Runaway electron study at the COMPASS tokamak using the Timepix3-based silicon pixel detector with SPIDR 10 GBps readout

S. Kulkov[1], M. Marcisovsky[1], P. Svihra[1], O. Ficker[1,2], J. Caloud[1,2], J. Cerovsky[1,2], E. Macusova[2], V. Weinzettl[2], J. Mlynar[1,2], M. Beuzekom[3], M. Fransen[3], D. Bren[1], V. Linhart[1], V. Svoboda[1], M. Tunkl[1] and the COMPASS team[2]

[1] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic*

[2] *Institute of Plasma Physics of the CAS, Prague, Czech Republic*

[3] *Nikhef, Amsterdam, Netherlands*

Introduction: Runaway electrons (RE) that appear in tokamak plasmas are considered dangerous for the integrity of the future tokamak-based fusion reactors due to a large amount of energy they carry [1]. Therefore, it is necessary to understand properties of such electrons in order to secure the success of future machines, e.g., ITER, which is one of the main topics of research at the COMPASS tokamak [2]. Semiconductor detectors, which are widely applied in high-energy physics, may be a suitable addition to plasma diagnostics as they are not affected by magnetic fields and are well-equipped for soft X-ray spectra measurements. A hybrid pixel detection system based on the Timepix3 readout chip [3] with a 200 µm thick silicon sensor (in the further text - Timepix3; see Figure 1) is a perfect example of such instrumentation.

The Timepix3 sensor consists of 256 × 256 pixels with a pixel size of 55 × 55 μm^2 and, therefore, provides a high spatial resolution. Combined with the SPIDR readout system [4], Timepix3 is capable of simultaneous recording of Time-of-Arrival (ToA) and Time-over-Threshold (ToT) signals as well as pixel coordinates where the detection occurs with temporal resolution of 1.5625 ns. Additionally, from the number of pixels where a hit was detected, Timepix3 is able to determine either a photon, an electron or a heavier particle was detected. This work presents results acquired with the Timepix3 during the 11th RE-dedicated campaign conducted in

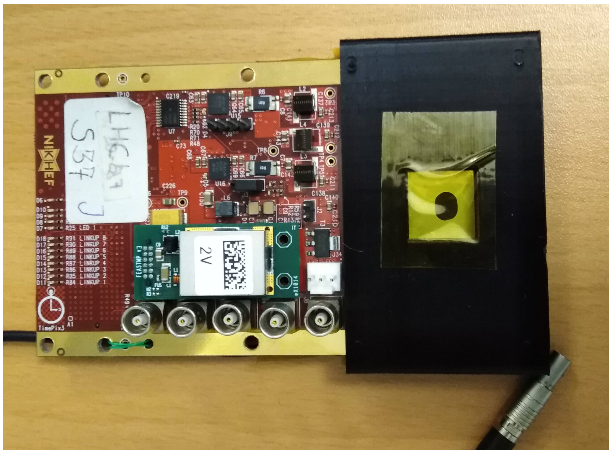

Figure 1: The Timepix3 chipboard. The hole in the Al layer on top of the sensor was cut out for laser experiments at Nikhef. The black plastic box around the sensor is used to shield the sensor from stray light and the yellow kapton tape keeps the sensor clean from dust.

January, 2020 at the COMPASS tokamak.

Experimental setup: During the campaign, the Timepix3 detector was installed at the radial midplane port with a clear view of the high-field side (HFS). In the port, a Be window, which ensures good X-ray transparency, was installed. In front of the sensor, a 1 cm thick Pb pinhole was mounted. The detector PCB was connected via an FMC cable to an FPGA board, which hosted the readout and analysis software SPIDR. The data measured were transferred from the FPGA board to the PC via a 10 Gb Ethernet connection. The detector sensor was biased with -150 V external voltage. Some of the tokamak diagnostics were used for comparison, mainly the plasma current measured by Rogowski coils and HXR signals from an unshielded NaI(Tl) and ZnS(Ag) in a 10 cm thick Pb shielding scintillating detectors. In addition, for confirmation of some of the results, snapshots from the Photron Mini UX100 and Photron SA-X2 fast cameras were used [5].

