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Aerogel RICH for forward PID at Belle II

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ABSTRACT

For the Belle II spectrometer we are preparing a proximity focusing RICH with aerogel as the radiator. It will be positioned in the forward direction of the spectrometer in the small space between the drift chamber and the electromagnetic calorimeter inside a strong magnetic field of 1.5 T. The Hybrid Avalanche Photo Diode used as a photo sensor, is able to detect single photons with a high efficiency, can operate in the magnetic field and is resistant to the expected neutron and gamma fluxes in the detector. By detecting more than 11 photons per incident 4 GeV/c pion, with 15 mrad single photon Cherenkov angle resolution, the designed aerogel RICH should enable an efficient separation of kaons from pions in the wide range of particle momenta from 0.5 GeV/c up to 4 GeV/c.

1. Introduction

The Belle II spectrometer at the SuperKEKB e^+e^- collider will be dedicated to precise measurements of rare processes in decays of B and D mesons, and tau leptons. It will collect a 50 times larger data sample compared to the Belle experiment. Due to much higher event rates and background, a significant upgrade of the detector is needed (Fig. 1) [1]. In the forward region of the spectrometer, in the small space between the drift chamber and the electromagnetic calorimeter, a particle identification device is envisaged, which should enable the identification of charged particles in the range from 0.5 to 4 GeV/c. Due to the limited space available, we have decided for the proximity focusing RICH with aerogel as the radiator.

The design criteria should meet the physics requirements of the identification system: the device should have improved π/K separation capability in the forward region with respect to the Belle threshold aerogel Cherenkov counter. It should enable a good π/K separation for $b \to d\gamma$ and $b \to s\gamma$ decays and improve purity in the fully reconstructed B decays. The detector should also offer low momentum (<1 GeV/c) $e/\mu/\pi$ separation (e.g. for B→Kll decays) and keep high the efficiency for tagging kaons.

2. Detector design

The particle identification device should offer the K/π separation capability of more than 4σ in the momentum region from 1 to 3.5 GeV/c. It has to operate inside the solenoidal magnetic field of 1.5 T and due to a very limited available space it should fit into the gap of 280 mm. During 10 years of expected operation the aerogel RICH will be exposed to high fluences of neutrons. The detector should therefore be able to withstand a neutron fluence of 10^{12} of 1 MeV equivalent n/cm^2 and a radiation dose of about 100 Gy.

To achieve the expected performance, on average more than 10 photons have to be detected per charged particle. The RICH will consist of a 4 cm thick aerogel radiator with two layers of different refractive indices (1.055 and 1.065) [2,3], an expansion volume, an

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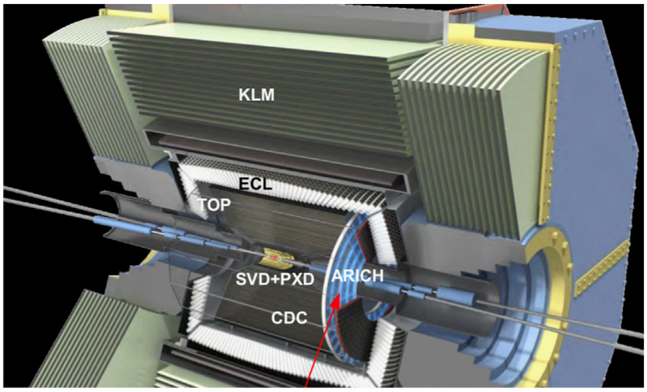

Fig. 1. Schematic view of the Belle II spectrometer with the main subsystems: vertex detector consisting of SVD – silicon vertex detector and PXD – pixel detector, CDC – Central drift Chamber, TOP – Time of propagation counter, ARICH – Proximity focusing Aerogel RICH, ECL – electromagnetic calorimeter, KLM – K_L and μ detector.

array of position sensitive photon detectors, and a readout system for the photon detector.

