Characterization of a Cherenkov Diagnostic for Fast Electrons Measurements in Tokamak Plasmas

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Introduction

Predicting and controlling plasma disruptions inside a tokamak is one of the key features for a reliable application of nuclear fusion. During disruptions, in fact, electrons can be accelerated to MeV levels thanks to Dreicer mechanism and avalanche effect, entering the so called runaway region [1], [2]. Consequently, a fraction of the pre-disruption plasma current can be converted into a runaway electrons (REs) current. Such events may severely damage plasma-facing components. Gamma rays are produced by REs through bremsstrahlung when they travel inside the plasma or when they hit plasma-facing materials. An optical diagnostic system based on Cherenkov effect has been installed and tested on FTU in 2013 in collaboration with the Polish National Centre for Nuclear Research (NCBJ) and it proved to be a valid diagnostic system to detect REs escaping the plasma. This paper describes the diagnostic and all the calibrations performed in laboratory, with different radiation sources.

Experimental setup

The single Cherenkov probe (Figure 1a) consists of a diamond detector mounted on a Titanium Zirconium Molybdenum (TZM, 99% Mo, 0.5% Ti, 0.1% Zr) support inserted inside the FTU vessel. The diamond (10 mm diameter, 1 mm thickness) exposed to the plasma is coated with a 100/200/1000 nm Ti/Pt/Au interlayer [3]. This coating allows to filter out visible and UV light from the plasma. Cherenkov effect occurs when a particle travels through a medium with a velocity higher than c/n_d where n_d is the refractive index of the material (in this case, for diamond, $n_d = 2.42$). This condition translates into a threshold energy of 49 keV that, taking into account the Ti/Pt/Au coating, is increased to 58 keV. Other important effects that should be taken into account are bremsstrahlung radiation and ionization. While the former becomes important at high energies (more than 10 MeV), the latter is not negligible between a few keV up to 10 MeV. The triple probe (Figure 1b) differs from the single one for the fact that it has three diamond detectors. Two of them have a further deposition of Mo, respectively 56 m and 164 m, and thus their threshold energies are 187 keV and 359 keV respectively, while the other is identical to the single probe's detector. The single probe's diamond sensor is coupled to a VIS/UV optical fiber (HCN-1000T model by Ensign-Bickford Optics Company).

Fig.1a single probe

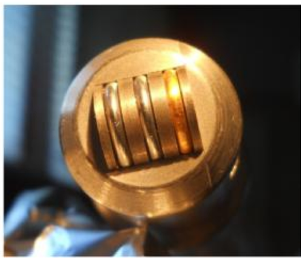

Fig.1b triple probe

The fibers are connected to four Hamamatsu R1104 photomultiplier tubes operating at high voltage (1 kV) with a detectable range of [185-850] nm. The sampling rate is 1.54 MHz over the duration of the discharge (2 s).

X-ray calibration

The Cherenkov probes inside the tokamak are shielded by visible and UV light due to the coatings, but X-rays can pass through them and generate signal by means of scintillating light. In order to quantify this possible contribution, measurements were performed with two X-rays sources, a Moxtek (MXT) 50 kV Bullet and a Micro Focus (MF) X-ray tube (Oxford Instruments SB-80-IM). The first one has an Ag anode and its High Voltage can be varied between 10 and 50 kV, with currents in the [1, 200] μA range. The second one High Voltage varying in the range [35, 80] kV and currents up to 2 mA. Both sources are absolutely calibrated. The number of photons per second of the two sources were

$$\frac{d\phi}{dt}\Big|_{MXT} \approx 2.4 \times 10^{10}\,\frac{ph}{s}$$

$$\frac{d\phi}{dt}\Big|_{MF} \approx 1.9 \times 10^{11}\,\frac{ph}{s}$$

Although these fluxes are very high with respect to the number of photons in the X-ray region that the probe encounters on FTU, measures proved that they do not produce any important response (max 13 mV, being the noise background about 3.5 mV, while in FTU discharges the response goes to 1-2 Volts).

Calibration with electrons

The single Cherenkov probe was preliminary calibrated at NCBJ (Polish National Centre for

Nuclear Research). The pulsed electron beam with adjustable electron energy E_e (from 40 keV to 100 keV) was generated by the NCBJ's electron accelerator. In particular, below E_e = 60 keV no appreciable signal is visible. Instead, in the case of E_e = 60 keV and E_e = 70 keV, a non-zero signal is present (particularly in the latter case), in agreement with Cherenkov threshold. Based on the previous scheme, the following formula was used to roughly evaluate the calibration coefficient K_{HV} and the corresponding applied voltage:

$$I_{cher} = K_{HV} J_e$$

where J_e is the electron beam current density measured on the diamond surface.

The result was K_{HV} = 90 cm^2 for U_{HV} = -1700 V.

