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Kinetic and Collision Process Effects on Magnetic Structures in Pre-Disruption Phase of Tokamak Plasmas

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Abstract

Oscillations of the parallel and perpendicular neutral fluxes that are observed during pre-disruption stage in recent experiments, show possibility of a structure in pre-disruption phase of tokamak plasmas. This structure oscillates simultaneously with the m = 2 mode until the damping of this mode. The perpendicular component of this structure is greater than the parallel one. From other side, there are a good correlation between MHD activity and behavior of charge exchange neutrals, and an enough good correlation between time behavior of charge exchange flux with high energy and OV line radiation in pre-disruption phase. These may witness possibility of a mechanism of losses-excitation of inner transition with help of heavy particles in pre-disruption phase. This mechanism plays an important role in magnetic structures in pre-disruption phase.

Keywords:

plasma, tokamak, disruption, pre-disruption phase, structural changes, charge exchange neutral flux

1. Introduction

A disruption of plasma current in a tokamak reactor causes an undesirable local escape of plasma energy (thermal shock) and significant electrodynamical loading (mechanical shock) upon structural elements of the chamber. Therefore, the disruptive current instability remains to be an objective of theoretical and experimental studies until now.

The increase in the transverse energy component of plasma ion and neutral fluxes during a rapid phase of major disruption were found in some experiments [1,2]. In recent experiments it is observed that during pre-disruption stage, in the periphery of the plasma column there are regular oscillations of the transverse fluxes of neutrals with energies $E_n < 1.5$ keV at a frequency of 8 kHz; the amplitude of these oscillations saturates nearly at the instant when the $m = 2$ is locked. The frequency of these oscillations is three times as low as the frequency of MHD fluctuations. Oscillations with the same frequency were observed in the longitudinal (with respect to the magnetic field) neutral flux in ref. [1]. Measurements of the spatial and energy distributions of the neutral fluxes arising during the fast disruption stage show that the groups of fast neutrals with energies E_n = 0.3–1.0 keV are injected in the plasma core from the edge plasma [1].

It is known that the behavior of the neutral component of plasma is related to the evolution of the ion distribution function because of charge exchange process. In fact, this relationship constitutes the basis of the ion temperature measurement technique involving

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the analysis of the spectra of neutral particles. Therefore, the behavior of the charge exchange neutrals is related to the kinetic and collision processes. The effect of the charge exchange neutrals due to the kinetic and collision processes on MHD modes causes the mode structure of the fishbone as an m = 2, n = 1 mode (Here m and n are poloidal and toroidal mode number, respectively) that has experimentally been investigated in this paper. In the present work, we investigate the effects of charge exchange neutrals on the magnetic structures in the pre-disruption phase of the Damavand tokamak. Experimental results show that the neutrals due to the kinetic processes strongly affect these structures. The role of kinetic and collision processes on the magnetic structures in pre-disruption phase has been investigated by using measurements of MHD activity, charge exchange neutrals, the emission of impurities and hard x-ray with a very high time resolution of 10 μs. We will show that the mechanism of losses-excitation of inner transition with help of heavy particles in pre-disruption phase [3] may play an important role in magnetic structures.

2. Tokamak Characteristics and Experimental Conditions

Damavand is a small tokamak that has a vertically elongated plasma cross section. The principal data of the tokamak are as follows [2]: $B_T = 1.2$ T, $R = 36$ cm, $a = 7$ cm, the plasma elongation $k = 1.2$, discharge time 1.5 ms, $I_p = 40$ kA, $n_e = 3 \times 10^{13}$ cm^{-3}, $T_i = 150$ eV, and $T_e = 300$ eV. In the present experiments, the toroidal magnetic field was $B_T = 0.8$ T, and the discharge duration was $t_p \leq 15$ ms, the q (safety factor) was equal to ~ 2.8 before current rising and was ~ 2.35 after current rising. To obtain a disruptive instability during quasistationary phase of discharge, we apply a current to the additional winding to raise the loop voltage V and to raise the discharge current I.

