DEVELOPMENT AND USE OF CHERENKOV-TYPE DETECTORS FOR MEASUREMENTS OF FAST ELECTRONS IN TOKAMAKS

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The paper reports on progress in design and use of novel detectors for experimental studies of fast (run-away and ripple-born) electrons in various experiments of the tokamak type. The idea of the use of a Cherenkov effect for direct on-line measurements of the fast electrons within tokamaks was presented by scientists from the NCBJ (former IPJ) several years ago. Successive efforts led to the development of prototype detector heads equipped with diamond or aluminium nitrate (AlN) crystals, which were shielded with very thin metal filters in order to eliminate the visible light from plasma and to enable a rough energy analysis of electrons. Those Cherenkov radiators were coupled through optical-fibre cables with fast photomultipliers. Those prototypes were applied for test measurements within the CASTOR experiment in Prague, and later in the ISSTOK device in Lisbon, but the main aim remained to develop the Cherenkov detectors for the TORE-SUPRA experiment in Cadarache.
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INTRODUCTION

High-temperature plasmas in tokamaks and stellarators usually contain large populations of high-energy electrons and ions. Determination of their parameters is indispensable part of plasma fusion studies. The NCBJ team, operating in a frame of the Association EURATOM/IPPLM, proposed Cherenkov-type probes for measurements of fast electrons within tokamaks because of their high spatial- and temporal-resolutions.

The Cherenkov radiation is emitted by a charged particle moving through a transparent medium with a velocity higher than the phase velocity of light in this medium. Emitted energy increases with an increase in a particle velocity and it is larger for a medium with a larger refraction coefficient. From a comparison of refraction index values and corresponding minimal energy values for different materials one can conclude that to record electron beams of lower energy it is necessary to use radiators made of diamond or rutile crystals.

The developed method enables the identification of electron beams, the determination of their spatial distribution, as well as the measurements of their temporal characteristics. Research on the time-correlations of the obtained data with the other phenomena within tokamaks, e.g. with the generation of X-ray pulses, the emission of neutrons and energetic ion beams, etc., are of primary importance for the verification of different theoretical models and for solving the plasma engineering problems.

The Cherenkov-type detector was applied for the first time in the CASTOR experiment in Prague [1-2]. On the basis of this experiment the Cherenkov probe was also manufactured and applied in the TORE-SUPRA facility. The results obtained during this experiment justified decision to continue the development of such probes in order to enable multi-channel measurements and more accurate estimates of electron energies.

1. EXPERIMENTAL RESULTS

1.1 ISSTOK TOKAMAK

Several detectors exploiting the Cherenkov effect were successfully applied for the investigation of electron beams within the CASTOR in Prague and ISTTOK in Lisbon some time ago. After preliminary measurements, which were performed by means of single-channel Cherenkov-type detectors, in order to make it possible an estimate of the energy range of the generated electron beams it was decided to construct a 4-channel probe with aluminium-nitride (AlN) crystals. Those Cherenkov radiators were coated with molybdenum (Mo) layers of different thickness in order to eliminate the visible radiation and to establish energy thresholds for the detected electrons.

In a new 2011 version of the 4-channel probe the use was made of modified AlN poly-crystals of 10 mm in diameter and 2.1 mm in thickness. Those radiators were separated by thin stainless-steel plates and pressed together to improve a heat transfer. Another improvement was the use of a new technique for the deposition of the Mo-filters on the AlN radiators. In the newest probe those filters were deposited by electrical-arc discharges under high vacuum conditions. This technique increased the adhesion of the Mo-layers to the radiator surfaces. The Cherenkov radiation emitted by fast electrons, which penetrated Mo-filters and radiators, was transmitted through separate optical cables to fast photomultipliers. To improve the photomultiplier shielding against hard X-rays, there was applied a box made of lead (Pb) blocks of 10 cm in thickness.

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 trough separate optical cables to photomultipliers, which were placed in another Pb-shielding box.

