Aerogel characterization

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Contents

1 Cherenkov Radiator

Silica aerogel is an amorphous solid network of SiO_2 nanocrystals with an extremely low macroscopic density. It is used since decades in Threshold Cherenkov counters for high energy physics. More recently, aerogel has been used as radiator material for Ring Imaging Cherenkov (RICH) detectors in several particle physics experiments (HERMES, LHCb, AMS, BELLE, etc). See e.g. [2] and references therein.

The optical properties of aerogel represent a crucial point for the performances of RICH detectors. For instance, any angular dispersion of the emitted photons affects the precision of the Cherenkov angle measurements. In addition, a high transparency (Transmittance) and a proper refractive index are required in order to collect a sufficient number of photons for a reliable ring reconstruction. For these reasons, a systematic characterization of the main optical properties has been carried out in laboratory on a number of different aerogel samples.

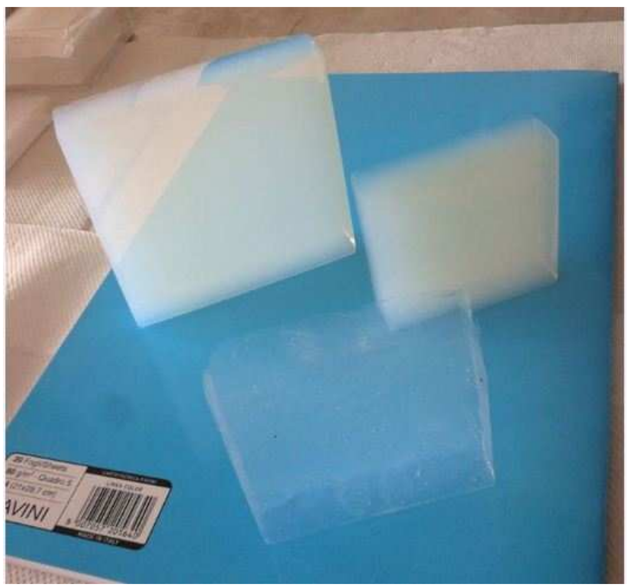

Figure 1: A typical appearance of aerogel tiles. Three tiles of different size and refractive index, produced by Aspen, are shown.

2 Aerogel samples

At present, aerogel tiles of large size and with optical properties suitable for the CLAS12 RICH are produced only by the Novosibirsk group. Samples of different refractive index, thickness and size, produced in different periods, have been tested by means of a spectrophotometer. For comparison, several aerogel samples produced by the Matsushita Company, with refractive index $n = 1.03$ and $n = 1.05$, were also tested. The one with $n = 1.03$ was successfully used in the Hermes RICH. Finally, we tested few sample recently produced by

Aspen (Fig. 1) with refractive indices $n = 1.01$ and $n = 1.05$. The complete list of the tested samples is reported in Table 1.

Table 1: Aerogel tiles tested

Manufacturer	Name	n	thickness (cm)	area (cm × cm)
Matsushita (Japan)	Jap 1.03 Tiles1-3	1.03	1.0	10×10
Matsushita	Jap 1.05 Tiles1-3	1.05	1.0	10×10
Novosibirsk (Russia)	Nov 1.04 2cm Tiles1-4	1.04	2.0	6×6
Novosibirsk	Nov 1.05 2cm Tiles1-4	1.05	2.0	6×6
Novosibirsk	Nov 1.06 2cm Tiles1-4	1.06	2.0	6×6
Novosibirsk	Nov 1.05 3cm Tiles1-4	1.05	3.0	6×6
Novosibirsk	Nov 1.06 3cm Tiles1-4	1.06	3.0	6×6
Novosibirsk	Nov 1.05 Samples1-8	1.05	2.0	10×10
Novosibirsk	Nov 1.05 Cern1-5	1.05	2.0	10×10
Novosibirsk	Nov 1.05 Cern6 Tiles1-4	1.05	2.0	6×6
Novosibirsk	Nov 1.05 AMS 1-4	1.05	3.0	10×10
Novosibirsk	Nov 1.05 1cm Old	1.05	1.0	10×10
Novosibirsk	Nov 1.05 2cm Old	1.05	2.0	10×10
Novosibirsk	Nov 1.05 3cm Old	1.05	3.0	10×10
Aspen (USA)	AME_1_1 & AME_2_1	1.05	1.7	9.5×9.5
Aspen	AME_3_1_A	1.05	1.7	6.5×6.5
Aspen	AME_3_3	1.01	1.7	6.5×6.5

