2021 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC) | 978-1-6654-2113-3/21/$31.00 ©2021 IEEE | DOI: 10.1109/NSS/MIC44867.2021.9875920

Correlations in Signals Generated by Runaway Electrons in the GOLEM Tokamak measured using the Timepix3 Detection Modules

Štěpán Malec, Vladimír Linhart, Vojtěch Svoboda

***Abstract*–An application study of modern pixel semiconductor detectors for characterization of runaway electron events in a tokamak is presented. This study is based on comparative techniques utilizing spectroscopy and timing measurements of X-rays produced by the runaway electrons. The measurements were performed on the tokamak Golem using three Advapix detection modules. The first two modules were based on a Timepix3 R/O chip with a 1 mm thick silicon sensor. The last module was based also on the Timepix3 R/O chip but with a 2 mm thick CdTe sensor. The modules were placed at different positions around the tokamak chamber and were triggered by a common trigger signal. We have observed that energy spectra measured by the two identical modules in the same place are identical. The spectra measured in different places show variations which can be used for runaway electron characterization. The time evolution of the signals from the detection modules are well correlated. Comparison of the time evolutions measured by the same two detection modules can be used for estimation of places where the runaway electrons interact with the tokamak matter.**

I. Introduction

THIS study is a continuation of our work presented at the conference IEEE NSS/MIC in Sydney, 2018 [1]. For a brief reminder, let us recapitulate the results from our previous study which are important for this presented study. In the previous work, we measured energy spectra and time evaluation of signals generated by X-rays produced by runaway electrons during plasma discharges in the tokamak Golem using an Advapix Timepix3 detection module with 1mm thick silicon sensor. We observed that the energy spectra have similar shape but with significant variation in numbers of events per shot. On a microsecond time scales, the signal time evolution measured by the detection device shows patterns in a form of unexpected or periodic-like increases of the intensity. We have also observed significant differences in number of events of the detected X-rays generated by the runaway electrons flying frontward and backward with respect to a limiter of the tokamak Golem.

Manuscript received December 12, 2021. This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS21/167/OHK4/3T/14 and by the Operational programs RDE CZ.02.1.01/0.0/0.0/16_019/0000778: Centre of Advanced Applied Sciences 2018-2023.

Štěpán Malec (corresponding author), Vladimír Linhart, and Vojtěch Svoboda are with the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague, Břehová 7, Prague 1, Czech Republic. (e-mail: malecste@fjfi.cvut.cz).

It is impossible to use repeated measurements because each shot on the tokamak is original. Therefore, we have used in this study two same detection modules for comparison of their results in each individual shot and one detection module for an additional task. The tasks of this study are:

- to repeat measurements with runaway electrons flying frontward and backward with respect to the limiter of the tokamak Golem but with two detection modules of the same type placed in different positions,
- to observe differences in energy spectra measured by two identical detection modules placed in different positions around the tokamak,
- to study differences in time evolution of signals measured by two identical detection modules on a microsecond time scale,
- to determine typical number of events registered in 100 ns window using CdTe sensors as the additional task.

II. Experimental tools

The presented study was performed on the tokamak Golem which is the same remotely-operated tokamak as was used in our previous work [1]. The tokamak parameters are: major radius of 0.4 m, minor radius of 0.085 m, toroidal field of 0.8 T, discharge duration of approximately 13 ms, electron temperature below 70 eV with a runaway component of the order of hundreds keV. The tokamak Golem is equipped with a limited set of plasma diagnostic instruments (see Fig. 1). [2]

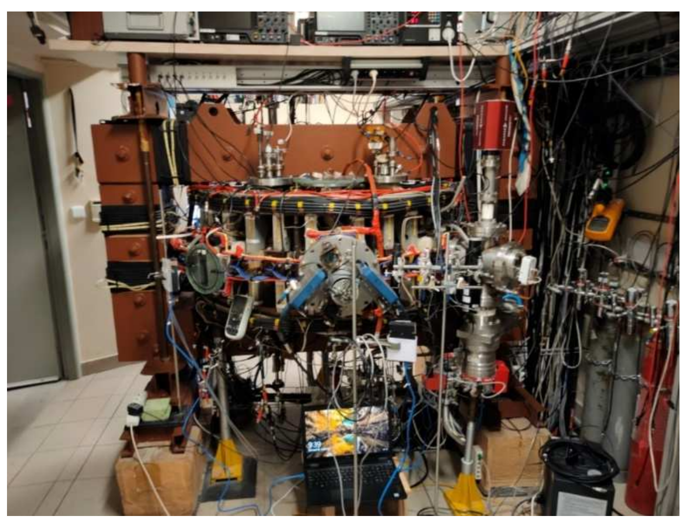

Fig. 1. Tokamak Golem equipped by a limited set of plasma diagnostic instruments.

