Studies of runaway electrons via Cherenkov effect in tokamaks

J Zebrowski1, L Jakubowski1, M Rabinski1, M J Sadowski1, M J Jakubowski1, R Kwiatkowski1, K Malinowski1, R Mirowski1, J Mlynar2, O Ficker2, V Weinzettl2, F Causa3,4, COMPASS2 and FTU3 Teams

1 National Centre for Nuclear Research (N CB J), 7 A. Soltana Str., 05-400 Otwock, Poland
2 Institute of Plasma Physics of the CAS, Za Slovankou 3, 182 00 Prague 8, Czech Republic
3 ENEA, C.R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy
4 Present affiliation: IFP-CNR, Istituto di Fisica del Plasma, Via R. Cozzi 53, 20125 Milano, Italy

Corresponding author e-mail address: Jaroslaw.Zebrowski@ncbj.gov.pl

Abstract. The paper concerns measurements of runaway electrons (REs) which are generated during discharges in tokamaks. The control of REs is an important task in experimental studies within the ITER-physics program. The NCBJ team proposed to study REs by means of Cherenkov-type detectors several years ago. The Cherenkov radiation, induced by REs in appropriate radiators, makes it possible to identify fast electron beams and to determine their spatial- and temporal-characteristics. The results of recent experimental studies of REs, performed in two tokamaks - COMPASS in Prague and FTU in Frascati, are summarized and discussed in this paper. Examples of the electron-induced signals, as recorded at different experimental conditions and scenarios, are presented. Measurements performed with a three-channel Cherenkov-probe in COMPASS showed that the first fast electron peaks can be observed already during the current ramp-up phase. A strong dependence of RE-signals on the radial position of the Cherenkov probe was observed. The most distinct electron peaks were recorded during the plasma disruption. The Cherenkov signals confirmed the appearance of post-disruptive RE beams in circular-plasma discharges with massive Ar–puffing. During experiments at FTU a clear correlation between the Cherenkov detector signals and the rotation of magnetic islands was identified.

1. Introduction
Runaway electrons (REs) are generated in tokamaks when the friction of electron collisions with plasma does not compensate the externally induced electrical force coming from the toroidal electric field $E_{\text{tor}}$. Such beams may reach energies up to several MeV. Therefore, some electrons may be accelerated and run away in the phase space, and finally escape from the magnetic trap. There are three main mechanisms of the runaways generation: i) Dreicer (primary) mechanism; ii) avalanche (secondary) mechanism, and iii) hot-tail mechanism. A so-called critical field is usually defined as a theoretical limit for the electrical field $E_{\text{tor}}$, below which RE cannot be produced by these mechanisms. The understanding of processes of the runaway electrons emission in tokamak-type devices is of importance because of a risk of serious damages of in-vessel components, which can ultimately lead to a shut-down of the facility. Such a risk makes very difficult to perform detailed experimental studies of the RE emission in tokamaks. In fact REs can be recorded in small- and medium-size tokamaks either during the current ramp-up or the flat-top phase [1, 2] when the electron density $n_e$ is low and/or
toroidal electric field $E_{tor}$ is higher than the critical field. In general, various observations noted that the spontaneous emission of the post-disruptive RE is not possible if $B_{tor}$ is below 2T [3]. However, the post-disruptive REs were achieved with $B_{tor}$ lower than 2T in discharges with the high-Z massive gas-, or high-Z pellet-injection [4].

The NCBJ (former IPJ) team proposed to study RE by means of Cherenkov-type detectors several years ago. The Cherenkov radiation, as induced by RE in appropriate radiators and recorded with photomultipliers, enables the identification of fast electron beams as well as the determination of their spatial- and temporal-characteristics to be performed [5]. It can be treated as a novel diagnostic technique which is very convenient for direct measurements of the escaping fast REs in different tokamak facilities [6-10]. In a Cherenkov-type probe, as designed especially for multi-channel measurements, several separate channels with different low-energy detection thresholds were applied. Those thresholds were determined by materials and thicknesses of the applied absorption filters. It made possible to estimate roughly some energetic characteristics of the investigated RE beams [11]. Integrals of the Cherenkov probe signals were proportional to the recorded local electron-fluencies.

This paper presents results of the RE-emission studies performed by means of the Cherenkov-type probes in two tokamaks: COMPASS in Prague and FTU in Frascati.

