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Estimation of ISTTOK runaway-electrons energies by means of a Cherenkov-type probe with modified AlN radiators

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Abstract. Measurements of fast electrons, as performed during recent few years in small tokamaks, demonstrated that detectors based on the Cherenkov effect are very useful tools for such studies. The modernized measuring heads, which were equipped with miniature aluminum-nitride (AlN) radiators, enabled to determine locations and instants of the fast electrons emission and to estimate their energy. A comparison of four measuring channels showed that in ISTTOK the most important role was played by electrons of energy < 90 keV.

Key words: ISTTOK • runaway electrons • Cherenkov detector • AlN radiators

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Introduction

Several tokamak regimes are characterized by the appearance of runaway electrons which can potentially damage the machine. Therefore, diagnostics need to be developed in order to study the emission of these runaways and other supra-thermal electrons. Electrons in a tokamak, which gain energy higher than some critical value, can be continuously accelerated by the toroidal electric field, and can run away. Studies of the runaway electrons make it possible to collect important information about plasma behavior. In large tokamaks the runaway electrons can gain enormous energy to cause serious damages of the first wall. Runaway electrons generated during plasma disruptions have been investigated intensively in several machines, e.g. [1–8, 10, 13], and it was found that their number and maximum energy depend on plasma parameters and vary during the discharge. More studies in the field of runaway electron diagnostics were cited in previous papers [2, 4, 13] and especially in the paper [3], where the advantages of the Cherenkov detectors were also discussed.

In the ISTTOK tokamak, plasma is produced at high toroidal electric fields, and the runaway electrons can be recorded [2, 4, 10]. In the past the runaway generation regimes in the ISTTOK tokamak have been characterized in the frame of a conventional theory, using the interpretative modeling of the plasma power-energy balance and calculations of the runaway electron current [9]. The application of Cherenkov-type detectors for studies of fast electron beams within tokamaks was proposed several years ago [12]. The technique based on the Cherenkov effect (i.e. the emission of the intense radiation by fast electrons in appropriate radiators) ensures direct, spatially well defined and instantaneous (rise time < 1 ns) measurements of the fast electron beams. This technique was tested in previous studies, e.g. [2, 4, 13]. The main aim of recent studies was to investigate correlations of Cherenkov signals (induced by the runaway electrons) with hard X-rays (HXR) peaks from ISTTOK discharges.

Measuring techniques for fast electron beams and hard X-rays (HXR) studies

Detectors exploiting the Cherenkov effect have successfully been applied for investigation of electron beams within the CASTOR-tokamak in Prague [13] and ISTTOK-tokamak in Lisbon [4]. After preliminary measurements with single-channel Cherenkov-type detectors, in order to make an estimate of energy range of the generated electron beams possible, it was decided to construct a 4-channel probe with aluminum-nitride (AlN) crystals. These Cherenkov radiators were coated with molybdenum (Mo) layers of different thickness in order to eliminate visible radiation and to establish energy thresholds for the detected electrons. Preliminary results of such measurements were presented in a previous paper [2]. In a new version of the 4-channel probe – discussed in the paper – the use was made of modified AlN poly-crystals (more translucent) of 10 mm in diameter and 2.1 mm in thickness. These radiators were separated by thin stainless steel plates and pressed together (see Fig. 1) to improve the heat transfer, and to avoid heating up of the crystals.

Another improvement was the use of a new technique for the deposition of Mo-filters on the AlN radiator. In the newest probe those filters were deposited by electrical-arc discharges under high vacuum conditions. This technique increased the adhesion of the Mo-filters to the radiator surfaces. In the newest construction (see Fig. 1) the investigated electron streams could interact with tips of the radiators visible from one side only (i.e. the direction of incoming e-beams). The described measuring head was fixed upon a movable probe which made it possible to locate the radiators at different position along the ISTTOK minor radius. The Cherenkov radiation emitted by fast electrons, which penetrated Mo-filters and radiators, was transmitted

