

TOF mechanics

17th July 2026

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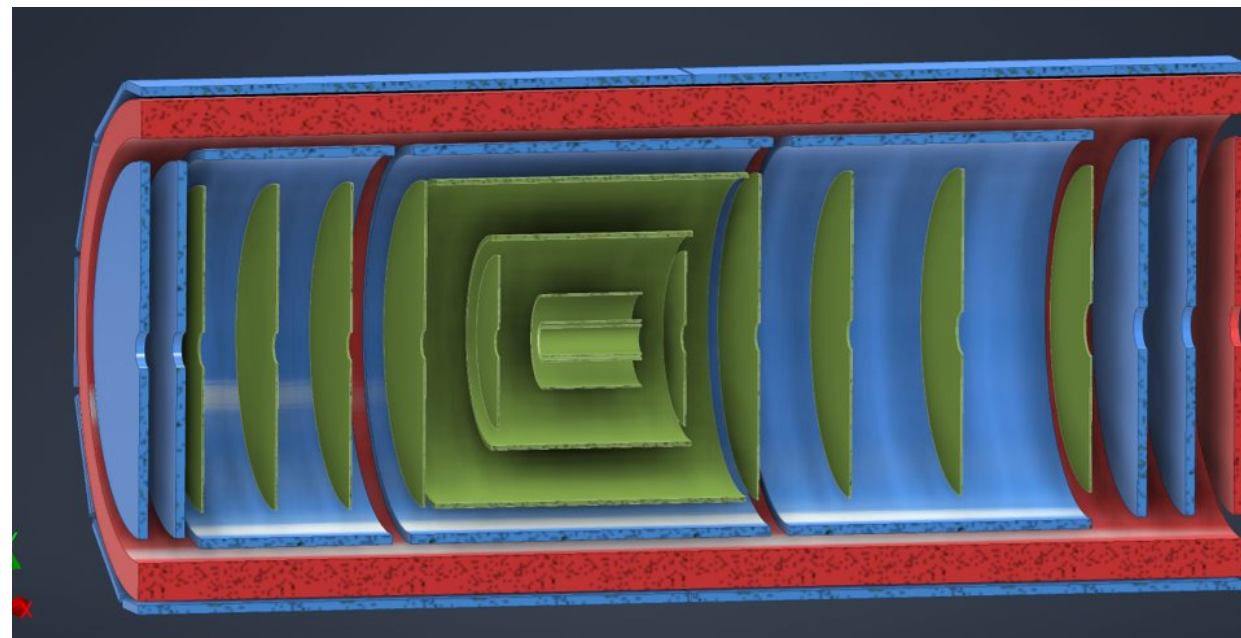
EPIC collaboration meeting

Part of the slides and design of CMS supports and global mechanics are credited to the CMS tracker mechanics team!



- Design of supports for inner detectors depends on support hierarchy and detector “integration” and assembly
 - Defined at the EPIC Mechanics workshop in May 2024
- Naturally, supports and interfaces are as light-weight as possible but services and “cooling” needs space and need to be considered
- Nomenclature: large global inner detector CF support tube or GST
- Lets first look at an integration sequence of “**inner detectors**”

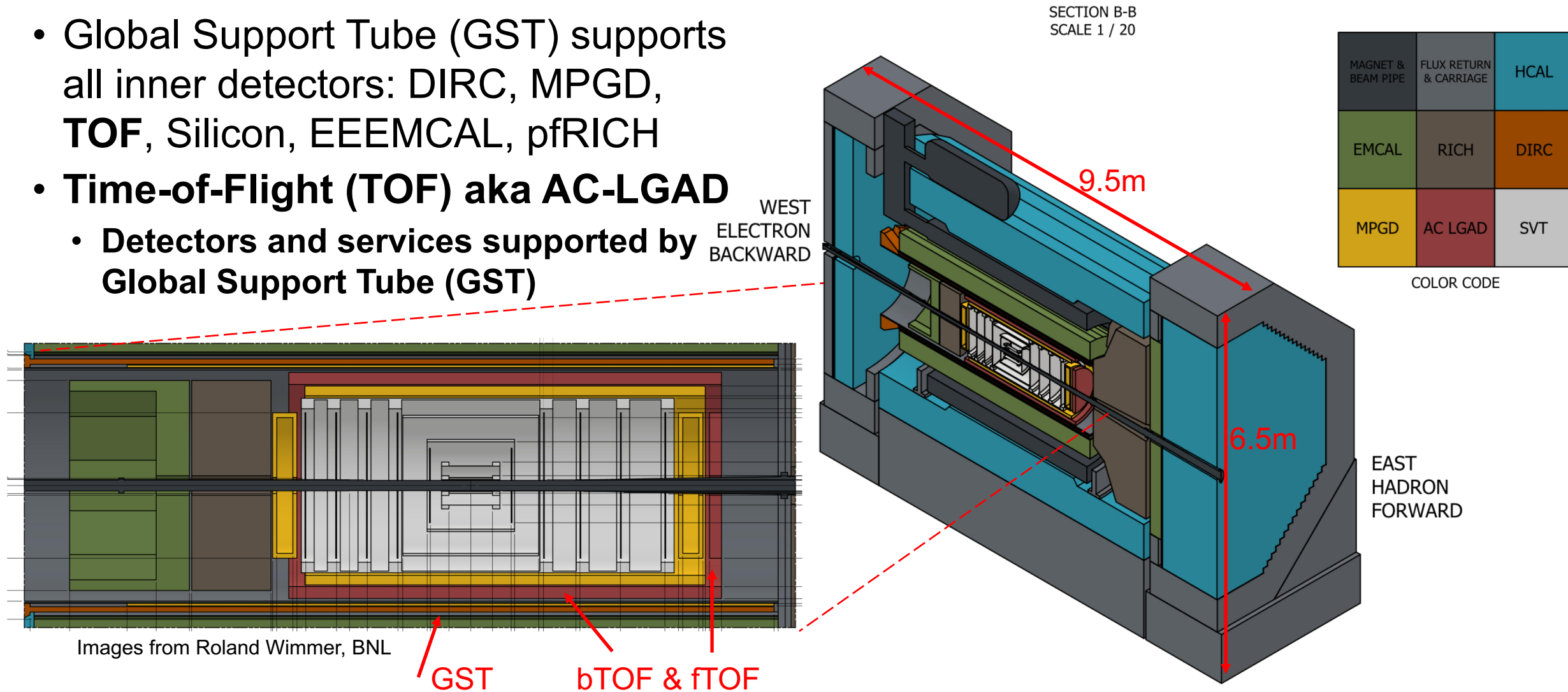
“Inner detectors” = inside of the large global CF support tube



Introduction to Support Structure

Charge 1, 2

- Global Support Tube (GST) supports all inner detectors: DIRC, MPGD, TOF, Silicon, EEEMCAL, pfRICH
- **Time-of-Flight (TOF) aka AC-LGAD**
 - Detectors and services supported by Global Support Tube (GST)

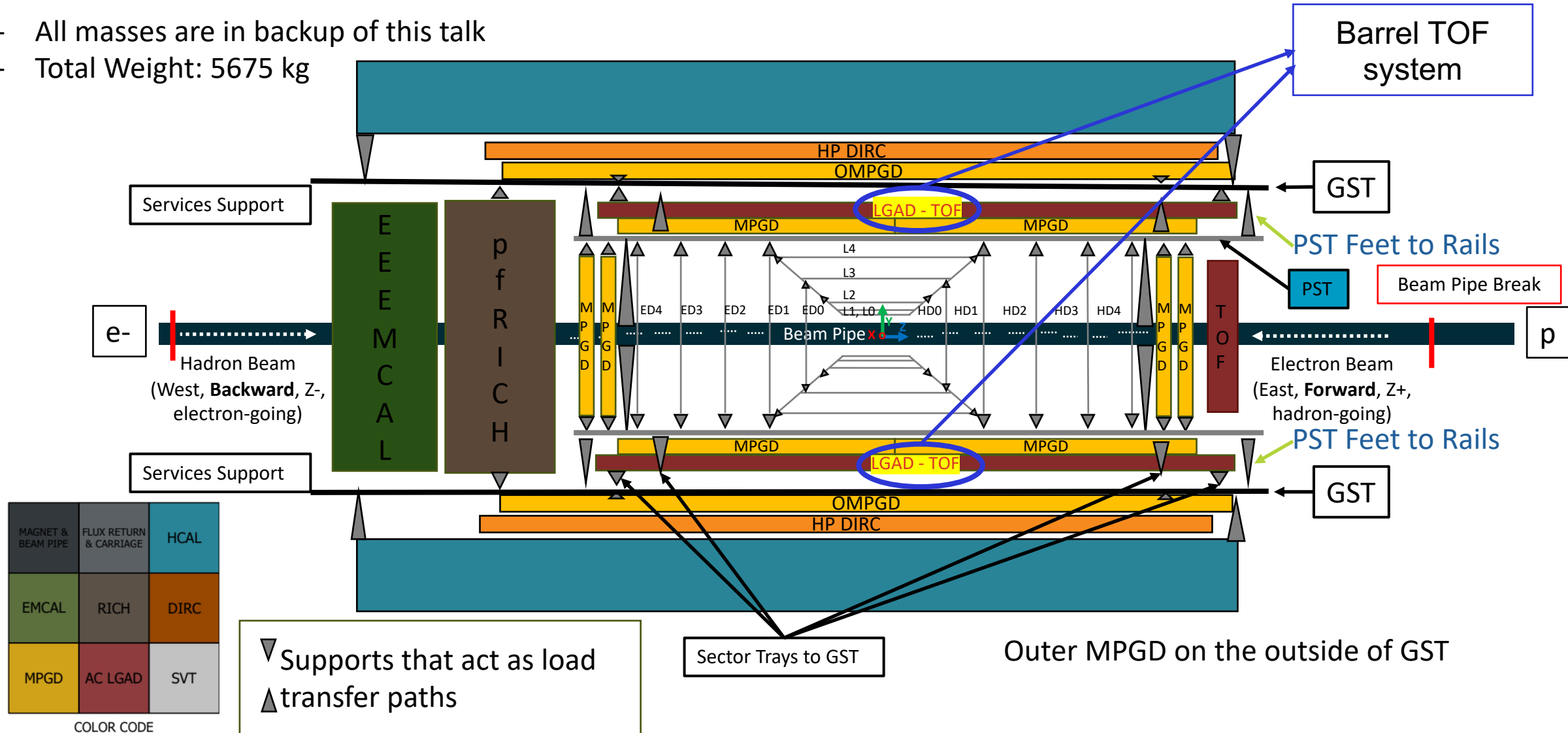


Inner Detector Support Hierarchy Y-Z View – current!

NOT TO SCALE – this is a Powerpoint sketch!

Charge 1, 2

- All masses are in backup of this talk
- Total Weight: 5675 kg

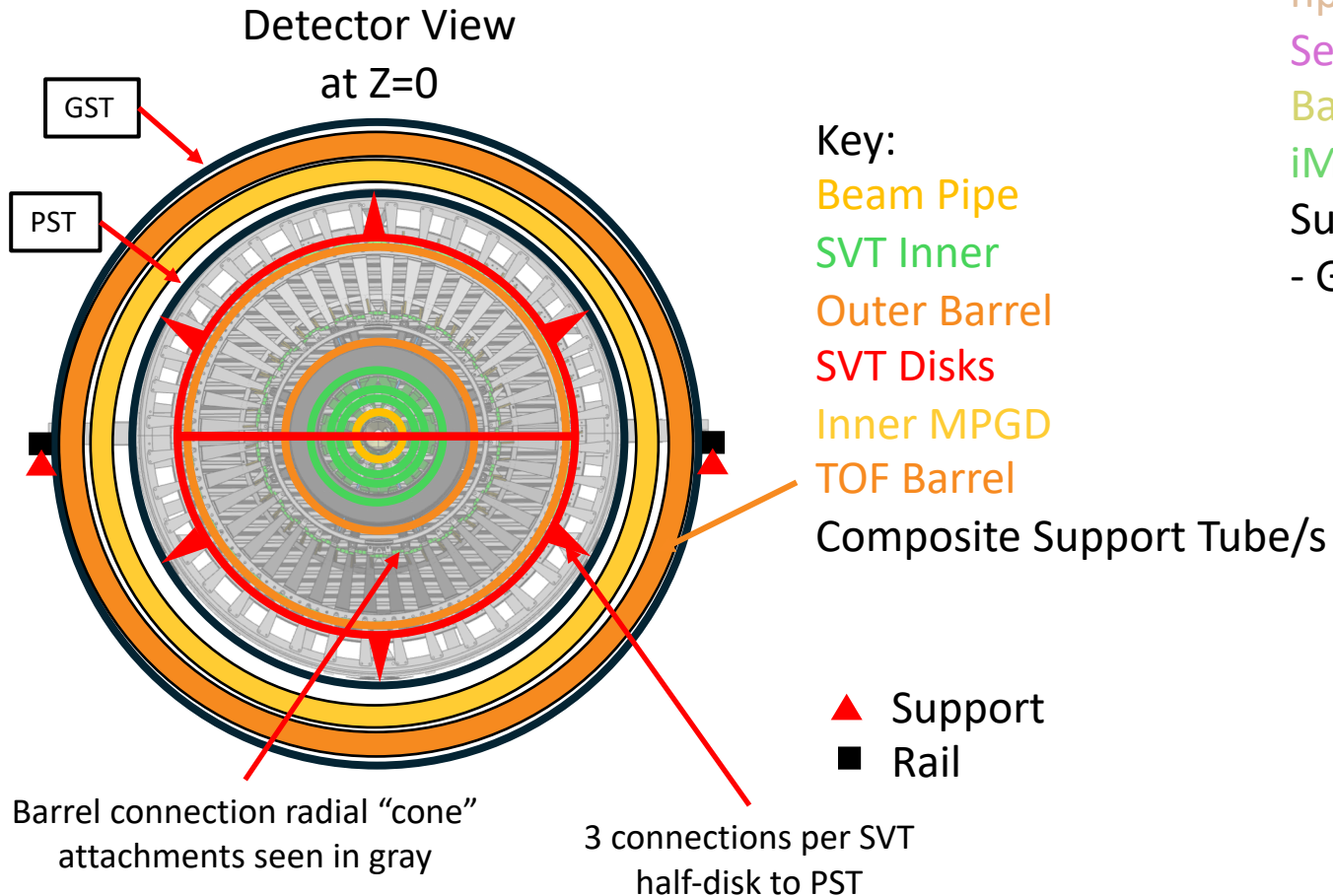


Inner Detector Support Hierarchy X-Y View - Oct 2025

NOT TO SCALE – this is a Powerpoint sketch!