3 Formalism

The combined effects of the scattering, reflection and absorption of the photons in a material are usually described in terms of: 1) *transmittance* T, which accounts for the residual light transmitted in the forward direction; 2) *transflectance* T_F, which is the fraction of light emerging in all directions from the sample; 3) *reflectance* R, the fraction of light emerging in backward direction. For a sample of thickness t (in cm), the transmittance can be expressed as

$$T = e^{-t(\frac{1}{\Lambda_A}+\frac{1}{\Lambda_S})} = T_F \; e^{-t/\Lambda_S} \; , \tag{1}$$

where Λ_A is the *absorption length*, Λ_S is the *scattering length* and $T_F = e^{-t/\Lambda_A}$.

The transmission in aerogel is usually parametrized through the Hunt formula (see, e.g., [3])

$$T = Ae^{-Ct/\lambda^4} \; , \tag{2}$$

which assumes that the absorption, parametrized by the coefficient A, is independent from the wavelength λ and that the Rayleigh scattering has a λ^{-4} dependence. The *clarity* coefficient C is proportional to the radiation scattered per unit of sample length, and is usually

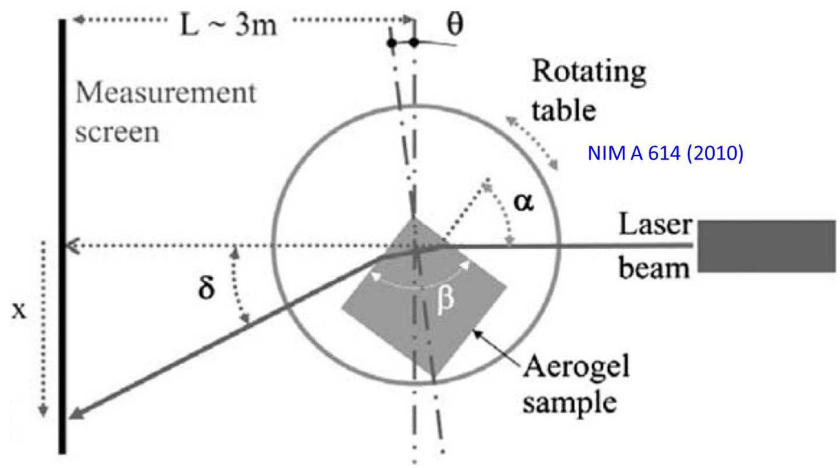

Figure 2: The prism method to measure the refractive index.

measured in μ^4/cm. Tiles with a good optical quality have values for A and C close to 1 and 0, respectively. Absorption length and scattering length (in cm) are related to A and C through:

$$\Lambda_{abs} = -t/lnA \qquad\qquad \Lambda_{sc} = \lambda^4/C \ . \tag{3}$$

Another important property of aerogel radiators is the chromatic dispersion, i.e. the dependence of their refractive index on the wavelength of the incident light. This effect has been estimated to be the largest contribution to the uncertainty on the Cherenkov angle. The prism method [4, 5], illustrated in Fig. 2, allows to measure the refractive index through the Snell-Descartes formula

$$\delta = \alpha - \beta + \arcsin\left(n \sin\left[\beta - \arcsin\left(\frac{\sin\alpha}{n}\right)\right]\right) \ , \tag{4}$$

which relates the angular displacement δ of the scattered photons with the refractive index n through the incident angle α and the fixed angle β. By varying α and measuring δ, one can extract n by fitting the data.

4 Refractive index measurements

The refractive index of some of the Novosibirsk tiles have been measured with the prism method using a laser beam of different wavelength: red (λ=632.8 nm), green (λ=532 nm), blue (λ=405 nm). The plots in Figure 3 show the measured displacements (expressed in mm) for the three laser wavelengths as a function of the incident angle α for a Novosibirsk aerogel tile with $n = 1.04$. The plot on the right is a zoom around the minima.