2. Three-channel Cherenkov probe measurements in COMPASS

The COMPASS tokamak [12] is a small-size device with the ITER-like plasma cross-section, major radius $R_0 = 0.56$ m, and minor radius $a = 0.23$ m. Its main advantage is large flexibility and low operational costs. It can be operated both in the limited- and diverted-plasma-configuration. During RE campaigns the discharge parameters were as follows: elongation $k = (1-1.4)$, plasma current $I_p = (130–180)$ kA, line-averaged electron density: $n_e = (1-5) \times 10^{19}$ m$^{-3}$, and toroidal magnetic field $B_T = (1.15-1.2)$ T. All the mentioned examples show limited plasmas with a short elongation phase ($k<1.2$) before reaching a current plateau to improve the discharge stability of scenarios with circular plasmas. The experiments were usually run with pure deuterium (with Glow Discharge Cleaning in He between the shots); the typical pulse length was about 0.4 s. The population of REs was observed at densities $n_e < 4 \times 10^{19}$ m$^{-3}$, with a strong dependence on the gas fueling scenario and plasma shape [13].

COMPASS has a relatively low plasma current and the REs cannot achieve very high energies and fluencies. Hence, severe damages of the vessel are rather improbable [14]. It makes the COMPASS device a suitable machine for RE studies. In the recent RE-dedicated experiments argon-triggered plasma disruptions were realized and post-disruption RE beams were successfully induced there (both in current ramp-up as well as in current plateau phase) [4, 15]. To monitor escaping REs three-channel Cherenkov probe, which was equipped with three CVD-type diamond radiators with the cylindrical-tablet shapes of 8 mm-in-diameter and 1.5 mm-in-thickness, was used and located in the scrape-off plasma. The front surfaces of the mentioned radiators were covered by metal layers of different thicknesses, and it made possible to diversify low-energy thresholds for the electrons recorded by the individual channels of the probe.

In the Cherenkov probe applied for measurements at COMPASS the front surface of the radiator in Channel No 1 was covered by a Ti/Pt/Au interlayer of 1.3 µm in the total thickness, in Channel No 2 - by the same interlayer and a 35-µm-thick Mo-layer, and in Channel No 3 - by such an interlayer and a 77-µm-thick Mo-layer. Due to different materials and thicknesses of these absorption filters low-energy detection-thresholds for electrons impinging upon the described radiators were as follows: 58 keV in Channel No 1, 145 keV in Channel No 2, and 221 keV in Channel No 3. The rough calibration of the first channel of the described probe was performed at the NCBJ laboratory by means of a 100-keV electron beam obtained from an accelerator.

The most important result of the recent RE campaigns at COMPASS, from the point of view of potential applications of Cherenkov-type detectors, was the possibility to obtain the confirmation of a dependence of RE-signals on the radial position of the Cherenkov probe measuring head for circular plasma produced by deuterium discharges, as shown in figures 1(a) and 1(b).
Figure 1. Comparison of electron-induced signals (obtained from the 3-channel Cherenkov probe) with the basic plasma signals: hard X-ray signal (HXR), photo-neutrons, U_loop, visible light emission, plasma current and line-averaged electron density for COMPASS shots with deuterium fuelling and the circular plasma. XET signal presents X-ray pulses recorded inside the shielded box of Cherenkov probe photo-multipliers. Signals intensities are shown as a function of time. Left part (a) shows signals recorded during shot #13136, with the measuring head at the position R = 0.785m (5 mm inside the tokamak vessel, 45 mm outside the midplane separatrix radius). Right part (b) shows signals recorded during shot #13138, with the measuring head at the position R = 0.765m (25 mm inside the tokamak vessel, 25 mm outside the midplane separatrix radius).

The changes of the measuring head position were performed by means of an appropriate manipulator on a shot-to-shot basis. An increase in integrals of the Cherenkov probe signals, taken for whole time of discharges, as observed for all the probe channels and presented in figures 1a and 1b, which corresponded to the increase in electron beams fluencies, was higher than two orders of magnitude.

The result of the probe position scanning, i.e. the determination of a radial dependence of RE beams fluency (obtained by the probe signals integration over the discharge time) on the radial position of the measuring head, is shown in figure 2. The presented results were taken from a series of subsequent COMPASS shots with the deuterium fuelling and the circular plasma at conditions similar to those which were applied earlier, for discharges presented in figure 1. Five radial positions of the measuring head was taken into account.