In this paper, the plasma current, the loop voltage, and MHD activity (six local magnetic probes positioned around the plasma poloidal cross section) have been measured with electromagnetic diagnostics. In the present work we have also used a neutral particle analyzer CX [4] for measurements of charge exchange neutral fluxes. The monochromator MDR-2 has been used for measurements of visible radiation spectroscopy (in visible part of radiation spectrum) for the line OV (λ = 2781 Å). Detectors of CX and visible spectroscopy have a possibility to scan the plasma column in the vertical direction with the spatial resolution of 1.5 cm and the time resolution of 10 μs. The zero time $t_d = 0$ μs corresponding to the fast disruption stage, has been chosen such that, at this instant, a negative spike has appeared in the loop voltage signal. Consequently, the negative value of t_d corresponds to the pre-disruption stage.

3. Experimental Results

The time dependences of charge exchange neutral fluxes during pre-disruption stage are shown in Fig. 1. These neutral fluxes are across the magnetic field and are typically measured over several discharges. The regular low-frequency oscillations, which begin about 900~1000 μs before disruption, can be seen in this figure. These oscillations became visible in the signals after their averaging (over 10 discharges). The frequency of these oscillations is $f \approx 8$ kHz that is three times as low as the frequency of MHD oscillations (f = 25 kHz).

Figure 1b shows the MHD oscillations in the signal of the magnetic probe measuring the tangential component of the poloidal magnetic field in the equatorial plane during 1ms before the ramp-up and the negative spike appearing in the loop voltage. The phase analysis of MHD oscillations from the various probes positioned around the torous shows that these oscillations correspond to the m = 2 mode. Their frequency is f = 25 kHz. The amplitude of these oscillations decreases about 200 μs before disruption, as usually occurs when the mode is locked. Nearly at the same time, the amplitude of oscillations of transverse neutral fluxes with $E_n < 1.5$ keV from the periphery ceases to grow. Immediately before and during the disruption, the m = 1 mode appears. Transformation of mode m = 2 to mode m = 1 shows a possibility of some reorganization of magnetic structure.

Figures 2a and 2b show the correlation between the high energy charge exchange neutral fluxes and OV line emission. The energy of neutrals in Fig. 2a is equal to $E_n = 2$ keV, and measurements are done for the chord z = 7.5 cm. In Fig. 2b the energy of neutrals is larger than 1.5 keV ($E_n > 1.5$ keV) and is obtained after their averaging over several discharge results.

Figure 3 shows the signals of MHD, Hard X-ray and charge exchange neutrals in pre-disruption phase. The MHD oscillations correspond to the m = 2 mode and the transformation of the mode m = 2 to mode m = 1 occurs in pre-disruption phase similar in Fig. 1b. The low-frequency oscillations of charge exchange neutral fluxes for energy $E_n = 0.7$ keV with the frequency $f \approx 8$

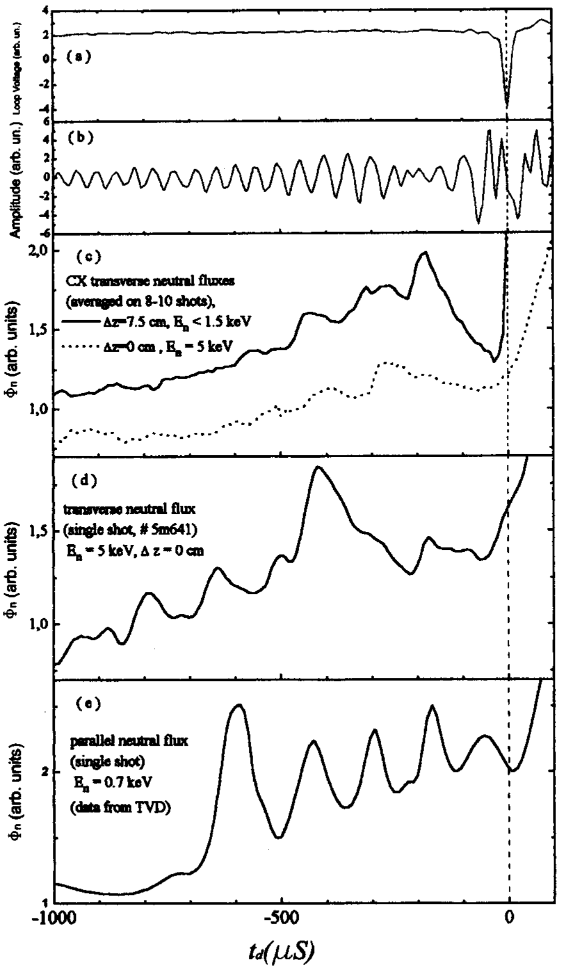

Fig. 1 Time dependences of (a) Loop Voltage, (b) MHD Oscillation, (c), (d) and (e) Perpendicular and Parallel Charge Exchange Neutral Fluxes (from ref. [2]).

