# Review of Cherenkov Imaging Devices in Particle and Nuclear Physics Experiments – Invited Talk at the 6th International Workshop on Ring Imaging Cherenkov Counters (RICH2007). Stazione Marittima, Trieste, Italy 15 - 20 October 2007.

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**Abstract**

This review summarizes the properties and performance of the detectors of focused Cherenkov radiation that are used in several current and future particle and nuclear physics experiments. The order of presentation is guided by the physics motivation, which in turn informs the choice of technology.

*Key words:* Particle Identification, Cherenkov detectors, RICH, RICH2007
*PACS:*

## 1. Introduction

This review summarizes the properties and performance of the detectors of focused Cherenkov radiation that are used in several current and future particle and nuclear physics experiments. The presentation is organised by attempting to answer three questions:

- what types of RICH detector are currently used or proposed ?
- why is the RICH detector used ?—i.e. the physics motivation
- how is the RICH detector used ?—highlighting specific features of the devices used in a selection of accelerator and collider experiments.

The selection is based on relevance to the conference programme and in this sense the review serves as a preview, or pointer, to several contributed papers.

The imaging function of a RICH detector is provided in different ways:

(a) The image is focused by a lens or mirror. This is the classical RICH detector design, pioneered by Jacques Seguinot and Tom Ypsilantis [1] in which the Cherenkov light is focused using spherical optics to a ring image, from which the Cherenkov emission angle is determined from the detector geometry.

(b) Proximity focusing, which effectively means no focusing. The Cherenkov light cone is detected directly and the inner and outer radius of the cone are limited using a "thin", usually solid or liquid, radiator.

(c) Pin-hole focusing, as used in the DIRC (Detector of Internally reflected Cherenkov light) shares some of the characteristics of proximity focused devices. The technique has been developed and successfully used by the BaBar [2] collaboration.

(d) Imaging using timing: the time of arrival of Cherenkov photons at the detector is crucial to the performance of the large water Cherenkov detectors and has the potential to reduce the, otherwise limiting, chromatic dispersion of the radiators in RICH detectors.

The physics motivation for most applications is based on the identification of "long-lived" charged particles by combining momentum measurement with velocity, as determined from the Cherenkov angle, and hence deducing the particle mass.

(a) Flavour physics and CP violation measurements have driven numerous applications and innovations of the RICH detector technique during the last ten years. Hadron identification is needed to identify the quark flavours that contribute to the decay of heavy-flavoured hadrons. In this category, contributions to this conference include those from the BaBar [2], BELLE [3], LHCb [4] and NA62 [5] collaborations.
(b) In nuclear structure physics the presence of charmed hadrons is a signature that the gluon is being probed. The COMPASS [6] and HERMES [7] experiments pursue this physics using RICH detectors to separate pions from kaons to enhance the charmed-hadron purity.
(c) Low $p_{\mathrm{T}}$ hadron physics requires particle identification to reconstruct the final states in hadron spectroscopy studies or measurements of particle production rates. COMPASS [6], MIPP [8] and PANDA [9] are examples of experiments that apply RICH detectors for this physics.
(d) A principal goal of relativistic heavy-ion physics is the study of the quark gluon plasma. Nuclear matter is relatively transparent to leptons, so these act as a probe of the interior. Electron identification is therefore an important feature of the RICH detectors used in the ALICE [10], CBM [11], HRS at JLAB [12] and three of the RHIC [13] experiments—PHENIX [14], BRAHMS [15] and STAR [16].
(e) Although not contributing to this conference the physics of neutrinos, in particular the measurement of the oscillation parameters, has successfully used (in K2K [17]) and will continue to use (with T2K [18]) the upgraded Super-Kamiokande [19] water Cherenkov detector.

The following sections contain a brief introduction to how the RICH detector technique is employed in these experiments, summarizing their main features and limitations, that are addressed in detail by the contributed papers.

## 2. Flavour Physics

The physics of flavour is described in the Standard Model through the CKM quark-mixing matrix. Measurements of the decays of b hadrons provide a rich source of data from which the CKM parameters can be extracted and the Standard Model description tested, including its description of CP violation. The high mass of b hadrons allows a large number of decay modes, implying that any given channel of interest has a small branching fraction. Knowledge of the underlying quark-level process in a given decay mode is essential and the purity of the sample requires hadron identification. This has motivated the wide and varied implementation of the RICH technique in several experiments. The RICH detector provides good separation between charged pions, kaons and protons at momenta beyond the range at which the direct time-of-flight measurement of the particle's velocity can be effective.

