Data Analysis and Simulation for the RICH Upgrade Test Beam

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Abstract
The LHCb experiment is one of the four particles physics experiments collecting data at the Large Hadron Collider. One of its key detector components is the Ring-Imaging Cherenkov (RICH) system. This provides charged particle identification over a wide momentum range, from 2–100 GeV/c. In order to increase the readout frequency from 1MHz to 40MHz RICH detectors will be upgrade in 2020. Prototypes are designed and tested by the RICH upgrade group of CERN. A full GEANT4 simulation have been programmed to reproduce the experimental test beam setup and to produce MonteCarlo data. Those data have been compared to data from the test beam in order to study and compared the photon yield and the Cherenkov angle resolution of the most recent version of RICH.

1. Introduction
RICH detector works by imaging and measuring of Cherenkov radiation. Those radiation occurs when a charged particle passes through a certain medium faster than light does. Then the particle emits a cone of light. By resuming the diameter of this cone, RICH can identifies the incoming particle.

Collision in LHC happens at a rate of 40MHz. The actual version of RICH can read events at a rate of 1MHz. The main goal of the upgrade is to increase this number to 40MHz to be able to collect the maximum amount of data. For this purpose, prototypes with new components like new MaPMT photo detectors or new readout system used CLARO chips have to be tested.

The test beam setup have been designed to provide data from a realistic environment. It was installed in the test beam area of Prevesin at CERN which provide the beam from the SPS at an energies of 180Gev/c. The experimental setup will be present.

In order to study properly the data from the test beam, MonteCarlo data from GEANT4 simulation will be present and compared to the real data. Quantities of interest are the number of Cherenkov photons detected per particle and the Cherenkov angle resolution provide by RICH.

2. Test Beam Setup
The setup of the test beam is presented in figure 1.

figure 1. View of the experimental setup. At the left a downstream view and at the right a side view

It is composed of a lens that plays also the radiator role, a column of 16 MaPMTs, some dark cover to isolate photons of interest and two scintillators for the trigger system.

Radiator
The radiator used for the test beam is a plano-convex lens in which Cherenkov photons are emitted when a particle go through. Photons are then totally reflected for a certain range of emission angle from the flat surface. A partial spherical mirror is putted on a part of the spherical side of the lens. Photons of interest are then totally reflected and photons with different direction are suppressed or can contribute to noise by internal reflection.

Figure 2. Scheme of the path of photons in the radiator
the lens. The radiator substrate is made of N-BK7 glass. This material is simulated by adding a refractive index table as a function of the wavelength. Its mean value is $n_{lens}=1.57$. All the transmission and reflection coefficient are taken in account in the simulation.

**Dark cover**

In order to reduce the background two dark cover are placed to absorb photon which we are not interesting with. The first one is placed upstream, around the spherical part of the radiator to cut photons generated by the beam before the radiator. The second one is a little disc putted in the middle of flat side of the radiator. This disc absorbs photon generated to near of the flat side or with a to low Cherenkov angle. By playing with the diameter of this dark cover, we are able change the range of Cherenkov angle and of emission point that we will collect in our data.

**Photo detector**

The detection system is arranged in 4 Elementary Cells which each contains 4 MaPMT from Hamamastu and a readout system as we can see in the figure 3. Each MaPMT contain 8x8 pixels and are sensitive to a single photon with wavelength in range 200-600nm. A photon which reaches the photo-cathode of a pixel have a probability to produce a photo-electron. This probability is calculated using quantum efficiency tables which give the probability of this process as a function of the wavelength. The electron is then amplified by a photo-multiplier tube to create a signal. This signal is read by an electronic chain to create a hit. The pixel size is a crucial parameter which determine the spatial resolution of the detector. This the biggest limitation for the Cherenkov angle resolution, this effect will be present later.

**Photon yield**

The photon yield is the number of photon which we are able to detect when a particle passes through the radiator. This value is influenced by many physical process like absorption of photon in the radiator, the quantum efficiency of the radiator or the probability of Cherenkov emission in the radiator.

The figure 5 shows the position of hits on a map. Each big square correspond to one MaPMT and each little square correspond to one pixel.

To compare properly real data and MC data some cuts are made in data. The number of hits...
per track is plotted only for hits which are near of the ring. Furthermore, event with only one track are selected and for which the track is near of the center of the lens.

![Hits per event in MC data](image1)

![Hits per event in real data](image2)

**Figure 6.** Plot of the total number of hits per event

The figure 6 shows the plot of the total number of hits per event in MC and real data. The mean value is 19.2 ± 1 photons detected for one track for real data and 19.4 ± 1 for MC data.

The uncertainty is mainly due to the absorption of photon in the radiator which is estimate as an average for the average photon path length.

The presence of a tail in the real data and not in MC data is explained by the noise. In the real setup, there is some noisy pixels which make increase the number of hits. Furthermore secondary particles are created in the radiator and generate more Cherenkov photon which increase also the tail. But by fitting without the tail, the mean value match perfectly with MC data.

The simulation software is able to reproduce the photon yield. It mean that this quantity is well understood.

