A ring imaging Cherenkov detector for CLAS12

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ABSTRACT

The energy increase of Jefferson Lab’s Continuous Electron Beam Accelerator Facility (CEBAF) to 12 GeV promises to greatly extend the physics reach of its experiments. This will include an upgrade of the CEBAF Large Acceptance Spectrometer (CLAS) to CLAS12, offering unique possibilities to study internal nucleon dynamics. For this excellent hadron identification over the full kinematical range of 3–8 GeV/c is essential. This will be achieved by the installation of a Ring Imaging Cherenkov (RICH) detector. A novel hybrid imaging design incorporating mirrors, aerogel radiators and Hamamatsu H8500 multianode photomultiplier tubes is proposed. Depending on the incident particle track angle, Cherenkov light will either be imaged directly or after two reflections and passes through the aerogel. The detector design is described, along with preliminary results on individual detector components tests and from recent testbeam studies.

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1. Jefferson Lab 12 GeV Upgrade and CLAS12

Jefferson Lab (JLab) (VA, USA) is currently undergoing an upgrade programme which involves the increase in energy of its electron accelerator from 6 GeV to 12 GeV. The upgrade will also see the enhancement of detector capabilities in the existing experimental halls, including Hall B’s CEBAF Large Acceptance Spectrometer (CLAS) [1] which will be upgraded to CLAS12 (see Fig. 1). CLAS12 will receive polarised beams with a maximum energy of 11 GeV and a luminosity of up to $10^{35}$ cm$^{-2}$ s$^{-1}$, providing a world-leading facility for the study of electron–nucleon scattering at these kinematics, with close to full angular coverage. The physics programme is extremely broad [2,3], but in particular will focus upon three-dimensional imaging of the nucleon through the mapping of generalised parton and transverse momentum dependent distributions at high $x_F$ with unprecedented precision. Other topics include quark hadronisation processes in the nuclear medium and spectroscopy studies. Efficient hadron identification is demanded across the entire kinematical range and, in particular, a $\pi/K$ separation of $\sim \pm 4\sigma$ at 8 GeV/c is the goal. Currently, charged Particle IDentification (PID) in CLAS12 is performed by Time-Of-Flight (TOF) detectors, Low and High Threshold Cherenkov Counters (LTCC, HTCC). These will not provide the necessary separation across the range of 3–8 GeV/c however, and thus a RICH detector has been proposed for installation into the forward region of CLAS12, replacing the LTCC.

2. RICH design

Since the RICH detector must fit into the original CLAS12 carriage there are several constraints imposed upon its design. Six radial sectors are required, each with projective geometry, limited gap depth of 1.2 m and $\sim 4.5$ m$^2$ entrance windows. Simulation studies favour a hybrid imaging Cherenkov detector design incorporating aerogel radiators, visible light photon detectors, and a focussing mirror system [4,5]. The focussing mirror system (see Fig. 2) will be used to reduce the detection area instrumented with photon detectors to $\sim 1$ m$^2$ per sector, minimising costs and influence on the TOF system.

For forward scattered particles ($\theta < 12^\circ$) with momenta of $p=3–8$ GeV/c a proximity imaging method will be used, where the Cherenkov cone is imaged directly. For particles with larger incidence angles of $12^\circ < \theta < 35^\circ$ and intermediate momenta of $p=3–6$ GeV/c the Cherenkov light will be focussed by an elliptical mirror, followed by two further passes through the radiator material and a reflection from planar mirrors before detection. The Cherenkov light will be produced from a thicker layer of aerogel material than it will be reflected through, to compensate yield losses whilst obtaining a focalised ring. The case will also exist where Cherenkov rings are imaged partly by both the direct and the reflected light cases simultaneously. For momenta below...
3 GeV/c the TOF system will provide the necessary $\pi/K$ identification for polar angles up to 40°.

The RICH detector is simulated within the CLAS12 Geant4 framework. This also allows the development of pattern recognition algorithms, which involve maximum likelihood methods and ray tracing ansätze. Results from simulations imply that, to achieve the $4\sigma \pi/K$ separation goal at 8 GeV/c, about 7 detected photons per ring are required in the direct light case.