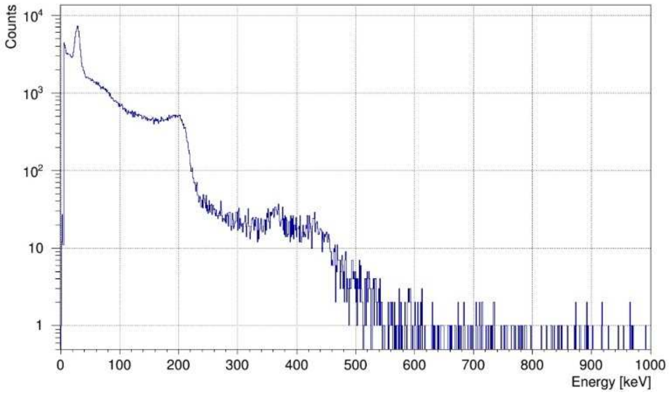

Fig. 2. An example of energy spectrum of ^{131}I measured using the Advapix detection module (H03-W0051) with Timepix3 R/O chip and 1mm thick silicon sensor.

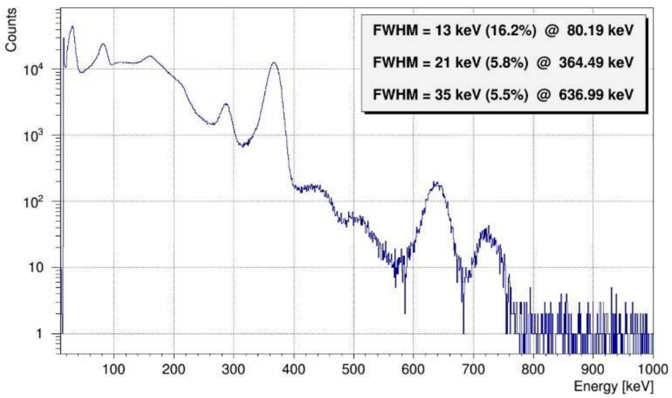

Fig. 3. An example of energy spectrum of ^{131}I measured using the Advapix detection module (F10-W0049) with Timepix3 R/O chip and 2mm thick CdTe sensor. Energy resolution given by FWHM at specific gamma lines is shown.

For the correlation measurements, we have used two Advapix detection modules with Model No. D08-W0044 and H03-W0051. Each module consists of a read-out chip Timepix3 and 1mm thick silicon sensor. The Timepix3 is a recently developed read-out chip for data acquisition based on 130 nm technology. This chip provides information about both the time of signal arrival (approximately 1.56 ns timing resolution) and energy deposited in sensor (90e electronic noise and cca. 1-2 keV energy resolution) using the time-over-threshold technique. This chip has 65 536 independent pixels arranged in a matrix with 256 rows and 256 columns with a pitch of 55 μm in both directions. [3]-[4]

In Fig. 2, there is an example of energy spectrum of ^{131}I radioisotope measured using the Advapix detection module with Timepix3 R/O chip and 1mm thick silicon sensor. This spectrum demonstrates spectroscopic properties of the detection module. The spectrum is composed of several Compton continua because most photons originated from the ^{131}I radioactive source interact with the silicon sensor through the Compton scattering. The only peak that is well visible is the one at approximately 30 keV, which is related to the characteristic X-rays from ^{131}I.

The additional task to determine typical number of events registered in 100 ns window using CdTe sensors was performed using an Advapix detection module with Model No. F10-W0049. This module was also based on the Timepix3 read-out chip. The sensor used in this module was a 2mm thick CdTe detector. Spectroscopic properties of this module are demonstrated in Fig. 3 by a spectrum of the ^{131}I radioisotope. We have observed that relative spectroscopic resolution given by Full-Width-at-Half-Maximum (FWHM) drops to 5.5% with photon energy increasing to 600 keV.

