# New forward hadron calorimeter for centrality and reaction plane determination at BM@N heavy ion experiments

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**Abstract.** It is proposed to replace existing Zero Degree Calorimeter of the BM@N setup at the Nuclotron (JINR) by a new forward hadron calorimeter for the measurement of the collision centrality and reaction plane orientation in heavy ions experiments. This calorimeter with transverse and longitudinal segmentation will be assembled from modules presently constructed for FHCal MPD and PSD CBM. The proposed design of the new calorimeter, simulation results for centrality and reaction plane determination by the new calorimeter, as well as radiation doses in the calorimeter simulated by FLUKA are discussed.The performance of hadron calorimeter supermodule studied at CERN is shown.

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## 1 Introduction

The BM@N experiment has a unique possibility to investigate hot and dense nuclear matter in heavy ion collisions at the Nuclotron beam energies between 2 and 6 AGeV [1]. The density of nuclear matter created in the collision zone at these energies exceeds the saturation nuclear density by a factor of 3-4 for gold-gold collisions [2]. The physics program of fixed target BM@N experiments includes the studies of strangeness production in heavy ion collisions, multi-strange hyperons production, the study of the hyper-nuclei production.The first results with the relativistic deuteron [3] and carbon [4] beams and recent experiments with Ar and Kr beams demonstrated the feasibility of these studies with light nuclei.

Different observables measured in the relativistic heavy-ion collisions - particle yields, transverse momentum spectra, rapidity and angular distributions, as well as fluctuations and correlations of hadrons, are studied as a function of the collision energy and centrality. The centrality (or impact parameter) in nucleus-nucleus collisions is determined by the length of the vector connected the centers of the colliding nuclei. To study such observables as collective flows of the identified particles, it is necessary to know also the reaction plane angle. The reaction plane is determined by the direction of the momentum of the incident

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nucleus and by the vector connecting the centers of the colliding nuclei. The impact parameter is not a measurable quantity, therefore, in the BM@N experiment Zero Degree Calorimeter is used to measure the centrality in light and medium nucleus-nucleus collisions. But, at the future heavy ion experiments, the ZDC will be replaced by another Forward Hadron Calorimeter (FHCal) with the beam hole in the center due to high beam intensity, up to $10^7$ per second. In this paper, the design, preliminary results of the Monte-Carlo simulation of the centrality and reaction plane determination by the new calorimeter, as well as results of radiation simulation of forward calorimeter by FLUKA and the experimental results of FHCal supermodule performance study are discussed.

## 2 BM@N set up

Schematic view of the BM@N experimental setup is shown in Fig. 1(left). The momentum measurements of produced charged particles are performed with high precision track measurements by central tracker based on two-coordinate triple GEM detectors located downstream of the target inside the magnet and the drift/cathode pad chambers (DCH/CPC) of the outer tracker placed behind the magnet. BM@N dipole magnet has the gap around 1 m between the poles. The maximum magnetic field of the magnet is up to 1.2 T and can be varied to get the optimal BM@N detector acceptance and momentum resolution for different processes and beam energies. Particle identification is done by TOF measured between T0 detectors and multigap resistive plate chambers (mRPC) with a strip read-out. The TOF detectors provide time resolution about 80 psec. and allow to discriminate hadrons ($\pi$, K, p) as well as light nuclei with the momentum up to few GeV/c produced in multi-particle events. To measure the collision centrality in nucleus-nucleus collisions, the ZDC is used. This hadron calorimeter is placed at the end of BM@N beam line at the distance 9 m from the target.

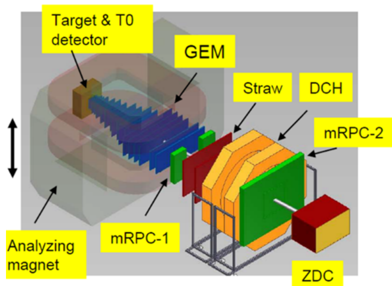


**Figure 1.** (Left) Schematic view of the BM@N set up. (Right) Photo of the ZDC installed at the end of the BM@N beam line

## 3 ZDC BM@N

Zero Degree Calorimeter (ZDC) measures mainly the energy of spectators: protons, neutrons and nuclear fragments. Most of spectators have a small transverse momentum and are emitted in a narrow cone near the primary beam direction.

