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Water Cherenkov Test Experiment:
Overview and Status

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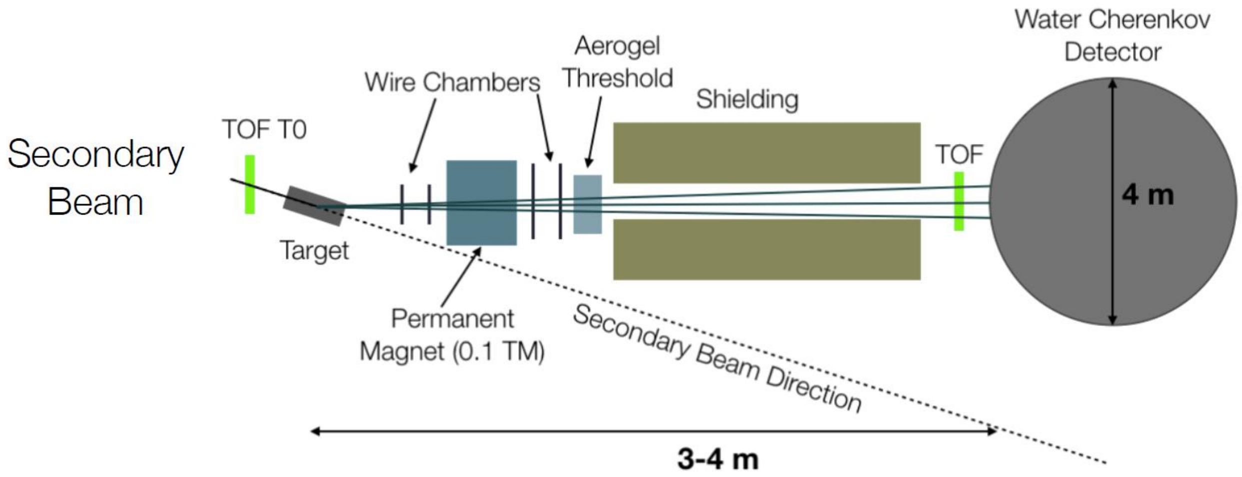
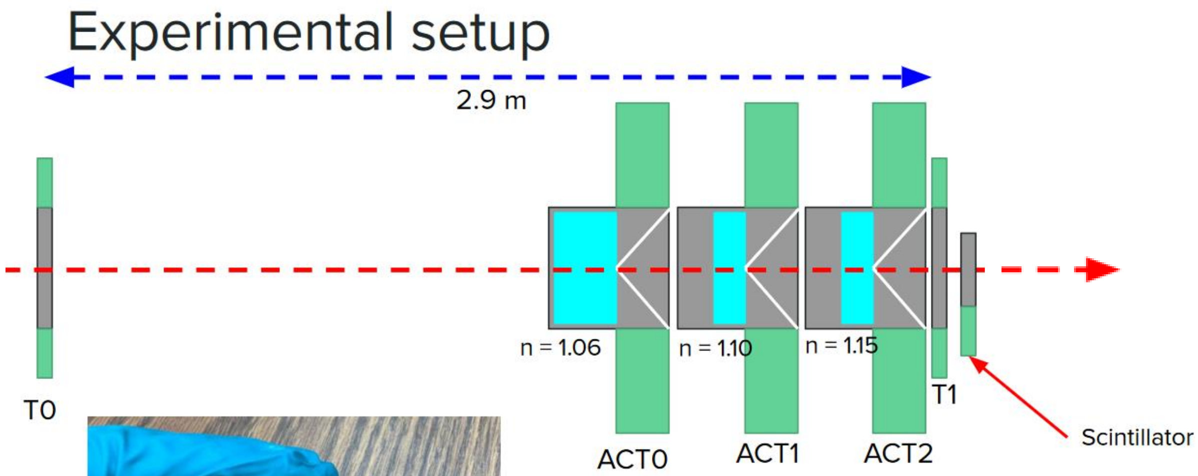
Water Cherenkov Test Experiment

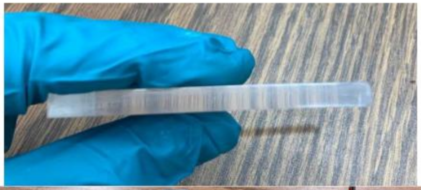
- Goal: study detector systems and detector response to pions, muons, electrons and protons from 200 MeV/c up to ~1100 MeV/c
  - Understand hardware and detector response for IWCD/HK
  - Physics: Cherenkov profile, secondary interactions, neutrons…

- Original proposal – tertiary beamline to reach low momenta



T9 Test Beam in July 2022





- Test performance of upgraded T9 beamline at low momenta (200 - 300 MeV/c)

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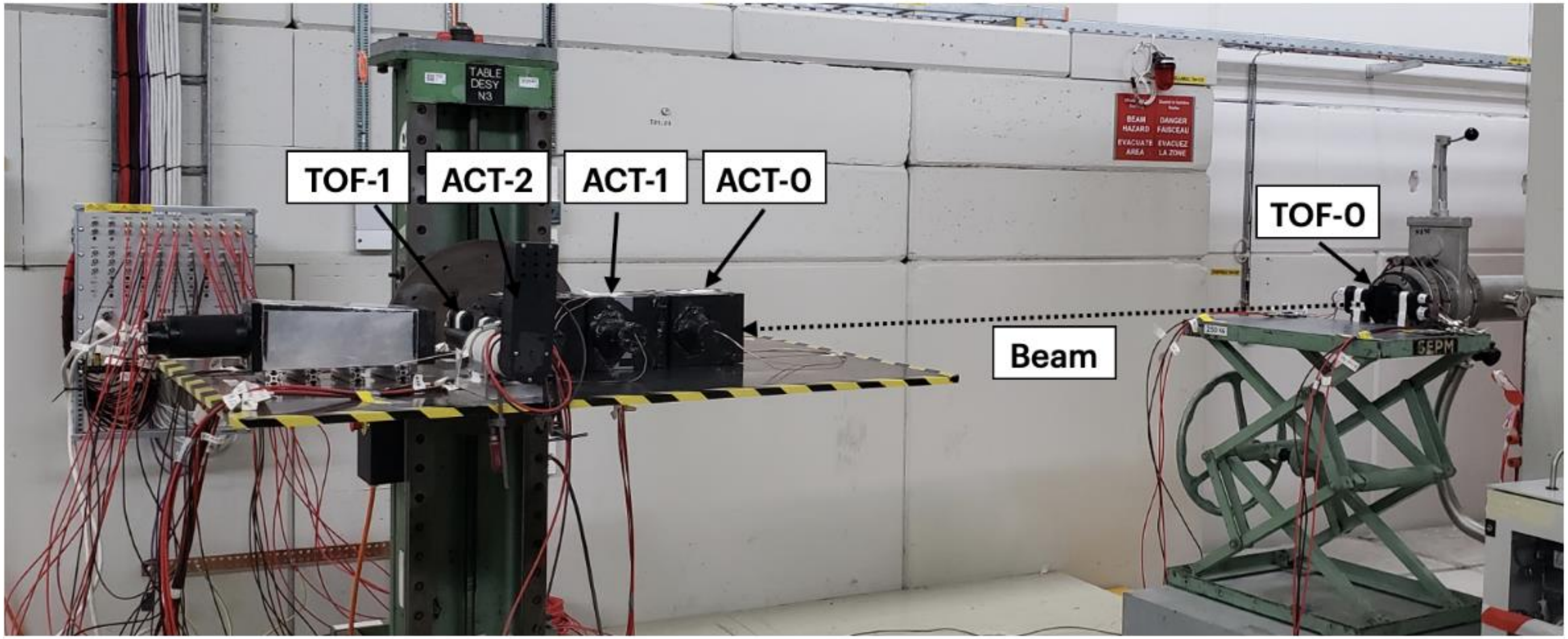
T9 Test Beam in July 2022



- Test performance of upgraded T9 beamline at low momenta (200 - 300 MeV/c)

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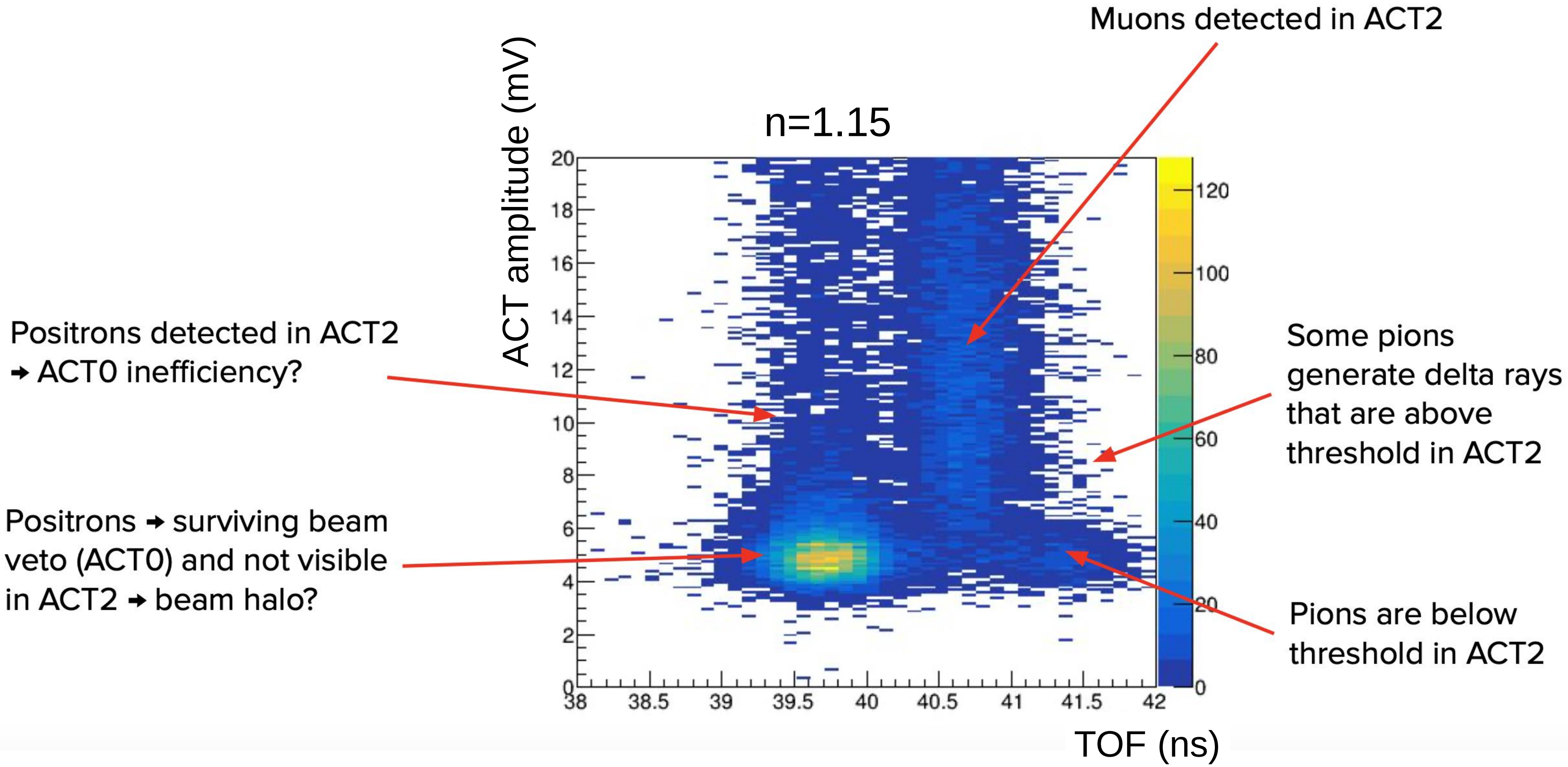
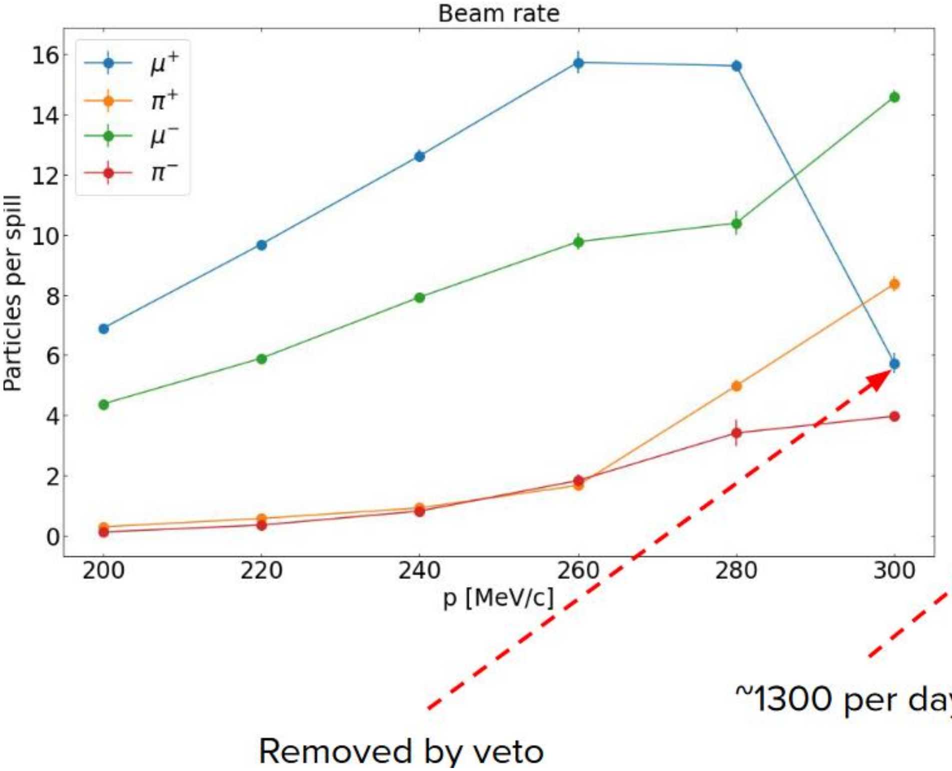
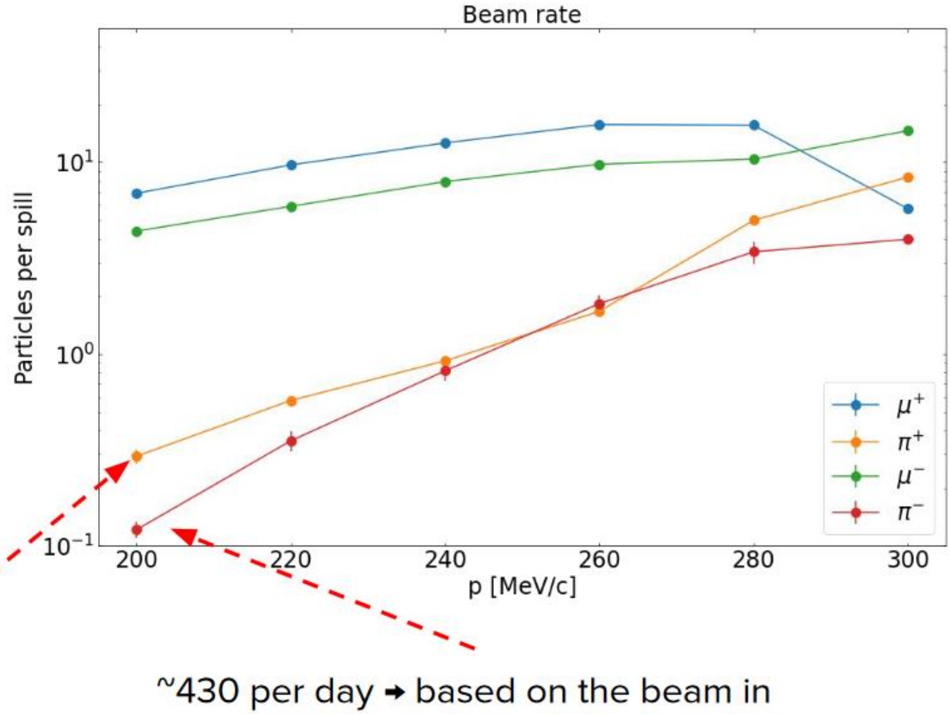
Beam test result in 2022 run



Muon and pion rate per spill





- Rate per spill for variety of particle momenta/species, expect rate in 2024 to be ~factor 5 higher
- Electrons were vetoed with 99.5% efficiency, π's rejected with 90% efficiency and μ's accepted with 80% efficiency
  - Aluminium target + tungsten radiator used (accidently)
  - May have enhanced electron/positron fraction of beam

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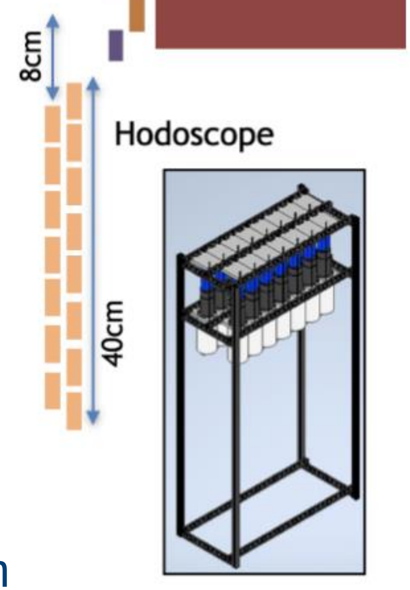
T9 Test Beam in July 2023

- Based on 2022 data we have updated design of ACTs and TOF system, and added hole veto system
  - Better charge + timing resolution, two detectors to reduce fake rate
  - Cut out beam halo
- Will provide >99% pure samples of muons, pions, electrons and protons at momenta from 200MeV/c to 1GeV/c
  - July 2023 beam time will test this setup

Tagged gamma beam



- Gamma rays are most significant background to electron events in water Cherenkov detectors
- ML reconstruction can separate electrons and photons, based on sub-structure of ring
- Require data to verify performance – tagged gamma beam
- Thin radiator + 1.7T, 0.16m long Halbach array permanent magnet from EMPHATIC experiment
- Plan to test this during July 2023 beam time as well

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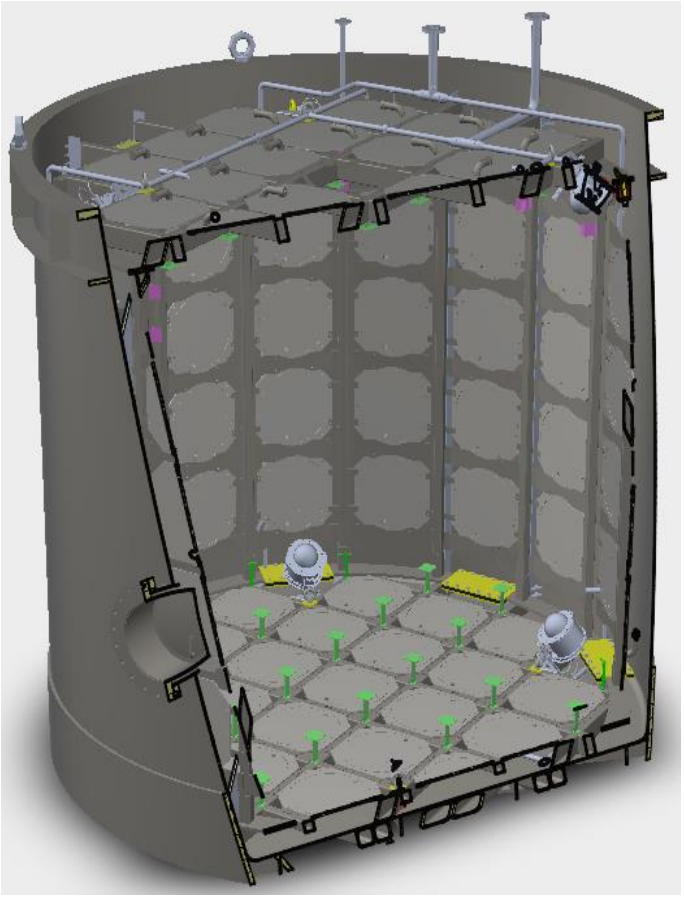
Mechanical design updates

- Switch to secondary beam configuration only means no tank moving system needed, and only a single beam window
- Major updates since last year:
  - Full model including all connections, cables and water pipes
  - Integration of utilities with lid
  - Integration of all calibration systems
  - Insulation of tank
  - Improved lifting and anchoring points after discussion with CERN engineers



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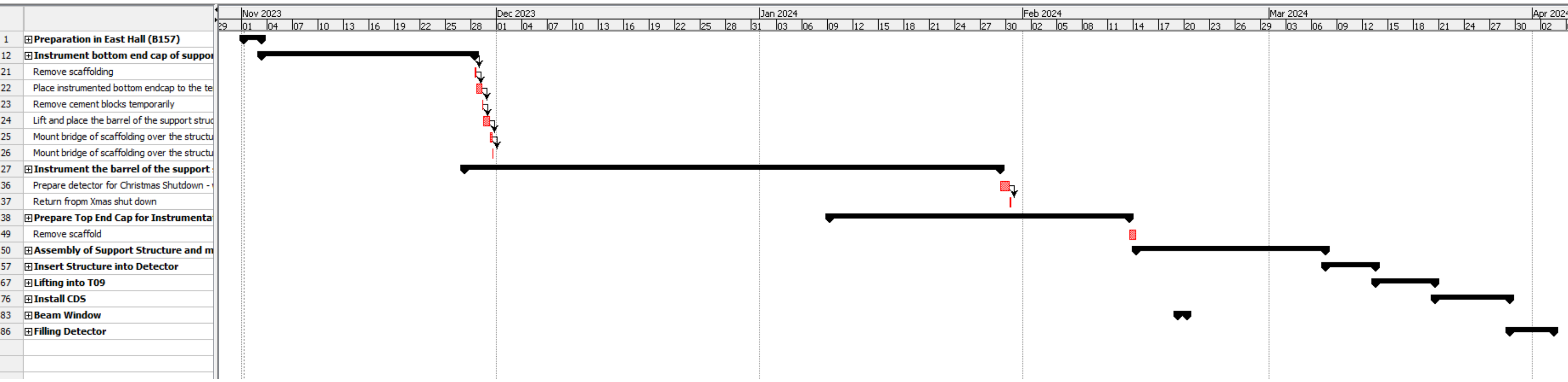
Mechanical design status and schedule

