First Measurement of X-rays Generated by Runaway Electrons in Tokamaks Using a TimePix3 Device with 1 mm thick Silicon Sensor

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Abstract–**An application study of modern pixel semiconductor detectors for characterization of runaway electron events in tokamaks is presented. Characterization techniques utilizing both spectroscopic measurements and monitoring of the intensity of secondary X-rays produced by the runaway electrons were used. Energy spectra of X-rays and time evolutions of their intensity on two tokamaks (Golem and Compass) were measured under different conditions and compared with results of standard runaway diagnostics. The energy spectra measured on both tokamaks have similar exponential shapes but with a significant variation in numbers of events per shot. The time evolutions of the X-ray intensity during several discharges on the tokamak Golem were measured using both the Timepix3 device and scintillation detectors (NaI:Tl and YAP:Ce). On a microsecond time scales, the signal time evolution measured by the TimePix3 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. This fact declares that the runaway electrons have relativistic velocities. The experiments on the tokamak Compass provide similar results. Measurements in the immediate vicinity of tokamak Compass were impossible to perform because of a rapid change of the tokamak magnetic field. Measurements performed in the distance of at least 0.5 m from a diagnostic port of the tokamak Compass gave millions of correctly measured events per shot and an unknown number of events affected by pileups. The correctly measured events were used for construction of energy spectra and the time evolutions of the X-ray intensity.**

Manuscript received December 17, 2018. This work was supported in part by the Czech Science Foundation under Grant No. GA18-02482S and co-funded by MEYS project LM2015045.

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I. Introduction

This work is focused on an application of semiconductor pixel detectors for characterization of runaway electrons in tokamaks using detection of X-rays produced by the runaway electrons in the walls of tokamak chambers.

The tokamak is one of the several types of magnetic confinement devices being developed to produce controlled thermonuclear fusion power. Especially, tokamak is a toroidal confinement plasma system, the plasma being confined by a magnetic field. [1]

In universe, four states of matter exist. Three of them are well known (solid, liquid, and gas); the last one (plasma) is less known, although it is the most common matter state in universe. The plasma can be defined as an ionized gas consisting of free ions, electrons and neutral entities interacting with each other in electric and magnetic fields. Collisions between charged particles in the plasma are governed by the long-range, small-angle scattering Coulomb interaction. A characteristic feature of this interaction is the rapid decrease of momentum transfer with increasing particle energy. For electrons of sufficiently high energy the friction force due to collisions with plasma particles does not compensate the externally induced electric force. These electrons are continuously accelerated and 'run away' in phase space and, therefore, they are called runaway electrons. Experimental studies of the runaway electrons are motivated by several arguments involving both diagnostic capabilities and effects of the runaway electrons on plasma behavior. [2]

Main motivation why to study the runaway electrons in the fusion research is that these electrons create a big potential risk for the tokamak ITER in future [3].

Properties of the runaway electrons can be studied using both direct and indirect detection. The direct detection means detection of the runaway electrons inside tokamak chamber. For this purpose, Cherenkov detectors are frequently used. Among others, the indirect detection is usually carried out using detection of soft and hard X-rays generated by the runaway electrons in tokamak vessel walls. Detectors of these X-rays are routinely placed outside tokamak in different positions and distances from this device and sometimes shielded by wall from lead bricks with different thickness. Frequently used such detectors are standard and modern

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scintillation detectors based on NaI:Tl or YAP:Ce material among others. Main disadvantage of these detectors is the fact that the very intensive X-rays are produced during very short times (typically from several tens to several hundred milliseconds) and, therefore, these detectors can often detect several X-ray photons simultaneously in a form of a summation event.

We try to suppress this disadvantage using semiconductor pixel detectors. The word pixel is an abbreviation from picture element because these detectors were designed for imaging techniques. Therefore, they have capability to resolve several simultaneous events using their imaging.

II. Experimental setups

Our experiments were performed on two tokamaks (Golem and Compass) using a Timepix3 device equipped by a 1mm thick silicon sensor.

A. Tokamak Golem

The tokamak Golem is remotely-operated[1] small tokamak (major radius R = 0.4 m, minor radius a = 0.085 m), which is located at the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague. It operates currently at a modest range of parameters, toroidal field $B_t < 0.8$ T, plasma current $I_p < 8$ kA, with a discharge duration about 13 ms, electron temperature T_e below 70 eV (with a runaway component of the order of hundreds keV) and with a limited set of plasma diagnostics instruments. Interaction of runaway electrons with limiter material (Molybdenum) provides low-intensity glints of the X-rays which are useful in comparison measurements with modern detectors and standard instrumentation. [4]

B. Tokamak Compass

The tokamak Compass installed at the Institute of Plasma Physics of the Czech Academy of Sciences, with its size (major radius 0.56 m, minor radius 0.23 m, Ip <= 400 kA, Bt: 0.9-1.56, elongation <= 1.6, and discharge duration about 300 ms) ranks it amongst medium-size tokamaks. This tokamak is capable of the H-mode operation, which represents a reference operation ("standard scenario") for the future ITER tokamak. More importantly, due to its size and shape the COMPASS plasmas correspond to one tenth (in the linear scale) of the ITER plasmas. Interaction of runaway electrons with limiter material or tokamak chamber walls provides the X-ray flashes with such high intensity that signals of almost all standard detectors saturate and, therefore, data analysis of such signals is difficult or practical impossible. Therefore, development of new diagnostic techniques suitable for high-flux environment is desirable. [5]

The tokamak Golem is an ideal instrument for first tests of the new diagnostics. In the case of the proof of diagnostic design the developed setups will be used and tested also on the tokamak Compass.

