Aerogel characterization for RICH applications

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Aerogel studies at INFN Bari

Silica aerogel has become an increasingly popular choice as a Cherenkov radiator in recent decades, owing to its unique combination of optical and structural properties. This material consists of a network of interconnected silica nanoparticles, resulting in a low-density solid with an open-cell structure.

One of its most remarkable features is the ability to finely tune its refractive index across a broad range (n = 1.008 – 1.13), allowing it to bridge the gap between gas and solid (liquid) Cherenkov radiators. Aerogel has emerged as a material well-suited to meet the diverse requirements of RICH detectors in upcoming high-energy physics experiments, such as ALICE 3-RICH and ePIC-dRICH (Figure 1). In recent years, several advanced fabrication techniques have been developed to enhance its performance and versatility, including the production of monolithic tiles with gradient or multi-layered refractive indices.

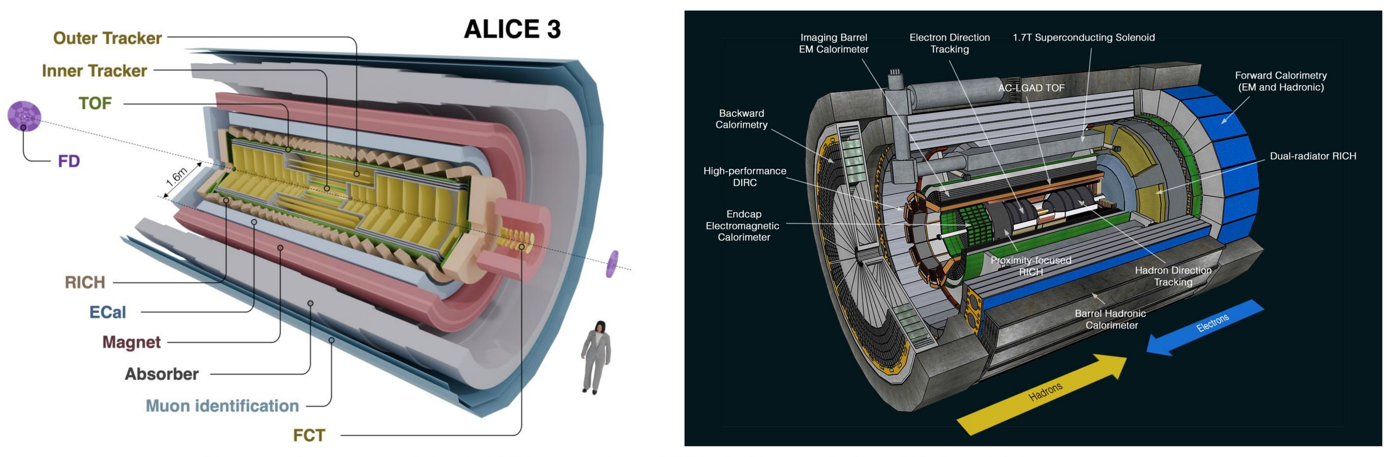

Figure 1. Structures of the ALICE3 upgrade at CERN (left) and ePIC at EIC (right) future experiments.

Figure 2. Top view of the Spectrophotometer Agilent – Cary 4000 at INFN Bari laboratories (left); Light spot on the aerogel tile (right).

At the INFN laboratories in Bari, a detailed optical characterization campaign is being carried out on hydrophobic silica aerogel tiles. Measurements are performed using an Agilent Cary 4000 spectrophotometer equipped with an integrating sphere, a versatile instrument capable of probing the optical properties of the material. A photograph of the spectrophotometer and the light spot on the aerogel tile are depicted in Figure 2.

The setup allows precise transmittance and reflectance measurements over a broad wavelength range from 200 to 700 nm, enabling the study of how the aerogel interacts with light across the ultraviolet to visible and infrared regions of the spectrum. These measurements provide critical information on the aerogel's transparency, scattering behavior, and overall optical performance for potential detector applications.

