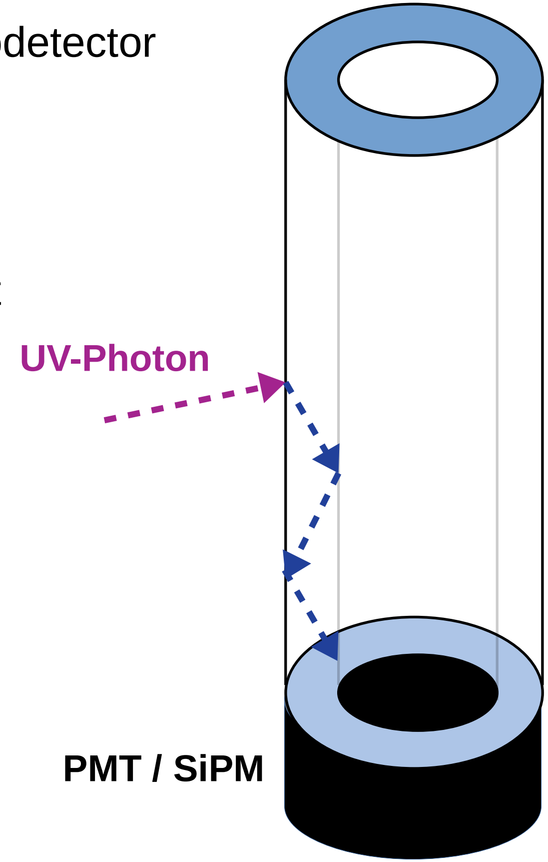
WOM Tube - Photon Exit Angle Distribution

Florian Rehbein, RWTH Aachen

3rd High-D Consortium Meeting
February 9, 2023

Wavelength-Shifting Optical Modules

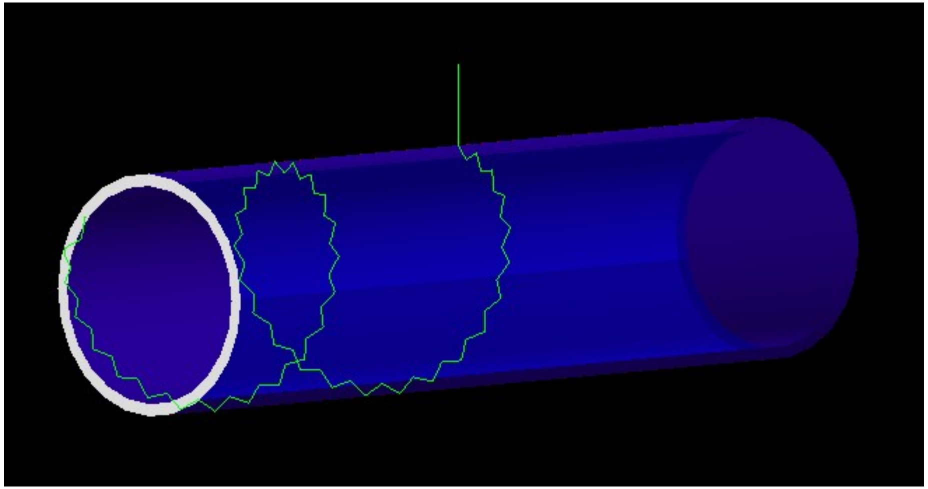
- **Wavelength-Shifting Optical Module (WOM)** = Large-Area Photodetector
- Cylindrical tube acts as **light collector**
- Outside of the tube coated with **wavelength-shifting paint**
  - ➔ Absorption of UV-photons, isotropic re-emission of visible light
- Internal **total reflection**, photons guided towards ends of tube
- Total capturing efficiency for secondary photons ≈ 73% (ideally)
- **PMTs / SiPMs**: Detection of photons



➔ Large effective area
➔ Large acceptance angle

Photon exit angle measurements - Motivation

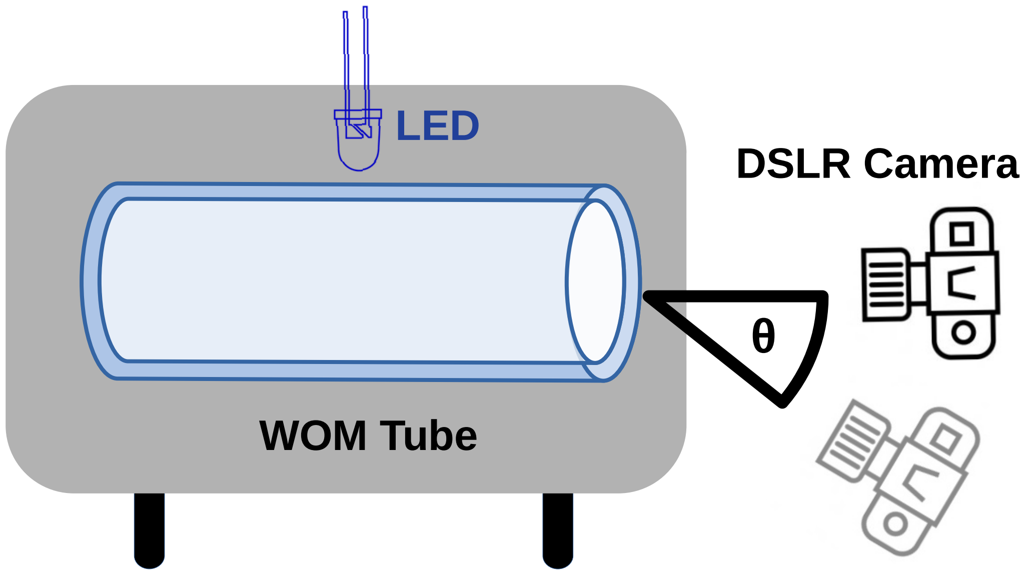
- **How much light can we effectively measure with SiPMs?**
  - ➔ Angular distribution of photons at exit window (SiPM angular acceptance)
- Optical properties of the WOM tube limit efficiency for detection of secondary photons
- Evaluate quality of WOM tube
  - ➔ Coating thickness
  - ➔ Surface quality
  - ➔ Efficieny of photon transport



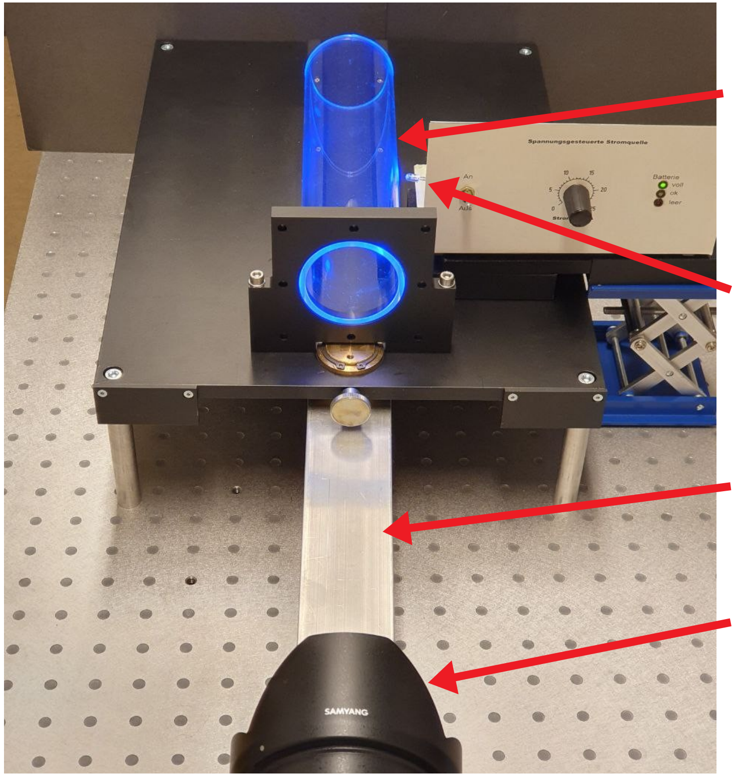
Photon path (Geant4)