[1] The term “remotely-operated tokamak“ means that the tokamak can be operated from any standard Internet device using a web interface. For details see web page: http://golem.fjfi.cvut.cz.

C. Timepix3 device

The Timepix3 device is a pixel detector consisting of a Timepix3 chip and a sensor connected with the chip using bump-bonding technique.

Timepix3 chip is a recently developed read-out chip for data acquisition based on 130 nm technology. This chip provides information about both time of signal arrival (approximately 1.56 ns timing resolution[2]) 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 pitch of 55 μm in both directions. [6]-[7]

The sensor connected with the Timepix3 chip was 1 mm thick high-resistivity silicon sensor operated under maximal allowed bias of 450V.

The Timepix3 device has timing resolution given by the timing resolution of the chip and time of charge collection of the sensor.

Let’s shortly remind some fundamentals about silicon sensors. Charge carriers ionized in silicon sensors are drifted by an external electric field of E with a drift velocity of $v = \mu E$, where μ is their mobility. The carriers drifted through whole active volume (so-called depleted region) with thickness d will be collected in time $t = d / v = d / (\mu E)$. In the case of the silicon material, the electric field has approximately linear shape. However, for this short mention, let’s the electric field be represented by a mean value of $E = U / d$, where U is bias. As the thickness d of the depletion region increases with increasing bias as $\sqrt{U}$, the time of collection $t = d^2 / (\mu U)$ is constant. If we connect the depletion region with whole bulk of the silicon sensor (e.g. the sensor is operated like fully depleted), this short mention gives us a simple result that all silicon radiation sensors with different thicknesses have approximately same time of charge collection. Typical collection time for electrons and holes is about 7 ns and a little bit greater than 20 ns, respectively. It is the fact why we have chosen 100 ns coincidence window which could cover the time of charge collections with a big reserve.

We have verified if the 100 ns coincidence window covers the charge collection time using determination of time differences between times of arrival of the first and last signals obtained from the same cluster (a track generated by one X-ray photon). Most of the electrons recoiled by photons of the hard X-rays performs tracks in the sensor in a form of 3D curved lines. Times of charge collection (given by times of arrival of signals provided by the Timepix3 chip) from different points of an electron track can be different but any difference could not be greater than time of charge collection through whole bulk if the sensor is fully depleted. Obtained resultant differences are shown on the Fig. 1.

[2] This resolution is given by frequency of a clock signal. The chip is driven by a crystal with frequency of the clock signal of 40 MHz which is corresponding to period of 25 ns. This frequency is multiplied by 16 in the chip. So, the final period is 25 / 16 = 1.5625 ns.

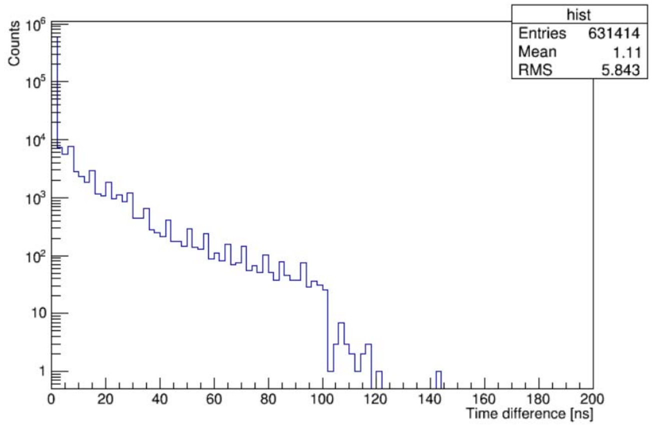

Figure 1 Time differences in times of arrival of signals created in the Timepix3 chip by signals from each individual electron track

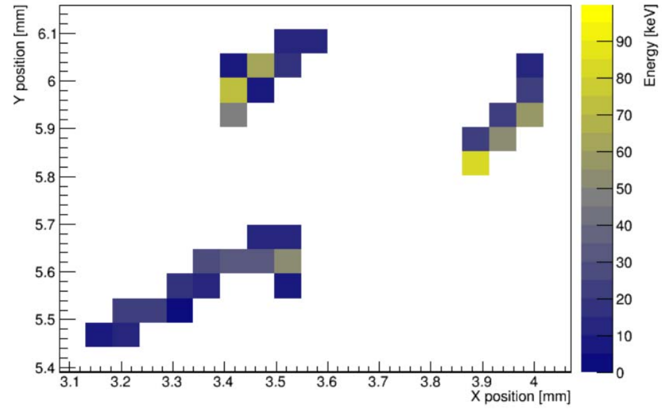

Figure 2 An example of three events detected by the Timepix3 device simultaneously

The Fig. 1 demonstrates that the silicon sensor is not fully depleted even it is operated under maximal bias reverse voltage (greater bias causes electric discharges) because the shown histogram of the time differences does not terminate on a time below 100 ns. Moreover, some events have time differences greater than the predefined limit of 100 ns and, therefore, they must be influenced by pile-up events. Number of such events is only 30 from more than 631 000 all measured events. It declares that the pile-up effect is negligible. Periodic-like increasing in counts shown on this histogram could be caused by the time discretization given by period of the multiplied clock signal which is 1.56 ns as mentioned above.

We have chosen the TimePix3 device as a detector of the X-rays for three reasons.

The first one is that this detector was in disposal although this device has not ideal functionality. Currently, new devices with improved functionality and also with new types of the sensors are tested and we will use them for verification and improvement of our results during next planned experiments.

