Development of Water Cherenkov Detector

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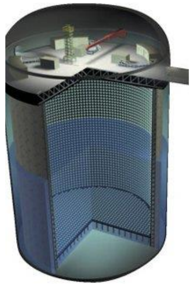
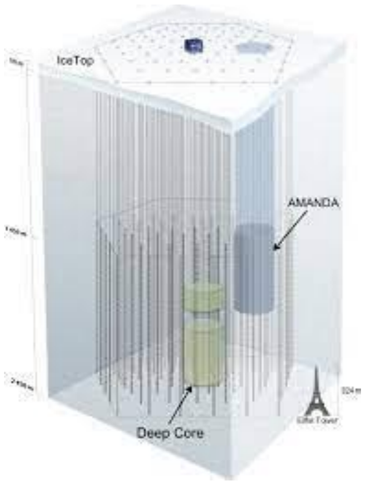
Timeline: Milestones in Water Cherenkov Detector Development

- 1934 — The first Cherenkov observation: P. A. Cherenkov
- 1937 — Development of theory: Igor and Tamm
- 1967 — Haverah Park experiment. Maybe the first water Cherenkov detector (WCD). The first surface WCD array
- 1970s — First Deep-water/large-volume concept (DUMAND). Mton~Gton.
- 1982, 1983 — IMB and KamiokaNDE. Earliest large underground WCD (~kton)
- 1986 —KamiokaNDE-II start. Upgraded for observation of solar neutrino. (1988: first observation)
- 1995 — Baikal NT-36. The first Lake-based neutrino telescope. (3 strings)
- 1997 — AMANDA. The first ice-based neutrino telescope. ~Mton
- 1999 — SNO (D_2O) heavy-water detector enables flavor-sensitive measurements.
- 2002 — KamLAND. The first instrumented water Cherenkov outer veto for a non-water main detector.
- 2003 — Concept of Gd loaded WCD for neutron tagging.
- 2006 — ANTARES. The first sea based neutrino telescope. ~10 Mton
- 2010s — R&D of Water based LS (WbLS)
- 2020 — Gd loaded Super-Kamiokande (SK-Gd) begins.

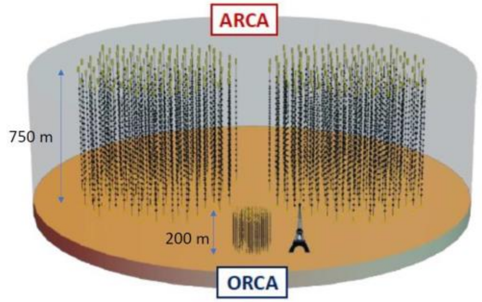
Water tank, Ice, Lake, Sea — distinctive techniques



- Water tank (eg. Super-Kamiokande): purification; radon removal (for low energy physics); recirculation; cleanroom assembly.



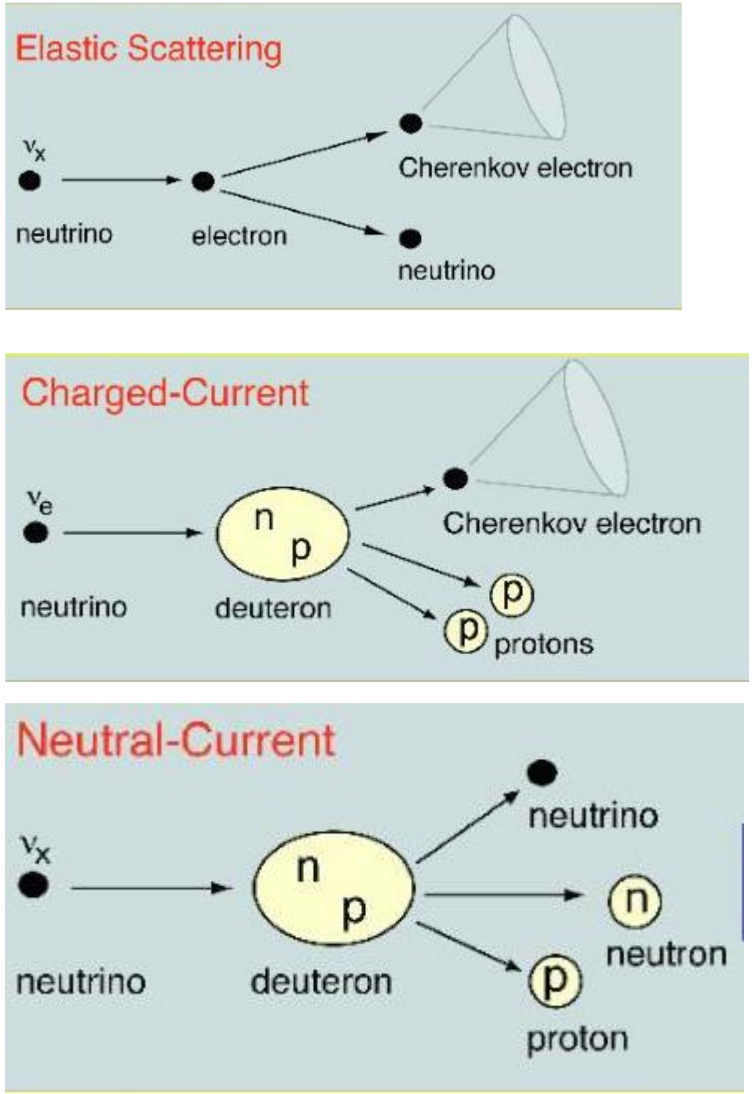
- Ice (eg. IceCube): drilling; permanent digital optical modules(DOM); cold-electronics; ice optical mapping.
- Lake/Sea (e.g., Baikal-GVD / KM3NeT): sealed optical modules; window fouling monitoring; acoustic positioning; corrosion protection; pressure housings; electro-optical cabling; ROV/AUV deployment.



