FEASIBILITY STUDY AND DESIGN OF CHERENKOV-TYPE DETECTORS FOR MEASUREMENTS OF FAST ELECTRONS WITHIN TOKAMAKS

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The paper presents feasibility and design studies of the Cherenkov-type detectors designed for measurements of energetic electrons within tokamak devices. The technique in question enables the identification of electron beams, the determination of their spatial distribution, as well as the measurements of their temporal characteristics. On the basis of the presented analyses, i.e. heat transfer studies, a prototype of the Cherenkov measuring head has been designed, constructed and tested within CASTOR tokamak. Obtained experimental results demonstrated that relatively intense Cherenkov signals appear particularly during the final phase of the discharge, when the expanding plasma column reaches the detector.

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1. INTRODUCTION

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 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.

Studies of pulsed streams of fast electrons in various experimental facilities, operated at the IPJ in Swierk, Poland, have been carried out by means of Cherenkov-type detectors for many years [1]. Thus, it was decided to use the accumulated experience for measurements of the ripple-born electrons inside tokamaks, e.g. CASTOR and TORE SUPRA facilities.

Measurements of fast electrons produced and escaping from tokamak-type facilities appeared to be of particular interest due to the fact that such electrons inform about non-linear processes occurring inside plasma. The IPJ 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. To lower the energy threshold of the electron detection the authors proposed to use radiators with the highest values of the refractive index. The practical application requires also the selection of appropriate radiators and consideration of geometrical as well as thermal limitations.

2. DESIGN ASSUMPTIONS

On the basis of measurements and theoretical analyses performed so far one can conclude that electron streams in question can be produced during the additional RF heating of plasma. The fast electrons and ions can drift along the izo-B surface deeply inside the volumes of the vertical diagnostic ports.

Energy spectrum of such electrons ranges from about 50 keV to above 300 keV, and the electron current density amounts to about 2 mA/cm^2. A pulsed stream of such electrons can bombard the internal surface of the tokamak vacuum chamber and deposit about 500 W/cm^2, what in turn can cause local destructions of the chamber walls and induce serious exploitation problems, e.g. vacuum or cooling-medium leaks.

The chosen Cherenkov-type radiator, which must be shielded by an appropriate absorption filter protecting the radiator against the plasma interaction, should be placed inside the tokamak vacuum chamber. Fast electron streams, which might penetrate through the filter and the radiator, induce the Cherenkov radiation if they have energy above the threshold value (determined by characteristics of the applied radiator and filters). The emitted radiation can be collected and delivered through optical cables to a control room, where it can be detected by means of fast photomultipliers and recorded within the electronic equipment.

The realization of the measuring scheme might induce, however, some serious problems. The main problem is an effective transfer of heat through the radiator and a shielding body, i.e. the formation of an appropriate heat sink as well as keeping temperatures of the radiator and its shield below the maximum admissible values. One should note that the power flux of about 500 W/cm^2, which might be brought by the investigated ripple-born electrons, is deposited mainly in a radiator surface layer of a few hundreds micrometers in the depth. The deposited heat must be dissipated quickly in order to eliminate local destructions of the radiator surface. The electron-induced intense heat stream requires the use of materials resistant to high temperature, the application of materials with high thermal conductivity, and the performance of all measurements during a relatively short time.

On the basis of a comparative analysis it was decided to apply the radiator made of a diamond crystal, which has an excellent thermal conductivity (four times higher than that of copper) enabling to dissipate heat deposited upon the radiator surface. Its refractive index is high enough to observe the Cherenkov radiation from electrons of energy above 50 keV. 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 must be placed in front of the radiator. As the absorption filter material was chosen molybdenum (Mo), due to its good thermal diffusivity and resistance to the sputtering.

Another problem for measurements of ripple-born electrons in TORE SUPRA facility constitutes trajectories of the investigated electrons, which are almost tangential to the front detector surface. It complicates the detector construction, since in typical constructions the radiator is usually placed behind a window in the shielding body, what limits the bombardment of the radiator by electrons and facilitates the dispersion of heat. In the considered case the radiator must be shifted behind the shielding. For such a configuration the heat transfer in the radiator itself must be very effective to limit a temperature rise.

Fig. 1 presents the radiators made of pure diamond plates, polished upon whole surfaces and coated by several metal layers, except for one corner which will be used to lead out the generated radiation. The shape of the radiator plates, as well as the polishing and multi-layer coatings assure effective internal reflections of the Cherenkov radiation and its collection at the uncoated corners. According to the proposed design four diamond plates should be assembled together with some small (~5°) angular shift which enables four optical cables to be connected vertically, as shown in Fig. 2.