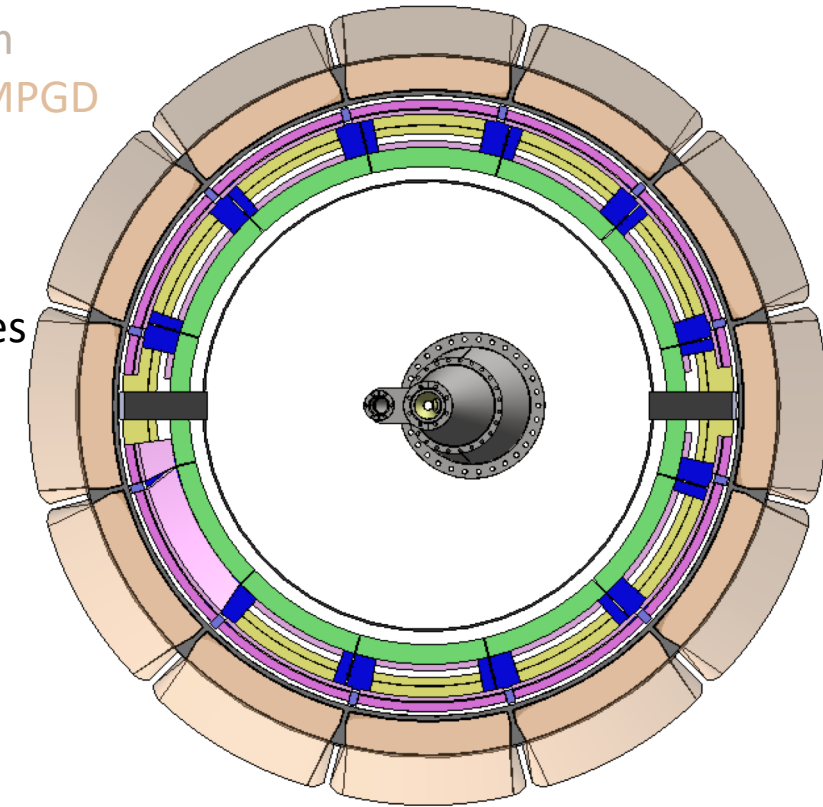
Charge 1, 2

To ease maintenance and integration the inner detectors (TOF, i- and o-MPGD) follow a 30 degree segmentation!



Key:

- hpDIRC Prism
- hpDIRC & oMPGD
- Services
- Barrel TOF
- iMPGD
- Support tubes - GST & PST



GST supports (provides adjustability)

Beampipe support plates via PST

Presentation Section 1: TOF-LGAD mechanics (supported by GST)

TOF Sub-Systems

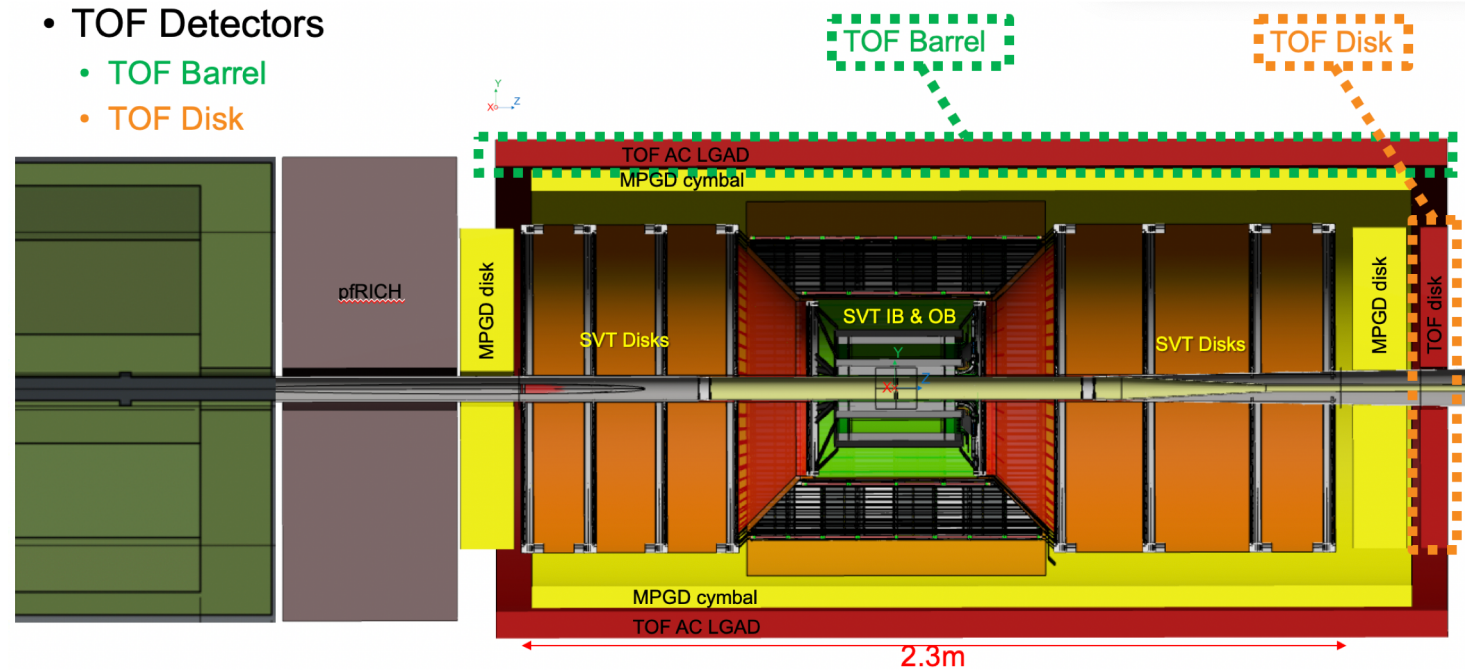
To ease maintenance and integration the inner detectors follow a 30 degree segmentation!

Charge 1, 2

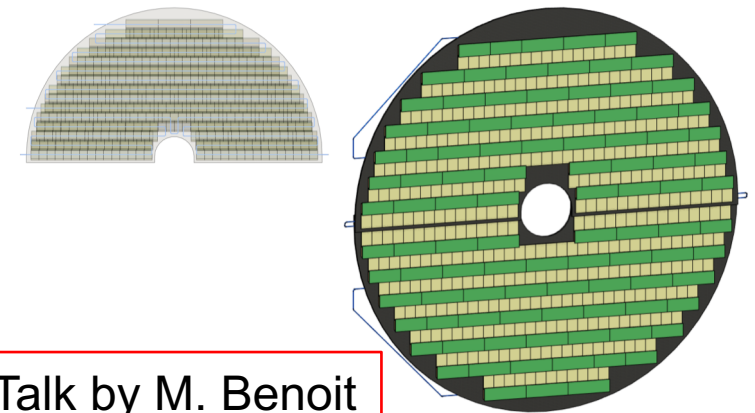
- TOF detector provides particle ID for EPIC
- Consists of AC-LGAD's
- Barrel “stavelet” base unit
 - 60mm wide, 160mm long
 - 2 x (7+1) stavelets per half-stave of 1280mm (z+-)
 - 7 stavelets are sensor stavelets
 - 1 “stavelet” space is used as service hybrids and power boards

→ 288 half staves yields 4608 stavelets

- TOF Detectors
 - TOF Barrel
 - TOF Disk



- Forward TOF (disc)
- Sandwich structure with cooling pipes
- Kinematic mount to PST - GST



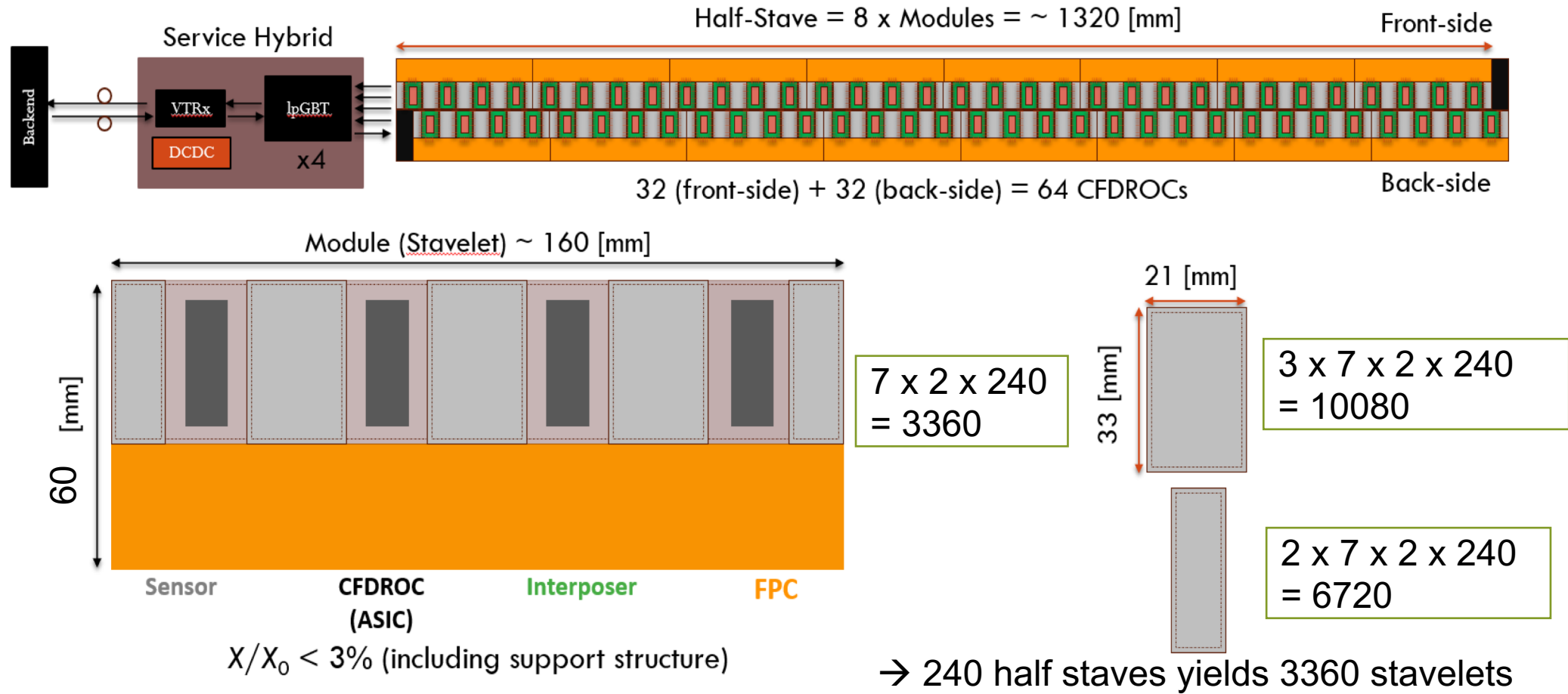
fTOF: Talk by M. Benoit

A bTOF “module”

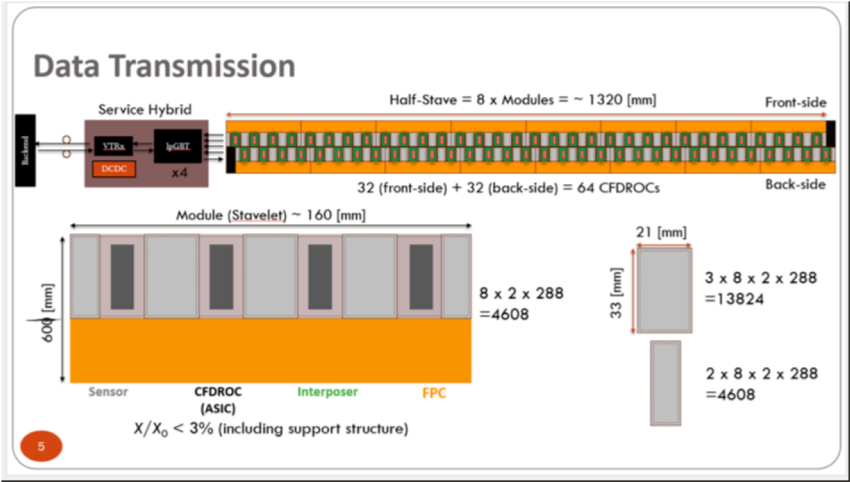
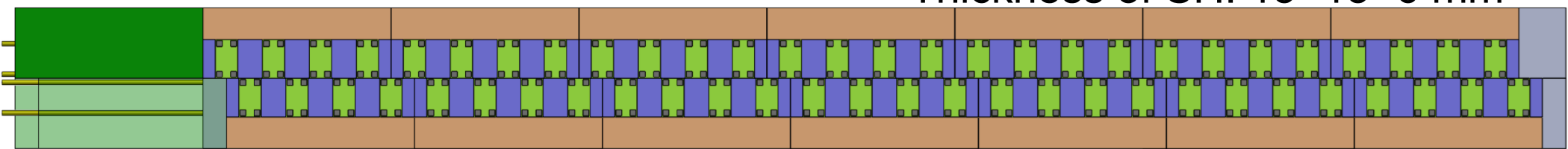
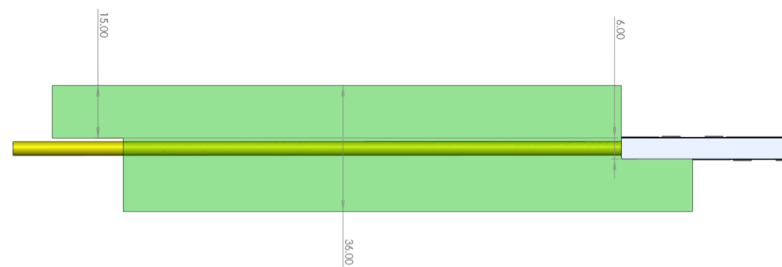
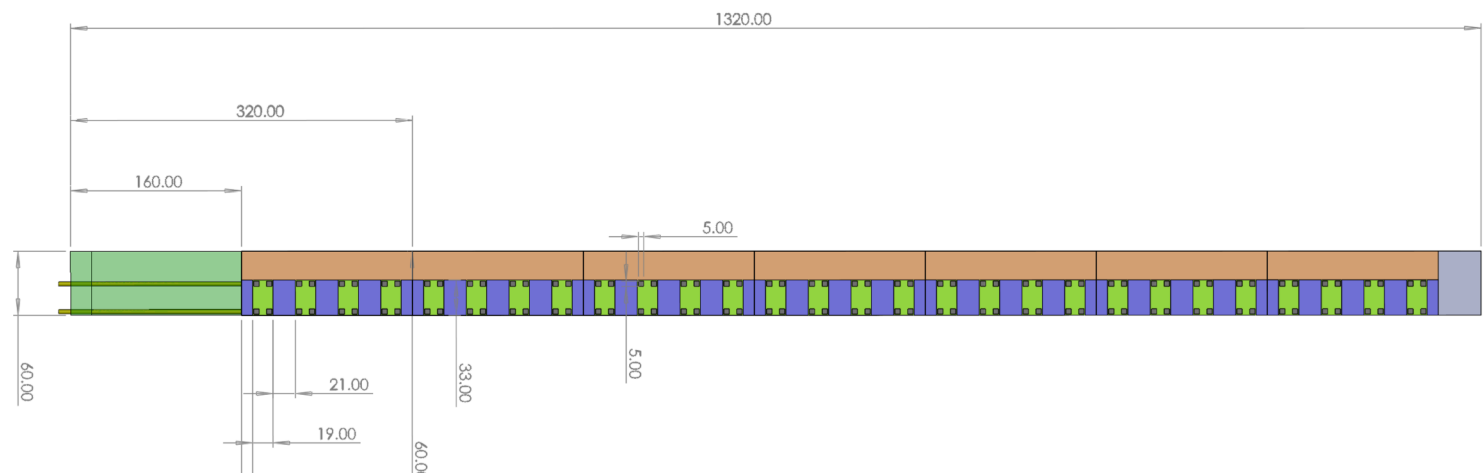
To ease maintenance and integration the inner detectors follow a 30 degree segmentation!

