Testbeam measurements and realistic simulation for the SPD straw drift tubes

Andrei Zelenov,[1] Vitaly Bautin,[2] Sofia Bulanova,[1] Temur Enik,[2]
Ekaterina Kuznetsova,[1] Victor Maleev,[1] Sergey Nasybulin,[1]
Kirill Salamatin,[2] Dmitry Sosnov,[1] and Ysmaiyl Kambar[2]
(for the SPD Collaboration)

[1]*Petersburg Nuclear Physics Institute, NRC «Kurchatov Institute», Gatchina, Russia*

[2]*Joint Institute for Nuclear Research, Dubna, Russia*

(Dated: January 28, 2023)

Trackers built of straw drift tubes are a perfect solution for precise track measurements in High Energy and Neutrino Physics experiments operating at low and moderate event rate. Straw Trackers will play crucial roles in such future detectors as Near-Detector Complex of the DUNE [1] experiment, Hidden Sector Detector of the SHiP [2] experiment and the NICA SPD [3] detector. Performance requirements on a Tracker and its read-out electronics are defined by the Physics goals. Proper evaluation of the designed Tracker performance demands realistic simulation and studies with tracker prototypes. Preliminary results of the muon beam measurements done with straw tube chambers at the CERN SPS test beam line are compared to predictions obtained with GARFIELD [4] simulation package interfaced to LTSpice [5] program for electronics circuit modeling.

I. STRAW TUBES OPERATION PRINCIPLES

Straws are gas-filled cylindrical tubes with a conductive inner layer being a cathode and an anode wire stretched along the cylinder axis. Primary electrons, created when an ionizing particle traverses the tube, drift towards the anode. In the vicinity of the anode wire, electrons are accelerated in the strong electric field and so gain sufficient energy to produce further gas ionization. Due to high field gradient, the avalanche charge amplification occurs. This allows to achieve charges induced at the electrodes to be a factor of several tens of thousands larger with respect to the primary ionization charge. This amplification factor is referred to as the gas gain. The signal is further amplified, shaped and discriminated with the read-out electronics.

The time needed for primary electrons to drift towards the anode depends on the distance to the anode wire, so the drift tubes are used as coordinate detectors. Figure 1 shows the drift paths of primary electrons (orange) and ions (red) to the anode wire and cathode respectively.

The drift time $\mathbf{t}_{\mathrm{drift}}$ is determined as the difference between time $\mathbf{t}_0$ when an ionizing particle crosses the straw, and the time when the induced straw signal exceeds a given threshold. To get the best spatial resolution of the track position, the threshold is usually set close to the charge produced by a few first primary electrons reaching the anode wire.

Drift time of first or second electron clusters closest to the anode represents well the distance $\mathbf{R}$ between the track and anode wire. $\mathbf{R}(\mathbf{t}_{\mathrm{drift}})$ dependence can be modeled or measured. A comparison of GARFIELD [4] simulation results and NA62 [6] measurements are shown in Fig. 2.

Time resolution, and, accordingly, the spatial resolution of the track coordinate measurement, is defined strongly by the straw read-out electronics. To investigate possible read-out options for the NICA SPD [3] Straw Tracker, both measurements with a muon beam and simulation studies of the straw response are being carried out. We present a comparison of the first measurement results to the simulation predictions.

II. STRAW READ-OUT ELECTRONICS

The SPD Straw Tracker will serve not only coordinate measurements, but also particle identification, exploiting the difference in the ionization energy losses of different particle kinds. This option requires measurements of both the drift time and charge of the straw signal. Currently two families of ASIC capable for those measurements are available: VMM3/3a [7, 8] and TIGER [9]. Figure 3 shows the basic features of the ASIC schematics and Table I compares their operation parameters.

III. STRAW SIGNAL SIMULATION

GARFIELD package for detailed gas detector simulation is used to predict the straw response to a muon of 1 GeV energy. Figure 4, left, shows an example of the signal induced at the straw anode as it is simulated with GARFIELD. To model the corresponding signal at the output of the read-out electronics, LTSpice [5] software is used. The package allows to define a certain electronics circuit model and to predict its response to a custom input signal shape. A straw response generated with GARFIELD is used as a signal at the input of the VMM3 circuit model. The corresponding output signal is shown in Figure 4, right.