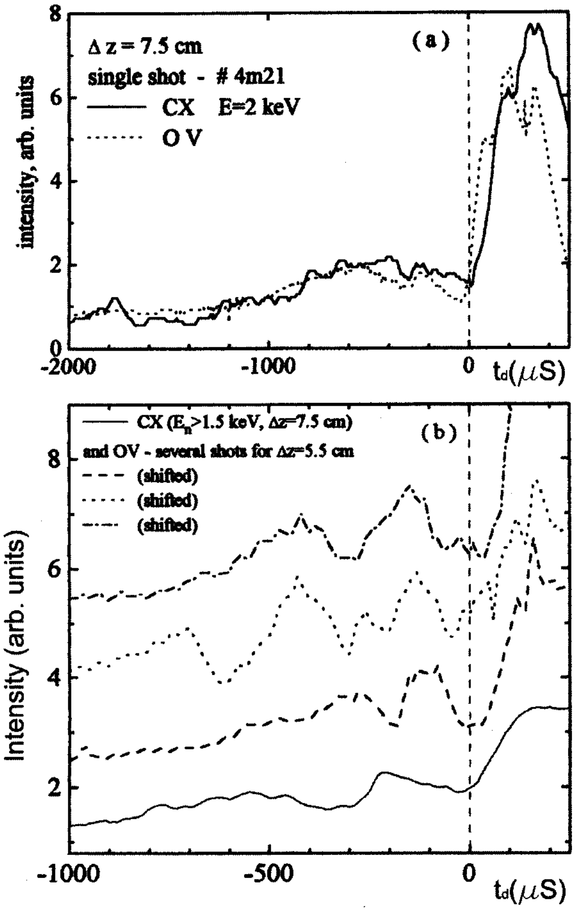

Fig. 2 The correlation between the high energy Charge Exchange neutral fluxes and OV line. (a) for energy E = 2 keV, (b) Energies more than 1.5 keV.

kHz may be seen in Fig. 3 similar in Fig. 1, but here these oscillations begin about 1500~1600 μs before disruption. The amplitude of these oscillations increases from the time $t_d = -700$ μs up to the disruption time. The bursts of large-amplitude MHD fluctuations, dubbed "fish-bones," are observed simultaneously with the increase of amplitude in the perpendicular charge exchange neutral fluctuations. There is a good correlation between the bursts of large-amplitude MHD fluctuations and charge exchange neutral oscillations. The oscillations of the hard X-ray signals with the same frequency as the CX fluctuations ($f \approx 8$ kHz) can be seen, which start about 2000 μs before disruption. These oscillations of hard X-ray finish about 600 μs before disruption.

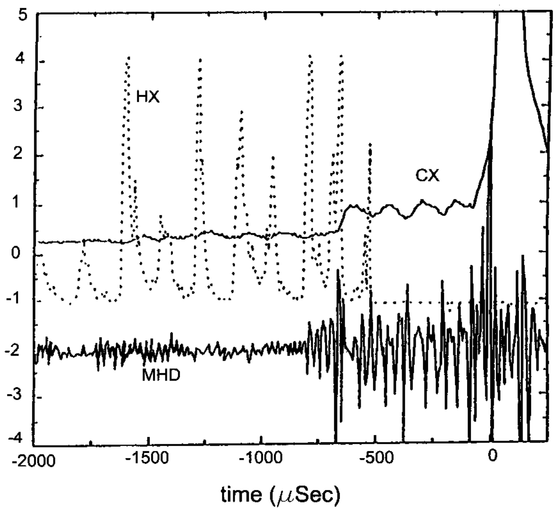

Fig. 3 Signals of MHD, Hard X-ray and Charge exchange neutrals in pre-disruption phase.

