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Application of Cherenkov Detectors for Fast Electron Measurements in CASTOR-Tokamak

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1. Introduction

To study fast electrons generated inside tokamak type devices, the IPJ team proposed and developed a novel diagnostic technique based on the Cherenkov effect [1-3]. The aim of this paper is to describe an improved version of the Cherenkov detection system (the previous version was reported in [4]) and to present results of the last experimental campaign with the CASTOR device. In particular the radial distributions of fast electron beams in a standard scenario, at different values of the plasma density n_e and plasma current I_p, are to be reported. Correlations of X-rays, originating from an interaction of plasma with solid materials, and the studied Cherenkov radiation pulses, are to be investigated.

2. Experimental Set-Up and Applied Diagnostic Methods

The modified detection head contained a Cherenkov-type radiator made of an aluminium nitride (AlN) crystal, which was coated with a 10-µm Ti layer. The entrance window had the effective diameter equal to 5 mm. The applied orientations of that window, at an angle of 45^0 in relation to the chamber axis or in the direction opposite to the plasma current, as well as the selection of the radiator and its coating enabled fast electrons (of energy above 80 keV) to be recorded. The Cherenkov detection head was fixed on the vertically movable support and introduced through the upper diagnostic port. The position of the entrance window could be changed from r = 60 mm (the position inside the confined plasma region) up to 100 mm (the position in a diagnostic port shadow). Local hard X-rays of energy ranging from 20 keV to 200 keV, which appeared in the close vicinity of the Cherenkov head, were monitored using a plastic scintillator shielded with a copper filter. The both described detectors were connected with fast photomultipliers through optical cables of 10 m in length. The photomultipliers, recording the obtained signals, were hidden inside a lead shielding (pill-box) with walls of about 15 cm in thickness.

The experimental data were collected from about 500 ohmically-heated discharges within the CASTOR tokamak. Each discharge lasted up to 25 ms. The investigated shots were performed at different toroidal magnetic field B_T values, ranging from 0.8 T to 1.4 T, and at the plasma current I_p varied from 5 kA to 15 kA. The measurements were limited to the discharges with relatively low plasma density n_e amounting to 0.5-1.5 x 10^{19} m^{-3}, and a relatively high acceleration voltage V_{LOOP} (typically higher than 2 V).

3. Experimental Results

The fast electrons generated during the inductive (ohmic) heating of CASTOR tokamak plasma were recorded by means of the Cherenkov detection system described above. Typical examples of the time-resolved Cherenkov signals, which were collected in the discharges with high and low plasma density, are presented in Fig. 1.

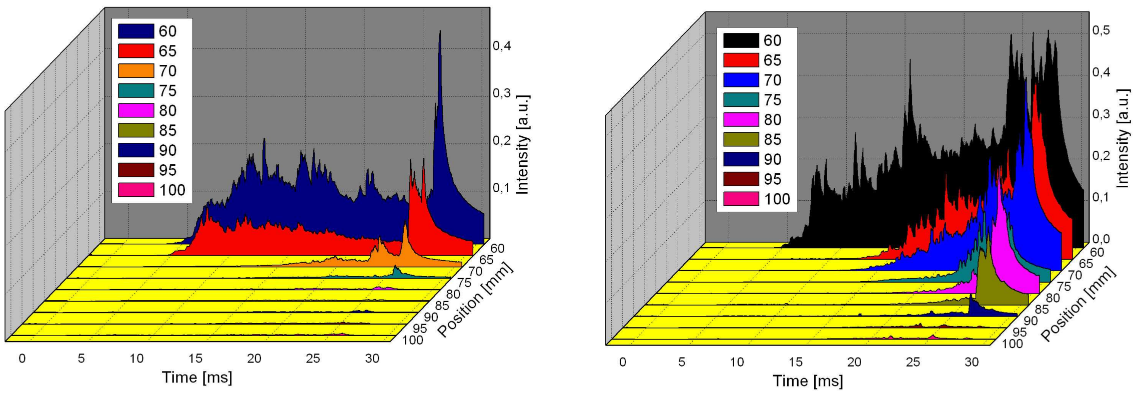

Fig. 1. Evolution of the Cherenkov signals as a function of the position of the detector head for high-density (left) and low-density discharges (right).

The character of the investigated signals depended very strongly on the radial position of the detector as well as on the plasma density. With an increase in the detector radial distance the Cherenkov signal decreased and it appeared later. It was observed that after 25 ms, when the transformer primary winding (inducing the ohmic-heating) was short-circuited and the stabilization system was turned-off, a strong increase in the signal intensity appeared as a result of the destruction of the plasma column. A considerable influence of the plasma density was also observed. In the high-density discharges the initial increase in the Cherenkov signal was followed by a stationary phase. It can be directly interpreted as a constant loss rate of the fast electrons. On contrary, the low-density discharges showed almost an exponential growth of the Cherenkov signals, lasting until the end of the discharge. The described effect might be connected with the magnitude of the acceleration electric field, which reached the critical value in the low-density discharges.