- Design documents (drawings, FEA analyses and Eurocode compliance) complete and passed to external + CERN reviewers
- Expect to finalise by end of May
- Detailed assembly schedule, completing in early April
  – Conservative schedule, will optimize to finish earlier



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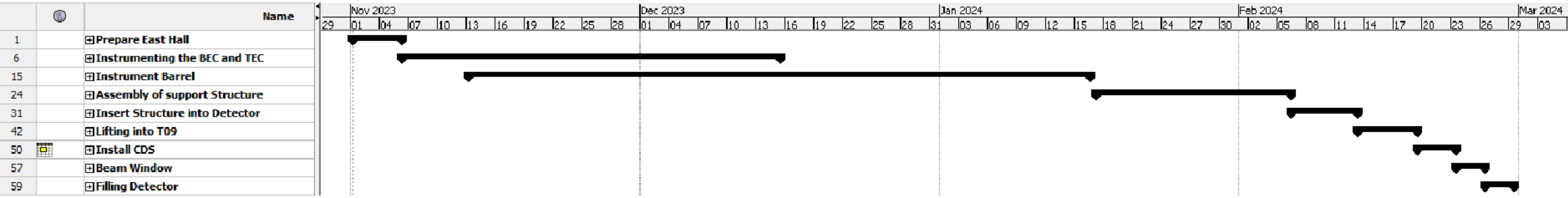
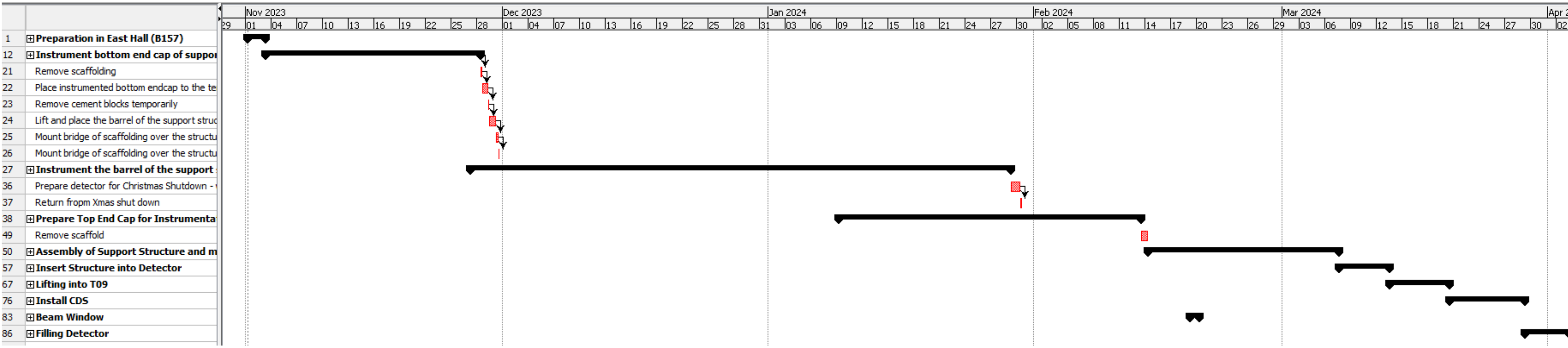
Optimistic vs conservative schedule

- Work in progress
- Instrumenting top and bottom end caps simultaneously would reduce assembly time by ~one month





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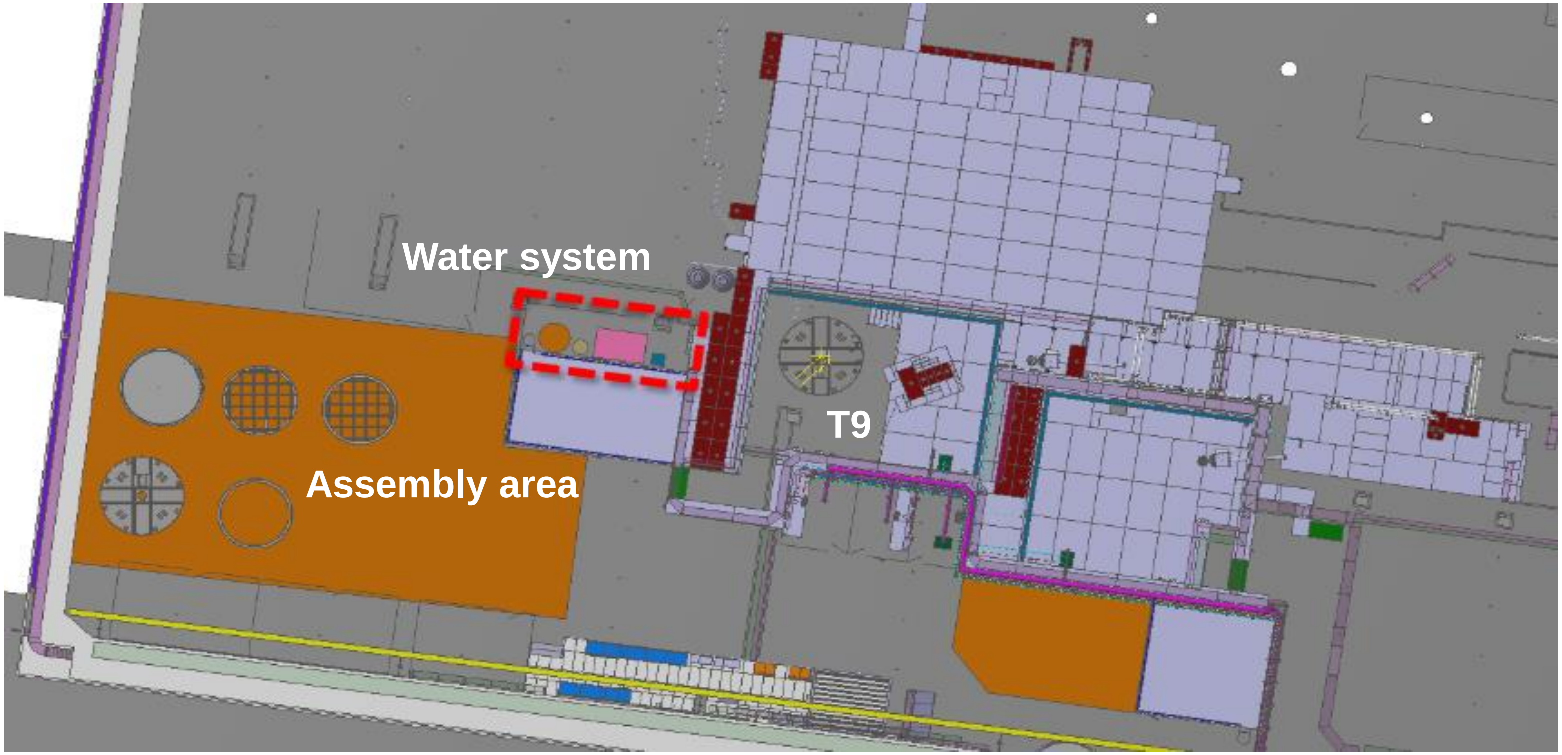
Layout in East Hall during assembly



- In discussion with CERN space group, East Hall group, safety and transport groups

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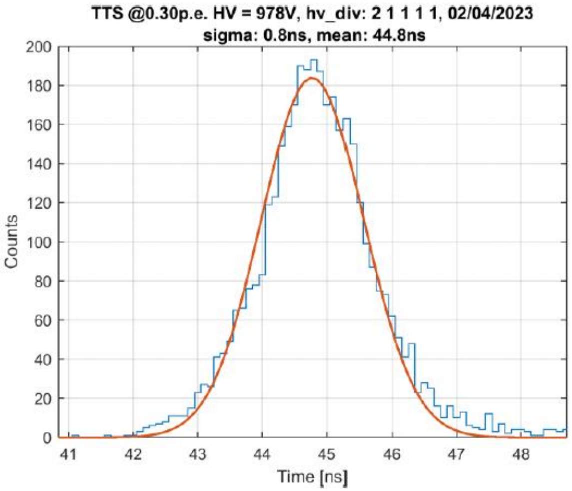
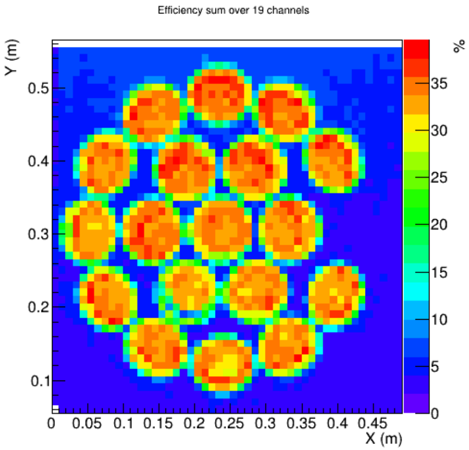
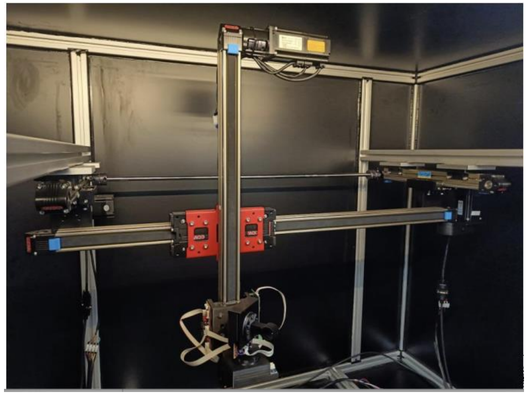
Multi-PMT status



- Final version of HV board has been finalized; measurements ongoing of PMT performance particularly TTS
- mPMT rev-2 mainboard finalized and is out for manufacture and assembly
- Recent improvements in assembly procedure suggest we have solved problems that caused air gaps at boundary of optical gel
- mPMT test stands coming online at WUT and TRIUMF





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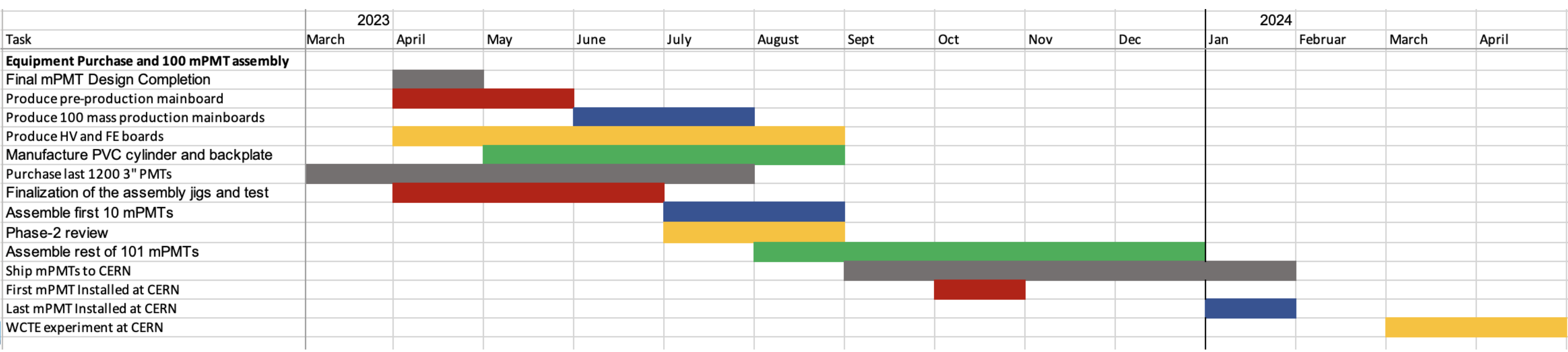
Multi-PMT production schedule

- Critical path is delivery of IWCD mPMT mainboard
  - Expect 100 final mainboards delivery in late June
  - Other items are also concern: HV production, feedthrough design, vessel manufacture.
- mPMT mass production starting this summer - production readiness review ongoing
- In parallel start shipping mPMTs to CERN
  - First mPMT to be installed in WCTE in Oct 2023
  - Last mPMT to be installed in WCTE in Jan 2024



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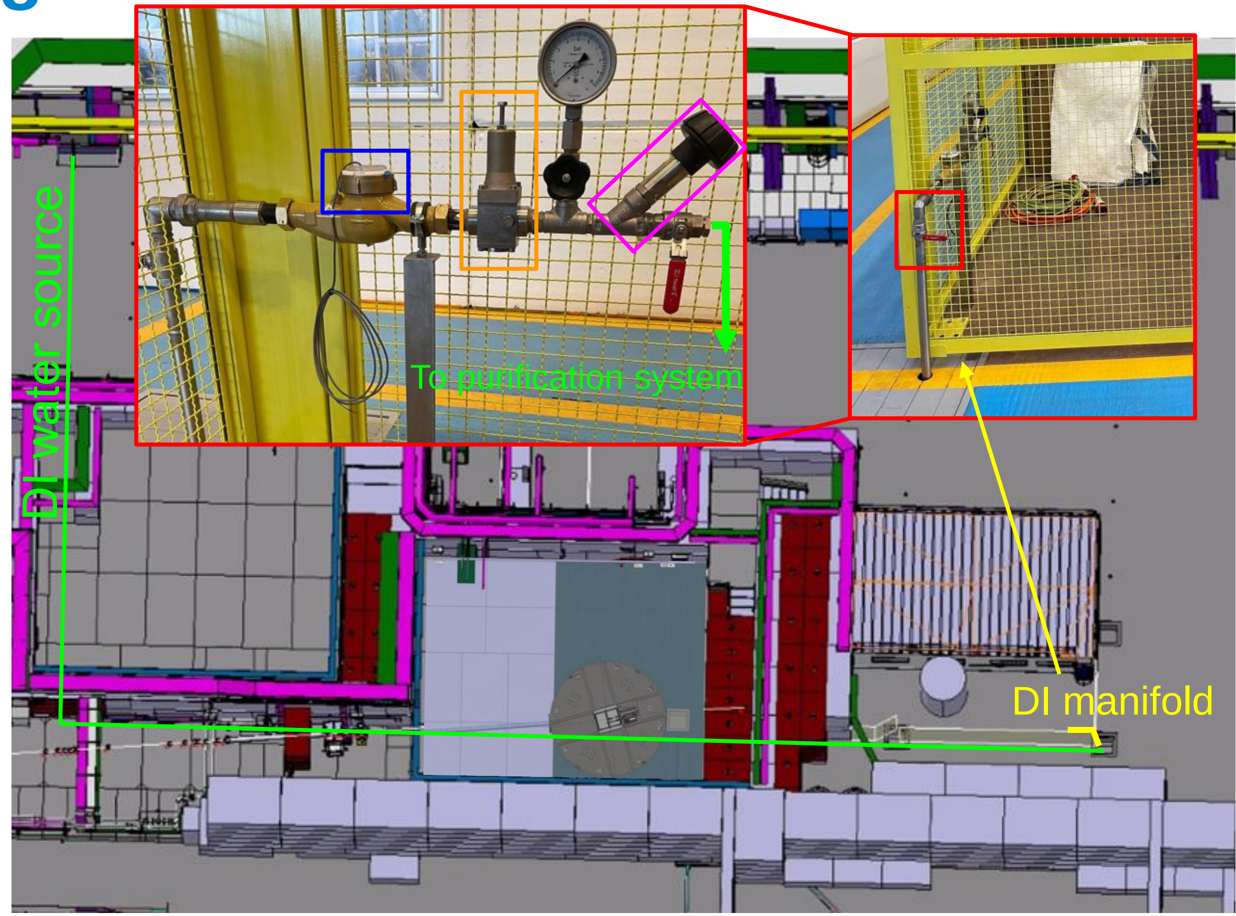
East Hall Plumbing

- 2 t/hr DI water source *completed by CERN*, including interface manifold:
  - Isolation valve, pressure reducing and balancing valves, water meter
- Drainage still TBD
  - No drain in building
  - Since there's a permanent DI line, considering a drain line to the outside
    - Simplify connection to lorries
    - Avoid flooding hall in emergency
    - Future experiments



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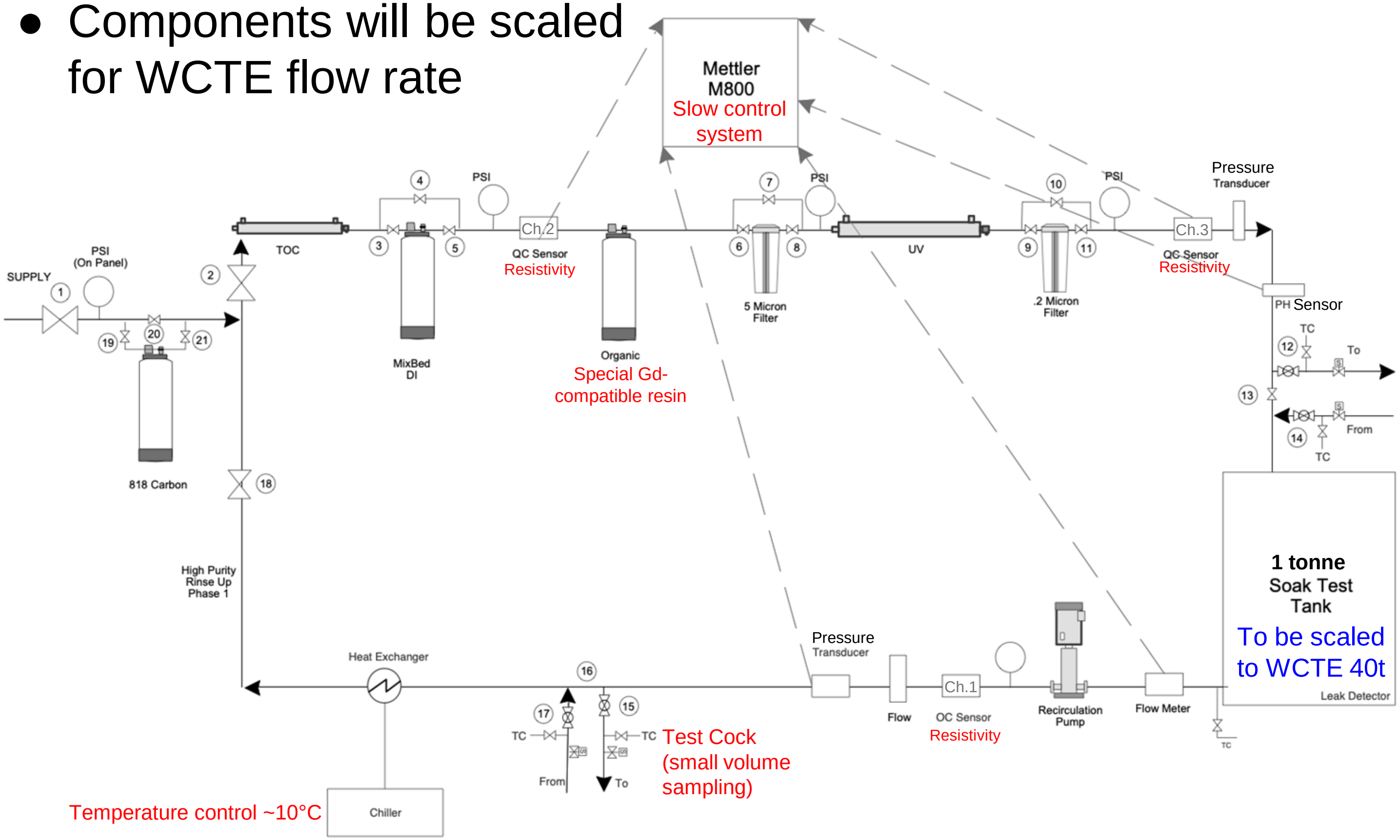
Prototype Water Purification System

- Gd-compatible system procured and testing at IPMU
- Components will be scaled for WCTE flow rate



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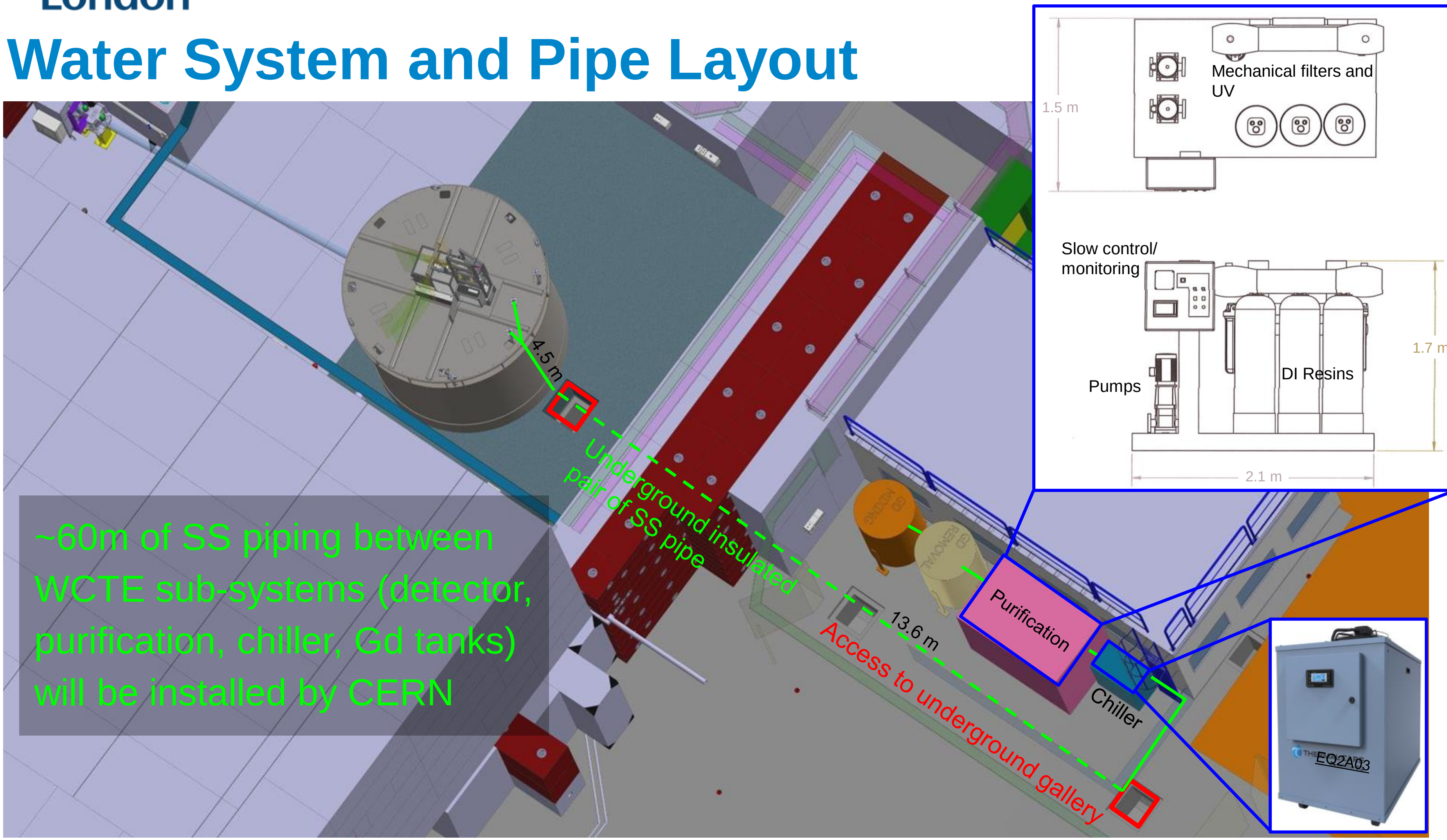
Water System and Pipe Layout