Choice of Water for Detector Tanks

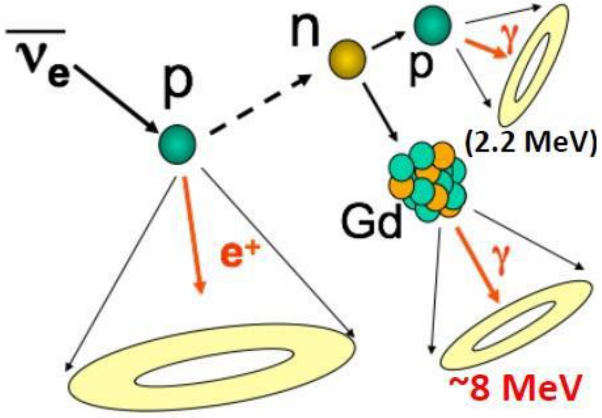
NC, CC indistinguishable

- Water (H_2O): the baseline Cherenkov medium. Only by elastic scattering. (NC, CC indistinguishable)
- Heavy water (D_2O) (e.g., SNO): isotopic medium for flavor-sensitive measurements; special handling and radiopurity.

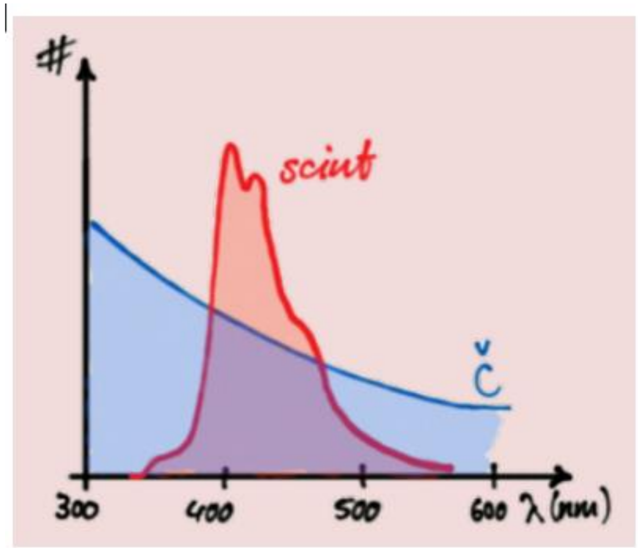


Choice of Water for Detector Tanks

- Gd-doped water (Gd-WCD): soluble Gd for neutron tagging; not ultrapure — requires Gd handling, monitoring, and dedicated recirculation/filtration.