The second reason comes from a requirement on low detection efficiency given by the high-intensity glints of the X-rays. The Timepix3 device satisfies this requirement because its each pixel, as independent radiation detector, has very small detection volume and, therefore, it has very small detection efficiency. Moreover, this device has 65 536 independent pixels per chip allowing detection of several thousand photons at the same time with a significant suppression of photon pileups. These facts can be demonstrated by a situation visualized on the Fig. 2.

The Fig. 2 represents three events registered by the Timepix3 device in a same time. Each event is represented by a track of an electron. Each track is given by several adjacent pixels stricken by the electron. Each pixel provides information about time of signal arrival and deposited energy. The time of signal arrival gives an additional condition if the adjacent stricken pixel is a part of a cluster. Summation of all energies provided by pixels of a cluster gives the energy deposited by one event. Using this information, it is possible to resolve and analyze the events independently.

In contrast with the facts written in the preview paragraph, when the three events imagined on the Fig. 2 would be registered by a scintillating mono-crystal, only one summation event would be detected.

The third reason is the fact that TimePix3 devices provide information about energy deposited to the sensor and time of arrival of each individual event. It allows plotting of two-dimensional time-energy spectra with excellent time resolution. In the cases when number of measured events is small for creation of the two-dimensional spectra, it is still possible to create time evaluation not only with total absorbed energy (as expected in the case of standard scintillator detectors) but also with other statistics based on statistical moments (e.g. time evaluation of mean absorbed energy or its standard deviation, skewness, and kurtosis). The first experiments, which we have performed, were oriented only on analysis of energy spectra and time evolution separately.

D. Scintillation detectors

Scintillation detectors for gamma spectroscopy are standard diagnostic instruments on tokamaks for recording of time evolution of the hard X-rays produced by the runaway electrons. In our work, we have used NaI:Tl and YAP:Ce for comparison of the time evolution of these X-rays measured by the Timepix3 device only on the tokamak Golem. In the case of the tokamak Compass, we did not perform this comparison, even though there were also diagnostic instrumentation based on scintillators, because time evolutions measured by the Timepix3 device have some unexpected artifacts (described below) which must be explained firstly.

Sodium iodide activated with thallium (NaI:Tl) is a standard and the most widely used scintillation material with good spectroscopic and timing properties. Its density is 3.67 g/cm^3, light yield is 38 photons/keV with wavelength of maximum emission of 415 nm, thickness to stop 50% of 662 keV photons is 2.5 cm, and 1/e decay time is approximately 230 ns. A small disadvantage of this material is that the sodium iodide is hydroscopic. [8]

Yttrium aluminum perovskite activated by cerium (YAP:Ce) is a modern scintillation material designed for applications with gamma rays. This material has excellent spectroscopic and timing properties. Its density is 5.37 g/cm^3, light yield at 300 K (27°C) is 18 photons/keV with wavelength of maximum emission of 370 nm, thickness to stop 50% of 662 keV photons is about 2 cm, and 1/e decay time is approximately 27 ns. This material is not hydroscopic. [9]

Both scintillators were optically connected with standard photomultipliers.

Signals from the scintillators were recorded by fast digital oscilloscopes. A Tektronix oscilloscope (model DPO 3014) with band-width of 100 MHz and maximal sampling rate of 2.5 GS/s was used for data acquisition of the signals from the YAP:Ce scintillator with time discretization of 10 ns. Lengths of the records were approximately 30 ms. A Rohde & Schwartz digital oscilloscope (model RTO 1024) with band-width of 2 GHz and maximal sampling rate of 10 GS/s was used for data acquisition of signals from the NaI:Tl scintillator with time discretization of 5 ns. Lengths of the records were approximately 50 ms. Both oscilloscopes were triggered by a start signal provided by driving electronics of the tokamak Golem.

The YAP:Ce detector connected with the Tektronix oscilloscope is already a part of the plasma diagnostic instruments of the tokamak Golem, whereas the detection complete of the NaI:Tl detector with the Rohde & Schwartz oscilloscope was used as an additional instrument. It is the fact why we have used the faster oscilloscope with the slower scintillator.

E. Description of measurements

Orientations of the Timepix3 device have always respected characteristics of the X-rays and its positions were selected on a base of specific intentions.

A fundamental characteristic of the runaway electrons is their maximal possible kinetic energy. This energy limit is possible to estimate using theoretical considerations and this limit are 3 MeV and 10 MeV for tokamak Golem and Compass, respectively. Furthermore, this limit gives also limit for maximal energy of the X-ray photons. Interactions of these high-energy photons with electrons in the sensors are governed dominantly by the Compton effect. Directions to which the electrons are recoiled by these photons are distributed around the directions from the photons arrived as more closely as the incident photon energy is higher. It is the fact why the Timepix3 device was always oriented horizontally as sketched on the Fig. 3 and placed at the midplane of the tokamak.

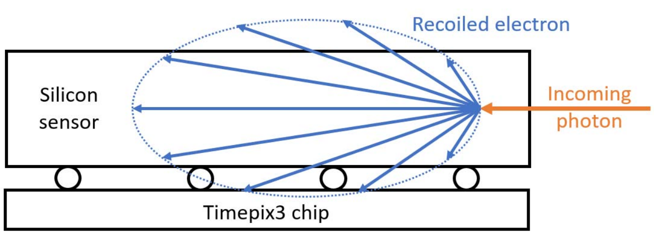

Figure 3 A visualization of the orientation of the Timepix3 device with respect to the direction from which the incoming photons arriving

This orientation maximize probability that the electrons with maximal recoiled energy remain in the active volume of the sensor. Nevertheless, due to ranges of the electrons with the highest energy, some electrons can escape from this volume and a part of their energy can be lost. This fact can have influence on measured energy spectra and it will be discussed below. For a declaration of this fact, it is possible to say that the range of 3 and 10 MeV electrons in silicon material is reaching of 8 and 22 mm, respectively, whereas the thickness of the silicon sensor is only 1 mm.

