Energy calibration and signal waveform analysis of the CBM Projectile Spectator Detector modules

N. Karpushkin, D. Finogeev, M. Golubeva, F. Guber, A. Ivashkin, A. Izvestnyy, S. Morozov and A. Strijak
for the CBM and BM@N collaborations
Institute for Nuclear Research, Moscow, Russia

Compressed Baryonic Matter experiment at FAIR

Forward hadron calorimeter tasks

To determine the global event characteristics in nucleus-nucleus collisions - the centrality of the collision, which is related to the number of participating nucleons, and the reaction plane orientation, the forward hadron calorimeters are used in the fixed target experiments – CBM, BM@N and NA61/SHINE.

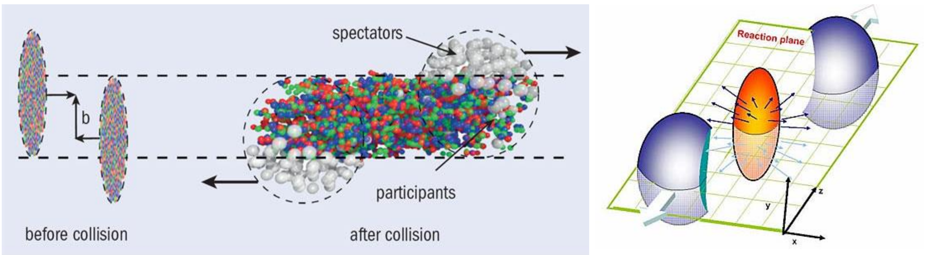
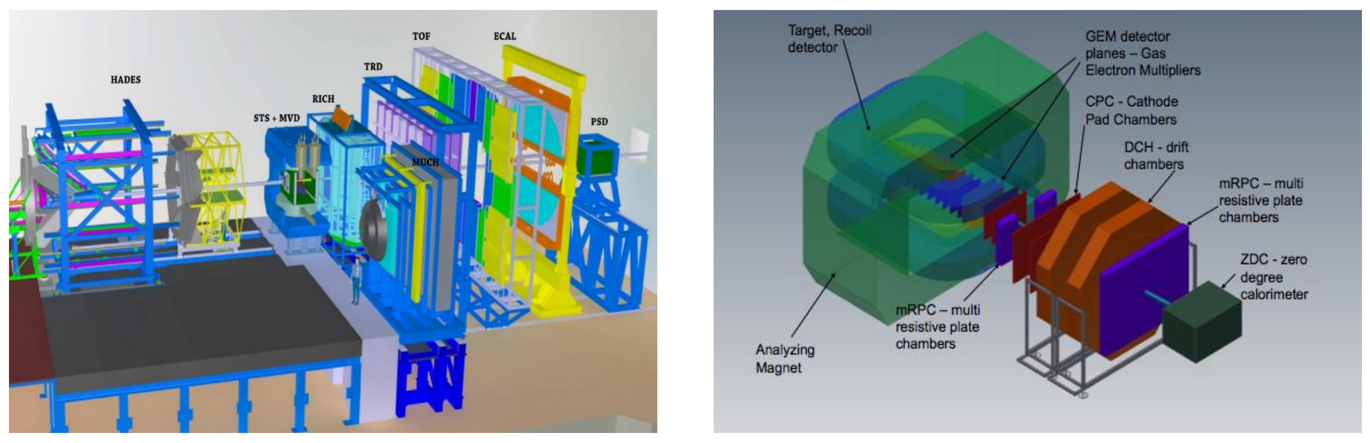


Fig.1 Centrality and Reaction plane

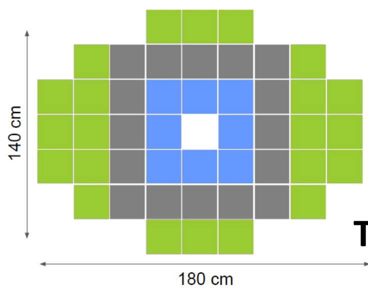
The event-by-event determination of the centrality and reaction plane orientation in heavy-ion interactions is one of important tasks in these experiments and is necessary to study the collective flow of identified particles, particle multiplicities and fluctuations and other observables.

