The Outer Detector System

JENNIFER2 Collaboration Meeting (J2CM)

KEK - 2 June 2024

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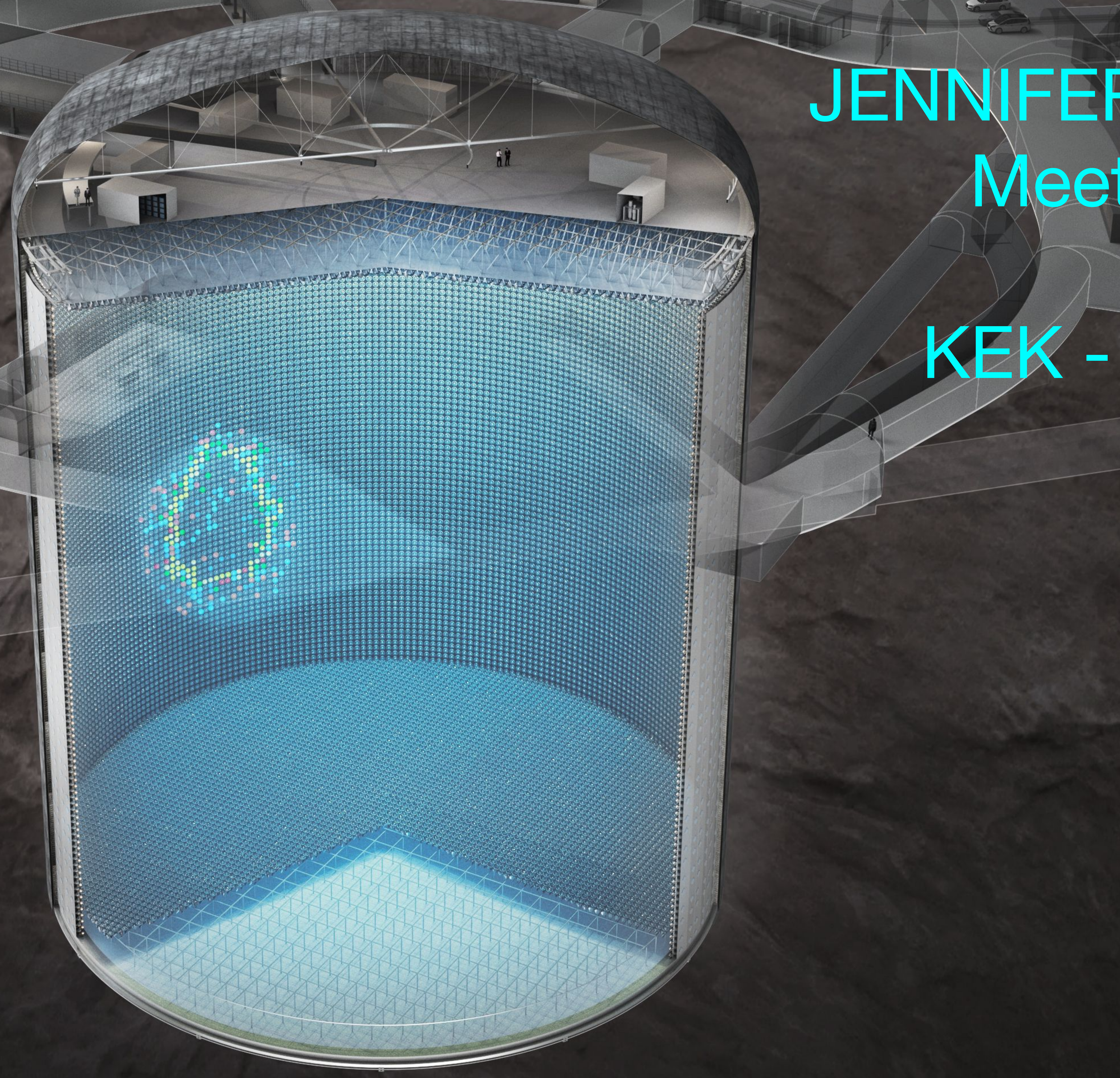


NIKKEN SEKKEI

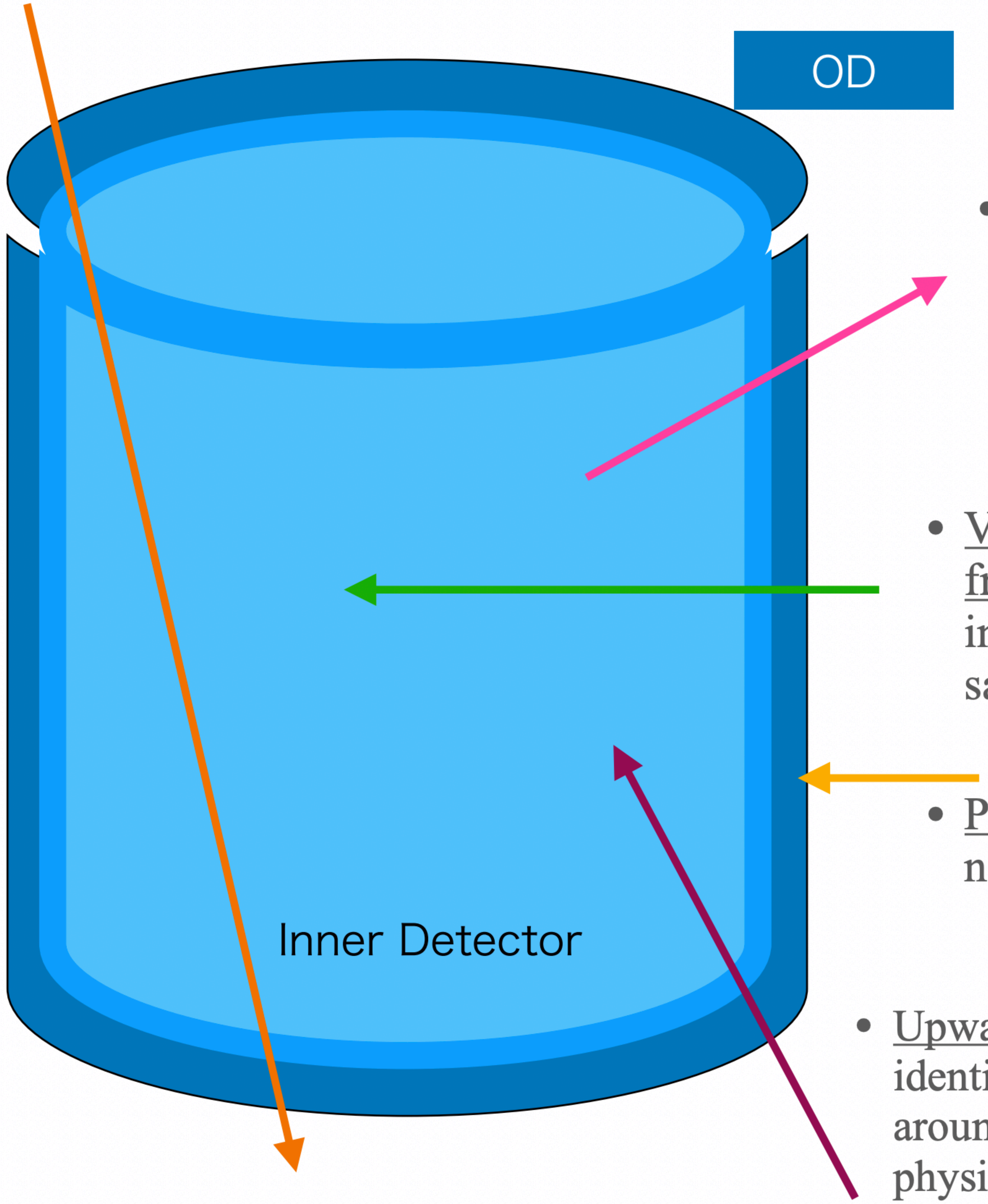
Outer Detector

- One of the themes in WP3 relates to our work on the Outer Detector system in Hyper-K.
- Recently, there has been a revision of the shared OD responsibilities to widen the funding support. Before then the responsibility was only shared between the UK and Russia.
- Although the UK still provides most of the OD funds, other countries contribute to the photo sensing system (Australia, Korea, Japan) and electronics (countries contributing to ID electronics).
- The sharing is currently being finalised. The OD PMT tendering will start soon.

Outer Detector: Role and Importance

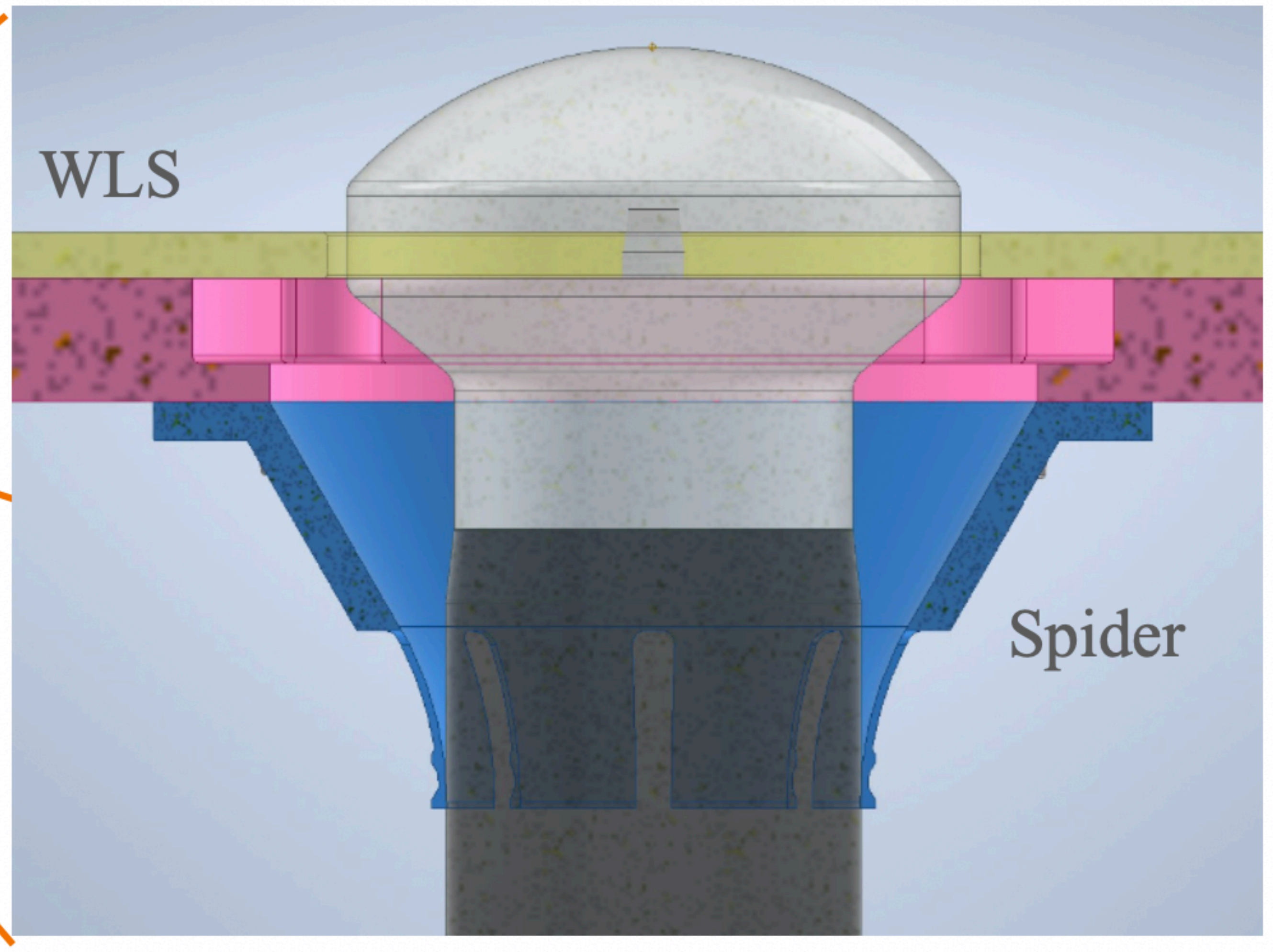
The following slides present a summary of the OD work. They are slides from several people and recently presented by R. Wendell to the HK PAC.

