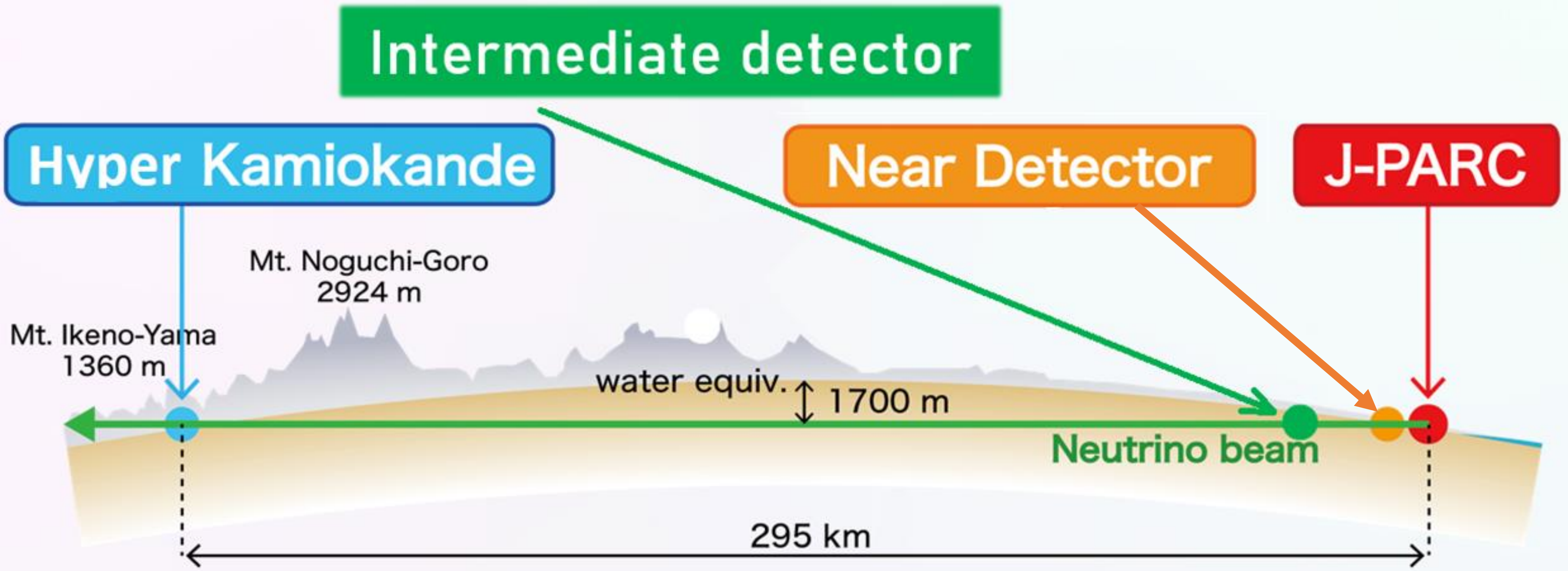
Production line and quality assurance of mPMT photosensors for WCTE

Krzysztof Dygnarowicz

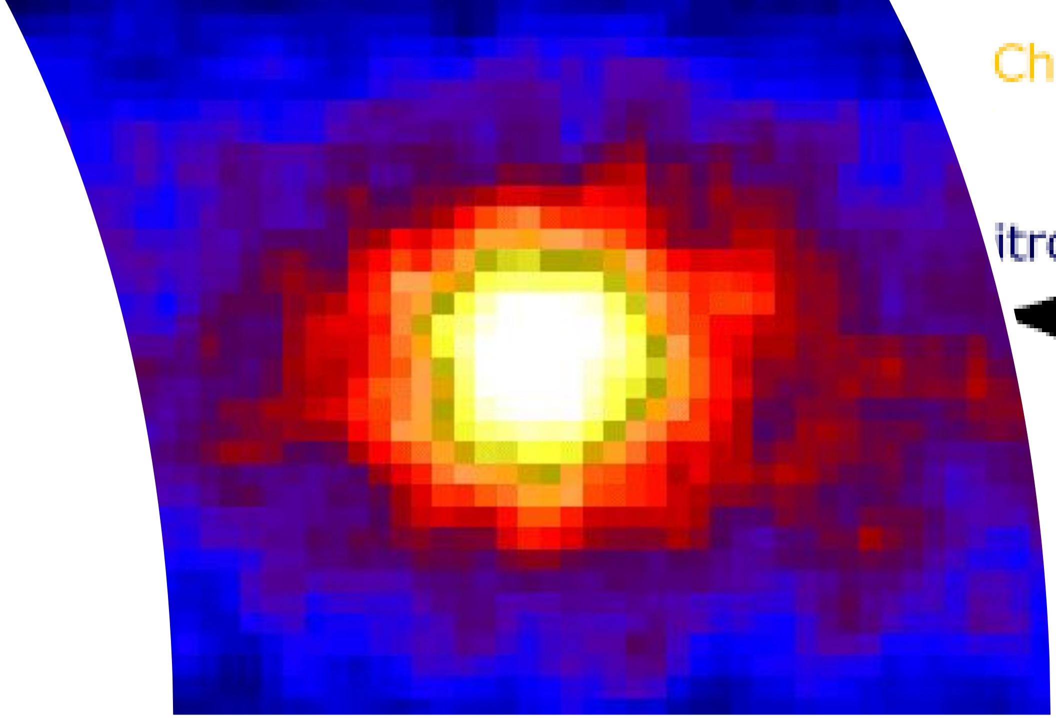
On behalf of The Water Cherenkov Test Experiment and The Hyper-Kamiokande Collaboration

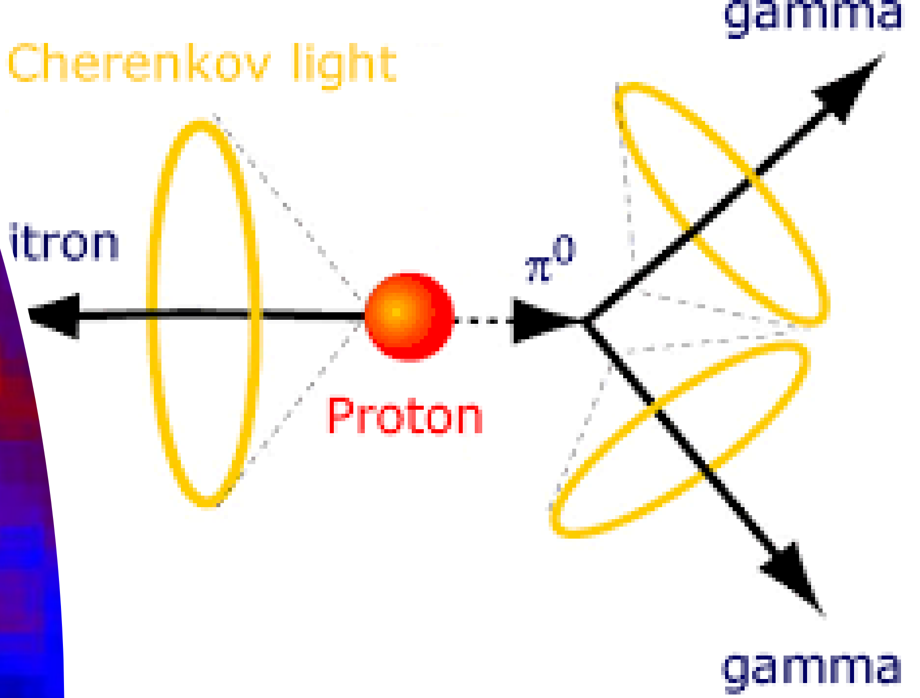
What is Hyper-Kamiokande

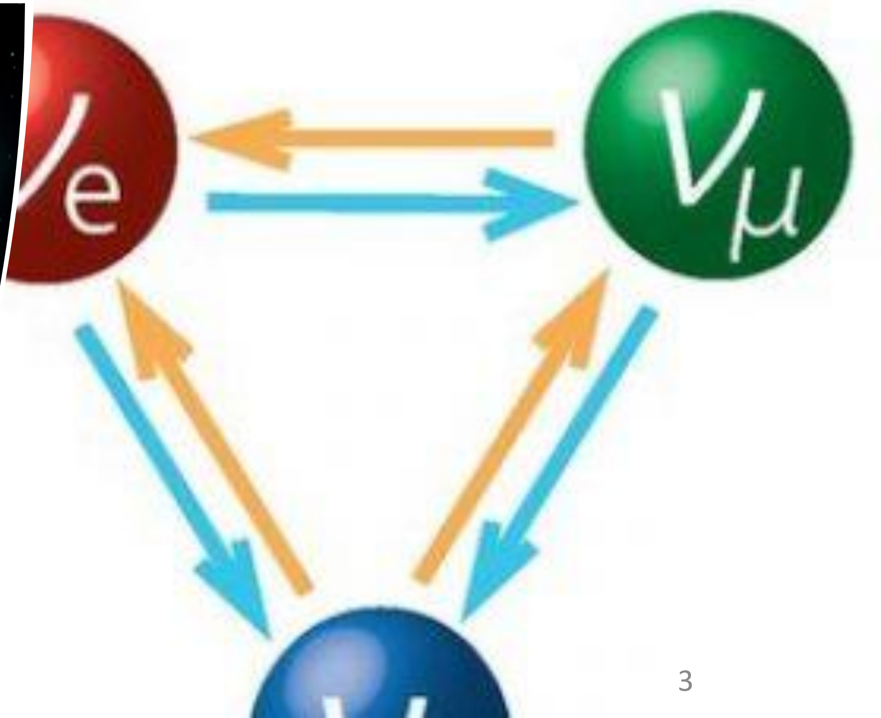


Warsaw University of Technology

Why Hyper-Kamiokande







Main research tasks of Hyper-Kamiokande:

- Neutrino oscillation
- Study of CP-violation
- Study of cosmic neutrinos
- Proton decay search
- Dark matter search

Source:
https://www-sk.icrr.u-tokyo.ac.jp/sk/sk/pdecay-e.html
NASA, ESA, J. Hester, A. Loll (ASU)
http://www.hyper-k.org/en/

Multi-PMT detector

Key features:

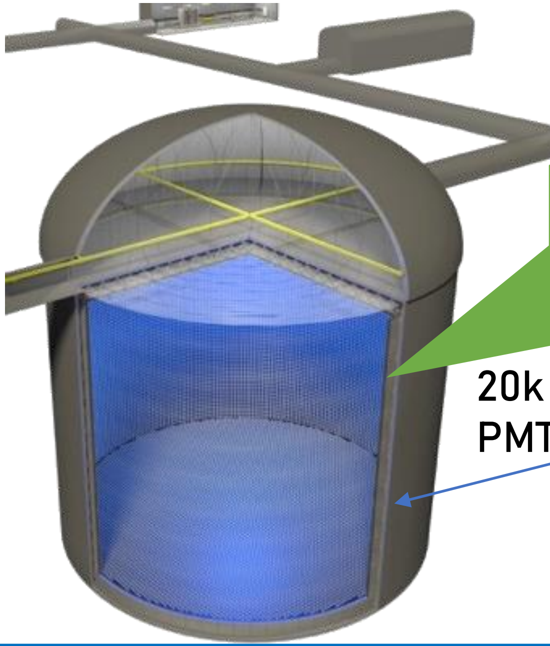
- Composite detector build from 19 PMTs (Hamamatsu R14374)
- Sealed in waterproof container
- Gel to improve optical contact between PMT and acrylic dome
- Weight 50 kg, diameter 0,5 m
- Integrated HV & readout electronics

mPMT benefits:

- Better time resolution (compared to 50 cm PMTs)
- Directionality
- Increased granularity

Where will we use mPMTs?