The measurements carried out by means of the three-channel Cherenkov probe showed also that the post-disruption RE beams were intensively produced in plasma discharges performed with the gas-puffing. The experiments dedicated to the RE control and mitigation at COMPASS [15-17], which were carried out with the argon-puffing, shoved that post-disruption RE beams can occur during the current ramp-up phase, and proved that the first fast-electron peak appears usually during the current quench phase, even before the hard X-rays (HXR) pulse. However, the most intense and distinct peaks
corresponding to RE losses, in all the channels of the Cherenkov probe, appear mainly during the emission of post-disruption RE beams.

The RE confinement was better in the divertor-type configuration and in the elongated limited plasma experiment, as compared to circular limited plasma [15]. The initiation of the relatively fast decay of the RE emission in the case of circular plasma, when density increased to \( n_e = 3 \times 10^{19} \text{ m}^{-3} \), was also observed. In the RE dominated discharges the maximum energy value of the REs might be estimated on the basis of the RE-generated synchrotron radiation, which could be directly measured by means of an infrared camera [17]. That estimation gave the energy value equal to about 25 MeV.

Figure 2. Dependences of the RE beams fluencies (recorded by means of the Cherenkov probe) on the radial position of the measuring head. The experimental data were taken from several COMPASS shots (from #14558 to #14563, but without #14561), which were performed with the deuterium fuelling and circular plasma.

Figure 3. Comparison of time-resolved electron-induced signals (obtained from the 3-channel Cherenkov probe) with the basic plasma signals: hard X-ray signal (HXR), photo-neutrons, \( U_{\text{loop}} \), visible light emission, plasma current and line-averaged electron density for COMPASS #13129 shot performed at the deuterium fuelling and circular plasma. The measuring head position was \( R = 0.775 \text{ m} \) (15 mm inside the tokamak vessel). The line-averaged electron density was equal to \( 4.4 \times 10^{19} \text{ m}^{-3} \). The front part of the Ch1 signal is a good example of a precursor character of relatively low-energy RE beams appearance in relation to the total REs and HXR emission.
It was observed that the RE beams of energy 60-140 keV, which were recorded only in channel No 1 of the Cherenkov probe for discharges with the deuterium circular plasma configuration, appeared as narrow spikes at the instant of the plasma discharge start, and at the maximum of the plasma discharge current, as can be seen in figure 3.

It should be noted that in the later phase of the plasma discharge, which was performed with the argon puffing and the circular plasma shape, the primary signal peaks recorded by means of channel No 1 (measuring electrons of energy > 58 keV) could also be treated as a precursor HXR signals which is due to high-energy RE losses [18].

During the COMPASS plasma experiments it was noticed that the appearance of magnetic islands changed completely dynamics of the RE losses in a comparison with that observed for MHD-quiescent plasma discharges. Periodic RE losses to the limiter, which are connected with the magnetic island rotation, were observed, and it was concluded that the maximum of such losses occurred when the O point of the island passed the limiter edge [16]. It was observed particularly during the last phase of the flat-top of the low-density discharges. The link between localized Cherenkov signals and MHD perturbations seemed to be a result of the plasma activity observed during disruptions caused by the massive gas injections, and particularly during those accompanied by the RE beams generation. In some discharges with magnetic islands the amplitude of RE losses seemed to be considerably lower, i.e., the magnetic island could probably confine some REs [16].

An example of multiple RE-spikes, as recorded by means of the three-channel Cherenkov probe, which usually appear during MHD instabilities presence, is shown in figure 4.

Figure 4. Comparison of electron-induced signals (obtained from the 3-channel Cherenkov probe) with the main COMPASS signals: hard X-ray signal (HXR), photo-neutrons, Uloop, visible light emission, plasma current and plasma density for the final part of COMPASS #13200 shot performed with the deuterium filling and circular plasma. XET signal presents X-ray pulses recorded inside the shielded box of Cherenkov probe photo-multipliers. Signals intensities are shown as a function of time. The measuring head position was R = 0.790 m (at the level of the tokamak vessel wall). The line-averaged electron density was equal to 3.5 x 10^19 m^-3. Multiple RE spikes, which are well recorded by means of the Cherenkov probe, appear usually during MHD instabilities.
3. Single-channel Cherenkov probe measurements in FTU
The FTU tokamak [20] is a compact high magnetic-field device with the circular poloidal cross-section, major radius \( R_0 = 0.935 \) m, and minor radius \( a = 0.30 \) m. The FTU vacuum chamber is made of a stainless-steel. There is a toroidal limiter made of molybdenum tiles at the high field side, and additionally an outer molybdenum poloidal limiter (at the low field side), and a vertical poloidal lithium-limiter. The tokamak parameters during RE studies were as follows: toroidal magnetic field \( B_T \) from 2 T to 8 T, plasma current \( I_p \) from 0.2 MA to 1.6 MA.