Figure 4 reports the results for one Matsushita tile with $n = 1.05$ (top left) and for three Novosibirsk tiles with n=1.04, 1.05 and 1.06. In each plot, the results have been fitted with

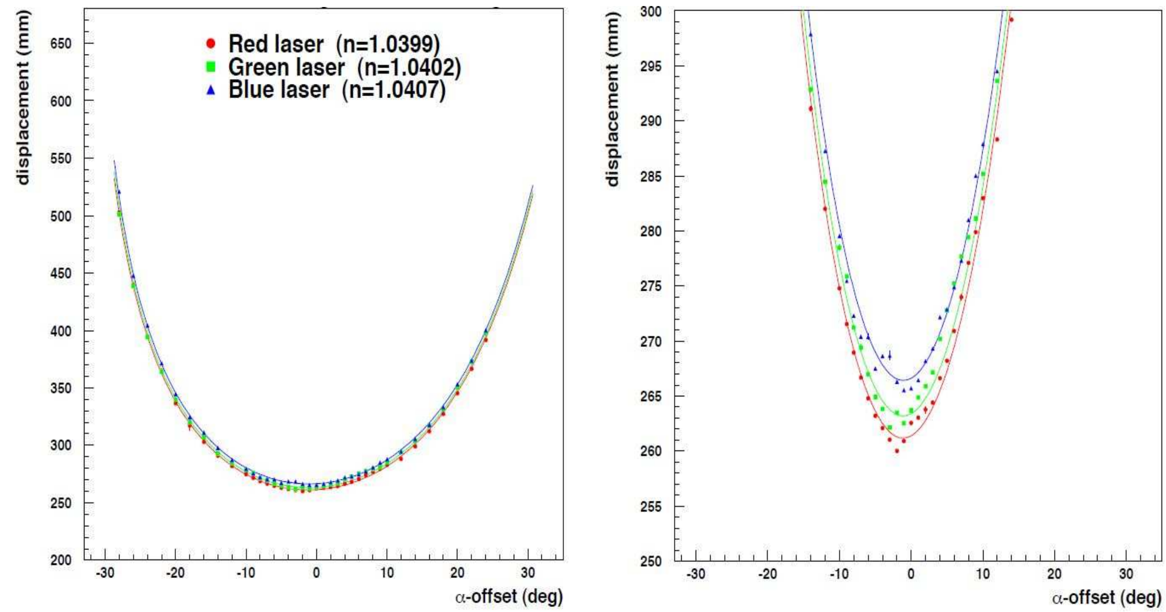

Figure 3: Displacements for the three laser wavelengths as a function of the incident angle α for a Novosibirsk aerogel tile with $n = 1.04$. The plot on the right is a zoom around the minima.

the dispersion relation

$$n(\lambda) = \sqrt{1 + \frac{P_1 \lambda^2}{\lambda^2 - P_2^2}} \tag{5}$$

where P_1 and P_2 are free parameters (black line) and compared with the expected phenomenological trend based on old generation aerogel measurements (purple line). The measured dispersion of the Matsushita tile is slightly larger than the expected, while for the Novosibirsk tiles is smaller than expected and also smaller than the Matsushita sample.

5 Spectrophotometer measurements

For precise measurements of the aerogel transmittance as a function of the light wavelength, a Lambda 650 S PerkinElmer spectrophotometer was used at INFN-Ferrara (Fig. 5). A systematic characterization of all the aerogel samples listed in Table 1 has been performed.

In Figure 6 the measured transmittance is reported as a function of the wavelenght for one Matsushita tile (Jap_1.05_tile1, red circles) and two Novosibirsk tiles (Nov_1.05_2cm_OLD, black squares, and Nov_1.05_3cm_OLD, blue triangles), all with $n = 1.05$ but with different thicknesses (1cm, 2cm and 3cm, respectively).

We see that at $\lambda = 400$nm, the reference wavelength for the CLAS12 RICH, the 2cm Novosibirsk tile exhibits about the same transmittance of the 3cm Matsushita one. From these measurements we can than conclude that for the CLAS12 RICH the optical quality of the Novosibirsk aerogel is superior to that of the Matsushita (the one used in the Hermes RICH).

