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Small- scale modes in T-10 tokamak

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ABSTRACT Small scale plasma perturbations and localised x-ray bursts are identified in T-10 tokamak with the use of toroidally viewing x-ray imaging system, in-vessel hard x-ray detector, and fast magnetic probes. Non-thermal x-ray spikes placed around X-points of the m=2 and m=1 magnetic islands are observed during the energy quench at density limit disruption and sawtooth crash. Analysis of the plasma perturbations indicates possible role of the supra-thermal electrons in the relaxation events.

INTRODUCTION Abrupt trigger of the sawtooth crash and energy quench during major disruption (see [1,2]) indicates that the relaxation events can not be described self-consistently in term of large-scale MHD modes with low poloidal wave numbers (*m=1-4*). Moreover, extended theoretical studies (see references in [2]) indicted that low-m MHD modes in some conditions can be accompanied by small-scale perturbations characterised by high-m wave numbers (*m=5-30*). One of the possible diagnostic for identification of the high-m modes is based on idea of the soft x-ray imaging system viewing in toroidal direction (see [3]). Integration of the soft x-ray intensity perturbations is provided in the case along the lines of sight of detector tangential to the helical mode. Calculations indicated that tangential measurements can provide considerably higher resolution of helical modes than in the case of conventional x-ray arrays [4,5]. Installation of the toroidally viewing x-ray imaging system in T-10 [5,6] allows identification of the small-scale modes in a variety of ohmically and auxiliary heated plasma.

EXPERIMENTAL SETUP Small-scale perturbations are analysed in T-10 tokamak with the use of the toroidally viewing x-ray imaging system [5,6] (1), standard x-ray tomographic arrays [7] (2-4), x-ray proportional counter (5), and fast magnetic probes [8] (6) (see Fig.1). The non-thermal x-ray emission is measured using crystal NaJ(Tl) monitor (7) and Ge PHA system (8). Plasma in T-10 is restrained by movable rail limiter (9) and guard poloidal limiter (10). Tangential x-ray (TX) imaging system is placed inside tokamak vacuum vessel at the low-field side of the torus bellow the equatorial mid-plane. The system consists of 2 by 2 set of the silicon surface-barrier diodes (xrp1-4) secured inside stainless steel container at the top of the movable rod. Changing vertical position of the TX system allows measurements of the x-ray radiation from the outer part of the plasma ($0.25<r/a_L$) with spatial resolution of order of 7x7mm. The set of metallic foils is used for choosing the energy range of the

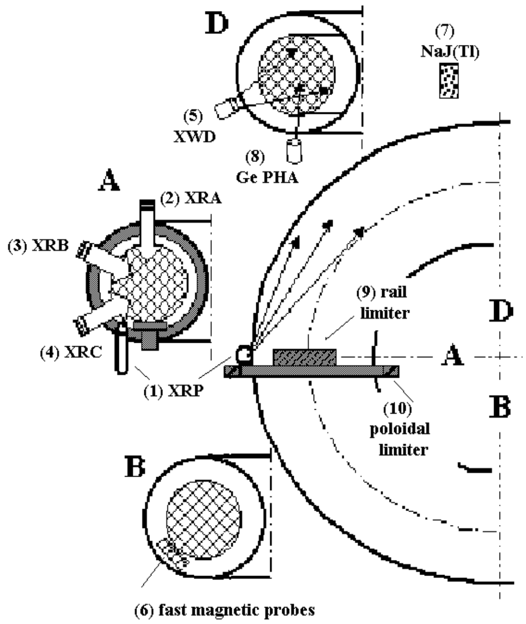


Fig.1. *Schematic view of the diagnostics used for analysis of the small-scale modes*

measured x-rays (cut off energy $E_{\gamma 0}$ > 2 - 2.5 keV).). Additional x-ray diode (xrp5) is placed inside the TX container for measurements of the non-thermal x-ray emission ($E_{\gamma 0}$ > 40-50 keV). Data acquisition and storage is provided by two independent systems based on CAMAC ADC modules (8μs, 8 bit, 8k/ch) and fast PC ADC card (PCI frame, 3μs, 12 bit).