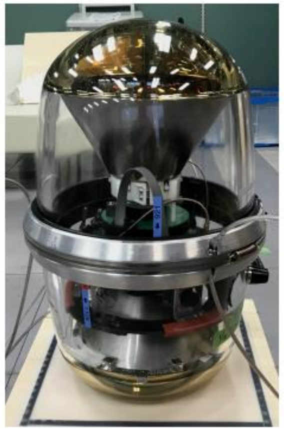
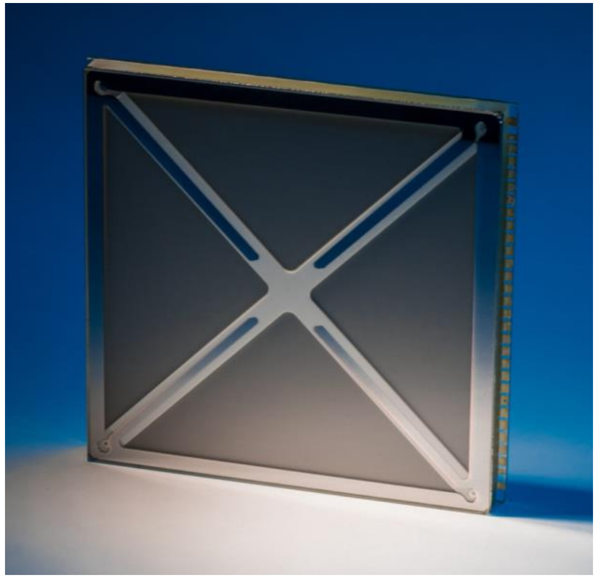
- Water-based liquid scintillator (WbLS): hybrid Cherenkov + scintillation; not ultrapure — demands chemical stability control, optical separation algorithms, and compatibility measures.



Photon sensors

- Sensor types: large PMTs; multi-PMT; LAPPDs

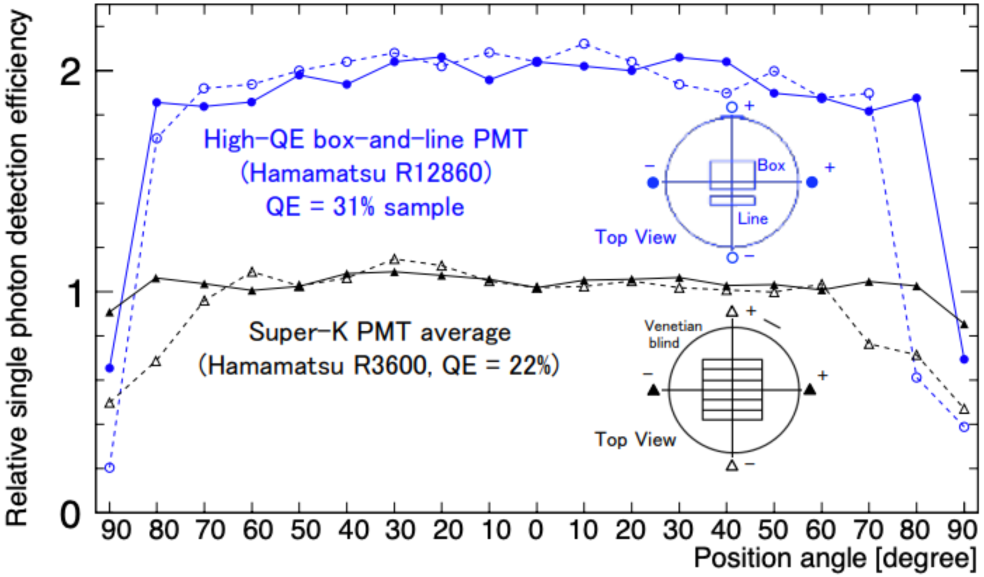


Photon sensors

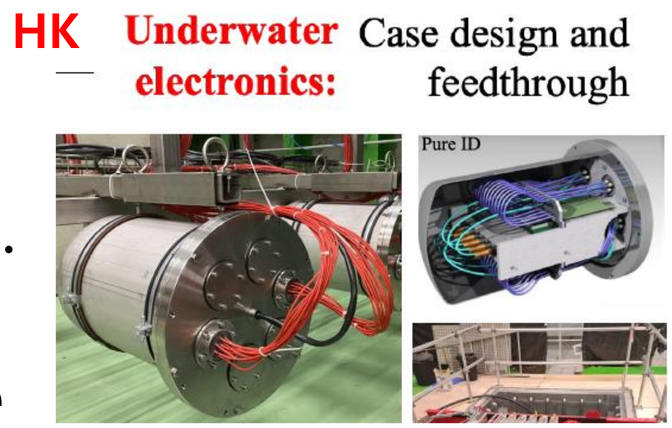
- Key specs: quantum efficiency; time jitter (TTS); dark rate; pressure and temperature ratings.

