Aerogel at Colliders

Tito Bellunato, Marta Calvi, Clara Matteuzzi, Marco Musy and Davide Luigi Perego*

Abstract—**Recent progress in the application of silica aerogel as Cherenkov radiator for present and future collider experiments are reviewed. A complete characterization of the optical and physical properties of silica aerogel will be described, as well as robustness tests towards potentially aggressive experimental conditions such as high irradiation or exposed to fluorocarbons are reported. Finally, recent tests performed with a multilayer aerogel block will be presented and discussed.**

I. Introduction

SILICA aerogel is a very low density solid material made of SiO_2. Thanks to its transparency and its refractive index which can be tuned within a wide range to match the physical requirements, silica aerogel is an appealing material for Cherenkov detectors. Depending on the manufacturing procedure, the final product can be hygroscopic or hydrophobic.

In the last decade a very intense R&D program has been carried out and several interesting results have been achieved in the application of silica aerogel as Cherenkov radiator for present and future collider experiments. Samples with very good optical properties and very large transverse size and thickness (up to 200×200 mm^2 and 50 mm respectively) are now available. Several tests[1] have been performed on hygroscopic tiles in order to study the robustness of the optical and physical properties of aerogel blocks. The result of this work provides a realistic information to be included in the full simulation for a detector in the design phase or for understanding the performance of an existing one.

II. Optical Properties of Silica Aerogel

The dominant contribution to photon scattering within an aerogel block, limiting its performance as a Cherenkov radiator, comes from the Rayleigh mechanism. This leads to the transmission of light with wavelength λ through a block of thickness L being proportional to e^{-CL/λ^4}, where the clarity coefficient, C, characterizes the transparency of the sample. The clarity is tipically of the order of $C = 0.0060$ μm^4/cm or even better [1]. A UV filter is often required in the set–up of the detector to absorb scattered photons.

Manuscript created on August 24, 2008; revised November 13, 2008.

T. Bellunato and D. L. Perego are with the Università degli Studi di Milano–Bicocca, Piazza della Scienza 3, 20126 Milano Italy and with CERN, CH–1211 Genève 23, Switzerland.

M. Calvi is with the Università degli Studi di Milano–Bicocca, Piazza della Scienza 3, 20126 Milano Italy.

C. Matteuzzi is with the Istituto Nazionale di Fisica Nucleare, Sezione di Milano–Bicocca, Piazza della Scienza 3, 20126 Milano Italy.

M. Musy is with the Universitat de Barcelona, Av. Diagonal 647, 08028 Barcelona Spain.

*Corresponding author; e–mail: Davide.Perego@mib.infn.it

[1]Measurements and tests discussed in this report have been done in the R&D activity for the aerogel radiator of the LHCb RICH detector.

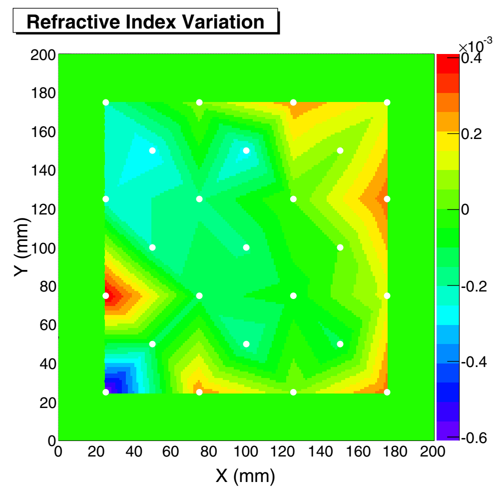

Fig. 1. An interpolated colour map showing the measured deviation from the average refractive index for each beam entrance point, represented as a white dot.

What makes silica aerogel particularly appealing to RICH designers is that its refractive index can be chosen in the wide range $1.008 - 1.1$. The manufacturer tunes the material density ρ, and n and ρ are related by $n(\lambda) = 1 + k(\lambda)\rho$, where k is a wavelength–dependent coefficient. Local density inhomogeneities lead to point–to–point variations of the refractive index within a monolith. These variations contribute to the Cherenkov angle θ_C uncertainty in RICH detectors. The refractive index inhomogeneities have been measured [2]. In an optical laboratory, a laser beam was directed perpendicular to the aerogel surface in order to measure deviations from the straight optical path. The deviation angle is proportional to the refractive index gradient. The biggest limitation of this method is that only one wavelength at a time can be used, and there is a certain arbitrariness in extrapolating the result to the full wavelength range relevant for the Cherenkov emission.