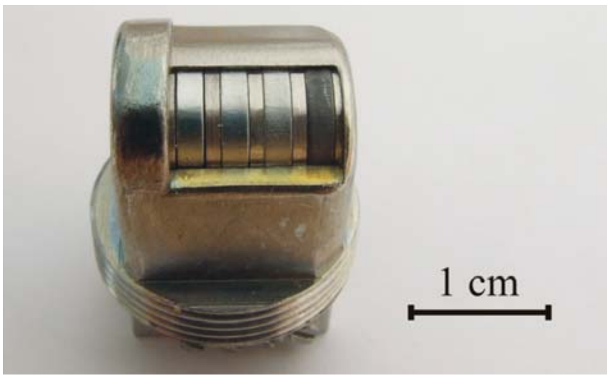

Fig. 1. Picture of the modified Cherenkov-type measuring head for fast electron studies.

through separate optical cables to fast photomultipliers of the Photonis XP-2020Q type, which ensured a signal amplification of about 10^7 and a wide spectral range of the photocatode. To improve the photomultiplier shielding against hard X-rays, a new box made of lead (Pb) blocks of 2 × 5 cm in thickness was applied.

In order to record hard X-rays (HXR) outside the ISTTOK chamber the use was made of two measuring heads equipped with NE102A plastic scintillation detectors of 1.5 cm in diameter and 1.5 cm in length. Light signals were transmitted through separate optical cables to photomultipliers of the XP1918 type, which were placed in another Pb-shielding box. The HXR detectors were placed outside the ISTTOK chamber, near the tokamak limiter, at a distance of 20 cm behind the 20 mm thick copper chamber wall. One measuring head was additionally shielded by a copper (Cu) plate of 10 mm in thickness. An analysis of differences in X-ray-induced signals from both the detectors made it possible to estimate HXR energies. Another set of HXR detectors was placed behind an ISTTOK quartz window of 3.3 mm in thickness, which enabled direct observation of radiation from the plasma column and the limiter. In that case the use was made of Cu-filters with a thicknesses from 0.2 to 2.4 mm. It enabled the measurements of softer X-rays. All the measuring channels were connected with a data acquisition system operating at a 2 MHz sampling rate.

Experimental results

In experiments reported here the Cherenkov head was placed in the ISTTOK equatorial plane, at a distance of about 20 cm toroidally from the graphite limiter. The data were collected from four Cherenkov radiators. The first radiator (CH1) had no filter, while the other ones (CH2, CH3 and CH4) were coated with Mo-layers of 8, 19 and 38 μm in thickness, respectively. The different channels should record electrons of energies higher than 66, 90, 117 and 158 keV, correspondingly. Before the Cherenkov probe installation within ISTTOK all the measuring channels (each consisting of the Mo-coated radiator, optical cable and photomultiplier with a supply unit) were tested at an electron accelerator, which could deliver electron beams of energy up to 6 MeV.

The investigated discharges in ISTTOK lasted 26 ms. The maximum current was ~ 4.5 kA, and the highest plasma density amounted to ~ 4×10^{18} m^{-3}. The electron-induced Cherenkov signals appeared usually after 10 and 18 ms, and amplitudes and length of the recorded signals depended on the discharge parameters. Cherenkov detectors signals reflected the presence of fast electron streams in the ISTTOK plasma. These fast electrons were the result of runaway generation process which, in the discussed series of measurements in ISTTOK, have been induced by a combination of plasma parameters (low densities, temperatures, Z_{eff} and high electric fields). In the discussed experiment such combinations appeared in the mentioned time ranges, meanwhile in other experiments the time ranges, when the fast electrons have been measured, were quite different. The fast electrons emission could be also connected with a high-energy tail of the distribution function. It is clear, however, that runaway electrons can escape from plasmas due to their natural drift and due to different plasma instabilities.

Measurements of electron beams

In order to compare experimental data, the electron signals were integrated over periods when the electron beams emission was recorded, i.e. over the periods between 8–12 ms and between 17–27 ms, which were denoted as regions I and II in a set of waveforms presented in Fig. 2.