1) Description of measurements performed on the tokamak Golem

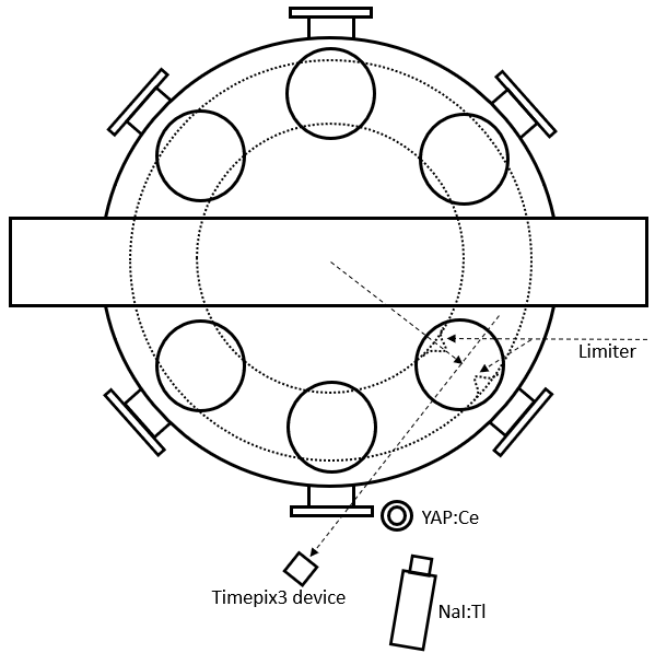

Figure 4 Floor projection of the tokamak Golem (see text for details)

The Fig. 4 represents a floor projection of the tokamak Golem with visualization of six diagnostic ports on top and next six diagnostic ports on side of this tokamak. Two dotted circles show position of the plasma chamber of the tokamak. In a place, diameter of this chamber is intentionally reduced to create a limiter (stopper). Main intention of the limiter is delimitation of plasma shape. In our work, we are using the limiter like a target of possible runaway electrons.

On the tokamak Golem, the Timepix3 device was placed in a tangential position relative to the electron beam in a place where the tangent of the electron beam crosses the limiter. This situation is imagined on the Fig. 4 together with positions of the scintillation detectors.

On this tokamak, we have performed three types of measurements. The first one is acquisition of energy spectra of the electrons recoiled by X-ray photons using the Compton scattering inside the active volume of the silicon sensor. The second one is recording of time evolution of intensity of the X-rays. The last one is verification of the fact incoming from theory of relativity that intensity of the produced continuous part of the X-ray (so called Bremsstrahlung) is higher in direction in which relativistic electrons arriving than in the opposite one. For this type of measurement, we did not change the position of the Timepix3 device but we reversed directions of all electric and magnetic fields of the tokamak with intention to flip over the direction of circulation of electrons in the plasma.

2) Description of measurements performed on the tokamak Compass

On the tokamak Compass, the Timepix3 device was placed in four different positions relative to the tokamak. The first one was on a diagnostic port with a Beryllium window for monitoring of events in the tokamak chamber producing low-energy X-ray photons. The second one was near this port but outside the region with high magnetic field. The third position was on a tangential position for similar measurement geometry to the measurement on the tokamak Golem. The last position was near a wall of the tokamak experimental hall with intention to analyze hard X-ray photons reflected from this wall.

III. EXPERIMENTAL RESULTS

A. Spectroscopic measurements on tokamak Golem

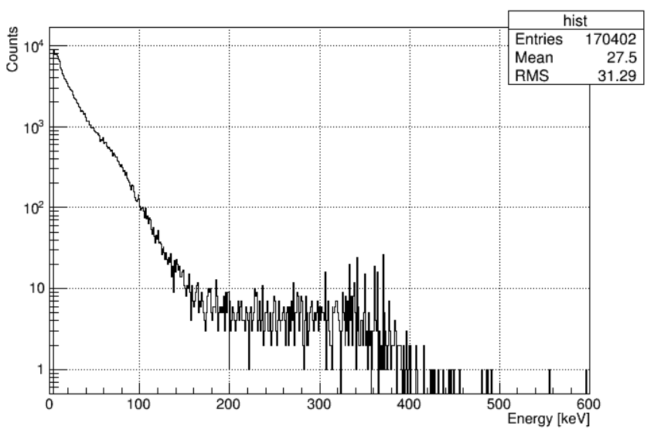

Figure 5 An example of energy spectrum of electrons recoiled by X-ray photons in the silicon sensor. The spectrum was measured during an experiment on the tokamak Golem (Shot No. 27758)

The Fig. 5 shows an example of energy spectrum measured on the tokamak Golem using the Timepix3 device with the silicon sensor. The spectrum represents a distribution of energies of the electrons recoiled by X-ray photons predominantly by means of the Compton scattering in the silicon sensor. Shape of this spectrum has two typical parts. The first one has an exponential-like shape (from 4 keV to cca. 150 keV) with a broad peak around 70 keV (roentgen-fluorescence from lead covered the TPX3 detector). The second part is represented by a plateau (from cca. 150 keV to 350 keV). This part is probably related to events when the recoiled electrons escaped from the silicon sensor due to the fact that their range is greater than the sensor thickness (as mentioned already above). This phenomenon will be studied using next experiments and analyzed using Monte-Carlo simulations.

