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Silica Aerogel Radiator for Use in the A-RICH System Utilized in the Belle II Experiment

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on behalf of the Belle II A-RICH Group

The Belle II A-RICH Group

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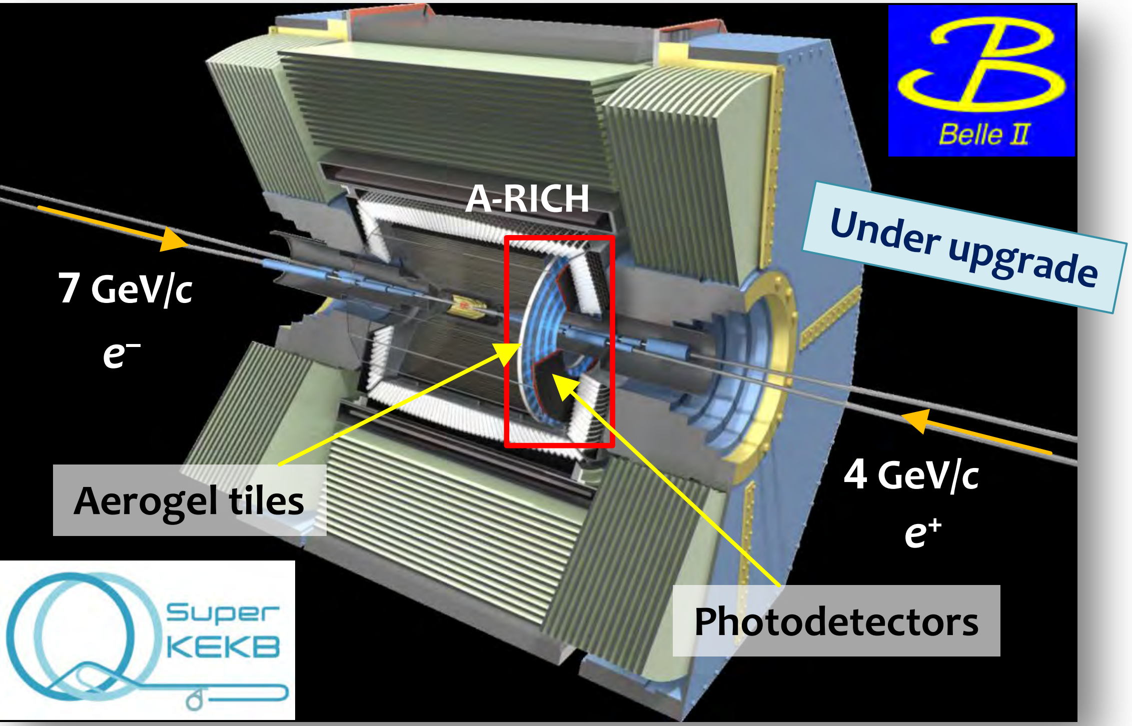
Outline

- Aerogel RICH for Belle II experiment
- Silica aerogel as Cherenkov radiator
- Production methods
- Optical performance
- Large tile production
- Beam test results
- Mass production status

Aerogel RICH

- **Belle II** experiment at the **SuperKEKB** accelerator in Japan (super *B* factory)
- Precise measurements of *CP* violation
- Flavor physics:
  - Rare *B* decays, *D* decays, lepton flavor violating τ decays, and etc.



- Threshold aerogel Cherenkov counter (ACC) for PID in the previous Belle detector

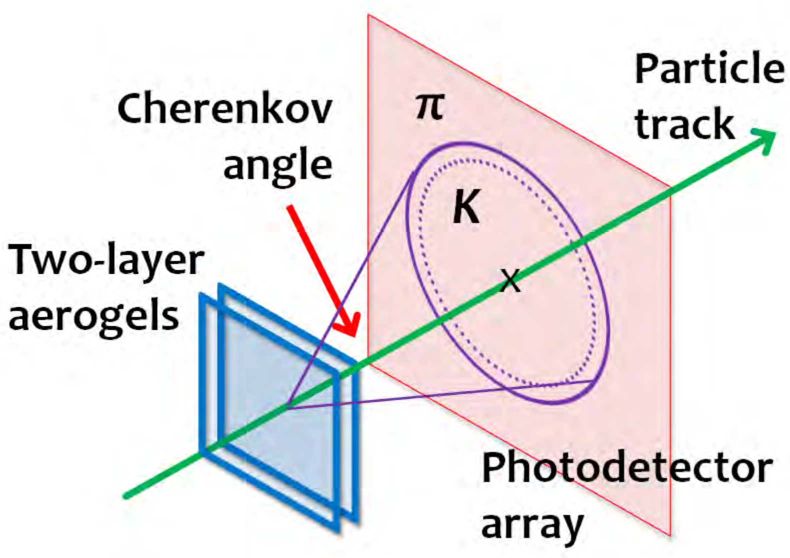
⇩ **Upgrade**

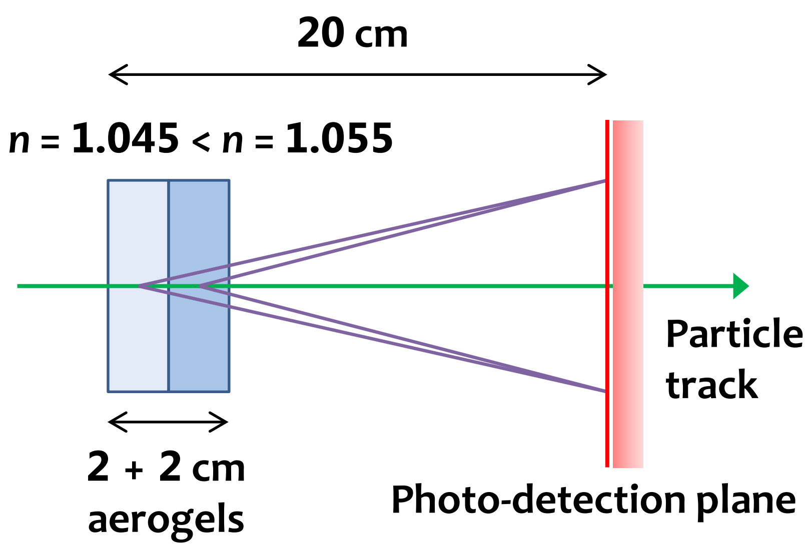
- **Proximity-focusing aerogel RICH** for forward end-cap PID in the Belle II detector

→ Our goal: **4σ π/K separation at 4 GeV/c**

Dual-layer-focusing Radiator

- A-RICH counter components
  - Aerogel radiator ($n \sim 1.05$)
  - Photodetectors
  - Readout electronics
  - 20 cm expansion distance