A radioactive sample of ^{90}Sr was used to attempt the probe's calibration in a different and higher energy range. This element decays into ^{90}Y emitting an electron of 0.546 MeV. ^{90}Y then decays again into stable ^{90}Zr emitting an electron of 2.28 MeV. The estimated number of electrons arriving on the Cherenkov probe was 2.9 10^5 $e^-/(s\ cm^2)$. Since it did not produce any signal, we put the probe under a more intense electron beam.

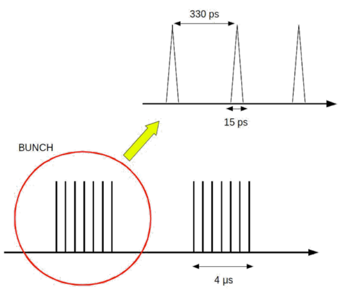

Fig. 2 Time structure of the electron pulses

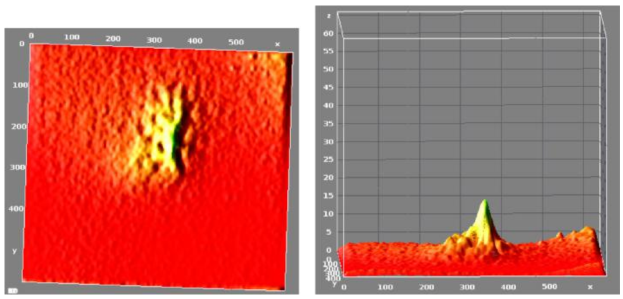

Fig. 3 3D rendering of the beam distribution

The probe was then moved to ENEA's Microtron facility, where an accelerator is able to generate a 2.3 MeV pulsed electron beam. The macropulses duration is 4 µs and each of them is made by 15 ps wide pulses that repeat every 330 ps. A schematic of the beam timing is shown in Figure 2. The output voltage of the PMT is linear with the elctron. The incident beam impinges on an alumina layer and fuorescence light emitted in the visible spectral range is imaged by an optical system (Fig. 3). The response of the diagnsotic is linear with the electron beam current (fig. 4). We got the calibration factor that 4.6 V corresponds to 1.2 10^9 e^- of 2.3 MeV.

Luminescence spectrum

Another measurement performed with the electron beam was made with the HR2000+ spectrometer, which allowed to obtain the spectrum in Fig. 5. Cherenkov emission [300-900 nm] should reach its maximum intensity between 300 and 400 nm. The lack of this peak demonstrate that luminescence plays an important role in this kind of sensors (as demonstrated also in [4]). In fact, in the region 1-10 MeV, ionization is the dominating radiative loss process and it produces a signal even 100 times more intense than the Cherenkov one.

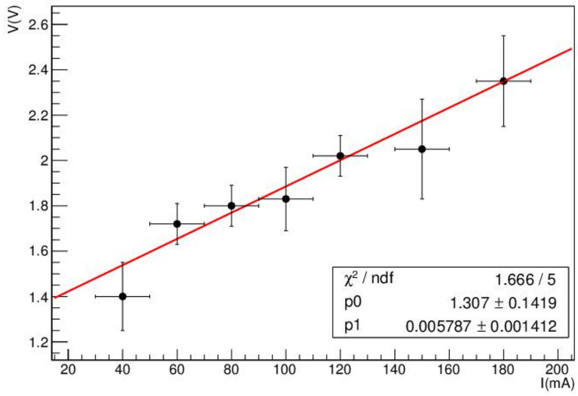

Fig 4 Probe response vs beam current

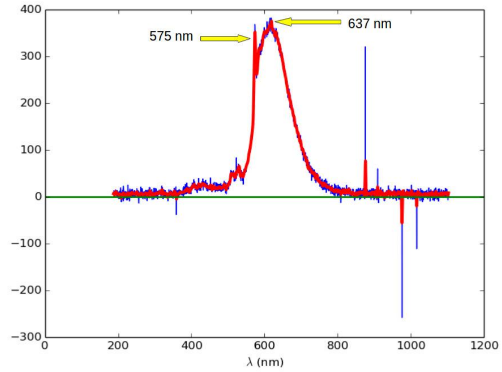

Fig.5 Spectrum of light produced in the diamonc

Since REs are expelled with energies between tens of keV to a few MeV during plasma discharges, the probes, thanks to the scintillating properties of the material, are able to detect them mainly via ionization processes in the MeV region. At low energy (100 keV), instead, Cherenkov effect seems to be the main source of signal.

Conclusions

Data acquired during the experiments at FTU clearly demonstrate that the probes are able to detect directly electrons escaping from the plasma. Signals are well correlated to those from other diagnostics and depict several and various phenomena, from MHD to kinetic instabilities (like magnetic islands rotation or Anomalous Doppler). The direct detection of escaping electrons, along with a high time resolution, demonstrated that Cherenkov probes are a valid diagnostic to study and monitor plasma scenarios involving REs generation.

References

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