EFFECT OF THE SUPRATHERMAL ELECTRONS ON PLASMA STABILITY IN HIGH-DENSITY TOKAMAK PLASMA

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Sawtooth oscillations observed in the central part of a tokamak plasma [1] are commonly connected with reconnection of the magnetic field lines around the q=1 magnetic surface [2,3]. Detailed analysis of the modern experiments indicated, however, that peculiarities of the non-linear plasma perturbations and sequence of events leading to a sawtooth crash can not be described self-consistently in term of only m=1,n=1 MHD mode. The most challenging contradictions with the classical reconnection theory [2] are connected with the following experimental observations:

- abrupt trigger of the sawtooth crash at relatively small amplitude of the MHD perturbations,
- fast time scale (t_{crash}~0.1ms) of the energy quench during the sawtooth crash in a large tokamak plasma (e.g. JET, TFTR), which is similar to values of t_{crash} in small tokamaks,
- small modification of the magnetic configuration during the sawtooth crash, as measured with the use of Faraday rotation and MSE diagnostics (see Ref. in [4]) in plasma with low values of the safety factor in the plasma core ($q_0 \sim 0.6$ -0.8).
- fast propagation of the plasma perturbations outside the q=1 surface just after the sawtooth crash (ballistic heat pulse propagation [5]).

While the contradictions were explained in part by the theoretical studies (see, review papers [3, 6-8]), the main uncertainties of the reconnection theory still complicate analysis of the sawteeth.

Some indication of the sawtooth mechanism was observed in resent experiments in T-10 tokamak using new tangential x-ray array installed inside the T-10 vacuum vessel [9]. The array provides superior resolution of the suprathermal x-ray radiation emitted in forward cone along the helical field lines (not resolved with conventional x-ray imaging systems with measurements in direction orthogonal to the plasma column). The tangential system has illuminated presence of the non-thermal x-ray bursts around X-point of the m=1,n=1 island during the sawtooth crash. The x-ray bursts were observed previously in several experiments (see [10]), but they were not analyzed in details so far. Analysis of the experiments [11] has revealed that the x-ray bursts can be connected with the suprathermal electrons (E_{γ} ~30-100keV) generated due to strong electric fields induced during magnetic reconnection around the X-points of magnetic islands. The mechanism of the electric field generation during the reconnection is established in theory (see pioneering work [12]) and was extensively examined in laboratory experiments (see review paper [13]) and astrophysics studies [14]. However, generation of the suprathermal electrons during the reconnection in high-temperature tokamak plasma was not studied in details so far.

The main objectives of present experimental studies are connected with analysis of generation of the suprathermal electrons during the sawtooth instability in T-10 tokamak. In addition to previous studies [11] tangential x-ray array is equipped with CdTe detector providing improved sensitivity to the non-thermal x-ray emission. Additional sets of the CdTe detectors are placed around the torus in order to measure spatial distribution of the non-thermal radiation.

Analysis of the x-ray emission using the tangential x-ray array in T-10 tokamak indicated that all sawteeth under study are superimposed with the non-thermal x-ray spikes (see for example, Fig.1). Growth rate of the x-ray emissivity during the spike, $\gamma_{spike}=(0.7-2)10^4 s^{-1}$, is up to 20 times higher than one of the conventional m=1,n=1 mode

 $(\gamma_{11}=10^3 \text{ s}^{-1})$. Fast x-ray spikes are superimposed at the maximum of the m=1,n=1 mode and are observed generally during the last period of the m=1,n=1 mode rotation at the moment of the sawtooth energy quench. However, the spikes can be observed sometimes in two subsequent cycles of the m=1,n=1 mode preceding the crash (see Fig.2). Analysis indicated that x-ray spikes have maximum amplitude around the q=1 surface (sawtooth inversion surface) and rotate with the m=1,n=1 mode (see Fig.1 and Fig.3). In subsequent sawtooth crashes the spikes can be initiated in various angular position (either at high or low field side of the torus) depending on the angular position of the m=1,n=1 mode.

