Effect of ECRH and resonant magnetic fields on formation of magnetic islands in the T-10 tokamak plasma

E A Shestakov and P V Savrukhin
National Research Center "Kurchatov Institute", Moscow

Abstract. Experiments in the T-10 tokamak demonstrated possibility of controlling the plasma current during disruption instability using the electron cyclotron resonance heating (ECRH) and the controlled operation of the ohmic current-holding system. Quasistable plasma discharge with repeating sawtooth oscillations can be restored after energy quench using auxiliary ECRH power when $P_{EC}/P_{OH} > 2–5$. The external magnetic field generation system consisted of eight saddle coils that were arranged symmetrically relative to the equatorial plane of the torus outside of the vacuum vessel of the T-10 tokamak to study the possible resonant magnetic field effects on the rotation frequency of magnetic islands. The saddle coils power supply system is based on four thyristor converters with a total power of 300 kW. The power supply control system is based on Siemens S7 controllers. As shown by preliminary experiments, the interaction efficiency of external magnetic fields with plasma depends on the plasma magnetic configuration. Optimal conditions for slowing the rotation of magnetic islands were determined. Additionally, the direction of the error magnetic field in the T-10 tokamak was determined, and the threshold value of the external magnetic field was determined.

1. Introduction
One of the most dangerous consequences of plasma disruption is the formation of runaway electron beams [1]. Analysis showed that runaway electrons can gain high energy (up to 30 MeV) and release it locally in the form of heat by interacting with the vacuum vessel internal elements. Moreover, high power density of the runaway beams (up to 3 GW/m²) [2] leads to surface damage or total destruction and failure of the vacuum vessel internal elements.

In previous experiments on tokamaks, it was shown that large magnetic field perturbations, in particular low-frequency and stationary MHD modes, can lead to weakening and disappearance of the runaway electron beams [3]. Therefore, suppression of the runaway electrons can be provided by reducing the longitudinal electric fields via ohmic and auxiliary plasma heating system and an MHD perturbations control system.

2. Effect of ECRH on dynamics of the MHD perturbations and runaway electron beams
Effect of ECRH on MHD perturbations and runaway electrons was studied in the T-10 tokamak in experiments with discharge recovery after density limit disruption [4]. The experiments showed that auxiliary ECRH is a flexible tool for controlling MHD perturbations in plasma, which allows to both stabilize the MHD perturbations and create large-scale MHD modes.

The results of experiments on the study of the ECRH effect on the dynamics of MHD perturbations and runaway electrons after thermal quench at limiting density are shown in figure 1. Energy quench
is usually accompanied by a series of total radiation power losses and hard X-ray radiation bursts that appear during the interaction of runaway electrons with edge plasma and limiter. Deposition of the ECR power in the central plasma regions (figure 1a, B_t = 2.4 T) leads to the formation of quasi-stationary MHD perturbations and subsequent disappearance of radiation bursts as well as runaway electrons.

Deposition of the ECRH power near the q = 2 resonant surface (figure 1b, B_t = 2.5 T) leads to stabilization of the MHD perturbations and complete disappearance of the runaway electron beams. Deposition of the ECR power outside the q = 2 resonance surface (figure 1c, B_t = 2.6 T) leads to the partial stabilization of MHD perturbation and disappearance of the nonthermal radiation bursts. However, after switching off the ECRH, the plasma becomes unstable and disruption occurs with a subsequent appearance of the secondary runaway electron beams.

3. Stationary MHD perturbations generation system on the T-10 tokamak
To study the effect of resonant magnetic fields on plasma stability, the T-10 tokamak was equipped with a system of eight saddle coils that are arranged symmetrically relative to the equatorial plane of the torus outside the tokamak vacuum vessel (figure 2). This geometric configuration allows to generate quasi-stationary magnetic fields with a toroidal harmonics n = 1–7. The windings have a rectangular shape, their height is 1.5 m, and length along the torus is 2 m. The windings have eleven turns and are wound with a cable with a conductor cross section of 120 mm².

Four independent power supplies with a total power of 300 kW are used to power the saddle coils. The type of power supply used is a thyristor converter with a rated current of 1250 A and the possibility of short time excess up to 1900 A. The maximum output voltage is 45 V. The power supply can be remotely switched on/off, and the output voltage can be regulated. The amplitude of external magnetic perturbations m = 2, n = 1 near the q = 2 resonant surface is approximately 20–30 G.
The saddle coils power supply control system, which is based on a programmable logic controller Siemens S7-417, was designed and equipped on the T-10 tokamak. The control system measures basic parameters of power sources (current, voltage, and logic current sensor), determines their operating mode, and records parameters in a database. The data is transmitted over the Profibus network and recorded on a computer in a common local area network of the T-10 tokamak control room.

4. Effect of resonant MHD perturbations on the magnetic islands in tokamak T-10 plasma

Experiments were carried out on the T-10 tokamak discharges with various plasma parameters \( I_p = 120–290 \text{ kA}, \quad B_t = 1.5–2.4 \text{ T} \). In these experiments, the total magnetic field of the windings with one pair of magnetic poles was created, which corresponds to the \( n = 1 \) magnetic configuration. Figure 3 shows the evolution of MHD perturbations in experiments with saddle coils operating in the optimal regime for controlling the MHD perturbations.

**Figure 3.** Time evolution of the MHD perturbations frequency (Freq) and amplitude (MHD2) in experiments with external magnetic fields (Isc is the amplitude of the total current in the saddle coils).

Typically, at a sufficiently large amplitude of external perturbation (figure 3, pulse 69067), the switching on of saddle coils slowed down the \( m = 2 \) magnetic perturbation rotation speed from 5 kHz to 1–2 kHz. The strongest effect on slowing the rotation of MHD modes is observed when the \( q = 3 \) magnetic surface is placed close to the plasma boundary (figure 4).

Preliminary analysis indicated that the direction of magnetic field at which the MHD mode rotation stops most effectively coincides with the direction of the tokamak T-10 error field. It is also shown that the rate of MHD perturbations slowing increases nonlinearly at a threshold current in saddle coils (figure 5).

**Figure 4.** Mode \( m = 2 \) rotation slowing at various currents \( I_{sc} \) in the external coils \( (I_p = 290 \text{ kA}, \quad B_t = 2.4 \text{ T}, \quad n_e \sim 1 \times 10^{19} \text{ m}^{-3}) \)

**Figure 5.** Experimental results of the T-10 tokamak error filed direction and external magnetic field threshold value determination.
5. Conclusions
Effects of the ECRH auxiliary heating and resonant magnetic fields on plasma stability were studied in the T-10 tokamak. The possibility of safe recovery of stable plasma discharge and runaway electron beam stabilization was shown when using ECRH for plasma heating and MHD perturbation burst stabilization. The external resonant magnetic fields generating system based on eight saddle coils is installed in the T-10 tokamak. The system is powered by thyristor converters and controlled via Siemens S7 controllers. Experiments with saddle coils demonstrated nonlinear effects of external magnetic fields on the m = 2 mode rotation speed. Preliminary analysis indicated that the effect of external magnetic fields on plasma stability strongly depends on the position of internal resonant magnetic surfaces with respect to the saddle coils and on the angular direction of external magnetic fields.

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