NA61/SHINE vertex detector for open charm measurements

Grigory Feofilov (for NA61/SHINE Collaboration)
St. Petersburg State University, RF
E-mail: grigory-feofilov@yandex.ru

Abstract.
In this report we present the motivation and general design of a new vertex detector (VD) for NA61/SHINE. Several practical solutions to meet the requirements for this VD are proposed and demonstrated.

1. Introduction
The SPS Heavy Ion and Neutrino Experiment (NA61/SHINE) [1] at CERN was designed to study the properties of the onset of deconfinement and search for the critical point of strongly interacting matter. These goals are being pursued by investigating proton-proton, proton-nucleus and nucleus-nucleus collisions at different collision energies from 13A to 158A GeV. Precise hadron production measurements have also been done by NA61/SHINE in order to improve calculations of the initial neutrino beam flux in long-baseline neutrino oscillation experiments as well as for more reliable simulations of cosmic-ray air showers.

Recently it was proposed [2, 3, 4] that measurements of hadrons containing charm quarks could be used in investigations of the initial stage of nucleus-nucleus collision at relativistic energies. Charm is considered an important probe in a deconfined medium formed in high energy A+A collisions and of the dynamic processes of thermalization of the QGP that could be used to test the color screening effects on the binding of charm quarks to color neutral $J/\psi$ mesons [2]. A schematic view illustrating $J/\psi$ production in p+p collisions is shown in Fig. 1 ([3]). According to the standard scenario of charmonium production and suppression in AA collisions [2]:

- Charmonia are produced before QGP formation
- Suppression takes place in the QGP
- Some charmonia may survive beyond some critical temperature $T_c$.

Matter induced changes in the yield of quarkonia were discussed in a recent paper [4] where the following contributing mechanisms are considered: color screening (see Fig. 2 upper left), ionization by thermal gluons (see Fig. 2 lower left) and recombination (see Fig. 2 right). Experimental studies in the charm sector provide important information for discriminating among theoretical predictions.

Figure 3 shows the results of a comparison [9] of meson abundances from central Au+Au reactions from SIS to RHIC energies predicted by Hadron String Dynamics (HSD) transport
calculations [8] and experimental data from central nucleus-nucleus collisions Ref.[9]. Calculated meson multiplicities show a monotonic increase with bombarding energy that is in approximate agreement with data. This allows for the use of the HSD predictions for $D(\bar{c})$, $D(c)$ and $J/\psi$ multiplicities as a basis for estimating the required efficiency of registration and beam intensity at the SPS. As one may see from these predictions, the measurements of $D(\bar{c})$, $D(c)$ and $J/\psi$ yields are rather challenging because the multiplicity is lower by orders of magnitude when compared to the other mesons.

Below, we present the motivations for open charm measurements in nucleus-nucleus collisions at SPS energies and the challenges and requirements to be met by the experiment and in the design of the new Vertex Detector for the NA61/SHINE apparatus. Some practical solutions are proposed and demonstrated based on previous experience.

2. **Open charm measurements at SPS energies**

The first experimental look at the open charm production at SPS energies was done by the NA60 experiment in In+In collisions [14].

A feasibility study for possible $D^{0}$ meson (Open charm) measurements via its decay into two charged daughter particles, pion and kaon, in central Pb+Pb collisions at the SPS energies was presented earlier [5]. A simulation framework was developed for these studies using such MC models as AMPT (A Multi-Phase Transport model [10]), HSD (Hadron String Dynamics model [11]) and the event generator PYTHIA[12]. It was shown [7] that 12 hours of beam time at the SPS should be sufficient to record about 200K events and to provide reconstruction for $D^{0} \rightarrow K^{-}\pi^{+}$ in 0-10% central Pb+Pb collisions at 158 A GeV. Model calculations and GEANT4 simulation of particle transport through the experimental setup [5, 6, 7] proved that
such experiments are possible. The result of reconstruction of $D^0 \rightarrow K^-\pi^+$ in these 0-10% most central Pb+Pb collisions at 158A GeV shows a clear $D^0$ peak (see Fig. 4).

A number of challenges and requirements for the design of the VD for the NA61/SHINE were established. The first challenge is the low yields of $D^0$, $D^+$, and $J/\psi$ mesons which require sufficiently fast detectors capable to provide high time resolution and high efficiency of track registration.