Several characterisation studies of the individual RICH components are underway, a subset of which is described below.

### 3. Photon detectors and the Hamamatsu H8500 MAPMT

There are several requirements limiting the choice of the photon detector which have been confirmed through the simulation studies [4], for example the granularity of the photon detection plane. Due to the imaging aspect of the RICH and since multiple photon detectors will be tiled into large arrays, it is crucial that the photon detector provides an active area with minimal dead space. The photon detector must also efficiently detect single photon level signals and, due to the aerogel radiator material, should be sensitive in the visible light wavelengths.

MultiAnode PhotoMultiplier Tubes (MAPMTs) exist as promising candidates for the CLAS12 RICH and the currently selected photon detector is the flat-panel Hamamatsu H8500 MAPMT, which offers an adequate compromise between detector performance and cost. The H8500 MAPMT comprises an 8 × 8 array of pixels, each with dimensions 5.8 mm × 5.8 mm, in an active area of 49.0 mm × 49.0 mm with outer dimensions of 52.0 mm × 52.0 mm. Furthermore, the device has a very high packing fraction of 89%. Although the H8500 MAPMT is not advertised as the optimal MAPMT for single photon detection purposes, several units have been successfully used by the CLAS12-RICH collaboration in a beam test experiment with a small-scale RICH prototype at the CERN T9 beam line [6] in 2011. The results demonstrated sufficient capabilities of the H8500 to detect Cherenkov light. For example, a mean value of ~11 photoelectrons per event (Cherenkov ring with 56.8% coverage) was obtained using a Novosibirsk tile [7], with a refractive index $n = 1.05$ and a thickness of 3 cm, in a mixed hadron beam set to 10 GeV/c.

Laser scanning facilities have been setup for in-depth characterisations of MAPMTs. One topic which has been studied extensively includes the uniformity of the H8500 response. For example, Fig. 3 shows the normalised single photoelectron signal efficiency response of an H8500 pixel and its surrounding area, obtained from a sub-mm precision laser scan. The signal efficiency is defined as the fraction of the single photoelectron distribution which lies above a 2σ pedestal cut. The pixel response demonstrates a dependency upon the dynode structure of the MAPMT, where there exist periodic drops in signal efficiency when the laser strikes dynode support structures. The magnitudes of these...
drops are however small, with ~ 5% less relative signal efficiency compared to when the laser strikes dynode chain openings, and are not a concern for the CLAS12 RICH. Such studies are further described in Ref. [8], and they may also be used to study the PMT response in dead-space areas and to evaluate the true active areas of the pixels.

Further characterisation tests performed include studies devoted to: crosstalk, where magnitudes of < 5% are extracted; single photoelectron signal loss (defined as the fraction of the single photoelectron distribution lying below a 3σ pedestal threshold), which is minimised to ~ 12% through the operation at ~ 1075 V, close to the suggested maximum operating voltage; response uniformity within pixel areas as a function of incident photon angles, which is unaltered up to tested angles of 30°; and pixel-to-pixel gain variations, which again did not cause concern for the RICH.

4. Prototype studies at testbeams

Testbeam studies of a prototype RICH detector were performed in 2012 with the T9 beam line [6] in the CERN-PS East Area, which provides secondary particles – mostly pions and kaons – with selectable polarity and momenta from 0–15 GeV/c. The prototype consisted of two setups, dedicated to study direct and reflected light imaging cases individually. Gaseous Electron Multiplier (GEM) chambers were used for particle tracking and a beam threshold Cherenkov counter, which was provided in the T9 beam area, was set for pions and kaons to be above and below threshold, respectively, and used in offline γ/K separation analyses. Furthermore, a second smaller scale RICH prototype incorporating silicon photomultiplier arrays as photon detectors was included in the beam test studies, however the results are not presented here.