The existing ZDC [5] is the scintillator/lead sampling hadron calorimeter similar to that used in WA98 [6] and COMPASS [7] experiments at CERN. The schematic view of the transverse cross section of ZDC for BM@N experiment is presented in Fig. 2(left). Central

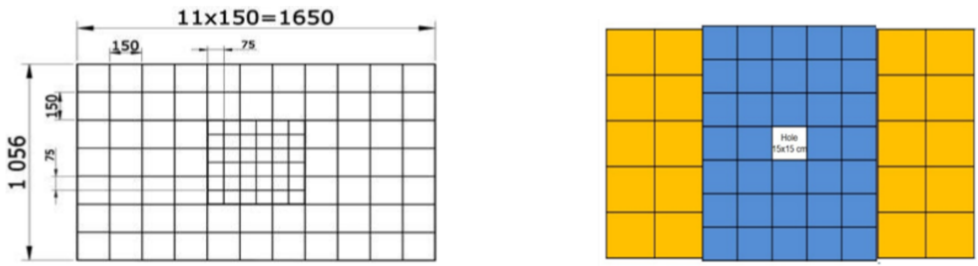


**Figure 2.** (Left) Schematic view of the ZDC BM@N. (Right) Proposed geometry of new FHCal BM@N

part of ZDC consists of an array of 6x6 modules with the cross section of 7.5x7.5 cm$^2$ each, while peripheral part contains 68 modules of 15x15 cm$^2$ transversal size.

The ZDC module has a sampling structure and consists of 64 scintillator/lead layers with thickness 5 mm and 10 mm, respectively that corresponds to about 5 interaction nuclear lengths. The light from all scintillator plates is collected and transmitted from one of scintillator sides with a fast wavelength shifter (WLS) plate 4 mm thick to a FEU-84 placed inside the $\mu$-metal screen and coupled with a high voltage base. The light output for module 15x15 cm$^2$ with FEU-84 measured on muon beam is about $N_{p.e.}$=80 [5].

## 4 New FHCal for the BM@N heavy ion experiments

Starting from 2020 new heavy ion experiments at BM@N are planned. It has been shown by FLUKA simulations, that the radiation doses from ionizing and non-ionizing particles in central part of the present ZDC expected for gold beam at energy 4 AGeV and beam rate 2x10$^6$ ions per second will be too high (see Fig. 5) and, therefore, the light output in central modules will be decreased and ZDC performance will be worse. To overcome the problem with irradiation of central ZDC modules, it is proposed to use new FHCal with a beam hole in the center of calorimeter. This new calorimeter will be assembled from already constructed and available modules for PSD CBM [8] at FAIR facility and FHCal MPD [9] at NICA facility. Schematic view of a new FHCal is shown in Fig. 2(right).

It is proposed to use twenty PSD CBM modules for outer modules of FHCal BM@N. The modules have transverse sizes of 20x20 cm$^2$ and active length corresponding to 5.6 nuclear interaction lengths. They have a sampling structure and consist of 60 lead/scintillator layers with a sampling ratio 4:1 (the thicknesses of the lead plates and scintillator tiles are 16 mm and 4 mm, respectively). Light readout from each scintillator is provided by WLS-fibers embedded in a groove in the scintillator plate. The WLS fibers from each 6 consecutive scintillator tiles are combined together and connected to a single photodetector at the end of the module. The longitudinal segmentation of modules into 10 sections allows to avoid the effect of non uniformity of the light collection along the module. Ten Hamamatsu MPPCs S12572-010P with active area 3x3 mm$^2$ are used as photodetectors in each module. The light yield measured with muon beam is about 40-50 p.e./section.

