On the possibility to use semiconductive hybrid pixel detectors for study of radiation belt of the Earth.

A. Guskov1,∗, G. Shelkov1, P. Smolyanskiy1, A. Zhemchugov1
1 Joint Institute for Nuclear Research, Dubna
E-mail: *avg@jinr.ru

Abstract. The scientific apparatus GAMMA-400 designed for study of electromagnetic and hadron components of cosmic rays will be launched to an elliptic orbit with the apogee of about 300 000 km and the perigee of about 500 km. Such a configuration of the orbit allows it to cross periodically the radiation belt and the outer part of magnetosphere. We discuss the possibility to use hybrid pixel detectors based on the Timepix chip and semiconductive sensors on board the GAMMA-400 apparatus. Due to high granularity of the sensor (pixel size is 55 µm) and possibility to measure independently an energy deposition in each pixel, such compact and lightweight detector could be a unique instrument for study of spatial, energy and time structure of electron and proton components of the radiation belt.

1. Timepix detectors
Pixel hybrid detectors consisted of the Timepix chip [1], developed at CERN, coupled with a semiconductive sensor are used as a particle detector in a variety of disciplines from the study of cosmic rays to biomedical imaging. Good spatial (pixel size is 55 µm) and energy (energy deposition can be measured individually in each pixel) resolution, low level of noise, compact size and radiation hardness are doubtless advantages of this type of detectors. Thin plates (0.3-1.0 mm) of silicon (Si) or gallium arsenide compensated with chromium (GaAs) with 256×256 square pixels are used as a sensor. GaAs sensors are developed and produced in the Tomsk State University (Tomsk, Russia)[4, 5, 6, 7]. The Joint Institute for Nuclear Research (Dubna, Russia) has wide experience in the production and operation of such kind of the detectors since 2008 [2, 3].

Layout of the Timepix detector is presented in Fig. 1. Sensitivity of the detector starts from about 6 keV for γ-quants, from 30 keV for electrons and from 500 keV for protons. Interaction of an incoming particle with the material of the sensor produces a cluster of energy deposition. Analysis of geometrical shape of such cluster and energy distribution over pixels provides possibility to classify clusters as produced by soft photons, low-energetic electrons, non-relativistic protons, neutrons, heavy ions and minimum ionizing particles (ultrarelativistic charged particles). Fig 2. shows response of the Timepix detector with 0.3 mm silicon sensor placed in the vicinity of the interaction point of 2 GeV deutron beam with lead target. Long straight horizontal lines correspond to the beam halo deuterons. Typical responses of the Timepix detector, equipped with 0.3 mm silicon sensor, irradiated with 350 keV electrons and with 2 MeV protons, coming to the surface at 90° angle, are presented on Fig. 3 (left) and (right) correspondently. Since for lowenergetic particles full energy deposition occurs inside the sensor,
the energy of incoming electrons and protons can be measured at least up to 0.3 MeV and 6 MeV in 0.3 mm silicon and up to 1.4 MeV and 17 MeV in 1 mm gallium arsenide sensors correspondently.

Basic properties of the Timepix detectors are presented in Tab. 1.

Figure 1. Layout of the Timepix detector

Figure 2. Response of the Timepix detector equipped with 0.3 mm silicon sensor placed in the vicinity of the interaction point of 2 GeV deuteron beam with lead target.

Table 1. Basic parameters of the Timepix detector.

| Parameter                                      | Value               |
|------------------------------------------------|---------------------|
| Mass of the detector and infrastructure (without cabling), g | 200                 |
| Dimensions $L \times W \times H$, cm           | $15 \times 5 \times 3$ |
| Power consumption, W                           | 2.5                 |
| Radiation hardness of Timepix chip, MGy        | 4.6 [8]             |
| Radiation hardness of Si sensor, MGy           | 0.1-0.5             |
| Radiation hardness of GaAs sensor, MGy         | 1.5 [9]             |
| Electric field strength, V/µm                  | 0.5-1.0             |
| Minimal frame length, ms                       | 0.01                |
| Amount of data, kB per frame with occupancy 10% | 20                  |
| Maximal frame rate, kHz                        | 100                 |
| Sensitivity range, keV                         | $>6(\gamma), >30(e), >500(p)$ |
| Working area, cm$^2$                           | 2                   |
Figure 3. Typical responses of the Timepix detector equipped with 0.3 mm silicon sensor and irradiated with 350 keV electrons (left) and with 2 MeV protons (right). Angle of incidence is 90°. Only a part of the frame is shown.

2. Timepix detectors at GAMMA-400

The magnetically confined radiation zones around the Earth populated with electrons and protons and named radiation belts are still the objects of intense study. On the one hand the detailed information about structure, intensity, composition, energy spectrum of the particle flows, their variation in time and correlation with the solar activity provides possibility to better estimate the radiation hazard for spacecraft. On the other hand this information is important for the tests of the models describing capture, acceleration, transport, precipitation and loss of radiation belt particles (see, for instance, [10, 11]. Possible correlation between high-energy particle flux in the radiation belts and seismic activity of the Earth is the special point of attention in resent years since such a correlation can help to predict earthquakes [12, 13].