Charge 1, 2

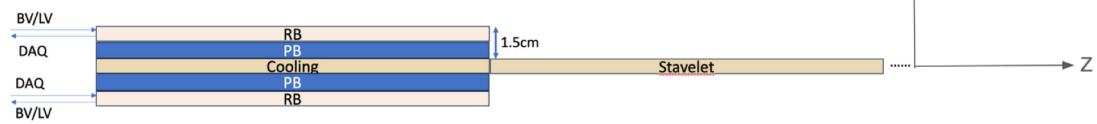
- Barrel “stavelet” base unit
 - 60mm wide, 160mm long



CAD drawings



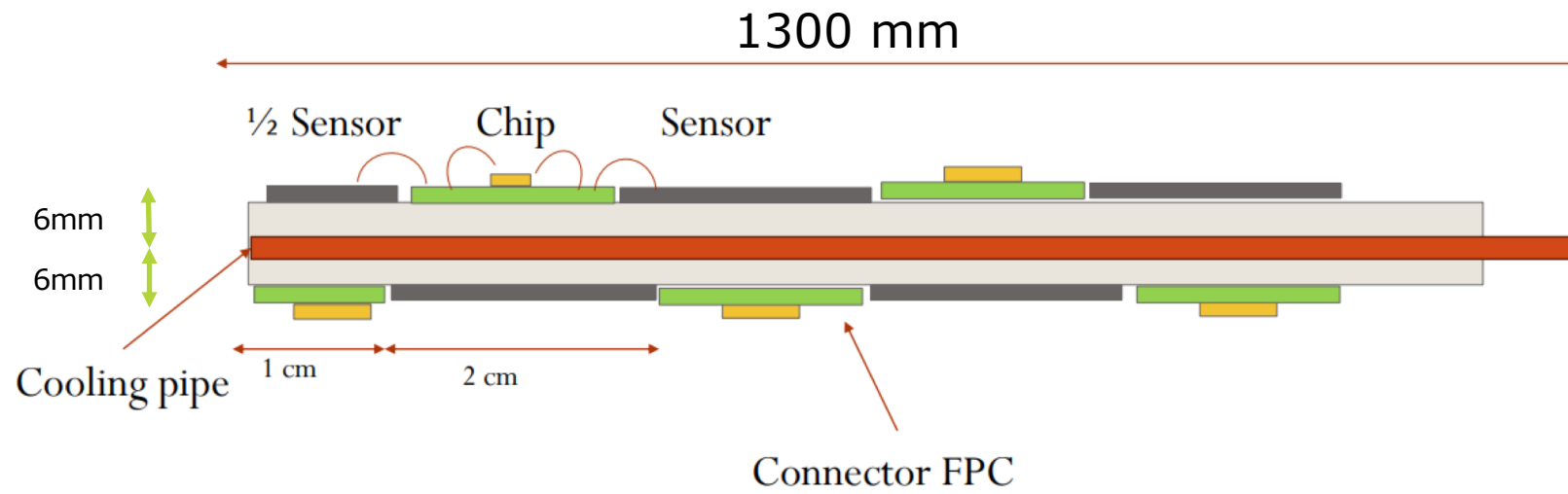
Barrel TOF service hybrids - design (Rice/BNL)



Thickness of SH: 15+15+6 mm

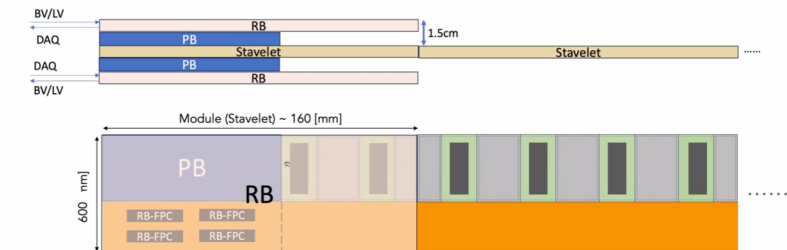
bTOF module mechanics

- The staves assembly does not fit in the given envelope of R625 to R700 mm for barrel TOF with the services with the current layout of the trays.
- Proposed support layout shown in the next slide
- Combination of the cooling manifold services on bTOF and Cymbal saves space.
- bTOF mounting mechanism inspired by ATLAS



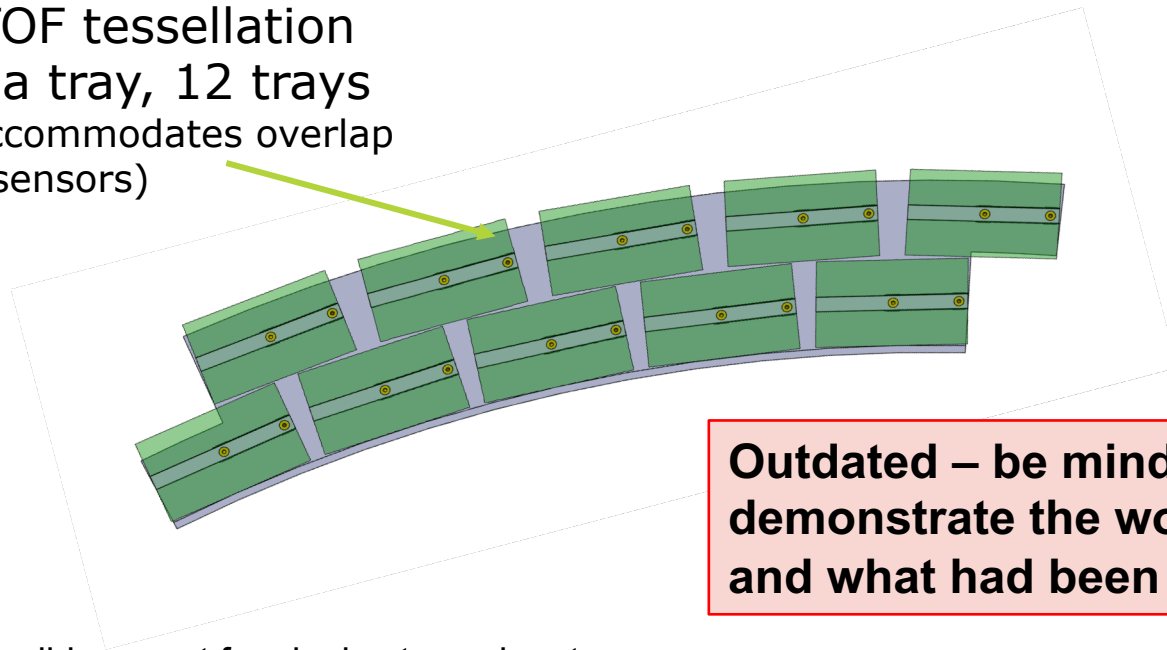
Barrel TOF service hybrids - current design

- Place SHs at the end of each half-stave, on both faces:
- PB mounted on the cooling structure, while RB on the top
 - Each RB+PB serve 32 ASICs+Sensors on one face of a half-stave



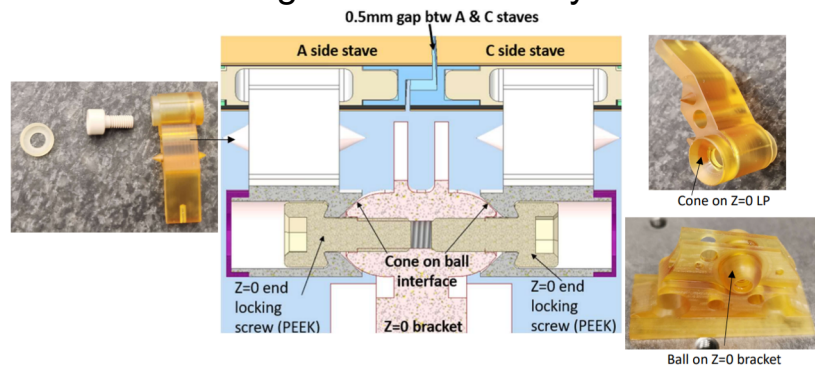
bTOF stave mounting in bTOF tray

bTOF tessellation
in a tray, 12 trays
(Accommodates overlap
of sensors)

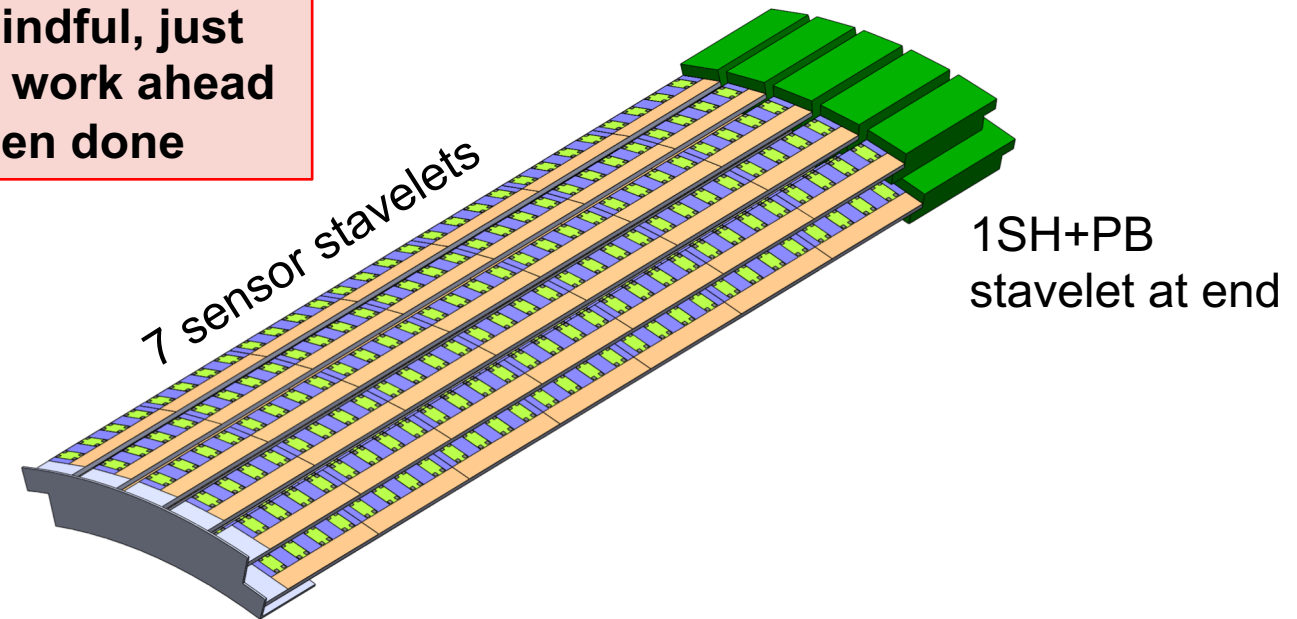


Outdated – be mindful, just demonstrate the work ahead and what had been done

Possible mount for single staves in a tray:



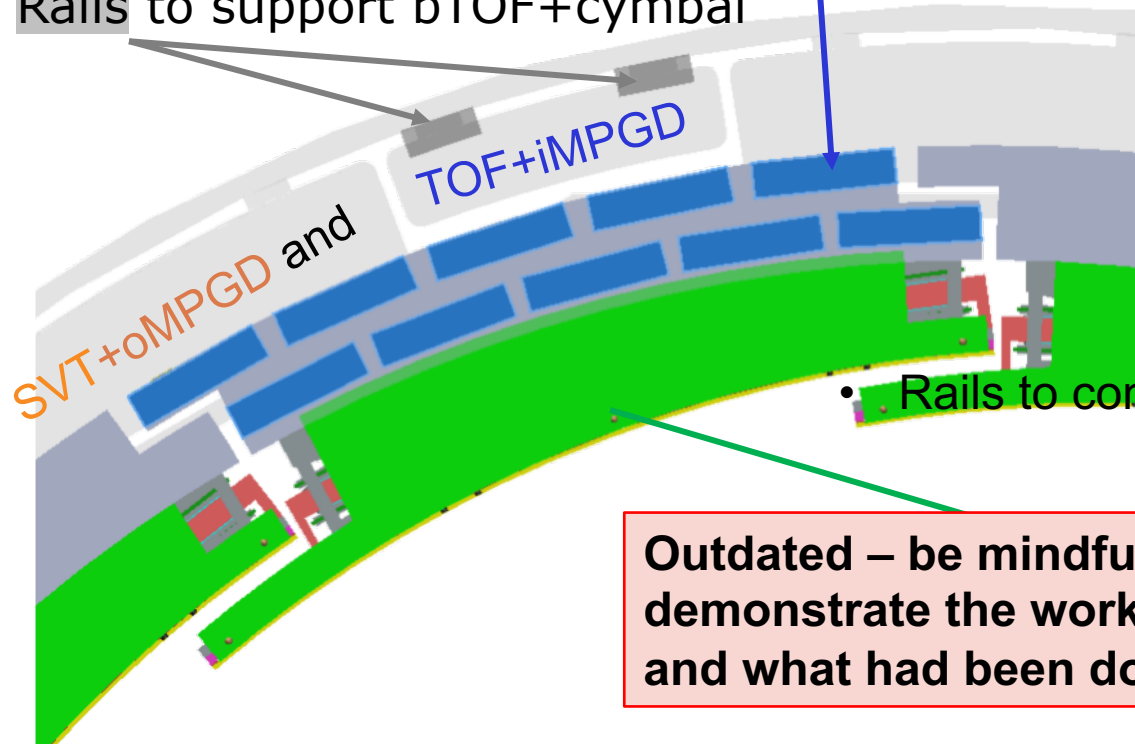
- Individual staves mounted into a bTOF tray for kinematic support (no stress)
- bTOF tray mounts staves into a single object to ease installation & maintenance



◉ Inspired by ATLAS - <https://cds.cern.ch/record/2899769/files/ATL-ITK-SLIDE-2024-127.pdf>

bTOF stave joined with a cymbal tray to form a “supertray”

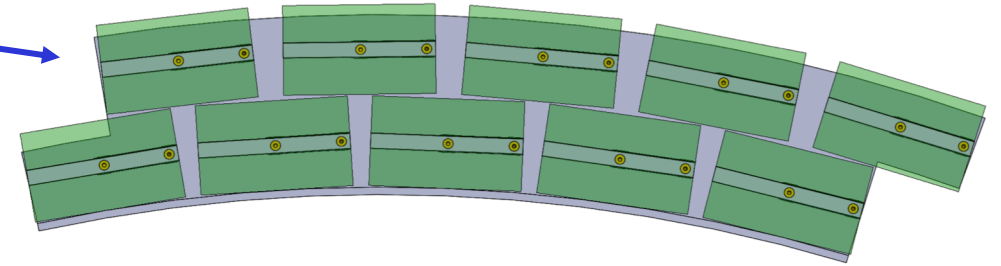
- bTOF tessellation in a tray, 12 trays
(Accommodates overlap of sensors)
- Rails to support bTOF+cymbal



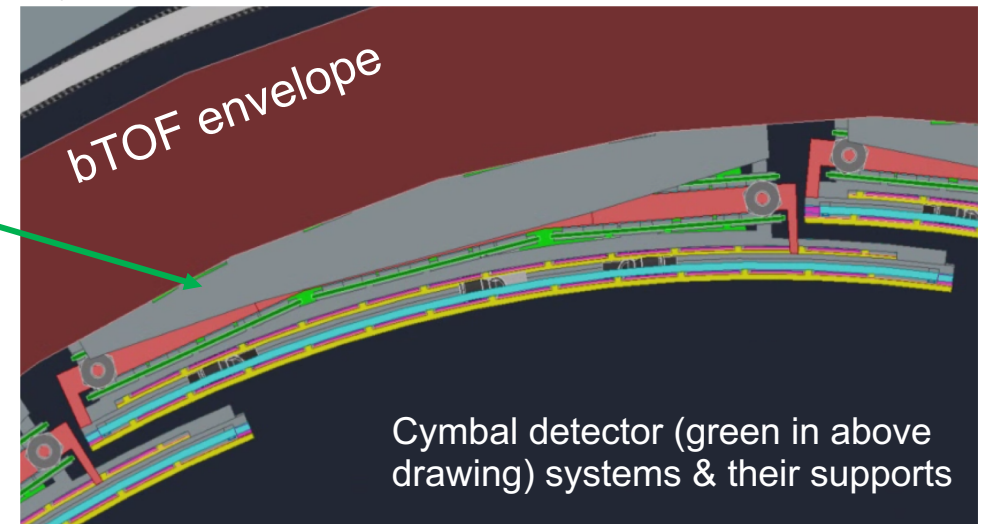
Outdated – be mindful, just demonstrate the work ahead and what had been done

