The CMS Phase 2 Outer Tracker

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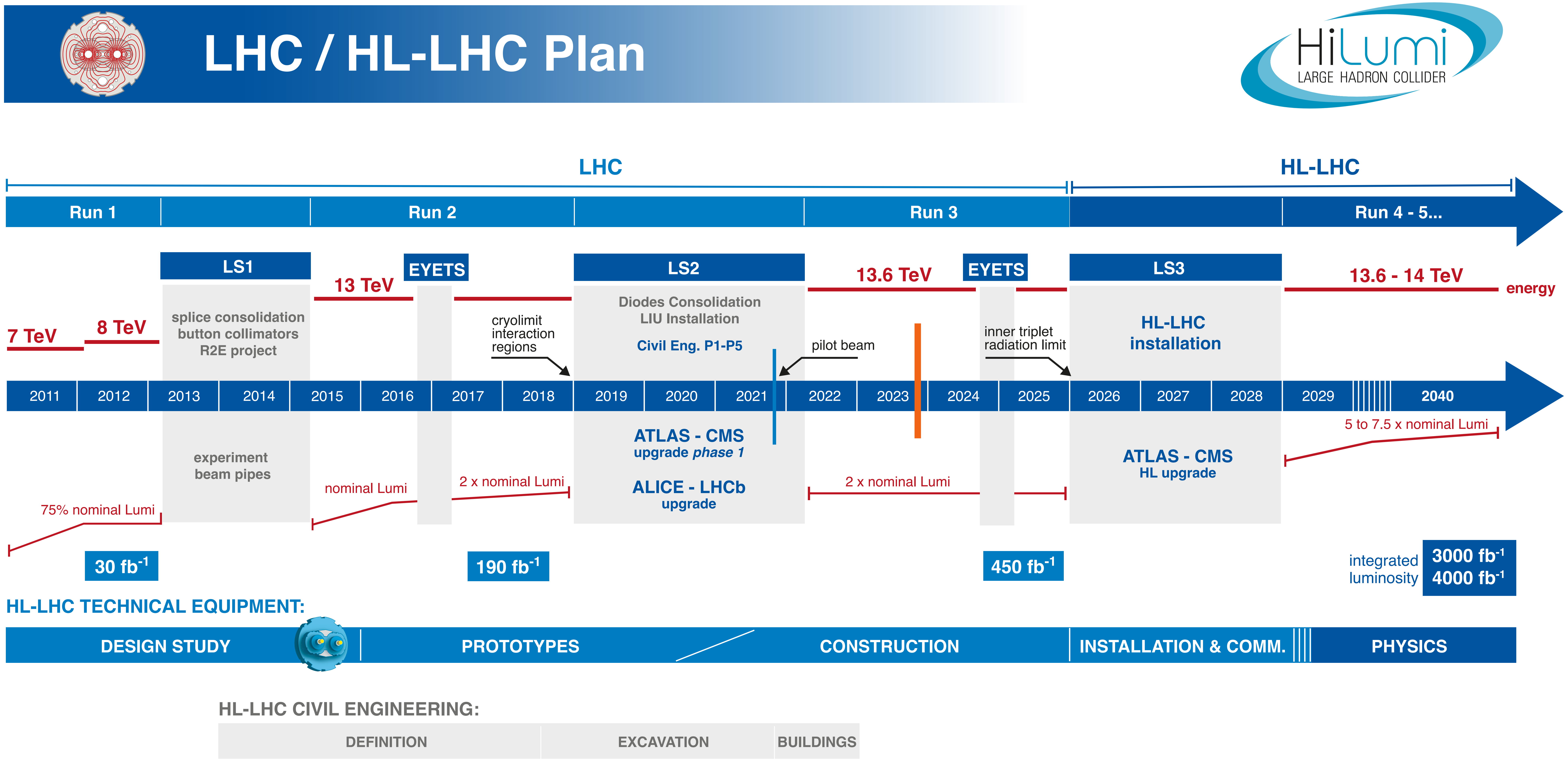
15/12/2023

Outline

- Introduction
- Module Designs and Assembly
- Sub-Detectors
- Outlook to Pre-Production and Production

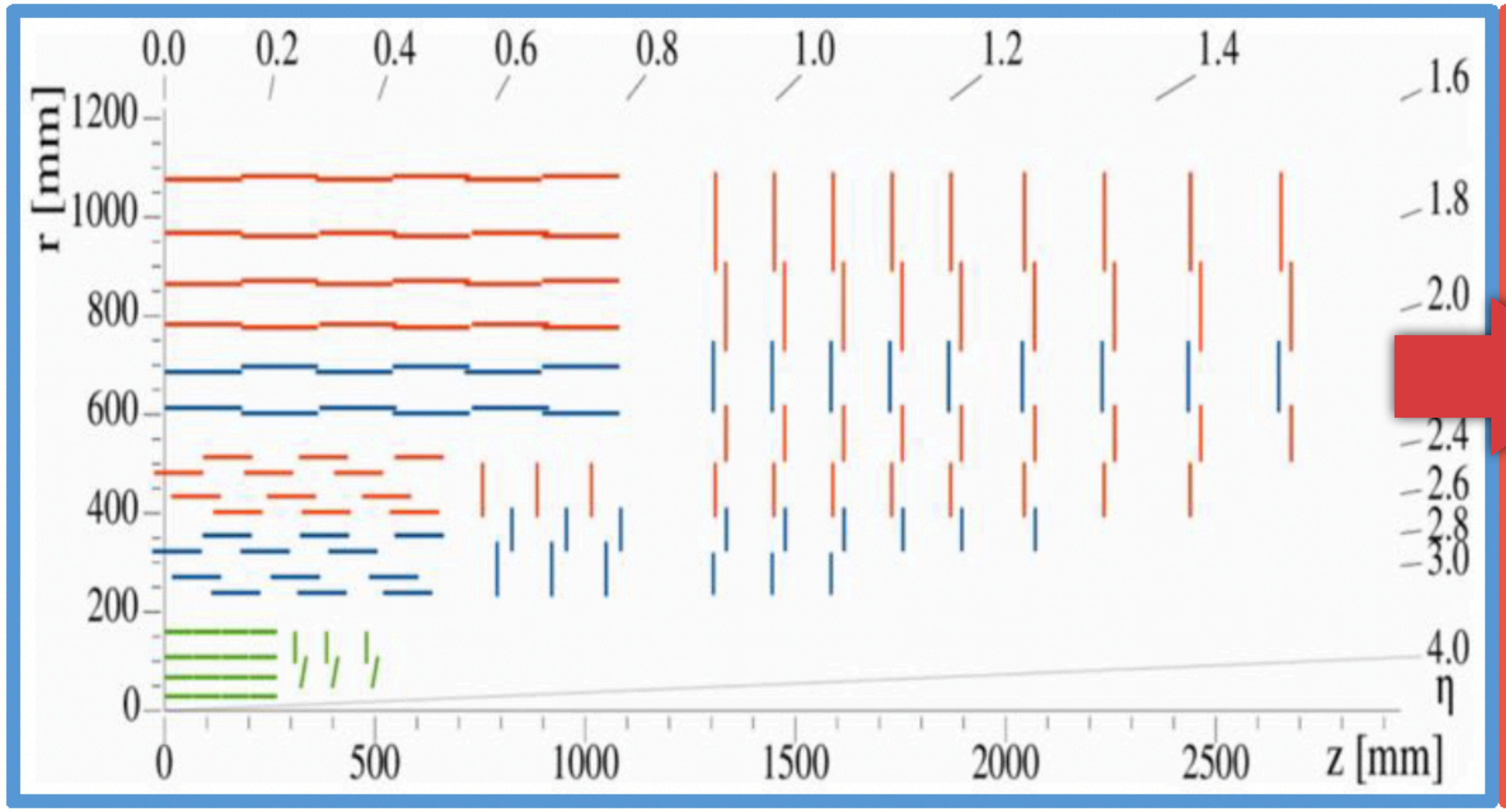
LHC/HL-LHC Schedule



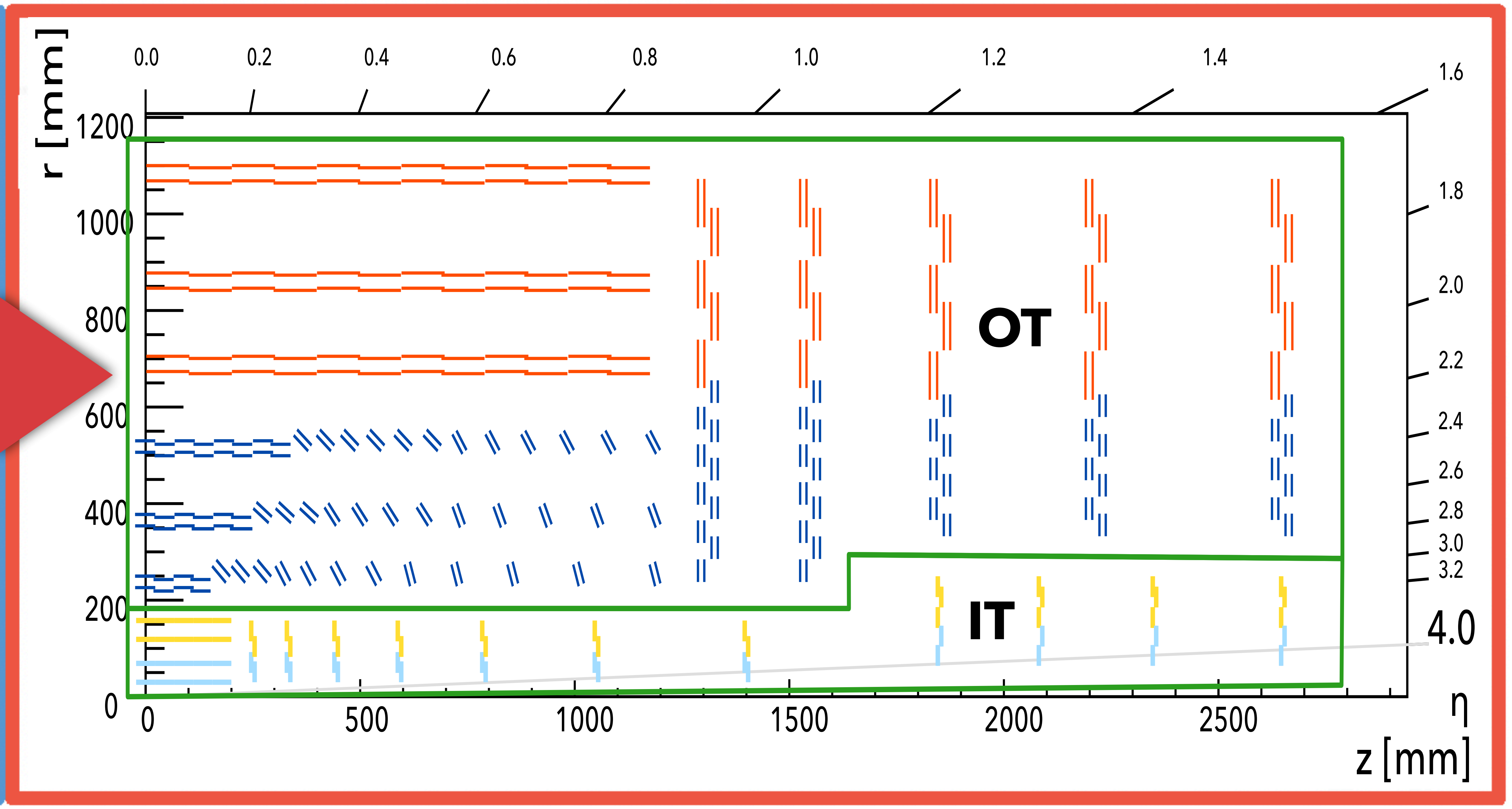
- During LS3 the accelerator will be upgraded to a peak instantaneous luminosity of $7.5 \cdot 10^{34}\ \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$
  - Expected pile-up of 200
- Integrated luminosity of $3000 - 4000\ \mathrm{fb}^{-1}$ during the expected running period
  - Unprecedented radiation levels of up to $1.1 \cdot 10^{15}\ \mathrm{n}_{eq} \cdot \mathrm{cm}^{-2}$

Phase 2 CMS tracker

CMS Phase 1 Tracker



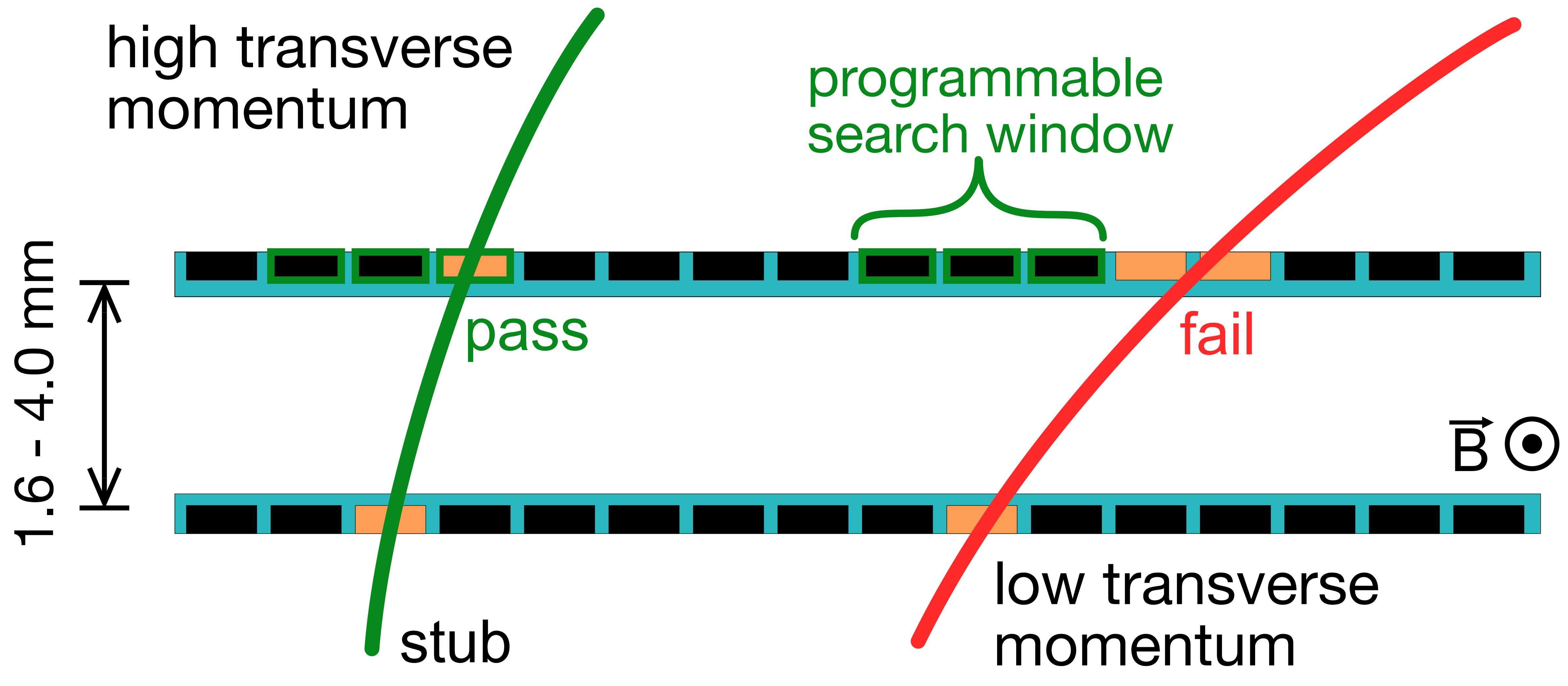
CMS Phase 2 Tracker

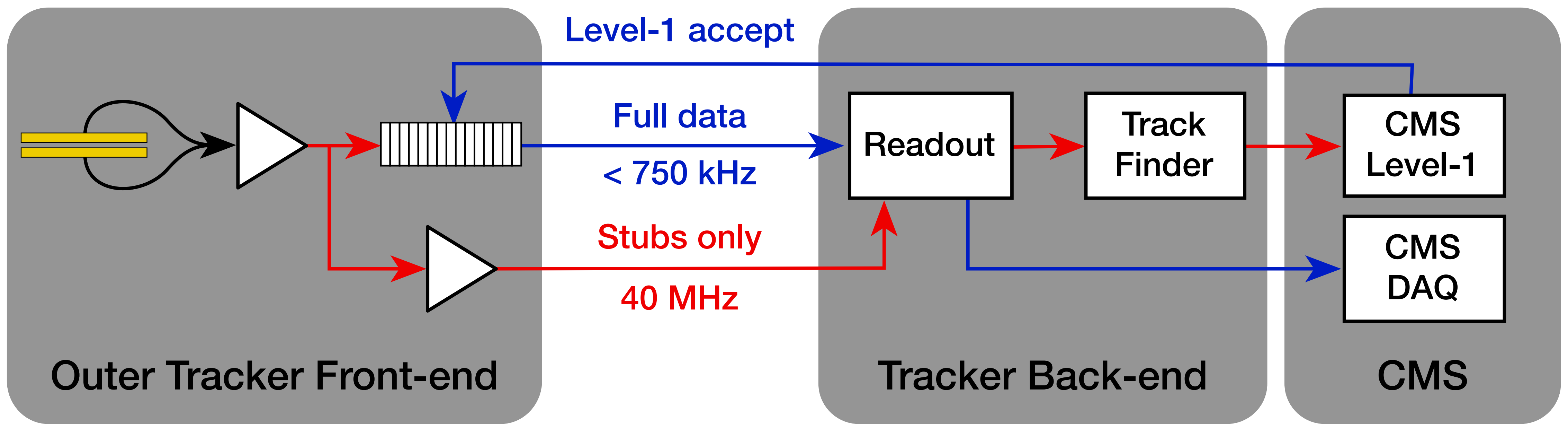


- General increase of granularity and radiation hardness
- Inner tracker (IT) will be covered in one of the next seminars
- This presentation covers the outer tracker (OT)
- Key features:
  - Tilted geometry in part of the outer tracker
  - On-module p_T discrimination
  - Reconstruction of the charged particle trajectory at trigger Level 1 (track trigger)

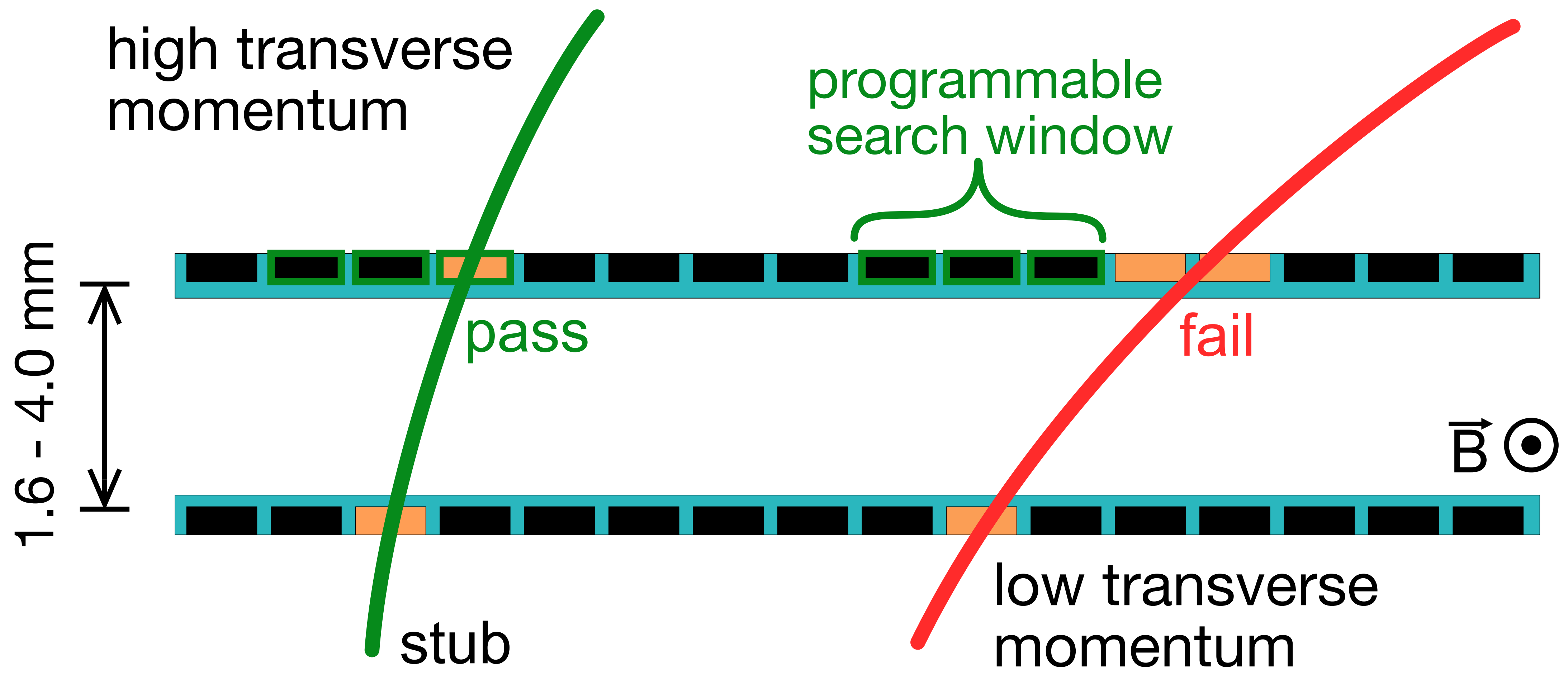
OT Module Concept

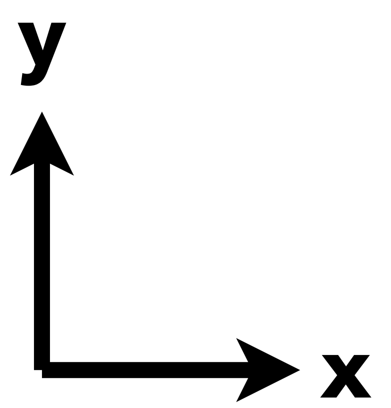
- Modules will have on-board p_T discrimination
  - Signals from two closely spaced sensors are correlated
  - Exploit strong magnetic field for local pt measurement
  - Local rejection of low-p_T tracks to minimize data volume
- Detector modules provide Level-1 and readout data at the same time
  - Whole tracker sends trigger data („stubs“) at each bunch crossing (40 MHz)
  - Readout data up to 750 kHz
- Stubs are used to form Level-1 tracks
  - Contain minimalistic information on position and bending
- Integrated at module level
  - Low power giga-bit transceiver (LP-GBT) as data link
  - Powering via DC-DC conversion
- Cooling via evaporative CO_2

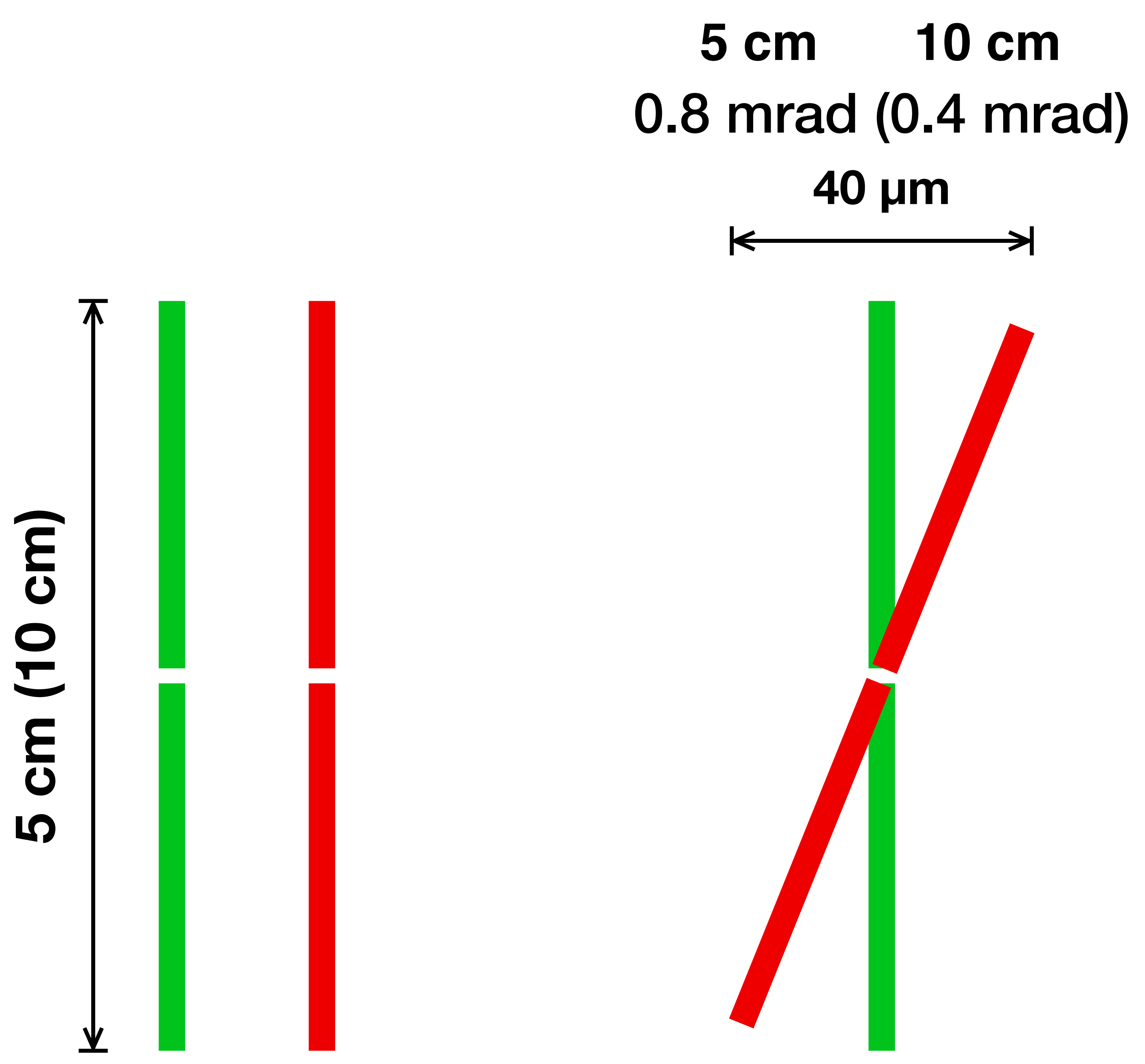




On-module p_T discrimination

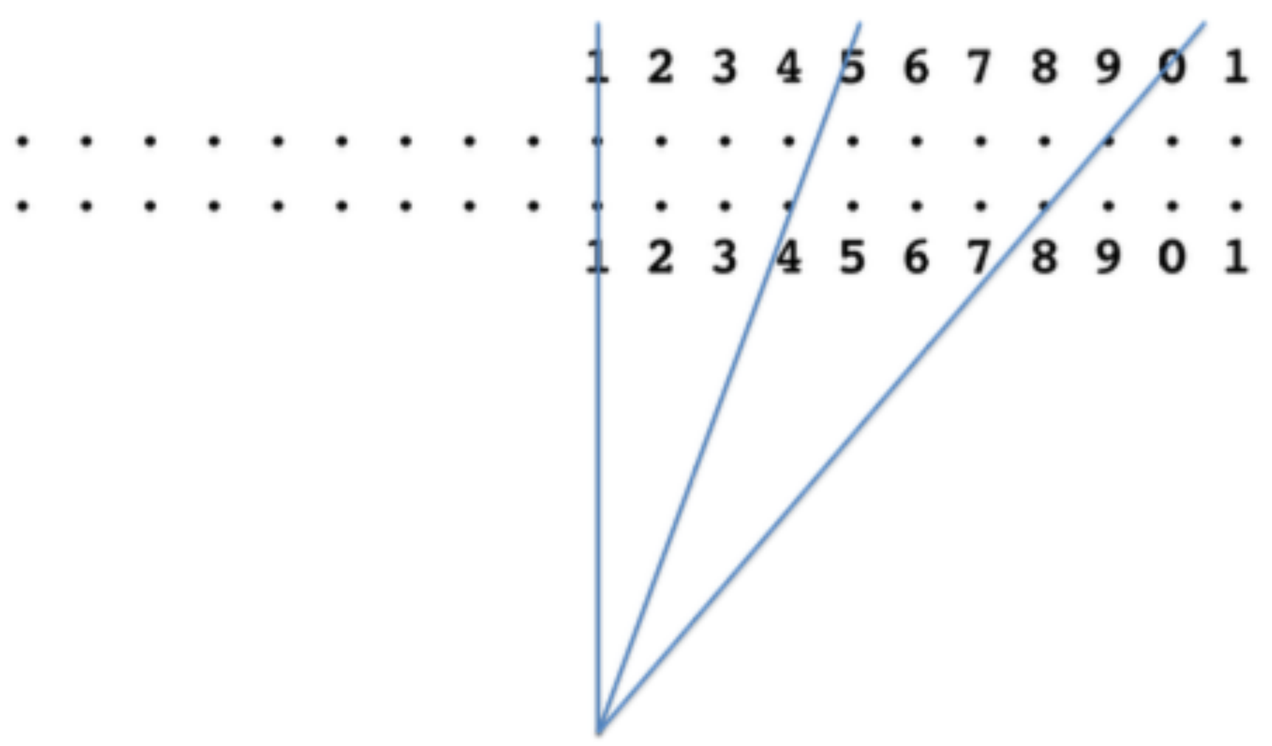




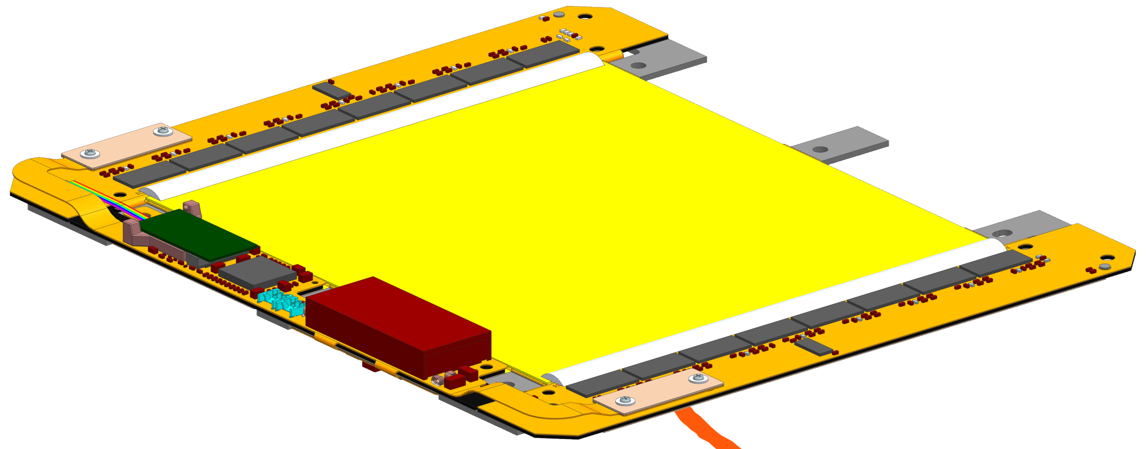


- On-module correlation of signals from both sensor to form stubs requires precise alignment already during module assembly
- Offsets along x can be compensated for in the stub finding logic of the ASICs
  - Straight trajectories do not cross the same strip on the sensors of a module
- A tilt of one sensor with respect to the other introduces a variation of the offset along the strip that cannot be corrected for
  - pT discrimination threshold becomes less well defined
- To minimize the effect on resolution tilt must be below 40 µm
  - 800 µrad misalignment for 5 cm long strips
  - 400 µrad misalignment for 10 cm long strips

