Performance study of the anisotropic flow and reaction plane reconstruction in the CBM experiment

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Abstract. The Projectile Spectator Detector (PSD) is a subsystem of the CBM experiment at the future FAIR facility designed to determine centrality and reaction plane orientation in the heavy-ion collisions. It will be done by measurement of the energy distribution of the heavy nucleons and nuclei fragments emitted close to the beam rapidity in forward direction. For the anticipated beam energies of FAIR SIS100 and SIS300 accelerators, different event generators (iQMD, UrQMD, DCM-QGSM, LA-QGSM and HSD) were used for the study of directed and elliptic proton flow in Au+Au collisions. Produced particles were transported with the GEANT4 Monte-Carlo using the CBM detector geometry. Performance of the reaction plane determination is shown for different PSD setups to demonstrate effects of the detector granularity and magnetic field. Simulation results are compared with the FOPI, AGS E877, E895 and STAR experimental data.

1. Introduction

Experimental estimate of global event characteristics in nucleus-nucleus collisions such as the centrality of the collision and the reaction plane orientation are challenging tasks for any high-energy heavy-ion experiment. One of the examples is the future Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany designed to provide a high-luminosity environment and will allow for a precision systematic measurement of production yields, phase-space distributions, correlations, collective flow and fluctuation observables for various particle species produced in nuclear collisions [2].

In order to understand the degree of thermalisation, the features of equation of state, and the in-medium properties of strange particles in collisions of different systems at beam energies in the SIS100-SIS300 energy range, a multi-differential flow measurements are needed for a number of hadron species [4]. Moreover, the accuracy of the collision centrality and the reaction plane...
determination depends on the multiplicity and the energy distribution of fragments, and on the strength of the directed flow that they carry.

The Projectile Spectator Detector (PSD) of the CBM experiment is a compensating lead-scintillator calorimeter, which will measure the energy distribution of the projectile nuclei fragments and nucleons (spectators) produced close to the beam rapidity [3]. The main design requirements of the PSD are forward rapidity coverage, fine azimuthal granularity and sufficient energy resolution to allow for precise collision centrality determination and reaction plane reconstruction. The 44 module design of the PSD shown in Fig. 2 covers large transverse area around the beam spot position such that most of the projectile spectator fragments deposit their energy in the PSD.

Directed and elliptic flows of protons are simulated for the collision events generated by iQMD, UrQMD, DCM-QGSM, LA-QGSM and HSD event generators in the energy range $E_b$ from 1 to 30 AGeV. The DCM-QGSM event generator appear to reproduce available data from the FOPI at GSI, E877 and E895 at AGS, and STAR at RHIC. The reaction plane reconstruction performance in terms of the reaction plane correction factor is studied using the DCM-QGSM generator. Produced particles and fragments were transported through realistic CBM detector geometry with help of GEANT4 Monte-Carlo simulation. The bias of reaction plane determination introduced by detector effects, such as PSD azimuthal granularity and particle tracks deflection due to a particle deflection in the magnetic field is accessed. Other event generators are used for a cross-check.

![Figure 1. The CBM experiment layout.](image1)

![Figure 2. The PSD detector layout.](image2)

2. Modelling the directed and elliptic flow at FAIR energies

Directed and elliptic flow in Au+Au collisions are deduced exploiting for five different heavy-ion collision event generators, namely iQMD [5], UrQMD [6], HSD [7], DCM-QGSM and LA-QGSM [8]. Simulations are performed for semi-central Au+Au collisions in the projectile beam energy range $E_b = 1 - 30$ AGeV.

The slope of proton directed flow ($d\psi_1/dy$) and elliptic flow ($v_2$) at midrapidity as function of beam energy $E_b$ simulated with different generators is compared in Fig. 3 with the FOPI [9], E895 [10], E877 [11] and STAR [12] data.