The combination of the GARFIELD and LTSpice packages allows to obtain realistic predictions of the measurements done with a straw tube and the VMM3-based read-out.

IV. TESTBEAM MEASUREMENTS

Three types of straw read-out electronics were tested with the SPS muon beams at CERN. To perform the measurements a test setup has been developed. The setup consists of:

- Reference tracking implemented with three MicroMegas detectors measuring the track coordinate perpendicular to the straw axis and an additional one for control measurement of the track coordinate along the tube. All MicroMegas have a pitch of 250 μm
- Reference timing implemented with scintillators read out with silicon photomultipliers running in a coincidence mode, The time resolution of the reference timing was found to be better than $\sim$1 ns.
- Straw tubes with a diameter of 6 mm operated with the 70% Ar + 30% CO_2 gas mixture and were read out with one of three types of the frontend electronics based on the VMM3a, VMM3 and TIGER ASICs.

The photo and schematic diagram of the test setup are shown in Fig. 5.

Measurements at the SPS test beam were made with three different read-out electronics solutions for the straws.

The first one, based on the VMM3a read-out, was done in November of 2021 [10]. VMM3a reliably operates in so-called “time-at-peak” mode, when the time of the signal peak is measured, and performs well as a read-out of the ATLAS New Small Wheel [11]. This operation mode can not be used in read-out of drift tubes, since the time of a threshold crossing rather than a signal peak time has to be measured. This possibility is implemented for VMM3/3a as well as a “time-at-threshold” mode, but has not been tested in detail. During the test beam measurements with the straw tubes, VMM3a was found to suffer of channel latching while operated in the “time-at-threshold” mode, as can be seen in Figure 6. Current information hints to an algorithmic issue in the cases when the time between the threshold crossing and signal peak is shorter than one clock period, which is often the case for the straw signals.

The observed problem makes it impossible to use VMM3a for straw read-out, so the previous version of the ASIC, VMM3, was tested as well. The measurements were performed in summer 2022 with SPS muon beams.

It was found that VMM3 has no such “latching” problem since implementation of the “time-at-threshold” mode slightly differs for VMM3 and VMM3a. Preliminary results of the data analysis are shown in Fig. 7, left. At this stage of analysis, only one of three MicroMegas is used to reconstruct the track coordinates, R. The plot shows the drift time $\mathbf{t}_{\rm drift}$ measured as the time of a signal threshold crossing with respect to the scintillator coincidence signal as a function of the reference track coordinate. The muon flux is uniform across the straw tube.

Fig. 7, right, compares the straw drift times obtained from the data analysis to the corresponding results of the GARFIELD simulation, followed by emulation of the read-out electronics in LTSpice. It can be concluded that the agreement between the model and data is quite good.

Straw read-out based on the TIGER ASIC was tested at SPS as well in autumn 2022. Preliminary results of the data analysis are shown in Fig. 8, with the reduced reference tracking information as well. Work on the reference track reconstruction using all MicroMegas detectors is ongoing. Improvement of the reference tracking will provide high precision of the $\mathbf{t}_{\rm drift}(\mathbf{R})$ distribution.

V. CONCLUSIONS

Intensive searches of possible solutions for straw read-out electronics are ongoing. A synergy of muon beam measurements and straw response simulation provides a good base for exploring different straw read-out options in order to find a good solution for front-end electronics of the Straw Tracker of the SPD experiment at NICA collider.

As existing possibilities, VMM3a, VMM3 and TIGER ASICs were studied. VMM3a was discarded due to the observed latching problem in the "time-at-threshold" operation mode, while VMM3 was found to be operational in that mode. Analysis of the measurements performed with the VMM3 and TIGER-based straw read-outs is ongoing, as well as simulation studies with the combined GARFIELD and LTSpice software.

Acknowledgments

We are very grateful to the RD51 Collaboration (CERN) and TIGER experts (Turin University).

[1] R. Acciarri *et al.* (DUNE) (2016), 1601.02984.

[2] C. Ahdida *et al.* (SHiP), Eur. Phys. J. C **82**, 486 (2022), 2112.01487.

[3] V. M. Abazov *et al.* (SPD) (2021), 2102.00442.