### 2.1. *BaBar*

The BaBar [2] detector operates at the SLAC PEPII electron-positron collider. Its principal aim has been to measure CP violating asymmetries in the decay of $\mathrm{B}^+$ and $\mathrm{B}^0$ mesons. The barrel region of the detector acceptance is equipped with a DIRC [20], providing $\pi-\mathrm{K}$ separation in the momentum range $0.5-4\,\mathrm{GeV}/c$. The layout of the DIRC is shown in Fig. 1. The Cherenkov radiator consists

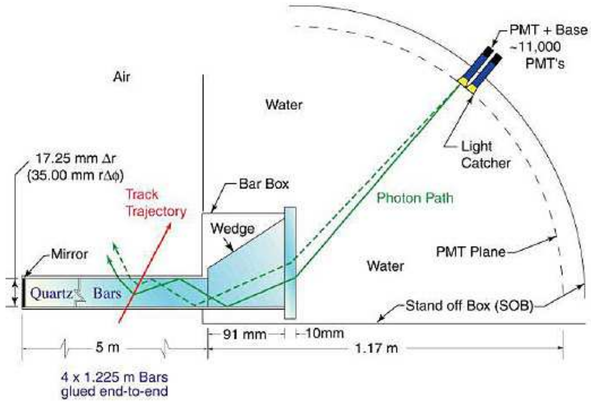


Fig. 1. Schematic of the BaBar DIRC.

of quartz bars, 17 mm×35 mm in section. The light is internally reflected and propagates to the end of the bar where it exits and is detected using an array of 11,000 29 mm photomultiplier tubes (PMTs). The cross-section of each bar is the effective pin-hole aperture and, as with any pin-hole imaging device, there is a trade-off between brightness and image quality. The BaBar DIRC provides 30 detected Cherenkov photons per track with an angular precision of about 10 mrad per photon. A typical measure of its impact on physics performance is a 6-fold reduction in the background to the $\mathrm{D}^0 \rightarrow \mathrm{K}\pi$ decay that contributes to an important fraction of B decays.

### 2.2. *BELLE*

The BELLE [3] detector at the KEK B-factory has run concurrently with BaBar and pursued the same physics programme, but using an aerogel Cherenkov detector in threshold mode. An upgraded detector [21] is proposed to handle a 100-fold increase in luminosity at a Super B-factory. Imaging Cherenkov counters are proposed to cover both barrel and end-cap regions.

The barrel will use the DIRC technique, supplemented by mirror-focused optics to improve the optical contribution to the angular precision and good timing resolution. Multi-channel plate (MCP) PMTs could provide $\sigma_t < 40\,\mathrm{ps}$ that can be used to measure the photon wavelength and thus reduce the chromatic error on the Cherenkov angle.

A proximity focused aerogel RICH is proposed for the end caps. By limiting the thickness of the aerogel tile to 20 mm the emission point error contributes about 10 mrad to the angular precision, but the yield is only six detected photons. This number can be increased by adding successive tiles of increasing refractive index, without degrading the emission-point error. The principle of the FARICH [22] (Focused Aerogel RICH) is shown in Fig. 2 and prototype measurements are reported at this conference.

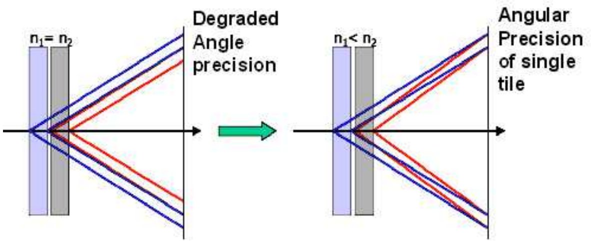


Fig. 2. Schematic of the FARICH.

### 2.3. *CLEOc*

Following a successful programme of beauty physics at the CESR electron-positron collider the CLEO experiment was upgraded and optimized for charm physics. The CLEOc [23] detector uses a proximity focused RICH with a 12 mm-thick LiF radiator. About 12 photons are detected per track using a $CH_4$-TEA gas photon detector. At $20\,\mathrm{m}^3$ it is the largest device of this type currently in use. It is segmented into 230k 8 mm×8 mm pixels that provide a Cherenkov angle precision of 14 mrad and $\pi$−K separation up to 3 GeV/$c$.