Hyper-Kamiokande Far Detector

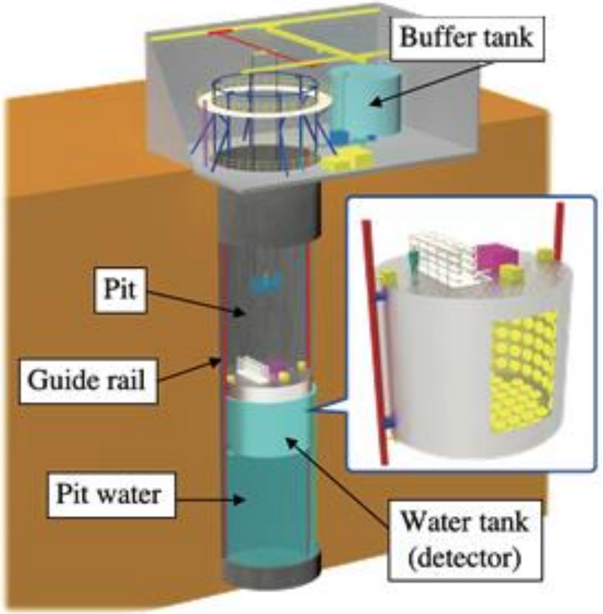


20k 50cm PMTs

Water Cherenkov Test Experiment (WCTE)

WCTE in CERN (2024):
- Pre-production versions of mPMTs
- Two versions of mPMT:
  - IWCD – ≈100 units
  - Far detector – 5 units
- Later to be sent to Japan

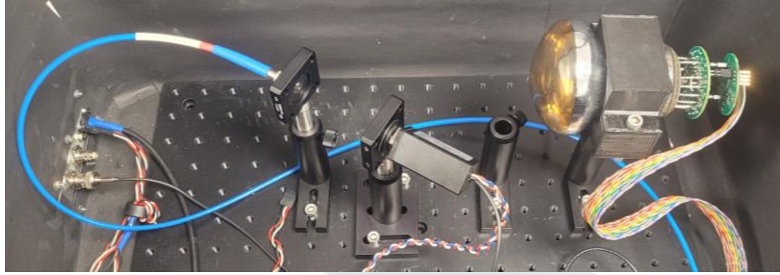
Intermediate Water Cherenkov Detector (IWCD)



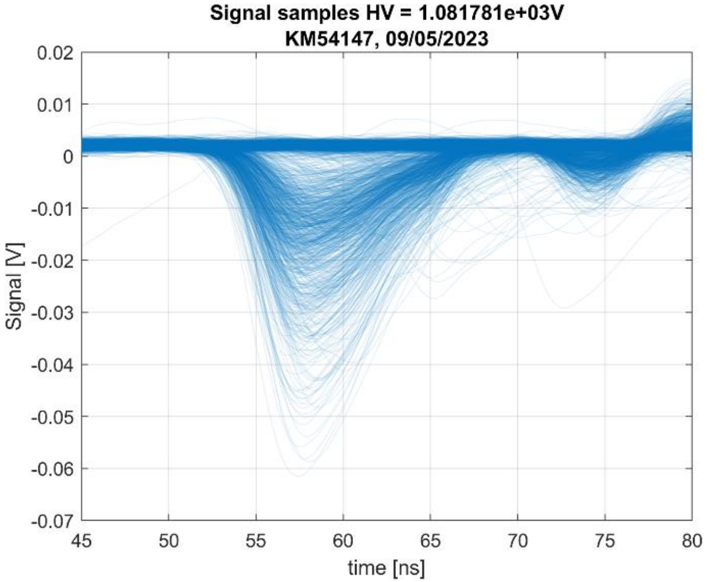
Far detector:
- Optimized for low power
- Need high reliability (at least 10 years of operation)
- High pressure working conditions (~1 MPa)

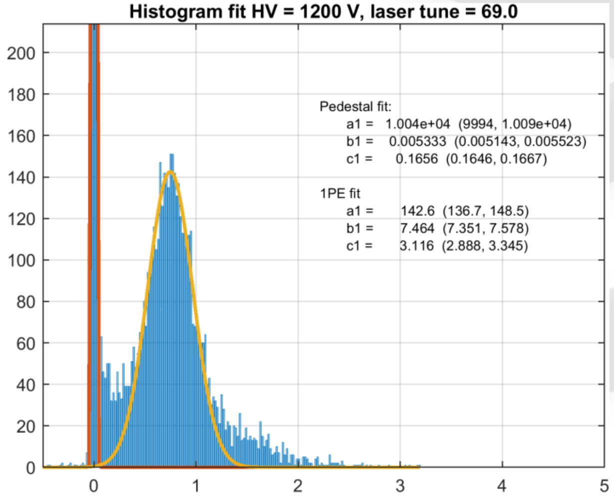
Intermediate detector:
- Optimized for high rate
- Flash-ADC type acquisition
- Less strict reliability requirements.
- Relaxed restriction on power consumption

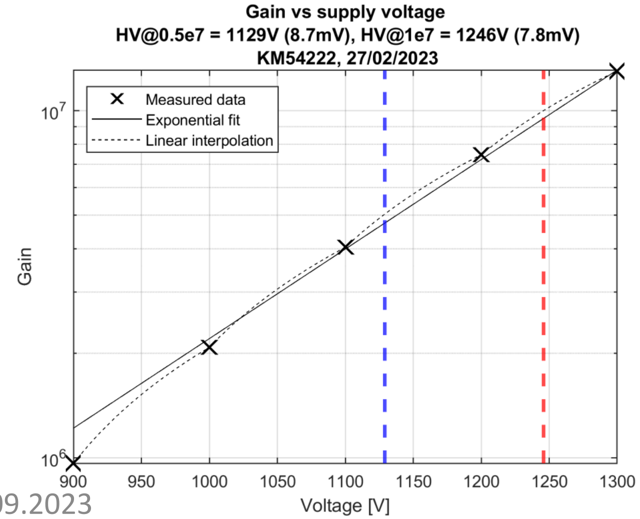
PMT Characterisation

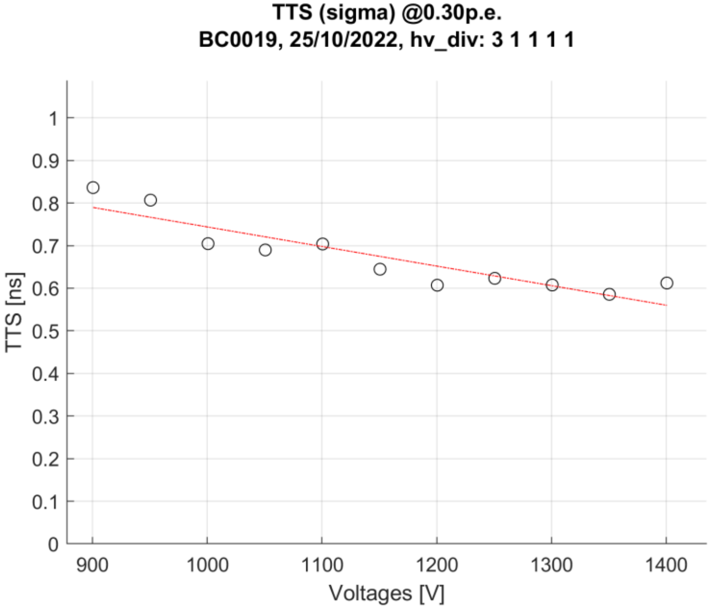


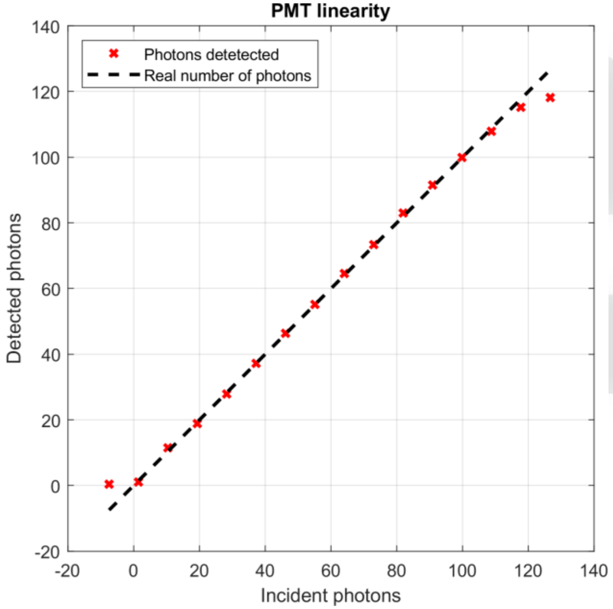
- Verify signal shaping circuit – rise/fall time, FWHM
- Calibrate gain for each PMT in mPMT for $5x10^6$
- Check Dark Rate
- Confirm linearity
- Calculate transit time spread (TTS) for PMT depending on divider ratio











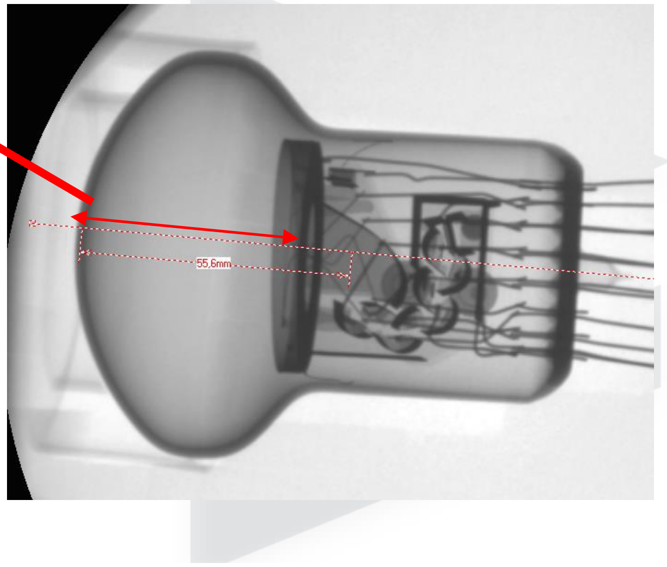
Afterpulse measurements

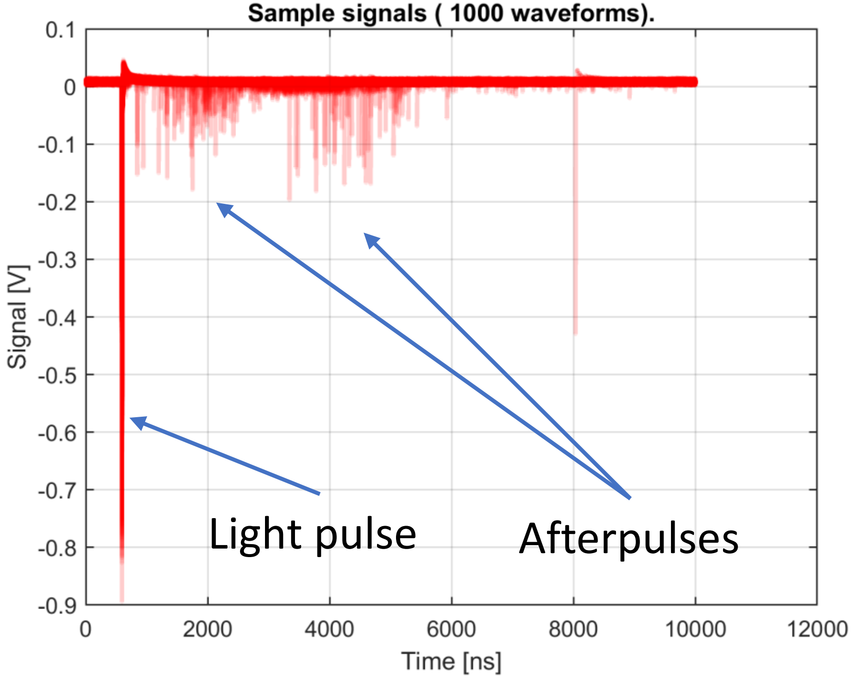
- Checking afterpulse dependence on the configuration of the HV divider.
- Most of afterpulses come from the 1st and the 2nd dynode

	V [kV]
K	**1,2816**
D1	1,0065
D2	**0,8234**
D3	0,7319
D4	0,6405
D5	0,5491
D6	0,4575
D7	0,3654
D8	0,2743
D9	0,183
D10	0,091
A	0

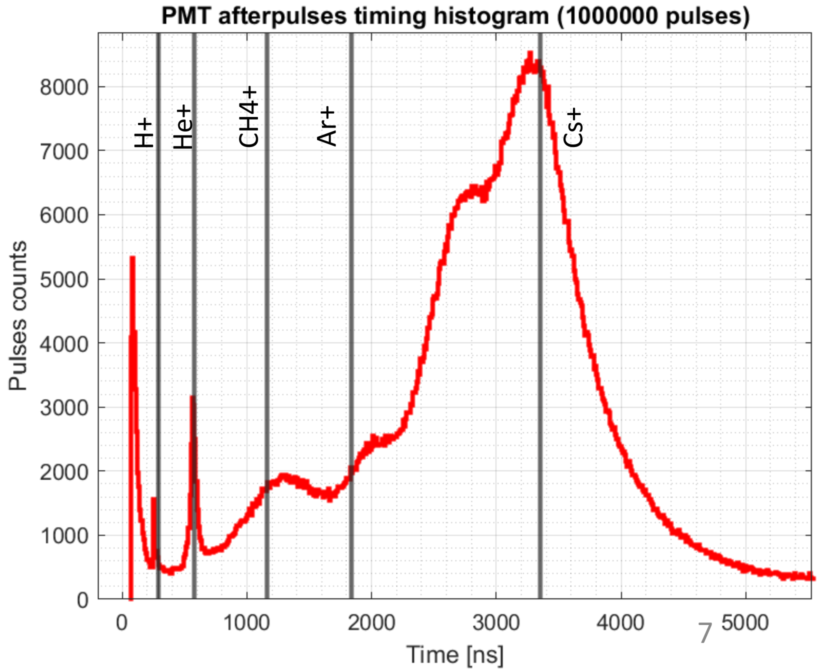
L [m]	0,055	
V [V]	**458,2**	
1 g/mol	1,66E-27	
	mass [g/mol]	delay [us]
H+	**1,007**	**0,29**
He+	**4,002**	**0,58**
CH4+	16,042	**1,16**
N2+	28,006	1,54
Co+	28,010	1,54
Ar+	39,948	**1,84**
Xe+	131,293	3,33
Cs+	**132,905**	**3,35**