For the direct light imaging case the prototype geometry was matched as close as possible to the CLAS12 RICH geometry, a schematic of the setup is shown in Fig. 4. Novosibirsk aerogel tiles, of dimensions 6 cm × 6 cm, were used as Cherenkov radiators. Tiles with several thickness values (t = 2–4 cm), transparencies and refractive indices (n = 1.04–1.06) were tested, and their corresponding impacts on the RICH prototype performance were studied. The radiator was placed at 1 m from a ring of 28 H8500 MAPMTs, which could be moved radially for imaging of differing ring radii. Both standard borosilicate and UV-extended window type MAPMTs were tested, to study yield differences and Rayleigh scattering resolution smearing effects. For the readout of the MAPMTs the Multianode ReadOut Chip MAROC3 electronics [9] was used and, although the chip offers a sparsified readout mode, the entire charge spectrum of all channels was recorded to accurately study the MAROC3 and H8500 responses.

An example ring image obtained with the direct light setup is shown in Fig. 5, where the beam momentum was 8 GeV/c and the radiator had a refractive index n = 1.04 and a thickness of 2 cm. Such images were used online as a check that ring properties behaved as expected – for example that the radii increased with the aerogel refractive index as is demonstrated in Fig. 6, where the refractive index is increased to n = 1.06. Moreover, already in the online data analysis, π/K separation has been observed. For example, Fig. 7 displays Cherenkov ring radii distributions extracted from 3-parameter ring fits (ring centre and radius) to the data obtained with a beam momentum of 6 GeV/c, aerogel refractive index n = 1.05 and a thickness of 2 cm. The beam threshold Cherenkov counter was used as an offline kaon trigger, and the corresponding kaon and pion events are shown in the hatched and empty filled histograms, respectively. The kaon distribution has been subjected to an amplitude scaling factor of 77, which is in rough agreement with the expected T9 beam composition at this momentum and negative polarity [6].

Further investigations are performed to extract final light yield and ring resolution results, which are also converging with simulation comparisons. Due to the similarity of the geometries, the testbeam results for the direct light imaging case may be extrapolated for CLAS12 RICH performance projections, and can also be used for model inputs in the simulations.

The main aim of the reflected light case testbeam study was to investigate the Cherenkov light yield loss caused by multiple
passes through aerogel. A schematic illustrating the testbeam prototype setup is shown in Fig. 8. A mirror, with focal length \( \sim 1 \) m, was used to reflect Cherenkov light radiated from the aerogel along the beam to a wall of 8 planar mirrors with aerogel tiles, called absorbers, placed in front of them. The Cherenkov radiators were as in the direct light setup, but with increased thicknesses (6–8 cm). The aerogel absorbers were 10 cm \( \times \) 10 cm \( \times \) 2 cm Novosibirsk tiles of varying transparencies and refractive index \( n = 1.05 \).

Fig. 9 shows an example ring image obtained with no absorber tiles placed in front of the planar mirrors, for a beam momentum of 6 GeV/c, and for a radiator with refractive index of \( n = 1.05 \) and thickness 6 cm. For these reflected light measurements less than the full ring circumference was instrumented, due to larger ring radii and setup shadowing effects. The corresponding image with absorbers in front of the planar mirrors is shown in Fig. 10. A lower Cherenkov yield (visible in the colour fill) is extracted as a result of multiple passes through the aerogel absorbers. Nonetheless, the ring remains discernible and preliminary studies indicate that the yield is sufficient to perform a likelihood pattern recognition analysis.

5. Summary

The installation of a RICH detector into CLAS12 for improved hadron identification over the 3–8 GeV/c momentum range will enhance its physics reach. A hybrid imaging design has been proposed, incorporating both proximity and reflected light imaging cases depending on the incident particle track angle. An in-depth characterisation programme of individual detector components, including H8500 MAPMTs and aerogel radiators, is underway. Furthermore a large-scale testbeam prototype has been studied and currently extensive data analysis and simulation comparisons are ongoing, with further results on Cherenkov yield and ring resolutions to follow. From the prototype testbeam results it is decided that H8500 MAPMTs with standard borosilicate glass windows only will be used in the CLAS12 RICH, since Cherenkov ring resolution degradations were observed with UV-extended window types. Further work includes the construction and the running of cosmic-ray prototypes for simulation validations, and projected performance studies.

References