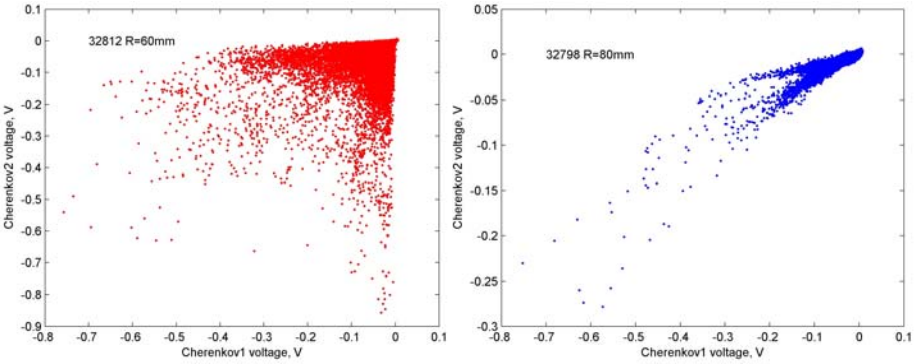

Fig.1. Correlation between Cherenkov signals in both channels in the ISTOK measurements at a distance of 60 mm (close to bulk plasma) and close to the limiter (R=80 mm).

In the ISTTOK experiment the Cherenkov head was placed in the equatorial plane, at a distance of about 20 cm from the graphite limiter. The data were collected from four Cherenkov radiators, and the different channels could record electrons of energies higher than 66 keV, 90 keV, 117 keV and 158 keV, correspondingly. Before the Cherenkov probe installation within the ISTTOK all the measuring channels were tested with an electron accelerator, which could deliver electron beams of energy up to 6 MeV.

The investigated discharges in the ISTTOK lasted about 26 ms. The maximum current was about 4.5 kA, and the highest plasma density amounted to about 4x 10^{18} m^{-3}. The electron-induced Cherenkov signals appeared usually after 10 ms and 18 ms, and amplitudes and length of the recorded signals depended on discharge parameters noticeably.

New test measurement in the ISSTOK have showed that that majority of fast electrons has energy < 90 keV. Correlations of such electrons with hard X-ray signals (measured simultaneously with X-ray probes) have also been investigated.

Measurements carried out within the ISTTOK facility in Lisbon [3-4] confirmed experimentally the emission of the run-away electrons at determined operational parameters. Since one of the most important characteristics is the electron energy distribution, the main aim of this study was to perform some estimations of an energy spectrum of the recorded electrons. Also important were measurements of hard X-rays emitted from ISTTOK discharges and a search for their correlation with run-away electrons, because previous studies of the fast electrons were based mainly on measurements of the hard X-ray emission.

The most interesting result obtained with two diamond radiators without molybdenum layers is presented in Fig. 1. Correlations between Cherenkov signals in both channels proved that electron beams in the neighbourhood of bulk plasma has chaotic character, while in the neighbourhood of a limiter electron beams are wider and/or they reach diamond detectors of the measuring head at an obtuse angle.

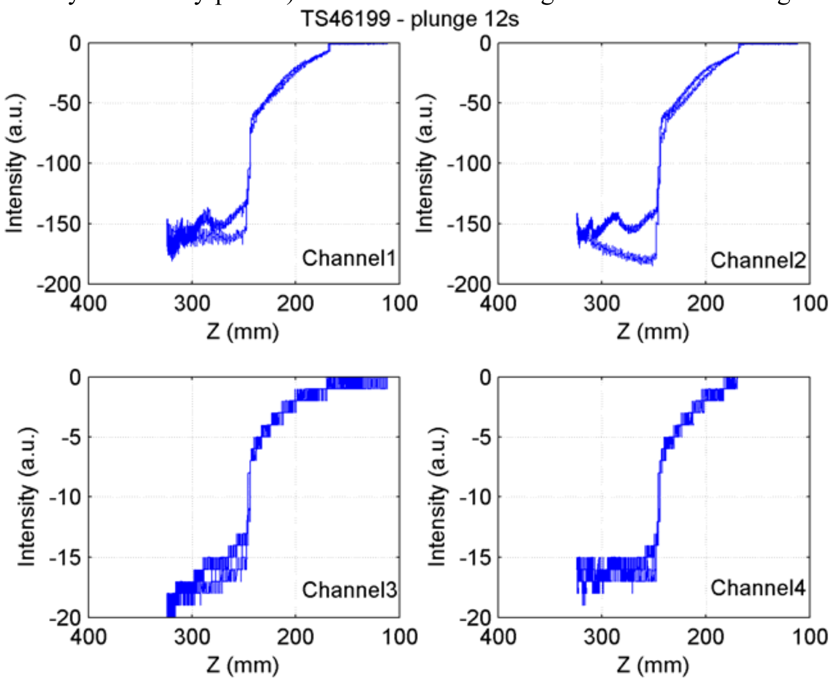

Fig.2. Signals, as obtained from all the channels of the Cherenkov probe at the instant t = 12 seconds (during the second insertion of the probe) for the toroidal magnetic field B_T = 3.75 T, discharge current I_p=1.2 MA, bulk plasma electron density $n_e(0)$ = 4.3x10^{19} m^{-3}, bulk plasma electron temperature $T_e(0)$=2.4 keV, LH power P_{LH} = 0.8MW, and presented as a function of the probe position. The minimum energy of electrons, which could be recorded by different channels was equal to 77 keV for CH1, 116 keV for CH2, 153 keV for CH3 and 195 for CH4.

