Development of Water-based Liquid Scintillator: Results from 1-ton and 30-ton Demonstrators at Brookhaven National Laboratory

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Abstract

Water-based Liquid Scintillator (WbLS) combines the high light yield of organic scintillators with the directionality and low cost of Cherenkov detectors, enhancing sensitivity to the CP-violating phase and to low-energy neutrinos. Brookhaven National Laboratory (BNL) moved to ton-scale demonstrators — a 1-ton (3 yr) and 30-ton (1 yr) detector validating long-term WbLS stability at scale. This poster details both detectors' operational stability, light yield, and a roadmap for WbLS in future neutrino experiments.

Advantages of Water-based Liquid Scintillator

Large neutrino detectors face a fundamental trade-off: water Cherenkov (low cost, scalable, directional, but insensitive at low energy) or organic liquid scintillator (low threshold, but costly and hard to scale). **WbLS disperses scintillator as nm-scale micelles in water, combining both signals in one medium.**

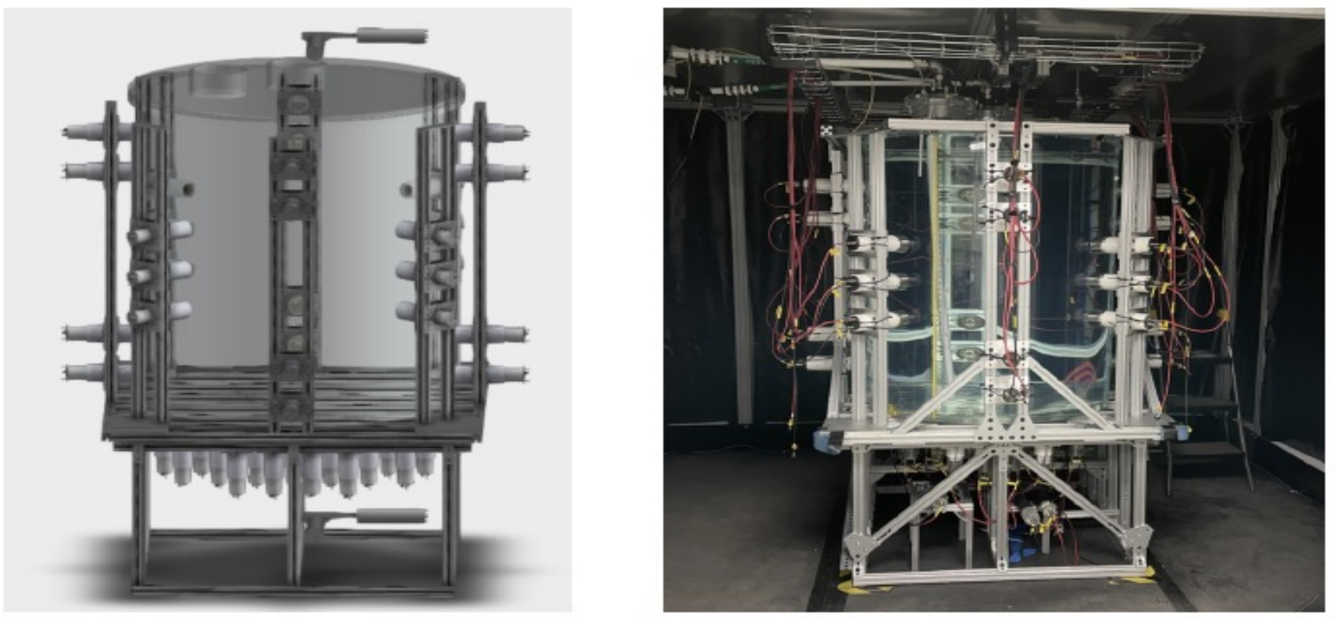
Hybrid light Simultaneous Cherenkov + scintillation → directionality with low threshold

Gd-compatible Aqueous base allows metal loading for neutron tagging

Tunable & scalable Concentration adjusted in situ; cost-effective path to kton scale (Theia, BUTTON 1kT)

Physics reach CP-phase sensitivity in long-baseline oscillations, low-energy solar & supernova neutrinos, neutrinoless double beta decay

