Generation of runaway electrons during the initial stage of the T-10 tokamak plasma discharge

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Abstract. The formation of runaway electron beams in the initial stage of discharge is one of the characteristic features of fusion facilities with magnetic plasma confinement, such as tokamaks. They are generated due to the presence of the high electric fields and strong plasma-wall interaction in plasma. The runaway electrons produced during the breakdown stage also remain in the plasma in the quasistationary stage of the discharge. Studies carried out at the T-10 tokamak show that the electron energy and the heat flux density can reach 5−10 MeV and 1−3 GW/m², respectively. Thus, the interaction with electrons causes erosion and damage to the limiter surface. In this article, the energy distribution of high-energy electrons formed in the initial stage of plasma discharge in the T-10 tokamak during the formation of runaway electron beams in a strong longitudinal magnetic field was studied. The effect of the plasma density and MHD perturbations on the generation and acceleration of runaway electrons was revealed. The energy distributions of runaway electrons were estimated for different stages of the plasma discharge development.

1. Introduction

Runaway electron beams are one of the main obstacles in designing a tokamak reactor. Electron beams are typically generated during the initial stage of plasma creation in the presence of high breakdown electric fields and a strong plasma-wall interaction. The runaway electrons generated during the breakdown stage remain in the plasma and further can be accelerated during the quasistationary stage of the discharge [1]. Furthermore, during the development of the disruption instability, electron energies can reach 5−10 MeV, and the heat flux density can be as high as 1−3 GW/m² [2]. The interaction of electrons with the limiter can cause erosion and damage to its surface. In the quasistationary stage, the generation of runaway electrons can result in the development of plasma oscillations and instabilities [3, 4]. Analysis of the production rate and energy distribution of runaway electrons during the initial stage of the discharge is one of the main goals of these T-10 experiments.

The experiments were performed at the T-10 tokamak (NRC Kurchatov Institute, Moscow, Russia). The tokamak has toroidal vacuum vessel with major and minor radii of 1.5 and 0.3 m, respectively.

2. Diagnostic techniques

Measurements of runaway electrons in the T-10 tokamak were carried out using the spectrometric detectors for the suprathermal (50−300 keV) and hard (0.5−10 MeV) X-ray emission:

Eurorad semiconductor detectors based on CdTe crystals with dimensions of 5 × 5 × 3 mm³ (C553S) and 1 × 1 × 1 mm³ (S111S) were used as spectrometers for suprathermal X-ray emission. A detector with dimensions of 5 × 5 × 3 mm³ was installed outside the vacuum vessel within direct view
of the circular diaphragm and rail limiter. A detector with dimensions of $1 \times 1 \times 1$ mm$^3$ was installed on the movable rod inside the vacuum chamber which makes it possible to measure the emission in the direction tangential to the electron trajectories. The in-vessel detector is equipped with a massive lead collimator which provides effective shielding from photons with energies below 300 keV (spatial resolution is $\sim 10$ mm on the plasma axis).

To record the hard X-ray emission with energies up to 10 MeV, a spectrometer based on NaI(Tl) scintillation crystals with dimensions of $\varnothing 150 \times h 100$ mm$^3$ (BDEG2-39) and two spectrometers based on LaBr$_3$(Cs) scintillation crystals with dimensions of $\varnothing 38 \times h 38$ mm$^3$ (Canberra LABR-1.5 $\times$ 1.5) were used. Scintillation detectors were installed outside the vacuum vessel.

In addition to spectrometric diagnostics, standard monitors were used in the stream mode to measure hard X-ray emission (based on the NaI(Tl) scintillation crystal with dimensions of $\varnothing 25 \times 25$ mm$^3$) and neutron emission (gas discharge chamber SNM-11).

### 3. Observations of runaway electrons in the initial discharge stage in the T-10 tokamak

The generation of runaway electrons in tokamak plasma occurs in the presence of increased longitudinal electric fields [2, 4]. During plasma breakdown in the T-10 tokamak, the loop voltage can reach 20–40 V, which corresponds to the electric field strength of 2–4 V/m (length of the torus bypass is 10 m). The typical time evolution of the plasma parameters during the initial stage of the T-10 shots under different plasma conditions is presented in Figure 1.

![Figure 1. Time evolution of plasma parameters in the initial discharge stage of the T-10 tokamak.](image)

Figure 1 shows that, on several occasions, in the initial stages of the T-10 tokamak shots, bursts of hard X-ray emission occurred during a breakdown voltage pulse, which indicated the occurrence of runaway electrons. However, generation of the initial beam of runaway electrons (hard X-ray bursts) during the breakdown has no direct effect on the formation of runaway electrons during the shot. Preliminary analysis showed that the formation of beams during the initial discharge stage depends on the global plasma parameters and peculiarities of the plasma-wall interaction. In particular,
considerably fewer runaway electrons are generated (both during the breakdown and quasistationary stages) in experiments when the vacuum vessel walls are covered with lithium.

4. Effect of the electron density on runaway electrons acceleration during the initial stage of the T-10 tokamak shots

The effect of the electron density on the runaway electron acceleration during the initial stage of the T-10 shot is shown in Figure 2. With increasing electron density, the number of runaway electrons and their energies decrease. Radiation associated with runaway electrons appeared 5–9 ms after the gas breakdown began (see t > 109 ms in Figure 2d).

Figure 2. (a)–(d) Time evolution of plasma parameters and (e) X-ray emission spectra measured in the T-10 tokamak shots with different electron densities.

Figure 3 shows the time evolution of the plasma parameters and changes in the hard X-ray spectra of runaway electrons measured in shots with different densities. At high plasma densities, the discharge is accompanied by growing MHD perturbations and a subsequent thermal quench at t = 560 ms. The radiation spectrum (measured with the help of the scintillation spectrometers) can be approximated by two logarithmic dependencies. The first one corresponds to bremsstrahlung emission with energies up to E < 2 MeV which are generated by runaway electrons. The second slope (E > 2 MeV) corresponds to the interaction of neutrons with the detector.

Neutrons are detected in the T-10 shots due to two simultaneous processes: photodecomposition of deuterium and D-D (D-T) fusion reactions. The threshold energy for the decomposition reaction is ~2.2 MeV, which corresponds to the detected energies of hard X-rays and the corresponding energies of runaway electrons. However, neutron energies should be equal to the difference between the neutron and proton binding energies (2.2 MeV) and the gamma photon energy. Spectrum flattening occurs in the energy range of 2–8 MeV, which corresponds to a runaway electron energy of at least 10 MeV.
Figure 3. Time evolution of the plasma parameters and hard X-ray emission spectra measured in the stages of current growth and constant current.

5. Conclusions

Suprathermal and hard X-ray energy spectra were measured in the initial stage of the T-10 shots with different plasma densities, impurity concentrations, plasma temperatures, and longitudinal electric fields. In experiments at the T-10 tokamak, hard X-ray emission was detected at t ~ 10 ms after the initial plasma breakdown. The delay time between the appearance of hard X-ray emission and the beginning of breakdown depends on the surface conditions of the vacuum vessel wall and on the development of MHD perturbations.

The energies of fast electrons reached 1 MeV during the first 20 ms of the discharge. Subsequently, during the discharge, the highest electron energies increased even more up to ~2 MeV. When neutron radiation occurred, the spectrum measured by the scintillation detectors became flattened in the energy range of 2–8 MeV.

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