The PSD@CBM and PSD modules at BM@N within FAIR-phase-0

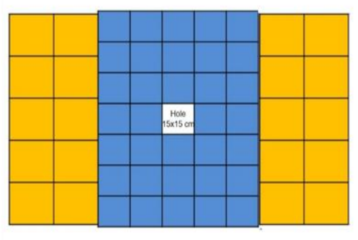


PSD@CBM [1] **FHCAL@BM@N [2]**

Fig.2 Hadron calorimeters of CBM and BM@N experiments



46 modules 200x200mm^2; Beam hole 20x20 cm^2; Total weight – 22t.



34 inner modules (MPD type); 20 outer modules (CBM type); Total weight – 17t.

All modules already constructed by the end of 2017

New FHCAL (instead of ZDC) already assembled at BM@N Sept. 2019

Fig.3 Left: PSD@CBM structure; Right: new FHCAL@BM@N assembled using the PSD@CBM modules

PSD modules structure

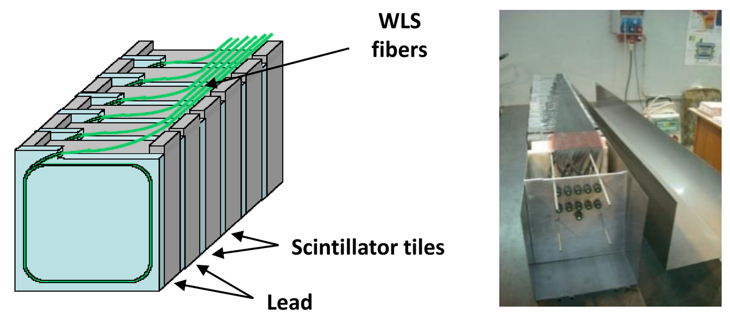
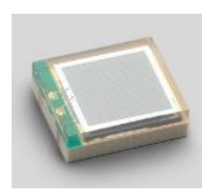


Fig.4 Modules structure

- **Module transverse size 200x200mm^2 .**
- **Longitudinal structure: 60 Pb/Scint tiles layers: (Pb(16mm), Scint(4mm) grouped in 10 sections.**
- **Total length is 5.6 λ_{int}.**
- **Weight of each module 500 kg.**
- **Light collection – by WLS fibers from 6 sequentially placed scintillator tiles in one section to one optical connector at the end of module.**
- **Light readout: 10 MPPC (3x3mm^2) per module.**
- **Readout electronics: sampling ADC.**



Hamamatsu S12572-010P
Sensitive area 3x3 mm^2
Number of pixels 90 000
Nominal gain 1x10^5
Pixel recovery time 10 ns

Waveform fitting

Advantages of the fitting procedure:

- **More correct determination of signal charge**
- **Working with small signals near the noise level**
- **Pick-up and pile-up identification**
- **True signal recovery**