The CH1, CH2 and CH3 signals from the Cherenkov detectors, as presented in Fig. 2, corresponded to electrons of energy equal to 66, 90 and 117 keV, respectively. It can be easily seen that the largest number of fast electrons was recorded by CH1 (the integrated values were $I_{\mathrm{I}} = 34.0$ and $I_{\mathrm{II}} = 252.7$), while the CH2 and CH3 channels recorded considerably lower electron numbers (where $I_{\mathrm{I}} = 4.6$ and 3.5, $I_{\mathrm{II}} = 39.6$ and 33.8, respectively). It means that the runaway emission from ISTTOK was dominated by electrons of energy below 90 keV. Runaway electron studies presented in Refs. [9, 10] have demonstrated that plasmas in the ISTTOK are characterized by very low energy threshold for the runaway generation (from 30–50 keV, depending on experimental conditions). On the other hand, small plasma sizes in ISTTOK are determining upper energy boundary, above which it is not possible to generate significant populations of runaway electrons due to their fast loss. It is evident that there were also some electron beams of higher energy, as it can be seen from small signals recorded in higher energy channels and HXR peaks. This conclusion was confirmed by the analysis of several dozens of ISTTOK discharges. The absence of signals in higher energy channels of Cherenkov detector signifies only that number of fast electrons with higher energies is not large enough to be recorded by means of the discussed detector.

Cherenkov detector seems to be insensitive to X-ray radiation since the Cherenkov signals diminish to the level equal nearly zero when the measuring head was removed from the plasma, and when the measuring head position was $r > 90$ mm (the limiter position). The only process which can affect discussed measurements is the detrimental influence of X-rays on photomultipliers. However, this effect was eliminated by an effective shielding of these units.

The obtained electron and X-ray signals are negative, because the –HV version of the photomultipliers dividers were applied. The electromagnetic disturbances were better prevent in such a case.

Measurements of hard X-rays (HXR)

The HXR pulses were measured by means of two sets of scintillation detectors placed outside the ISTTOK experimental chamber. The X-ray detectors measure the total radiation which were caused by interaction of electrons with limiters and detecting head inserted to the plasma. The first set was located outside the chamber, near the limiter (which was in the observation field), but the total X-ray radiation observation solid angle was relatively large. The second set was situated behind a quartz window, and it could observe the limiter surface through the whole plasma column. In the first diagnostic set the first detector used as a filter only the Cu-chamber wall of 20 mm in thickness, while the second detector was shielded additionally by a Cu-plate of 10 mm in thickness. The HXR signals from these detectors are presented in Fig. 2, as traces Xray1

