PROCEEDINGS OF SCIENCE

Simulating the X-ARAPUCA, DUNE's next generation light sensors

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The word *arapuca* refers to a bird trap built by the indigenous peoples of Brazil. On the other hand, our ARAPUCA is a photon trap for Noble Gases' scintillation light and it is the sensitive element upon which DUNE's whole photon detection system is based on. Here we present a glimpse of our state-of-the-art simulation of such device, the **ArapucaSim**, highlighting its philosophy and main components. As an application, we present here one of the studies being carried out, on the effects of light reflections inside the light guide and how affects the overall photon detection efficiency. Based on these results, we are able to not only acquire a better understanding of the device but also impose limits on the quality of the mechanical polishing of such surfaces. The ArapucaSim was developed with two main goals in mind: to assist in R&D by allowing short turnout times between new ideas and experimental tests, and to bridge the gap between high-precision time-consuming hardware simulations and the full-scale models for DUNE's Photon Detection System. This research also led to the development new algorithms for simulating wavelength shifting/scintillation processes and dichroic filters, which will be properly described in future publications.

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1. The X-ARAPUCA Device

Chosen by the Deep Underground Neutrino Experiment (DUNE) as the basic element for its first far detector's (FD-1) photon detection system (PDS), the X-ARAPUCA is the latest iteration of the ARAPUCA family[1]. These devices work by employing a fine-tuned combination of wavelength shifters and dichroic filters, trapping photons long enough as to increase the probability of being detected by a silicon photo-multiplier (SiPM). Figure 1 illustrates the trapping process with an energy-level diagram. Photons from liquid Argon VUV scintillation light (peaking at 127 nm, or 9.8 eV) arrive at the acceptance window, covered with deposited p-Terphenyl (PTP), which down-shifts those photons to a range between 320 and 350 nm. Half of these re-emitted photons cross the dichroic filter, reaching the light-guide doped with the EJ-286 wavelength shifter. Again, photons are down-shift to a secondary range between 413 and 460 nm, which is both outside the dichroic transmission band and inside the SiPM's detection efficiency.

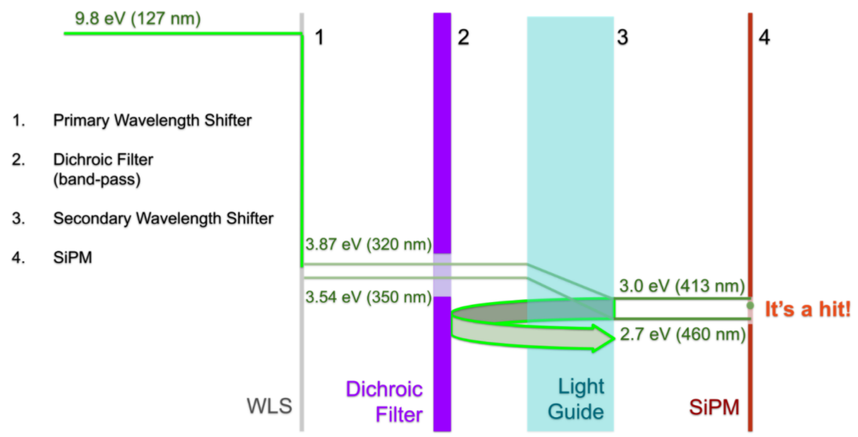

Figure 1: The ARAPUCA's trapping explained in terms of the photon's energy (vertical axis) and how it is shifted by each active layer. (1) Incoming VUV photons are shifted by the p-terphenyl to pass through the dichroic filter (1 → 2). (3) The commercial wavelenght shifter EJ-286 brings the photon's energy down enough so it fall below the filter's transmittance band, being trapped either between the filter and the Vikuiti reflector (not shown here) or inside the light-guide. Trapped photons have an increased probability of being registered as a hit on the SiPM (4).

2. ArapucaSim

Simulations have been a part of the ARAPUCA research since early on its development, with specific models developed for each new setup. With maturity came the need for a broader, more centralized implementation capable of modeling all the different configurations. This software, called **ArapucaSim**, is developed over a Geant4 backbone with personalized managers for Primary Generators, Geometries, Materials, and Physics, the last two being of particular interest. The Materials library managers virtual materials characterized by experimental data. The Physics Library offers custom classes for wavelength shifting, scintillation, and dichroic filters.

