Progress in the Development of Silica Aerogel as a RICH Radiator in the Belle II Experiment

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***Abstract*—This paper describes recent progress in the development of large-area hydrophobic silica aerogel tiles for use as a radiator in the aerogel-based ring-imaging Cherenkov (A-RICH) counter that will be installed in the forward end cap of the Belle II detector. The proximity-focusing A-RICH counter is designed to efficiently identify charged pions and kaons; our goal is a separation capability of more than 4σ at momenta up to 4 GeV/c. We plan to fill the large end-cap area of 3.5 m^2 with 124 segmented dual-layer-focusing aerogel combinations with different refractive indices ($n \sim$ 1.05). It is crucial to minimize the number of aerogel tiles to reduce tile boundaries because the number of detected photoelectrons decreases at the boundaries. As a step toward achieving high performance in the actual detector, we performed test productions of large-area (over 18 $\times$ 18 $\times$ 2 cm^3) aerogel tiles using both conventional and pin-drying methods. In view of the crack-free production yield, we have decided to mass-produce both upstream and downstream aerogel tiles by the conventional method in the Belle II program, although the pin-dried aerogels showed excellent transparency. We also used an electron beam at DESY to conduct a beam test for investigating the performance of a prototype A-RICH counter. When we used a basic counter configuration with dual-layer-focusing aerogels having $n \sim$ 1.045 and 1.055 produced by the conventional method, we confirmed a π/K separation capability better than 4σ at a momentum of 4 GeV/c.**

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I. Introduction

The aerogel-based ring-imaging Cherenkov (A-RICH) counter is one of the particle identification devices for the Belle II experiment [1] that will be performed using the SuperKEKB accelerator at KEK, Japan. The Belle II is a super B-factory experiment searching for new physics beyond the standard model of particle physics through flavor physics and precise measurements of CP violations. Because the forward end cap of the Belle II detector has a limited space, the A-RICH system is designed as a proximity-focusing RICH counter. To efficiently separate charged pions from kaons at momenta (p) up to 4 GeV/c (our goal is a π/K separation capability of more than 4σ), we need a highly transparent Cherenkov radiator with a refractive index $n \sim$ 1.05; therefore, since the early 2000s, we have been developing high-quality silica aerogels. In addition, the A-RICH group has developed 144-ch multi-anode hybrid avalanche photodetectors (HAPD) [2], [3] as Cherenkov light sensors with Hamamatsu Photonics K.K. using dedicated readout electronics (ASIC) [4].

II. Development of Silica Aerogel as a Cherenkov Radiator

Silica aerogel, an amorphous solid of silicon dioxide (SiO_2), has been widely used as a Cherenkov radiator because of its tunable, intermediate refractive index and optical transparency. We are developing aerogels based on our unique production methods. Our conventional method developed at KEK in the 1990s [5] was modernized in the mid 2000s by introducing a new solvent in the wet-gel synthesis process [6]. The conventional method is characterized by a simple wet-gel synthesis procedure (sol–gel step) and can produce aerogels with n = 1.003–1.11. To suppress age-related degradation caused by moisture absorption, our method makes the aerogels hydrophobic. The procedure is simply described as follows: (i) wet-gel synthesis, (ii) hydrophobic treatment, and (iii) supercritical drying. Our conventional method is summarized in more detail in [7].

Our recent method, the pin-drying technique, can generate ultrahigh-refractive-index aerogels up to $n \sim$ 1.26. This novel method allows us to produce aerogels having $n \sim$ 1.06 that are highly transparent compared with those produced by the conventional method. The production procedure in the pin-drying method is concisely described as follows: (i) wet-gel synthesis, (ii) pin-drying, (iii) hydrophobic treatment, and (iv) supercritical drying. The pin-drying method was first reported in [8] and is briefly described in [9].