Photon exit angle measurements - Setup

- Idea: Use **DSLR camera** to capture photons of the WOM tube
- Change **exit angle** of captured photons by adjusting **camera angle θ**
- Light source: **UV LED**
  - λ_{peak} = 375 nm
  - $\Delta\lambda$ = 9.0 nm
  - Opening angle ≈ 40°
  - Placed in the middle of the tube in close distance to surface (≈ 2 cm)
  - ➔ **Most photons hit the WOM surface approximately vertically**



Photon exit angle measurements - Setup

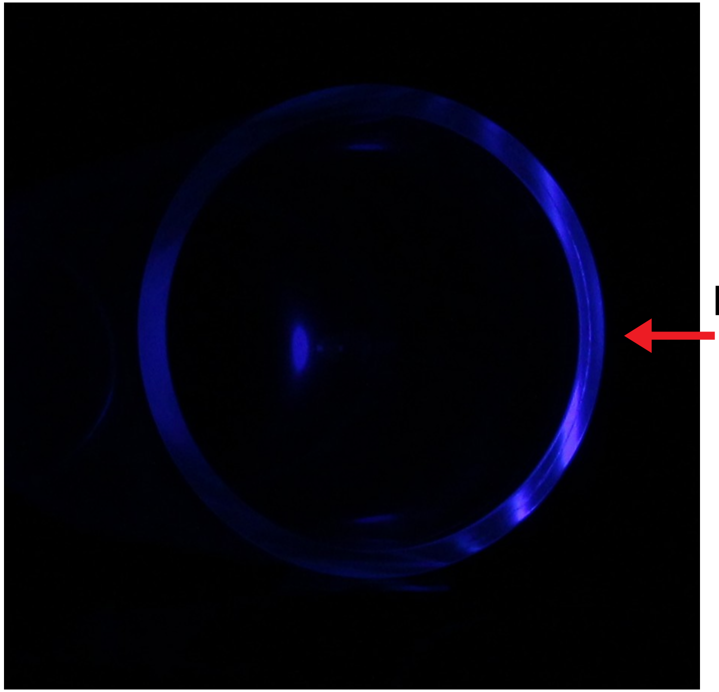


WOM tube

LED

Lever arm

Camera

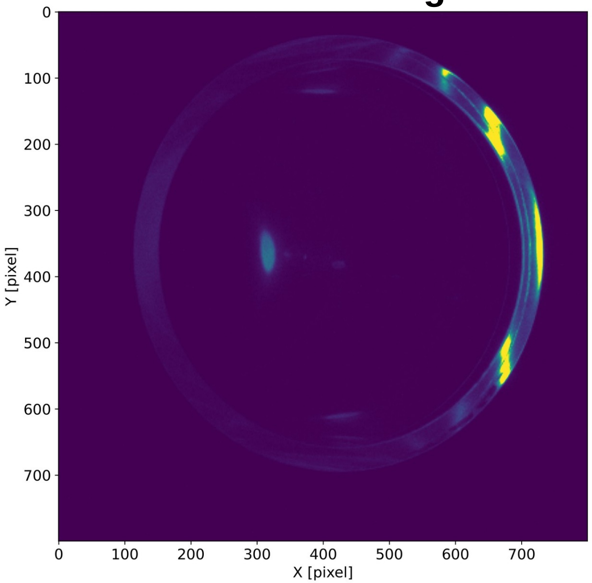


Light source position

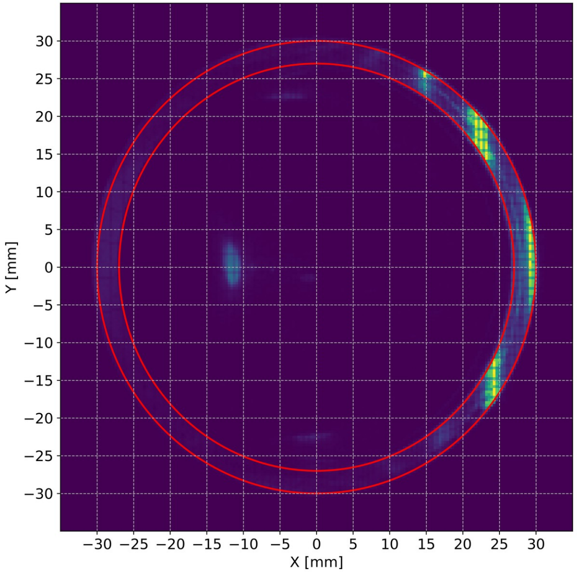
20°

Photo Processing

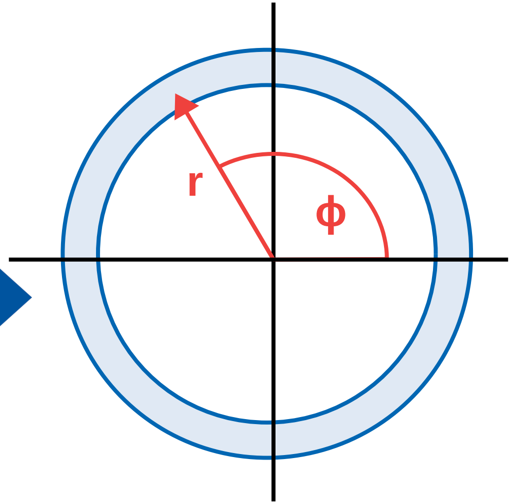
20° camera angle



Raw image



Reconstructed WOM surface

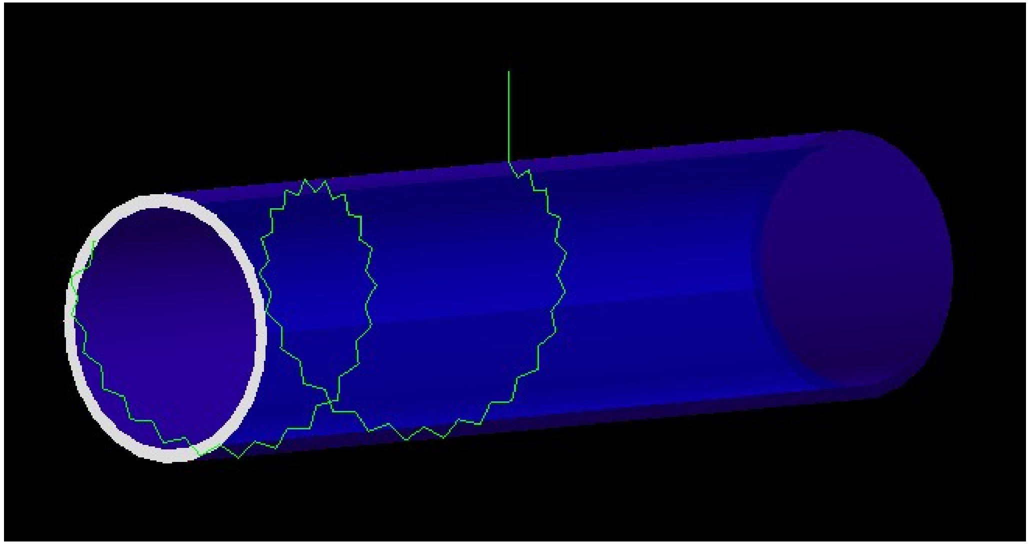


- Camera sensor: **blue**, red, and green pixels
- Algorithm identifies WOM surface on the photo
- Pixel coordinates of the camera sensor are transformed to reconstruct the geometry of the WOM surface (resolution ~ 0.1mm)