- Integration elements: base electronics; HV supply; magnetic shielding; optical coupling.



Timing & DAQ architecture

- Timing goals: sub-ns to few-hundred-ps synchronization.
- Clock distribution: GPS / White Rabbit / optical timing; local oscillator resynchronization.
- DAQ modes: triggered vs continuous streaming; waveform digitizers vs TDCs; data reduction strategies.
- Scaling issues: scale-out distributed architecture (edge processing, hierarchical aggregation); network and storage scalability; real-time processing pipelines and fault tolerance.

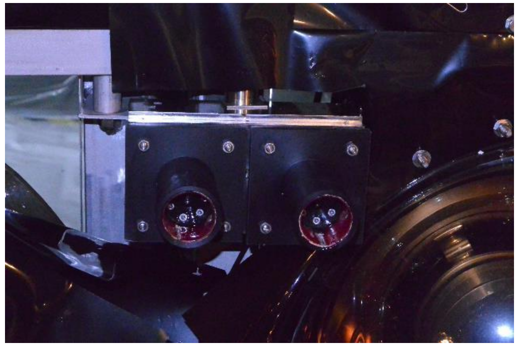


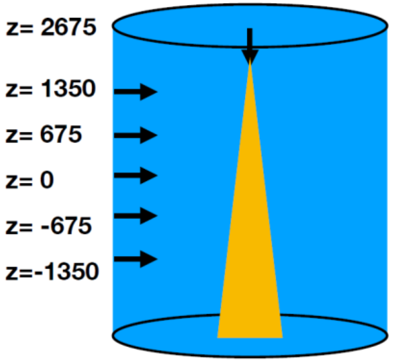
Calibration and environmental monitors

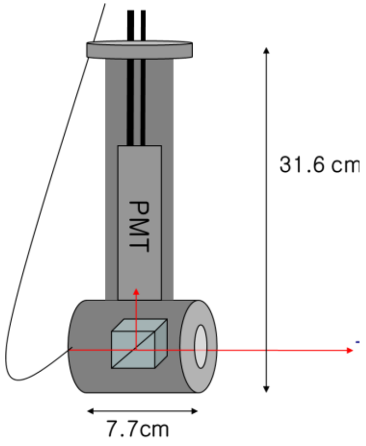
- Calibration: regular gain/timing scans; in-situ optical property measurement etc.
- Environmental monitor: turbidity, conductivity, radon, temperature, biofouling monitors.
- Scaling issues: distributed beacon networks with synchronized timing; automated remote calibration and scheduling; sampling design (gridded beacons) and simulation-driven optimization.

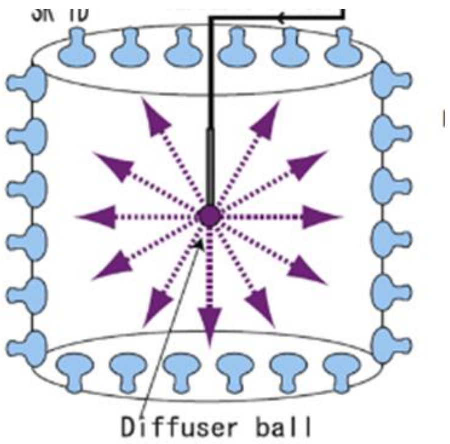
Calibration light sources

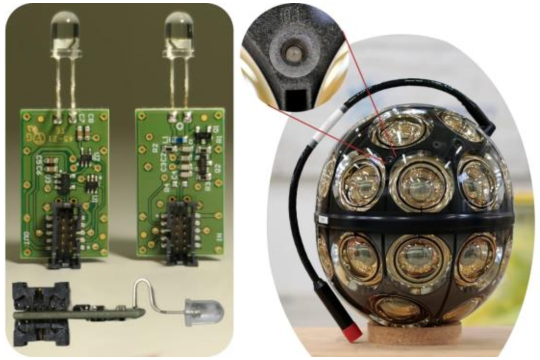
- Fixed/mobile light injector; embedded LEDs; fiber-based beacon network; Diffuser