- Cosmic ray muon background (45 Hz ~ 1 million/day) must be tagged by the OD and removed from physics analysis

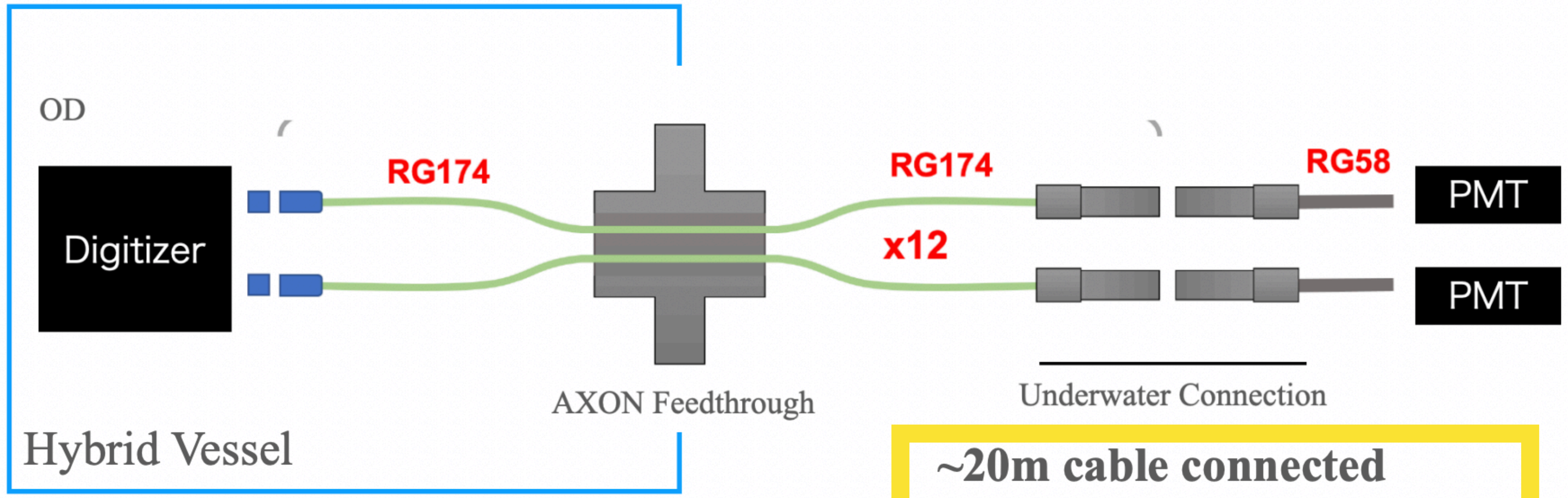


- Fully-contained and Partially Contained event Separation: Determine if particles originating in the ID remain therein (best resolution) or exit
- Veto neutrino-induced rock events from J-PARC beam: Removes beam-induced background from analysis samples
- Passive shield against incoming neutron and gamma radiation
- Upward-going muon neutrino tagging identifies neutrino interaction in the rock around HK; important for various oscillation physics

Outer Detector System Components



- **3,600 3-inch PMTs**
- **30cm x 30 cm WLS Plate**
- Black/White Tyvek behind WLS Plate
- Injection moulded mount (“spider”)



~20m cable connected underwater just before electronics vessel

- Single sheet of **“Black/White” (B/W) Tyvek** on structure
  - Reflection into OD region, light shielding into ID

- Double layer Tyvek on floors and outer walls of detector
  - Termed “**White/White” (W/W) Tyvek**
  - Bounce light back into PMTs on structure

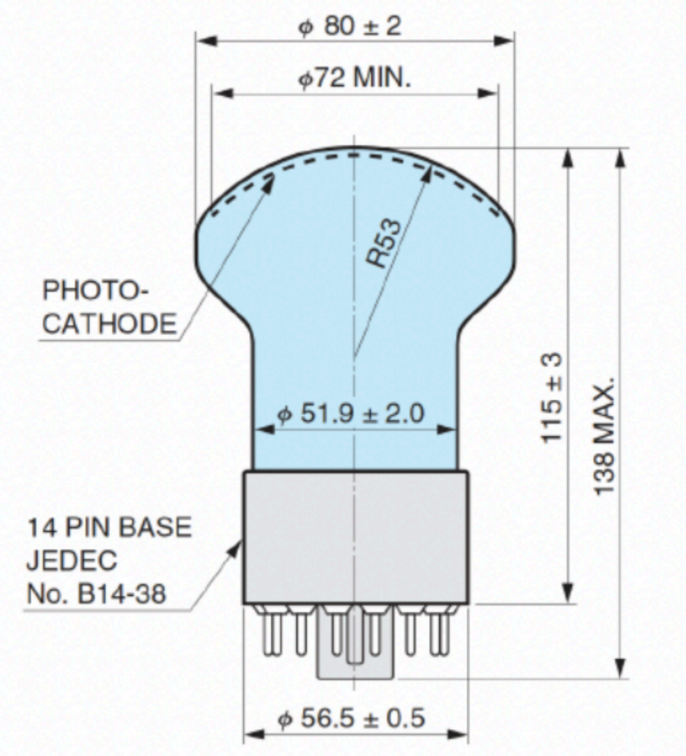
Outer Detector System and Components

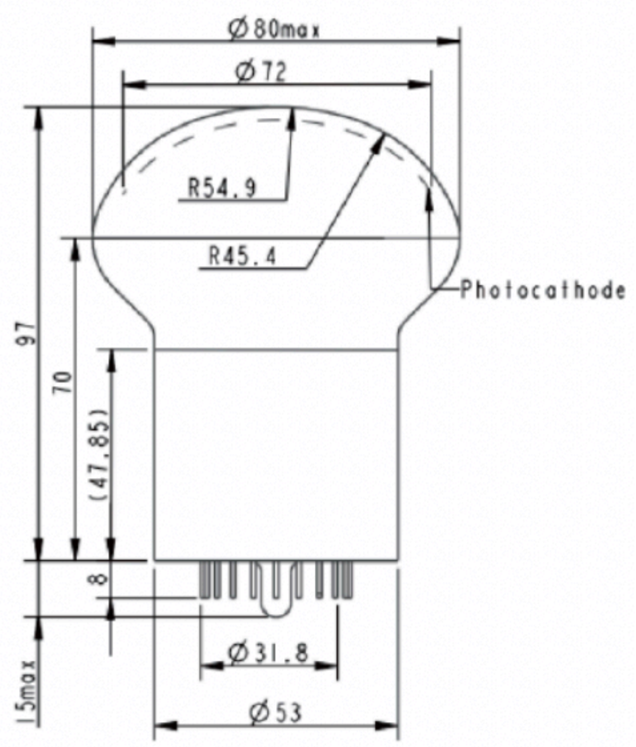
PMTs : Specs

- Two candidate 3” PMTs
  - Hamamatsu (HPK) R14374-31
  - NNVT N2031

- Towards tendering:
  - Waterproofed HPK Tubes with 20m cables have been characterized
  - Waterproofed NNVT Tubes now characterized

●R14374





N2031光电倍增管结构图
N2031 PMT structure

HPK

GENERAL

Parameter		R14374	R14689	Unit
Spectral response		300 to 650		nm
Wavelength of maximum response		420		nm
Window material		Borosilicate glass		—
Photocathode	Material	Bialkali		—
	Minimum effective area	φ72	φ81	mm
Dynode	Structure	Circular and linear-focused		—
	Number of stages	10		—
Base		JEDEC No. B14-38		—
Operating ambient temperature		-30 to +50		°C
Storage temperature		-30 to +50		°C
Suitable socket		E678-14W (Sold separately)		—

MAXIMUM RATINGS (Absolute maximum values)

Parameter		R14374	R14689	Unit
Supply voltage	Between anode and cathode	1500		V
	Between anode and last dynode	300		V
Average anode current		0.1		mA

CHARACTERISTICS (Typ.) (at 25 °C)

Parameter		R14374	R14689	Unit
Cathode sensitivity	Luminous (2856 K)	90		μA/lm
	Radiant at 420 nm	90		mA/W
	Blue sensitivity index (CS 5-58)	11.0		—
	Quantum efficiency at 380 nm	27.5		%
Anode sensitivity	Luminous (2856 K)	900		A/lm
	Radiant at 420 nm	9.0×10^5		A/W
Gain		1.0×10^7		—
Anode dark current (After 30 minute storage in darkness)		50		nA
Time response	Anode pulse rise time	2.9	2.9	ns
	Electron transit time	35	36	ns
	Transit time spread (FWHM)	1.3	1.5	ns

NNVT

产品型号/ Product Model	N2031			
产品结构/ Product structure	80mm (3") / 10-stage			
玻璃材料/Window material	硼硅酸盐玻璃/ Borosilicate Glass			
光电阴极/Photocathode	双碱/Bialkali			
倍增结构/Dynode structure	盒型和线性聚焦/Box and Linear Focused			
	Min	Typ	Max	Unit
光谱范围/Spectral range		290-650		nm
405 nm下的量子效率 /Quantum Efficiency at 404 nm		26.5		%
增益系数/Gain slope (vs supp. Volt., log/log)	6.5	7.3	8.0	
工作电压/Supply voltage	900	1150	1300	V
增益/Gain		5×10^6		--
暗计数率/Dark count rate		1000	2000	Hz
峰谷比/Peak to Valley ratio		2.5		
上升时间/Anode Pulse Rise Time		1.9		ns
渡越时间离散/Transit time spread (FWHM)		1.8	3	ns

Outer Detector System and Components

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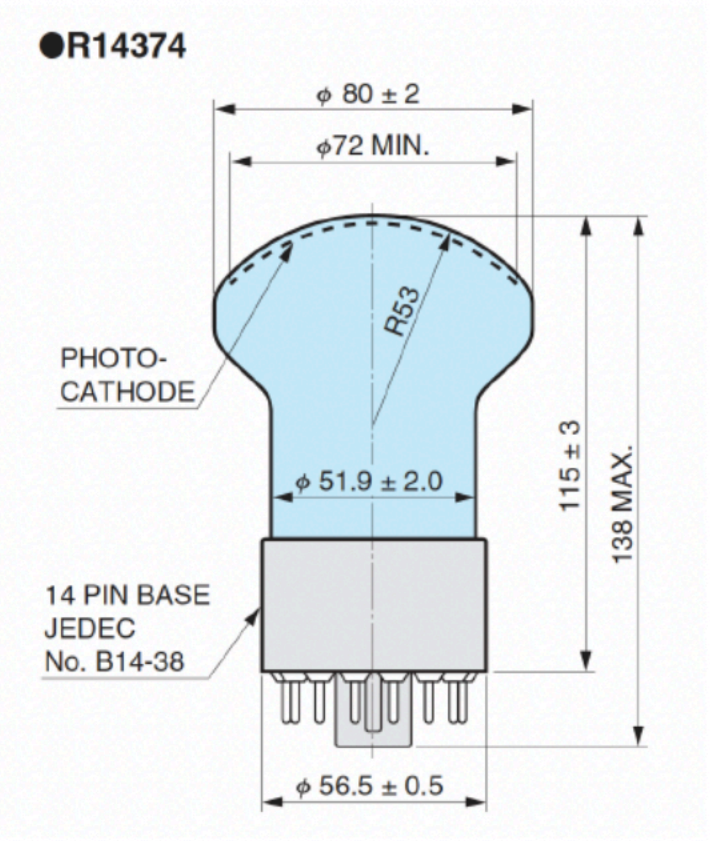
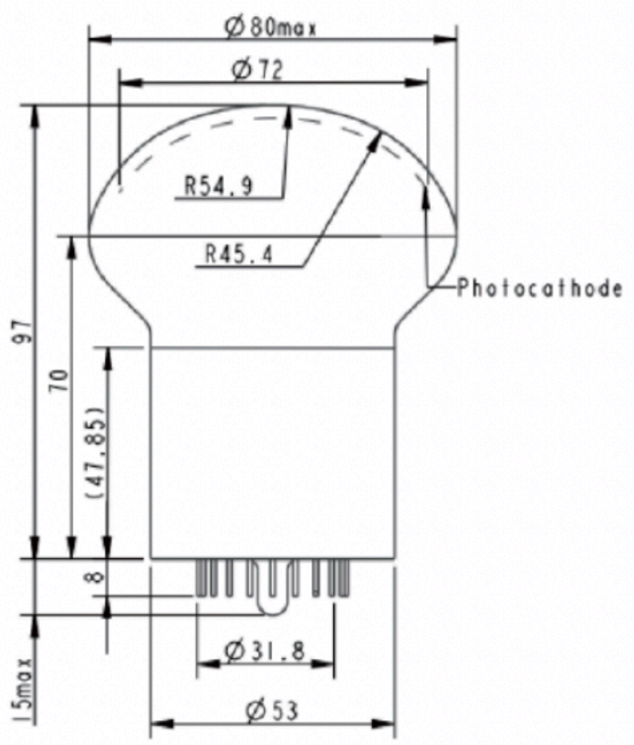