X-ray image of PMT





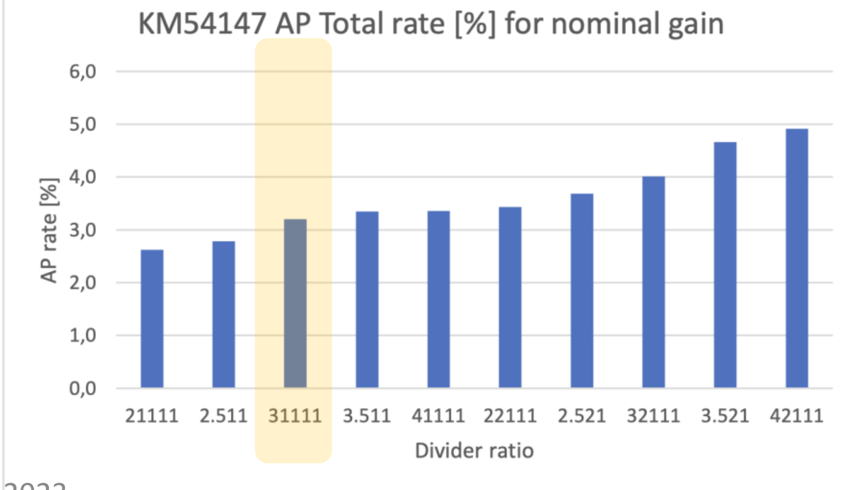
$$t = \frac{\pi}{4}\sqrt{\frac{2m}{qV_0}}L$$



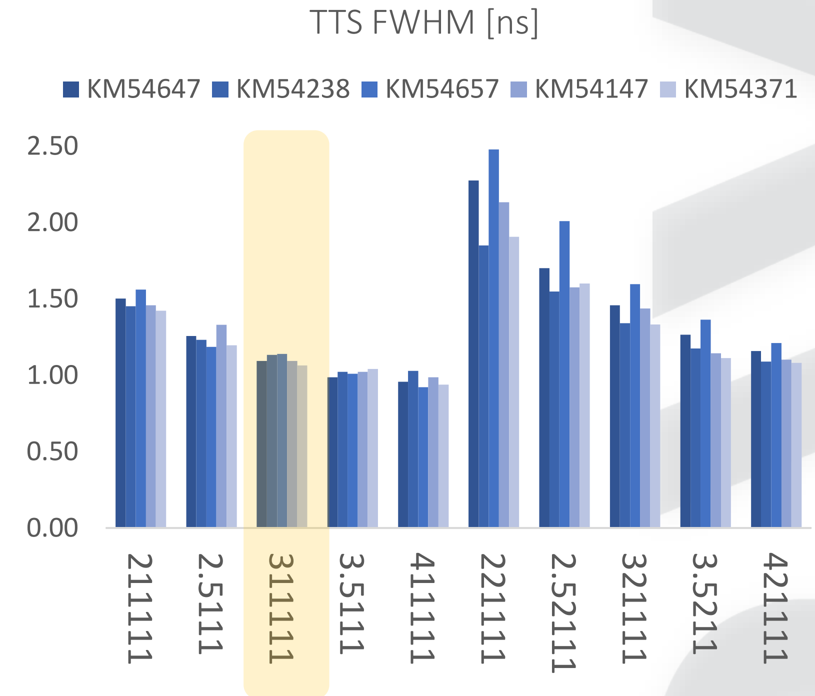
TTS @ divider ratios

- Test stand with independent control of each dynode voltage
- Averaged TTS from 5 PMTs (different ratios):
  - Ratio 3111 -> 1.11 ns
  - Ratio 3211 -> 1.43 ns
- Efficiency not influenced by divider
- Decision -> 3-1-1-1-1 … -1 divider

Afterpulses rate vs HV divider



TTS



Divider	KM54647	KM54238	KM54657	KM54147	KM54371	Average [ns]
211111	1.50	1.45	1.56	1.46	1.42	1.48
2.5111	1.26	1.23	1.19	1.33	1.20	1.24
311111	1.09	1.13	1.14	1.09	1.07	1.11
3.5111	0.99	1.02	1.01	1.02	1.04	1.02
411111	0.96	1.03	0.92	0.99	0.94	0.97
221111	2.28	1.85	2.48	2.13	1.91	2.13
2.52111	1.70	1.55	2.01	1.58	1.60	1.69
321111	1.46	1.34	1.60	1.44	1.33	1.43
3.5211	1.27	1.18	1.36	1.15	1.11	1.21
421111	1.16	1.09	1.21	1.10	1.08	1.13

mPMT main mechanical components

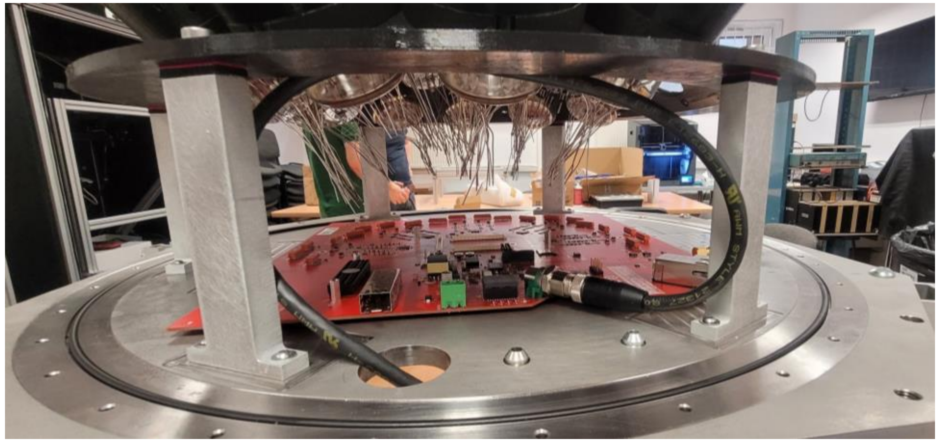
1. Backplate with feedthrough
2. Matrix - 3D printed from PETG
3. Acrylic Dome – UV transparent
4. POM-C Cylinder
5. Pillars mounted on backplane
6. Cross-section of mPMT CAD model

1.


2.


3.


4.


5.


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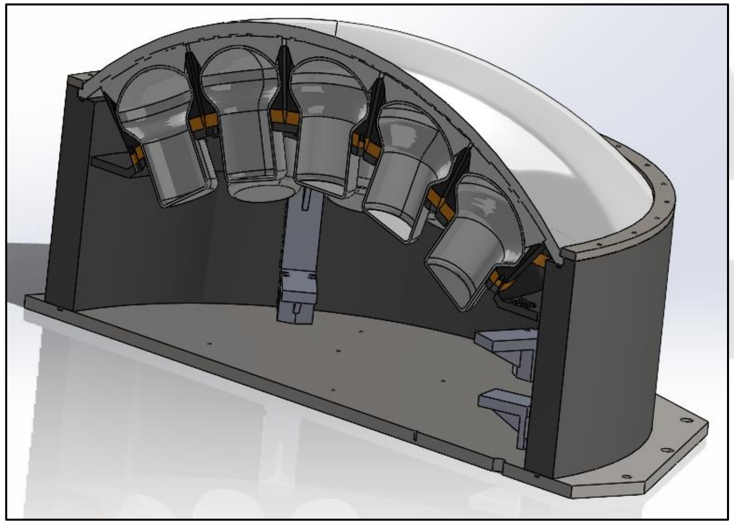
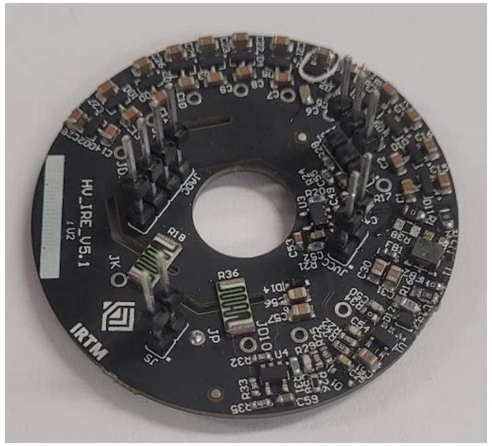


mPMT electronic components

1. High Voltage supply board (HV)
2. Front End board (FE)
3. Photomultiplier with soldered HV and FE
4. Mainboard - Big Red Board (BRB)
5. BRB mounted on backplane with twisted pair ribbon cables terminated with micro-match connectors

1.



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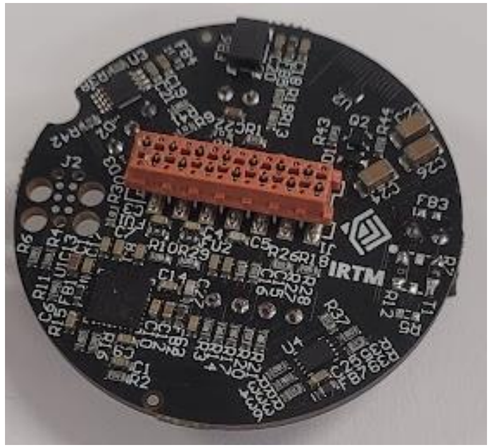

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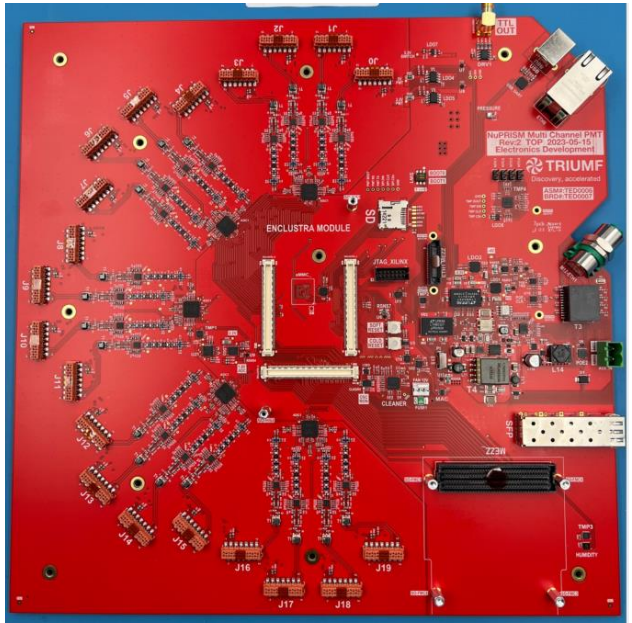
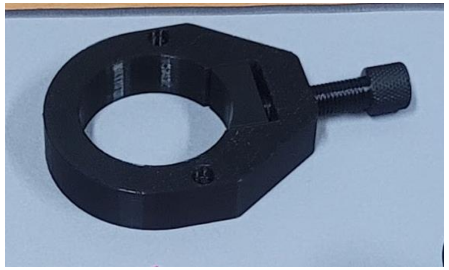


5.

PMT gelling

1. Bottom Mould
2. Top Mould
3. Photomultiplier in cup with reflector
4. Clamp
5. Locking pins with tool
6. Final inspection before screwing bottom mould

2.



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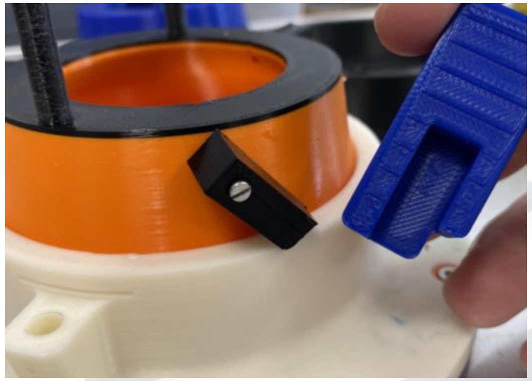

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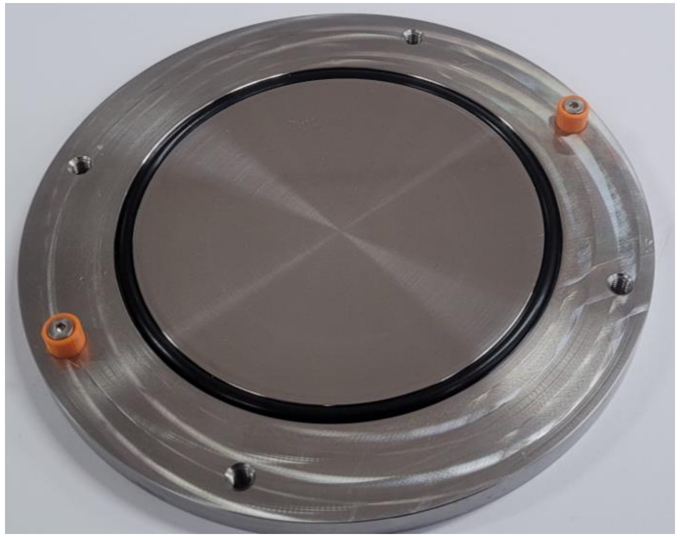


1.

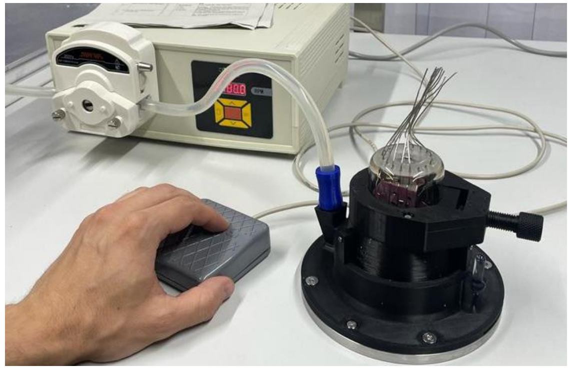
3.

