Study of the hadron calorimeters response for CBM and BM@N experiments at hadron beams

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Abstract. The results of beam tests of the hadron calorimeter with transverse and longitudinal segmentation and with the micropixel photodetectors light readout performed at CERN T9 and T10 beamlines in proton momentum range 2 - 10 GeV/c are shown. The new signal processing technique based on the waveform fitting of calorimeter signals using the Prony least squares method is proposed. This technique allows to identify weak signals comparable to the level of electronic noise, which is important for performing a muon calibration of calorimeter sections. For the energy calibration of the hadron calorimeter sections with cosmic muons, a new approach that uses the reconstruction of the muon track in the calorimeter is proposed.

1. Introduction
The existing BM@N (Barion Matter at Nuclotron) experiment [1] and the future Compressed Baryonic Matter (CBM) [2] experiment at the Facility for Antiproton and Ion Research (FAIR) are aimed to explore the Quantum Chromodynamics (QCD) phase diagram in the region of high baryon densities. At present, the BM@N operates with light and medium ion beams with energies up to 4 AGeV and beam interaction rates up to 1 MHz, whereas the CBM will operate in the beam energy range of 2 - 11 AGeV and beam interaction rates up to 10 MHz. The forward hadron compensating lead/scintillator calorimeter - the Projectile Spectator Detector (PSD) [3], with transverse and longitudinal segmentation and with the micropixel photodetectors light readout will be used in the CBM experiment to measure the event centrality and the reaction plane orientation in heavy-ion collisions. The ZDC calorimeter, which is now used in the BM@N experiment for the same task, will be replaced by a new calorimeter consisting of modules designed for the CBM experiment and modules with a similar structure developed for the MPD/NICA experiment [4]. The results of a detailed study of the PSD response in a low proton kinetic energy range 1- 9 GeV at the CERN T9 and T10 beamlines are presented. The newly developed waveform fitting procedure based on the Prony least squares method is discussed. This procedure allows to select true signals near the noise level, which is especially important for the energy calibration of longitudinal sections of calorimeter modules by muons due to the small amplitudes of muon signals and the presence of electronic pick-up noises. A new approach to the energy calibration with cosmic muons, which uses the reconstruction of muon tracks in longitudinally segmented modules, is discussed.
2. Results of the hadron calorimeter response tests
To conduct measurements of the PSD response in the proton momentum range 2 - 10 GeV/c the PSD CBM supermodule assembled from 9 modules in array of 3×3 with transverse size 60×60 cm$^2$ has been used. Due to the sufficiently large transverse size of the PSD supermodule, the lateral hadron shower leakage is quite small compared to previous tests of a single PSD module [5]. The description of the PSD supermodule and methods of measurements at the T9 and T10 test beamlines can be found in [6]. The obtained results of the energy resolution and linearity of the response of the supermodule, measured at proton beam, are shown in Fig. 1.

\[
\frac{\sigma_E}{E} = \sqrt{\left(\frac{0.54}{\sqrt{E}}\right)^2 + 0.94^2 + \left(\frac{0.5}{E}\right)^2}
\]

Figure 1. The PSD supermodule resolution (left) and the response linearity (right).

3. Energy calibration of the PSD supermodule
The muon beam at the T9 and T10 beamlines was used for energy calibration of all ten sections in each of the 9 modules. Identification of muons was done using the two-dimensional correlation between the particle energy depositions in the first five sections and the last 5 sections in each module (Fig. 2, left). These energy depositions for muons should be practically the same. The

\[
\text{Counts}
\]

Figure 2. The correlation between the energy deposition of particles in the first five sections and the last 5 sections of the central module in a supermodule (left). Typical amplitude spectra in one of the sections of the calorimeter module (right).
distribution of the muon energy deposition in one of the calorimeter sections is shown in Fig. 2, right. The maximum in the amplitude distribution corresponds to the muon energy losses of 5 MeV in scintillators with the total thickness of 24 mm in a single calorimeter module section. The coefficients obtained from the muon calibration of each section for all 9 modules are used thereafter to determine the proton energy deposition in all sections of the supermodule.