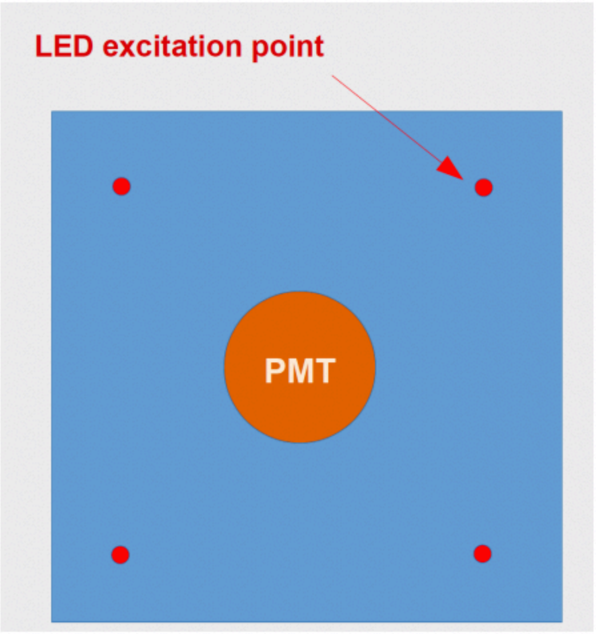


N2031光电倍增管结构图
N2031 PMT structure

Indications that HPK Outperforms NNVT

- Relative photon yield
  - HPK tubes see ~**17%** more PE using reflected Cherenkov spectrum
    - N.B. Low statistics:1 PMT each

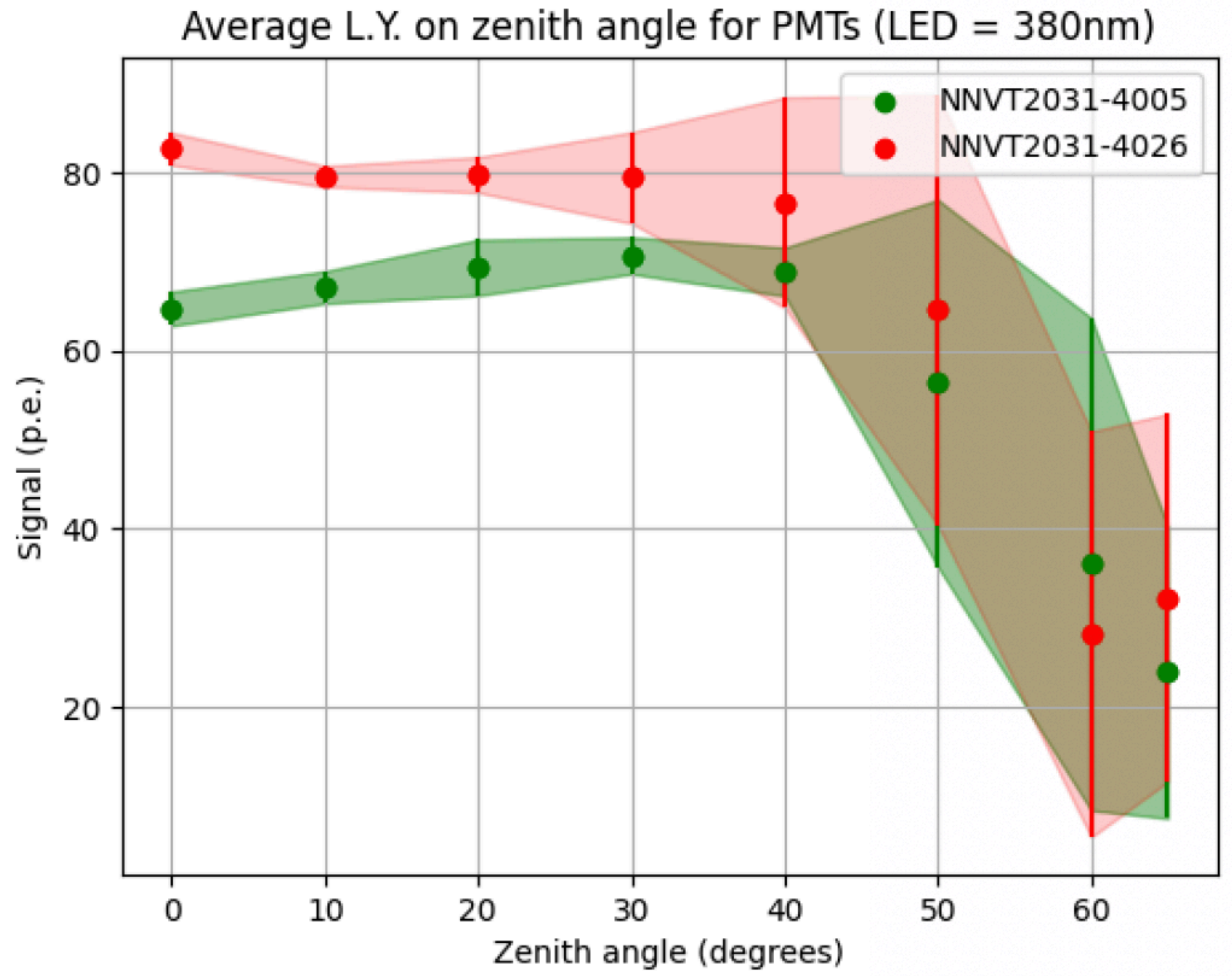
  - LED illumination tests on four corners of WLS show
    - HPK - **17%** variation in PE over corners
    - NNVT - **35%** variation
    - **30%** ***fewer*** PE observed in NNVT relative to HPK
      - 3 NNVT tubes tested show the same tendency
    - NNVT photocathode may be "thin" on the "sides" of the bulb



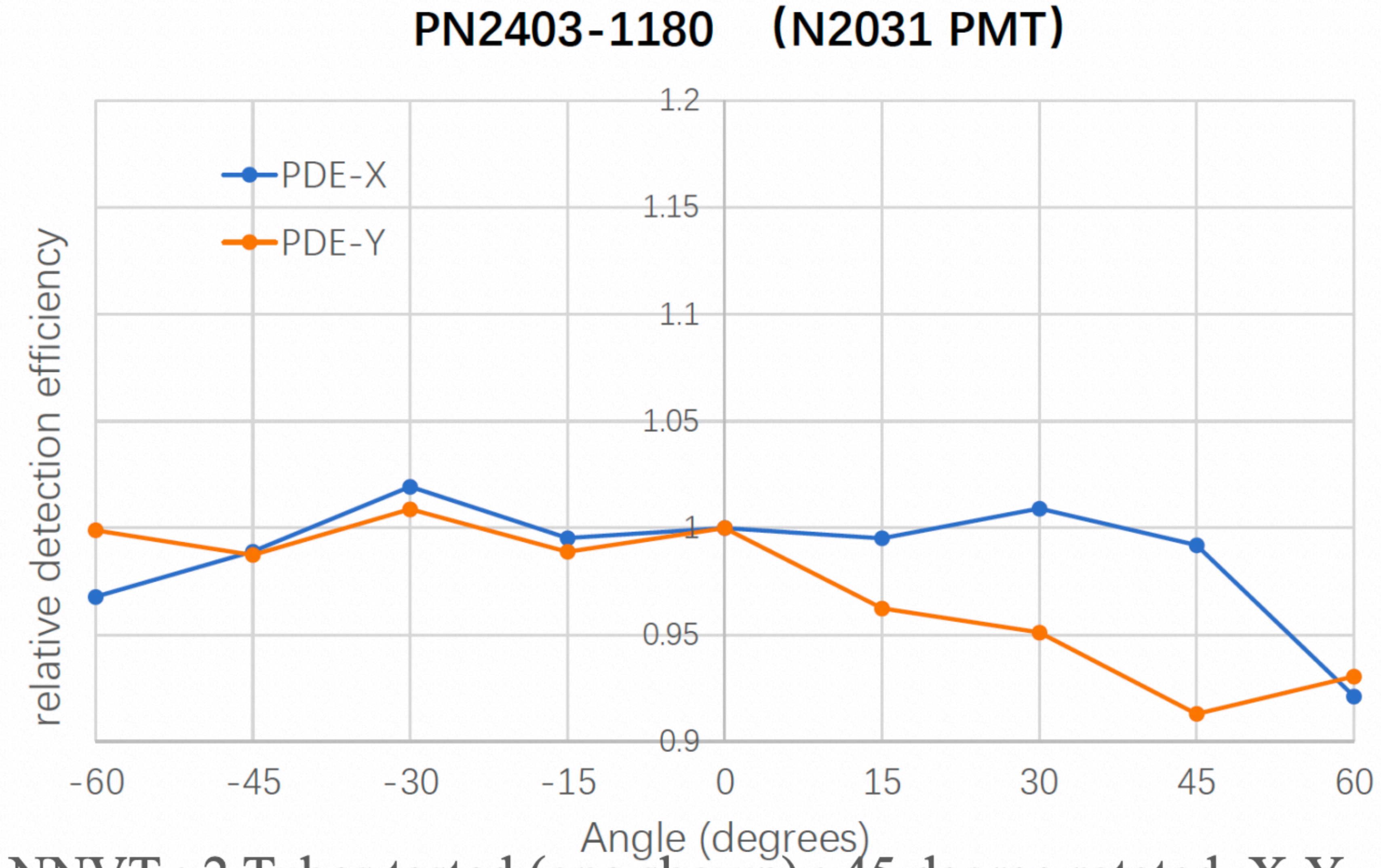
Outer Detector System and Components

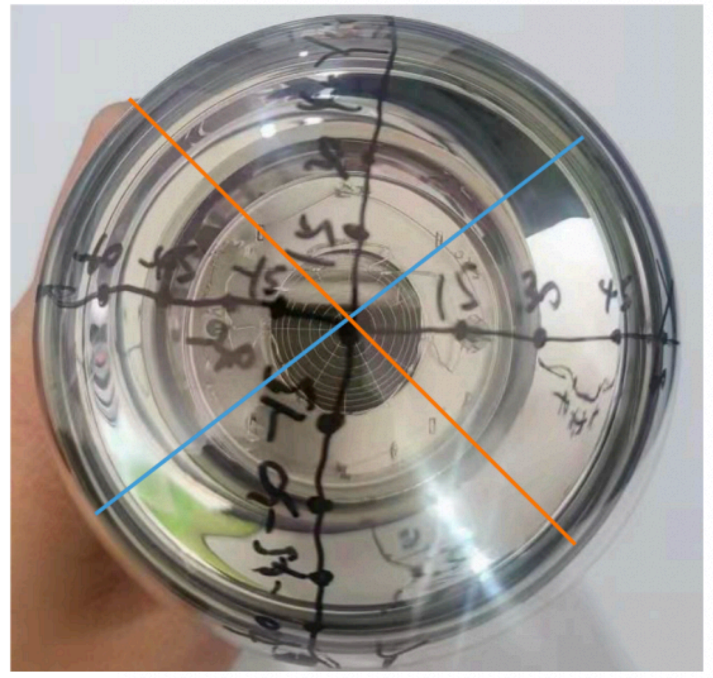
NNVT Collection Efficiency, Measured by NNVT