An alternative method was therefore developed, based on the use of a charged particle beam of velocity $\beta \simeq 1$; this method exploits the Cherenkov effect itself and it is appropriate to study the influence of refractive index variations convoluted with the emission spectrum on the Cherenkov angle reconstruction performance [2]. A colour map of the refractive index homogeneity measured with a $200 \times 200 \times 50$ mm^3 aerogel block is shown in Figure 1. The overall variation of the refractive index is $\sigma(n-1)/(n-1) = 0.76\%$; the result of this measurement demonstrates that the production of large transverse size tiles with uniform refractive index is possible.

The dependence of the refractive index on the wavelength has been also investigated [3]. Refractive indices at several

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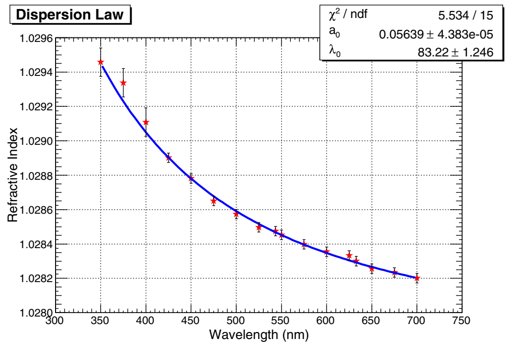

Fig. 2. Chromatic dispersion measured in a hygroscopic silica aerogel tile. A one–pole Sellmeier parameterization has been fitted to experimental data.

wavelengths have been measured using the prism method. A monochromator coupled to an Xe UV–vis lamp has been used, selecting wavelengths in the range $200 - 900$ nm, with a resolution of 1 nm. The dispersion law of aerogel can be parameterized by a multipole Sellmeier formula which can be written as a function of the wavelength λ as:

$$n^2(\lambda) - 1 = \frac{a_0\lambda^2}{\lambda^2 - \lambda_0^2} + \frac{a_1\lambda^2}{\lambda^2 - \lambda_1^2} + \ldots \qquad (1)$$

Data and fit to (1) are shown in Figure 2. The results for a single–pole expansion give $a_0 = 0.05639 \pm 0.00004$ and $\lambda_0 = 83.22 \pm 1.25$ nm. An attempt to fit experimental data with a two–pole Sellmeier formula in the range $350 - 700$ nm gives two superimposed poles.

III. Ageing effects and long–term stability

If the position inside a detector of the aerogel radiator is very close to the beam pipe, it can be exposed to a significant particle flux. Possible ageing of aerogel due to intense irradiation has been investigated [4]. Aerogel tiles have been exposed to very intense γ radiation from a ^{60}Co source (dose up to $\sim$ 230 kGy) and to proton and neutron high intensity beams (fluence up to 5.5×10^{13} particles/cm^2). The transmittance has been monitored, studying the clarity factor as a function of the increasing dose of irradiation. No detectable degradation of the optical parameters was observed for γ and proton irradiation. A small worsening of the clarity due to neutron irradiation has been observed.

The behaviour of hygroscopic aerogel when exposed to humid air has also been explored [4]. Here a modification of the optical properties is expected. The tests revealed that a prolonged exposure to humid air degrades the clarity which however can be completely restored by baking the sample at high temperature (500 °C for several hours, with a 2 °C/minute ramp–up to avoid cracks due to thermal stress).

In the LHCb RICH detector, the aerogel will be in contact with the gaseous C_4F_{10} radiator [5], [6]. Generally, air fills the porous structure of the solid, and a replacement of air with C_4F_{10} is expected. Consequences of this have been investigated. Several tiles have been stored in a C_4F_{10}–filled box with the clarity factor being periodically monitored to evaluate possible effects due to the gas. The behaviour of the clarity factor and also the relative variation of the expected number of photoelectrons $\Delta\mathcal{N}/\mathcal{N}_0$ as a function of elapsed time in C_4F_{10} are shown in Figure 3. The number of photoelectrons $\mathcal{N}$ is analytically evaluated by integrating the Cherenkov spectrum convoluted with the transmittance of the aerogel which is clarity–dependent and considering all the others factors such as quartz window transparency, mirror reflectivities, photon detector (LHCb–like pixel Hybrid Photon Detectors) quantum efficiency and geometrical active area coefficient.