### 2.4. *HERA-B*

The HERA-B [24] experiment completed data taking a few years ago with the 900 GeV HERA proton beam interacting on fixed wire targets. This brought to a close a programme of charm and beauty physics in which the RICH detector played a vital part. The HERA-B RICH [25] uses the classic optical layout with spherical focusing mirrors and secondary plane mirrors to reflect the imaged rings onto photon detectors outside the spectrometer acceptance. HERA-B has pioneered the use of multi-pixel vacuum-tube photon detectors, in this case the M4 and M16 Hamamatsu [1] multi-anode PMTs (MAPMT), equipped with lenses, that performed consistently well during its five-year run. A 3 m-long $C_4F_{10}$ gas radiator provided 30 detected photons per track with Cherenkov angle precision below 1 mrad per photon.

### 2.5. *LHCb*

The LHCb [4] detector is a single arm spectrometer, designed for precision CP violation and rare decay measurements in b-hadron decays, at the CERN LHC. The dynamics of b-quark production in 14 TeV p-p collisions favour a forward spectrometer configuration very similar to that of HERA-B. Hadron identification is required over a momentum range from 1 GeV/$c$ up to and beyond 100 GeV/$c$ and the photon detector must have readout electronics capable of operating at the 40 MHz LHC bunch-crossing frequency.

The momentum range for $\pi$−K separation, with positive kaon identification, extends from the kaon threshold momentum up to momenta at which the difference in Cherenkov angle $\theta_\pi - \theta_{\mathrm{K}}$ is comparable to the angular precision. Even with perfect optics the precision will be limited by the chromatic dispersion of the radiator and in practical detectors this momentum range, $p_{\max} : p_{\min}$ for $\pi$−K separation is about a factor 6. So the LHCb RICH detector [26] incorporates three radiators, aerogel and $C_4F_{10}$ gas in RICH 1, upstream of the dipole spectrometer magnet and $CF_4$ in RICH 2, downstream of the magnet and optimized for high-momentum hadron identification.

The LHCb RICH team has developed custom photon detectors [27] together with industry, the lead

[1] Hamamatsu Photonics K.K., Hamamatsu City, Japan.

partner being Photonis-DEP [2]. The hybrid photon detector (HPD) uses a multialkali photocathode deposited on the internal surface of a quartz-windowed vacuum tube. Photoelectrons are accelerated by a 20 kV potential and focused onto a segmented silicon sensor that is solder bump-bonded to a custom readout chip. The sensor and its readout are encapsulated within the vacuum. Each HPD has 1000 pixels and the 484 HPDs cover about $3\,\mathrm{m}^2$ with a granularity of $2.5\,\mathrm{mm}\times 2.5\,\mathrm{mm}$. Figure 3 shows the accumulation of Cherenkov rings, detected using three HPDs, from $C_4F_{10}$ gas in a charged particle beam with 25 ns bunch separation.

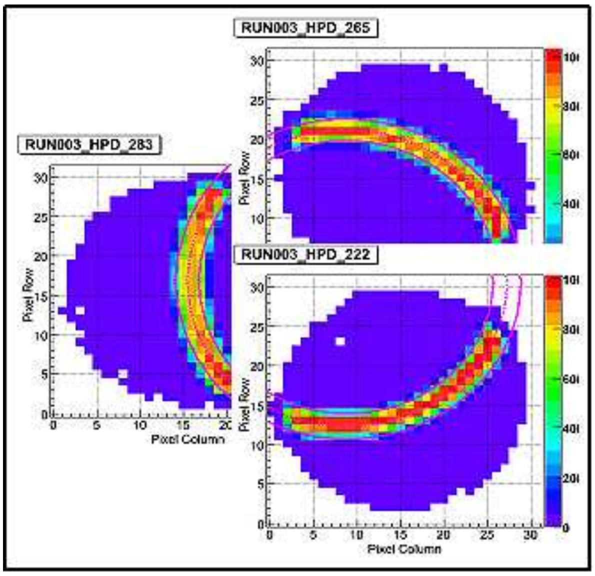


Fig. 3. Display of accumulated Cherenkov rings in the LHCb HPDs.

