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ELEMENTARY PARTICLES AND FIELDS
Experiment

Development of the SPD Beam–Beam Counter Scintillation Detector Prototype with FERS-5200 Front-End Readout System

A. V. Tishevsky[1)*], F. A. Dubinin[2),3)], A. Yu. Isupov[1)], V. P. Ladygin[1)], G. A. Nigmatkulov[2)], S. G. Reznikov[1)], P. E. Teterin[2)], I. S. Volkov[1)], A. M. Zakharov[2)], and A. O. Zhurkina[2)]

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Abstract—The Spin Physics Detector is an experiment at NICA designed to study the spin structure of the proton and deuteron and the other spin-related phenomena using polarized beams. The collision energy is up to 27 GeV and the luminosity is up to 10^{32} cm^{-2} s^{-1} in *pp* mode. Two scintillator-based detectors, Beam–Beam Counters (BBC), will be installed upstream and downstream the interaction point and will serve as a tool for beam diagnostics including local polarimetry. In this paper, we present the design of the BBC prototype based on the tiles with green WLS and SensL SiPM readout. FERS-5200 is used as the front-end readout system. The amplitude and timing resolutions for different tiles using radioactive source and cosmic rays are obtained.

Keywords: BBC, CAEN FERS-5200, SiPM, WLS, optical cement, “Mylar”, “Tyvek”, “Janus”, “FersRun” framework, ToT, ToA

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1. INTRODUCTION

The first stage of the SPD experiment will be devoted to the study of polarized and non-polarized phenomena at low energies and reduced luminosity using heavy ion and polarized proton and deuteron beams. Details of the SPD experimental setup is described in Conceptual Design Report [1].

One of the SPD subsystems is two Beam–Beam Counter (BBC) detectors, which will be installed symmetrically upstream and downstream the interaction point. The BBC detector should consist of two parts: the inner and the outer one, which are based on the use of the plastic scintillators. The main purpose of the BBC is the permanent monitoring of the beam polarization using the azimuthal asymmetry of the inclusive charged particles’ yield, as well as the monitoring of the beam collisions. The feasibility of such type of local polarimetry is demonstrated by the correlation between the measurements of the CNI polarimeter and the azimuthal asymmetry of the inclusive charged particle yield in the BBC STAR detector [2, 3].

The outer part of the SPD BBC has been updated after the CDR [1] design to increase radial and azimuthal granularity. Schematic view of the one of 16 scintillator sectors with 25 tiles in each one is presented in Fig. 1*a*. There are several options of scintillator tile, wavelength shifting (WLS) fiber, optical cement (OC), and silicon photomultiplier (SiPM) to choose some optimal combination.

The 7 tiles scintillation detector prototypes (see Fig. 1*b*) have been developed. In this work, we consider different covering option of the BBC prototype scintillation tiles, as well as methods of SiPM calibration, and test the scintillation tiles with Saint-Gobain Crystals (BCF92, fast) WLS fiber [4] and CKTN-MED (mark E) OC [5] with several options of SensL C-Series SiPM readout.

2. THE BBC 7 TILES PROTOTYPES

The four innermost layers of the proposed sector with different covering options of scintillator tiles for each prototype have been produced. The scintillation tiles with a thickness of 10 mm with grooves for laying of 3 WLS turns were manufactured by the Uniplast Enterprise (Vladimir). The scintillation tile content was 98–98.5% of polystyrene Styrolution ^{124}N, 1.5–2.0% of p-Terphenyl (CAS 92-94-4) and 0.01–0.04% of POPOP (CAS 1806-34-4).

R & D stage is dedicated to the selection of material for the detector. Some options of coverage of the scintillation tiles were studied. The first option was

[1)]Joint Institute for Nuclear Research, Dubna, Russia.
[2)]National Research Nuclear University MEPhI, Moscow, Russia.
[3)]Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia.
[*]E-mail: tishevskiy@jinr.ru

(*a*) (*b*)