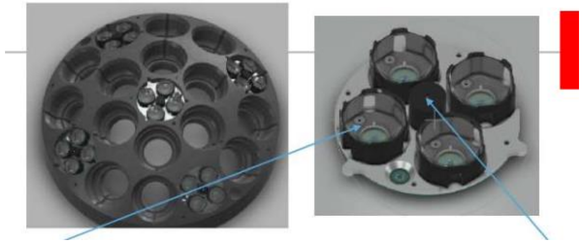






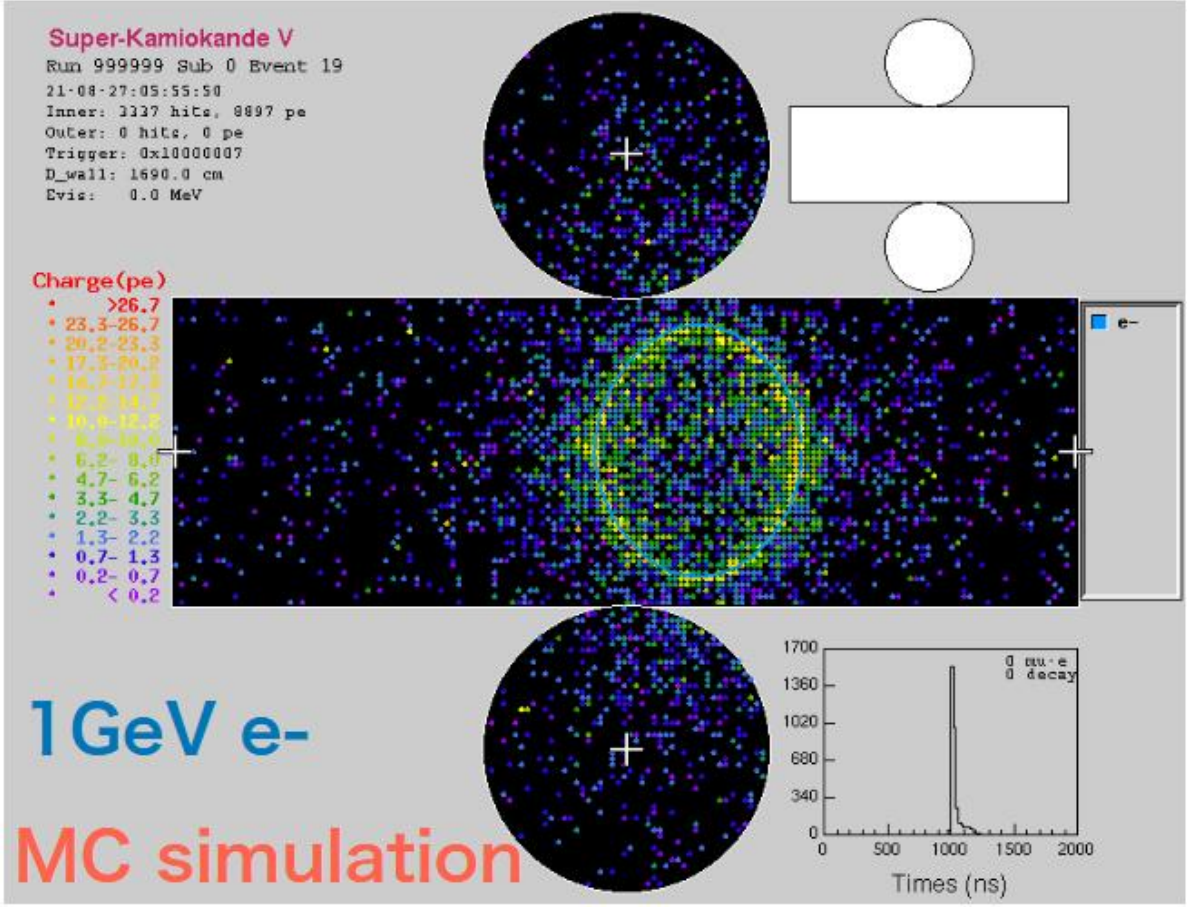






Optical Calibration

- Light interaction: absorption; scattering; reflection.
- Impact: shape and timing of Cherenkov rings → reconstruction bias.
- Scale: larger detectors amplify delays and attenuation.