III. Experiments and Results

In this section, three different experiments are described in two subsections. Each subsection contains experimental setup, description of obtained rough data and results.

A. Correlation measurements with two identical 1mm-thick Si@Timepix3 Advapix modules

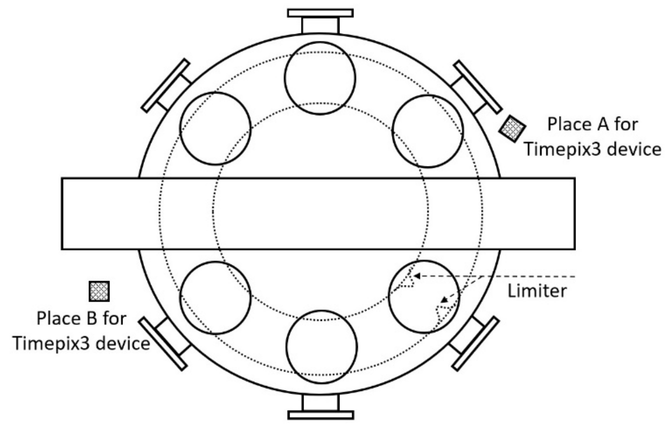

Fig. 4. A sketch of the tokamak Golem with visualization of two different positions around the tokamak where the Advapix detection modules were placed.

In Fig. 4, there is a floor projection of the tokamak Golem with visualization of two places (A and B) where the detection devices were installed. In the first step, the module with the Model No. D08-W0044 was installed and operated at the place A and the module with the Model No. H03-W0051 at the place B. After several shots, both modules were installed and operated at the place A with intention to verify if both modules provide the same responses.

1) Number of total events

In the previous work [1], we observed different number of events in frontward and backward direction given by altering the circulation of electrons in plasma. In order to verify this result, we have repeated this measurement with these two detection modules.

Fig. 5 represents results of 23 measurements with Shot No.:

- 36459, 36461, 36466, and 36469 (the first series; first 4 blue dots),
- 36475, 36480-36487 (the second series; next 9 red dots),
- 36490-36499 (the last series; last 10 blue dots).

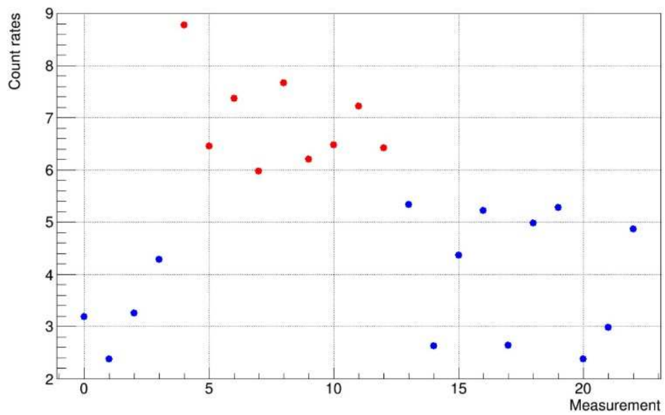

Fig. 5. Results of repeated measurements given by number of events with energy greater than 10 keV measured by the D08-W0044 module divided by number of events with the same condition measured by the H03-W0051 module.

Data in the first and the last series (blue dots) represent results when electrons in the tokamak plasma circulate in the anticlockwise direction. In this case, the runaway electrons hit the limiter in the direction towards the D08-W0044 module (at the place A). Data in the middle series (red dots) represent results when electrons in the tokamak plasma circulate in the clockwise direction and, therefore, the runaway electrons hit the limiter in the direction towards the module H03-W0051 (at the place B). The results are given by number of events with energy greater than 10 keV measured by the D08-W0044 module (at the place A) divided by number of events with the same condition measured by the H03-W0051 module (at the place B).

Based on the previous experiment, we expected that the rate will be less than 1 in the case of the red series and higher than 1 in the case of the blue series. This expectation corresponds with the idea that bremsstrahlung photons are produced in frontward direction with higher probability than in backward direction with respect to the direction in which the electrons hit the limiter. However, data presented in Fig. 5 do not correspond with this idea. The result shown in Fig. 5 can be partly explained by an idea presented in the next paragraph.