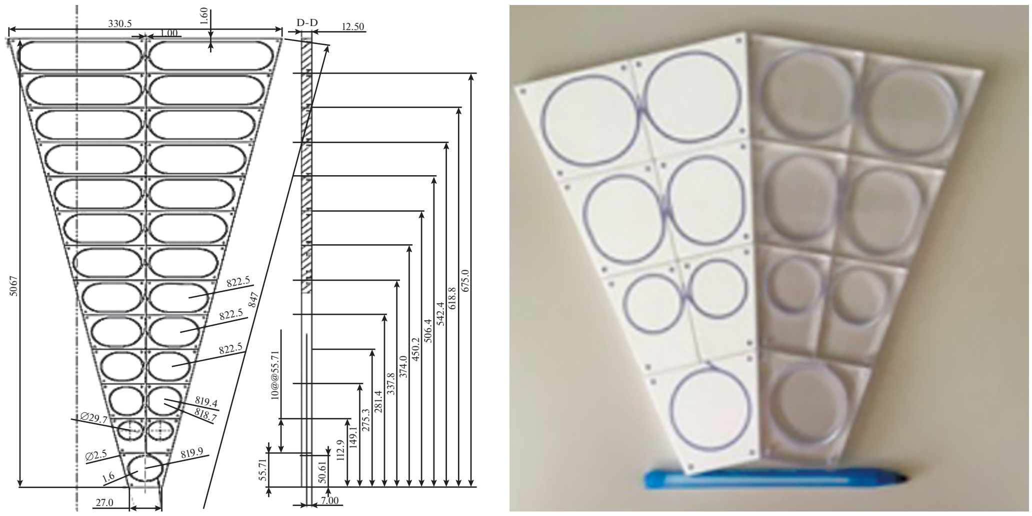

Fig. 1. Schematic view of the one of 16 scintillator sectors with 25 tiles (*a*). The 7-tiles sector of BBC detector prototype (*b*).

the scintillator tiles matted by chemical etching and painted reflective white coating by production (so-called matted). The second option was the polished tile which required some reflective and light-shielding coating. The most common coatings are Mylar and Tyvek. The actual task of this work is to compare both covering options and choose the final one.

The most important condition is the scintillator parameters should be matched to the WLS, as well as the interface between them—optical cement. The requirements for the latter are complex:

- the optical effects that impair the light collection should be minimized;
- optical cement should not immediately begin to harden, should be fluid and prevent the formation of an air gap, and reliably fix the WLS inside the tile, that are essential at mass production;
- high radiation resistance is advisable to ensure long-term operation without replacement of detector elements.

The main candidate for optical cement was CKTN MED mark E (CKTN). The manufacturer gives some values of optical parameters: refractive index (1.606), spectral characteristics (92–96% for 500 nm), viscosity (15×10^3 cPs), etc. CKTN is viscous, which increases the working time with them during mass production. After solidification, it is elastic and similar to a sealant, but at the same time reliably holds of 3 WLS turns.

We are considering Saint-Gobain Crystals WLS fiber of BCF92S series, as a compromise decision between cost, availability, and optical characteristics such as decay time (∼2.7 ns), emission peak (∼492 nm), etc. The light output from one WLS end is supplied to SiPM.

The comparison of 1×1 mm^2 and 3×3 mm^2 SensL SMT SiPMs [6] is also actual task of this work. The 3×3 mm^2 SiPM was used as a starting option while has a large geometric inefficiency (the sensitive area too large to WLS. CAEN FERS-5200 [7] was adopted as the main solution for the SiPM readout).

3. CAEN FERS-5200 FRONT-END READOUT SYSTEM

CAEN FERS-5200 is an extendable front-end readout system: the same FERS unit can be used both stand-alone and as part of the tree network for the readout of large arrays of detectors with the possibility channels' number up to 8192. An important advantage is the ability to work with trigger-less data streaming mode, which is extremely promising both for future testbeams and "phase zero" experiments at BBC SPD. DT5202 specifically designed for the readout of SiPMs was used for starting the prototype research [7].

The DT5202 is an all-in-one readout system which integrates two Citiroc 1A chips for a total of 64 acquisition channels, an integrated power supply module for the SiPM bias (range of 20–85 V), an FPGA, multiple communication interfaces (USB, Ethernet, and TDlink (optical)) and general purpose I/Os. The bias for the SiPM can be finely tuned channel by channel through an individual 8-bit DAC (2.5 or 4.5 V range) in the Citiroc 1A. A temperature

