Design and tests of Cherenkov detector for measurements of fast electrons within CASTOR Tokamak

L. Jakubowski, J. Stanislawski, M. J. Sadowski, J. Zebrowski

The Andrzej Soltan Institute for Nuclear Studies (IPJ),
05–400 Otwock–Swierk,
Association Euratom/IPPLM, Poland
e-mail: jakubowski@ipj.gov.pl

V. Weinzettl, J. Stockel

Institute of Plasma Physics
Association Euratom/IPP.CR, AS CR, Prague, Czech Republic

Received 29 April 2006

The paper concerns a novel diagnostic technique applicable for indirect, spatially resolved measurements of energetic electrons generated inside tokamak–type facilities. Such measurements can be performed making use of the Cherenkov–effect induced by fast electrons inside a transparent medium (radiator). A construction of the Cherenkov–type detectors adapted for tokamak research is presented and preliminary results of the first measurements carried out within the CASTOR tokamak operated at IPP in Prague are reviewed.

PACS: 41.75.Ht, 41.60.Bq, 52.70.La
Key words: electron beams relativistic, Cherenkov radiation, X-rays in plasma diagnostics

1 Introduction

Diagnostic techniques used for measurements of energetic electrons have been improved continuously. These techniques make now possible the identification of electron beams, the determination of their spatial distribution, and measurements of their temporal characteristics. Research on time–correlations of electron beams with other phenomena, e.g. with the generation of X–ray pulses, with the emission of neutrons and energetic ion beams, etc., are of primary importance not only for the verification of different theoretical models, but also for possible technological applications [1].

Measurements of fast electrons produced and escaping from tokamak–type facilities [2] appeared to be of particular interest due to the fact that such electrons inform about non–linear processes occurring inside plasma, and in some cases they can cause a strong erosion of the vacuum chamber walls. The main aim of our recent research was to develop a diagnostic technique applicable for measurements of fast electrons within the CASTOR tokamak, operated by IPP in Prague. The IPJ team, operating in a frame of the Association EURATOM/IPPLM, proposed to use probes based on the detection of the Cherenkov radiation [3] because it is emitted immediately (with a delay > 0.1 ns), and its intensity is very high. Such detectors can also have high spatial– and temporal resolutions. Appropriate Cherenkov radiators enable to record electrons of energy > 50 keV. On the basis of the performed analyses, we designed and constructed a prototype of the Cherenkov measuring head adapted to CASTOR experimental conditions. The paper also reports preliminary results of the first fast electron measurements within the CASTOR facility.

2 Experimental setup and diagnostic equipment

Experimental studies of generated electron beams have been performed within the 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 $n_\mathrm{e} \sim 10^{19}$ m^{-3} and electron temperature T_e equal to about 200 eV. The electron and ion temperature values at the plasma edge are typically of the order of 10 eV, and the edge plasma density is below 10^{18} m^{-3} [4].

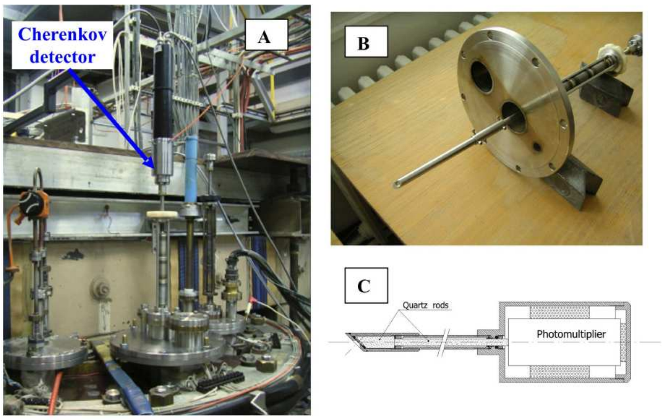

Fig. 1. Overview of the Cherenkov–radiation detection system. The measuring head (indicated by an arrow), which was mounted upon the top diagnostic port of the CASTOR tokamak at IPP in Prague (A); its view (B) and scheme (C). The Cherenkov–radiator was hidden inside the diagnostic port and connected with the photomultiplier through a quartz light–pipe; both parts were well shielded against X–rays by the stainless–steel tube.

In order to carry out the described 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 itself 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 confined plasma region. A prototype of the Cherenkov–type detector, which was adapted to the available diagnostic port and a manipulator used within the CASTOR facility, is shown in Fig. 1.