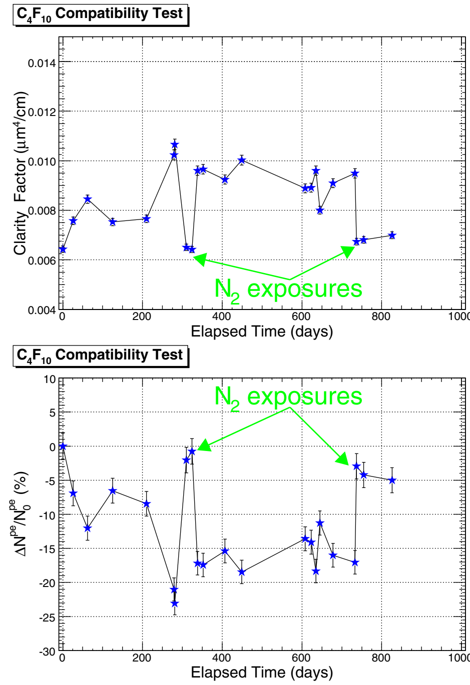

Fig. 3. Variations of the clarity factor (*top*) and expected photoelectron yield (*bottom*) as a function of time during the C_4F_{10} gas exposure test.

As shown in Figure 3, the clarity coefficient rises with C_4F_{10} exposure time, with a corresponding decrease in the photoelectron yield. Following this rise, between day 281 and 310, the tile was kept in a dry N_2 atmosphere to check the possibility of restoring the aerogel to its initial optical conditions. The N_2 regeneration demonstrates that there is no permanent degradation of the clarity. On resumption of the C_4F_{10} exposure, it can be seen that the clarity again degrades, before reaching stability. The N_2 regeneration procedure is then repeated successfully at the end of the test.

Natural ageing variations have been monitored by keeping a tile in a humidity–controlled laboratory. The typical relative humidity of the air inside the laboratory was in the range $15\% - 35\%$. Results are reported in Figure 4. During four years of monitoring, the clarity variation is $\sim 4\%$ per year. The fluctuations of both n and C can be ascribed to uncontrolled absorption of water vapour or rejection of humidity previously absorbed, depending on the relative humidity level of the laboratory during measurements. The seasonal modulation is well described by the function:

$$y(t) = (p_0 t + p_1) + p_2 \cdot \sin(p_3 t + p_4) \qquad (2)$$

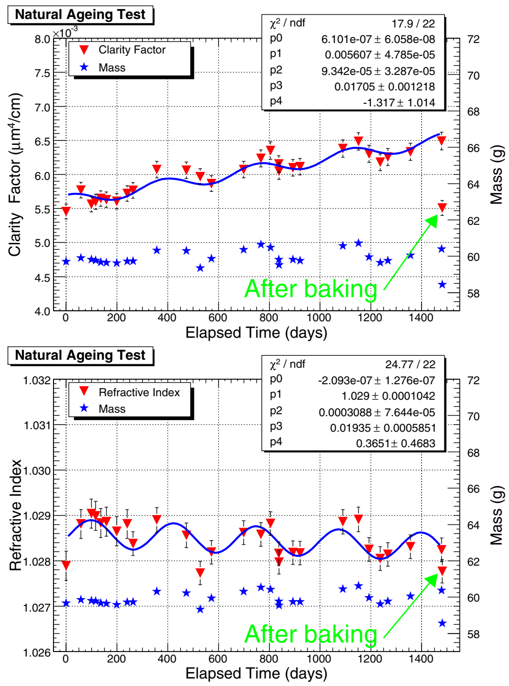

Fig. 4. Variations of the clarity factor (*top*) and refractive index (*bottom*) as a function of time in the natural ageing test. The refractive index is measured at $\lambda = 543.5$ nm. The results of the fit to (2) are superimposed.