Transmittance and reflectance

The transmittance of silica aerogel quantifies the fraction of light that propagates through the material without undergoing absorption or scattering. Complementary to this, reflected light, both specular and diffuse, is characterized through reflectance curves.

At INFN Bari, the experimental setup enables measurements of total and diffuse transmittance, as well as reflectance. The linear transmittance is determined from the relation $T_{lin} = T_{tot} - T_{diff}$, while all other quantities are obtained directly from experimental data. For each aerogel tile, the combined results allow the construction of a comprehensive plot, providing a complete characterization of its optical properties.

The linear transmittance dependence on the radiation wavelength is usually defined by the Hunt Formula:

$$T_{linear}(\lambda) = e^{-\frac{t}{\Lambda_T}} = A\,e^{\frac{-C\cdot t}{\lambda^4}}$$

Where C takes into account the aerogel clarity, A represents the surface scattering coefficient, t is the sample thickness and Λ_T is the transmission length. All contributions for the optical characterization of an aerogel tile and fitting procedure for $T_{lin}(\lambda)$ are shown in Figure 3. At short wavelengths, reflected photons are those Rayleigh back-scattered while at larger wavelengths, reflectance is practically zero, as expected from the low refractive index of aerogel.

The Hunt formula fit was observed to have low accuracy, and a new model can be implemented trying to better explain transmission phenomena in aerogel tiles. The extension of the Hunt formula [1] considers that the transmission length is related to the scattering (Λ_{scatt}) and absorption lengths (Λ_{abs}) by the following relation:

$$\frac{1}{\Lambda_T} = \frac{1}{\Lambda_{scatt}} + \frac{1}{\Lambda_{abs}}$$

The final formula for the extended Hunt formula is then:

$$T_{linear}(\lambda) = e^{-t/\Lambda_{abs}}e^{-t/\Lambda_{scatt}} = A\,e^{\frac{-B\cdot t}{\lambda^8}}\,e^{\frac{-C\cdot t}{\lambda^4}}$$

With Λ_{abs} defined as the "absorption length" and Λ_{scatt} defined as the "scattering length", the coefficient B is the additional contribution for the absorption part. Extrapolating the values of A, B and C from the fit achieves the characteristic lengths curves for the aerogel tile examined and the completion of its optical characterization.