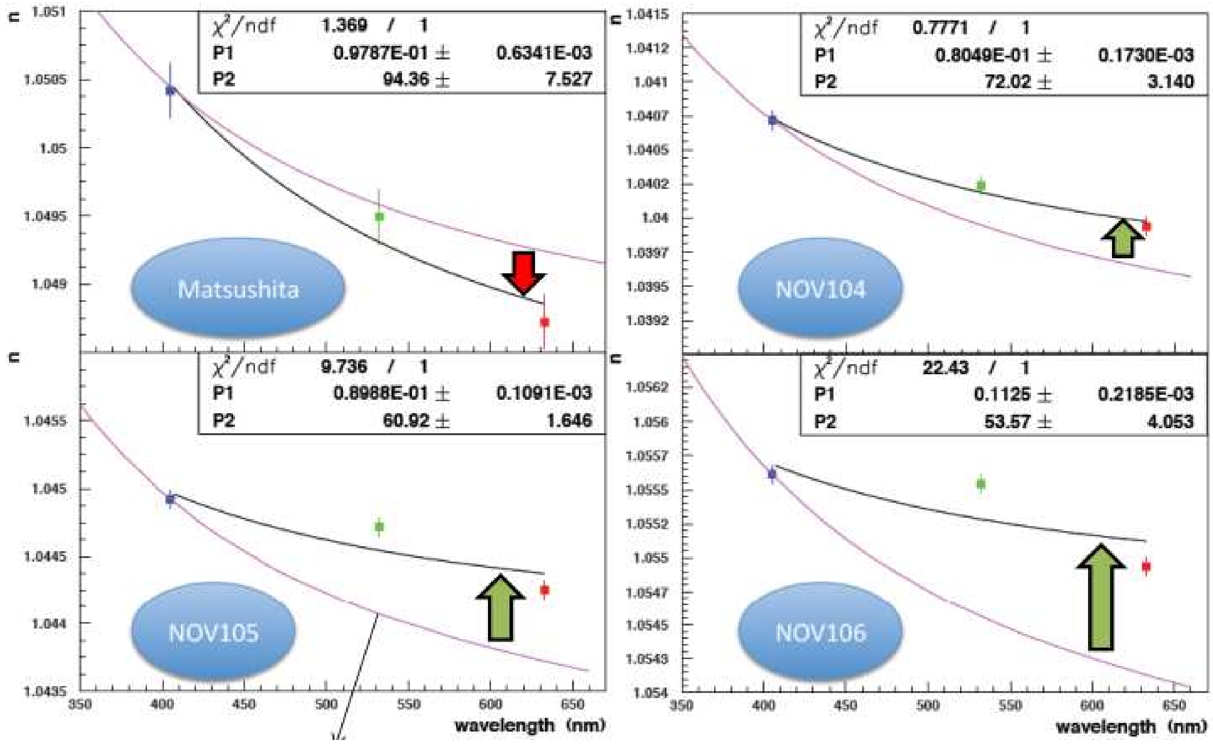

Figure 4: Refractive index measured at three wavelengths for a Matsushita tile with $n = 1.05$ (top left) and three Novosibirsk tile with $n = 1.04$ (top right), $n = 1.05$ (bottom left), $n = 1.06$ (bottom right).

Recently, the Aspen Company has also started the production of aerogel tiles that may potentially be suitable for the CLAS12 RICH (Fig. 1). In Fig. 7, the transmittance and the scattering length measured for one Aspen tile with $n = 1.01$ (the "AME_3_3", blue circles) and for three tiles with $n = 1.05$ (green, red and yellow circles) is reported as a function of the wavelength. For comparison the measurements for the "CERN5" sample from Novosibirsk (black circles) are also shown. The only Aspen tile with reasonable performances is the one with $n = 1.01$, though it is still considerably below the performances of the Novosibirsk aerogel. Therefore, we consider the Aspen aerogel not an option at the moment.

Fitting the measured transmittance with the Hunt formula (eq. 2) and using eqs. 3 one can extract the transflectance and the absorption and scattering lengths. In Fig. 8, the measured transmittance (top left) and the extracted transflectance (top right), absorption length (bottom left) and scattering length (bottom right) are shown as a function of the wavelength for the eight "Sample" tiles (see Table 1). Basically no differences in the scattering length have been found, while, apart from one tile, the absorption length maximal variations are of the order of 25%.

The uniformity of the optical quality has been also checked by performing measurements in different points on the surface of each tile. In Fig. 9 we compare the transmittance and the scattering and absorption lengths measured at $\lambda = 400$nm in six different spots indicated by the different symbols. Small deviations are observed.

Figure 5: The Lambda 650 S PerkinElmer spectrophotometer at INFN-Ferrara.

