STUDIES OF RUN-AWAY ELECTRON BEAMS AND HARD X-RAY EMISSION IN ISTTOK TOKAMAK

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The paper describes measurements of fast run-away electron beams emitted from a plasma torus in the ISTTOK tokamak, which were performed by means of a new Cherenkov-type detector equipped with four radiators made of aluminium-nitrate (AlN) crystals of 10 mm in diameter and 2.5 mm in thickness each. The measuring head was fixed to a movable support, which enabled the radiators to be placed in chosen positions along the minor radius of ISTTOK. The radiators were coated with molybdenum (Mo) layers of different thicknesses since the main aim of this study was to estimate an energy spectrum of the recorded electrons. Attention was also paid to measurements of hard X-rays emitted from ISTTOK and to their correlations with run-away electrons. The investigated correlations showed that the both emissions are strongly coupled.

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1. INTRODUCTION

In tokamaks a discharge current within a ring-shaped experimental chamber is driven initially by an externally induced electrical field. Such a field can also lead to the generation of so-called “runaway electrons” [1] if the friction force (from collisions) is not compensated by the accelerating electrical force. The runaway electrons can influence the plasma behavior since they can carry a substantial part of the plasma current. They are practically collision-less, but losses of highly energetic runaway electrons can cause heavy damages of internal walls in fusion facilities. Therefore, the run-away electrons have been studied in different tokamaks for many years with various techniques. To measure run-away electrons directly the IPJ team developed detectors using the Cherenkov-effect in specially chosen radiators [2]. A Polish-Portuguese team applied a Cherenkov detector in the ISTTOK facility to detect energetic electrons (of energy > 60 keV) and to determine their spatial and temporal behaviour [3], but information delivered by a single-channel detector was very limited.

The main aim of the recent experimental studies within ISTTOK was to investigate the emission of fast electrons in more details by means of a four-channel Cherenkov measuring head.

2. DIAGNOSTICS OF ELECTRON BEAMS AND HARD X-RAYS

The previous measurements of run-away electrons in ISTTOK have been performed by means of a measuring head equipped with four separate Cherenkov radiators [4]. The detectors were made of aluminium-nitrade (AlN) poly-crystals of 10 mm in diameter and 1.0 mm in thickness. They were separated by stainless-steel plates and pressed together to improve a heat transfer. The investigated electron streams interacted only with parts of the detectors sides, which were coated with molybdenum (Mo) layers of different thicknesses in order to determine the chosen energy thresholds. The Cherenkov radiation emitted by fast electrons (penetrating the radiators) was transmitted through four separate optical cables to fast photomultipliers of the Photonis XP-1918 type. An analysis of the collected experimental data showed that the recorded electron-induced signals were too low to ensure an appropriate signal-to-noise ratio. During the measurements within ISTTOK it was observed that some parts of the Mo-filters upon the radiators were destroyed (by plasma discharges) and the shielding of the photomultipliers against hard X-rays was found to be unsatisfactory. Therefore, a new version of the four-channel measuring head was designed and manufactured (Fig. 1).

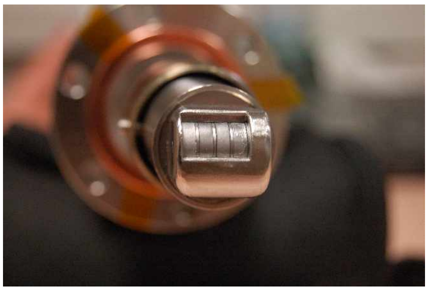

Fig. 1. New measuring head equipped with four Cherenkov radiators coated with Mo-filters

In the new measuring head the use was made of four AlN crystals of 10 mm in diameter and 2.5 mm in thickness. The increased thickness and orientation of the radiators sides along electron trajectories made possible to achieve almost 10-times larger effective detection surface. During the recent experiments the detection of the Cherenkov signals was performed by means of new photomultipliers of the XP2010Q type, which ensured the signal amplification equal to about 10^7. Those changes made possible to obtain electron-induced signals, which were about 2 orders of magnitude higher than those in the previous measurements. To improve the photomultiplier shielding against X-rays there was applied a new box made of lead (Pb) blocks of 5.0 cm in thickness. Another improvement was the application of the radiators with Mo-filters deposited by electrical-arc discharges under high vacuum conditions. It increased the adhesion of the

Mo-filters to the radiator surfaces. The new measuring head was fixed upon a movable probe which made possible to locate the radiators at different position along the ISTTOK minor radius.

To record hard X-rays (HXR) outside the ISTTOK chamber the use was made of two measuring heads equipped with NE102A plastic scintillators of 2.0 cm in diameter and 1.5 cm in length. Light signals were transmitted trough separate optical cables to XP1918 photomultipliers placed in another Pb box. The HXR detectors were placed near the ISTTOK limiter, at a distance of 20 cm behind the 20-mm-thick copper chamber wall. One measuring head was additionally shielded by a copper plate of 10 mm in thickness. An analysis of differences in X-ray-induced signals from the both detectors made possible to estimate HXR energies. All the measuring channels were connected with a data acquisition system with a 2 MHz probing.