The second challenge comes from the short mean life-time of D mesons (see values of $\tau$ in Table 1). Therefore, one expects a rather small distance between the decay vertices of D mesons and the primary production vertex.

The following general requirements for the VD were obtained [5, 6, 7] as a result of the simulations:

- Precise vertexing and tracking accuracy (at the level of 10 - 20 $\mu m$ in the transverse plane)
- The lowest possible material budget in the tracking region in order to increase the efficiency of open charm measurements
- High granularity of vertex tracking detectors capable to register the multiple tracks in nucleus-nucleus collisions
- Large acceptance.

CMOS technologies and the use of MIMOSA-26 chips were proposed [5] to meet these requirements and to ensure high accuracy of tracking of charged particles and of secondary vertex reconstruction. A high precision VD needs to be developed that is capable of providing an accuracy of charged particle tracking to the vertices on the level of tens of microns. It is also required to have an extremely low material budget (of the order of below 0.3% $X_0$) in order to minimize multiple scattering of low-momentum particles, which would reduce the efficiency of $D^0$ reconstruction.

Table 1. Decay channels, branching ratios and values of $\tau$ for various D mesons.

| Meson | Decay Channel | $\tau$ | Branching Ratio |
|-------|---------------|-------|-----------------|
| $D^0$ | $D^0 \rightarrow K^- + \pi^+$ | 122.9 $\mu m$ | $(3.91 \pm 0.05)\%$ |
| $D^0$ | $D^0 \rightarrow K^- + \pi^+ + \pi^+$ | 122.9 $\mu m$ | $(8.14 \pm 0.20)\%$ |
| $D^+$ | $D^+ \rightarrow K^- + \pi^+ + \pi^+$ | 311.8 $\mu m$ | $(9.2 \pm 0.25)\%$ |
| $D_s^0$ | $D_s^0 \rightarrow K^- + K^- + \pi^+$ | 149.9 $\mu m$ | $(5.50 \pm 0.28)\%$ |
| $D_s^{*+}$ | $D_s^{*+} \rightarrow D^0 + \pi^+$ | — | $(61.9 \pm 2.9)\%$ |

Figure 4. Reconstruction of simulated events: yield for $D^0 \rightarrow K^-\pi^+$ in 200k events (12 hours of beam) for the most central 0-10% Pb+Pb collisions at 158A GeV (perfect PID is assumed) [7].
Figure 5. Layout of the NA61/SHINE apparatus with the new VD planned to be positioned downstream of the target.

3. The NA61/SHINE Vertex Detector project based on CMOS pixel detectors

The Vertex Detector will be positioned between the primary vertex and the first VTPC of the NA61/SHINE apparatus (see Fig. 5). Four planes of coordinate-sensitive detectors will provide the first four hits on charged particle tracks coming from the vertices. Detectors and the relevant supporting elements will form stations, called VDS1-VDS4, located at 5, 10, 15 and 20 cm distance from the target. The tracks registered by the VD will be matched with the tracks of the time-projection chambers (VTPCs) of NA61/SHINE in which the PID will be performed.

High coordinate resolution MIMOSA-26 sensors [15] whose architecture is based on the Monolithic Active Pixel Sensor (MAPS) with fast binary readout have been chosen [7] as the basic detection element of these VD stations.

3.1. MIMOSA-26 sensor

The sensitive area of the MIMOSA-26 chip is 1.06x2.12 cm² with a pixel pitch equal to 18.4 µm (= 663.5k pixels/chip). This dimension of the pixels of 18.4 µm were found to be sufficient for the required charged particle tracking accuracy. The MIMOSA-26 Si-chips are thinned down to 50 µm, providing a significant reduction in material budget. Therefore, the multiple scattering of low momentum charged particles in the detector volume is negligible (X/X₀ = 0.064%).

MIMOSA-26 is suited for detecting charged particles with density up to 10⁶ hits/cm²/s. The selection of this chip was mostly driven by the very high hit occupancy expected in the stations. Estimates show that the hit occupancy generated by a single central Pb+Pb collision at the top SPS energy of 158A GeV reaches value of about 5 hits/mm²/event in the innermost part of the VDS1 station.

