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Progress in HXR diagnostics at GOLEM and COMPASS tokamaks

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Abstract: Scintillation detectors are widely used for hard X-ray spectroscopy and allow us to investigate the dynamics of runaway electrons in tokamaks. This diagnostic tool proved to be able to provide information about the energy or the number of runaway electrons. Presently it has been used for runaway studies at the GOLEM and the COMPASS tokamaks. The set of scintillation detectors used at both tokamaks was significantly extended and improved. Besides NaI(Tl) (2 × 2 inch) scintillation detectors, YAP(Ce) and $CeBr_3$ were employed. The data acquisition system was accordingly improved and the data from scintillation detectors is collected with appropriate sampling rate ($\approx$300 MHz) and sufficient bandwidth ($\approx$100 MHz) to allow a pulse analysis. Up to five detectors can currently simultaneously monitor hard X-ray radiation at the GOLEM. The same scintillation detectors were also installed during the runaway electron campaign at the COMPASS tokamak. The aim of this contribution is to report progress in diagnostics of HXR radiation induced by runaway electrons at the GOLEM and the COMPASS tokamaks. The data collected during the 12th runaway electron campaign (2020) at COMPASS shows that count rates during typical low-density runaway electron discharges are in a range of hundreds of kHz and detected photon energies go up to 10 MeV (measured outside the tokamak hall). Acquired data from experimental campaigns from both machines will be discussed.

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KEYWORDS: Gamma detectors (scintillators, CZT, HPGe, HgI etc.); Nuclear instruments and methods for hot plasma diagnostics

Contents

1 Introduction

In recent years the generation of runaway electrons has been recognised as a serious threat for tokamak operation as a loss of RE beam can result in the melting of plasma facing components and the destruction of underlying structures. It lead to the development of different diagnostic techniques in order to study runaway electron dynamics. Most of the techniques are based on detection of radiation, which is emitted by relativistic electrons due to the presence of a magnetic field (synchrotron radiation) [1] or due to interaction with material (braking radiation). Spectroscopy of hard X-ray radiation is becoming a common tool for investigation of runaway electrons at the present day tokamaks [2], which can provide estimates of maximum energy and numbers of runaway electrons. Moreover, it was demonstrated that under some assumptions the distribution function of runaway electrons can be reconstructed from the radiation spectrum.

The aim of this contribution is a description of experiments which were carried out at the GOLEM [3] and COMPASS [4] tokamaks with the intention to investigate runaway electron behaviour. For the runaway electron studies, the set of various scintillation detectors with an appropriate fast data acquisition system was installed at both devices. In the first part of the contribution, the diagnostic equipment and its properties are described. The second part is devoted to experiments performed at the mentioned tokamaks. The experimental layout used during the runaway electron campaign is discussed and a representative example of acquired data is shown. Also the comparison of acquired data by standard hard X-ray radiation diagnostics at the COMPASS tokamak with newly installed detectors is given to demonstrate enhanced diagnostics capabilities.

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2 Diagnostics equipment

2.1 Scintillation detectors

At the GOLEM and COMPASS tokamaks, a set of five scintillation detectors was used for the detection of the hard X-ray radiation. Their types are specified in table 1 (material of scintillation crystal, size and photomultiplier type). The former set of scintillation detectors based mainly on detectors with NaI(Tl) crystals was extended by purchase of two $CeBr_3$ detectors with exchangeable scintillation crystals (possibility of replacement by YAP(Ce) crystals). $CeBr_3$ scintillation detectors provide a low radiation background alternative to $LaBr_3$(Ce), which was used for hard-X ray spectroscopy at several devices. The comparison of evolution of single pulses recorded by detectors with different scintillation crystals is displayed in figure 1. It can be clearly seen from figure 1 that an advantage of the $CeBr_3$ detectors over classical NaI(Tl) detectors lies mainly in an approximately ten times shorter decay time. Besides a shorter decay time, the typical energy resolution of $CeBr_3$ detector is superior to NaI(Tl) for energies above 200 keV (4% at 662 keV).

Table 1. Specification of the used detectors during the experimental campaigns at the GOLEM and the COMPASS tokamaks. Material of the scintillation crystal, its size and type of a photomultiplier is given.