In the limited expansion distance between the aerogel radiator surface and photodetector surface (20 cm in our case), a multilayer-focusing radiator (with different refractive indices) using thick aerogels was proposed and demonstrated [10] to increase the number of detected photoelectrons with no degradation in the resolution of the Cherenkov angle. In past beam tests using a prototype A-RICH counter, we achieved a π/K separation capability of more than 5σ at 4 GeV/c with a basic detector configuration [2], [11]. In this configuration, $n_{\rm tag}$ = 1.054 and 1.065 aerogels produced by the pin-drying method were used as upstream and downstream radiators, respectively, where $n_{\rm tag}$ is the refractive index measured at the corner of the aerogel tiles by the Fraunhofer method with a 405-nm semiconductor laser [7]. Because pin-dried aerogels in this refractive index range used in the beam tests had refractive index gradients in the transverse planar direction [12], the local refractive indices at the tile center penetrated by the beam were estimated to be $n \sim$ 1.048 and 1.058 for the upstream and downstream aerogels, respectively.

This high detector performance was achieved mainly by introducing pin-dried aerogels with excellent transparency. Long transmission length aerogels are necessary to increase the number of Cherenkov photons that reach the photodetectors with no Rayleigh scattering. The transparency of the downstream aerogel, with a higher refractive index, is of particular importance for detector performance because all emitted Cherenkov photons must pass through the downstream layer to reach the photodetectors. However, in previous studies, we had only demonstrated detector performance using small pin-dried aerogels with dimensions of 9 $\times$ 9 $\times$ 2 cm^3. Therefore, a special concern has been the production of large aerogel tiles.

A. Radiator Tiling Scheme

Since the mid-2000s we have been studying a method for producing a monolithic multilayered-focusing aerogel comprising different refractive indices [6], [13] or, alternatively, an aerogel with a refractive-index gradient along the thickness direction [14]. These studies were partially successful in producing small samples; however, we found that large-area aerogels with thicknesses of over 3 cm were difficult to obtain with no cracking. Therefore, in the late 2000s, we opted to simply fabricate dual-layer-focusing aerogels with different refractive indices. Each aerogel layer with a thickness of 2 cm (a total of 4 cm) is separately manufactured and is to be stacked during the installation stage of the A-RICH counter.

To reduce adjacent boundaries of aerogel tiles, at which the number of detected photoelectrons decreases, the total number of tiles should be minimized for the large end-cap area of 3.5 m^2 in the Belle II detector; however, the tile dimensions should also be realistic for production. In view of the capacity of our autoclave used in the final phase of aerogel production

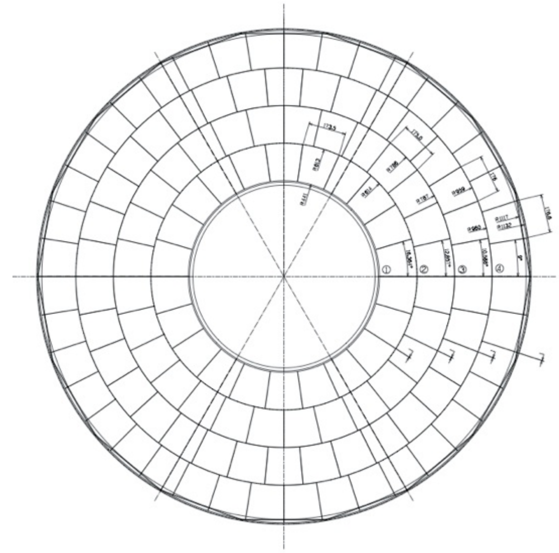

Fig. 1. CAD drawing of the planned A-RICH radiator tiling scheme. Maximum radius of the cylindrical end cap of the Belle II detector is 1.14 m.

