Reconstruction of Cherenkov ring from the first test beam data of dRICH detector of the Electron-Ion Collider (EIC) experiment

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Introduction:

Understanding the internal structure of the nucleons and the fundamental interactions that govern the particle behavior such as mass, spin and distribution of momentum among quarks and gluons is crucial to reveal a clearer picture of the Standard Model of Particle Physics. To probe these, Electron-Ion Collider (EIC)[1] experiment will be built, which will unlock the secrets of the strong force in nature, by colliding electron-proton and electron-ion at Brookhaven National Laboratory (USA). It is set to start operation in early 2030.

One of the main scientific objectives of the EIC is mapping the parton distribution functions inside nucleons. To identify various particles (such as protons, kaons, and pions) created in high energy collisions at EIC; accurate Particle Identification (PID) is pivotal. To achieve precise PID across a broad range of momenta, dual-radiator Ring Imaging Cherenkov (dRICH)[1] detector to be employed in the EIC.

As the Part of R&D for dRICH; in October 2023, a Testbeam[2] was performed at CERN, to validate the performance of various components of the detector e.g., readout electronics, irradiation and annealing studies of the SiPM. In the test beam, a polarized beam of $\pi-$ (pions) with collision energy of 10GeV is projected. PID is done using a dual-radiator Ring Imaging Cherenkov detector with Aerogel (n = 1.02) and C2F6 (n=1.0008) acting as the two radiators.

This work presents a comprehensive analysis of the Cherenkov ring detected by the dRICH detector within the testbeam setup with a primary objective to study the ring parameters, the background noise/dark count rate, and the intensity of photons that are striking individual SiPMs. The estimated parameters are validated for accuracy and reliability by employing various fitting techniques.

Estimation of Average Background:

To estimate the background, SiPMs which have not recorded any signal are identified first and then the hits in this region are calculated to measure the dark count rate(DCR)/background count. The number of hits of each SiPM was populated in a 2D-histogram (refer Fig. 2), estimating the DCR count of each SiPM in a selected area and the frequency of hits at each DCR count. The estimated mean background from the Gaussian fit of this distribution is 48.938 ±0.60 hits with a standard deviation of 10.376.

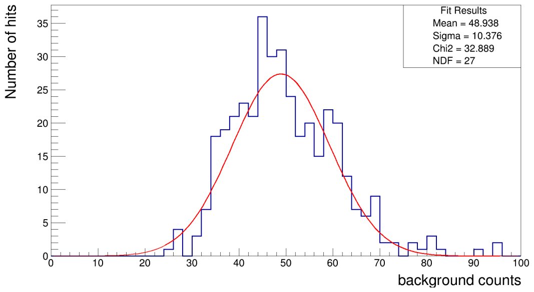

Fig 1. Distribution of dark count rate as calculated from the dRICH Testbeam data.

Deciding the total number of bins is very important so as to get a more precise fit value for estimating the background. One of the ways to do this is to check the goodness of fit. From the analysis, the best value of χ^2 is 32.889 and the number of degrees of freedom(NDF) is 27 which is obtained for a total bin size of 50, as shown in Fig. 1.

Reconstruction of Ring:

The Cherenkov ring is reconstructed using 3 essential parameters: its radius, coordinates of the center (x_0, y_0) and the width of the ring. It is assumed that the center can be located anywhere and not necessarily at (0,0) i.e., the ring can be off-centered.. To estimate the radius, hits recorded from SiPMs are plotted and y_0 is estimated from the hist distribution along the y coordinate axis(refer to Fig. 2). The predicted value of y_0 to be used to estimate the initial value of radius of the Cherenkov ring. As shown in the figure, the initial value of radius is (73.347+70.309)/2 = 71.82 ±0.60 mm with sigma 2.99 ±0.61 mm.

To improve the accuracy further, the distribution over radius w.r.t the angle φ is calculated and fitted with a sinusoidal function, where φ values are within the range $-\pi$ to π as shown in Fig. 3. Following this step, the radius of the ring is updated to 73.22 ±0.25 mm.

The next step is to locate the coordinates of the center (x_0, y_0) of which y_0 is already known from the process explained above and x_0 to be calculated. The value of x_0 is estimated at each value of radius, and a histogram is populated with the data obtained (Fig. 4).

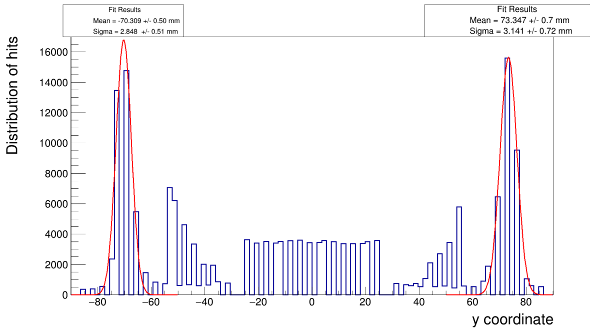

Fig 2. Distribution of density of hits along with their coordinates

In the plot, the x axis indicates the location of x_0 and along y axis is the no. of occurrences of the radius having the x_0 value as the x center offset. The data in the histogram is analyzed using normalized gaussian fit and the fitted mean is $x_0 = 2.609 \pm 0.43$ mm.