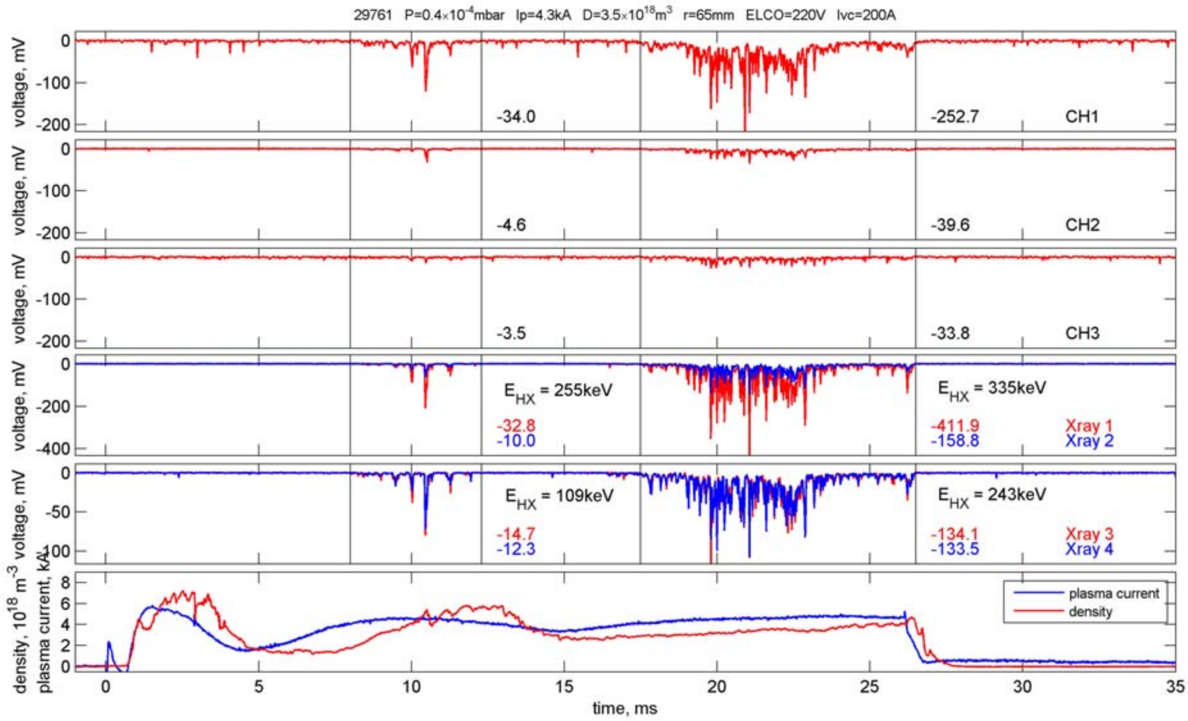

Fig. 2. Temporal changes of intensities of electron beams (traces CH1-CH3), and hard X-rays (traces Xray 1–4) in relation to the discharge current and plasma density (two bottom traces).

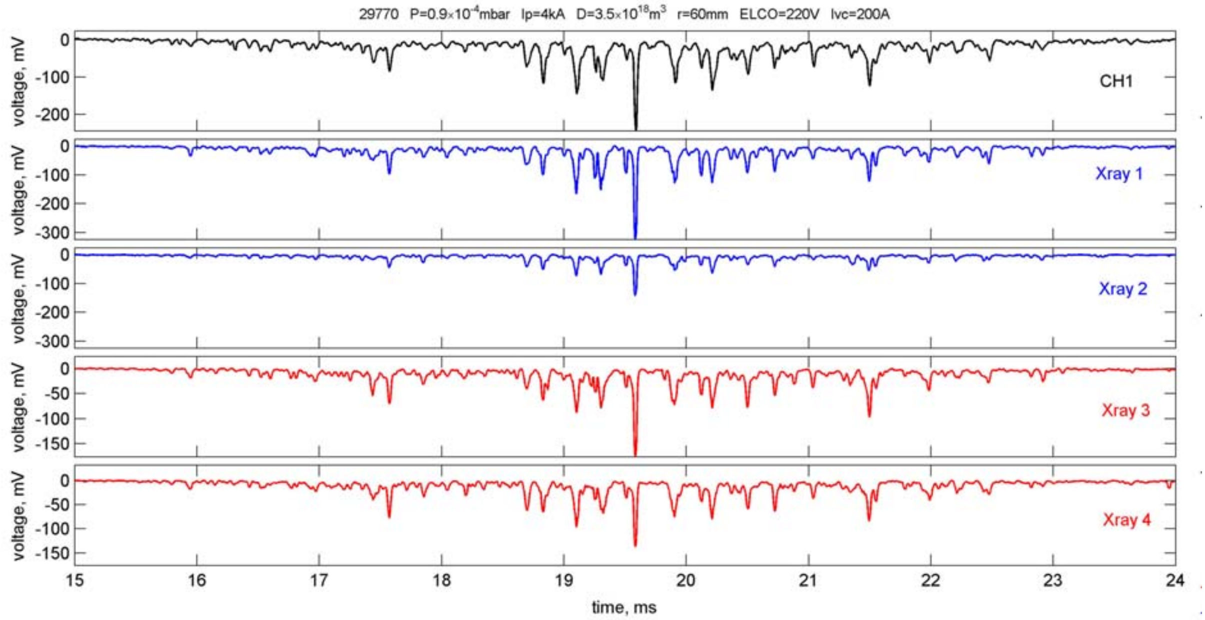

Fig. 3. Correlation of runaway electron signals (CH1) and HXR waveforms (traces 2–5 from top).