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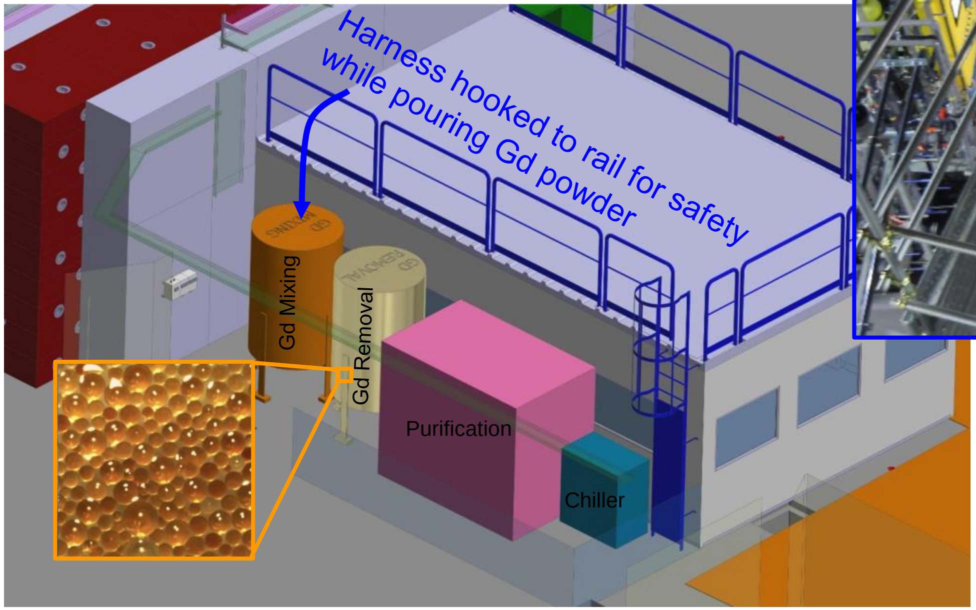
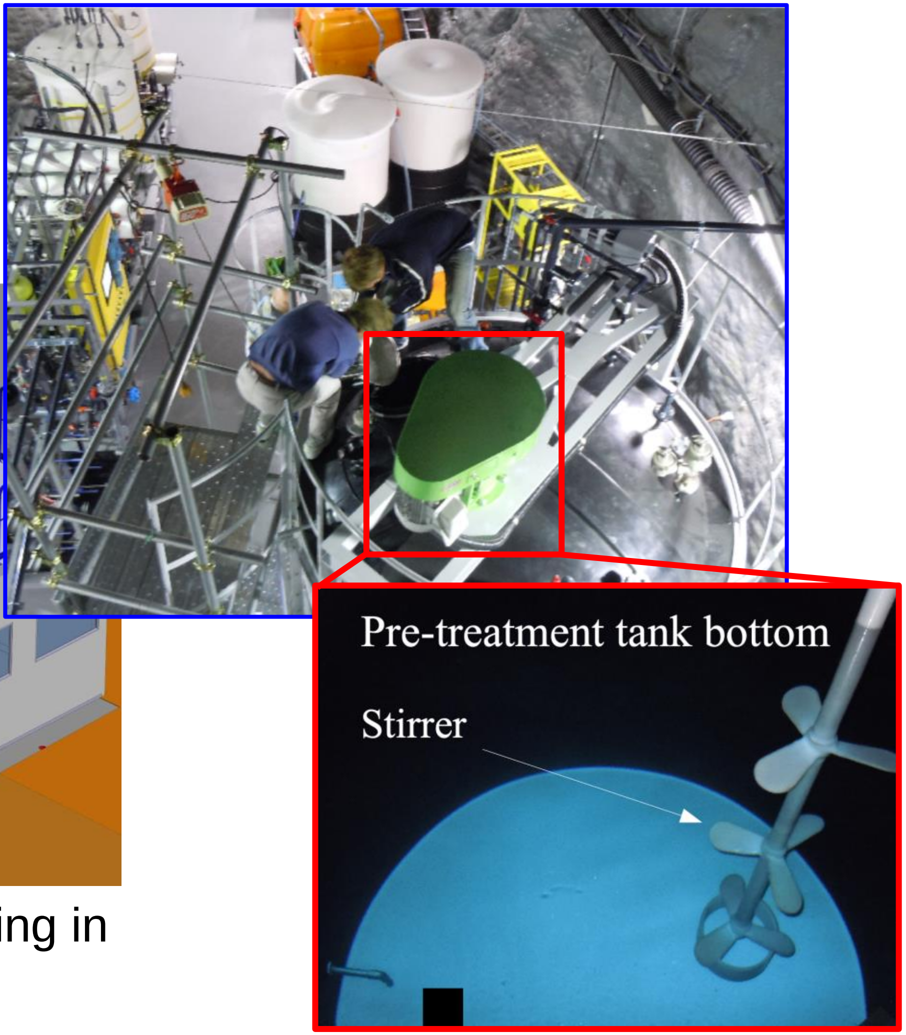
Gadolinium Loading

Plan to add ~100 kg Gd-sulfate powder into top of mixing tank with motorized stirrer



Researchers adding Gd through hole at top of EGADS mixing tank



Gd removal via cation resin exchange resulting in sodium sulfate in wastewater effluent

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Disposal Scenarios (in order of increasing expected cost)

1. CERN Sewage Network

Drain

Piping/pump to drain ~70m away by company (Vallier)

<0.0001 mg/L Gd, <10 mg/L Na_2SO_4

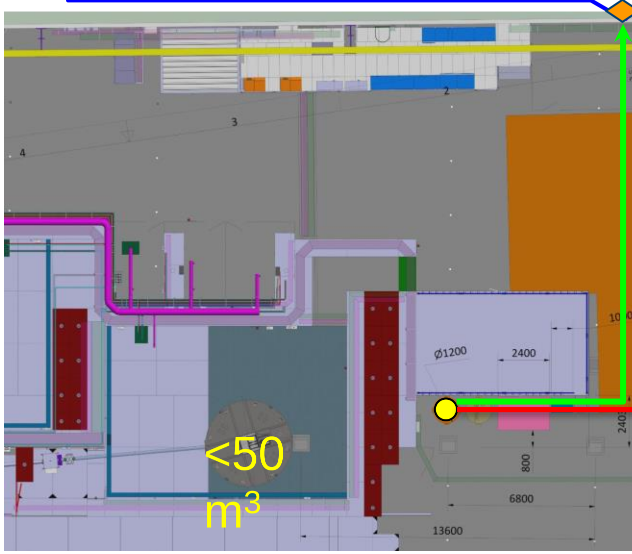
else

10 m³ lorry (Vallier)

2. CERN Evaporation Plant (Leonel Marques Ferreira)

3.Contract treatment to company

~100 kg residual salts



After multiple passes through removal resin, measure concentrations at external ICP-MS

Drain pipe/hose to outside (TBD)

~500 kg Gd-loaded resin

CERN Chemical Waste Coordination (Claudia Bruggmann)

External company

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WCTE Water System Schedule

- Schedule presented last July slightly slipping but still on track:

- Estimated 6 months for design and 8 months for procurement, assembly and delivery to CERN
  - Based on experience from IPMU prototype system
- Design is still ongoing, but included few months contingency in production/shipping
  - Gd-tanks procurement already started, aiming for mid-July delivery
- Allows for ~4 months of assembly, commissioning, detector filling and water quality stabilization before nominal beam start in March

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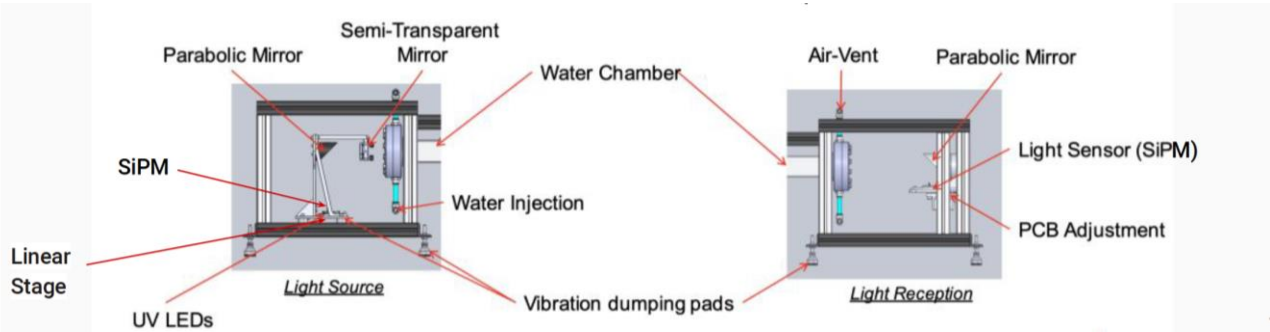
Calibration systems status – water monitoring

- The first mechanical prototype has been built and operated; optical components are being installed
  - Prototype will be used for WCTE
- Fast pulsed LEDs to measure scattering of light
  - < 1 ns FWHM throughout the wavelength range (235 nm to 470 nm)
- Will operate inline with water system



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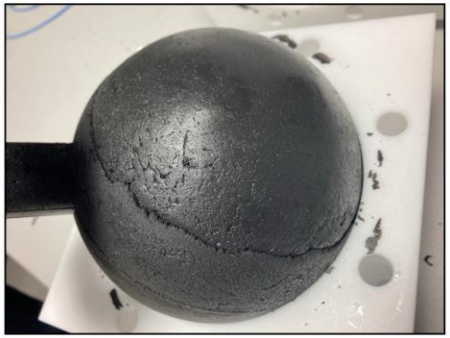
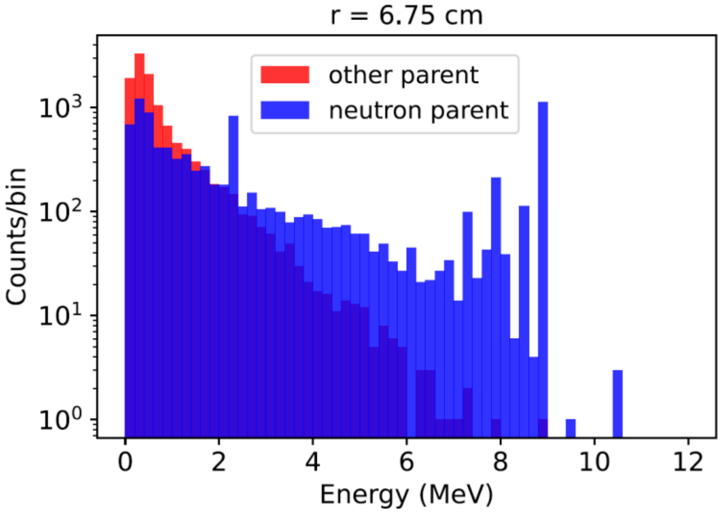
Calibration systems status – NiCf source





- First prototypes of nickel ball created (NiO powder suspended in epoxy)
  - Currently machining hole for Cf source and smoothing surface

- Spectra comparison (Geant4 simulation of gammas escaping the source, 100k 252Cf decays):
  - For r = 6.75 cm: 9249 neutron-induced gammas and 11544 other gammas

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Summary

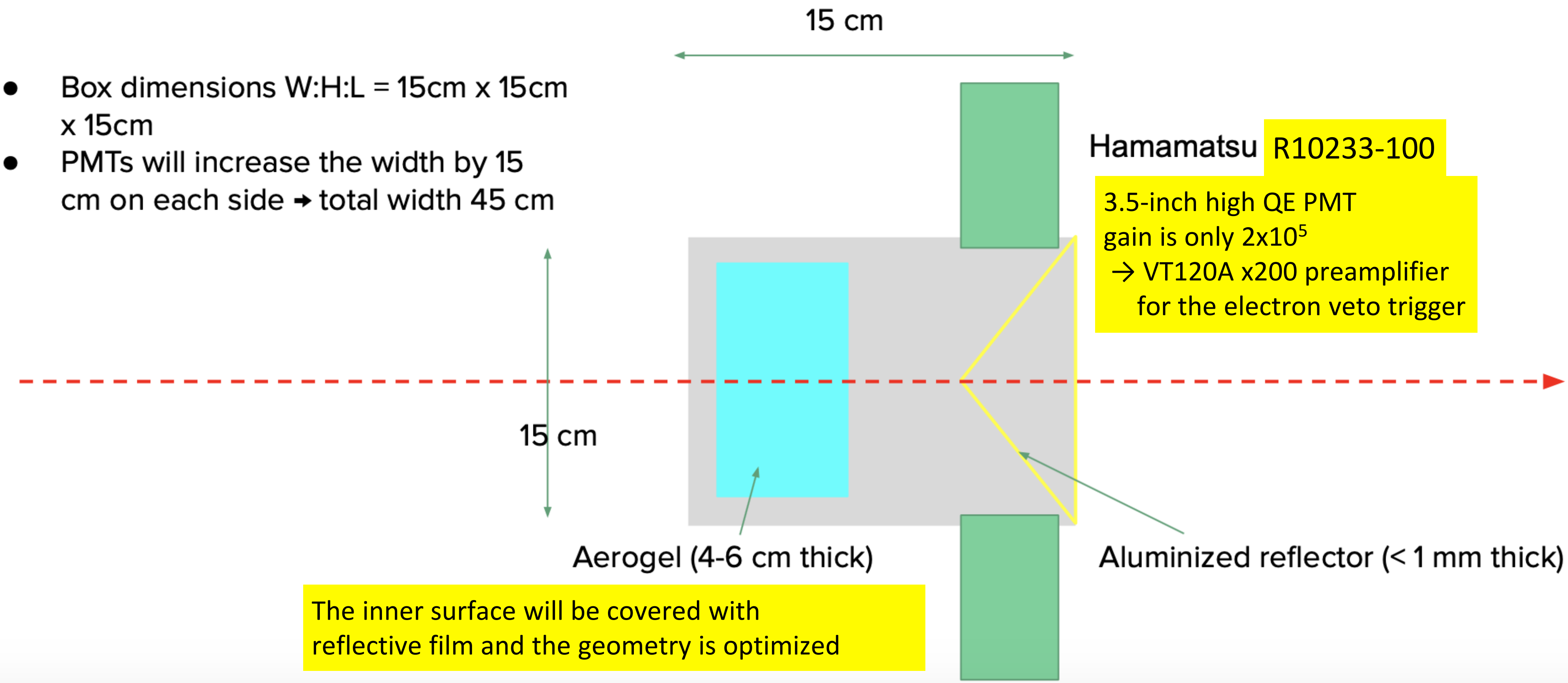
- Upgrades to T9 beam remove the requirement for tertiary beamline
  - Significantly simpler experiment design
- All aspects of WCTE design are currently being/have been finalized
  - Mechanical design under external review, assembly process will be reviewed in near future (end of May)
  - mPMT mass production in readiness review, start production in July
  - Test beam run in 2023 to test final beamline hardware and demonstrate tagged gamma beam
- Working to define physics run plan to optimize data collection time
- Working closely with CERN groups and East Hall coordinators

Critical steps during assembly

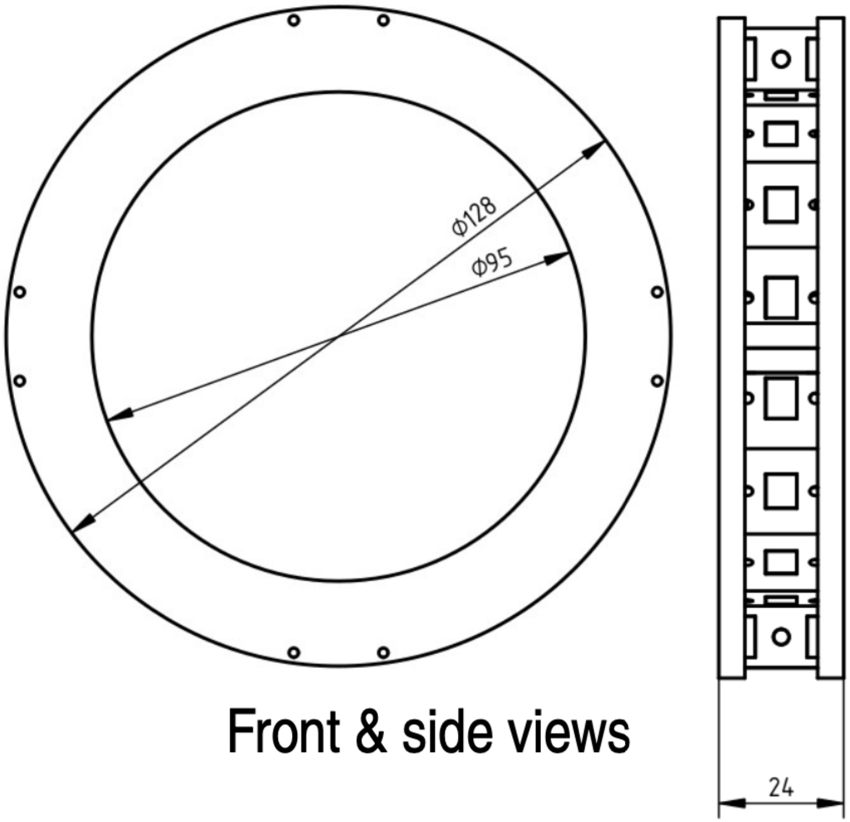
- Caveat that exact assembly process still to be finalized
    1. Prepare East Hall for assembly
    2. Testing of individual mPMTs after shipment from Canada/Poland
    3. Instrumentation of the support structure sections (barrel, end caps)
    4. Assembly of the support structure
    5. Testing of mPMTs before placing support structure in tank
    6. Inserting the fully instrumented support structure into the tank
    7. Transfer WCTE detector to T9 and position in beam line
    8. Placement of lid, calibration deployment system and interfacing to utilities, DAQ
    9. Connect and test water system
    10. Fill detector with UP water

Aerogel Cherenkov counters

- Box dimensions W:H:L = 15cm x 15cm x 15cm
- PMTs will increase the width by 15 cm on each side → total width 45 cm



Time of Flight (TOF) counters



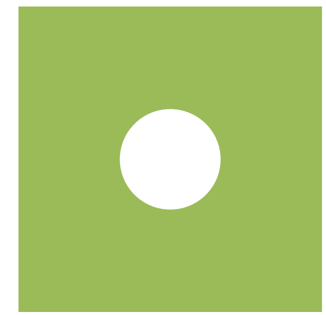
Front & side views

- Scintillator
  - 10cm diameter EJ-228 scintillator
- Photosensor (each plate):
  - 16 Hamamatsu MPPC S14160-6050HS (6x6mm)
- Fast readout
  - CAEN/Weeroc CITIROC 1A

Hole counters and hodoscopes

- Trigger counters
  - TOF counter used in 2022 July run
  - 9x9cm and 6mm scintillators
  - readout by four 1-inch PMTs

- Hole counters
  - 15x15cm and 10mm-thick scintillator
  - 45mmφ hole at the center (hole-0)
  - 60mmφ hole at the center (hole-1)

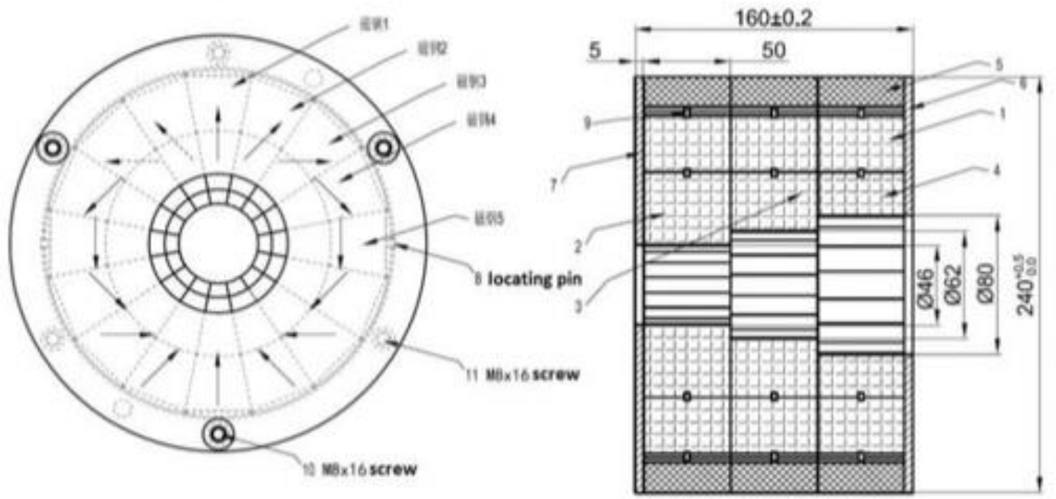


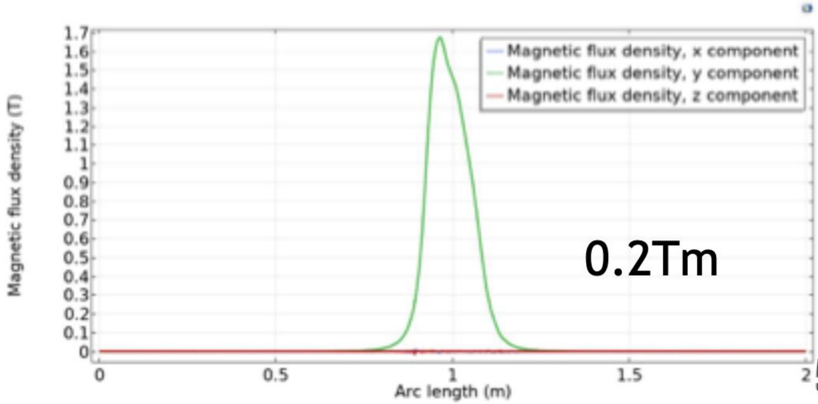
- Hodoscope
  - 5cm x 10cm scintillator plates
    - 7 plates in the front
    - 8 plates on the back