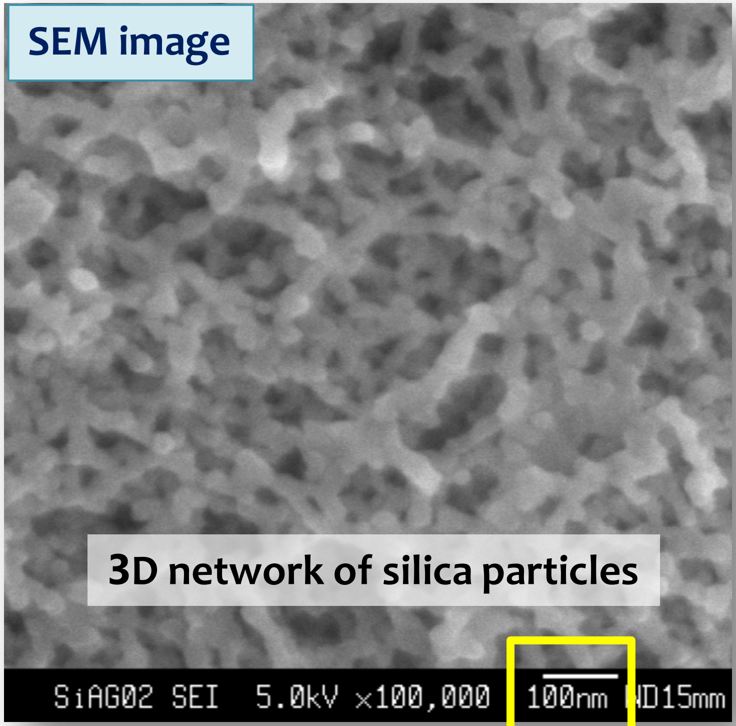


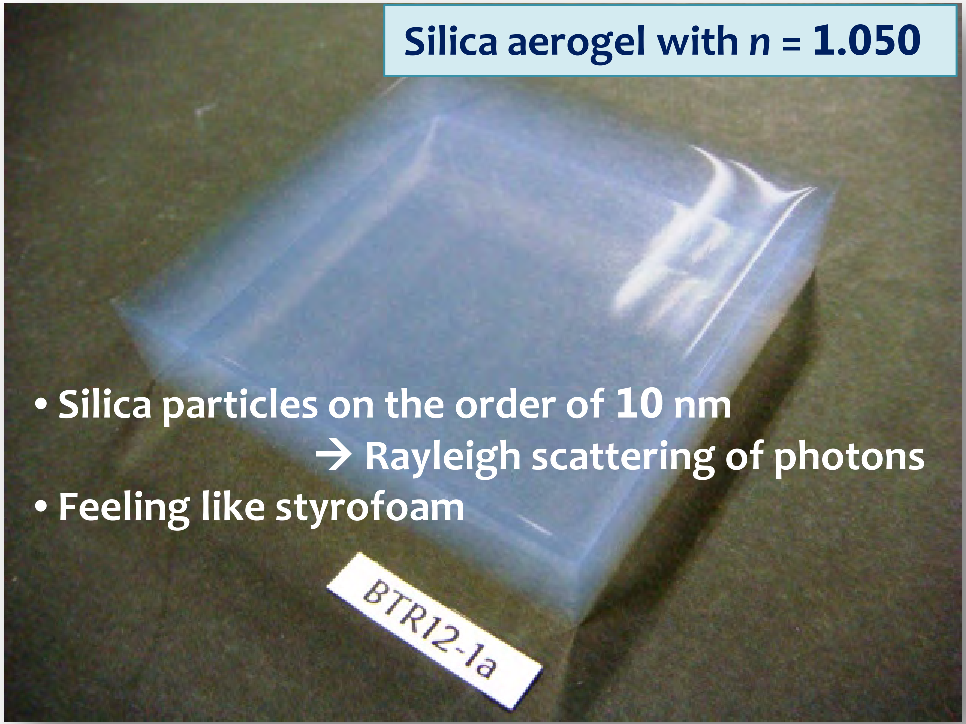


- **Multilayer-focusing radiator scheme**
- Simplifying mechanical structure
  - → Two-layer aerogel
  - → **Aerogels as large area as possible**
- Needs for **highly transparent aerogels for the downstream layer**

Silica Aerogel

- Amorphous solid of silicon dioxide (SiO_2)
- Highly porous: Typically 90% of the total volume is air.
- **Tunable refractive index** ← Tunable bulk density ←Tunable silica–air ratio
- **Highly transparent** depending on production methods





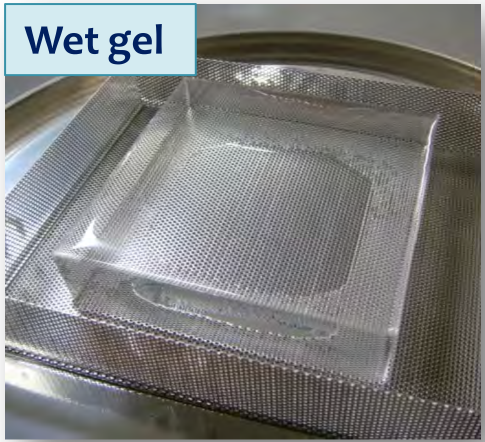
Production Methods

- We have two options for producing aerogels:
  - **Conventional method**
  - **Pin-drying method** (recent developed)
- Common procedures (~1 month in total):
  - **Wet-gel synthesis** and processing
  - **Hydrophobic treatment**
  - **Supercritical drying** using carbon dioxide

Homebuilt supercritical extraction equipment

At Chiba Univ.

Wet gel



Water drop on aerogel

Conventional Method

- **Sol–gel synthesis** of wet gel (Hydrolysis, condensation, and polymerization):

$$CH_3O[Si(OCH_3)_2O]_nCH_3 + (n+1)H_2O \rightarrow (SiO_2)_n + (2n+2)CH_3OH$$

Polymethoxysiloxane Water Silica Methanol

Wet-gel processing
Wet-gel synthesis
Hydrophobic treatment

⇨ **Supercritical drying**

- **Refractive index control in the wet-gel synthesis process** (by recipe)
- First developed using methanol as solvent at KEK in the early 1990s, and modernized using *N*,*N*-dimethylformamide at Chiba Univ. in the mid 2000s
- Well-established method → **Outsourcing**

  Wet-gel processing: Panasonic Corp. → Japan Fine Ceramics Center (JFCC)

  Supercritical drying: Mohri Oil Mill Co., Ltd.

Pin-drying Method

- Fine-structure modification and bulk density increment by **shrinking wet gel**

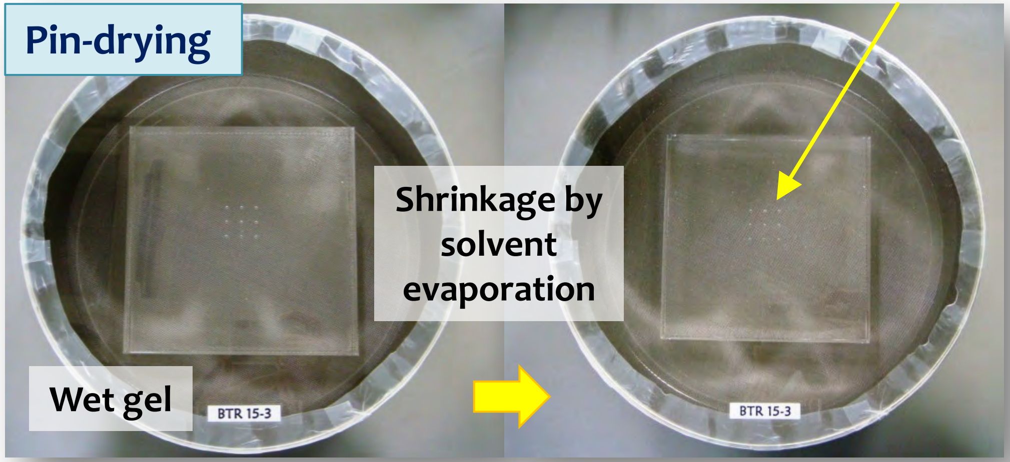
Wet-gel processing
- **Wet-gel synthesis**
- **Pin-drying**
- **Hydrophobic treatment**

→ **Supercritical drying**

→ **Improving transparency**

→ **Increasing refractive index**
e.g., $n = 1.05 \rightarrow 1.06$
$n_{max} = 1.26$!