EXPERIMENTAL STUDIES

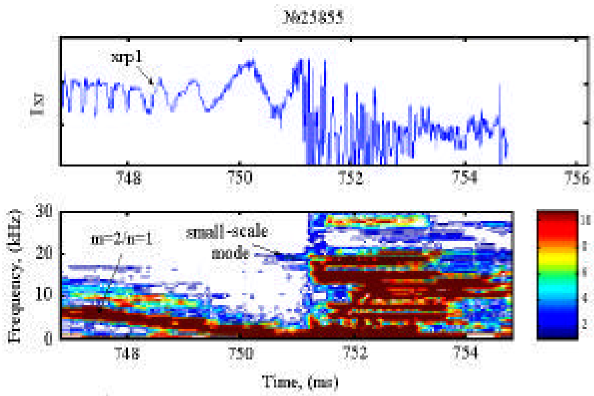


Fig.2. *Small-scale modes prior the density limit disruption in T-10*

Plasma perturbations at the radiative density limit disruption are studied in ohmically heated plasma (I_p=0.2-0.3MA, B_t=2-2.4T, a_L=0.25-0.3m, $<n_e>$=3-4.5 $10^{19}m^{-3}$). Energy quench in such conditions is preceded by coupling of the m=1 and m=2 (n=1) modes with subsequent slowing down of the modes rotation. The low-m MHD modes are superimposed by small-scale perturbations observed with the TX array (see t ~ 747-751ms in Fig.2). The small mode is a solitary high-frequency perturbation moving in the same direction as low-m internal modes (electron diamagnetic drift direction). Repetition rate of the small perturbations (f_{sc} ~ 19-20 kHz) is up to twenty times higher than one of the m=2 mode. Measurements of the perturbations amplitude at various vertical position of the TX array indicate that the mode is localised around the m=2 magnetic island. Small-scale oscillations are also observed at the plasma periphery with the use of the fast magnetic probes. Such oscillations were previously identified as micro-tearing modes (m ~ 10-15) [8]. However, present experiments indicate that phase shifts of the small-scale oscillations in poloidal direction are equal or smaller than one of the m=2,n=1 mode, which seems contradicts the tearing mode theory. In some conditions magnetic perturbations can be symmetrical in poloidal direction (m=0), while the oscillation frequency is up to 20 times higher than one of the m=2,n=1 mode. Such unusual behaviour can indicate the non-tearing nature of the small modes. Solitary nature of the perturbations observed in the experiments, instead of excitation of the broad spectrum of the modes seems contradicts possible excitation of the secondary magnetic islands due to toroidal and tree-wave coupling of the large-scale modes (e.g. m=1 and m=2 modes) [2].

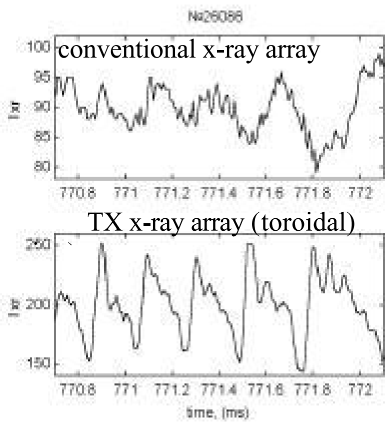


Fig.3. *Small-scale modes at the top of the m=2,n=1 perturbation*

Small-scale modes initially identified as tiny continuous quasi-coherent waves (see Fig.2) are often transformed to bursts of the oscillations with maximum amplitude at the growing phase and at the top of the m=2,n=1 mode (Fig.3). Moreover, prior the disruption the bursting modes are replaced by spikes of the x-ray radiation observed periodically in phase with the m=2 mode (Fig.4). The x-ray spikes are identified with the use of TX detectors and are not observed with conventional (orthogonal) x-ray array. This indicates preferred emission in forward cone around the equatorial mid-plane, which is typical for the high energy electrons [9],[10]. Energy quench at density limit (Fig.4) is initiated during the consecutive x-ray spike at the moment when perturbation from the m=2 mode is placed in front of the rail limiter. The x-ray bursts are observed in the case not only with the TX array but also with conventional x-ray detectors looking at the narrow spot at rail limiter. Narrow localisation of the radiation spot differs from the x-ray bursts observed later in the discharge on all x-ray arrays when avalanche of the runaway electrons hit not only the rail limiter but also poloidal one.

Small-scale oscillations observed in the outer part of the plasma are considerably increased in presence of the m=1 mode. Moreover, the sawtooth crash by itself is often preceded by spikes of the non-thermal radiation observed around the q=1 surface (see also [11]). Fast x-ray spikes are superimposed at the maximum of the m=1,n=1 mode (X-point of the m=1 magnetic island) and rotate with the m=1 mode prior the sawtooth energy quench (Fig.5). During the sawtooth crash x-ray spikes, initially observed at the X-point, move further outside to larger radii and can be seen at the top of the (ballistic) heat pulse propagating through the plasma. It should be noted here, 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 fraction of millisecond (δt<0.1ms). In subsequent sawtooth crashes internal x-ray spikes appear either at low or high field side of the torus. Observation of the x-ray spikes at the high-field side of the torus seems excludes possible ballooning origin of the perturbations (see [12]) which should be important only in the area of non-favourable field line curvature at the low field side of the torus. The x-ray spike during the sawtooth crash can be transformed to the mode with one full cycle of rotation. Such mode at the sawtooth crash look similar to perturbations observed at the outer radii prior the density limit disruption. The similarity is connected with both the spectral characteristics of the perturbations (burst frequency f_{sc}=10-20kHz, growth rate $\gamma_{sc}=10^4 s^{-1}$,) and with direct connection of the small-scale perturbations with the large m=2 and/or m=1 modes. This can probably reflect similar nature of the phenomena in both cases. Moreover, joint rotation of the spikes with the m=1 mode indicates that physical processes at X-point of the magnetic islands can be important in initiating the instability.