3. EXPERIMENTAL RESULTS

The new measuring head was placed in the ISTTOK equatorial plane, at a distance of about 20 cm from the graphite limiter. The data were collected from four Cherenkov radiators, which were coated with Mo-layers of 4 (CH1), 19 (CH2), 38 (CH3) and 60 μm (CH4) in thickness. Hence, the different channels should record electrons of energies higher than 78, 117, 158 and 198 keV, respectively. Before the probe installation in 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 delivered electron beams of energy up to 6 MeV. Unfortunately, the test electron beam destroyed partially the CH_4 channel, which could not be used in further measurements, but three measuring channels were tested successfully.

During the experiments within ISTTOK the active measuring channels could record electrons of energies higher than about 80 (CH1), 120 (CH2) and 160 keV (CH3), as shown in Fig. 2.

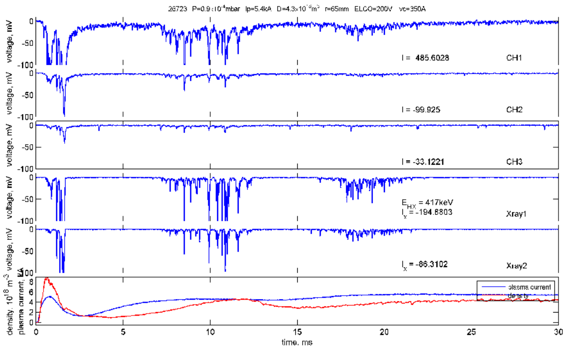

Fig. 2. Comparison of electron-induced signals (CH1, CH2 and CH3), hard X-rays (Xray1 and X-ray2) with discharge current and plasma density traces

It should be noted that the three Cherenkov channels recorded electron beams inside ISTTOK, while the fourth HXR channel recorded the high-energy X-ray emission (behind 20-mm-thick ISTTOK Cu-wall), and the fifth one recorded still harder X-rays (penetrating the ISTTOK wall and 10-mm-thick Cu-shield). The discharges lasted about 30 ms. The maximum discharge current was about 9.5 kA, and the highest plasma density amounted to about 4×10^{18} m^{-3}. One can easily notice that electron signals appeared usually after 2 ms (during the acceleration phase) and during plasma density disturbances after 10 and 18 ms. Amplitudes and length of the recorded electron-induced signals depended on discharge parameters.

To compare the experimental data one can use signals values integrated over the whole discharge period (I), as given in Fig. 2. It can be easily seen that the largest number of fast electrons was recorded in the CH1 (I = 530), while the CH2 and CH3 recorded considerably lower electron numbers (I = 104 and 34, respectively). These differences are even stronger when one compares signals without those from the acceleration phase. It means that in the run-away emission from ISTTOK is dominated by electrons of energy below 120 keV.

Examples of HXR signals, which were obtained from the X-ray measuring heads described above, have also been presented in Fig. 2. In that case the integrated values were I = 201 and 87.7, correspondingly. Since, the signals were recorded behind different Cu-layers (20 and 30 mm, respectively), it was possible to compute the absorption coefficient, which might be determined from the simple relation $\mu(E) = ln\ (I_1/I_2)/\rho(d_2-d_1)$, where ρ is the copper density, d_2 and d_1 are thicknesses of the applied copper filters. The obtained $\mu(E)$ corresponded to X-rays of energy equal to about 400 keV. That energy value characterized X-rays measured behind thick Cu-filters and corresponded to a high-energy tail of the Maxwellian distribution of the X-ray emission.

It should be noted that temporal shapes of the electron-induced and X-ray signals were very similar, what was confirmed by a comparison of time-extended traces. Similarity of these signals and their good temporal correlations suggested that HXR was probably generated by interactions of the fast electron beams with the limiter and chamber walls.

Investigation of the run-away electrons within ISTTOK was performed by means of the new Cherenkov measuring head at different positions on the minor radius of the experimental chamber. Those measurements were carried out under different experimental conditions, e.g. at various initial pressures. The obtained results were very similar to those recorded for $p_0 = 0.9 \times 10^{-4}$ mbar, which are shown in Fig. 3.