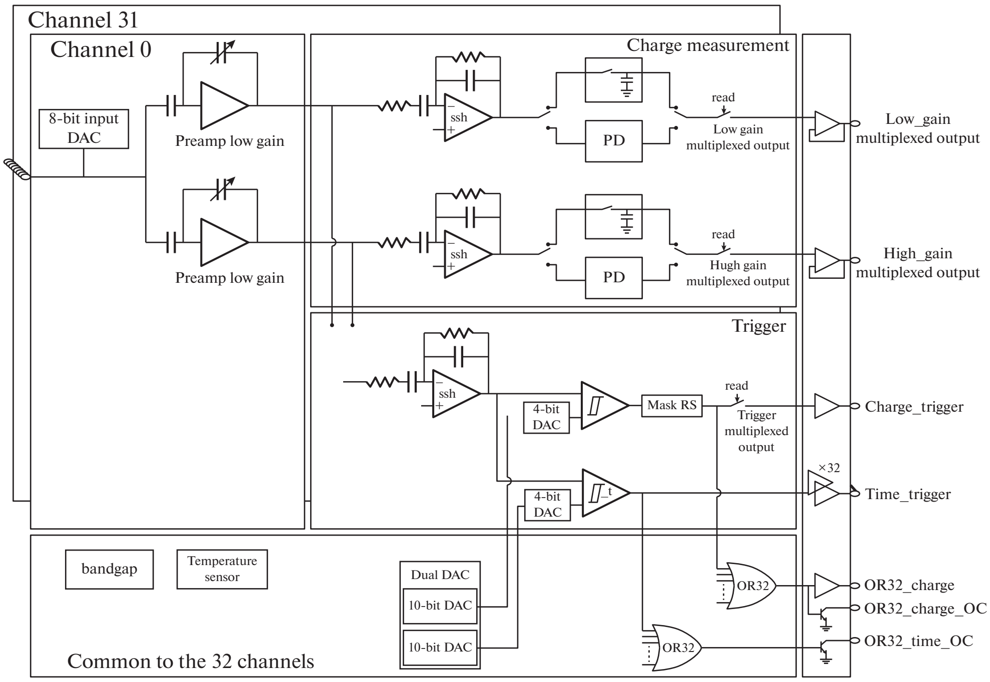

Fig. 2. Citiroc-1A block scheme.

feedback circuit is also available to compensate the gain drift.

Each readout channel is composed of (more details are in Fig. 2 [8]) two charge measurement (Pulse Height Analysis, PHA) lines with different gain (1 to 10 ratio), which are working in parallel in order to maximize the dynamic range, as well as fast shaper followed by a discriminator. The 64 outputs of the discriminators, i.e. the channel self-triggers, are used in the FPGA both to feed the trigger logic functions (OR, Majority, etc.) and to acquire the timing information Time of Arrival (ToA) and Time over Threshold (ToT) could be used in combination with the PHA as well as standalone.

Citiroc-1A outputs the 32-channel triggers with a high timing resolution (better than 100 ps RMS), even though it does not have an internal TAC/TDC to acquire the timing measurement. However, the FPGA of the DT5202 is programmed for this purpose and a low resolution TDC (0.5 ns) was implemented to calculate the time distance (ΔT) between a reference signal and the input pulses [9].

The “Janus” software for Windows® and Linux®, allowing to manage the DT5202 module and the data acquisition, as well as to save output files (in ASCII and/or Binary formats), is provided by CAEN.

4. SOFTWARE AND DATA ANALYSIS TOOL

Janus is software composed of two parts, one written in C, which is the real heart of the application, second written in Python which manages only the user interface and communicates with the C program via socket. The plots are executed through an external gnuplot tool [10].

The GUI has configuration and runs control panels that simplify the data acquisition management. Both console and GUI modes permits to acquire data from multiple boards, manage the event building and timing histograms, display data statistics of the run (counts, events lost, trigger rate, data throughput, etc.), and save output files, both histogram and event list.

In both ASCII and binary formats, each file is composed by a header with the information regarding the data format and software version, the acquisition mode, the energy spectrum total channels, time conversion, and the time stamp of the start of the acquisition. The output files can contain the PHA, ToT and ToA main information for each event, where ToA and ToT are expressed in ns or LSB (least significant bit). The output depends on the selected acquisition mode. The DT5202 acquisition modes are in particular:

- Spectroscopy (PHA);
- Timing (ToA and possibly ToT);
- Spectroscopy + Timing (Hybrid Mode).