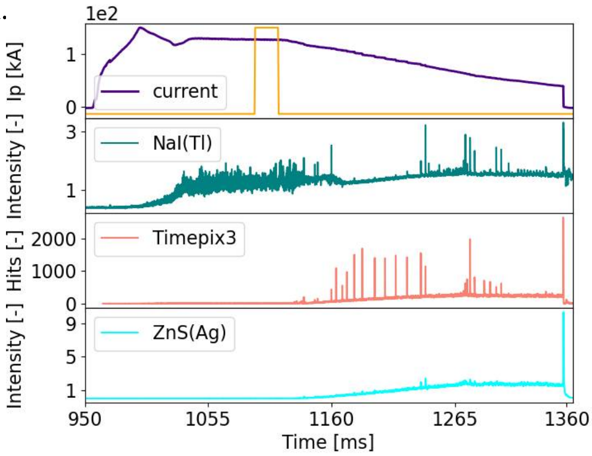

Figure 2: Shot #20055, plasma current I_p with Ar puff (top), NaI(Tl) (middle), Timepix3 (bottom).

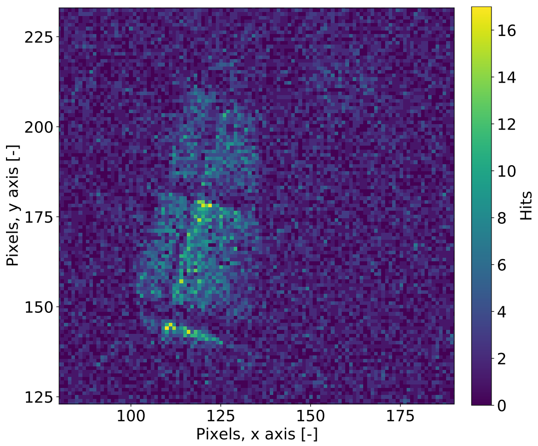

Figure 3: Shot #20068, hitmap. The rectangular structure seen is graphite blocks of the limiter on HFS.

With a rising intensity of the RE-produced radiation, Timepix3 became frequently saturated. This was solved via two approaches: first, a set of 5 cm thick Pb blocks was added to the setup for shielding of stray tangential hard radiation component; secondly, the number of active pixels was lowered - in some shots, down to 1600 pixels - in order to facilitate the sensor readout. The window of active pixels was centered around the pinhole. Most of the shots were conducted with an impurity gas puff (Ne, Ar, and Kr) to produce RE beams. Additionally, Timepix3 supports an external trigger, which helps with the comparison with other diagnostics.

Results: During the campaign, almost 150 shots were conducted at the tokamak. However, only 49 shots were fully useful with non-saturated signals. This is mainly due to a lack of experience in operation of hybrid pixel detectors in the tokamak environment. As the RE intensity was underestimated, during the first days of the campaign, the sensor was not shielded by any Pb blocks. Nonetheless, the results obtained look very promising. A comparison between the NaI(Tl), ZnS(Ag), and the Timepix3 detectors from shot #20055 is shown in Figure 2.

The shot with length of approx. 400 ms was conducted with an Ar puff during 1094-1114 ms, after which a RE beam was formed. The consequent disruption at 1357.05 ms is seen in the sudden loss of plasma current and a strong signal from all X-ray diagnostics. Many strong peaks can be seen in the Timepix3 signal in the interval from 1160 to 1245 ms. This is arguably due to a minor instability enveloped after the Ar puff during 1094-1114 ms. Though it is not clear from the figure, a weak signal of less than 580 hits/ms is present before the Ar puff at the interval 950-1125 ms.

A hitmap (a sensor snapshot with all hits detected) from shot #20068 can be seen in Figure 3. The structure shown was most probably generated by radiation coming from the carbon blocks of the limiter on HFS in the time interval 950-1100 ms. However, as the fast camera settings were often changed in an attempt to catch a pellet explosion, there are no useful data available for the shot #20068. As an example, a snapshot from the shot #20056 is used instead, see Figure 4. Both X-ray and visible radiation from the tiles is caused by the bombarding REs that appeared in the first half of the shot. Therefore, Timepix3 is a suitable diagnostic which can be utilized, e.g., in observations of interactions between REs and the plasma-facing components.

