Plasma arcs formation in the plasma periphery during disruptions in the T-10 tokamak plasma

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Abstract. Fast-scale plasma perturbations (0.5–2 MHz) are studied during disruption instability in the T-10 tokamak. A system of movable magnetic probes is used to measure magnetic field perturbations in the plasma periphery. Spatial distribution of soft X-ray oscillations is measured using silicon surface-barrier detectors. A possible connection between the fast-scale electromagnetic and X-ray oscillations and arc discharges in the plasma edge near localization of the MHD modes during plasma disruption is considered.

1. Introduction
Stabilization of disruptions and prevention of accelerated electron beams are important tasks in the design of a reliable thermonuclear reactor. Practical implementation of disruption stabilization systems is complicated due to the variety of plasma perturbations, which are observed prior to the plasma collapse. The initial stage of disruption is associated, as a rule, with the nonlinear growth of magnetohydrodynamic (MHD) modes with low poloidal and toroidal numbers (m = 1–5, n = 1–3). However, the amplitude of MHD perturbations can differ by an order of magnitude before the disruptions under various experimental conditions, which leads to the need for complex adaptation of the control system parameters. The critical conditions of disruption can be detected using multiparametric analysis with neural networks. However, the adjustment of such systems requires a preliminary study of a significant number of disruptions, which is difficult under the tokamak reactor conditions. Analysis of the critical conditions for the energy disruption development and the generation of trigger signals for the initiation of disruption stabilization systems is one of the main tasks of modern experiments.

Experiments on the T-10 tokamak have shown that the initial stage of plasma disruptions at high density is accompanied by the development of rapidly varying oscillations of electromagnetic fields [1], which are possibly associated with the formation of arc plasma discharges in the peripheral regions of plasma. The formation of local arc discharges, which has been studied in detail earlier in the laboratory experiments with a low-temperature plasma, is indirectly confirmed in the T-10 tokamak plasma in the form of characteristic damages of the tokamak vessel elements. Registration of high-frequency perturbations of magnetic fields at the initial stage of disruption can be used to generate trigger signals for the initiation of disruption stabilization systems.

2. Diagnostic systems of magnetic probes and soft X-ray radiation in the T-10 tokamak
Magnetic probes are widely used in the studies of plasma perturbations in tokamak research. In the experiments with high-temperature plasma, magnetic probes are usually located at a considerable distance from the plasma boundary and are protected by additional screens of graphite and stainless
steel. Such an arrangement of probes makes it difficult to measure fast-oscillating plasma oscillations with frequencies above $f \sim 100 \text{ kHz}$. An additional limitation is associated with currents that are induced in conductive structures on which the magnetic probes are fixed.

The system of magnetic probes in the T-10 tokamak [1] consists of the horizontal and vertical coils that are fixed to a movable rod. The probes are made of nickel wire in ceramic insulation and are located inside a ceramic container that is separated from a supporting metal structure. The signals from magnetic probes are digitized via ADC converters ADM214x100M (14 bits, 60 MHz).

To study the fast-scale soft X-ray oscillations, a diagnostic tool that is based on silicon surface-barrier detectors DKPs-50 with a high-speed amplifier is installed in the T-10 tokamak. The X-ray data acquisition system is based on an L-783M multifunction high-speed ADC board (12 bits, 3 MHz) that is located in close proximity to the T-10 tokamak.

3. Results of the experiments in the T-10 tokamak
A system of magnetic probes was used in the experiments in the T-10 tokamak to study plasma perturbations during the density limit disruption, which is induced by additional gas puffing at the quasi-stationary stage of the discharge. The typical evolution of plasma parameters in these experiments is shown in Fig. 1a. A thermal quench (energy collapse) is initiated at time $t \sim 719.4 \text{ ms}$. Along with large-scale MHD perturbations ($m = 2-3$, $n = 1$), magnetic fluctuations in the fast-scale range ($f_{\text{fast}} \sim 0.2-0.5 \text{ MHz}$) are observed just before the thermal quench. Amplitude of the fast-scale oscillations decreases much more rapidly than the amplitude of the $m = 2$ mode when the probe is moved away from the plasma boundary (see Fig. 1b). Analysis shows that the fast-scale oscillations are characterized by a wide spectrum of harmonics (see $t = 719.45-719.51 \text{ ms}$ in Fig. 2a).

