The direct detection of runaway electrons using the semiconductor strip detector

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During plasma discharge in a tokamak, a number of electrons can be accelerated to high velocities and gain energy in the order of MeVs. These so-called runaway electrons (RE) can have a serious detrimental effect on the vacuum vessel and associated instrumentation. Presence of RE loses is usually measured indirectly by hard X-ray (HXR) detectors outside of the vacuum vessel of a tokamak. Development of new diagnostic methods is needed for better understanding of RE generation and transport. Silicon semiconductor detectors are widely used in high energy physics as particle tracking detectors. This type of detectors could provide information about time and position of RE when they lose confinement.

Semiconductor detectors. Modern semiconductor radiation detectors emerged in high-energy physics (HEP) and presently they are widely used in physics research because they have unique properties, such as fast signal collection, large signal amplitude and can be manufactured using commercial semiconductor processes. They can measure both the intensity and the energy of incident radiation. Of the existing semiconductor materials, silicon is primarily used for charged particle detectors (especially in tracking detectors in HEP) and soft X-ray detectors. In silicon, passing ionizing particle creates an electron-hole pairs along its path. The mean energy for the creation of a single electron-hole pair is approximately 3.6 eV. By applying an electric field and with help of properties of semiconductors, electrons and holes drift to the opposite sides of the sensor. An induced current is amplified and measured by sensitive electronic circuits. Semiconductor sensors are usually segmented into channels, which can be arranged as pixels or sensitive strips. Each channel is connected to the charge-sensitive amplifier in the application specific integrated circuit (ASIC), which amplifies and converts analog pulse to digital signal [3].

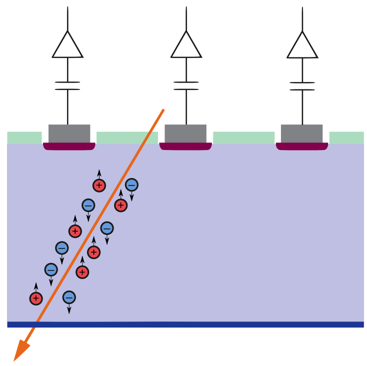

Figure 1: *The working principle of semiconductor radiation detectors. Passing ionizing particles liberate electron-hole pairs whose movement induces signal on the pickup electrodes.*

The PH32 is an ASIC designed for the readout of the hybrid semiconductor strip detectors. It was developed by Center of Applied Physics and Advanced Detection Systems (CAPADS) at FNSPE CTU in Prague. The detector setup consists of the PH32 readout chip, a silicon strip sensor and the USB readout interface. The PH32 ASIC was manufactured using commercial 180 nm CMOS technology and contains 32 identical channels. ASIC input channels are wire bonded onto the AC pads of the silicon sensor. The sensor is of the n^+ on p type with thickness of approximately 500 μm. Each of the strips has dimensions of 250 $\mu\text{m} \times 18$ mm. The detector can operate in two modes of input signal amplitude. The high gain mode is suitable for X-ray and Compton electron detection and low gain mode for alpha particles and heavy ions. The detector can be set to particle counting or measuring deposited energy by the Time over Threshold (ToT) method. Measured values are stored in 16bit counter which can be read as a shift register, the time needed for reading the register and their setting to initial value gives the dead time of the detector, which is approximately 180 μs. In addition, the output from one strip can be connected directly to an oscilloscope. Configuration and transmission of measured data from a chip are possible via SURE (Simple USB Readout Equipment) data acquisition readout card [2].

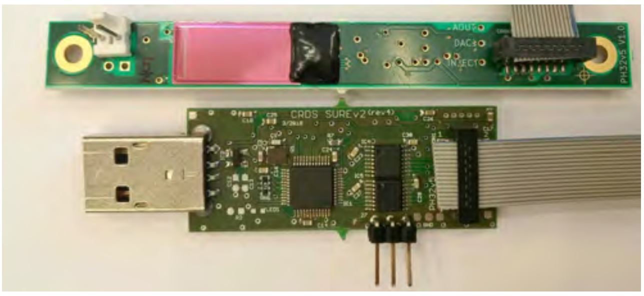

Figure 2: *PH32 chip with SURE (Simple USB Readout Equipment) data acquisition card. The ASIC is hidden by a layer of epoxide to protect sensitive wire bonds.*

The GOLEM tokamak, located at the FNSPE CTU in Prague, is the oldest operational tokamak in the world. It serves primarily for educational purposes for domestic as well as foreign students via remote control. Its compact size ($R_0 = 0.4$ m; $a = 0.85$ m) and parameters of plasma discharge ($U_{\text{loop}} = 4-6$ V; $B_t < 0.8$ T; $I_{pl} < 8$ kA; pulse length < 15 ms; $n_e \sim 10^{18}\,\text{m}^{-3}$) presents favorable conditions for testing new diagnostics in strong magnetic and electric fields [5]. RE are generated in this device during

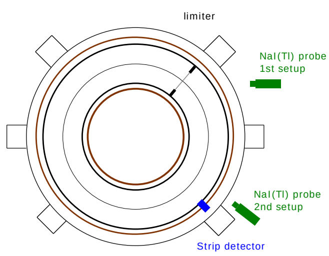

Figure 3: *The schematic layout of the experiment.*

normal operation, due to low plasma density and relatively large loop voltage [1].

Experimental setup. The PH32 detector placed in a metal box with a hole above the sensor, the hole was covered with a thin aluminum sheet to ensure electromagnetic shielding of the detector. In addition, an optical USB cable was used for connecting SURE to a computer and an external electric field in a sensor was sustained by a battery to eliminate EMPs. Metal box with the detector was mounted on a radial manipulator and placed inside vacuum vessel of the GOLEM tokamak. Side view of a port with the detector inside is shown in figure 4. Measured data were compared with output from HXR NaI(Tl) scintillator, which is standard diagnostic for measurement of RE loses at GOLEM. Normally, the scintillator is placed near the limiter, but for one session it was moved next to the port in which semiconductor detector is placed. The layout of the experiment is shown in figure 3. Strips number 13 and 14 were expected to provide a false signal due to damage in wire bonding.