### 2.6. *NA62*

CERN experiment NA62 [5] plans to probe the CKM matrix using charged kaon decays. The principal goal is a measurement of the decay $\mathrm{K}^+ \to \pi^+\nu\overline{\nu}$ branching fraction to extract the parameter $V_{\mathrm{td}}$. The Standard Model prediction is about $10^{-11}$, so a formidable rejection against the $\mathrm{K}^+ \to \mu^+\nu$ mode is needed and a RICH detector [28] of the classic design will contribute to this. It will be 18 m long, using a neon radiator (with very low chromatic dispersion) and 8 mm PMTs to deliver a Cherenkov angle precision $\sim 60\,\mu$rad with e-$\mu$-$\pi$ separation over the momentum range 12–60 GeV/$c$.

[2] Photonis-DEP BV, 9300 Roden, NL.

## 3. Nucleon Structure Physics

The origin of the nucleon's spin is an enigma. Current evidence indicates that the spin of the quarks contributes little and measurements of the gluon contribution are needed to improve our understanding. By scattering polarized leptons on polarized nucleons, experiments have used charmed particle production as a signature of the photon-gluon fusion process. RICH detectors have been crucial in the selection of charmed particle data samples of high purity.

### 3.1. *HERMES*

Like HERA-B, the HERMES [7] detector ran at HERA, but used the polarized electron beam to scatter from polarized hydrogen and deuterium gas targets. HERMES has pioneered the use of aerogel as a RICH radiator, and as shown in Fig. 4, like the LHCb RICH 1 it combines aerogel and $C_4F_{10}$ gas radiators within the same detector [29]. It has just completed seven years of stable running with the aerogel yielding 10 detected photons with an angular precision of 7 mrad. By combining the two radiators, $\pi-$K separation over the range $2-15$ GeV/$c$ is achieved.

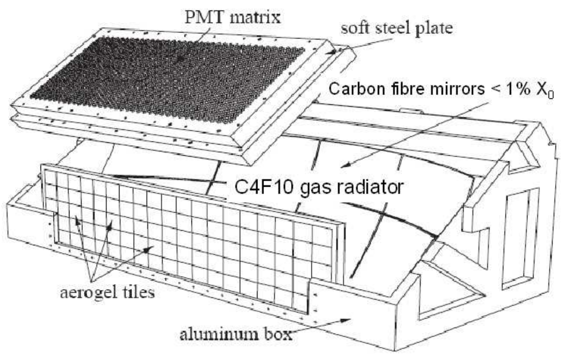


Fig. 4. The HERMES RICH combines aerogel and gas radiators.

### 3.2. *COMPASS*

The COMPASS [6] experiment pursues similar physics aims using 160 GeV muons from the CERN SPS, interacting in a polarized target. The polarized target does not allow the use of a vertex detector to identify charmed particles and the RICH is essential. COMPASS RICH [30] uses a $C_4F_{10}$ gas radiator


Fig. 5. The COMPASS RICH with central CsI photon detectors replaced by MAPMTs.

with a $20\,\mathrm{m}^2$ focusing mirror. Cherenkov photons are converted using $5\,\mathrm{m}^2$ of CsI photocathode with photoelectrons detected with 1 cm precision using MWPCs.

During the last year's run the central CsI + MWPCs have been replaced by M16 MAPMTs—see Fig. 5. This change in technology has brought significant performance improvements. The yield of detected photons increases from 14 to 60, the $\pi$−K separation extends up to $55\,\mathrm{GeV}/c$ (previously it was $40\,\mathrm{GeV}/c$) and the timing precision $\sim 1$ ns (previously $\sim 3\,\mu$s) provides a powerful tool in reducing backgrounds in high-intensity running. COMPASS will use this upgraded RICH in its future hadron spectroscopy programme and will contribute to the physics covered in Section 4.

## 4. Low-$p_\mathrm{T}$ Hadron Physics

This heading covers hadron spectroscopy, including the search for exotic quark molecules, glueballs and hybrid bound states, and systematic particle production measurements. The latter provide a useful source of data to inform and verify simulation codes.

### 4.1. *MIPP*

The Main Injector Particle Production experiment [8] at FNAL uses a near-100% acceptance spectrometer to collect data from $\pi$, K and proton beams. The spectrometer features a classic $CO_2$ RICH [31], equipped with 3000 PMTs providing $\pi$−K separation up to $90\,\mathrm{GeV}/c$.

### 4.2. *PANDA*

A varied particle and nuclear physics programme is planned for the future FAIR (Facility for Antiproton and Ion Research) complex at the GSI, Darmstadt. Among the detectors being designed is PANDA [9] that will provide near-100% acceptance for the products of antiproton-proton annihilations, particularly aimed at exotic hadron states. As shown in Fig. 6 the spectrometer features a variety of RICH detector types [32]. The barrel detector will use a BaBar-style DIRC while the end-cap will be covered by a "Disc-focusing" DIRC, a novel design that uses a one-dimensional readout to perform the imaging. Higher momentum particles at low polar angles are identified using a HERMES-style aerogel+gas RICH.