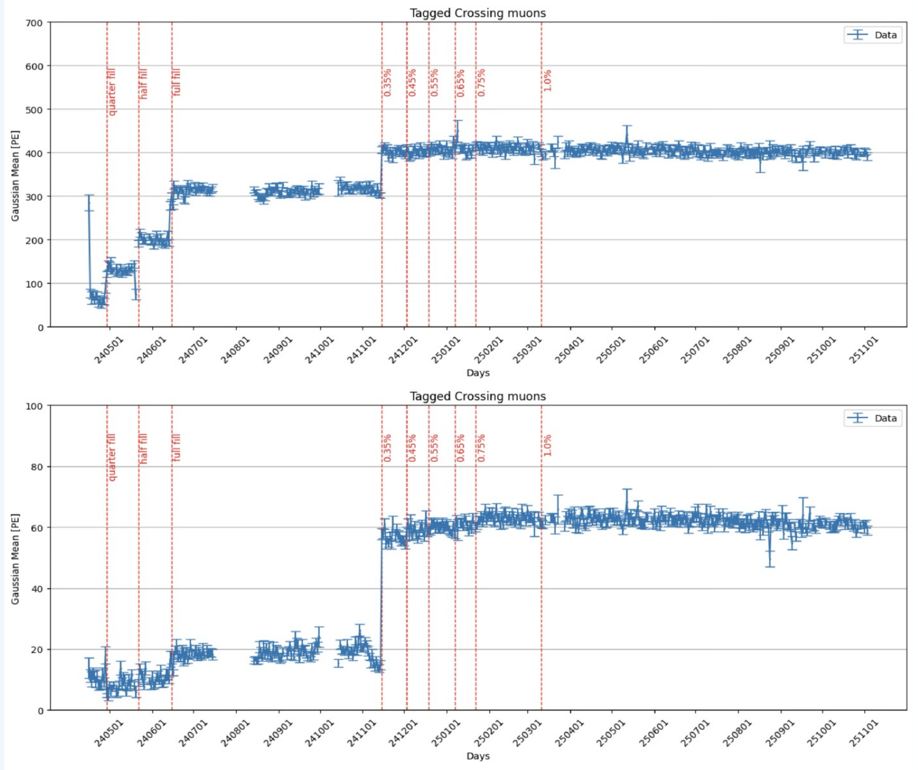
The 1-ton Demonstrator (since 2022)



Acrylic tank (Ø1150 × 1275 mm) in a light-tight dark box[1].

- 58 PMTs coupled to the acrylic vessel: 30 × 2-inch (bottom) + 28 × 3-inch (side, seven rows)
- Triggers: top/bottom paddles (crossing muons), bottom-PMT majority (since Oct 2024), tagged ^{210}Pb α source
- Daily SPE gain calibration with the in-situ α source; continuous circulation keeps optical purity

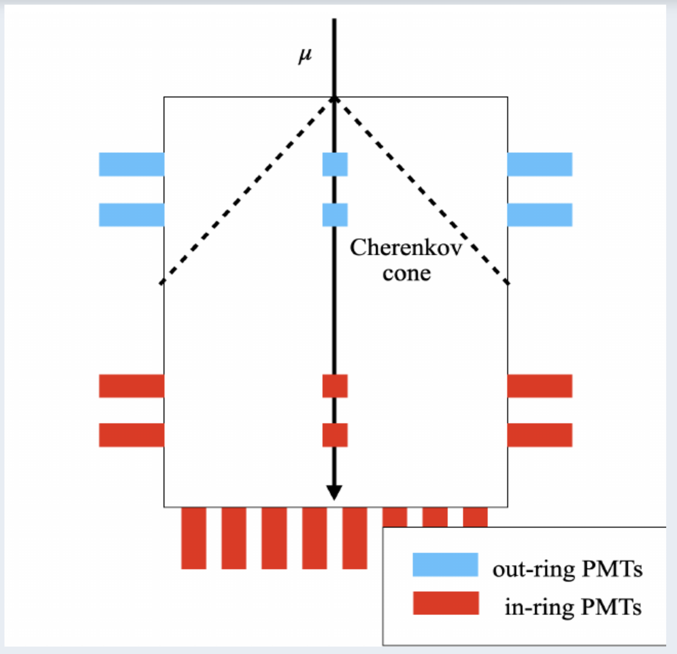
1-ton: Stepwise Injection & Long-term Stability



Daily mean PE of crossing muons, in-ring (top) and out-ring (bottom), across water fills and WbLS concentrations 0.35% → 1.0% [1].

