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Runaway electrons diagnostics using segmented semiconductor detectors

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ABSTRACT

A novel application of strip and pixel silicon radiation detectors for study and characterization of run-away electron events in tokamaks is presented. Main goal was to monitor runaway electrons both directly and indirectly. The strip detector was placed inside the tokamak vacuum chamber in order to monitor the run-away electrons directly. Whereas the pixel detector was placed outside the tokamak chamber behind a pin hole for monitoring the run-away electrons indirectly via radiation produce by interaction of the electrons with the plasma facing material. Results obtained using the silicon detectors are compared with already existing diagnostic methods consisting of scintillation devices detecting X-rays and photo-neutrons, providing the same results in the observable comparisons. Tests with the pixel detector proved that the pinhole camera is able to extract spatial information of interaction point (a place where the runaway electrons hit on the facing material) and the strip detectors indicate presence of additional signal from throughout the discharge. The performed experiments are innovative, illustrating possible development of new and easy to use diagnostic method.

1. Introduction

During various stages of plasma discharge in a tokamak a number of electrons can be accelerated to very high energy – these are so called runaway electrons (RE) [1–3]. Population of such particles may end up interacting with the tokamak components, delivering vast amount of energy by ionization of surrounding material. This interaction may be detrimental to the device [4] and since the exact generation and transport processes are still not fully understood, new diagnostic methods are necessary, to provide information about time and position of either trajectory or impact of an electron beam on the plasma facing components. Experimental effort focused on understanding RE related processes is strongly pursued by tokamak COMPASS (IPP CAS in Prague) [5–7], where most of the proposed measurements took place.

Silicon semiconductor detectors are from a category of solid-state detectors, commonly used in high energy physics (HEP) experiments. The recent advances in this field allow for the development of new diagnostic methods, utilizing their particle detection capabilities, including unprecedented dynamic range as well as energy, spatial and temporal resolutions. In tokamaks, these capabilities can be exploited for detection of runaway electrons.

The radiation tolerance of the semiconductor detectors is well established in the HEP, the detectors currently in development have a lifetime TID tolerance up to 10 MGy and NIEL up to 10^{16} n/cm^2 [8]. However, the ionizing and especially NIEL fluxes in large fusion experiments will exceed those values in a relatively short operation time, measures would have to be taken to limit the flux of incoming radiation.

2. Semiconductor detectors

Semiconductor detectors are typically segmented into multiple detection channels, which can be arranged in a strip (sensitive lines) or pixel (sensitive matrix) configuration. Their primary advantages relevant to the plasma experiments are fast signal collection and detector readout, minimal dead time and well-defined radiation tolerance.

The detection process in general requires ionizing radiation to produce electron-hole pairs (average energy for generation of one pair

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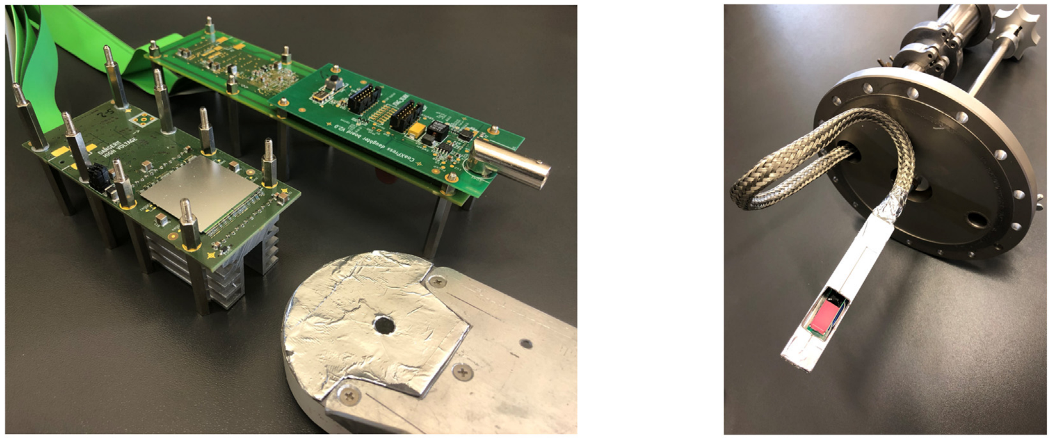


(a) Medipix2 detector with CoaXPress readout and lead pinhole, used during RE related COMPASS campaigns.

(b) PH32 detector attached to a radial manipulator, used during RE related GOLEM campaigns.

Fig. 1. Utilized semiconductor detectors.

