PROGRESS IN DEVELOPMENT AND APPLICATIONS OF CHERENKOV-TYPE DETECTORS FOR FAST ELECTRON STUDIES IN TOKAMAKS

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The paper presents advance in a new method developed in the Institute for Nuclear Studies (IPJ) for direct detection of high-energy (super-thermal, runaway) electrons generated in tokamaks. The technique in question is based on registration of the Cherenkov radiation, emitted by energetic electrons, moving through a transparent medium (radiator body) with a velocity higher than the velocity of light in this material. The main aim of the presented studies was to develop a diagnostic technique applicable for investigation of fast electron beams within magnetic confinement fusion (MCF) facilities.

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1. INTRODUCTION

High-temperature plasmas in tokamaks and stellarators usually contain and emit many high-energy electrons and ions. Determination of their parameters is indispensable part of plasma fusion studies. The IPJ team, operating within a frame of the Association EURATOM/IPPLM, proposed to use Cherenkov-type probes for measurements of fast electrons escaping from 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 rutil 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.

2. MEASUREMENT HEAD DESIGN

The realization of the Cherenkov-type diagnoctics described above induces, however, some serious problems. First of all the detector must be shielded by an appropriate absorption filter protecting the radiator against the plasma. One should note that the heat loads of about 5 MW/m^2 is deposited mainly in the radiator surface layer of a few hundreds micrometers in the thickness (determined by the electron range in the radiator material). The deposited heat must be dissipated as quickly as possible in order to eliminate local destructions of the radiator material. Thus, the main problem is an effective heat transfer through the radiator and a shielding body, the formation of an appropriate heat sink as well as keeping temperatures of the radiator and its shield below the admissible values. The electron-induced intense heat flux induces the use of materials resistant to high temperature, the application of materials having high thermal conductivity, and the performance of all measurements during a relatively short time.

Another problem is connected with an energy spectrum of fast electrons, and particularly with its lower limit. Because of a threshold character of the Cherenkov phenomenon, the detection of electrons of energy equal to about 50 keV requires the application of a radiator characterized by a relatively high refractive index, e.g. diamond or aluminium nitride (AlN) crystal.

It was also decided to split the whole electron energy spectrum into four energy channels. Each channel should have the lower energy threshold determined by a thickness of the applied absorption foil filter, which should be placed in front of the radiator. Molybdenum (Mo) was chosen as the absorption filter material, due to its high melting temperature and resistance to the sputtering.

Computations of a heat transport and temperature distributions inside the Mo filters, diamond radiators and shielding body were performed, and different constructions of the Cherenkov detector head were considered. Results of the numerical simulations showed that the lowest temperatures values can be achieved with the filter deposited directly upon the diamond surface, when the radiator is connected directly with the shielding body (forming a heat sink). It was also decided that such measurements should be carried out several times during a single tokamak discharge, and the Cherenkov detector should be introduced into a region of electron fluxes for a short period only.

On the basis of the feasibility studies [1] some prototypes of the one- and four-channel measuring head have been designed, constructed and tested within several small, medium and large devices. In particular, the measurements have been performed within the CASTOR, ISTTOK and TORE-SUPRA tokamaks.

3. EXPERIMENTAL RESULTS

3.1. CASTOR TOKAMAK

Preparing the use of Cherenkov detections in the large-scale tokamaks, IPJ team designed and used prototype detector within the CASTOR facility in Prague

(Czech Republic). The experimental data were collected from about 500 ohmically heated discharges, each lasting about 25 ms. After the first series of experiments carried out in autumn 2006 a modified version of detection system was constructed and used for diagnostics.

The analysis of results showed that character of the Cherenkov detector signals depends strongly on the detector radial position as well as on the plasma density. It was also observed that after t = 25 ms, when the transformer primary winding was short-circuited, a strong increase in signal intensity appeared as a result of the plasma column destruction [2-3].

3.2. ISTTOK TOKAMAK

Fig. 1 presents a general view of Cherenkov-type detector designed and manufactured on the basis of the ISTTOK plasma probe console. Detector itself consists of a measuring head equipped with a 5-mm in diameter input window, positioned at an angle of 45^0 in relation to the vacuum chamber axis. It was connected optically, through a well-polished inner surface and thin-wall metal tube, with an optical fiber cable. High-energy electrons penetrating through the windowed AlN crystal with a titanium coating caused the Cherenkov radiation emission. The 10-µm-titanium coating layer served as a filter for energetic electrons increasing the measuring energy threshold.

