PROCEEDINGS OF SCIENCE

C-Arapuca: a new device for Cherenkov radiation detection

Anderson Campos Fauth,[a,*] Ana Amélia Bergamini Machado,[a] Vinicius do Lago Pimentel,[b,c] Ettore Segreto,[a] Gabriel Botogoske,[a] Maria Cecilia Queiroga Bazetto,[c] Jorge Andres Molina Insfran,[d] Andre Fabiano Steklain Lisbôa,[e] Márcio Rostirolla Adames,[e] Jorge Henrique de Andrade Pacheco Reis,[a] Frederico Luciano Demolin[a] and Heriques Frandini Gatti[f]

[a] *Universidade Estadual de Campinas, IFGW, Rua Ségio Buarque de Holanda 777, Campinas-SP, Brazil*

[b] *Centro de Tecnologia da Informação Renato Archer, DIPAQ, Rodovia Dom Pedro I 21500-km 143, Campinas-SP, Brazil*

[c] *Laboratório Nacional de Astrofísica, R. dos Estados Unidos 154, Itajubá-MG, Brazil*

[d] *Universidad Nacional de Asuncíon, Facultad de Ingeniería, Campus de la UNA, Km 11, Asunción, Paraguay*

[e] *Universidade Tecnológica Federal do Paraná, DAMAT, Avenida Sete de Setembro 3165, Curitiba-PR, Brazil*

[f] *Universidade Federal do ABC, CCNH, Av. dos Estados 5001, Santo André-SP, Brazil*

E-mail: fauth@unicamp.br

*Speaker

Abstract
Many high-energy physic experiments use Cherenkov radiation as a detection method. Photomultiplier tubes are typically used to convert the radiation into an electrical signal. In this work, we present the development of a new device dedicated to the detection of Cherenkov radiation photons that could replace photomultiplier tubes in experiments that detect this radiation. C-Arapuca is the name given to this device, as it uses the concept of photon trapping in a box, already used in the Deep Underground Neutrino Experiment, but now adapted for the detection of a range of energies of Cherenkov radiation photons. Calculations of efficiency, design, and performance of the C-Arapuca are described, highlighting its performance compared to photomultiplier tube in the detection of Cherenkov radiation. A shortpass dichroic filter with a cut-off wavelength at 400 nm was used in the C-Arapuca window, and the inner part of the box, covered with highly reflective material, contains a blue-emitting wavelength-shifting plastic slab and Hamamatsu silicon photomultipliers. In this study, a cylindrical tank containing 550 liters of ultrapure water was used, in which two C-Arapucas and a photomultiplier tube with a photocathode of 110 mm in diameter were installed. The useful area of the optical window of a C-Arapuca is 70.0 x 93.0 mm². Relativistic muons from local cosmic radiation passing through the water volume were used as a source of Cherenkov radiation detected by both the C-Arapucas and the photomultiplier tube, allowing for a relative comparison of the performance of the new device.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

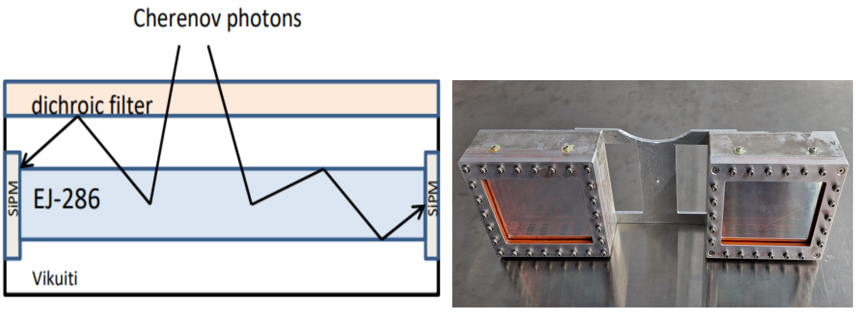
1. Introduction

Cherenkov radiation in water is utilized in numerous experiments in high-energy astroparticle physics for the detection of electrically charged relativistic particles. The so-called Water-Cherenkov detector (WCD) is one of these widely used detectors in experiments such as the Pierre Auger Observatory [1] and the LAGO Collaboration [2]. The extensive use of this technique is due to its proven robustness in various environments and high performance.