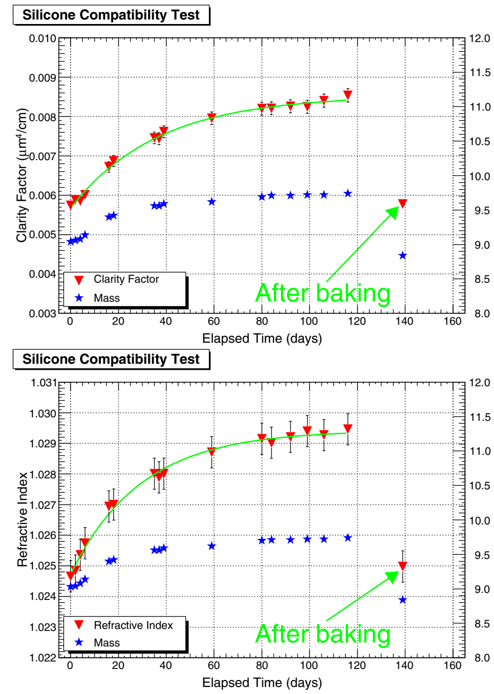

Fig. 5. Clarity factor (*top*) and refractive index (*bottom*) as a function of time during the black silicone compatibility test. The refractive index has been measured at $\lambda = 632.8$ nm.

where $y(t)$ can be either the clarity factor or the refractive index. The p_3 parameter is the frequency of the oscillatory pattern measured during the test. For the clarity, the period of the oscillatory pattern is $T = 2\pi/p_3 = (368 \pm 26)$ days, in good agreement with the seasonal hypothesis. The initial optical quality of this sample has been restored by baking it.

IV. Integration of Aerogel in a RICH Detector

In general, RICH detectors consist of a gas– and light–tight vessel in which radiators are placed. The internal part of the enclosure is painted with black varnish to avoid unwanted reflections of Cherenkov photons. In this case the aerogel is exposed to possible residual outgassing of the varnish inside the vessel. A compatibility test of the aerogel with varnish[2] outgassing has been performed by monitoring both the refractive index and the aerogel transmittance as a function of time. An aerogel tile was kept in a box which has been painted black inside. To speed up the test, the aerogel was put in contact with the painted surfaces and the box was locked with screws. This set–up corresponds to a more hostile environment than will be experienced in the final detector.

At the end of the test, the tile was baked for several hours, and the clarity factor and the refractive index were measured again. The values of C and n are compatible with the ones measured at the beginning of the test, hence no permanent degradation has been detected.

A more realistic compatibility test was then performed with the same kind of varnish. This time, the aerogel block was not in contact with the varnish, and a realistic period for the varnish to outgas was allowed to elapse. After ~ 200 days of exposure, a variation of 0.1% on n and of 20% on C has been observed.

Black silicone rubber is usually used to seal items, such as gas pipes and connectors, within the volume of a RICH detector. A small $50 \times 50 \times 29$ mm^3 hygroscopic sample was kept in a small box with some black acetic–type silicone sealant[3]. The procedure used is the usual one, and also in this case the set–up corresponds to a more hostile environment than the one experienced in a final detector. Results are plotted in Figure 5. After about 120 days of exposure, both the clarity factor and the refractive index reached a *plateaux*, corresponding to a variation of $+46\%$ and of $+19\%$ for the clarity and the refractive index $(n-1)$ respectively. Data are well described by:

$$y(t) = p_0\left[1 - \exp\left(-p_1 t\right)\right] + p_2 \qquad (3)$$

where p_1 is the time constant of the process. The test ended with the bake–out of the tile used. As displayed in Figure 5, initial conditions have been successfully restored.

V. Multilayer Aerogel Block

Experiments at the next generation Flavour Factories (upgrade of the existing ones or new facilities) require powerful

[2]The varnish is a “JalPrim Fond Adherent, Noir Mate”, produced by Jallut S.A. Peintures, and used to paint the LHCb RICH detector.

[3]Sigillante Acetico by TEKNICA – Tecnologia Italiana.

