Performance of Forward Hadron Calorimeter at MPD/NICA

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Abstract. Forward Hadron Calorimeter is a part of MPD experiment setup at NICA beam facility. FHCal structure and purpose are presented in this proceedings. Methods of collision centrality and event plane reconstruction are discussed. Simulation, beam test results and production status are presented.

1. Introduction
Nuclotron-based Ion Collider fAcility (NICA) [1] is an accelerator complex at JINR, Dubna in Russia. It is under construction now and after commissioning it will provide a wide variety of beam species for studies of properties of dense baryonic matter, including heavy ion beams with energy of up to 4.5 GeV per nucleon.

One of two interaction points at the collider facility is occupied by the Multi Purpose Detector (MPD) experiment. Cross-section of the MPD setup is shown in Fig.1. It is a cylindrical superconducting magnet densely populated by several layers of tracking detectors, Time of Flight (TOF) detectors, Electromagnetic Calorimeter (ECal), Forward Detector (FD) and Forward Hadron Calorimeter (FHCal). This design provides capabilities for precise 3D track reconstruction and high performance particle identification in the energy range of the NICA facility.

Figure 1. Schematic view of MPD experimental setup.
Study of observables like collective flow, particle multiplicities and fluctuations requires event-by-event estimation of global event characteristics, such as centrality (commonly represented by impact parameter $b$) and reaction plane (spanned by vector $b$ and beam axis). Collision centrality can be determined either by measuring multiplicity of particles produced in the participant zone or by measuring energy carried by projectile spectators (non-interacting nucleons), which are detected by forward calorimeter. Estimation of reaction plane can be obtained from transverse momentum distribution of the spectators deflected off the beam axis due to momentum transfer during the collision.

2. Forward Hadron Calorimeter structure design

Forward Hadron Calorimeter (FHCal) consists of two symmetrical arms positioned at the beam axis on both sides of the interaction point at the distance of 3.2 meters from it. Each arm is assembled of 44 independent modules as shown in Fig.2. Each module contains 42 polystyrene based 4 mm thick scintillator tiles wrapped in white reflector (TYVEK paper) and interposed between 16 mm thick lead degrader plates. This sampling ratio of 4:1 is close to satisfying the compensation condition. Each scintillator plate has an Y11(200) wavelength shifting optical fiber [2] glued into a spiral groove. To improve light collection the embedded end of the fiber is coated by silver reflective paint, thus preventing the leakage of collected light back into the scintillator tile. Outer ends of WLS fibres from each six consecutive tiles are glued into individual optical connectors and polished. This way a module is divided in 7 sections which allows to measure the longitudinal shower profile and to compensate for greater optical attenuation in longer WLS fibres by calibrating the sections separately. Transverse size of one module is $15 \times 15$ cm$^2$, total length is 106 cm. Scintillator and degrader tiles are bound together by 0.5 mm thick stainless steel band which is spot welded to lower part of the outer box also made of 0.5 mm thick stainless steel. Upper half of the stainless box completely overlaps the lower part on the lateral sides of a module where they are spot welded together.

Silicon photomultipliers (SiPM) are the photodetectors used to convert light from WLS fibres into electrical signal. They were chosen because of their compact size, high internal gain and ability to function in strong magnetic fields. Seven SiPMs are mounted on a common PCB and directly coupled to optical connectors in the rear of an FHCal module. A Front-End Electronics (FEE) board is connected directly to the PCB with the SiPMs and provides high voltage supply and monitoring as well as two stage amplification and pulse shaping of the signal which is fed into a sampling ADC via a twisted pair ribbon cable. The SiPMs used in FEE prototypes are Hamamatsu S12572-010 MPPCs. The ADC is a 64 channel 12 bit 62.5 MS/s ADC64s2 board produced by AFI Electrinics, Dubna [3].

As of May 2019, 80% of FHCal modules are assembled and ready for testing (see Fig.3). Production of all FHCal modules will be completed in 2019.

![Figure 2. Schematic of FHCal modular composition (front view).](image1)

![Figure 3. FHCal modules assembled on transportation frames.](image2)
3. Event plane reconstruction

While the reaction plane $\Psi_{RP}$ is not directly measurable in experiments, its orientation can be estimated by analysing the azimuthal asymmetry of particle production or deflection of spectators in non-central collisions. Because of transverse segmentation of the FHCal, spectator deflection information can be obtained from energy deposition in each of the FHCal modules. Using this information one can produce an estimation of the reaction plane on event-by-event basis, so called event plane $\Psi_{EP}$.

Limited number of spectators in every collision and its fluctuations for a given value of the impact parameter result in difference between event plane and reaction plane angles which is quantified as the event plane resolution (a Gaussian width of distribution of $\Psi_{RP} - \Psi_{EP}$).