Figure 4: Shot #20056, one snapshot from the fast camera in the visible light. Carbon tiles of the HFS limiter radiate due to the bombarding by REs.

The third type of data collected by the Timepix3 detector is the ToT signal. The ToT signal depends on the energy deposited in the sensor material. Therefore, this can be used to estimate the energy of the REs. Primarily, ToT signal is saved in units of arbitrary binary values. These can be converted into mV using the charge injection method [6]. For an absolute calibration in units of eV, one should measure X-rays with defined energy such as coming from a nuclear source. However, as there are 65536 pixels in the sensor and each pixel is different due to the nature of production process, calibration of the

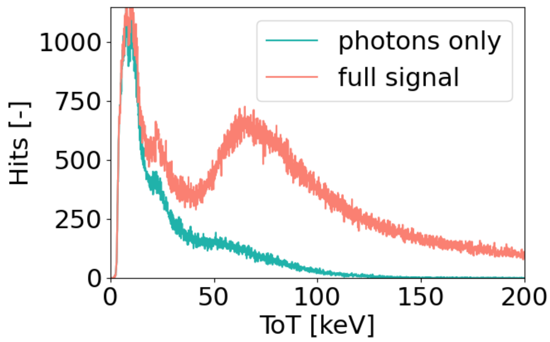

Figure 5: Shot #20055, calibrated ToT signals: a full signal and the one generated only by photons.

Timepix3 detector essentially means calibration of 65536 detectors. Therefore, signals for all pixels should be collected and processed separately. The primary result from the calibration of the ToT signal from shot #20055 is shown in Figure 5. Caused mainly by software, the error of the calibration is estimated at $\approx 20\%$.

Combining all of the ToT and ToA signals, one can plot a two-dimensional histogram of both signals, see Figure 6. Such signals combine time evolution, number of hits, and energy deposited in one figure.

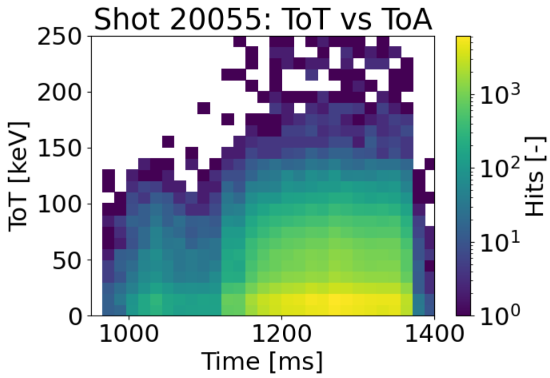

Figure 6: Shot #20055, the two-dimensional histogram of the calibrated ToT signals and time evolution calculated from ToA signals. The signal is generated by photons only.

Discussion: The results presented show that Timepix3 is a suitable diagnostic tool that can supply tokamak plasma diagnostics for both routine X-ray measurements and special experiments, e.g., for observation of interactions between RE beams and plasma facing components. Compact dimensions of the detector enable installation close to the vacuum vessel. However, a sufficient shielding is required in order to keep the detection system from saturating. Additionally, for a good spatial resolution and useful hitmaps, installation on the tokamak port is required. As the number of ports at tokamaks can be scarce, this may be difficult. For routine measurements of the X-ray time evolution, installation at some distance from the tokamak is also feasible. Timepix3 will participate in the upcoming RE-dedicated campaigns at the GOLEM tokamak (FNSPE, CTU in Prague). The calibration via the charge-injection method requires further investigation and the results will be published later.

Acknowledgement: The author would like to express his gratitude to Nikhef for lending the Timepix3 detector for measurements at the COMPASS and GOLEM tokamaks. This work was supported by Centre of Advanced Applied Sciences CZ.02.1.01/0.0/0.0/16-019/ 0000778 co-financed by the European Union. The COMPASS operation was co-funded by MEYS project LM2018117.

References

[1] T. C. Hender et al., 2007 Nucl. Fusion **47** S128.

[2] J. Mlynar et al., 2019 Plas. Phys. Contr. Fusion **61** 014010.

[3] T. Poikela et al., 2014 JINST **9** C05013

[4] J. Visser et al., 2015 JINST **10** C12028

[5] V. Weinzettl et al., 2017 JINST **12** C12015

[6] F. Pitters et al., 2019 JINST **14** P05022