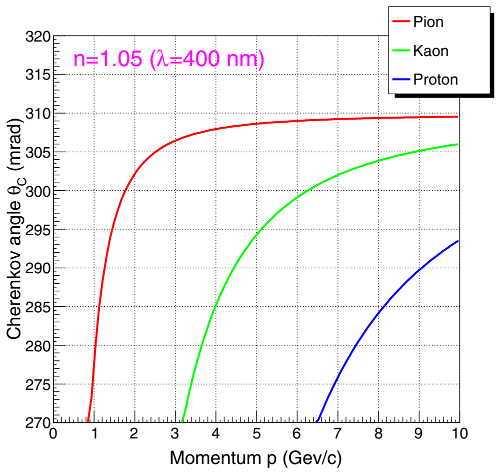

Fig. 6. Cherenkov angle θ_C distribution as a function of momentum for three particle hypothesis, π, K and p. The graph has been prepared fixing the refractive index of the Cherenkov radiator to $n = 1.05$ at $\lambda = 400$ nm.

π/K separation in the forward regions where space constraints are very tight. A Cherenkov detector with a proximity focusing configuration and silica aerogel radiator is considered as a possible choice.

Figure 6 shows the Cherenkov angle θ_C distribution as a function of the momentum for three particle species, assuming the refractive index of the radiator media to be $n = 1.05$ (at $\lambda = 400$ nm). Under this hypothesis, for particle identification at 4 GeV/c, a $\theta_\pi - \theta_K \sim 23$ mrad is foreseen.

From calculation, to have 5σ separation, 4.6 mrad resolution per track is required. Therefore the aim is to have good Cherenkov angle resolution. As shown in Figure 7, in a proximity focusing detector, one of the limiting factor of the Cherenkov angle resolution is the thickness of the radiator. Doubling, for example, the thickness of the radiator, the photoelectron yield $\mathcal{N}$ doubles, but approximately so does the single photon angular resolution σ_θ. This is because the reconstruction algorithms assume the origin of the photons to be in the middle of the radiator length, so the emission point uncertainty increases proportionally to the thickness. To limit this effect, one can use a radiator consisting of two or more tiles with different indices of refraction, or a single tile with refractive index varying along the thickness. With such a radiator, the photoelectron yield is determined by the total thickness of the material but the Cherenkov angle resolution improves.

A hygroscopic monolithic three–layer block has been produced recently by the Boreskov Institute of Catalysis in close collaboration with the Budker Institute of Nuclear Physics (Novosibirsk). Its dimensions are $100 \times 100 \times 41$ mm^3 and it has very good optical properties. This tile has been fully characterized in terms of optical properties (refractive index, clarity factor and density uniformity) using a laser beam in the laboratory. Table I lists the values of the thickness of the three layers and the refractive indices measured with X–rays and with laser beam. The clarity factor extracted from