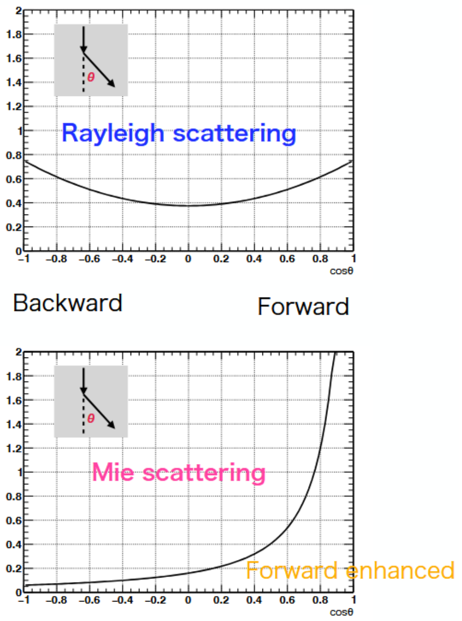


Optical Calibration

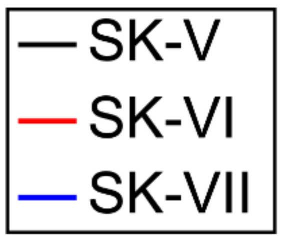
- Measure: absorption and scattering coefficients, including angular dependence of scattering.

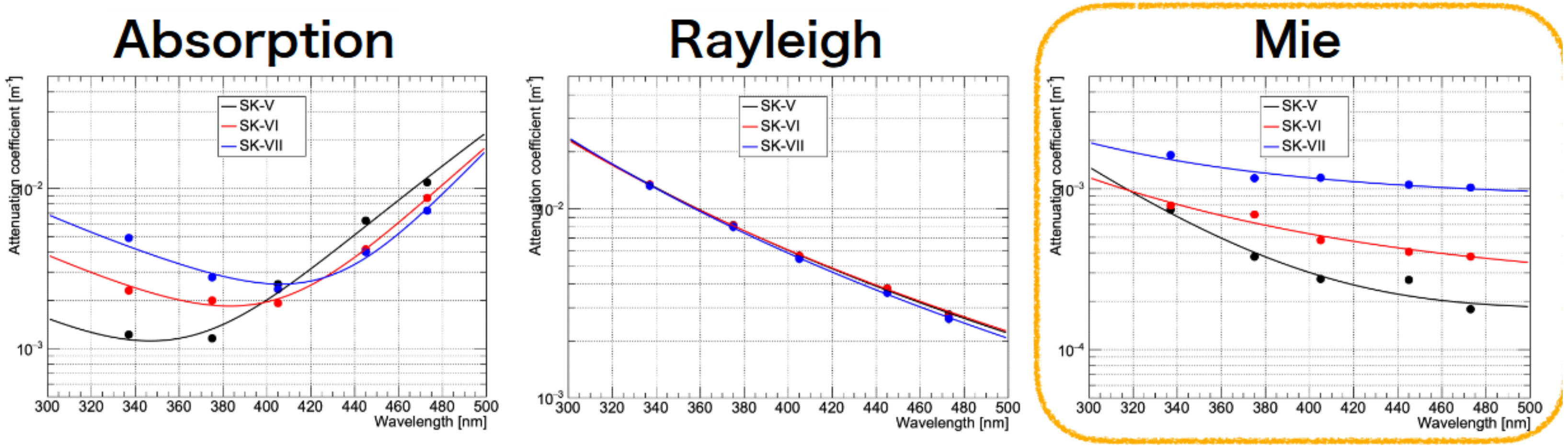
- Sensitivity: strongly dependent on impurity type, particle size, and concentration.

Scattering angular dist.