The “FersRun” framework has been designed by us to work with both output data formats. The framework has a wide functionality, which allows user to

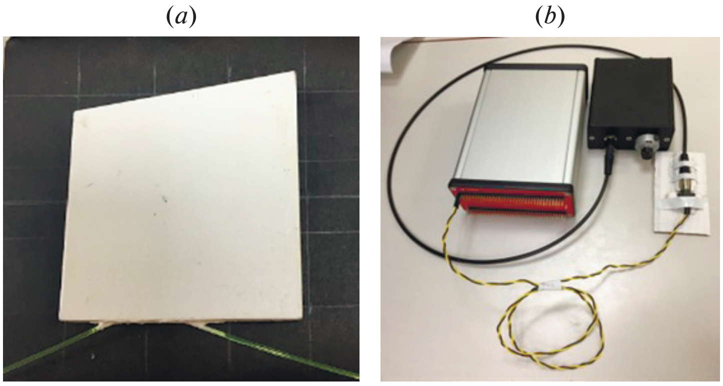

Fig. 3. Calibration of SiPMs: matted tile with two WLS outputs (*a*); calibration stand with LED (*b*).

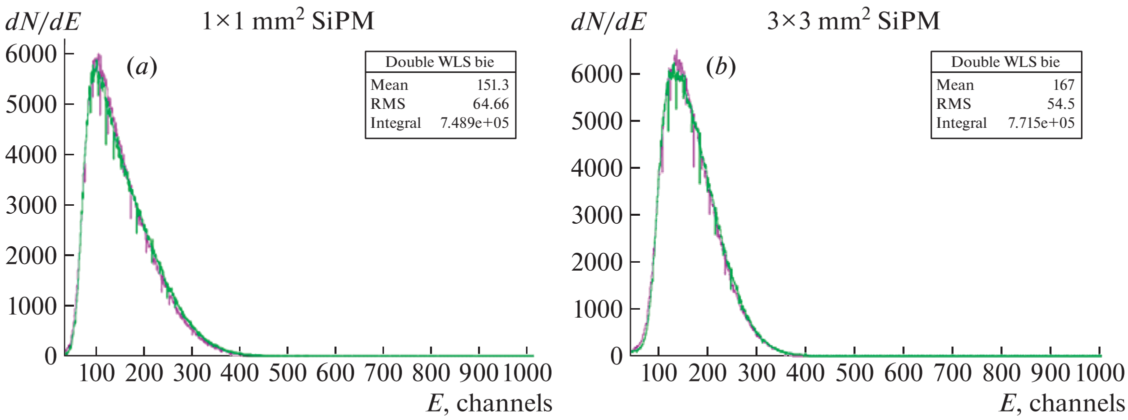

Fig. 4. Result of the 1×1 mm^2 (*a*) and 3×3 mm^2 (*b*) SiPM calibration with radioactive source.

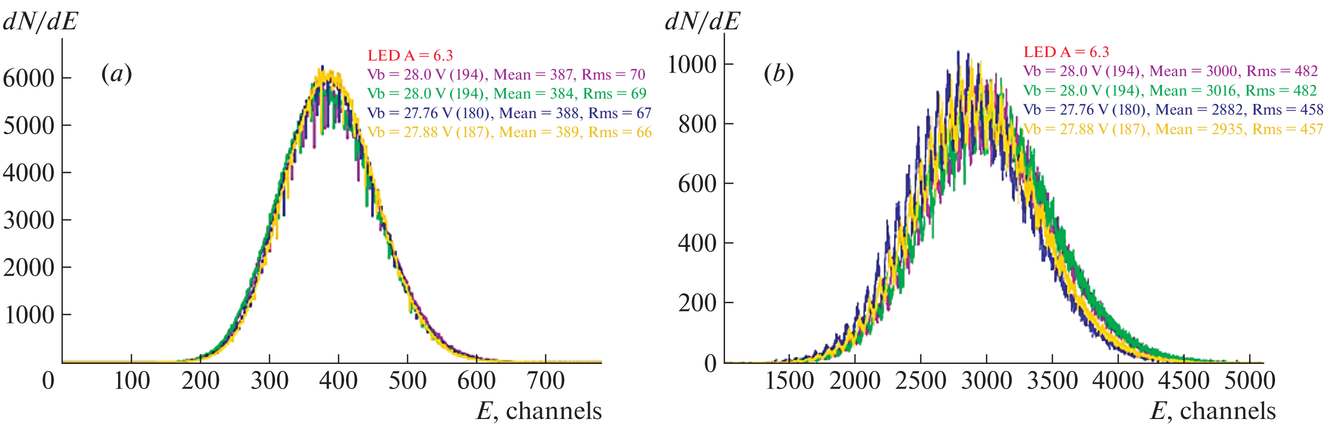

Fig. 5. Result of the 3×3 mm^2 SiPM calibration with LED for: low gain (*a*); high gain (*b*).

automatically determine the data format depending on the conditions of the data run, implement a software trigger, both for all channels (global) and for particular one (local), and apply cuts to select events. It is useful to be able to build correlations of the obtained values in Hybrid Mode. It also uses ROOT framework to visualize obtained distributions.