4. Waveform fitting procedure

The signals from calorimeter modules sections have been measured by ADC64s2 boards with a sampling period of 16 ns [7]. In order to have more points per signal, a shaper, extending the signals to 200 ns was used. Fig. 3 shows an example of the signal from the hadron calorimeter section obtained in the supermodule test at the hadron beam at CERN [6]. The same waveform on an enlarged scale is shown on the right.

To fit a signal waveform of equidistant experimental points, a new technique based on the Prony least squares method was proposed [8]. The shape of the scintillation signal is described by the composition of two exponents, with a characteristic pulse rise time \( \tau_r \) and decay time \( \tau_d \):

\[
f(t) = A(1 - e^{-t/\tau_r})e^{-t/\tau_d}.
\]

(1)

Figure 3. Blue line shows an example of a waveform obtained in a test at hadron beam using the ADC64s2 board. The red line is a fit function obtained by the Prony least squares method. The same waveform on an enlarged scale is shown in the inset on the right.

The Prony least squares method, discussed in detail by S.L. Marple [9], can be divided into three stages. The first two stages are necessary to determine the attenuation coefficients of the corresponding exponents (arguments of the exponents) and can be performed separately from the third stage, the task of which is to find the amplitudes of the mentioned exponents. Since the shape of calorimeter signals in accordance with Eq. (1) is described by two exponents, the three stages of the Prony least squares method are reduced to solving systems of linear equations of the second and third orders and finding the roots of the square polynomial. The simplicity of mathematical operations distinguishes the Prony least squares method from various iterative methods and consumes significantly less computational resources.

To assess the quality of the model constructed by the Prony method, the coefficient of determination [10] in the form of \( R^2_{adj} = 1 - R^2_{adj} \) is used. The \( R^2_{adj} \) thus determines the
fraction of the variance of the dependent variable, which is unexplained by the model. With this construction, events well approximated by the model will be grouped around zero of $\hat{R}^2_{adj}$. Noises, pick-ups and signal pile-ups demonstrate huge difference in shape from the true signals consisting of two exponents, which allows to reliably separate true events. Fig. 4 shows the dependence of the coefficient of determination $R^2_{adj}$ on the signal charge. Events with signal interference (pick-up) are allocated in a separate group and do not participate in further analysis.

5. 3D energy calibration with muon tracking
Since obtaining a muon beam in the CBM and BM@N experiments is not possible, a new approach to cosmic muon calibration, which uses longitudinal segmentation of hadron calorimeter modules is proposed. Signals from cosmic muons passing through the sections of the hadron calorimeter are proportional to the thickness of the scintillator passed. Considering this circumstance, the reconstruction of muon tracks and the subsequent correction of energy deposition for the thickness of the material passed is used. The reconstruction of the muon track is done using the least squares method taking into account the 3D spatial arrangement of the triggered sections and the corresponding energy depositions as weight coefficients. Fig. 5 shows the distribution of energy deposition in the section of the hadron calorimeter before and after applying the correction procedure. The distribution of the corrected energy deposition has a more clearly defined maximum, which allows for a more accurate energy calibration.

6. Conclusion
The results of the PSD supermodule response measurements demonstrate that performance of lead/scintillator calorimeter with the micropixel photodetectors light readout satisfy the requirements of the CBM and BM@N experiments. Application of the new fitting procedure based on the Prony least squares method allows to obtain more accurately the charge of the signal. Moreover, fitting signals with a known function allows to extract weak signals comparable
Figure 5. The distribution of energy deposition in the section of the hadron calorimeter before (blue) and after (green) the correction.

to the level of electronic noise, and to obtain undistorted information about signals. Since the noise is random, fitting it with a fixed function gives a low probability of identifying noise as a useful signal. This property is especially useful when performing muon calibration of calorimeter sections, since the signals from muons have a low amplitude comparable to the noise level. The speed of the proposed fitting procedure is several orders of magnitude faster than the standard iteration methods and allows the on-line signal analysis. The developed method also makes it possible to identify the pile-up signals at a high counting rate.

Acknowledgments

This work was partially supported by RFBR grant 18-02-40081.

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