The energy spectrum shown on the Fig. 5 is drawn using a semilogarithmic plot with a base-line interval from 0 to 600 keV with intention to well imagine its shape. However, some events with energy higher than 600 keV were also registered. During 23 shots (from Shot No. 27738 to Shot No. 27762; except unsuccessful shots No. 27751 and 27754) 893 717 events were registered. Only 49 events from these events have energy higher than 600 keV. During one shot, from 0 to 7 with mean value of approximately 1.8 events with energy higher than 600 keV were stored. Maximal registered energy was cca. 2.47 MeV.

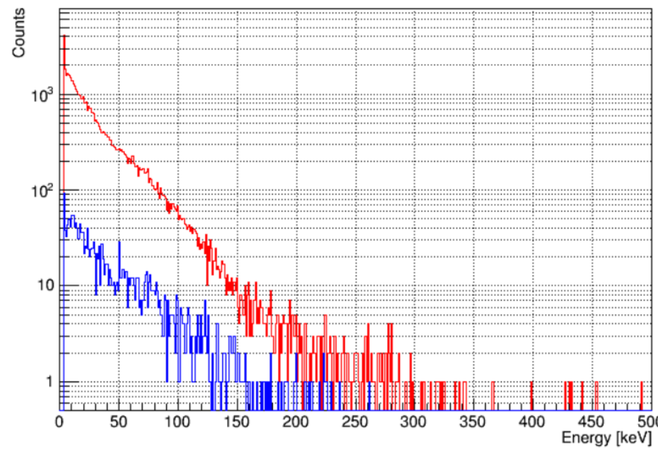

Figure 6 Comparison of two spectra measured under two opposite circulation of the plasma electrons. The red spectrum represents the situation when the runaway electrons hit the limiter in same direction in which the Timepix3 device was placed. The blue spectrum represents the opposite situation.

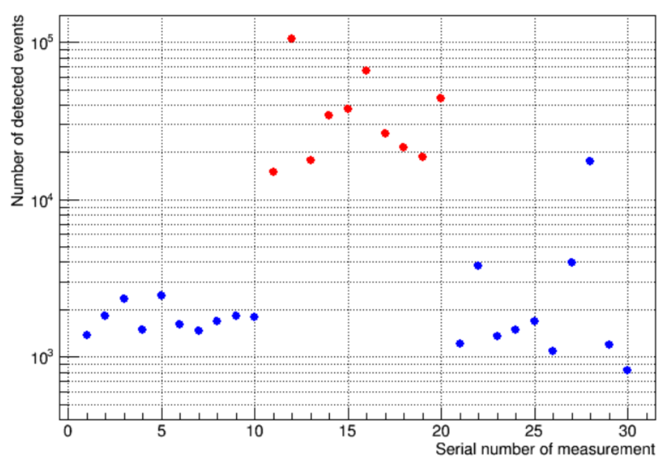

Figure 7 Result of repeated measurements representing intensities of the X-rays in backward (blue points) and frontward (red points) direction

We have also observed that energy spectra are different for opposite directions of circulation of the plasma electrons and, as we expected, with opposite directions of fly of the runaway electrons. Fig. 6 shows an example of two typical spectra. The spectrum drawn with red color was measured in the situation when the runaway electrons hit the limiter in the same direction in which the Timepix3 device was placed (so called frontward direction). The spectrum drawn with blue color is measured under the opposite direction (so called backward direction). These spectra have approximately same shape (similar as discussed above). The difference is only in numbers of detected events. It means that intensity in frontward direction is higher than in the backward one. It declares that the runaway electrons have relativistic velocities.

Since each shot on tokamaks is original and repeated measurements are influenced by high fluctuation, we measure three series of measurements under as same condition as possible, except the direction of electric and magnetic fields in the case of the second series. Our results are visualized on the Fig. 7.

Each point of the Fig. 7 represents an intensity of the X-rays in the term of a number of events detected by the Timepix3 device. Blue color represents intensities in backward direction, the red one in opposite direction. The first series (Serial number: 1-10) is related to the shots with numbers 26967-26970, 26972-26975, and 26977-26978. The second series (Serial number: 11-20) is related to the shots with numbers 26989-26998. The last series (Serial number: 21-30) is related to the shots with numbers 27007-27016. The shot number of the measurement with the highest number of the detected events of this third series is 27014. The last series was measured with intention to show that the number of the detected events will return on similar values (except some fluctuation) like the values in the case of the first series when we turn over again all electric and magnetic fields.

Measured data shows that intensity of the X-rays in frontward direction is approximately 15 times higher then the intensity in the opposite one. The work for physical interpretation of this result is still under way.

B. *Timing measurements on tokamak Golem*

We have measured time evolutions of the X-rays using the Timepix3 device and using standard diagnostic techniques based on NaI:Tl and YAP:Ce scintillators for comparison. The measured records are shown on the Fig. 8.

The measured records show very small correlation, e.g. around the time of 4 ms, there is practical no signal in all three records. Other characteristics are very different. The differences are higher under higher intensity of the X-rays and, of course, the records are more similar under lower X-ray intensity, as declared by the Fig 9.

The Fig. 9 shows four groups of pulses measured using both scintillators under low intensity X-rays. The intensity was so low that the Timepix3 did not provide any data. Even though these four groups happen in approximately same time in the case of both records, their structures are different (namely in the case of the records in interval from 5 to 9 ms).

Using comparison of the records obtained from the scintillators and imagined on the Fig. 8 and 9, we are deducing that the differences between the records stored under the condition of the high-intensity X-rays are caused more likely by read-out electronics whereas the differences between the records stored under the condition of the low-intensity X-rays are caused probably by high fluctuation in both number of detected events and deposited energies given by different detection efficiencies of the scintillation materials. These both reasons will be considered during next experiments which will be oriented on explanation of observed differences.