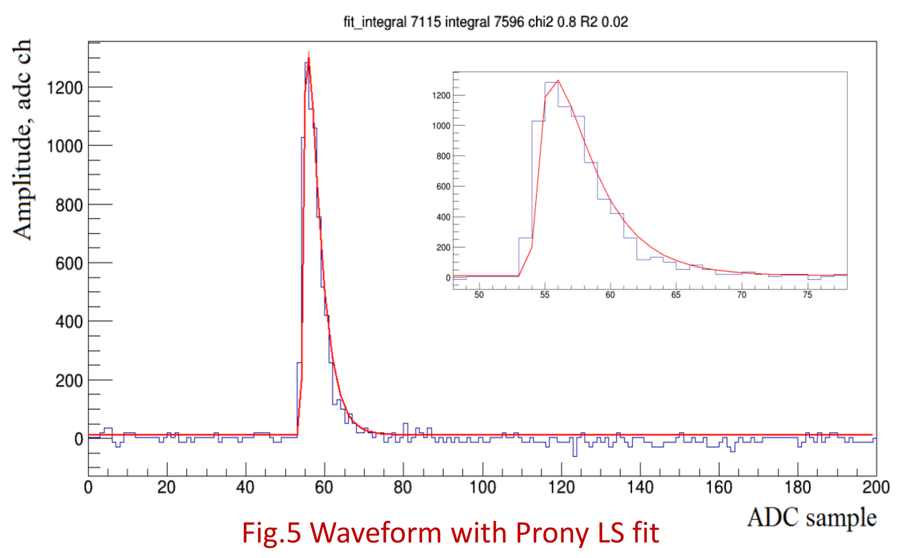


Fig.5 Waveform with Prony LS fit

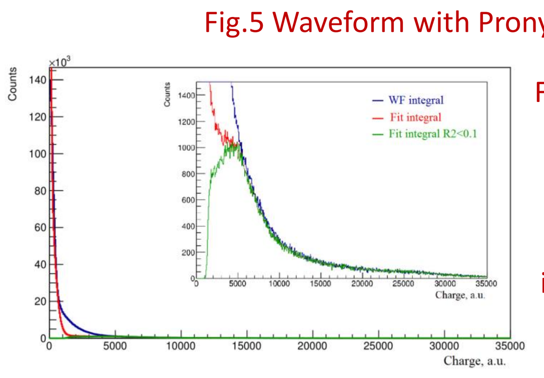


Fig.6 Charge distributions calculated by waveform integral (blue), fitting function integral (red) and fitting function integral with true events selection (green)

Prony Least Squares method

Allows to estimate a set of complex data samples x[n] using the p-term model of exponential components [3]:

$$\hat{x}[n] = \sum_{k=1}^{p} A_k \exp[(\alpha_k + j2\pi f_k)(n-1)T + j\theta_k] = \sum_{k=1}^{p} h_k z_k^{n-1}$$

n = 1, 2, ..., *N*, *T* – sampling interval. $\boldsymbol{h_k} = A_k exp(j\theta_k)$, $\boldsymbol{z_k} = exp[(\alpha_k + j2\pi f_k)T]$.

Objects of estimation are: amplitudes of complex exponentials A_k, attenuation parameters α_k, harmonic frequencies f_k and phases θ_k.

3 algorithm steps:
1.Composing and solving SLE 2×2
2.Polynomial factorization } z_k
3.Composing and solving SLE 3×3 → h_k

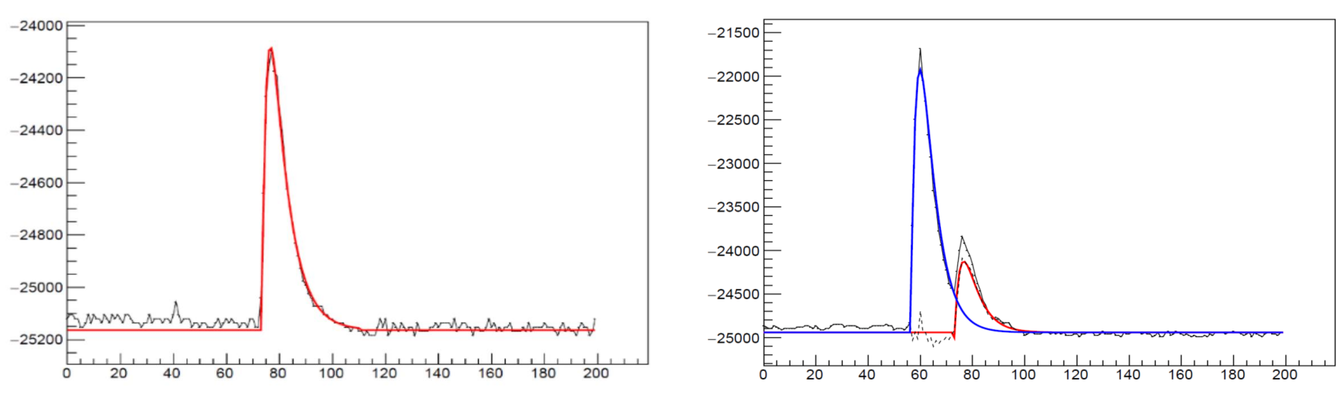


Fig.7 Left: Typical waveform example with Prony LS fit; Right: Pile-up event example. Blue line – pile-up, dashed black line -- waveform after pile-up rejection, red line – true signal fitting function.

Fit quality assessment

Coefficient of determination*

$$R^2 = \frac{\sum_{n=1}^{N}(x[n] - \hat{x}[n])^2}{\sum_{n=1}^{N}(x[n] - \bar{x})^2}$$

$x[n]$ and $\hat{x}[n]$ are the experimental and model values of the variable, respectively. $\bar{x}$ is the experimental values average.

Adjusted coefficient of determination *

$$R^2_{adj} = R^2 \frac{N-1}{N-\lambda}$$

N is the number of measurements, λ is the number of model parameters.