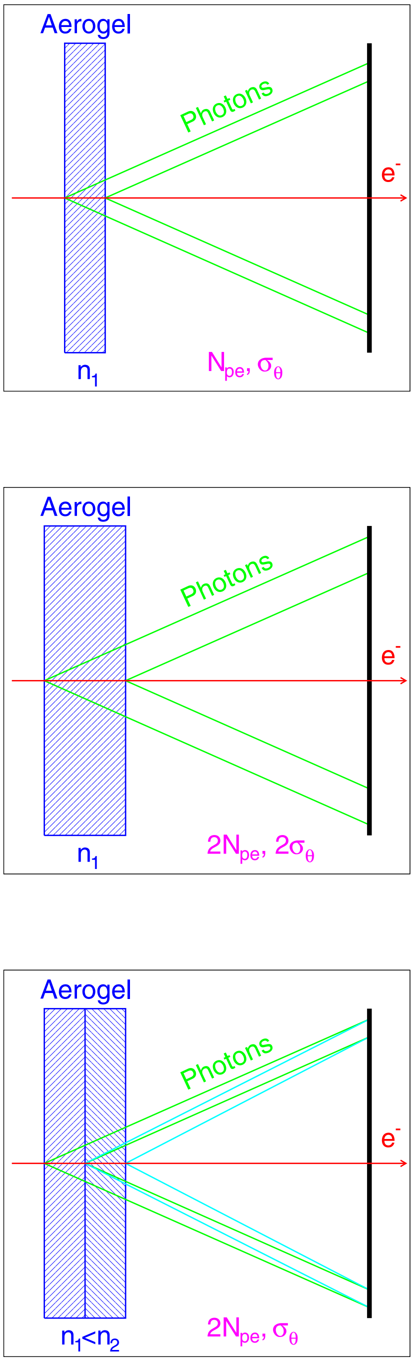

Fig. 7. Comparison between a single aerogel tile with thickness t (*top*), a mono–index tile with thickness $2t$ (*middle*) and a two–index tile of total thickness $2t$ (*bottom*). With a multilayer block, the number of detected photons is enhanced without degrading the single photon angular resolution.

the transmittance measurements over the thickness of 41 mm is $C = 0.0055$ μm^4/cm; Table II lists the refractive index

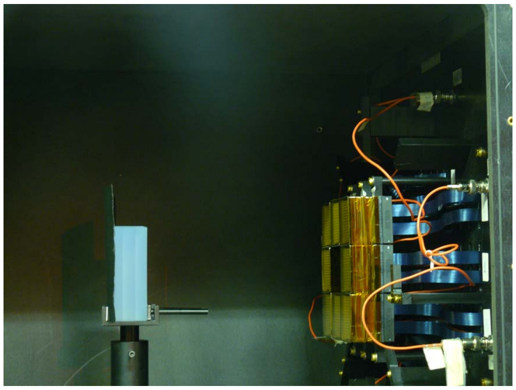

Fig. 8. Photograph of the set–up used during the multilayer test beam.

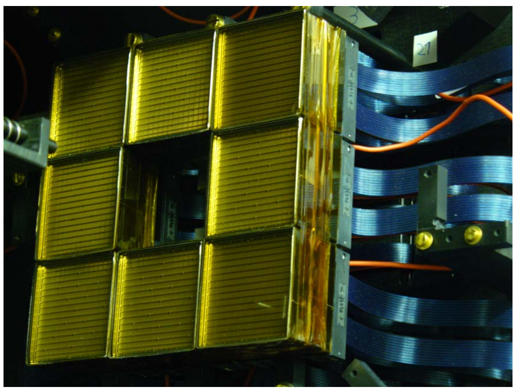

Fig. 9. The photon detectors installed inside the vessel for the test–beam.

TABLE I
OPTICAL PARAMETERS OF THE THREE–LAYER SILICA AEROGEL TILE

Layer	Thickness (mm)	n measured with X–rays	n measured (632 nm)	n scaled (400 nm)
1	12.6	1.046	1.045	1.046
2	13.2	1.041	1.038	1.039
3	15.2	1.037	1.033	1.034

TABLE II
REFRACTIVE INDEX UNIFORMITY OF THE THREE–LAYER AEROGEL TILE

Layer	$\sigma(n-1)/(n-1)$
1	3.01%
2	0.84%
3	1.61%

homogeneity measured for the three layers with the laser beam method [2].

Recently it has been tested with a charged particle beam at the DAΦNE Beam Test Facility (INFN, Frascati) [7] in order to validate the principle of self–focusing and to measure the Cherenkov angle resolution together with the photoelectron yield [8].

A photograph of the set–up is shown in Figure 8. A light tight anodized aluminium vessel provides the housing for all the components of the test. The volume is flushed with dry nitrogen to avoid as much as possible a variation of the optical properties of the aerogel due to the absorption of humidity. Cherenkov photons are produced by the 500 MeV electron beam (50 Hz repetition rate; 1 ns bunch length; particle multiplicity tunable down to one electron per bunch) and they are detected by an array of eight Hamamatsu H9500 flat panel MAPMTs. These photon detectors have 16×16 channels, each pixel is 2.8×2.8 mm^2 in size and the pitch is 3.04 mm; they have been chosen because of their excellent packing factor and their good quantum efficiency in the $300 - 500$ nm wavelength interval. The readout electronics consists of PCOS IV digital modules (from the HERMES RICH experiment [9]) adapted via interface boards to the photon detector layout, and it provides a binary response, with no photon multiplicity information. Figure 9 shows the integration of the photon detectors used for this test.