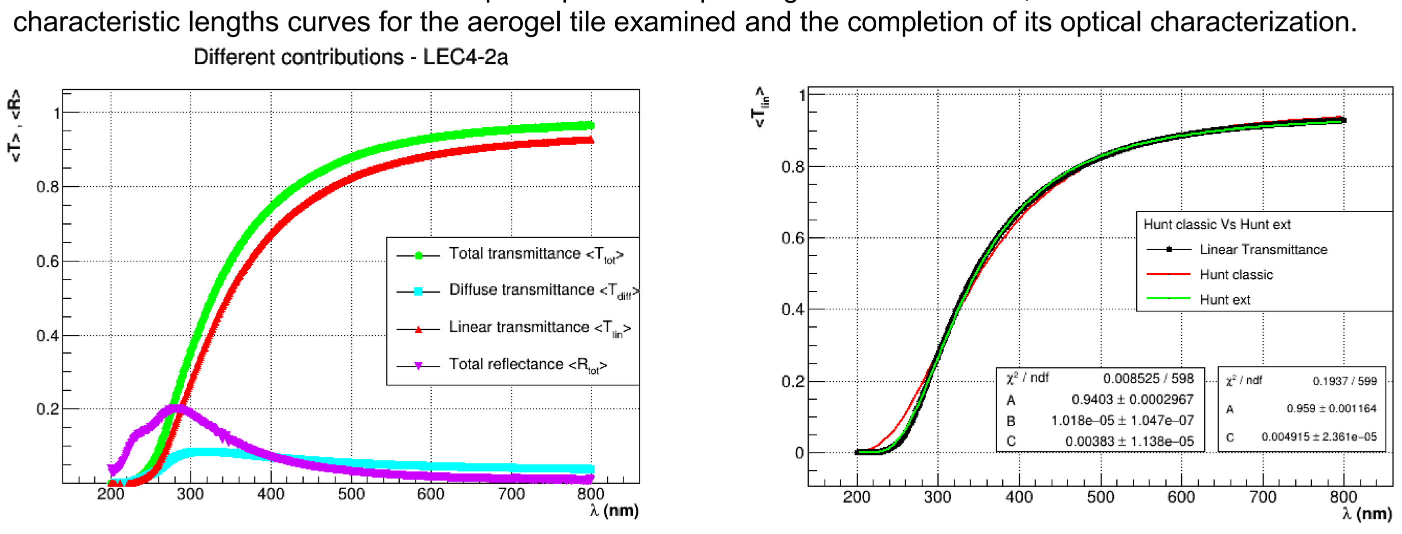

Figure 3. Example of transmittance and reflectance measurements for an aerogel tile (left) and fitting procedure results with both Hunt formula and the extended version (right).

[1] E. Nappi et al., Aerogel and its applications to RICH detectors, Nuclear Physics B - Proceedings Supplements, Volume 61, Issue 3, 1998, Pages 270-276.

Additional studies

The characteristic optical lengths as a function of wavelength were extracted from a fit of the transmission data using the Extended Hunt formula. The results are shown in Figure 4.

The average tile thickness was derived from dedicated metrology measurements performed at CERN. These measurements revealed that the aerogel tiles exhibit a non-uniform geometry, with a concave profile on one side and thickness variations across different sampling points as illustrated in Figure 6. To account for this, multiple positions were probed using a custom-built mechanical holder in the spectrophotometer, and the results were averaged.

A longitudinal study was conducted by repeating the transmittance measurements on the same tiles after a two-year interval. From an example in Figure 5, **a clear degradation of the optical properties was observed: both the transmission length and the linear transmittance decreased over time**. This trend suggests a time-dependent deterioration process, indicative of an "optical ageing" effect. The results highlight that prolonged exposure and repeated experimental use can significantly reduce the transparency of aerogel materials.

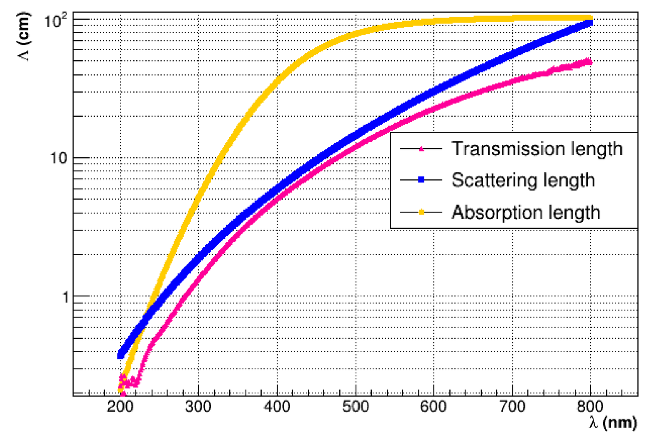

Figure 4. Characteristic lengths of an aerogel tile as a function of the wavelength (top) and the expected relations extrapolated from the extended Hunt formula (bottom).