5. CALIBRATION (RADIOACTIVE SOURCE)

The DT5202 is a complex electronics system. The CAEN manufacturer standardizes the installed electronic components (preamps, shapers, DACs, etc.), and subsequently performs a calibration procedure for each electronics channel. We assume that when

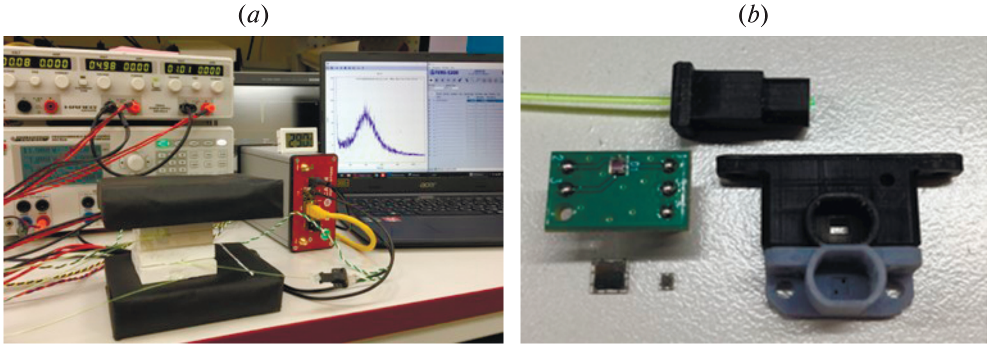

Fig. 6. Picture of the cosmic rays stand for the tiles studies with CAEN FERS-5200 (*a*). The connectors and SiPMs (*b*).

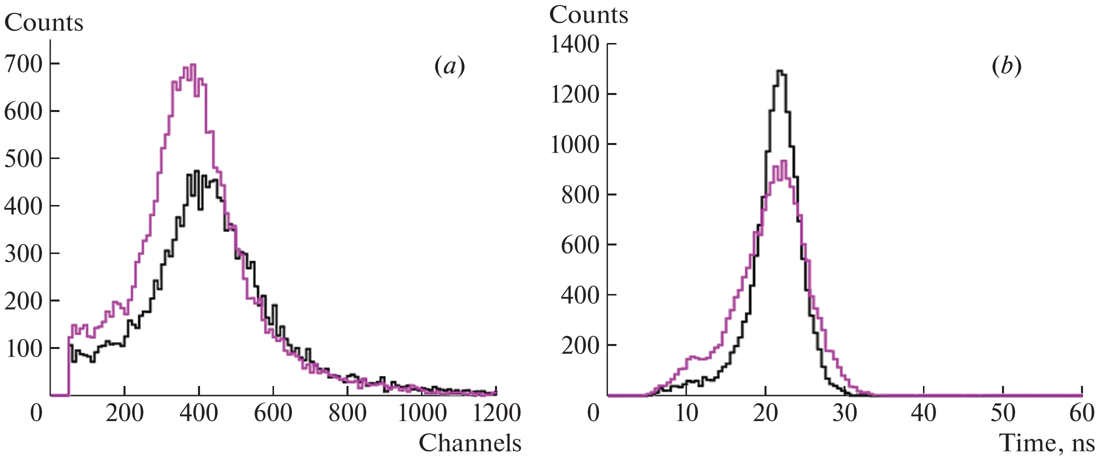

Fig. 7. The amplitude (*a*) and time spectra for ToT (*b*) of central layer of the BBC prototype scintillation tile coupled with 1×1 mm^2 (black) and 3×3 mm^2 (violet) SensL SMT SiPM (*a*).

adding SiPMs to an electronic circuit, there may be a signal difference from channel to channel for various SiPMs caused not only due to SiPMs breakdown voltage difference, but also because of different gains of DT5200 distinctions too. For this reason, the calibration methods, where each SiPM was assigned to its own channel of board, were proposed.