6.

Gelling process – Wacker SILRES® 604 A 96:B 4

1. Pour gel into form with peristaltic pump
2. Unscrewing form after 24h of baking in 30°C
3. PMT before releasing it from bottom mould
4. Gelled PMT with added black collar at edges

- Each form is filled with ~105 g of gel - may vary due irregularity of PMT bulbs
- Aimed at achieving good quality of gel edges



1.

2.

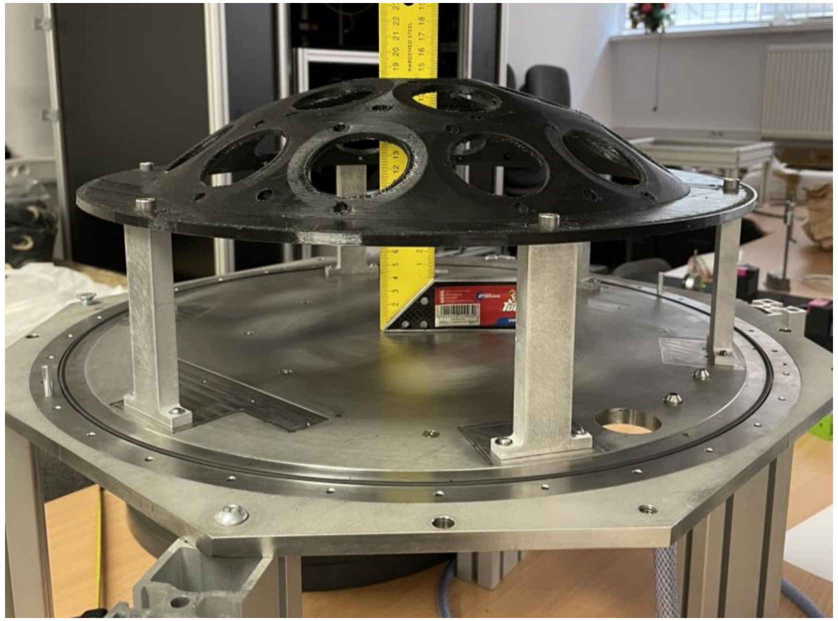
3.

4.

Assembly of mPMT

1. Matrix on pillars
2. Gelled PMTs in matrix
3. Assembly Jig with a winch
4. Assembly Jig
5. Secured PMT with good contact

1.



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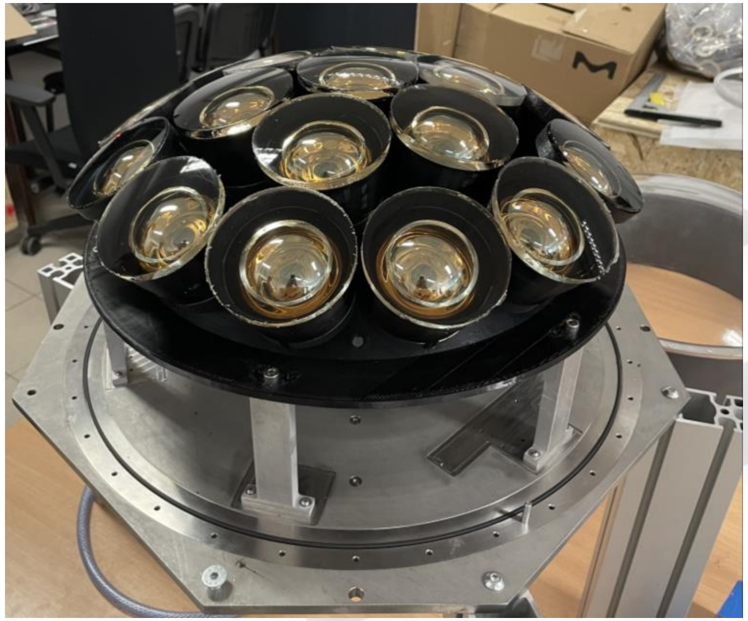

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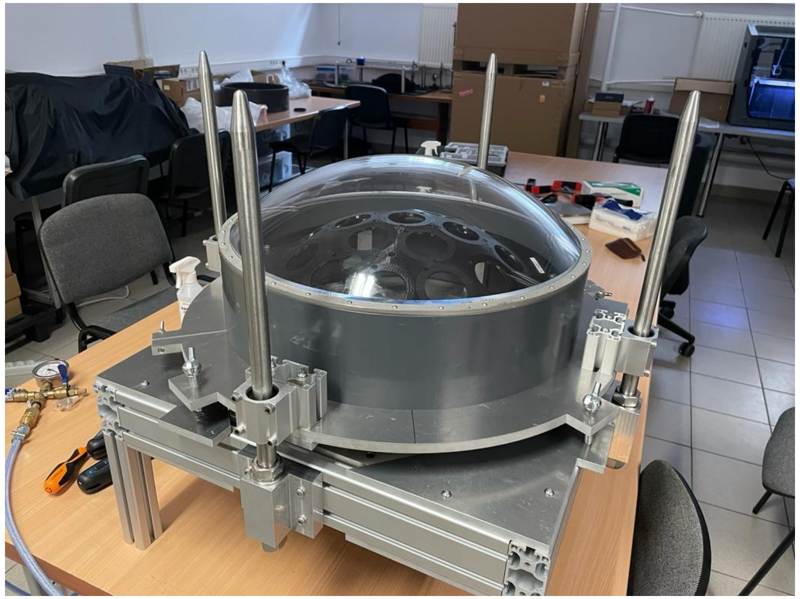
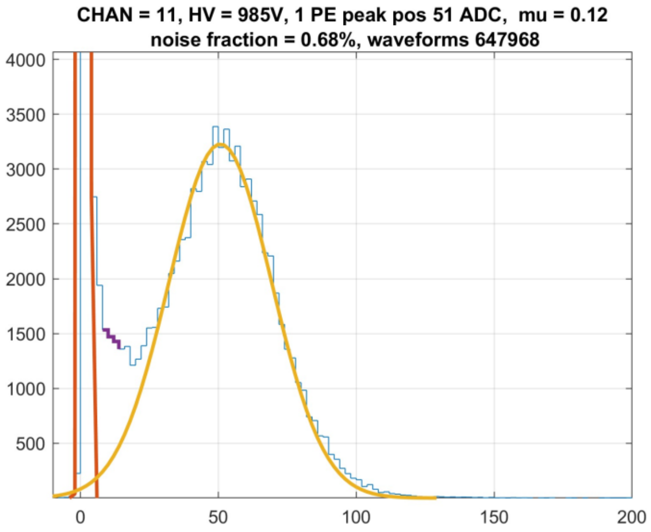
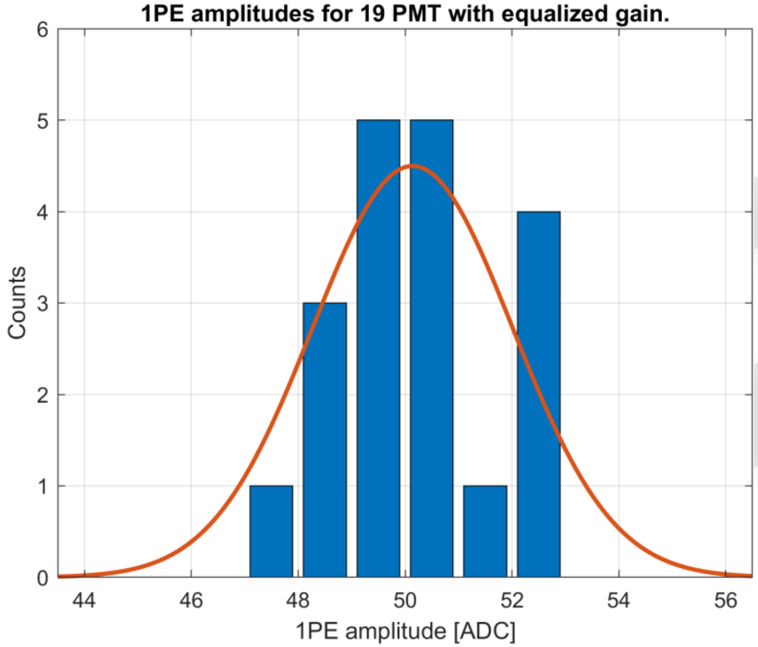


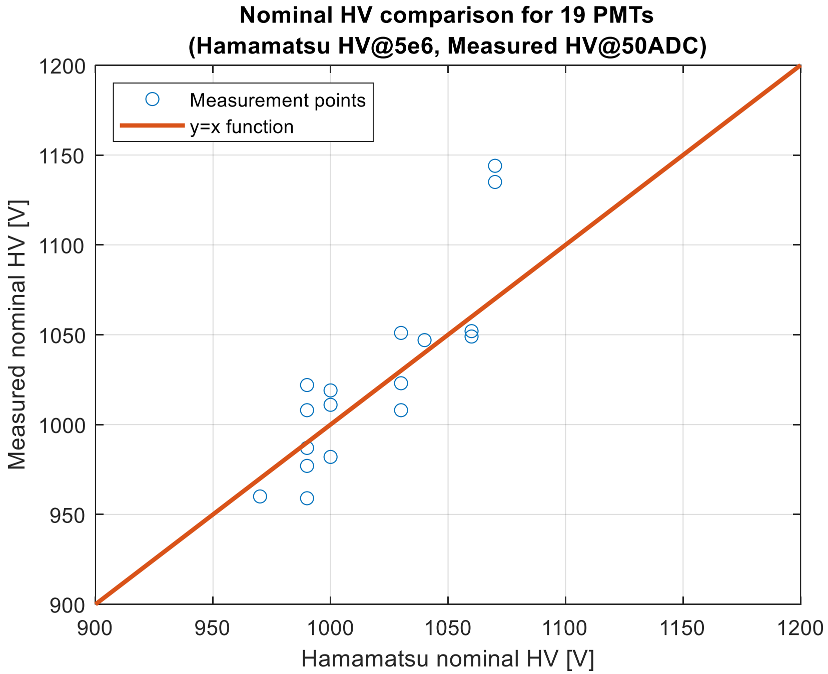
5.

Quality assurance

- HV+FE testing
  - Dedicated test device
  - uC programming, HV calibration, signal check
- BRB testing:
  - Dedicated tester (in development)
  - Analog path, acquisition, clocks, power supply
- **3" PMT assemblies**
  - Assembly = PMT + HV + FE card
  - **Verification before** gelling and mounting in the mPMT module
  - A set of 21 PMTs will be tested in parallel – now 19
  - Checks: gain, dark count
- mPMT modules:
  - Check operation in dark box using final DAQ
  - Selected mPMTs checked in test stand using a picosecond laser





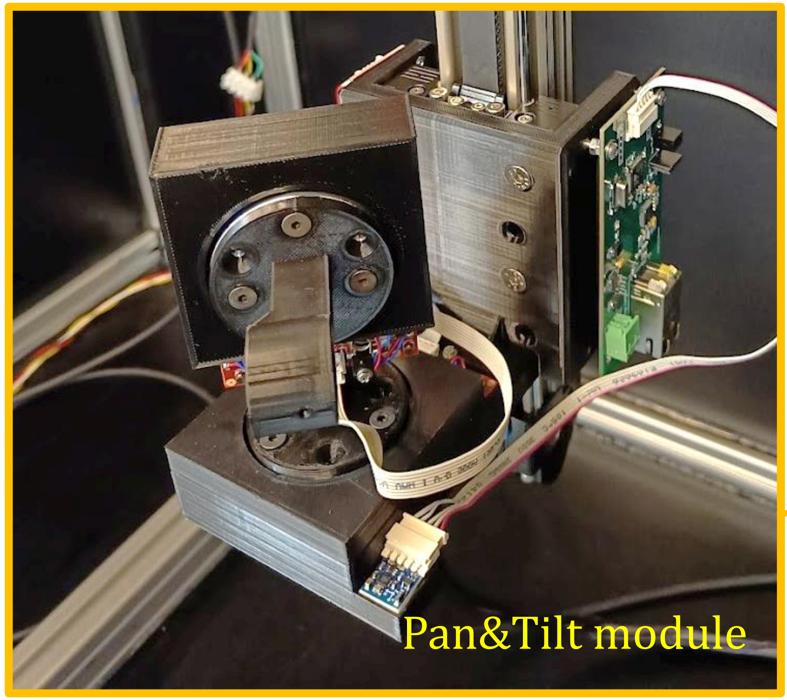


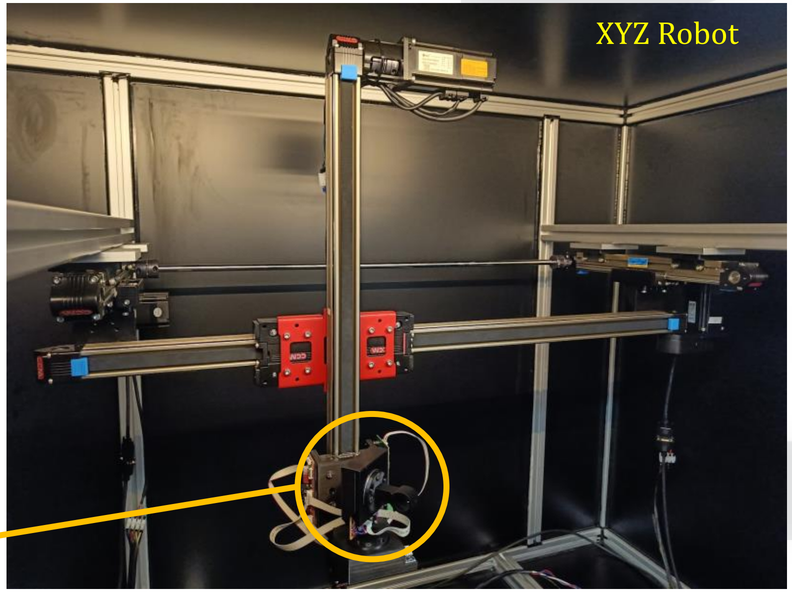
Measurement setup for fully assembled multi-PMT