## 5. Heavy-Ion Physics

The passage of leptons and hadronic states through nuclear matter can be used as a probe of the bulk properties of the strongly interacting matter that is produced in relativistic heavy-ion collisions. Particle identification, even if only over a limited acceptance, can provide a powerful tool.

### 5.1. *ALICE*

The ALICE [10] detector for heavy-ion collisions at the CERN LHC uses a proximity-focused RICH [33] (HMPID, High Momentum Particle IDentification—the high momentum in this case is relative to what can be covered using the time-of-flight technique). The HMPID covers about 5% of the barrel acceptance with seven $2\,\mathrm{m}^2$ modules of $C_6F_{14}$ liquid radiator and CsI+MWPC photon detector. An upgrade [34] is planned to extend the hadron identification capability up to $30\,\mathrm{GeV}/c$ by employing a 1 m $C_5F_{12}$ gas radiator and a mirror-focused RICH. Again, a CsI photocathode is the chosen technology, but with GEM readout.

### 5.2. *HRS at JLAB*

The High Resolution Spectrometer [12,35] at the Jefferson Laboratory has used the same RICH technology as the ALICE HMPID for its hypernuclei production studies. Electrons scatter inelastically from nuclear targets and charged kaon emission is

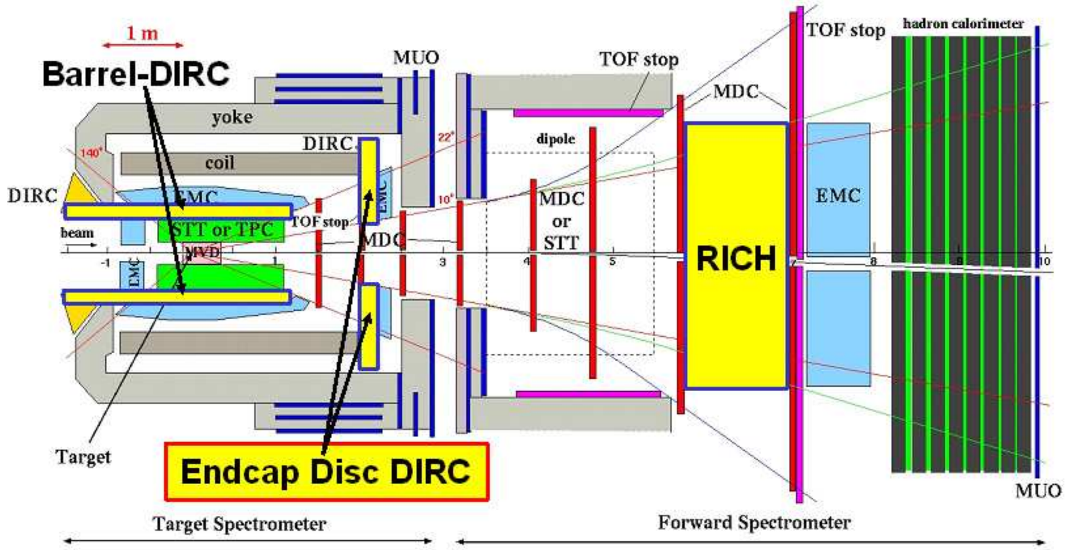


Fig. 6. The three RICH detectors of the proposed PANDA spectrometer at FAIR.

the signature for hypernuclear states, whose properties are important for the physics of neutron stars. The purity of the K identification is crucial and a pion rejection factor of 1000 is obtained in the momentum range 0.8–3 GeV/$c$.

### 5.3. *CBM*

The Condensed Baryonic Matter [11] detector is planned to study 15–35 AGeV heavy-ion collisions with fixed nuclear targets at the FAIR facility. Low mass vector mesons, decaying into leptons, are an important signature for interesting events and particle identification up to 10 GeV/$c$, with excellent electron purity, is required. Unlike the PANDA detector's 100% coverage the CBM RICH [36] acceptance is limited to the forward direction and a more conservative design is foreseen. A classic mirror-focused RICH using gas radiator with MAPMT photon detectors is expected to provide the physics performance required.

