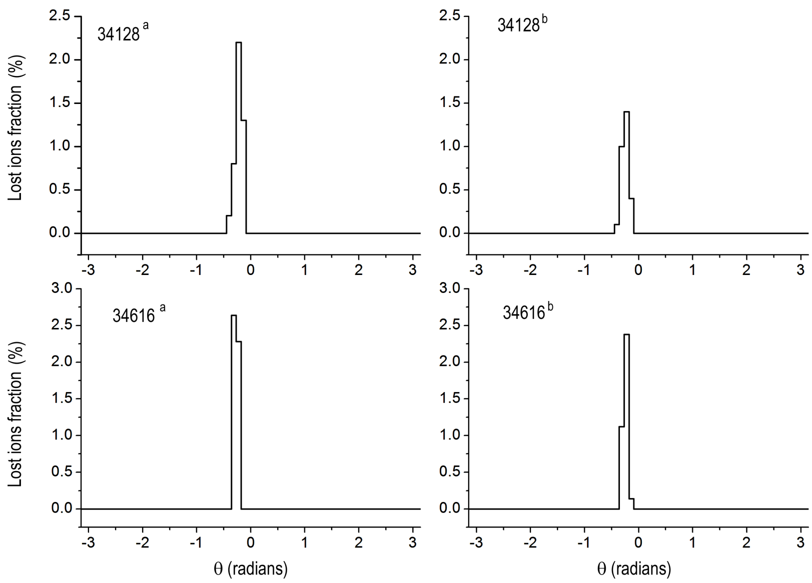

Fig.6 The poloidal distribution of the neutral beam ion loss fraction during $\tau_\varepsilon/2$

The above results show that the ripple losses of neutral beam ions are greatly enhanced by the presence of collisions. This collisional effect can be reduced by reducing the pitch angle scattering rate and shortening the energy slowing down time. The pitch angle scattering rate is proportional to $n_e Z_{eff}$, so operating at low n_e and Z_{eff} will reduce the pitch angle scattering rate. Since the energy slowing down time is proportional to $1/n_e$, the control of ripple losses needs to tune the density to find the optimal value, so as to both reduce the pitch angle scattering rate and shorten the energy slowing down time.

5 Conclusion

A Monte Carlo Hamiltonian coordinate drift orbit guiding center code was used to study the ripple losses of neutral beam ions in EAST experiments. The simulation results showed that 6%∼16% of the injected neutral beam ions were lost during the period $\tau_\varepsilon/2$. The lost ions were strongly localized and caused a maximum heat load of ∼0.05 MW/m^2 on the first wall. A synergistic enhancement of ripples and collisions was found to increase the total losses of the neutral beam ions. Consideration of the pitch angle scattering rate and the energy slowing down time suggests that operating at low Z_{eff} and optimal density will reduce the ripple losses of neutral beam ions.

Acknowledgments

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