Performance of FHCal for event plane determination was simulated using LA-QGSM model [4] as a collisions generator for $Au + Au$ reaction. Event plane angle is calculated from energy depositions in FHCal modules by constructing a two-dimensional flow $Q$-vector [5] in the plane transverse to the beam axis:

$$\vec{Q} = (Q_x, Q_y) = \left( \sum w_i \cos(\varphi_i), \sum w_i \sin(\varphi_i) \right).$$

Here $\varphi_i$ is azimuthal angle of the center of the $i$-th FHCal module in the transverse plane, $w_i$ is a weight used to improve sensitivity of the event plane to the reaction plane. The weight $w_i$ was chosen to be the energy deposited in a given module $i$. In terms of $Q$-vector components event plane angle is defined as:

$$\Psi_{EP}^{L(R)} = \arctan \left( \frac{\sum E_i \sin \varphi_i}{\sum E_i \cos \varphi_i} \right), \sin \varphi_i = \frac{y_i}{\sqrt{y_i^2 + x_i^2}}, \cos \varphi_i = \frac{x_i}{\sqrt{y_i^2 + x_i^2}}.$$  

Here $x_i$ and $y_i$ are the coordinates of the centre in transverse plane and $E_i$ is the deposited energy for the $i$-th FHCal module. Index $L(R)$ denotes the left (right) arm of FHCal. The resulting event plane angle $\Psi_{EP}$ is a weighted sum of the $\Psi_{EP}^{L(R)}$ which improves the event plane resolution by a factor of about $\sqrt{2}$ over the resolution provided by a single arm of the FHCal. Results of the simulation are presented in Fig.4. The optimal resolution is achieved for medium centrality events where number of spectators deposited in FHCal is the greatest. Worse resolution for the peripheral events is caused by lower spectator multiplicity in FHCal.

![Figure 4. Dependence of event plane resolution on the value of impact parameter for several beam energies in the $Au + Au$ reaction.](image-url)
4. Centrality measurements

Collision centrality as the magnitude of the impact parameter is not experimentally observable but can be estimated from multiplicity of produced particles in the interaction zone or from multiplicity of projectile spectators. Spectator multiplicity provides an independent source of centrality information which allows to study event-by-event fluctuations of particles production as a function of collision centrality. While central events produce least spectator nucleons and peripheral events produce the most, for high values of impact parameter many spectators are lost in the beam hole and do not contribute to the deposited energy. This results in inability to distinguish central events from peripheral using solely the total deposited energies.

This ambiguity can be resolved by employing segmentation of FHCal to analyse transverse distribution of deposited energy. A few experimental observables can be constructed to distinguish central and peripheral events [6]. One can introduce transverse energy $E_T$ and longitudinal energy $E_L$:

$$E_T = \sum E_i \sin \theta_i, \quad E_L = \sum E_i \cos \theta_i.$$  \hspace{1cm} (3)

Here $E_i$ is the energy deposition in section $i$, $\theta_i$ is the angle between beam axis and vector connecting interaction point with center of section $i$.

![Figure 5. Correlation between $E_T$ and $E_L$ for $Au + Au$ collisions at $\sqrt{s_{NN}} = 11$ GeV. Different colors correspond to 10% centrality bins. Upper branch of distribution corresponds to the most central events.](image1)

![Figure 6. Impact parameter resolution as a function of centrality taken from $E_T$ and $E_L$ correlation plot for $\sqrt{s_{NN}} = 11$ GeV. Blue (red) dots correspond to the most central (peripheral) events.](image2)

Fig.5 shows correlation between longitudinal and transverse energy. $E_T$ is sensitive to transverse distribution of spectators and allows to separate peripheral and central events in different classes. Impact parameter resolution simulated for this centrality reconstruction method is shown on Fig.6.

5. Beam tests

A series of tests of CBM PSD [7] modules with similar longitudinal structure were performed at the T9 and T10 beam lines of Proton Synchrotron, CERN. Nine modules with transverse size of $20 \times 20 \text{ cm}^2$ in a 3 by 3 assembly were tested with secondary proton beams in the energy range from 1.25 GeV to 5.15 GeV. These modules have longer active parts with 60 scintillator tiles subdivided in 10 sections instead of 42 tiles in 7 sections in FHCal modules. Using the data collected in these tests one can estimate the effect on the energy resolution for shorter FHCal module length caused by the tight geometrical constraints of the MPD setup.
Fig. 7. Longitudinal profile of deposited energies. Black and red lines correspond to a proton beam energy of 1.25 GeV and 5.15 GeV respectively.

Fig. 8. Energy resolutions for a 3x3 array of calorimeter modules for active lengths corresponding to different numbers (from 4 to 10) of longitudinal sections. Black and red dots correspond to a proton beam energy of 1.25 GeV and 5.15 GeV respectively.

Fig. 7 presents the longitudinal shower profile in modules for minimum and maximum beam energies. Most of the shower is contained in first 7 sections. This indicates that module length of seven sections is sufficient for spectator energies expected in MPD experiment. Energy resolution calculated for different lengths of active part is shown in Fig. 8.

6. Conclusion
FHCal at MPD is a unique tool for the measurements of the geometry of heavy ion collisions. Due to detection of all spectator types (protons, neutrons, fragments) of both colliding nuclei the angular resolution of the event plane achieves 20%. The beam hole in FHCal constitutes a serious problem for the centrality reconstruction because of the leakage of heavy fragments. Transverse distribution of the spectator deposited energy resolves the ambiguity in total energy deposition for central and peripheral events. New experimental observables can be constructed to improve the centrality measurements.

Acknowledgments
The authors thank MPD/NICA collaboration for discussions. This work was supported by RFBR grant No. 18-02-40065.

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