- Light tight box for whole mPMT module
- XYZ robot with pan&tilt module with piezoelectric motors
  - (5-axial control of light source position & direction)
- Integrated magnetic field measurement module
- Fully automated scan of whole mPMT photosensitive area
- Similar setups available at other assembly stations
- Light source: picosecond laser (through an optical fibre)

Open cover, sliding mPMT mount

Closed cover

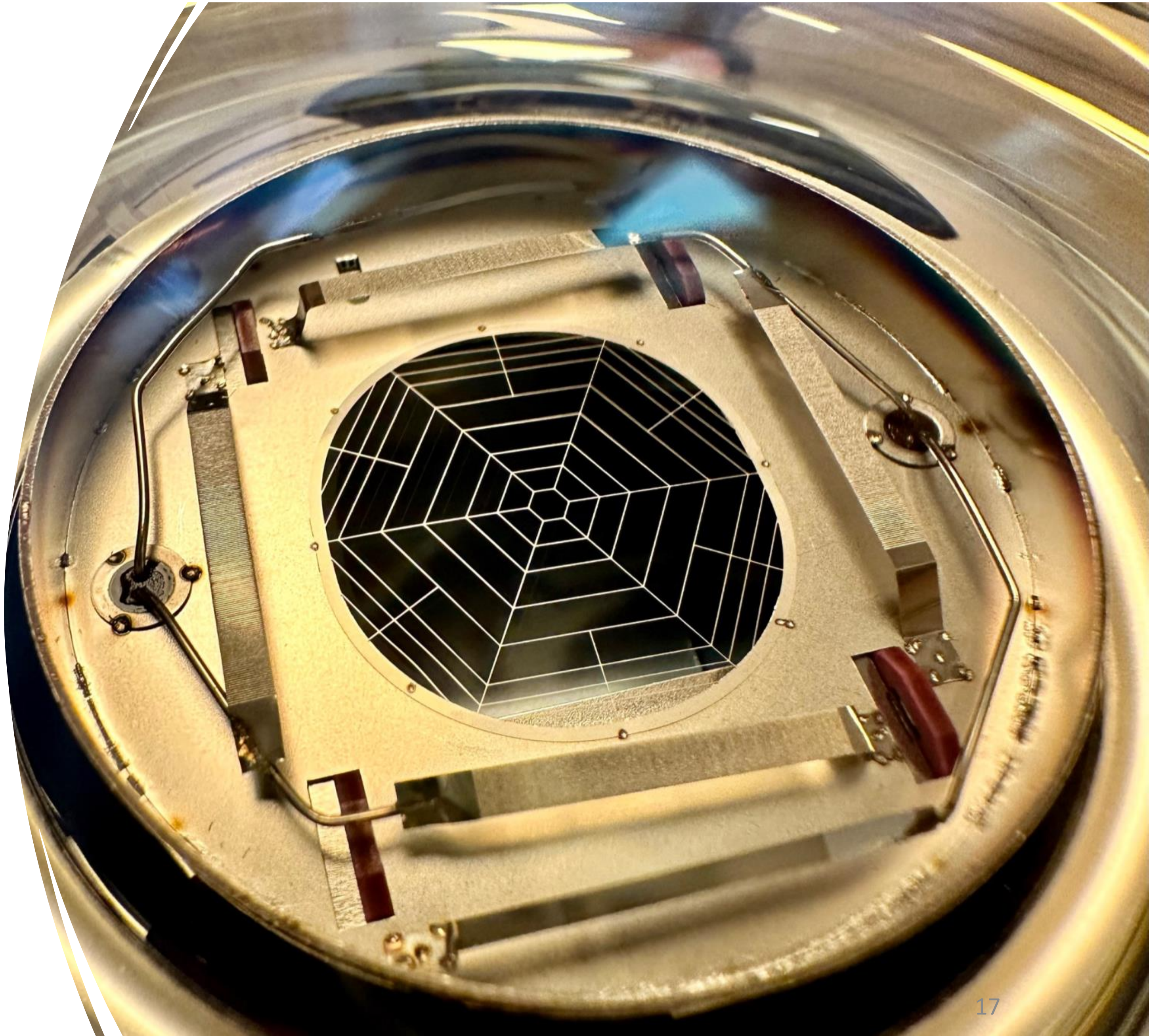




Summary

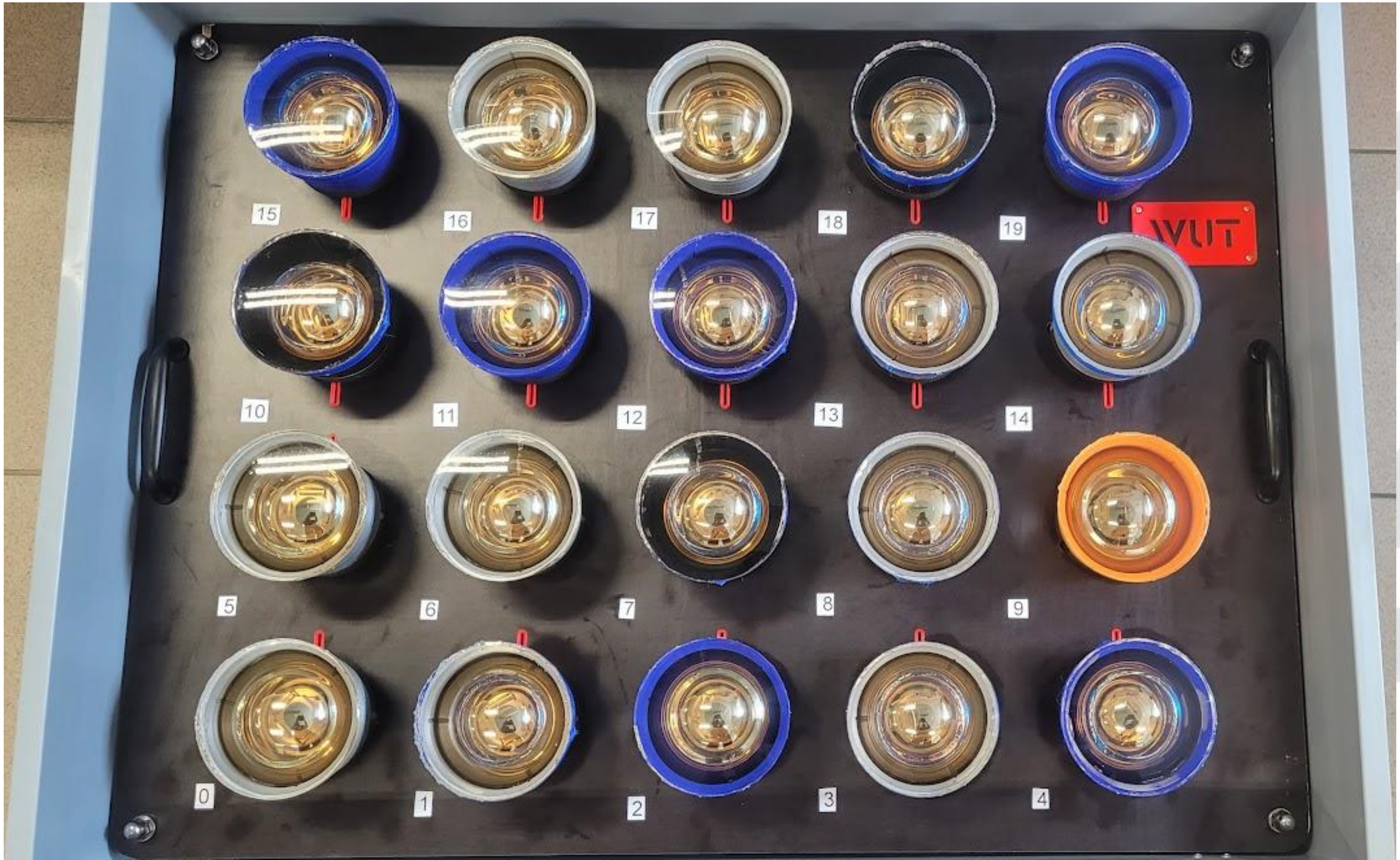
- mPMTs is an international project
  - Czech Republic, Canada, Italy, Japan, Mexico, Poland, …
- 3 assembly lines in preparation
  - Canada, Italy, Poland
- We are now starting mPMT production with final design
- PMT characterization complete, decided on operational gain (5×10^6) and HV divider configuration
- Construction of WCTE will start late November this year, data taking in 2024