[4] R. Veenhof, Conf. Proc. C **9306149**, 66 (1993).

[5] *LTSpice simulator*, https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html, accessed: 2023-01-14.

[6] E. Cortina Gil *et al.* (NA62), JINST **12**, P05025 (2017), 1703.08501.

[7] G. Iakovidis (ATLAS Muon), EPJ Web Conf. **174**, 07001 (2018).

[8] G. Iakovidis, J. Phys. Conf. Ser. **1498**, 012051 (2020).

[9] M. Greco *et al.*, PoS **MPGD2017**, 049 (2019).

[10] V. Bautin *et al.*, Nucl. Instrum. Meth. A **1047**, 167864 (2023).

[11] T. Kawamoto *et al.*, Tech. Rep. (2013), ATLAS New Small Wheel Technical Design Report, URL `http://cds.cern.ch/record/1552862`.

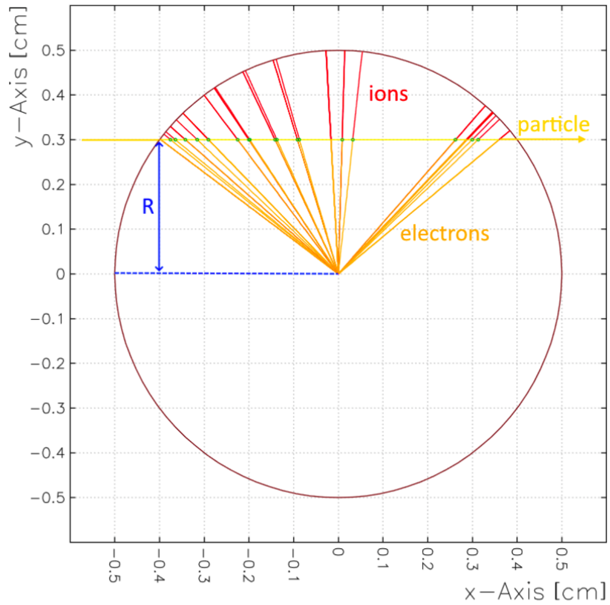

FIG. 1: An ionizing particle crossing a straw tube at the distance of 3 mm from the anode wire, as simulated with GARFILED package. Primary electrons (orange) and ions (red) originated from the ionization clusters (green points) drift towards the anode wire and cathode respectively.

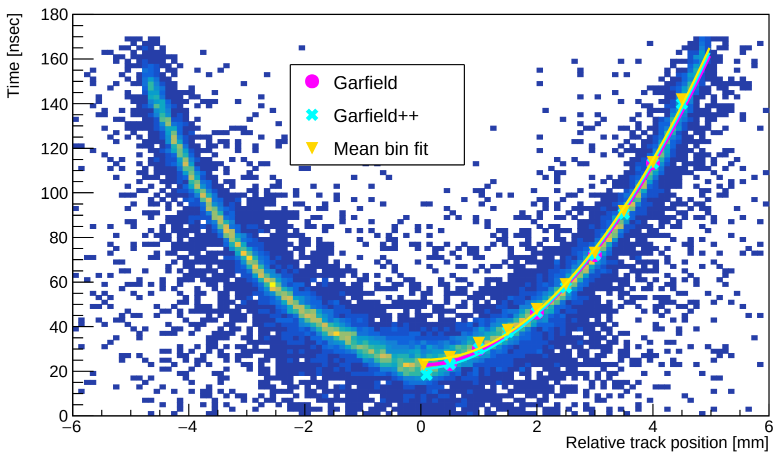

FIG. 2: Example of the calibration $\mathbf{t}_{\rm drift}(\mathbf{R})$ dependence measured for an NA62 straw compared to GARFIELD simulation of the signal arrival time for first primary ionization cluster.