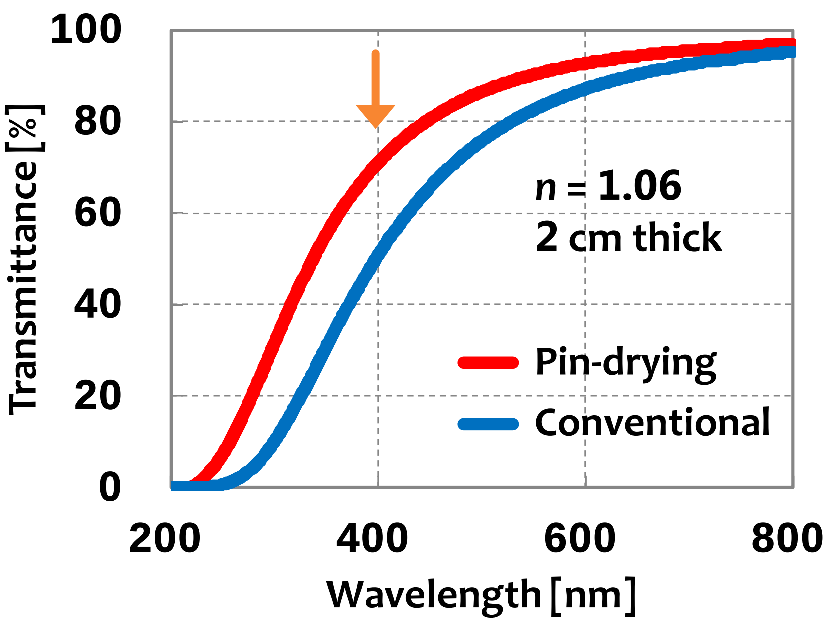
Semi-sealed container with pinholes

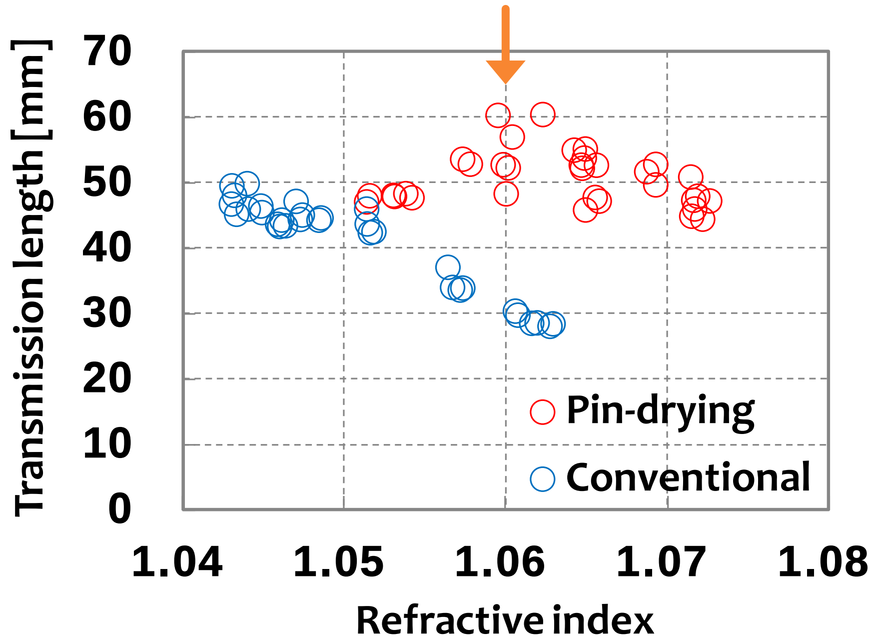


From several weeks to months later

- **Refractive index control in both the wet-gel synthesis and pin-drying processes** (by recipe and shrinkage)
- **In-house development** at Chiba Univ. since the mid 2000s

Optical Performance





- Optical parameters taken from aerogel tiles smaller than 10 cm
  - Refractive index measured using a 405-nm laser
  - Transmission length (Λ_T) at 400 nm calculated from transmittance and aerogel thickness
- **Higher transmittance in a wide range of wavelengths independent of refractive index by the pin-drying method**

Aerogel Tiling

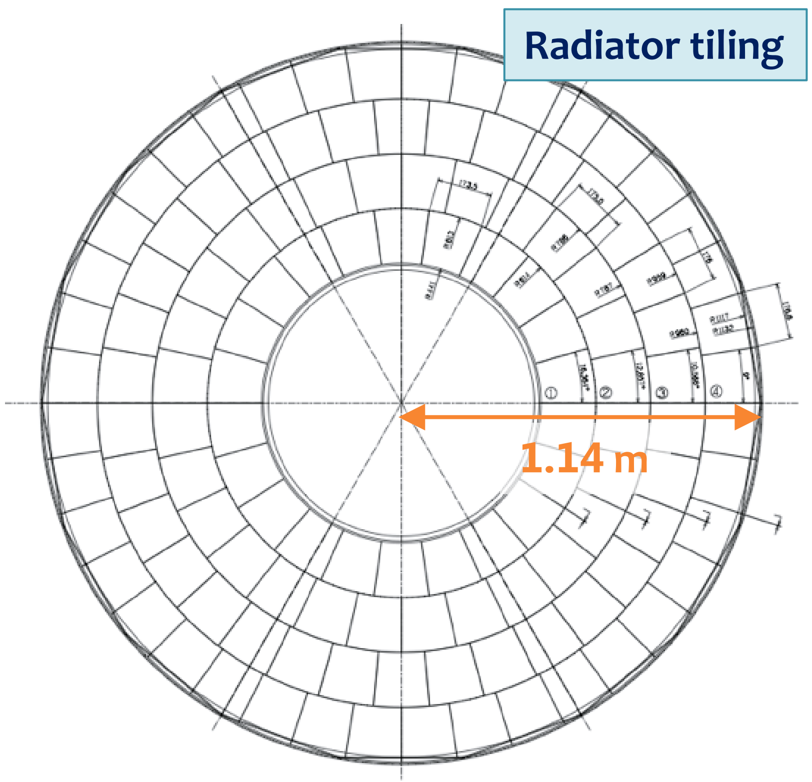
- **3.5 m^2** cylindrical forward end cap of the Belle II detector
- **Reducing adjacent boundaries of aerogel tiles**,
  at which the number of detected photoelectrons decreases
- Minimizing the total number of tiles with realistic dimensions for production
- Simplifying mechanical structure

→ **2 cm × 2 layer-focusing** aerogels

→ **18 × 18 × 2 cm^3** large tiles

→ **248 tiles** in total

→ Cutting aerogels in **fan shapes**



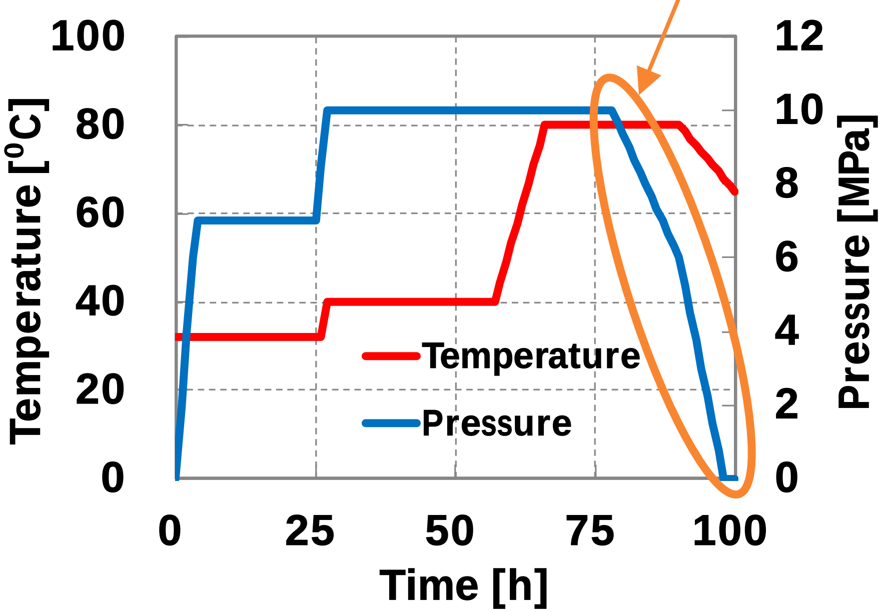
Large Tile Production

- Collaboration with JFCC and Mohri Oil Mill Co., Ltd.
- Large-area aerogels can be **cracked** in the supercritical drying (SCD) process.