} **primary assembly requirement**

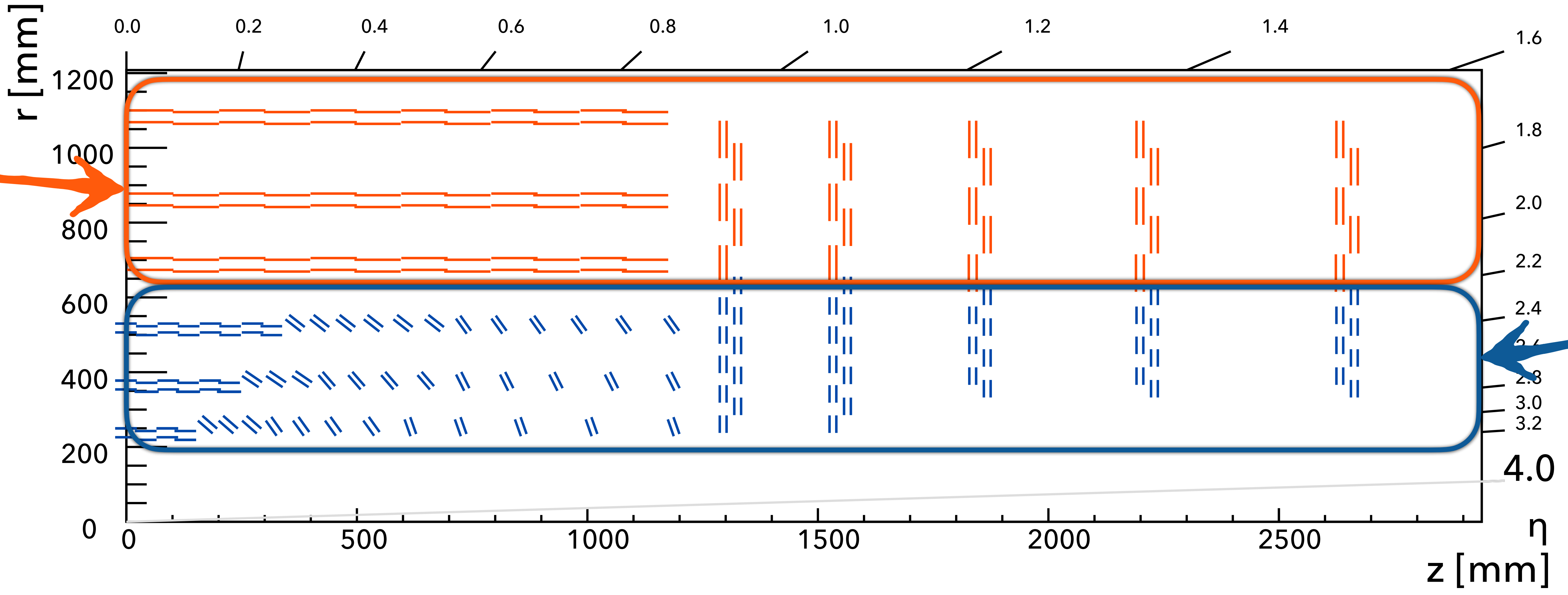


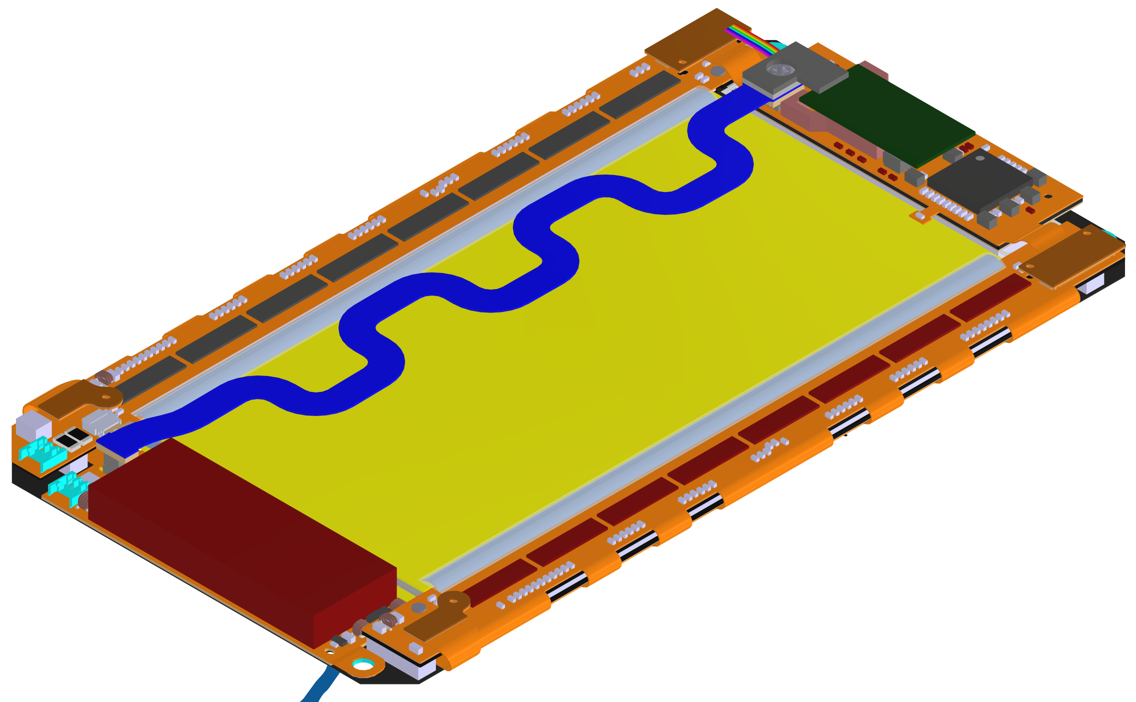
Outer tracker layout



2S Module

- stack of two strip sensors (2S)
- installed at r > ~60 cm
- sensor spacings: 1.8 mm and 4 mm

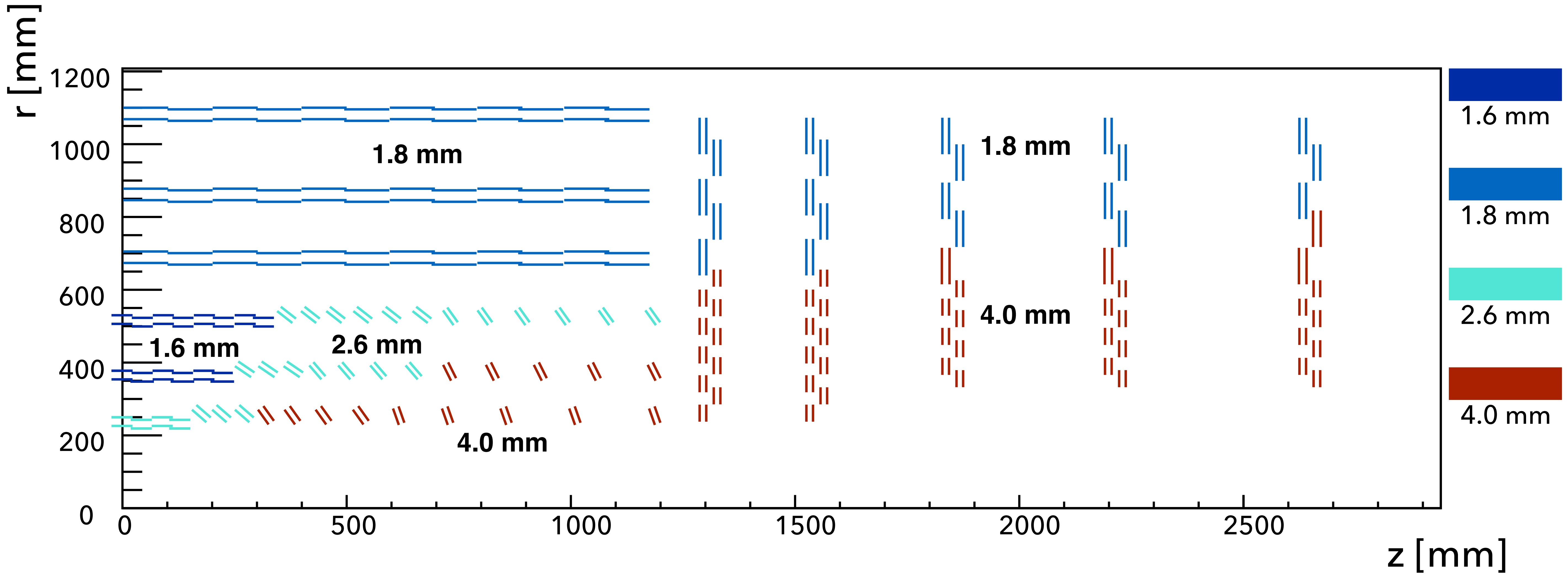




PS Module

- stack of pixel and strip sensor (PS)
- installed at r < ~60 cm
- sensor spacings: 1.6 mm, 2.6 mm and 4 mm

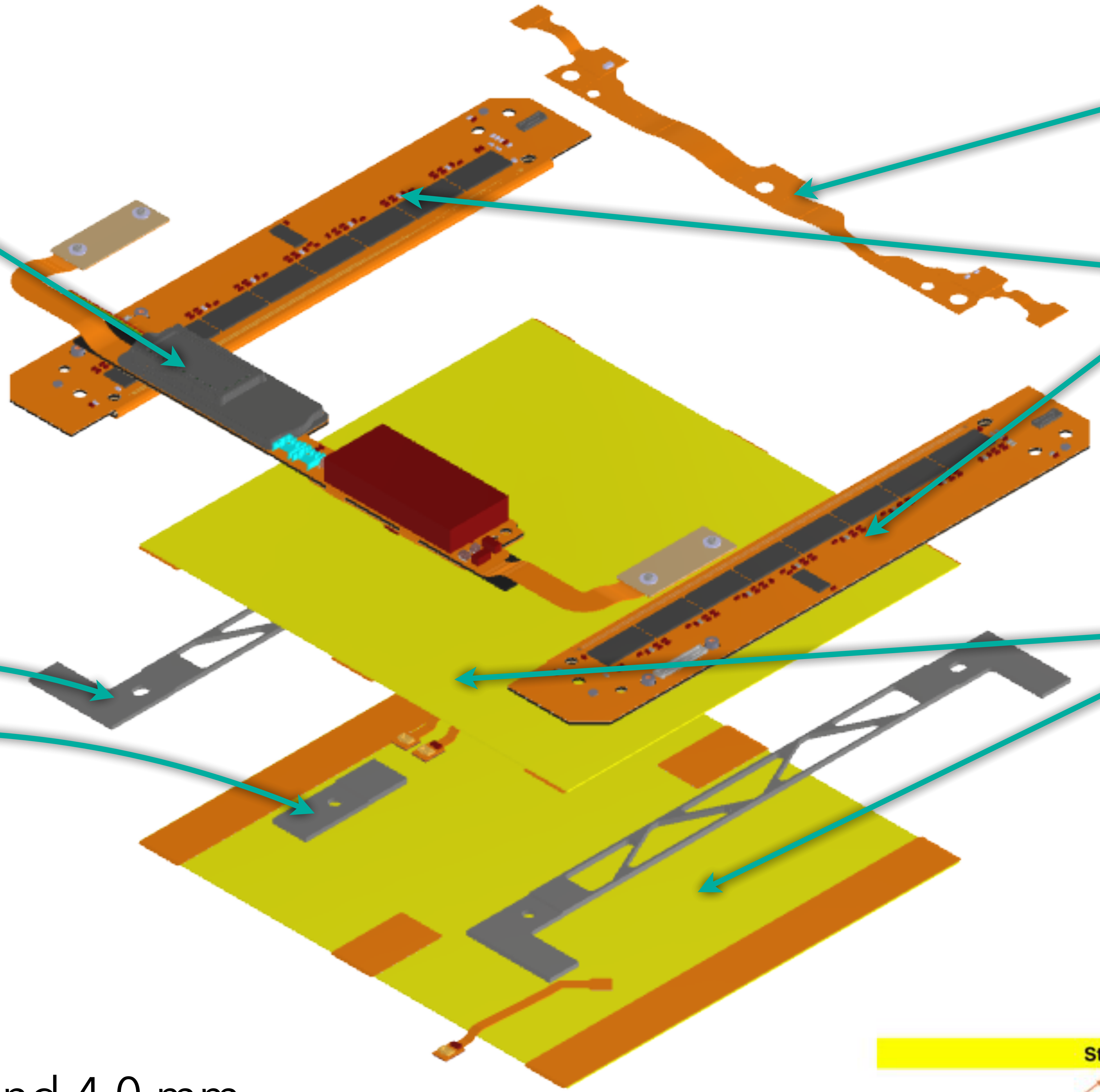
- Modules arranged in 6 barrel layers and 5 end cap double-disks
- Only two different module types
  - different sensor spacings are treated as variants with as many as possible identical components
  - requires optimization of only two designs



2S module design

SEH
- DCDC converter for powering
- lpGBT & VTRx+ for data transmission

Al-CF Bridges
- C-Fiber reenforced Al
- Positioning and cooling
- 2 main bridges
- 1 or 2 stump bridges
- Define sensor spacing

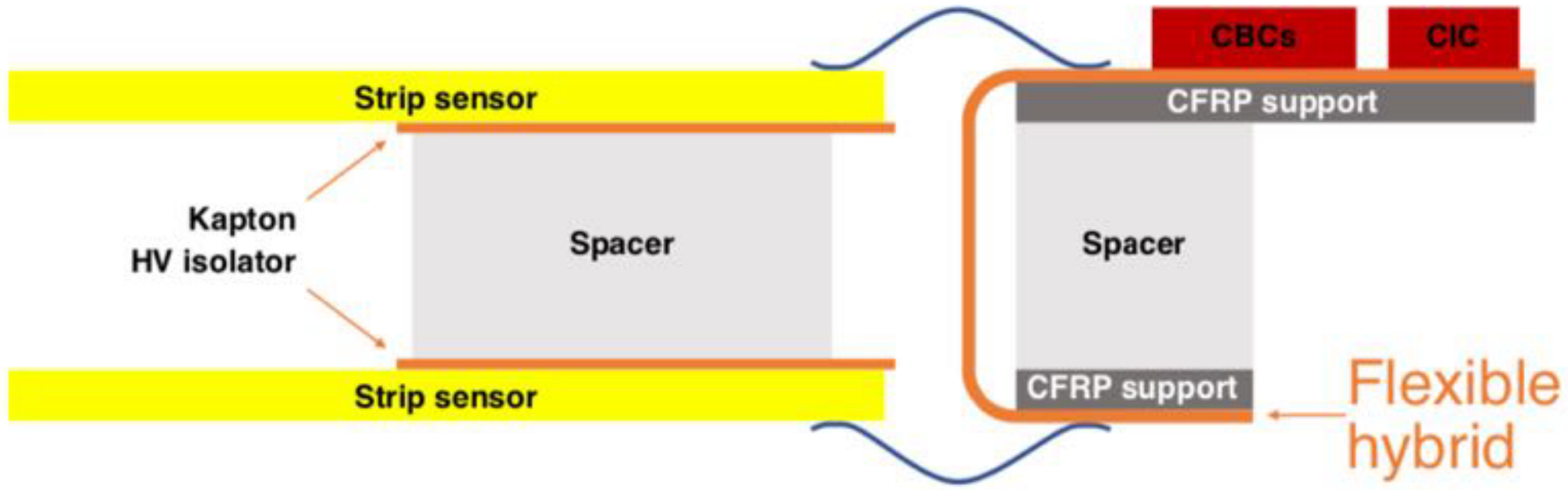


Ground Balancer
- connects left and right FEH

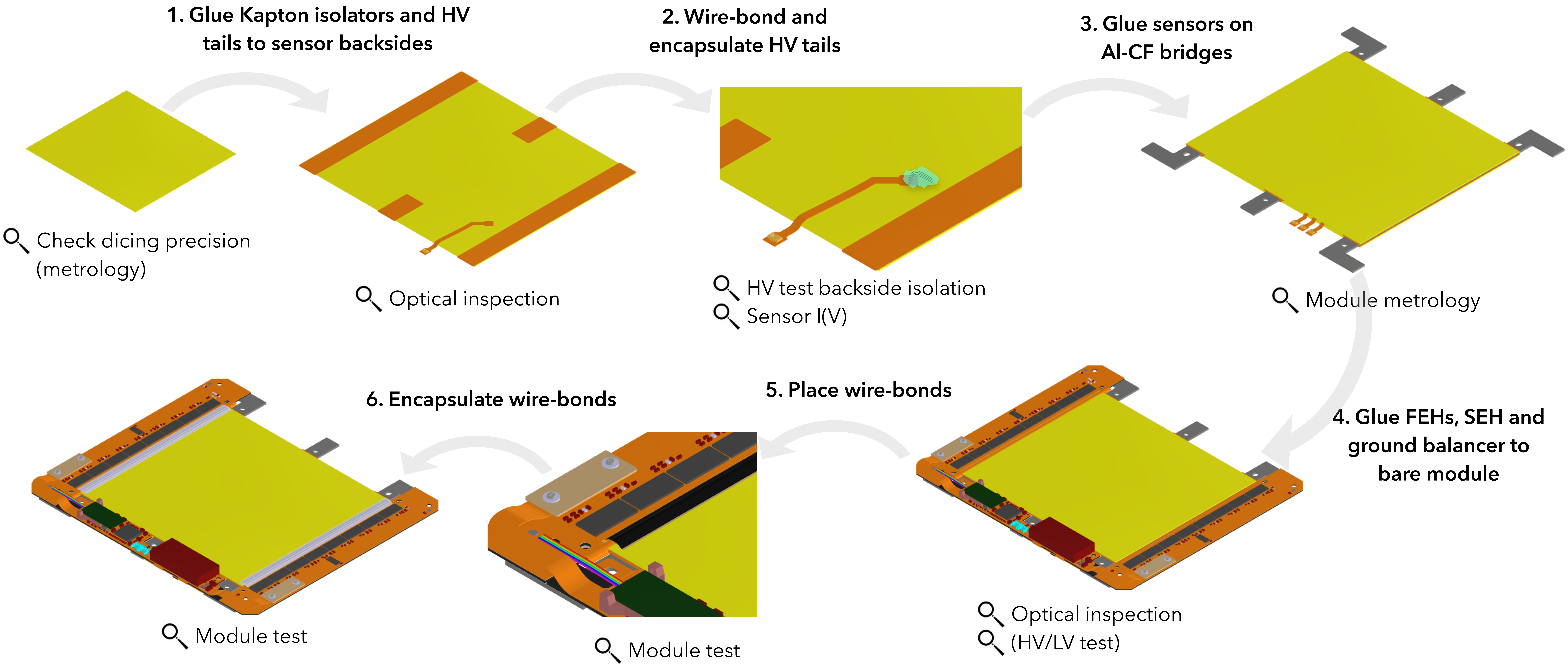
FEH
- 8 CBC
- 1 CIC
- Folded around AlN spacers to connect to both sensors

2 x Strip Sensor
- 2 x 1016 strips each
- 290 µm (320 µm) active (physical) thickness
- ~10 cm x 10 cm
- ~5 cm long strip

- Installed at radii > ~60 cm
- Sensor spacings: 1.8 mm and 4.0 mm
- Cooling through 5 or 6 cooling contacts
- Correlation logic implemented in CMS Binary Chip (CBC)

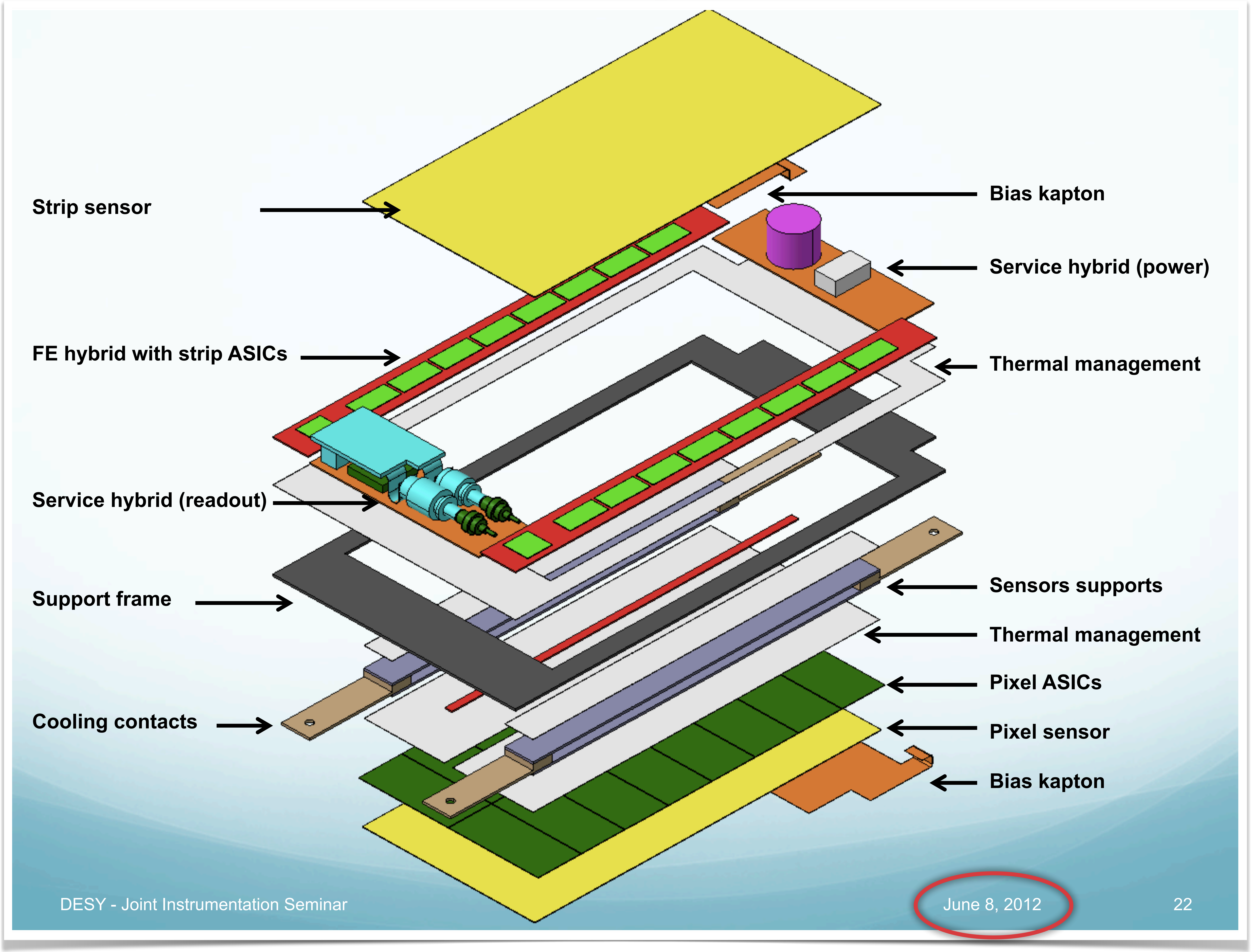


2S module assembly



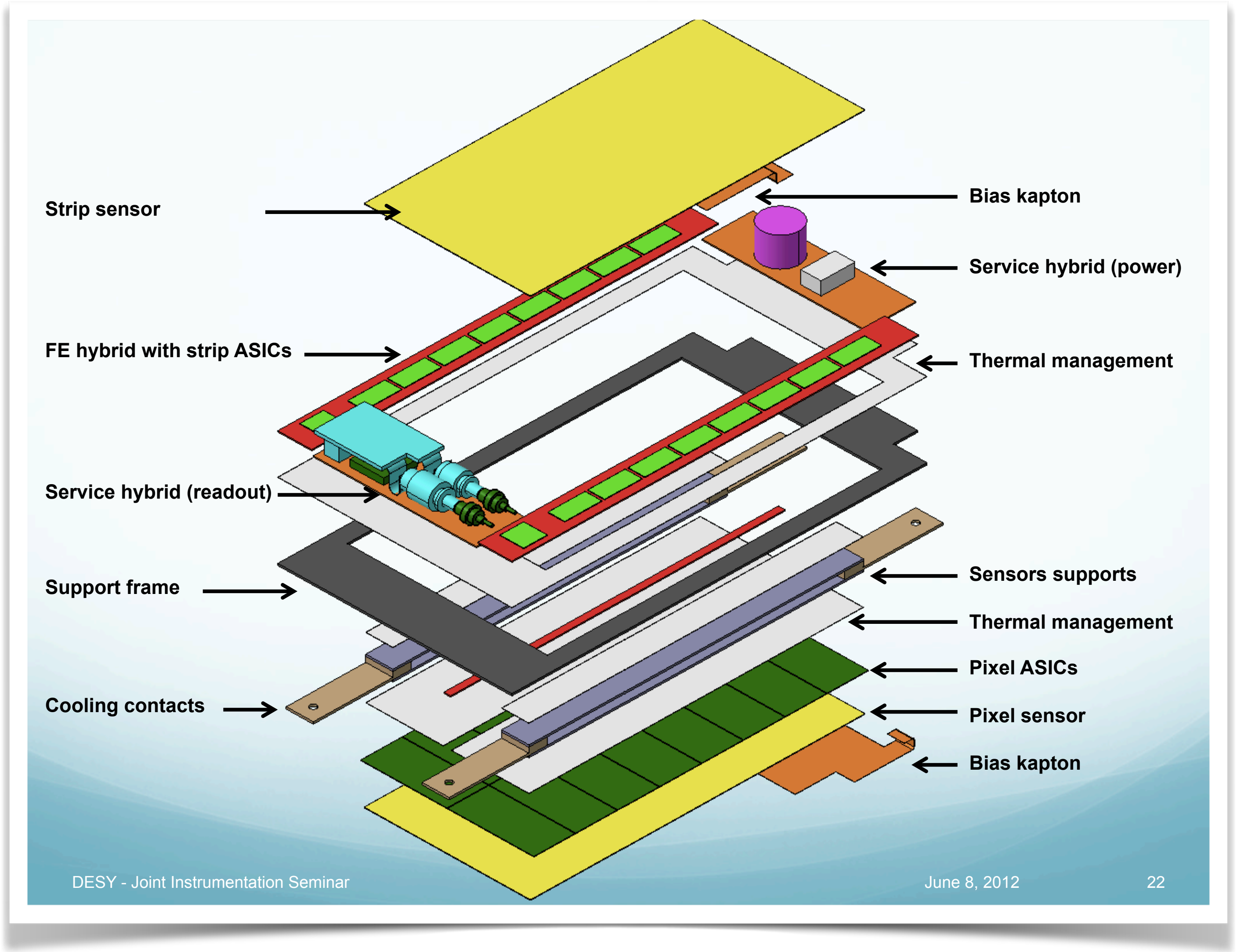
- In bare module assembly (3) sensors are pushed against precision stops on a fixture
- Module assembly precision relies on precision of sensor dicing