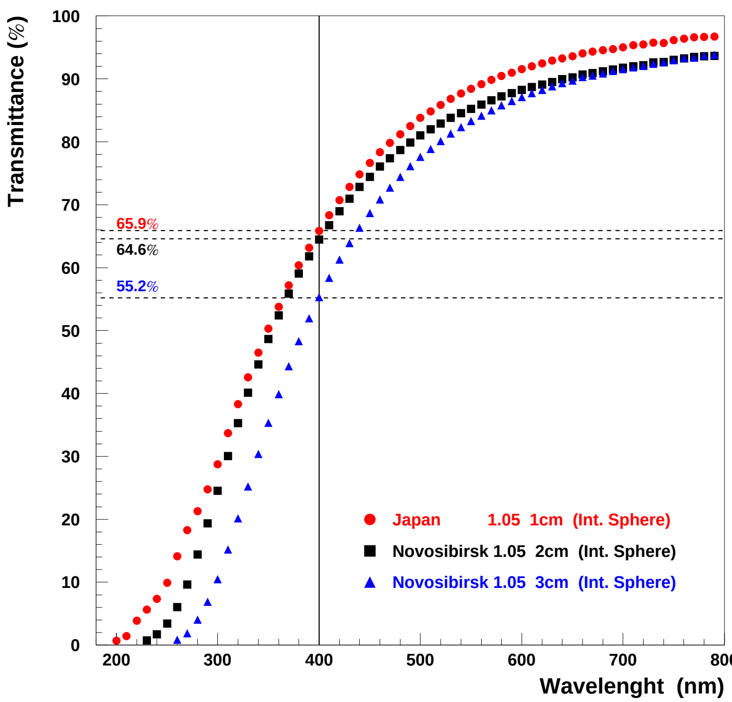

Figure 6: Comparison of the transmittance measured as a function of the wavelength for one Matsushita tile (Jap_1.05_tile1, red) and two Novosibirsk tiles (Nov_1.05_2cm_OLD, black, and Nov_1.05_3cm_OLD, blue).

The various Novosibirsk aerogel tiles belong to different productions made in 2012 or earlier. The "AMS" are the oldest ones (produced before 2012), the "Old" and "Tiles" have been produced at beginning of 2012, the "Samples" in June 2012 and the "CERN" in

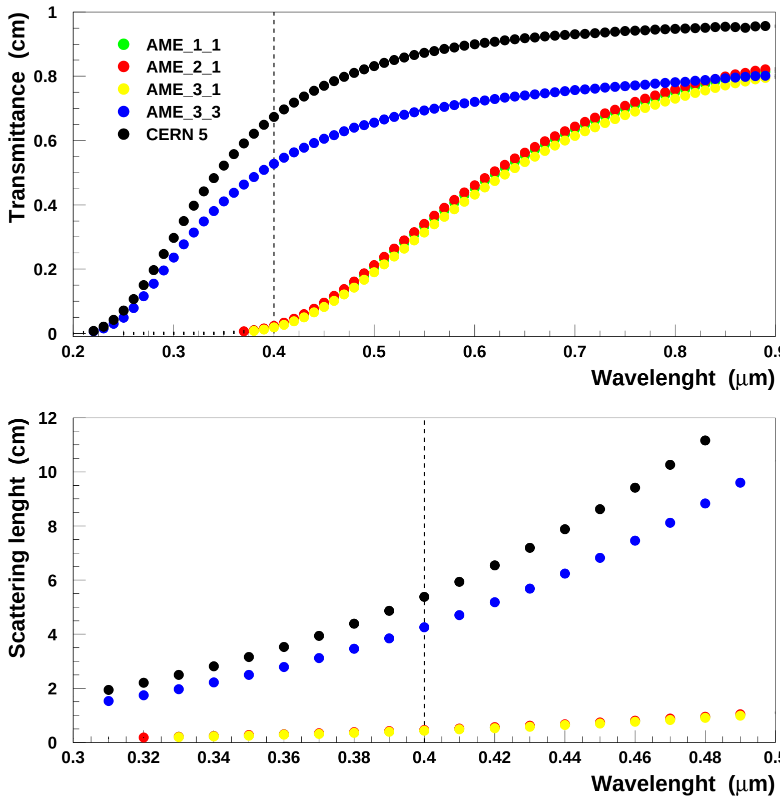

Figure 7: Transmittance and scatt. length of the $n = 1.01$ Aspen tile (“AME_3_3“, blue) and three $n = 1.05$ Aspen tiles (green, red and yellow) compared with the $n = 1.05$ Novosibirsk tile “CERN5” (black).

November 2012, just before the beam test at CERN. The scattering length of the tiles with $n = 1.05$, measured at $\lambda = 400$nm, is shown as a function of the production time in Fig. 10. There is a clear trend showing that the production technique and the resulting quality of the aerogel is significantly improving in time.