- Other solidly filled areas (light gray) are “reserved” for service of SVT+oMPGD and TOF+iMPGD

bTOF tray as single object



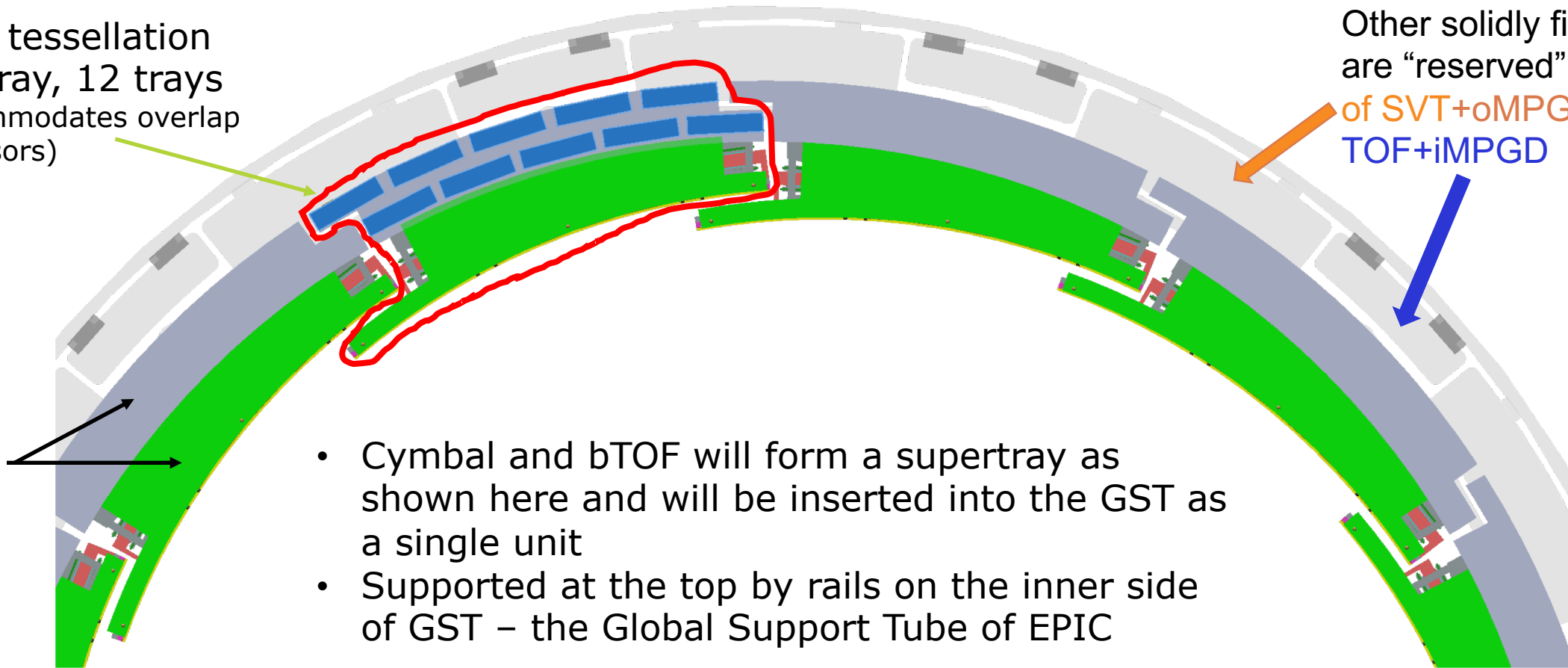
Cymbal detector tray as single object is



bTOF+cymbal “supertray” mechanical support structure

bTOF tessellation
in a tray, 12 trays
(Accommodates overlap
of sensors)

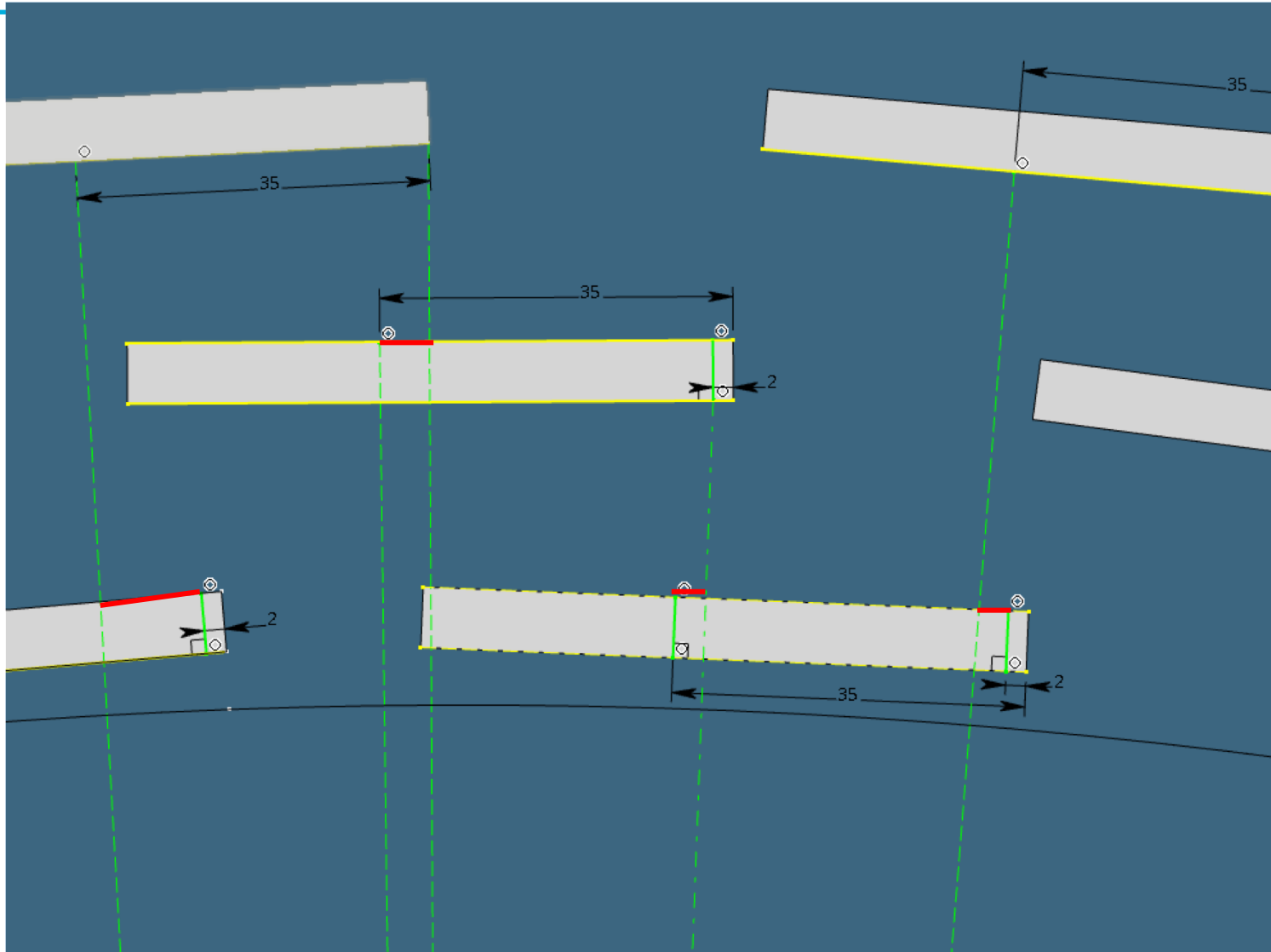
Other solidly filled areas
are “reserved” for service
of SVT+oMPGD and
TOF+iMPGD



- Cymbal and bTOF will form a supertray as shown here and will be inserted into the GST as a single unit
- Supported at the top by rails on the inner side of GST – the Global Support Tube of EPIC

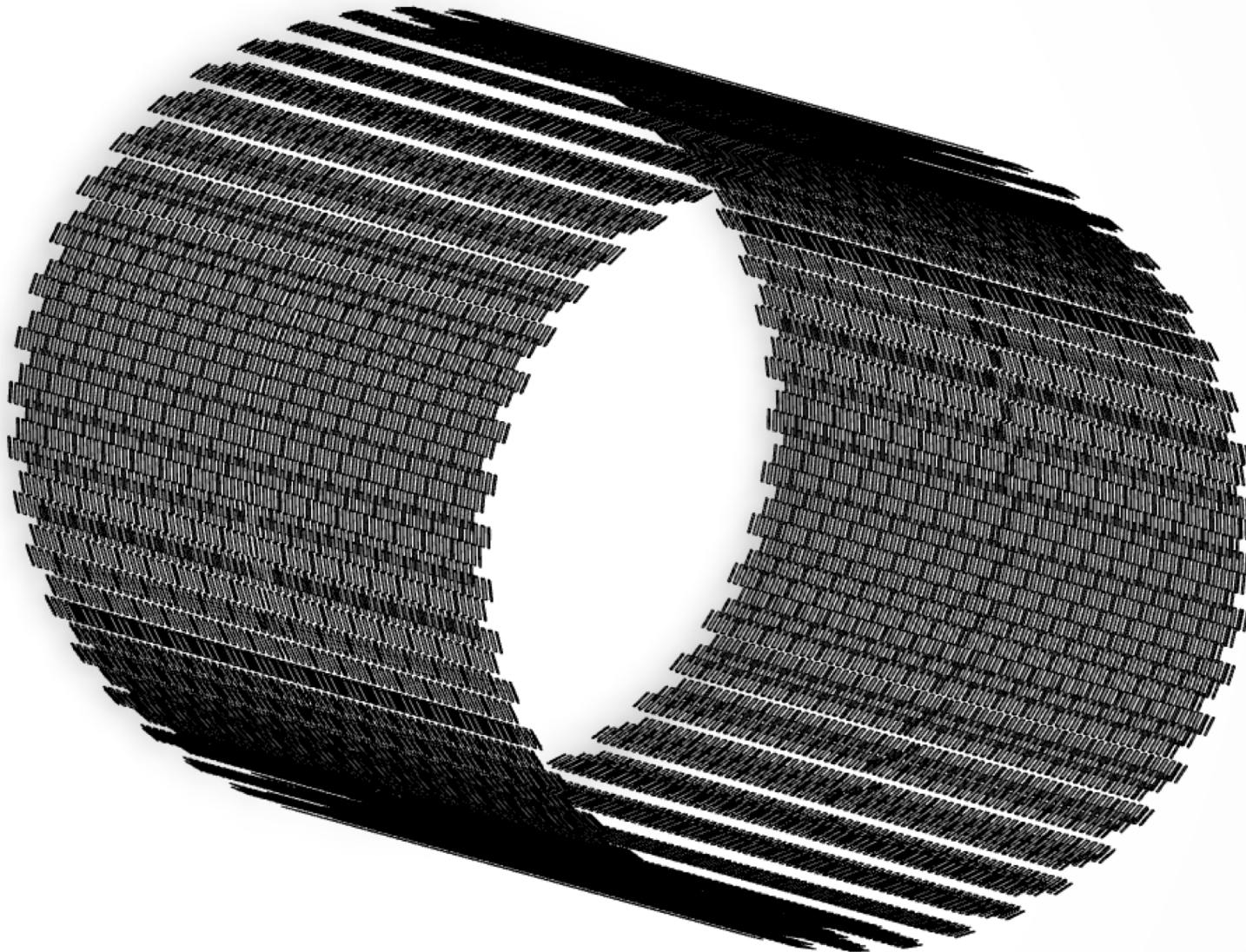
**Outdated – be mindful, just
demonstrate the work ahead
and what had been done**

Resolving issues – Updates since review: Sensor Overlap

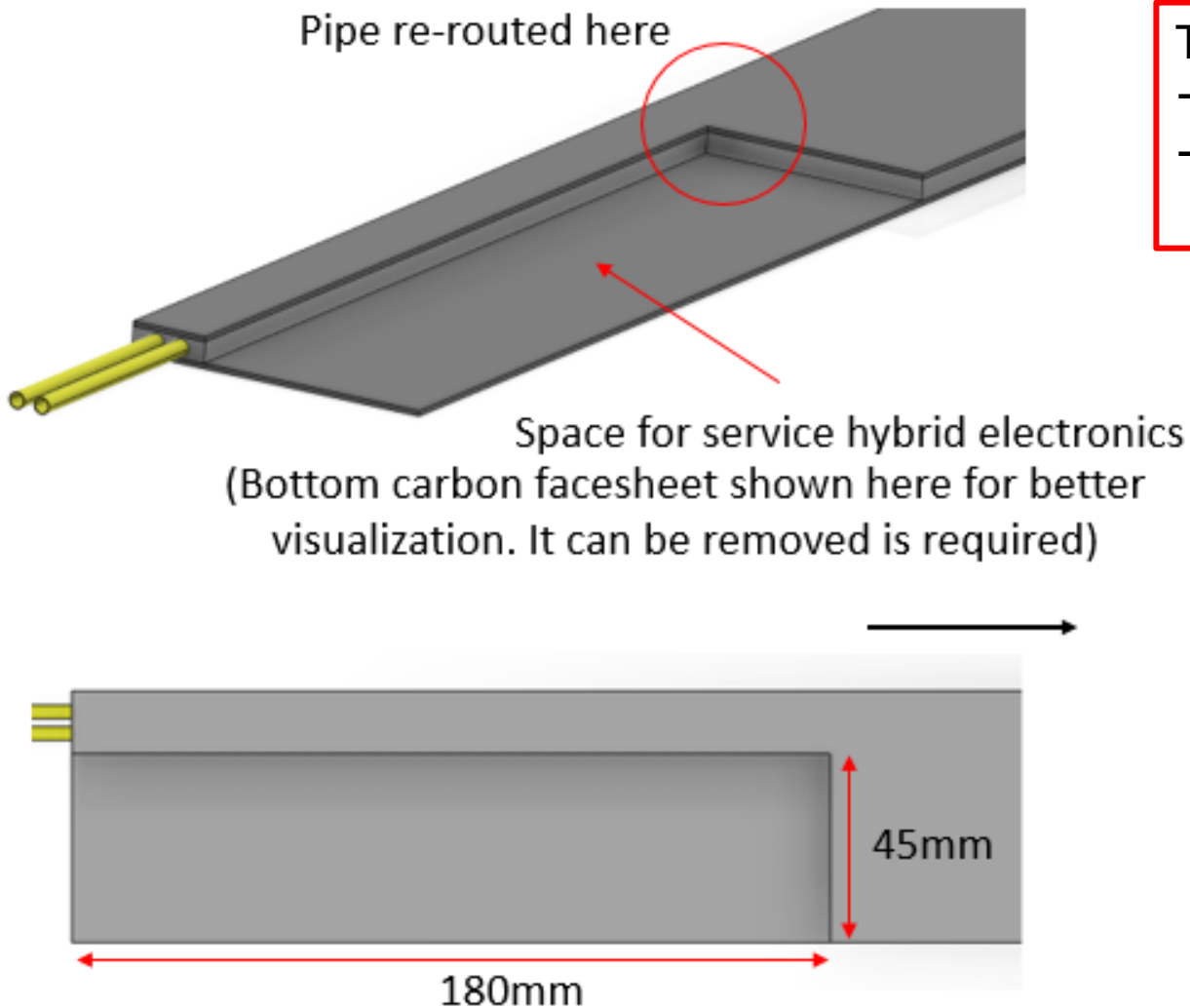


- There is a minimum overlap of 3mm in R-φ (overlap in red)
- The staves are placed in 3 rows/layers each being 25mm above one another
- The angular spacing is of 7.84° between each stave of each row
- All the staves are tangent to the pitch circles, hence reduction in complexities

Resolving issues – Updates since review: Sensor Overlap



Stave with Service Hybrid – Concept



Tight space/Clash in service hybrid region:

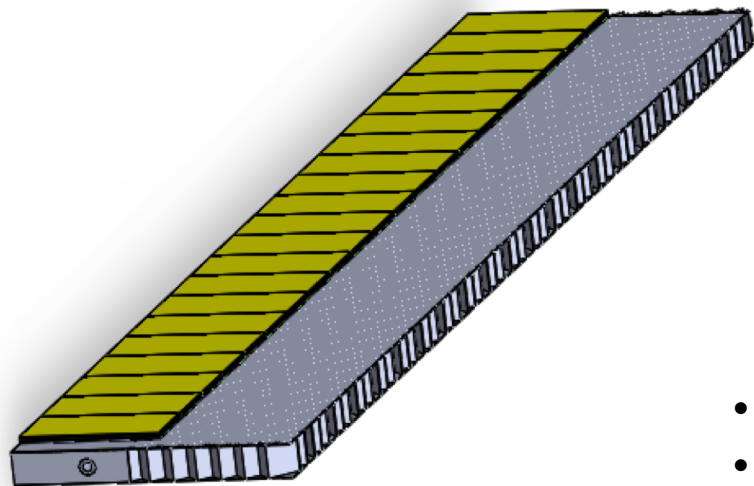
→ 15mm high SH design x3 is problematic!