Differences between records measured by the scintillation detectors and the Timepix3 device are also interesting. All records on the Fig. 8 and 9 have a form of a superposition of many pulses or peaks with random position and height. Only in the case of the record stored using the Timepix3 device it is possible to see several periodic-like structures of the peaks.

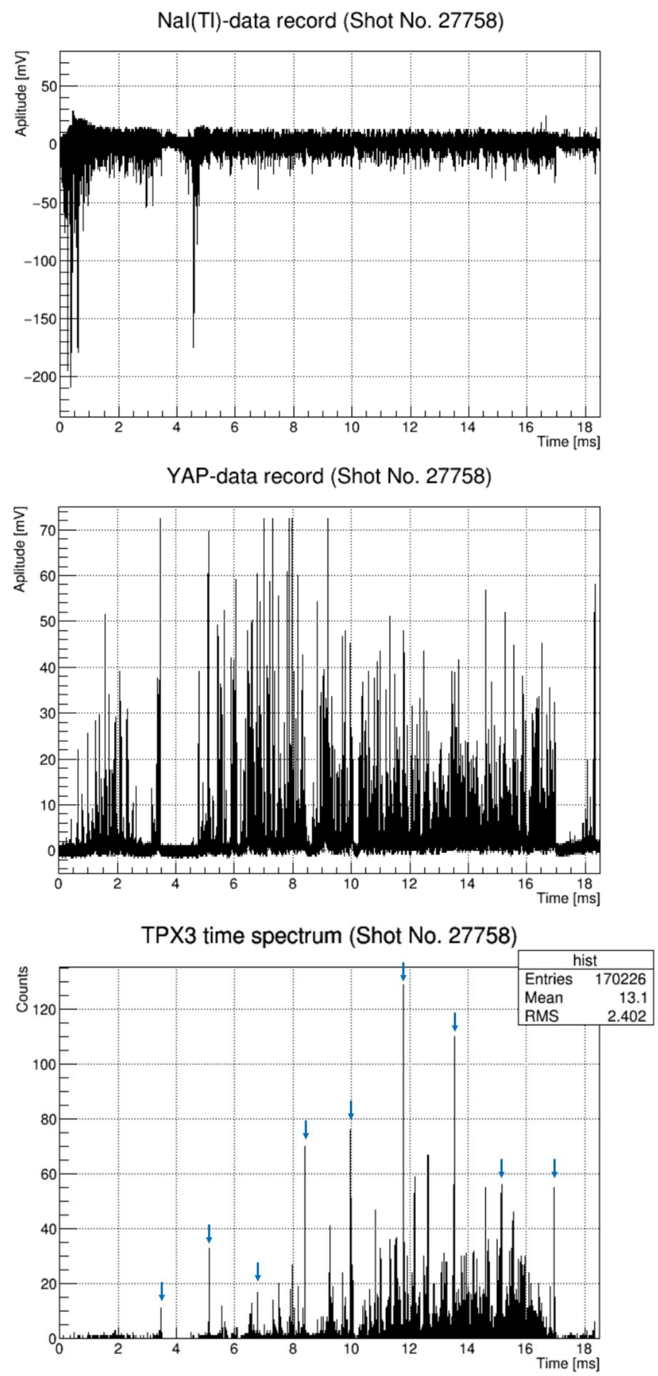

Figure 8 An example of three records obtained using NaI:Tl and YAP:Ce scintillators and Timepix3 device during Shot No. 27758

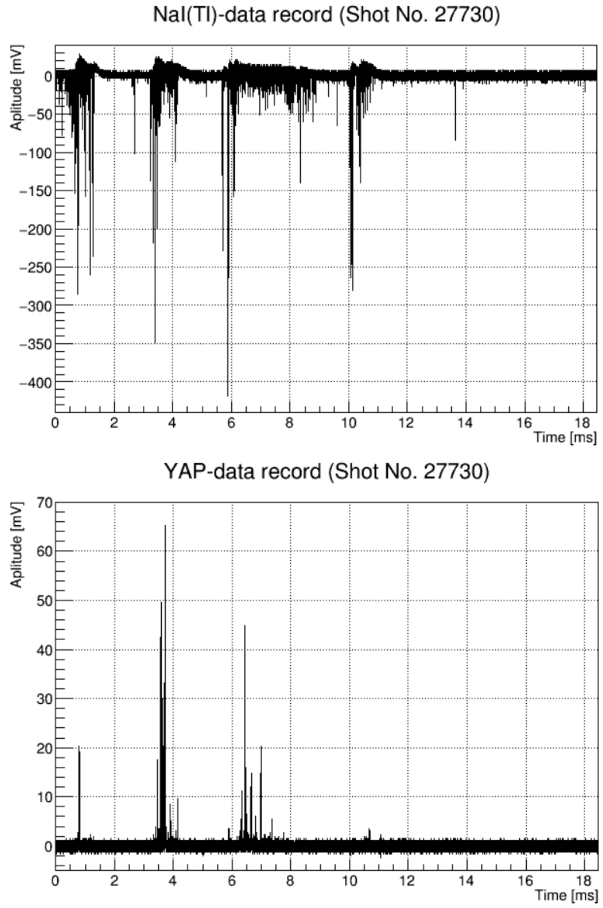

Figure 9 An example of records obtained by NaI:Tl and YAP:Ce scintillators under low-intensity X-ray glimmer

One series of these peaks is shown on the last plot of the Fig. 8 using nine blue arrows. Main difference between the record measured by the Timepix3 device and the records measured by the scintillation detectors is that the Timepix3 record is given by numbers of detected events whereas the records obtained by the scintillation detectors are given by time evolutions of deposited energy.