6 Monitoring the transparency at the CERN test-beam

A prototype of the CLAS12 RICH was tested at the T9 facility at CERN using a 6-10 GeV pion/kaon beam extracted from the PS. During the two test-beam (August and December 2012) most of the Novosibirsk aerogel tiles listed in Table 1 were employed.

The Novosibirsk aerogel is hydrophilic, i.e. tends to absorb water molecules from the air, resulting in a degraded transparency. In order to reduce the absorption of humidity from the air and to partially expel the water already absorbed, several approaches were attempted:

- storing the tiles in a dry-atmosphere cabinet (Fig. 11)
- storing the tiles in a box fluxed with nitrogen (August CERN test-beam)

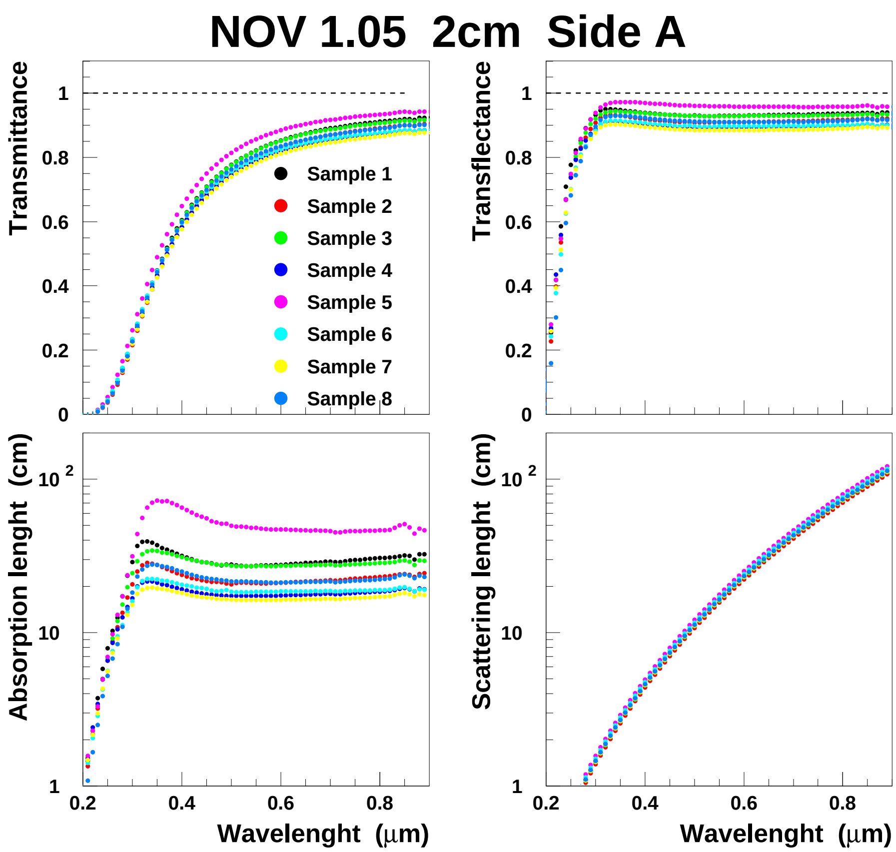

Figure 8: Comparison of the transmittance, transflectance, absorption and scattering lengths as a function of the wavelength for the eight Novosibirsk "Sample" tiles.

- baking tiles at a few hundreds (Celsius) degrees for a few hours (August CERN test-beam)
- sealing the tiles within small plastic bags after use (December CERN test-beam)

In order to monitor the status of the aerogel during the two test-beams, the transmittance of the each tile was measured several times, usually before and after being used on beam (i.e. exposed to air). The measurements were performed with a simple setup made by a laser (blue light, 405 nm), a photodiode and a multimeter, as shown in Fig. 12. The aerogel tiles were placed between the laser and the photodiode, and the output signals (in mA) from the latter were recorded by the multimeter. For each measurement, the photodiode signal was recorded with ($I_{aerogel}$) and without (I_0) the aerogel tile in front of the laser. The transmittance was then evaluated as the ratio between the two: $T = I_{aerogel}/I_0$. The final results for the transmittance of each aerogel tile were evaluated as the average of the values obtained in 10 independent measurements. This method has the advantage of being very fast (a few minutes for each set of measurements) but introduces several systematic effects. The

RMS of each set of measurements was then assigned as an estimate of the global systematic uncertainty ΔT (see e.g. the error bars in Fig. 13).