The detection head (see Fig. 1B) contained a Cherenkov–radiator made of a small aluminium–nitride (AlN) crystal protected from the visible light emitted from surrounding plasma by the deposited Ti–layer of about 10 µm in thickness (the circular entrance window of 5 mm in diameter). The AlN crystal radiator was chosen due to its relatively low energy threshold, good thermal conductivity and a relatively low price. That radiator was fixed upon a light–pipe, which was made of a polished quartz rode placed inside the stainless–steel tube. The induced Cherenkov radiation was detected by means of a photomultiplier placed inside an appropriate shielding located above the CASTOR experimental chamber.

3 Experimental results

Using standard CASTOR diagnostics and the Cherenkov–type detector described above, several series of fast electron measurements were performed within the CASTOR device.

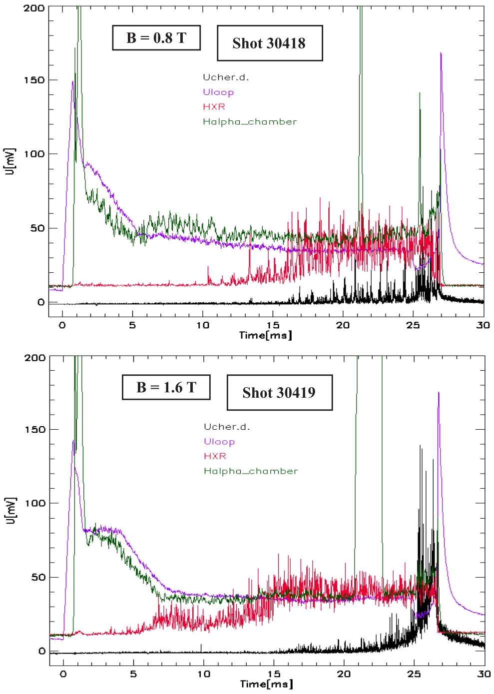

Fig. 2. Typical traces recorded during tests of the Cherenkov detector in the CASTOR facility at different external magnetic field. The red waveforms show signals from the hard X–ray detector (HXR), while the black curve presents signals obtained from the tested Cherenkov–detector head, which was placed at $R = 75$ mm. The other traces show $\mathrm{U_{loop}}$ and $\mathrm{H_\alpha}$ signals

To determine the distribution of fast electrons over minor radius, two scans of the detection head position (i.e. its displacement from the diagnostic port shadow into the confined plasma region) were performed both for the electron– and ion–orientations of the detector entrance window. To evaluate a relation between measured signals and the hard X–ray radiation (originating from the plasma–wall interaction), the different vertical– and horizontal–positions and detector placements were tested. Additionally, magnetic field (0.8 ÷ 1.6) T, electron density $(6 \div 12) \times 10^{18}$ m^{-3}, via different gas puffing) and plasma current (6 ÷ 14) kA scans were realized to trace dependences of the measured Cherenkov–light emission on these discharge parameters.

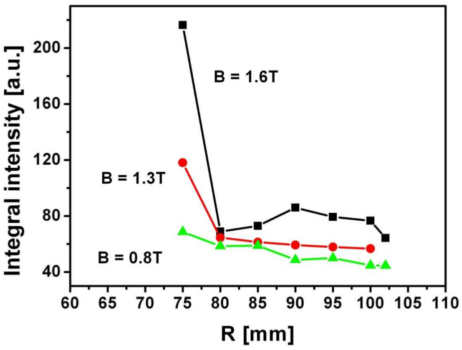

Fig. 3. Dependence of the integrated intensity of the Cherenkov signal on the radial position of the Cherenkov detector, as measured for different values of the CASTOR magnetic field.

Signals obtained from the Cherenkov–detector were recorded by a fast data acquisition system with the temporal resolution of 1 μs, other signals like magnetic field B_{T}, line averaged electron–density n_{e}, plasma current I_{p}, loop voltage U_{loop}, and intensities of hard X–ray (HXR) and H_{α}–line radiation were collected with the temporal resolution of 25 μs. To study fine structure correlations between HXR and Cherenkov signals, the HXR–signal was moved to the fast data–acquisition channel. It should be noted that the hard X–ray detector was placed above the experimental chamber, vertically at a distance of 2.5 m from the limiter.

The traces presented in Fig. 2 show typical results of measurements, performed for two successive discharges at different values of the magnetic field, B equal to 0.8 T and 1.6 T. In these shots, the tested Cherenkov–detection head was placed at a radial distance $R = 75$ mm from the chamber axis. Comparing the presented traces one can easy see different temporal behavior between signals corresponding to the hard X–rays, H_{α} signal (the most intensive line of the visible radiation) and those obtained from the Cherenkov detector. The difference between the Cherenkov– and H_{α}–signals confirms that the Cherenkov detection head was well protected against the visible radiation. The correlation between the hard X–rays and Cherenkov signals will be discussed later.