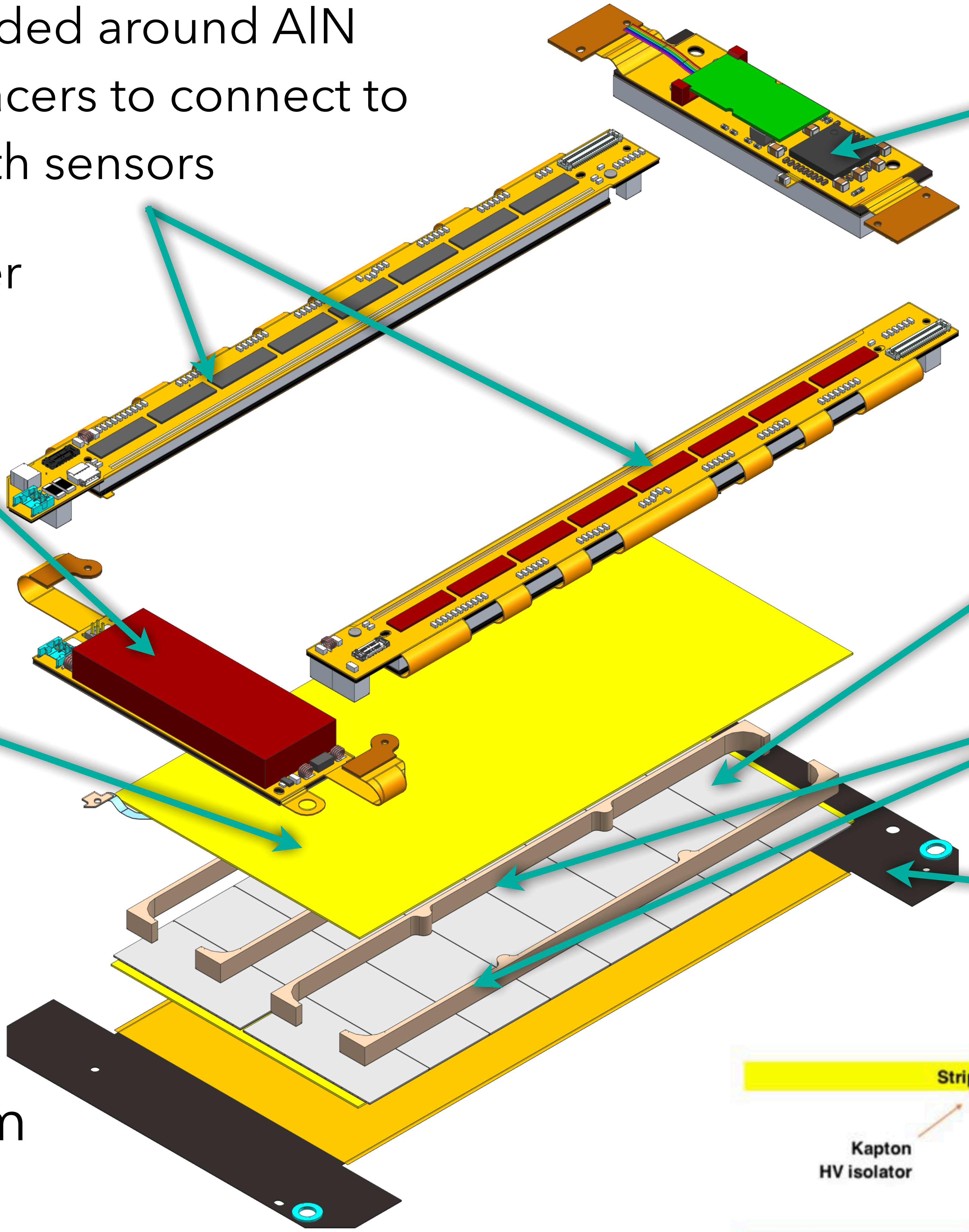
PS module design - how it all started



- The early ideas of a PS module as presented by Duccio Abbaneo in the Joint Instrumentation Seminar on 8 June **2012**

PS module design (evolution)





FEH
- 8 SSA
- 1 CIC
- Folded around AlN spacers to connect to both sensors

ROH
- lpGBT & VTRx+ for data transmission

POH
- DCDC converter for powering

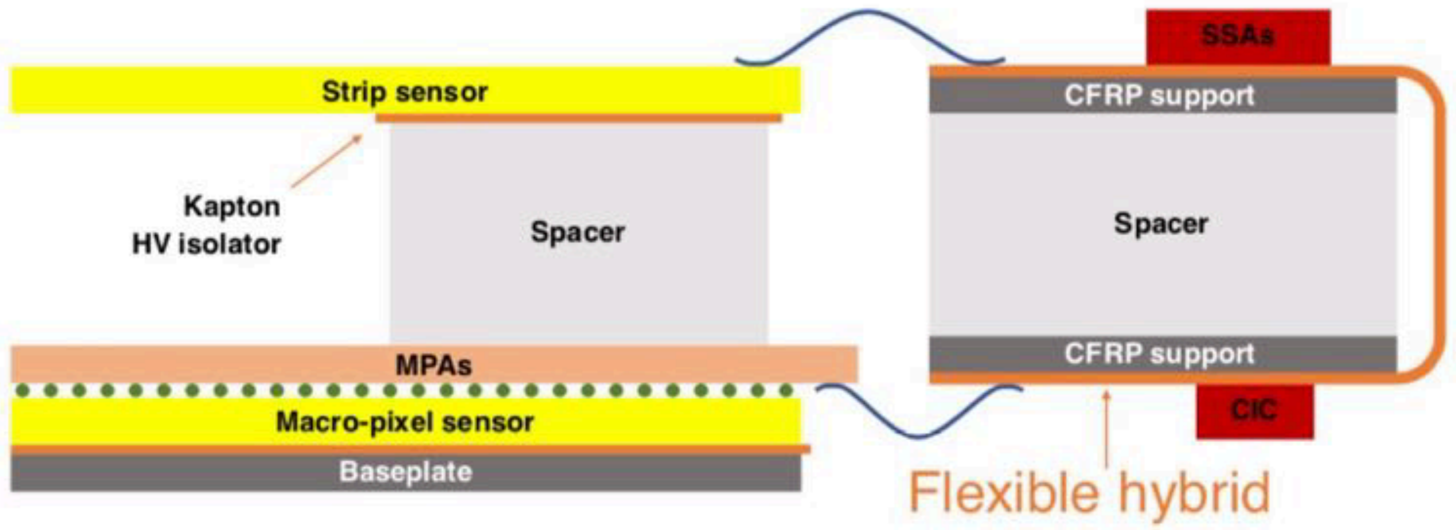
MaPSA
- Macro Pixel ASIC
- ~ 10 cm x 5 cm Macro Pixel Sensor (PSp)
- 290 µm (320 µm) active (physical) thickness

Strip Sensor (PSs)
- ~ 10 cm x 5 cm area
- 290 µm (320 µm) active (physical) thickness
- ~2.5 mm strip length

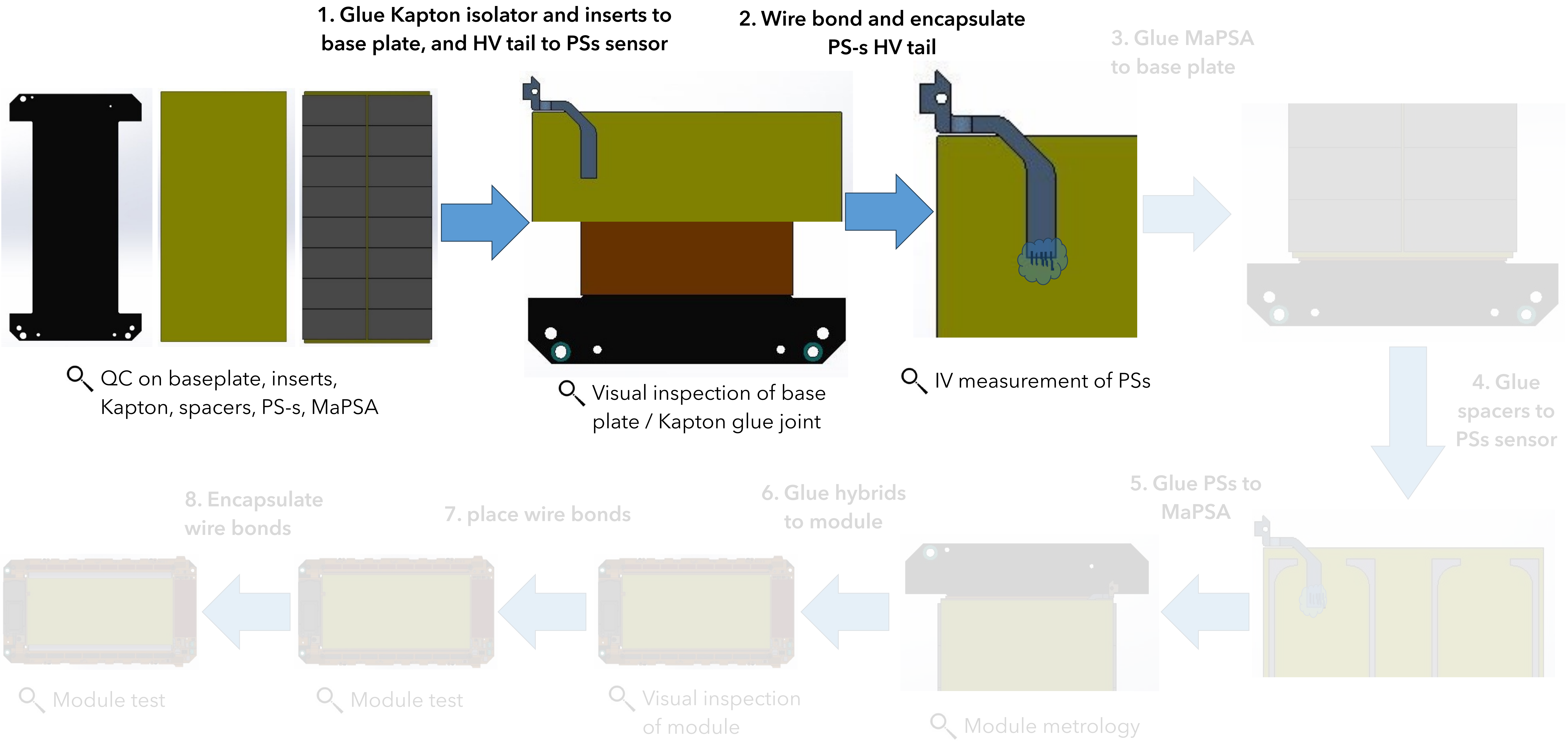
AlN Spacer
- Define sensor spacing

CFRP Base Plate
- 200 µm thickness

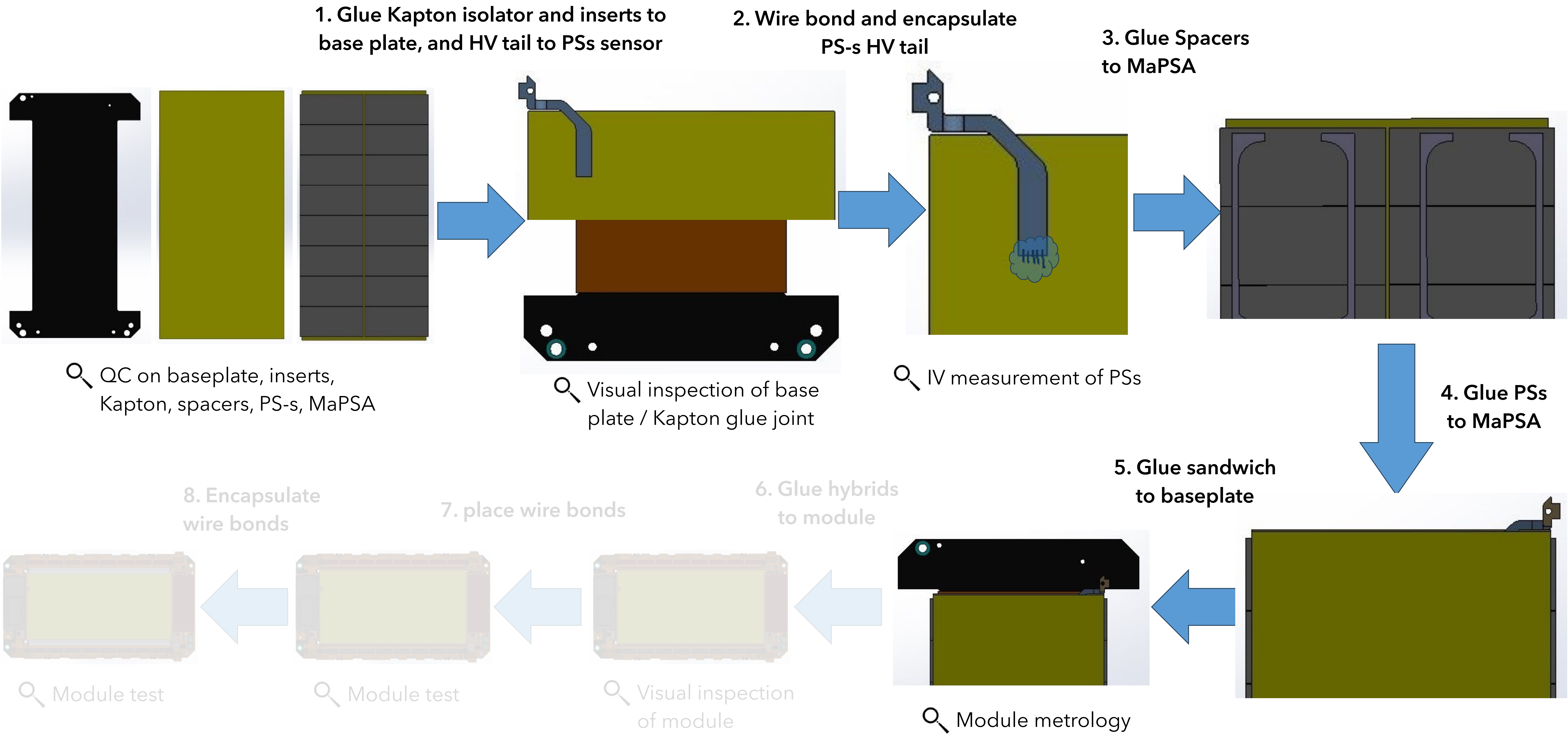
- Installed at radii < ~60 cm
- Sensor spacings: 1.6 mm, 2.6 mm and 4.0 mm
- Cooling through CFRP base plate
- Correlation logic implemented in Macro-Pixel ASIC (MPA)



PS module assembly

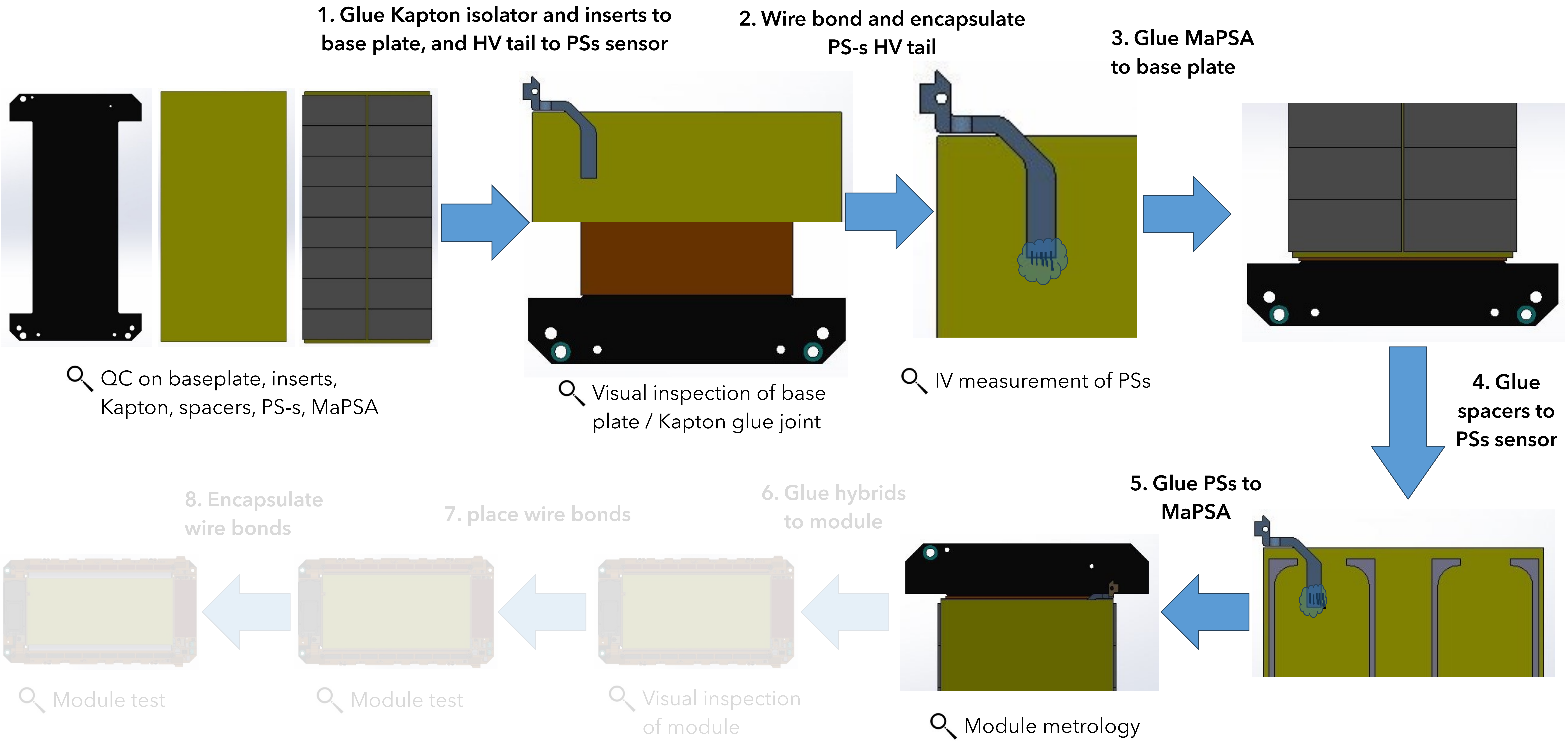


PS module assembly - fixture-based bare module



- For bare module assembly (3-5) sensors are pushed against precision stops on a fixture

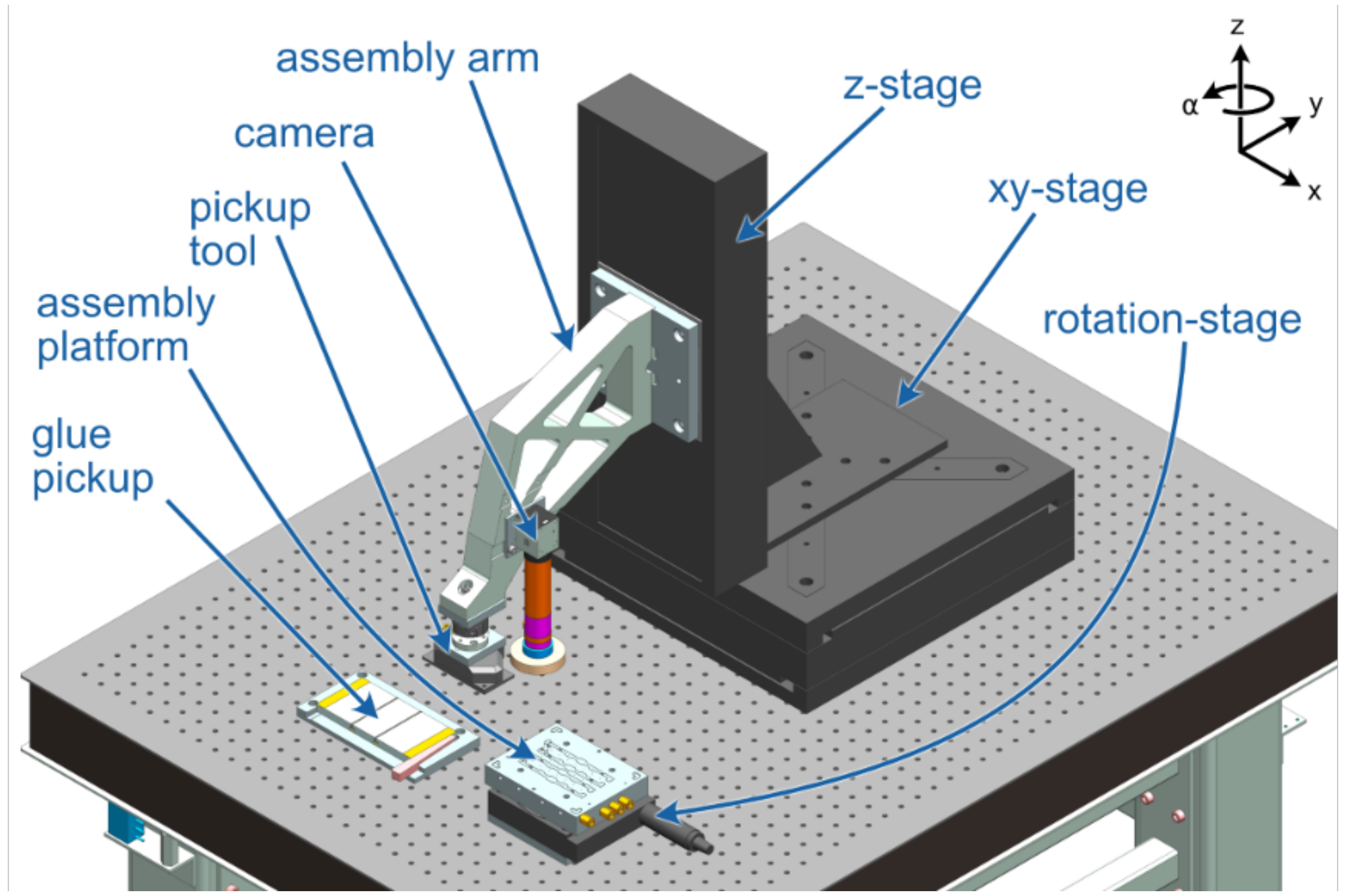
PS module assembly - robot-assisted bare module

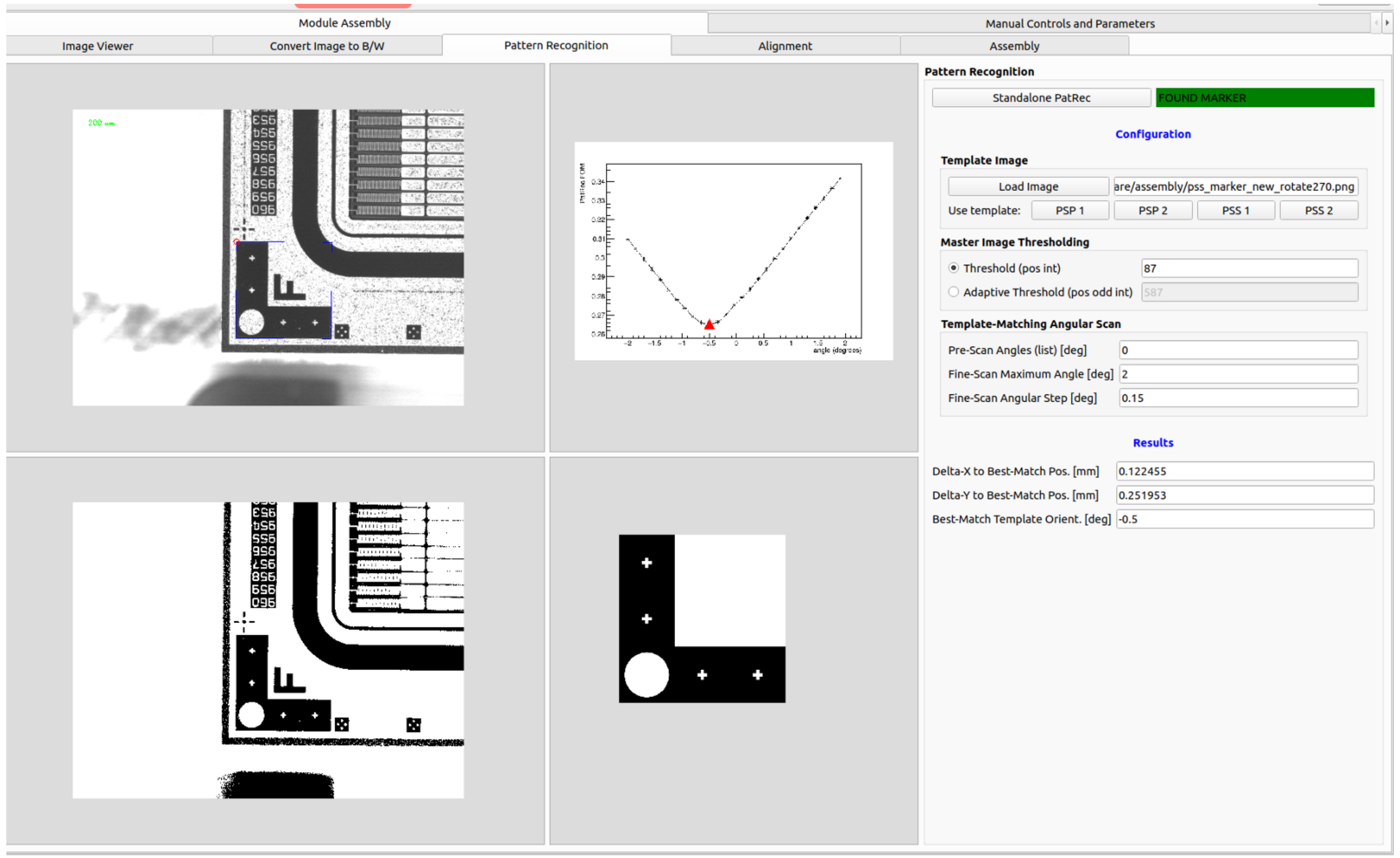


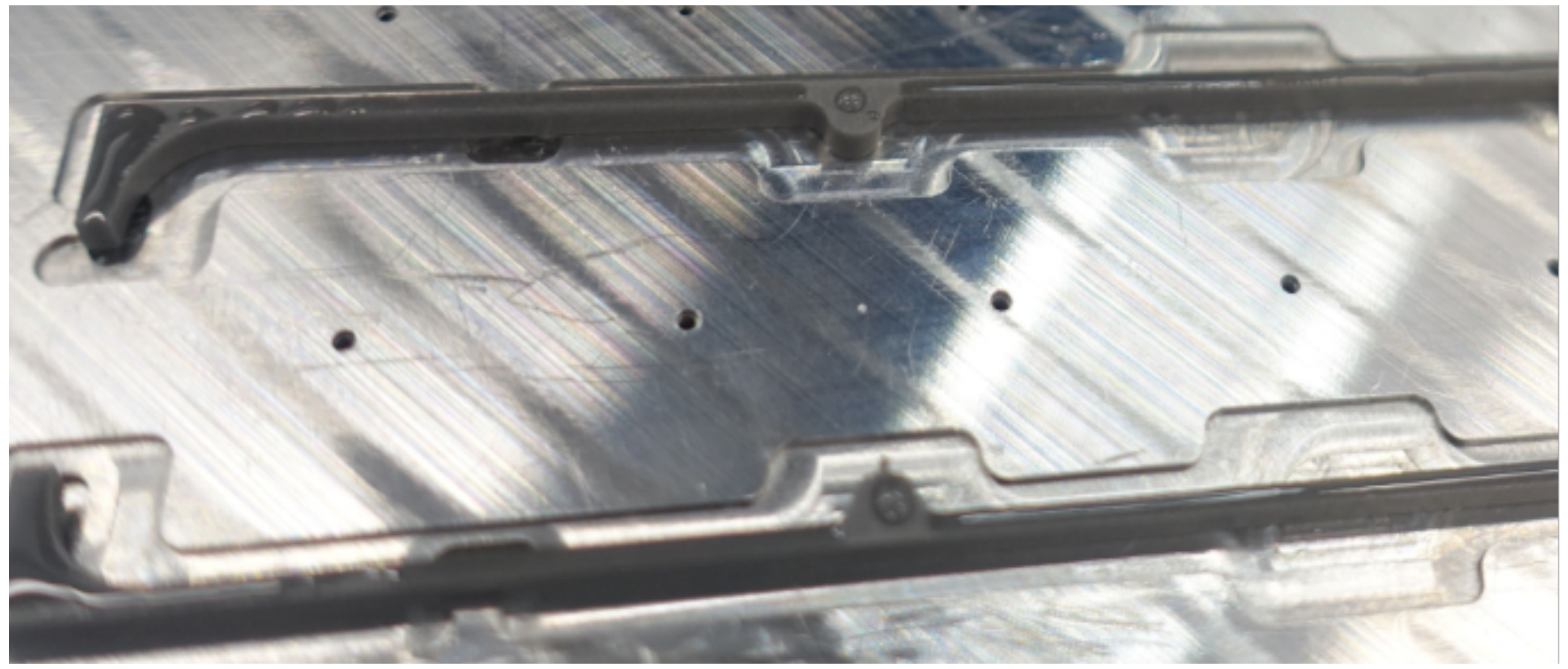
- Robot assisted bare module assembly (3-5) possible due to fiducials on both sensors facing upwards