For this purpose the matted tile with two WLS outputs (see Fig. 3*a*) of single fiber for tests and in particular for SiPM calibration with radioactive source were developed. Both WLS outputs were coupled to the 1×1 mm^2 or 3×3 mm^2 SiPMs pair connected to the DT5202. Each channel can generate a Time Discriminator (TD) self-trigger signal when the pulse from the Fast Shaper crosses a configurable threshold. The self-triggers of each channel are then processed at firmware level in order to create a logic trigger signal. This internal bunch trigger signal was used for Spectroscopy Mode (SM) of the DT5202 and consequent calibration.

The amplitude histograms for both SiPM sizes with the set voltages are shown in Fig. 4*a*, 4*b*). For the first and second channels, the voltages were 28.00 and 27.68 volts, respectively. The similar signals for both SiPM sizes is acceptable result, but we prefer the way of calibration with CAEN SP5601 LED driver (LED).

CALIBRATION (LED)

The main advantage of the next method is same conditions for calibration candidates. The experimental stand consists of: fiber that transmitted light pulses to surface of SiPM; 3d printed connector for coupling; LED, as stable signal source. LED has external logical trigger signal. This external bunch trigger signal was used for Spectroscopy Mode of the DT5202 and consequent calibration.

The experimental stand for the SiPM calibration and the results of the SiPM calibration are shown in Fig. 3*b* and Fig. 5*a*, 5*b*, respectively. One can see that all four channels have similar effective gain after calibration procedure. The calibration method with LED for 1×1 mm^2 and 3×3 mm^2 SensL SMT SiPMs and obtained voltages were used for the following tests with cosmic rays.

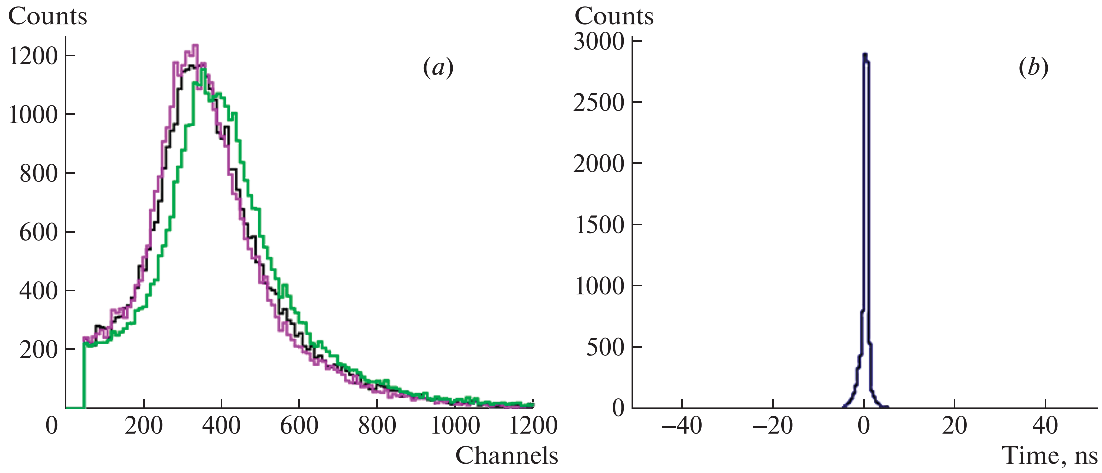

Fig. 8. The amplitude spectra of third layer of the BBC prototype scintillation tile coveing with matted (green), and coatings with Mylar (violet) and Tyvek (black) options coupled with 3×3 mm^2 SensL SMT SiPM (*a*). The time resolution for the third layer tiles coupled with two 1×1 mm^2 SMT SiPM (*b*).

6. MEASUREMENTS OF COSMIC RAYS ENERGY LOSS

The BBC 7 tiles prototypes consist of 4 first layers. We label the bottom layer tile as the central, and others by their position relative to the central one: first, second, and third correspondingly.

The comparison of 1×1 mm^2 and 3×3 mm^2 SensL SMT SiPMs has been done. The central layer of the BBC prototype scintillator was used.

In addition, the comparison of third scintillation tile covered with matted, and coatings with Mylar and Tyvek options has been done. The BBC tiles prototypes were alternately tested on cosmic rays with first SiPM. The SiPM bias voltage was 27.95 V. A similar scintillation tile with two 1×1 mm^2 SMT SiPM was used to estimate the time resolution.