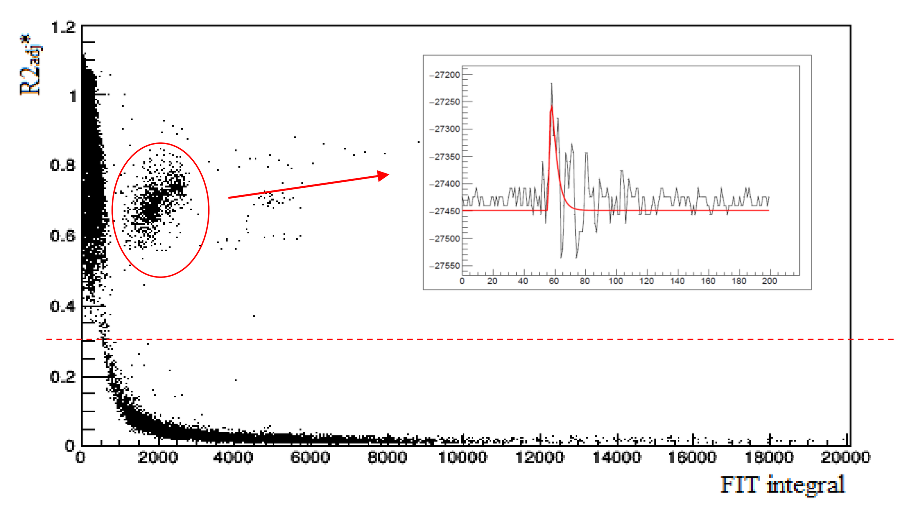


Fig.7 Coefficient of detemination : SignalCharge

Energy calibration approach

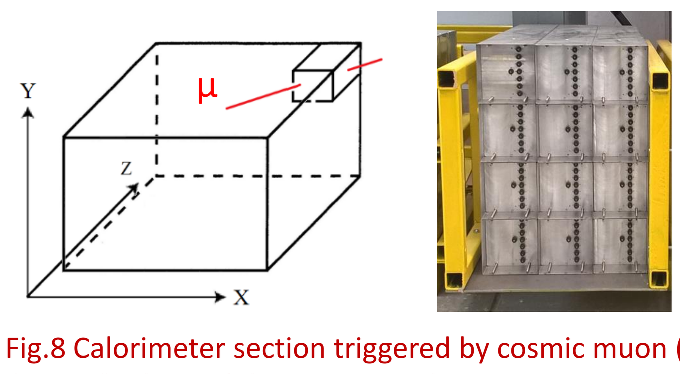


Fig.8 Calorimeter section triggered by cosmic muon (left); Photo of calo modules system with common trigger (right).

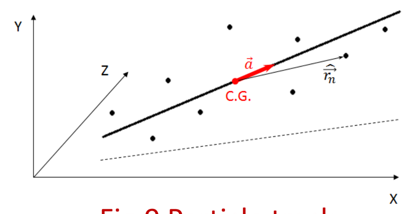


Fig.9 Particle track reconstruction illustration.

1) Selection of triggered sections by fit QA
2) Shift reference system to the center of gravity:

$$\vec{R}_{C.G.} = \frac{1}{N}\sum_{n=1}^{N} E[n]\,\vec{r}[n].$$

3) Extremum search: $\varphi = \sum_{n=1}^{N} \hat{r}_i a_i \hat{r}_j a_j \rightarrow max$

$$M = \begin{pmatrix} \sum_{n=1}^{N} r_n^x r_n^x & \sum_{n=1}^{N} r_n^x r_n^y & \sum_{n=1}^{N} r_n^x r_n^z \\ \sum_{n=1}^{N} r_n^y r_n^x & \sum_{n=1}^{N} r_n^y r_n^y & \sum_{n=1}^{N} r_n^y r_n^z \\ \sum_{n=1}^{N} r_n^z r_n^x & \sum_{n=1}^{N} r_n^z r_n^y & \sum_{n=1}^{N} r_n^z r_n^z \end{pmatrix} \xrightarrow{\textit{Jacobi rotations}} \overrightarrow{EV}$$

Calibration results

The cosmic muon track in calorimeter is specified by:

- **Charge center position**
- **Zenith angle [0, π/2]**
- **Azimuth angle [0, 2π]**

Adjusted charge is calculated taking into account the thickness of the scintillator material traversed by the cosmic muon track.