For the inner part of the new calorimeter 34 modules of FHCal MPD are offered to use. They have transverse sizes of 15x15 cm$^2$ and are shorter, only 7 longitudinal sections. Total length of inner modules corresponds to about 4 nuclear interaction lengths. The light yield measured with muon beam for these modules is about 50-60 p.e./section. Energy resolution of the PSD CBM supermodule assembled from 9 PSD CBM modules (Fig. 3) has been tested at CERN T9/T10 hadron beams [10]. Results of measured energy resolution and linearity response are shown in Fig. 4(left and right). Stochastic term of energy resolution is about $54\%/\sqrt{E}$(GeV) in the given proton energy range.

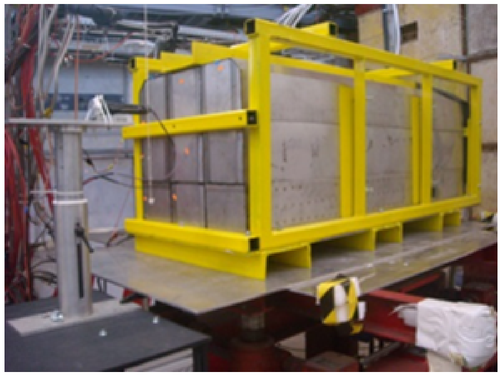

**Figure 3.** Photo of PSD CBM supermodule at CERN T10/T9 beam line

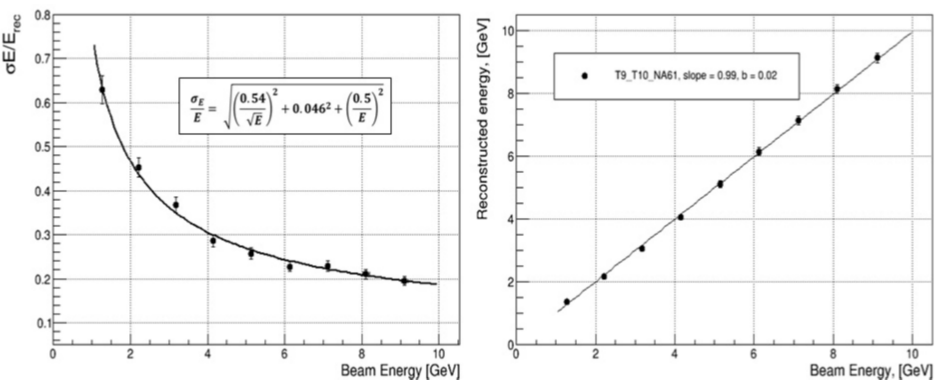


**Figure 4.** The measured supermodule energy resolution and linearity response are shown in the left and in right figures, correspondingly

The FHCal has a beam hole in the center, which is done by removing one of the modules in the center of the FHCal. Results of FLUKA simulations of radiation doses from ionizing and non-ionizing particles in the FHCal expected after 2 month of continues operation with gold beam at beam energy 4 AGeV and beam rate $2\text{x}10^6$ ions per second are shown in Fig. 5 (upper row).

In the third column the expected activation of calorimeter after 1 month of beam shutdown is shown. It is seen, that all modules of FHCal have acceptable doses due to irradiation during physics runs contrary to the situation with present ZDC without the beam hole (bottom row in Fig. 5). The FLUKA simulations of neutron fluence at MPPCs positions at rear sides of modules show that fluence does not exceed $2\text{x}10^{11}$ $n_{eq}/\text{cm}^2$ at the same beam rate.