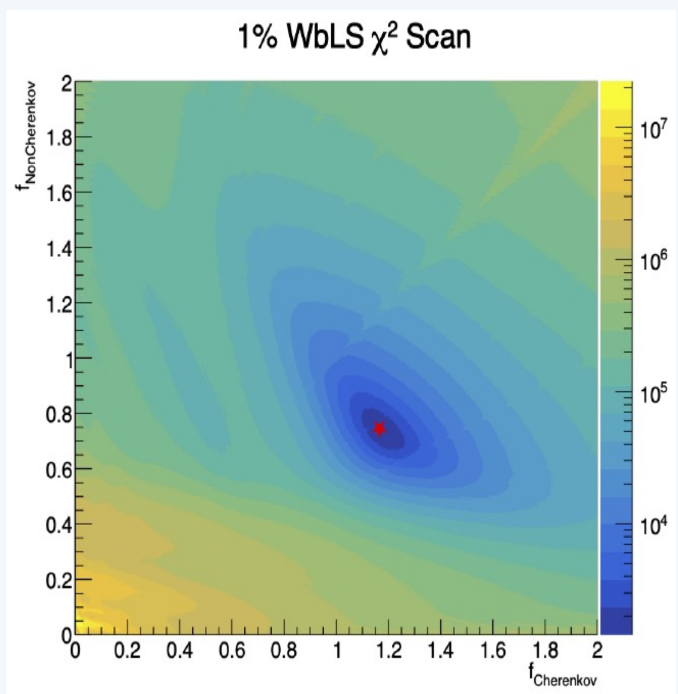
- First injection (0.35%): PE jump as UV Cherenkov photons (< 350 nm) are re-emitted into the PMT-sensitive band — "Cherenkov conversion" along with scintillation
- 1.0% WbLS stable over a year: daily monitor

Separating Cherenkov & Scintillation



Vertical crossing muons: in-ring PMTs (red) see Cherenkov + scintillation; out-ring PMTs (blue) see mostly isotropic scintillation[1].