Robot-assisted bare module assembly

- Development of procedure started by DESY
  - Partly funded by Helmholtz Detector Portfolio common fund
- Key features
  - Vacuum pickup tool and microscope camera mounted on a precision xyz-stage
  - Assembly platform on a rotation table
- Basic principle of procedure
  - Object 1 (e.g. PSs sensor) is placed on assembly platform
  - Position is measured with microscope camera
  - Object 1 is lifted from platform with pickup tool
  - Object 2 (e.g. AlN spacers) is placed on assembly platform and position is adjusted with rotation table
  - Object 1 is lowered and glued to Object 2
- Procedure adopted by US East and US Midwest assembly centers



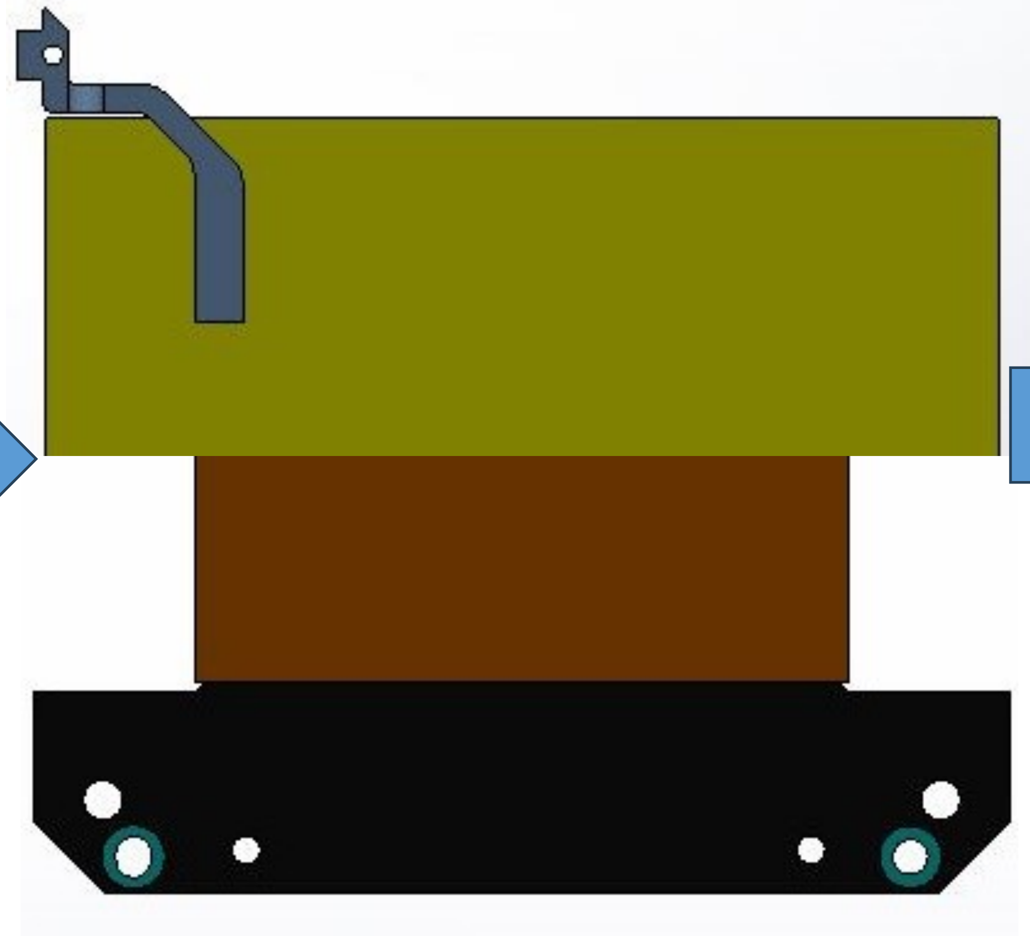




PS module assembly

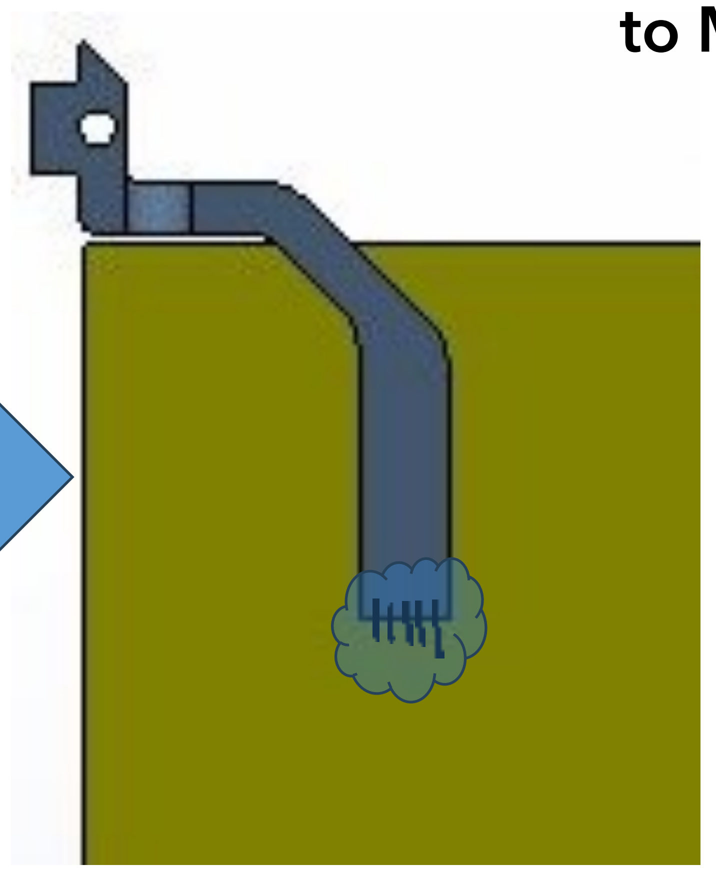
1. Glue Kapton isolator and inserts to base plate, and HV tail to PSs sensor

QC on baseplate, inserts, Kapton, spacers, PS-s, MaPSA



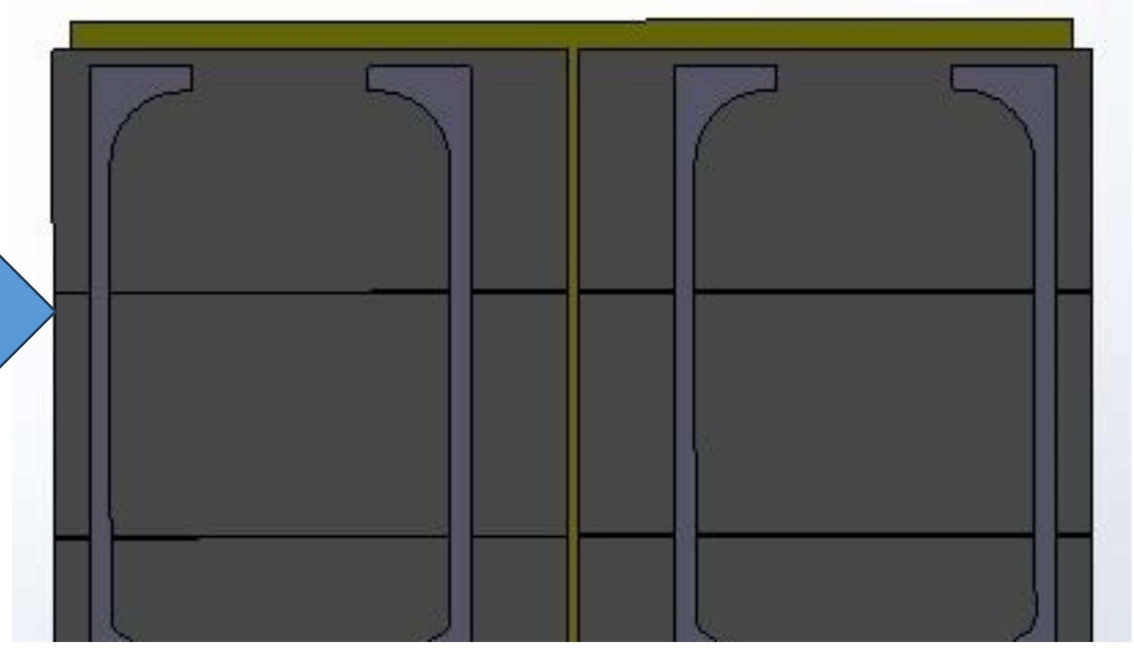
Visual inspection of base plate / Kapton glue joint

2. Wire bond and encapsulate PS-s HV tail



IV measurement of PSs

3. Glue Spacers to MaPSA

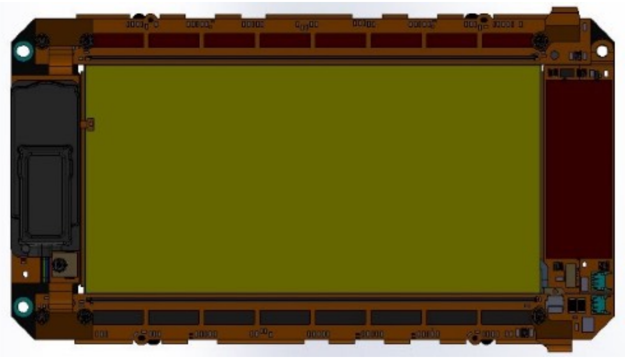


4. Glue PSs to MaPSA

5. Glue sandwich to baseplate

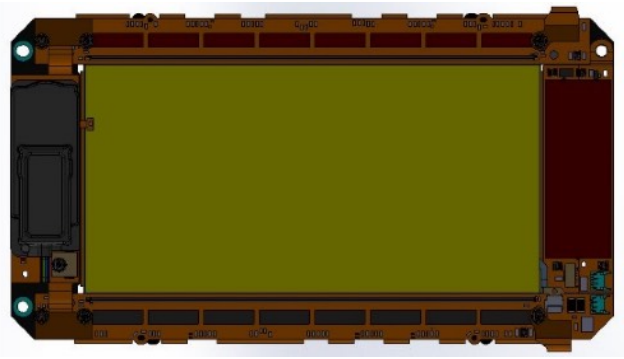
Module metrology

6. Glue hybrids to module



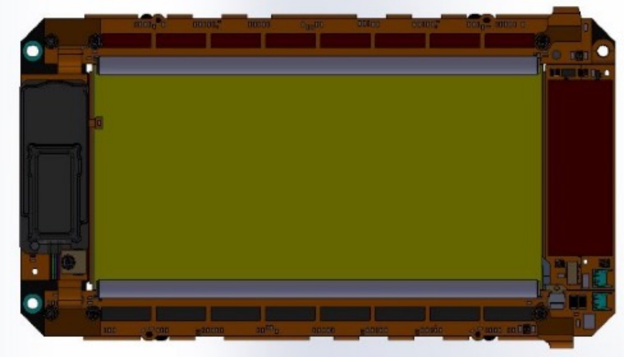
Visual inspection of module

7. place wire bonds



Module test

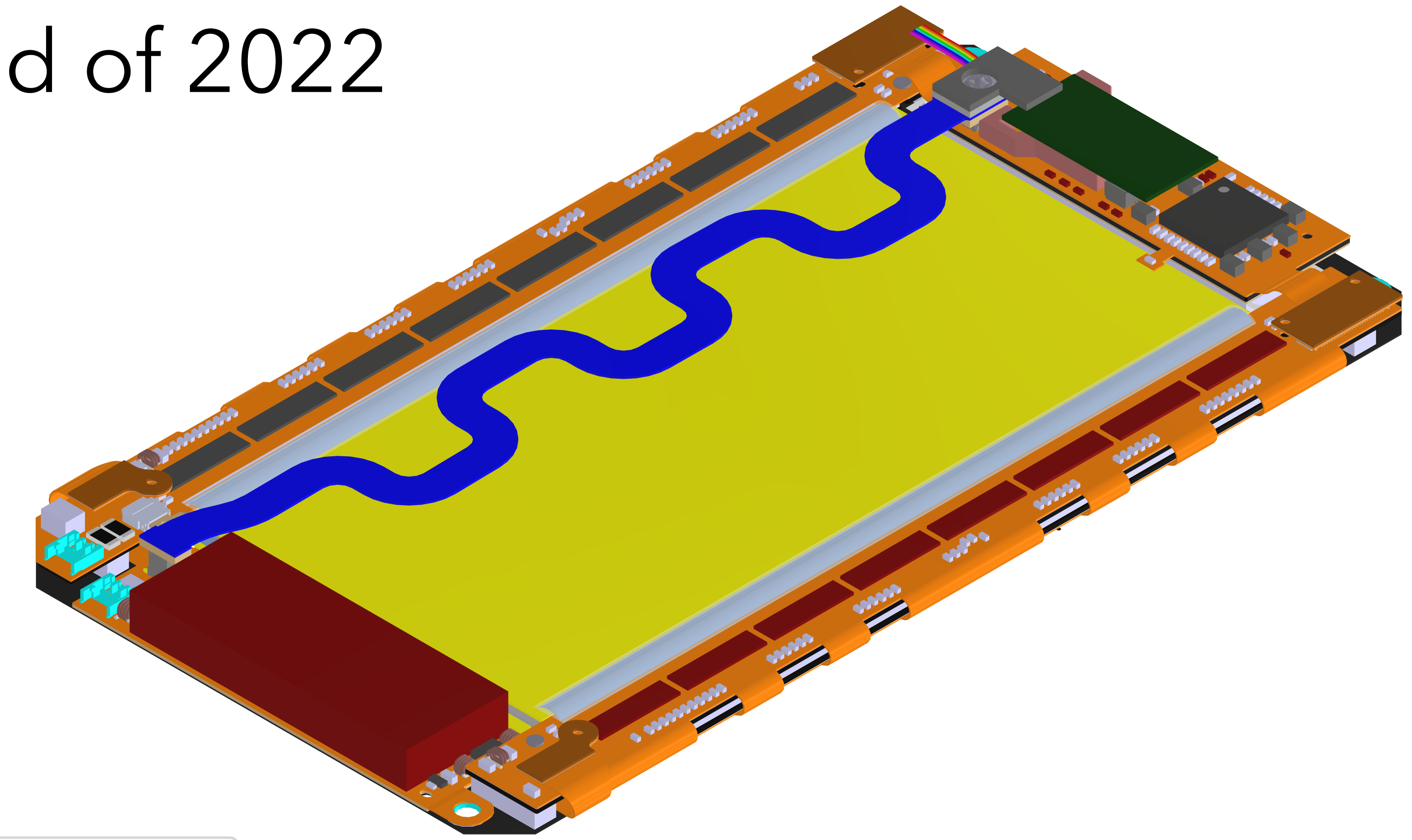
8. Encapsulate wire bonds

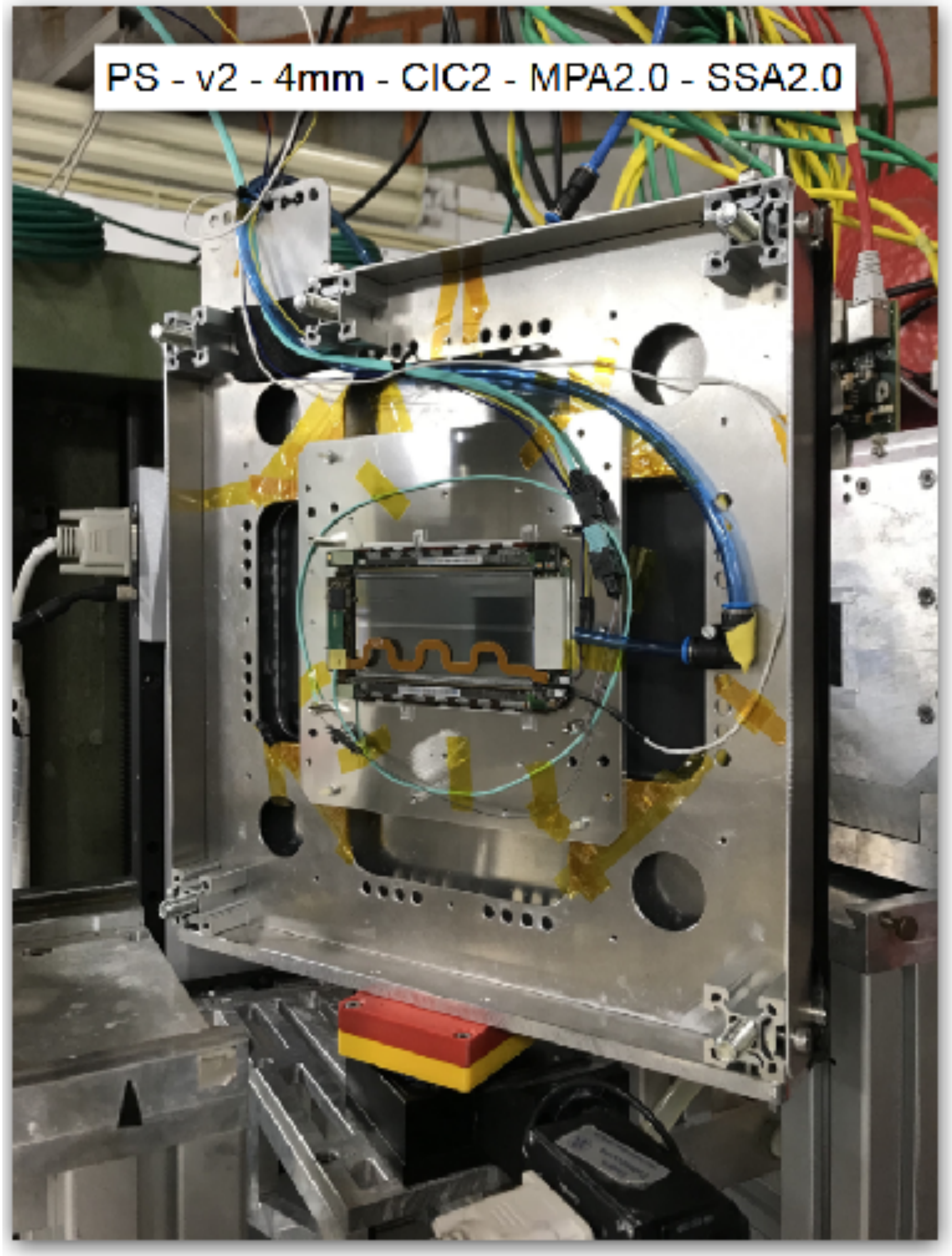


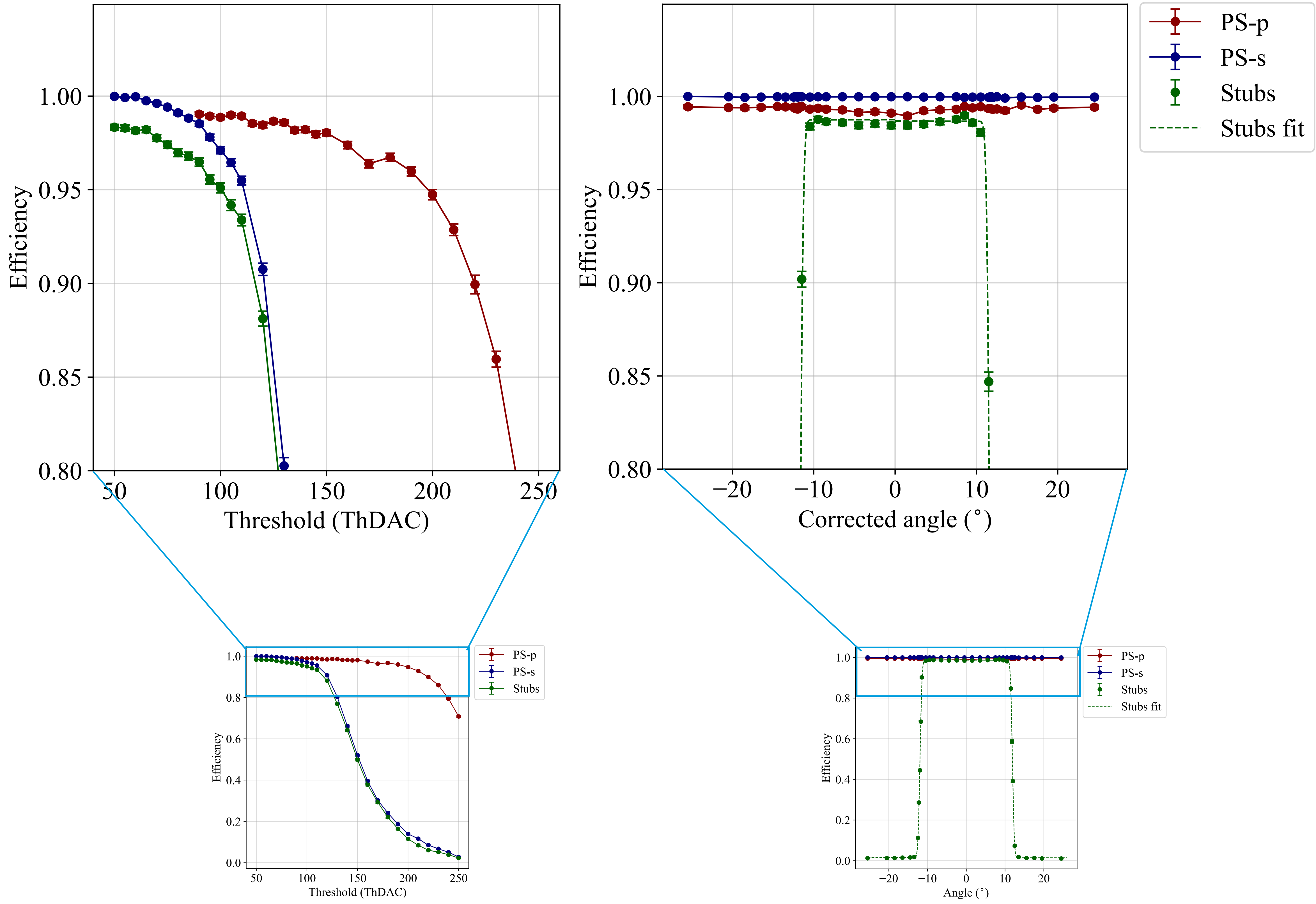
Module test

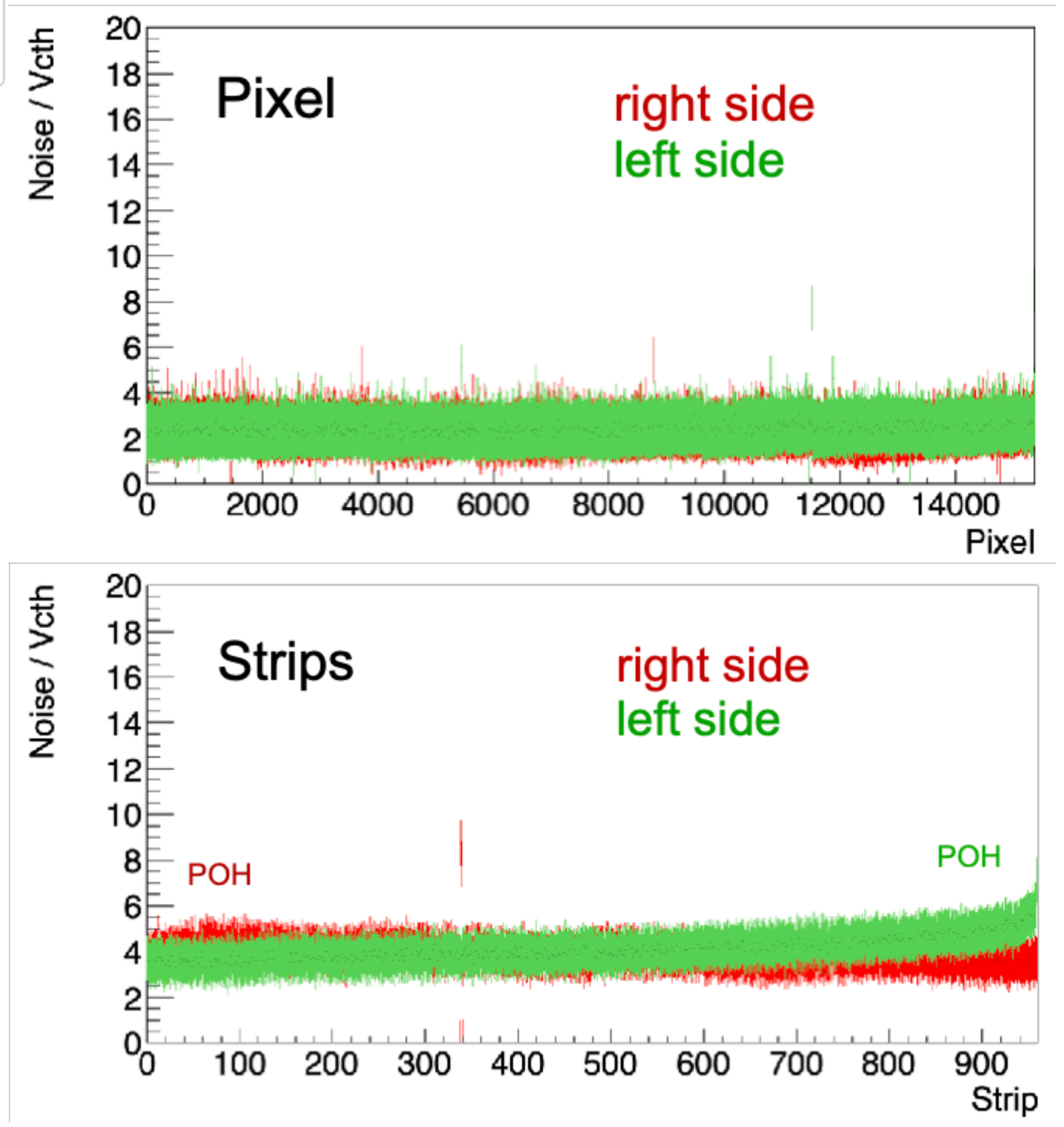
PS module performance

- PS prototype module with final design MPAs tested at DESY test beam end of 2022
  - Good performance
  - Stub turn-on at expected angle
  - High efficiency in threshold and bias scan
- Latest modules with pre-series components show expected noise
  - Slightly increased noise on strips towards power hybrid