The photon sensor has been chosen among three candidates capable of operation in the magnetic field: Hybrid Avalanche Photo Detector (HAPD), Micro channel plate photo-multiplier (MCP PMT) and the silicon photo-multiplier (SiPM). All three types of sensors have been extensively tested on the bench and in the test beams [4–6]. The silicon photo-multiplier, which would be an excellent choice and would be able to detect more than 30 photons per incident charged particle at 4 GeV/c, is damaged during neutron radiation. The HAPD was finally chosen due to higher number of Cherenkov photons per ring.

The HAPD sensor (joint development of Belle II collaboration and Hamamatsu Photonics) is a vacuum based photo sensor with bi-alkali photo-cathode with peak quantum efficiency of 28% at 400 nm. The photo electrons are accelerated in the high electric field towards the segmented avalanche photo-diode. The 144-channel photon sensor with a pad size of 5.1 mm $\times$ 5.1 mm has a bombardment gain of about 1700 and an avalanche gain of about 40. For the readout of the signals of about 60000 e^-, special readout electronics has been designed [7]: a digitizer ASIC which consists of a preamplifier, a shaper and a comparator (SA02) is followed by an FPGA (Xilinx Spartan-6 XC6SLX45), where the hit information is recorded and communicated to further stages of the experiment data acquisition.

An example of a threshold scan for one of the channels during the illumination with pulsed laser light is shown in Fig. 2. One can clearly see the transitions between steps corresponding to the noise and the signal. During operation, the board will be irradiated with neutrons. The leakage current due to bulk damage in the HAPD will increase and the signal gain will drop. To maintain the optimal signal-to-noise ratio, the ASIC amplifier gain can be varied from 2 to 7.5 V/pC and the shaping time can be shortened from the initial 1 μs in four steps down to about 100 ns.

An additional feature of the ASIC is an output of a selected channel, which enables monitoring of the signal at different stages of signal path. This is particularly important for sensor calibration and in diagnosing the causes of errors during operation. An oscilloscope image of an amplified signal triggered by the laser pulse is shown in Fig. 3. Again the signals due to photons are well separated from the noise.

3. The beam test

A prototype detector close to the final design has been tested in a 120 GeV/c pion test beam at the CERN SPS in November 2011.

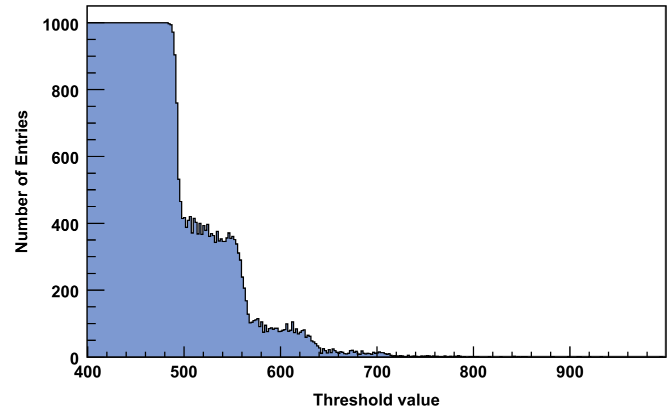

Fig. 2. A response of the HAPD to pulsed laser light: number of recorded events as a function of internal discriminator threshold.

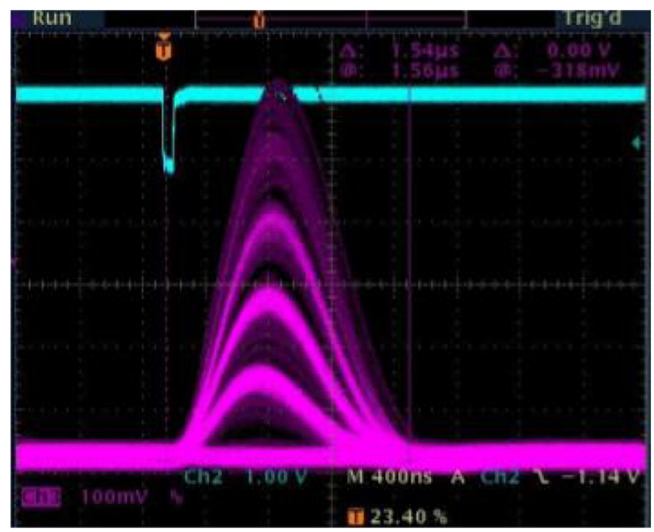

Fig. 3. Waveform from HAPD.