INR Tests: 2 Tubes

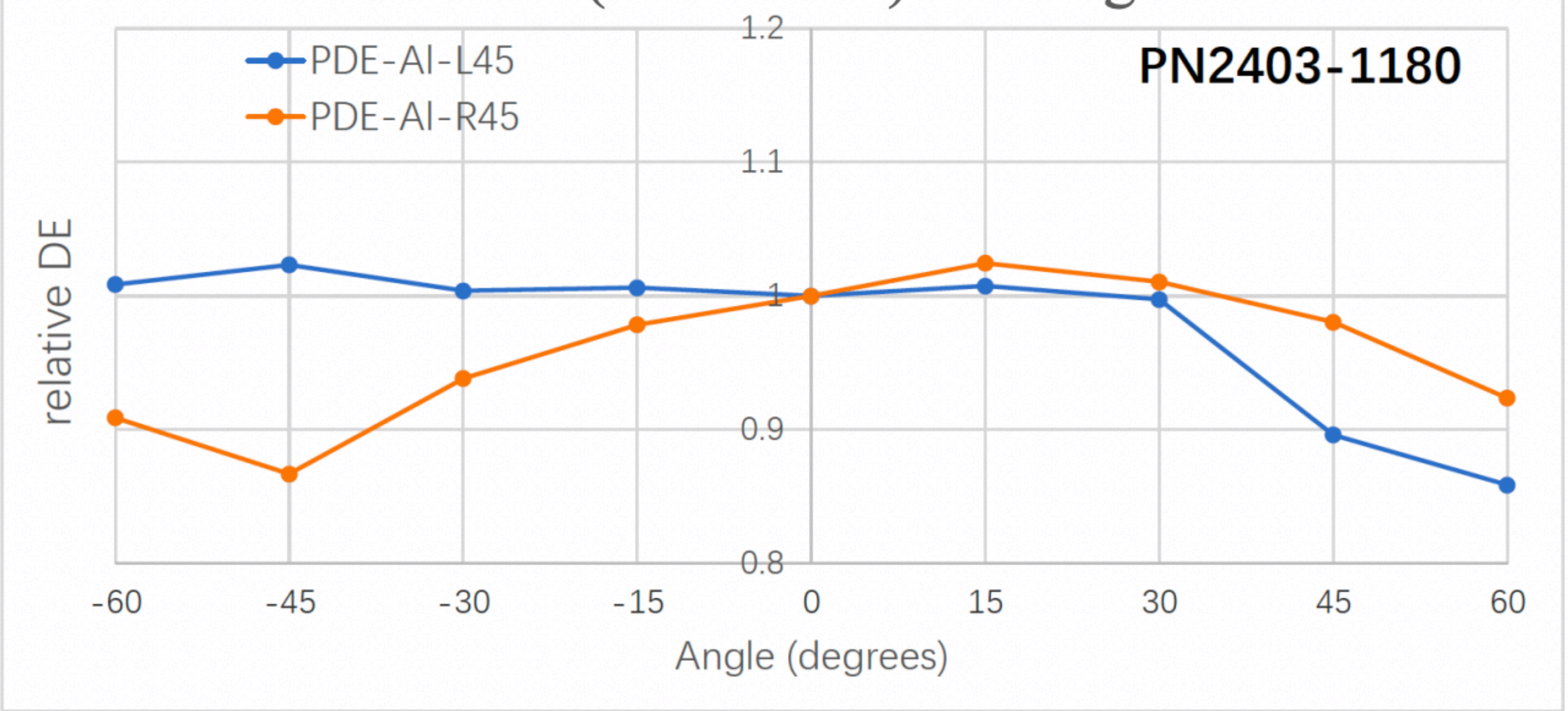


NNVT : 2 Tubes tested (one shown) X-Y Direction





NNVT : 2 Tubes tested (one shown) : 45 degree rotated X-Y



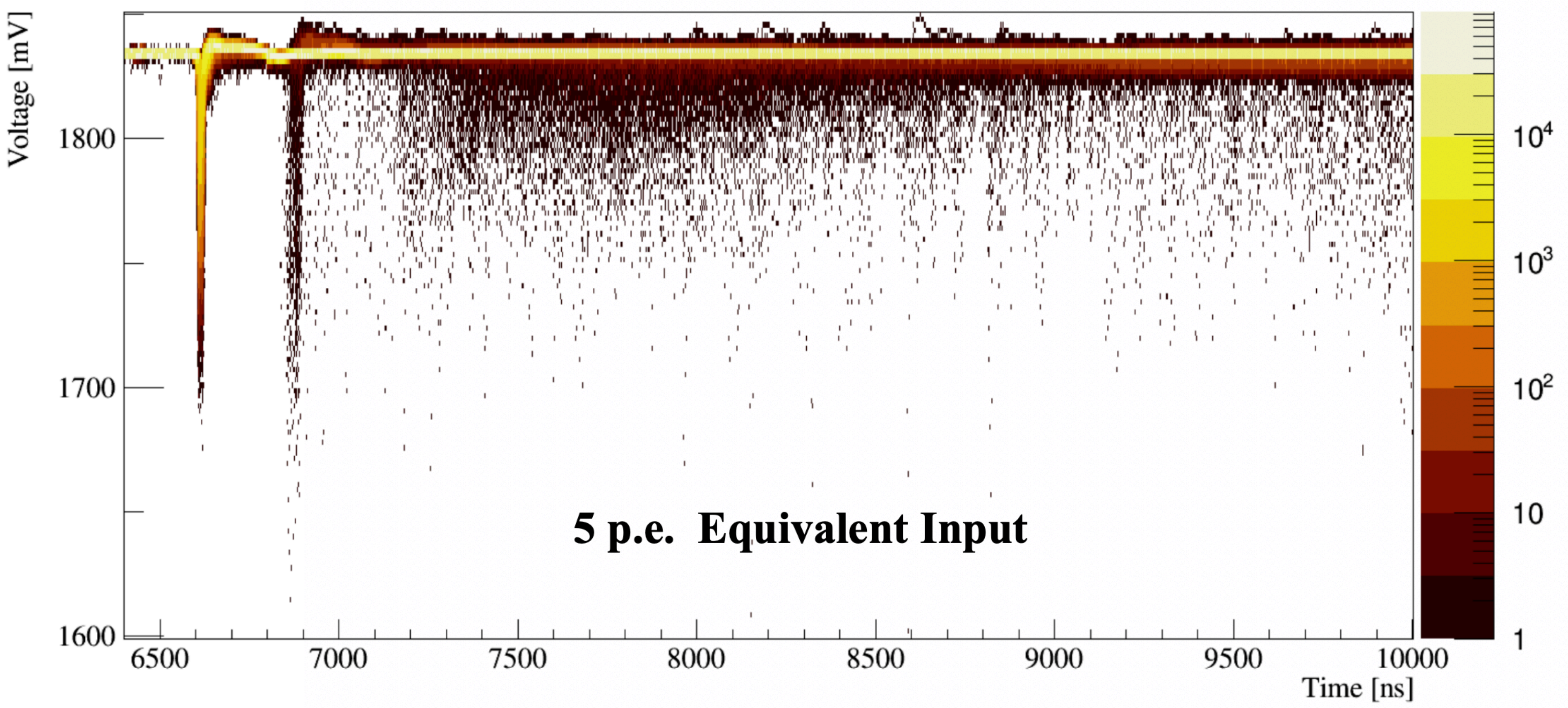
- In contact with NNVT concerning cathode non-uniformity
  - INR found ~30-40% drop in yield from 0-60 degrees, NNVT finds about 10% drop
  - Now testing additional tubes in INR, KOR, and KCL

Outer Detector System and Components

Recent Updates

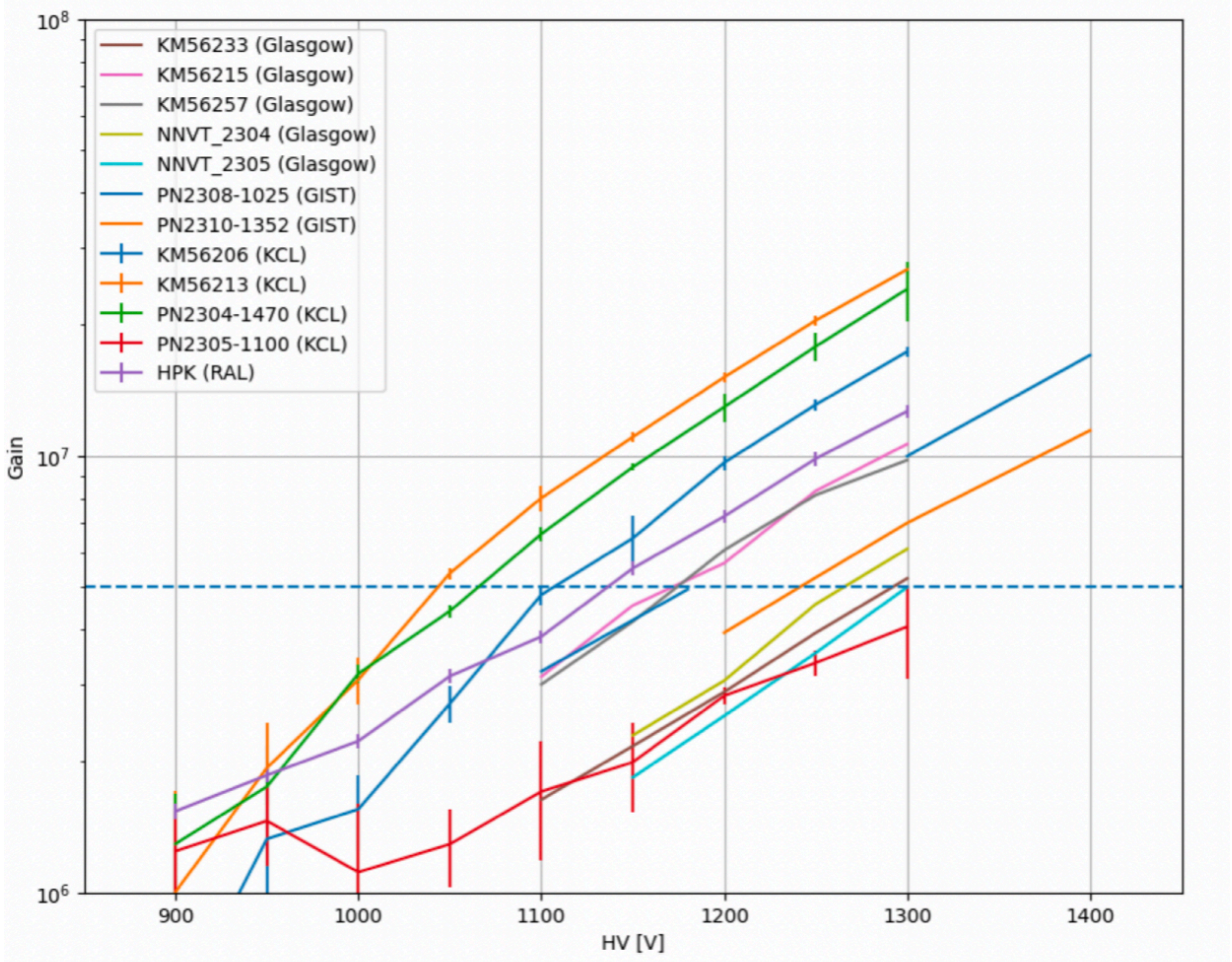
Jeeseung [5/14 FD3 Meeting]

