Literature Review

Particle Identification in Modern Cherenkov Detectors

Danny Markhoff

[a] *University of Edinburgh, School of Physics and Astronomy, Mayfield Road, EH9 3FD, Edinburgh, United Kingdom*
[b] *GSI, Planckstrasse 1, 64291, Darmstadt, Germany*

Abstract

With major detector assemblies lining up for construction at high-energy facilities such as EIC and FAIR, technologies for particle identification are becoming ever more relevant. This review motivates the theory of the field, introduces the technologies behind modern Cherenkov detectors, and discusses the implementation of these detectors into upcoming experiments. Emphasis is placed on ...... Persistent challenges include ...... We conclude by outlining promising future developments for ......

Keywords: Particle Identification, Cherenkov Detectors, DIRC, RICH, PANDA, EIC, GSI

For PwYA Literature Review 6th January 2026

Placement Supervisor: Dr. Jochen Schwiening j.schwiening@gsi.de
Edinburgh Advisor: Dr. Moritz Pascal Reiter mreiter@ed.ac.uk

Email address: `d.markhoff@sms.ed.ac.uk`, `d.markhoff@gsi.de` (Danny Markhoff)

Contents

1. Introduction

2. Theoretical Foundations

2.1. Cherenkov Radiation

Cherenkov radiation is a phenomenon that occurs when a charged particle travels through a dielectric medium with refractive index $n(\lambda)$ at a speed greater than the phase velocity in that medium. This effect was first observed by Pavel Čherenkov in 1934 [1] and later explained theoretically by Ilya Frank and Igor Tamm [2].

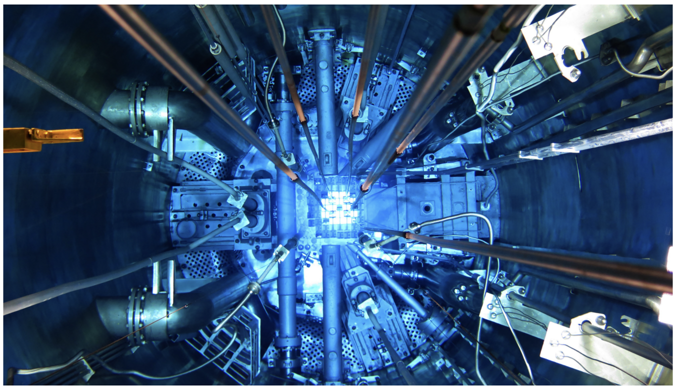

Figure 1: **Cherenkov radiation in a nuclear reactor pool.** The characteristic glow is indicative of relativistic electrons moving through the water. (Photo: IAEA)

From Maxwell's equations arises that electromagnetic propagation with wavelength λ will have its phase velocity modified by the medium it is travelling through. This leads to the idea of refractive index $n(\lambda) = c/v$, defined as the ratio between the speed of light in vacuum c and the phase velocity v in the medium. The condition for Cherenkov radiation to occur is then given by $v > c/n$.

The Cherenkov radiation itself propagates at the phase velocity of the medium. As such, the radiation forms a conical wavefront with characteristic angle θ, similar to how shock cones are formed by supersonic aircraft. The angle θ can be derived from simple geometric considerations shown in Fig 2, yielding the following:

$$\cos\theta = \frac{v_p}{v} = \frac{c}{nv} \tag{1}$$

The main principle behind a Cherenkov detector is to measure the angle θ of the emitted photons, which can then be used to determine the velocity v of the charged particle. With an associated momentum measurement from a forward tracking detector, the mass of the particle can be inferred, allowing for spectroscopy. This velocity spectroscopy for various particle species is shown in Fig 3. It can be seen that pions, for example, will produce a larger Cherenkov angle than kaons or pions at the same momentum, due to them being less massive.

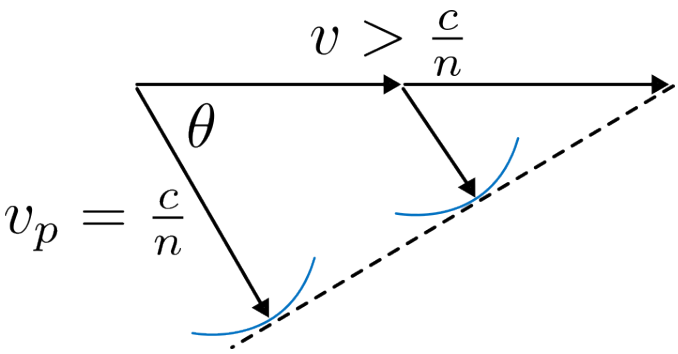

Figure 2: **Schematic of a Cherenkov cone.** A particle travels through a medium with velocity v. Photons are emitted at the phase velocity v_p and angle θ to the path of travel of the particle, giving the characteristic blue shock cone.