Traditionally, the conversion of Cherenkov radiation photons into electrical pulses is performed through photomultiplier tubes (PMTs), which are vacuum tubes with a quartz window where a photocathode is located. Within the tube, there is also amplification, typically on the order of $G = 10^7$, of the electrical signal. PMTs usually consume 2 Watts of power and require a continuous high-voltage power supply that provides voltages of approximately 2000 Volts with high precision.

The photoelectric device described in this work uses the concept of photon trapping employed by the X-ARAPUCA device [3, 4], which is being used by the Deep Underground Neutrino Experiment (DUNE) [5] and also by the Short-Baseline Near Detector (SBND) [6]. However, this work is dedicated to the detection of Cherenkov radiation, initially in water, so we refer to it as C-Arapuca. "Arapuca" is a word in the Tupi-Guarani language of the native peoples of Brazil, which means a device for capturing wild animals.

2. The C-Arapuca

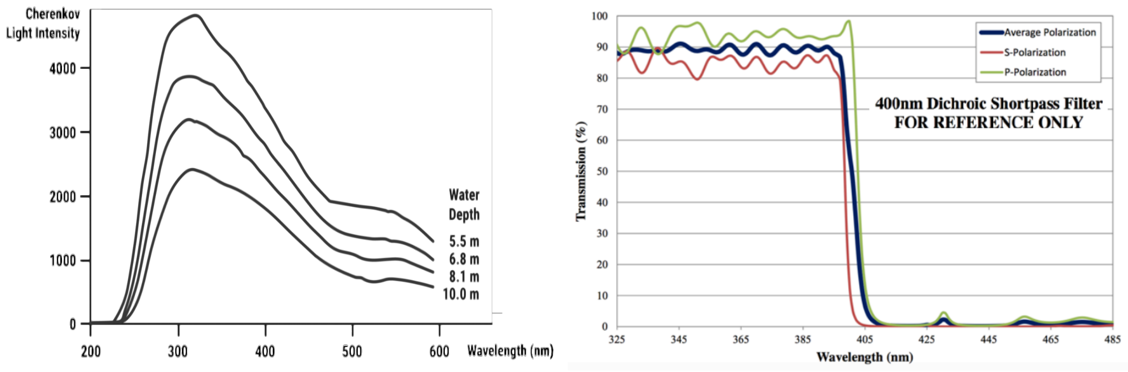


(a) (b)

Figure 1: (a) Schematic drawing and (b) photograph of the C-Arapucas Jaci and Guaraci.