Figure 13 shows the enhancement of the aerogel transmittance after being stored for more than 100 hours in the box fluxed with nitrogen. Similar trends were observed for other tiles. Storage periods shorter than 60 hours do not result in appreciable improvements. Also shown are measurements performed in Ferrara a few months later using both the laser setup and the spectrophotometer. During these months the aerogel was sealed in small plastic bags. The laser measurement demonstrate that the transmittance is preserved if the aerogel is sealed. The spectrophotometer systematically provides smaller values than the laser setup.

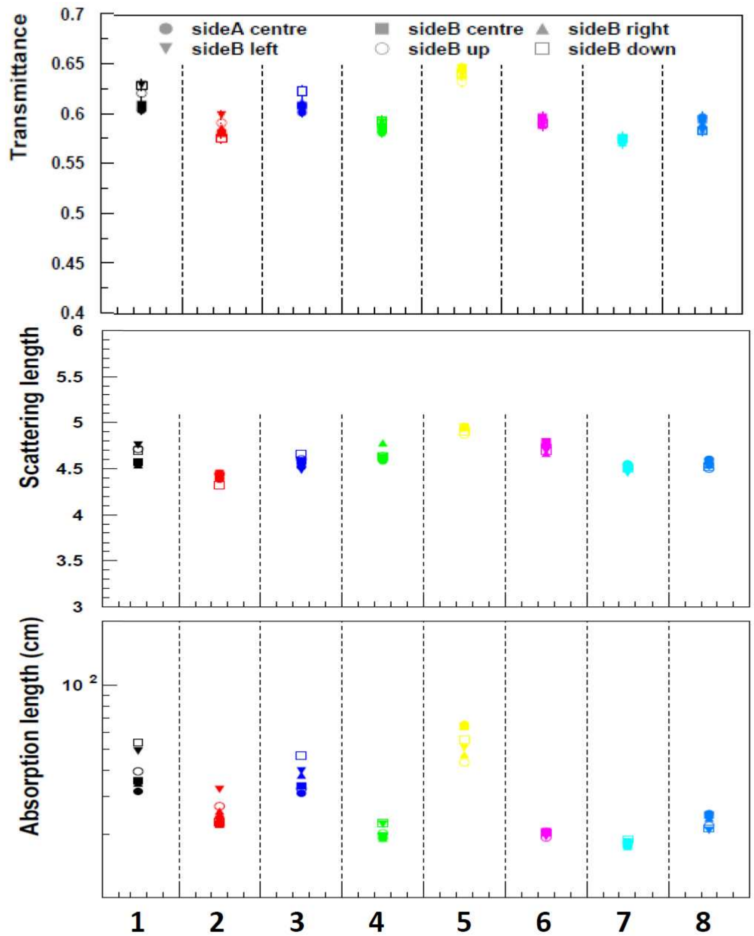

Figure 9: Comparison of transmittance, scattering and absorption lengths measured at $\lambda = 400$nm in different spots (different symbols) on the surface of the eight Novosibirsk "Sample" aerogel tiles.

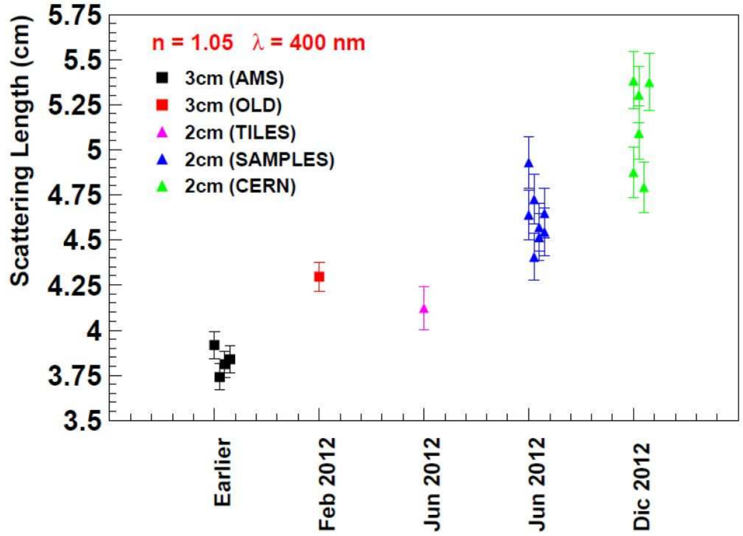

Figure 10: Scattering length at $\lambda = 400$nm for the $n = 1.05$ Novosibirsk tiles versus the production time.