Scintillation material	Size	PMT type
NaI(Tl)	$2'' \times 2''$	N/A[a]
YAP(Ce)	$1'' \times 1''$	Hamamatsu R6094
NaI(Tl)	$2'' \times 2''$	ET Enterprises 9266B
$CeBr_3$/YAP(Ce)	$1'' \times 1''$	Hamamatsu R3998-02
$CeBr_3$/YAP(Ce)	$1'' \times 1''$	Hamamatsu R1234A

[a] Detector type: Envinet SNG.D40.0.2DN (PMT: 126512).

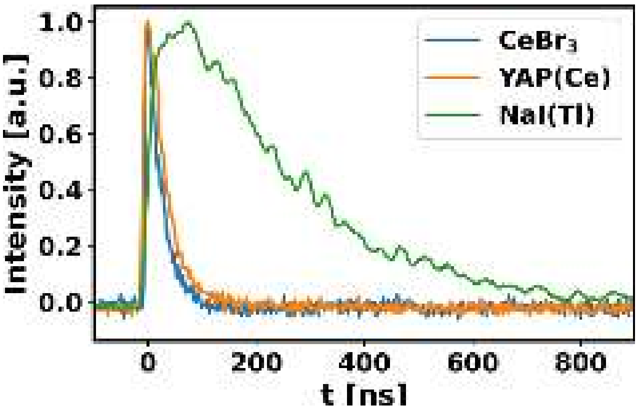

Figure 1. Comparison of pulses with normalized height recorded by various scintillation detectors.

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A detailed view of the single pulse of $CeBr_3$ is shown in figure 2. It can be seen that the decay time is roughly equal to 28 ns, which allows to operate this type of detector at count rates of several MHz and therefore it is a good candidate for runaway electron experiments, where high count rates are expected. Detector outputs are directly recorded by a data acquisition system without pulse shaping.

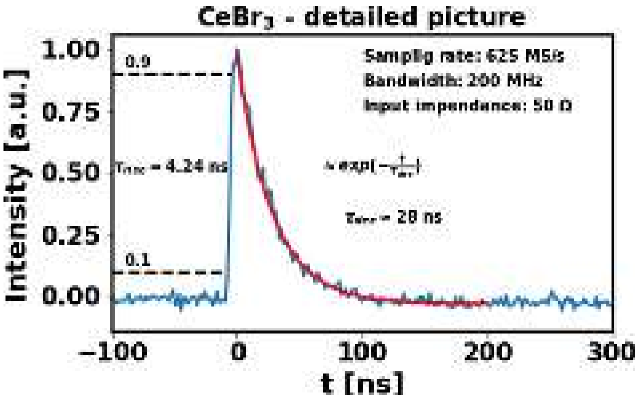

Figure 2. A close up view of one pulse, which was recorded by the $CeBr_3$ scintillation detector. Maximal pulse height was normalized to one.

Usually the PMT voltage was set below 550 V and adjusted based on experimental conditions. All detectors were calibrated by ^{137}Cs. X-ray peak, backscattering peak, gamma peak and also Compton edge were considered in the calibration procedure and were fitted in acquired spectra. The X-ray peak wasn't visible in spectra, when PMT was operated with a voltage lower than 600 V and thus it can't be used for calibration in whole operation range of PMT. Energy calibration was assumed to be linear.

It should be noted that all considered calibration points were obtained below 662 keV, but the region of interest lies in the MeV range. The chosen calibration procedure may have led to slight overestimation of photon energies. Careful calibration using more radionuclides (e.g. ^{60}Co, ^{24}Na, etc.) is foreseen. One example of the collected pulse height spectra of ^{137}Cs by $CeBr_3$ is displayed in figure 3. The spectrum was recorded for 1800 ms by Red Pitaya with built in FPGA and implemented pulse height analyser enabling real time data processing [5]. As it can be seen from the figure, all important features of the ^{137}Cs spectra were captured.

2.2 Data acquisition system

For direct digital acquisition of output signals from the detectors the Tektronix MSO58 oscilloscope was used, which has a sufficient memory to record data from the whole discharge with a satisfactory sampling rate. The obtained data is further stored in the storage and processed after the experiment.