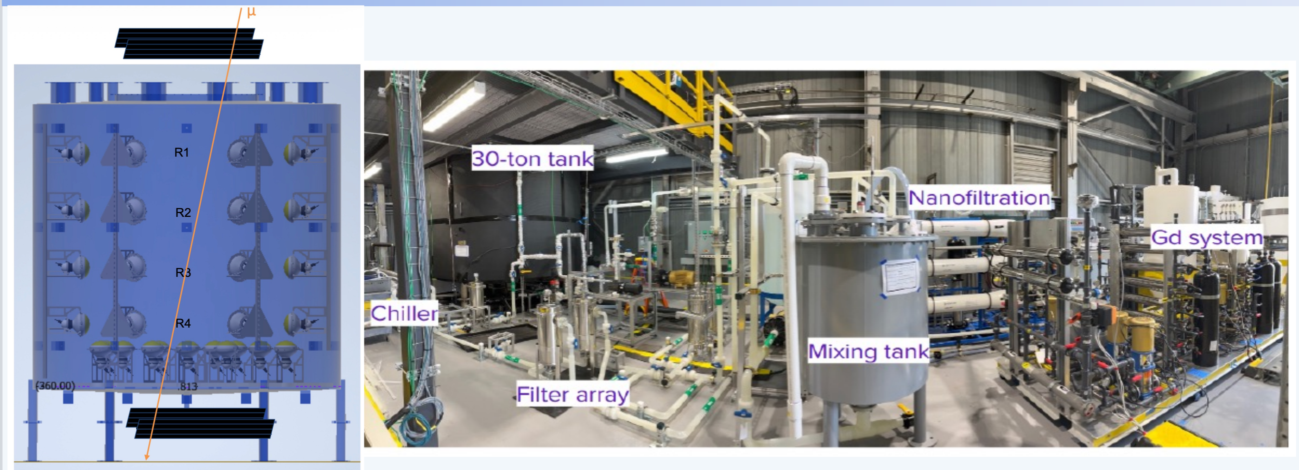
Cherenkov / Non-Cherenkov Decomposition



- 2-D χ^2 scan of MC scaling factors vs measured PE shape

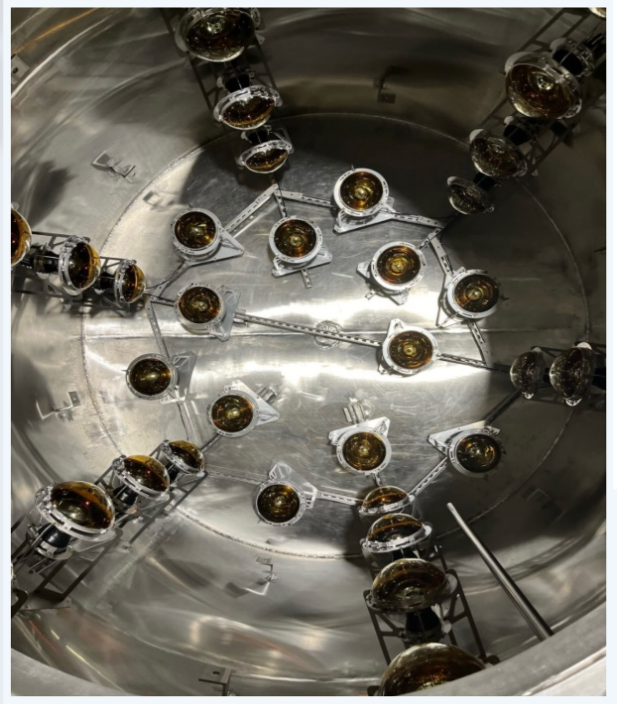
χ^2 map, 1.0% WbLS; red marker = best fit [1]

Scaling Up ×30: the 30-ton WbLS detector

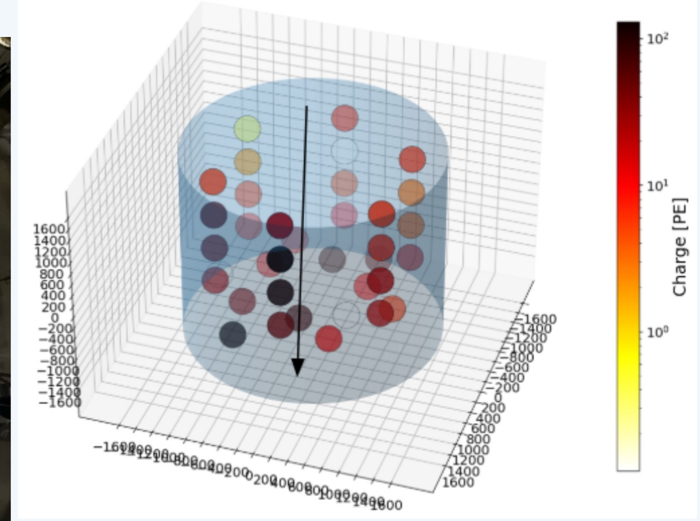


Total 36 10-inch PMTs in the tank (left); detector hall with circulation, nanofiltration and Gd systems (right) [2]

- Passivated 316L stainless-steel tank (r = 1.63 m), WbLS in direct contact
- 36 × 10-inch Hamamatsu R16367 PMTs submerged in the liquid (2-month soak test: no degradation)
- Dual trigger: top/bottom paddle coincidence + bottom-PMT majority; ^{210}Pb α-source calibration path
- Sequential Exchange Array commissioned (14.3 mg Fe/g resin, Gd-selective); nanofiltration + Gd-H_2O band-pass filter ready for future runs

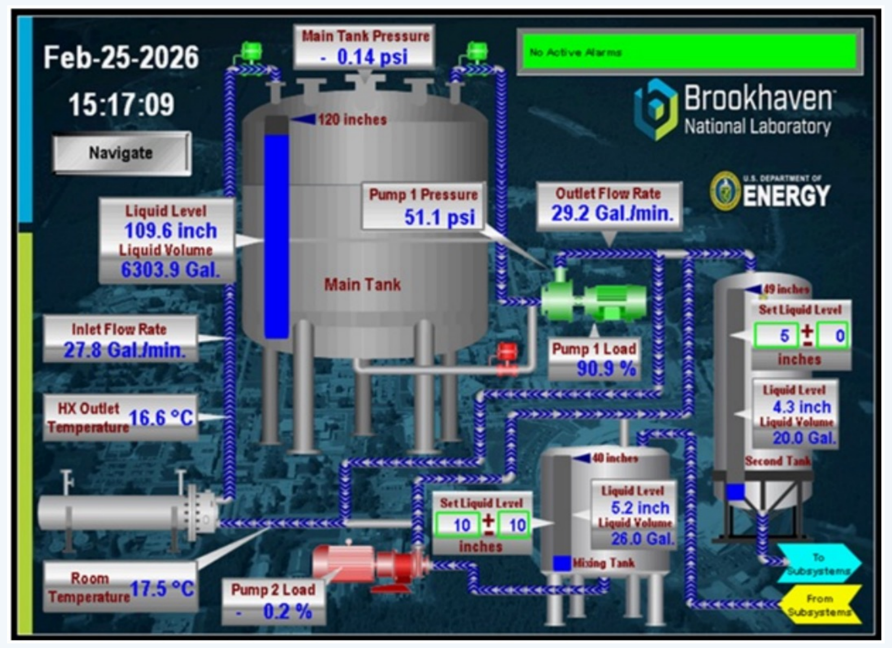


Inside the 30-ton demonstrator: 10-inch PMTs mounted on the stainless-steel tank wall and support array [2]