→ Our proposal: thin down the stave and rely on single layer of CF substrate

- ⦿ A proposed concept for placement of service hybrid to reduce the overall stave thickness and maintain radial clearance in bTOF.
- ⦿ Cooling pipe can be re-routed to ensure space for electronics at the end of the stave.

Presentation Section 2: Stave design & thermal FEA

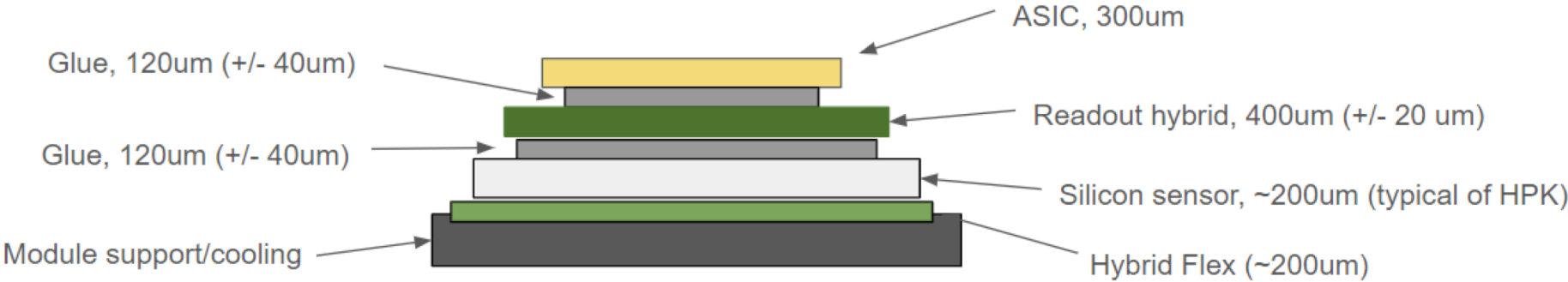
bTOF: stave design



- The below is individual material X_0 numbers so a track needs to **hit all of these to "see" $\sim 7\% X_0$**

Case	Cfoam 6 mm	2× K13D2U facesheets	Pipe walls	Water	Total
Steel pipe + water	0.28%	0.15%	5.68%	0.83%	6.94%

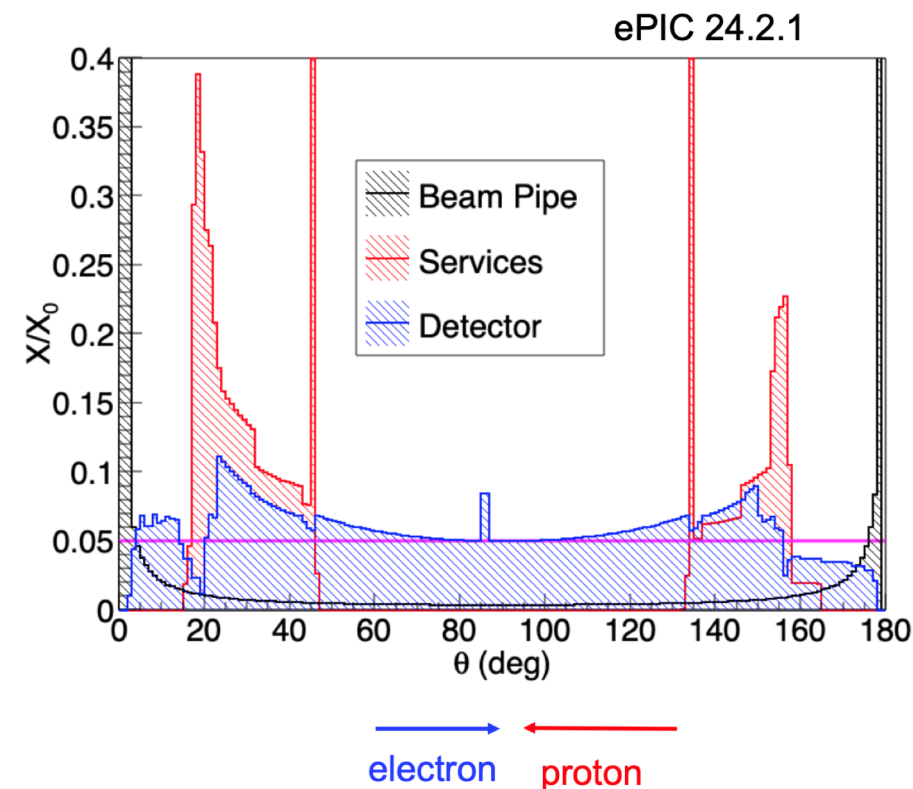
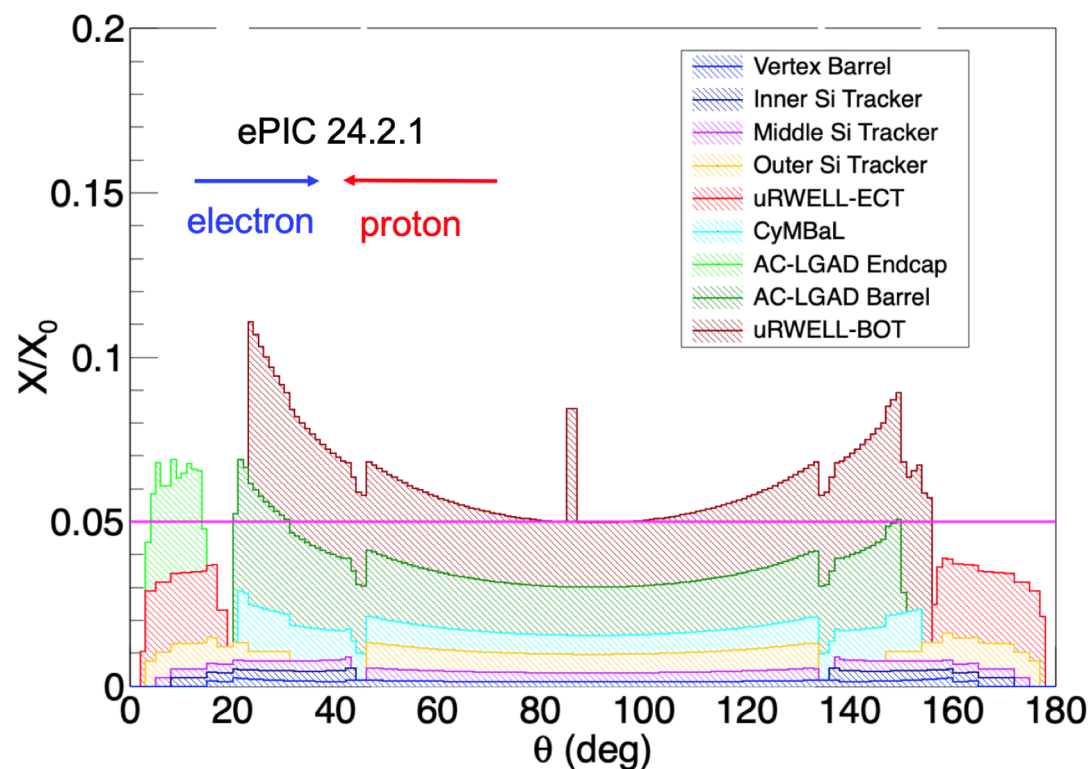
- All numbers in table are in % of X_0
- Averaged X_0 is 0.8% for a "slice" of stave (smearing out pipe)**





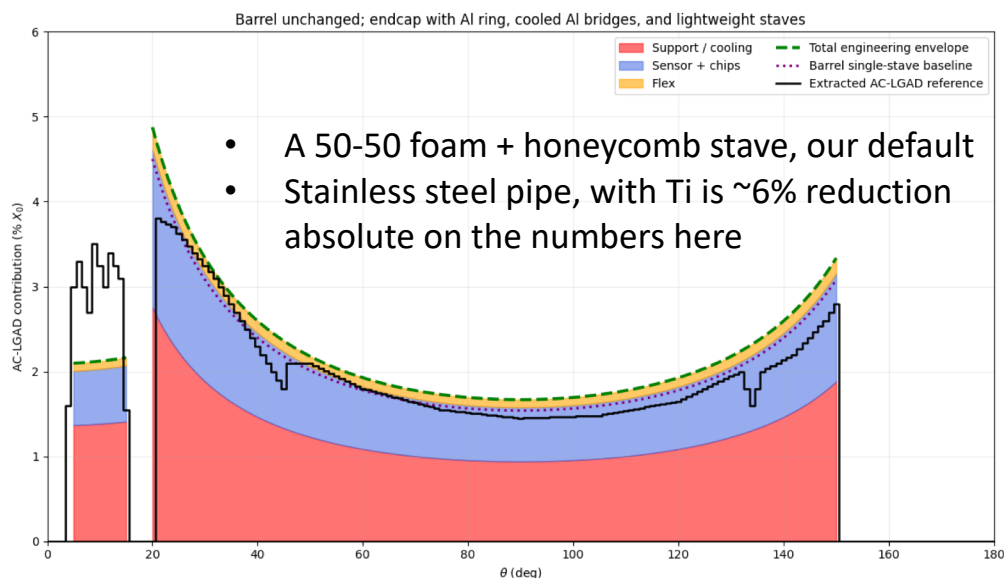
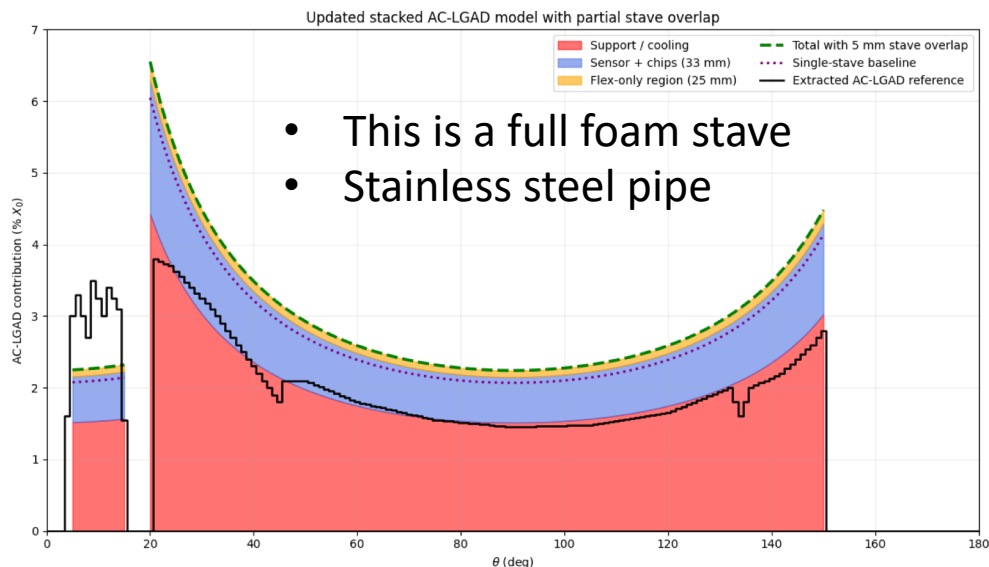
Is the material realistic in the EPIC sim plots ?

- Plots are “official EPIC sim ingredients” – this is what is in the simulation in my understanding
- Always question on fTOF budget and how realistic is bTOF ?
- Services are apparently not in the left map but separate in right map, much of that is SVT cables but some are ofc other detectors too, this might not map latest knowledge on the detector mechanics engineering design team.





Is the material realistic in the EPIC sim plots ?



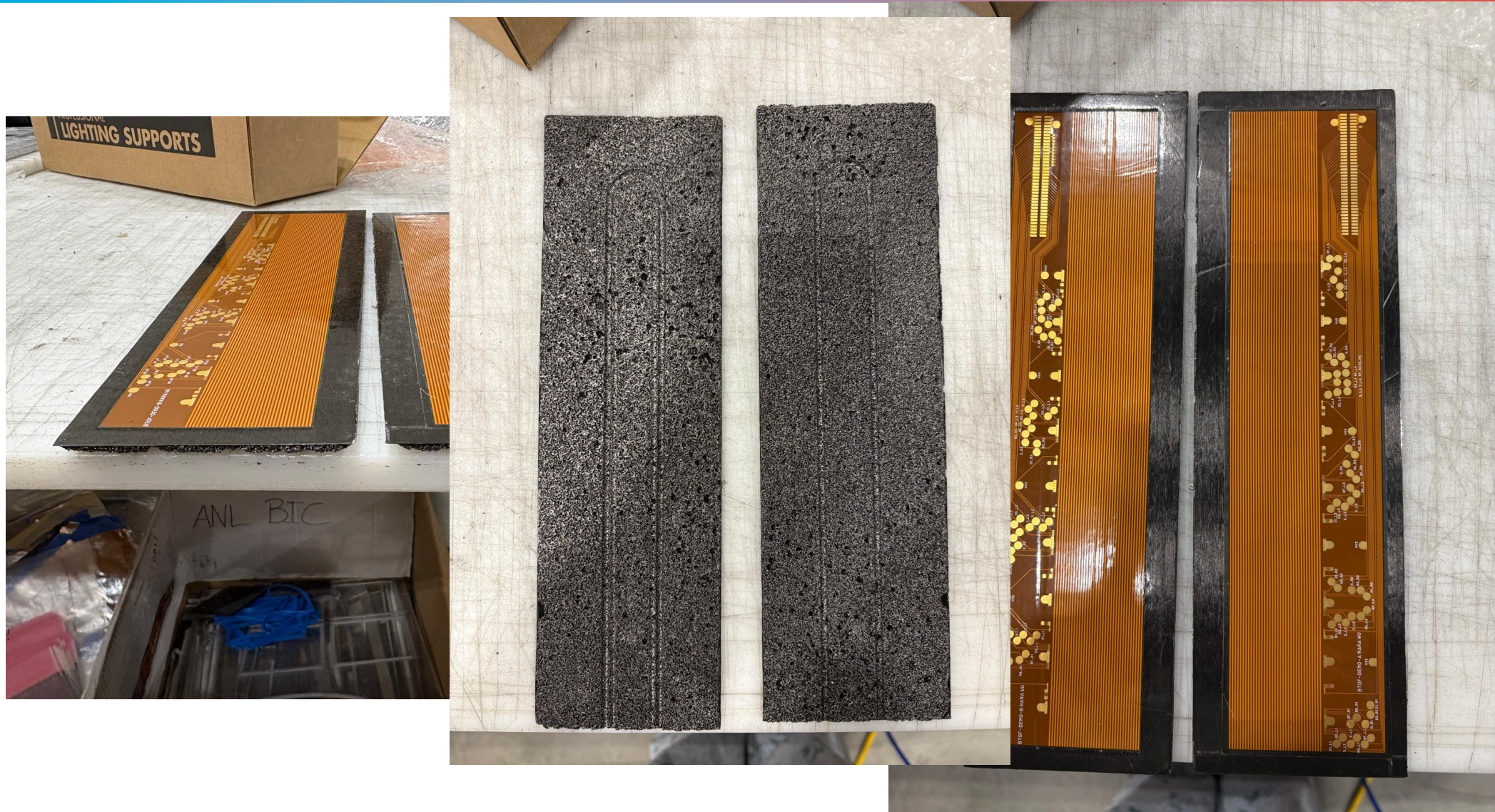
- Black is extracted from previous slide map, the filled histo is according to our mechanics design team numbers
- With current design in barrel and fTOF able to meet those demands
- Assumptions sensor + R/O\ASIC is 500 micron, flex is 50 micron with 30% 4 layer traces (realistic ?)