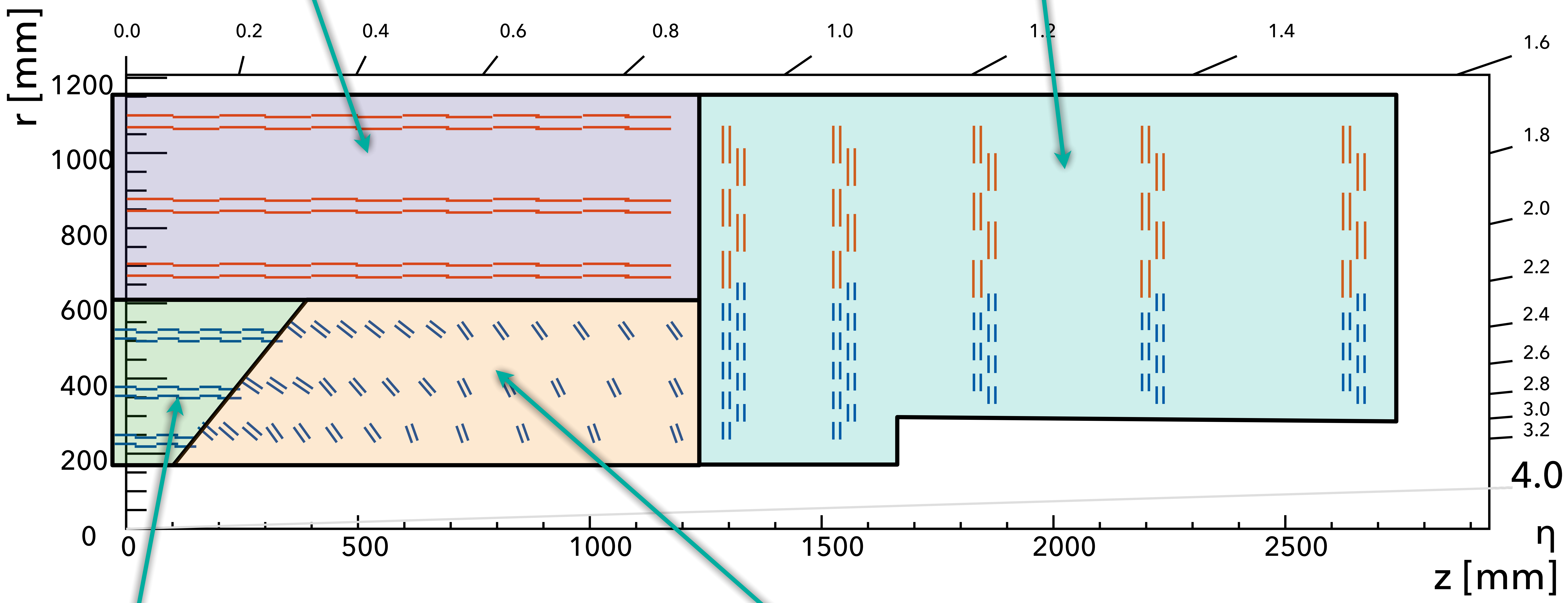




Sub-detectors

Tracker Barrel 2S (TB2S)
- 1.8 mm 2S modules

Tracker End Cap Double Disks (TEDD)
- 1.8 mm and 4.0 mm 2S modules
- 4.0 mm PS modules

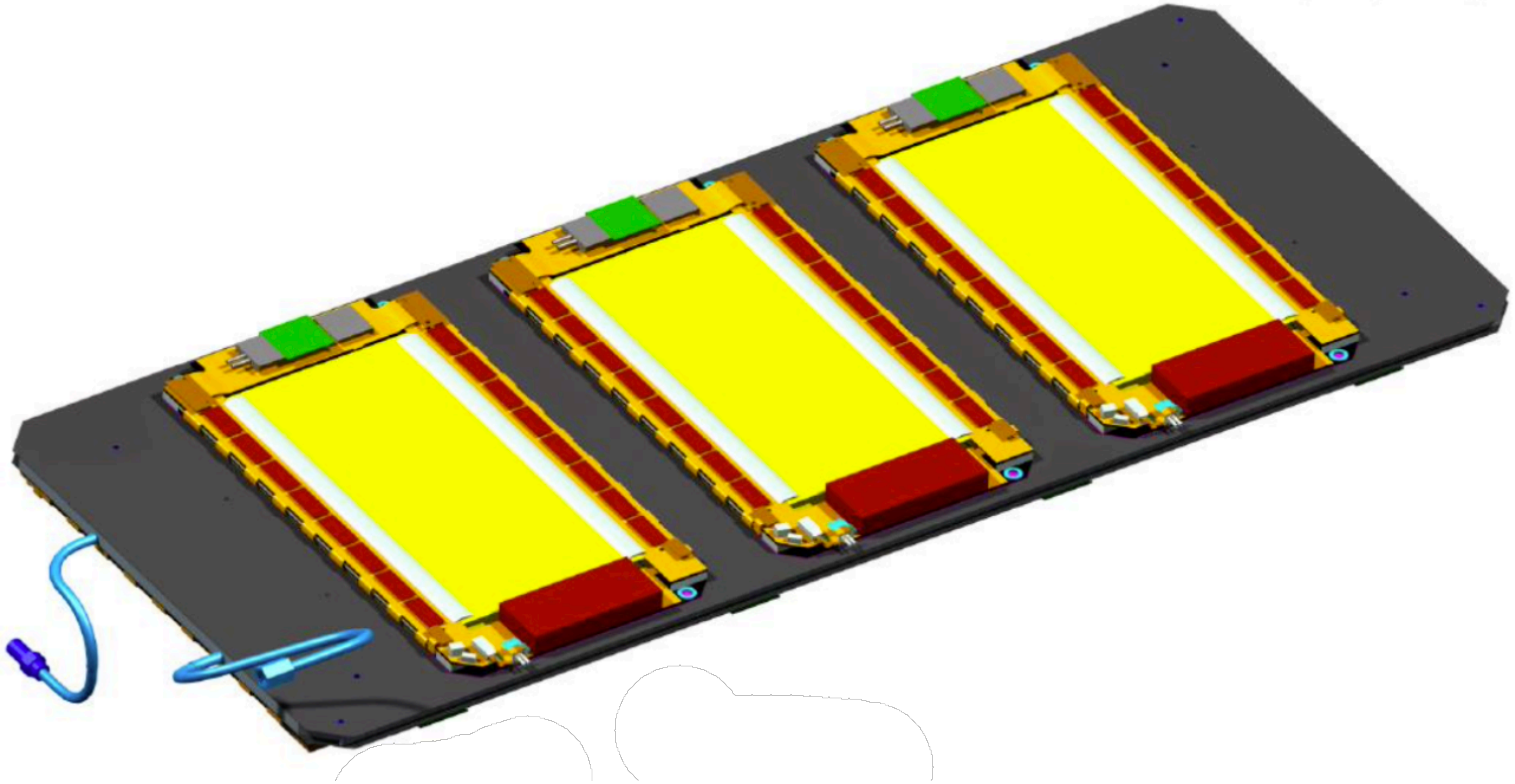


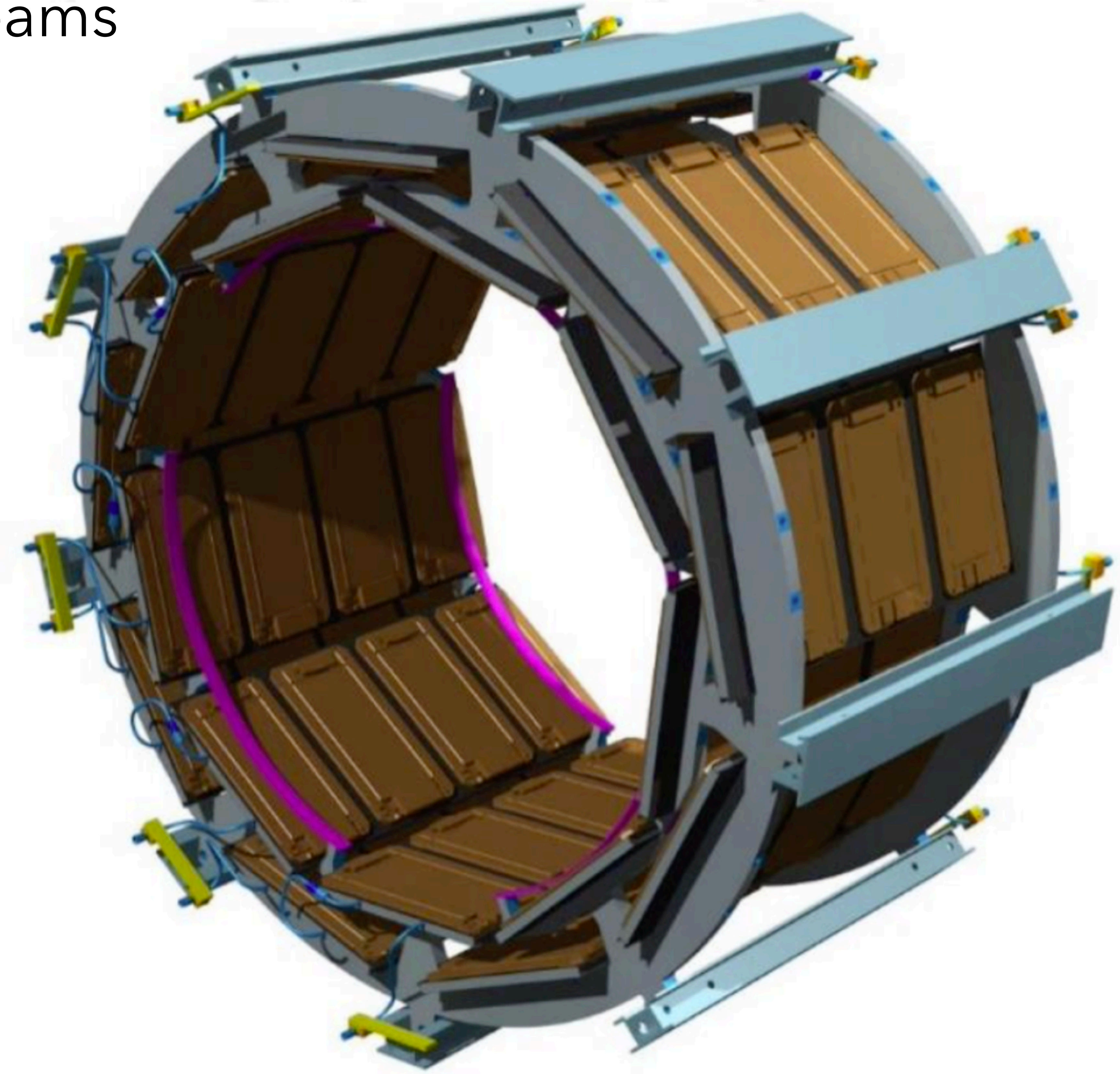
Flat Tracker Barrel PS (flat TBPS)
- 1.6 mm and 2.6 mm PS modules

Tilted Tracker Barrel PS (tilted TBPS)
- 2.6 mm and 4.0 mm PS modules

Flat TBPS

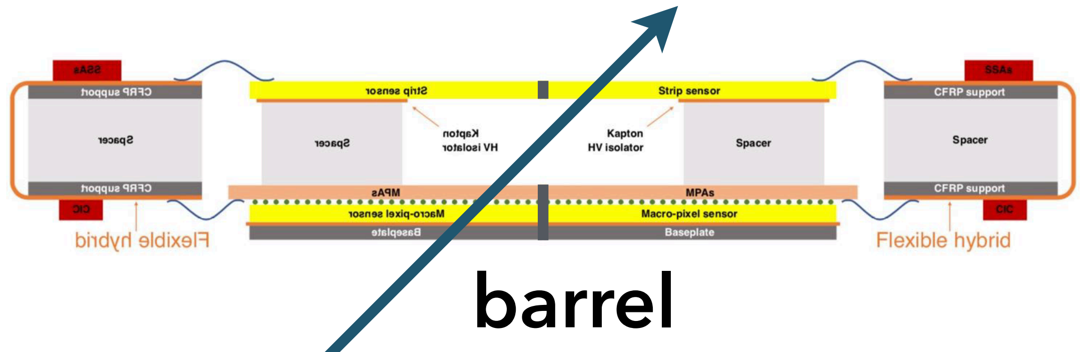
- Flat TBPS is the center portion of the TBPS
  - 3 detector layers populated with PS module
  - Tracking coverage up to $\eta < 0.6$
- Each layer is composed of carbon fiber/carbon foam composite sandwiches ➟ plank
- PS Modules will be installed onto the planks using phase-change TIM
  - Once PS modules are place, the whole plank is baked to 55°C in a vacuum oven
- Planks are supported by carbon foam end rings and carbon fiber i-beams

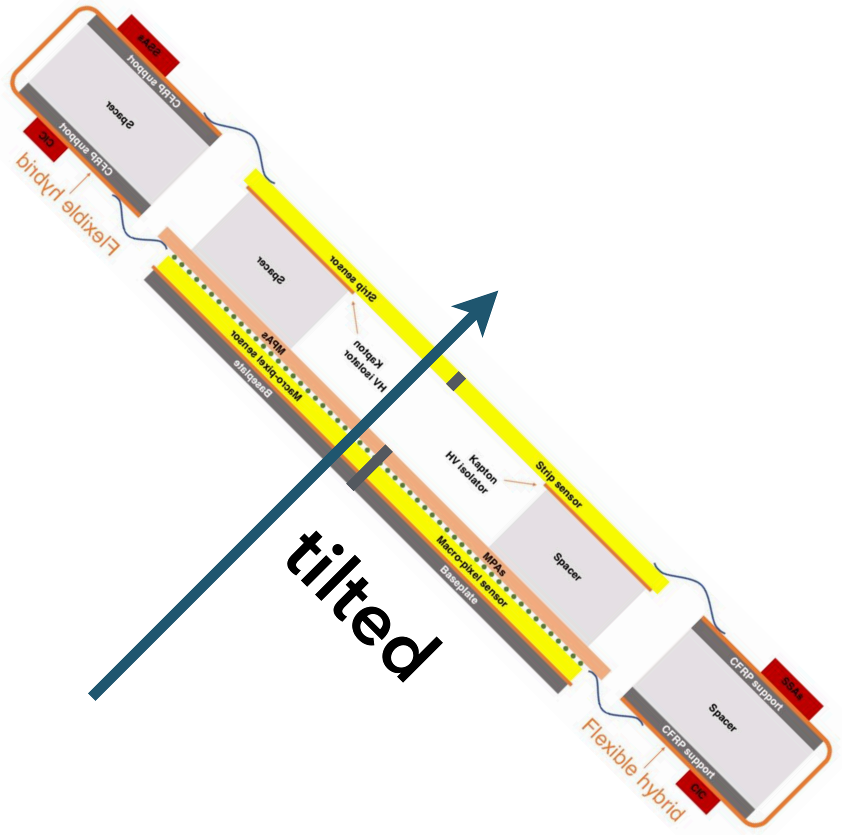


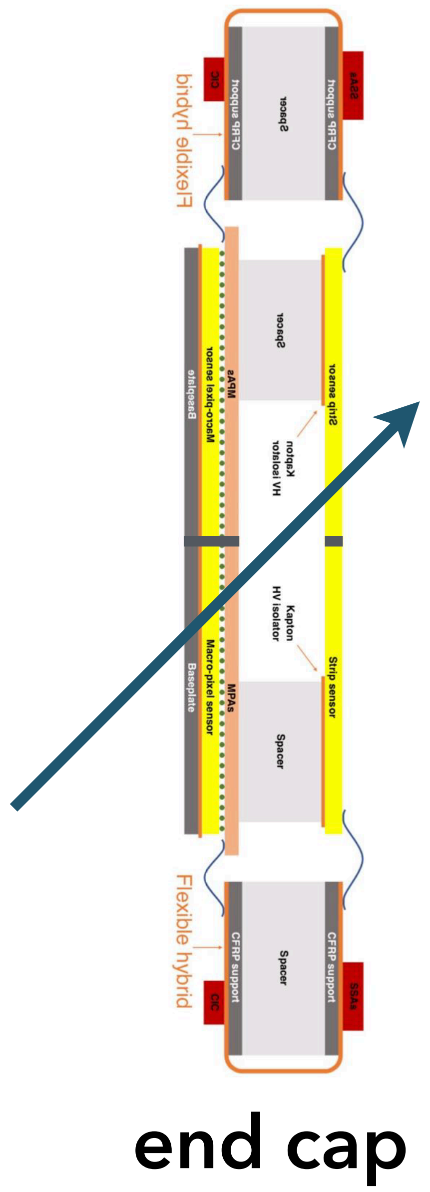


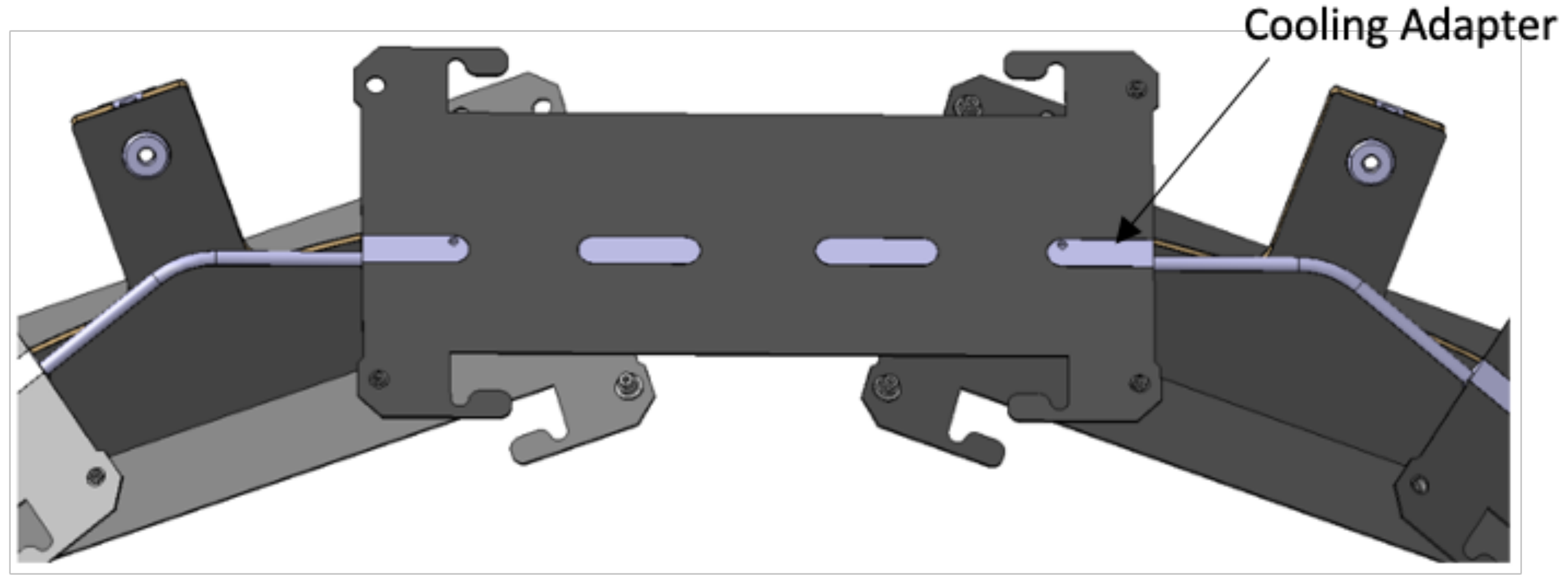
Tilted TBPS

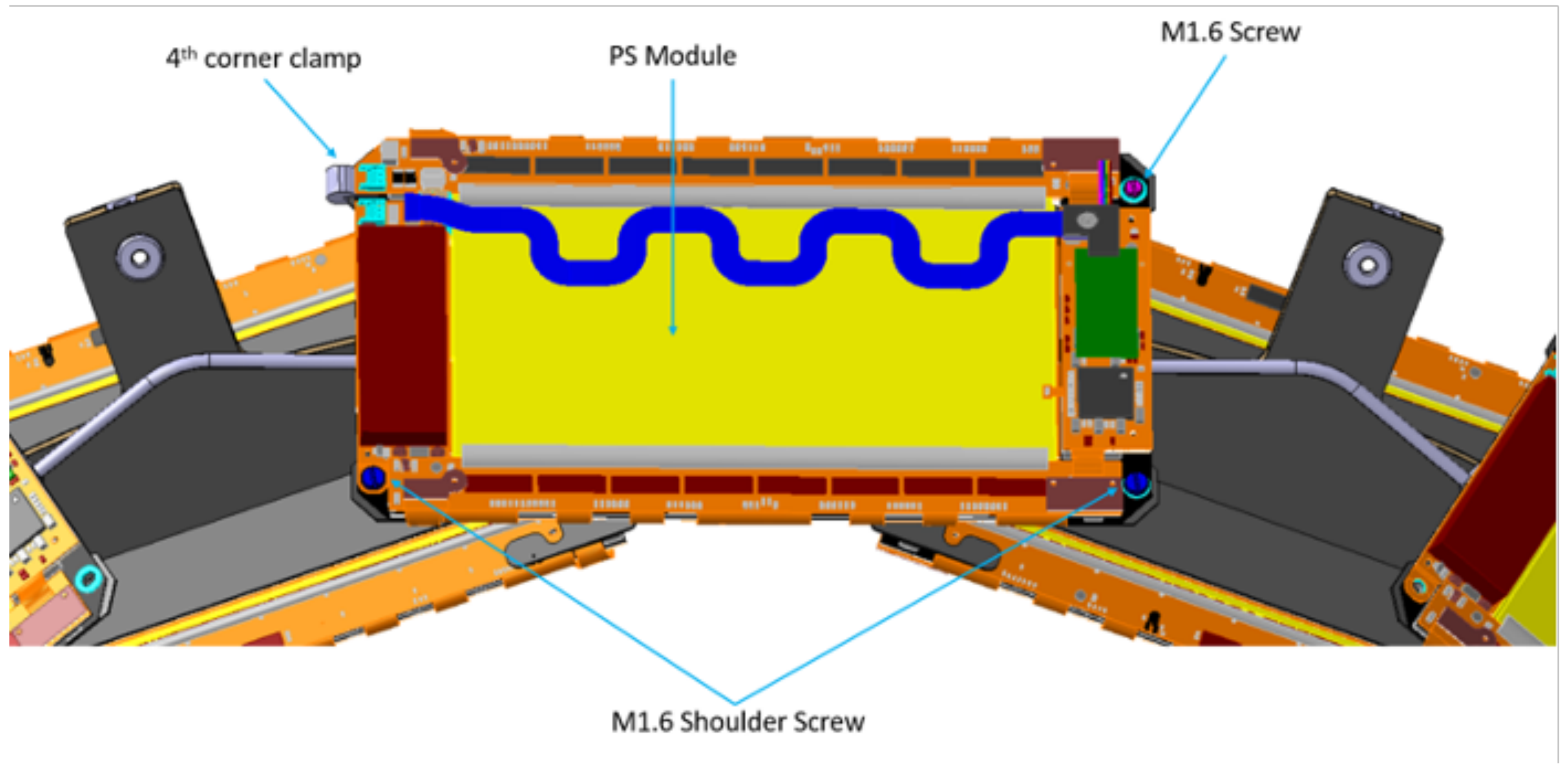
- Mechanics for tilted geometry is more complicated than a 'simple' barrel / end cap geometry - Why go for it anyway in the transition between barrel and end caps?
  - Less modules needed compared to classical design
  - Tilted modules improve acceptance for p_T discrimination logic
- Tilted TBPS consists of Carbon fibre sandwich rings
  - with cooling adapters and CFRP cooling plates
  - PS modules are mounted on cooling plates with RT-curing TIM
- Tilt angles limited to 47°, 60° and 72°