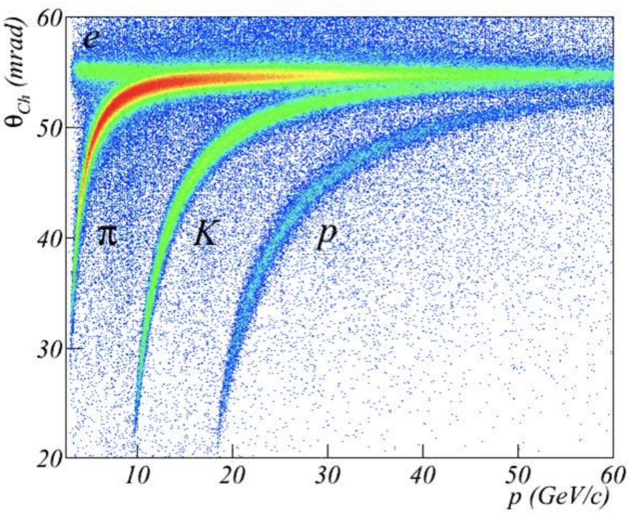

Figure 3: **Cherenkov spectroscopy of the COMPASS RICH-1 detector at CERN.** There are clear curves for different particle species. These curves can be determined mathematically using (1) and relativistic dynamics. (Photo: [3])

The energy dE emitted per unit length is given by the Frank-Tamm formula, which can be expressed as

$$\frac{dE}{dx} = \frac{q^2}{4\pi} \int_{v > \frac{c}{n(\omega)}} \mu(\omega)\omega \left(1 - \frac{c^2}{v^2 n^2(\omega)}\right) d\omega \tag{2}$$

for a particle with charge q and frequency ω, moving through a medium with permeability μ and refractive index $n(\omega)$. The integral is taken over all frequencies where the Cherenkov condition $v = c/n(\omega)$ is met. By changing variables to wavelength λ and using that $E = Nh\omega$, one can show that the number of photons N emitted per unit length is inversely proportional to the square of the wavelength. This explains the characteristic blue of Cherenkov radiation, as shorter wavelength (blue light) photons are emitted more.

2.2. Relativistic Kinematics

Relativistic kinematics is the study of the motion of particles at near-light speeds. The purposes of this review do not require an exhaustive treatment of the subject, but a few key concepts pertaining to Cherenkov radiation and detector physics are summarised.

The famous energy-mass relation is written as:

$$E^2 = p^2c^2 + m_0^2c^4 \tag{3}$$

for a particle with energy E, momentum p and rest mass m_0. The Lorentz factor arises from considering the four-velocity, and defines a mapping between the rest frame of the particle (the frame in which the particle's velocity is zero) and the observer's frame. It is defined as:

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \tag{4}$$

where $\beta = v/c$ is the velocity of the particle as a fraction of the speed of light. We can use the Lorentz factor to transform Newtonian quantities into their relativistic equivalents using the equations

$$p = \gamma m_0 v \tag{5}$$

$$E = \gamma m_0 c^2 \tag{6}$$

Using (5) and (6) we can rewrite the Cherenkov angle condition from (1) as

$$\cos\theta = \frac{c}{nv} = \frac{E}{npc} = \frac{\sqrt{p^2+m^2c^2}}{np} \tag{7}$$

where one can clearer see how a combination of the Cherenkov angle and the momentum measurements can be used to infer the mass of the particle. This equation can be used to plot the theoretical curves for the experimental data in Fig 3.

Often in detector assemblies, the Cherenkov detectors will receive momentum measurements from forward detectors. Then, the statistics from the Cherenkov detectors are so impressive, that the detectors are usually able to decisively improve on the forward detector's measurements. This is especially true for DIRC detectors, which have an excellent angular resolution. The back-and-forth between detectors often creates friendly competition within experimental collaborations.

2.3. Optical Detector Theory

2.4. Particle Physics Motivation

2.5. Statistical Event Reconstruction Methods

2.6. Radiation-Matter Interactions

3. Photomultipliers

3.1. MCP-PMTs

3.2. SiPMs

3.3. LAPPDs

3.4. HRPPDs might get cut

4. Photon Optics might get cut

4.1. Lenses and Reflections

4.2. Laser Calibration

5. Ring Imaging Cherenkov Detectors (RICH)

6. Detection of Internally Reflected Cherenkov Light (DIRC)

7. Neutrino Identification with Cherenkov Detectors might get cut

7.1. Atmospheric Muons

7.2. Water Cherenkov Detectors

8. Applications at Future Facilities

8.1. PANDA DIRC at FAIR

8.2. hpDIRC at ePIC Brookhaven

8.3. Other Proposed Far Future Detectors might get cut

9. Current Challenges and Limitations

9.1. ML PID

9.2. High Rate Environments

9.3. Radiation Damage

9.4. Budget Constraints

10. Emerging Technologies

10.1. HRPPDs

10.2. Advanced Optics

10.3. New Materials

11. Summary

[4]

References

[1] P. A. Čerenkov, "Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light," *Phys. Rev.*, vol. 52, pp. 378–379, Aug 1937.

[2] I. M. Frank and I. E. Tamm, "Coherent visible radiation of fast electrons passing through matter," *Compt. Rend. Acad. Sci. URSS*, vol. 14, no. 3, pp. 109–114, 1937.

[3] F. Tessarotto, P. Abbon, M. Alexeev, R. Birsa, P. Bordalo, F. Bradamante, A. Bressan *et al.*, "Long term experience and performance of COMPASS RICH-1," *Journal of Instrumentation*, vol. 9, p. C09011, 2014.

[4] B. Singh, W. Erni, B. Krusche, M. Steinacher, N. Walford, B. Liu, H. Liu *et al.*, "Technical design report for the $\overline{\mathrm{P}}$ANDA Barrel DIRC detector," *Journal of Physics G: Nuclear and Particle Physics*, vol. 46, no. 4, p. 045001, 2019.