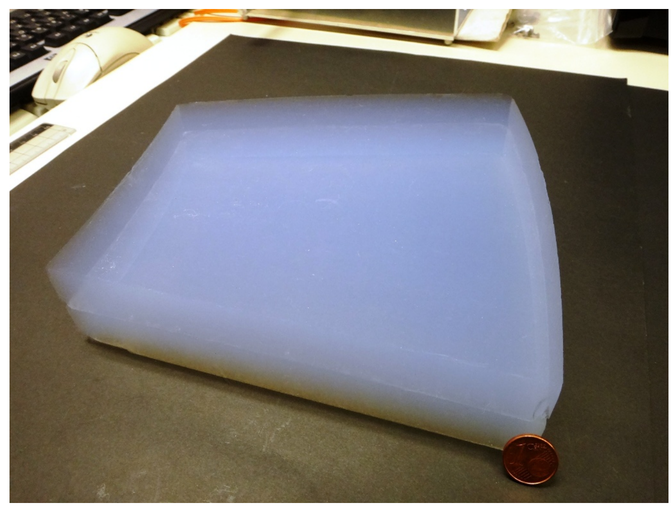

Fig. 2. Fan-shape water-jet-machined aerogel samples with a euro cent. These samples were cut from 18 $\times$ 18 $\times$ 2 cm^3 tiles and stacked. The refractive indices of the upper (ID: REM2-3) and lower (ID: REM2-17) tiles were 1.0464 and 1.0548 (a focusing combination), respectively.

(supercritical drying), we plan to manufacture aerogel tiles with dimensions of 18 $\times$ 18 $\times$ 2 cm^3. Fig. 1 shows a CAD drawing of the planned aerogel radiator tiling scheme in the forward end cap. Prepared aerogel tiles are cut in fan shapes according to layer (first to fourth layers counting from the inside) with a water jet cutter. The total number of tiles in the dual-layer-focusing radiator scheme is 248 (124 tiles in each layer). Water jet trimming makes the best use of the hydrophobic features of our aerogels. Fig. 2 shows samples of water-jet-machined aerogel tiles.

B. Test Production Results for Large-area Aerogel Tiles

We plan to produce more than 350 tiles (including spares) with no cracking. For these large (18 $\times$ 18 $\times$ 2 cm^3), high-refractive-index (n $\sim$ 1.05) aerogels, cracking in the supercritical drying phase is a critical issue. Moreover, an aerogel of this size has not yet been produced using the pin-drying method. Studies of large-tile production by both the conventional and pin-drying methods are the key to achieving high performance over the actual detector. Therefore, for four years, we have studied a technique for producing large-area aerogels with no cracking.

In a test production, we succeeded in manufacturing 18 × 18 × 2 cm^3 aerogels with n = 1.045–1.055; in the four most recent batches (112 tiles); using the conventional method, the crack-free yield increased to 89%. To suppress tile cracking, we found that a very slow, stable ramp up/down of the internal pressure in the autoclave was highly significant during the supercritical drying phase. In 2012, the first 17 × 17 × 2 cm^3 tile with $n_{\rm tag}$ = 1.059 was obtained with no cracking by the pin-drying method [15]. In the final step, in 2013, we performed a two-batch test production of 19 × 19 × 2 cm^3 tiles with $n_{\rm tag}$ = 1.055–1.060 by the pin-drying method; however, no crack-free samples were obtained. We intend to produce tiles as large as possible and then trim the tile corners because this is where the refractive index steeply increases [15].

The optical parameters of the recently produced large tiles have been measured and found to be suitable. Fig. 3 shows the transmission length measured at 400 nm as a function of the refractive index ($n_{\rm tag}$). We previously studied the optical performance of aerogels using small samples [9], [12]. In [15], we confirmed that high optical qualities can be obtained even in large aerogel tiles. This is further confirmed in Fig. 3. Moreover, refractive index measurements of pin-dried aerogels from the most recent batch suggest that uniformity in the refractive indices (positional dependence) of monolithic tiles has sufficiently improved.

We have two options for producing aerogel tiles. The first option uses the conventional method for fabricating both upstream and downstream aerogels. This is a promising option because large-area (18 × 18 × 2 cm^3) aerogel tiles can be obtained with a high crack-free yield. In view of the transparency of the downstream aerogels, we consider a focusing refractive index combination not of 1.050 and 1.060 but of 1.045 and 1.055 [12]. The second option uses the conventional method for manufacturing upstream aerogels and the pin-drying method for producing downstream aerogels. The pin-drying method provides more transparent aerogels than the conventional method; however, the cracking issue is very critical, and uniformity in the refractive index should be investigated by an X-ray absorption technique [12] and beam test. From the above test production results for large-area aerogels, we have conclusively decided to mass-produce both the upstream (n = 1.045) and downstream (n = 1.055) aerogels by the conventional method (the first option). We have just started mass production of large-area aerogel tiles.