  → **Improving SCD operation** [conventional (Panasonic) → Chiba pattern]

Very slow pressure reduction (one day)

SCD operation pattern (Chiba)



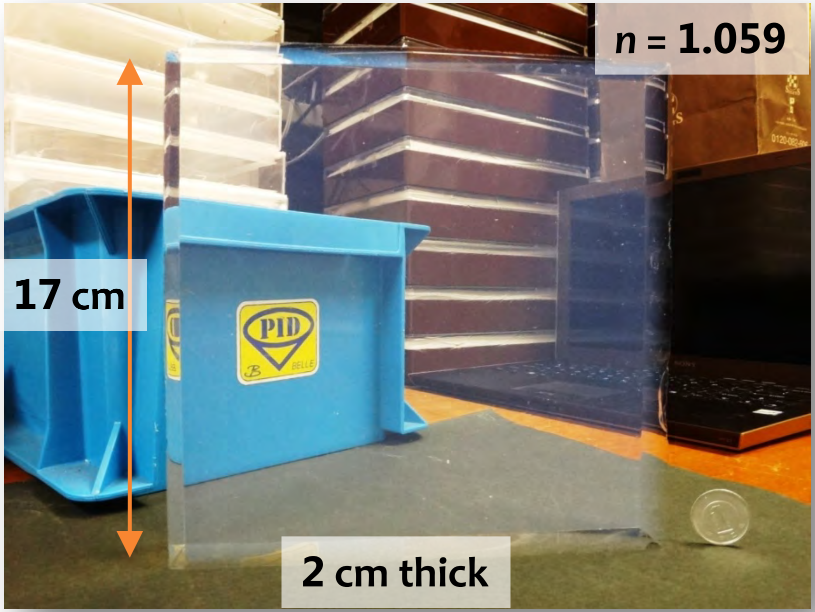
Recent test production results

- Using the **conventional method**
- 18 × 18 × 2 cm^3 tiles
- n = 1.045–1.055
- **28 tiles/batch** (SCD capacity)
- **5 batches** since 2012
- **89% crack-free** tile yield

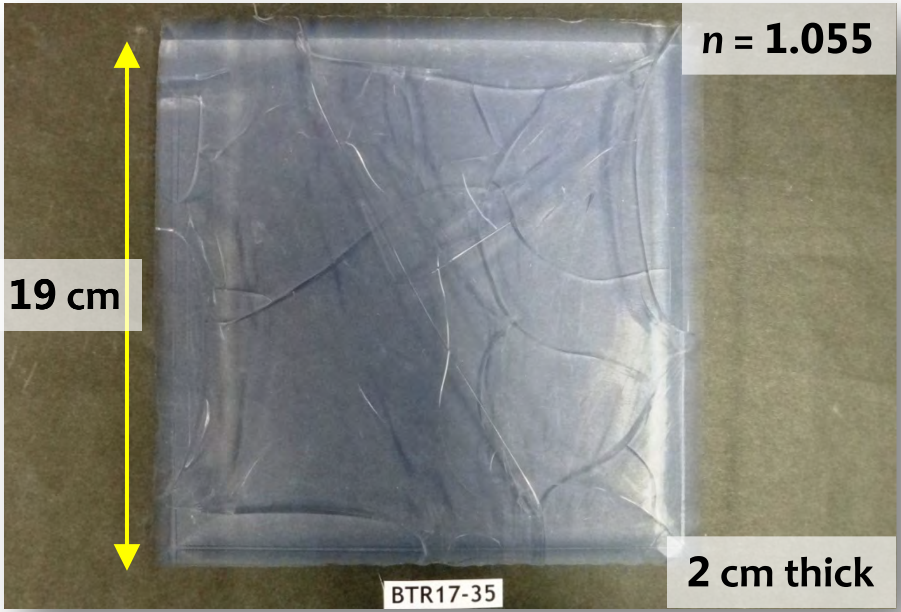
Pin-dried Large Tile Production

- Pin-dried aerogels are easily cracked in the SCD process in even small tiles.
- Large tile production by the pin-drying method is fairly challenging.
- We obtained **several 17 cm samples with no cracking** in trial productions.
- **No crack-free tiles were obtained in the final test production** in 2013.

Pin-dried large aerogel with no cracking



Final test aerogel with cracking



Our Decision

- Upstream aerogel → n = 1.045 or 1.050 using the conventional method
- Downstream aerogel → n = 1.055 or 1.060 using …

  Conventional method or **Pin-drying method**

- The **transparency** of the downstream aerogel is important because all the emitted Cherenkov photons must pass through the downstream layer.
- Another important issue is to use **crack-free** aerogels.
- **Our decision** based on the test productions of large aerogel tiles

  → Using the **conventional method**

  → ***n* = 1.045 and 1.055** (producing each 2 cm thick tile separately)

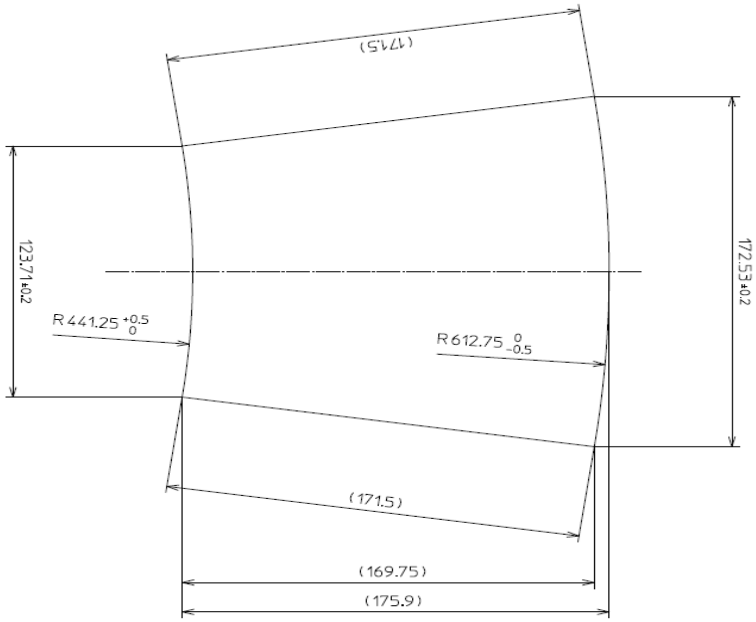
- We will perform **further developments for pin-dried aerogels at Chiba Univ.** independent of the Belle II program.

Water Jet Trimming

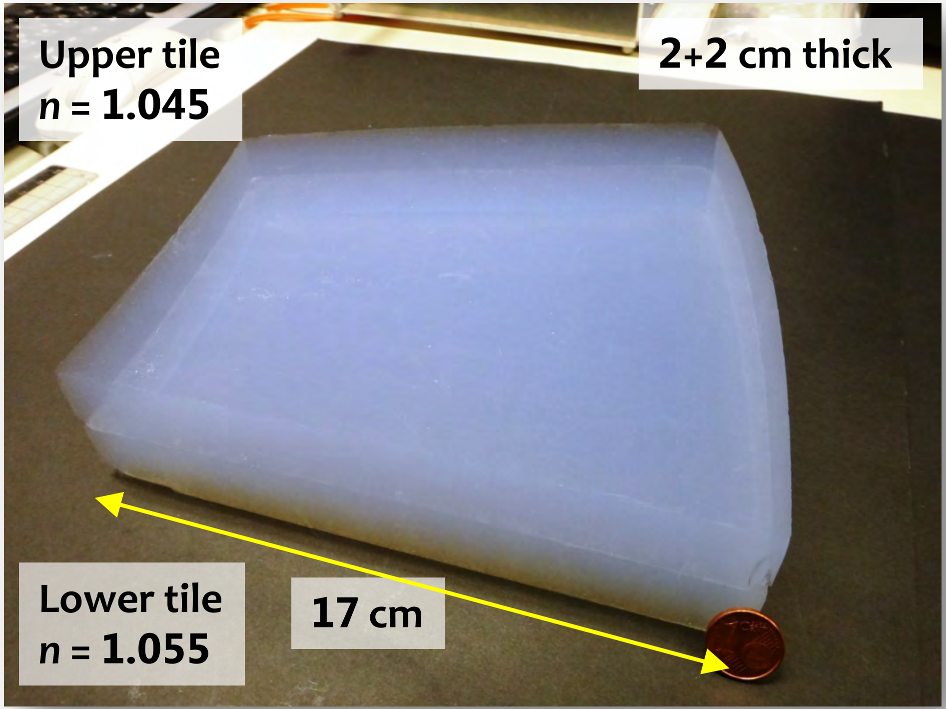
- Demonstrating the feasibility of aerogel trimming to fan shapes with a water jet cutter → Outsourcing to machine a large number of tiles
- **No degradation of the optical parameters**
- **Dimension error below 1%**