Component	(X/X ₀)
Two 500 μm CF facesheets	0.445%
30 mm C-foam + 30 mm honeycomb core	0.164%
Two 3 mm stainless pipes	0.173%
Water	0.057%
Epoxy	0.030%
Support and cooling subtotal	0.869%
Sensor + chips, 33/60 mm	0.587%
Flex-only region, 25/60 mm	0.084%
Single-stave total	1.540% (X₀)

bTOF: Thermo-Mechanical mock-ups



bTOF: Thermo-Mechanical mock-ups



Thermal FEA: single bTOF stave – boundary conditions

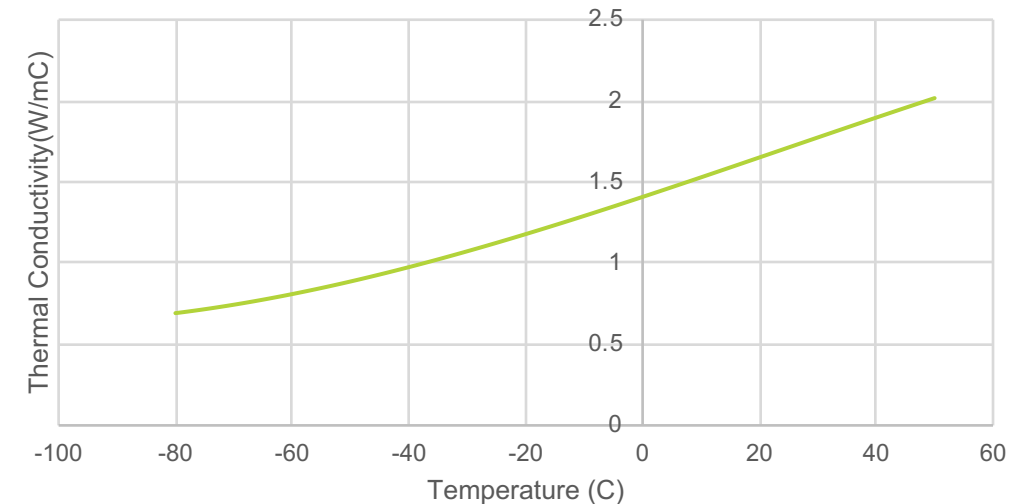
Heat Load Summary

- **Based on 23 kW system total, 70% Sensor + ASIC array / 30% SH+PB split**
- 240 staves (12 trays $\times$ 10 staves $\times$ 2 halves) = 95.8 W per stave
 - ASIC Modules — 2259 W/m² heat flux on top surface (12.65 W total across all ASIC faces)
 - ROC/Interposer Modules — 1550 W/m² heat flux on top surface (54.45 W total across all ROC faces)
 - Service Hybrid + Power Board — 85,522 W/m³ volumetric heat generation (28.75 W total, 30% of per stave power budget)
 - **Power split between ASIC and ROC is preliminary, pending confirmation*
- Pipe Cooling — 18°C Water
 - $h = 3153 \text{ W/m}^2\text{K}$
 - Nusselt Number = 4.36, fully developed flow with constant heat flux
- Ambient Air Cooling — $h = 5 \text{ W/m}^2\text{K}$ at 22°C
 - Applied to all exposed stave surfaces

Thermal FEA: single bTOF stave – boundary conditions

<u>Part Name</u>	<u>Thermal Conductivity (W/mK)</u>	<u>Thickness (μm)</u>
ROC and ASIC (Kapton properties)	0.97	400 and 300
Silicon Module	148	200
Carbon Face Sheet	Kxx - 180 Kyy - 150 Kzz – 0.70-2.01(Shown in graph)	200
Carbon Foam	25	6420
Loctite Epoxy	1.28	120
Stainless Steel Pipe	16	716

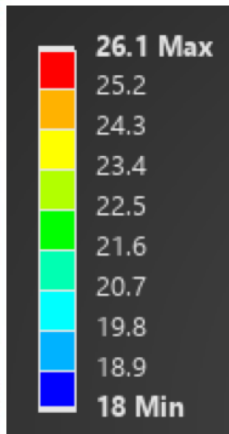
Thermal Conductivity vs Temperature for CF facesheet



Reference:

- <https://www.physics.purdue.edu/jung/tc-data/index.html>
- JINST in preparation

Thermal FEA: single bTOF stave – boundary conditions



Connection	Heat Flux	Avg Temp.	
To Cooling Pipe	-97 W	Stave	21 °C
To Ambient Air	14 W	Sensor Hybrid	25°C

18 C Water

- bTOF stave cooling performance is at $\Delta T \sim +8^\circ\text{C}$ between coolant and Max
- In the sensor array $\Delta T < 5^\circ\text{C}$ and for most part this is $\Delta T < 2^\circ\text{C}$
- “Heating” to ambient is a potential concern, ~240 half-staves leads to substantial number

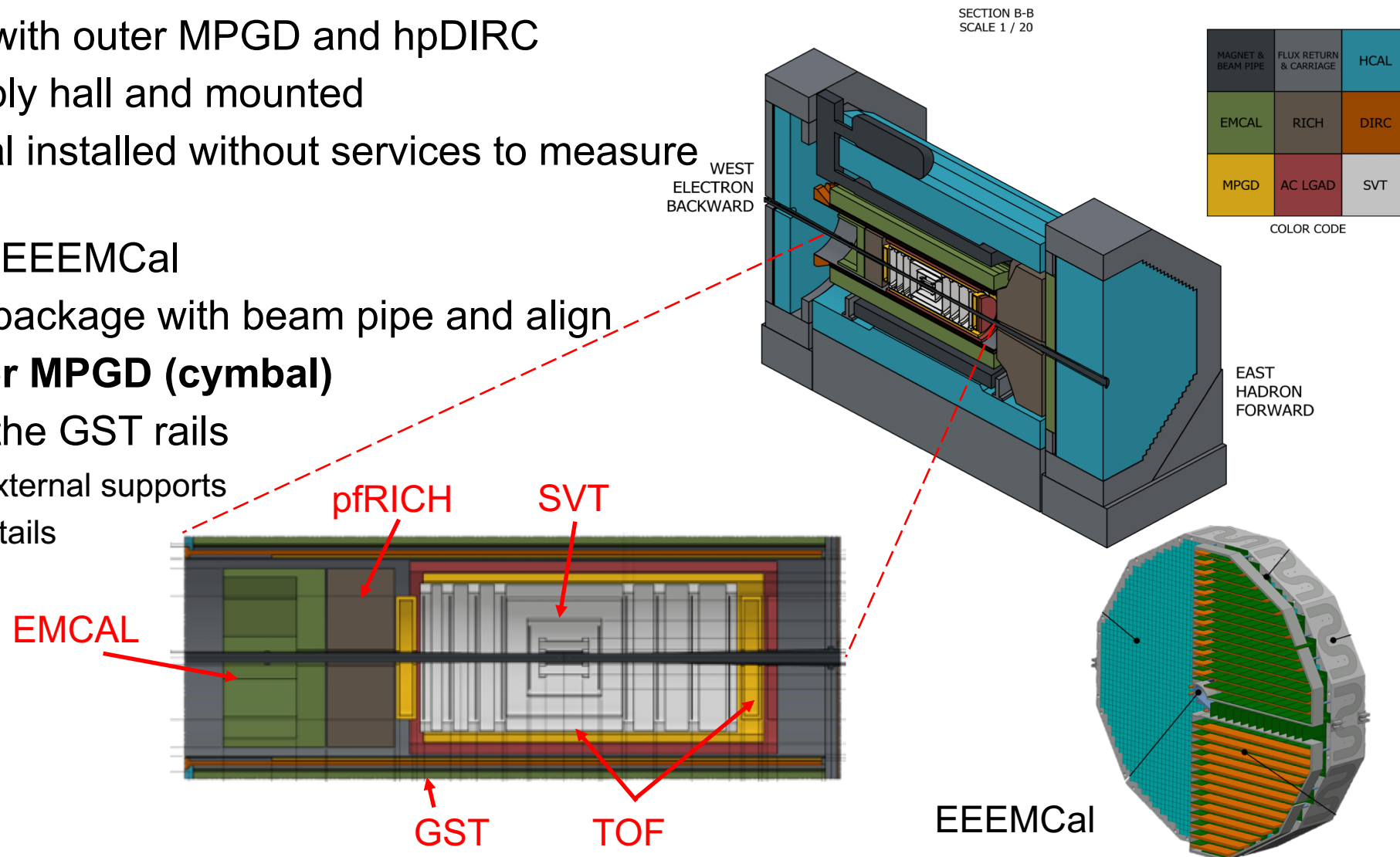


Presentation Section 3: bTOF – Integration and Insertion/Assembly Plan

Assembly sequence

Charge 3, 6

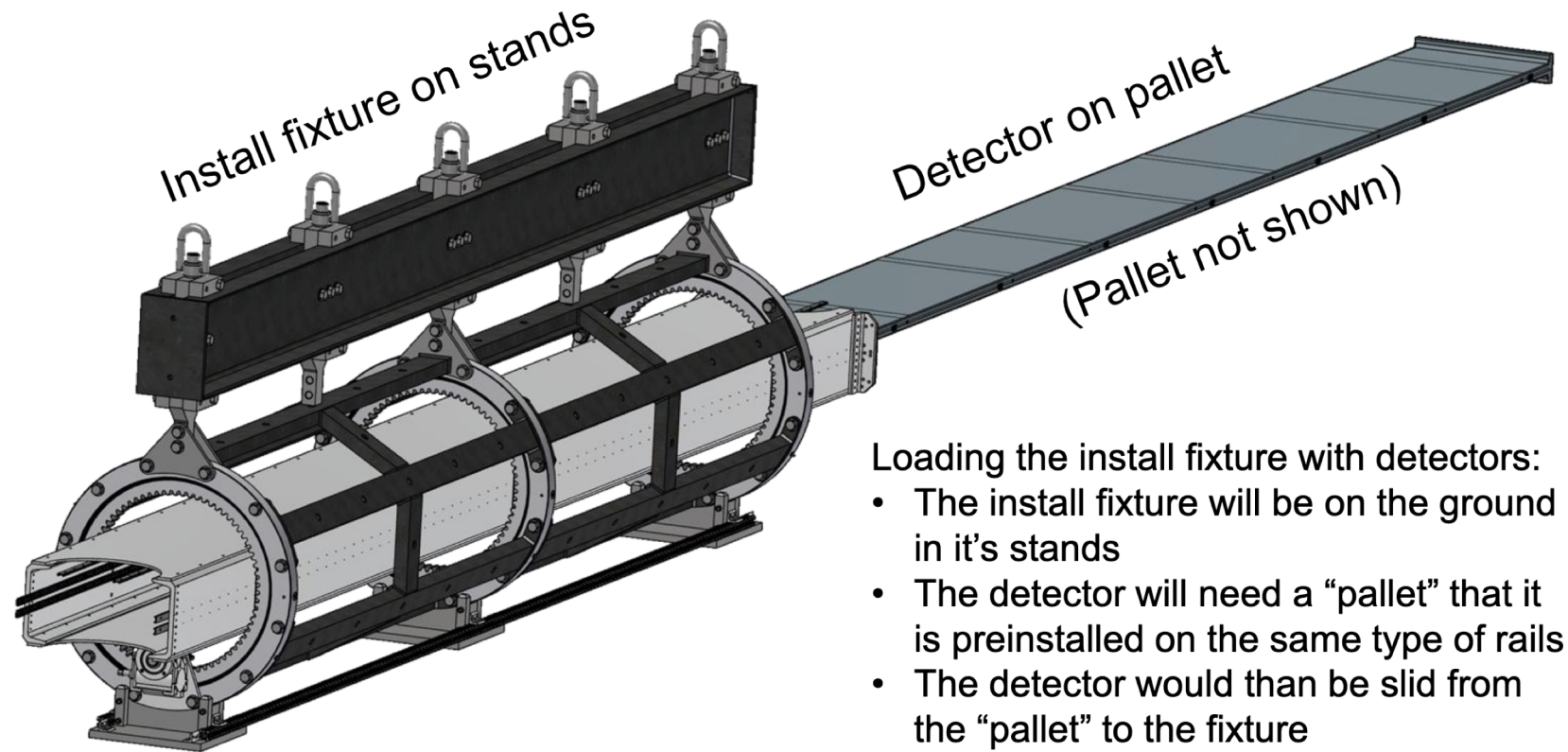
1. GST gets integrated with outer MPGD and hpDIRC
2. Moved inside assembly hall and mounted
3. pfRICH and EEEMCal installed without services to measure deflection
4. Remove pfRICH and EEEMCal
5. Install PST and SVT package with beam pipe and align
6. **Install TOF and inner MPGD (cymbal)**
7. Put PST front feet in the GST rails
 1. Back of PST rests on external supports
 2. See Dan Cacace for details
8. Install pfRICH
9. Install EEEMCal
10. TOF disc



sPhenix Installation tooling

Charge 3, 6

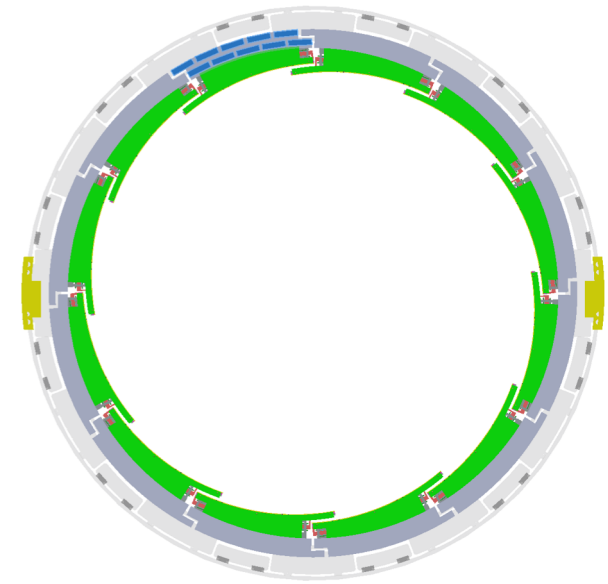
- Slides by Dan Cacace, IDR Dec 2025
- Use sPhenix installation tooling to install supertrays of TOF + cymbal