- Map each camera sensor pixel to position on WOM surface
- Allows for comparison of different camera angles

WOM Tube Simulation

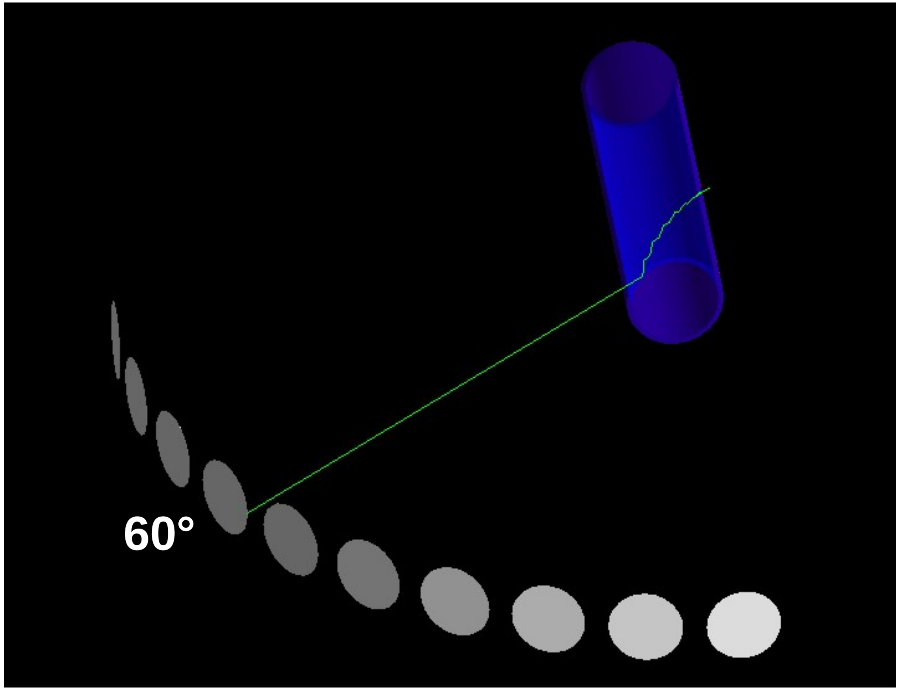
- Based on simulation toolkit Geant4
- Simulation of light source (LED): Position, direction, wavelength distribution, opening angle
- Simulation of the WOM tube: Wavelength-shifting properties of the paint, reflection and attenuation of photons



Photon path
(Geant4)

Simulated Images of WOM surface

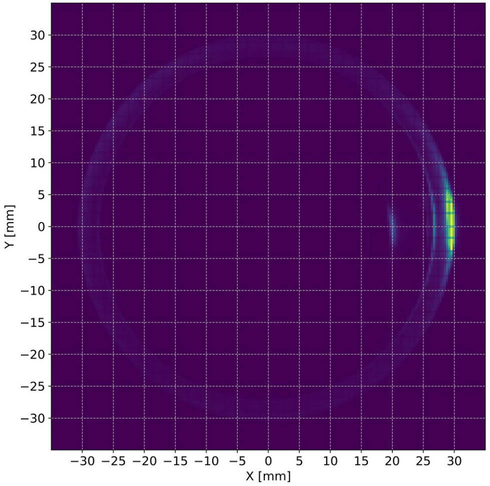
- Simulation of camera lens at different angles
- Lens diameter and distance to tube correspond to real measurement setup
- All photons leaving the tube and end up hitting a simulated camera lens at given angle contribute to the reconstructed image
- Reconstruction of image = reconstruct the position of the photon when exiting the WOM tube



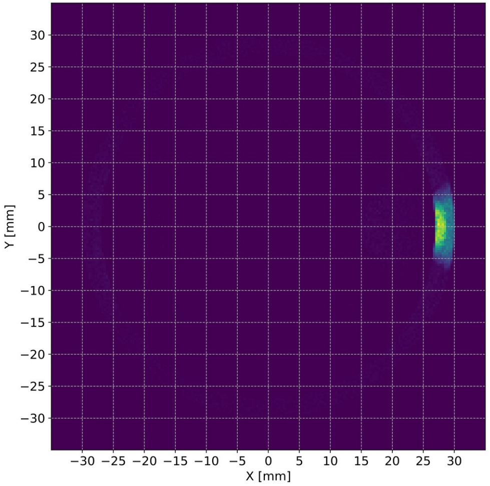
Different simulated camera lens angles (Geant4)

Simulation vs Measurement

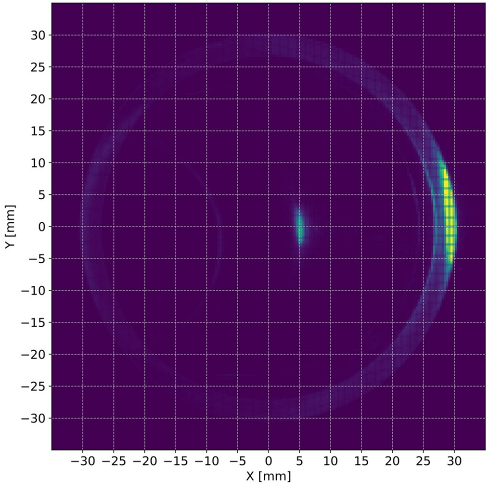
Real Photo, 0°



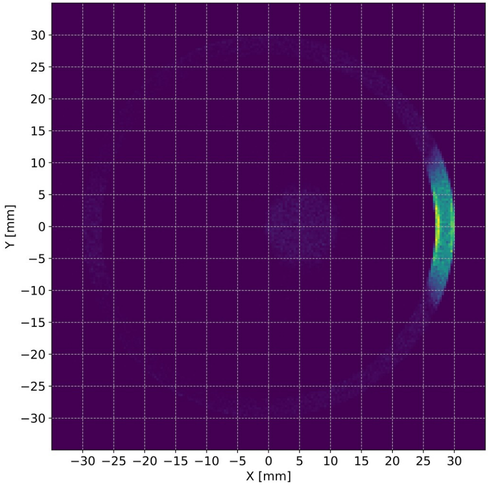
Simulation, 0°



Real Photo, 10°



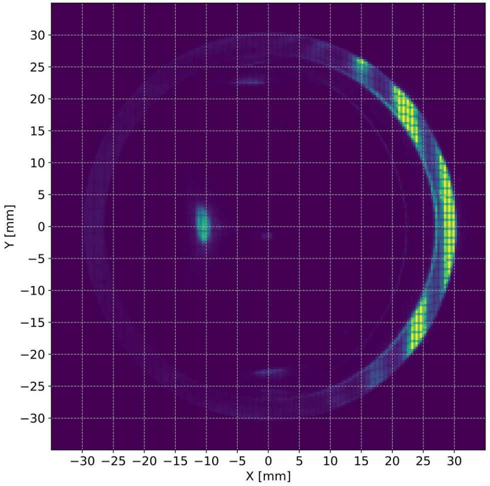
Simulation, 10°



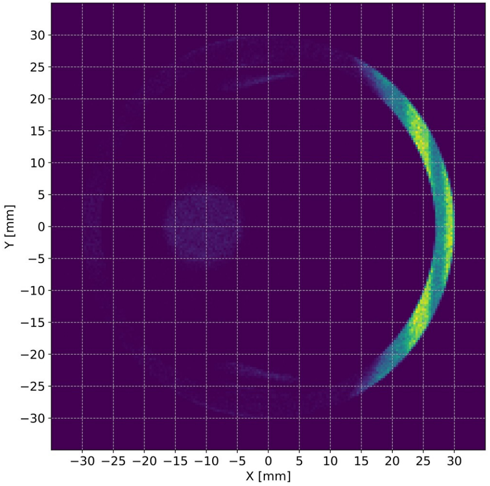
- WOM surface better visible in real photos (more homogeneously illuminated)
  - ➔ Simulated surface perfectly smooth, real surface has roughness/scratches/...
- **Structural similarities** clearly visible

