Calibration of FHCal with cosmic muons at the BM@N experiment

A Izvestnyy\textsuperscript{1}, N Karpushkin\textsuperscript{1,2}, F Guber\textsuperscript{1,2}, S Morozov\textsuperscript{1,3} and O Petukhov\textsuperscript{1,3}

\textsuperscript{1}Institute for Nuclear Research RAS, Moscow, Russia
\textsuperscript{2}Moscow Institute of Physics and Technology, Moscow, Russia
\textsuperscript{3}Moscow Engineering Physics Institute , Moscow, Russia
E-mail: aizvestn@inr.ru

Abstract. The forward hadron calorimeter (FHCal) is one of the sub-detectors of the BM@N experimental setup at JINR, Dubna. It consists of 54 lead-scintillator "sandwich" type modules of two types with the transverse sizes $20 \times 20 \text{ cm}^2$ and $15 \times 15 \text{ cm}^2$. These two types of modules are subdivided into 10 and 7 individual longitudinal sections, respectively. Each section provides the independent light and amplitude signal readout with one silicon photomultiplier (MPPC). High signal to noise ratio of MPPC allows to detect cosmic rays with low energy depositions in FHCal longitudinal sections. A method for cosmic muon track reconstruction is discussed. A procedure for energy calibration based on muon track length and energy deposition in each section is proposed. Experimental results of FHCal cosmic calibration are presented.

1. The FHCal at the BM@N
The BM@N (Baryonic Matter at Nuclotron) is a fixed target experiment for studying interactions of various ion beams with different targets. The BM@N setup is shown in Figure1. It is based at the Nuclotron/NICA accelerating complex at JINR, Dubna. Kinetic energy of the ion beams provided by Nuclotron ranges between 1 and 6 GeV per nucleon. Data taking with beams of carbon, argon and krypton has already been performed. The gold and bismuth beams are planned for the future [1]. The FHCal has been assembled and installed in the BM@N experimental area in 2019, see Figure 2. Like Zero Degree Calorimeter (ZDC) in previous runs, it will be used for event plane and centrality determination. It consists of 54 lead-scintillator

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Schematic view of the BM@N setup.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{The FHCal during the installation procedure.}
\end{figure}
modules with a 15 cm by 15 cm square beam hole and is mounted on a moving platform in place of the ZDC.

![Figure 3. Schematic view of the internal structure of an FHCal module.](image)

![Figure 4. An FHCal module during assembly.](image)

![Figure 5. Schematic picture of the FHCal composition. NICA/MPD modules are shown in blue, CBM modules are shown in yellow.](image)

2. Calorimeter modules

Two types of modules are used in FHCal: 34 modules with 15 × 15 cm² transverse size identical to ones used in future NICA/MPD setup and 20 larger modules with 20 × 20 cm² transverse size designed for CBM experiment shown on Figure 5 in blue and yellow respectively. Modules contain 16 mm lead and 4 mm polystyrene scintillator tiles with WLS fiber light collection, see Figure 3. Every six consecutive scintillators are read out by one photodetector, optical connectors visible on Figure 4. Smaller modules are about 4 radiation lengths and contain 42 scintillator tiles while larger modules are about 5.6 radiation lengths with the total of 60 scintillator tiles.

![Figure 6. The front side of an FEE board.](image)

![Figure 7. The rear side of a FEE board.](image)

![Figure 8. An ADC64s2 unit.](image)

3. Electronics and trigger

Front-End Electronics (FEE) boards for FHCal modules were produced at JINR, Dubna. As shown on Figure 6, they include Hamamatsu MPPC photodetectors for every section in a module with individual voltage adjustment capability. Each channel has preamplifier and ADC driver analog stages, shown on Figure 7. One FEE board has a temperature sensor, an externally synchronizeable LED for photodetector tests and an attenuated analog sum output for use in trigger systems. All FEE boards are remotely controlled via a System Module unit which allows to adjust the voltages for gain compensation with change of temperature.

Data acquisition is performed by eight ADC64s2[2] units manufactured at JINR, Dubna, see Figure 8. This model of 64 channel 62.5 MS/s 12-bit sampling ADCs was previously used for ZDC signal readout and therefore can be easily integrated into BM@N data acquisition system.
ADC64s2 units are capable of time synchronization via White Rabbit network and can function both in external trigger and self-triggered modes. FHCal modules connections with ADC64s2 units are shown by colors on Figure 9.

![Figure 9. Rear view map of the FHCal ADC64s2 connections.](image1)

Custom 12 channel analog sum modules with adjustable attenuation for every channel were produced at JINR, Dubna. These modules were used to produce the sum of all signals in central part of the FHCal consisting of 34 smaller modules. Connections of FHCal modules to analog sum units are shown on Figure 10 and Figure 11. This signal was then used to trigger synchronous data readout for 8 ADC64 units.

![Figure 10. FHCal modules grouped by their connection to analog sum units.](image2)

![Figure 11. Analog sum signal propagation path.](image3)

Data taking for cosmic calibration was performed using BM@N run control system. Data was recorded in mstream[2] binary format. At the first stage of data processing binary files were decoded and waveform was analyzed to produce time and amplitude characteristics. At the second stage these variables were used to reconstruct a track of the cosmic particle. Then energy deposited in the sections of the calorimeter was corrected to the track length in every section. Both stages of data processing were done using software developed at INR, Troitsk.

4. Cosmic calibration
Since muon beams are unavailable at the BM@N setup, energy calibration of the FHCal can only be performed by using cosmic particles. This is complicated by variation of deposited energy in dependence of track position and orientation. Longitudinal and transverse segmentation of the calorimeter allow to reconstruct muon tracks to improve calibration efficiency. Figure 12 shows cosmic muon track hitting several sections of the FHCal.

![Figure 12. A track passing through several sections of the calorimeter.](image4)

![Figure 13. A typical waveform fit by Prony least squares method.](image5)

![Figure 14. Reconstruction of signals in a pileup event.](image6)
5. Waveform analysis
Prony least squares method[3] was used to analyze waveforms acquired by ADCs. This method uses a linear combination of exponential components to fit a data sample and has been shown to be able to reconstruct individual signals from pileup events and to reject noise by using fitting function quality assessment criterion. Results of a waveform fit and pileup signal subtraction are shown on Figure 13 and Figure 14 respectively. After completion of fitting procedure signal amplitude, waveform integral and time of arrival are available for further analysis.

6. Track reconstruction
Least squares method [4] was used for track reconstruction. First, the center of gravity of deposited energy in the sections of the calorimeter is found. Then, as shown on Figure 15, a quadratic form $\varphi$ on a unit vector $\vec{a}$ is maximized to find an eigenvector corresponding to a maximum eigenvalue. This vector provides the track direction. After that signal amplitudes from the track hits are corrected to the known track lengths in the scintillator tiles of the calorimeter sections. Results of correction procedure for a single section are presented on Figure 16.

7. Summary
The forward hadron calorimeter (FHCal) with its electronical systems has been installed and configured for data taking on cosmic muons. The cosmic data collected from several runs has been processed using muon track reconstruction method to improve calibration efficiency. Trigger configuration adjustments and further data taking will be performed in the future.

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