Our proposal is to place one or a few Timepix detectors onboard the GAMMA-400 apparatus [14, 15] to monitor continuously the flux of low energy charged particles along the orbit of the apparatus. There is already a positive experience to use the Timepix detectors in space. It is used on board the International Space Station to accurately monitor radiation doses from various sources [16]. NASA has used the Timepix detector during the first test flight of the "Orion module" - part of the next generation of manned US spacecraft [17]. It was also installed on board the ESA Proba V satellite launched in 2013, where it first operated out of the shielding in a vacuum without any problems with thermoregulation [18].

To minimize the perturbation of the radiation environment by the body of the apparatus the sensors could be attached to the external constructions together with the magnetometers or the star sensors out of the thermoshielding. To keep possibility to detect protons with energy above 1 MeV and electrons with energy above 50 keV the shielding of the working area should be on the level of about 2 mg/cm² of a light material like mylar or aluminum foil. Readout and control of the Timepix detector can be performed via the dedicated FPGA-based service board. The service board can be connected to the SDAS by means of a high-speed interconnect like RapidIO. Tunable HV power supply controlled by the service board is necessary to bias the sensor of the Timepix detector up to -500 V.

The initial elliptic orbit of the apparatus will have the following parameters: the apogee of about 300 000 km, the perigee of about 500 km, the inclination 51.8° and period of about 7 days. Since the perigee lies low enough, the apparatus will periodically cross both external
and internal radiation belts and be out of the magnetosphere. The Timepix detector is able to
monitor effectively the flux of protons and electrons separately basing on the cluster shape and
energy distribution analysis if the sensor occupancy is below $\sim 10\%$. That corresponds to the
flux $\Phi_0$ of about $3 \times 10^7 \text{c}^{-1}\text{cm}^{-2}$ and the minimal frame length of 10 $\mu$s. The maximal general
flux of protons with energy above 1 MeV and electrons in with energy above 50 keV through a
solid angle of $2\pi$ in the radiation belts was estimated according to the AE-8/AP-8 model [19, 20].
It is about $2 \times 10^8 \text{c}^{-1}\text{cm}^{-2}$ for maximal and about $7 \times 10^7 \text{c}^{-1}\text{cm}^{-2}$ for minimal solar activity.
So at the part of the orbit where particle flux is lower than $\Phi_0$ the Timepix detector could
operate as a precise monitor of the electron and proton flux with variable time window to keep
reasonable occupancy at the level of a few per cent, while in the region of higher flux it could act
as a rough indicator of the general flux using the minimal time window. The measurement of
the energy spectrum could also be available for low energy component dominating in the outer
part of the radiation belt.

In parallel with monitoring of the radiation belt the Timepix detector could be a
unique instrument for investigation of charged particles flux in the outer region the Earth’s
magnetosphere. Such data can be combined with an information about the solar activity and an
information from the magnetometer planned to be installed at GAMMA-400. Study of energetic
component of the solar wind out of the magnetosphere and its interaction with the magnetic
field of our planet could be another promising task for the Timepix detector. This program will
be especially important when the orbit will become more circular with a radius of about 100
000 km.

Acknowledgments
This work is supported by the Ministry of Education and Science of Russian Federation under
the contract No. 14.618.21.0001.

References
[1] Llopart X et al. 2007 NIM A 581 485
[2] Tlustos L, Shelkov G and Tolbanov O 2011 NIM A 633 103
[3] Butler A et al. Physics of Particles and Nuclei Letters 12 59
[4] Ayzenshtat G et al. 2002 NIM A 487 96
[5] Tyazhev A et al. 2003 NIM A 509 34
[6] Ayzenshtat G et al. 2003 NIM A 509 268
[7] Ayzenshtat G et al. 2004 NIM A 531 121
[8] Plackett R et al. 2009 Proc. TWEPP-09 p157
[9] Afanaciev K et al. 2012 JINST 7 11022.
[10] Summers D et al. Dynamics of the Earth’s Radiation Belts and Inner Magnetosphere (Washington: American
Geophysical Union)
[11] Lemaire J et al. 2013 Geophysical Monograph Series 97
[12] Gal’per A et al. 1995 Advances in Space Research 15 131
[13] Hayakawa M (2015) Earthquake Prediction with Radio Techniques (Singapore: John Wiley & Sons)
[14] Topchiev N et al. 2015 arXiv:1507.06246
[15] Topchiev N et al. 2015 Bulletin of the Russian Academy of Sciences. Physics 79 3 417
[16] Stoffle A et al. 2015 NIM A 782 143
[17] Bahadori A et al. 2015 NASA/TP-2015-218575
[18] Francois M et al. 2014 International Journal of Remote Sensing 35 7 2548
[19] Sawyer D and Vette J 1976 AP-8 trapped proton environment for solar maximum and solar minimum NASA
TM-X-72605
[20] Vette J 1991 The AE-8 trapped electron model environment NSSDC/WDC-A-R&S 91-24