Magnet for the tagged γ beam

- Halback array permanent magnet
  - Bore: 46-80mmφ
  - 160mm-long
  - BL=0.2Tm
  - peak field = 1.7T
- Currently in use for EMPHATIC@Fermilab

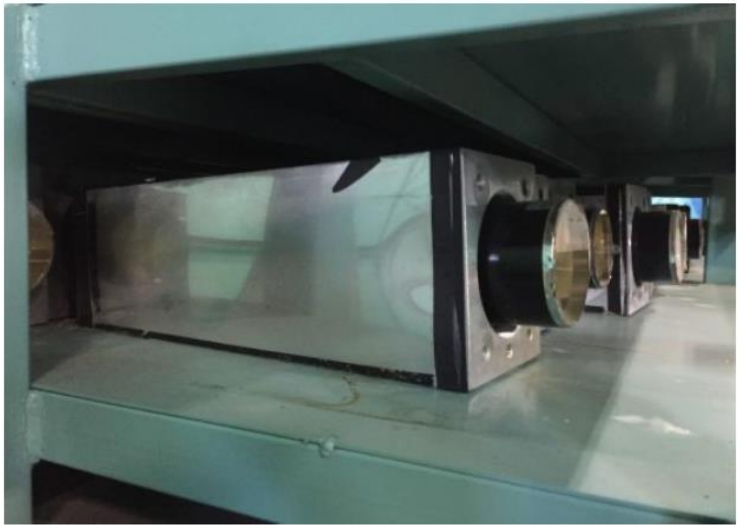
Shipping in May





Lead Glass calorimeter

- Old lead glass from Topaz experiment (KEK)
- Only one module will be used
- H:W:L = 10cm x 12 cm x 36 cm + 16 cm PMT length
- Read out by a single PMT (Hamamatsu R6231-100)



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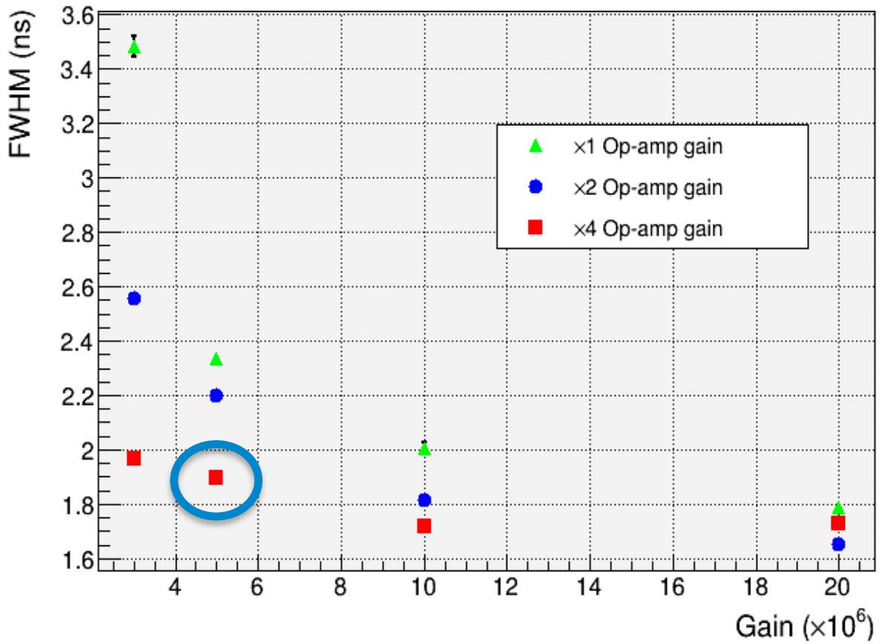
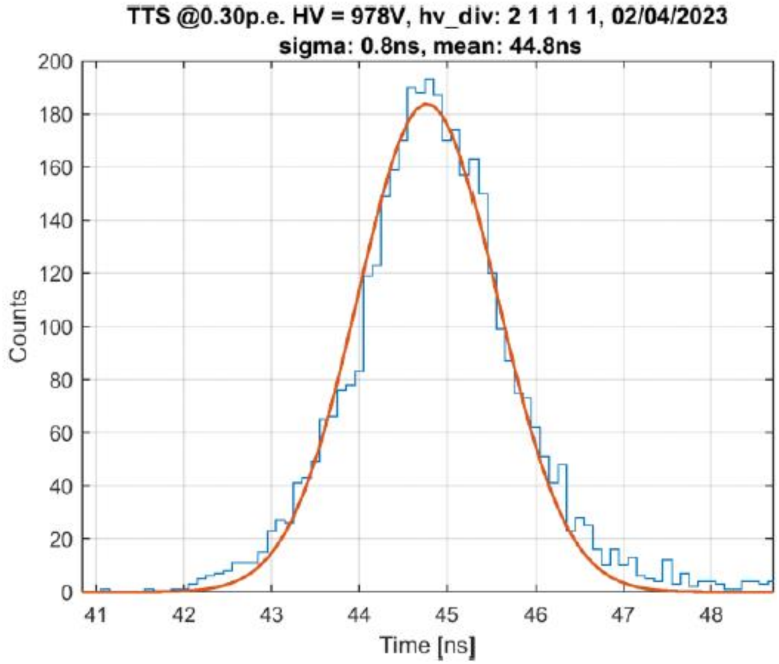
Multi-PMT timing

- Combined timing resolution of digitizer and PMT shown on bottom left, plot of transit time spread (TTS) on bottom right
- PMT timing resolution is ~1.5ns, combined resolution is ~1.9ns (both FWHM)
- Dominated by PMT, but hope to improve time extraction technique





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WCTE Water Purification System

- System designed for both pure water and Gd-loaded water operation
- Not a band-pass system, using same process as SK.
  - Gd-compatible resin will filter water during operation but leave Gd in solution
  - Mixed-bed DI will be bypassed during Gd operation
- Aiming for 0.1% Gd by weight (0.2% Gd sulphate) since we know transparency can be maintained at this level from EGADS experiment
- All resins procured and currently stored in Kashiwa
- Underground piping (next slide) in T9 area recommended by Francesco Dragoni and East Hall coordinators to minimize interference with cable trays above shielding blocks

Changes in the mechanical design

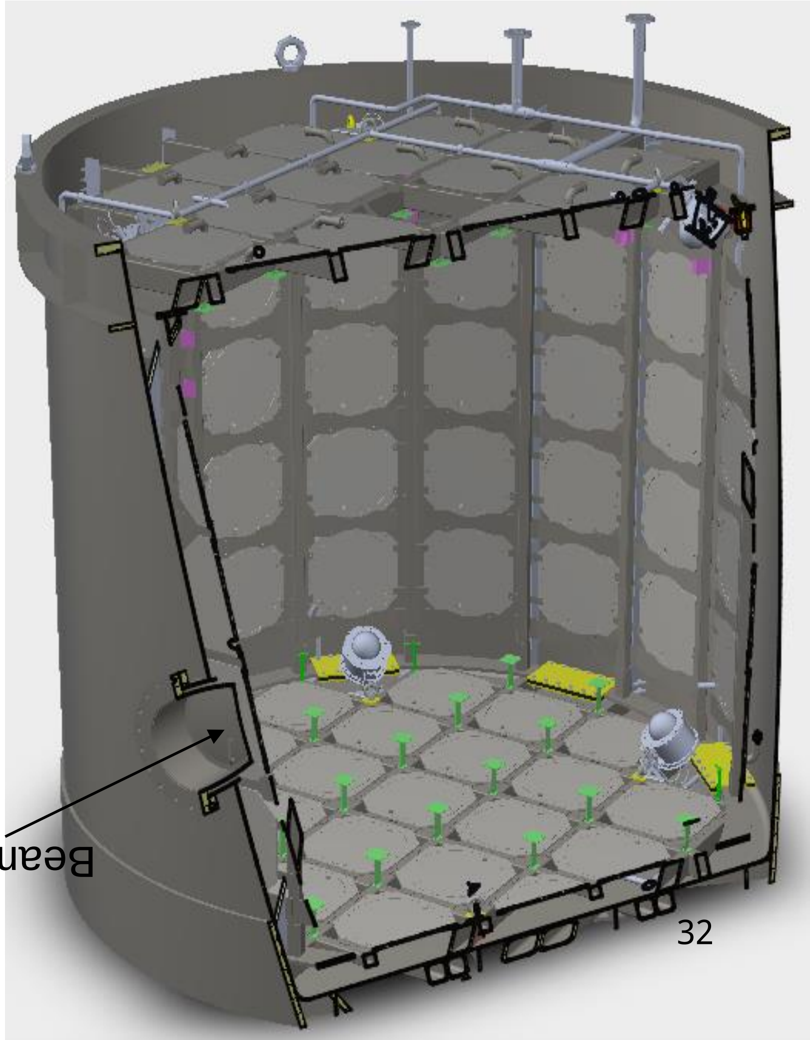
Thanks to the T9 beam upgrade and after the 2022 summer test beam, we concluded we did not need to access both secondary and tertiary beams, but only the former.

- No rails or moving system required
- Only one beam window

Updated the detector design accordingly.

Other updates of the design:

- New connectors for the mPMTs to avoid touching the detector walls
- Cables and water pipes routing including the integration with the lid
- Integration with CDS (central deployment system), cameras and lights
- Lifting and anchoring points for assembly
- New design of black sheets surrounding the mPMTs
- Insulation for the tank to reduce cooling power needed by the water system



Changes in the mechanical design

Currently, the design is finished; the documentation is being finalised including drawings, FEA analyses and Eurocode compliance.
This documentation has been reviewed internally, is being reviewed externally, shared with companies and reviewed by CERN soon.

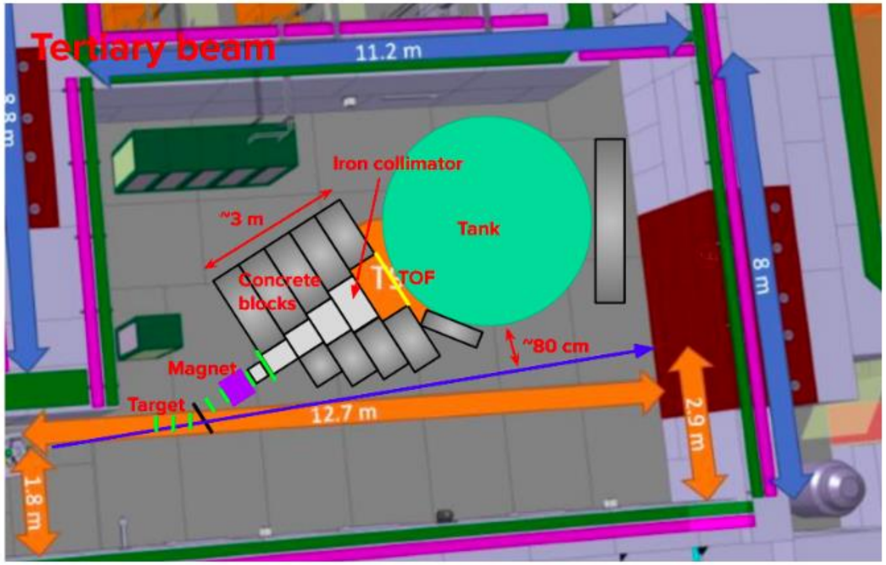
The assembly procedure is almost ready with detailed timeline and all the required items for it:

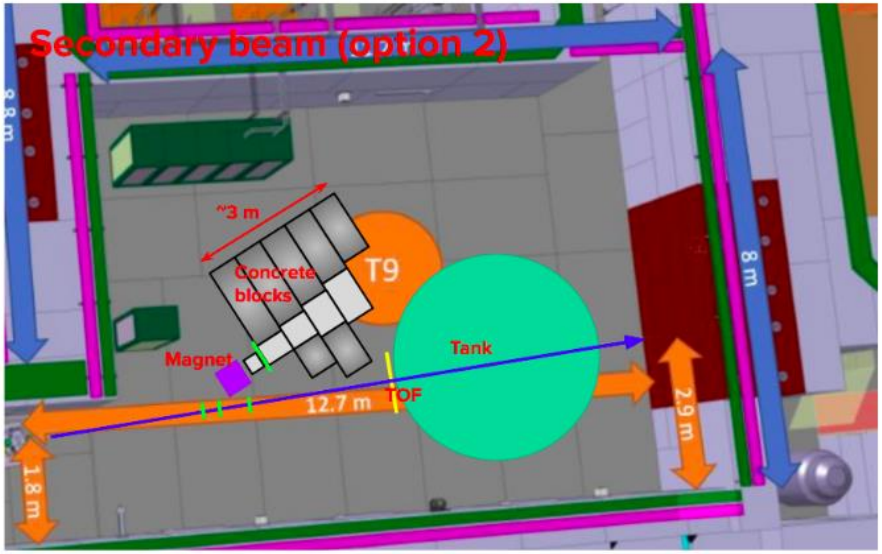
- Space for assembly and storage
- Scaffoldings
- Crane and crane operators

Beam configuration

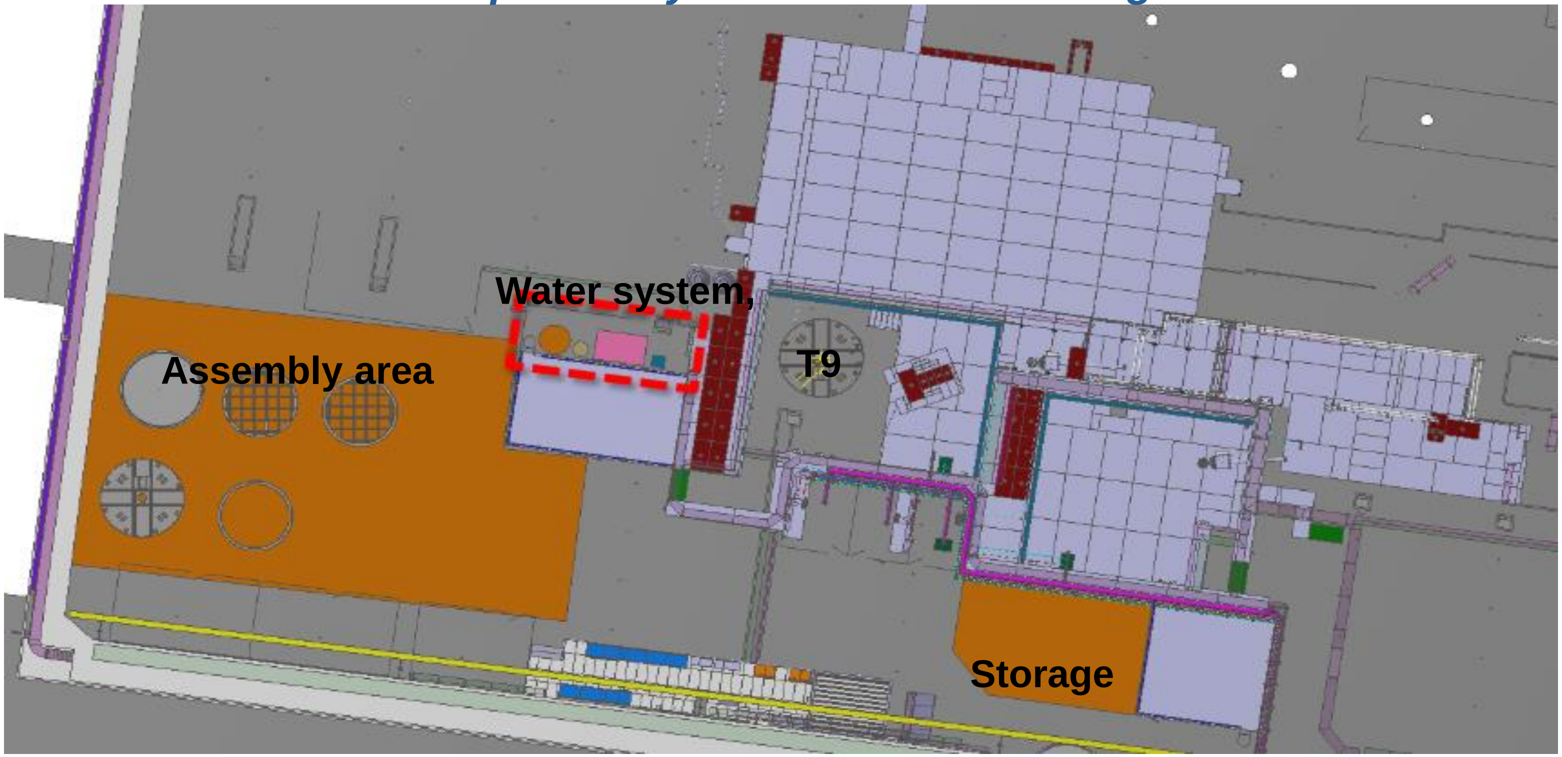
- Original proposal used tertiary and secondary beams
  - Tertiary: Low momentum particles (pions)
  - Secondary: Muons and electrons