Simulation vs Measurement

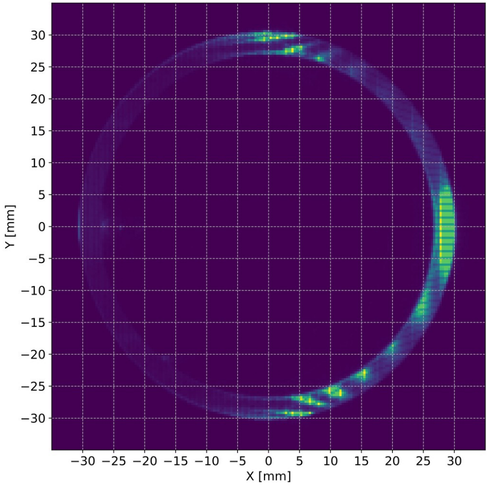
Real Photo, 20°



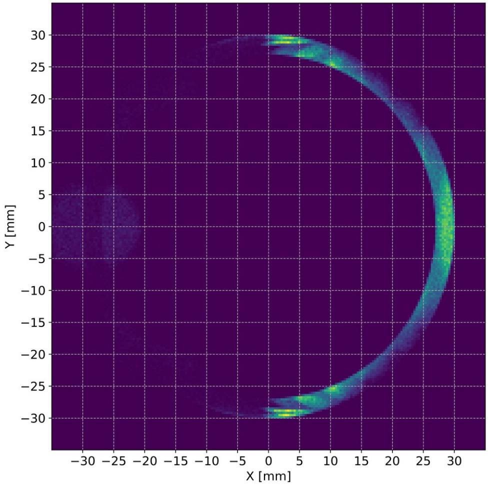
Simulation, 20°



Real Photo, 30°



Simulation, 30°



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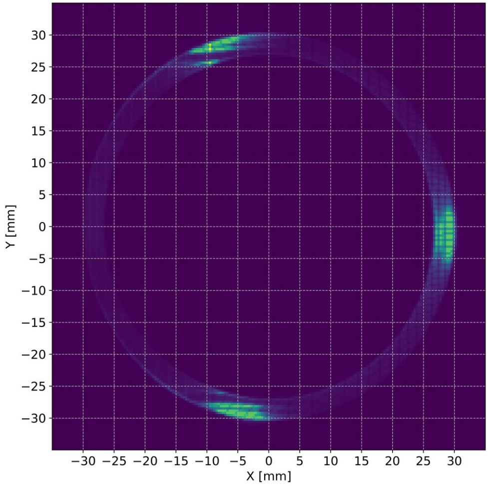
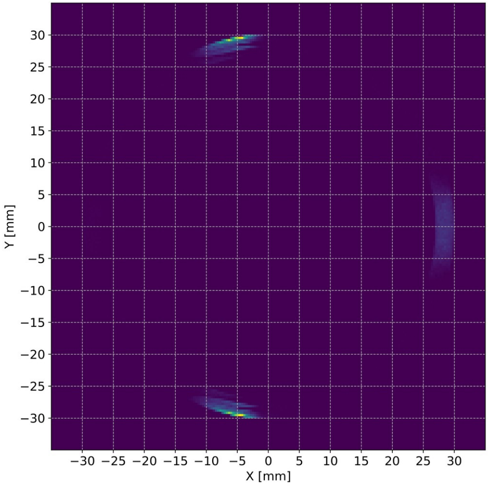
Simulation vs Measurement

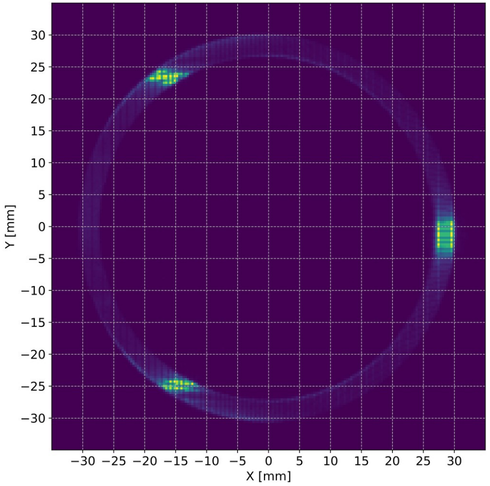
Real Photo, 40°



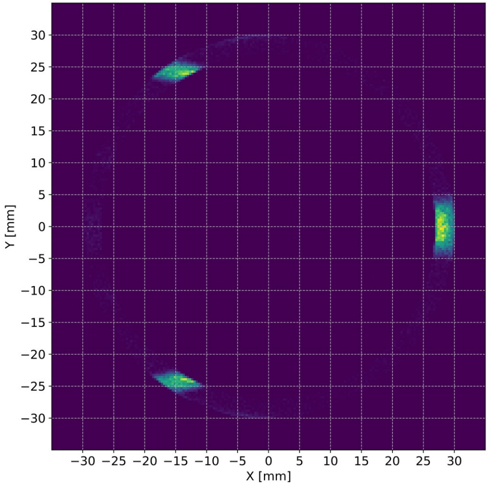
Simulation, 40°



Real Photo, 50°



Simulation, 50°



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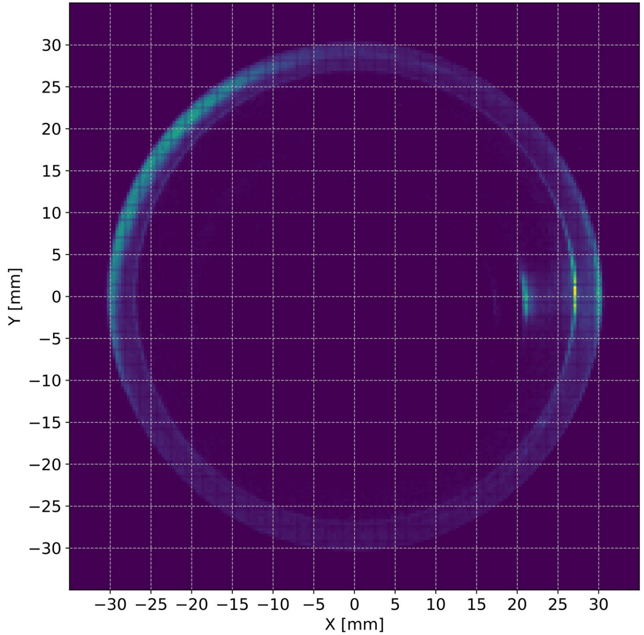
➔ What can we learn from the photos?