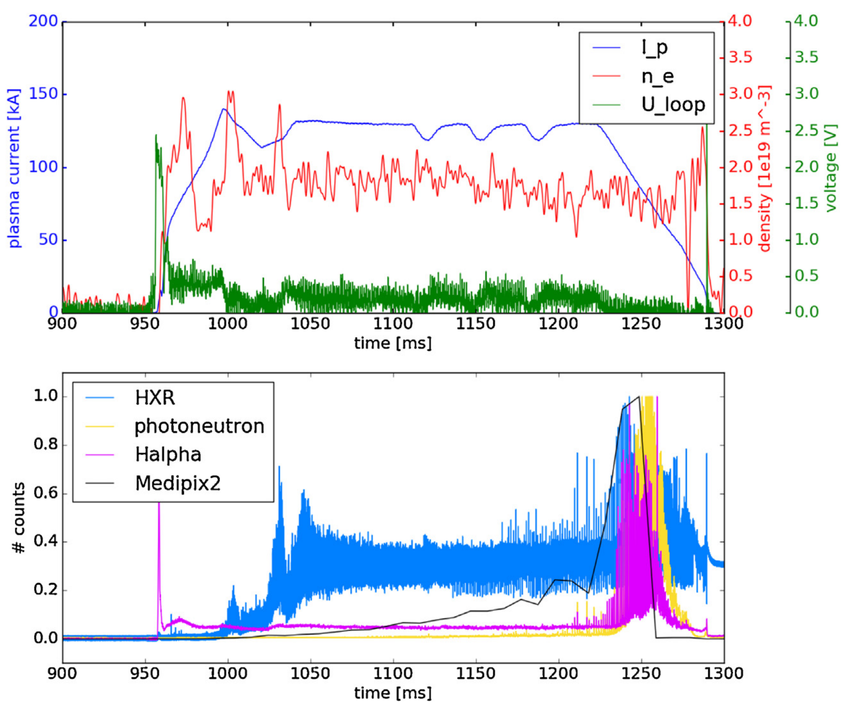


Fig. 2. Comparison of COMPASS selected diagnostics with Medipix2 detector for discharge number 14513. Upper plots show evolution of parameters of plasma discharge – plasma current I_p, electron density n_e and loop voltage U_{loop}. Lower plots show different X-ray diagnostics (HXR and photo-neutron scintillators), H-alpha spectral line intensity and Medipix2 hit-counts, all normalized to the respective maximum value.

is 3.6 eV) in the sensor medium. Utilizing properties of semiconductors as well as applying electric field, these electrons and holes drift to the opposite sides of the sensor, generating induced current on the collecting electrodes.

Each of the detection elements (either strip or pixel) is connected to an application specific integrated circuit (ASIC), in which a conversion from an analog current pulse to a digital signal is performed. Readout of the detector is ensured by a data acquisition system, which provides communication to and from the computer.

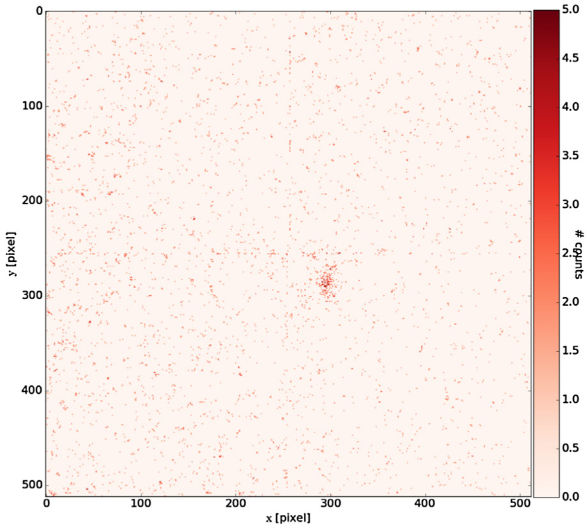
In presented measurements detectors Medipix2 and PH32 have been used.

2.1. Medipix2

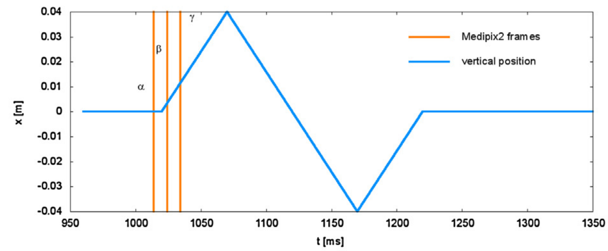
Medipix2 [9] is a hybrid pixel detector primarily designed for photon-counting X-ray imaging applications. It was developed by the Medipix2 collaboration at CERN. The single chip has a matrix of 256 × 256 pixels with a 55 × 55 μm pixel pitch. Larger detection area can be achieved by butting several detectors side-to-side – such "quad" 2 × 2 configuration was used in the presented measurement.