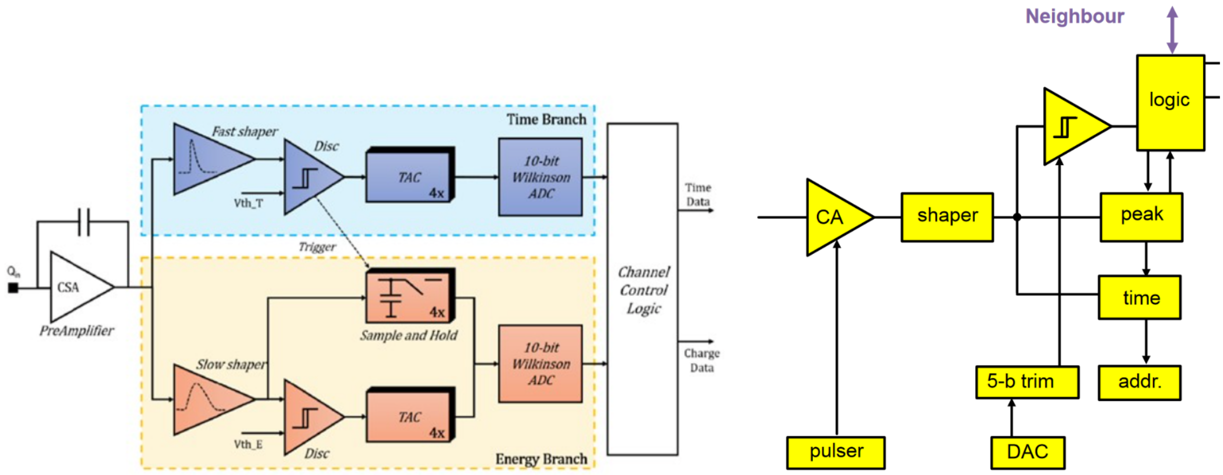

FIG. 3: Basic features of the ASIC schematics – TIGER (left) and VMM3/3a (right).

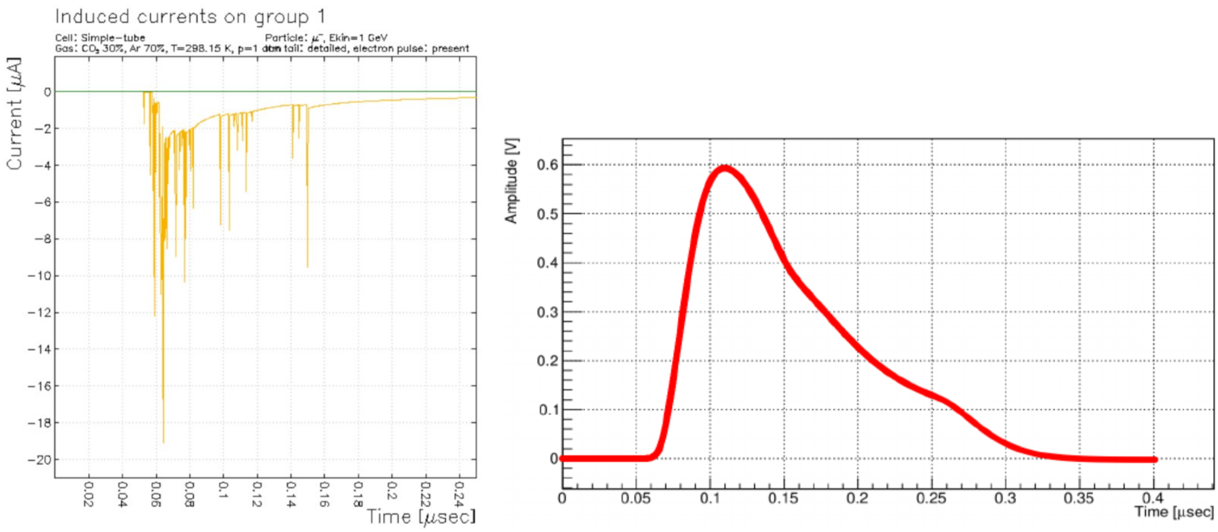

FIG. 4: A signal from the straw tube predicted by GARFIELD (left) and the corresponding response of the VMM3 amplifier and shaper emulated with LTSpice (right).