During the sawtooth crash x-ray spikes, initially observed at the X-point, move further outside to larger raddii and can be observed at the top of the heat pulse propagating through the plasma. This is illustrated in Fig.4e representing time evolution of the x-ray emissivity measured using conventional vertical imaging array. In this particular example, x-ray spikes are expelled outside to the high-field side of the torus. In various sawtooth crashes x-ray spikes can proceed in any direction, while propagation outside the q=1 surface is asymmetric in poloidal direction. Amplitude of the x-ray spikes decays monotonically as they propagate to the outer raddii. It should be noted, that normal heat pulses (inverted sawteeth) induced during the sawtooth crash outside the q=1 surface decay at considerably slower rate in comparison with the x-ray spikes disappearing in a fraction of millisecond ($\delta t < 0.1 \text{ms}$).

The x-ray spikes observed during a sawtooth crash are not accompanied by the hard xray bursts from the rail limiter. This observation seems can exclude possible role of the plasma-wall interaction in generation of the non-thermal emission during the sawtooth crash. Moreover, observation of the x-ray spikes at any position along the poloidal circumference (including high-field side of the torus) seems also excludes possible connection of the perturbations with the ballooning modes (important only in the area of non-favorable field line curvature at the low field side of the torus [14].) Joint rotation of the x-ray spikes with the m=1 mode indicates that physical processes at the X-point of the m=1 magnetic island (maximum of the m=1 perturbation) can be important in initiating the non-thermal emission.

Production of the runaway electrons during disruption has been the subject of a number of theoretical investigations [15-20]. In a simplified way, the time evolution of the density of runaway electrons (N_r) generated with application of electric field (E) in thermal plasma with density n_e can be described by the equation:

 $dN_r/dt = n_e/\tau_{dr} + N_r/\tau_{av} - N_r/\tau_{loss}$

where $1/\tau_{dr}$ and $1/\tau_{av}$ are the production rates of the primary runaway electrons (Dreicer acceleration) [15] and secondary knock-on avalanche [16], accordingly, and τ_{loss} represents time constant of the runaway losses. Dreicer acceleration rate is a function of $\delta_0 = E/E_c$: $\tau_{dr}^{-1} \approx 0.3 v_e \, \delta_0^{-3/8} \exp(-1/4\delta_0 - (2/\delta_0)^{1/2})$, where E_c is the critical (threshold) electric field given by $E_c = e^3 n_e ln \Lambda / (4\pi\epsilon_0^2 m_e v_{th}^2)$, v_e is the collision frequency of the electrons at the thermal velocity v_{th} (it is assumed for simplicity that $Z_{eff} \approx 1$). The time constant of the knock-on avalanche is described by relation $\tau_{av} \approx 2m_e c \ln \Lambda / eE$ [16]. Macroscale magnetic turbulence constitute the dominant loses of the runaway electrons during the disruption [17,18]. Time constant τ_{loss} can be described in the case by relation: $\tau_{loss} \approx k_t (\delta B/B_t)^{-2}$, where $k_t \approx 6 \, 10^{-12} s$ and magnetic field perturbations are considered as radial function decaying outside the resonant magnetic surface.

Calculations of the runaway production rate depend critically on amplitude of the electric field generated during the reconnection. Detailed calculations of the field require 3-D MHD simulations (see [14]), which are complicated in the real experimental conditions. In a simplified way, longitudinal electric field induced during the sawtooth

crash around the q=1 surface can be estimated from calculation of the inductive response to reduction of the poloidal magnetic flux during the sawtooth crash. Generation of the electric field up to $E \sim 10 V/m$ for time duration of $t_{crash} \sim 100\mu$ s can be predicted in the case. Similar values of the electric field can be obtained. Schematic view of the process is shown in Fig.4a. Calculations indicate that electric field of order of E=10V/m can induce runaway avalanche with density $n_r \sim 5-7 \ 10^{17} m^{-3}$ in a narrow region around X-point of the magnetic island (see Fig.4b,c). Magnetic turbulence generated during the sawtooth crash leads to outward displacement of the runaway beam (see Fig.4.d), which can produce x-ray bursts at outer raddii. Calculated growth rate of the electron avalanche ($\gamma_r \sim 10^4 s^{-1}$) and velocity of the electron beam propagation outside the q=1 surface agrees with ones observed in the experiments (see Fig.4.e).