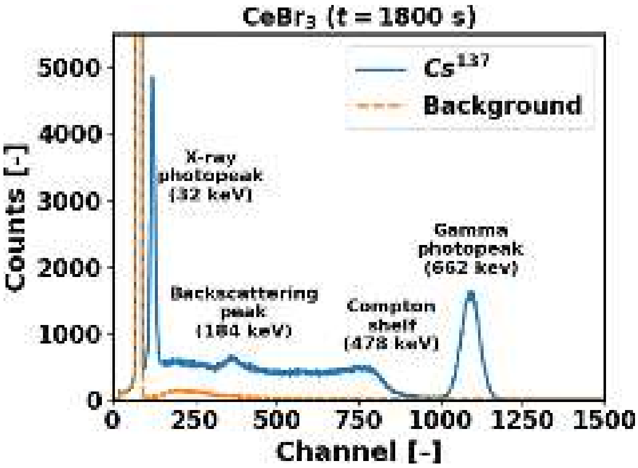

Figure 3. The gamma-ray spectrum of ^{137}Cs recorded by the CeBr$_3$ scintillation detector, where all characteristic features of spectra are displayed.

Although the data is stored in a binary format, it has high demands on the size of the data storage (typically 0.8 GB per channel). Specification of the used data acquisition system is shown in table 2.

Table 2. Specification of the data acquisition system applied during experimental campaigns at GOLEM and COMPASS tokamaks.

Data acquisition system:	Tektronix MSO58
Sampling rate	2 GS/s[a]
Number of channels	8
Record length	500 Mpts
Bandwidth	1 GHz
Vertical resolution	12 bit[b]
Input impedance	50 Ω (1 MΩ)

[a] In experiment usually used sampling rate ⩽625 MS/s.
[b] Up to 16 bit in high resolution mode.

3 Experiments at tokamaks

3.1 COMPASS

The described set of scintillation detectors was installed at the COMPASS tokamak during the 12th runaway electron campaign (Autumn 2020) in order to increase diagnostic capabilities and provide more precise measurement of hard X-ray radiation. Standard HXR diagnostic at COMPASS relies on one scintillation detector (NaI(Tl)) operated in a current mode (in the following denoted

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as HXR) and one shielded neutron detector (HXR-S) with the EJ410 scintillator, which is also sensitive to HXR radiation. Both detectors are situated in the tokamak hall in the vicinity of the tokamak.

Due to expected high photon fluxes, the new detectors were installed outside the tokamak hall and the placement inside lead bunkers with various wall thickness was possible. Experimental setup is shown in figure 4. A new set of the installed detectors proved to be useful especially during experiments devoted to investigating properties of runaway electron beams intentionally generated by an impurity gas puff injection. An example of evolution of relevant plasma parameters can be seen in figure 5. In this particular scenario a RE beam is generated by an application of the neon gas puff into a low density discharge. From figure 5 it is apparent that some RE population is generated already during the plasma breakdown and it is detected by the standard HXR detector (HXR).

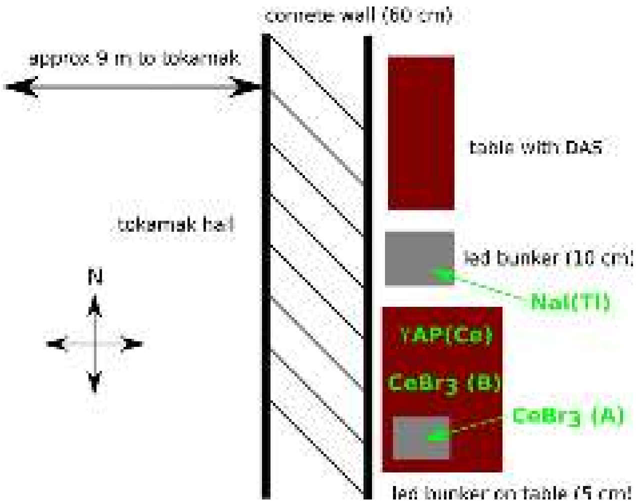

Figure 4. Experimental setup at the COMPASS tokamak.