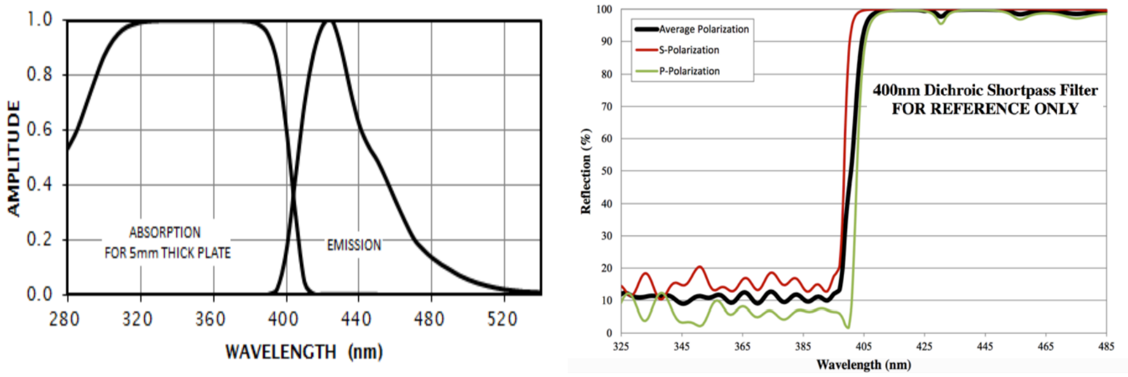
To trap Cherenkov photons in the C-Arapuca, we use a dichroic filter transparent for wavelengths below 400 nm, produced by Opto Eletrônica SA [7], and a blue-emitting wavelength shifting (WLS) plastic with strong broad absorbance in the near-UV, model EJ-286 manufactured by Eljen Technology [8]. This WLS not only shifts the wavelength but also serves as a light guide to direct photons to the SiPMs. Figure 1(a) shows the schematic drawing illustrating the operating principle of the C-Arapuca, and in Figure 1(b), a photograph of the two prototypes installed in the tank. We named them Jaci and Guaraci, names that mean Moon and Sun in the Tupi-Guarani language. In this work, we compared the performance of Jaci alone and a PMT.

The most commonly used Water Cherenkov Detectors (WCDs) in cosmic ray experiments have a water reservoir with a height of approximately one meter. The spectrum of Cherenkov photons produced by relativistic particles in water for a typical WCD is shown in Figure 2(a). The transmittance of the dichroic filter we use in the C-Arapuca, shown in Figure 2(b), allows the entry of these photons with wavelengths up to 400 nm.



(a) (b)

Figure 2: (a) Cherenkov scpectrum in water [9] and (b) dichroic filter transmitance.



(a) (b)

Figure 3: (a) Wavelenght shifting absorption and emission of the EJ-286, and (b) dichroic filter reflectance.

Inside the C-Arapuca box, photons can be absorbed by the wavelength shifting (WLS) material, and in ~1.2 ns, photons with a greater wavelength are emitted. Figure 3(a) shows the absorption curve as well as the emission curve of the WLS EJ-286. The majority of these photons emitted by the WLS are trapped inside it due to the difference between the refractive indices of the light guide, n_{wls}=1.58, and that of air, n_{air}=1.00. The dichroic filter's reflectance cut-off at 400 nm, showed in Figure 3(b), trap the other photons that escape from the light guide. All internal walls of the C-Arapuca box have been covered with Vikuiti™ Enhanced Specular Reflector [10], a highly reflective film produced by 3M. To convert the photons into electrical pulses, we use eight Hamamatsu S13360-6050VE model SiPMs [11]. Each SiPM has an effective area of 6x6mm, and four of them are installed on one side of the WLS, while the other four are installed on the opposite side. This model of SiPM has a photon detection efficiency maximum of 40% at 450 nm. The optical coupling between the WLS and the SiPMs was performed using optical silicone.

3. The Water-Cherenkov tank

The performance study of the C-Arapuca was conducted by placing two prototypes in a tank containing 550 liters of ultrapure water. A Tyvek bag was installed along the inner walls of the tank. A 110 mm in diameter photocathode Philips XP2040 photomultiplier tube was also installed in the tank. Two plastic scintillators were used to select vertical muons. Each scintillator measures 38x40x2.5 cm³. Figure 4 shows the stainless steel tank and the trigger scintillators.

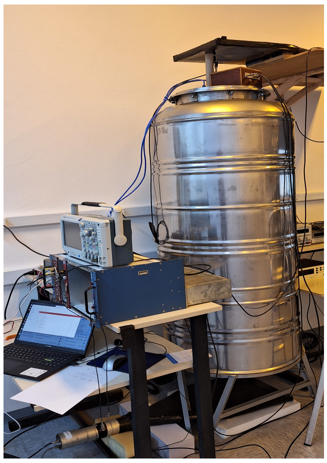


Figure 4: The tank, plastic scintillators (one above and other below the tank), and data acquisition system.