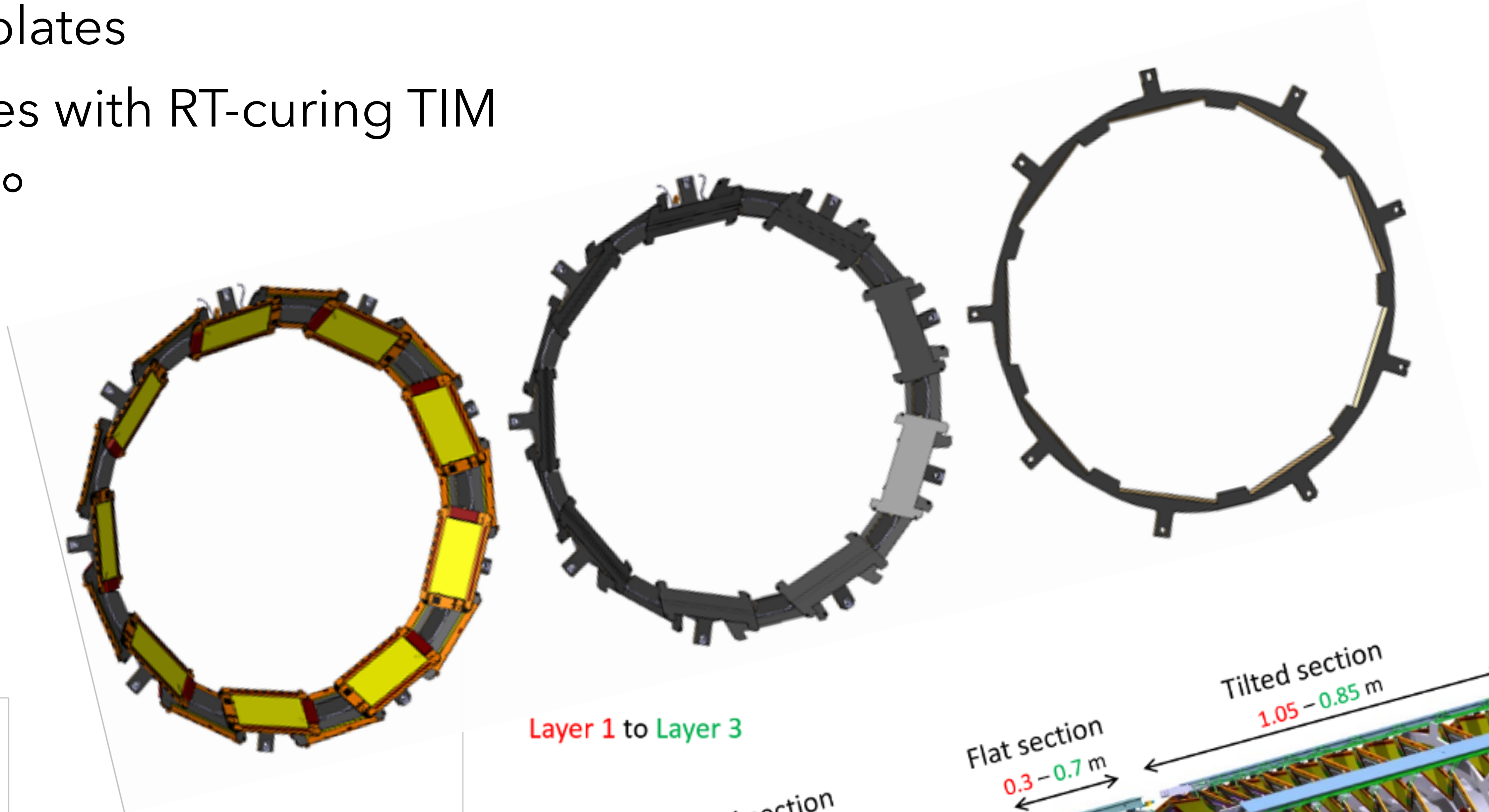


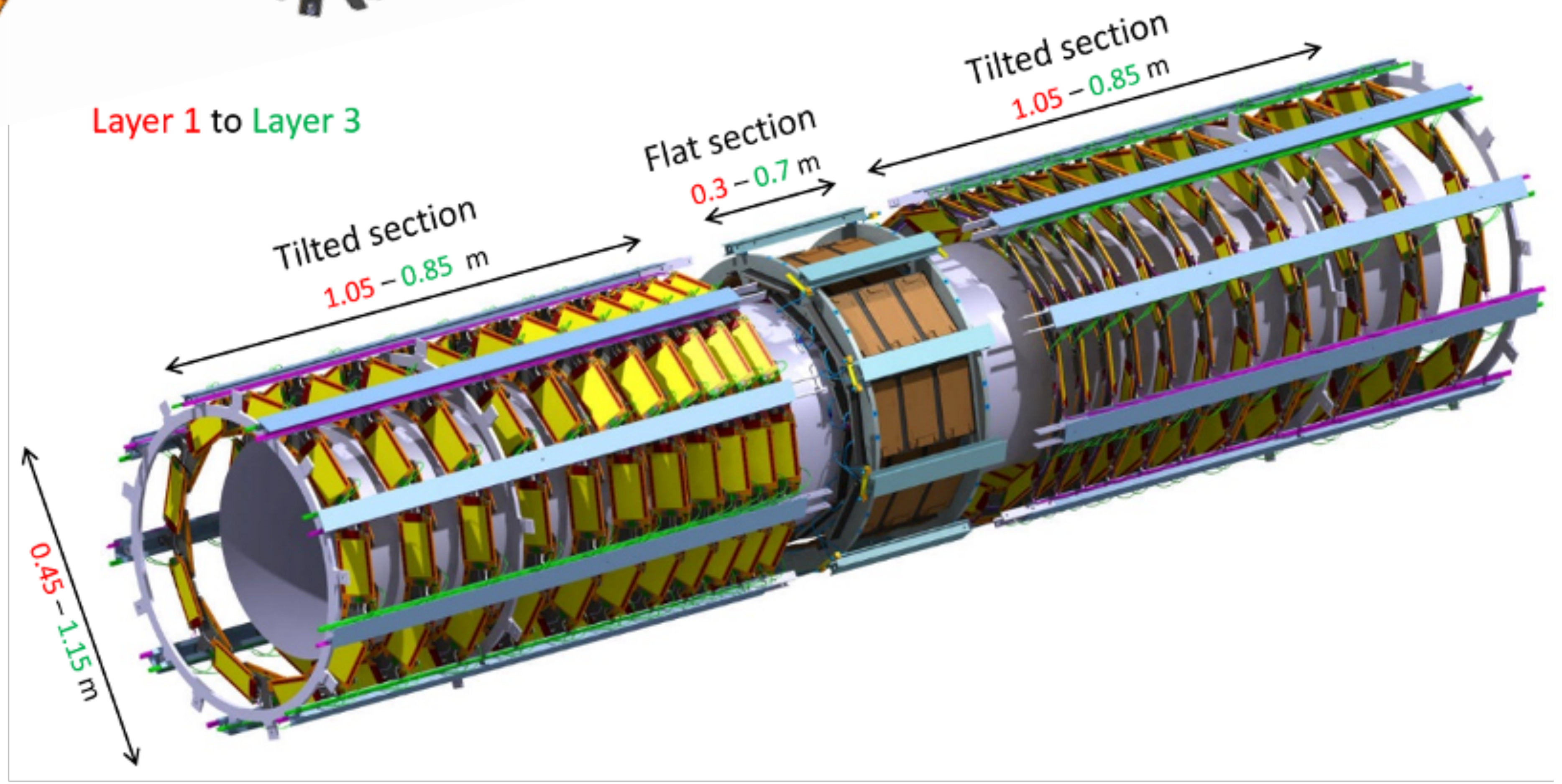






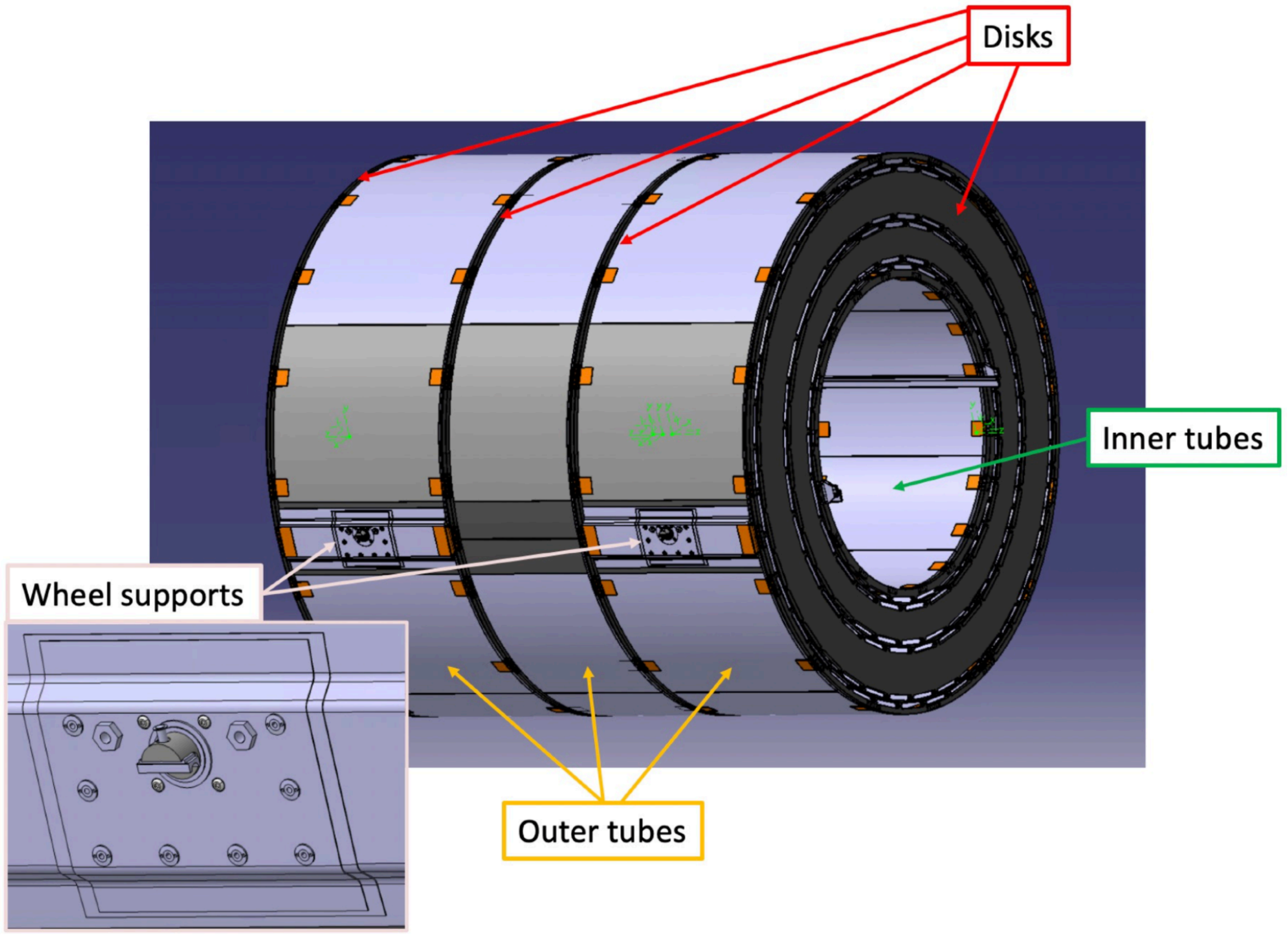


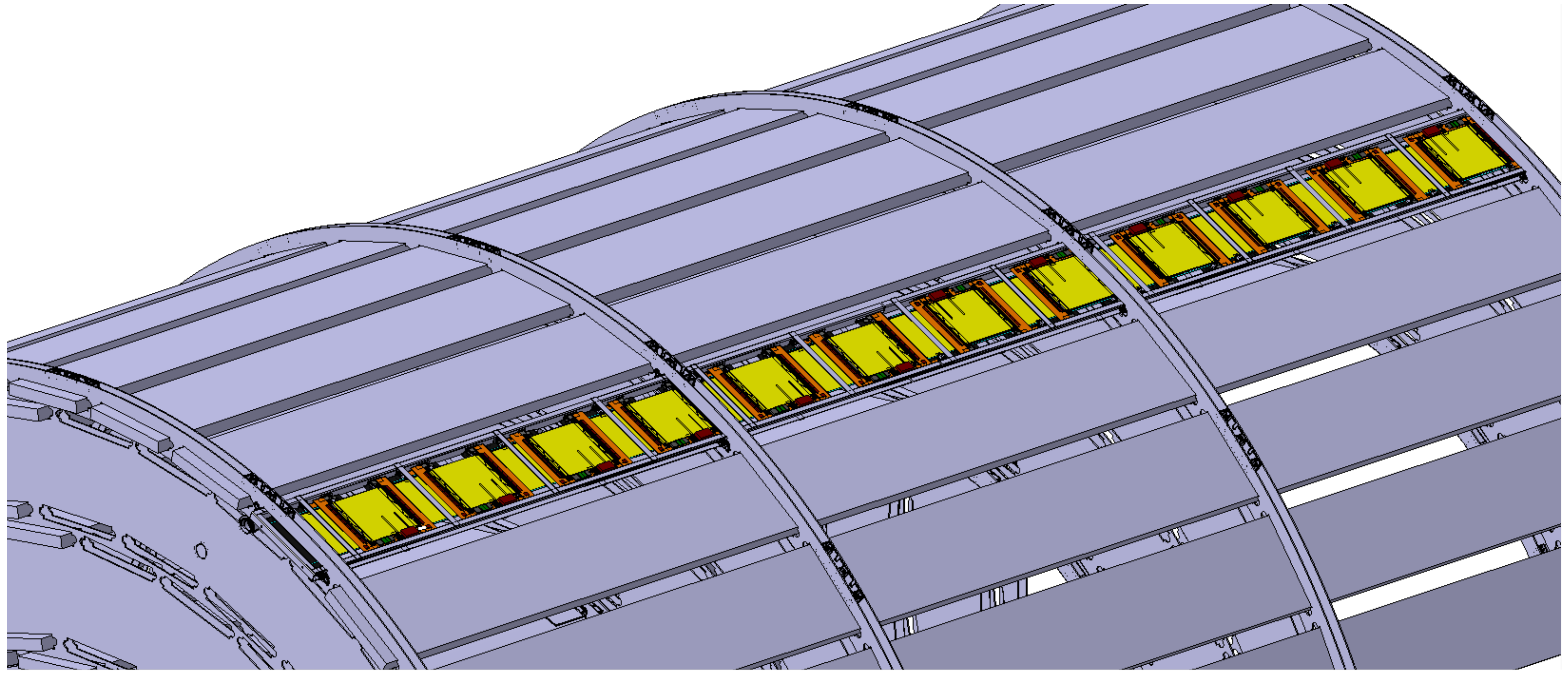


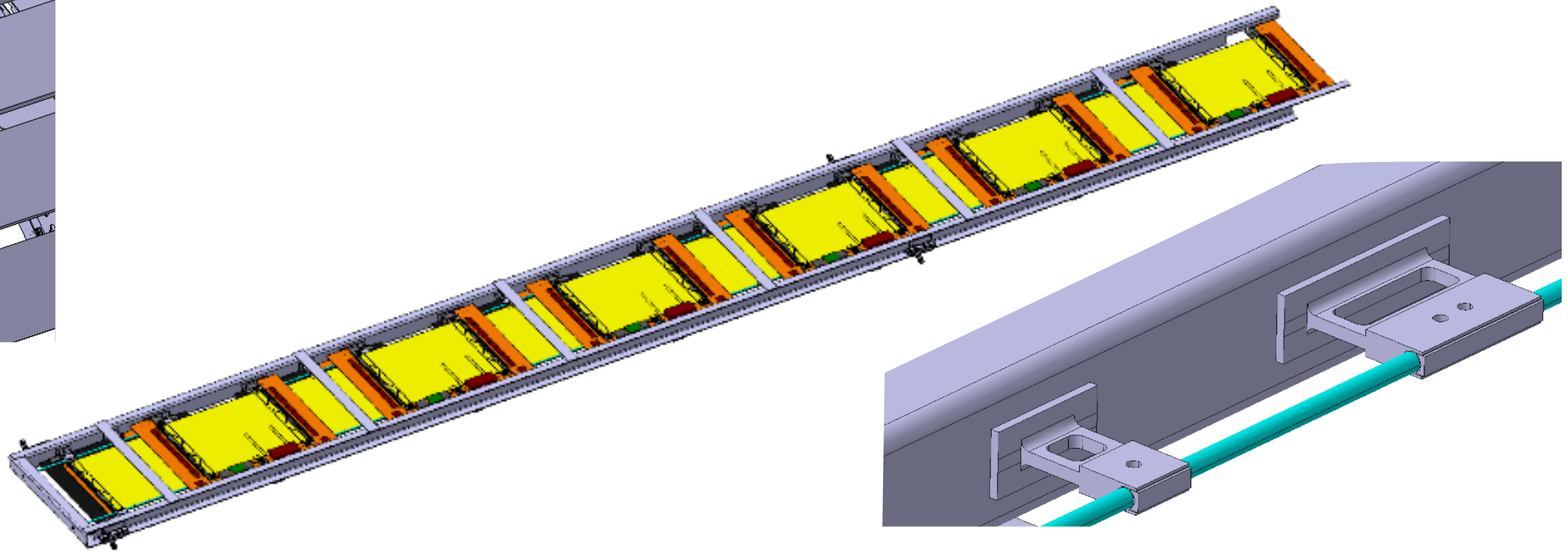


TB2S

- Design inherits from the existing tracker outer barrel (TOB) mechanics in the overall concept
- Ladder-shaped local sub-structures
  - Holding twelve 2S modules each
- Wheel-shaped global mechanical structure
  - Populated ladders are inserted from both ends
- Largest barrel sub-detector
  - Supports TBPS and a good fraction of the Inner Tracker

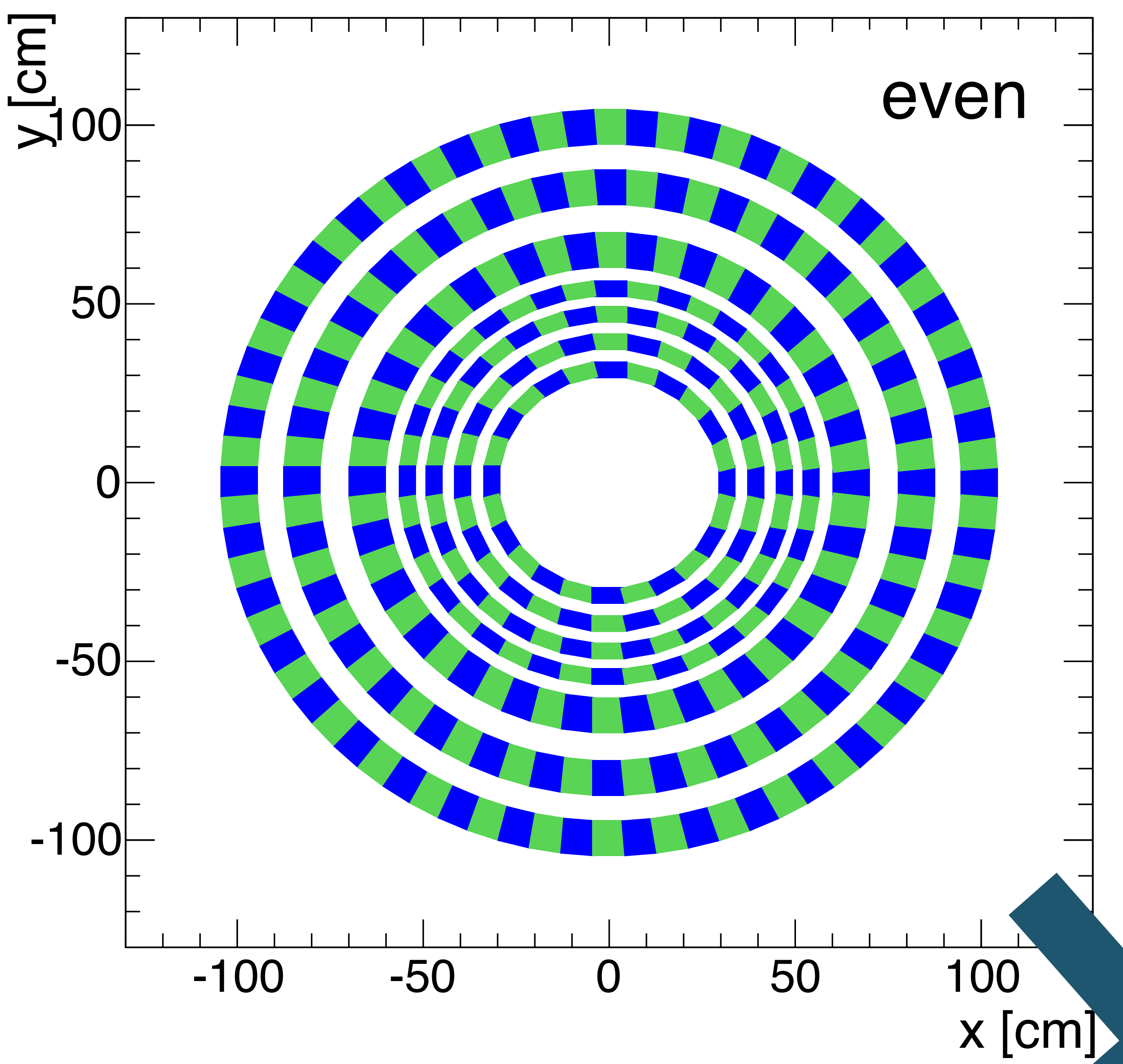


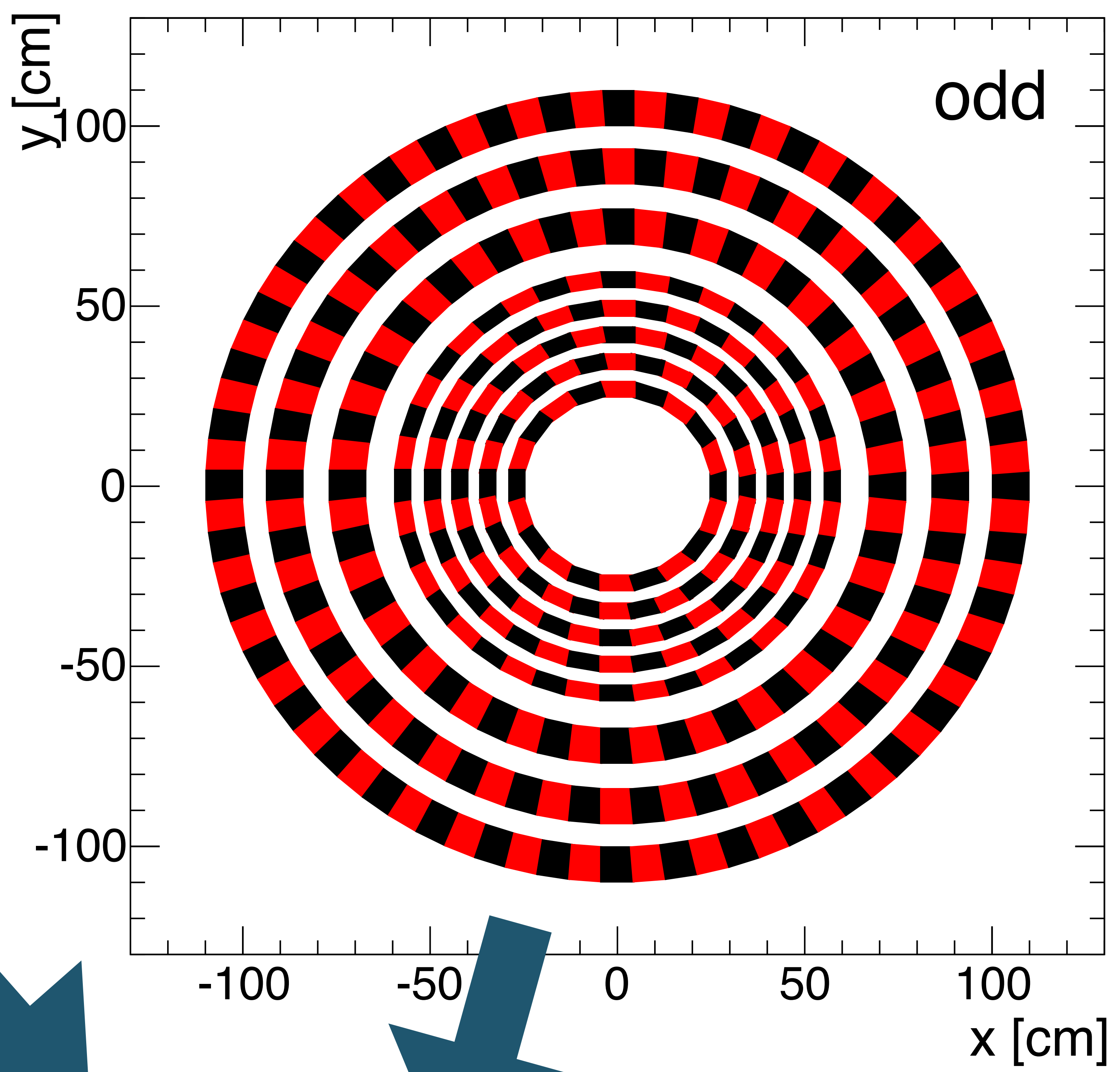


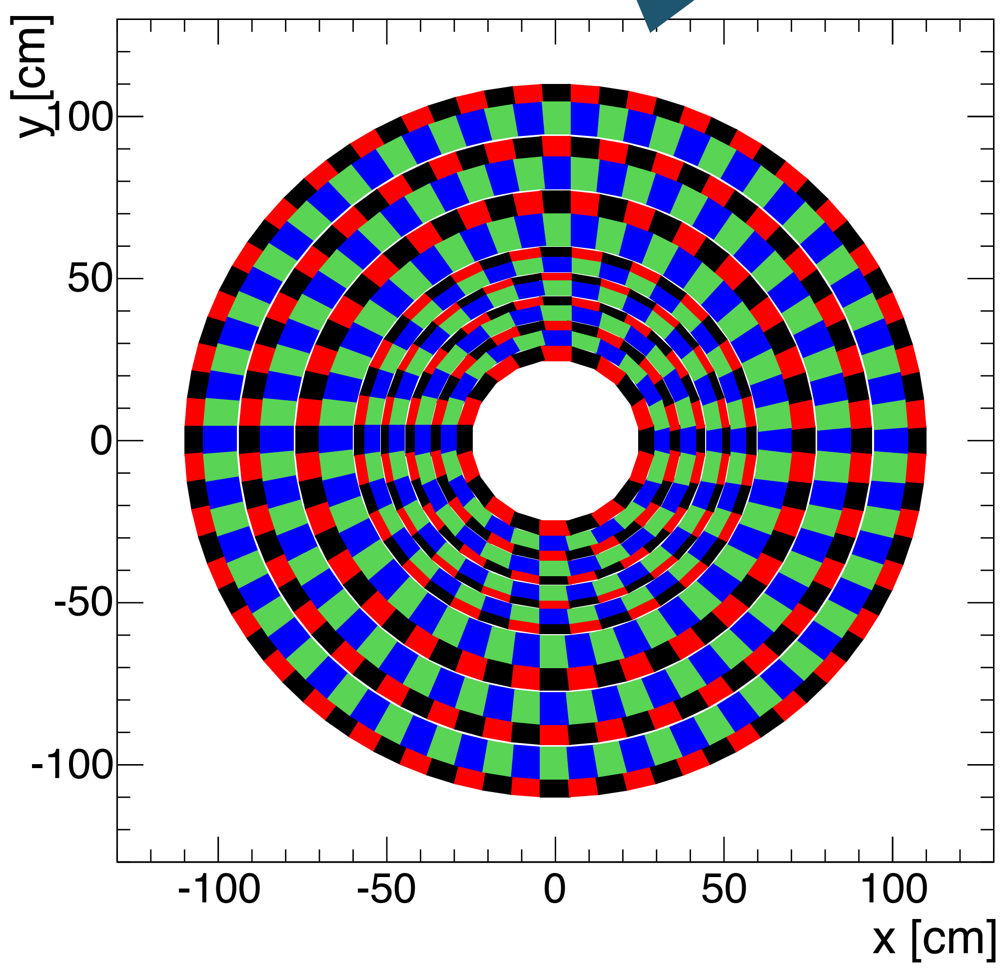


TEDD design concept

- Only two module designs with rectangular sensors
  - No wedge-shaped sensors in TEDD
  - Extra mass only in sensitive material
    - Module periphery is needed in any case
    - More overlaps are better for tracking and alignment
- Modules are arranged in rings on both faces of two support disks
  - Alternating in phi between front- and backside of a disk
    - Green/blue and red/black
  - Alternating in radius between disks
    - Even/odd rings
- Support structure design constraints
  - As light-weight as possible
  - Minimize number of different structure types
    - 1 x for modules in even rings, 1 x for modules in odd rings
  - Minimize number of modules per ring ➟ keep overlaps at a minimum
  - Exploit symmetries as much as possible