Fig. 10 shows time duration of typical X-ray flashes generated by the runaway electrons. The duration is usually up to 10 μs. The shown detail of the record obtained during the Shot No. 27758 is on the beginning of this record when the X-ray intensity was low (see Fig. 8). In this case, the profile of the peaks looks like to by symmetric. However, asymmetric profiles were also stored.

Fig. 11 represents another phenomenon. This detail shows a very short record with numbers of detected events in 100 ns length intervals. Except one, these numbers vary from zero to seven with the mean value of cca. 1.32 and standard deviation of cca. 1.65. The value of twenty counts registered in one case is therefore approximately of 11 standard deviations above the mean value. What happens during so short interval that the Timepix3 device registered unexpected higher number of detected events? Moreover, the obtained standard deviation does not correspond the standard deviation of the Poisson distribution. By which statistics are governed the fluctuations of the numbers of detected events?

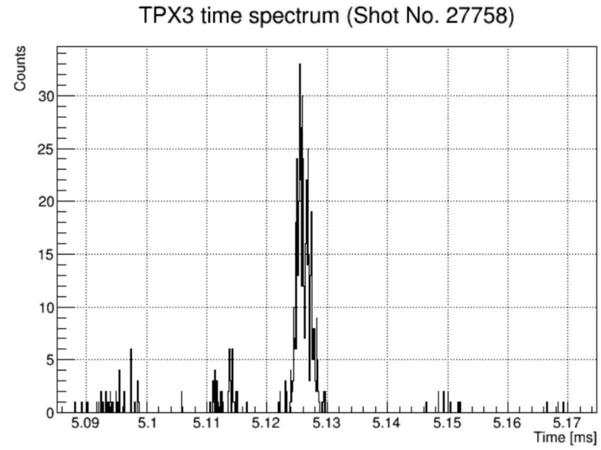

Figure 10 A detail of the record measured by the Timepix3 device demonstrating that X-ray flashes have duration up to 10 μs

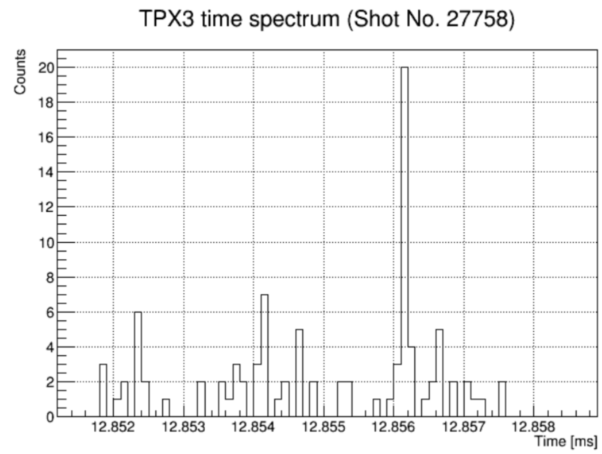

Figure 11 A deatil of the recors measured by the Timepix3 device showing infrequent phenomenon of sudden increase of counts (the number of detected events) in a very short time (less than 100 ns)

It is evident that results of our measurements give more questions than answers. We will try to find answers on these and also other questions during planned experimental studies.

C. Spectroscopic measurements on tokamak Compass

The measurements on the diagnostic port with a Beryllium window for monitoring of events in the tokamak chamber producing low-energy X-ray photons were unsuccessful (probably due to fast changes of the strong magnetic field).

Data analysis of the measurements performed beside the tokamak was successful only in the case of lower intensities of the X-rays produced by the runaway electrons. Such condition was during day 11.04.2018 (Shot Numbers: 16669-16683). The facts shown below were observed from these measurements. Processing of other data are still under way.

Fig. 12 shows a typical spectrum measured by the Timepix3 device on the tokamak Compass. Shape of this spectrum is similar like the spectra measured on tokamak Golem. Only number of events with higher energy is higher and the plateau is more significant than in the case of measurements on the tokamak Golem (sometimes the plateau has a form of a broad peak). Both observed facts have reason in higher intensity of the X-rays.

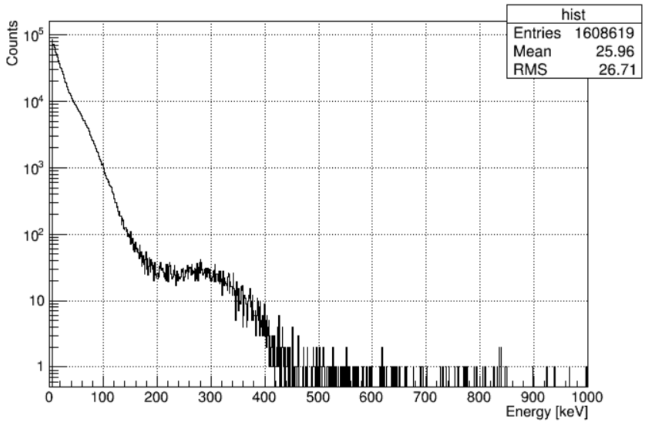

Figure 12 An example of energy spectrum measured on the tokamak Compass using the Timepix3 device. The spectrum was obtained during Shot No. 16683.