$$\Lambda_T = -\frac{t}{ln(T(\lambda))}$$

$$\Lambda_{scat} = \frac{\lambda^4}{C}$$

$$\Lambda_{abs} = \frac{\lambda^8 t}{Bt - \lambda^8 lnA}$$

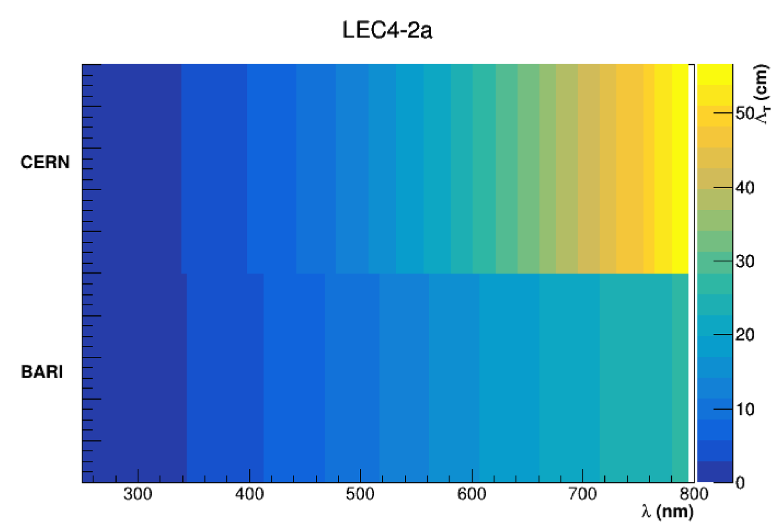

Figure 5. Comparison for the transmission length as a function of the wavelength between Bari measurements (2024) and CERN measurements (2022) for the same aerogel tile.

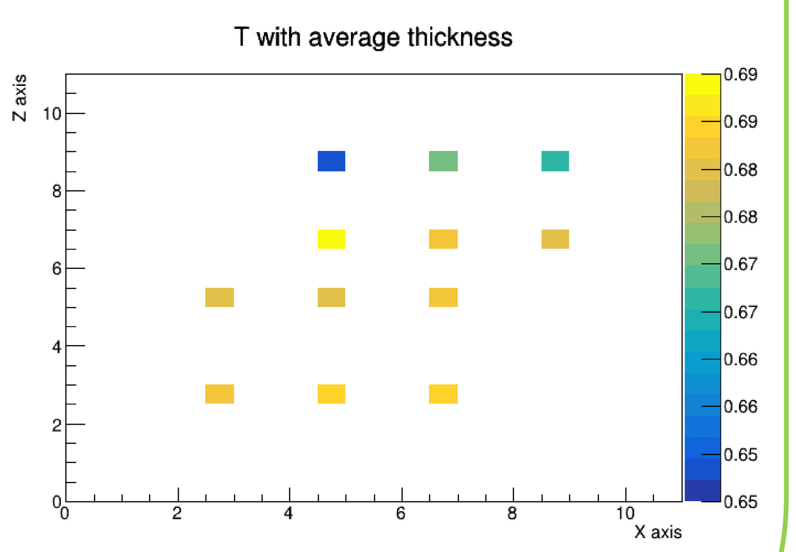

Figure 6. Linear transmittance at a wavelength of 400 nm in the different sampling points investigated during the measurements.

Refractive index measurement

The refractive index of the aerogel tiles has been measured using the minimum angle deviation method with the setup shown in Figure 7. This is the standard procedure for a refraction index measurement.

The method consists in measuring the deviation angle of incident light with different wavelengths (**405 nm, 523 nm, 635 nm**). Rotating the tile, the minimum deviation angle δ_{min} can be obtained and used in the following formula to compute the tile's refraction index:

$$n = \frac{sin\left(\frac{\delta_{min}+\alpha}{2}\right)}{\sin\left(\frac{\alpha}{2}\right)}$$

Where α is the corner angle of the tile. The angle δ_{min} is obtained as $\arctan(d_{min}/l)$, referring to the schema.

This approach is widely used for low-index silica aerogels employed in Cherenkov radiators and enables precise, wavelength-resolved measurements of $n(\lambda)$ (and hence dispersion) when repeated with different laser beams.

Key systematics include the calibration of the apex angle, the angular readout, beam collimation, and environmental conditions (air refractive index, temperature, humidity).

In silica aerogels, n is close to unity and correlates with bulk density, so high angular precision is required to resolve small variations and possible in-tile gradients. This protocol aligns with established aerogel-RICH characterization practices and with general prism-spectrometer methodology.

The resolution of a RICH counter is limited by the optical dispersion of its radiator. Accurate knowledge of this dispersion is essential for detector design, as variations in the refractive index affect angular resolution that can have an impact on the detector's geometry itself.