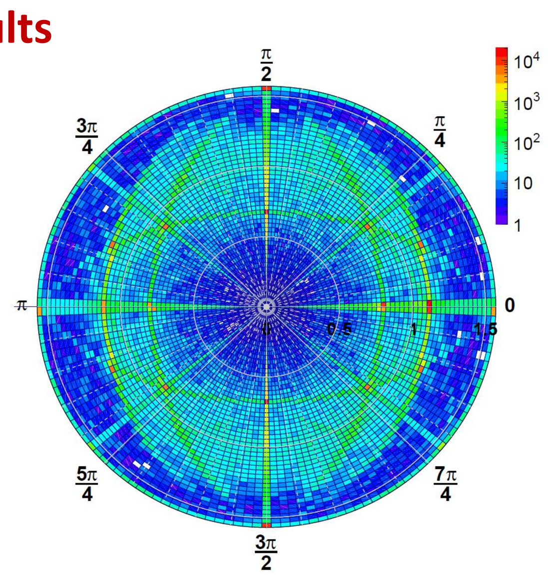


Fig.10 Particle track Zenith and Azimuthal angles. Distinct lines correspond to the topology of the calorimeter.

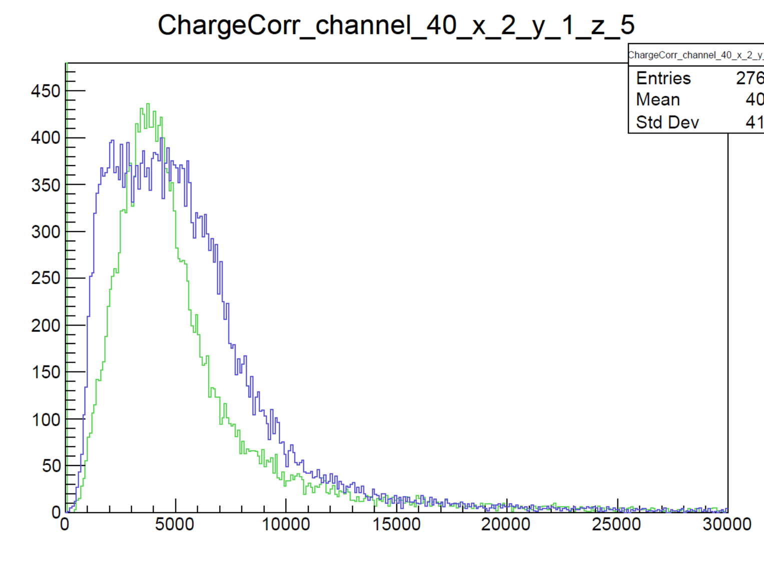


Fig.11 Charge distribution in calorimeter section before and after correction

Similar charge distributions are observed in all sections of the tested modules. The strongly-pronounced peaks allow to conduct a reliable energy calibration of the forward hadron calorimeter.

Conslusions

- **A new method of waveform fitting is developed**
- **The fit QA is used to reject noise and pick-ups and to identify pile-up events.**
- **Since the muon beam is absent in the CBM@FAIR and BM@N experiments, the energy calibration of the hadron calorimeter sections is possible only with cosmic muons.**
- **The presence of longitudinal segmentation of the calorimeter modules made it possible to use a new approach to the muon calibration, adjusting the energy deposition in calorimeter sections by the thickness of the scintillator traversed.**
- **The corrected energy deposition distribution has a more clearly defined maximum resulting in a more accurate energy calibration.**

References

1. Guber F, et al., "Technical Design Report for the CBM Projectile Spectator Detector (PSD)", 2015.
2. Guber F, et al, "New forward hadron calorimeter for centrality and reaction plane determination at BM@N heavy ion experiments" EPJ Web of Conferences. 204. 07007. DOI 10.1051/epjconf/201920407007, 2019.
3. N.Karpushkin, F.Guber, A.Ivashkin "Application of the Prony least squares method for fitting signal waveforms measured by sampling ADC", AIP Conference Proceedings. 2163.1., DOI 10.1063/1.5130092, 2019.

THE 28TH INTERNATIONAL CONFERENCE ON ULTRARELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS
QUARK MATTER 2019
Wuhan, China 4-9 November

Acknowledgements

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