Data acquisition was performed using a CAEN digitizer, model DT5730S, 14-bit, 500 MS/s, utilizing the CoMPASS software [12].

The trigger for vertical muons was generated by the temporal coincidence (80 ns) of pulses from two scintillators, one placed on the top and the other below the tank. A CAEN NIM high voltage module, model N140, was used to supply power to the PMT, along with a discriminator and a logic unit to generate the trigger. The trigger pulse was used as the External Trigger for the DT5730S digitizer. The rate of the vertical muon trigger was 0.4 Hz. The SiPMs were powered and amplified 20x by an APSAIA module produced by AGE [13].

4. Results

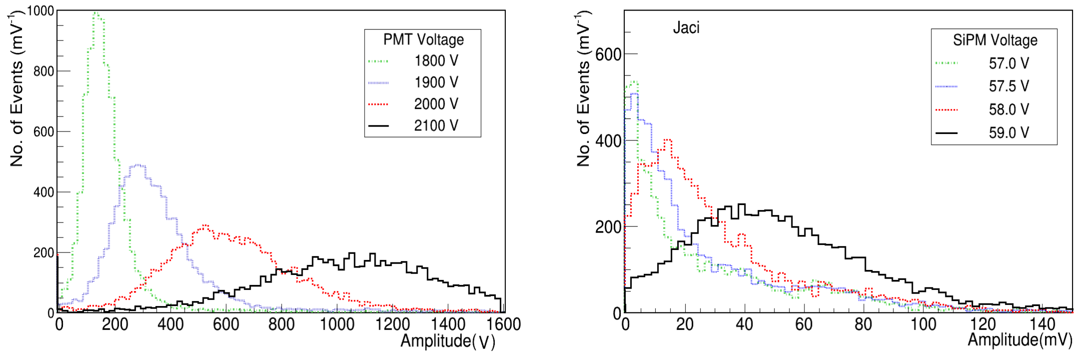
To determine the counting efficiency of vertical muons from cosmic radiation at the Earth's surface for this tank, amplitude spectra of pulses from the C-Arapuca and PMT were obtained. Figure 5 shows the spectra for SiPM voltages ranging from 57.0V to 59.0V and PMT voltages ranging from 1800V to 2100V.

The counting efficiency, $\epsilon_{threshold}$, was calculated using the following equation:

$$\epsilon_{threshold} = \frac{N_{threshold}}{N_{triggers} - N_{accidental}} \tag{1}$$

where:
$N_{triggers}$ = number of triggers
$N_{threshold}$ = number of events with amplitude greater than the threshold
$N_{accidental}$ = number of accidental double coincidence events

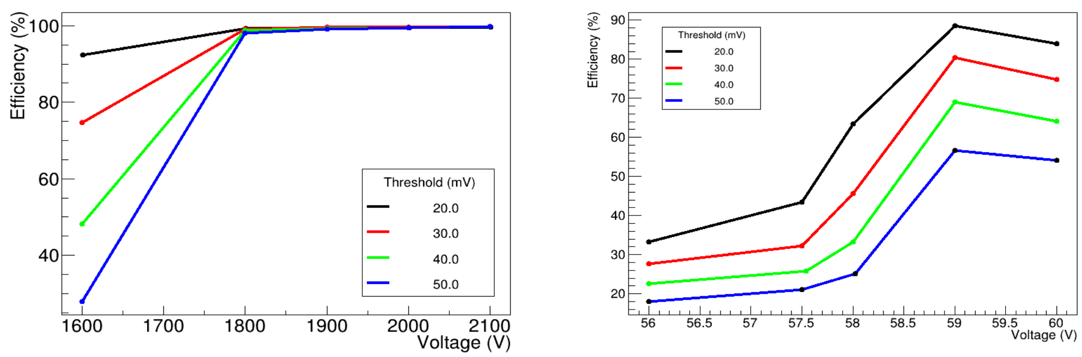
Figure 6 shows the behavior of the counting efficiency as a function of voltage and pulse discrimination threshold. The rise times of the PMT and C-Arapuca pulses have similar values, around 2 ns. For a given counting efficiency, the amplitude of the C-Arapuca pulses is much lower



