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The magnetic distortion calibration system of the LHCb RICH1 detector

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ABSTRACT

The LHCb RICH1 detector uses hybrid photon detectors (HPDs) as its optical sensors. A calibration system has been constructed to provide corrections for distortions that are primarily due to external magnetic fields. We describe here the system design, construction, operation and performance.

1. Introduction

The LHCb experiment [1] is dedicated to precision measurements of CP violation and rare decays of B hadrons at the Large Hadron Collider at CERN. Key measurements of the LHCb physics program are outlined in Ref. [2]. Excellent discrimination among different particle species is vital to study decays with similar topologies and to suppress combinatorial backgrounds.

LHCb has two RICH detectors to provide hadron identification in the momentum range 2–100 GeV/*c*. A schematic view of RICH1 is given in Fig. 1. Both RICH detectors use arrays of hybrid photon detectors (HPDs) to detect the Cherenkov photons created in their radiators [1,3,4]. The photon detectors need to provide accurate photon position measurements. This is a critical component of the Cherenkov angle resolution, which determines the separation power of different particle species, particularly at high momentum. Indeed, at all momenta, good photon position resolution is required by the likelihood function that is typically used in particle identification algorithms.

The HPD used in the LHCb RICH detectors [5,6] is a cylindrical optoelectronic imaging vacuum tube that has a quartz window of spherical section, an S20 multi-alkali photocathode, and a silicon pixel sensor. This is shown in Fig. 2. Its internal electrodes are operated at 16–20 kV, setting up an electric field cage in which the photoelectrons are cross-focused, and follow long ($\sim$125 mm) drift trajectories from the photocathode to the pixel sensor. The pixel sensor is bump-bonded to a custom binary readout chip. There are 32×32 effective pixels in the sensor, each of area 0.5×0.5 mm^2. However, each effective "LHCb" pixel actually consists of eight physical "ALICE" pixels of area 0.5×0.0625 mm^2. The eight ALICE pixels are grouped together in the readout to form a single LHCb pixel (termed "pixel" herein). The nominal electrostatic demagnification factor of five gives a measurement granularity of 2.5×2.5 mm^2 at the exterior of the quartz window.

HPDs are well known to be sensitive to external magnetic fields [7–9]. The magnetic Lorentz force deflects photoelectrons from their nominal trajectories causing pinwheel and shift distortions of the entire image and hence a subsequent loss of accuracy in the detected photon position. Depending on the angle of the magnetic field, this distortion can be quite severe (up to several pixels), completely compromising the photon position resolution. Consequently, they are efficient only below 1.5 mT axial fields, and less so if the field is off-axis.

Both LHCb RICH detectors are affected by the fringe magnetic field of the spectrometer magnet, but it is most pronounced in the RICH1 detector which is located immediately upstream of the magnet. The field is reduced by an iron shield surrounding RICH1 (seen in Fig. 1), and further by cylindrical Ni–Fe alloy shields around each HPD. Even so, initial estimates indicated up to 3.0 mT fields at the HPDs. With possible inhomogeneities and saturation effects, the resulting non-uniform fields could produce serious

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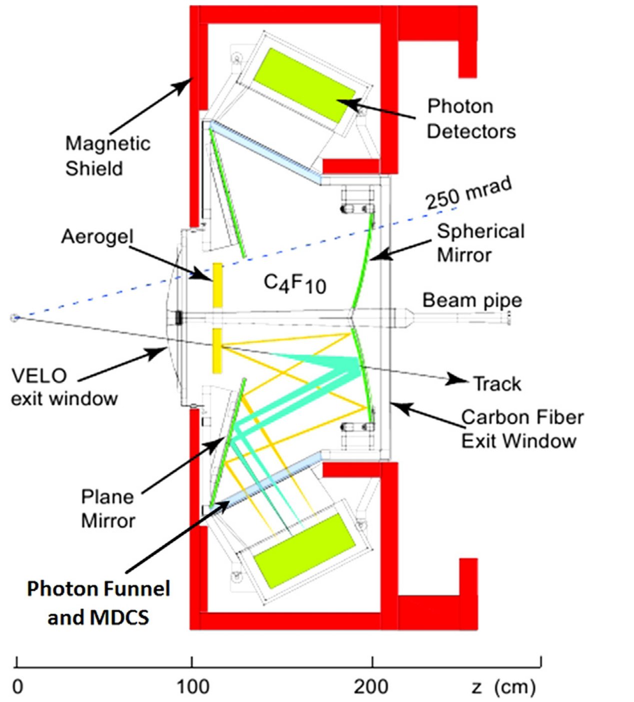

Fig. 1. Schematic view of the RICH1 detector. The MDCS system sits in the photon funnel, which is located just outside the C_4F_{10} gas enclosure. There are two MDCS systems, one each for the upper and lower HPD arrays. Each HPD array has 7 columns of 14 HPDs.