Thank You for Your attention

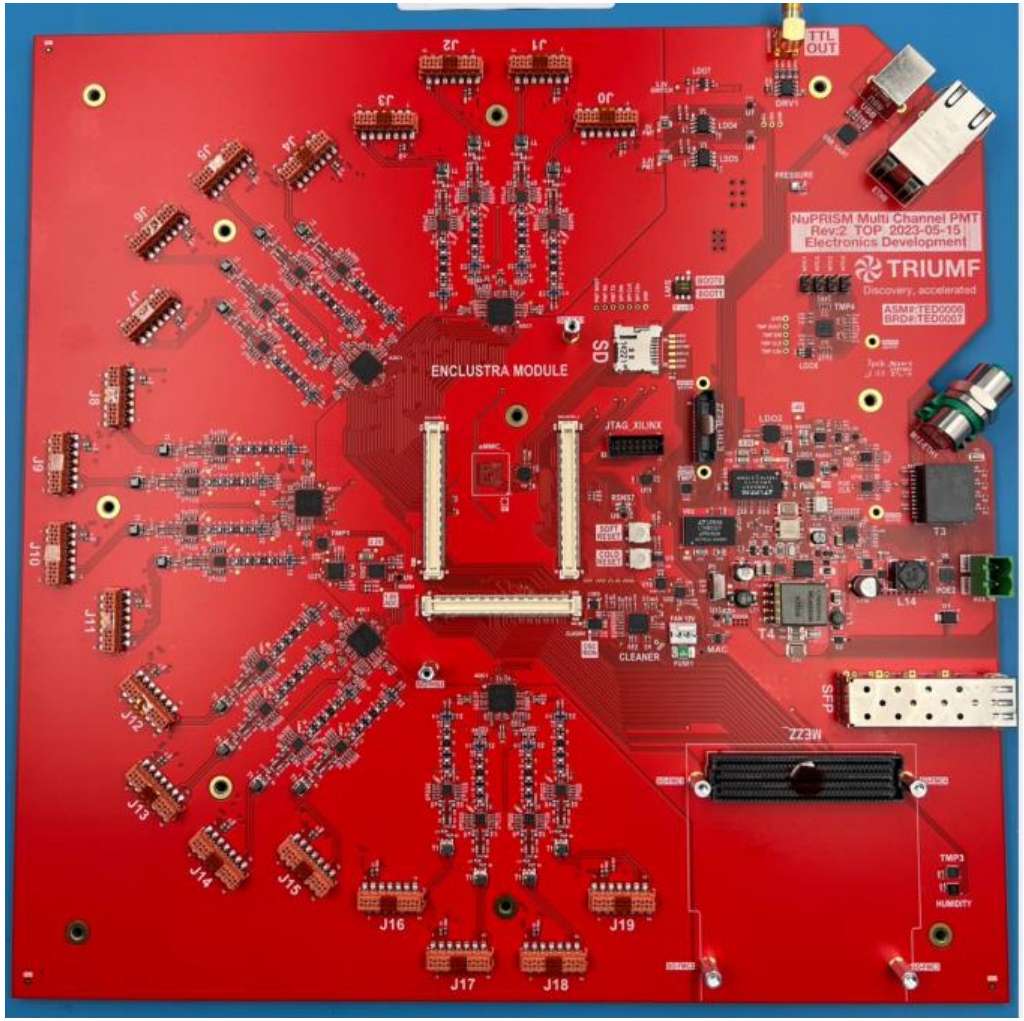


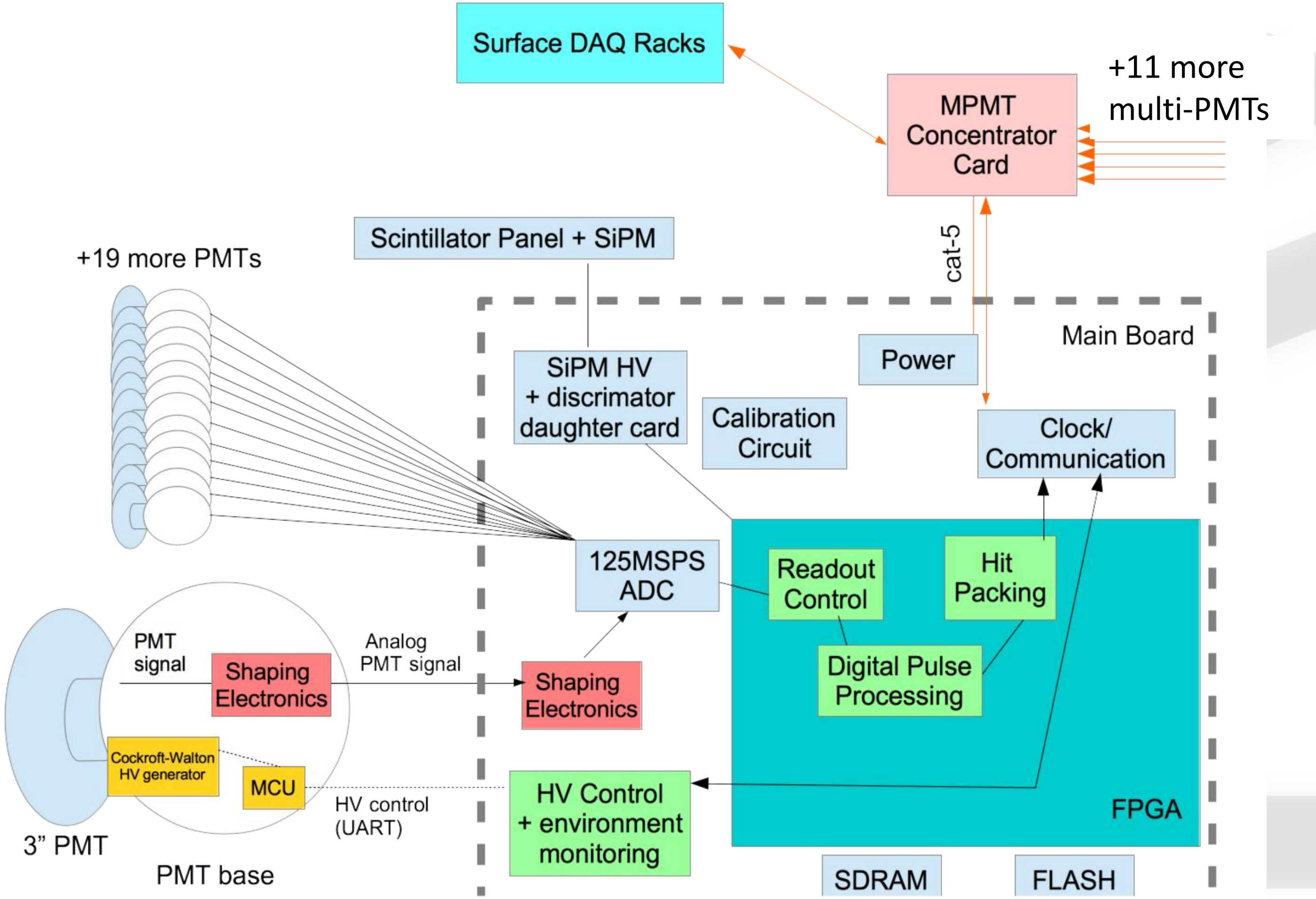
BACKUP

Results of batch gelling



Digitizer module of mPMT

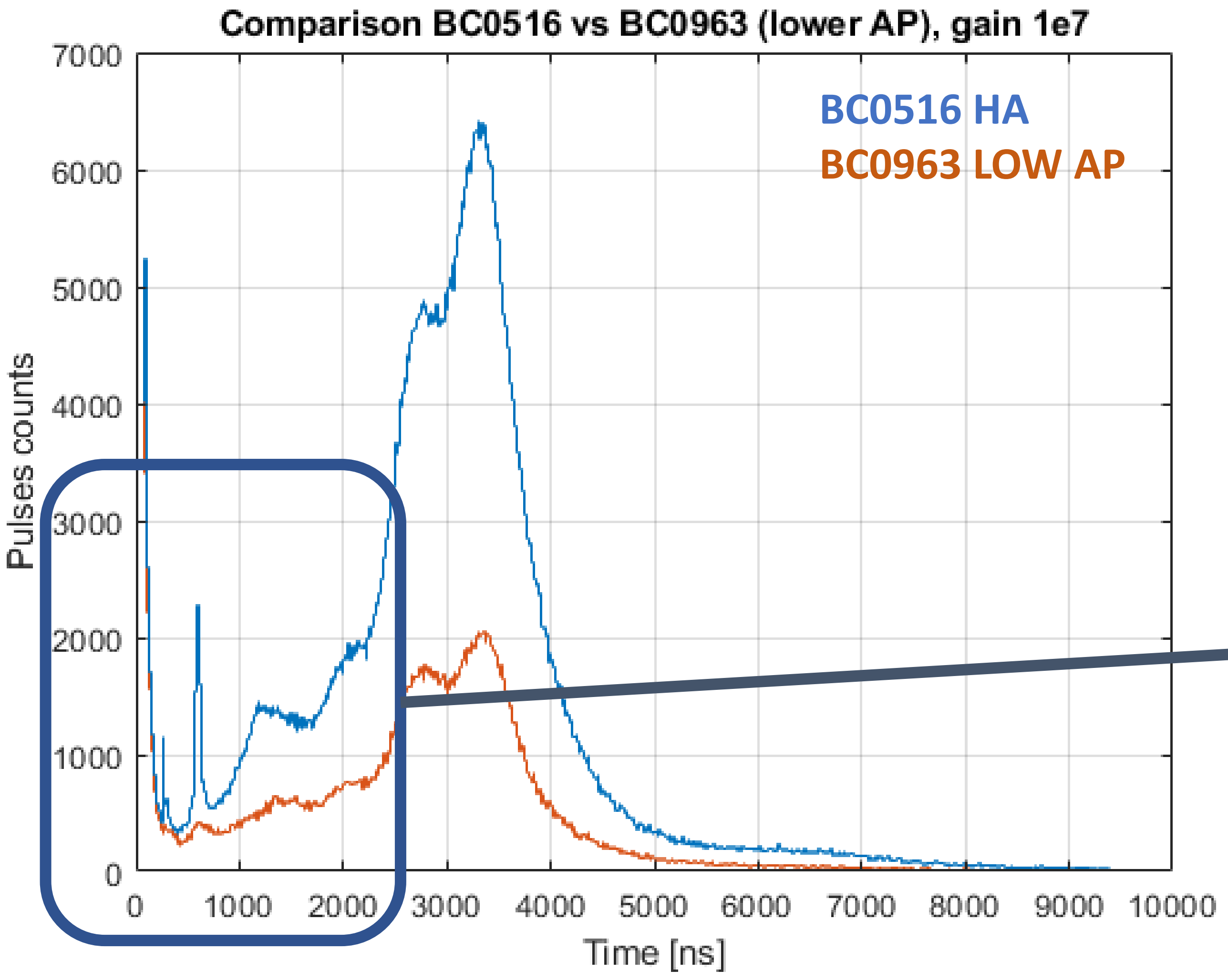


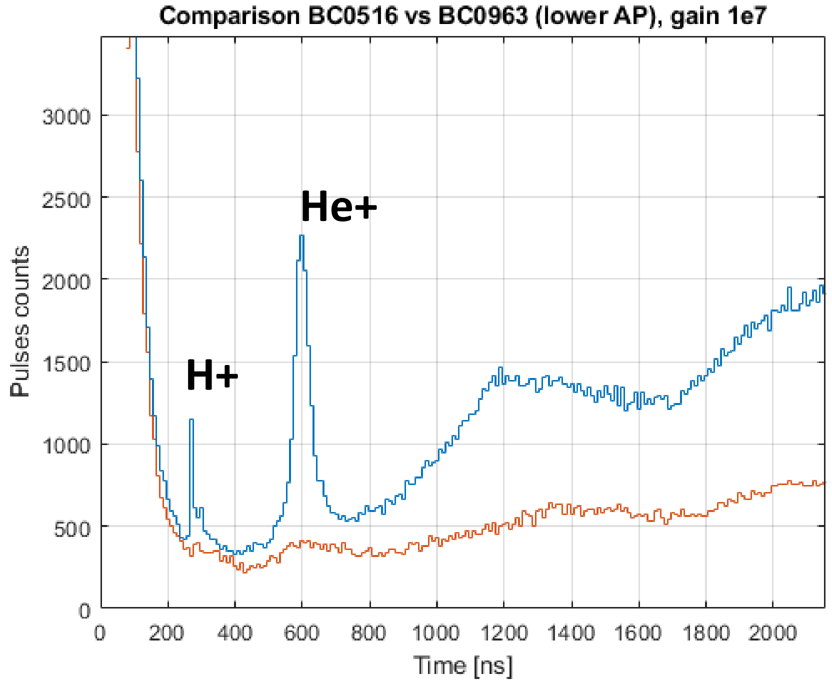


Low AP PMT version performance

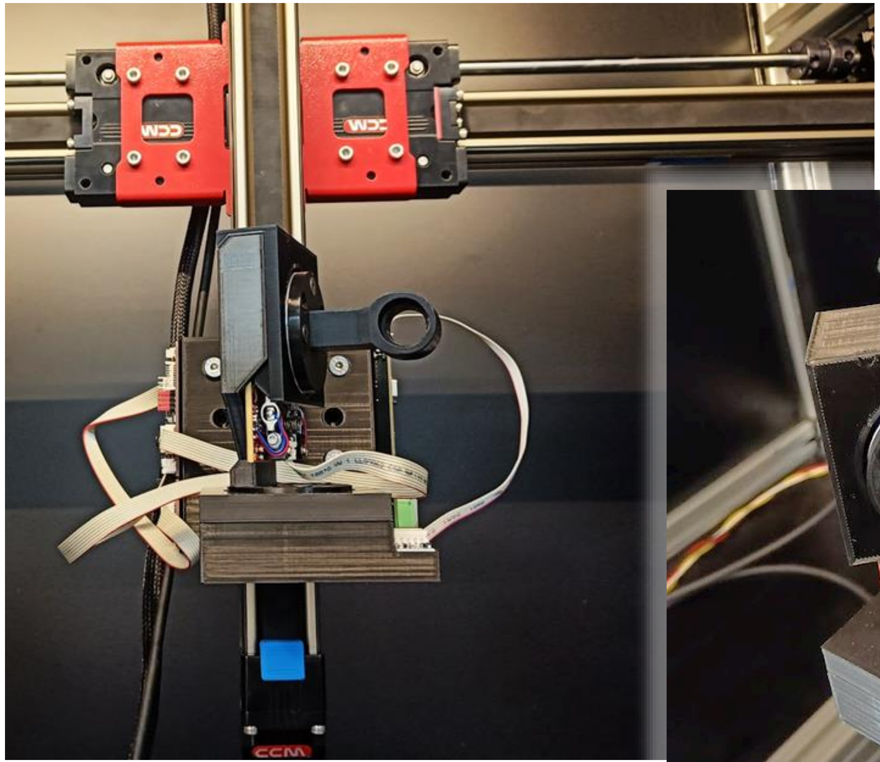
$$AP_{rate}[\%] = \frac{Q_{afterpulses}}{Q_{signal}}$$

	BC0516	BC0963
AP /1e3 pulses	1 522	**417**
AP_{rate} (5e6)	4.8 %	**1.5 %**
AP_{rate} (1e7)	6.4 %	**1.9 %**

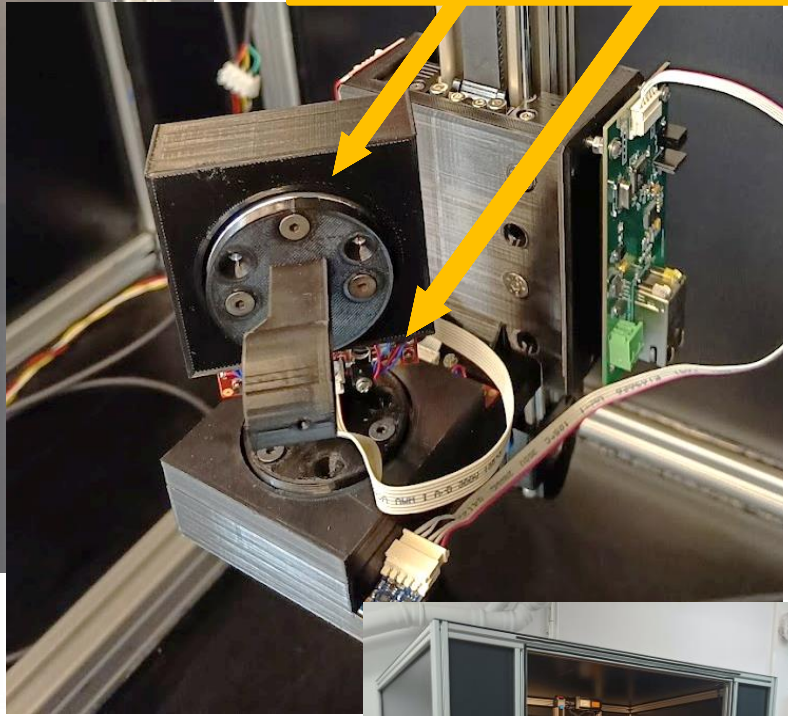


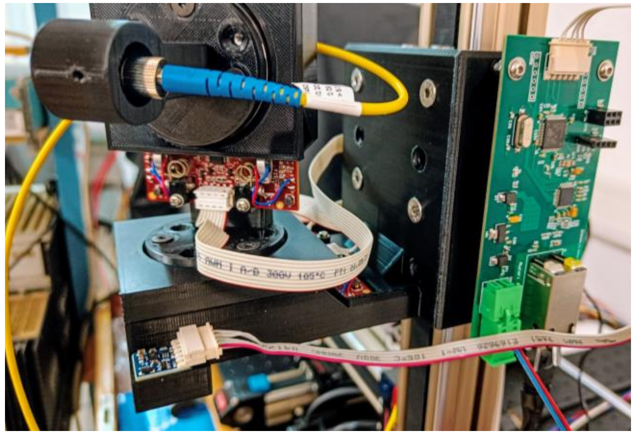


Rotation Stages with Resonant Piezoelectric Motors ELL18/M (Thorlabs)