### 5.4. *RHIC*

The Relativistic Heavy-Ion Collider at Brookhaven serves four intersection points where three of the experiments, BRAHMS [15], PHENIX [14] and STAR [16] employ RICH detectors to measure, *inter alia*, differences in the meson/baryon and lepton/hadron production ratios in p-p vs A-A collisions. Of these only the PHENIX detector [37] is reported at this conference. It uses a $CF_4$ gas radiator with CsI photocathode and GEM readout to provide hadron-blind electron identification. The BRAHMS RICH uses a heavy fluorocarbon gas mix with M4 MAPMTs giving hadron identification up to 30 GeV/$c$. Finally, STAR is yet another user of the ALICE-like proximity focused RICH, with $C_6F_{14}$ liquid radiator, CsI photocathode and MWPC readout. The expected ALICE HMPID performance of $\pi$-K-p separation in the 1-3-5 GeV/$c$ momentum range is justified by the STAR RICH results.

## 6. Neutrino Physics

The T2K [18] experiment, due to start running in 2009, will direct a neutrino beam from the J-PARC synchrotron over 300 km to the SuperKamiokande water Cherenkov detector to measure the parameters that govern the physics of neutrino oscillations, in particular the mixing angle $\theta_{13}$ between first and third generation neutrinos. The SuperKamiokande detector, with 50 ktonnes of water radiator viewed by 13,000 20 inch PMTs, is by far the largest Cherenkov device operating in an accelerator-based experiment. Its large dimensions, combined with time of propagation, provide effective proximity focused imaging of the entire neutrino event. Following recent repair of the photon detector array, the detector readout has been upgraded to provide deadtime-less data acquisition, allowing a refined trigger and lower ($\sim 2\,\text{MeV}$) threshold.

## 7. Summary

The contributions to the scientific programme of this conference testify to the ubiquity of the RICH detector. Many accelerator and collider experiments use or plan to use some form of imaging Cherenkov device to provide particle identification. The previous sections cover the wide range of physics that benefits from their use. But there is a noteworthy absence of RICH technology in high-$p_{\rm T}$ hadron physics, featuring neither in the Tevatron detectors, nor in the LHC general purpose detectors. It is not easy to see how Cherenkov radiation detection from high-energy particles could be accommodated effectively in the hermetic collider detectors but, on the other hand, there does not appear to be a compelling physics motivation to develop an innovative solution.

In the spirit of this conference the term RICH is taken to include all Cherenkov detectors that provide a measurement of the Cherenkov emission angle and the diversity of imaging methods gives rise to the different types of RICH detector currently used and planned. The choice is informed by the physics requirements, the space constraints and cost. My personal observation from the fields of particle and nuclear physics is that the classic mirror-focused gas RICH is the technique of choice for high-energy particle identification, $\gamma > 10$ say, using vacuum tube photon detectors wherever feasible. For very large area coverage the proximity focused CsI photocathode, combined with MWPC or GEM, photon detector remains a viable technology but is limited to lower-energy particles $1 < E < 5\,\text{GeV}$. However, for the same energy range and in the barrel configuration, the DIRC is clearly emerging as a favoured technique.

Looking towards future trends, I foresee a continuing R&D effort to explore the benefits of precise timing. Measurement of the time-of-propagation (TOP) of the Cherenkov photons provides a way of determining the photon wavelength, thus reducing the, otherwise irreducible, limit on resolution due to the chromatic dispersion of the radiator. The timing precision required to use the TOP effectively is of order 10-20 ps. Vacuum tubes with microchannel plate (MCP) multipliers are already approaching this precision. The ongoing R&D on solid state photon detectors is motivated by several potential applications, and RICH detectors will surely benefit from this development. The specific features desirable for the RICH are: large area coverage, room temperature operation, good time resolution. All these mean that low noise performance is not easy to achieve. While there is no consensus on the appropriate generic name for such devices there is a strong effort in collaboration with industry to develop semiconductor devices with internal amplification that can deliver the low noise performance required for the single-photon sensitivity in a RICH application. I am optimistic that the next conference in this series will include reports from successful tests of these devices in a RICH context.

## 8. Acknowledgments

Firstly, my thanks to the organizers for the invitation to deliver this review. They have chosen a beautiful location in Trieste and successfully run an enjoyable conference, with both scientific and social programme full of interest and novelty. Secondly, since the content of this review is not my own work, I acknowledge the many collaborations who have provided information, either directly or through presentation material on their websites. Any errors and omissions are of course due to me alone and for these I apologize.

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