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Silica aerogel radiator for use in the A-RICH system utilized in the Belle II experiment

Makoto Tabata [a,b,*], Ichiro Adachi [c], Nao Hamada [d], Koji Hara [c], Toru Iijima [e], Shuichi Iwata [f], Hidekazu Kakuno [f], Hideyuki Kawai [b], Samo Korpar [g,h], Peter Križan [i,h], Tetsuro Kumita [f], Shohei Nishida [c], Satoru Ogawa [d], Rok Pestotnik [h], Luka Šantelj [h], Andrej Seljak [h], Takayuki Sumiyoshi [f], Elvedin Tahirović [h], Keisuke Yoshida [f], Yosuke Yusa [j]

[a] *Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan*
[b] *Department of Physics, Chiba University, Chiba, Japan*
[c] *Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba, Japan*
[d] *Department of Physics, Toho University, Funabashi, Japan*
[e] *Kobayashi–Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Japan*
[f] *Department of Physics, Tokyo Metropolitan University, Hachioji, Japan*
[g] *Faculty of Chemistry and Chemical Engineering, University of Maribor, Maribor, Slovenia*
[h] *Experimental High Energy Physics Department, Jožef Stefan Institute, Ljubljana, Slovenia*
[i] *Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia*
[j] *Department of Physics, Niigata University, Niigata, Japan*

A R T I C L E I N F O

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A B S T R A C T

This paper presents recent progress in the development and mass production of large-area hydrophobic silica aerogels for use as radiators in the aerogel-based ring-imaging Cherenkov (A-RICH) counter, which will be installed in the forward end cap of the Belle II detector. The proximity-focusing A-RICH system is especially designed to identify charged kaons and pions. The refractive index of the installed aerogel Cherenkov radiators is approximately 1.05, and we aim for a separation capability exceeding 4σ at momenta up to 4 GeV/c. Large-area aerogel tiles (over $18 \times 18 \times 2\ \mathrm{cm}^3$) were first fabricated in test productions by pin drying in addition to conventional methods. We proposed to fill the large end-cap region (area $3.5\ \mathrm{m}^2$) with 124 water-jet-trimmed fan-shaped dual-layer-focusing aerogel combinations of different refractive indices (1.045 and 1.055). Guided by the test production results, we decided to manufacture aerogels by the conventional method and are currently proceeding with mass production. In an electron beam test undertaken at the DESY, we confirmed that the K/π separation capability of a prototype A-RICH counter exceeded 4σ at 4 GeV/c.

1. Introduction

We are developing an aerogel ring-imaging Cherenkov (A-RICH) counter [1] as one of the particle identification devices for the Belle II experiment [2]. Belle II will involve the SuperKEKB electron–positron collider, under upgrade at KEK, Japan. This super B-factory experiment, investigating flavor physics and precision measurements of CP violations in the intensity frontier, will search for physics beyond the standard model of particle physics. Because the installation space of the forward end cap of the Belle II detector is limited, the A-RICH system was designed as a proximity-focusing RICH counter. The A-RICH system is an upgrade of threshold aerogel Cherenkov counters [3] installed in the previous Belle spectrometer [4].

To efficiently separate kaons from pions at momenta (p) up to 4 GeV/c (our goal is to exceed 4σ K/π separation capability), we require a highly transparent Cherenkov radiator with a refractive index n of approximately 1.05. To this end, we have been developing high-refractive index, high-quality hydrophobic silica aerogels since the early 2000s [5–8]. Together with Hamamatsu Photonics K.K., Japan, we have also been developing 144-ch multi-anode hybrid avalanche photodetectors (HAPD) [9] as position-sensitive Cherenkov light sensors using dedicated readout electronics (ASIC) [10].

Given the limited expansion distance between the aerogel upstream surface and the photodetector surface (20 cm in our case), we first proposed and demonstrated a multilayer-focusing radiator

* Corresponding author at: Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan.
E-mail address: makoto@hepburn.s.chiba-u.ac.jp (M. Tabata).

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scheme using aerogels with different refractive indices [11]. This thick aerogel combination aimed to increase the number of detected photoelectrons without degrading the resolution of the Cherenkov angle. In previous beam tests, the K/π separation capability of a prototype A-RICH counter exceeded 5σ at 4 GeV/c [12]. Such high separation capability was achieved using highly transparent (but small size) aerogels developed by the pin-drying method described in the next section.

Silica aerogel, an amorphous, highly porous solid of silicon dioxide (SiO_2), has been widely used as a Cherenkov radiator because of its tunable, intermediate refractive index and optical transparency. Its refractive index is related to its bulk density, which depends on the silica–air volume ratio (typically 1:9) tuned in the production process. The typical length scale of three-dimensional networks of silica particles (revealed by our scanning electron microscopy observations) is on the order of 10 nm. Hence, the transmission of Cherenkov photons in an aerogel is described by Rayleigh scattering. Although aerogels are generally transparent, their transparency strongly depends on the production technique.

2. Production methods

Our aerogels are produced in two ways: conventional and pin-drying methods. Our conventional method, developed at KEK in the 1990s [13], was modernized in the mid-2000s by introducing a new solvent in the wet-gel synthesis process [5]. The conventional method, which requires approximately 1 month, adopts a simple wet-gel synthesis procedure (sol–gel step). The refractive indices of the resulting aerogels reach $n = 1.11$ [14]. To suppress age-related degradation caused by moisture absorption, our aerogels are rendered hydrophobic [14,15]. In the final step, the wet gels are dried by the supercritical carbon dioxide extraction method.