Best use of hydrophobic feature

CAD drawing of tile trimming



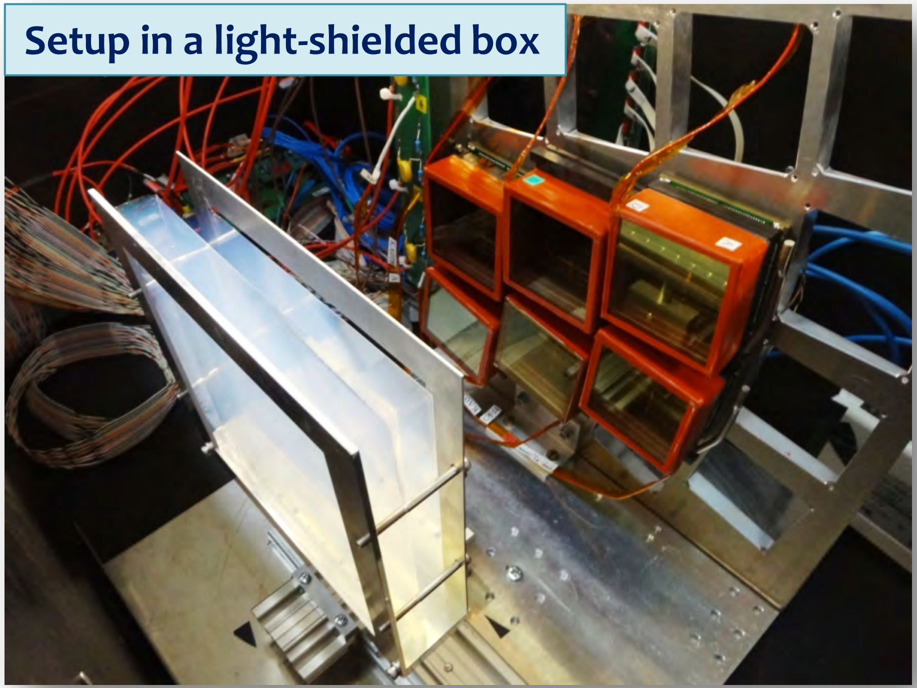
Water jet trimmed aerogels (test)



Beam Test: Setup

- Test beam experiment using 5 GeV/c electron beams in 2013 at DESY
- Prototype A-RICH counter (part of the actual detector layout)
  - Two-layer-focusing large-area aerogel
    (several variations from the conventional and pin-dried samples)
  - 2 × 3 array of 144ch hybrid avalanche photodetectors (HAPD)
    (prototype: Q.E. ~ 25%)
  - Front-end boards with ASIC
    (close to the final design)
- 2 trigger scintillation counters
- 4 tracking MWPCs

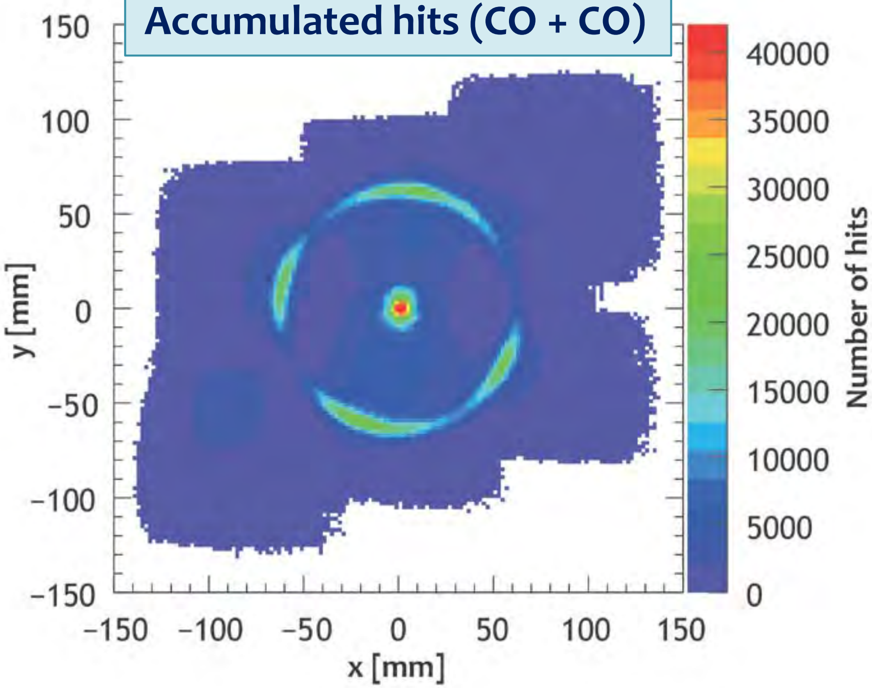
Setup in a light-shielded box



Beam Test: Results

- Analyzing "aerogel study runs" — except for aerogels, an identical (however, not the best) detector configuration
- Comparing the following conventional and pin-dried aerogel combinations
  - **CO + PD**: Conventional (n = 1.0467, Λ_T = 47 mm) + pin-drying (n = 1.0592, $\boldsymbol{\Lambda_T}$ **= 59 mm**)
  - **CO + CO**: Conventional (n = 1.0464, Λ_T = 42 mm) + conventional (n = 1.0548, $\boldsymbol{\Lambda_T}$ **= 34 mm**)

Accumulated hits (CO + CO)



- Naïve estimation from accumulated Cherenkov hits

$$\frac{\Delta\theta_C \sqrt{N_{\mathrm{p.e.}}}}{\sigma_\theta}$$

$\Delta\vartheta_C$ = 23 mrad (π/K) at n = 1.05, p = 4 GeV/c

4.5σ (CO + PD combination)

σ_θ **= 15.0 mrad,** $N_{\mathrm{p.e.}}$ **= 8.6**

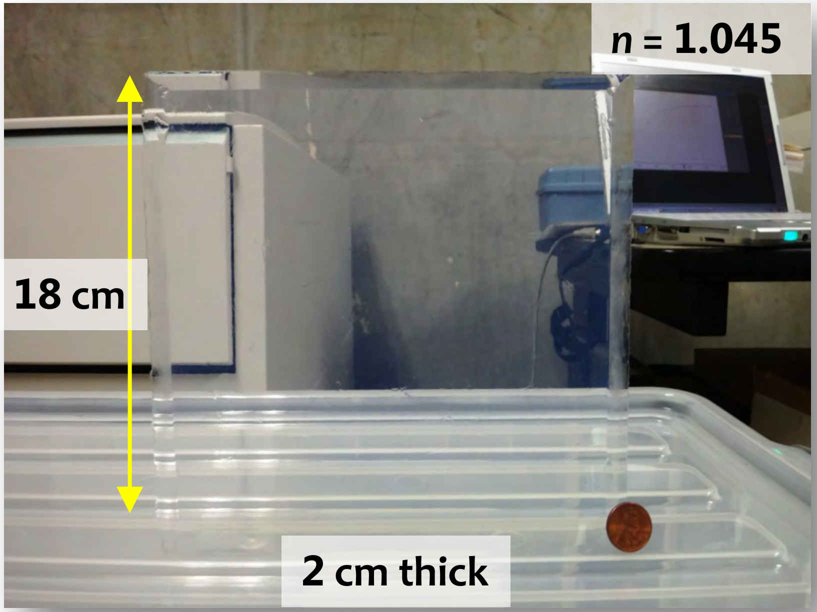
4.1σ (CO + CO combination)

σ_θ **= 14.5 mrad,** $N_{\mathrm{p.e.}}$ **= 6.6**

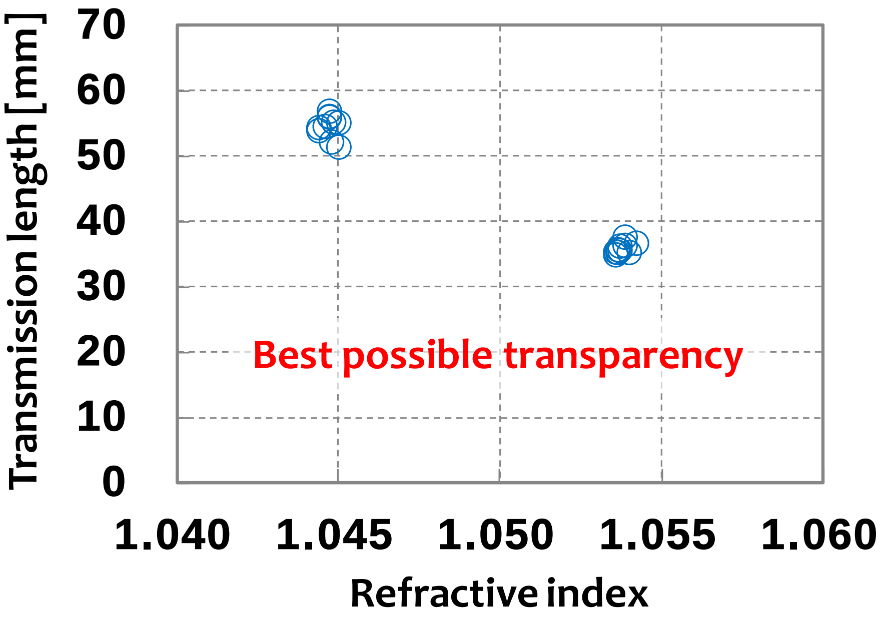
Mass Production

- **Mass production** started using the **conventional method** in late September.
- The 1st batch was delivered from JFCC to KEK in early November.
- Visual check and optical measurements were completed.
- **Crack-free** tile yield was **77%** (20 out of 26 tiles) → Close to our target (80%)