The shielded detector (HXR-S) started to have a signal after generation of the RE beam. Raw data recorded by newly installed scintillation detectors can be seen in figure 6. It is clearly visible that energetic photons are almost exclusively registered only during the RE beam phase and evolution of the signals resembles the signal from the HXR-S detector. A comparison of the post processed data from the $CeBr_3$ detectors and the data acquired by the standard diagnostics can be seen in figure 7, where also the evolution of maximal detected energy is shown. It is obvious that with the generation of the RE beam the standard HXR detector saturates and can be used only for indication of the RE beam presence. The shielded neutron detector (HXR-S) shows similar behaviour as both $CeBr_3$ spectrometers, where count rates were evaluated in 5 ms windows. In the case of the unshielded $CeBr_3$(B) detector count rates were in the range of few MHz during the RE beam phase. Recorded spectra of HXR radiation from $CeBr_3$ detectors can be seen in figure 8.

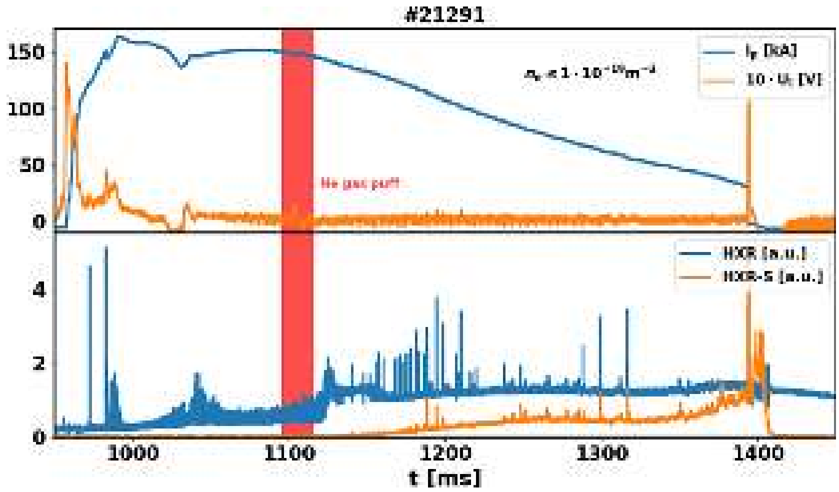

Figure 5. Evolution of basic parameters and radiation diagnostics during discharge #21291 at the COMPASS tokamak.

From that figure, where recorded spectra from both $CeBr_3$ spectrometers are compared, it could be easily recognized that the maximal detected photon energy grows during the discharge and stops at 10 MeV. Overall, it should be noted that photons up to 15 MeV were detected and count rates around 3 MHz were observed during the 12th runaway electron experimental campaign at the COMPASS tokamak.

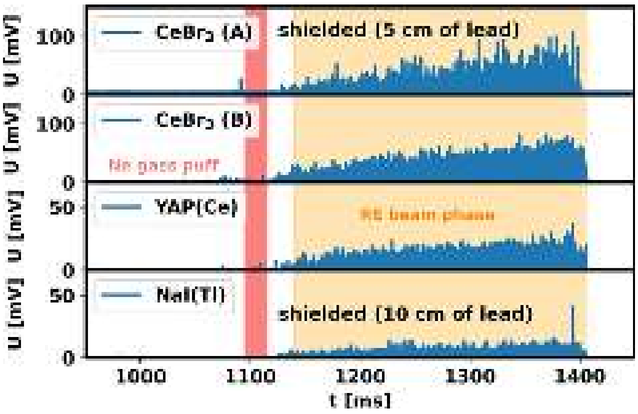

Figure 6. Evolution of signals from scintillation detectors during discharge #21291 at the COMPASS tokamak.

3.2 GOLEM

Experimental conditions at the GOLEM tokamak [6], which can be characterized by low plasma density ($n_e \approx 10^{18}$ m^{-3}) and a relatively high toroidal electric field ($E_T \approx 4$–7 V/m), are favorable