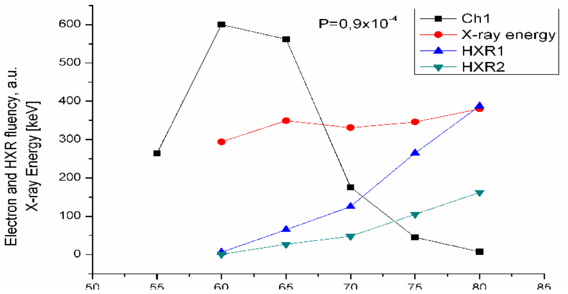

Fig. 3. Fluency of fast electrons (CH1) and X-rays (a.u.) determined as a function of the Cherenkov probe position. For a comparison there are shown changes in X-ray energies (X-ray-en)

The diagram showed the maximum electron fluency at r = 60…65 mm, but one should note that the deeper insertion of the probe disturbed the plasma column. The HXR1 and HXR2 signals became weaker when the probe was shifted into the plasma region. In contrary, changes in the HXR energy value showed a weak dependence on the Cherenkov probe position. In the presented case the computed HXR energy changed from about 300 to about 400 keV. It should be added that the maximum fast-electron fluency, which was investigated as a function of the initial pressure p_0 at the constant probe position at r = 65 mm, was observed at $p_o = 1.0\times10^{-4}$ mbar. The same referred to the HXR emission.

On the basis of the measurements described above it was possible to estimate energy spectra of the runaway electrons, as shown in Fig. 4.

It can be easily seen that the largest population of the fast electrons has energies below 120 keV.

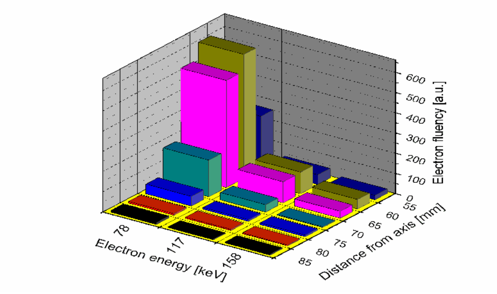

Fig. 4. Electron energy spectra estimated for different positions of the Cherenkov measuring head

4. SUMMARY AND CONCLUSIONS

Although the Mo-filters on the Cherenkov radiators have been partly destroyed during a series of ISTTOK shots, the qualitative estimations of the measurements seem to be reasonable. The use of the modernized Cherenkov measuring head (with thicker AlN radiators) and improved detection systems in ISTTOK enabled new data about run-away electrons to be collected. It was found that: 1 - the most run-away electrons have energies below 120 keV, 2 – electron populations in higher energy ranges is considerably smaller, 3 - the HXR radiation outside the tokamak chamber has energy in the range of 300…400 keV. This radiation is well correlated with the run-away emission, it is probably produced by interactions of the fast electrons with the limiter and the chamber walls, and it evidently corresponds to the high-energy tail of the energy distribution. The maximum emission of the run-away electrons (as well as HXR) appears at $p_0 = 1.0\times10^{-4}$ mbar. A dependence of the run-away production on other ISTTOK parameters requires further investigation.

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ИССЛЕДОВАНИЯ УБЕГАЮЩИХ ЭЛЕКТРОННЫХ ПУЧКОВ И ЖЕСТКОГО РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ В ТОКАМАКЕ ISTTOK

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Описываются измерения быстрых убегающих электронных пучков, испускаемых из плазменного тора в токамаке ISTTOK, которые были выполнены с помощью новых черенковских детекторов, оснащенных четырьмя радиаторами из нитратаалюминия (AlN) с кристаллами диаметром 10 и толщиной 2,5 мм каждый. Измерительная головка была установлена на подвижном основании, что позволило размещать радиаторы в выбранных позициях по малому радиусу ISTTOK. Радиаторы были покрыты молибденовыми (Mo) слоями различной толщины, поскольку основной целью данного исследования было оценить энергетический спектр регистрируемых электронов. Внимание было также уделено измерению жесткого рентгеновского излучения из ISTTOK и его корреляции с убегающими электронами. Исследованные корреляции показали, что оба излучения сильно связаны.

ДОСЛІДЖЕННЯ ВТІКАЮЧИХ ЕЛЕКТРОННИХ ПУЧКІВ І ЖОРСТКОГО РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ У ТОКАМАЦІ ISTTOK

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Описано виміри швидких втікаючих електронних пучків, що випускаються з плазмового тора в токомаці ISTTOK, що було виконано за допомогою нових черенковських детекторів, оснащених чотирма радіаторами з нітратуалюмінію (AlN) із кристалами діаметром 10 і товщиною 2,5 мм кожний. Вимірювальна голівка була встановлена на рухливій підставі, що дозволило розміщати радіатори в обраних позиціях по малому радіусі ISTTOK. Радіатори були покриті молібденовими (Mo) шарами різної товщини, оскільки основною метою даного дослідження було оцінити енергетичний спектр електронів, що реєструються. Увага була також приділена виміру твердого рентгенівського випромінювання з ISTTOK і його кореляції з втікаючими електронами. Досліджені кореляції показали, що обоє випромінювання сильно зв'язані.