Loading the install fixture with detectors:

- The install fixture will be on the ground in it's stands
- The detector will need a "pallet" that it is preinstalled on the same type of rails
- The detector would than be slid from the "pallet" to the fixture

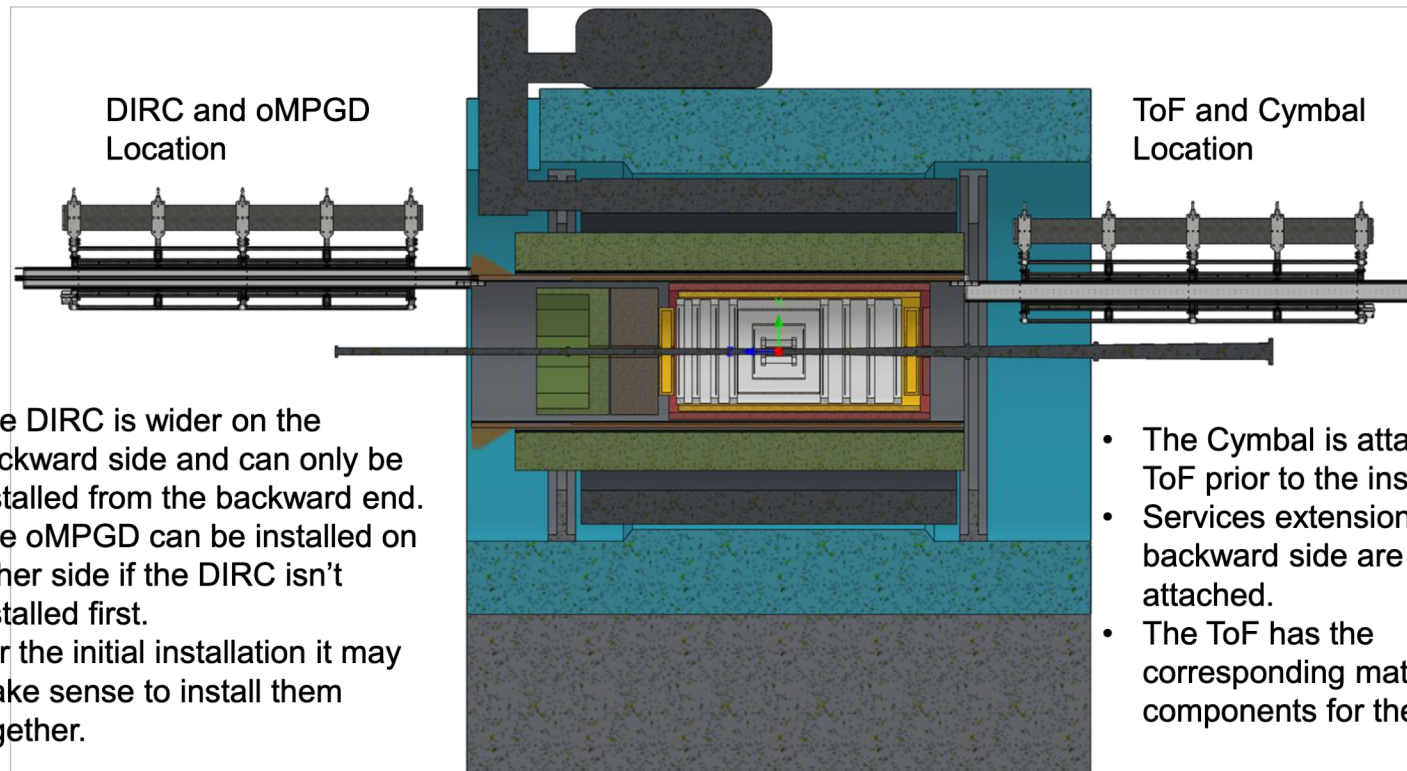
12 supertrays to install



sPhenix Installation tooling

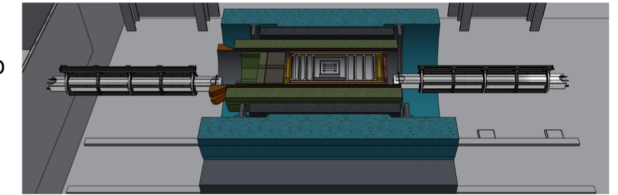
Charge 3, 6

- Slides by Dan Cacace, IDR Dec 2025
- Space for maintenance available
- Interventions possible – eases maintenance of TOF and cymbal!



Assembly Hall

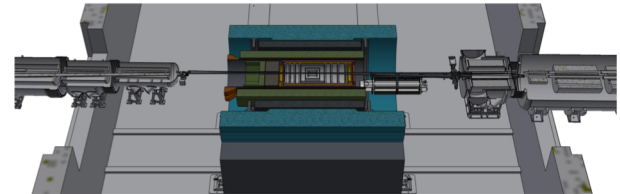
DIRC and oMPGD Location



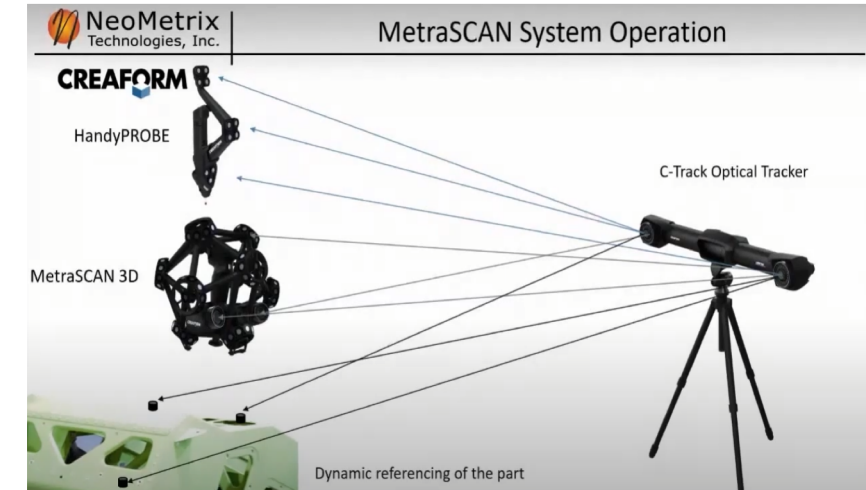
ToF and Cymbal Location

Experimental Hall

oMPGD, ToF and Cymbal Maintenance Location



- Metrology and loading case scenarios based on realistic EPIC parameters
 - Rely on existing experience with CMS HL-LHC projects: ITST, SC & BTST projects
 - Large area metrology system “Creaform MetraScan” (received!)
 - Best circular fit and deviations point-by-point from expected one
- Metrology and deformation studies
 - Deformation only studies (safe loads)
 - Adjust FEA to match deformation only
 - Compare to FEA to reproduce data
- **Predict** behavior of full structures in all aspects & measure all
 - Deformation only + FEA match
 - Loading scenarios + FEA match
 - Predict and extrapolate to CMS conditions

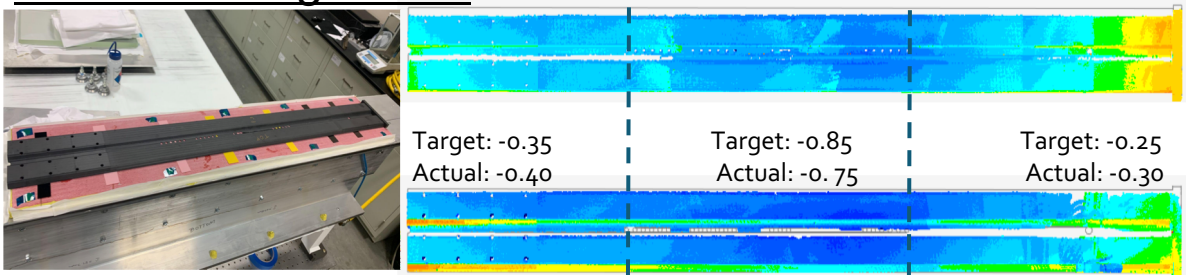


QA/QC procedures informed by CMS experience

Charge 3

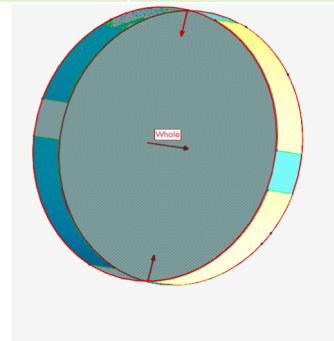
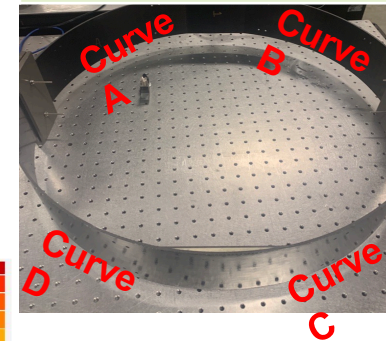
- Following best practice and lessons learned from CMS upgrade projects
 - Iteration of FEA of manufacturing method, performance under load, metrology
 - QA/QC during and at end of the process → repeat!
- Prototyping using non-final materials
 - Smaller prototypes with final material, FEA driven
- Met tolerances – we typically achieve:
 - 1 – 2mm cylindricity (~ 6m length & 2.4m diameter)
 - $< 500\mu\text{m}$ cylindricity (Solid skin tube)
 - $50\text{-}100\mu\text{m}$ parallelism (Rail/Track alignment)

ITST track alignment:

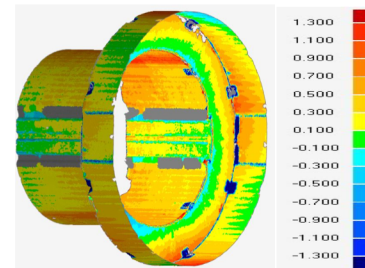


CMS IT tube end section cylindricity:

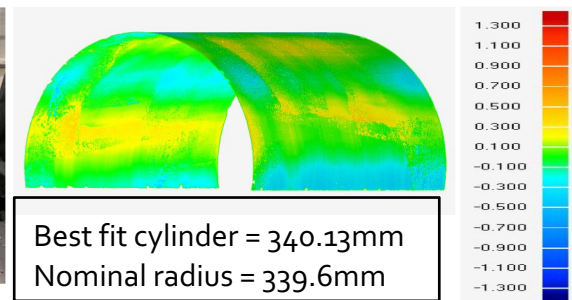
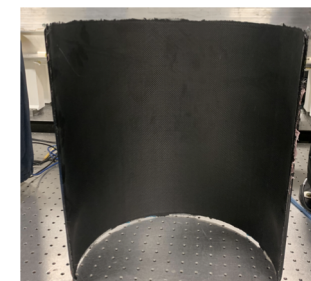
Target Diameter	606 mm
Measured dry assembled diameter	605.47 mm



Tube transition to mid section:



Pixel Service Cylinder cylindricity:



Next steps

- Mature design for TOF – cymbal “supertray” mounting mechanism
- Thermal FEA to be validated by prototype & thermal heating of other subsystems
- Mechanical FEAs
- Finalize envelopes for bTOF and installation sequence

Summary

- The current designs for TOF support structures are well developed for the current phase of the project
- The designs are all integrated into the larger central detector model
- The current procedure and approaches for the installation of the inner detectors and their support structures are well developed for the current phase of the project
 - Separation of inner detectors and outer detectors eases separations!
- Adjustments and optimizations are quickly worked into the larger integrated model

Backup

Charge 4

- Group of PI Yi Yang, Taiwan (mechanics)
- Group of PI A Jung, Purdue (mechanics)
- Group of co-PI M Jones, Purdue (modules)

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Few words on material budget...

- Comparing a few numbers to give a reference
- CO2 is factor ~2 lower than water or glycol-based systems

Material	Radiation Length (g/cm ²)	Density (g/cm ³)	Radiation Length (cm)
Water (H2O)	~36.08	~1.00	36.08
Ethylene Glycol (C2H6O2C_2H_6O_2	~41.4	~1.11	37.3
CO ₂ (2-phase state, 20 bar)	~19.9	~0.7–1.0	28.4 to 19.9

Details on material budget and breakdown for TOF, get a sense of scale of choices

- Path hitting the pipe: $X_0 = 2.19$ to 3.14% (Ti vs stainless)
- Path hitting only structure: $X_0 = 0.83$ to 0.94% (K9 vs c-foam)
- 2-phase CO2 is 40% lower then liquid coolant but "in stave" this is 8-9% material savings

Comparing my estimates with the material budget map provided by Matt / central sim

- Roughly consistent with what's in the central "map" but that includes the sensor...so, something is missing in central map which is not too surprising

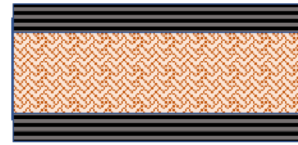


Presentation Section 2: TOF Interfaces – Global Support Tube (GST)

Global Support Structure (GST)

Charge 1, 4, 6

- GST supports the 2 “outer” detector systems (hpDIRC & oMPGD) and all inner detectors, all supported by the Global Support Tube
 - Total weight GST + inner and outer detectors + services: ~ 5600kg
 - For comparison: CMS is similar!
- “Double-decker” sandwich structure with internal beams and I-beam cells
 - Made from honeycomb core and two face sheets on either side bonded to it + 5mm skin further out
 - 2mm face sheets + 6mm core
 - ~425kg self weight
- Two Inner detector support rails:
 - 5.3m long (or 2.65m x 2); ~14x20mm cross section
 - Support ~**3100 kg** inner detectors



Facesheet = 2mm thick

HoneyComb = 6 mm thick (1/4 inch)

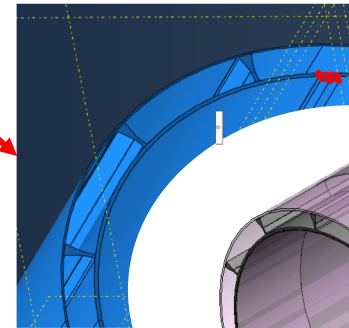
Facesheet = 2mm thick

Face sheets:

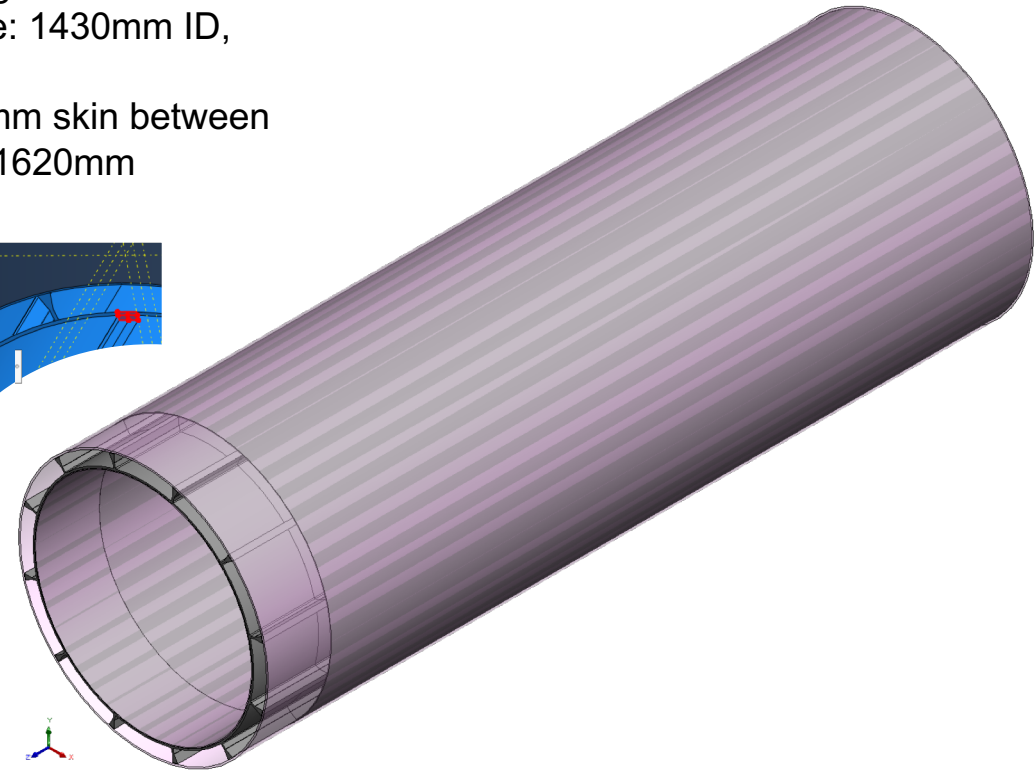
“Carbon Fiber Reinforced Polymer” or CFRP