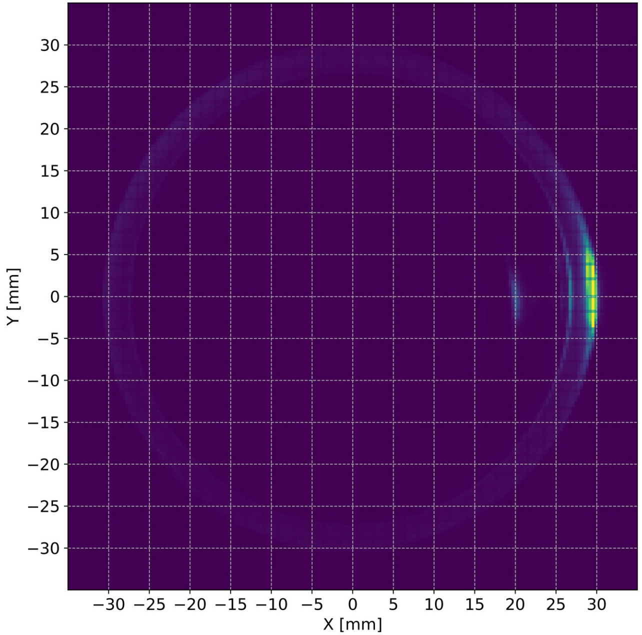
Tubes comparison

0° camera angle



- Single coating = single layer of paint
- ~ 5 micrometer thickness

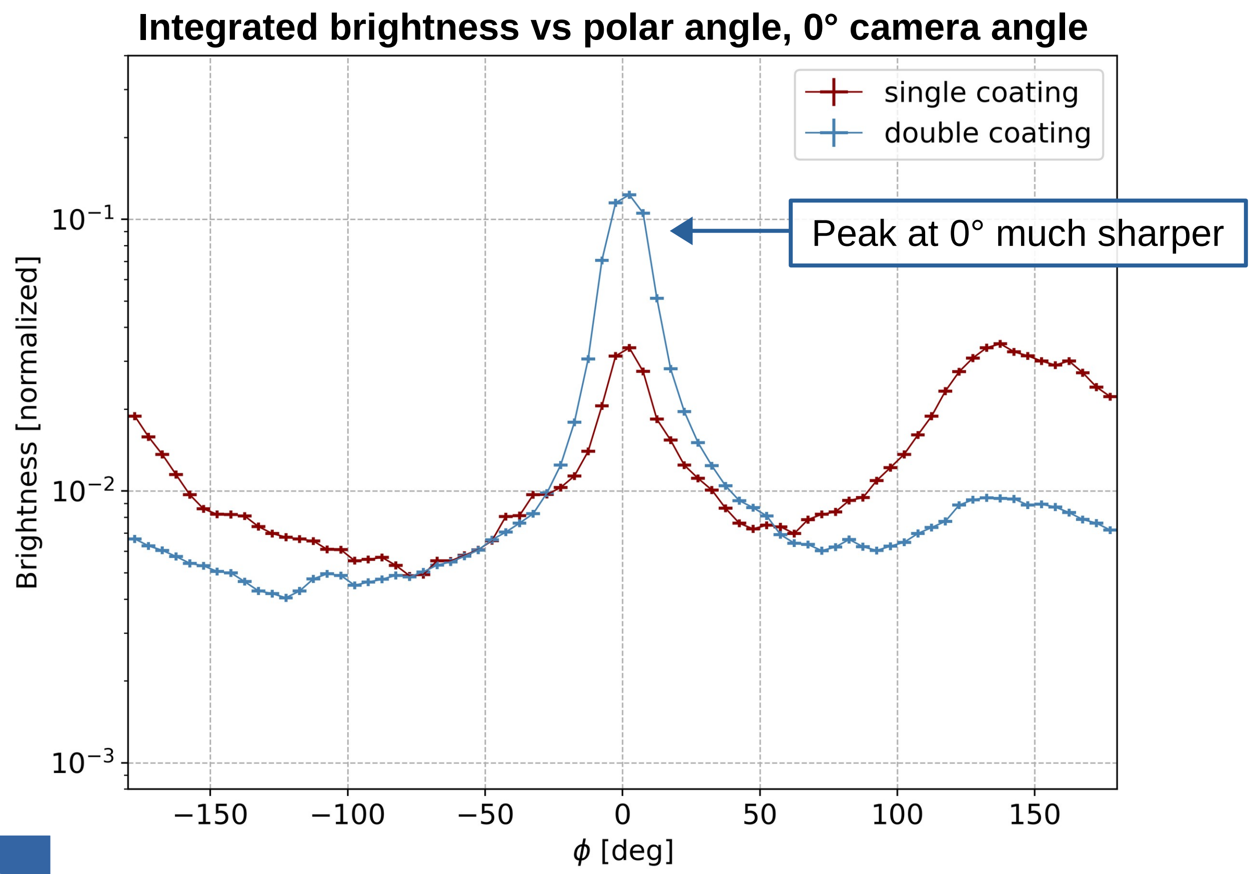
0° camera angle

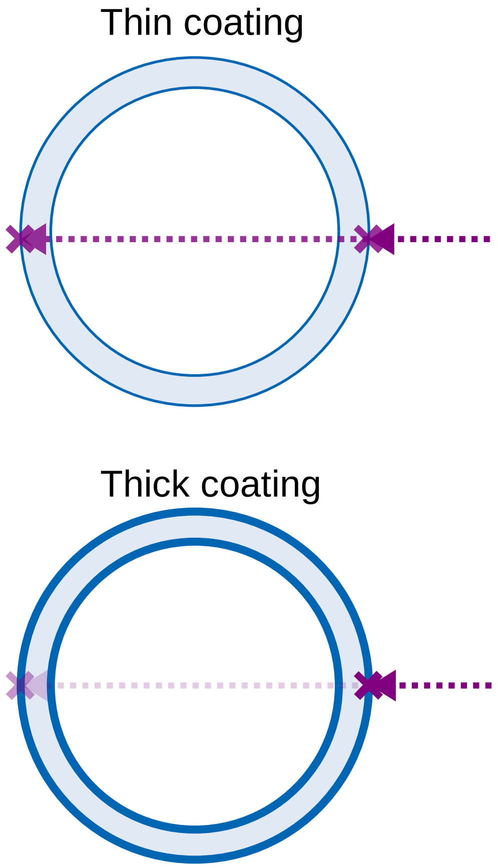


- Double coating = two layers of paint
- ~ 20 micrometer thickness

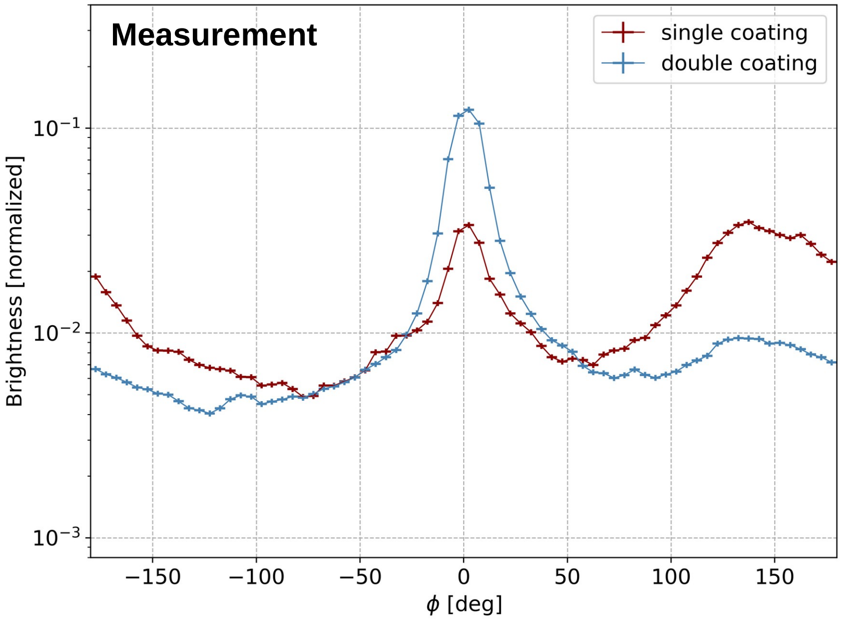
➔ Why are the distributions so different?