Electrons in tokamak are trapped by several magnetic fields. It means that electrons move in circular curves in the tokamak chambre. If these electrons hit the limiter, their velocities drop rapidly and, therefore, curvatures of their traces are sharper in the limiter than in the chambre. In a limit case, it is possible to imagine that runaway electrons in the limiter circulate many times before their stop. To speak about frontward and backward directions has, therefore, no sense. Directionality in production of the hard X-rays by the runaway electrons in the limiter is smoothed by the strong magnetic field. The differences in the so-called frontward and backward directions are given dominantly by absorption of the X-ray photons in the limiter. If the electrons circulate in tokamak in the anticlockwise direction (blue series), the runaway electrons hit the limiter in the direction towards the D08-W0044 module (at the place A) and this module must detect smaller number of events (due to the absorption of the X-ray photons in the limiter) than in the case of the clockwise direction (red series).

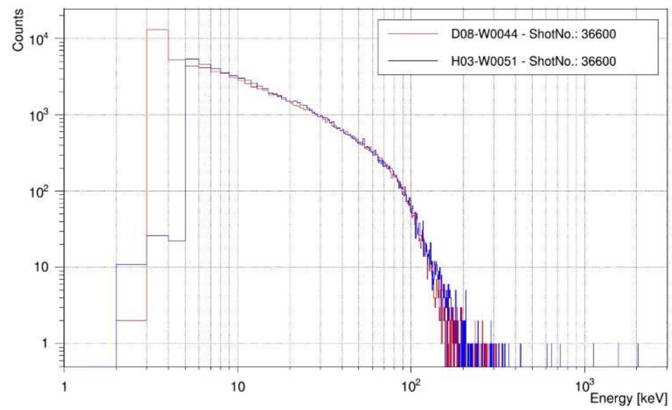

Fig. 6. Comparison of energy spectra measured in the same position (place A).

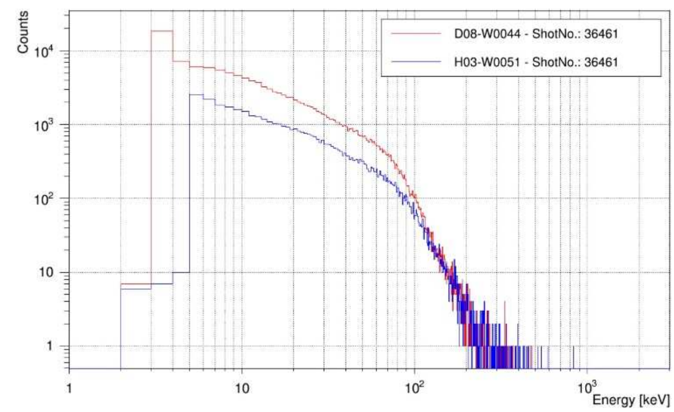

Fig. 7. Comparison of energy spectra measured in the place A using the module D08-W0044 and in the place B using the module H03-W0051.

The question why all count rates are higher than one is more complicated. In our opinion, it is an effect of different absorption of the X-rays passing through different matter of the tokamak and its equipment given by different positions in which the detection modules are installed. To reduce this effect on measured values (we are interested in properties of the runaway electrons – their energies and intensities) it will be necessary to use only the events caused by photons with higher energies.

2) Energy spectra

Fig. 6 represents an example of energy spectra measured by two identical detection modules (D08-W0044 and H03-W0051) in the same place A. The spectra are identical. This fact was obtained repeatedly using 11 measurements with Shot No.: 36592 – 36602. However, it is necessary to be sure that bremsstrahlung photon beams pass through the same matter between their origin point in the limiter and the sensors of the detection modules placed outside the tokamak chamber. Differences in materials (in dimensions and densities as well) through which the photons must penetrate could make differences in the energy spectra.

In contrast with Fig. 6, Fig. 7 shows an example of energy spectra measured using same detection modules but placed in different positions. The module D08-W0044 was still installed in the place A whereas the module H03-W0051 was reinstalled in the place B. Shapes of the spectra are different.