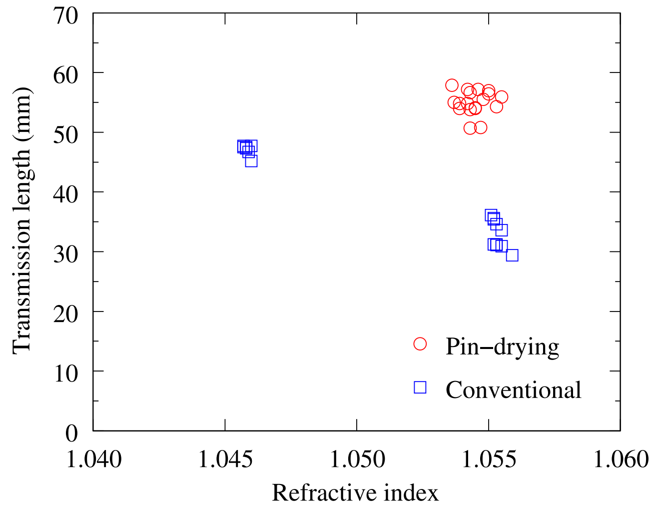

Fig. 3. Transmission length at 400 nm as a function of refractive index. The refractive index at 405 nm was measured at the tile corners ($n_{\rm tag}$). Large-area tiles produced by the conventional (blue, 18 × 18 × 2 cm^3) and pin-drying (red, 19 × 19 × 2 cm^3) methods were investigated. The pin-dried samples from the most recent batch had an excellent transmission length; however, all samples had cracking.

III. Beam Test of a Prototype A-RICH Counter

To evaluate the performance of recently developed aerogels, HAPDs, and ASICs, we performed, in May 2013, a beam test using a p = 5 GeV/c electron beam in the T24 beam area at DESY. Our primary goal was to determine the refractive index combination from the focusing aerogel candidates because the test production of pin-dried aerogels was still in progress. (However, based on the results of the test production, we later chose to mass-produce the aerogel tiles using the conventional method.) All the above detector components were properly placed in the 20-cm expansion distance between the aerogel surface and HAPDs in a light-shielded box, forming a prototype A-RICH counter (as part of the real size counter), as shown in Fig. 4. A 2 × 3 array of six HPADs was positioned with some gaps based on the geometry of the real counter, where the pixel size of the 144-ch position-sensitive HAPDs was 4.9 × 4.9 mm^2. To track the charged beam, four multiwire proportional chambers were attached on the upstream and downstream sides of the light-shielded box.

We tested several focusing aerogel combinations and individual single-layer aerogels produced by both the conventional and pin-drying methods as well as different parameter settings for the HAPDs and ASICs. Performance of the A-RICH detector is very simply estimated by the following equation:

$$\frac{\Delta\theta_{\rm C}\sqrt{N_{\rm p.e.}}}{\sigma_\theta},$$

where $\Delta\theta_{\rm C}$ (∼23 mrad) is the difference in Cherenkov angles between π and K at n = 1.05 and p = 4 GeV/c, $N_{\rm p.e.}$ is the number of detected photoelectrons, and σ_θ is the resolution of the observed Cherenkov angle distribution per single photon. Here, we describe a run that used a focusing aerogel combination of n = 1.0464 and 1.0548 with tiles produced by the conventional method; in this run, the electron beam impacted perpendicular to a default position (around the center of the tiles) of the radiator (run number = 53). These aerogel tiles were trimmed to a fan-shape with a water jet cutter (see Fig. 2). In a preliminary analysis of the data, we obtained $N_{\rm p.e.}$ = 6.6