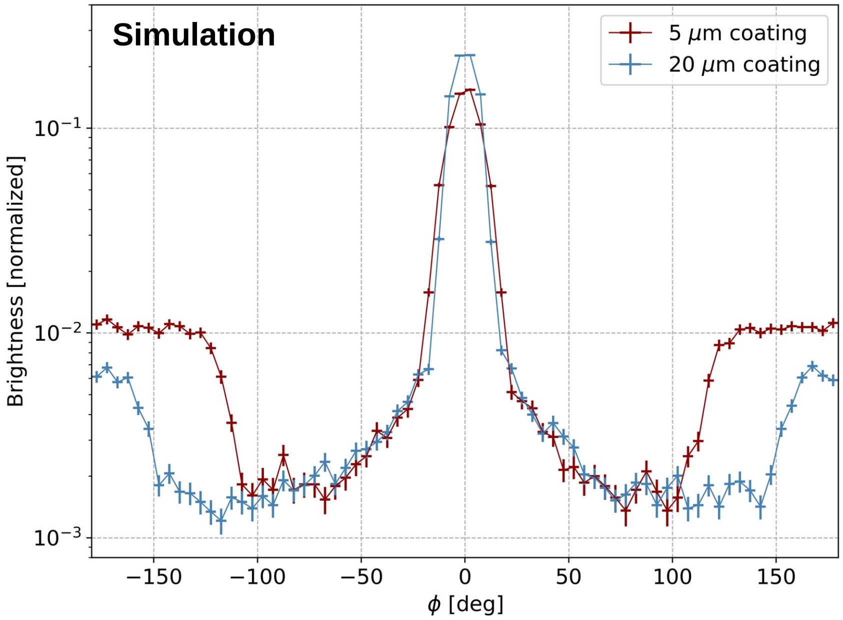
Tubes comparison





Tubes comparison

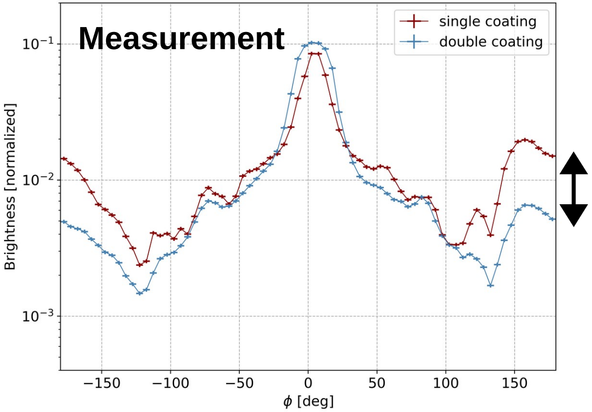


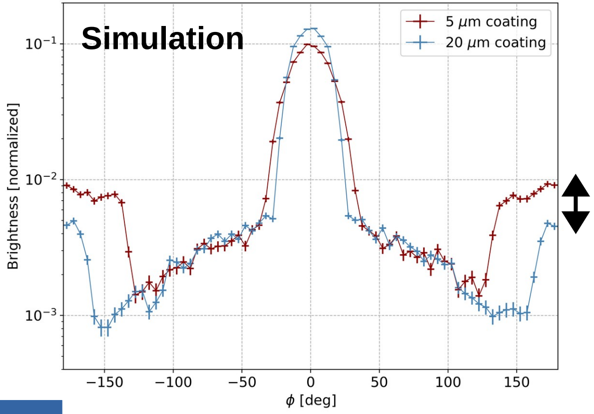


- Simulation with significant differences, but seems to support the assumption

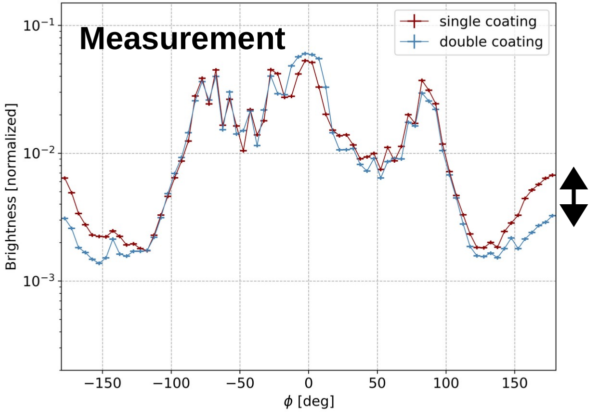
Tubes comparison

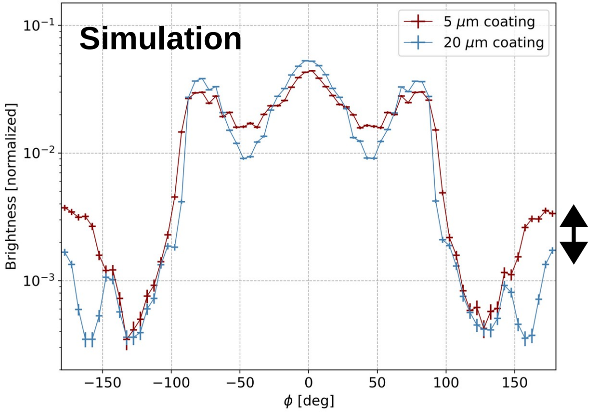
10° camera angle





30° camera angle

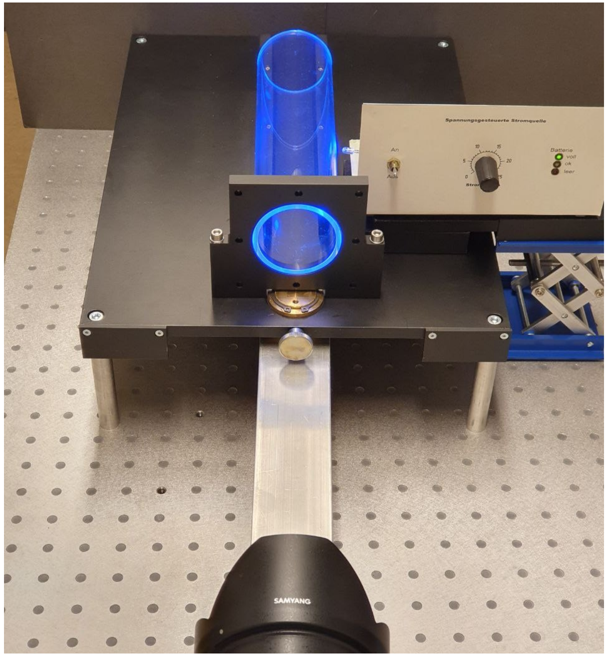


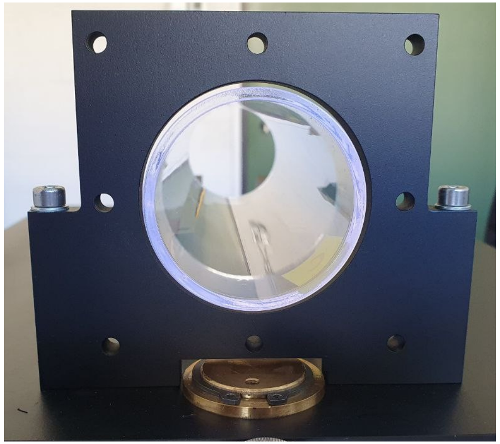


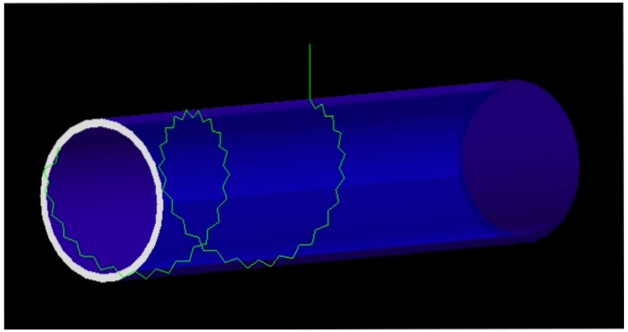
- Simulation confirms: Thicker layer of coating results in more photons on the other side of the tube
- Experimental setup provides measurement of coating thickness
- Quality control?

Summary

- WOM tube simulations show good agreement with the measurement: structures can be reproduced
- Measurement setup sensitive to thickness of WLS paint
  ➔ Quality control
- Outlook: Automated setup with adjustable light source position
- Add grid of LEDs for calibration





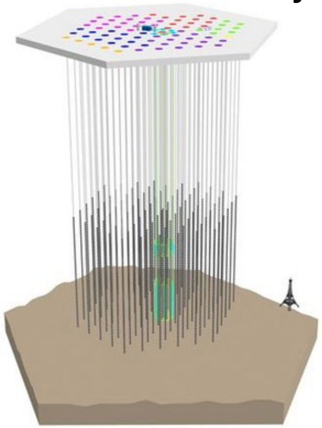


Backup

Wavelength-Shifting Optical Modules

- First proposed for large-scale water Cherenkov detectors in neutrino physics (e.g. IceCube) [1]