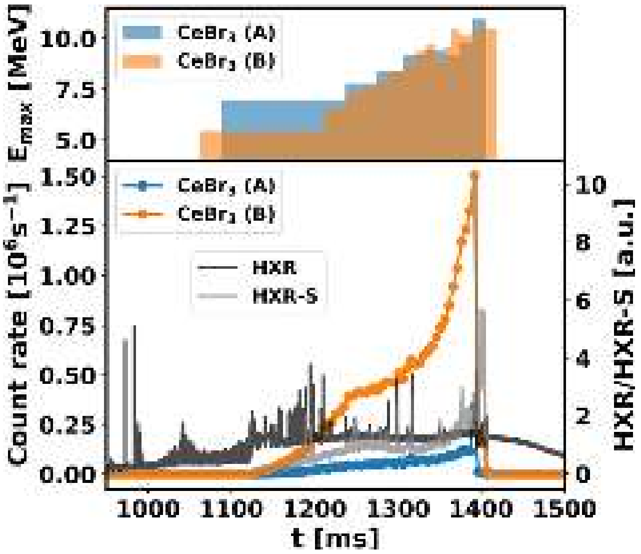

Figure 7. Comparison of signals from standard HXR diagnostic at the COMPASS and newly installed CeBr$_3$ spectrometers. Upper sub-figure shows evolution of maximal energy of detected HXR radiation.

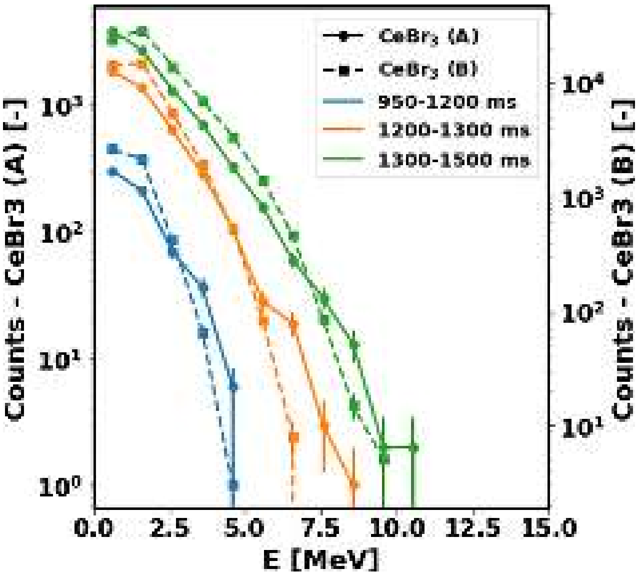

Figure 8. Comparison of HXR energy spectra acquired by two CeBr$_3$ spectrometers, where one of spectrometers (CeBr$_3$(A)) was inside lead shielding with the wall thickness of 5 cm. Another one (CeBr$_3$(B)) was unshielded.

for the generation of runaway electrons. Due to its size and high repetition rate of plasma discharges the GOLEM tokamak serves as a test bed for the development of novel diagnostics and

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techniques for the detection of runaway electrons or induced hard X-ray radiation, see the past investigations [7]. As it was mentioned in the previous sections, the set of scintillation detectors is ordinarily installed at the GOLEM tokamak to provide information about HXR radiation together with additional diagnostics such as Timepix [8] or strip detectors [9]. These scintillation detectors are usually placed in the vicinity of the tokamak in the equatorial plane close to the molybdenum poloidal limiter.

The evolution of basic plasma parameters (I_p, U_l, B_T) during a typical plasma discharge can be seen in figure 9. Due to its size an expected energy range of runaway electrons at the GOLEM tokamak lies below 1 MeV, which is in agreement with previous observations done at the CASTOR tokamak, where photons up to 500 keV were registered during dedicated experiments [10]. The GOLEM tokamak was previously operated under the name CASTOR at the Institute of Plasma Physics in Prague. Contrary to experiments carried out at the COMPASS tokamak, scintillation detectors were installed in the same room as the tokamak itself due to estimated lower photon fluxes. After analysis of the acquired data it was apparent that the signals strongly suffer from pile-up events. A typical evolution of the signals from the scintillation detectors recorded at the GOLEM tokamak are shown in figure 10, where also detailed pictures of signals recorded by $\mathrm{CeBr_3}$ spectrometers show multiple pile-up events. The experimental setup at the GOLEM tokamak needs to be changed to reduce photon flux registered by scintillation detectors and thus to allow studying runaway electron physics as was done at the COMPASS tokamak. The $\mathrm{CeBr_3}$ scintillators proved to be a functional solution for the measurement of high count rates at the COMPASS and it was expected that the spectrometers would be working without the need for shielding at the GOLEM. The design of the collimator and appropriate shielding is foreseen for future runaway electron studies.