4. Discussion

These experimental data concerning the time evolution of the neutral components of the plasma during pre-disruption and disruption phases testify that the observed phenomena cannot be interpreted in the framework of existing models [5-11], because generally these models comprise a classification of disruption types and stages, the role of impurity in the energy balance, the contraction of the electron temperature profile completed by a temperature collapse, the time scales of various processes, the evolution and interaction of different perturbation modes, the evolution of the internal structure of perturbations, the fluctuations of the plasma density, and so on. The oscillations of the perpendicular neutral fluxes (Fig. 1), and the parallel one which has already been observed in ref. [1], give us a possibility to propose that in pre-disruption phase there is some structure that is oscillated simultaneously with m = 2 mode up to damping of this mode. The perpendicular component of this structure is greater than parallel one because the data show that parallel component has oscillations only for a flux of neutrals with energies less than 1.5 keV and directed along the plasma current.

The correlation between the behaviors of the high energy charge-exchange neutral flux and of OV line emission (Fig. 2) gives us a possibility to propose that there is a mechanism of losses-excitation of inner transition with help of heavy particles [12,13] in pre-disruption phase [3]. It can be treated qualitatively in the same manner as in experiments on fast neutral injection to plasmas (e.g. [14,15]). The neutral-atom "injection" in our case leads to a fast supply of an additional neutral-atom flux, mainly, from the periphery to the plasma bulk [1,2]. This supply is due to the charge exchange, and is provided by the transverse-energy component of fast ions. According to [12], the radiation loss due to impurity ions can be increased by injecting beam neutrals. When an intensive beam of neutrals is introduced into the plasma, the distribution of the impurity ions according to their multiplicity is greatly influenced by the charge-exchange of neutrals in the impurity. Therefore, the presence of neutrals shifts the distribution toward the low multiplicities of impurity ions, which in turn can increase the radiation loss. Thus, according to Fig. 2, we propose that the change of OV line radiation can be qualitatively attributed to the effect of the observed increase in the number of fast neutral particles.

The most interesting result may be seen in Fig. 3. As mentioned before, the bursts of large-amplitude MHD fluctuations have been observed simultaneously with the increase of oscillations of the perpendicular neutral fluxes (Fig. 3). There is a good correlation between the bursts of large-amplitude fluctuations and charge exchange neutral oscillations. Detailed experimental measurements have identified the mode structure of the bursts as an m = 2, n = 1 mode. It seems the bursts of MHD activity are associated with losses of the energetic beam ions, which are injected nearly perpendicularly [2]. There is an interaction between the charge exchange particles and MHD perturbation. The interaction is of the resonance type characterized by Landau damping, but here causing growth. The resonance is between the toroidal wave velocity of instability and the toroidal drift experienced by trapped particles. It was shown [16] that a mode with low toroidal and poloidal mode numbers, rotating toroidally in resonance with the trapped particles, is capable of rapidly ejecting them from the plasmas. The effect of an energetic trapped-particle population on MHD modes in a tokamak has been explored with use of a variational formalism [16-18]. In the presence of an energetic trapped-particle component such that produced by neutral beam injection (due to charge exchange at the plasma periphery) in pre-disruption phase, the resistive internal kink mode is described by the dispersion relation [19] as follows:

$$\delta W_{\mathrm{c}}+\delta W_{\mathrm{k}}-\frac{8i\,\Gamma\Big(\big(\Lambda^{3/2}+5\big)\Big)\Big[\omega\big(\omega-\omega_{*\mathrm{i}}\big)\Big]^{1/2}}{\Lambda^{9/4}\Gamma\Big(\big(\Lambda^{3/2}-1\big)/4\Big)\omega_{\mathrm{A}}}=0\,, \quad (1)$$

where $\Lambda = -i[\omega(\omega-\omega_{*\mathrm{e}})(\omega-\omega_{*\mathrm{i}})]^{1/3}\gamma_R$, $\gamma_R = S^{-1/3}\omega_{\mathrm{A}}$ the resistive growth rate, $\omega_{*\mathrm{e}}$ and $\omega_{*\mathrm{i}}$ are diamagnetic frequencies, S the magnetic Reynolds number, and ω_{A} the shear Alfven frequency $\omega_{\mathrm{A}} = v_{\mathrm{A}}/(\sqrt{3}Rrq')$ with the Alfven velocity v_{A}, R and r the major and minor radii, respectively, and $q' = \mathrm{d}q/\mathrm{d}r$ with the safety factor q. δW_{c} is the minimized ideal variational energy, and δW_{k} is the kinetic contribution coming from the trapped particle distribution:

$$\delta W_{\mathrm{k}} = \omega \int \frac{\phi(\omega,v)}{\omega_{\mathrm{d}}-\omega}\, d^3v\,. \quad (2)$$