  - ➔ Instrumentation with large number of photosensitive devices (IceCube: PMTs)
  - ➔ Sensitivity limited by mass of instrumented volume, instrumentation density and photo collection area of each sensor
  - ➔ More photodetectors: significant cost factor
  - ➔ Larger photodetectors increase noise rate
- Solution: Increase sensitive area of each detector with light collector

IceCube Observaory



physik.hu-berlin.de

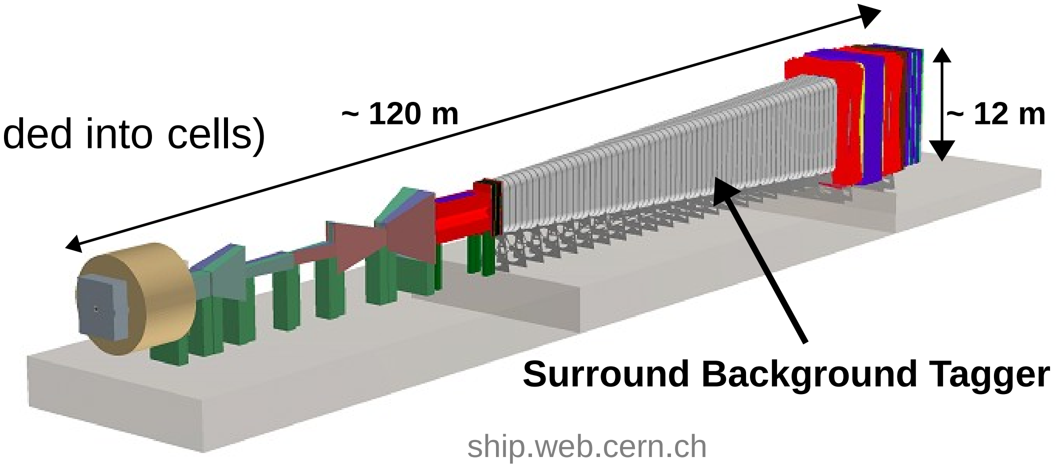
20“ PMT, Super-Kamiokande

C. Warner, SPIE (2016)

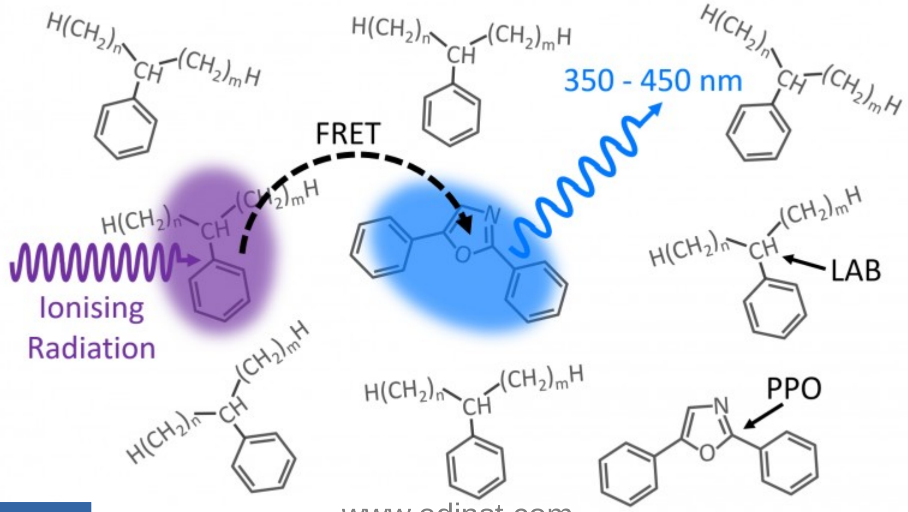
[1] The Wavelength-shifting Optical Module (arXiv:2112.12258)

WOMs in large-area liquid-scintillator detectors (SHiP-SBT)

- **SBT** (**S**urround **B**ackground **T**agger)
  - ➔ Filled with ~300 m³ liquid scintillator (divided into cells)
  - ➔ Solvent: LAB (Linear alkylbenzene)
  - ➔ Fluor: PPO (2,5-diphenyloxazole), 2g/l



ship.web.cern.ch



www.edinst.com

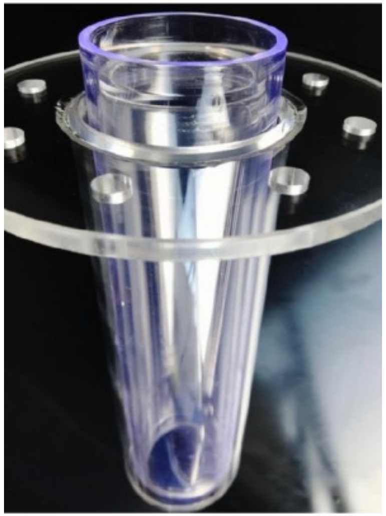
Challenges for detection of scintillation photons:

- Energy resolution and energy threshold limited by properties of photo sensors → **Highly efficient**
- Large volume → **Cost-effective**

WOMs in large-area liquid-scintillator detectors (SHiP-SBT)