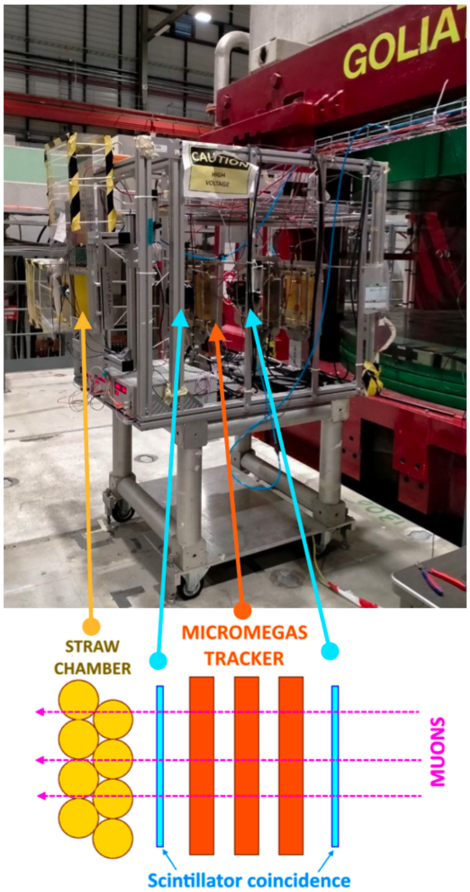

FIG. 5: Photo and schematic description of the test setup.

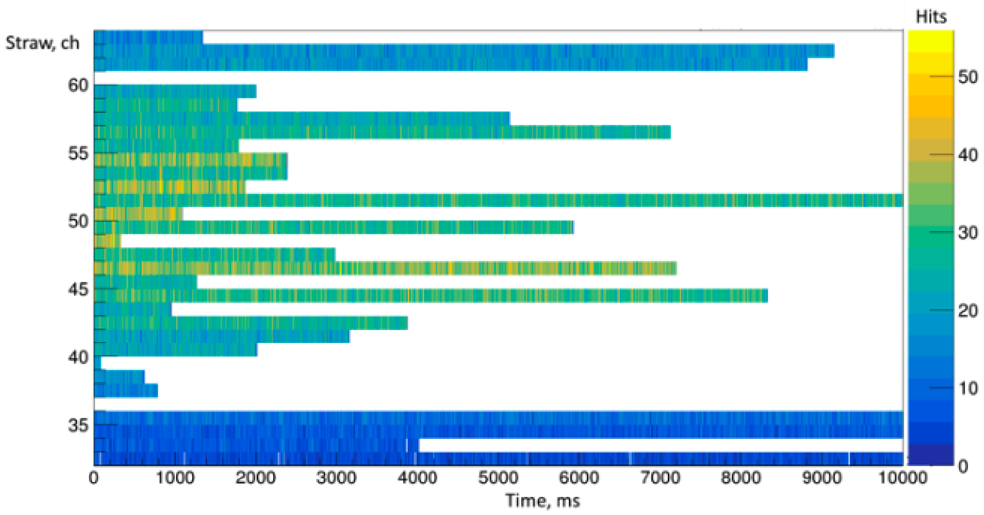

FIG. 6: VMM3a channels latching in the "time-at-threshold" mode – after several seconds of operation no response from the most of VMM3a channels is observed.