A dependence of the integrated intensity of the Cherenkov signal on the radial position of the Cherenkov detector is presented in Fig. 3. The experimental points in this figure show Cherenkov signal integrated over the discharge period ranging from 15 ms until 30 ms. A comparison of the experimental data obtained at three different values of the toroidal magnetic field shows an evident increase in the Cherenkov signal at the radius smaller than 80 mm. It confirms the presence of the fast electrons inside the plasma confinement region. The position of a separatrix was monitored by the rake of Langmuir–type probes. Moreover, an increase of the signal with B_{T} is in agreement with theoretical predictions of the connection of longer confinement times with higher magnetic fields, and consequently with a longer period for the fast particle generation.

Analyzing experimental curves shown in Fig. 2, it can easily be deduced that there were completely different temporal behaviors of the signals corresponding to the hard X–rays and Cherenkov radiation. On the other hand, it was found that the correlation between them (calculated with the standard technique) was surprisingly high (up to 80 %). An example of the correlation values computed for 2–ms discharge interval chosen between 18 ms and 20 ms, which were determined as a function of applied magnetic field B, are presented in Fig. 4.

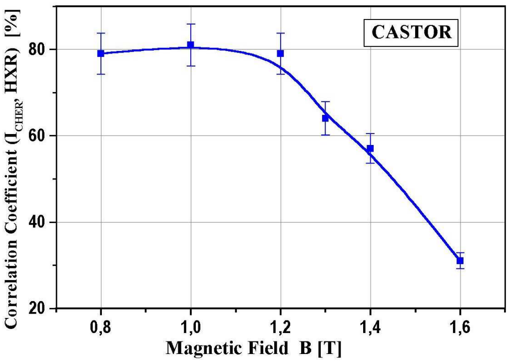

Fig. 4. The correlation coefficient of the Cherenkov signal and hard X–rays (HXR) as a function of the toroidal magnetic field B for the Cherenkov head position inside the plasma confinement region ($R_{\mathrm{cd}} = 75$ mm)

The obtained results show that the Cherenkov detector circuit might be influenced by intense hard X–rays. To determine such an influence, a more detailed analysis of the experimental data is needed. In order to eliminate the X–ray influence, some changes of the detector head might be required, particularly in the construction of the light–pipe and the shielding of a photomultiplier.

4 Summary and conclusions

An analysis of the obtained experimental results demonstrates that relatively intense Cherenkov signals appear particularly during the final phase of the CASTOR discharge, when the expanding plasma column reaches the Cherenkov detector. The averaged values of the recorded signals depend on the radial position of the Cherenkov detection head in the edge plasma, and they increase strongly at the radial positions corresponding to the plasma confinement region. This observation confirms that the recorded signals correspond to the appearance of the fast electrons in the investigated plasma. Moreover, the anticipated dependence of such signals on the magnetic field value, which was measured experimentally, constitutes another experimental evidence of the fast particle generation within the CASTOR tokamak–facility.

Experimental data from the CASTOR experiments, together with additional laboratory tests, showed a relatively strong influence of hard X–rays on the Cherenkov radiator and optical channel. It might be induced by the generation of some Bremstrahlung within the Cherenkov detector shielding and the interaction of that with the AlN–crystal and quartz light–pipe. One should take into account also some immediate influence of hard X–rays on the photocathode and dynodes of the applied photomultiplier. Such effects will require further investigation.

The reported studies have been carried out as the P3 task of the research program supported by the EUROATOM Community under the Contract with the Association EUROATOM–IPPLM, Poland (Contract No. FU06–CT–2004–00081). This research was also supported by the Ministry of Education and Science, Poland, under contract No. 47/EURATOM/2005/7. The experiment at the CASTOR facility was supported by a research grant No. AV0Z20430508 of the Czech Republic.

References

[1] L. Jakubowski, M. J. Sadowski, E. O. Baronowa: Czech. J. Phys. **54** Suppl. C (2004) C291.

[2] R. Jaspers: *Relativistic runaway electrons in tokamak plasmas.* Technische Univesiteit Einhoven, Nederlands 1995.

[3] L. Jakubowski, M. J. Sadowski, J. Zebrowski: J. Techn. Phys. **35** (1997) 141.

[4] J. Adamek, J. Stockel, M. Horn, et al.: Czech. J. Phys. **54** Suppl. C (2004) C95.