- Working on PMT specification, based on ID specification with appropriate changes
- Now have TTS measurements, after pulse, and magnetic field susceptibility from from 2 NNVT PMTs in Korea (few ns)



Less than 5% (0.1%) of pulses have 1pe-level-afterpulse within 10us (300ns)

Gain versus HV (Hayashida, KCL)



Outer Detector System and Components

Characteristics		
Base:	Waterproof	
Voltage:	Anode at $+V_{op}$ (positive high voltage)	
Voltage divider:	Non-tapered in later stages	
Output cable:	Single output cable to carry both signal and high voltage	
Cable type:	50 ohm cable (eg RG-58) (with connector to be specified)	← RG58,with SHV

Status of FD3 Tests	Requirements		
Untested	Aging:	> 20 years	
OK	Pressure:	<10 bar	
OK	Gain:	$> 3 \times 10^6$ $(900 < V_{op} < 1300\text{V})$	
OK	Timing resolution:	< 10 ns (for 1 p.e. at V_{op})	← Tested on NNVT tubes in Korea ~3 ns; HPK specs state 2.9 ns
OK	Charge resolution:	50% σ (for 1 p.e. at V_{op})	
OK	Single-photon peak-to-valley ratio:	> 2 at V_{op}	
OK	Dynamic range:	0.2 to 100 p.e. at V_{op}	
OK	Dark rate:	< 1 kHz above a threshold of 0.25 p.e. at 20°C	
Marginal	Quantum Efficiency:	$> 25\%$ in the 300–500 nm range	
OK	Magnetic field gain variation:	10% at 100 mG	← Tested on NNVT tubes in Korea
OK	Power consumption:	< 1 W at V_{op}	

Table 1: PMT requirements for the OD.

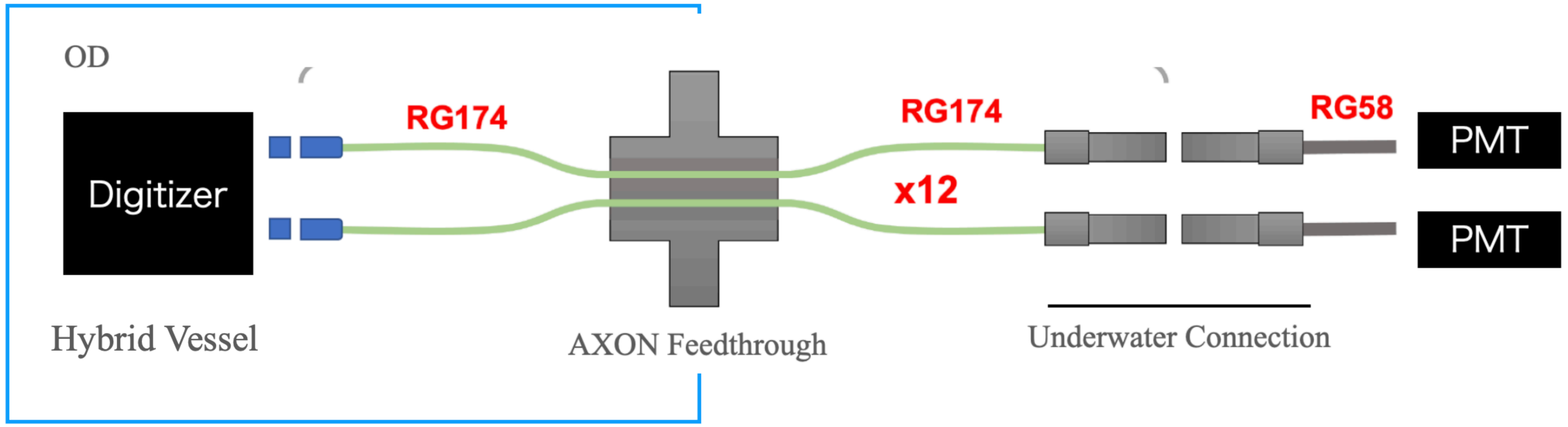
- Both NNVT and Hamamatsu PMTs satisfy minimum requirements outlined in this table
  - Tested using sample PMTs with full configuration (20m + waterproof)

- <u>Aging</u> : vendors quote >20 year lifetimes [hard to test] ; SK OD supports this for HPK
- <u>Quantum efficiency</u> : Quote by vendors sufficient, tests with samples on-going
- <u>Magnetic field</u> : <5% variation in NNVT response between 500mg and 100mg measurements

- Tender documentation now in preparation based on these specifications, start procurement process this summer

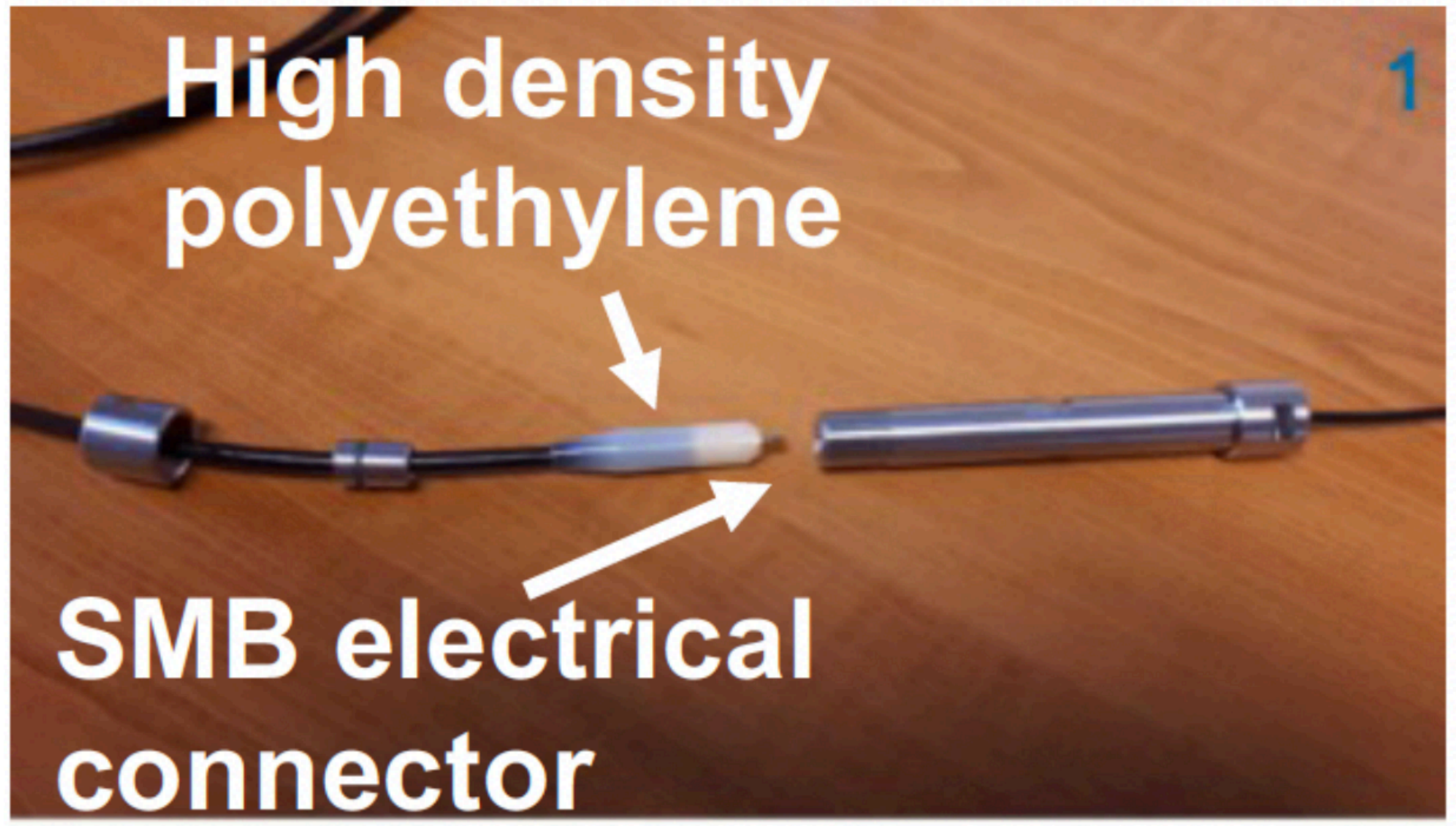
Underwater connection

Underwater Connections : Outstanding Issue

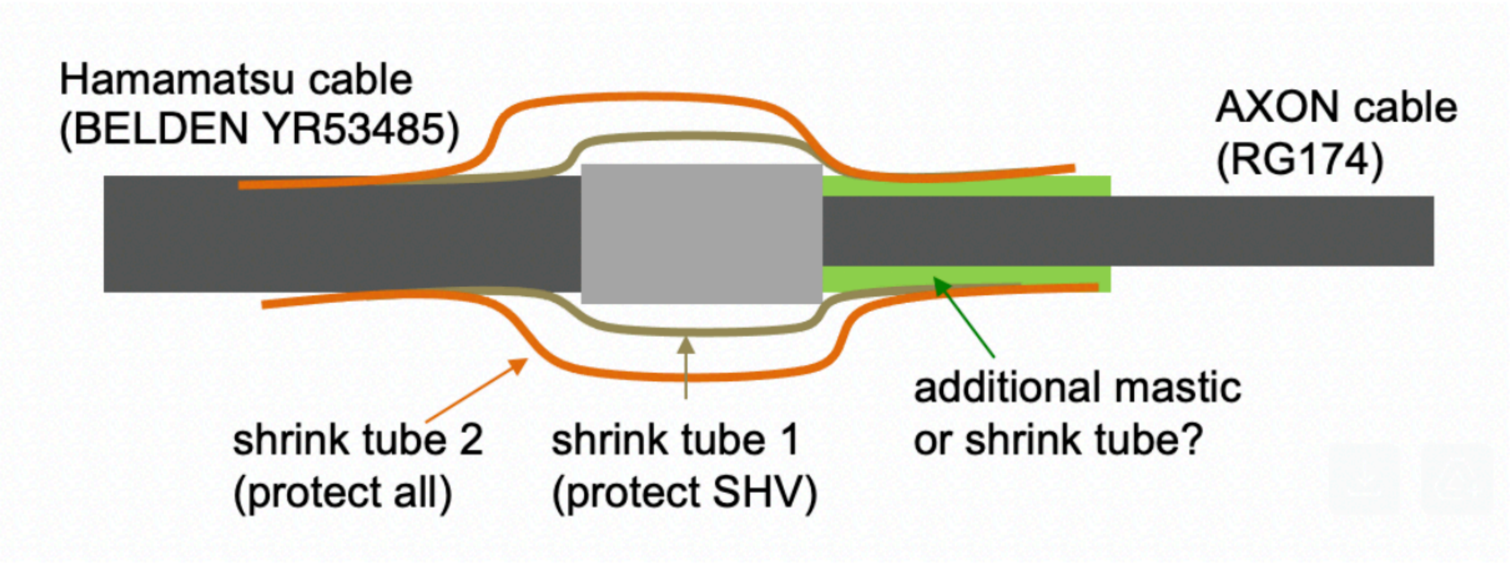


- An underwater connection is needed join PMT cables to vessel cables
- Two options: **Underwater connect**or or wrap in mastic/heat shrink