- Requires extra complexity, extra cost and extra runtime

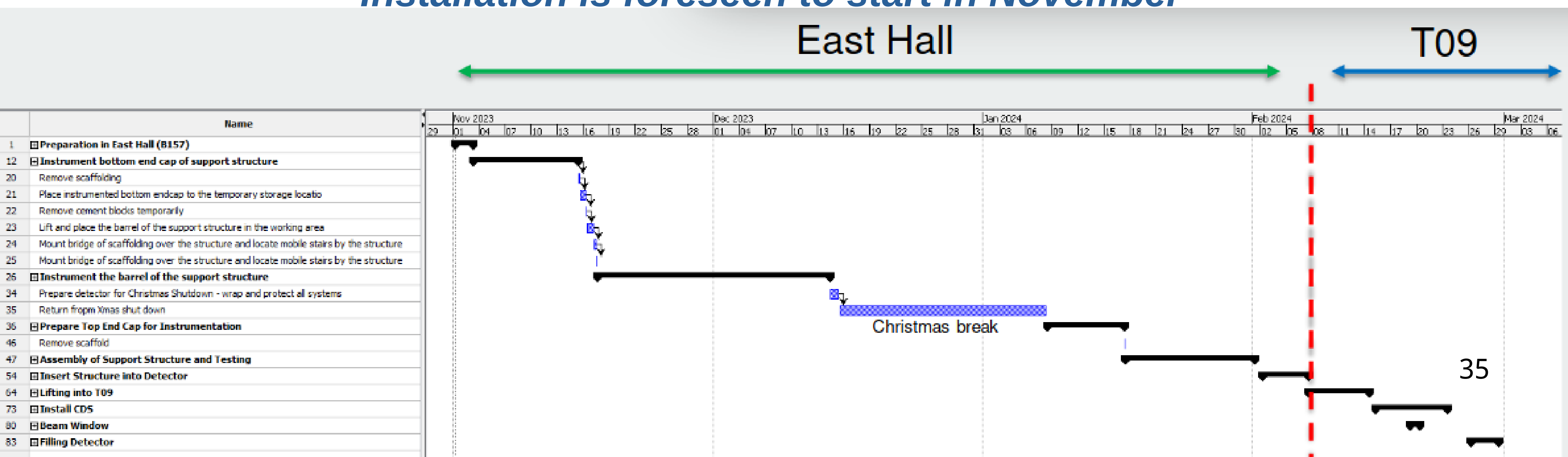


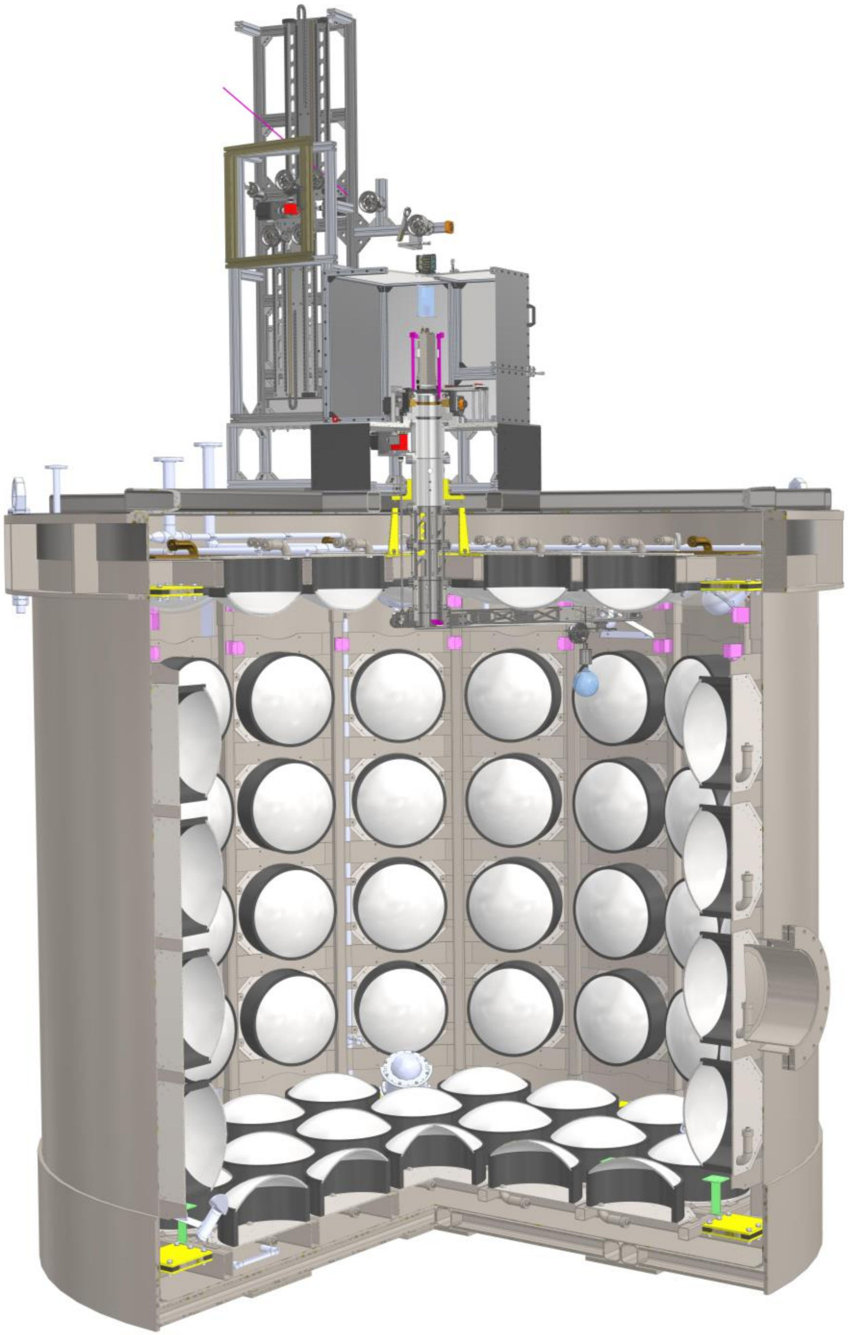


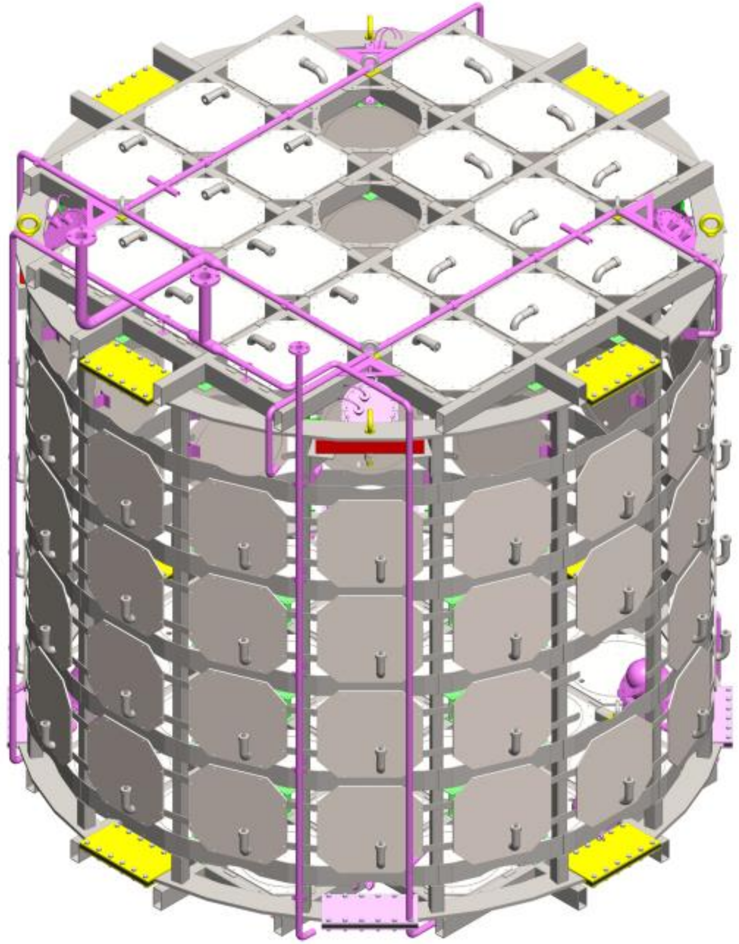
Proposed layout at East Hall during



Installation is foreseen to start in November

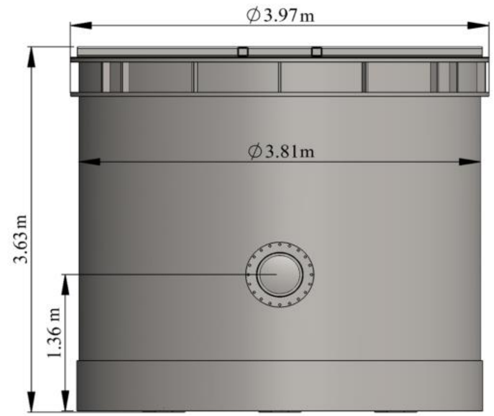




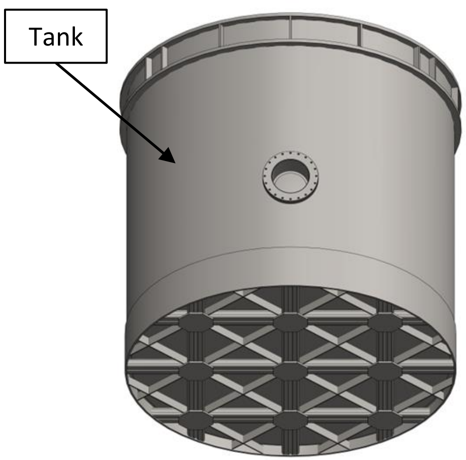


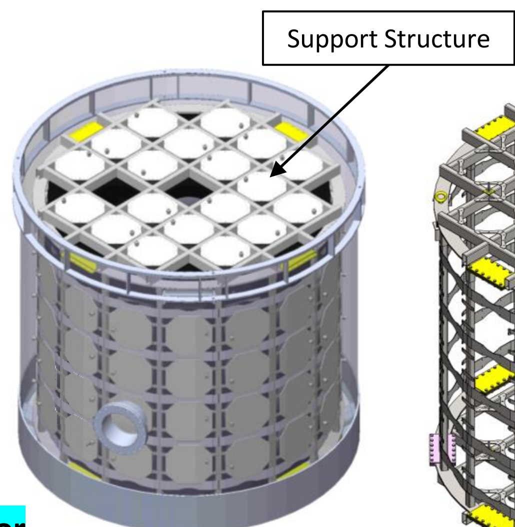
WCTE Design Overview

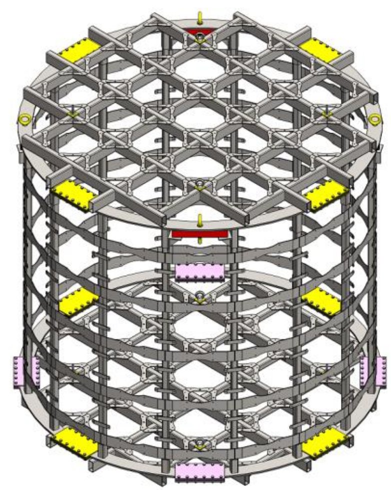
- The detector consists of the Support structure and the tank assembly
- The support structure will be placed inside the tank and the is filled with ultrapure water
- Total mass of the detector excluding water is **15 tonnes.**
- During the experiment **ultra-pure** water will fill inside the tank in that case the total mass of the detector will be **56 tonnes**



Overall dimensions





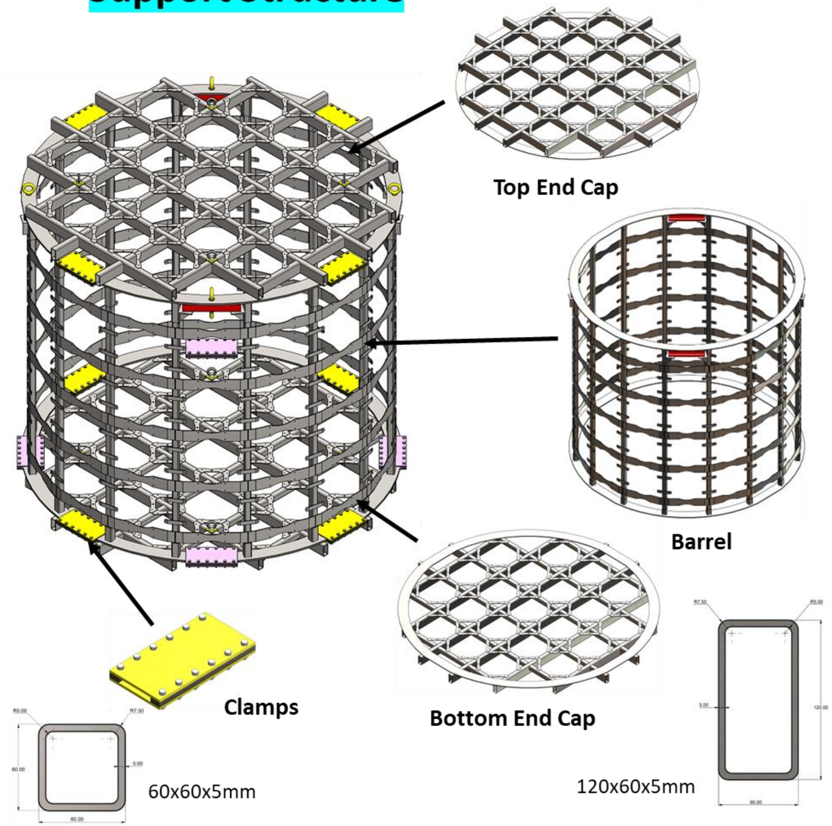


Detector

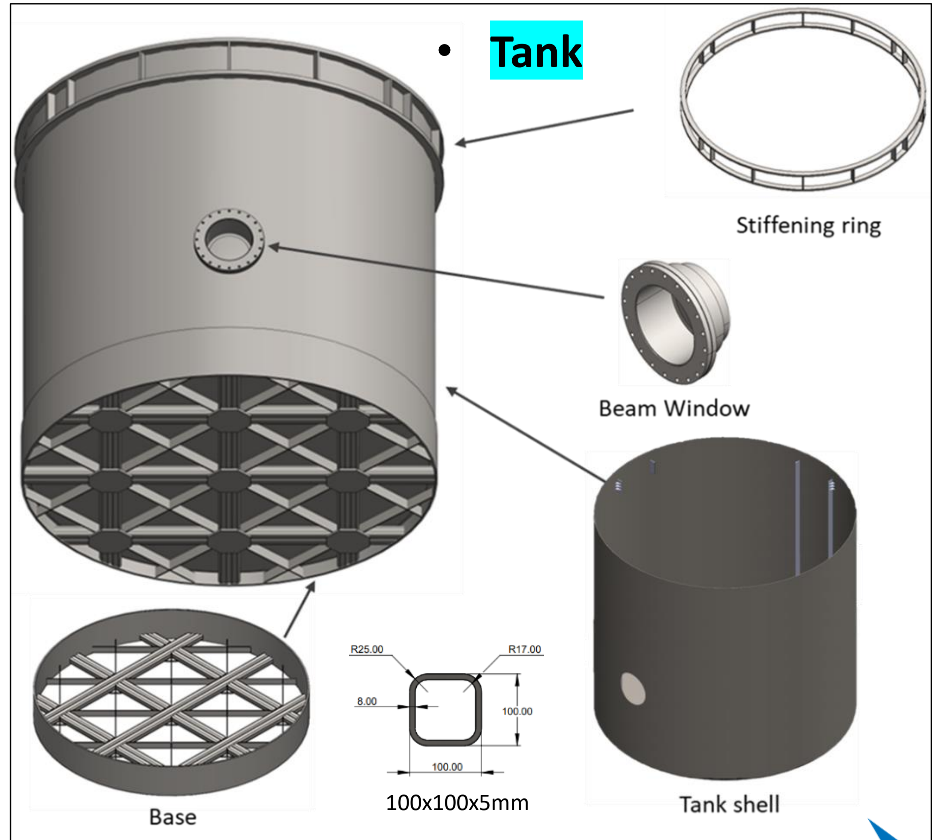
- On the support structure **103 mPMT** will be mounted
- The weight of a single **mPMT** will be **50kg**
- Total weight of the support structure is approximately **9.5 tonnes**

WCTE detector design

- **Support Structure**



- **Tank**



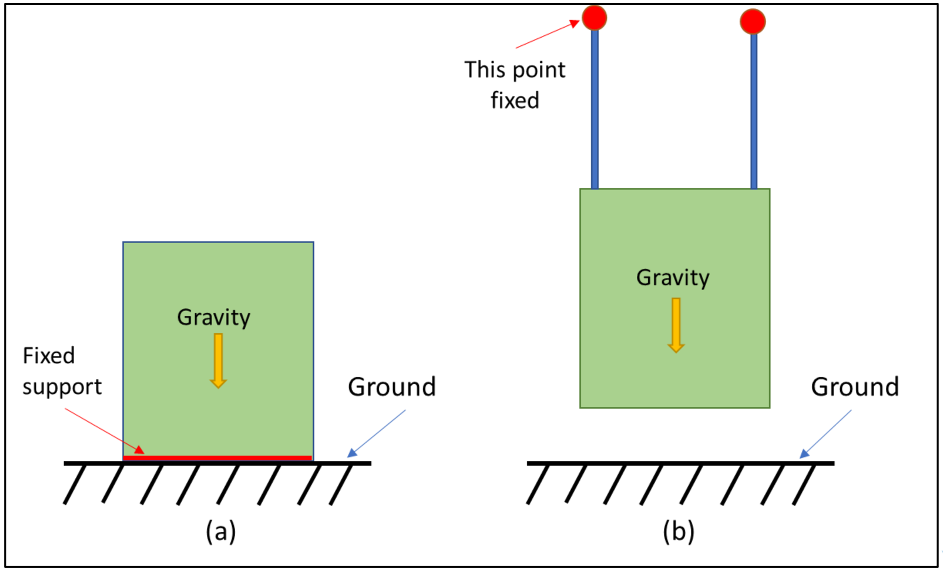
Finite Element Analysis (Using Ansys2020 R2)

The FEA validates two loading conditions:

i. During operation – Sitting on ground with load factor 1.35g, *EN 1990: Eurocode - Basis of structural design, Table A1.2(B)(fig. a)*

ii. During Installation – Lifting condition with load factor 1.5g as suggested by CERN safety engineer(fig. b)

FEA	Simulation	Status
Support Structure	On ground	Completed
	Lifting	Completed
	Lifting - local analysis of BEC (with preload on clamp bolts)	In progress
Detector (Including Tank assembly with support structure inside it)	On ground	
	Lifting	



Eurocode validation

- The design calculations are evaluated using Dlubal RFEM Software (Free trial version for Students)
- The results obtained from this software show deviation of 2-3% from the hand calculations.
- Hand Calculations are based on " Shingley's Mechanical Engineering Design"
- The calculations obtained in Dlubal software are complaint with Eurocode

The case study involves the analysis of a square hollow section (S.H.S) made of material S235H. The S.H.S is fixed at both ends length of the S.H.S is 3755 mm, (100x100x8) and it is subjected to a uniformly distributed load of 9 kN/m

Table 1 Result Summary for Case Study

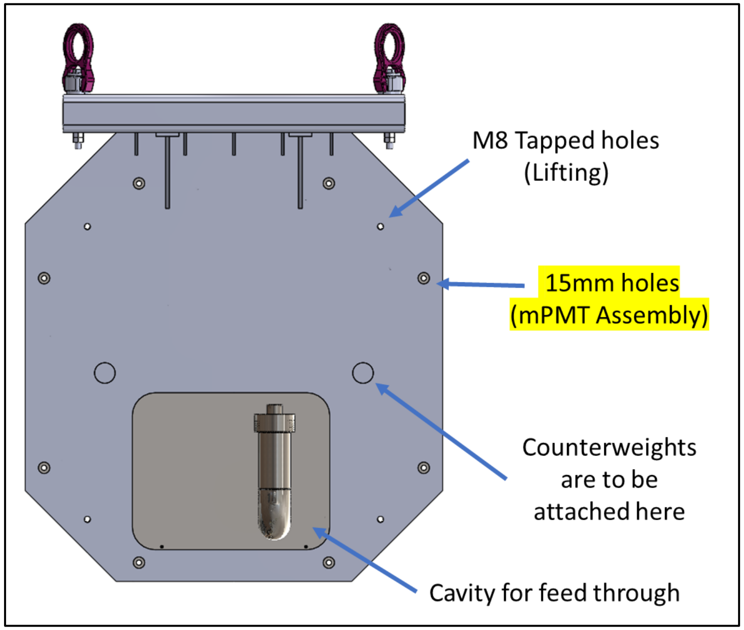
Design Check	Hand Calculations	RFEM Calculations	Ratio	Load Combination factor	% Difference
Bending about y-axis	0.458	0.634	1.38	1.35	2.22%
Shear in z-axis	0.086	0.120	1.39	1.35	2.96%

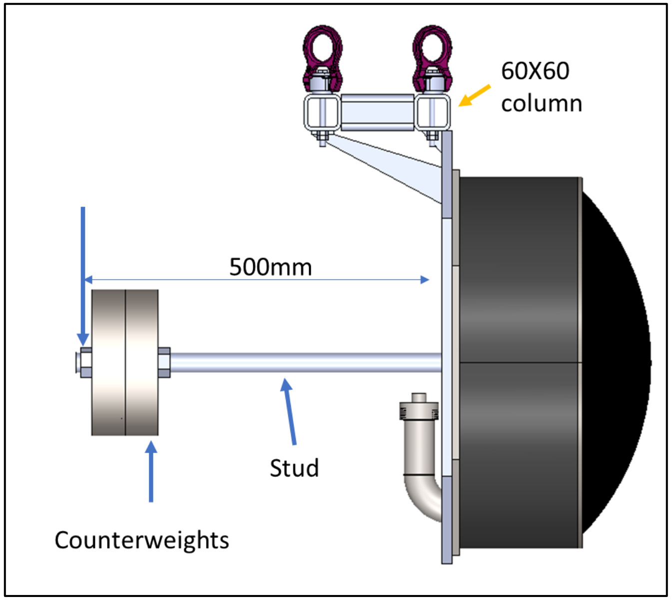
Hence, this Case Study establishes the credibility of the calculation results obtained from RFEM simulations conducted for the WCTE structure.

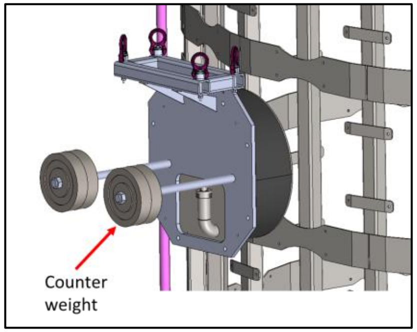
Eurocode validation

Items	Eurocode	Status	Remarks
Hollow Section verification	EN1993-1-1	Completed	Safe
Bolted connection	EN1993-3-8	Completed	Safe
Welding connection	EN1993-3-8	In- progress	
Tank shell Thickness	EN 1993-4-2	Completed	Safe
Nozzle (Beam window)	EN 1993-4-2	Completed	Safe (for the old design of beam window)
Lifting jig for mPMT		Pending	

Design of Lifting Jig for mPMT Assembly



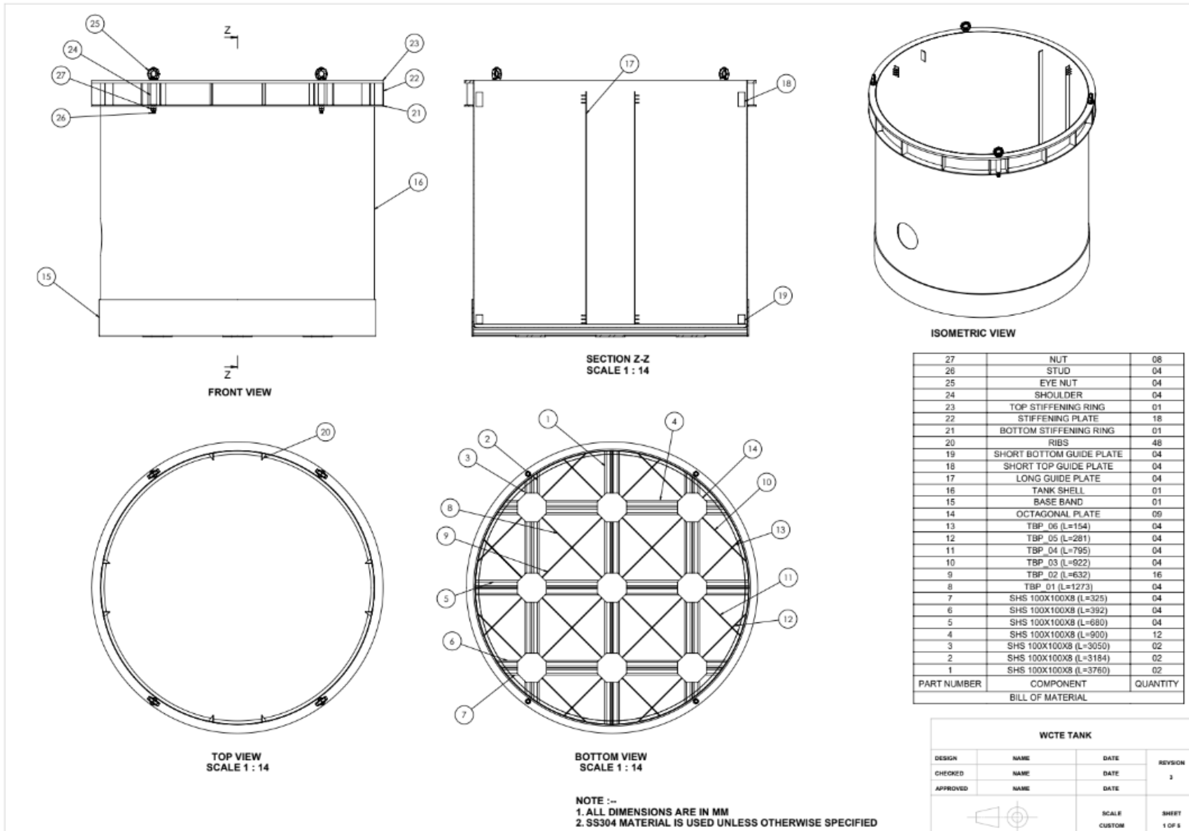




Engineering drawing

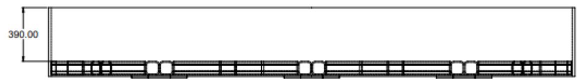
Engineering drawing		Status
Structure	1st Revision (without GD&T)	Completed
	2nd Revision (with GD&T)	In progress
Tank Assembly	1st Revision (without GD&T)	Completed
	2nd Revision (with GD&T)	Yet to start