1.2 TORE-SUPRA TOKAMAK

As regard the electron measurements planned within the TORE-SUPRA facility, in 2011 the new measuring head (a so-called DENEPR-3 probe) was designed and manufactured at the NCBJ. The construction of this head made it possible to perform calibration measurements outside the tokamak chamber, without any changes of optical contacts in all measuring channels.

Particular attention was paid to the presentation of amplitudes of the Cherenkov signals as a function of the probe position. An example of the analysis of signals from the Cherenkov detectors is presented in Fig. 2.

Another new Cherenkov probe has been designed and manufactured for TORE-SUPRA experiments. Some preliminary measurements have shown that in the scrape-off-layer region there appear many electron beams of energy < 150 keV. In order to calibrate this probe a small electron accelerator has been constructed and used. The electron-induced signals from calibration measurements enable now more accurate estimation of electron energy in tokamak experiments to be carried out. The main issues of the Cherenkov measurements performed so far have been summarized and discussed.

CONCLUSIONS

As regards the ISTTOK experiments one can conclude that the dominant role was played by electrons of energy < 90 keV, but some electrons of higher energy were also detected. Electron beams in the neighbourhood of bulk plasma has chaotic character, while in the neighbourhood of limiter are wider and/or they reach detectors at obtuse angles.

Results from the TORE-SUPRA experiments proved that the Cherenkov detectors can be useful for studies of fast electrons in large tokamaks.

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РАЗРАБОТКА И ИСПОЛЬЗОВАНИЯ ДЕТЕКТОРОВ ЧЕРЕНКОВА ДЛЯ ИЗМЕРЕНИЯ БЫСТРЫХ ЭЛЕКТРОНОВ В ТОКАМАКЕ

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В этой статье представлен прогресс в разработке и использовании новаторских детекторов для экспериментального исследования быстрых (убегающих и генерируемых на неоднородностях) электронов в различных экспериментах на токамаке. Идея использования эффекта Черенкова для прямых измерений быстрых электронов в режиме реального времени в токамаке был представлен учеными из НЦЯП (бывший ИЯП) несколько лет назад. Последовательные усилия привели к разработке прототипа детекторных головок оснащенного кристаллами алмаза или нитрата алюминия (AlN), которые были покрыты очень тонкими металлическими фильтрами для исключения влияния видимого света из плазмы и позволяющими грубо оценить энергию электронов. Эти счетчики Черенкова были соединены через волоконно-оптические кабели с быстрыми ФЭУ. Эти прототипы были применены для тестовых измерений в экспериментах на CASTOR в Праге, а затем в Лиссабоне на установке ISSTOK, но главной целью остается разработка детекторов Черенкова для экспериментов на Tore-Supra в Кадараше**.**

РОЗРОБКА І ВИКОРИСТАННЯ ДЕТЕКТОРІВ ЧЕРЕНКОВА ДЛЯ ВИМІРЮВАННЯ ШВИДКИХ ЕЛЕКТРОНІВ В ТОКАМАЦІ

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У цій статті йдеться про прогрес у розробці та використанні новаторських детекторів для експериментального дослідження швидких (утеклих і тих., що генеруються на неоднорідностях) електронів в різних експериментах на токамаці. Ідея використання ефекту Черенкова для прямих вимірювань швидких електронів в режимі реального часу в токамаке був представлений вченими з НЦЯП (колишній ІЯП) кілька років тому. Послідовні зусилля привели до розробки прототипу детекторних головок оснащеного кристалами алмазу або нітрату алюмінію (AlN), які були покриті дуже тонкими металевими фільтрами для виключення впливу видимого світла з плазми і дозволяють грубо оцінити енергію електронів. Ці лічильники Черенкова були з'єднані через волоконно-оптичні кабелі з швидкими ФЕУ. Ці прототипи були застосовані для тестових вимірювань в експериментах на CASTOR в Празі, а потім в Лісабоні на установці ISSTOK, але головною метою залишається розробка детекторів Черенкова для експериментів на Tore-Supra в Кадараші.