Results. Even though measurements were conducted with the strip detector being set in low gain mode, the output from amplifiers in ASIC was often saturated. Periodic noise is present in the analog output from one strip. This periodic noise comes from the electric interference from the readout system induced onto the ASIC input. Time between pulses is different in figures 5 and 6, in the first case acquisition time was 1090 μs in latter 200 μs. When the detector operates in the hit-count mode, a saturated signal is interpreted as one hit by counting electronics (see channels 0 to

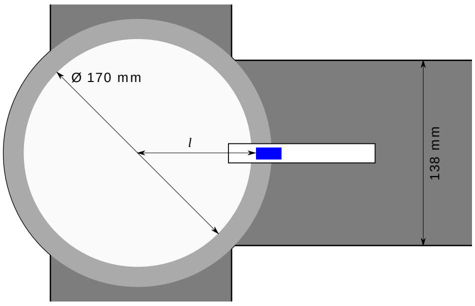

Figure 4: *The side view of the port with detector inside*

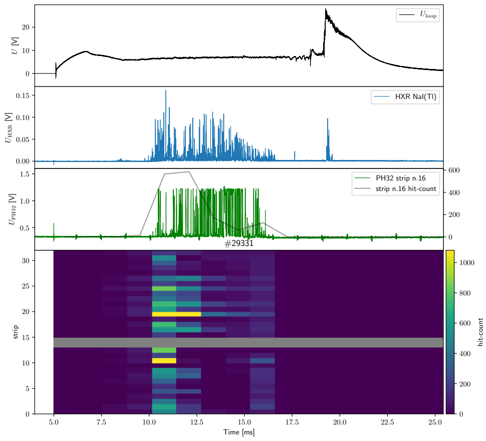

Figure 5: *Comparison of PH32 measurement with other diagnostics. Shot no. #29331, the distance of the sensor from the center of the tokamak chamber* $l = 109$ mm*, sensor facing up, 1st setup.*

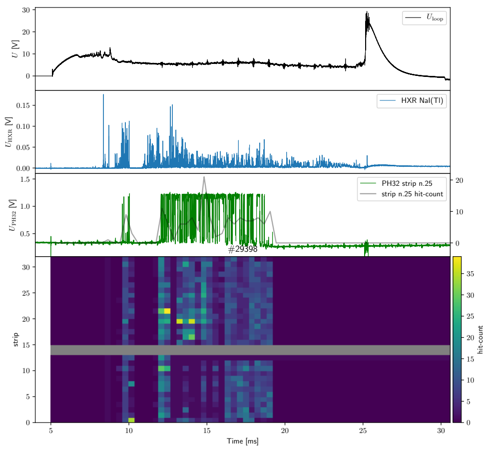

Figure 6: *Shot no.#29398,* $l = 110$ mm*, sensor facing up, 1st setup.*

13 in time between 12 ms and 16 ms in figure 6).

The ToT mode gives values more comparable to an analog output. Spatial distribution of incoming radiation was observed when the sensor was placed closer to the plasma surface (fig. 7). When the scintillator detector was placed beside the port, where the strip sensor was located, a significant correlation between both diagnostics was observed (fig. 8).

Conclusions. The silicon strip detector based on a PH32 readout chip was tested in strong electromagnetic fields near the plasma edge. The analog output shows a correlation with the signal from HXR diagnostics. Hit-count mode is unsuitable due to frequent saturation of the ASIC amplifiers. Spatial information of detected radiation is present in a digital readout. For further studies, better electromagnetic shielding and wider dynamic range is necessary. A smaller version of the strip detector is being prepared which will be optimized for measurements close to the plasma. A new sensor will be used to observe RE in scrape-off-layer and/or for monitoring radiation originating from RE impacting the limiter.

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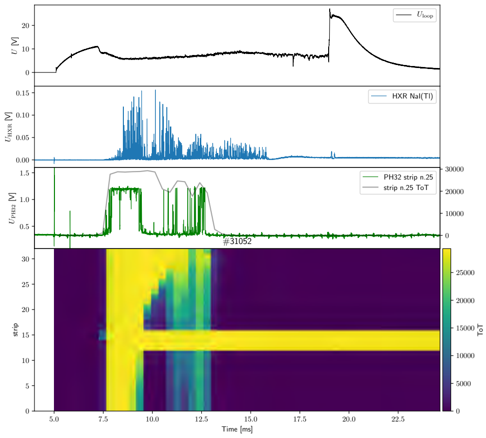

Figure 7: *Shot no. #31052, $l = 101$ mm, sensor facing left, 1st setup.*

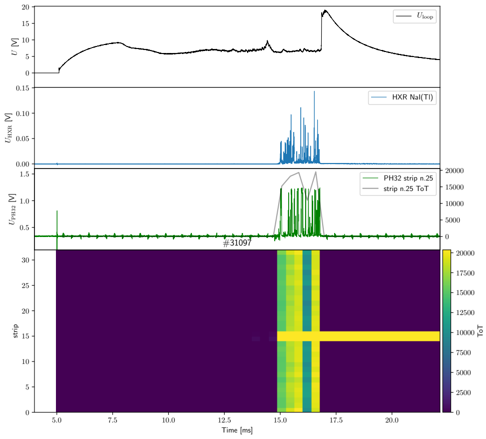

Figure 8: *Shot no. #31052, $l = 110$ mm, sensor facing up, 2nd setup.*

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