Tank Assembly

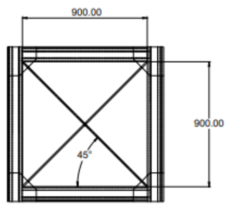


PART NUMBER	COMPONENT	QUANTITY
27	NUT	08
26	STUD	04
25	EYE NUT	04
24	SHOULDER	04
23	TOP STIFFENING RING	01
22	STIFFENING PLATE	18
21	BOTTOM STIFFENING RING	01
20	RIBS	48
19	SHORT BOTTOM GUIDE PLATE	04
18	SHORT TOP GUIDE PLATE	04
17	LONG GUIDE PLATE	04
16	TANK SHELL	01
15	BASE BAND	01
14	OCTAGONAL PLATE	09
13	TBP_06 (L=154)	04
12	TBP_05 (L=281)	04
11	TBP_04 (L=795)	04
10	TBP_03 (L=922)	04
9	TBP_02 (L=632)	16
8	TBP_01 (L=1273)	04
7	SHS 100X100X8 (L=325)	04
6	SHS 100X100X8 (L=392)	04
5	SHS 100X100X8 (L=680)	04
4	SHS 100X100X8 (L=900)	12
3	SHS 100X100X8 (L=3050)	02
2	SHS 100X100X8 (L=3184)	02
1	SHS 100X100X8 (L=3760)	02
BILL OF MATERIAL		

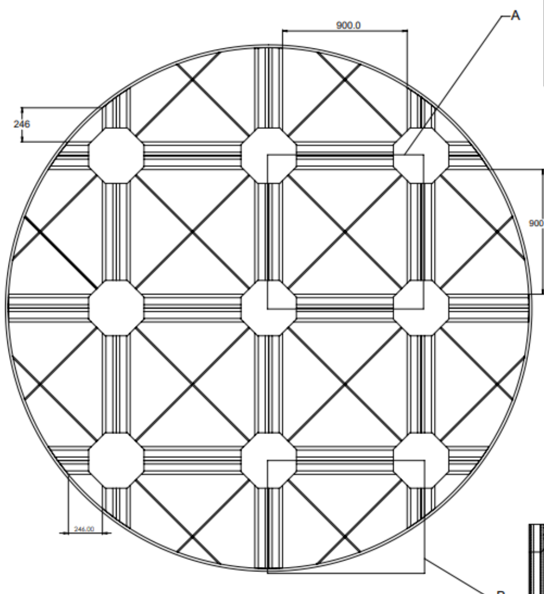
Tank Assembly



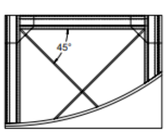
BASE COLUMN ASSEMBLY



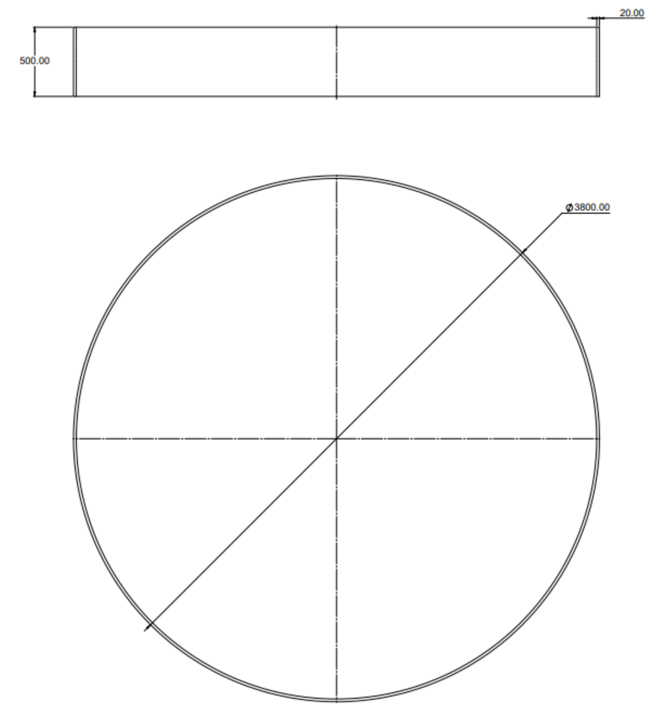
DETAIL A
SCALE 1 : 10



BOTTOM VIEW
SCALE 1 : 10

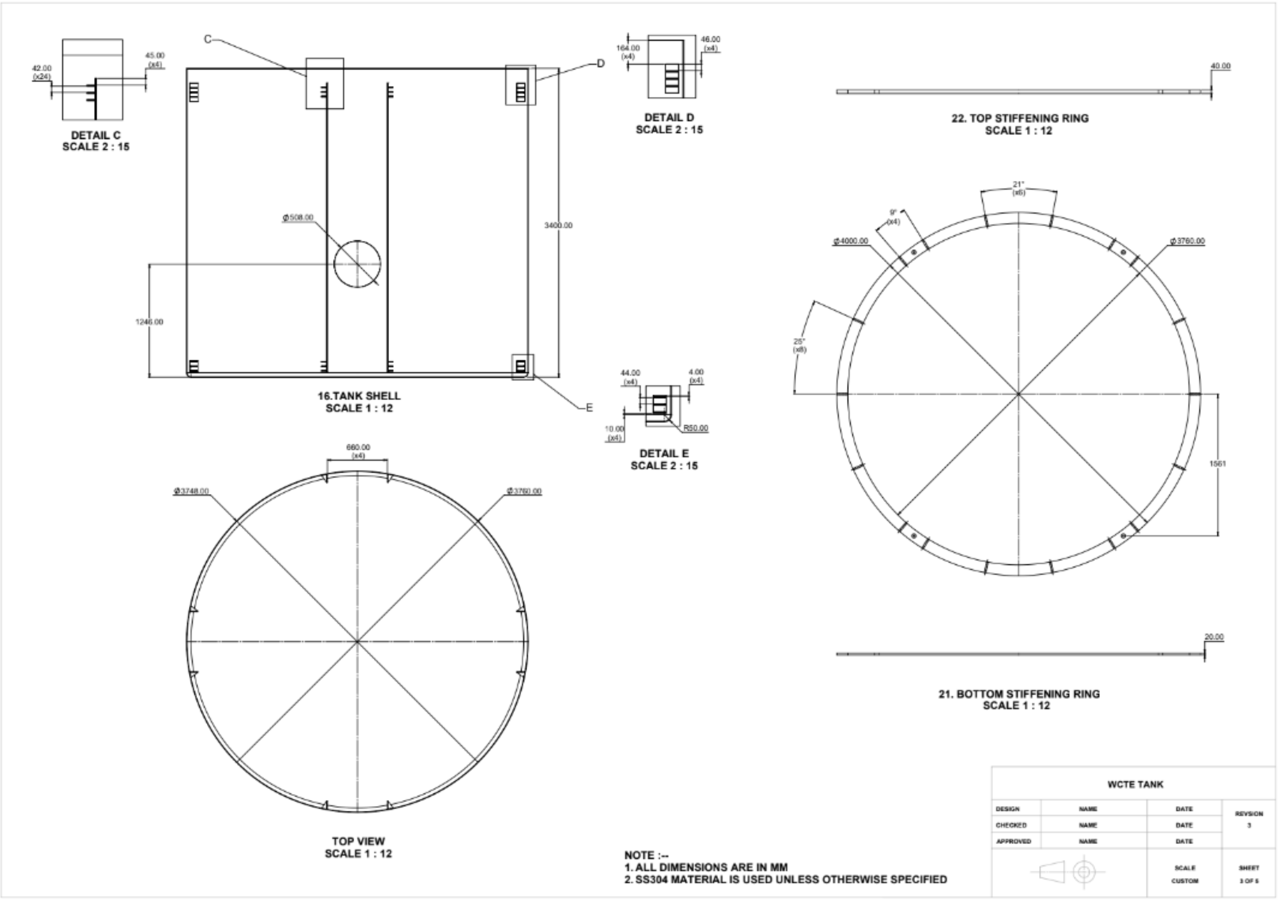


DETAIL B
SCALE 1 : 10

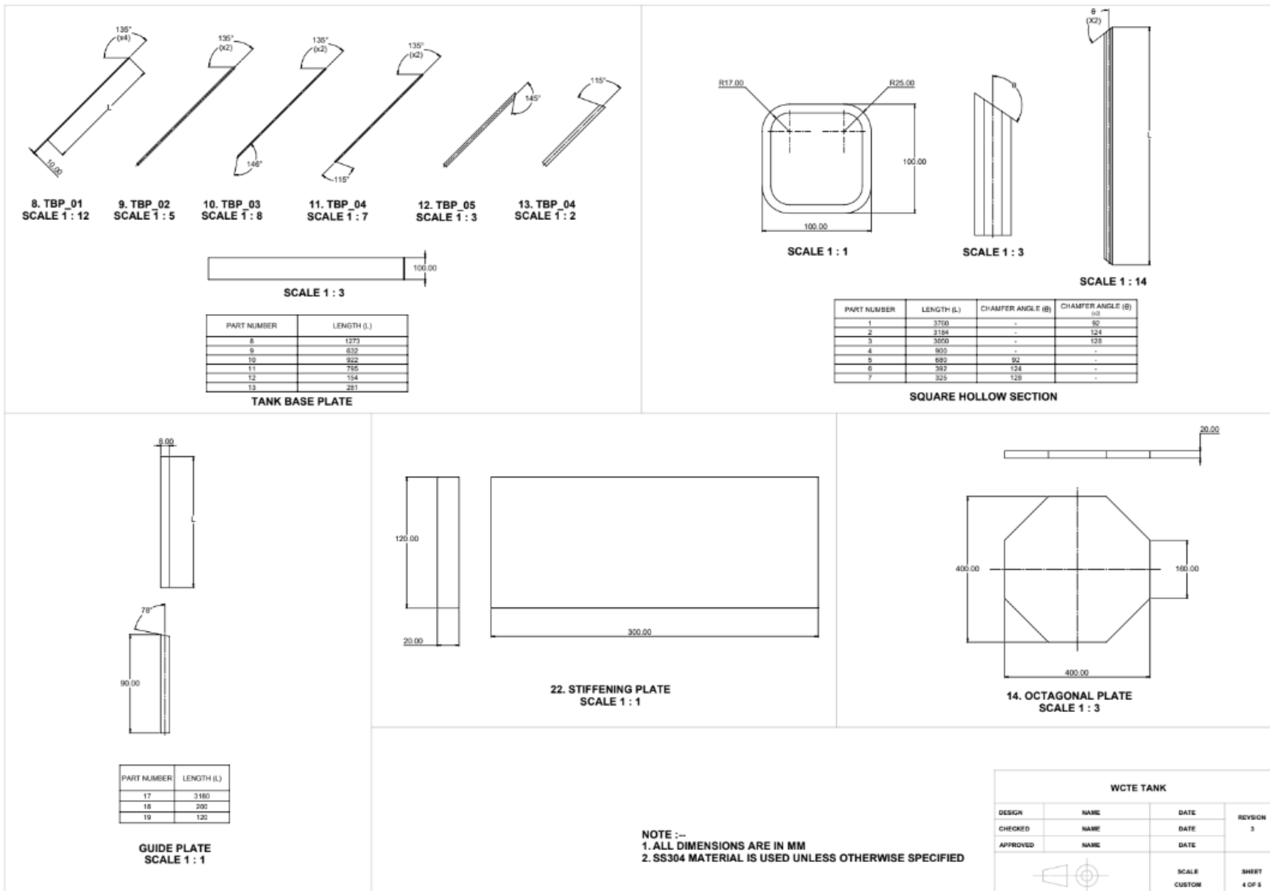


15.BASE BAND
SCALE 1 : 10

Tank Assembly



Tank Assembly



PART NUMBER	LENGTH (L)
8	1273
9	632
10	922
11	795
12	154
13	281

TANK BASE PLATE

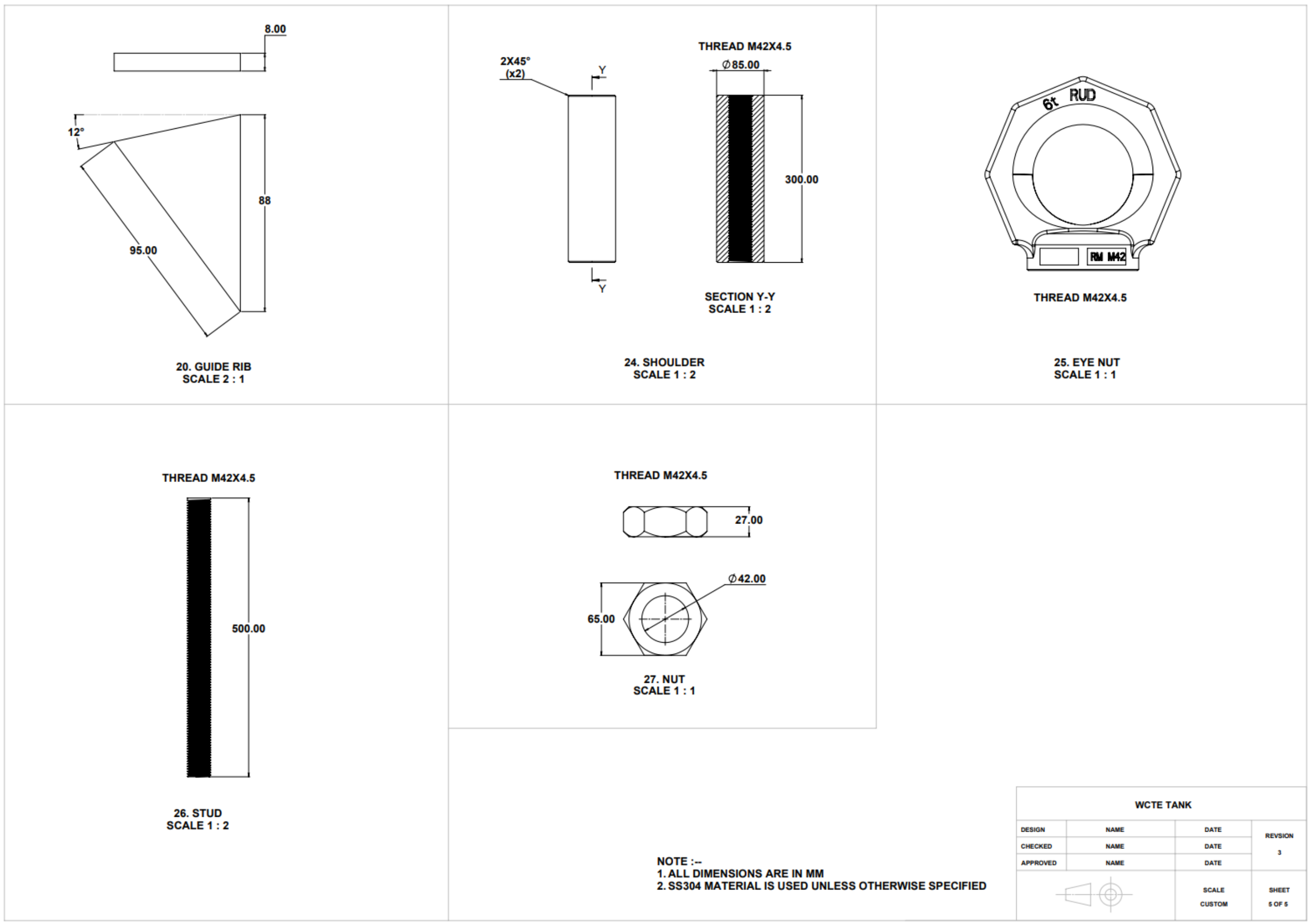
PART NUMBER	LENGTH (L)	CHAMFER ANGLE (θ)	CHAMFER ANGLE (θ) (x2)
1	3700	-	92
2	3184	-	124
3	3050	-	128
4	900	-	-
5	680	92	-
6	392	124	-
7	325	128	-

SQUARE HOLLOW SECTION

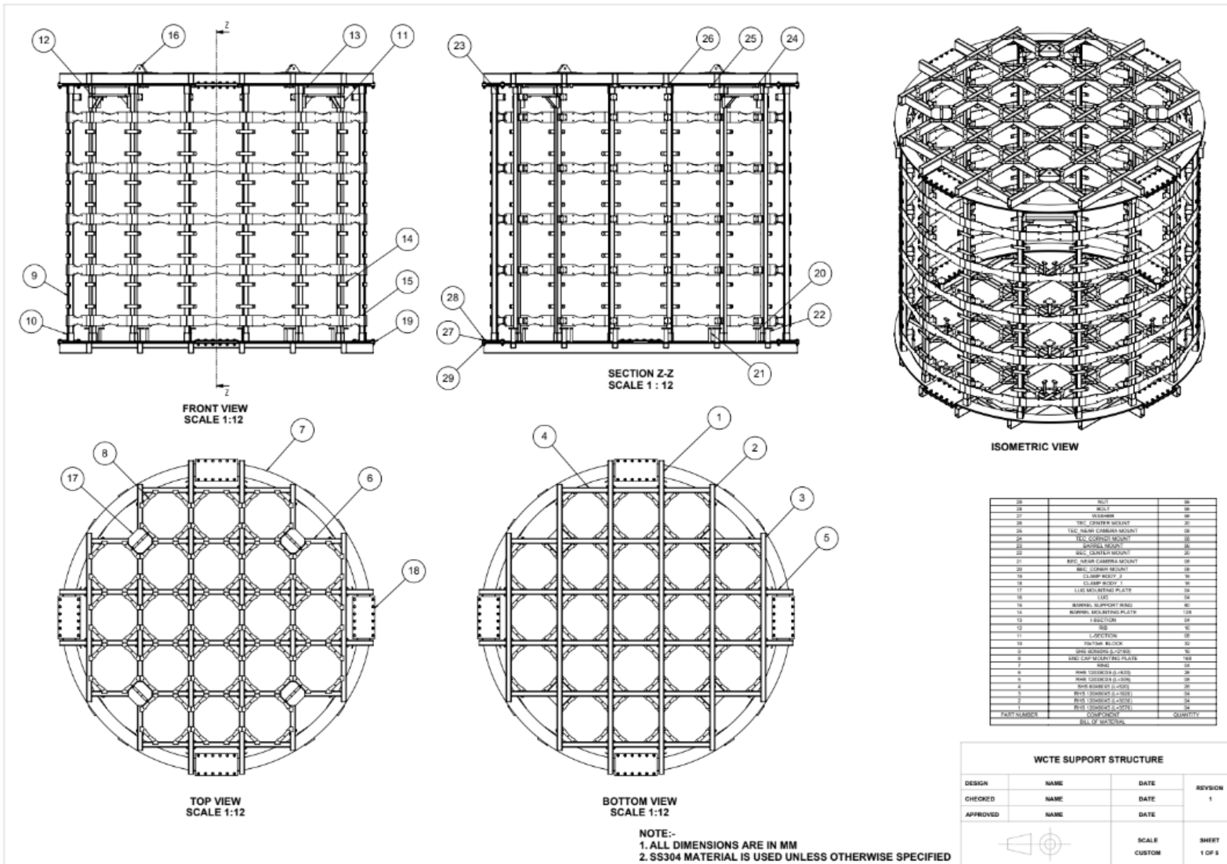
PART NUMBER	LENGTH (L)
17	3180
18	200
19	120