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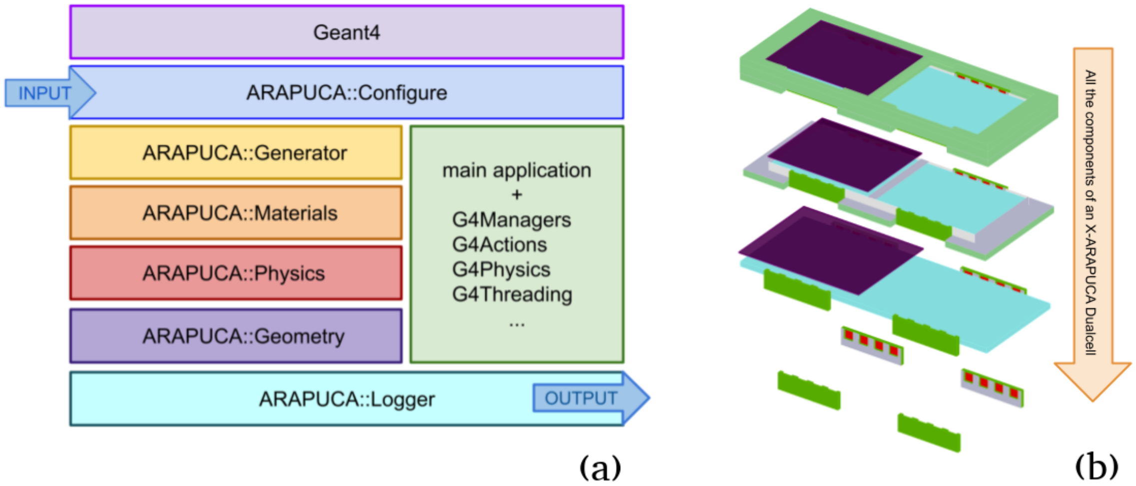

Figure 2: (a) Block diagram of the software **ArapucaSim** developed to simulate the behavior of the X-ARAPUCA sensor. The main four blocks, Generator, Materials, Physics, and Geometry, kept up-to-date with experimental data, interacting with a Geant4 backbone. (b) Computer rendering of a particular X-ARAPUCA model called a dual-cell, showing how their components, from top to bottom: G10 frame (green), dichroic filters (purple), light guide (light blue), Vikuiti reflectors (gray), and SiPM (red).

3. Results

One of the few unknowns about the X-ARAPUCA is how non-ideal micro-reflections inside the light guide impact the overall photon detection efficiency (PDE). These can change the photon's direction randomly, reducing the trapping effect. We modeled this effect via a combination of specular and Lambertian reflections, with the proportion between these given by a free parameter. Figures 3.a and 3.b show how the predominance of Lambertian and specular reflections, respectively, change the photon dispersion inside the light-guide. Figure 3.c shows the resulting PDE (averaged over the dichroic filter's surface area) as a function of the specularity. With this non-linear relation, we estimate how specular the real light guides are, based on the measured efficiencies. With PDE values previously reported between 2.0[3] and 3.5 %[2], specularity must be in the 0.7 to 0.9 range.

ArapucaSim also allows for the mapping of the PDE over the X-ARAPUCA's sensitive area. The resulting map, seen in Fig. 4, exhibits the same distribution as previously reported[3], without the need for fine-tuning or back fitting. With a matching distribution over the windows, the average PDE value can be made to match the real devices by setting a suitable value for the specularity. A proportion of 90:10 specularity-to-Lambertian seems to reproduce the observed PDE.

4. Next Steps

The modeling of both dichroic filter and wavelength shifter represent an advancement over the current ones found in Geant4's optical package. Their implementations in ArapucaSim employ novel algorithms, being computationally efficient and producing more accurate descriptions. These two models are in the final steps of being validated for future publications.