To investigate possible inhomogeneities across the aerogel tile, the refractive index was measured at different positions using the minimum-deviation method [2]. For each wavelength and aerogel tile, lateral displacement of the emerging beam was recorded at different incidence angles. The displacement was converted into angular deviation, which provides a direct observable to extract the refractive index.

For each measurement position (Top, Middle, Bottom) and at four corners of the tile, the deviation angle δ was measured as a function of the incidence angle θ. The fit function is derived directly from Snell's law applied to a prism-like aerogel tile and an example of the fit result can be observed in Figure 8 on the left.

$$\delta(\vartheta; n) = \vartheta - \frac{\pi}{2} + \arcsin\left(n\cdot\sin\left(\frac{\pi}{2} - \arcsin\left(\frac{sin\vartheta}{n}\right)\right)\right)$$

The angular deviation $\delta(\theta)$ represents the total deflection of a laser beam passing through the tile as a function of incidence angle θ and refractive index n. By fitting the measured deviation curve, the local refractive index can be extracted.

At each vertical position (Top, Middle, Bottom), the results from the four corners were averaged to obtain a representative value of the refractive index.

[2] M. F. Villoro et al., Measurement of the dispersion law for hydrophobic silica aerogel SP-25, Nuclear Instruments and Methods in Physics Research A 480 (2002) 456–462.

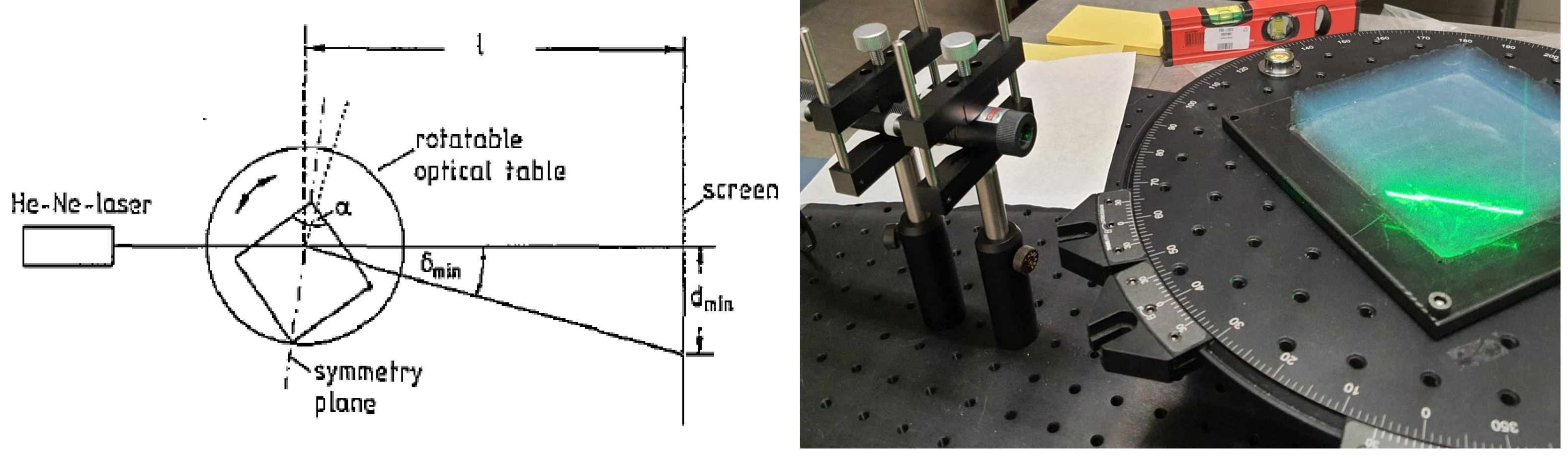

Figure 7. Schematic view of the experimental setup for the aerogel tiles refraction index measurement (left). Photograph of the real experimental setup at INFN laboratories in Bari (right).