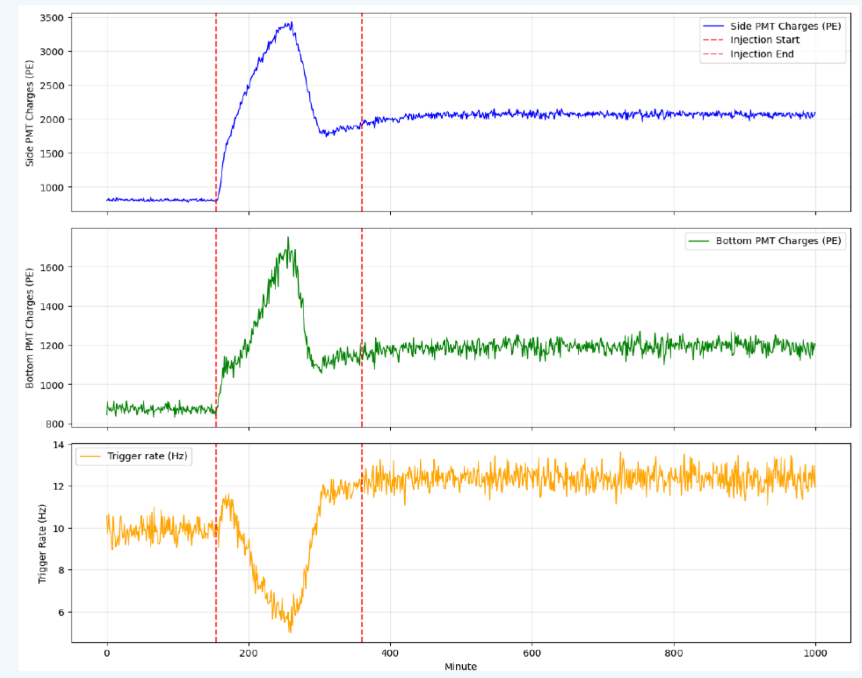
3D event display of a cosmic-muon candidate. Each circle corresponds to one PMT, and the color scale represents the charge collected. The expected ring-shaped pattern in the PMT charge response of the 30-ton detector appears when a muon produces Cherenkov light [2].

Slow Control & Monitoring



- Process data monitoring interface of the WbLS 30 – ton detector central control system [2].