For measurements of RE beams escaping from plasma in the FTU tokamak the use was made of a dedicated one-channel Cherenkov probe designed by the NCBJ team. A titanium-zirconium-molybdenum (TZM) alloy was applied to manufacture the measuring-head body. That head was equipped with a CVD-type diamond radiator of the cylindrical-tablet shape of 10 mm in diameter and 1 mm in thickness. The front surface of the radiator was coated with a Ti/Pt/Au layer of 1.3 µm in the

Figure 5. Comparison of the Cherenkov-probe signals with the MHD activity signals (recorded by means of a Mirnov coil), as well as signals from neutron- and gamma- detectors, and waveforms showing the plasma current amplitude and line-averaged electron density for the FTU shot #37607, performed at \( B_T = 5.3 \) T and \( I_p = 500 \) kA: (a) – general view of the observed correlations, (b) – a period of the discharge (zoomed up), when the rotation of magnetic islands was identified.
total thickness. The low-energy detection threshold for electrons impinging upon the radiator was 58 keV. The Cherenkov radiation from this radiator was transferred, in the first section, through a polished metal tube and then it was coupled to a high-gain photomultiplier through a VIS/UV optical fiber.

During the reported experiments the Cherenkov probe was inserted into the FTU tokamak vessel at variable positions in a shadow of the limiter. The detector was not sensitive to the background electromagnetic emission, i.e. the visible-, synchrotron- and gamma- radiation.

Cherenkov signals were observed not only during discharge disruption, but also in correlation with MHD instabilities [21, 22].

Signal modulation was due to the passage of the magnetic island in front of the probe, as demonstrated by the clear phase-relation between the Cherenkov signals, the ECE signals, and those from a proton-recoil NE213 scintillator detector. The Cherenkov signal vanished when the O-point moved away from the probe, and it reached maximum when the O-point of the island is in front of the probe [22]. The last rotation of the magnetic island before disruption was clearly detected by the Cherenkov probe as a relatively large signal.

An example of close correlations of signals obtained from the Cherenkov probe, Mirnov coils (MHD activity), neutron- and gamma-cameras, and soft x-ray cameras, as well as signals describing of plasma current intensity and linear-averaged plasma density, is shown above in figure 5. It should be mentioned that in the FTU shot #37607 (analyzed in this figure) some amount of neon was puffed in the vessel at the instant t = 0.5 s for 50 ms in order to seed MHD activity.

The reported studies provided an evidence of a loss of the confinement of fast electrons, which was driven by high-amplitude magnetic islands. In addition, as discussed elsewhere [22, 23] the Cherenkov-probe signals can prove that an additional RE expulsion mechanism is the magnetic perturbation due to amplitude fluctuations of a magnetic island.

4. Conclusions

During the recent RE campaigns at COMPASS the fast electron-beams measurements, which were performed by means of the three-channel Cherenkov probe, confirmed good capabilities of such a probe, particularly for the carrying out an analysis and drawing conclusions concerning energetic characteristics of RE beams. The Cherenkov-type probe has also proved experimentally a strong dependence of the RE signals on the radial position of the measuring head.

The RE dynamics in the presence of magnetic islands at COMPASS could also be studied by means of multi-channel Cherenkov probe. Research on the correlation of the localized Cherenkov signals with MHD perturbations could provide insight into the analysis of the influence of the magnetic island on RE losses. It should be noted that the Cherenkov probe was able to detect prompt losses of low energy RE beams, which accompanied the current quench phenomena. It was also stated that the RE losses (measured by means of the Cherenkov probe or HXR detector), as well as bursts of magnetic perturbations and fast-particle-related signals (recorded by the ECE diagnostics), were well correlated with images of plasma filaments (observed by the fast visible-radiation Phatron camera) [18].

The observations of correlations of signals from the Cherenkov-probe with those obtained from the other diagnostics, including signals of the primary MHD activity in the FTU tokamak, revealed significant opportunities for the use of the Cherenkov-type diagnostics in order to widen the knowledge of RE losses physics, particularly in scenarios involving plasma instabilities which can lead to disruptions.