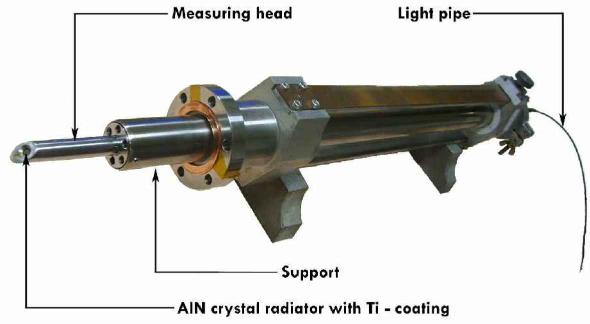

Fig. 1. Movable support with the Cherenkov-type detector used for measurements of fast electrons in ISTTOK

System described above allowed the detection of fast electrons with energy of about 80 keV. A movable support has made possible the detection of fast electrons in different radial positions with the deepest measuring position at the radius of 52 mm, where the detector still did not disturb the bulk plasma considerably.

The studies of the fast electron emission as a function of the Cherenkov probe positioning along the minor radius showed the distinct maximum for r = 6,5 cm. The measurements of HXR, as performed outside the tokamak chamber, showed a relatively intense radiation for the Cherenkov probe positioning within the radial region of r = 6,5…9,0 cm. The HXR emission originated probably from the fast electrons Bremsstrahlung in the limiter and metal walls of the tokamak facility [4-5].

3.3. TORE-SUPRA TOKAMAK

Interesting results and valuable experience gained from the experiments described above enabled the Cherenkov detectors in the larger-scale TORE-SUPRA experiment to be used. A scheme of the designed four-channel Cherenkov-type detection head is presented in Fig. 2.

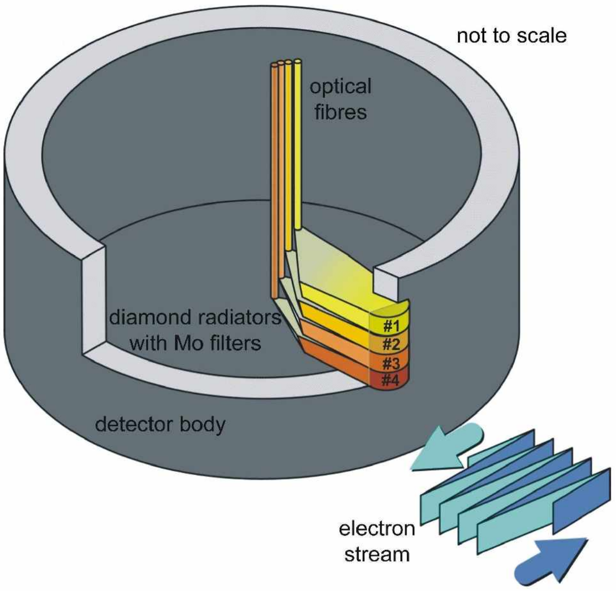

Fig. 2. Four-channel measuring head for TORE-SUPRA experiment; the spatial arrangement of diamond radiators (with metal coatings) and separate optical fibres [6]