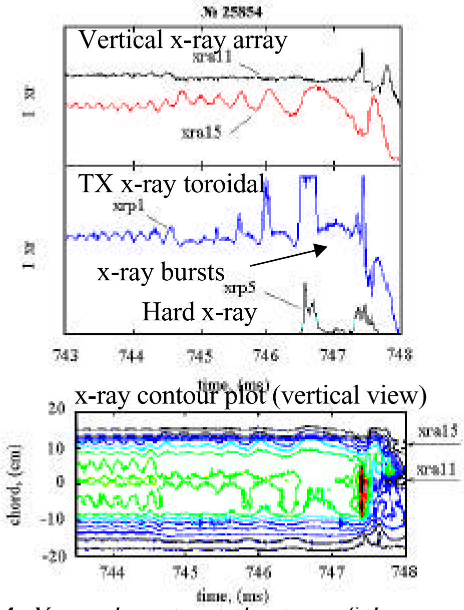
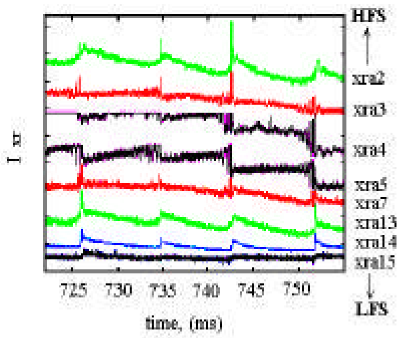


Fig.4. *X-ray bursts at the top of the m=2, n=1 mode prior the disruption*

DISCUSSION Previous experiments in tokamak indicated that energy quench at density limit disruption and sawtooth crash are often preceded by bursts of the non-thermal x-ray and ECE radiation (see references in [1,2,6,13]). Such non-thermal bursts have long been connected with presence of the runaway electrons. Resent experiments in JET [9] and TEXTOR [10] as well as pioneering experiments in PLT [14] and Pulsator [15] indicated possible connection of the runaway beams with internal MHD modes. Measurements of the x-ray radiation in T-10 using tangentially viewing array and conventional x-ray tomographic system seems provide first direct experimental evidence of the narrow localisation of the non-thermal radiation around the rational surfaces (q=1,q=2) at specific points of the m=1 and m=2 magnetic islands (X-points). In the case x-ray spikes can appear as a result of the forward bremsstrahlung produced by the runaway interaction with the residual plasma. Analysis of the angular and energy distribution of the x-ray radiation measured with various x-ray arrays in T-10 experiments indicated that energy of the runaway electrons in flight is of order of 20-100keV. Presence of the runaway electrons in the specified energy range is found also from measurements of the x-ray spectrum using Ge PHA spectrometer. Calculations based on the runaway current measured after disruption [6] indicate that total number of the supra-thermal electrons confined around X-points of the m=2 mode (in area within 25% of the m=2 island size) is of order of $N_E \sim 1.5x10^{15} m^{-3}$ prior the energy quench. It should be noted that frequency of the small-scale modes observed in the experiments is close to Langmuir frequency (5-15 kHz) associated with the electrons beams.

Small-scale modes identified in ohmically heated plasma are also observed during ECRH. Initial experiments indicate no strong difference in amplitude, frequency, and localisation of the perturbations in ECRH heated plasma. Moreover, analysis indicates no strong difference of the small-scale modes in plasma with various electron densities. This can probably indicate that small-scale modes are not connected directly with classical runaway electrons (1-30 MeV) depending on the bulk plasma parameters. Observation of the small-scale modes and x-ray spikes close to the q=1 and q=2 surfaces can confirm the idea [14] that non-thermal electrons are placed at the resonance surfaces. Such non-thermal electrons can be born due to strong electric fields induced during magnetic field lines reconnection in X-points of the m=1,m=2 magnetic islands [2]. The perturbations in the case should depend on the processes in the reconnection layer rather than the external conditions, which can explain in part weak dependence of the modes on the plasma parameters.

CONCLUSIONS Small-scale plasma perturbations and spatially localised x-ray spikes are identified in T-10 tokamak prior the density limit disruption and during the sawtooth crash. Small-scale perturbations and x-ray spikes are coupled to the m=2 and m=1 modes and can be transferred to the bursts of the non-thermal radiation prior the energy quench. Analysis of the experiments indicates that small-scale modes and spikes are probably connected with supra-thermal electrons generated around X-points of the magnetic islands.



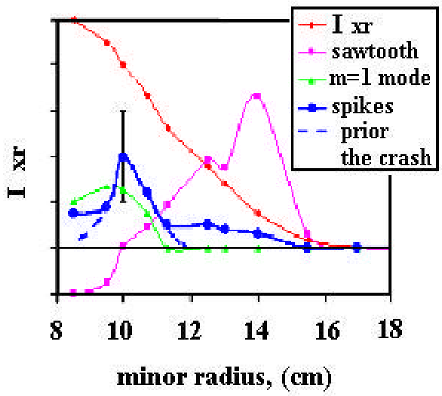


Fig.5. *X-ray spikes at the top of the m=1, n=1 mode at sawtooth crash*

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