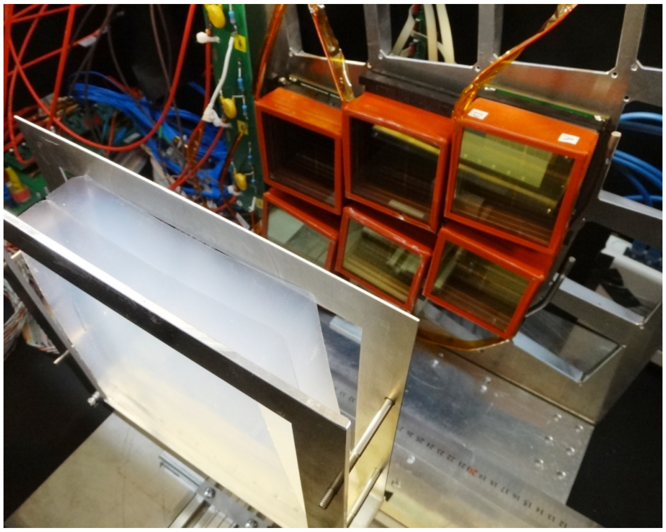

Fig. 4. Experimental set up of the prototype A-RICH counter in the light-shielded box.

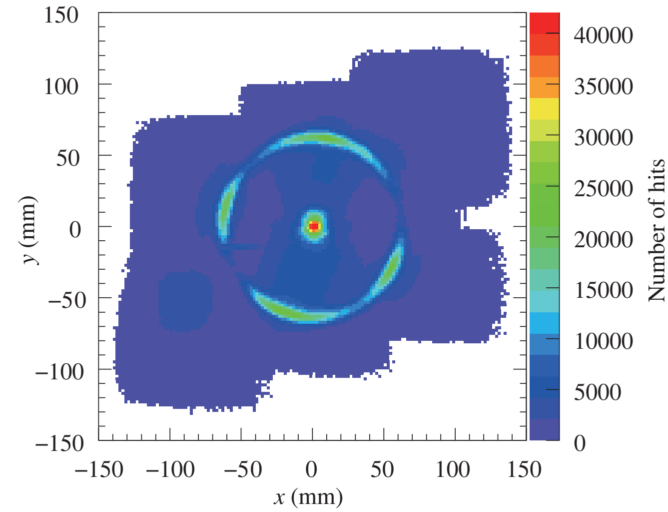

Fig. 5. Cherenkov ring observed from run 53. During the run, the hit distribution of Cherenkov photons in each event was accumulated on the photodetection plane. For each hit, the difference between the beam position and photodetector hit position is plotted.

and σ_θ = 14.5 mrad, resulting in a π/K separation capability of 4.1σ and observed a clear Cherenkov ring, as shown in Fig. 5. This aerogel configuration, which we chose based on the aerogel production method, roughly satisfied our requirements for detector performance. By fine-tuning the refractive index combination of aerogels and using HAPDs and ASICs of the final specifications, further improvements in the detector performance are expected.

Analyses are still in progress run by run; in particular, data using tiles produced by the pin-drying process are being studied. In such a large-area aerogel, the positional dependence of the mean and resolution of the Cherenkov angle distribution should be thoroughly investigated, particularly for the pin-dried aerogels because those tiles exhibited significant nonuniformity in refractive index [15]. In very preliminary analyses, nonuniformities in the large-area pin-dried aerogels seem to be within our requirements and are acceptable. Moreover, we detected more Cherenkov photons from the pin-dried aerogels with high transparency. More detailed results will be given elsewhere [16].

IV. Conclusions

As part of the Belle detector upgrade program, an A-RICH counter is under investigation for use as a particle identification detector in the forward end cap. We studied a technique for producing large-area silica aerogel tiles for use as Cherenkov radiators and examined the crack-free yield and optical performance of samples produced by both conventional and pin-drying methods. Based on results from test productions, we have chosen to mass-produce both upstream (n = 1.045) and downstream (n = 1.055) aerogel tiles by the conventional method. Mass production has just started. To test the performance of aerogels produced in the test productions, we performed a beam test at DESY. In the basic configuration of a prototype A-RICH counter using the conventionally produced aerogel tiles, we confirmed that the prototype counter satisfied our requirements in a dual-layer-focusing radiator scheme. Further developments in producing pin-dried aerogels with higher transparency will be conducted independent of the Belle II program.

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