- **PMMA tube:**
  - 23 cm length, 60 mm diameter, 3 mm thickness
  - Coated with wavelength-shifting (WLS) paint (Bis-MSB)

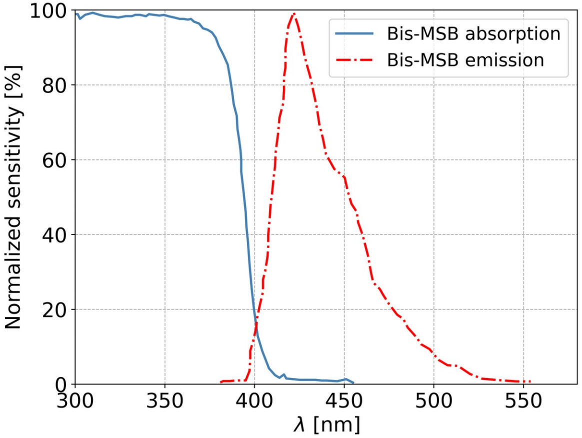
WOM tube



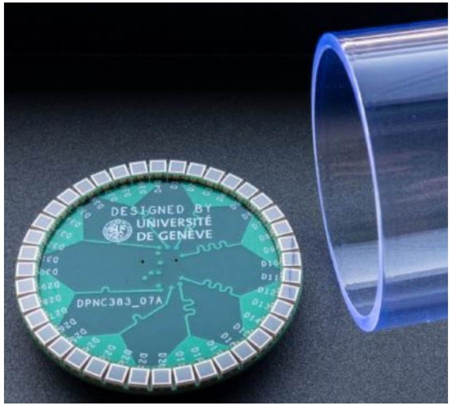
Vessel

- **PMMA vessel:**
  - Insulation from liquid scintillator
- **Photosensors:**
  - 40 SiPMs directly coupled to the exit surface of the tube
  - 3 mm x 3 mm sensitive area

arXiv:2107.10194

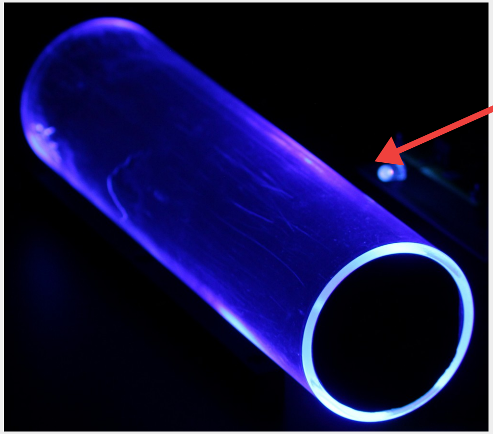


WLS coating

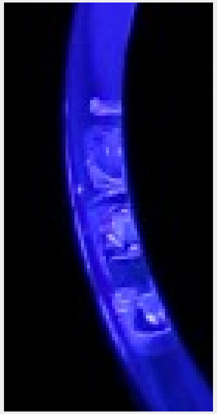


40-SiPM PCB

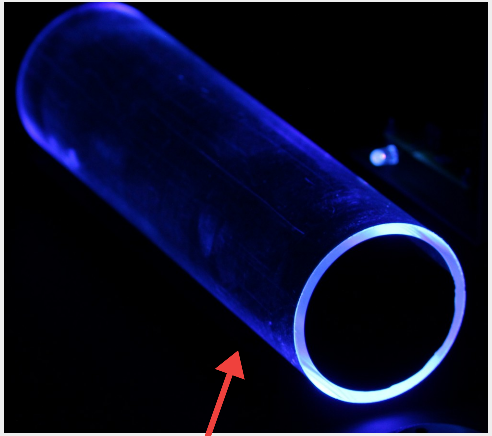
WOM Tubes and Surfaces



Double-sided coating



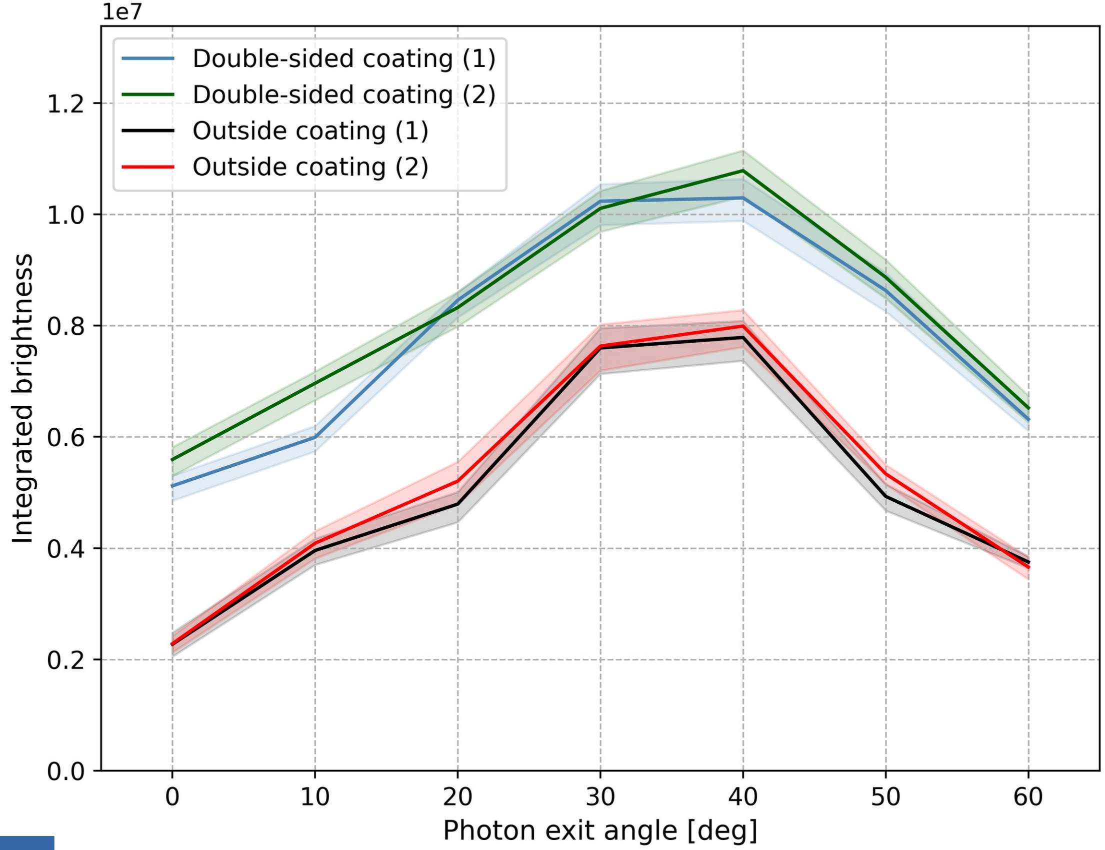
Visible scratches/ cracks

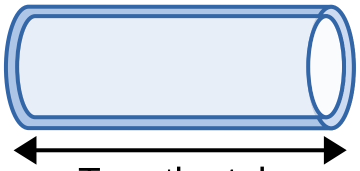


Outside coating

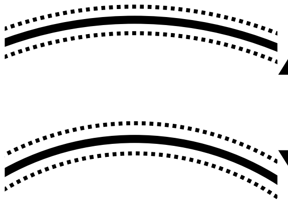
Residue from coating process on one of the surfaces (both tubes)

Photon exit angle distribution





- Error bands: Variation of radius by ± 0.1 mm



- No significant differences between the two surfaces of each tube