TABLE III
PRELIMINARY RESULTS FROM DATA ANALYSIS

Radiator	Radius (mm)	θ_C (mrad)
four tile stack	64.8 ± 1.3	306.0 ± 6.2
single four–layer tile	61.6 ± 1.1	291.7 ± 5.7
single three–layer tile	67.4 ± 1.1	273.9 ± 4.3

Several tiles in different configurations have been tested: the large monolithic three–layer block, a four–layer single tile with indices of refraction in the range $1.039 - 1.050$ and a stack of four tiles with refractive indices corresponding to the four layer one.

The data analysis is at a preliminary stage. At present the proximity focusing RICH is used as an essentially stand–alone detector, with very limited information on track direction and bunch multiplicity from four silicon strip planes placed in front of the vessel. Also the photon detector characterization (in terms of cross-talk, charge–sharing and electronic noise) has not been completed yet. The Cherenkov angle resolution analysis has been done on an event–by–event basis clustering the hits on the photon detector plane, fitting a ring using cluster centre of gravity. A cut on the reduced χ^2 is applied to exclude events with two or more well separated electrons and on the tracking station cluster size to reject events with two or more close electrons.

Figure 10 shows the hits accumulated in a run with 40k triggers and the distribution of the radii of the rings fitted event per event[4]. Preliminary results are listed in Table III. In the comparison between the stack of four tiles and the single four–layer tile, the improvement in the Cherenkov angle resolution is significant. Also the single three-layer tile presents a good resolution, very close to the expected one.

VI. CONCLUSIONS

Extensive tests of ageing and robustness have been performed on silica aerogel to assess its compatibility with a collider RICH environment. All relevant optical parameters have been monitored. The radiation hardness of the aerogel and its compatibility with C_4F_{10}, black varnish and black

[4]Unfortunately one out of eight MAPMTs turned out to be broken.

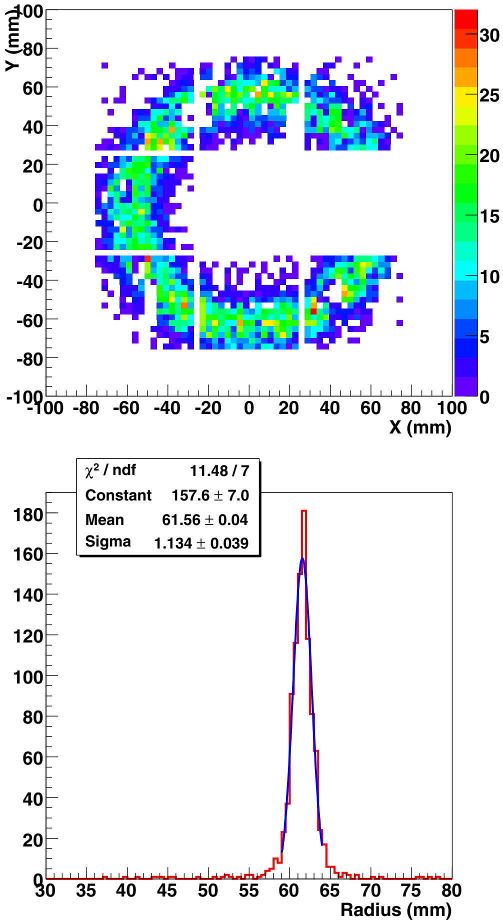

Fig. 10. Cherenkov photons accumulated during the beam test (*top*) and reconstructed ring radii for the same run (*bottom*).

silicone rubber have been proven. No permanent degradation of the excellent optical properties has been detected in any of the performed tests. Recovery procedures such as exposure to dry atmosphere (gaseous N_2) or baking at 500 °C have shown that the original quality of the exposed samples have been restored. Recently a high–quality multilayer aerogel block has been produced and tested with an electron beam. Data are still being analyzed.

Acknowledgment

We gratefully acknowledge the technical support of F. Chignoli and R. Mazza. We thank our students F. Bianchi and L. Tamburello for their collaboration. The financial support by INTAS–5579, by JRA9 of I3HP and by PRIN–$2006 - 027885$ is acknowledged.

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