On the other side, due to the beam hole in the center of the FHCal there is a problem for independent centrality selection only by the calorimeter. This is shown in Fig. 6(left), where the simulation results for the energy deposition in FHCal vs the centrality of collision

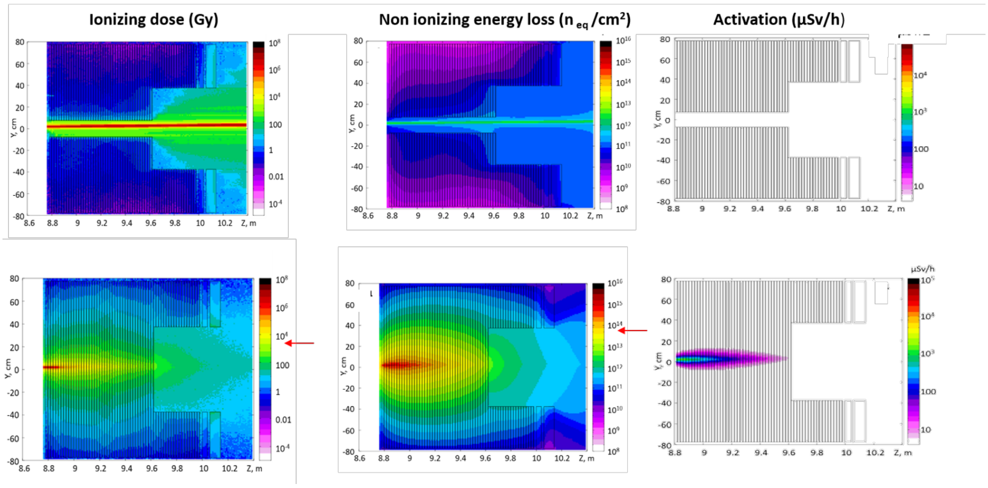


**Figure 5.** Results of FLUKA simulations of radiation doses from ionizing and non-ionizing particles and activation in the FHCal with a beam hole (upper row) and in the present ZDC (bottom row)

are shown. The observed non-monotonic behavior is due to fragments energy not measured in the beam hole. The FHCal simulations have been done for reaction Au+Au@4.5 AGeV for events generated with by LAQGSM code and use bmnroot framework with FTFP-BERT physics list. The smearing of the beam spot on the target ($\sigma_x = \sigma_y = 3$ mm) has been done also.

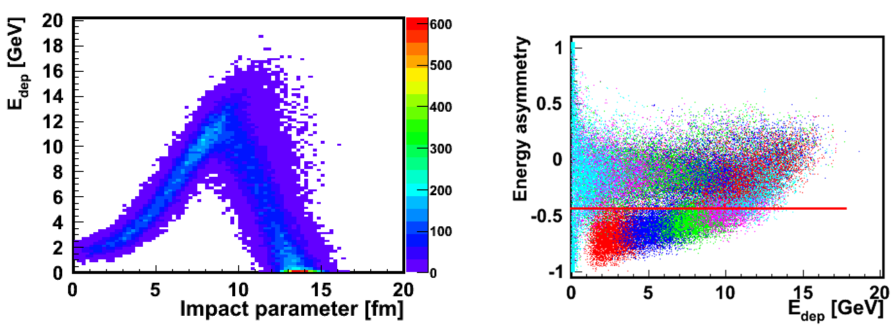


**Figure 6.** (Left) Dependence of energy deposition in FHCal with a beam hole as function of centrality collision. (Right) Energy asymmetry in FHCal as function of energy deposition in the FHCal. Here, different colors correspond to 10% of the centrality bins. Lower band corresponds to the most central events

Due to non-monotonic behavior of energy deposition in FHCal vs the centrality of collisions it is not possible to select central events by cut on the energy deposition, as it is usually done in the case of the ZDC.

To overcome this problem, a new observable is proposed to use - the energy asymmetry in the FHCal. This is, by definition, the ratio of difference in energy depositions in inner and outer modules to the total energy deposition in FHCal. The dependence of energy asymmetry from the the energy deposition is shown in Fig. 6(right). It is seen, that on trigger level about 30% of the most central events can be selected only by FHCal by using a cut on this new observable.

The centrality resolution as function of centrality determined by selection of regions in asymmetry vs deposited energy plot is shown by dots in Fig. 7(left).