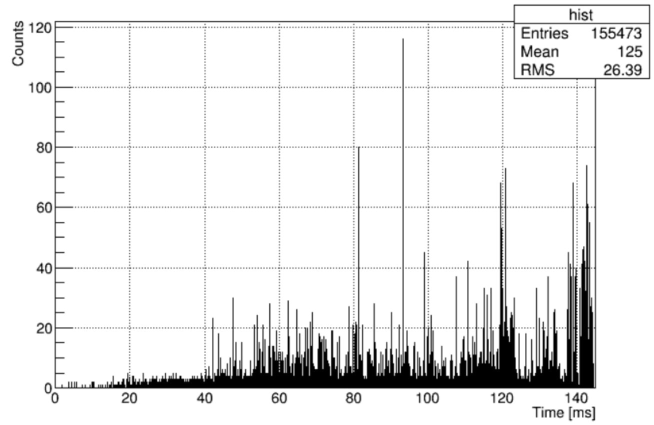

Figure 13 An example of time evolution of low-intensity X-rays. The record measured during Shot No. 16682.

D. Timing measurements on tokamak Compass

Fig. 13 shows a typical record of X-ray intensity monitored by the Timepix3 device under condition when number of registered events is low (e.g. up to several hundred thousand per shot). Such records provide same information like the records measured on the tokamak Golem with similar quality. Only with the difference that the records measured on the tokamak Compass are approximately ten times and even longer than the records measured on the tokamak Golem.

On the other hand, in the cases when number of registered events is high (e.g. above one million events per shot), the records are distorted by unwanted artefacts. Such typical artefacts are periodically fallings in counts as demonstrated by Fig. 14. The count fallings can be caused by loss of some date during the process of preprocessing and storage of previous data.

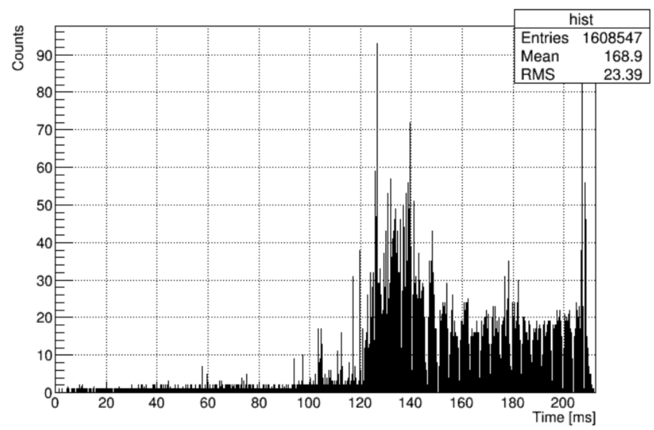

Figure 14 An example of time evolution of higher-intensity X-rays. The record measured during Shot No. 16683.

Almost measurements on the tokamak Compass were influenced by inability to record all detected events. The TPX3 device was able to store even more than one million events but unknow number of events was lost. Work with intention to solve this problem is under way.

IV. Discussion and Conclusion

Main goal of this work was to find if the Timepix3 device is able to provide relevant spectroscopic and timing data about X-rays produced by the runaway electrons when it is placed beside tokamaks. It is a step in our long-term endeavor to investigate segmented semiconductor detectors as a runaway diagnostic. Other results can be observed for example in [10].

This goal was achieved in the case of the tokamak Golem. On this tokamak, we have measured time evolution of X-ray intensity with time discretization of 100 ns. We have observed that duration of the X-rays flashes is up to 10 µs and we have measured profiles of these flashes which can be now analyzed. We have also measured spectrum of energies of the electrons recoiled by X-ray photons in silicon sensor of the Timepix3 device.

The energy spectra are probably deformed by expected escape of the recoiled electrons from the sensor active volume due to their higher range in silicon given by their higher energy. Even so this disadvantage, the Timepix3 device is suitable for construction of detection systems dedicated for detection of the tokamak hard X-rays.

In the case of the tokamak Compass, the situation is different. Main problem is that the Timepix3 device is not able to store all registered events due to very high X-ray flux. Since the electronics for the Timepix3 chip is designed by the way that it is possible to send all data read from the chip, the problem can be in the personal computer used for data storing. In next experiments, we try to store the data directly on SSD or RAM disc without any preprocessing. If it will not help then it means that the Timepix3 device is receiving so many events that it is not able to send all data and some events are lost. In this case, we can increase the distance between the tokamak and the device or we can use a suitable shielding. If it will not help, we will have to wait if the new Timepix4 chip, which is now developed, will be faster and, therefore, more suitable for measurement on the tokamak Compasss.

We have used the Timepix3 device because it was in disposal. However, during meantime, new electronics and software were improved and new sensors were tested with the Timepix3 chip. Therefore, during currently planned experiment, we will use new Timepix3 devices with both silicon sensors with intention to verify repeatability of our results and GaAs and CdTe sensors for their reproducibility.

Moreover, the GaAs is one of the detector-grade materials with the highest mobilities of the charge carriers and, therefore, its charge collection is very short. Its typical time of the charge collection is about 1 ns or less. Since the period of the multiplied clock signal of the Timepix3 chip is about 1.56 ns then combining of these two values we can use the time discretization less than 4 ns which is 25 times finer than the discretization used in this work.

In contrast, the CdTe is a detector-grade material developed and tested for detection of gamma rays. Namely due to its high density and high proton number (in contrast with the silicon) and due to ability to manufacture such sensors with greater thicknesses (e.g., 2 mm), its detection efficiency is significantly greater than the detection efficiency of the Timpeix3 device used in this work. Using experiments with CdTe@Timepix3 devices, we will verify if these devices will have still capability to store all detected events. If yes, we will use them in the construction of the detection systems (e.g. Compton camera).

Finally, we will be also explored new fast detection scintillators for such situations in which the Timepix3 devices are not applicable.

ACKNOWLEDGMENT

We thank Advacam s.r.o. for lending of the Timepix3 device for the presented work and we also thank operators of both used tokamaks for permit and support of the performed experiments.

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