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Measurement of the refractive index of silica aerogel in vacuum

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Abstract

The photo injector test facility at DESY Zeuthen (PITZ) uses Cherenkov radiation of electrons inside aerogel to measure the bunch length of an electron beam. To evaluate the results the refractive index of the aerogel has to be precisely known. The aerogel is used either at atmospheric pressure or in vacuum. The pressure dependence of the refractive index of two aerogel samples is investigated in the range between high vacuum (10^{-5} mbar) and atmospheric pressure.

Keywords: Aerogel; Refractive index; Vacuum

1. Introduction

The photo injector test facility at DESY Zeuthen (PITZ) has been developed with the aim to deliver low emittance electron beam and study its characteristics for future applications at linear accelerators and free electron lasers. The energy of the electron beam varies in the range between 4 and 5 MeV. A detailed description of PITZ can be found, e.g. in Ref. [1].

One of the important properties of the delivered beam is the electron bunch length. At PITZ the measurement of this value is based on a method, which uses the partial conversion of the energy of the electron bunch via, e.g. Cherenkov radiation into a flux of photons with the same time properties as those of the original electron bunch. The photon bunch length can be measured in turn by a streak camera. As a Cherenkov radiator the silica aerogel (SiO_2) is used due to its low refractive index which allows to reach a good time resolution [2].

Two possibilities of the aerogel arrangement in the diagnostics section of the photo injector have been considered, namely placing the aerogel either under atmospheric pressure or in vacuum. This paper presents the study of the behaviour of the aerogel refractive index at different pressures.

Two aerogel samples, referred in the following as the first and the second one, have been investigated. The first sample is used for the Ring Imaging Cherenkov detector at the HERMES experiment at DESY [3]. The second sample was provided by BINP, Novosibirsk, Russia. The measurements of the refractive indices of these aerogel samples are described in Refs. [4,5].

Inside a vacuum chamber the aerogel starts to outgas. Water molecules are the main component

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of the residual gas. As a result of this outgassing the density of the aerogel and therefore the refractive index changes. The measurements [6] show that this process is slightly reduced, once the aerogel was placed in vacuum before. The refractive indices of the two aerogel samples under different pressure conditions were studied.

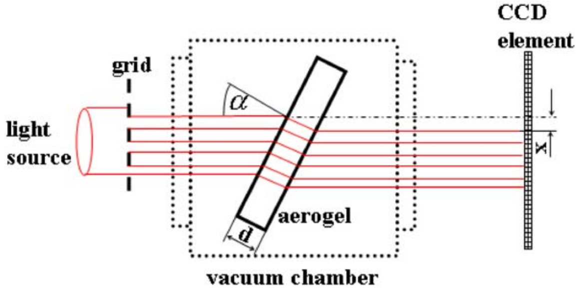

Fig. 1. Schematic view of the experimental setup.

2. Measurement

2.1. Setup

The experimental setup is shown in Fig. 1. An illuminated grid was imaged by an optical lens with a focal length of 3 m onto the surface of a CCD-element. The aerogel sample was inclined by an angle α with respect to the optical axis. Once the tilt was changed, the image of the grid detected by the CCD-element was shifted. Evaluating the value of this shift, x, it is possible to obtain the value of refractive index, n, using the following relations:

$$x = \frac{\sin(\alpha - \beta)}{\cos\beta} d, \quad \beta = \arcsin\left(\frac{n^{\mathrm{air}}(p)}{n} \sin\alpha\right). \quad (1)$$

Here d is the thickness[1] of the aerogel ($d = 10.841 \pm 0.018$ mm for the first sample and $d = 0.891 \pm 0.021$ mm for the second sample), while $n^{\mathrm{air}}(p)$ denotes the refractive index of air at pressure p.

2.2. Calibration

The image of the grid is magnified of the lens. Therefore the shift of the image detected by the CCD-camera is larger than in the reality. The calibration gives the dependence of the real and the imaged shift. It is done using the known pitch of the grid shown in Fig. 2. The real distance of the neighbouring grid bars is 25 μm. Displayed on the monitor connected to the CCD-camera, the pitch is in the cm range.

[1] The thickness measurements have been performed using the high precision length measurement device TESA 3D, MICRO-MS 454 on an effective area of 5×5 mm^2.

Fig. 2. Image of the grid detected by the CCD-element.

For each investigated pressure a separate calibration is done. One example is shown in Fig. 3. The accuracy of the monitored pitch is 0.2 mm. Together with the slope of the linear regression analysis it results in a resolution of the shift value of 1.5 μm.

2.3. Results

The tilt was varied between $-50°$ and $50°$ in steps of $5°$. The measured dependence of the aerogel refractive index on the tilt was fitted using the functions:

$$x = \frac{\sin((\alpha - \alpha_0) - \beta)}{\cos\beta} d + x_0$$

$$\beta = \arcsin\left(\frac{n^{\mathrm{air}}(p)}{n} \sin(\alpha - \alpha_0)\right) \quad (2)$$

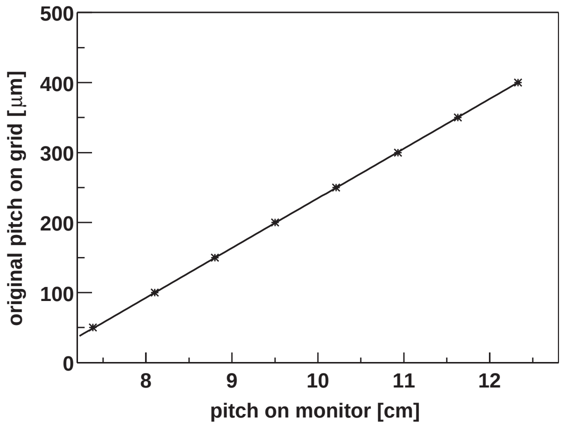

Fig. 3. Image size calibration.