Our recently developed pin-drying method [16] produces more transparent aerogels (with $n \sim 1.06$) than the conventional method. Originally, this novel method was developed to yield ultrahigh-refractive-index aerogels (up to $n = 1.26$) at Chiba University, Japan [17]. In this method, individual wet gels (originally designed with $n \sim 1.05$) are subjected to a special treatment, intermediate between the wet-gel synthesis and the hydrophobic treatment. Specifically, to increase its silica density, the wet gel is shrunk by partial drying in a semi-sealed container punctured with pinholes to suppress cracking (pin-drying process). The refractive index of the aerogels is determined by two factors: shrinkage extent of the wet gel and the volume ratio of chemicals used in the wet-gel synthesis. By contrast, the refractive index is controlled only by the wet-gel synthesis process in the conventional method. Potential disadvantages of the pin-drying method include the time consumed in the pin-drying process (approximately 2 months), difficulties in obtaining uniform tile density, and cracking in the supercritical drying phase. However, the method achieves long transmission length (Λ_T) [8], as shown in Fig. 1.

3. Tiling in the end cap

When filling the large (3.5 m^2) end-cap region, tile boundaries must be reduced by minimizing the total number of aerogel tiles (i.e., by maximizing aerogel dimensions). This is important because unintended scattering at the boundaries of adjacent aerogel tiles reduces the number of detected photoelectrons. Meanwhile, the tile dimensions should also be realistic for production. Considering the capacity of our autoclave used in the supercritical drying phase, installed at Mohri Oil Mill Co., Ltd., Japan, we planned to manufacture aerogel tiles with dimensions $(18 \times 18 \times 2)$ cm^3.

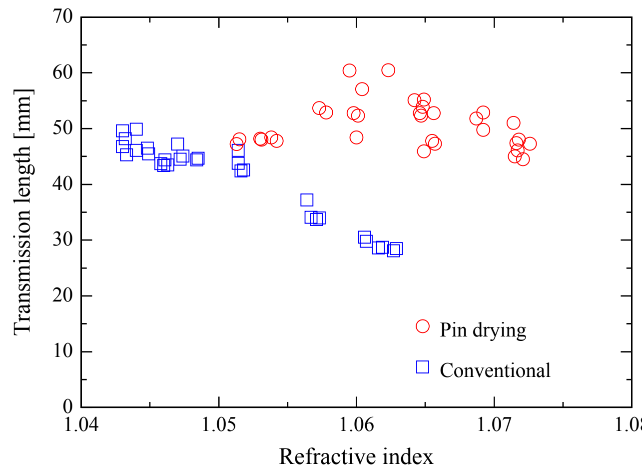

Fig. 1. Transmission length at 400 nm as a function of refractive index. The transmission length was calculated from the aerogel thickness and transmittance measured with a spectrophotometer [14]. The refractive index was measured at the tile corners by the Fraunhofer method with a 405-nm semiconductor laser [14]. The plot compares aerogel samples smaller than $(10 \times 10 \times 2)$ cm^3 produced by the conventional (squares) and pin-drying (circles) methods.

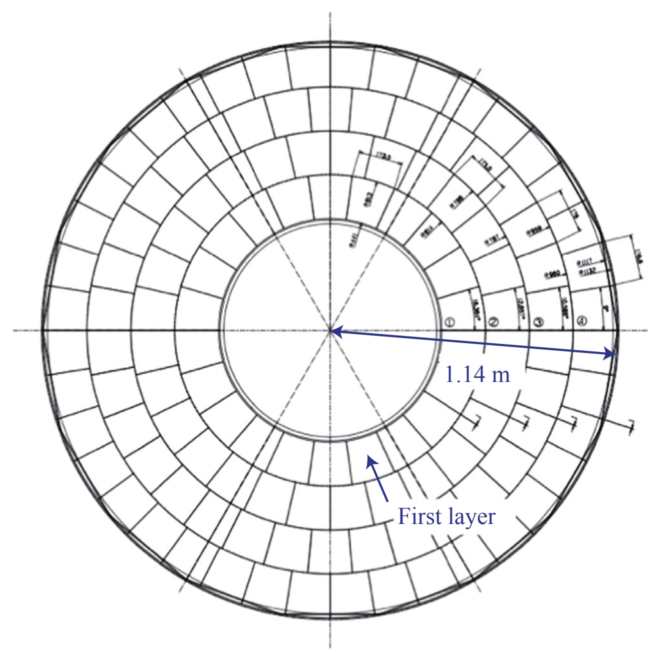

Fig. 2. CAD drawing of the planned A-RICH radiator tiling scheme in the cylindrical forward end cap of the Belle II detector.

To simplify aerogel production, we propose to fill the cylindrical end-cap region with 124 segmented dual-layer-focusing aerogel combinations (a total of 248 tiles) with different refractive indices. Fig. 2 shows a CAD drawing of the planned aerogel radiator tiling scheme. Each 2-cm-thick aerogel layer (dual layer thickness = 4 cm) is separately fabricated and will be stacked during the installation of the A-RICH system.

Prepared aerogel tiles are cut into fan shapes that fit their layer (concentric layers 1–4, counting from the inside of the end cap; see Fig. 2) by a water jet cutter. Water jet trimming best exploits the hydrophobic features of our aerogels. Fig. 3 shows water-jet-machined aerogels cut from $(18 \times 18 \times 2)$ cm^3 test production tiles fabricated by the conventional method. The integrity of the optical

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