Investigation of surface homogeneity of mirrors for the CBM-RICH detector and low-mass di-electron feasibility studies

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Abstract. The Compressed Baryonic Matter (CBM) experiment at the future FAIR facility will investigate high net-baryon density matter at moderate temperatures in A+A collisions from 4-45 AGeV. One of the key observables of the CBM physics program is electromagnetic radiation as a probe of strongly interacting matter in heavy-ion collisions, carrying undistorted information on its conditions to the detector. This includes detailed investigations of low-mass vector mesons in their di-electron channel. A clean and efficient identification of electrons is required for such measurements. In CBM the electron identification will be performed by a Ring Imaging Cherenkov detector and several layers of Transition Radiation Detectors. The RICH detector will be operated with CO2 radiator gas, MAPMTs as photodetector and spherical glass mirrors as focusing elements. A high quality of the mirrors in terms of reflectivity and surface homogeneity is required. In the first part of the contribution results on measurements of the mirror surface homogeneity are presented. Results on the feasibility studies of low-mass di-electron measurements with realistic detector response are discussed in the second part of the contribution.

1. Introduction
The Compressed Baryonic Matter (CBM) experiment [1] is designed for precision measurements of multidimensional observables including particles with very low production cross sections using high-intensity heavy-ion beams provided by the future FAIR accelerator. One of the essential requirements of CBM is good electron identification, which will be performed by a Ring Imaging Cherenkov detector and Transition Radiation Detectors (TRD). A Time-of-flight detector (TOF) is used to improve electron identification for low momenta electrons ($p < 1.5 \text{ GeV}/c$).

2. $D_0$ measurements
A gaseous RICH detector is being planned in a standard projective geometry with focusing mirror elements and photon detector planes [2, 3]. One of the important criteria for the selection of appropriate mirrors is their optical surface quality. It defines the imaging quality of projected Cherenkov rings, and directly effects the ring finding and fitting performance. The optical surface quality can be estimated by the so called $D_0$ measurement: $D_0$ then is the diameter of a circle containing 95% of total light intensity reflected by a mirror surface when illuminated with a point source. In the ideal case the reflected light image on the camera is point-like. In reality it is a non homogeneous spot due to mirror surface deformations caused by the manufacturing processes (such as polishing, cutting), the mirror holder and deformations due to gravity.
A sketch of the $D_0$ measurement setup is shown in Figure 1. It consists of a mirror (a) and a CCD camera with close-by laser point-like source (b+c) which illuminates the whole mirror surface. CCD camera and point source (diameter $\approx 200 \mu m$) are located exactly at the distance equals to the mirror curvature radius $R$. The projected image of the point source is centered on the CCD sensor. Camera and laser are installed together on a stepper motor (50 mm range) allowing movement along the optical axis of the mirror. Andor iKon CCD camera with $1024 \times 1024$ pixel ($13.3 \times 13.3$ mm) and a laser point source with wavelength 650 nm were used.

Figure 1. Experimental setup for $D_0$ measurements.

Four mirrors from JLO Olomouc for the RICH prototype were tested. In addition $D_0$ measurements were done for a mounted mirror in order to investigate the effect of gluing the mirror holder to the glass tile. Two different measurements of $D_0$ were performed: 1) at the nominal radius $R_{\text{nominal}}$, 2) at the distance $R'$ where the best results of $D_0$ were obtained. Figure 2 shows spots of reflected light in the CCD chip. The results for all mirrors are summarized in Table 1.

Figure 2. CCD camera image of reflected light. Left: for $R_{\text{cam.}} = 3$ m. Right: for smallest spot at $R_{\text{cam.}} = R'$.

All tested mirrors have effective radii $R'$ larger than the nominal one ($R_{\text{nominal}} = 3$ m). The difference $\Delta R = R' - R_{\text{nominal}}$ ranges between 5 mm and 12 mm. The results on $D_0$ (below 3 mm) are well below the anticipated photon detector pixel granularity of 5-6 mm. Also no differences were observed comparing the results of the mounted mirror with non-mounted mirrors. Presumably the mirror thickness of 6 mm ensures enough stability.

