Runaway Electrons in COMPASS Tokamak

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Abstract. In order to obtain information about the runaway electron population in COMPASS tokamak we employed 21 pinhole HXR camera borrowed from CEA Cadarache which detects HXR created when the runaway electron hit into the tokamak chamber. In this paper we show calibration of the camera and the first results—HXR energy spectra and energy loads in channels. At the end of the paper we discuss two different mechanism giving an upper limit on runaway electrons energy in COMPASS tokamak.

Introduction

Runaway electrons present a serious threat for a successful operation for the future large tokamaks. They are created during disruptions when there is created a large parallel electric field and they can reach energies (up to several 100 MeV) and intensities capable to damage tokamak’s plasma facing components. Therefore there is a large international effort to find methods for their mitigation which has to be ready before the start of ITER [Ikeda, 2007].

COMPASS tokamak can help to test various mitigation methods (e.g. Resonant Magnetic Perturbations, Massive Gas Injection) which can be used in ITER. For achieving this goal it is necessary to have (next to the undergoing theoretical and numerical research) diagnostic system capable to detect runaway electron population. The NaI scintillation detector is already installed on COMPASS tokamak but requires calibration, in-vessel Cherenkov radiation detector is going to be installed. Last type of diagnostics capable to detect runaway electron population on COMPASS tokamak is 21 pinhole HXR camera based on semiconductor detectors. Similar type of measurement have been performed, e.g., at the JET tokamak [Esposito, 1996]. In the present paper we describe first measurements with this camera. We describe more closely design of camera, experimental setup, we show results of calibration and finally proper measurements for real discharges.

Description of 21 pinhole HXR camera and experimental setup

The 21 pinhole HXR camera consists on an array of 21 cadmium telluride (CdTe) semiconductors detectors. To the every detector there is connected a bias voltage 79 V which rises a current when the incidenting HXR photon creates electron-hole pairs. The size of each CdTe detectors is 5×5 mm² surface area and 2 mm thickness. Stopping efficiency for the CdTe is maximal for ≈ 100 keV dropping down to the ≈ 1/5 of the maximal value at ≈ 600 keV range of photon energies. The generated current is amplified by pre-amplifiers and the signal is acquired by ATCA data acquisition system with a sampling frequency 2 MHz. More detailed information can be found in the paper [Peysson et al., 1999]. A schematic picture of HXR camera can be found at page 3993 of the cited paper. We should remark that the camera was originally used for the measurements of non-thermal brehmstrahlung where the measured spectrum ends below ≈ 100 keV.
Figure 1. Schema of experimental setup. 21 pinhole camera is placed outside of the tokamak chamber behind the port covered by a 15 mm thick stainless steel flange. View angle is $\approx 30^\circ$ covering the central part of circular plasma column.

Figure 2. Measured plasma current, loop voltage, plasma line density and HXR signal from channel #1 of the HXR camera of the shot #3332.

A schema of an experimental setup together with real distances is shown in Figure 1. Typical temporal evolution of plasma parameters (plasma current, loop voltage and density from reflectometry measurements) for a lower density discharge with a circular plasma cross-section where a larger population of runaway electrons population is created is depicted in Figure 2.

Calibration of 21 pinhole HXR camera

We have performed a calibration of the HXR camera by a radiative source Cesium 137, which is the source of a monochromatic HXR radiation with an energy of 661.7 keV and a decay time equal to 11019 days. The radiative intensity is/was rather low namely $9.829 \text{ kBq}$, slightly less than $10 \text{ kBq}$, a limit which is set by the Czech health safety norms for a free manipulation with radioactive sources. This intensity represents approximately 10000 photons
per second into full spatial angle. By one HXR camera detector only a small fraction of this number is detected due to the small volume of the detector and a finite distance ($\approx 1$ cm) where we can place at the nearest the Cs$^{137}$ radiative source to the detector. This constraints result for a high demand on the acquisition time length needed for the calibration. Because of this reason we have used a new COMPASS data acquisition system D-TACQ 216 capable to save data for a time of 50 s instead of maximal 2 s by using the ATCA data acquisition system. Another inconvenience represents an impossibility of the removal of detectors from a lead shielding camera case which give rise to too many Compton scattered photons with a lower energy than the maximal 661.7 keV as we shall see from the photon energy spectra.