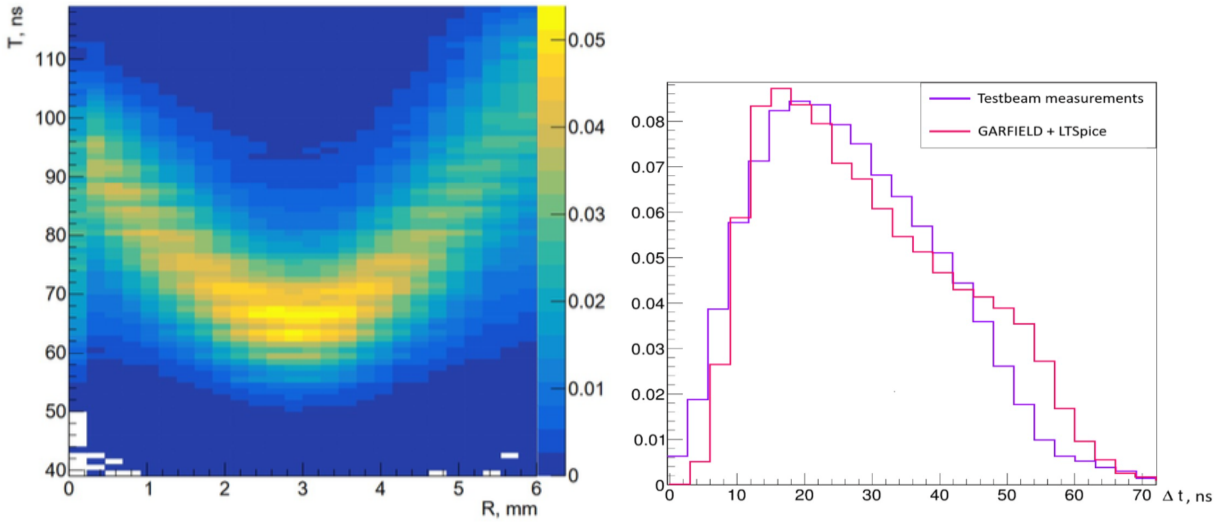

FIG. 7: Preliminary results of the $\mathbf{t}_{\mathrm{drift}}(\mathbf{R})$ measurements done with the VMM3-based read-out – left, and a comparison of the drift time distribution obtained with the muon beam data (magenta) to the corresponding GARFIELD + LTSpice prediction (red) – right.

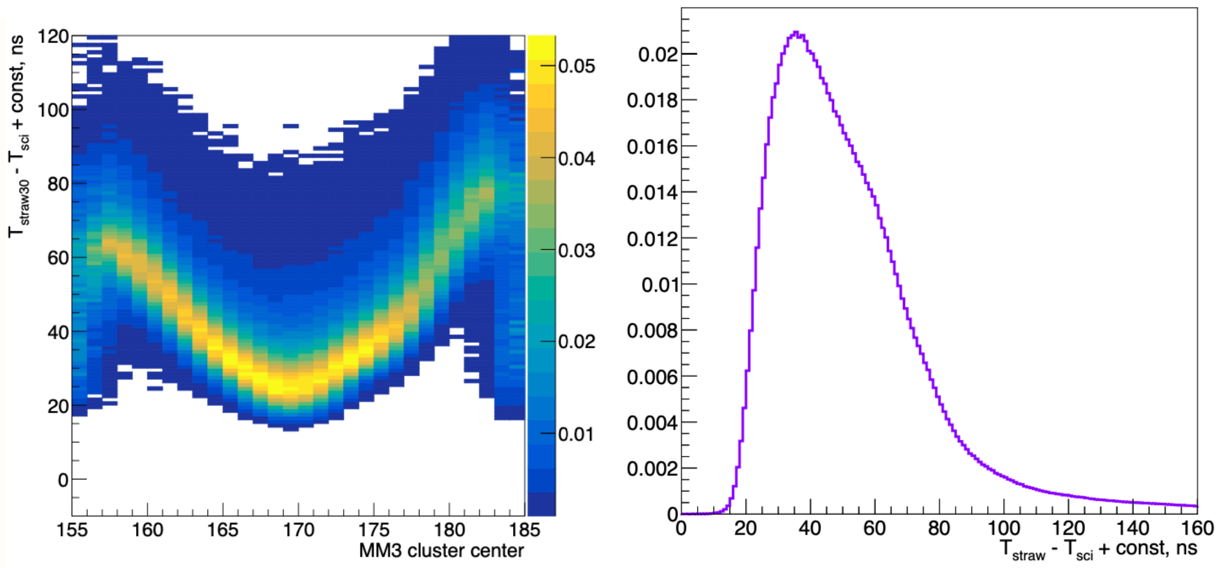

FIG. 8: Preliminary $\mathbf{t}_{\mathrm{drift}}(\mathbf{R})$ dependence measured with the TIGER-based read-out – left, and the drift time distribution – right.

TABLE I: Comparison of VMM3/3a and TIGER operation parameters.

	VMM3	**TIGER**
Number of channels	64	64
Clock frequency	10...80 MHz	160...200 MHz
Input capacitance	$<$300 pF	$<$100 pF
Dynamic range	Linearity within $\pm$2% up to 2 pC	50 fC
Gain	0.5, 1, 3, 6, 9, 12, 16 mV/fC	12 mV/fC
ENC (energy branch)	$<$3000	$<$1500
TDC binning	$\sim$1 ns	50 ps
Maximum event rate	140 kHz/ch	60 kHz/ch
Consumption	15 mW/ch	12 mW/ch