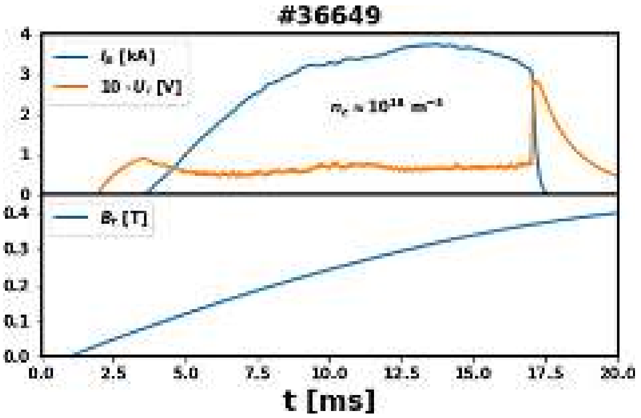

Figure 9. Evolution of basic signals during discharge #36649 at the GOLEM tokamak.

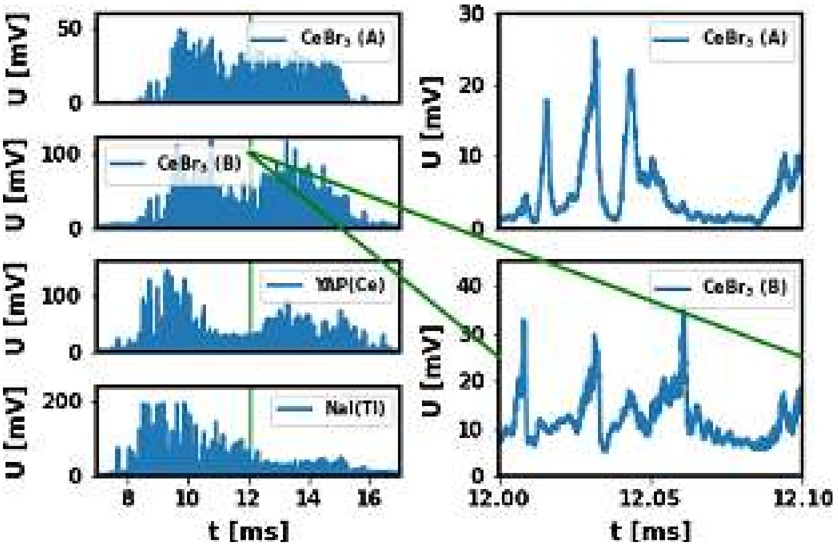

Figure 10. Evolution of signals from scintillation detectors during discharge #36649 at GOLEM tokamak.

4 Conclusion

The measurements of hard X-ray radiation generated by runaway electrons were carried out at the COMPASS and the GOLEM tokamak with a set of scintillation detectors, which was extended by two $CeBr_3$ detectors. The new detectors proved to be useful especially for the investigation of properties of runaway electron beams (e.g. evolution of maximal RE energy) and it was shown that they can provide additional information to standard HXR detectors installed at the COMPASS tokamak as the standard HXR detector can give limited information due to typical early saturation. During the 12th runaway electron experimental campaign at the COMPASS tokamak photons with maximal energy of 15 MeV were recorded and count rates up to 3 MHz were reached. The REGARDS spectrometer, which was installed for 11th runaway electron campaign, also recorded maximal count rates in a range of few MHz and demonstrated importance of gain control [11]. PMT non-linearity was also observed at the $CeBr_3$ spectrometers (abrupt decrease of output signal amplitude) during some plasma discharges. In this case the experimental setup was changed (additional shielding etc.) to mitigate the influence of the high count rates. Lack of PMT gain control was compensated by different detector shielding to keep at least one detector in linear regime.

Despite smaller photon fluxes and lower expected energies of runaway electrons at the GOLEM tokamak, acquired signals suffer from large number of multiple pile-up events, which prevents from proper analysis of the data. For future successful operation of $CeBr_3$ spectrometers during runaway electron experiments at the GOLEM the development of collimator or additional shielding is necessary. Better understanding of radiation transport in the vicinity of a tokamak would be beneficial for optimization of the experimental setup. This could be attempted by one of general purpose Monte Carlo codes such as FLUKA [12] or GEANT4 [13].

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