The 1st tile with no cracking



Result of optical measurements



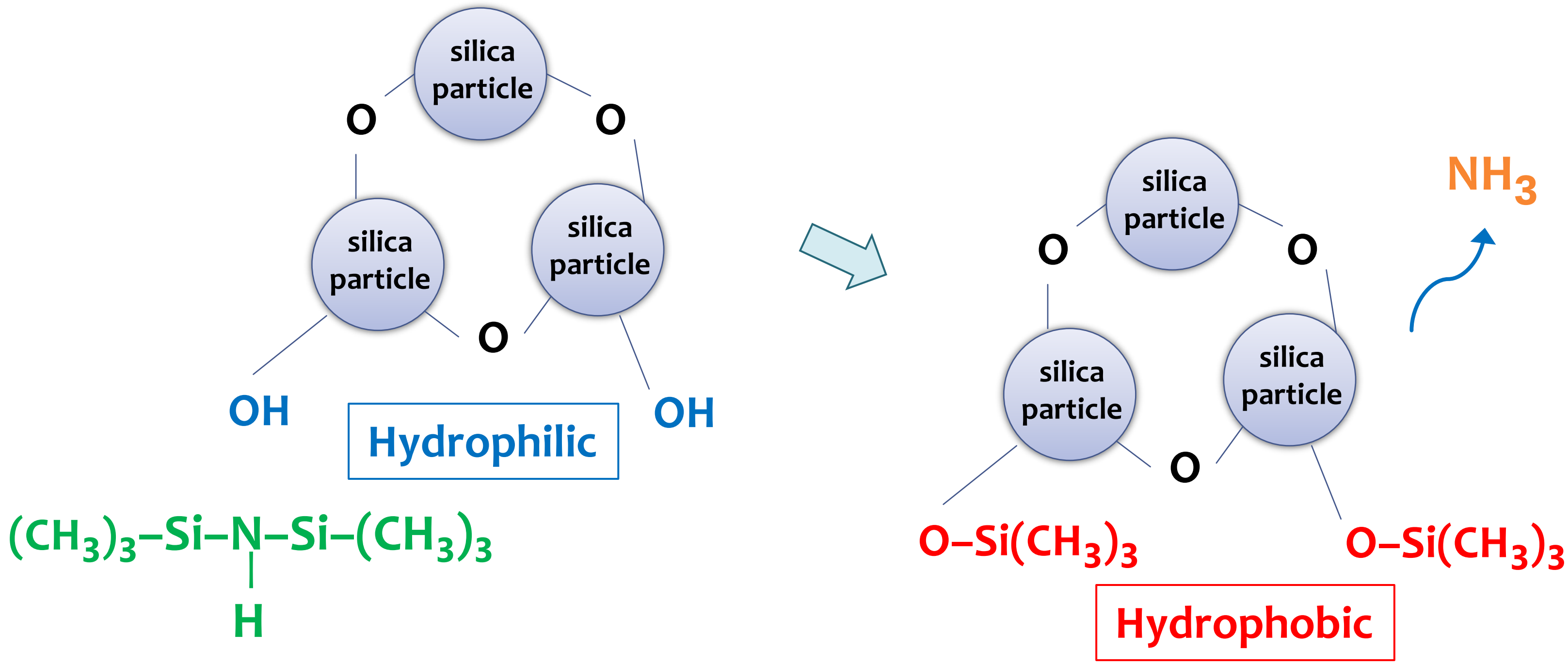
Summary

- Aerogel radiator is a key component of our RICH counter under development for use in the Belle II experiment.
- We developed the pin-drying method for fabricating high-refractive-index aerogels with excellent transparency.
- For four years, we have studied a technique for producing large-area aerogels with no cracking.
- **We have decided to manufacture both the upstream (n = 1.045) and downstream (n = 1.055) aerogels separately by the conventional method, and mass production has just been started.**
- **In a beam test, we confirmed that a prototype A-RICH counter fulfills our requirement for detector performance in a naïve estimation.**
- Further development for the pin-drying method will be conducted independent of the Belle II program.

Appendix

Hydrophobic Treatment

- Hydroxyl groups (–OH) on the surface of SiO_2 particles are likely to be charged and can easily react with other ions.
- Suppressing age-related degradation caused by moisture absorption



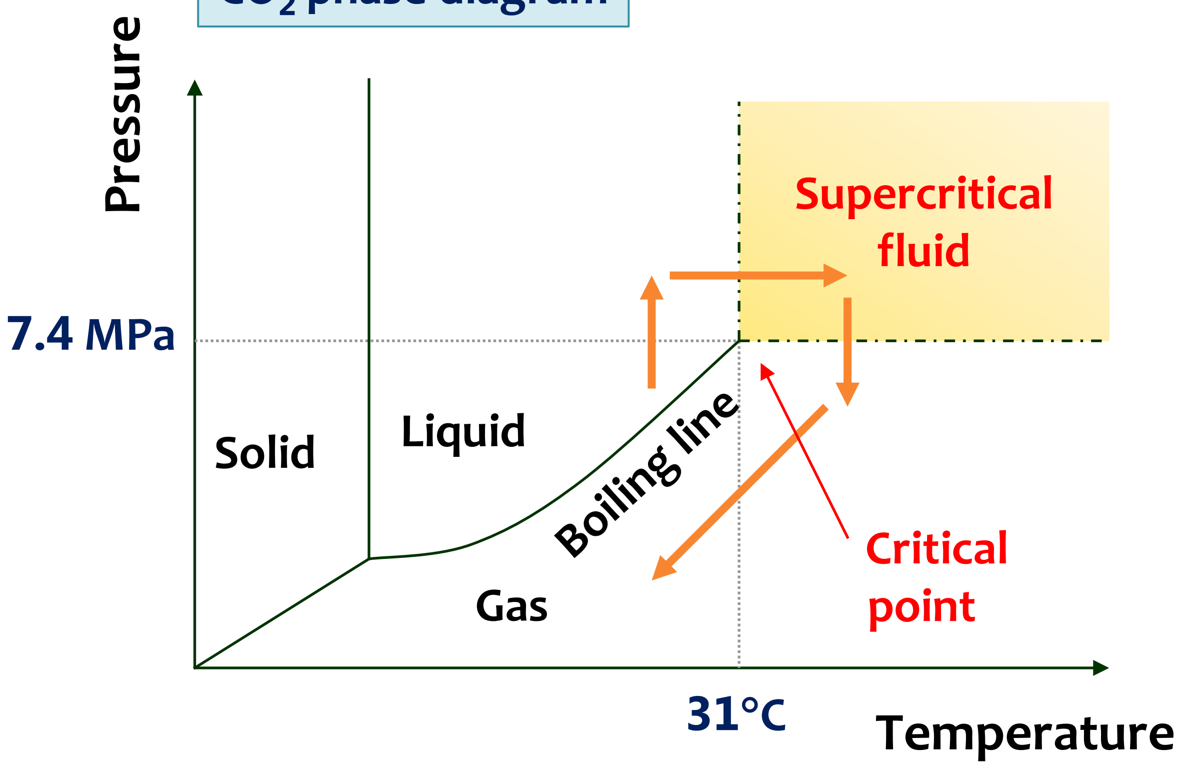
$$2(-OH) + ((CH_3)_3Si)_2NH \rightarrow 2(-OSi(CH_3)_3) + NH_3 \uparrow$$

Hydroxyl group Hexamethyldisilazane Trimethylsiloxy group Ammonia

Supercritical Drying

- Extracting liquid contents in wet gels under the supercritical phase.