Figure 11: Dry cabinet for aerogel storage in Ferrara

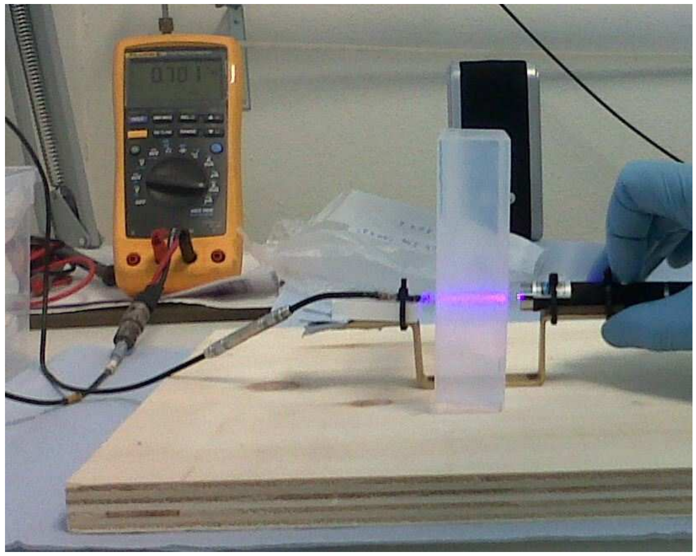

Figure 12: Simple setup used for fast measurements of aerogel transparency at 405 nm.

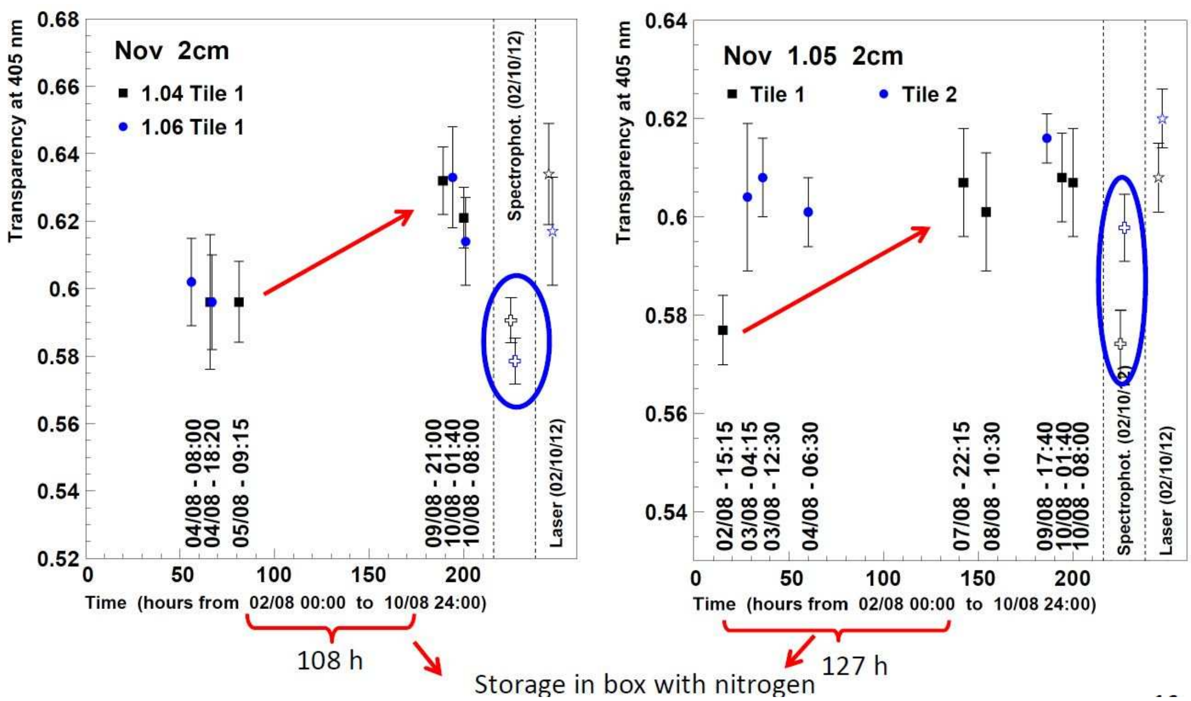

Figure 13: Measurements of aerogel Transmittance with the laser setup before and after long periods (> 100 h) of storage in box fluxed with nitrogen. More recent measurements performed at Ferrara are also shown (see text).

References

[1] CLAS12, FT[20]

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