Here ϕ is a function that depends on the velocity distribution function. The velocity space integral has a resonance in $\omega_{\mathrm{d}} = v_{\mathrm{d}\phi}/R$ for velocity $\omega = \omega_{\mathrm{d}}(v_\perp)$, where $v_{\mathrm{d}\phi}$ is the toroidal drift velocity of the banana circuits

$$v_{\mathrm{d}\phi} = \frac{qv_\perp^2}{2\omega_{\mathrm{c}}r} \quad (3)$$

where q, $v_\perp$ and ω_c are safety factor, perpendicular velocity and the cyclotron frequency, respectively. If we put the tokamak and experimental data (R = 36 cm, r = 7 cm, q ~ 2.35, $1/2mv_\perp^2 = 0.7$ keV, B = 0.8 T) we get $f_d = \omega_d/2\pi \sim 8$ kHz which is confirmed by experimental results.

5. Conclusions

1. Oscillations of the parallel and perpendicular neutral fluxes that are observed during pre-disruption stage in recent experiments, show there is some structure in pre-disruption phase that has oscillated simultaneously with the m = 2 mode until the damping of this mode. The perpendicular component of this structure is greater than parallel one.

2. The transformation of mode m = 2 to mode m = 1 in pre-disruption phase shows a possibility of the reorganization of magnetic structure.

3. A good correlation between the behavior of the high energy charge-exchange neutral fluxes and of the OV line emission confirms a mechanism of losses-excitation of inner transition with help of heavy particles in pre-disruption phase [3]. This mechanism may affect magnetic structures through the effect on radiation losses.

4. The neutral-atom injection in pre-disruption phase that leads to a fast supply of an additional neutral flux can play an important role in magnetic structures of pre-disruption phase. The bursts of large-amplitude MHD fluctuations that have experimentally been observed simultaneously with the increase of oscillations of the perpendicular neutral fluxes, show a mode structure of the fishbone as an m = 2, n = 1 mode. Since the behavior of these perpendicular neutral fluxes is related to the kinetic and collision processes, the magnetic structures can be affected by the kinetic and collision processes. The perpendicular component of the neutral flux may be trapped and have a destabilizing effect on the kink modes in tokamaks. In some regimes this flux can significantly decreases the growth rate of the resistive kink mode, leading to a prolongation of pre-disruption stage.

References

[1] A.V. Bortnikov, N.N. Brevnov *et al.*, Plasma Physics Reports **21**, 634 (1995).
[2] R. Amrollahi, E. Farshi *et al.*, Plasma Physics Reports **23**, 561 (1997).
[3] E. Farshi, N. Brevnov, A. Bortnikov *et al.*, Phys. Plasmas **8**, 3587 (2001).
[4] Y.V. Gott and A.G. Motlich, Nucl. Instrum. Meth. **155**, 442 (1978).
[5] B.B. Kadomtsev, Fiz. Plazmy **1**, 710 (1975).
[6] V.B. Parial and G.V. Pereverzev, Fiz. Plazmy **6**, 27 (1980).
[7] M.A. Dubois and A. Samain, Nuclear Fusion **20**, 1101 (1980).
[8] J.A. Wesson, Plasma Phys. Contr. Nucl. Fusion **28**, 243 (1986).
[9] J.A. Wesson, Nucl. Fusion **30**, 2545 (1990).
[10] D. Anderson *et al.*, *CTH-IEFT*/PP-1922-22, Gothenburg: Institute for Electromagnetic Field Theory and Plasma Physics (1992).
[11] D.J. Ward and J.A. Wesson, Nucl. Fusion **32**, 1117 (1992).
[12] V.A. Krupin *et al.*, JETP Letters **29**, 218 (1979).
[13] V.A. Abramov *et al.*, Fiz Plazmy **10**, 400 (1984).
[14] S. Suckewer *et al.*, Phys. Rev. A **22**, 725 (1980).
[15] W.H.M. Clark *et al.*, Nucl. Fusion **22**, 333 (1982).
[16] R.B. White *et al.*, Phys. Fluids **26**, 2958 (1983).
[17] L. Chen *et al.*, Phys. Rev. Lett. **52**, 1122 (1984).
[18] R.B. White *et al.*, Phys. Fluids **28**, 278 (1985).
[19] R.B. White *et al.*, Phys. Rev. Lett. **60**, 2038 (1988).