Simple model described in the paper allows phenomenological description of the runaway production, while detailed simulations using kinetic and MHD codes are required for detailed analysis of the process. Meanwhile, consideration of the suprathermal electrons during the sawtooth crash can provide possible explanation for the contradictions of the reconnection model (abrupt trigger and similar crash time of the sawteeth in tokamak of various size). Moreover, while total number of the suprathermal electrons is small, they can induce runaway current comparable with one inside the q=1 surface (I_r is of order of 20 kA). Generation of such current can probably veil modification of the equilibrium magnetic configuration during the sawtooth crash (as revealed from Faraday and MSE measurements [3,4]).

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Fig.1. Time evolution of the x-ray intensity measured (a,b)using tangential (xrp1)and conventional (XRB) x-ray arrays during the sawtooth crash (t~725.3ms). The non-thermal spikes are superimposed with the m=1mode. Also shown (c) are radial profiles of the maximum x-ray perturbations during the sawtooth crash (1) and the non-thermal spikes (2) measured with the tangential-array. The x-ray spikes have maximum amplitude around the *q*=1 surface (sawtooth inversion surface $r=r_s$).



742

Fig.3. Time evolution of the x-ray $\delta t_{crash} \sim 0.1 ms$ in subsequent sawt intensity measured along chords (t=742.6ms and t=751.8ms) specific tangential to the q=1 surface using experiments (see, signal of x-ray array tangential TX (a) and conventional (b) x-ray arrays during the sawtooth crash. (N_{r1}) at the q=1 surface and conton The non-thermal x-ray spike (rotating with the m=1 mode in clockwise frames (c) and (d), accordingly. Can direction) is observed consecutively drift of the runaway beam is conalong chords with various pitch angle starting starting from the equatoriamid-plane: $\theta \approx 0^{\circ}$ (a14), $\theta \approx -60^{\circ}$ (b7), θ $\approx -120^{\circ}$ (c6), $\theta \approx -180^{\circ}$ (a5), $\theta \approx -240^{\circ}$ measured during the sawtooth crash). (b14).

743

time (ms)



Fig.2. Time evolution of the xray intensity measured with the tangential array (xrp1) and conven-

tional x-ray detector (sxra14) illustrating x-ray spikes during two subsequent cycles of the m=1,n=1 mode.



t (ms) 751.6 752.0 751.6 t (ms) 752.0FIG.4. Schematic view of the runaway generation process (a). Electrons are accelerated in electric field *E* induced around *X*-point of the *m*=1 magnetic island during the reconnection. Beam of the electrons is displaced to outer radii due to magnetic perturbations ($\delta B/B$) arisen during the sawtooth crash (see dash line). In numerical simulations (see (b)-(d)) longitudinal electric field E_1 around the q=1surface ($\delta r/r_s \sim 0.1$) is ramped up to $E \sim 10V/m$ during $\delta t_{crash} \sim 0.1 ms$ in subsequent sawtooth crashes (t=742.6ms and t=751.8ms) specified from the experiments (see, signal of x-ray array xra5). Time evolution of the calculated runaway electron density (N_{rl}) at the q=1 surface and contour plot of the electron density $n_r(r)$ at outer radii are shown in frames (c) and (d), accordingly. Calculated radial drift of the runaway beam is comparable with outward movement of the non-thermal x-ray spike observed in the experiments (see, dark area in frame (e) representing contour plot of the x-ray intensity