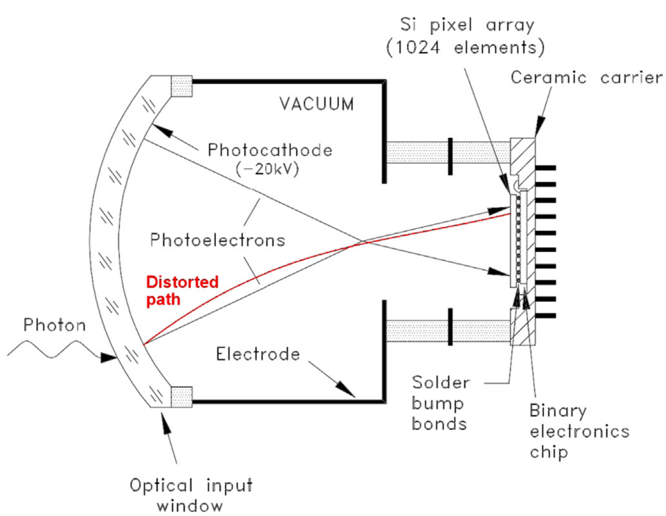

Fig. 2. Schematic view of the LHCb RICH HPD. Photons impinge on the spherical quartz input window and are converted to photoelectrons which are cross-focused onto a silicon pixel array with custom readout. A typical photoelectron trajectory that is distorted due to an external magnetic field is indicated.

distortions which would be impossible to predict in an a priori manner. The calibration system described in this paper is dedicated to mapping and correcting these magnetic distortions in RICH1 [10]. A different system is employed for this purpose in RICH2 [11]. In addition to magnetic distortions, there are electrostatic distortions possible from variations in the applied HPD high voltages, and optical distortions from the quartz window. Distortions from all sources are combined, and this calibration system will correct for these effects as well.

In the next section, the overall design of the magnetic distortion calibration system (termed MDCS herein) is provided, followed by a description of the relevant details of the system, its testing and installation. Subsequently, the data-taking procedure and analysis method are developed, then the main performance metrics and results are presented. Concluding remarks follow.

2. System design

The basic requirement on the MDCS system is to remove the potentially severe distortions from the array of HPDs. The corrected photon position should contribute an error small in comparison with the intrinsic spatial resolution of the HPD.

The strategy for the MDCS is implemented in two steps. First, a light spot is projected at a precisely known position on the quartz window of a given HPD in the array. The spot has a small size in comparison to the pixel size, and is oriented front-on to minimize refractive effects at the window and shadowing by the magnetic shield surrounding each HPD. The spot is moved to scan the HPD array in two dimensions, with small enough step sizes to map out the distorted image of the pixels. The data taken from this scan form a "direct" mapping of the distortion at a given magnetic field. Second, an "inverse" mapping is created, assigning a given distorted pixel hit to its real position on the entrance window. This may be done by a parameterized functional fit to the data if the distortion is sufficiently smooth to do so with a small enough reconstruction error, or alternately by a look-up table if the distortion is too severe or non-uniform. With proper survey information, this strategy can provide an absolute positional calibration of each pixel in the HPD array.

Implementing this strategy for the MDCS system required consideration of the tight physical constraints on the system in terms of overall area ($1283 \times 540\ \mathrm{mm}^2$), form factor ($<40$ mm high), and maintenance of a clear photon aperture for the HPD array. Additional considerations were made due to operation in a magnetic and radiation environment.

The basic system design is shown schematically in Fig. 3. Instead of a single light spot moving in two dimensions, spatial constraints on the system size forced a solution having a long bar with many individual light sources (LEDs), termed a "light bar." Each LED in the light bar can be individually powered, and each is collimated in order to project a small light spot onto the HPD focal plane. The light bar is mounted as a gantry between two linear-motion control stages. The movement of a given light spot in the direction of the stages is very fine and nearly continuous, while the positioning of the light spot in the direction along the light bar is discrete, effected by powering adjacent LEDs in turn. This choice is dictated by the spatial constraints on the system.

3. System description

Two identical and independent MDCS systems were designed and constructed for RICH1, one for each of the upper and lower HPD enclosures. In this section, the description pertains to only one of the two systems.

3.1. Light bar

The light bar consists of two long carbon fiber side rails, on which are mounted a series of 19 LED PCB units, custom designed for this application.[3] Due to spatial constraints, one of these units was half-sized. The HPD active area was covered completely.

Each LED PCB unit consists of a six-layer PCB, on which are mounted four LED arrays (two for the half-sized unit), an on-board

[3] Design and fabrication of these LED PCB units (and controller) were made in conjunction with SenSyr LLC, 111 College Place, Syracuse, NY 13244, ⟨www.sensyr.com⟩.