Conception and design of a control and monitoring system for the mirror alignment of the CBM RICH detector

J Bendarouach for the CBM collaboration
Justus-Liebig-University Giessen, Germany
E-mail: jordan.bendarouach@exp2.physik.uni-giessen.de

Abstract. The Compressed Baryonic Matter (CBM) experiment at the future Facility for Anti-proton and Ion Research (FAIR) complex will investigate the phase diagram of strongly interacting matter at high baryon density and moderate temperatures created in A+A collisions. For the SIS100 accelerator, the foreseen beam energy will range up to 11 AGeV for the heaviest nuclei. One of the key detector components required for the CBM physics program is the Ring Imaging CHerenkov (RICH) detector, which is developed for efficient and clean electron identification and pion suppression. An important aspect to guarantee a stable operation of the RICH detector is the alignment of the mirrors. A qualitative alignment control procedure for the mirror system has been implemented in the CBM RICH prototype detector and tested under real conditions at the CERN PS/T9 beamline. Collected data and results of image processing are reviewed and discussed. In parallel a quantitative method using recorded data has also been employed to compute mirror displacements of the RICH mirrors. Results based on simulated events and the limits of the method are presented and discussed as well. If mirror misalignment is detected, it can be subsequently included and rectified by correction routines. A first correction routine is presented and a comparison between misaligned, corrected and ideal geometries is shown.

1. Introduction
The Compressed Baryonic Matter (CBM) experiment at the future Facility for Antiproton and Ion Research (FAIR) complex will investigate the phase diagram of strongly interacting matter at high baryon density and moderate temperatures in nucleus-nucleus collisions. The beam energy will range from 2 up to 11 AGeV for the heaviest nuclei at the SIS 100 accelerator setup. In future the energy scope might be expanded to 35 AGeV beam energy, by installing the additional SIS 300 accelerator. For a characterization of the strongly interacting matter created during such collisions, electromagnetic probes appear to be very promising. Due to their penetrating nature, the information carried by these probes remains undistorted, when they reach the detector. Furthermore photons and dileptons are emitted during each stage of a heavy ion collision, therefore revealing the complete story of the collision.

For this CBM physics program to be successful, an efficient and clean electron identification (for momenta up to 8 GeV/c) together with a combined pion suppression factor of 1000 to 5000 (with the Transition Radiation Detector (TRD)) are required in a wide acceptance. One of the key detector components foreseen to satisfy these performances is the Ring Imaging CHERENKOV
(RICH) detector. In addition, 4 layers of TRD will be installed in the SIS 100 setup. The RICH detector will be made of a CO$_2$ gaseous radiator, Multi-Anode Photo-Multipliers for photon detection and about 80 trapezoidal glass mirror tiles, equally distributed in two half-spheres and used as focussing elements with spectral reflectivity down to the UV range [1, 2].

One specific aspect of a high quality RICH performance, in particular in the expected high track density environment of CBM, is a precise and stable mirror alignment. Each individual tile will be mounted with a three point fixation system and aligned such that their center of curvature all coincide in one virtual point. During the primary detector assembly, an initial mirror alignment will be done with a theodolite in autoreflection method, a procedure similar to what has been done for the COMPASS experiment [3]. Moreover it is crucial to control the stability in time of the initial alignment. Misalignments induce ring distortions and ring splitting, which thus harm reconstruction efficiencies and particle identification [4].

Two techniques are currently under development to provide stable alignment and will be presented consecutively. The first one is used to qualitatively control mirror alignment, using the Continuous Line Alignment Monitoring method (CLAM) [5, 6]. The second technique allows to quantify misalignments using data [7, 8]. Once misalignments have been revealed this information is included in correction routines.

2. Qualitative control of mirror misalignment

2.1. Qualitative control in the CBM RICH prototype

The alignment control method, inspired from the COMPASS experiment and employed to qualitatively monitor mirror displacements, is called Continuous Line Alignment Monitoring method (CLAM) [5, 6]. It uses retro-reflective stripes and target dots, which are glued at the entrance window of the RICH vessel. A camera surrounded by LEDs next to the photodetector plane illuminates the grid through the mirrors. For the measurement PMTs are switched off and LEDs turned on. Mirror edges are seen as black cuts on the stripes and a fast qualitative assessment regarding alignment can be made. Indeed if the stripes appear broken at mirror edges, it is obvious that the mirrors are misaligned with one another.

![Figure 1](image.png)

**Figure 1.** Pictures of the reflected grid after the initial mirror alignment (top left) and after artificial misalignment has been induced (top right). Corresponding single event rings in these configurations are shown on the bottom pictures, where the black and blue lines correspond to a ring and an ellipse shape, respectively.

This method has been implemented in a downscaled prototype of the CBM RICH detector and tested under real conditions at the CERN PS/T9 beamline. The prototype is made of a...
square mirror wall, made of 4 square tiles. The mirrors can be remotely controlled via actuators, allowing artificial misalignments. The vessel was placed in the beamline, such that the beam was traversing between the two lower mirrors. In Figure 1, a picture of the system after the initial alignment (top left), along with a typical reconstructed single event ring (bottom left) for this mirror configuration are depicted. The lower left mirror was then artificially misaligned by 4 milliradians [mrad] around a vertical axis going through the tile center. A picture of the misaligned system is shown in Figure 1 (top right), along with a corresponding reconstructed ring (bottom right). The vertical lines are now clearly appearing broken and the reconstructed ring is more elliptical (blue line). Indeed the induced misalignment moved the ring half reflected on the lower left mirror towards the half reflected by the right one in the photodetector plane.