AXON Connector

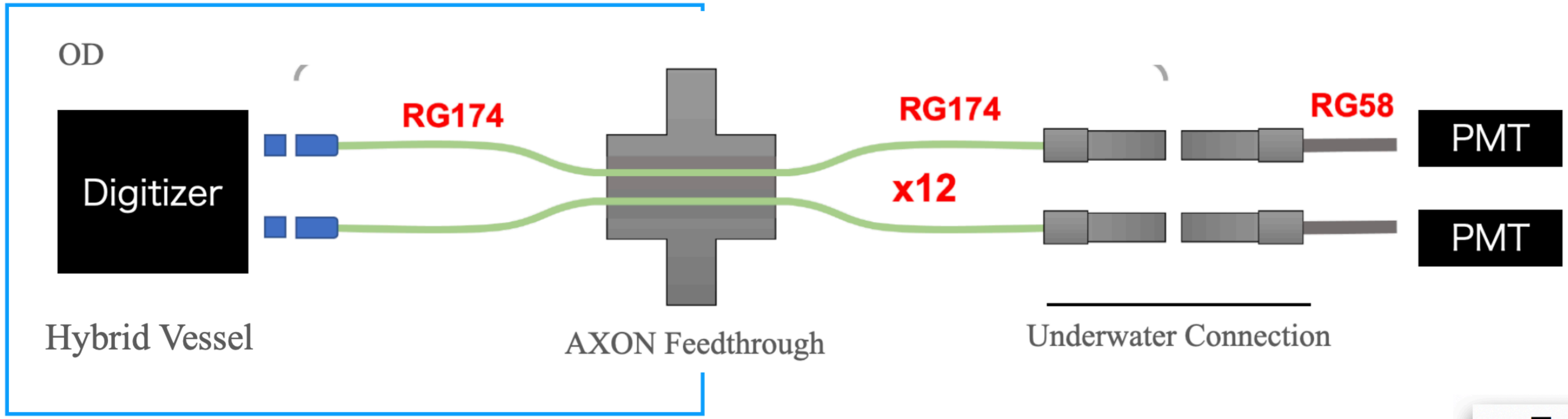


Mastic Option

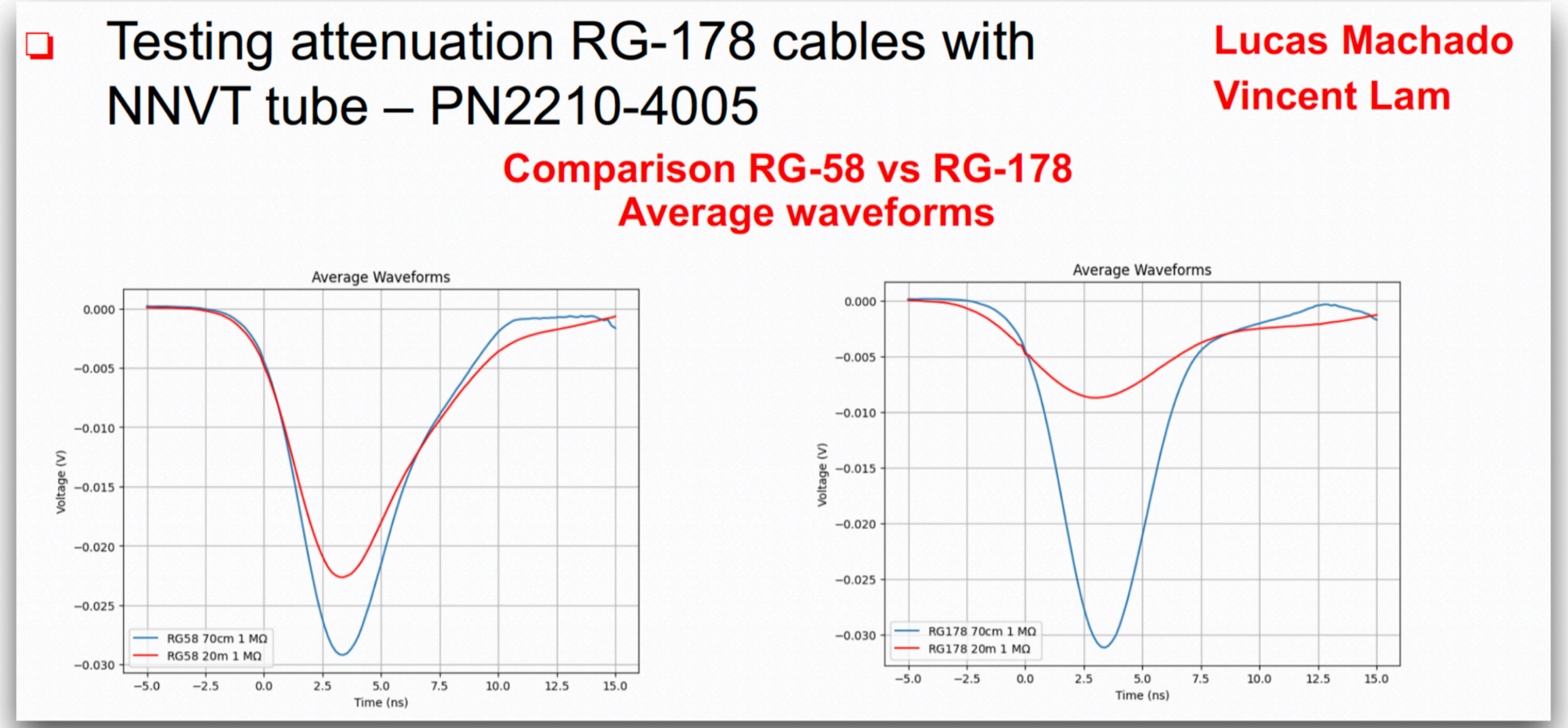


Underwater Connection

Underwater Connections : Path Forward



- FD3 Design:
  - Proceed with a mastic-based solution for underwater connection
    - AXON connectors will remain a back-up
  - Ask NNVT to develop RG58-based PMT for bid



- SHV with Mastic Option
  - RG58-SHV-RG174
    - Biggest issue is size differences among three pieces
  - Development in progress in the UK
  - Not Cheap, introduces more Rn contamination

Testing and Management of PMTs: Quality Assurance Tests

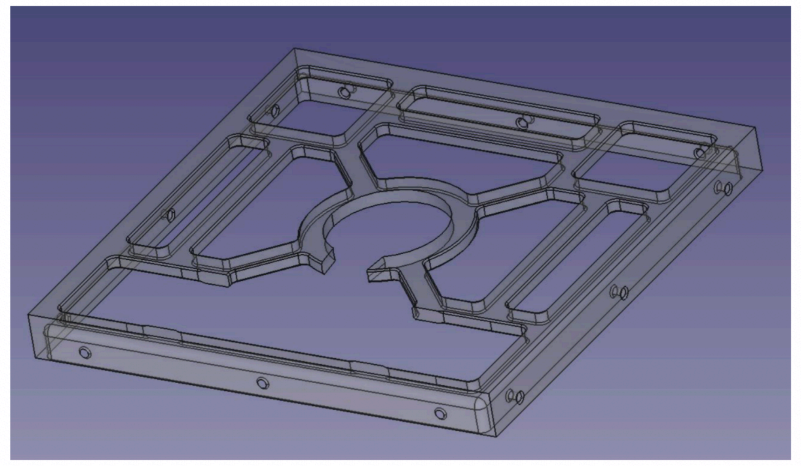
(S. Zsoldos, KCL)

- Planning to characterize all OD PMTs prior to transportation into the mine
  - Run in parallel with PMT assembly process

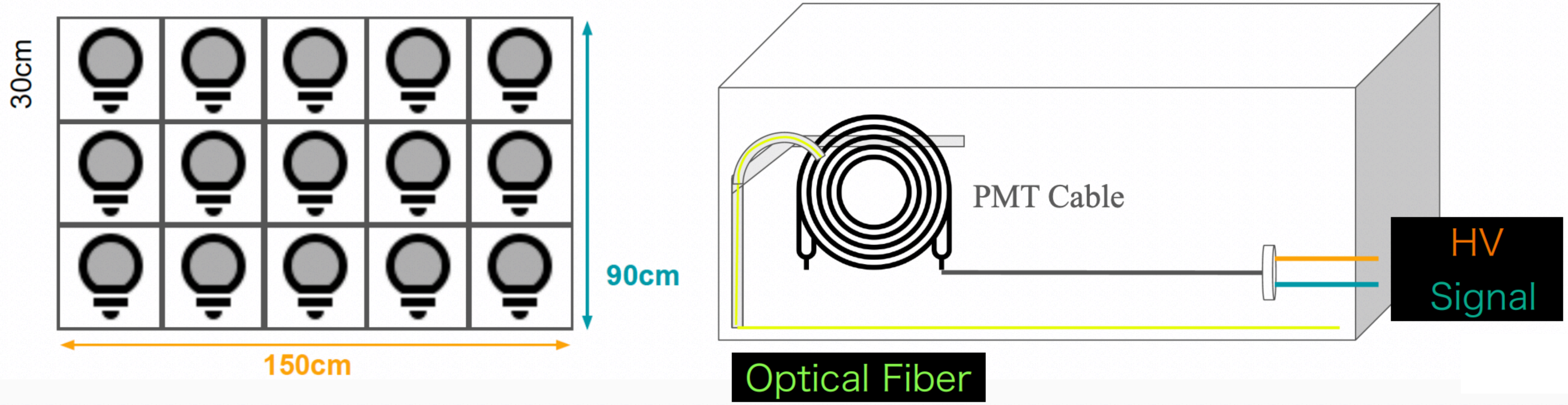
TEST	REQUIREMENTS	DURATION	💡
Gain	3.10^6 @[900, 1300]V	1h	✅
Single PE	PE width to Pedestal = 2 @ 3.10^6	few mins	✅
Relative QE	<20% variation @ 3.10^6	few mins	✅
Dark rates + stability	<kHz	~10h	

Dark Box

PMT QA Mount



- Process measurements on 30 PMTs mounted in two dark boxes
  - LED coupled to optical fiber distributed to each PMT



Testing and Management of PMTs: Detailed precalibration

- Plan to fully characterize roughly ~1% of OD PMTs+WLS using ID PMT precalibration systems developed in Korea and Australia
  - ~40 PMTs
  - Performed at the tail of ID precalibration campaign

TEST	COMMENTS	DURATION	💡
QE + CE	Calibrated LED + Calibratred Si PMT	~1h	⊥ ✅
B field	Turn PMT 90° and measure CE	30mins	✅
CE with WLS plate	Calibrated LED, 1 point measurement	~1h	⊥ ✅