An external trigger counters (ETC) based on two $100 \times 100 \times 10$ mm^3 BC-404 scintillation plates coupled with Hamamatsu H10720-110 PMTs [11] readout has been developed. The tiles were between ETC (see Fig. 6*a*). The coincidence of ETC with time resolution equal to 650 ps was used as time reference (T_{ref}) signal for Spectroscopy + Timing (Hybrid) Mode of the DT5202. T_{ref} signal opens/closes an acquisition window of programmable size and only the hits belonging to that time window appear in the output. The ToA information is then computed as the time difference between the T_{ref} signal and the individual hits. The ToT of these individual hits, giving a rough estimation of their energy, is also saved. The detector prototype tiles were tested in the light shielding box, at 25 ± 1°C temperature.

7. RESULTS OF THE TESTS WITH COSMIC RAYS

The results of amplitude and time spectra measurements using the central layer of the BBC detector prototype tile have been obtained. The amplitude spectra difference for the 1×1 mm^2 and 3×3 mm^2 SensL SMT SiPM signals is less than 5%, and presented in Fig. 7*a*. The values on the mean, RMS and integral of the obtained amplitude histograms are given in Table 1. The ToT time spectra for both SiPM are shown in Fig. 7*b*. The minimal difference between SiPM channels is visible. However, more attention for small amplitudes region is needed, when the signal arrives later in time, due to the signal delay often called the "time-walking" effect. One of the methods for correcting time spectra for such an effect was proposed in [12]. At the moment, the removal of this effect is discussed.

In addition, the results of amplitude and time spectra measurements using the third layer of the BBC detector prototype tile have been obtained. The amplitude spectra difference for several covering option

Table 1. Mean, RMS and integral values for central layer of the BBC prototype scintillation tile and several options of SMT SiPM

	Central layer tile	
	3×3 mm^2	1×1 mm^2
Mean	396.2	411.6
RMS	145.5	129.4
Integral	20 550	15 650

Table 2. Mean, RMS and integral values for third layer of the BBC prototype scintillation tile with several covering option and same 3×3 mm^2 SMT SiPM

	Mylar (Violet)	Tyvek (Black)	Matted (Green)
Mean	344	355	385
RMS	181.1	186.6	196.7
Integral	37 920	38 161	37 860

of scintillation tile with 3×3 mm^2 SensL SMT SiPM is no more than 10%, and shown in Fig. 8*a*. The values on the mean, RMS and integral of the obtained amplitude histograms are given in Table 2.

The raw estimation of the time resolution for the third layer tiles coupled with two 1×1 mm^2 SMT SiPM was carried out (Fig. 8*b*). It was estimated by the RMS of the distribution divided by the $\sqrt{2}$ as about 0.8 ns.

8. CONCLUSIONS

The tests of scintillation detector prototype with CAEN FERS-5200 front-end readout system have been started. The obtained data were processed with "FersRun" framework.

The calibration method with LED for various SiPMs has been proposed. Each SiPM was assigned to its own channel of board. The obtained voltages were used for the following tests.

The 1×1 mm^2 and 3×3 mm^2 SensL SMT SiPMs have been compared. The main differences between them are the difficulty of soldering and the sensitive area for WLS. The results for both readout options are similar. The main candidate for further testing is the 1×1 mm^2 SensL SMT SiPM, but the development of a PCB with a higher SiPM density for the final option of the BBC SPD detector is required.

The comparison of different covering option of the BBC prototype scintillation tiles has been done. Matted one proved to be more efficient in amount of reflected light by ∼8% for Tyvek, and ∼11% for Mylar. In addition, matted covering option is convenient from the mass production point of view and has a higher priority as the final option for the BBC detector.

The first results of time spectra measurements has been obtained. The ToT spectra for both readout options are shown in Fig. 7*b*. Still one can see the difference observed in Fig. 7*a*. The ToT spectra allows us to estimate the signal amplitude, and is available in combination with the amplitude information (Hybrid Mode) or without it (Timing Modes). The further correction procedure is under consideration, but results with ToT have become first step to Timing Mode using, which is the only option for trigger-less data streaming mode. The additional studying of ToT option is required.

The first result of time resolution has been obtained. Given the suboptimal of FPGA of the DT5202 with a low resolution TDC (0.5 ns), the result is promising. We are waiting for DT5203 board that uses the picoTDC chip produced by CERN for high-resolution time measurements.

The future step is to assembly and test the 7-tiles sector with selected options.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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