Dimensions:

- Structure is 5050 mm long; with the outer being shorter 4600 mm
- Sandwich tube: 1430mm ID, 1450mm OD
- Outer tube: 5mm skin between 1610mm and 1620mm



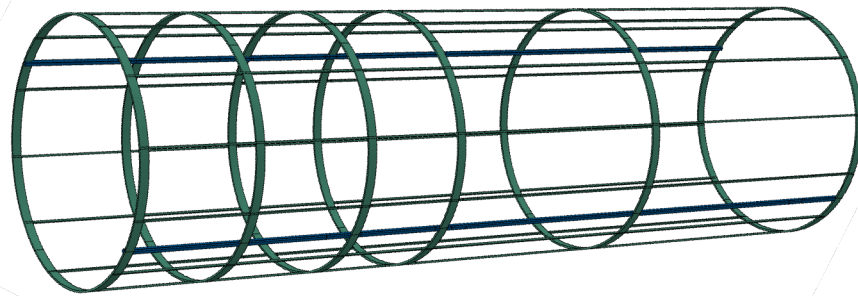
*Isometric



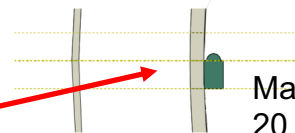
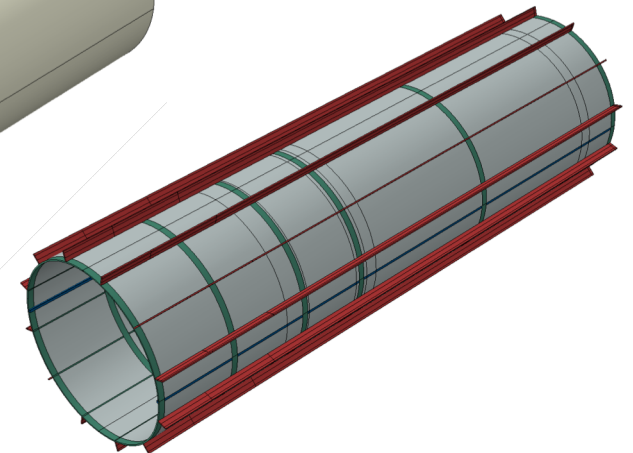
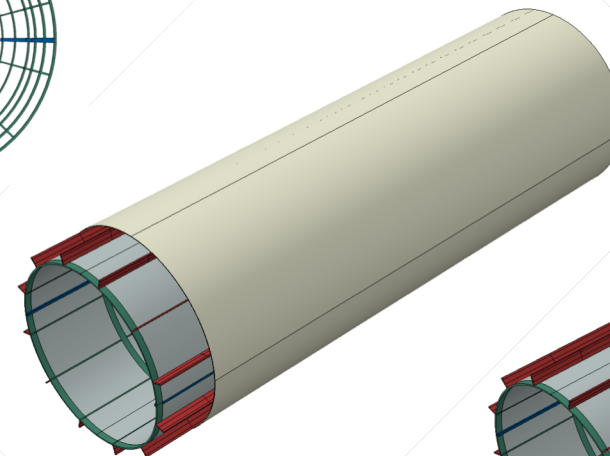
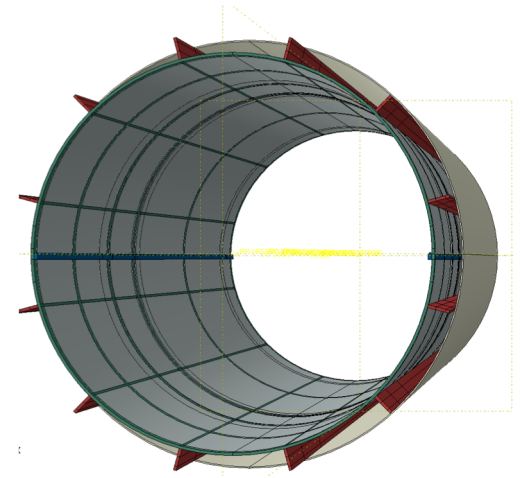
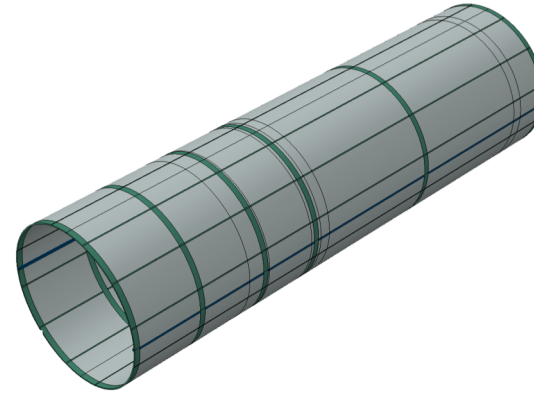
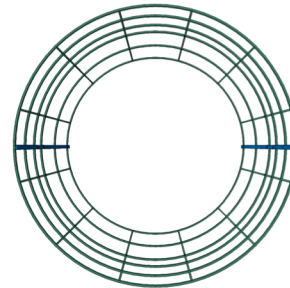
GST – internal rip structure

Charge 1, 4, 6

- Internal rip structure to stiffen GST as needed to support >5t
- End rings to provide support for GST bracket and to distribute load, more rings in EEEMCal area



Electron direction
(EEEMCal direction)



Massive CFRP
20 x 14mm, full length

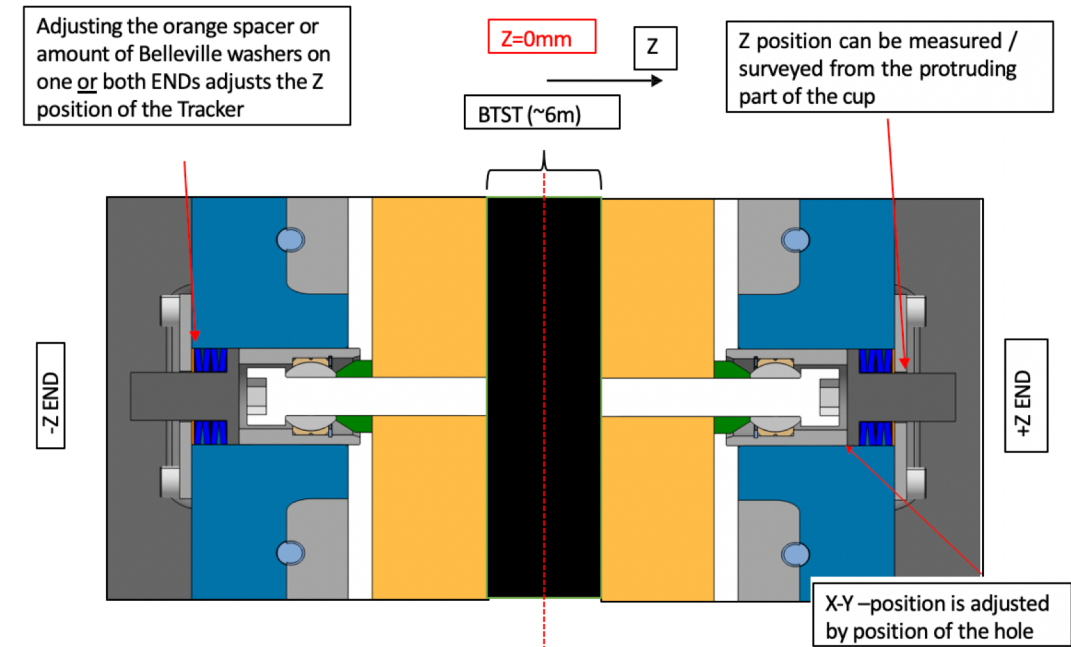
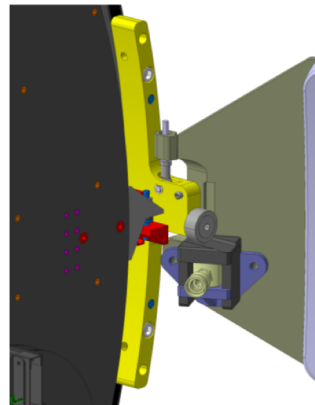
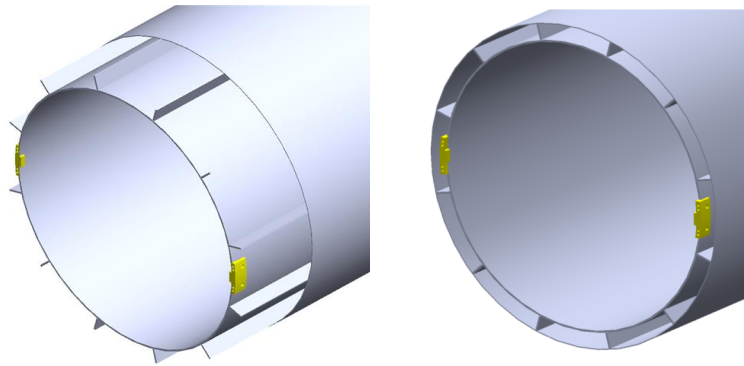
- GST support rails for PST feet

GST tolerances/constraints and mount points

Charge 1, 4, 6

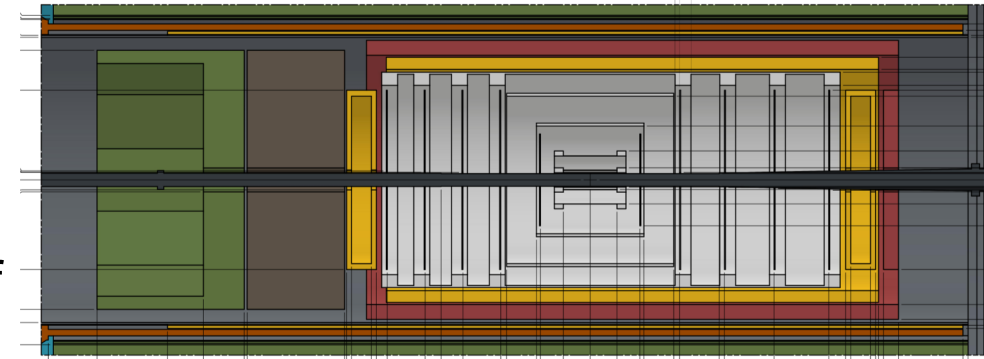
- Variety of support rails are provided by GST to support
 - PST feet
 - Mountpoints for pFRICH, EEEMCAL
 - GST itself is mounted to HCAL and EMC
 - End rings (50mm massive CRRP) to distribute load of “brackets” for GST support
- Adjustability of PST $\pm 3\text{mm}$ and of GST $\pm 10\text{mm}$

- Envelope inner radius is 715 to 725mm
- Inner installation clearance is 710 to 715 mm
- Inner cylinder (sandwich) is $z = -1900\text{ mm}$ to $+3125\text{mm}$
- Envelope outer radius = 805 to 810 mm
- Outer installation clearance = 810 to 820 mm (this is the clearance between GST and the barrel EMcal (BIC))
- Outer Cylinder (CFRP) $z = -1900$ to $+2700\text{ mm}$



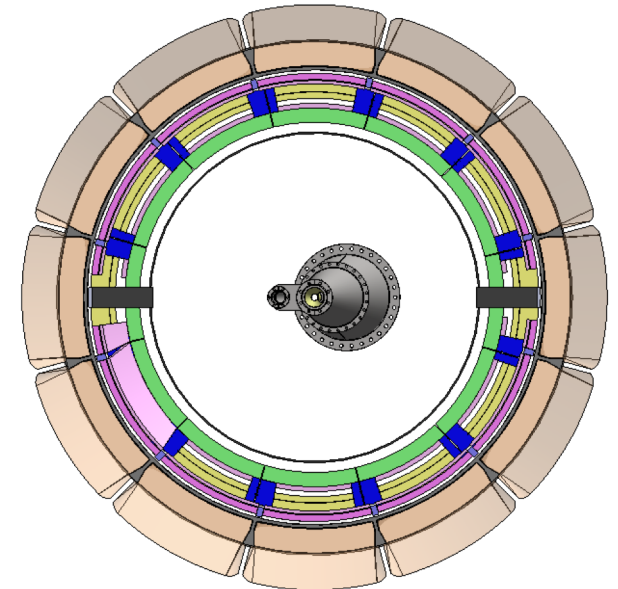
GST envelope and constraints

- Expected deflections, tolerances, geometric tolerances:
 - Deflections in final operation setup: ± 2.5 vs ± 2.0 mm
 - Manufacturing: ± 1.5 mm, Core: ± 0.5 mm & Cylindricity of 2mm
 - Face sheets: ± 0.1 mm + Core yields ± 0.7 mm max deviation
 - Geometric to fit within envelope in worst case: ± 1.5 mm
 - Envelope is ± 10 mm for insertion
 - Worst case: ± 1.5 mm $\pm 2.5/2.0$ mm = $\pm 4/ \pm 3.5$ mm
 - Can consider more local add. stiffening structures
- Adjustability of PST ± 3 mm in x-y and ± 5 mm in z
→ Tolerance is ± 1 mm
- Adjustability of GST ± 10 mm in all directions
→ Tolerance is ± 3 mm



Key:

- hpDIRC Prism
- hpDIRC & oMPGD
- Services
- Barrel TOF**
- iMPGD
- Support tubes - GST & PST



FEA: Loads of detector systems supported by GST

- Total weight is 5,675 kg
 - Comparable to CMS timing layer + all of the tracker
- Services are included in the respective detector subsystem
 - Additional service mass outside the respective detector volume is added in addition
- GST properties:
 - weight is ~ 420 kg
 - CFRP rails are 5 kg
 - For comparison if made in stainless steel GST weight is 3082 kg (7x GST), and in Al it would 1040 kg (2x GST)

		Load distribution	
		z-coordinate	Mass (kg)
1	EEEMCal Crystals	1842.5	2000
2	EEEMCal Electronics	2212.5	500
3	HPDIRC Bars	425	1400
4	HPDIRC Prisms	3060	400
5	oMPGD	125	100
6	AC LGAD TOF	-212.5	150
7	Cymbal	-212.5	150
8	SVT	-100	285
9	pfRICH	1500	97
10	pfRICH Services	2437.5	13
11	SVT Services Zp	2187.5	50
12	SVT Services Zm	-1725	15
13	Cymbal TOF Services Zp	2150	50
14	Cymbal TOF Services Zm	-1725	15
15	EEEMCal Services Zp	2815	30
16	GST self weight	xx	420
		TOTAL	5675

Finite element analysis of GST

- The current GST design of a composite “double-decker” Carbon Fiber tube can support all inner detector masses within **2.5mm deflection**
- Currently assumed: HM63 + EX1515 matrix (fairly stiff, other choices exist) – Material properties are in backup
- **Sufficient within the envelope!**
- **To come:** Alternative materials and alternative sandwich