Pure
Gd 0.01%
Gd 0.03%



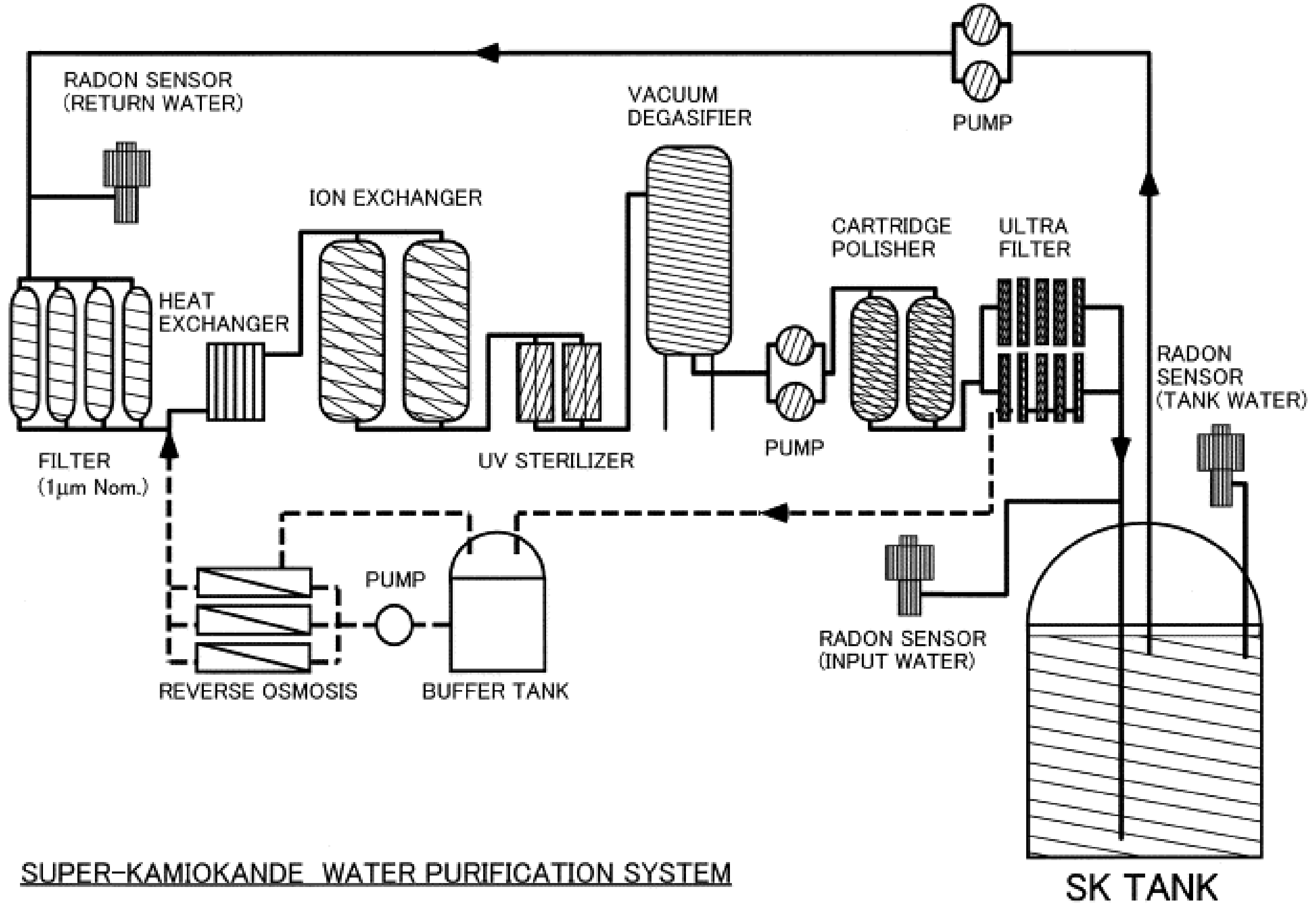


Materials, housings and anti-fouling

- Housings: pressure ratings; optical window materials; sealing and connector design.
- Material selection: corrosion-resistant alloys; chemical compatibility with WbLS/Gd.
- Anti-fouling measures: non-stick coatings; UV mitigation; mechanical wipers or ROV cleaning plans.

Background control

- Radon removal & monitoring: continuous radon suppression and real-time radon sensors.
- Data-driven noise removal: online filtering and offline algorithms to suppress environmental and instrumental backgrounds.
- Priority for low-energy physics: radon control is critical for solar-neutrino sensitivity.



Deployment, maintenance & background control

- Deployment procedures: drilling / ship / rope / ROV operations; wet-mate connectors; recovery plans.

- Maintenance: seasonal access constraints (lakes); ROV/AUV operations (sea); emergency replacement strategies.

Summary

- History: Water Cherenkov detectors have been used since the 1950s for neutrino and cosmic-ray physics.
- Medium diversity: Depending on the physics goal, use ice, seawater, lake water, ultrapure H_2O, D_2O, or chemically doped media (WbLS/Gd).
- Design dependence: Detector structure, calibration, and maintenance differ with the chosen medium.
- Scaling impact: Larger detectors increase demands not only on hardware but also on DAQ, calibration, and monitoring systems.
- Low-energy requirement: For low-energy physics (e.g., solar neutrinos), stringent radon removal and background control are essential.