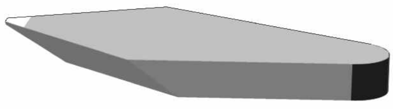

Fig.1. A single diamond radiator designed for TORE SUPRA experiments. The metal coatings (grey) should be deposited upon all the radiator surfaces, except for the part marked in white. The front (rounded) corner of the diamond radiator should be coated by a Mo-filter

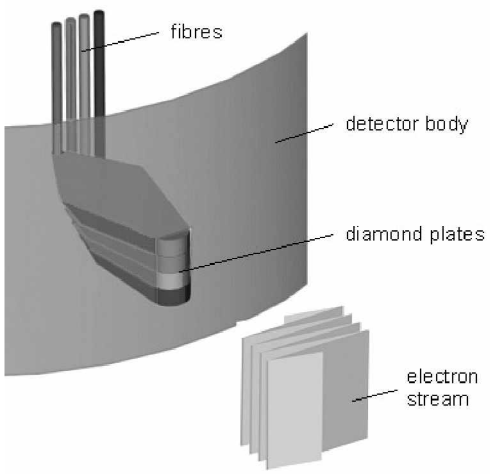

Fig.2. Spatial arrangement of four diamond radiators and separate optical fibres of a 4-channel Cherenkov-type detector proposed for TORE SUPRA experiments

3. THERMAL ANALYSIS

The design of Cherenkov-type detectors, which are to be exposed to intense electron streams within tokamaks, requires an analysis of thermal effects connected with the deposition and dispersion of relatively high power fluxes. Modelling of the transient temperature distributions in structural components of measurement head requires the use a computational programme [3] solving the above problem numerically. Detailed computations of a heat transport inside the Mo filters, diamond radiators and shielding body were performed for the assumed power flux equal to 500 W/cm^2. Different constructions of the detector head were considered.

With neglecting the anisotropy of the considered body in the direction perpendicular to main heat-conduction gradient, the thermal problem can be reduced to the one-dimensional. Nevertheless thermal properties of the modelled structure are depth dependent. Since the majority of the heat dissipated by the structure will flow through the substrate into the heat sink located at the distance peripheries, the heat loss through the thermally isolated side surfaces may be assumed as negligible. As a result of that assumption the thermal system can be approximated by a one-dimensional slab sandwich composed of outer filter, diamond and bulk metal plate. The analysed sandwich plate is assumed to be insulated along the side surface except the heat source area at the front end and the bottom, where the radiative heat transfer boundary condition of Stefan-Boltzman type has been applied. The value of the panchromatic emissivity of the surface has been selected of the order typical for oxidized metals (i.e. 0.6).

The simulation for a sequence of six 0.5-second-long heat loads is presented in Fig. 3. The presented analysis considers the disk-shaped sandwich composed of a thin metallic filter of 100 μm in thickness, 1-cm-thick diamond plate and bulk metal (Mo), with the heat flux acting on the top surface. Nonlinearity of the heat conduction problem causes that with the shortest heat pulses one can observe the slightly lower temperatures achieved at the front end surface in comparison with one heat load lasting for 3 seconds, although energy passed to sandwich plate is the same. In general the simulations confirm the positive effect of the proposed solution. From a point of view of heat engineering it seems to be promising to replace the continuous Cherenkov measurement with the sequence of short pulses, i.e. to introduce and withdraw the detector from plasma.

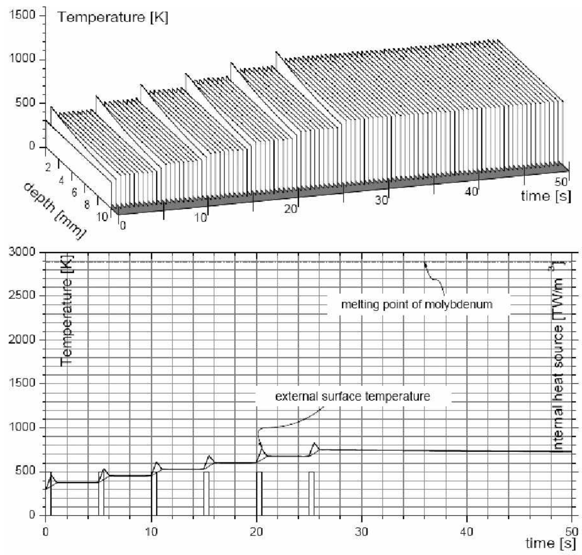

Fig.3. Transient temperature distributions in the analysed structure

4. EXPERIMENTAL RESULTS

Experimental studies of generated electron beams have been performed within CASTOR facility (major radius = 40 cm, limiter radius = 8.5 cm, minor chamber radius = 10 cm) operating at a magnetic field B ranging from 0.8 T to 1.6 T, plasma current I_p = 10 kA, the line-averaged electron density $n_e \sim 10^{19}$ m^{-3} and electron temperature equal to about 200 eV. The electron and ion temperatures at the plasma edge were of the order of 10 eV, and the edge plasma density was below 10^{18} m^{-3}.