In Figure 3a we plot zoom for one peak which shows that we have used appropriate sampling frequency, i.e., 2 MHz. In Figure 3b there is shown a measured HXR energy spectrum of Cs$^{137}$ as obtained by detector #4 with a total measurement time 600 s. Because of the aforementioned restrictions the measured energy spectrum does not give a pronounced peak at high energy (right) side corresponding to Cesium 661.7 keV decay process (see Figure 3c). However we can infer from it with a calibration constant to be $(3.3 \pm 0.4 \text{ V})/661.7 \text{ keV}$ with an error $\pm 0.1 \text{ V}$ from a signal peak-to-peak noise and estimated $\pm 0.3 \text{ V}$ from peak position uncertainty. This seemingly higher error estimate is still satisfactory for our purposes. (D-TACQ 216 was setup to measure in a range from $-10 \text{ V}$ to $+10 \text{ V}$ what corresponds to $\pm 32.768$ ADC levels.)

**Measurements results**

**Raw signal from 21 channels**

In Figure 4a we present signals of measurement with all 21 channels. We can see that a temporal evolution of the signal at different channels is quite similar. In a first phase runaway hit into a chamber wall with an increasing energy during flat-top phase because a majority of them is created already during the current rump-up phase and then they are continuously accelerated by a low toroidal electric field of this phase (see also Figure 1b) until their almost full depletion toward the beginning of the current rump-down phase. At the very end of the discharge we see a next rise of HXR intensity which is probably connected with an expletion of well confined runaway electrons from the core of the plasma column which is at the final stage destroyed by strong MHD instabilities.

**Energy spectra**

In Figure 3a we show HXR energy histogram as recorded by channel #1 in shot #3332. We can see using the calibration factor $3.3 \text{ V}/661.7 \text{ keV}$ that HXR spectrum ends approximately at 1.8 V corresponding to $\approx 400 \text{ keV}$. (We took as the end of the spectrum the value 1.8 V because higher much less frequent higher energies correspond to rare multi count events.) It is on the
(a) Energy histogram. (b) Attenuation factor [Kocmanová, 2012].

Figure 4. (a) HXR energy histogram for shot #3332 as measured by channel #1 (Grey bars) and the calculated influence of an attenuation of 15mm stainless steel flange (Black bars). The attenuation factor/function with respect to HXR energy is plotted in panel (b).

lower limit of that what one would expect from theory for tokamak COMPASS [Kocmanová, 2012] where the runaway electrons should reach ≈ 1 MeV. There can be more reasons why we get this smaller energy. Among others it can be (i) reasons in discharge itself, (ii) runaway electrons convert just a part of their energy into HXR (in a given observation angle) even in the most effective transfer events, (iii) small volume of CdTe detectors. This smaller then expected HXR energy will be subject of our further investigation. Next to theoretical investigation/calculations we will have also opportunity to compare HXR camera results with NaI scintillation detector (when the calibration is done) and with newly installed Cherenkov detectors.

Profiles of 10 ms time averaged energy loads

Vertical profiles of runaway electrons energy deposition are the most interesting quantity which we can measure with the 21 pinhole HXR camera because the spatial non-homogeneity of incidenting runaway electrons can adversely impact ITER walls as well as positively contribute to finding of the solution of runaway electrons mitigation problem.

In Figure 4b we plot sums of peaks in 10 ms intervals in individual channels at different times of the discharge #3332. From analysis of first measurements we can see the at the beginning the profile is single peaked with the top directing to plasma center/midplane while later during the course of the discharge it starts to be two peaked profile with a hole around the midplane. We should note that we had to remove a few channel because it was clear from raw data that they either do not measure or they are too noisy.

Discussion and Conclusion

We have installed, calibrated and performed first measurements with the 21 pinhole HXR camera lent from CEA Cadarache, France. The calibration gave us calibration factor (3.3 V ± 0.4 V)/661.7 keV and showed the fact that not all energy of HXR is deposited and detected at count event because of a low stopping efficiency of high energy photons. From energy spectra we can estimate runaway electron energy to be ≈ 0.5 MeV what is slightly less that theoretically expected value in order of units of MeV. This can be caused/explained either by the properties and experimental conditions of plasma discharge or by the nature of the detector. Future measurements with another two detectors (i.e. calibrated NaI scintillation detector and in-vessel Cherenkov detector) will hopefully help to the better interpretation of measurements with HXR camera. As regards the practically most interesting quantity obtainable with 21 pinhole camera—energy load profiles, we get from our first measurements an indication of an interesting behaviour. At the beginning peaked profile changed during discharge/splitted into the two-
Figure 5. 10 ms time averaged energy load received by particular channel.

peaked profile. This behaviour should be confirmed on a statistical basis during the nearest COMPASS experimental campaign.

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References