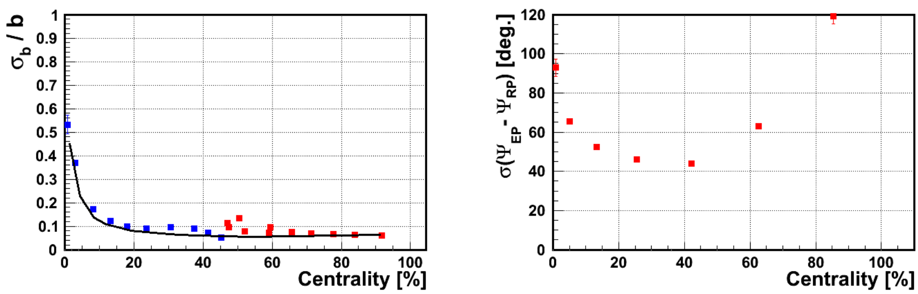


**Figure 7.** (Left) Dependence of centrality resolution of FHCal as function of centrality. (Right) The reaction plane angle resolution for FHCal with beam hole

The black curve here is the centrality resolution obtained for particles from LAQGSM generator, which hits the entrance of the FHCal without the beam hole - "ideal" resolution.

Due to the modular structure of FHCal the precision of reaction plane angle (RPA) is possible to determine on event-by-event base using information of energy deposition in each module. The simulated precision of RPA for reaction Au+Au@4.5 AGeV is shown in Fig. 7(right). For semi-peripheral collisions the precision of RPA is about 40 degrees.

The precision of centrality and RPA determination can be improved with additional detector in the beam hole of the FHCal. For this purpose Cherenkov quartz hodoscope is offered to use for the fragment charge measurements. Assume that fragments are spectators, the contributions of fragment energies into FHCal energy deposition can be reconstructed. Dependence of energy asymmetry on energy deposition in FHCal is more monotonic in this case (Fig. 8(left)) in comparison to that shown in Fig. 6(right). Centrality resolution is also improved for central and semiperipheral collisions due to taking into account the energy of identified charged spectators (Fig. 8(right)). More sophisticated simulations in this direction are in progress.

## 5 Conclusion

To measure centrality and angle of the reaction plane in heavy ion collisions at future BM@N experiments, a new FHCal with transverse and longitudinal segmentation is proposed to use. Despite the beam hole in the center, which is necessary to operate with high intensity heavy ion beams, the new hadron calorimeter can measure centrality of heavy ion collisions with a good precision. It has been shown, that it will be possible to select also the most central events on the trigger level by using a new proposed observable - asymmetry in the energy deposition in the calorimeter.

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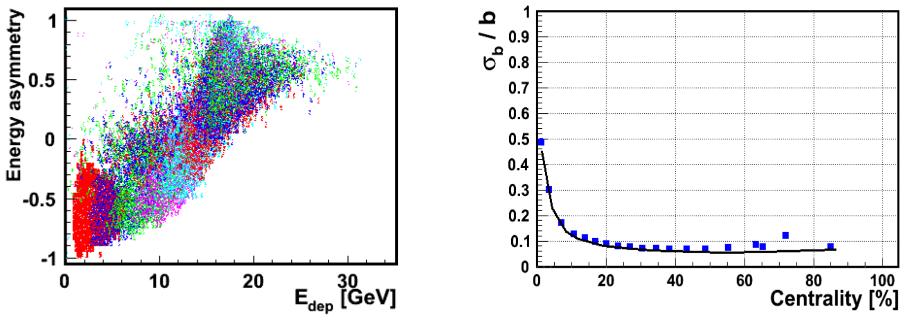


**Figure 8.** (Left) The reconstructed energy asymmetry in the FHCal as function of energy deposition when the energy of fragment spectators in the calorimeter beam hole is taken into account. Here, different colors correspond to 10% of the centrality bins. (Right) Dependence of centrality resolution of FHCal with beam hodoscope in the beam hole as function of centrality

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