It consisted of a light-tight box with two MWPC chambers for particle tracking. Inside the box, two layers of aerogel and a mechanical aluminum frame for the HAPDs were mounted 20 cm apart. The frame, which mimics the innermost part of the Belle II Aerogel RICH detector, was partially equipped with six HAPDs with front-end boards, which were readout by the VME IO register and stored on the disk. In the analysis, the Cherenkov angle distribution was plotted and the mean and the width of the peak were extracted. With two 2 cm thick aerogel layers in a focusing configuration [2], with refractive indices of 1.050 and 1.065, we detected 11.4 photons and the single photon Cherenkov angle resolution was 15.8 mrad. The measured values are in agreement with expectations and with previous beam tests. With such performance, we expect to achieve more than a 5σ separation of kaons from pions in the Belle II experiment.

4. Operation in the magnetic field

The magnetic field of 1.5 T in the Belle II spectrometer will change the photo-electron trajectories in the HAPD. To minimize the possible interactions with the field, neither the photo sensor nor the readout board consist of magnetic parts. To test the position sensitivity and the operation of the electronic components, the tests were performed in the magnetic field of 1.5 T. The HAPD with the readout board was installed in a light tight aluminum box, which partially penetrated the magnet opening. The triggered laser light source on a non-magnetic arm was moved over the HAPD sensitive area. The digitized hit pattern was recorded for each event by using a CAEN V1495 general purpose board and then stored on disk for further analyses. In parallel, an analog signal of one channel was digitized by the sampling analog to digital converter CAEN V729. The pulse height spectrum was then extracted from the data. The results for a measurement with the magnetic field and without it are shown in Fig. 4. One clearly sees the differences in the regions between the peaks of the spectra. Note the improvement in the separation of the photo-electron and the noise peak in the magnetic field, which can be attributed to a reduction of the effect of the backscattered photoelectrons (Fig. 5). The backscattered electrons are curled up in the magnetic field and their effective range is much shorter, i.e., they usually end up at the same pad from which they were scattered.

5. Operation of electronics during neutron and gamma exposure

In the Belle II environment the elevated radiation levels are expected to reach 10^{12} n/cm^2 in ten years of operation. In a series of tests we tested the photon sensors during and after neutron and gamma irradiation. After these tests we selected the type of HAPD which is most radiation resistant, i.e. shows the least increase in the leakage current and has the highest signal to noise ratio [11].

Separately, the electronics has been irradiated with neutrons in the TRIGA Mark II reactor at the Jožef Stefan Institute, Ljubljana [12]. No permanent errors have been found in the board operation after irradiation with an 1 MeV equivalent neutron fluence of 4×10^{11} n/cm^2 and a gamma radiation dose of 150 Gy.

Due to event upsets the configuration memory of the software core inside the FPGA is corrupted, which leads to malfunction in the operation of the board. By including the Soft Error Mitigation (SEM) controller [13], the majority of single bit flip errors can be corrected. We have monitored the operation of the SEM controller during irradiation with two different neutron fluxes. Although the expected neutron spectrum in the Belle II Aerogel RICH (Fig. 6) differs from the reactor spectrum (more thermal neutrons in the reactor), we assumed the same response and obtained upper limit values for the expected number of event upsets (Table 1). The data in the table are normalized to the expected neutron flux in the Aerogel RICH detector. Different numbers can be attributed to the dead time of the controller. During the data acquisition in the experiment, where the fluxes will be approximately 200 times lower, the SEM controller information will be used to reload the firmware in the FPGA, thus ensuring the correct operation of the electronics.