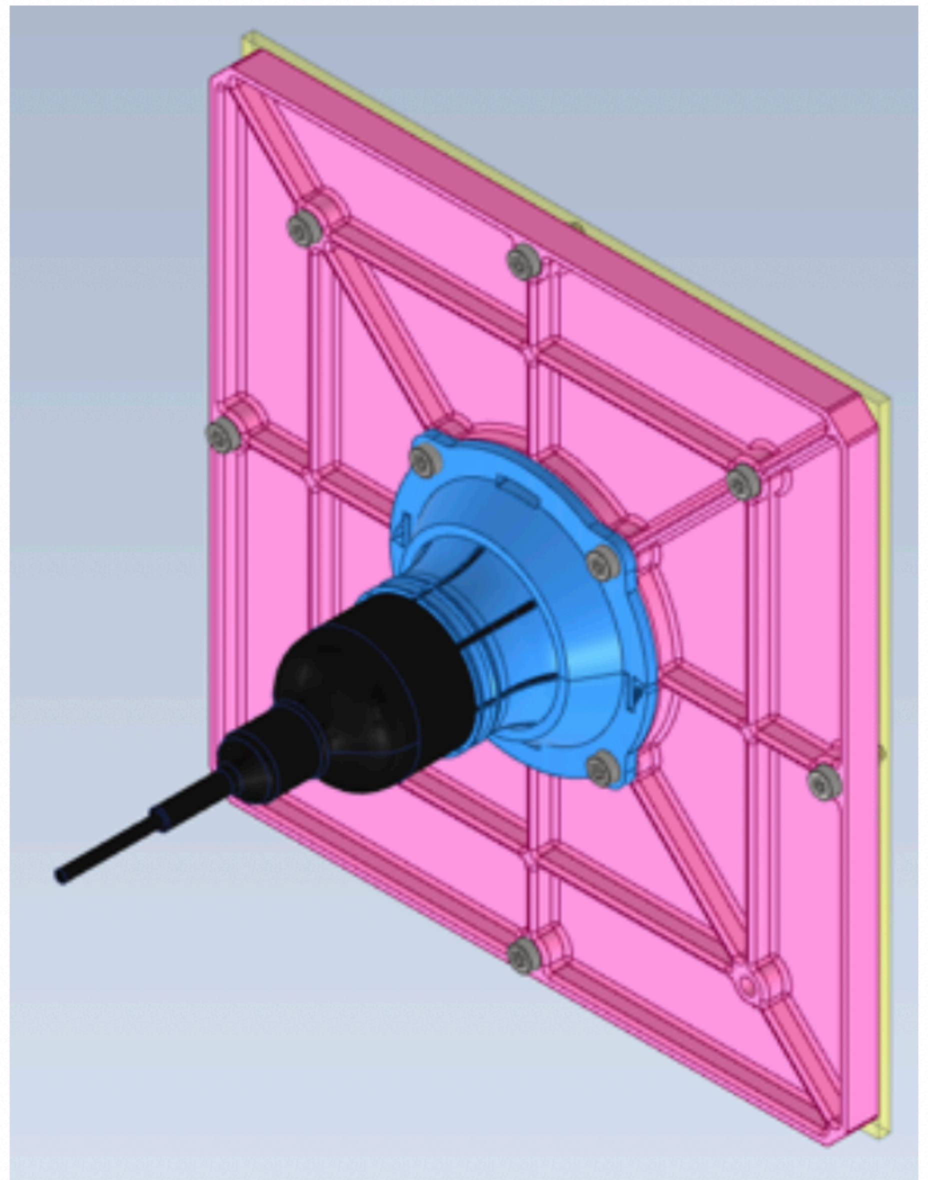
- Considering additional measurements with light source injected obliquely, 45 degrees and 90 degrees
  - May only be possible with a subset of tested PMTs

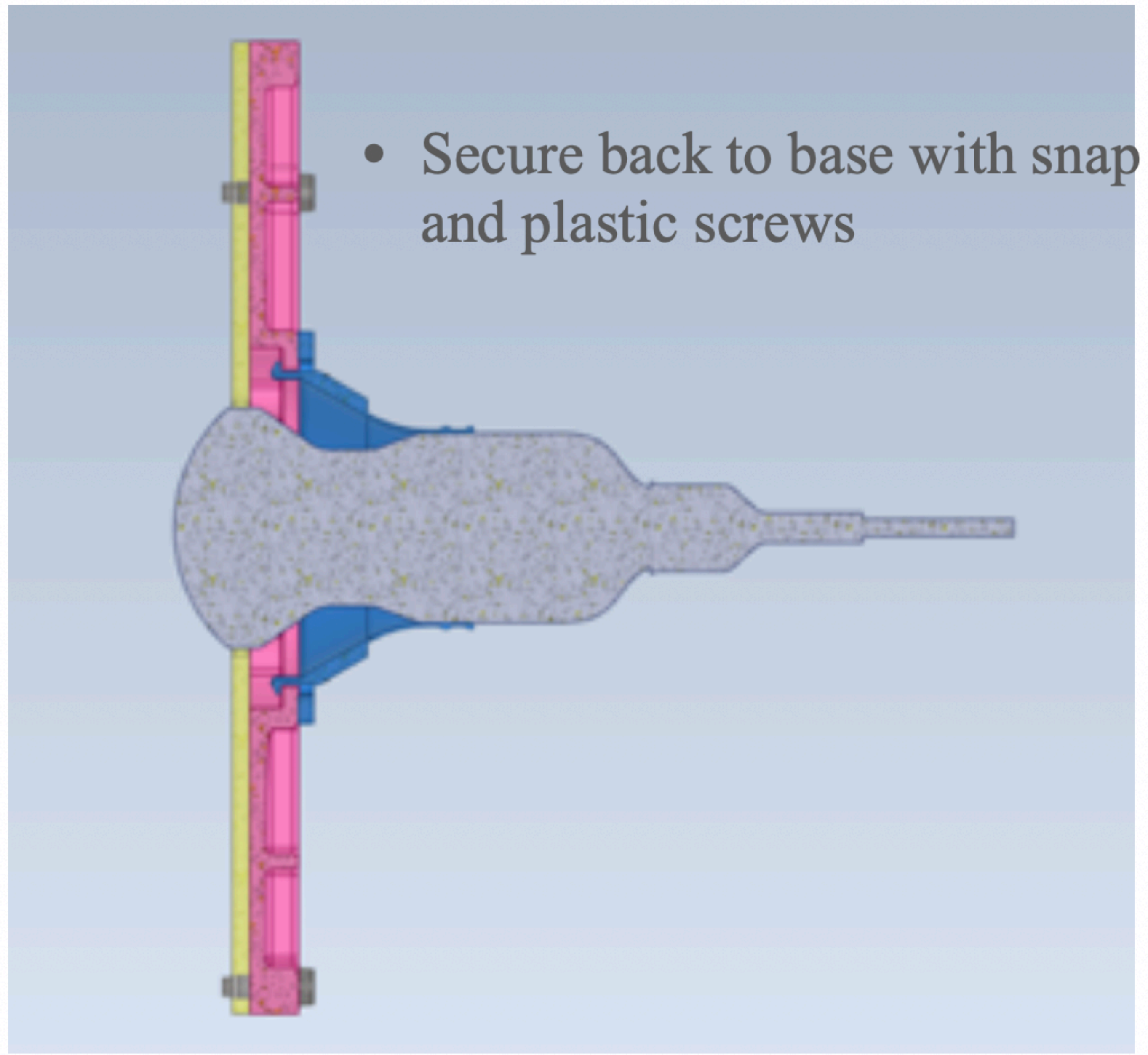
- Measurements will serve as references extrapolated to remaining 99% of PMTs

PMT Mounting

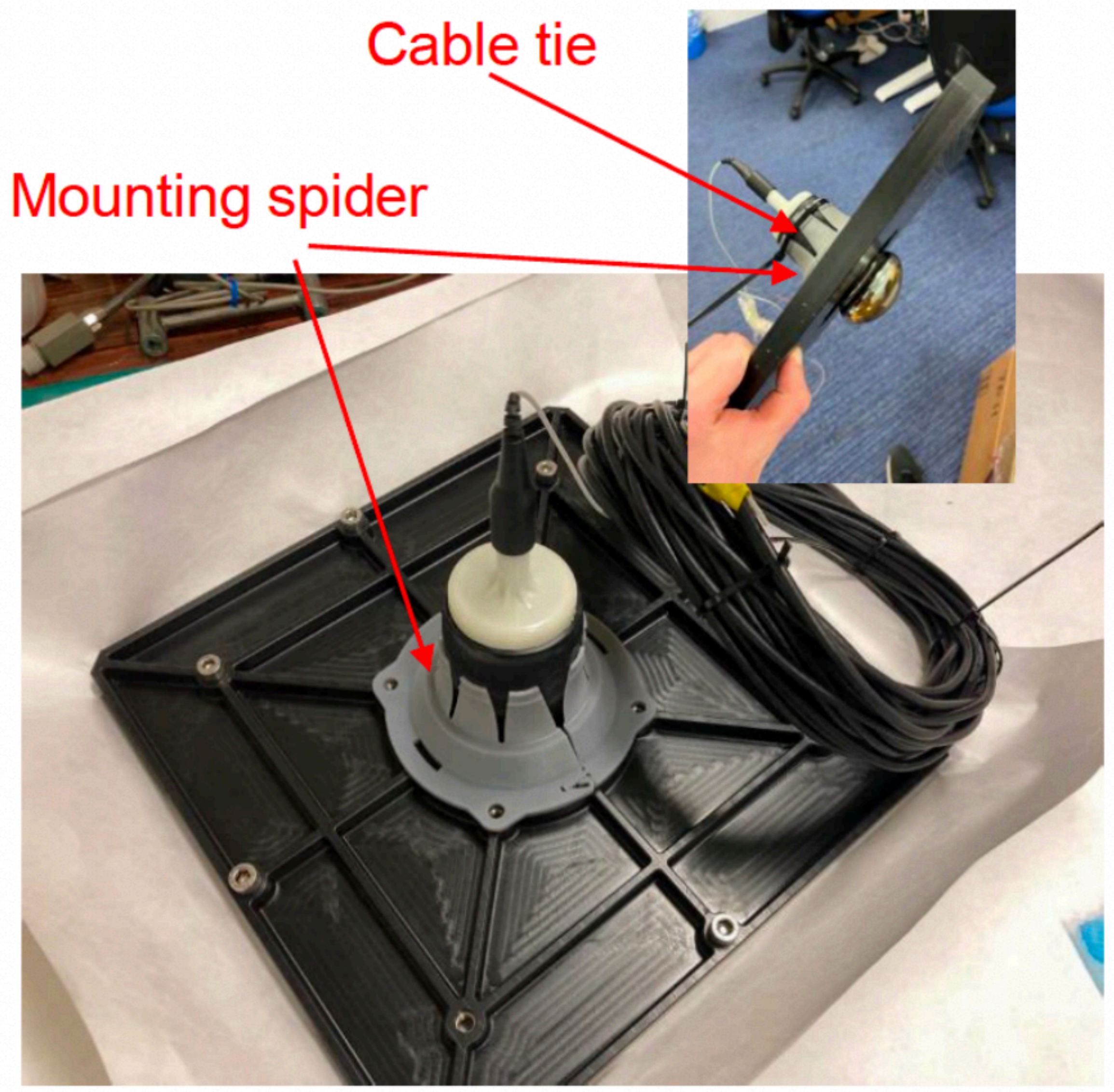
(A. York, Oxford)

- Mostly Light-tight base





- Secure back to base with snap and plastic screws



- Groove to secure PMT with cable tie

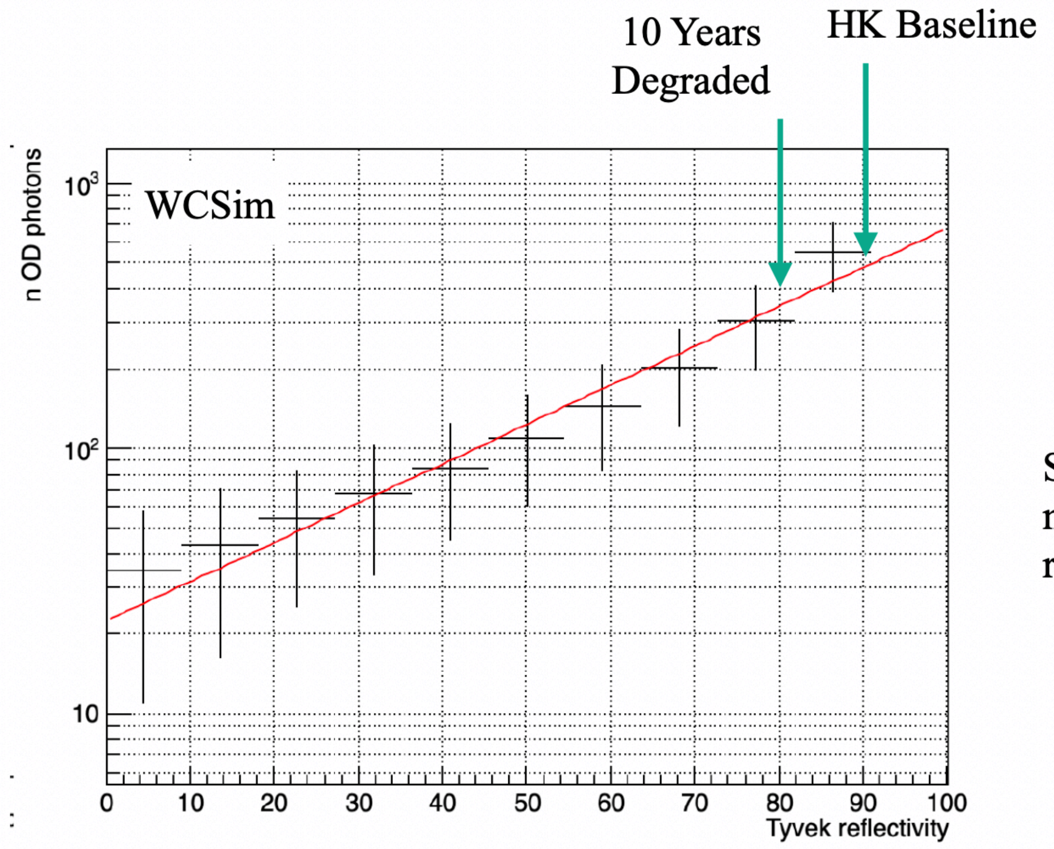
- Minor changes to design reported at December 2023 CM
  - → Converged for HPK tubes
- "Spider" backing produced by injection moulding