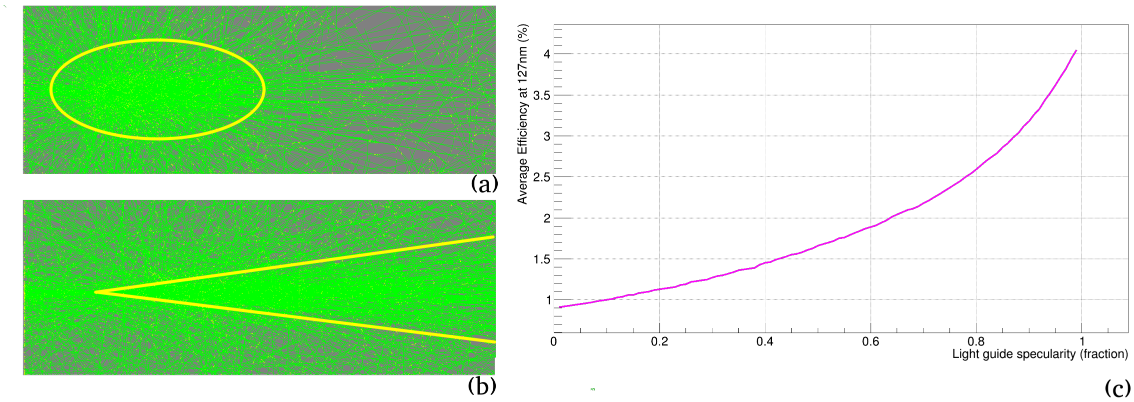

Figure 3: The effects of light guide surface polish, modeled by ArapucaSim as a proportion between specular and Lambertian reflection. (a) The path of 1000 random photons originating at the same vertex when the ratio specular to Lambertian reflections is 10:90. (b) The same, but with a 90:10 ratio. (c) Detection efficiency (averaged over the filter's surface area) as a function of specularity/Lambertian ratio. As expected, the system becomes more efficient in the high-specularity regime since this prolongs the total internal reflection lifetime of the photon.

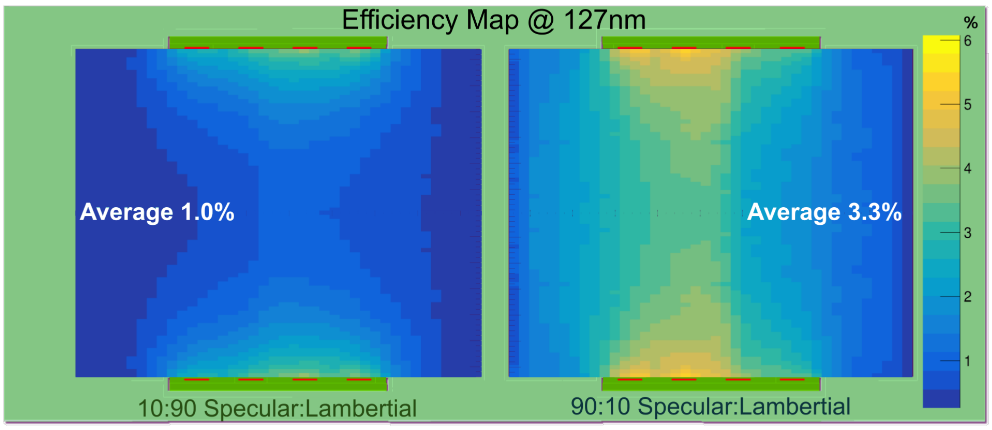

Figure 4: Photon Detection Efficiency (PDE) map over the filter's surface area, for 127 nm light. The map is illustrated on top of a dual-cell X-ARAPUCA, showing its distribution over the geometry. On the left, the map corresponds to a simulated specularity/Lambertian ratio of 0.1, resulting in a 1.0 % average detection efficiency over its area. On the right, the ratio is 0.9, resulting in 3.3 % average efficiency.

References

[1] A. A. Machado *et al*, *The X-ARAPUCA: an improvement of the ARAPUCA device*, JINST **13**, N. 04 (2018) DOI:10.1088/1748-0221/13/04/C04026

[2] H. V. Souza *et al*, *Liquid argon characterization of the X-ARAPUCA with alpha particles, gamma rays and cosmic muons*, JINST **16**, N. 11 (2021) DOI:10.1088/1748-0221/16/11/P11002

[3] C. Brizzolari *et al*, *Enhancement of the X-Arapuca photon detection device for the DUNE experiment*, JINST **16**, N. 09 (2021) DOI:10.1088/1748-0221/16/09/P09027