In both tokamaks, i.e in COMPASS and FTU, fast electron losses could be effectively monitored by means of diagnostic technique based on Cherenkov effect occurring in the appropriate radiators located inside the tokamak vessels. It made Cherenkov probes potentially interesting for applications in the prediction and control of RE phenomena associated mainly with strong MHD activity in tokamaks.
Acknowledgments
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The reported scientific studies were partly supported by the Polish Ministry of Science and Higher Education within a framework of the scientific financial resources in the years 2016-2017, allocated for the realization of the international co-financed projects. The experiments on COMPASS were supported by the MEYS CR project No. LM2015045.

References
[1] Jaspers R J E 1995 
Relativistic runaway electrons in tokamak plasmas PhD Thesis Technical University, Eindhoven (158pp)
[2] Esposito B, Martin-Solis J R, Poli F M, Mier J A, Sanchez R and Panaccione L 2003 
Physics of Plasmas 10 (6) 2350-23
[3] Gill R D, Alper B. de Baar M, Hender T C, Johnson M F, Riccardo V and contributors to the EFDA-JET Work programme 2002 Nuclear Fusion 42 (8) 1039-1044
[4] Vlaić, M. Mlynar J, Cavalier J, Weinze ttl V, Paprok R, Imrišek M, Ficker O, Varavin, Vondracek M P, Noterdaeme J-M and the COMPASS Team 2015 J. Plasma Phys. 81 475810506
[5] Sadowski M J, Jakubowski L and Szydlowski A 2004, Czech. J. Phys. 54, C74-C80
[6] Jakubowski L, Stanisławski J, Sadowski M J, Zebrowski J, Weinze ttl V and Stockel J 2006 Czech. J. Phys. 56 Suppl. B B98-B103
[7] Zebrowski J, Jakubowski L, Sadowski M J, Malinowski K, Jakubowski M J, Weinze ttl V, Stockel J, Vacha M and Peterka M 2008 AIP Conf. Proc. 993 255-258
[8] Jakubowski L, et al. Rev. Sci. Instrum. 81 (2010) 013504 (9pp)
[9] Jakubowski L, Malinowski K, Sadowski M J, Zebrowski J, Płysunin V V, Rabinski M, Fernandes H, Silva C, Duarte P and Jakubowski M J 2010 Nucl. Instr. Meth. A 623 686-689.
[10] Jakubowski L, et al. 2013 Rev. Sci. Instrum. 84 016107 (3pp)
[11] Jakubowski L, Płysunin V V, Sadowski M J, Zebrowski J, Malinowski K, Rabinski M, Fernandes H, Silva C, Duarte P and Jakubowski M 2012 Nukleonika 57 (2) 177-181
[12] Panek R, et al. 2016 Plasma Phys. Control. Fusion 58 014015 (9pp)
[13] J. Mlynar J, et al. 2016 EUROFUSION WPMSTI-CP(16) 15152 - submitted for publication in Proc. 26th IAEA Fusion Energy Conference (8pp)
[14] Vlaić M, Mlynar J, Weinze ttl V, Paprok R, Imrišek M, Ficner O, Vondracek P and Havlíček J 2015 Nukleonika 60 (2) 249-255
[15] Mlynar J, et al. 2015 in Proc. 42nd EPS Conf. on Plasma Physics (Lisbon, Portugal) ECA Vol. 39E P4.102 (4pp)
[16] Ficker O, et al. 2017 Nucl. Fusion 57 076002 (10pp)
[17] Vlaić M, et al. 2015 in Proc. 42nd EPS Conf. on Plasma Physics (Lisbon, Portugal) ECA Vol.39E P4.108 (4pp)
[18] Rabinski M, et al. 2017 J. Instrum. 12 C10014 (7pp)
[19] Ficker O, et al. 2017 in Proc. 44th EPS Conf. on Plasma Physics (Belfast, Northern Ireland) ECA Vol.41F P5.126 (4pp)
[20] Pucella G, et al. 2015 Nucl. Fusion 55 104005 (11pp)
[21] Causa F, Pucella G, B. Esposito E, Buratti P, Giovannozzi E, FTU Team, Jakubowski L, Malinowski K, Rabinski M, Sadowski M J and Zebrowski J 2015 Proc. of Science Vol. ECPD2015 066
[22] Causa F, Buratti P, B. Esposito E, Pucella G, Giovannozzi E, Jakubowski L, Malinowski K, Rabinski M, Sadowski M J, Zebrowski J and the FTU Team 2015 Nucl. Fusion 55 123021(9pp)
[23] Esposito B, et al. 2017 Plasma Phys. Control. Fusion 59 014044 (12pp)