In the low-energy region (e.g., between 10 and 70 keV), the numbers of events measured by the H03-W0051 module (blue line) are smaller than the numbers of events measured by the D08-W0044 module (red line). However, in the case of the high-energy region (e.g., above 70 keV), the numbers of events are nearly similar. It means that relative part of the blue-line spectrum is greater than the same relative part of the red-line spectrum.

In order to study features of the relative parts of measured spectra, it is necessary to perform new definitions which are described in this paragraph. Firstly, let us divide energy axis in two regions – low- and high-energy region. The bottom border of the low-energy region is equal to 10 keV. This choice is given by the fact that energy spectra measured by Advapix modules are destroyed around thresholds. Since standard thresholds of these modules are several keV, the events with energy 10 keV and higher are apart enough from the problematic region. The top border of the low-energy region is chosen on 70 keV because the spectra drop down more rapidly around this energy as seen from Fig. 7. Therefore, the high-energy region starts at 70 keV. Let us denote by n_{ij} the numbers of events of the blue and red spectrum in the low- and high-energy region. The first index is equal to *b* or *r* and it denotes blue and red spectrum, respectively. The second index is equal to *l* or *h* and it denotes the low- and high-energy region, respectively. For example, in the case of the Shot No. 36461, the numbers of events in the low- and high-energy regions are: n_{bl} = 29 868 ± 173, n_{bh} = 5 247 ± 72, n_{rl} = 74 637 ± 273, and n_{rh} = 8 663 ± 93. The errors are the standard deviation given by the Poisson statistics. Using these numbers, it is possible to define the relative parts p_{ij}, where the indices *i* and *j* have the same meaning:

$$p_{ij} = \langle p_{ij} \rangle \pm \sigma_{p_{ij}} = \frac{n_{ij}}{n_{il}+n_{ih}} \pm \sqrt{\frac{n_{il}.n_{ih}}{(n_{il}+n_{ih})^3}}. \qquad (1)$$

For example, relative parts of the high-energy regions are p_{bh} = 0.149 ± 0.002 and p_{rh} = 0.104 ± 0.001. In order to assess how much a relative part is higher or lower than the corresponding relative part from a second spectrum, the rate r_j can be defined in the following way:

$$r_j = \langle r_j \rangle + \sigma_{r_j} = \frac{p_{bj}}{p_{rj}} \pm \sqrt{\left(\frac{1}{p_{rj}}\right)^2 \sigma_{p_{bj}}^2 + \left(\frac{p_{bj}}{p_{rj}^2}\right)^2 \sigma_{p_{rj}}^2}, \qquad (2)$$

where the index *j* has the same meaning as it is described above. For example, the rate of the high-energy parts of the blue and red spectra of the Shot No. 36461 is r_h = 1.437 ± 0.015. This number is shown in Fig. 8 as the measurement No. 1.

Fig. 8 shows a nice result. If we focus on the first nine measurements, the rates are very similar, even though the first four blue dots represent measurements under the anticlockwise regime (the runaway electrons hit the limiter towards the D08-W0044) and the next five red dots represent measurement under the clockwise regime (the runaway electrons hit the limiter from the opposite side). Since the limiter is made of Molybdenum, a material of a high density, these rates are not affected by absorption in the limiter. Therefore, we deduce that the rates could be influenced mainly by properties of the runaway electrons and, therefore, the rate defined by (2) is a good candidate for characterization of the runaway electron properties.

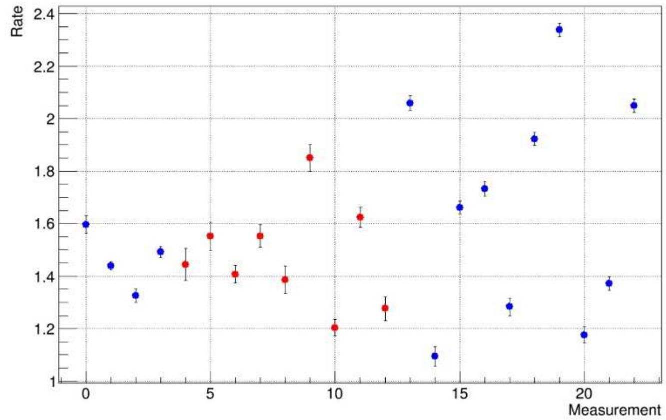

Fig. 8. Rates of the high-energy range calculated by (1) and (2) for the same shots used in Fig. 5 with the same denoting of the three series (blue dots for the anticlockwise regime and red dots for the clockwise circulation of electrons in the tokamak).