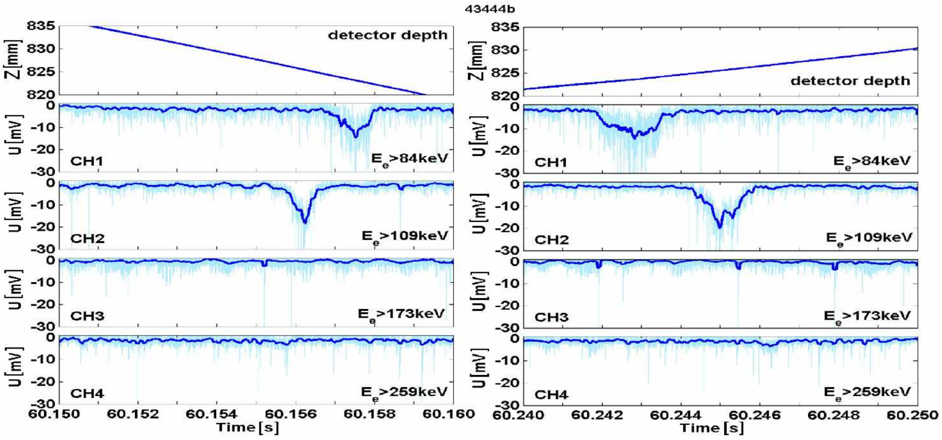

Fig.3. Examples of the results obtained within TORE-SUPRA tokamak [6]: changes in the vertical position of the Cherenkov head and electron-induced signals from four measuring channels during the inward motion of the probe (on left), and during the outward motion (on right)

Diamond crystals have been selected as radiator material because of a relatively low value of the energy threshold 51 keV and high thermal conductivity (five times better than copper). The special shape of a diamond radiator cut was worked out to create an optical coupling with the appropriate light pipe. All the radiator surfaces were well polished and metal coated, except for a corner part to be used for the coupling with an optical fibre. Only the front part of the radiator was exposed to fast electron streams. Therefore, the front surface of diamond radiators was coated with the thin molybdenum layer, constituting the light-tight protection and absorption filter. The shape and dimensions of the radiator were chosen taking into consideration geometrical requirements and thermal conduction efficiency.

The example experimental results, which were obtained with the help of the Cherenkov-type measuring head, is presented in Fig. 3. The recorded electron-induced signals confirm the appearance of a thin fast electron sheath of 1…2 mm in thickness.

CONCLUSIONS

The applications of the presented diagnostics have proved the usefulness of the one- and four-channel versions of the detecting head for fast electron studies in tokamaks.

The most important results, as obtained with the described Cherenkov-type diagnostics, have proved that the one- and four-channel versions of the detecting head can easily be applied for studies of the fast (ripple-born and runaway) electrons in different experiments. An adaptation of the described solutions to other MCF facilities is possible, and experience collected during the studies allows to introduce some changes in the radiator configuration and to modify the Cherenkov probe design. In general, the use of diamond radiators seem to be the best solution for measurements of electrons above about 60 keV, taking into account necessity to use a thin light-tight Mo filter. For measurements of electrons of considerably higher energy, one should take into account different absorption filters, but they must withstand high thermal loads during measurements, and their adhesion to the radiators should be satisfactory all the time.

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ПРОГРЕСС В РАЗРАБОТКЕ И ПРИМЕНЕНИИ ЧЕРЕНКОВСКИХ ДЕТЕКТОРОВ ДЛЯ ИЗУЧЕНИЯ БЫСТРЫХ ЭЛЕКТРОНОВ В ТОКАМАКАХ

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Представлены достижения нового метода, разработанного в Институте ядерных исследований (ИЯИ) для прямой регистрации высокоэнергетических (надтепловых, убегающих) электронов, генерируемых в токамаках. Технически задача основана на регистрации черенковского излучения, испускаемого энергитичными электронами, движущимися через прозрачную среду (излучательное тело) со скоростью выше скорости света в данном материале. Основной целью представленных исследований была разработка диагностической методики, применимой для изучения быстрых электронных пучков в термоядерных магнитных ловушках (ТМЛ).

ПРОГРЕС У РОЗРОБЦІ І ЗАСТОСУВАННІ ЧЕРЕНКОВСЬКИХ ДЕТЕКТОРІВ ДЛЯ ВИВЧЕННЯ ШВИДКИХ ЕЛЕКТРОНІВ У ТОКАМАКАХ

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Представлено досягнення нового методу, розробленого в Інституті ядерних досліджень (ИЯД) для прямої реєстрації високоенергетичних (надтеплових, втікаючих) електронів, генеруємих у токамаках. Технічно задача заснована на реєстрації черенковського випромінювання, що випускається енергитичними електронами, які рухаються через прозоре середовище (випромінювальне тіло) зі швидкістю вище швидкості світла в даному матеріалі. Основною метою представлених досліджень була розробка діагностичної методики, застосовної для вивчення швидких електронних пучків у термоядерних магнітних пастках (ТМП).