- Prototype ready, "shake" testing underway
  - Installation testing etc. with RAL mockup and Japanese mock-up mostly successfull

- No major issues though some design modifications may be needed installation (more later)

Tyvek

- Cost of Tyvek from primary source - Chinese company DADAO (“DD”), nearly doubled at end of 2023
  - In contact with them, trying to understand cost increases
- Looking for alternate suppliers for double-sided W/W … or, revert to SK-style single-sided Tyvek
- Currently no alternative for B/W Tyvek



Federico

Single-layer Tyvek may start with less reflectivity

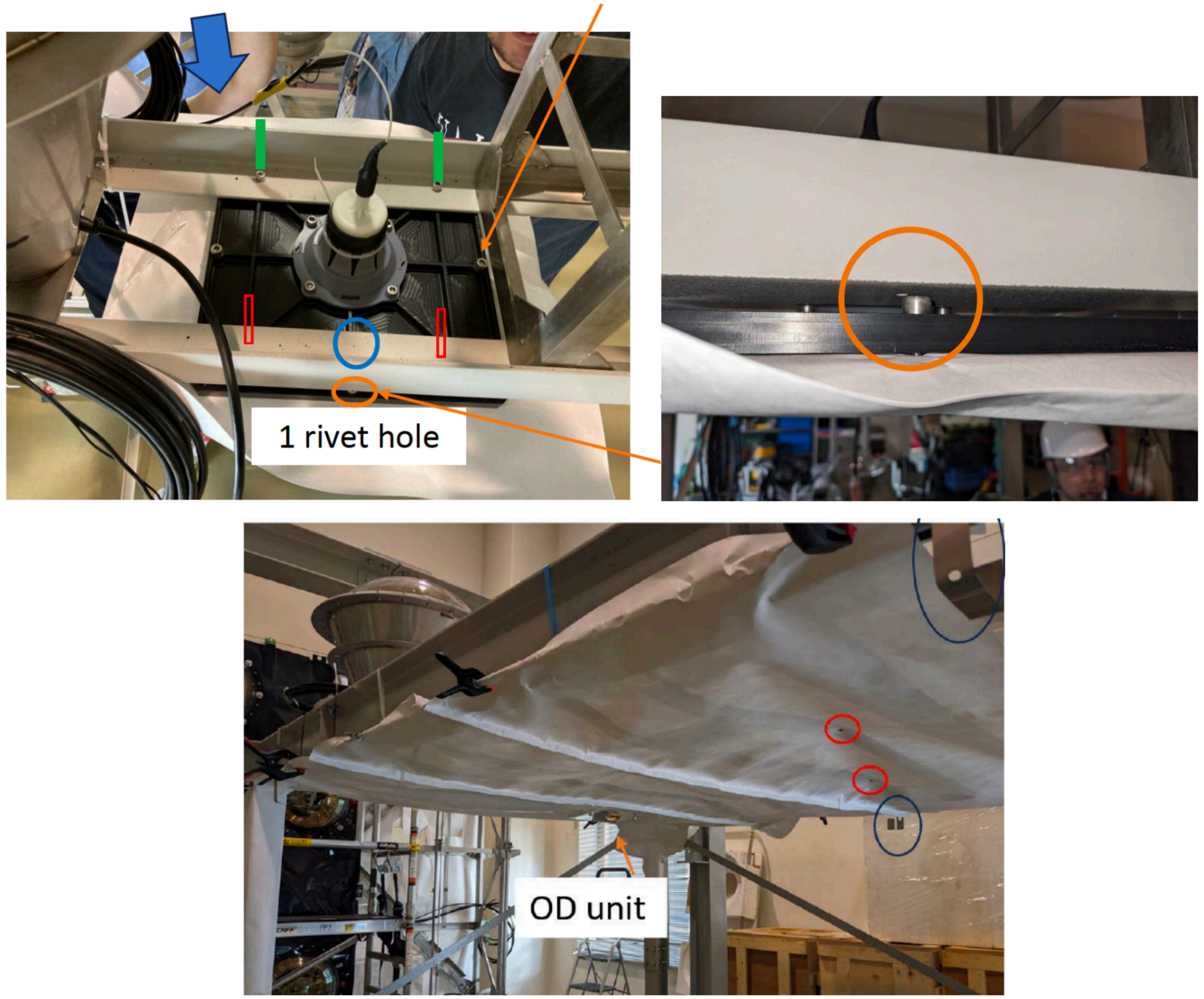
- Studies of Tyvek reflectivity in Super-K using cosmic ray muons indicate low level of degradation in reflectivity over 10 years of SK-IV
  - …not a perfect measurement, possibly other competing effects
- Assumed 10% (abs) drop in reflectivity over 20 years for Hyper-K seems OK, probably even conservative
- Cosmic studies indicate single-layer Tyvek *may be* sufficient for HK
  - Would help cut costs since there are many more suppliers
  - Better for schedule management as well

Installation

Installation

Federico [4/16 FD3 Meeting]
Rory [5/21 FD3 Meeting]

- Installation tests at RAL (barrel), Kashiwa (barrel, top, bottom)
  - Several minor issues identified with rivet positioning, interference with other modules,..
  - Established first pass of installation procedures, with many lessons learned, but no show-stoppers



OD Bottom Installation in Kashiwa

Barrel installation at RAL

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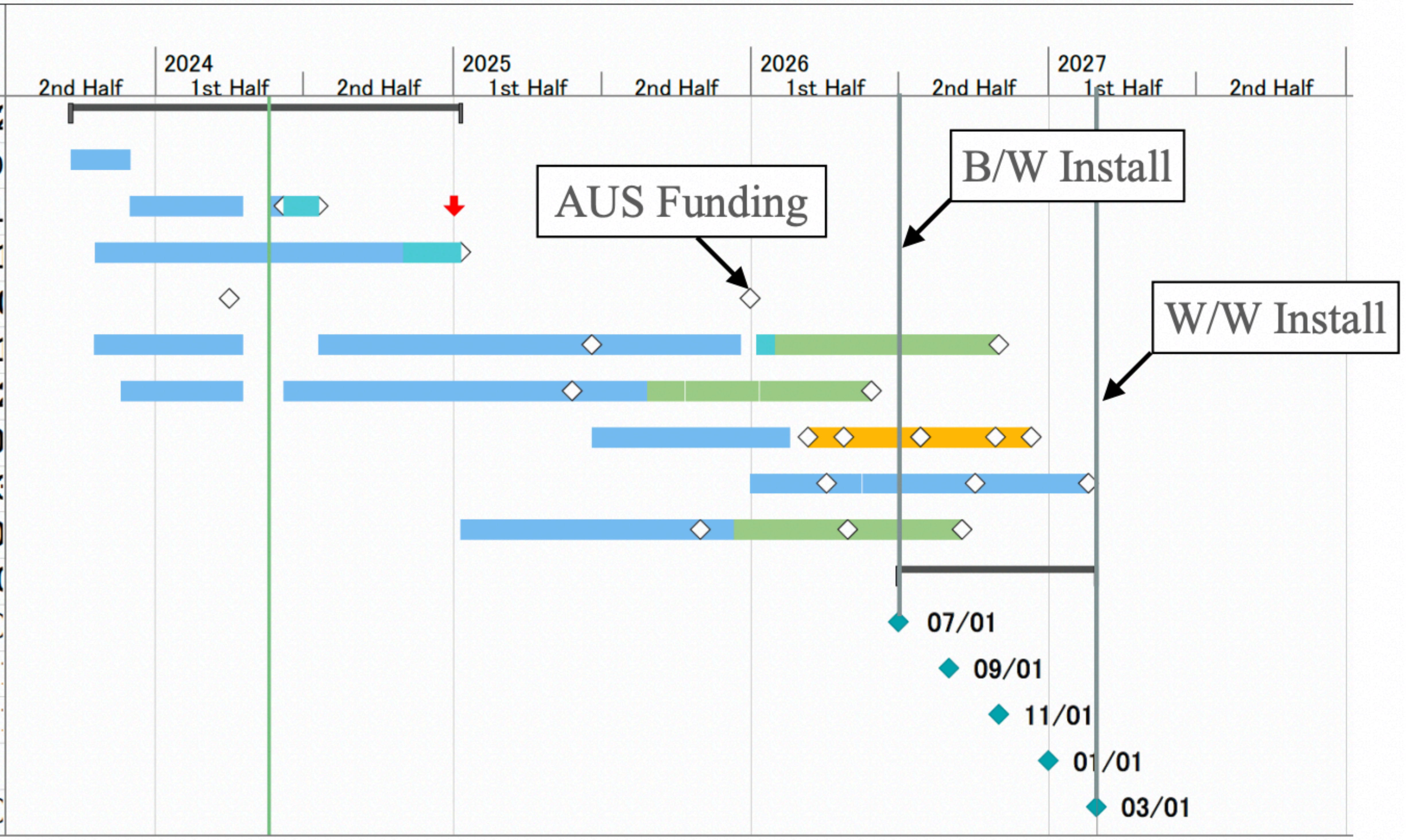
Outer Detector: Schedule

Schedule

Name	Duration	Start
Overall design	**341.5da**	**Wed 23/09/2**
Engineering Design Review	52days	Wed 23/09/20
Design Except Tyvek	**165days**	**Fri 23/12/01**
Tyvek Design	**321days**	**Wed 23/10/1**
Funding	**458days**	**Mon 24/04/0**
PMT	**795days**	**Wed 23/10/1**
WLS plate	**660days**	**Mon 23/11/2**
PMT+WLS QA/Assembly	**388days**	**Fri 25/06/20**
Tyvek W/W	**298days**	**Wed 25/12/3**
Tyvek B/W	**440days**	**Thu 25/01/0**
Installation Targets	**174days**	**Wed 26/07/0**
Top	0days	Wed 26/07/0
Upper Barrel	0days	Tue 26/09/0
Lower Barrel	0days	Sun 26/11/0
Bottom	0days	Fri 27/01/01
End of PMT	0days	Mon 27/03/0



- Design of OD system on track for finalization
  - Tyvek choices will be finalized later in 2024
  - These can arrive later, allowing time to search for additional vendors and funding sources

- PMT procurement will start this summer with first deliveries expected in early 2026

Outer Detector: Conclusion

- The OD design and testing is being finalised on the different fronts: PMTs, WLS plates, Tyvek, cables, electronics, calibration, installation.
- Related technical notes were written and submitted to the review committee in January.
- They are currently being updated with newest results and taking into account the reviewers' comments. The final design review will start in June.