To reveal the dominant perturbations of magnetic signals, a wavelet transformation is used in the analysis. An example of the analysis of the magnetic probe signal using continuous wavelet transformation (CWT) algorithms, which are based on Daubechies wavelets of the $4^{\text{th}}$ order, is shown in Fig. 2b. This plot confirms the multi-scale origin of perturbations and highlights periodicity, which is observed at a scale coefficient of the $50^{\text{th}}$ order (which is equivalent to regular oscillations at frequencies $f < 450 \text{ kHz}$). Inspection of the CWT coefficients plot for this signal reveals patterns among the scales that show some features of the signal’s chirping from high (low frequencies) to low (high frequencies) scales (see, for example, $t > 719.49-719.51 \text{ ms}$ in Fig. 2b).

At the initial stage of disruption, fast-scale perturbations are also observed in the form of soft X-ray oscillations ($f \sim 0.5-1 \text{ MHz}$), which are recorded using Si detectors with a direct view of the graphite diaphragm that limits the plasma boundary (see Fig. 3). This indicates that there may be a possible connection between the fast-scale perturbations and processes of interaction of local plasma discharges with the surface of limiters.

When the large-scale MHD perturbations are rotated, the fast-scale oscillations manifest themselves most clearly at the moment of passage of the O-points of the magnetic islands near magnetic probes, which are located at the boundary of the annular poloidal limiter (see Figure 4). This effect can be related to the enhancement of the plasma-wall interaction during the passage of the O-points of the magnetic islands near the surface of the limiter. The role of the interaction of plasma with the limiter surface in the development of fast-scale oscillations is also confirmed by a significant decrease (up to 100 times) of the amplitude of magnetic perturbations, which is measured with magnetic probes that are located far from the limiters (when displaced in the toroidal direction by 180 degrees).

4. Discussion and Conclusions
The new system of magnetic probes is installed in the T-10 tokamak. The system is based on high-sensitivity magnetic probes that are located inside the vacuum vessel on a movable rod, which ensures the positioning of probes near the plasma boundary. The important result of this study is the detection of rapidly varying ($0.2-0.5 \text{ MHz}$) perturbations of magnetic fields at the initial stage of disruption. Measurements of the radial and angular distributions of the toroidal and poloidal components of the
Fast-scale magnetic perturbations show that the fast-scale perturbations cannot be connected with the helical perturbations (micro-tiring mode). The detection of similar fast-scale perturbations of soft X-ray radiation in the plasma periphery indicates a possible connection between the fast-changing oscillations and the processes near and on the surface of diaphragms that limit the plasma discharge boundary.

The analysis of damage to the limiters in the T-10 tokamak confirms the development of arc plasma discharges in the peripheral regions of plasma. In addition, perturbations in the range of a few MHz were observed during arc discharges in laboratory experiments with an electric spark (50 V, 120 J), which was used for calibrating the magnetic probes in the T-10 tokamak.

Experiments, which were carried out on the T-10 tokamak, have shown a possible connection between the fast-scale magnetic and X-ray oscillations and arc plasma discharges in the peripheral regions of the discharge. Registration of the high-frequency magnetic field perturbation at the initial stage of disruption can be used to generate trigger signals for switching on the systems of disruption stabilization.

**Figure 1.** (a) Temporal evolution of plasma parameters in the T-10 tokamak in the regime with disruption at high density. Along with large-scale MHD perturbations (m = 2, n = 1), fluctuations in the range f_{fast} ~ 0.2–0.5 MHz are observed just before the thermal quench (t ~ 719.4 ms). (b) Radial dependence of the oscillation amplitudes due to the m = 2 mode (circles) and fast-scale oscillations of magnetic fields (squares).
**Figure 2.** Time evolution of magnetic field perturbations in the T-10 density limit disruption. Also shown are the results of (a) Fourier analysis of magnetic perturbations and (b) the image of expansion coefficients in wavelet functions.

**Figure 3.** Time evolution of the soft X-ray intensity and results of the Fourier analysis of fast-scale X-ray perturbations in the T-10 density limit disruption.

**Figure 4.** Time evolution of magnetic field perturbations prior to the density limit disruption. Fast-scale magnetic perturbations are observed most clearly close to the O-points of magnetic islands.

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**References**

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