GUIDE PLATE

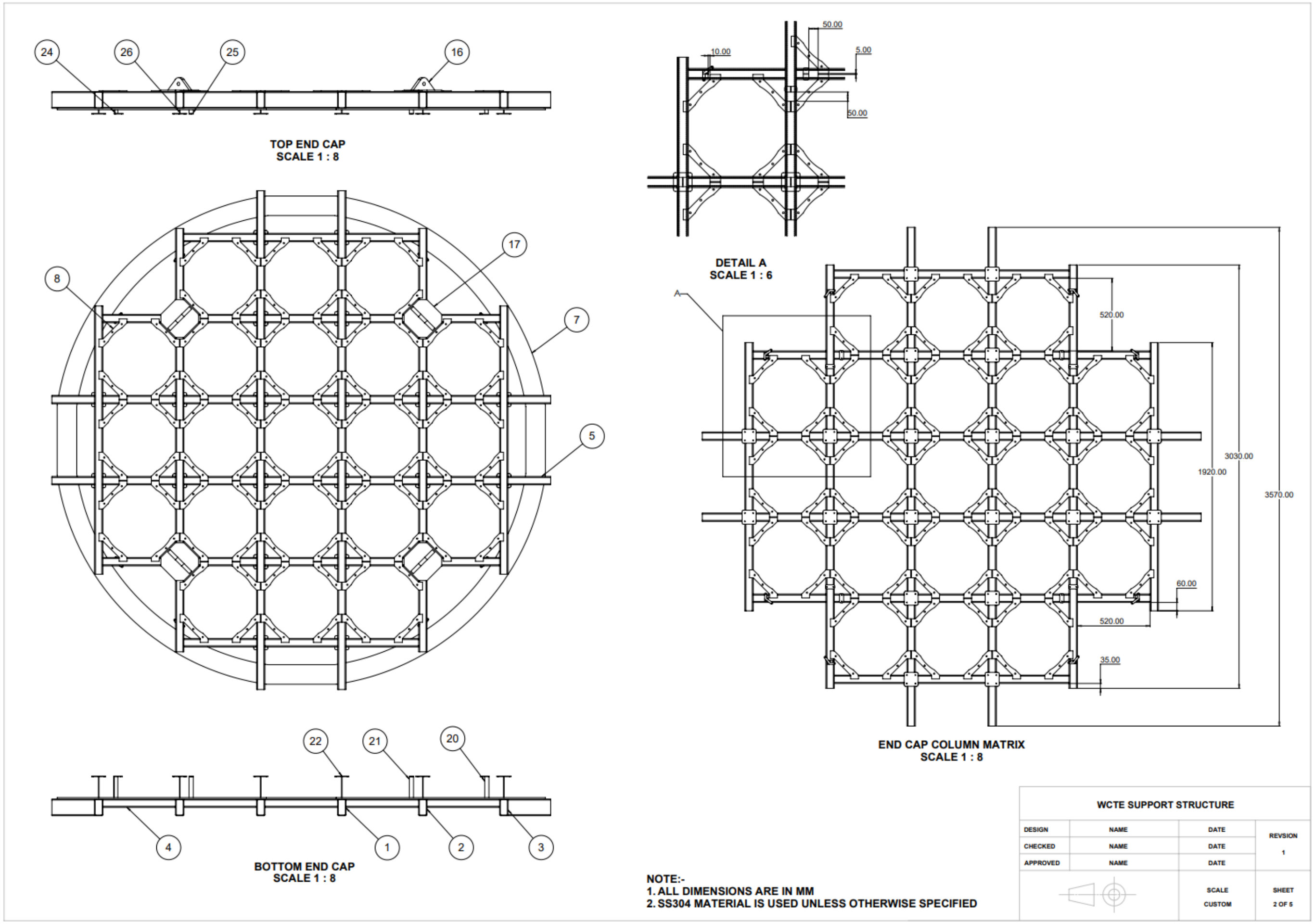
Tank Assembly



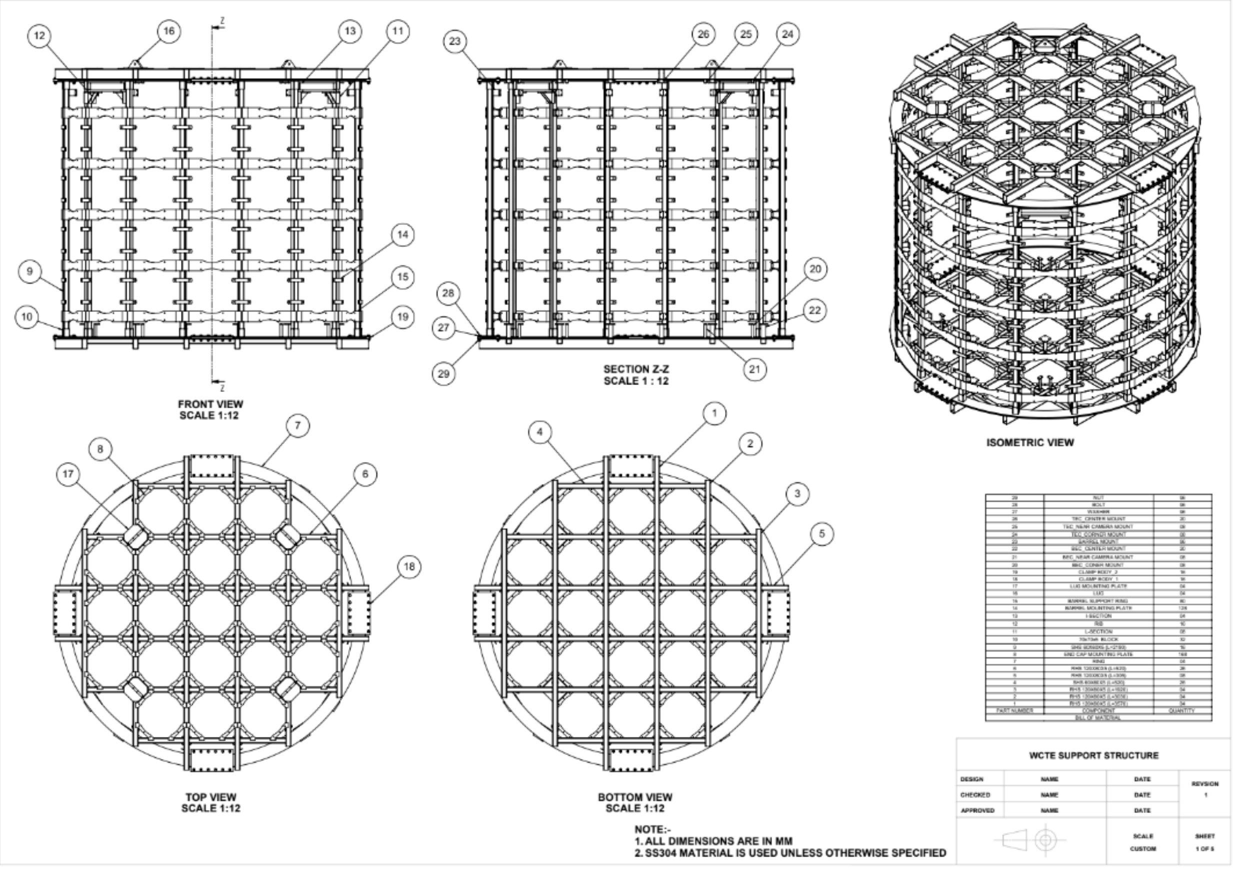
Support Structure



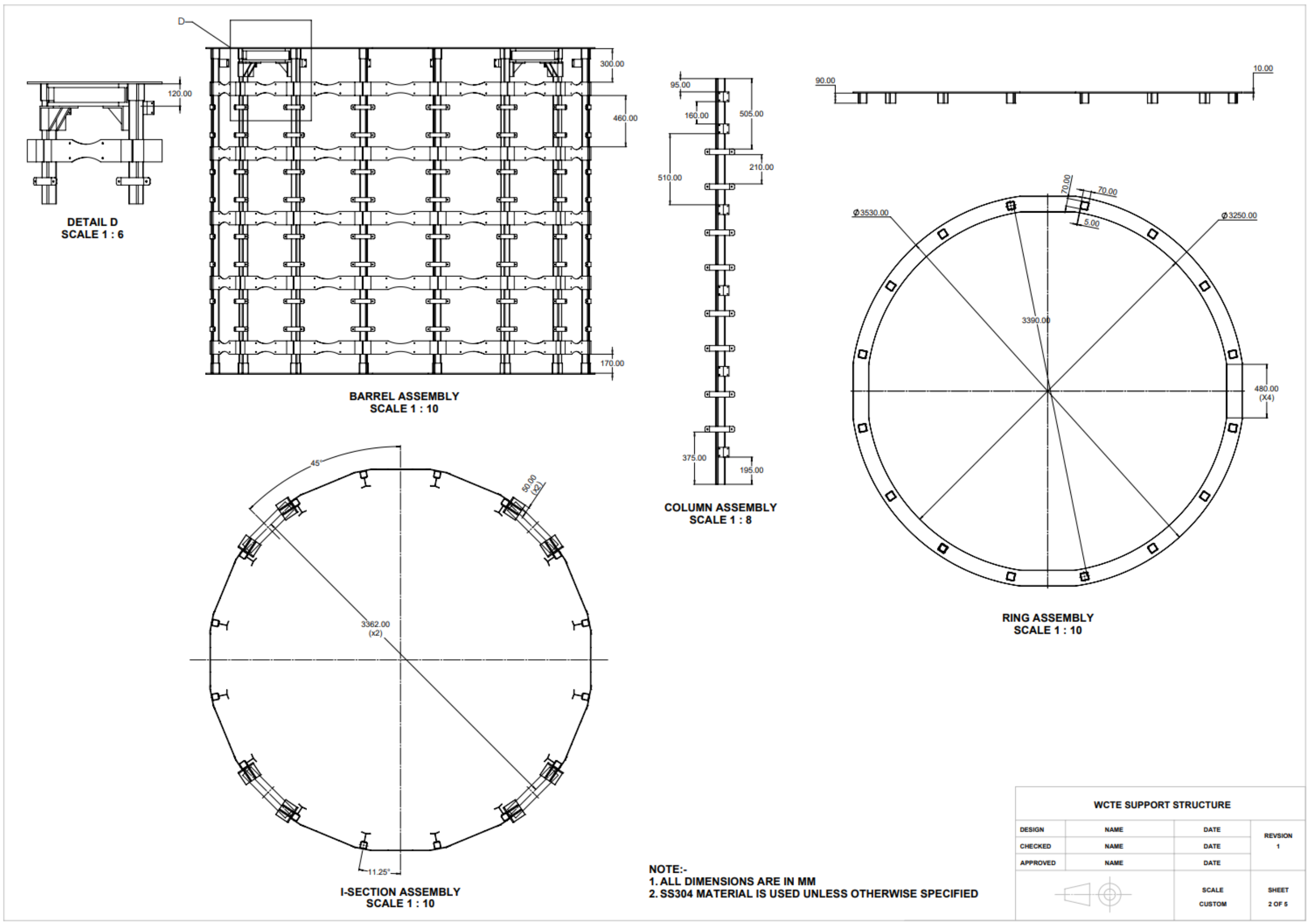
Support Structure



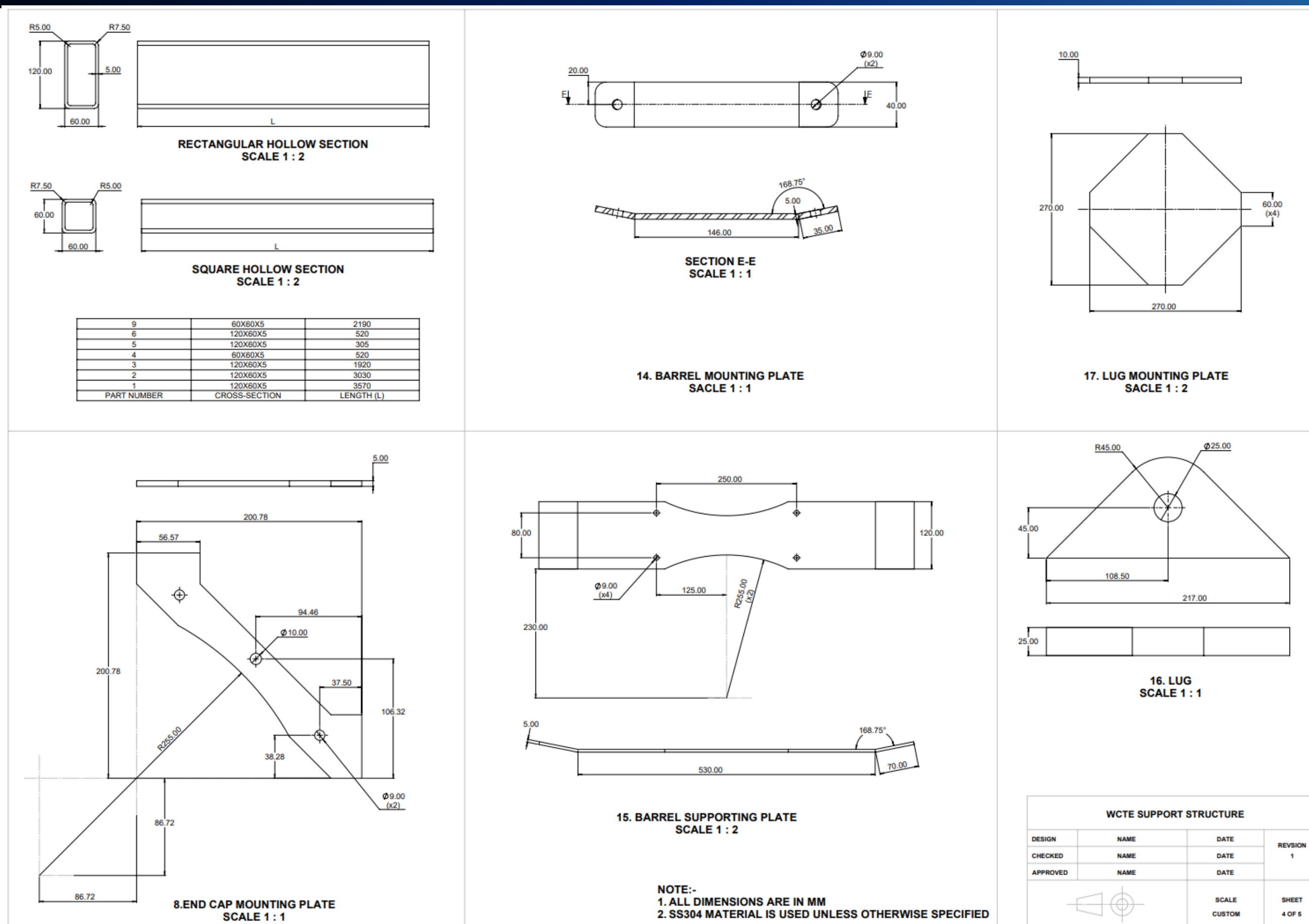
Support Structure



Support Structure

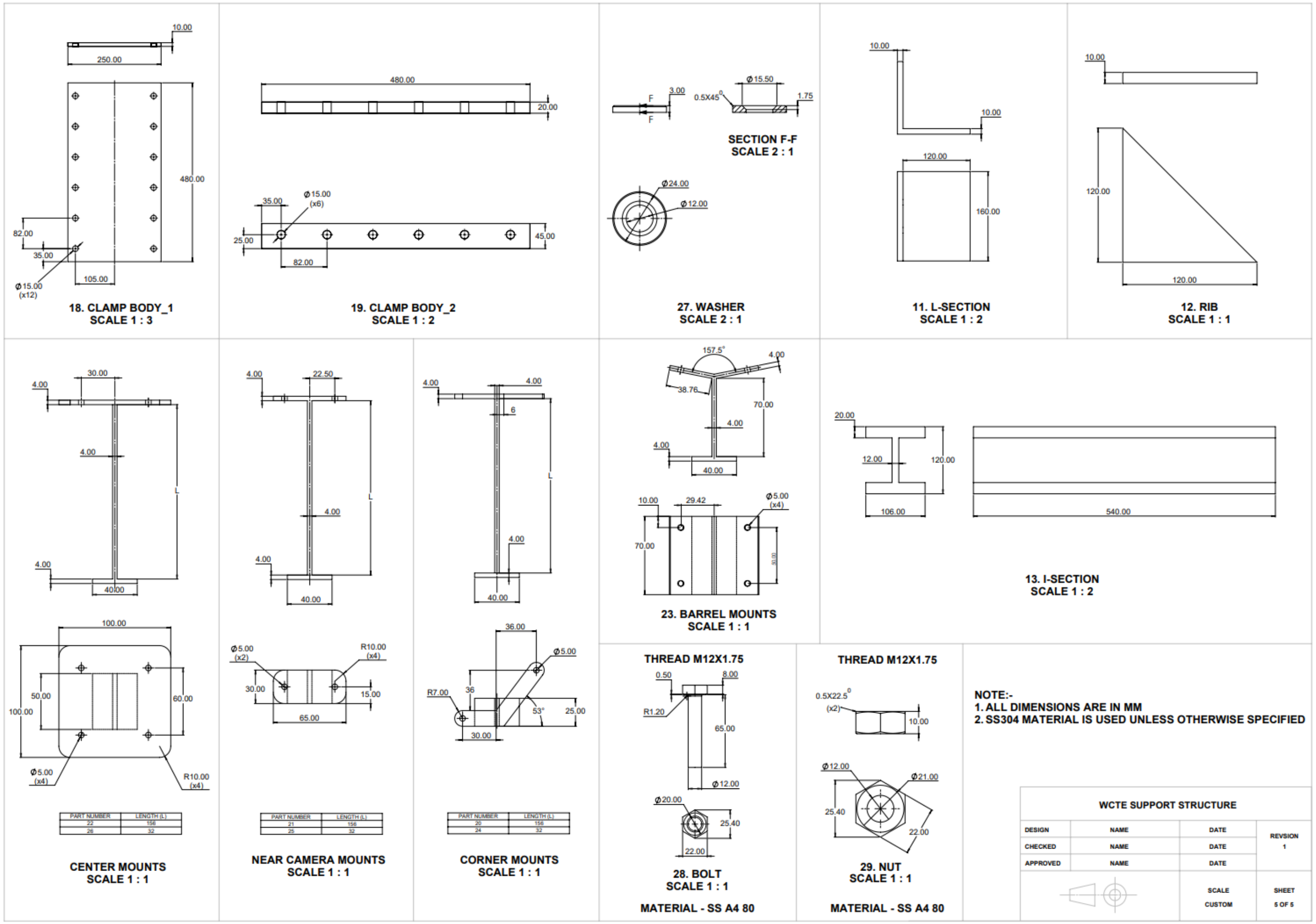


Support Structure



PART NUMBER	CROSS-SECTION	LENGTH (L)
9	60X60X5	2190
6	120X60X5	520
5	120X60X5	305
4	60X60X5	520
3	120X60X5	1920
2	120X60X5	3030
1	120X60X5	3570

Support Structure

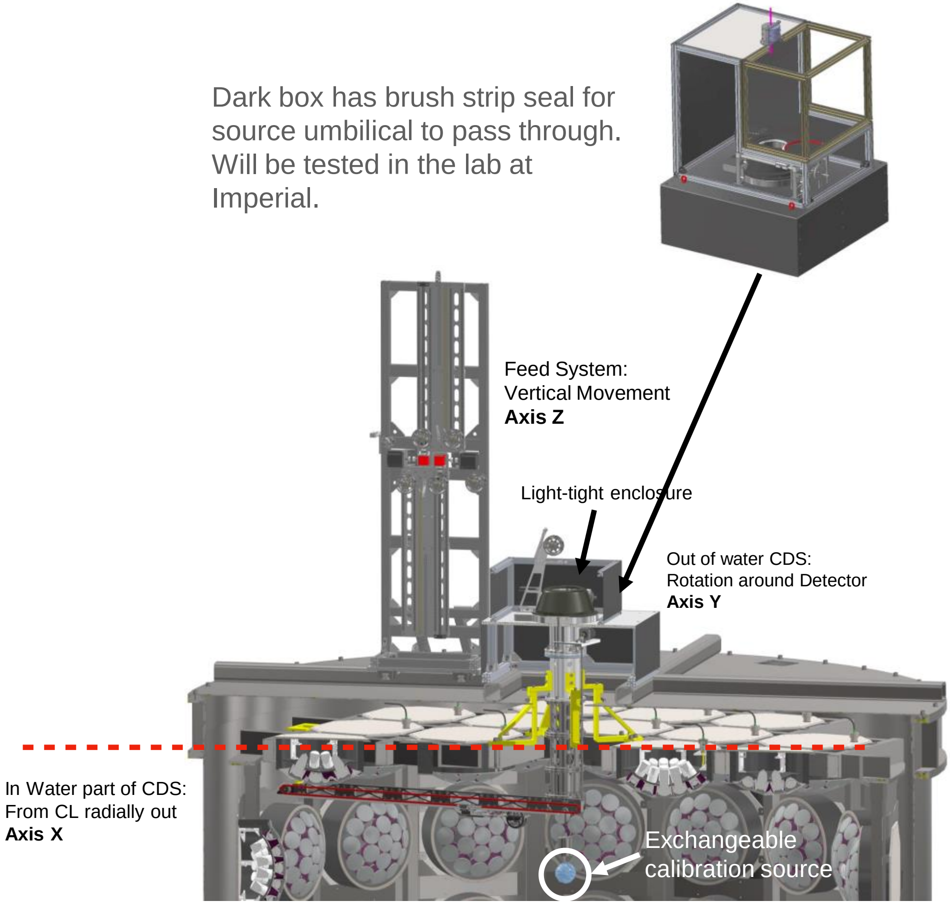


VISHWAKARMA INSTITUTES

Central Deployment System (CDS)

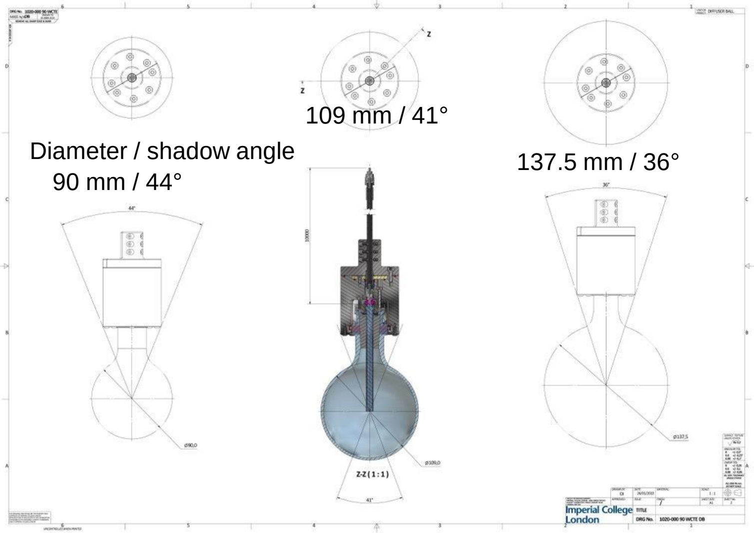
- Designed to deploy swappable calibration source
- Design and prototyping at ICL
  - Z Axis – 90% complete
    - Encoders has been fitted
    - Electronics cabinet to be added
    - The Feed system has been raised up on an aluminum frame to accommodate larger payload of the CDS
    - Perspex safety cover
  - Y Axis – 80% complete
    - Vertical shaft to be manuf.
    - Dark box to be built / small frame to raise up
    - Encoder fitted since last meeting
    - Currently being disassembled ready for anodizing
  - X Axis - 70% complete
    - Modification to arm stiffness
    - To be remade in SS316 (prototype is Al)

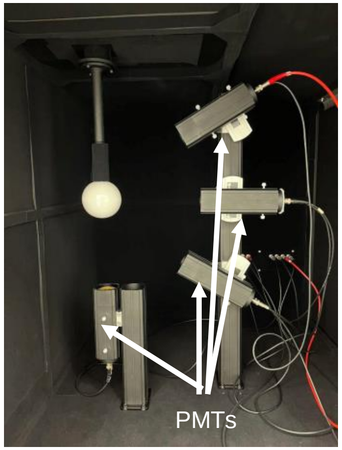
Dark box has brush strip seal for source umbilical to pass through. Will be tested in the lab at Imperial.