(a) (b)

Figure 5: (a) Amplitude spectrum of the PMT, and (b) amplitude spectrum of the Jaci C-Arapuca.

than that of the PMT, but the pulse duration is significantly longer for the C-Arapuca. A study of the C-Arapuca gain is being conducted to quantify the performance of this new device.



(a) (b)

Figure 6: Counting efficiency (a) for the PMT and (b) for the C-Arapuca.

5. Conclusions

In this work, we demonstrate that the C-Arapuca has a counting efficiency comparable to the PMT, despite having a smaller window that is 69% of the size of the PMT's photocathode area. The concept of the Arapuca design allows compensating for the reduced area of the SiPM by increasing the effective photon collection area. Since SiPMs operate at voltages in the range of a few tens of volts, the power supply system is simpler when compared to PMTs, which require high voltages of over 1000V. An additional advantage of this new Cherenkov photon detection device is that the volume of the C-Arapuca is much smaller than an equivalent PMT. Furthermore, the geometry of the C-Arapuca is flexible and can be modified. The device can be shaped as cylindrical, cubic, pyramidal, or other forms, providing versatility in its application and integration into different experimental setups.

Overall, the C-Arapuca presents a novel approach to Cherenkov photon detection, offering comparable counting efficiency to PMTs while providing benefits such as lower voltage operation, compact size, and design flexibility.

Acknowledgments

This work is supported by the São Paulo Research Foundation (FAPESP), grant 2021/13538-5. ACF thanks the Brazilian National Council for Scientific and Technological Development (CNPq), grant 308231/2021-0, VLP thanks to CNPq grants MCBQ 380629/2023-2 and 382018/2023-0, and MRA tanks CNPq postdoctoral fellowship.

References

[1] The Pierre Auger Collaboration, *The pierre auger cosmic ray observatory*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **798** (2015) 172.

[2] LAGO collaboration, *The Sites of the Latin American Giant Observatory*, in *Proceedings, 34th International Cosmic Ray Conference (ICRC 2015): The Hague, The Netherlands, July 30-August 6, 2015*, vol. ICRC2015, p. 665, 2016, DOI.

[3] A. Machado, E. Segreto, D. Warner, A. Fauth, B. Gelli, R. Máximo et al., *The X-ARAPUCA: an improvement of the ARAPUCA device*, *Journal of Instrumentation* **13** (2018) C04026.

[4] E. Segreto, A. Machado, A. Fauth, R. Ramos, G. de Souza, H. Souza et al., *First liquid argon test of the x-ARAPUCA*, *Journal of Instrumentation* **15** (2020) C05045.

[5] DUNE, "Deep Underground Neutrino Experiment." , https://www.dunescience.org/, accessed: 2023-06-05.

[6] SBND, "Short-Baseline Near Detector." , https://sbn-nd.fnal.gov/index.html, accessed: 2023-06-05.

[7] "Opto Eletrônica S.A." , https://www.opto.com.br/, accessed: 2023-07-10.

[8] "Eljen Technology." , https://eljentechnology.com/, acessed: 2023-07-11.

[9] "International Atomic Energy Agency." , https://www.iaea.org/newscenter/news/what-is-cherenkov-radiation, acessed: 2023-07-11.

[10] "Vikuiti 3M." , https://www.3m.com/, accessed: 2023-07-11.

[11] "Hamamatsu Photonics." https://www.hamamatsu.com/, accessed: 2020-08-05.

[12] "CAEN SpA." , https://www.caen.it/, accessed: 2023-07-11.

[13] "AGE Scientific srl." , http://www.agescientific.com, accessed: 2023-07-16.