The sensor was 300 μm thick silicon, providing energy range from around 5 keV up to 50 keV. Even though the detection efficiency of the silicon sensor decreases sharply with increasing photon energy, the higher energy signal component might be registered as noise in the image due to interaction of particles in the shielding material producing secondary radiation.

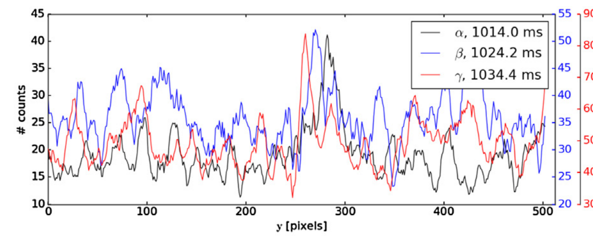
For the device operation CoaXPress [10] readout card was used. Its main advantage is usage of a coaxial cable between the setup and a computer, which simultaneously protects PC and provides the maximum readout speed of the Medipix2 chip – approximately 100 Hz. The dead time needed for the single chip to process the signal and transfer data is (256 × 256 × 14)/100 MHz ≈ 9.2 ms, however, multiple chips are read out in parallel without any extra dead time.



(a) Medipix2 hit-map for t = 1014.0 ms.



(b) Request on vertical position of the plasma center and Medipix2 frames.



(c) Y-axis histogram of hit-counts for three different time frames. Movement of a soft X-ray hot-spot can be observed.

Fig. 3. Results of vertical positioning of plasma at the COMPASS tokamak (discharge 14555) with detector using geometric optics, imaging HFS limiter. Both size and movement of the hot-spot are approximately 25 pixels, corresponding to 1.39 cm (in comparison to the current centroid movement of around 1.2 cm).

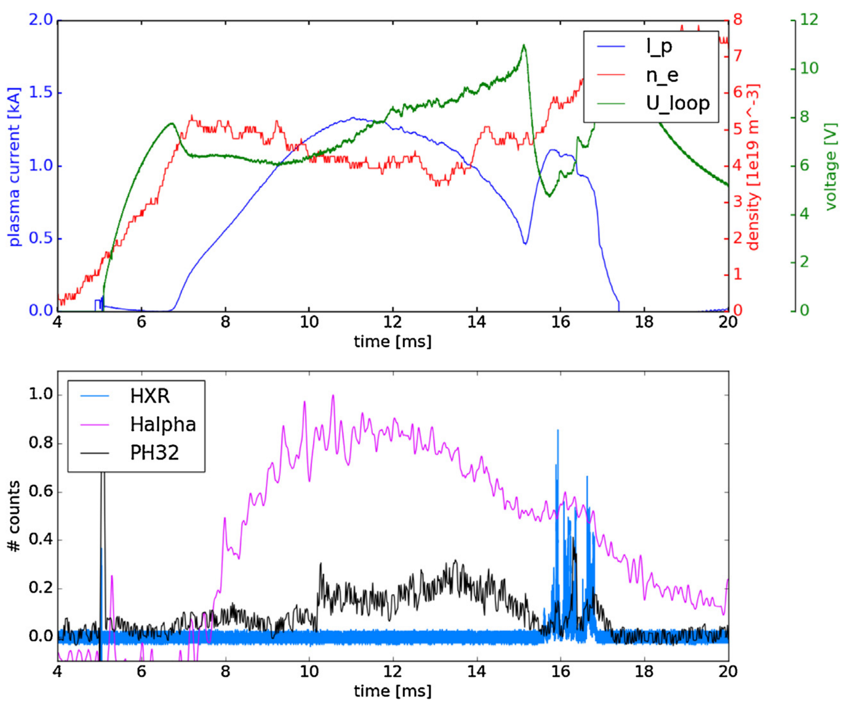


Fig. 4. Comparison of GOLEM selected diagnostics with PH32 detector for discharge number 27487. Upper plots show evolution of parameters of plasma discharge – plasma current I_p, electron density n_e and loop voltage U_{loop}. Lower plots show HXR scintillator, H-alpha spectral line intensity and PH32 high-gain mode hit-counts, all normalized to the respective maximum value.

2.2. PH32

The detector PH32 [11] is a hybrid strip detector developed at the Center of Applied Physics and Advanced Detection Systems (CAPADS) at FNSPE CTU in Prague. It has 32 detection strips with a pitch of 250 μm, each strip is 18 mm long. The PH32 detection capabilities in this application are exceeding those of Medipix2, namely shorter dead time and different modes of operation at the cost of a lower number of detection channels.

The time needed to process the data is 60 μs, which results in more than 10 times higher frame-rate in comparison to Medipix2. Operation of the detector can be set to hit-counting or deposited energy measurement with time over threshold method (TOT). Furthermore, it can operate in high gain mode (sensitive to the energy of soft X-rays) or low gain mode (sensitive to large deposited energies such as those deposited by protons and heavy ions). Besides, the new version of the PH32 chip allows the Time-of-Flight (TOF) functionality, which can be used in various applications ranging from particle tracking to ion mass spectroscopy [12].