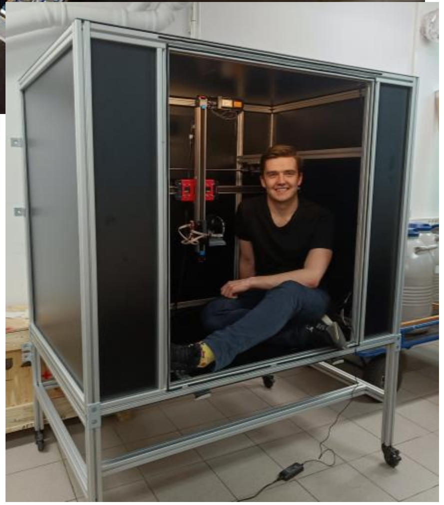


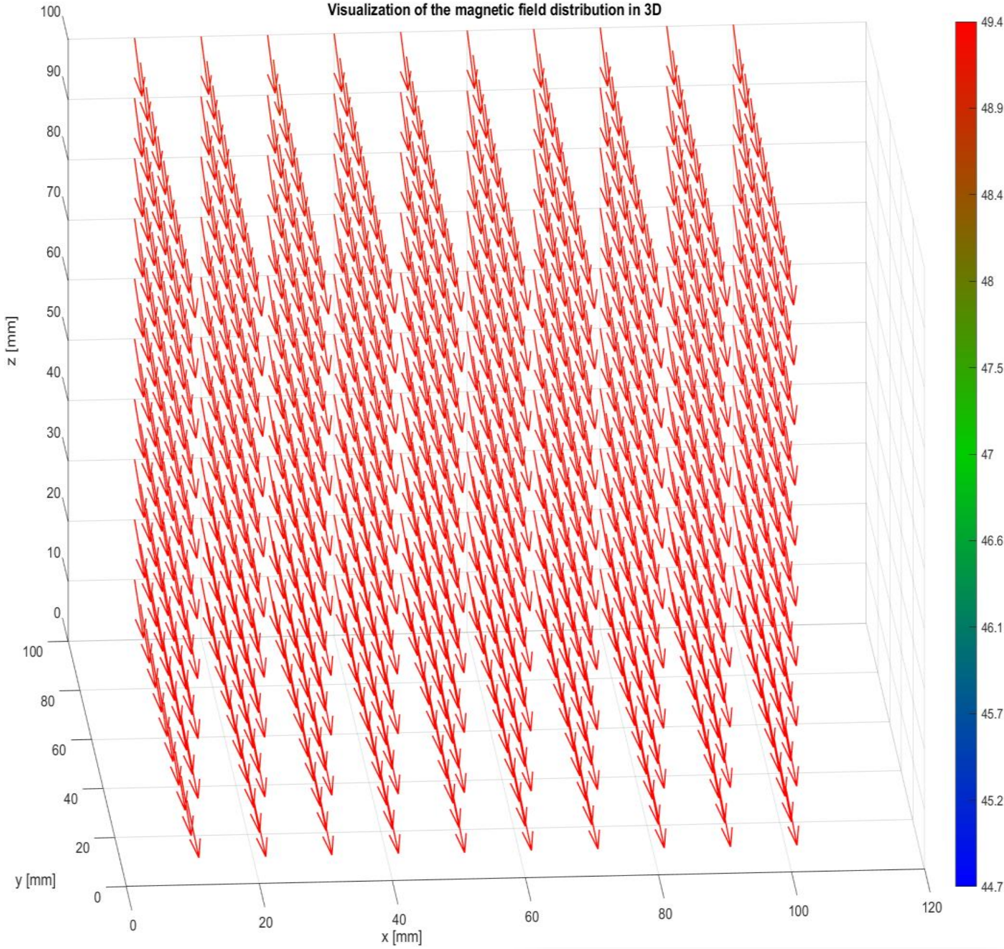
Pan&Tilt module mounted on xyz robot





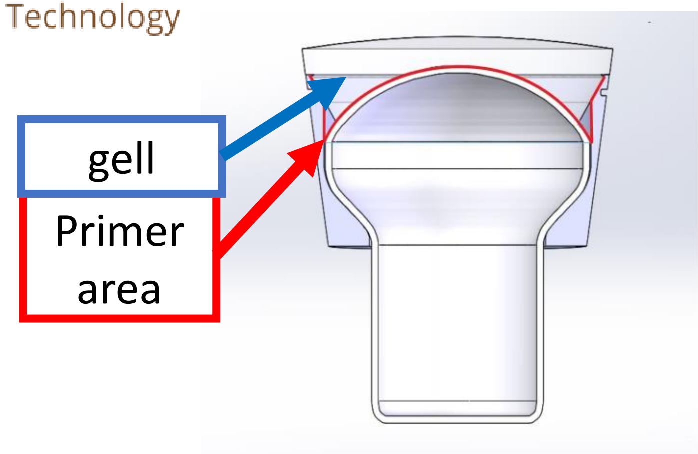
Magnetic field measurement module



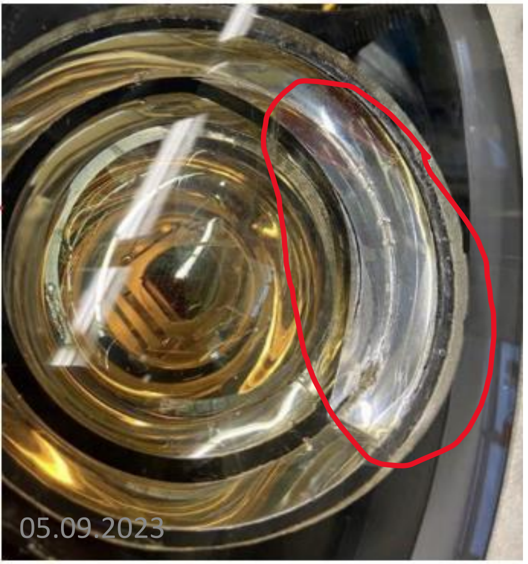


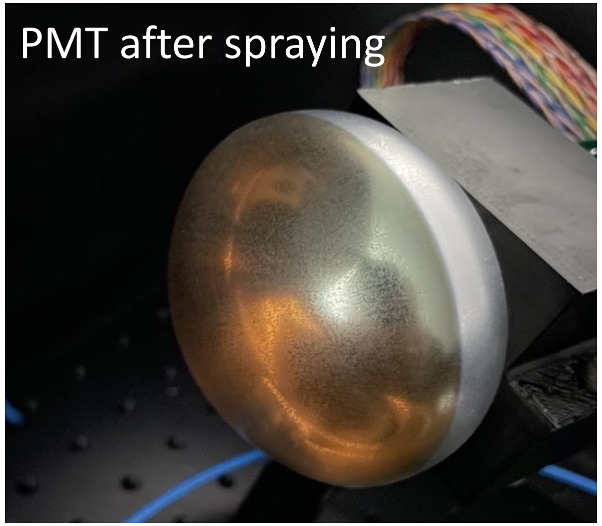
Visualization of the magnetic field distribution in 3D [μT]

Primer on PMT



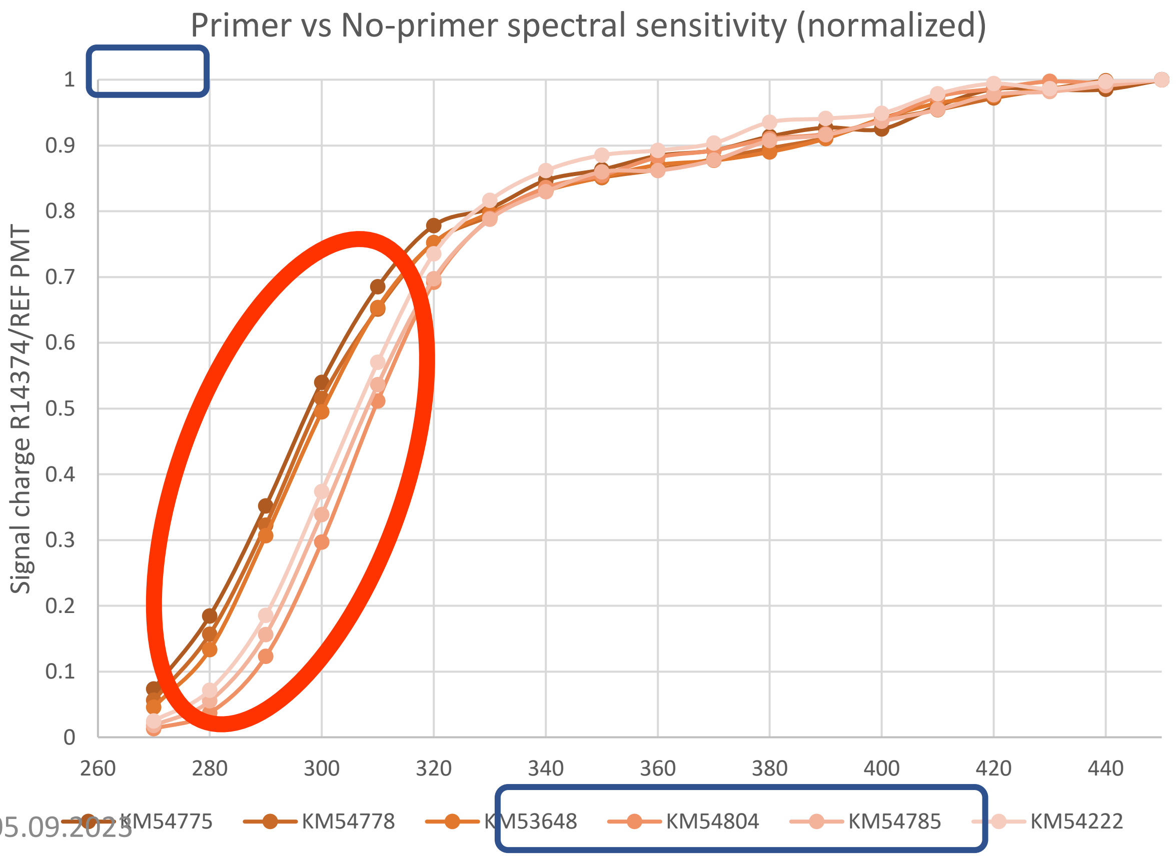
- Why? To improve gell adhesion on PMT glass
- What we used: Wacker Primer G790
- How? Spray bottle used
- Effect: matt surface of primer
- dedicated airbrush?
- 6 PMTs gelled
- 3 PMTs sprayed with primer before gelling