CO_2 phase diagram

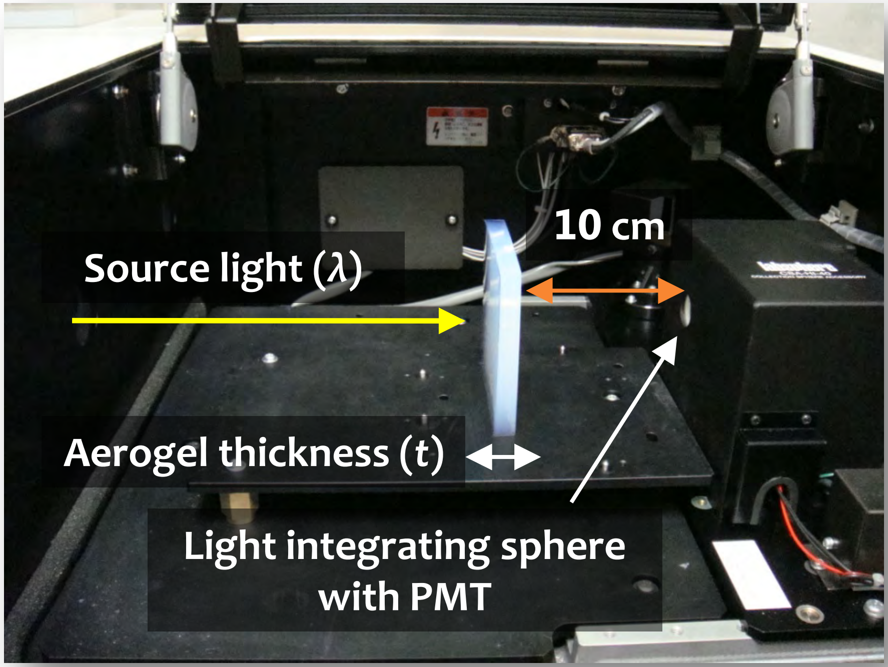


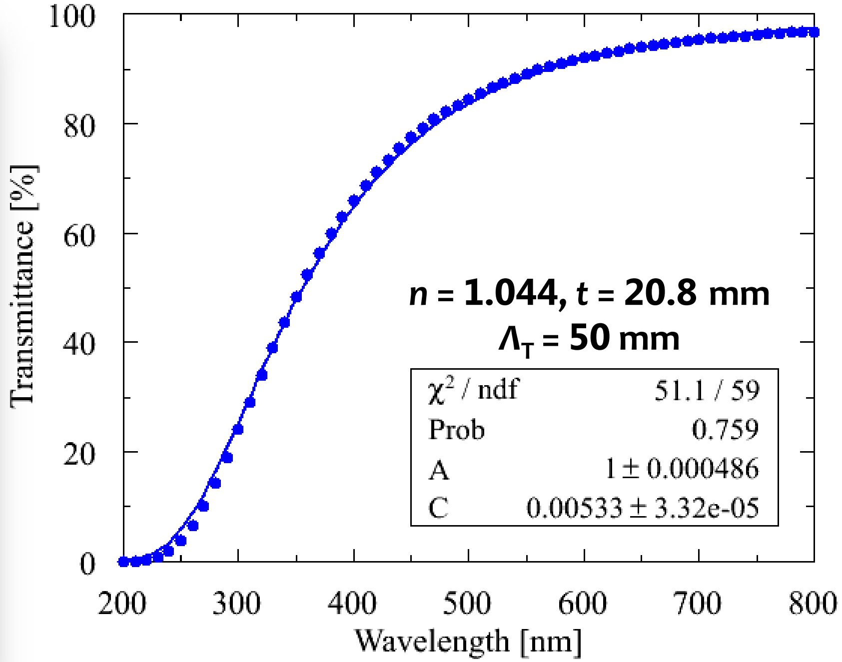
Broken aerogel by ambient pressure drying

Transmittance Measurement

- Measuring aerogel transmittance (T) using a spectrophotometer
  - Detecting only light going straight
  - $T = A\exp(-C \cdot t/\lambda^4)$ A, C: clarity parameters
- Transmission length at 400 nm wavelength: $\Lambda_T = -t/\ln T$