MIMOSA-26 pixel columns are read out in parallel, row by row. The chip readout time is 115.2 µs. Each pixel includes amplification and Correlated Double Sampling (CDS) units and each end of column is equipped with a discriminator. After the analogue to digital conversion, digital signals pass through zero suppression circuits. The readout electronics boards for MIMOSA-26 chips are being developed by NA61/SHINE in synergy with the CBM collaboration.
Table 2. Material budget for the carbon fiber cooling and support structure with the MIMOSA-26 Si-sensor according to the design developed in synergy with ALICE [16].

| Material                                | Thickness (µm) | /X₀ (cm) | X/X₀ (%) |
|-----------------------------------------|----------------|----------|----------|
| Polyimide cooling pipe wall             | 25             | 28.4     | 0.003    |
| Carbon fleece                           | 40             | 106.8    | 0.004    |
| Water                                   | 1000           | 35.76    | 0.032    |
| Carbon fiber plate K13D2U               | 70             | 26.08    | 0.027    |
| Graphite foil                          | 30             | 26.56    | 0.011    |
| Thermal grease (glue)                   | 100            | 44.37    | 0.023    |
| Si-sensor                               | 50             | 9.36     | 0.064    |
| Total                                   |                |          | 0.154    |

at FAIR. The major components include the Front-end Board connected to the Si-sensors by the flex polyimide cable and the Converter Board.

3.2. General design of the Vertex Detector

The geometry of the full acceptance VD used in the GEANT4 simulations is shown in Fig. 6. As the first stage of the VD development it is planned to use the limited acceptance VD pictured in Fig. 7. Straight track reconstruction was performed for these simulations and provided the following results for the accuracy of secondary vertex determination: σₓ, σᵧ, ~ 7µm, σz, ~ 70µm, where a realistic material budget (see Table 2) of the stations was taken into account in the GEANT4 transport of charged particles. This design of the NA61/SHINE VD ensures X/X₀ ≤ 0.2% per sensitive layer of Si-detectors (including the chip and services).

The conceptual layout of the VD for NA61/SHINE is shown in Fig. 8. The design includes four VD stations – four planes of coordinate sensitive detectors – that are formed by MIMOSA-26 chips mounted on extra-lightweight vertical carbon fiber panels.

These extra-light support, cooling and precise positioning carbon fiber structures with MIMOSA-26 chips are precisely mounted on the C-shape support frames depicted in Fig. 9. The number of MIMOSA-26 chips, forming each sensitive plane, will vary depending on the distance to the target.

The C-shape support frames are mounted on two movable platforms. Thus the MIMOSA-26 chips can be moved in and out of the measuring position by using the high accuracy (5µm) linear translation stage step motor. The C-shape frames also provide cooling water manifolds (see Fig. 10) for cooling panels with the detectors mounted.
Figure 8. Conceptual view of the Vertex Detector for NA61/SHINE. The four sensor planes are formed by MIMOSA-26 chips mounted with support and cooling carbon fiber panels on the C-shape frames and placed inside the He-filled box.

Figure 9. The C-shape supporting frames mounted on two movable platforms (called "left" and "right"). Only one carbon fiber structure with MIMOSA-26 chips is shown per each C-shape frame. The flat polyimide cables (FPCs) and the readout boards will also be fixed to the additional holders of these C-shape supporting frames (not shown here).

Figure 10. Conceptual design of cooling liquid distribution manifolds mounted on the C-shape frames.

All VD components are housed inside a hermetic box structure (see Fig. 8 filled with He (at atmospheric pressure). This He gas inside the box helps to further minimise the multiple scattering in the sensitive region of tracking of low-momentum charged particles. The movable
target holder of the VD (not shown) will be positioned on the beam line in front of the VDS1 station.

**Figure 11.** The ALICE type [16] design of the extra-lightweight (1.5 g) support and cooling carbon fiber structure of 30 cm length used for precise positioning of MIMOSA-26 chips.

**Figure 12.** Eight MIMOSA-26 chips of the 1st station VDS1 mounted on vertical extra-lightweight support and cooling carbon fiber structures. Flat readout cables, going left and right from the center of the VDS1 station, are shown schematically.

**Figure 13.** The cross-section of the ALICE type [16] design of the cooling and support carbon fiber panel for MIMOSA-26 chips: 1 – polyimide cooling pipe (D=1mm); 2 – carbon fleece (20 µm); 3 – graphite foil (30 µm); 4 – carbon fiber plate K13D2U (70 µm); 5 — thermal grease; 6 — Si-sensor (60 µm).