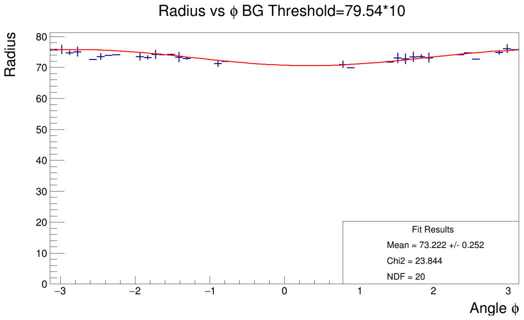

Fig 3. Radius of the ring as a function of φ

To optimize the result further the procedure is repeated multiple times by implementing an iterative Optimization Algorithm. To materialize this approach, the x_0 value obtained in the last step is passed to the calculation of Radius vs φ for another iteration. Subsequently the radius obtained in the preceding step is again incorporated to estimate the x_0 value. Multiple iterations are done to converge the values of radius and x_0 to improve accuracy. The algorithm converges when the values of the current iteration are equal to the previous iteration and the radius and x_0 are finally extracted.

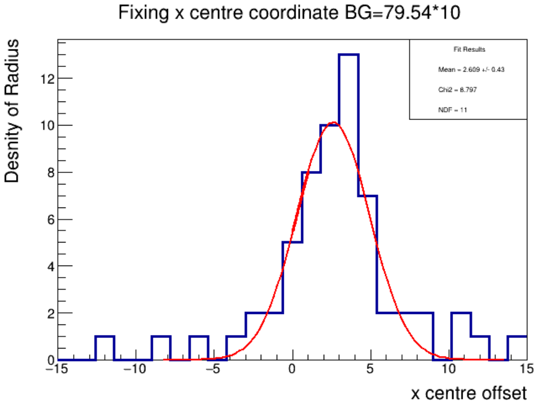

Fig 4. Distribution of x centre-offset coordinates to calculate x_0

Results and Discussion

The background noise of the SiPMs in the Testbeam setup is calculated from the dark count rate and the projected mean background noise is 48.938 ±0.60 counts with a sigma of 10.37 ±0.48.

The total number of bins is chosen as 50 based on the goodness of fit (χ^2/NDF) with the value of 1.21 which indicates a good fit.

To reconstruct the ring parameters the radius vs φ distribution is fitted with a sinusoidal function and the obtained value of radius is 73.22 ±0.25 mm. The x coordinate of the center is extracted using this radius and the fitted histogram yields to $x_0 = 2.609 \pm 0.43$ mm. Finally the reconstructed Cherenkov ring is visualized in Fig. 5. The center of the circle represents the exact location of the ring and simultaneously the inner and outer circles depict the spread of the ring.

Iterative optimization algorithms, goodness-of-fit evaluations, and several fitting techniques were utilized to guarantee the precision and dependability of the retrieved parameters.

While the proposed approach achieves significant outcomes, it doesn't allow us to distinguish between pion and kaon rings, which will be addressed in future study. Also the inability to determine the exact location of photon hits on the SiPM microcell introduces minute uncertainties caused by hardware specifications and limitations, which need to be considered during the data analysis. The algorithm has been tested for multiple runs of the testbeam and is found to give consistent results.

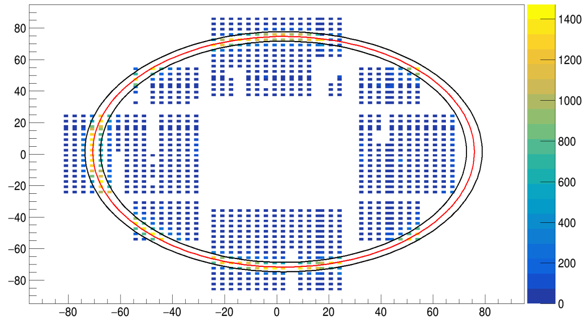

Fig 5. Reconstructed Cherenkov ring from the dRICH Testbeam 2023 data.

References:

1. E. U. G. EIC Yellow Report. Science requirements and detector concepts for the electron-ion collider: EIC yellow report. Technical report, 2022.
2. Beam Test Results for dRICH," [Online]. Available: https://indico.bnl.gov/event/22785/contributions/89357/attachments/53431/91458/%5B20240320%5D%5BdRICH%5D%20beam%20test%20.pdf..