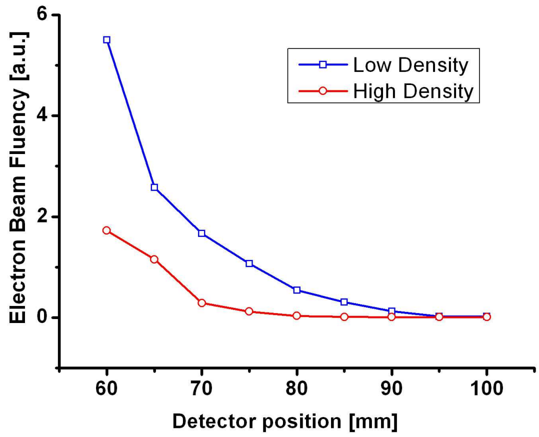

Fig. 2. Dependence of the electron fluence on the position of the Cherenkov detector along the CASTOR minor radius, as recorded for the different values of the electron density n_e ~ 6.5 x 10^{18} m^{-3} (black curve) and 1.2 x 10^{19} m^{-3} (red curve).

Particular attention was paid to the radial distribution of fast electrons and dependences of the integrated Cherenkov signal on various plasma parameters. The results (averaged for several discharges), which were obtained at two different values of the plasma density, are shown in Fig. 2. The plots show the values integrated over time-interval lasting from 5 ms to 30 ms. The recorded Cherenkov signals were proportional to the fast electron streams reaching the detector. The presented curves, showed the fast electron fluence as a function of the minor radius *r*. During measurements the position of the Cherenkov head was changed vertically from a shadow of the diagnostic port (r > 100mm) to a confined plasma region (r ~ 60mm; at the limiter radius r_L = 85mm). Other parameters were kept to be constant at standard values, i.e. I_p = 10-11 kA, B_T ~ 1.3-1.4 T. The experimental data, which were obtained for discharges of a relatively low-density, showed that in that case the fast electron flux rose up strongly for the detector radial positions below 80 mm. For discharges of higher density (>10^{19} m^{-3}) the electron flux was considerably lower, in particular for r = 60-80 mm.

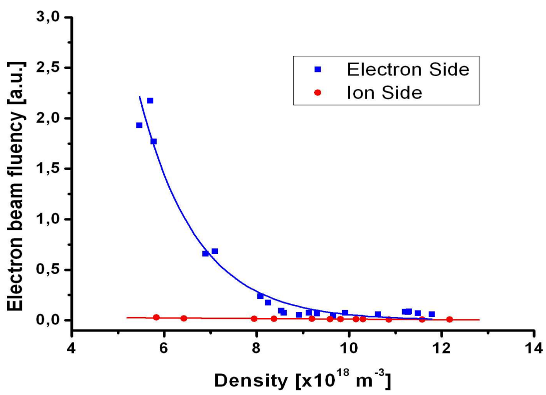

Fig. 3. Integrated Cherenkov emission as a function of the plasma density. The blue curve corresponds to the orientation of the detector allowing fast electron measurements, the red curve shows electron signal at the opposite detector orientation.

The described density effect was clearly demonstrated in the tokamak shots performed at the fixed detector position (r = 70 mm), as shown in Fig. 3. Going to low plasma densities, one could observe a distinct growth of the integrated Cherenkov intensity. During an analysis of the experimental results particular attention was paid to the observation performed with the Cherenkov detector head was turned around its axis by 180^0, i.e. when the inlet opening was oriented in the so-called ion side (see Fig. 3 – red curve). In that case the recorded signals were very low (practically negligible). It proved that the measuring circuit was well protected against electromagnetic interferences, and the secondary X-rays (e.g. Bremsstrahlung from the detectors shielding) was not recorded.

The measured Cherenkov emission depended also on the plasma current value. The fast electrons fluence was nearly linearly proportional to the main plasma current at the same other experimental conditions. simultaneously with studies of the Cherenkov emission, there were performed measurements of local hard X-rays (HXR). The use was made a separate scintillation detector placed in the horizontal diagnostic port at the same poloidal plane as the Cherenkov head. The total HXR flux was measured with the detector located 5 m above the tokamak vessel. Hence, it was possible to observe X-ray signals originating from the bombardment of Cherenkov detector by fast electrons and to compare the local and total HXR emissions. Exemplary traces, which show a comparison of time-resolved hard X-ray signals and the Cherenkov signals for the standard discharge, are presented in Fig. 4. One can easily see that the total hard X-ray radiation was different from the Cherenkov signals, although there were some peaks corresponding to interactions of fast electrons with the Cherenkov detector head. The correlation of the Cherenkov and local HXR signals was about 70 % and this value did not practically depend on the detector position, plasma density and toroidal magnetic field.

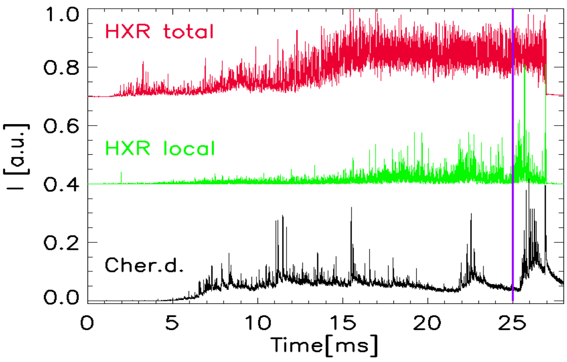

Fig. 4. Example of the temporal evolution of the Cherenkov emission measured at r = 60 mm, the local hard X-ray, and the total hard X-ray intensity.

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