**Cherenkov angle reconstruction**

To be able to reconstruct the Cherenkov angle from the data, the reconstruction software needs several information. First, parameters from the geometry are used: the center of curvature of the mirror, the mirror radius and the photon emission point. The two first one are provide by the manufacturer of the mirror and the third one is taken as the middle of the range where photons are created and not blocked by the downstream dark cover. Then the two last parameters are provided by the data: the hit position measured by MaPMTs and the beam direction. For the beam direction, approximation of a perfect beam (perpendicular and in the center of the radiator) is made.

![Reconstructed Cherenkov angle from real data](image3)

![Reconstructed Cherenkov angle from MC data](image4)

**Figure 8.** Reconstructed Cherenkov angle from real and MC data

The hit position, the photon emission point and the center of curvature of the mirror define a plane on which the true mirror reflection point is. Then, the intersection of this plane with the mirror sphere gives two solution for the location of the mirror reflection point. The good one is the one located on the side of the mirror. By mirroring the photon emission point by the flat side of the lens, the imaged photon emission point is created. The angle between the line define by the imaged emission point and the true reflection point and the beam direction is the Cherenkov angle. This method is used to plot the Cherenkov angle for each hit near of the ring for real and simulated data.
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induce a shift of the total mean value and the total sigma. This effect can be corrected by adding data from the tracking system to know the exact direction of each particles in future analysis. Furthermore, the multiple peaks shape of plots is an effect of the pixel size. This effect will be discuss later.

Cherenkov angle resolution

The Cherenkov angle resolution is measured by fitting the reconstructed Cherenkov angle with a Gaussian. The plot of the reconstructed Cherenkov angle only for PMTs from the left side in real data shows that the simulation can be consider as coherents values. Indeed for left side, real data gives \( \Theta_{\text{real, left}}=(909\pm18)\text{mrad} \) which is in great agreement with MC data. Consequently, to study the Cherenkov angle resolution and its components, the total sigma value \( \sigma_{\text{tot, mes}}=(17\pm1.3)\text{mrad} \) from MC data can be used as real data.

Theoretically, the Cherenkov angle resolution has three components: the pixel size effect, the emission point error and the chromatic error. Each one of those can be estimate by plotting different information provide by the simulation.

The pixel size effect is due to the fixed size and position of pixels. Indeed, for a given track, hits can be anywhere on the pixel but it will always considered as in the center of the pixel. This will induce an uncertainly on the detection point. Furthermore, hits of a given position on the ring can be over more then one pixel. So for each pixel, a specifically Cherenkov angle will be associated. At the end, it will produce multiple peaks on the reconstruction and increase the wide of the Gaussian. Those effects can be estimated by subtracting the Cherenkov angle reconstructed from the hitted pixel center and from the true hit position. The figure 10 shows this plot and provide the pixel size contribution of \( \sigma_{\text{Pix}}=13.7\text{mrad} \).

The exact position of the emission point can't be measured an it will induce an uncertainly. As we said before, the emission point is taken as the middle of the range where photons are created and not blocked by the downstream dark cover. By plotting the substation between the angle reconstructed from this point and from the true emission point, this contribution can be estimated. The figure 12 shows this plot and provide the emission point uncertainly as \( \sigma_{\text{Em}}=6.8\text{mrad} \). The refractive index of the radiator is considered as uniform with a value of \( n_{\text{lens}}=1.57 \) in by reconstruction software. The wavelenght spectrum of Cherenkov radiation goes from 300nm to 700nm and it induce a variation of the refractive index around \( \Delta n_{\text{lens}}=0.05 \). This variation creates an uncertainly on the reconstructed angle. By plotting the distribution of the real generated angle, the wide of this distribution should be only due to this effect. The figure 12 shows this plot an provide the chromatic error as \( \sigma_{\text{Chr}}=3.6\text{mrad} \).

From those three contributions the total uncertainly can by calculate by using the next formula.

\[
\sigma^2_{\text{tot, calc}} = \sigma^2_{\text{Pix}} + \sigma^2_{\text{Em}} + \sigma^2_{\text{Chr}}
\]
It gives $\sigma_{\text{tot,calc}} = 15.7\text{mrad}$ against $\sigma_{\text{tot,mes}}=(17\pm1.3)\text{mrad}$ for the measured one. The value of $\sigma_{\text{tot,calc}}$ should be a little bit higher. It explained by the fact that the chromatic error is not fully estimate with this plot. It doesn’t take in account the variation of the refractive angle with the refractive index when photons leave the radiator.

Values of sigma are in great agreement with the uncertainly. The Cherenkov angle resolution is dominated by the pixel size effect. This resolution could be improve by decreasing the size of the pixels.

4. Conclusion

During this three month of project, the RICH upgrade has been tested. A full GEANT4 simulation has been design to reproduce the Test Beam setup. Using the simulation and other input, photon yield and Cherenkov angle have been reconstructed by a reconstruction software. A study of the resolution has been realized an shown that contributions of the resolution are understood. Some improvement can be done in future analysis like to add data from the tracking system to correct the misalignment of the setup. Nevertheless, the great agreement between MC and real data shows that physics process happened in the RICH upgrade are well understood also and so that this prototype is ready to be installed on LHCb. The 2017 RICH upgrade Test Beam is a full success.