Laser Diffuser

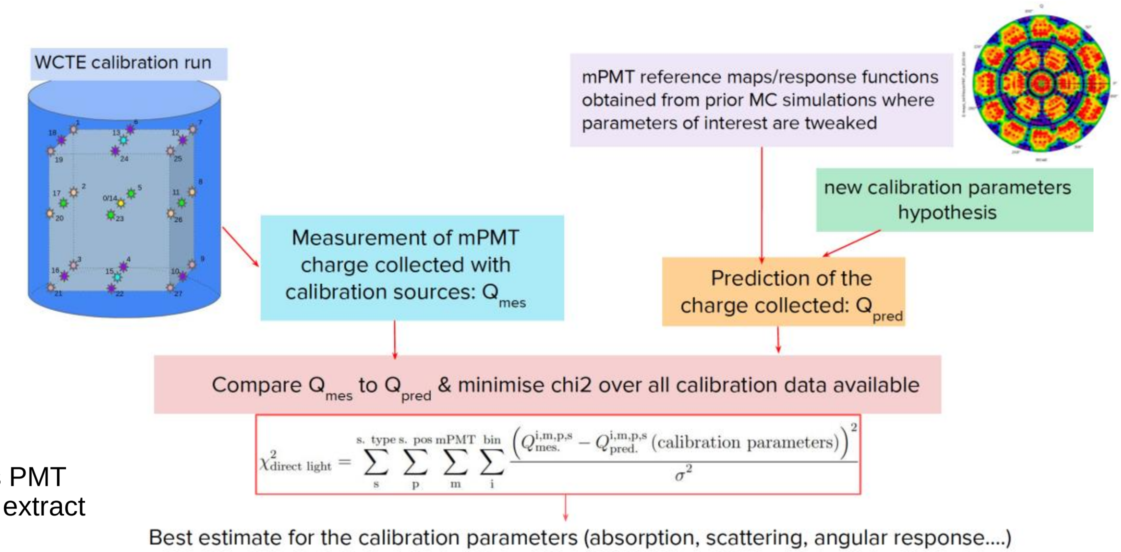
- First prototypes have been made at ICL
  - Buoyancy tests were successful; further submersion tests are needed after redesign of preload
- More prototypes with different flask diameters and variations in light guide exposure within gel will be made
- Test stand has been set up to characterize the light emission profile of the ø109 mm prototype
  - Preliminary measurements showed an inhomogeneity of less than 35%
  - Instability in current method; improvements are being made to ensure better consistency
  - Measurements with finer angular resolution will be conducted





Calibration analysis

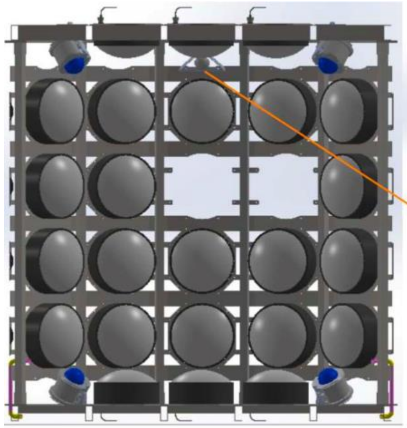
- An analysis framework is being developed to calibrate key detector parameters, including water absorption and scattering length and PMT response
  - Build a reference mPMT map by using a wide range of photon incoming angles and distances to the mPMT
  - Use the reference mPMT map to extract detector parameters
  - Currently only using the laser diffuser and only water parameters are being fitted:
    - Simulate photons shot towards the bottom end cap central mPMT from various positions in θ and Φ around the mPMT centre.
    - The distance R between the mPMT dome and the source is fixed.
    - The non-digitized charge collected over the whole mPMT is stored as a function of the source position to make an efficiency map of the mPMT.
    - The absorption and Rayleigh scattering lengths in the simulation are then varied to retrieve the mPMT response function to a change in attenuation length.

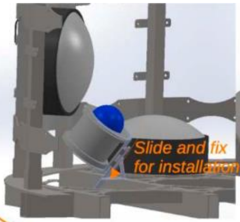


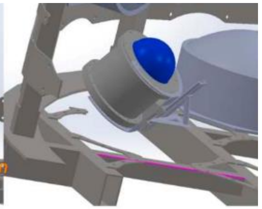
- More calibration sources and detector parameters such as PMT angular response will be implemented in the framework to extract detector parameters simultaneously

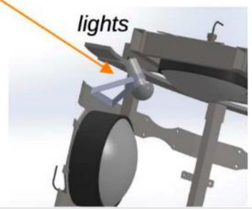
Photogrammetry

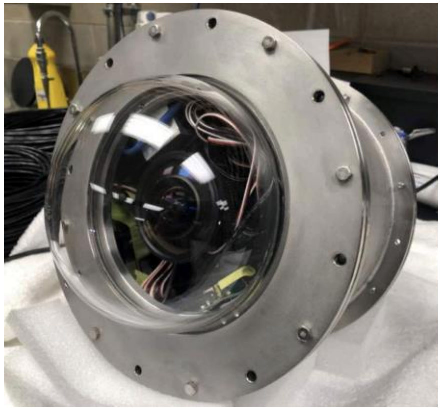
- The design of camera housing and mounting structure is finalized and procurement is ongoing
  - Camera housings will be delivered to UWinnipeg shortly
  - Purchase order for dome port and camera mounting structure in WCTE has been submitted
- Camera DAQ has been successfully operated outside housing assembly
  - Separate paths for video and control: HDMI for live-streaming video; USB for control and image capture
  - Simultaneous multiple camera views
  - Power over ethernet to power all electronics including camera
- Camera housing will be assembled and tested at UWinnipeg
- Camera calibration after assembly will be conducted at a dedicated dark pool facility at UWinnipeg before shipment to CERN





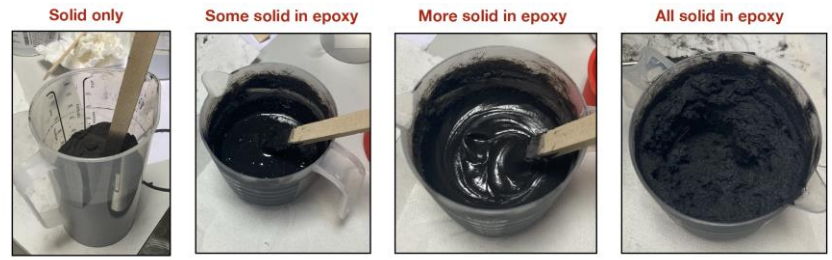


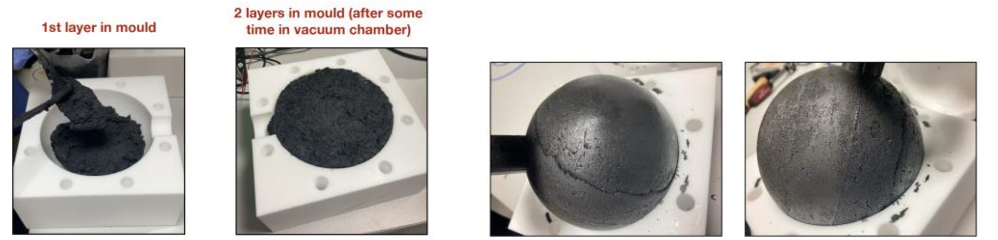


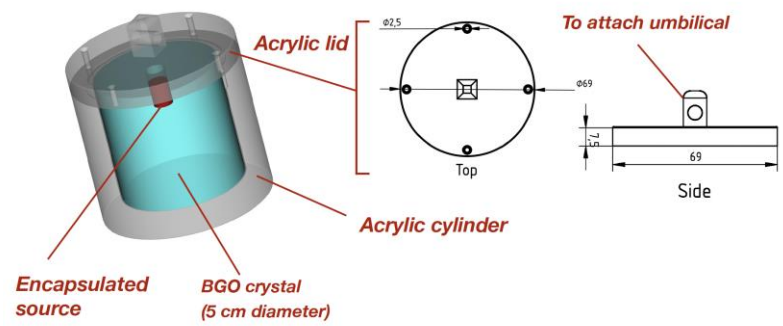


Radioactive source

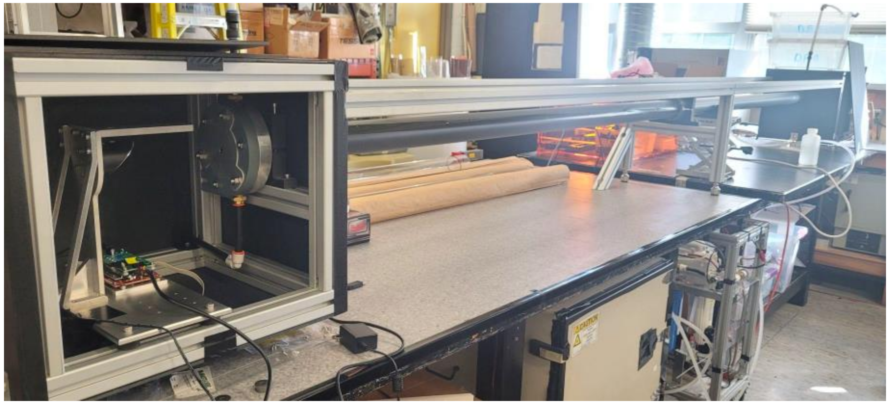
- NiCf source:
  - First attempt at a prototype source for WCTE has been carried out
  - Work on this prototype continues
    - Prototype sent to a company for machining (smoothing surface, drilling hole for rod): initial results show improved surface
    - Mixture test performed with some of remaining material; additional material ordered for future prototypes
- AmBe source:
  - Continuing with simulation studies
  - Prototype construction for WCTE will start soon
    - Quote requests for PMMA bar and BGO crystals have come back
- Simulation studies of both sources are ongoing



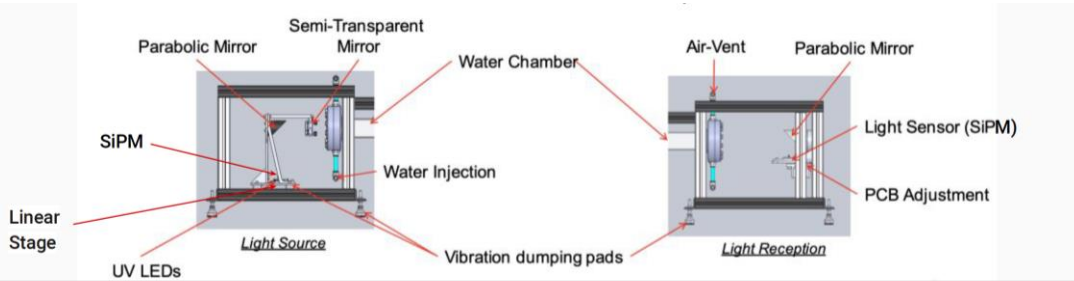


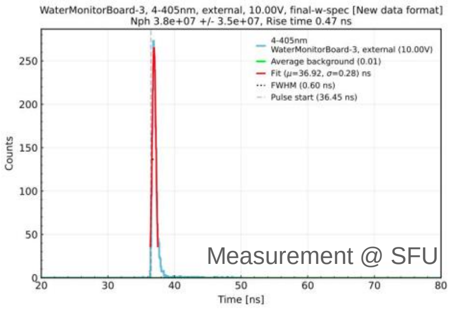


Water monitoring



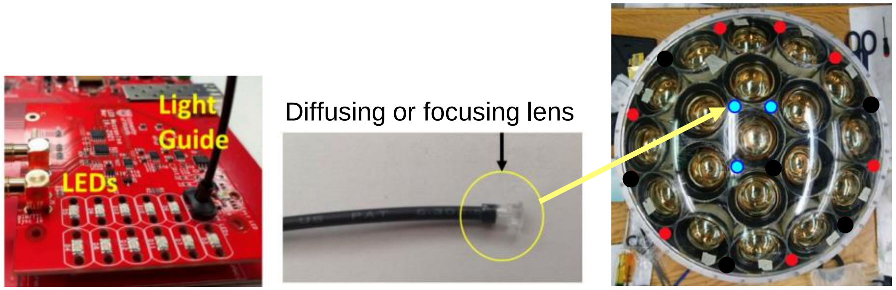
- The first mechanical prototype has been built and operated with the water circulation system at TRIUMF. The optical components are being installed in the prototype
  - Initial alignment study is successful
  - Improvements are being made
  - This prototype will be delivered to CERN and used by WCTE
- The performance of the fast pulsed LEDs has been evaluated
  - < 1 ns FWHM throughout the wavelength range (235 nm to 470 nm)

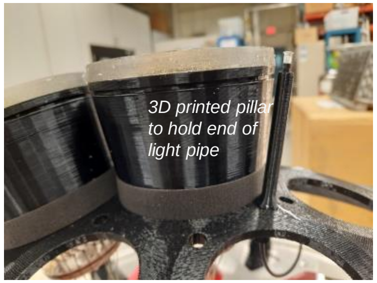


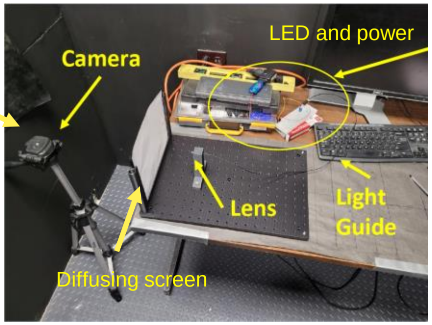


mPMT LEDs

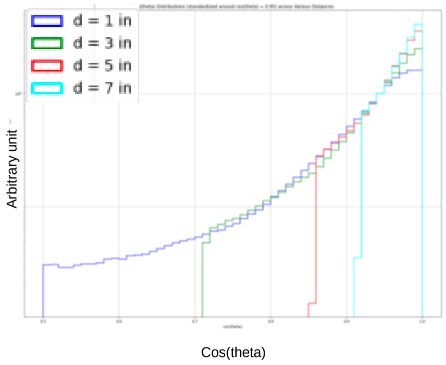
- Each mPMT module will contain 6 continuous LEDs as photogrammetry target and 3 fast pulsed LEDs for in-situ detector calibration
  - The same LED driver with sub-nanosecond pulses as the water monitoring system will be used
  - LEDs are coupled to light pipes to bring light to the front
- A framework has been developed to characterize the light emission profile of light pipes
- The selection of light pipes will be finalized and purchase order will be placed soon
- Calibration study using the 3 fast LEDs is ongoing





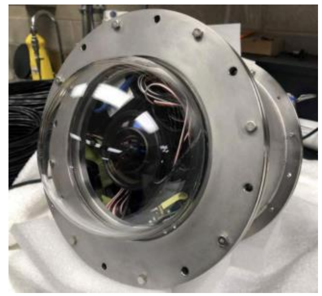


Distance between lens and diffusing screen



Central Deployment System Prototype

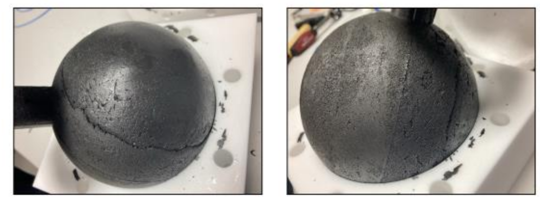
Photogrammetry Prototype



Diffuser Ball Prototype

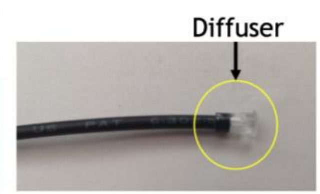
Water Purity Monitoring System Prototype

Nickel Oxide Ball for NiCf Gamma Source



LED Light Sources Inside the multi-PMT Module

Diffusing or focusing lens



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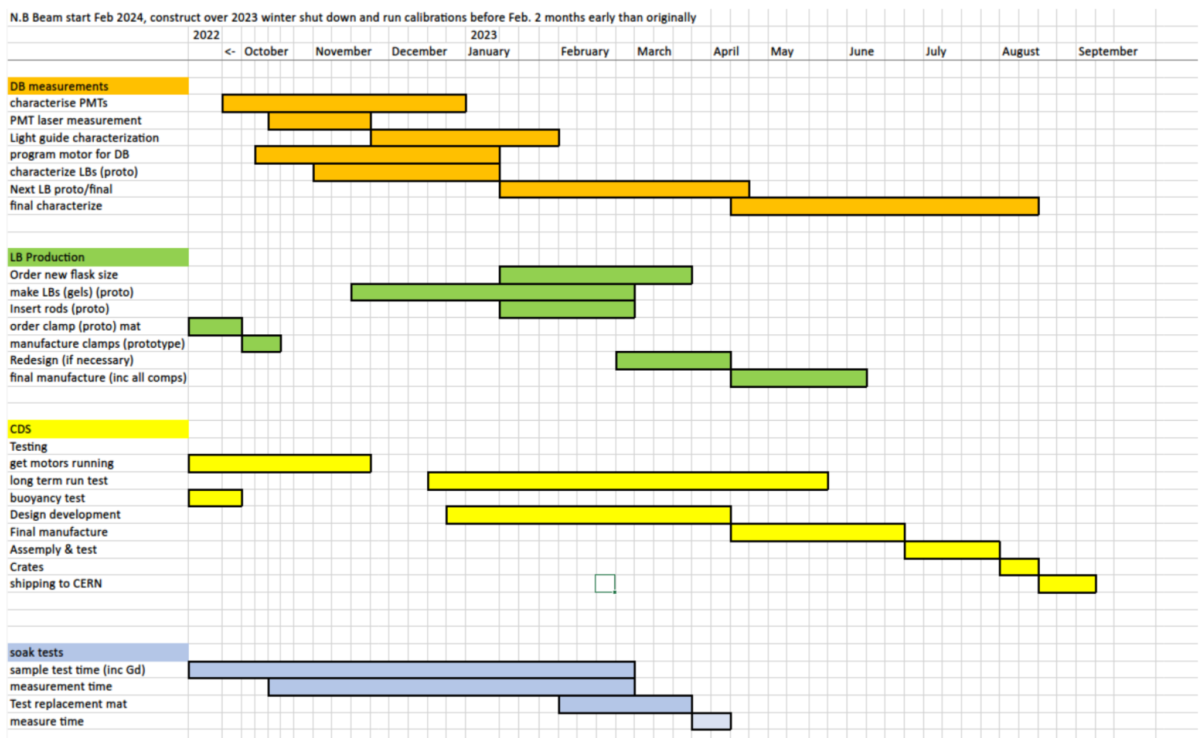
CDS
03/03/23

CDS System Timeline for WCTE



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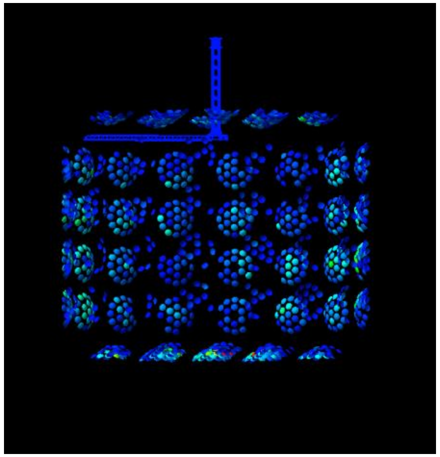
Simulation and reconstruction studies

- Large contributions to improving simulation and providing easier install for users

- First release of WCTE software container successful – L.Anthony
  - Positive feedback along with useful user inputs
  - Plan to release v2 with updated simulation package

- WCSim – N.Prouse, P.de Perio, L.Anthony
  - Updated geometry and CAD import – L.Anthony
  - Updated with many bug fixes and improvements
  - Updated photocathode model for more accurate simulation of mPMTs – K.M. Tsui, X.Li
  - Fix black sheet issues
  - Better construction of detector layout and mPMT placement
  - Update to root6 and GEANT4...... whilst still remaining back compatible



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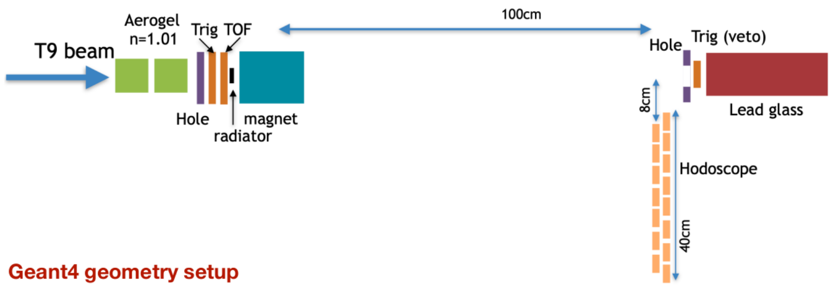
Physics and reconstruction

- Electron nucleon scattering studies using GEANT4 – L.Cook
- Tagged photon beam studies for WCTE test beam – J.Renner

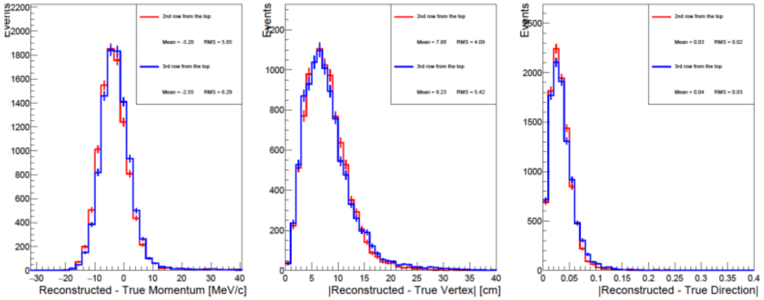
- **Tagged γ beam (Eγ = 0.25-0.55 GeV), from Akira (WCTE collaboration meeting Jan. 2023)**



- **Geant4 geometry setup**

- Beam window studies with fiTQun – Y.Alj Hakim

FiTQun reconstruction comparison 16c-4r geometry
150 MeV muons



- Differences in the reconstruction between these two beam start positions are observed.
- We can notice a small increase in the RMS of the vertex resolution and momentum resolution distributions in the 3rd row configuration

Y. Alj Hakim 4

- FiTQun tuning and reco improvement – N.Prouse, L.Anthony, G.Diaz, R.Matsumoto
- Calibration analysis fitter – A.Craplet