The ALICE design of the extra-light support, cooling and precise positioning carbon fiber structures (Fig. 11) is used as a baseline. The proven ALICE technology is currently being improved for the upgrade of the ALICE Inner Tracking System [16]. The extra lightweight carbon fiber cooling panel of 30 cm length was designed and tested for support and efficient drain of heat from the MIMOSA-26 chips. It is equipped with precise positioning elements and allows high accuracy alignment and mounting of chips.

The layout of eight MIMOSA-26 chips, that are forming the first detector plane VDS1, are shown in Fig. 12 together with the readout flat polyimide cables (FPCs). In the current NA61/SHINE application, contrary to ALICE, the FPCs used for readout of the MIMOSA-26 chips are oriented horizontally (see Fig. 12). This design ensures the required minimisation of multiple scattering in the sensitive area.

The cross section layout of the thermoconductive carbon fiber cooling panel with embedded miniature cooling arteries is shown in Fig. 13. The panel ensures heat drain capability up to 0.5 W/cm² and will allow the operation of MIMOSA-26 chips at ambient temperature.

The first carbon fiber panels for detector support and cooling were successfully produced (see Fig.14) and are being used for mounting of detector chips. This will allow to instrument the limited acceptance VD and start with the first measurements of $D^0$ production. Subsequently the
large acceptance vertex detector will be completed which is planned to be ready after the Long Shutdown-2 of the CERN accelerator chain in 2020.

Figure 14. The first batch of extra-lightweight 30 cm long detector support and carbon fiber panels with the embedded cooling arteries produced for the NA61/SHINE VD.

4. Summary
Open charm measurements in A+A collisions at top SPS energy are possible with NA61/SHINE after construction of the Vertex Detector. The proposed design is based on proven technologies and includes:

- Sensors — MIMOSA-26 CMOS chips (IPHC-Strasbourg).
- Readout electronics boards – in synergy with CBM.
- Extra-light support, cooling and precise positioning – in synergy with ALICE.
- Mechanical layout of the VD by NA61/SHINE.

4.1. Acknowledgments
This work is supported for G.F. by the Saint-Petersburg State University research grant 11.38.242.2015.

[1] N. Abgrall et al. (NA61 Collaboration), 2014, JINST 9, P06005.
[2] T. Matsui and H. Satz, 1986, Phys. Lett. B 178, 416.
[3] Helmut Satz, 2013, arXiv:1303.3493
[4] Berndt Müller, 2013, arXiv:1309.7616.
[5] Yasir Ali and Pawel Staszel for the NA61/SHINE collaboration, 2014, in Proceedings of 14th International Conference on Strangeness in Quark Matter (SQM2013), Journal of Physics: Conference Series 509 012083.
[6] Yasir Ali, Pawel Staszel, 2014, EPJ Web of Conferences, 71, 00004.
[7] Yasir Ali, Pawel Staszel, 2013, Acta Physica Polonica B Proceedings Supplement 6, No 4, 1081.
[8] W. Cassing, E. L. Bratkovskaya, and A. Sibirtsev, 2001, Nucl. Phys. A691, 753.
[9] O. Linnyk et al., Int. J. Mod. Phys., 2008, E17, 1367; [arXiv:0808:1504 [nucl-th]].
[10] Zi-Wei Lin, Che Ming Ko, Bao-An Li, Bin Zhang, and Subrata Pal, 2005, Phys.Rev.C72, 064901.
[11] W. Cassing, E.L. Bratkovskaya, arXiv:0907.5331; The open Hadron String Dynamics source code and papers can be found at http://www.th.physik.uni- frankfurt.de/ brat/hsd.html.
[12] PYTHIA, 2001, Comput.Phys.Commun.135, 238.
[13] NA60 Collaboration, A. Foerster et al., 2006, J. Phys. G 32, S1.
[14] NA60 Collaboration, R. Shahoian et al., 2005, Phys.J. C43, 209-213.
[15] MIMOSA26 User Manual, Institut Pluridisciplinaire Hubert Curien IN2P3-CNRS.
[16] The ALICE Collaboration, 2013, Technical Design Report for the Upgrade of the ALICE Inner Tracking System ALICE-TDR-017, CERN-LHCC-2013-024.