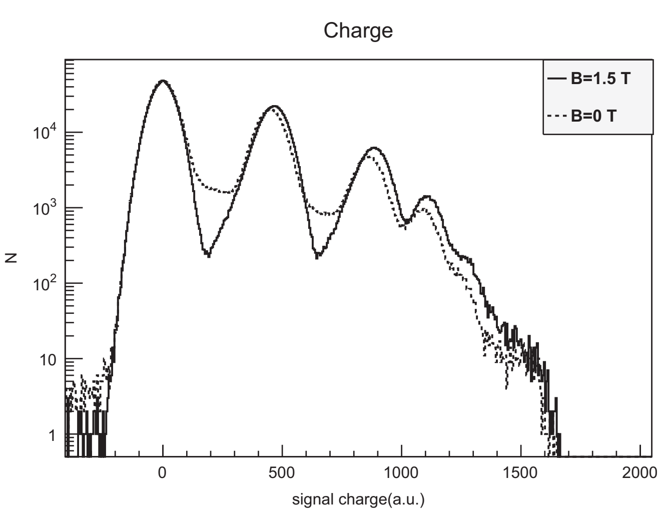

Fig. 4. Pulse height spectra for one of the channels of the HAPD with and without magnetic field. The peaks correspond to the noise, single, double and three detected photons.

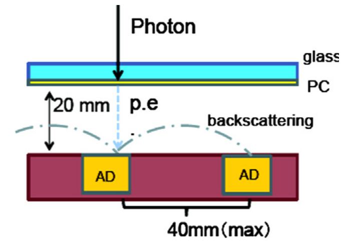

Fig. 5. Electron backscattering from the anode of the HAPD: Photoelectrons from the photo-cathode (PC) are accelerated towards the anode (AD) in the high electric field of about 8 kV/2 cm and are partially back scattered. Due to a ballistic effect they are detected on the other channel. For the geometry of the sensor, the maximal distance is 40 mm, but is reduced in the magnetic field.

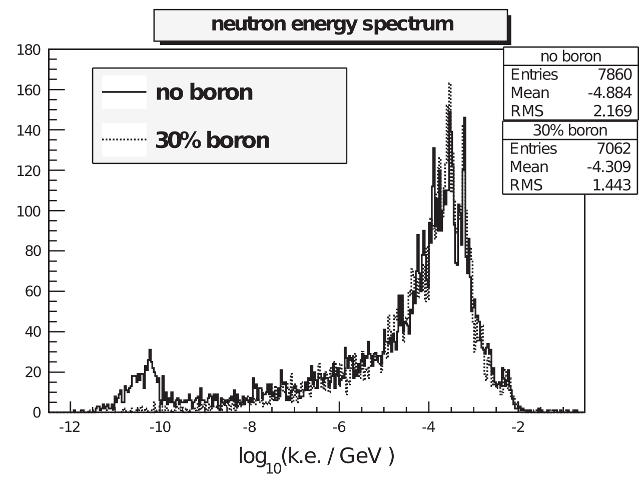

Fig. 6. Simulated neutron spectrum in the Aerogel RICH detector. Most of the thermal neutrons are absorbed if boron is added to the polyethylene beam pipe shield.

Table 1
Expected Belle II Aerogel RICH hourly rate of configuration errors extracted from the data during irradiation of the readout board with neutrons.

Error type	Reactor power 10 kW	Reactor power 100 kW
Correctable	5.06	3.04
Uncorrectable	0.15	0.49

6. Simulated performance

The detector design has been supported also by the simulation results of the detector response. The simulations were performed in the BASF2 framework [1,8] based on Geant4 [9]. In the simulation the detector follows the designed structure; it consists of two 2 cm thick layers of trapezoidal aerogel ($n_1 = 1.045$ and $n_2 = 1.055$) and 420 HAPDs, positioned in 7 concentric rings around the beam pipe. In the reconstruction we have used the extended two dimensional likelihood [10] for discrimination of different particle species.