Our deduction described in the previous paragraph must be verified and, therefore, the work on interpretation of the rates is still under way.

3) Time evolution of recorded signals

As already mentioned above, the Advapix modules equipped with the Timepix3 R/O chip are able to provide not only information about energy depositions to their sensors but also times when particles were registered. It allows to perform timing measurements and to combine such measurements with spectroscopy.

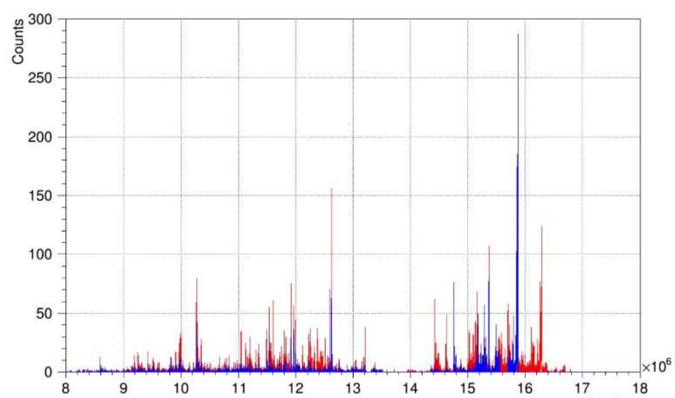

Fig. 9. An example how number of events is distributed in time during plasma disruption. The data is related to the Shot No. 36461. The red data are recorded by the module D08-W0044 whereas the blue data are recorded by the module H03-W0051.

Fig. 9 shows time evolution of number of events registered during shot No. 36461. This evolution has two parts. In the first part, the red data is regularly above the blue data. This fact corresponds to the spectrometric measurement shown in Fig. 7. The same fact is visualized in Fig. 10. In the second part, the blue signal is sometimes above the red one and sometimes is vanished. The behavior of signals in the second part is untypical and it indicates that runaway electrons would not interact only with the limiter.

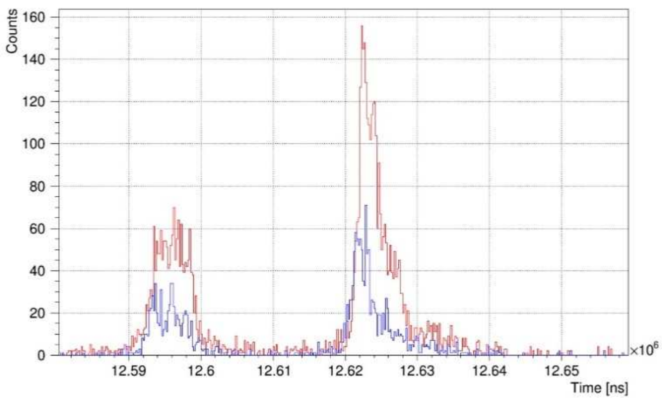

Fig. 10. A detail of the record shown in Fig. 9.

In the next step, we verified if it is possible to compute rates in a similar way as performed above for the whole spectra but this time with data only in some short pulses. Therefore, we selected 11 pulses with sufficient heights from the record visualized in Fig. 9 (Shot No. 36461) and we performed all computation given by (1) and (2) only with the selected data. The resulting rates for the high-energy region are shown in Fig. 11.

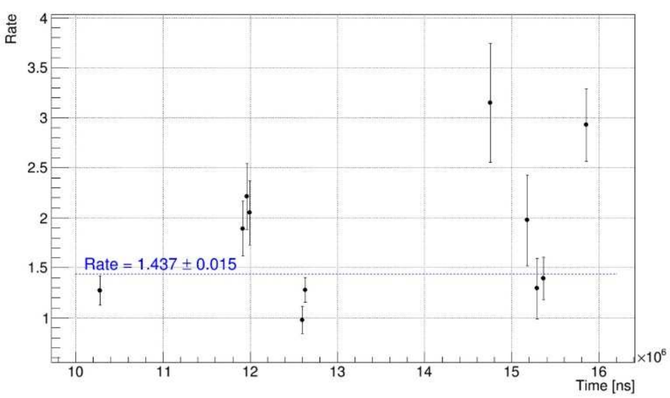

Fig. 11. Rates computed for 11 selected pulses from the record shown in Fig. 9 which is related to the Shot No. 36461. Blue line represents the rate value computed from all data of this shot.