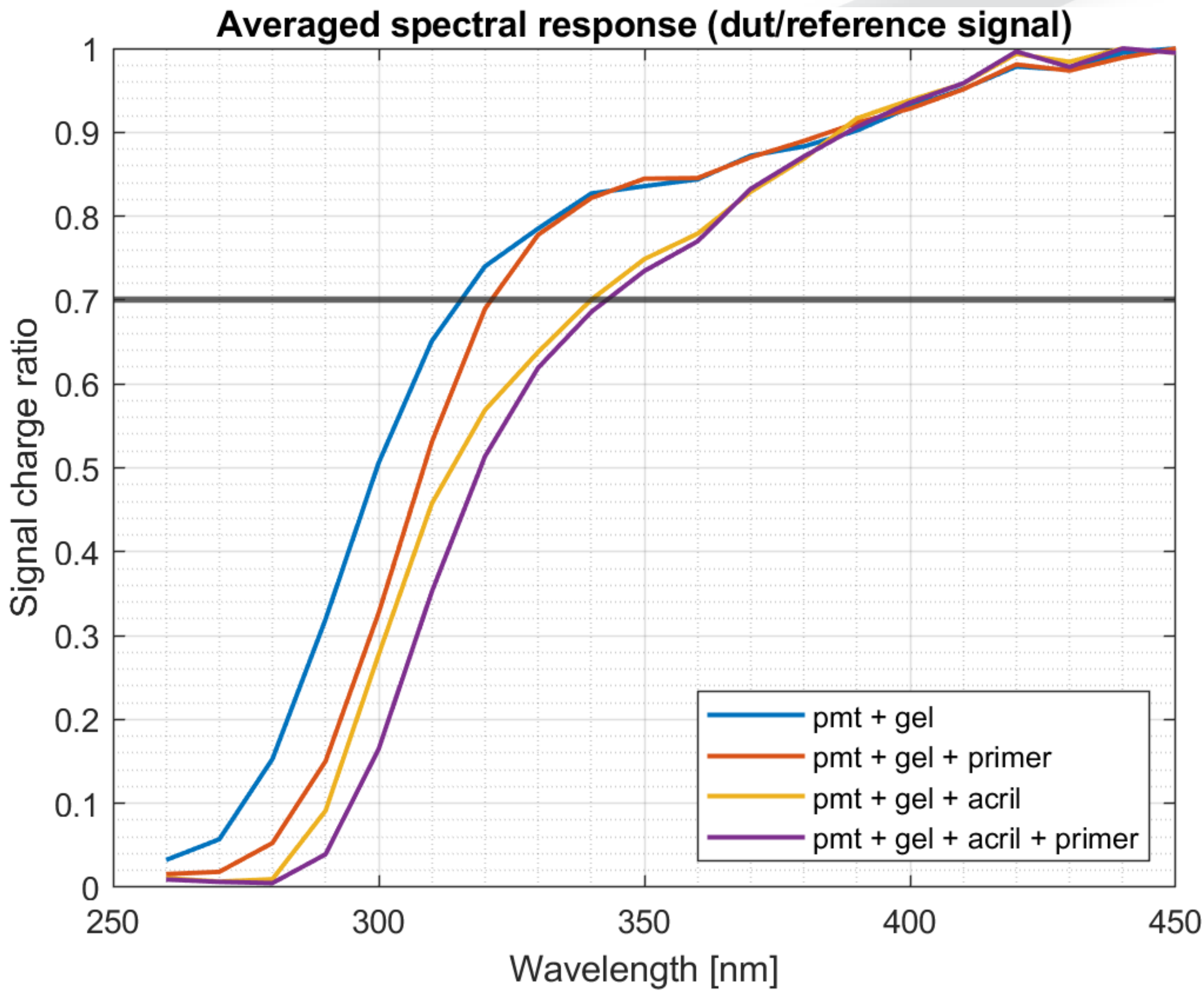




Spectral sensitivity with primer

- Variation in cathode luminous sensitivity visible
- No visible change in range from 340nm to 450nm
- UV sensitivity edge moved by 10nm -> visible for normalized data
- Adhesion improved -> UV sensitivity decreased
- Primer thickness should be as low as possible

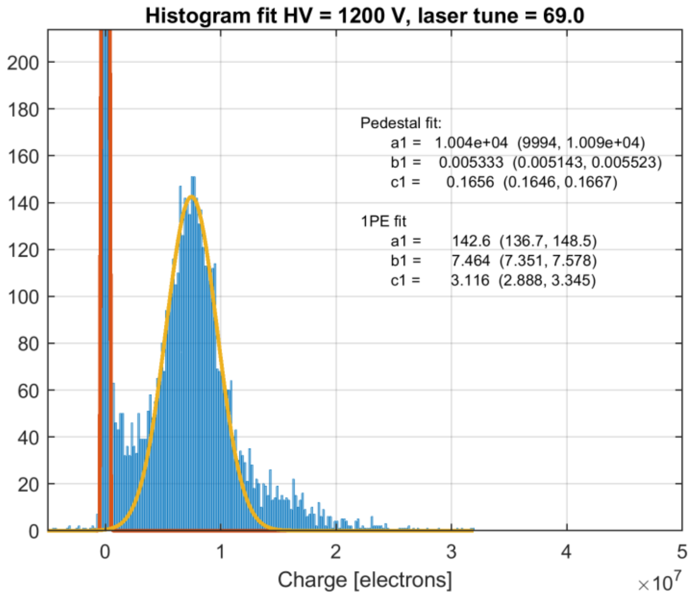


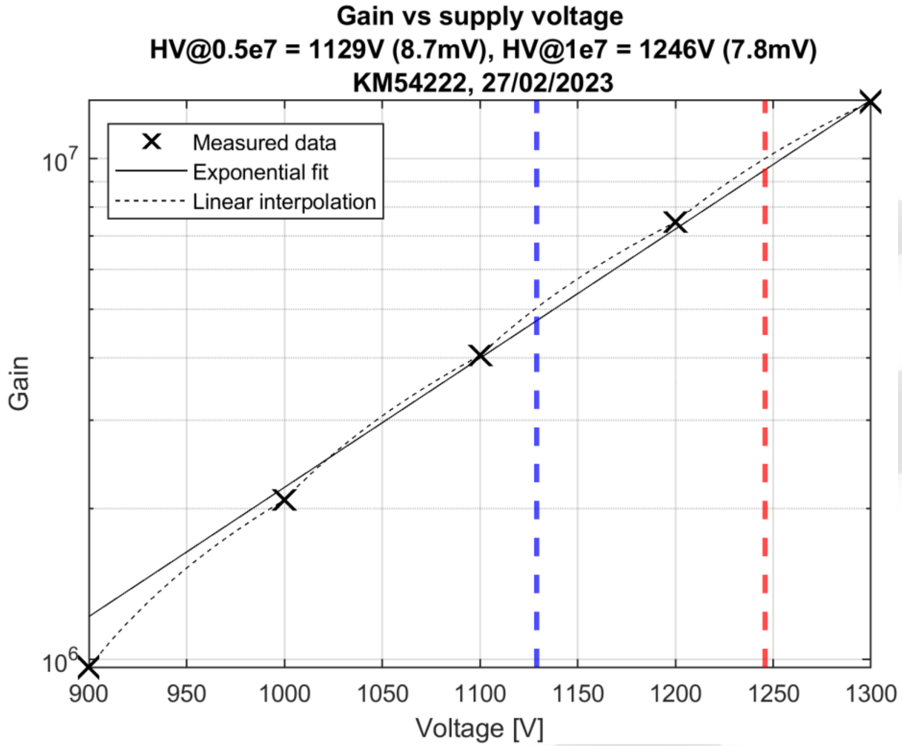


Gain scan results during primer

Gain calculation:

- Low amplitude laser pulses: mean 0.3PE
- Gauss FIT of pedestal and 1PE on each charge histogram
- Exponential fit for 900:100:1300V



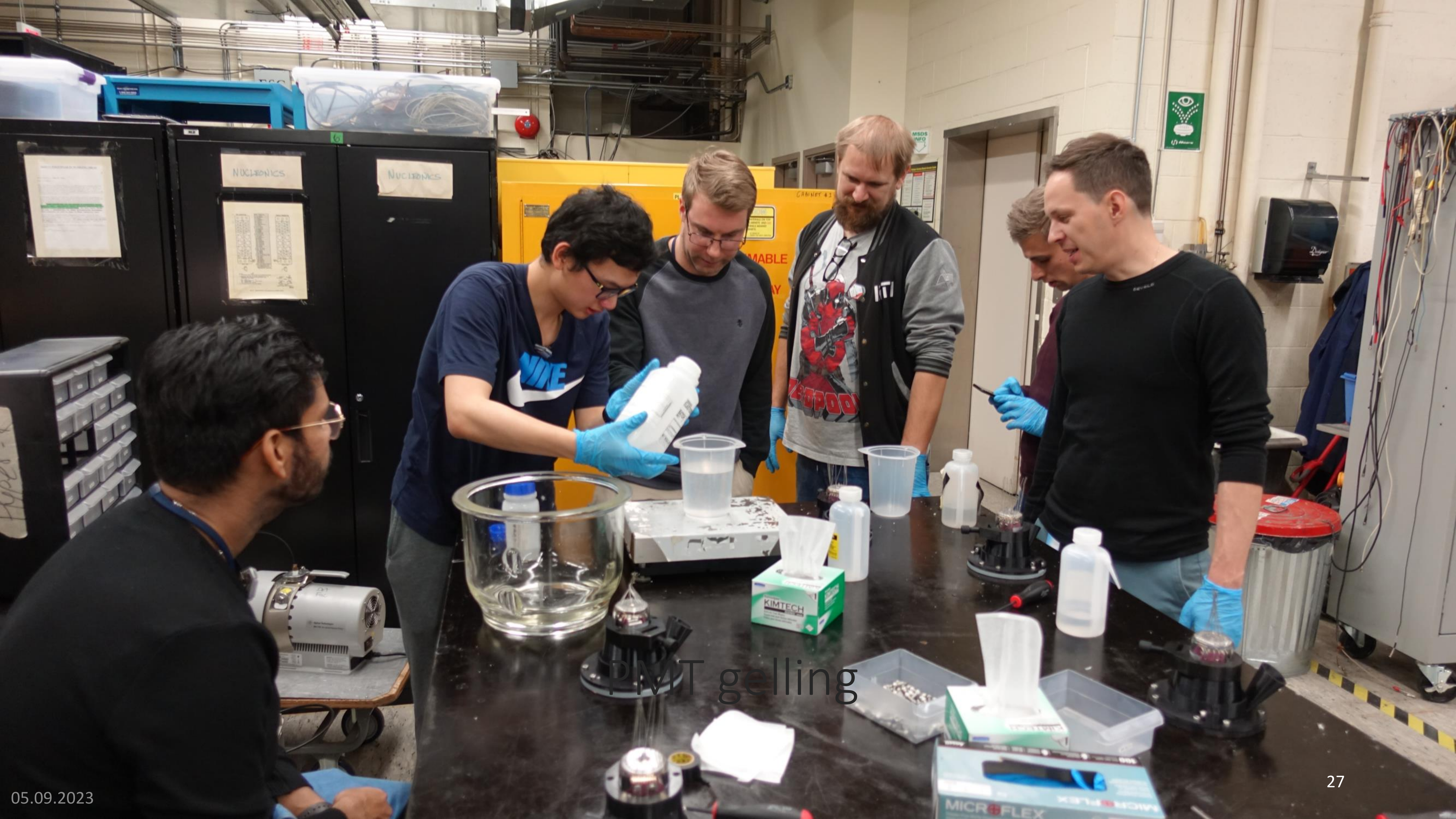


PMT	primer	Cathode Sens. µA/lm	Hamamatsu HV [V]	Measured HV [V]
KM54775	no	112	1050	1162
KM54778	no	104	1040	1125
KM53648	no	102	1050	1110
KM54804	yes	105	1020	1105
KM54785	yes	104	1060	1136
KM54222	yes	105	1050	1129

Conclusions:

- Hamamatsu HV settings are for 3 1 1 1 divider
- Our measurements was 3 2 1 1 1 divider version.
- Hamamatsu data will be a starting point for gain scan.

Assembly



PMT gelling

Bottom molds

Top molds

mPMT production schedule

One set of molds

<table>
<tr><th></th><th>Mon</th><th>Tue</th><th>Wed</th><th>Thu</th><th>Fri</th></tr>
<tr><td>08:00</td><td rowspan="3">Gelling</td><td></td><td></td><td rowspan="3">Gelling</td><td></td></tr>
<tr><td>09:00</td><td></td><td></td><td></td></tr>
<tr><td>10:00</td><td></td><td rowspan="2">mPMT assembly</td><td></td></tr>
<tr><td>11:00</td><td></td><td>Disasembly</td><td></td><td>Disasembly</td></tr>
<tr><td>12:00</td><td></td><td rowspan="3">Gelling</td><td></td><td rowspan="2">mPMT assembly</td><td></td></tr>
<tr><td>13:00</td><td></td><td></td><td rowspan="2">mPMT assembly</td></tr>
<tr><td>14:00</td><td></td><td></td><td></td></tr>
<tr><td>15:00</td><td></td><td></td><td>Disasembly</td><td></td><td></td></tr>
<tr><td>16:00</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Two sets of molds

<table>
<tr><th></th><th>Mon</th><th>Tue</th><th>Wed</th><th>Thu</th><th>Fri</th></tr>
<tr><td>08:00</td><td rowspan="3">Gelling x2</td><td></td><td rowspan="3">Gelling</td><td rowspan="3">Gelling</td><td></td></tr>
<tr><td>09:00</td><td></td><td></td></tr>
<tr><td>10:00</td><td></td><td></td></tr>
<tr><td>11:00</td><td></td><td>Disasembly x2</td><td rowspan="4">mPMT assembly x2</td><td>Disasembly</td><td>Disasembly</td></tr>
<tr><td>12:00</td><td></td><td rowspan="3">Gelling</td><td></td><td></td></tr>
<tr><td>13:00</td><td></td><td rowspan="4">mPMT assembly x2</td><td></td></tr>
<tr><td>14:00</td><td></td><td rowspan="2">mPMT assembly</td></tr>
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<tr><td>16:00</td><td></td><td></td><td>Disasembly</td><td></td></tr>
</table>

20 PMTs + HV + FE test facility - software

- Test procedure will be implemented using BRB (main board) acquisiton path and ToolDAQ
- Tests will be made automatically using a script sending slow control commands to the main board and PC
- Procedure:
  - Create waveform data and monitoring data files on the PC side
  - Set up FE boards (set voltage value and turn on HV)
  - Start measurement
  - Collect waveform data and save it to the files
  - Collect monitoring data and save it to the files
  - Stop measurement
  - Change Laser parameters and repeat
  - Plot results during measurement