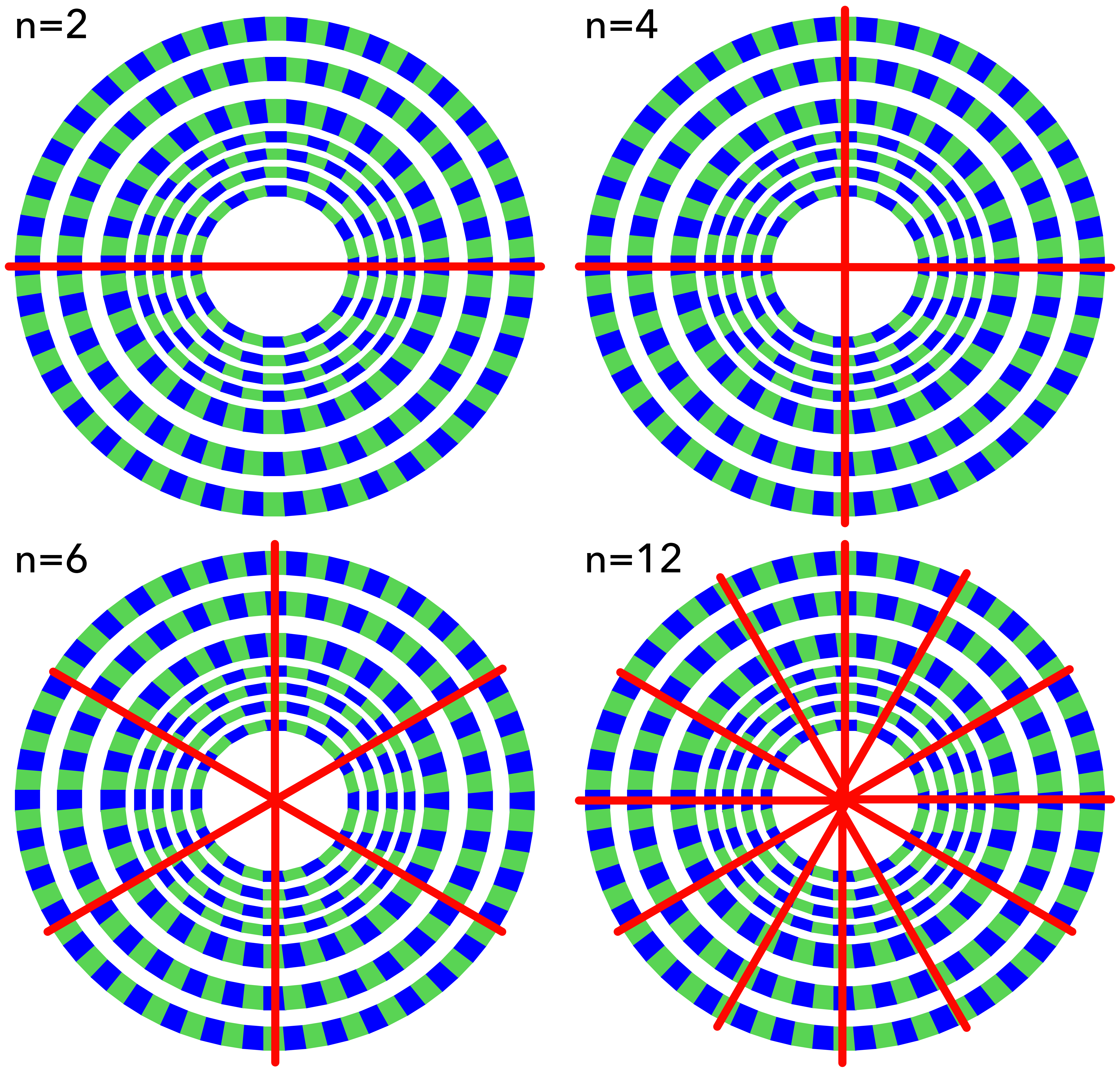






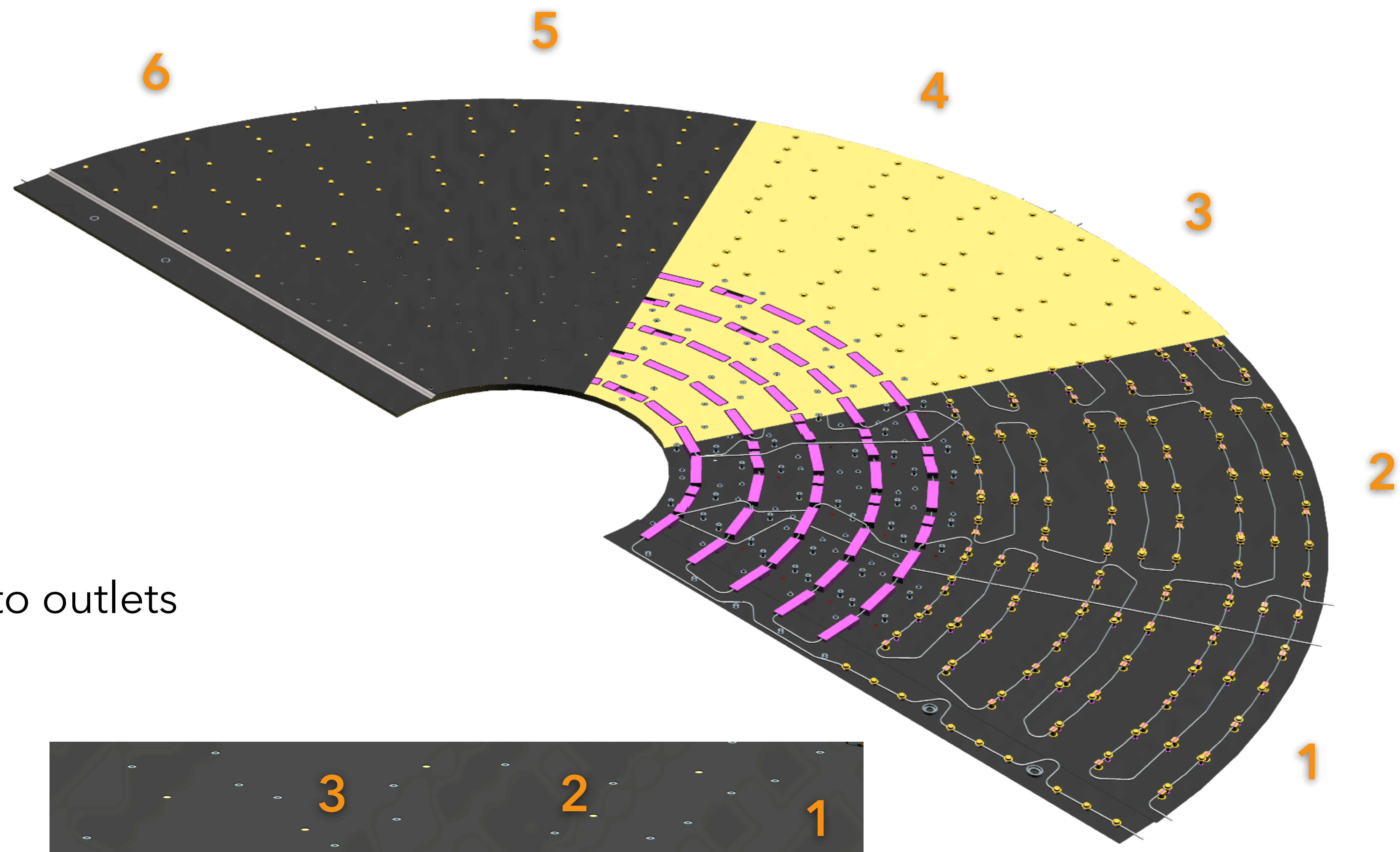
TEDD design concept

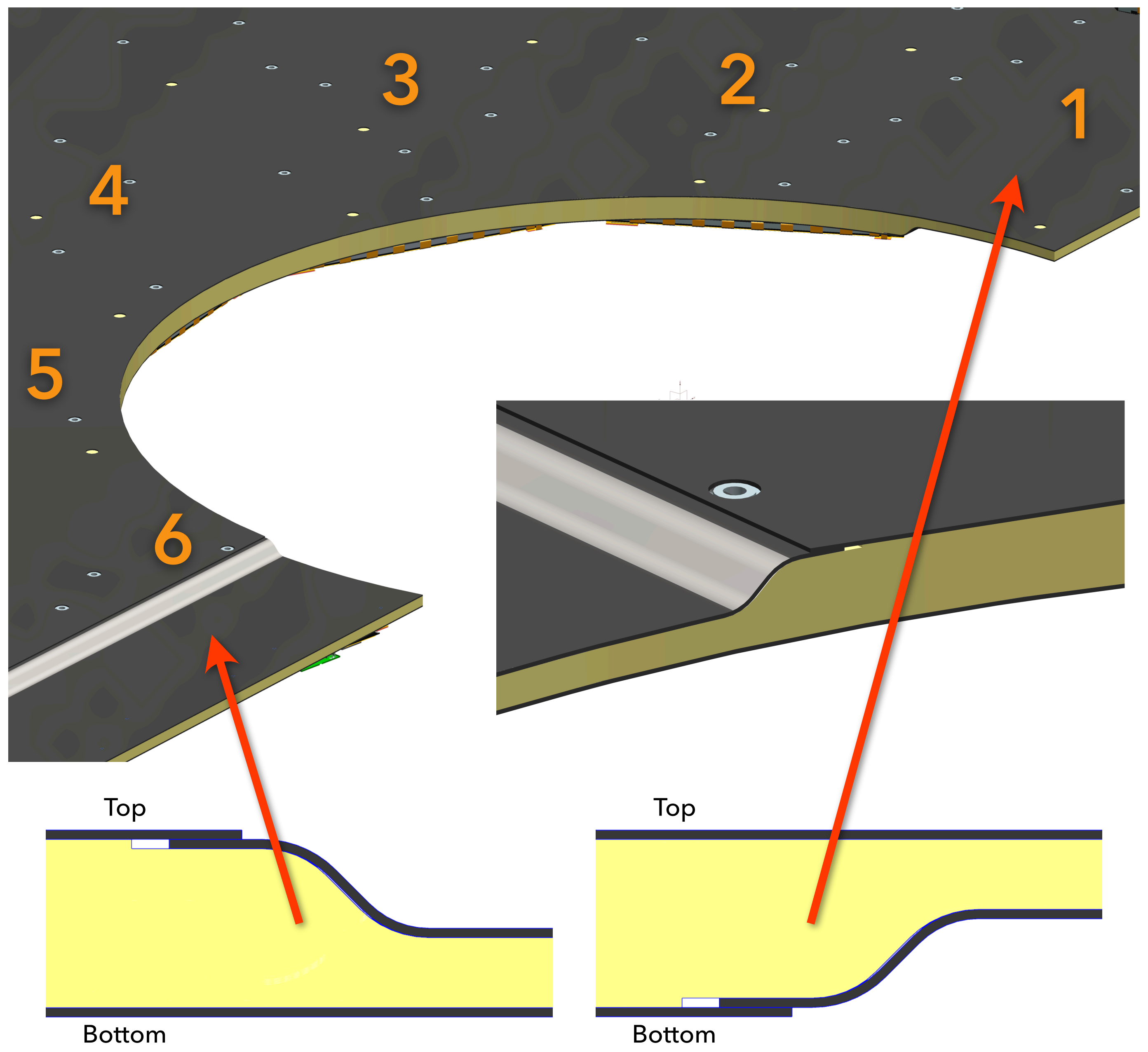
- A single support structure of that size is a challenge
  - Production of CFRP requires really special/large autoclaves
  - Machining in that size requires special machines
  - O(180) modules per structure is also challenging from a handling point of view
- Divide structure in ***n*** parts
  - Number of modules per ring must be dividable by n because of ‚minimize number of different structure types' design constraint
- With increasing ***n*** handling becomes easier but overlaps become an issue
  - Transition to wedge-shaped sensors needed for ***n*** > 6
- For smaller ***n*** the support structure can contribute more to the global mechanics
- From a mechanical point of view a CFRP sandwich structure can take much more load than just ~180 module of 50 g each (incl. services)
- Why not exploit this?



Dee design

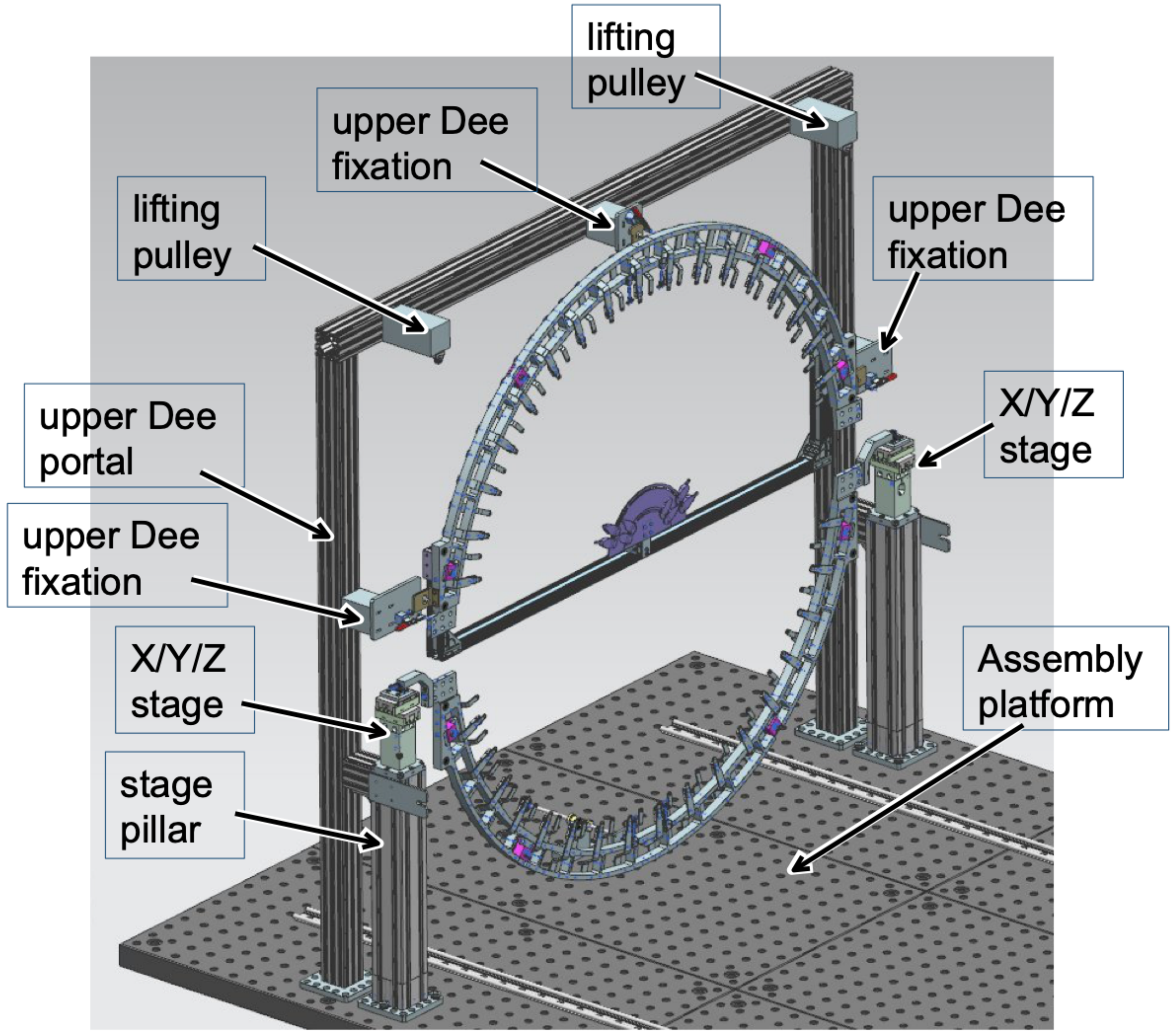
- Highly embedded 10 mm thick sandwich
  - Airex core
  - CFRP facings
- Symmetries as much as possible exploited in the design
- Six cooling sectors
  - Routed in two tiers inside Dee
    - Allows cooling sectors to overlap and avoids 3D pipe bending
  - Identical design for sectors 1 & 6, 2 & 5, and 3 & 4
  - Ring 15 2S modules are close to inlets, ring 1 PS modules are close to outlets
- Step at straight edge of Dee
  - Pipe routing requires step to be on opposite sides
    - Cooling sector 1 is routed in top tier ➟ sector 6 is in bottom tier
- Inserts for module positioning
  - Six per 2S module incl. cooling
  - Three per PS module
- Additional inserts for
  - Definition of Dee coordinate system for metrology
    - Accessible from both sides even when modules are mounted
  - Dee-to-Dee and Disk-to-Disk assembly
  - Patch panel support ring and global TEDD mechanics mounting
- One Carbon foam cooling block per PS modules

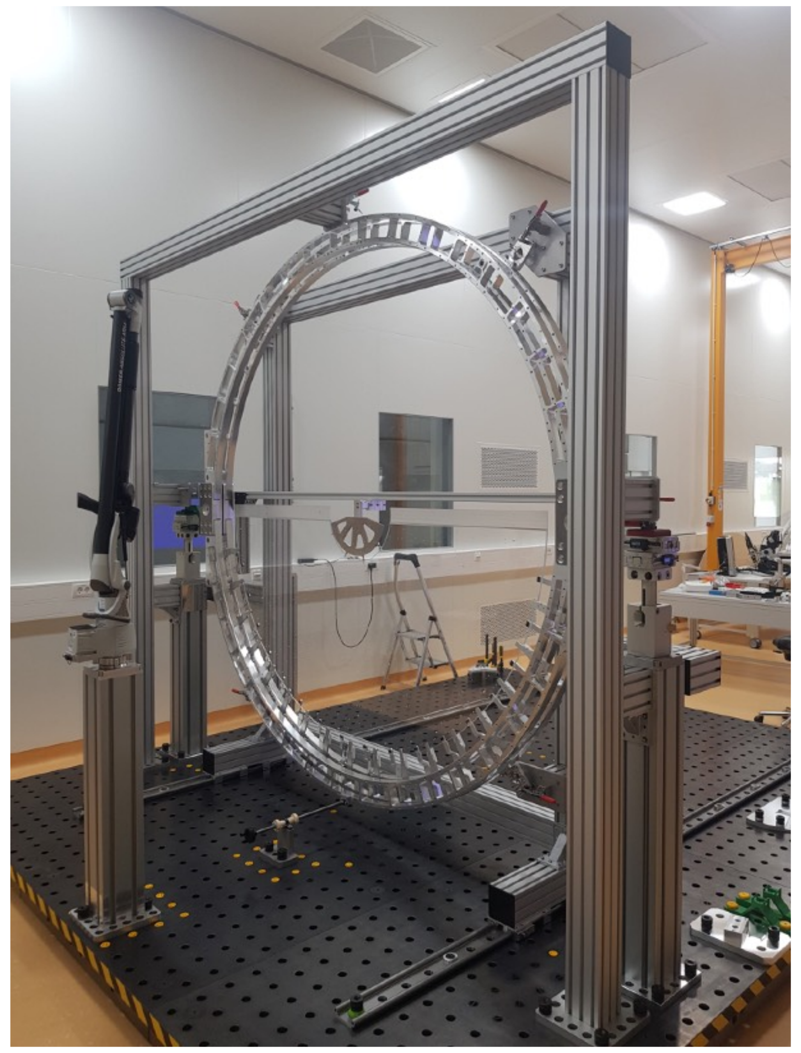


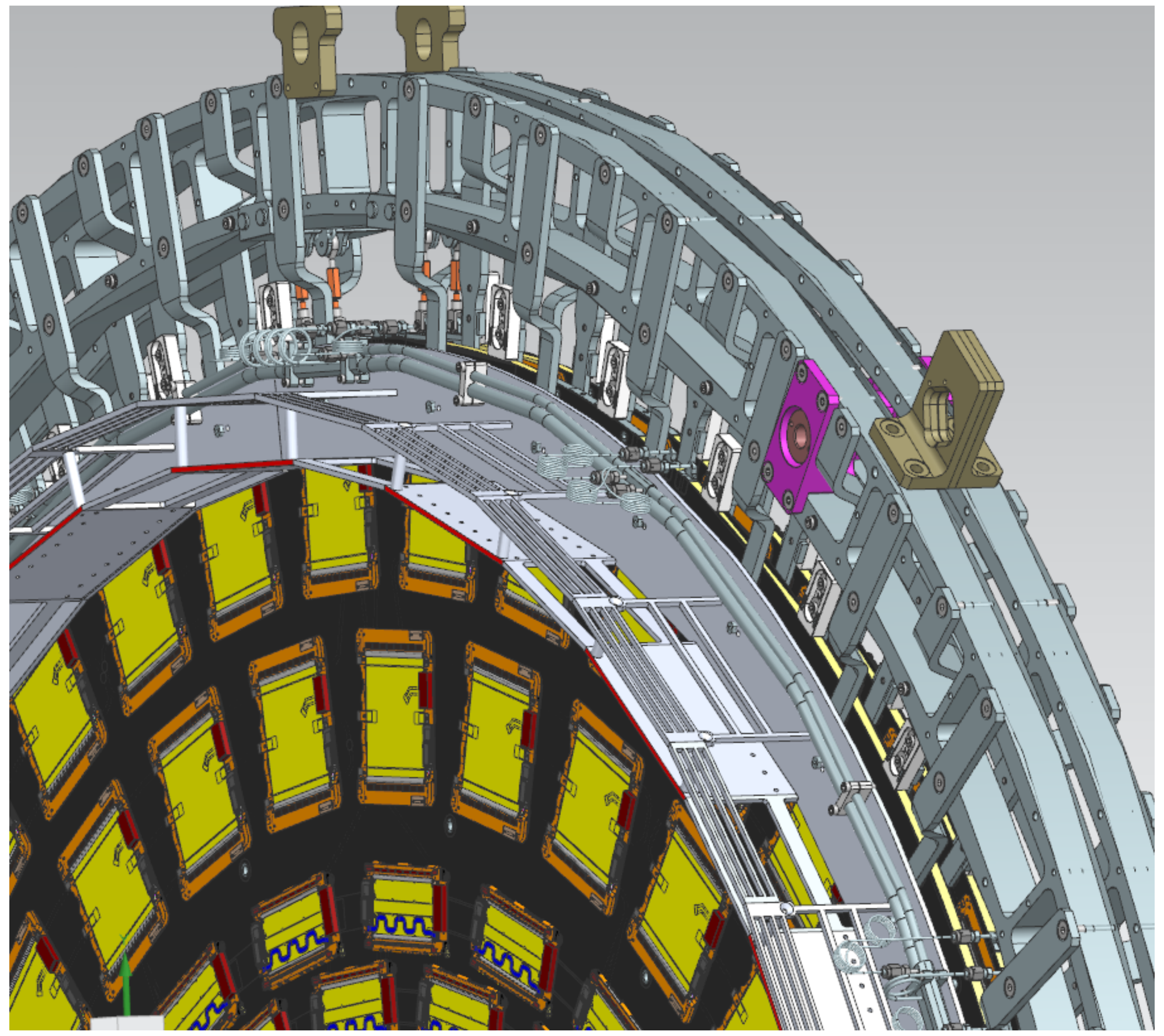


Disk and Double-Disk assembly

- Modules are mounted up to ~1 mm from edges of Dee
  - Dedicated handling tool required through the integration and assembly process
    ➟ Arc frame
- Upper Dee in Arc frame is mounted on upper portal
- Lower Dee in Arc frame is placed on x/y/z stages and positioned relative to upper Dee
  - Iterative process with measurements between movements
- When both Dees are align they are mechanically connected
  - Mainly serves to fix the relative positioning
- Upper and lower Arc frames are mechanically connected
- Very similar procedure for Double-Disks but with odd and even Disks instead of Dees