2.2. Impact of misalignment on ring parameters
In the testbeam experiment a detailed study on the impact of misalignments on ring ellipticity has been conducted. The mirrors were in the same configuration as depicted before, i.e. the beam traversed between the two lower mirrors. To improve the beam focussing, a finger scintillator detector was used as triggering device and an additional cut was used directly on data to enhance the split ring events. Figure 2 illustrates the ring ellipticity distribution, referred to as B/A, corresponding to the minor axis of the ellipse divided by the major axis. Four different cases are presented: after reference alignment (red), with a misalignment of 1 mrad (dashed red), with a misalignment of 4 mrad (green) and with a cut enhancing the 4 mrad misaligned data sample (blue). For the last curve, one clearly sees an ellipticity drop below 0.9, with regard to the reference. Reconstruction efficiency for those rings drops from close to 100% down to 90% [9].

![Figure 2. Dependence of ring ellipticity, B/A, with regard to mirror misalignment. After the initial mirror alignment (red), with a 1 mrad rotation (dashed red) and with a 4 mrad misalignment (green). The blue curve was obtained using a cut to enhance the 4 mrad misaligned data sample, i.e. events, for which the beam went between the two lower mirrors are selected more cleanly. For the blue curve, the mean ellipticity drops below 0.9. The distributions are normalized to the number of events used for each curve.](image)

3. Quantitative determination of mirror misalignments
Once mirror misalignments have been located, a dedicated system is required to quantify the misalignment. The applied technique, inspired from the HERA-B experiment [7], uses data and has been tested in the simulation framework of the CBM RICH detector. The principle is illustrated in Figure 3. When a particle enters the RICH vessel, it emits Cherenkov light, which is reflected by one or several mirror tiles to the photodetector plane (red crosses). These photon hits are then reconstructed together as a ring, C’ in Figure 3. The point C, represents the extrapolated particle hit to the photodetector plane, if the incident particle had been reflected by the same aligned mirror tiles. In case of misalignment, the points C and C’ differ from one another. Measuring Cherenkov distances $\theta_{Ch}$ and angles $\Phi_{Ch}$ for each photon hit, a sinusoidal dependence has been demonstrated between these two parameters:
\[
\theta_{Ch} = \theta_0 + \Delta \Phi \cos(\Phi_{Ch}) + \Delta \lambda \sin(\Phi_{Ch})
\]  

(1)

For a sufficient number of accumulated events hitting a particular mirror tile, those measurements quantify the misalignments of the considered tile, by fitting the data to equation (1) and obtaining the \(\Delta \Phi\) and \(\Delta \lambda\) parameters (see Figure 3 right plot) [8].

![Figure 3. Principle of the method for quantifying mirror misalignment.](image1)

This technique has been adapted and tested for the CBM RICH detector with simulations in the CbmRoot framework. It produces good results for misalignments ranging from 0.1 mrad up to 12 mrad, as seen in Figure 4. For misalignments greater than 12 mrad, the point C starts lying out of the reconstructed ring, which makes the technique unstable.

![Figure 4. Performance test of the method to quantify mirror misalignments. The method yields reliable results for misalignments ranging from 0.1 mrad (left) up to 12 mrad (right). The results obtained for these misalignments using the described technique are 0.11 mrad and 11.49 mrad, respectively.](image2)

4. Correction routine

In the presented example (see Figure 5), a mirror tile has been artificially misaligned by 5 mrad around its horizontal axis and its misalignment has been evaluated using the method described in Sec. 3. The extracted misalignment is 5.26 mrad around the horizontal axis and 0.37 mrad around the vertical axis. In the correction procedure, the track projection yielding the extrapolated point (C in Figure 3) is then calculated using corrections from these misalignments. Figure 5 shows the projected distances on the horizontal (X) and vertical (Y) axes between the
fitted ring center and the extrapolated track hit (C’ and C in Figure 3). These distances are presented for three different cases, namely the misaligned (red), the corrected (green) and the ideal correction (blue). The latter can be directly obtained from the geometry. One sees (Figure 5 right) a clear vertical discrepancy of 1.6 cm, which is expected given the rotation applied to the tile. The slight difference in the horizontal direction (Figure 5 left), is due to the detector geometry, as the photodetector plane does not face perpendicularly the mirror wall, but with a slight tilt. For both projections the corrected distances are close to the ideal ones, indicating a proper operation of the correction routine.

![Difference in X ideal cm](image)

![Difference in Y ideal cm](image)

**Figure 5.** Distance between the points C and C’ on the photodetector plane, projected in the horizontal (X) and vertical (Y) directions for the misaligned (red), corrected (green) and ideal (blue) cases.

### 5. Conclusion

A first alignment correction cycle for the CBM RICH detector has been presented. The system has been implemented in a RICH prototype and is able to detect misalignment qualitatively. Furthermore it is possible to quantify the detected misalignment with data. A fist correction routine has been performed and shows promising results.

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