3. Low mass vector meson reconstruction

Feasibility studies of a measurement of low mass di-electrons in central Au-Au collisions at 8 AGeV (SIS100) and 25 AGeV (SIS300) beam energies are discussed in this section. All simulations were performed using the CbmRoot framework [4]. The following setup with most up-to-date realistic detector descriptions was used: STS (Silicon Tracking System), RICH, TRD and TOF detectors. For simulations at 8 AGeV beam energy the TRD detector was excluded. Hadrons (including $\pi^0$ and $\eta$) and photons were generated using UrQMD [5]. GEANT3 [6] performs the particle transport through detectors. The phase space distributions of $e^{\pm}$ from purely leptonic and semi-leptonic decays of light vector mesons ($\rho, \omega, \phi$ and $\omega$-Dalitz) were obtained using the PLUTO event generator [7]. To enhance statistics for these rare decays
Table 1. Summary results of $D_0$ and radius of curvature measurements for the 4 prototype mirror tiles (SP01 - SP04) and a mirror tile with glued holders.

| Mirror   | $D_0$ [mm] | $\Delta R$ [mm] | $D_0$ ($R = 3$ m) [mm] |
|----------|------------|-----------------|------------------------|
| SP01     | 1.15       | +5              | 1.59                   |
| SP02     | 1.42       | +12             | 2.58                   |
| SP03     | 0.88       | +5              | 1.81                   |
| SP04     | 1.3        | +13             | 2.89                   |
| Mounted  | 0.98       | +3              | 1.4                    |

one decay of a vector meson was embedded into each UrQMD event. Then in the analysis the contributions from these artificially enhanced contributions were normalized according to the multiplicities as predicted by the HSD model [8] and the respective branching ratios.

In the analysis, electron candidates are selected requiring them to be a primary vertex track reconstructed in all detectors (STS, RICH, TRD and TOF) and identified as electron in all ID detectors [9]. Dominant sources of the background are random combinations of $e^\pm$ from $\pi^0$-Dalitz decays and $\gamma$-conversion. About 700 $\pi^\pm$ are produced in central Au-Au events at 25 AGeV beam energy and can potentially contribute to the background if being misidentified. The combination of all ID detectors provides a pion suppression factor of $10^4$ for momenta below 6 GeV/c, thus misidentified pions are a minor background source only. This factor is around 5000 for the measurement at 8 AGeV beam energy because the TRD detector is excluded from the setup. In order to efficiently reject misidentified pions an additional upper momentum cut of 5.5 GeV/c is applied in this case. To avoid a significant contribution of $\gamma$-conversion in the first place a single 25 $\mu$m gold target was used. Further suppression of background contributions from $\gamma$-conversion and $\pi^0$-Dalitz decays was done by track cuts in three steps. The strategy for background subtraction was described in details in previous works [10, 11, 12].

$\gamma$-conversion cut: Conversion pairs have very small invariant masses and are thus essentially located below 25 MeV/c$^2$. All reconstructed pairs which have an invariant mass smaller than 25 MeV/c$^2$ are assumed to originate from $\gamma$-conversion. Tracks forming such pairs are fully removed from the further analysis.

Track topology cuts: The next two cuts are track topology cuts trying to reject electron candidate tracks stemming from an $\gamma$-conversion or $\pi^0$-Dalitz decay where the second partner is lost due to detector acceptance or the final particle identification efficiencies. Figure 3 shows the different track types used in the cut. A track segment is a track reconstructed only in the STS detector. These are low momentum tracks, after reconstruction only the momentum information is available. The second track type is a global track which is reconstructed in all detectors but is not identified as electron. The third track type is an electron track candidate (electron track). First, for each electron track candidate the track segment with the smallest opening angle ($\theta_{e^\pm,\text{segment}}$) is searched for. A two dimensional cut is placed which is based on the opening angle between the identified electron track to this closest neighbour track segment ($\theta_{e^\pm,\text{segment}}$) and the momentum product of these two tracks ($p_{e^\pm} \cdot p_{\text{segment}}$). This cut is illustrated in Figure 4. The same holds for electrons from $\pi^0$-Dalitz decays. The second track topology cut works similarly, only this time all global tracks are combined with electron candidates.

Transverse momentum cut: Last, a transverse momentum cut may be applied. Typically a lower cut of 0.2 GeV/c is used.