Data shown in Fig. 11 declare that each shot on the tokamak Golem suffering by runaway electrons can contain several peaks with sufficient number of events for detailed data analysis. Estimated values have greater error (in terms of standard deviation - sigma) due to the fact that number of events in each pulse is much smaller than number of events in the whole shot. Moreover, the errors are greater if the estimated values are further away from the rate computed from all data in the shot. This value is visualized using a blue line in this figure. As can be seen, the rates are closer than one sigma only in two cases, two sigmas in five cases, three sigmas in two cases, and more sigmas in another two cases. Such variations do not correspond to the normal distribution and, therefore, the variations must be influenced by properties of the runaway electrons. Because data indicates that runaway electrons would not interact only with the limiter, analysis of data of each pulse separately could be useful for estimation in which place the runaway electrons hit either the limiter or the tokamak chambre side.

B. Typical numbers of events in 100 ns window measured by the CdTe@TPX3 device

We have a plan to use the Advapix detection module with the 2mm thick CdTe sensor as a Compton camera and to verify if such camera could be useful for visualization of the places where runaway electrons hit either the limiter or the tokamak chamber side. Since the Compton camera is based on coincidence measurements, the number of registered events in a coincidence window is crucial. The best case is to have no more than one registered event in the coincidence window (registration of a photon together with its scattered resultants is taken as one event). The coincidence window is given by the collection time of charge carriers. In the case of the 2mm thick CdTe sensor, the coincidence window can be estimated on 100 ns. Therefore, we have chosen four different positions around the tokamak (see Fig. 12) and we have measured time spectra several times for each position. Each time spectrum has equidistant binning with bin size equal to 100 ns.

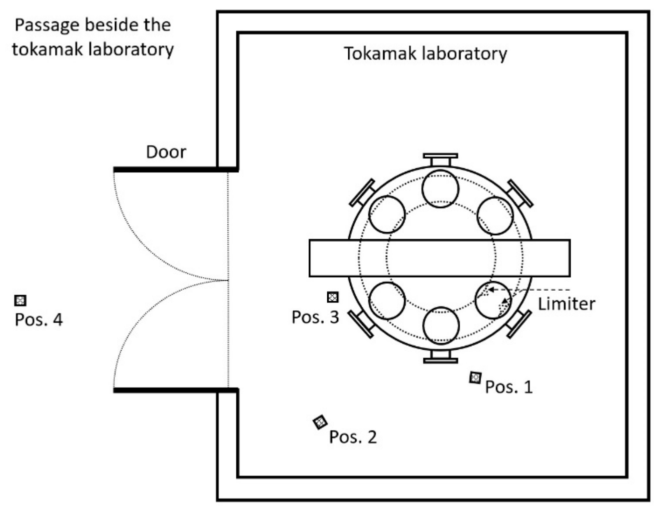

Fig. 12. A sketch of the tokamak room with visualization of the tokamak Golem and four positions where time spectra were measured.

Fig. 13 is an example of the time spectrum created by events with absorbed energy greater than 10 keV at position 4. The numbers of events per 100 ns are too high. However, if we increase the threshold on the level of 50 keV, the numbers of events per 100 ns are significantly reduced and the Compton camera could be used.

Similar situation was measured many times on all chosen positions. Our work on one-chip and multi-chip Compton camera is still under way.