and Xray2, respectively. There were also computed the integrated values I, which in the first region (see above) amounted to 32.8 and 10.0, while in the second region – 411.9 and 158.8. Since, the analyzed signals were recorded behind different Cu-layers (20 and 30 mm, respectively), it was possible to compute the absorption coefficient. It was determined from the simple relation $\mu(E) = \ln(I_1/I_2)/\rho(d_2 - d_1)$, where ρ is the Cu density, d_2 and d_1 are the thicknesses of the applied Cu filters. The obtained $\mu(E)$ corresponded to HXR of energy equal to about 255 keV in the first region and to 335 keV in the second one. These energy values corresponded to a high-energy tail of the Maxwellian distribution of the X-ray emission.

To record X-rays of lower energies the use was made of a second set of scintillation detectors mentioned above, which were equipped with thinner Cu-filters of 0.2 and 2.4 mm in thickness. Those detectors were located (behind a quartz window) at a distance of about 1.5 m from the limiter and were oriented at an angle of 120° to the detectors of the first set. The use of thinner filters made it possible to record X-rays of energies equal to 109 keV in the first region and 243 keV in the second one, in agreement with results of another work [11].

It should be noted that temporal waveforms of the electron- and HXR-signals are very similar, as one can see from time-extended traces presented in Fig. 3.

A comparison of the electron-induced signals (particularly from the CH1 channel) with HXR signals (from both sets of scintillation detectors) showed good temporal correlation and evident proportionality of these signals. One could also notice good correlations of the HXR signals obtained from the first and second set of the detectors, what suggested isotropic character of the X-ray emission. Another evidence of the correlations between electron and HXR signals was delivered by a diagram presenting a dependence of amplitudes of CH1 and Xray1 signals, which is shown in Fig. 4.

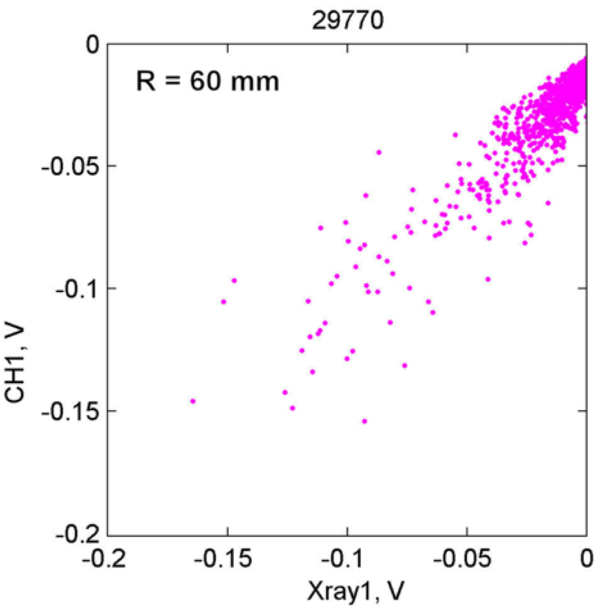

Fig. 4. Correlation of CH1 and Xray1 signals.

The similarity of the considered signals and their good temporal correlations suggested that the HXR was generated by interactions of the fast electron beams with the tokamak chamber elements.

Summary and conclusions

The most important results of this study can be summarized as follows: 1) Signals induced by the visible radiation of plasma in the AlN radiator without any filter might be neglected, and small holes (or cracks) in Mo-filters (applied on the other radiators) did not disturb the recorded signals considerably. 2) In the described ISTTOK experiments the dominant role was played by electrons of energy < 90 keV, but electrons of higher energy were also detected. 3) The electron-induced Cherenkov signals and HXR signals were well correlated and mutually proportional, and the HXR was generated by the fast electrons during their interactions with the limiter and tokamak walls as it was expected.

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