Setup in a spectrophotometer



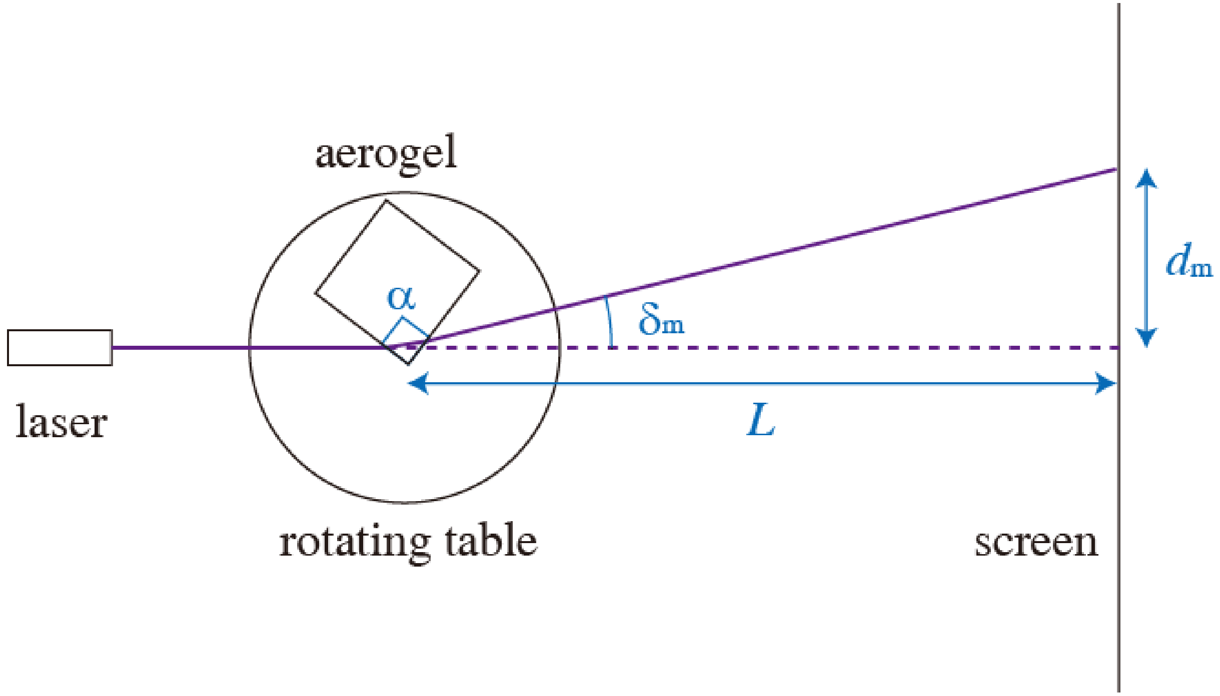


Refractive Index Measurement

- Fraunhofer method using a 405-nm laser

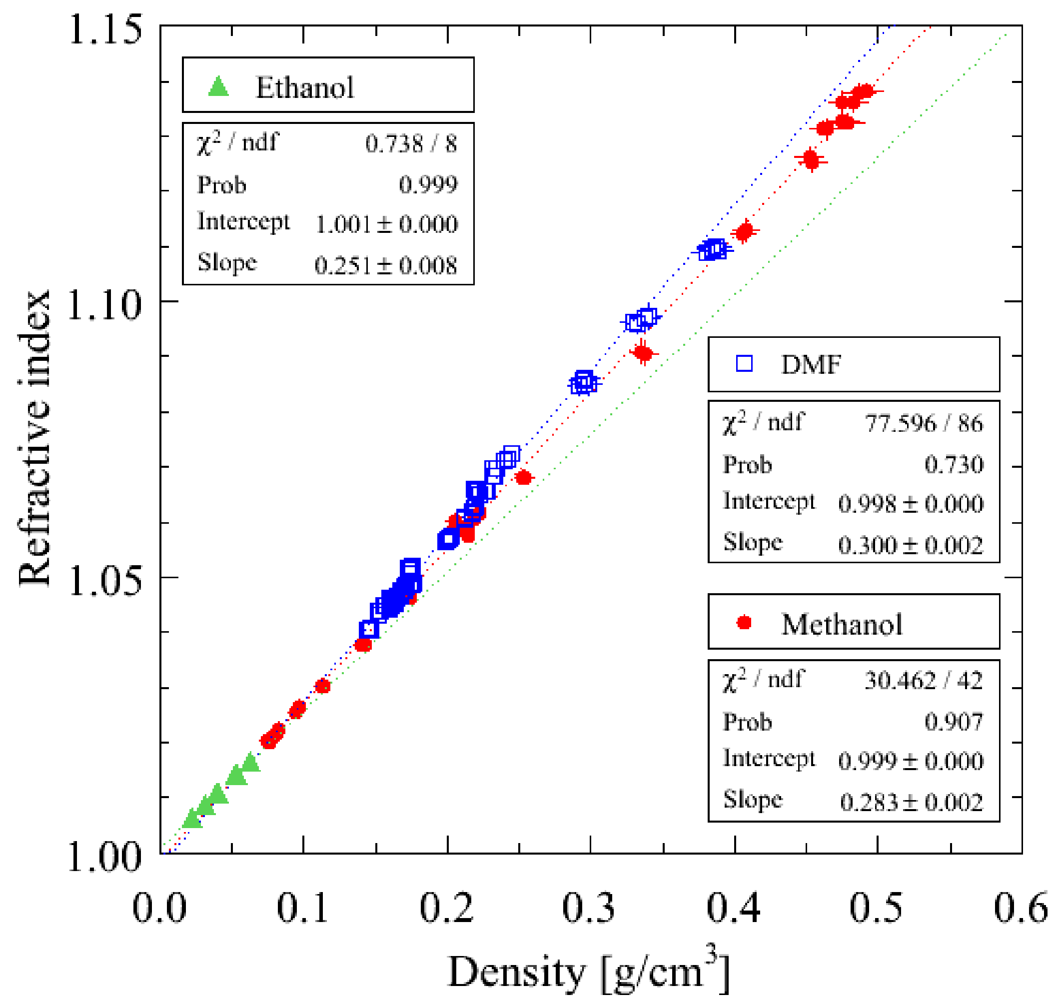
- Prism formula: $$\frac{n}{n_{air}} = \sin\left(\frac{\alpha+\delta_m}{2}\right)\left[\frac{1}{\sin(\alpha/2)}\right]$$

$$\delta_m = \tan^{-1}(d_m/L)$$



Refractive Index and Density

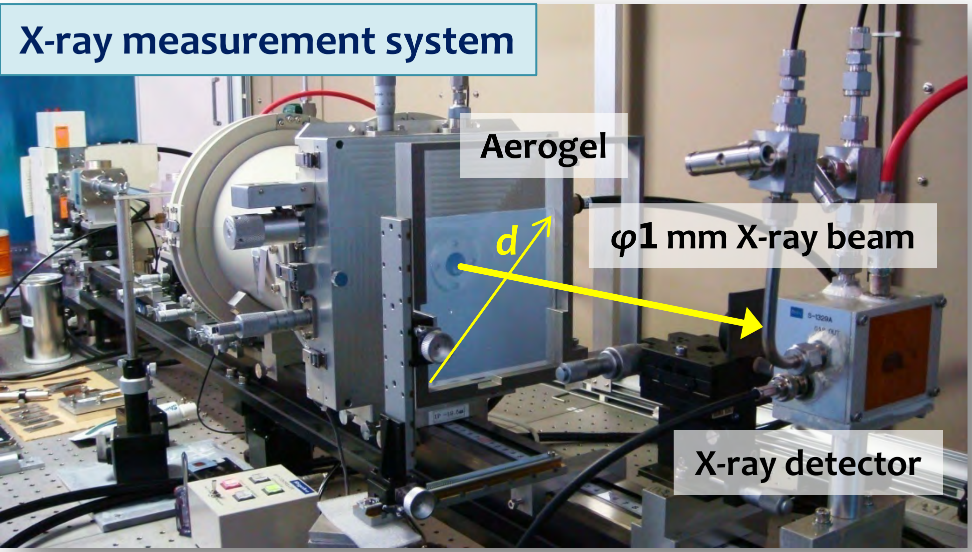
- Lorentz–Lorenz equation:
  $n^2 - 1 \propto \rho$
- Experimental equation:
  $n - 1 = k \cdot \rho$



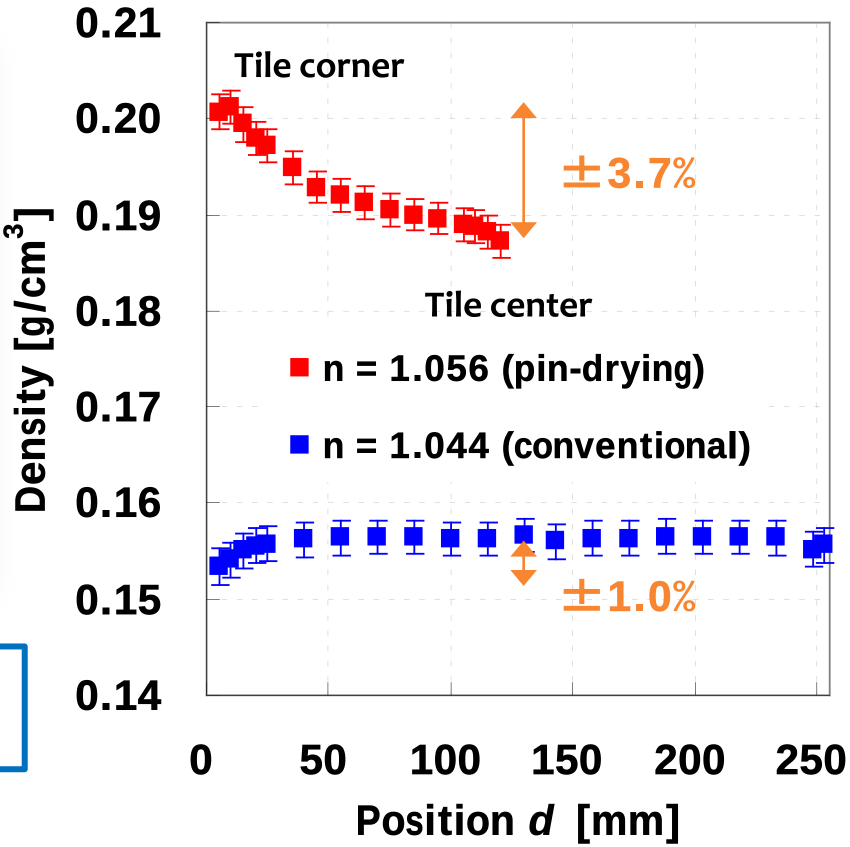
Density Uniformity Measurement

- X-ray absorption measurement is a promising technique for measuring density uniformity of an aerogel monolith.

X-ray measurement system



Data taken in 2012



Our requirement for the refractive index uniformity
$|\delta(n-1)/(n-1)| < 4\%$

- Large tiles produced by both the conventional and pin-drying methods fulfill the requirement for the density (i.e., refractive index) uniformity.

References

- Papers in this workshop
  - "Aerogel RICH Counter for the Belle II Forward PID," by S. Nishida
  - "144-channel HAPD for Aerogel RICH at Belle II," by S. Korpar
  - "Readout ASIC and Electronics for the 144ch HAPD for Aerogel RICH at Belle II," by H. Kakuno (Poster)
  - "Monte Carlo Study of a Belle II Proximity Focusing RICH with Aerogel as a Radiator," by S. Korpar (Poster)
- Journal papers

  - "Development of transparent silica aerogel over a wide range of densities," M. Tabata *et al.*, *Nucl. Instrum. Methods A* 623 (2010) 339.
  - "Hydrophobic silica aerogel production at KEK," M. Tabata *et al.*, *Nucl. Instrum. Methods A* 668 (2012) 64.
  - "Recent progress in silica aerogel Cherenkov radiator," M. Tabata *et al.*, *Physics Procedia* 37 (2012) 642.
  - "Optical and radiographical characterization of silica aerogel for Cherenkov radiator," M. Tabata *et al.*, *IEEE Trans. Nucl. Sci.* 59 (2012) 2506.