The contributions of the different background sources to the combinatorial background after applying all cuts are shown in Figure 5. In central Au-Au collisions at 25 AGeV beam energy in 84% of the cases at least one of the $e^\pm$ tracks comes from $\pi^0$-Dalitz decays and in 50.1% of the cases at least one of the tracks comes from $\gamma$-conversion.
The final invariant mass spectrum of electron pairs is shown in the left panel of Figure 6 and Figure 7. The right panel shows the transverse momentum versus rapidity distribution of measured $\rho^0$ mesons after applying all cuts. For collisions at 25 AGeV beam energy the region around mid-rapidity is well covered while at 8 AGeV the acceptance is shifted slightly into the forward region. For both cases a very good coverage of low transverse momenta is achieved.

Summary results of low mass vector meson reconstruction after full event reconstruction, electron identification and applying all background rejection cuts are presented in Table 2.

The cocktail-to-background ratio around 100 for masses around 0.5 GeV/c\(^2\) is very well compatible with existing di-lepton experiments and will allow for a precise investigation of low-mass di-electron pairs.

Acknowledgments
This work was supported by the Hessian LOEWE initiative through the Helmholtz International Center for FAIR (HIC for FAIR), Helmholtzzentrum GSI, and the German BMBF-Verbundforschung (05P12RGFCG).
Figure 6. Left: invariant mass spectra after applying all cuts. Right: transverse momentum versus rapidity distribution for the $\rho^0$ meson after applying all cuts. Mid-rapidity lies at 2. The simulation was performed for 200k central Au-Au collisions at 25 AGeV.

Figure 7. Left: invariant mass spectra after applying all cuts. Right: transverse momentum versus rapidity distribution for $\rho^0$ meson after applying all cuts. Mid-rapidity lies at 1.4. The simulation was performed for 100k central Au-Au collisions at 8 AGeV.

Table 2. Summary results of low mass vector meson reconstruction and different invariant mass regions for central Au-Au collisions at 25 AGeV beam energy with and without transverse momentum $p_T$ cut. Efficiencies are normalized to $4\pi$ emission of the respective particle.

| $p_T$ cut | $p_T > 0.2$ GeV/c efficiency [%] | No $p_T$ cut efficiency [%] |
|-----------|---------------------------------|--------------------------|
| Mesons, mass ranges |                                |                          |
| $\rho^0$ | — 4.39                          | — 5.27                   |
| $\omega$ | 0.31 5.53                        | 0.25 6.15                |
| $\phi$   | 0.11 7.08                        | 7.24 7.10                |
| $M_{ee} < 0.2$ GeV/c² | 1.44 —                        | 0.55 —               |
| 0.2 < $M_{ee}$ < 0.6 GeV/c² | 0.019 —                    | 0.010 —              |
| 0.6 < $M_{ee}$ < 1.2 GeV/c² | 0.053 —                     | 0.042 —              |

References
[1] Compressed Baryonic Matter Experiment. http://www.gsi.de/documents/DOC-2005-Feb-447-1.pdf
[2] Höhne C et al 2008 Nucl. Inst. and Meth. A 595 187
[3] Höhne C et al 2011 Nucl. Inst. and Meth. A 639 294
[4] M Al-Turany et al 2012 J. Phys.: Conf. Series 396 022001
[5] Bass S et al 1998 Prog. Part. Nucl. Phys. 41 255–370
[6] GEANT - Detector Description and Simulation Tool. CERN Program Library Long Writeup W5013.
[7] Froehlich I et al 2007 arXiv:0708.2382v2 [nucl-ex]
[8] Cassing W, Bratkovskaya E 1999 Phys. Reports 308 65–233
[9] Lebedev S et al 2012 J. Phys.: Conf. Series 396 022029
[10] Galatyuk T 2009 Ph.D. thesis at the Uni. Frankfurt http://www.gsi.de/documents/DOC-2009-Oct-252-1.pdf
[11] Höhne C 2008 J. Phys. G: Nucl. Part. Phys. 35 104160
[12] Galatyuk T et al. 2006 CBM note http://www.gsi.de/documents/DOC-2006-Feb-110-1.pdf