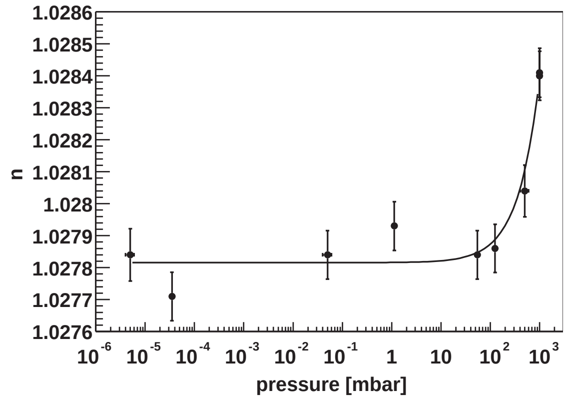

Fig. 5. The pressure dependence of the refractive index for the first aerogel sample.

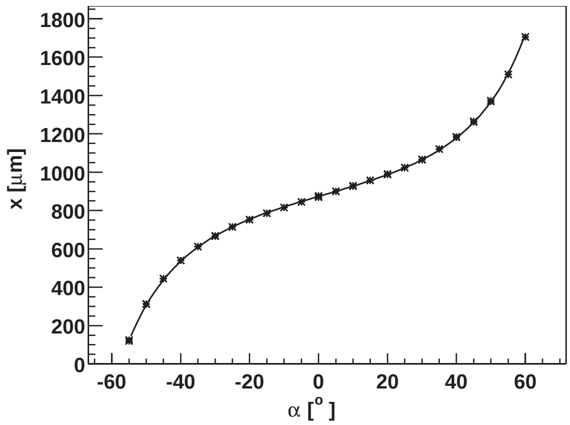

Fig. 4. Measurement of the shift values x in dependence on the tilt angle α for the first aerogel sample at atmospheric pressure.

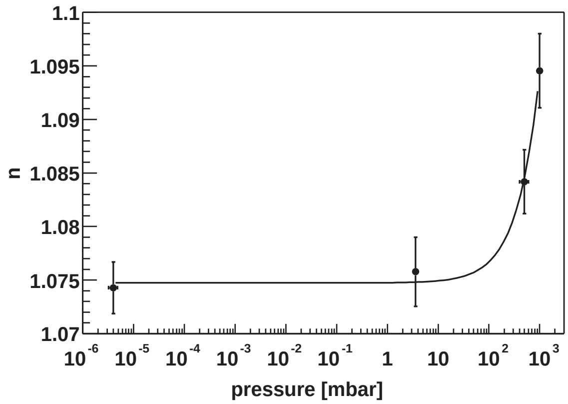

Fig. 6. The pressure dependence of the refractive index for the second aerogel sample.

with refractive index n, initial tilt α_0 and initial shift x_0 as fit parameters. The refractive index of air depends linearly on the pressure [7]. A measurement for the pressure of 1000 mbar is shown in Fig. 4.

The dependence of the refractive index on the pressure for the first aerogel sample is shown in Fig. 5. At atmospheric pressure the refractive index of $n = 1.02888 \pm 0.00006_{st} \pm 0.00005_{syst}$ for this sample was obtained. The statistic uncertainty resulted from the regression analysis. The uncertainty of the thickness measurement is propagated into the systematic uncertainty. Once the aerogel sample was held in vacuum and than measured at atmospheric pressure a few days later, this value decreases to $1.02840 \pm 0.00006_{st} \pm 0.00005_{syst}$. Increasing the pressure the value of the refractive index keeps constant up to about 10^{-1} mbar. Above this value it starts to rise linearly with pressure.

The dependence of the refractive index on the pressure for the second aerogel sample is shown in Fig. 6. It was possible to measure the refractive index of this sample only after some preliminary water outgassing in vacuum. Increasing the pressure up to 1 mbar the refractive index kept constant $n = 1.0743 \pm 0.002_{st} \pm 0.002_{syst}$. Above this value it increased up to a value of $n = 1.0945 \pm 0.003_{st} \pm 0.002_{syst}$.

Note the refractive index is depending on the mass density [5]:

$$n(\varrho) = 1 + 0.21\varrho\left[\frac{\mathrm{g}}{\mathrm{cm}^3}\right]. \quad (3)$$

The mass density of the second sample at atmospheric pressure is measured to $\varrho = (0.272 \pm 0.007)\,\mathrm{g/cm}^3$. Using Eq. (3) a refractive index of $n = 1.057 \pm 0.002$ is obtained. The difference between this value and the one obtained by the optical measurement can be explained by different water content inside the aerogel material. The aerogel sample was stored for several months under normal air. Therefore, the content of water changed compared to the measurement conditions at the producer, i.e. the phenomenological formula (3) cannot describe any longer the relation in this case.

3. Summary

The refractive index of the two aerogel samples has been measured in dependence of the pressure. It was proven that the refractive index for both samples behaves stable below 1 mbar. Above this value it increases linearly with pressure. The refractive index depends on the content of water, i.e. the vacuum conditions or the storage conditions.

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