To carry out the fast-electron measurements, a movable support with the Cherenkov radiation detection-system was installed upon an upper diagnostic port situated 135° toroidally from the limiter. It enabled the measurements in different positions along the minor radius to be performed. In the most outer position, the detector was well hidden inside the diagnostic port, then it could be moved to the shadow of the limiter, and finally after a deeper insertion, it could reach a plasma region.

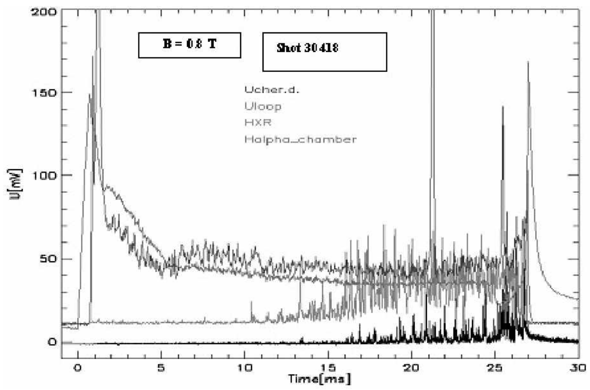

Fig.4. Typical traces recorded during tests of the Cherenkov detector in the CASTOR facility

The detection head contained a Cherenkov-radiator made of a small aluminium-nitride (AlN) crystal protected from the visible light by a Ti-layer of about 10 μm in thickness. The AlN crystal radiator was chosen due to its relatively low energy threshold, good thermal conductivity and a relatively low price. The traces presented in Fig. 4 show typical results. The difference between the Cherenkov- and H_α-signals confirms that the Cherenkov detection head was well protected against the visible radiation.

The obtained results show that the Cherenkov measuring circuit might be influenced by intense hard X-rays. To eliminate the X-ray influence, some changes of the detector head might be required, e.g. in the construction of the light-pipe and shielding of a photo-multiplier.

CONCLUSIONS

An analysis of thermal loads, which are produced by pulsed electron streams within tokamak facilities, has been performed. In particular the thermal loads expected within the CASTOR and TORE SUPRA facilities have been analysed numerically.

The design and preliminary tests of the Cherenkov detector, used for measurements of fast electrons within the CASTOR tokamak have been reported and some results of such measurements have been presented.

A technical design of a prototype Cherenkov detector head, which was designed especially for TORE SUPRA experiments, has been described.

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ИССЛЕДОВАНИЯ ВОЗМОЖНОСТИ ПРИМЕНЕНИЯ И РАСЧЁТ ДЕТЕКТОРОВ ЧЕРЕНКОВА ДЛЯ РЕГИСТРАЦИИ БЫСТРЫХ ЭЛЕКТРОНОВ В ТОКАМАКАХ

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Исследуются возможности применения и расчёта детекторов Черенкова для регистрации высокоэнергетических электронов в токамаках. Рассматриваемый метод позволяет идентифицировать электронные пучки, определять их распределение в пространстве, а также измерять их временные характеристики. На основе представленного анализа, то есть изучения теплопередачи, разработан и изготовлен прототип измерительной головки детектора Черенкова, который был испытан на токамаке CASTOR. Полученные экспериментальные результаты показывают, что довольно интенсивные сигналы с датчика Черенкова появляются, в частности, на конечной стадии разряда, когда расширяющийся плазменный шнур касается детектора.

ДОСЛІДЖЕННЯ МОЖЛИВОСТІ ЗАСТОСУВАННЯ ТА РОЗРАХУНОК ДЕТЕКТОРІВ ЧЕРЕНКОВА ДЛЯ РЕЄСТРАЦІЇ ШВИДКИХ ЕЛЕКТРОНІВ В ТОКАМАКАХ

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З'ясовуються можливості застосування та розрахунку детекторів Черенкова для реєстрації високоенергетичних електронів в токамаках. Метод, що розглядається, дозволяє виявляти електронні пучки, визначати їх просторовий розподіл, а також вимірювати їх часові характеристики. На основі проведеного аналізу, тобто вивчення теплопередачі, був розроблений та виготовлений прототип вимірювальної головки детектора Черенкова, який було випробувано на токамаці CASTOR. Одержані експериментальні результати показують, що досить інтенсивні сигнали з датчика Черенкова виникають, зокрема, на останній стадії розряду, коли плазмовий шнур, що розширюється, торкається детектора.