3. Measurement methods

The proposed measurement of RE was done using two different approaches – indirect (measurement of X-ray radiation from interaction of RE with material) and direct (measurement of RE in vacuum vessel close to the plasma surface). Data from tens of discharges were then compared to the H_α spectral line intensity and existing X-ray diagnostics [6] at tokamaks COMPASS (IPP CAS in Prague) and GOLEM (FNSPE CTU in Prague).

3.1. Indirect measurement

The Medipix2 based detector setup was placed on a diagnostic port covered with a beryllium window, enabling transmission of generated soft X-rays. To obtain spatial information, geometric optics consisting of a lead pinhole (see Fig 1 a) was used, projecting high field site (HFS) limiter (distant 50.0 cm) to the sensor surface (distant 0.5 cm).

The acquisition window of detector was set to 1 ms and the readout was triggered externally at the beginning of the discharge. All parts of the diagnostic unit are shown in Fig. 1a, the measurements were made during the RE campaigns at the COMPASS tokamak. Since the temporal resolution of Medipix2 limits which events may be recorded (due to the speed of the ASIC readout), its application is mainly to verify its feasibility and detectors with faster readout and better timing resolution should be used in the future measurements.

3.2. Direct measurement

A proof of concept measurement consisted of utilization of the PH32 detector inside the vacuum vessel, placed on a radial manipulator. Data were read out by connecting the analog output from one strip to the oscilloscope, triggering measurement at the beginning of the discharge. The final setup is shown in Fig. 1b. Measurements took place at tokamak GOLEM, whose compact size enables variability in testing and short pause between discharges (short inter-shot period). The tokamak is ideal for finding the operational limits of semiconductor detectors in variable electromagnetic field close to the plasma surface.

4. Results

4.1. Indirect measurement

Overall hit-counts measured by Medipix2 setup at tokamak COMPASS are well correlated with signal from scintillators registering hard X-rays (HXR) and photo-neutrons/gammas with very high energy (see Fig. 2). It can be observed that the HXR scintillator quickly reaches saturated-like signal and amount of photo-neutrons peak during plasma termination phase, however, the measured signal from the detector is steadily increasing, also peaking during the plasma termination phase. This behavior was consistent for all discharges which were tagged as producing RE (i.e. known operation state of the tokamak), otherwise no signal was measured.

As an advantage of the use of a segmented detector, spatial information using the geometric optics oriented towards the HFS protruding limiter was obtained. Experiments with the required vertical movement of the plasma ring were performed, resulting in a visible movement of the soft X-ray hot-spot, recorded by the detector as shown in Fig. 3. The hot-spot size and movement of approximately 25 pixels (from 1014.0 ms to 1034.4 ms) corresponds to 1.39 cm, which is in reasonable agreement given the precision and geometry of the plasma column with respect to the limiter. The signal from hot-spot is dominant against the background only at the beginning of the discharge, due to lack of highly energetic photons whose amount increases over time.

In order to make the measurement more precise with a higher S/N ratio, improved shielding of the detector and better understanding of the data, a 3D simulation of interaction of particles with the tokamak components should be performed.

4.2. Direct measurement

The proof of concept measurements using the PH32 detector provided a measurable signal throughout the most of the discharge, with sharp peaks during plasma termination which are in agreement with the signal from scintillators (see Fig. 4). No other dependence of the signal is visible, however, further experiments need to be performed in order to exclude effects of induced current due to the rapid change of the electromagnetic field. No signal was measured during the vacuum discharge.

Semiconductor detectors are commonly operated in strong (usually static) electromagnetic fields in high-energy physics experiments. The rapid change of magnetic fields may induce current in the readout system or in the sensor ASIC, resulting in fake signal or causing the configuration of/communication with the detector to be lost. The former effect is not yet fully understood and the latter one was rarely observed, and the device performed without any issues. These effects can be mitigated in the future experiment by the proper PCB design techniques of the readout interface such as minimizing the number of ground loops.

5. Conclusions

Semiconductor pixel detectors were demonstrated to be a functional new addition to the RE diagnostic methods at tokamaks. Recorded secondary photon hit data correlate well with other used diagnostic methods. In addition to that, semiconductor detectors could provide information about position of interaction or trajectory of RE. Since their full potential in this field of research is not yet exploited, their application should be studied further. They represent very compact solution enabling simple integration into the system. Therefore a novel segmented semiconductor detection system is being developed as a new method of diagnostics, providing both spatial and temporal resolution throughout the plasma discharge.

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