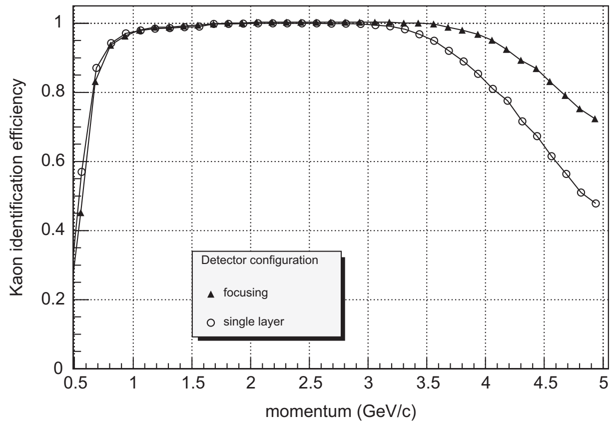

Fig. 7. Kaon identification efficiency as a function of momentum for 1% pion misidentification probability.

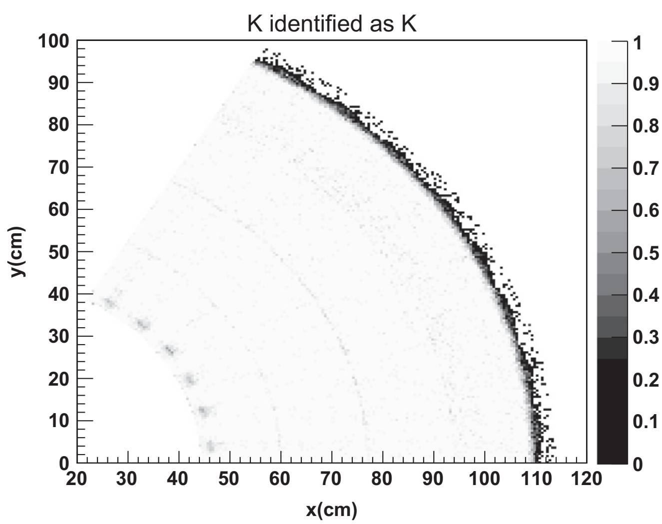

Fig. 8. Kaon identification efficiency variation in one sextant of the aerogel RICH detector.

The Cherenkov angle distributions of the simulated detector response were compared to the test beam results and a good agreement has been found.

The momentum dependence of kaon identification efficiency plotted for the pion misidentification probability of 1% is shown in Fig. 7. Note that the efficiency is high for the large momentum region. The improvement with the use of the double aerogel layer with respect to the single layer of the same thickness is clearly visible for momenta above 3 GeV/c. This efficiency refers the perpendicular incidence of charged particles. In Belle II, the particles will be incident on the Ring Imaging Cherenkov Detector at angles ranging from 17 to 34°. To test the uniformity of identification, we plotted the spatial dependence of the kaon identification efficiency for 3 GeV/c particles. The efficiency is uniform over a wide area of the detector (Fig. 8). The areas at the border correspond to particles, whose photons are partially not detected. Nevertheless the efficiency in these regions is still above 70%.

7. Summary

The proximity focusing RICH with aerogel as the radiator will be installed in the small space in the forward direction of the spectrometer. It will consist of double layers of aerogel in a focusing configuration and an array of Hybrid Avalanche Photodiode Detectors. The detector is able to operate in the high magnetic field of 1.5 T, can detect photons with high efficiency and can withstand the high irradiation levels of 1 MeV equivalent neutron fluence of 10^{12} n/cm^2 and radiation dose of 100 Gy. With the expected 11 detected photons and a single photon Cherenkov angle resolution of about 15 mrad, the kaon identification efficiency will be above 95% for a relatively low pion misidentification probability of 1% over the wide range of particle momenta from 0.5 GeV/c up to 4 GeV/c.

Acknowledgments

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