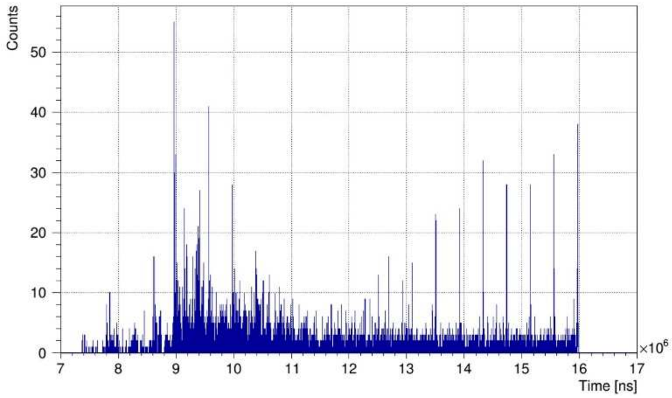

Fig. 13. Time evolution of a shot with Shot No. 36602 in a form of histogram with binning size of 100 ns filled by events with absorbed energy greater than 10 keV. The Advapix module with the CdTe sensor was placed on the position 4.

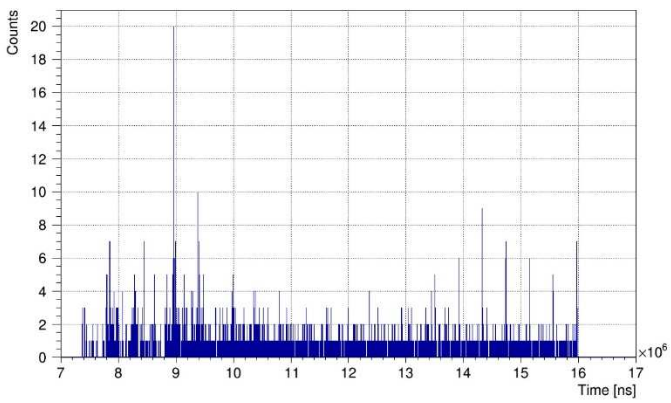

Fig. 14. Time evolution of the same shot as it is visualized in Fig. 13 but using only events with absorbed energy above 50 keV.

IV. Conclusion

In this work, we have repeated measurements with runaway electrons flying frontward and backward with respect to the limiter of the tokamak Golem but with two identical detection modules placed in different positions. We have observed that the numbers of detected events are significantly influenced by absorption in the limiter and other materials of the tokamak. However, if we focus on events with higher energies (e.g., above 70 keV in the case of the silicon sensors), the rates of numbers of such events detected by two identical detectors placed in different positions are not so influenced by the absorption. Such rates could be used for characterization of the runaway electrons in tokamaks.

Some shots measured during experiments show that the runaway electrons interact not only with the limiter but also with walls of the tokamak chamber. Therefore, any detection techniques to be developed for runaway electron characterization should be designed so that it would be able to estimate also places where the runaway electrons interact with the tokamak matters.

The results described in the two previous paragraphs will be verified by the detection modules with CdTe sensors and also using Monte-Carlo techniques.

The last information which we have observed is the fact that numbers of events detected during 100 ns time window are too high. Estimation of the right coincidence events for the Compton camera will be difficult.

V. Acknowledgement

In this work, we used three Advapix detection modules. Two of these modules were purchased and one module was borrowed from the Advacam, s.r.o. Commissioning of the modules in coincidence measurements was achieved through consultations with employees of this company. Many thanks to Advacam, s.r.o. for their support of our work.

References

[1] V. Linhart, D. Bren, A. Casolari, J. Čeřovský, et al.: " First Measurement of X-rays Generated by Runaway Electrons in Tokamaks Using a TimePix3 Device with 1 mm thick Silicon Sensor", *2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC)*. IEEE, 2018.

[2] V. Svoboda, B. Huang, J. Mlynar, G.I. Pokol, J. Stockel, and G. Vondrasek: “Multimode Remote Participation on the GOLEM Tokamak”, *Fusion Engineering and Design*, vol. **86**, no. 6-8, pp. 1310–1314, 2011.

[3] M. De Gaspari,, J. Alozy, R. Ballabriga, M. Campbell, E. Fröjdh, et al.: “Design of the analog frontend for the Timepix3 and Smallpix hybrid pixel detectors in 130 nm CMOS technology”, *Journal of Instrumentation*, vol. **9**, no. 01, C01037, 2014.

[4] E. Frojdh, M. Campbell, M. De Gaspari, S. Kulis, X. Llopart, T. Poikela and L. Tlustos, “Timepix3: first measurements and characterization of a hybrid-pixel detector working in event driven mode.”, *Journal of Instrumentation*, vol. **10**, no. 01, C01039, 2015.