The impact parameter range is chosen to be $b = 3.3 - 6.0$ fm for $E_b = 1.2$ AGeV, $b = 5 - 7$ fm for $E_b = 2 - 8$ AGeV, and $b = 4.5 - 9.2$ fm for $E_b = 30$ AGeV. The lower $p_T$ cut is 0.3 GeV/c for $E_b = 1.2$ AGeV, 0.1 GeV/c for $E_b = 2$, 4 AGeV, 0.2 GeV/c for $E_b = 6$, 30 AGeV and 0.4 GeV/c for $E_b = 8$ AGeV. The $p_T$ and impact parameter (centrality) cuts are chosen to match those used in the experimental data analysis. The flow signals vary strongly with event generators. At the lowest energy $E_b = 1.2$ AGeV, which corresponds to that measured by FOPI
and recently by HADES at SIS18, the iQMD agrees well with the data. For the SIS100/SIS300 energy range $E_b = 2 - 30$ AGeV which corresponds to collisions anticipated for CBM at FAIR, the DCM-QGSM model is the best in describing the E895, E877 and STAR data.

3. Reaction plane reconstruction performance with CBM

The collective flow develops along the reaction plane, which is spanned by the beam direction and the impact parameter of the collision. The vector plane can be estimated by nucleons and fragments, which do not participate in the collision (spectators). The reaction plane is determined from the position and energy deposited by the spectators in the PSD modules. The PSD have good energy resolution and segmentation to measure the transverse distribution energy with high accuracy.

The finite number of fragments and the fluctuation of the particle multiplicity from one collision to another result in a difference between the event plane deduced from the spectators and the reaction plane orientation. The event plane resolution correction factor $R_{EP}$ for directed flow corrects for the finite event plane angle resolution relatively to the reaction plane and is defined as

$$R_{EP} = \langle \cos(\Psi_{EP} - \Psi_{RP}) \rangle. \quad (1)$$

In case of the simulation, the event plane angle $\Psi_{EP}$ is deduced from PSD data, while the true reaction plane angle $\Psi_{RP}$ is taken directly from the event generator input. $R_{EP}$ value ranges between zero (very poor resolution) and unity (ideal resolution).

The PSD performance for the reaction plane reconstruction is studied within CBMROOT environment using GEANT4 Monte-Carlo simulations and various detector setups and event generators. Figure 4 shows the concept of the simulation setup without the detector geometry and corresponding GEANT transport procedure, where the MC-tracks from generators are chosen to fit to the PSD acceptance by corresponding $\theta$-angle cut (referred as "PSD-accept." in Fig. 6 (left panel)). Figure 5 shows the simulated geometry of the CBM detector including
Au target, dipole magnet, silicon tracking stations (STS) detector, the beam pipe and the PSD. In Fig. 6 (left panel) this setup is referred as "PSD-geom.,B=0" and "PSD-geom.,B>0" with magnetic field turned-off/on respectively.

Figure 6 (left panel) shows the reaction plane resolution correction factor of the PSD as a function of the beam energy simulated with the DCM-QGSM event generator for three different detector setups. The comparison of the reaction plane resolution correction factor achieved with "PSD-accept." and "PSD-geom.,B=0" setups shows that the azimuthal segmentation of PSD does not introduce any significant bias into the measurement. The splitting of spectators into neutral and charged fragments due to magnetic field decreases resolution correction factor over the whole beam energy range by about $5 - 10\%$.

Figure 6 (right panel) shows the reaction plane resolution correction factor of the PSD as a function of the beam energy simulated with various event generators for the realistic detector setup with turned-on magnetic field. Despite the strong variation of the collective flow magnitude in models, reaction plane resolution correction factor does not differ much between various event generators. The correction factor around $E_b = 10$ AGeV (and thus the PSD reaction plane resolution) is comparable to that of the target (TCal) and participant (PCal) calorimeters used for the collective flow measurements in Au+Au collisions by the E877 experiment at AGS, which had a maximum of about $R_{EP} = 0.8$ in semi-central collisions (see Fig. 5 in [11]).

4. Conclusion
Performance of the PSD reaction plane reconstruction for the CBM experiment is studied using various detector setups and heavy-ion event generators and GEANT Monte-Carlo response of
the detector components. The simulation is performed for semi-central Au+Au collisions in the beam energy range $E_b = 1 - 30$ AGeV using iQMD, UrQMD, DCM-QGSM, LA-QGSM and HSD heavy-ion event generators. The slope of the proton directed flow at mid-rapidity simulated with various event generators at various energies differs significantly from the experimental data. The DCM-QGSM generator seems to be the best in describing experimental data on proton flow in SIS100/SIS300 energy range. The PSD reaction plane resolution correction factor for semi-central collisions is similar for different generators and geometry setups and is comparable with E877 data.

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