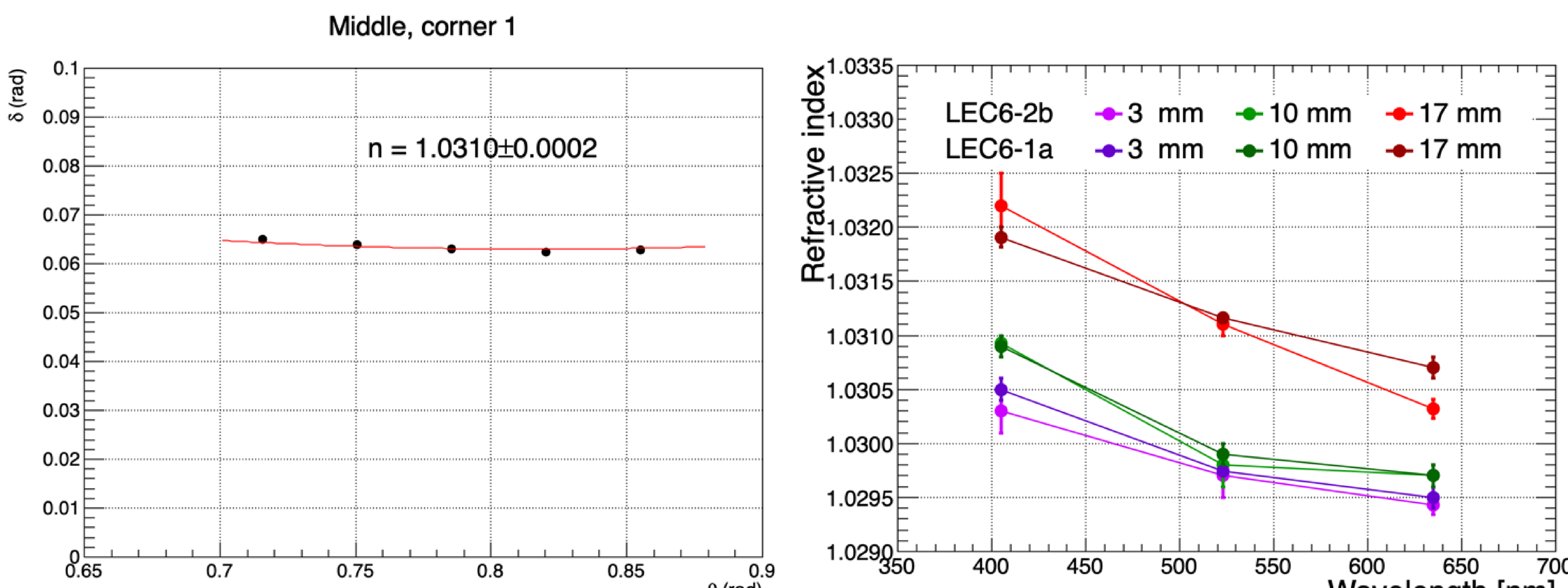

Figure 8. Example of the fitting procedure for the extraction of the refraction index using the minimum angle deviation method for one corner in the middle position of the tile thickness (left). Results for the refractive index for two aerogel tiles as a function of the wavelength in different laser positions with respect to upstream face (right).

Results indicate a refractive-index gradient of ~0.001 across the tile thickness for all tiles examined, with minor wavelength and tile dependence (Figure 8, right). This gradient can lead to either defocusing or focusing of Cherenkov photons, depending on the relative orientation of the refractive index gradient and the particle trajectory, and reduces the uniformity of the refractive index across the aerogel tile.

Simulations show that when the refractive index increases along the particle traversal direction, the photons are effectively focused, improving the Cherenkov angle resolution. Such variations are not negligible and should therefore be carefully considered in the detector design.

The implemented method achieves refractive-index measurements with a precision up to 0.1%, underlining the critical importance of controlling the gradient for optimal Cherenkov detector operation.

These results demonstrate that highly precise characterization of the refractive index is feasible, providing valuable guidance for detector design and quality assurance.