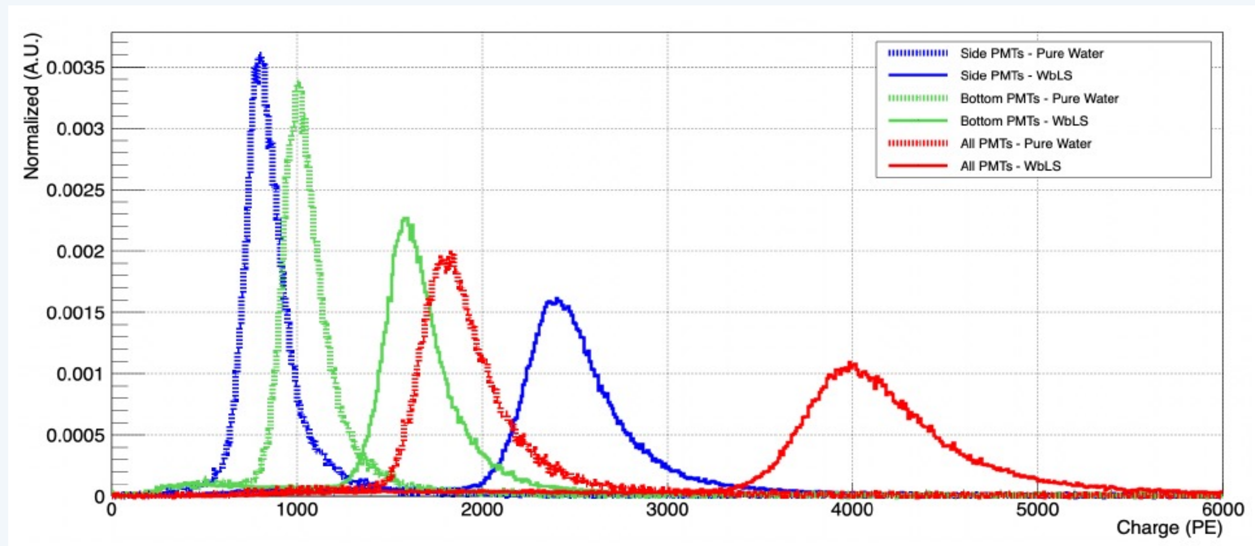
Water → 0.35 % WbLS: Mixing Dynamics



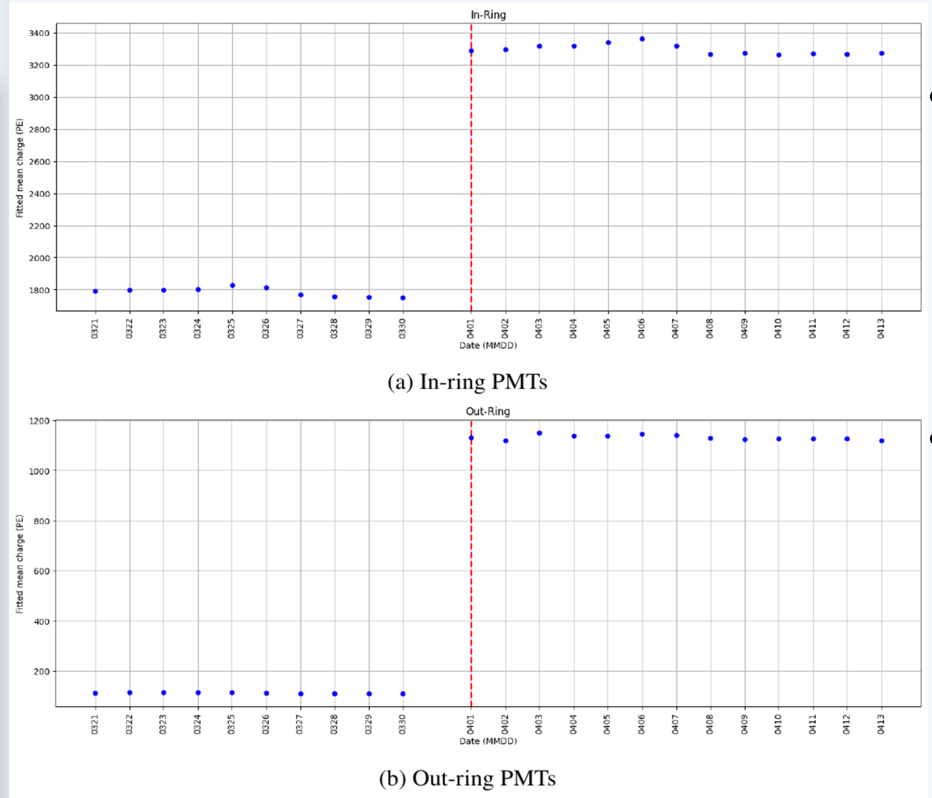
Side / bottom PMT charge and trigger rate during injection (dashed lines: start / end) [2].

- Staged injections (0.3% → 0.75% → 1%) from BNL's ton-scale LS Production Facility, April–May 2025
- Transient rise–dip–recovery: a micelle-dense region near the injection point scatters Cherenkov light and suppresses the majority trigger until circulation homogenizes the volume

30-ton Performance



Crossing-muon charge, pure water (dashed) vs 1% WbLS (solid): side, bottom and all PMTs [2].



- Mean photoelectron yield of crossing muons as a function of date
- Stable operation before the injection and after the injection monitored for several days

Mean PE yield, in-ring (top) / out-ring (bottom); red line: injection day[2].

Summary & Outlook

- **Both detectors running successfully** — 1-ton stable for 3 years, 30-ton for 1 year with 1% WbLS — long-term stability demonstrated at scale
- Gd-WbLS validated at 1-ton with neutron capture — Gd loading next in the 30-ton

Clear path to a deep-underground, ton-to-kiloton-scale WbLS detector (Theia, BUTTON 1kT)

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References:
[1] PHYSICAL REVIEW D 113, 092015 (2026)
[2] arXiv:2603.20019