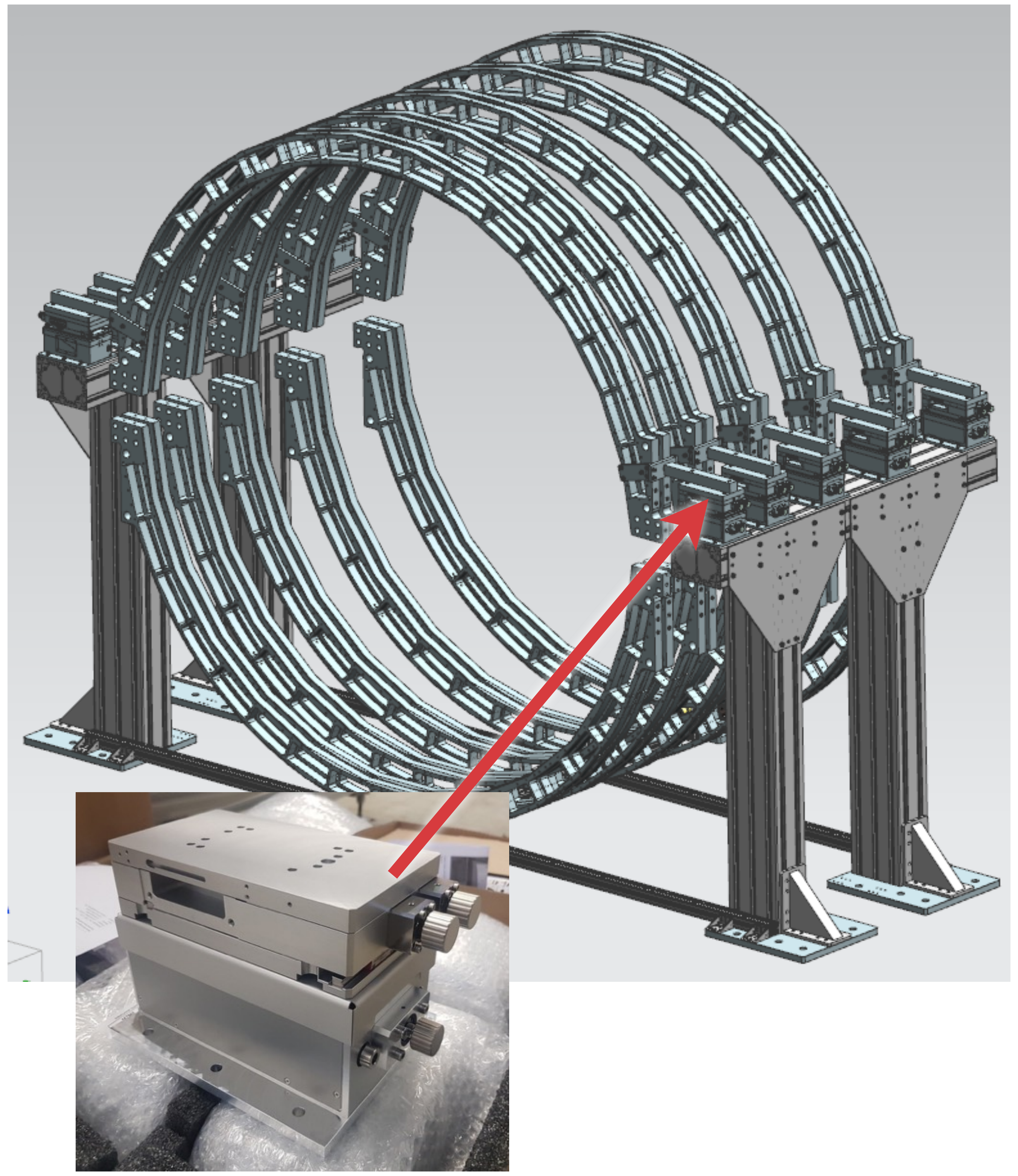


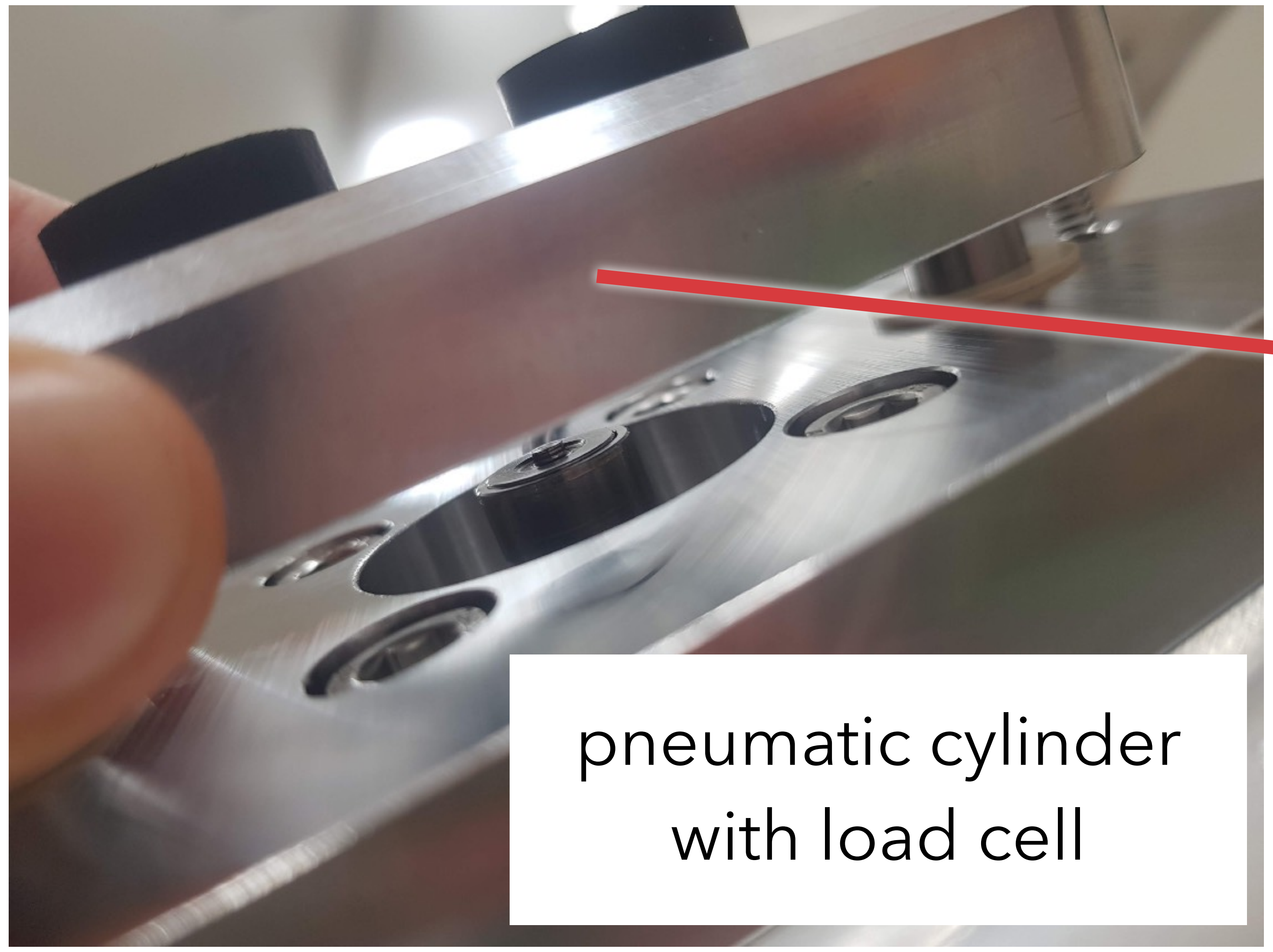




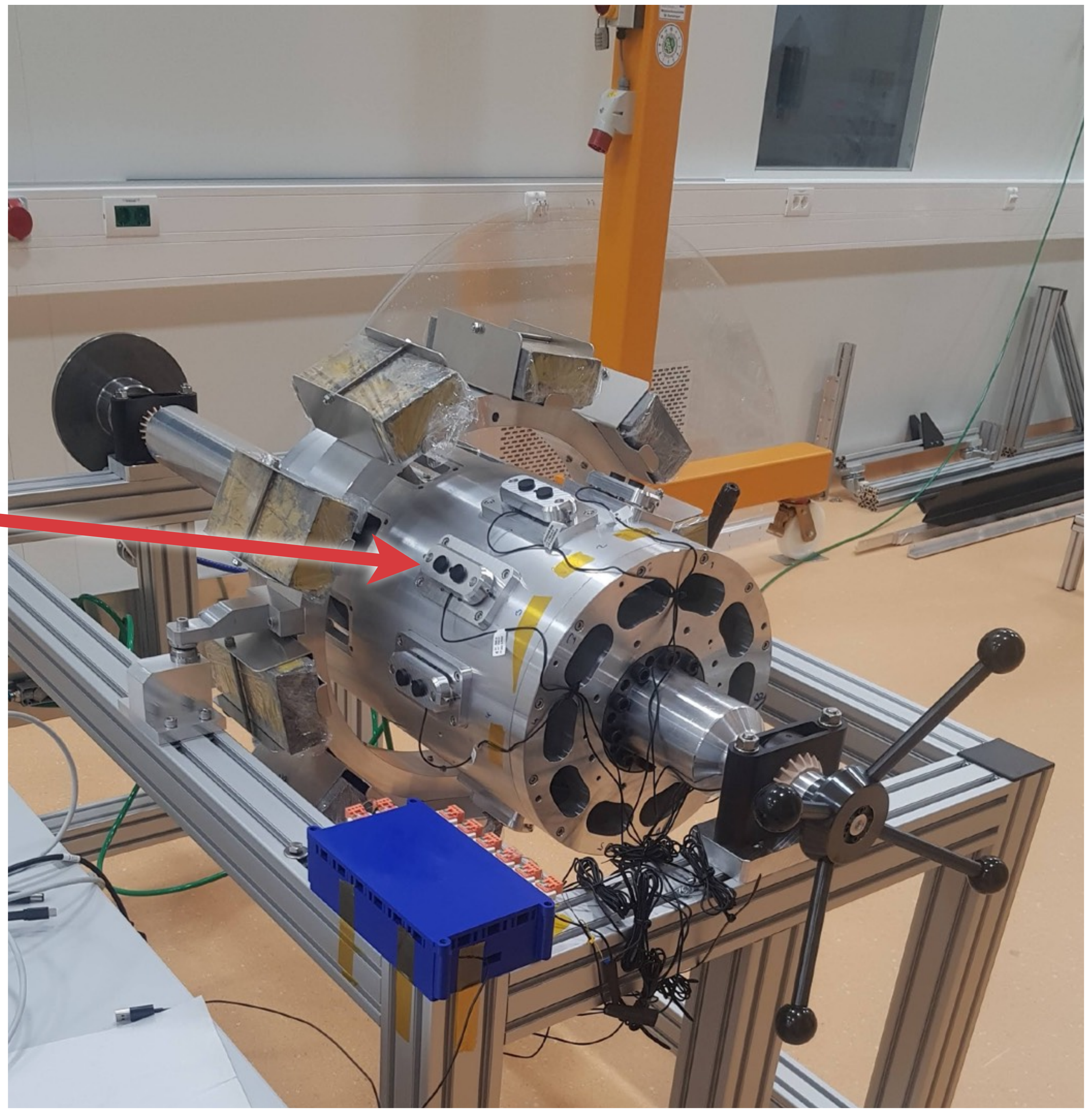
TEDD assembly

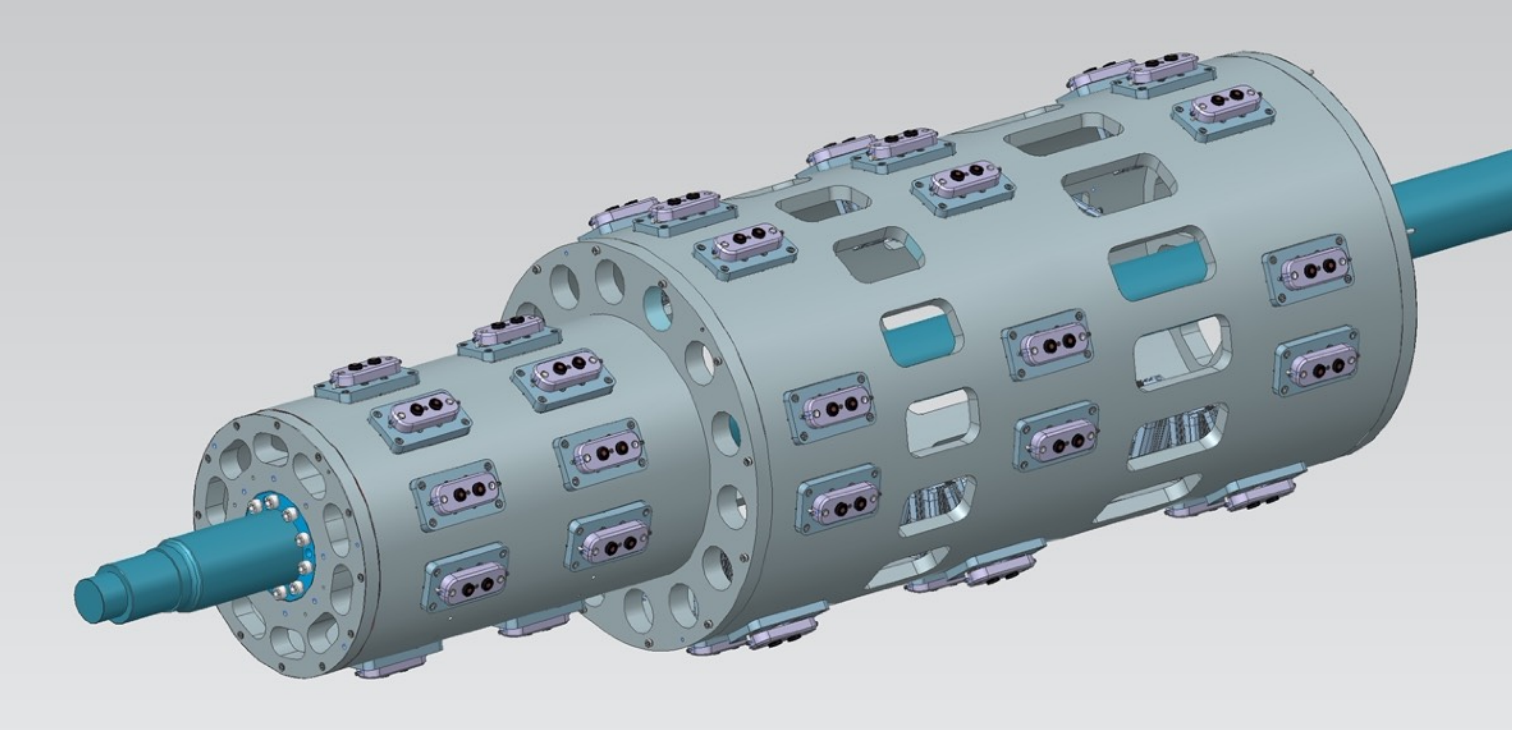
- All five DDs are supported by DESY designed EASy stages
  - +/- 12 mm in X, Y and Z with 250 kg load capacity
- Once DDs are positioned relative to each other longitudinal beams and inner tube are installed
  - At this stage TEDD is supported at the outer radius by Arc frames
- For services installation Arc frames have to be removed
  - TEDD will be supported from the inner bore on a tooling that allows rotation around central axis



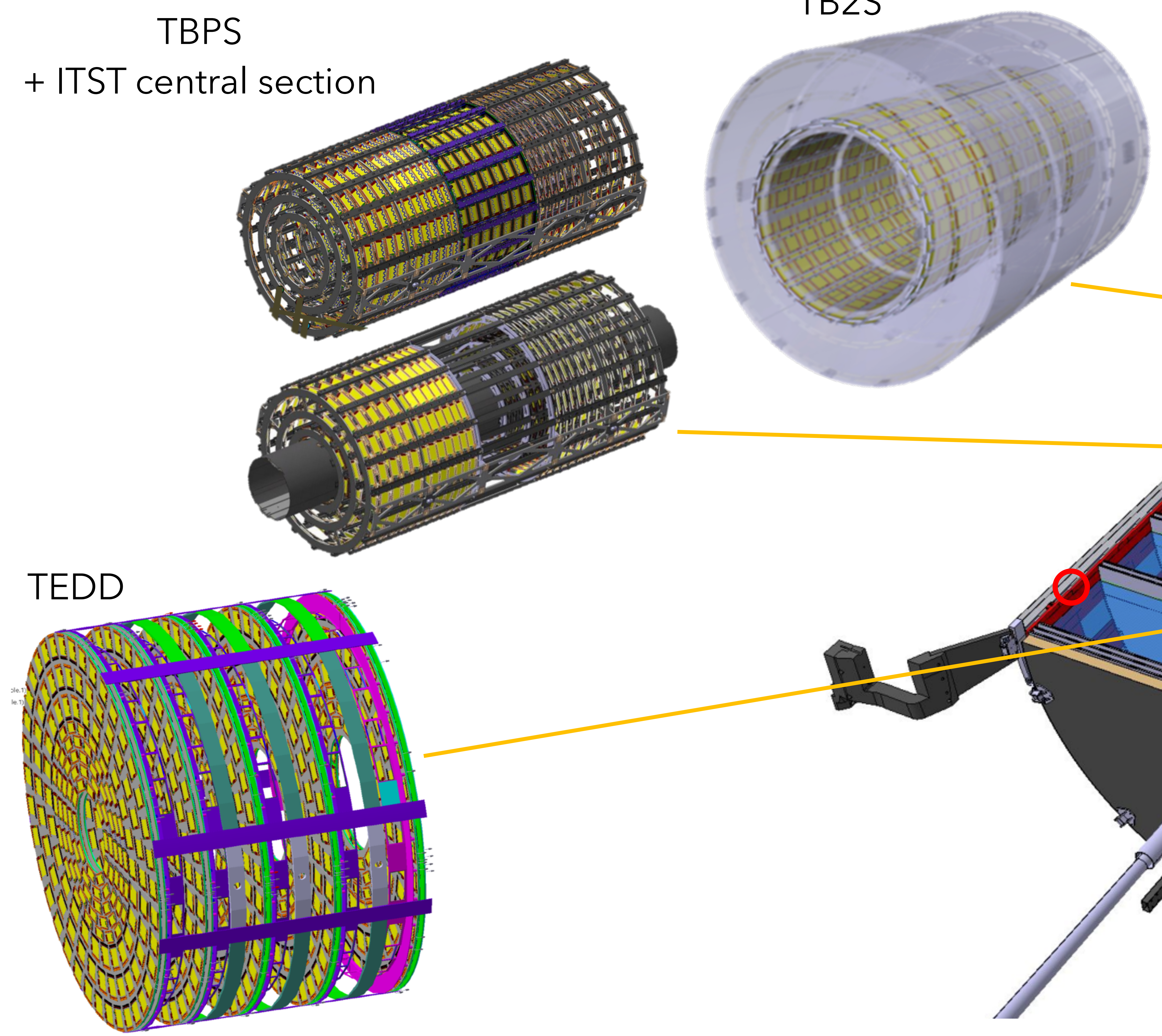


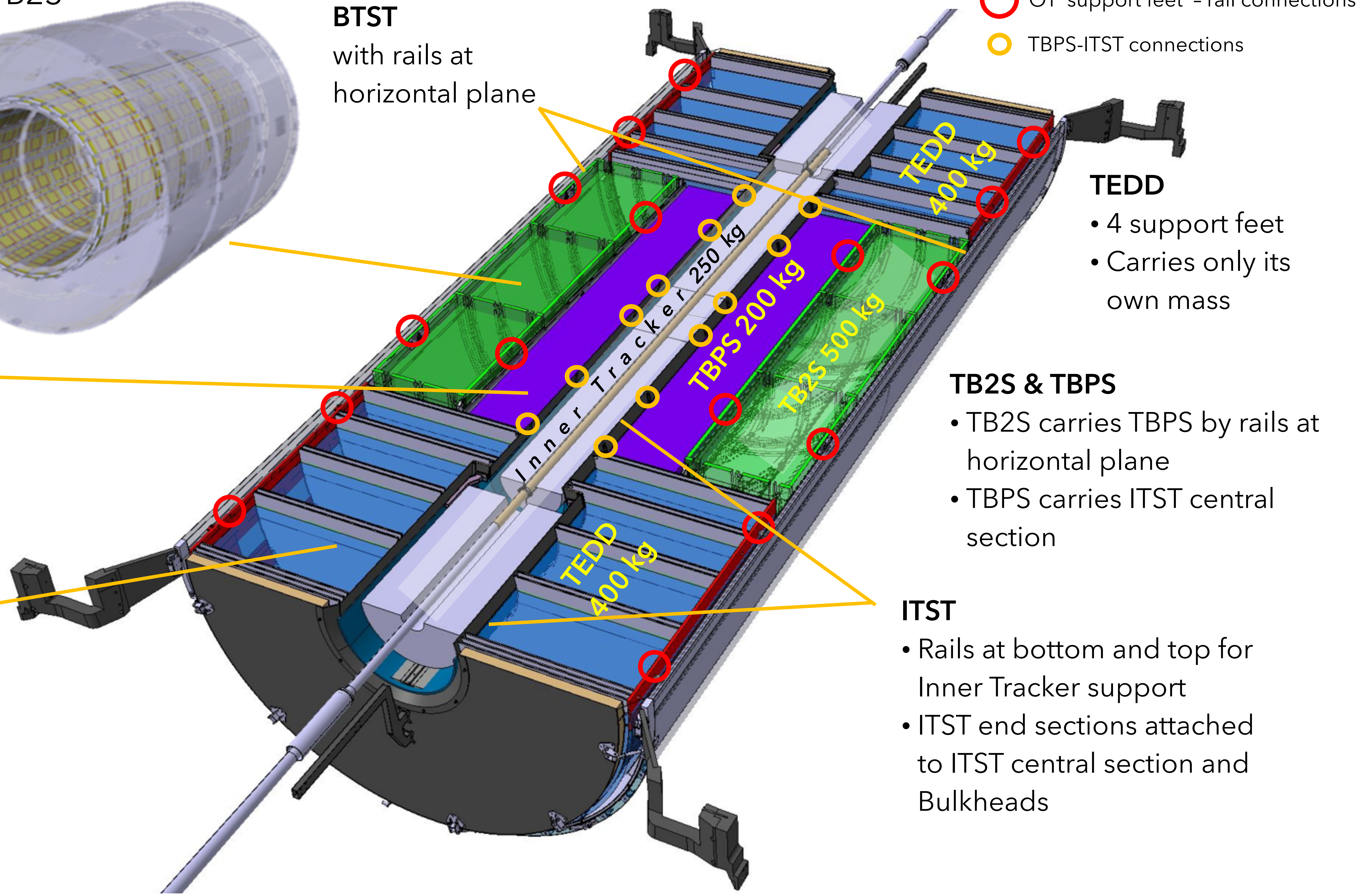
pneumatic cylinder with load cell





Tracker integration

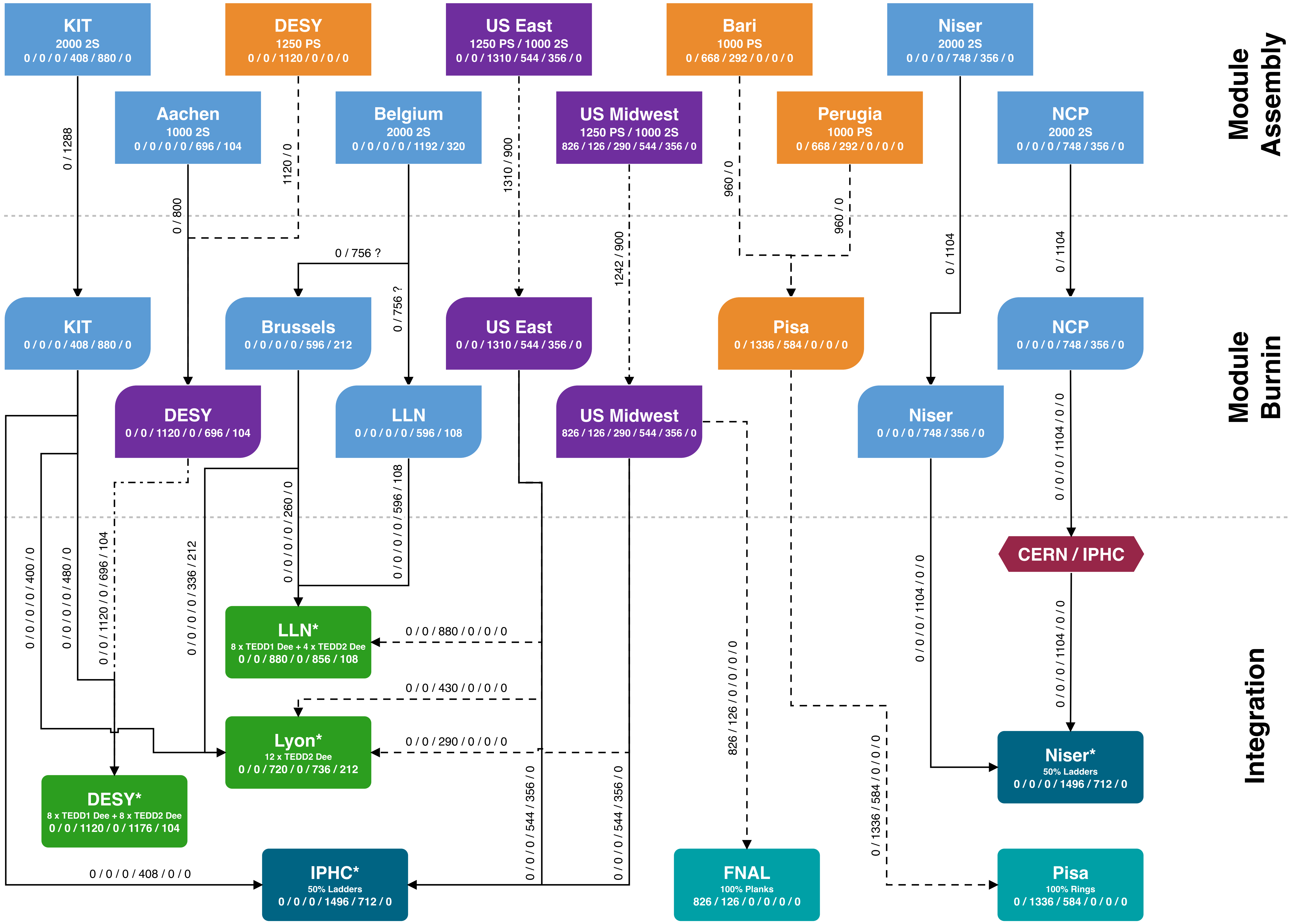




- Barrel Timing Layer (BTL) and all tracker sub-detectors are supported by BTL-Tracker Support Tube (BTST)
- Insertion sequence into BTST: BTL ➡ TB2S ➡ TBPS ➡ TEDDs ➡ Bulkheads ➡ ITST

Outlook to production

- 13200 modules needed in total
  - 7608 2S and 5592 PS
- Ten module assembly and burn-in centers
  - burn-in: 24h temperature cycle stress test of each module
- Flowchart only covers integration of local support structures
  - Planks, Rings, Ladders and Dees
- Every module assembly center plans for a throughput of 4 modules per day
  - minimum of 4 sets of tools required



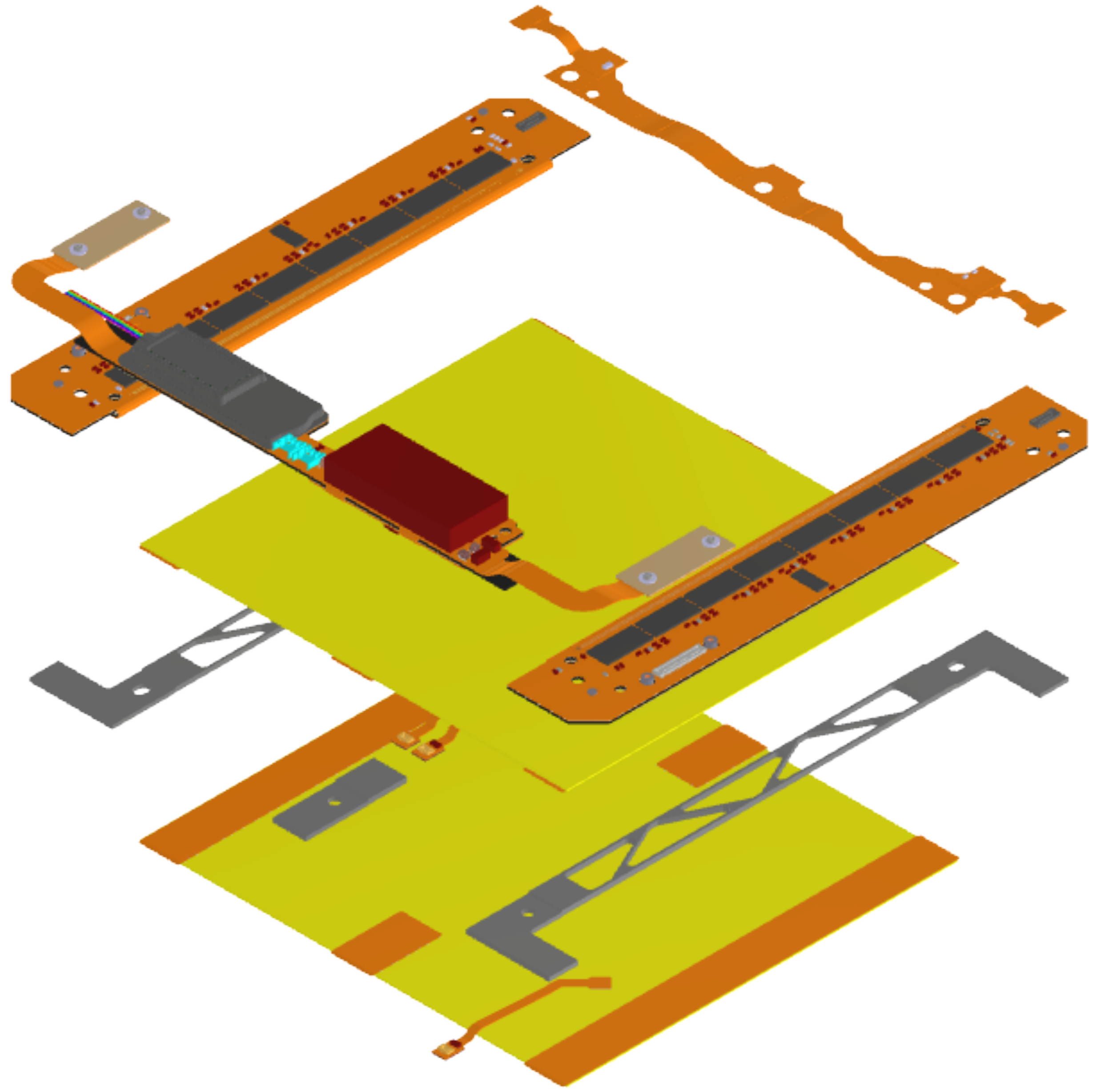
Module type list: 1.6 mm PS / 2.6 mm PS / 4.0 mm PS **/** 1.8 mm 2S 5CP / 1.8 mm 2S 6CP / 4.0 mm 2S

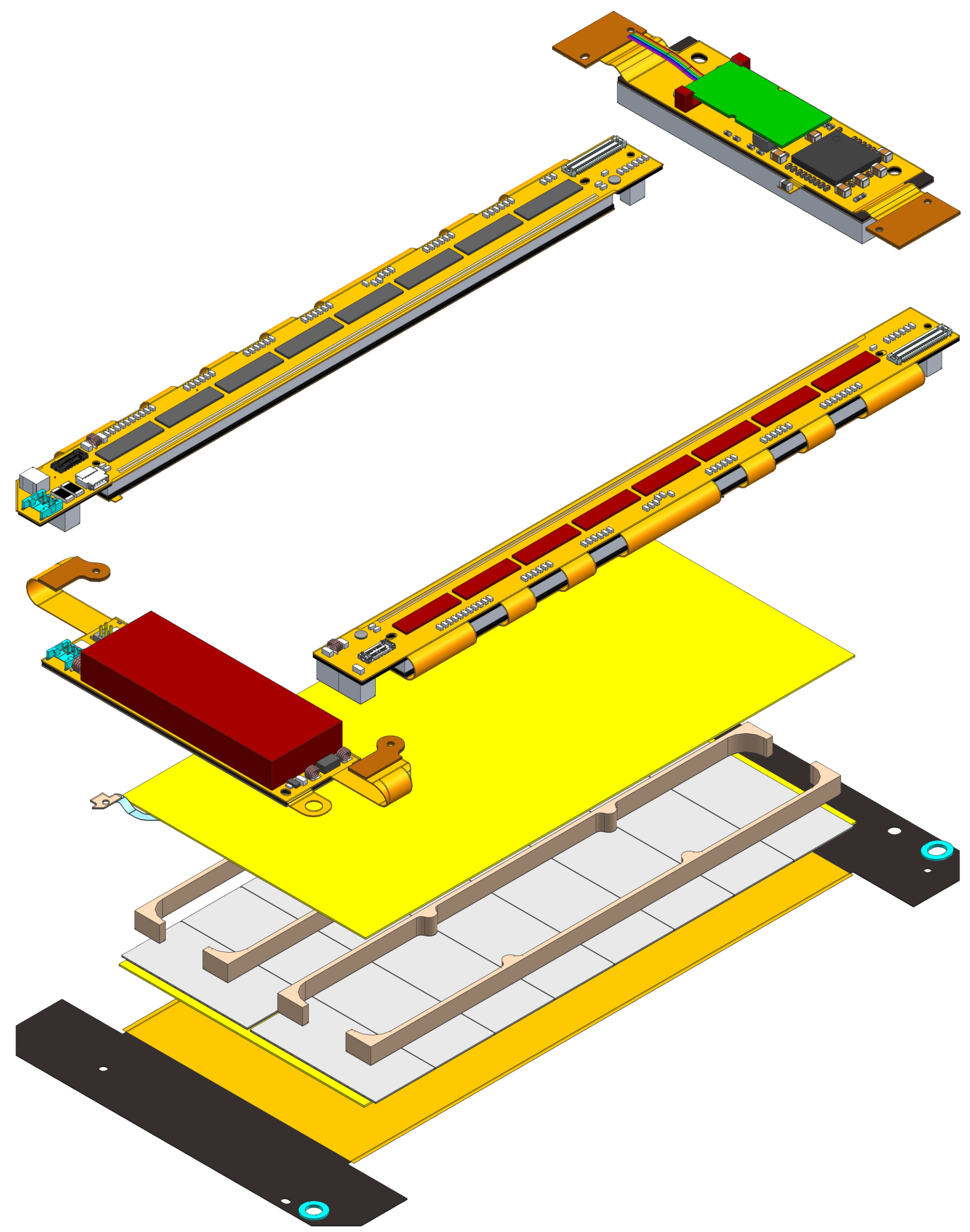
* Integration centers requiring setup for quick module reception tests

2S | PS | 2S & PS | TBPS | TB2S | TEDD

2S
PS
2S & PS

Module components and assembly tooling



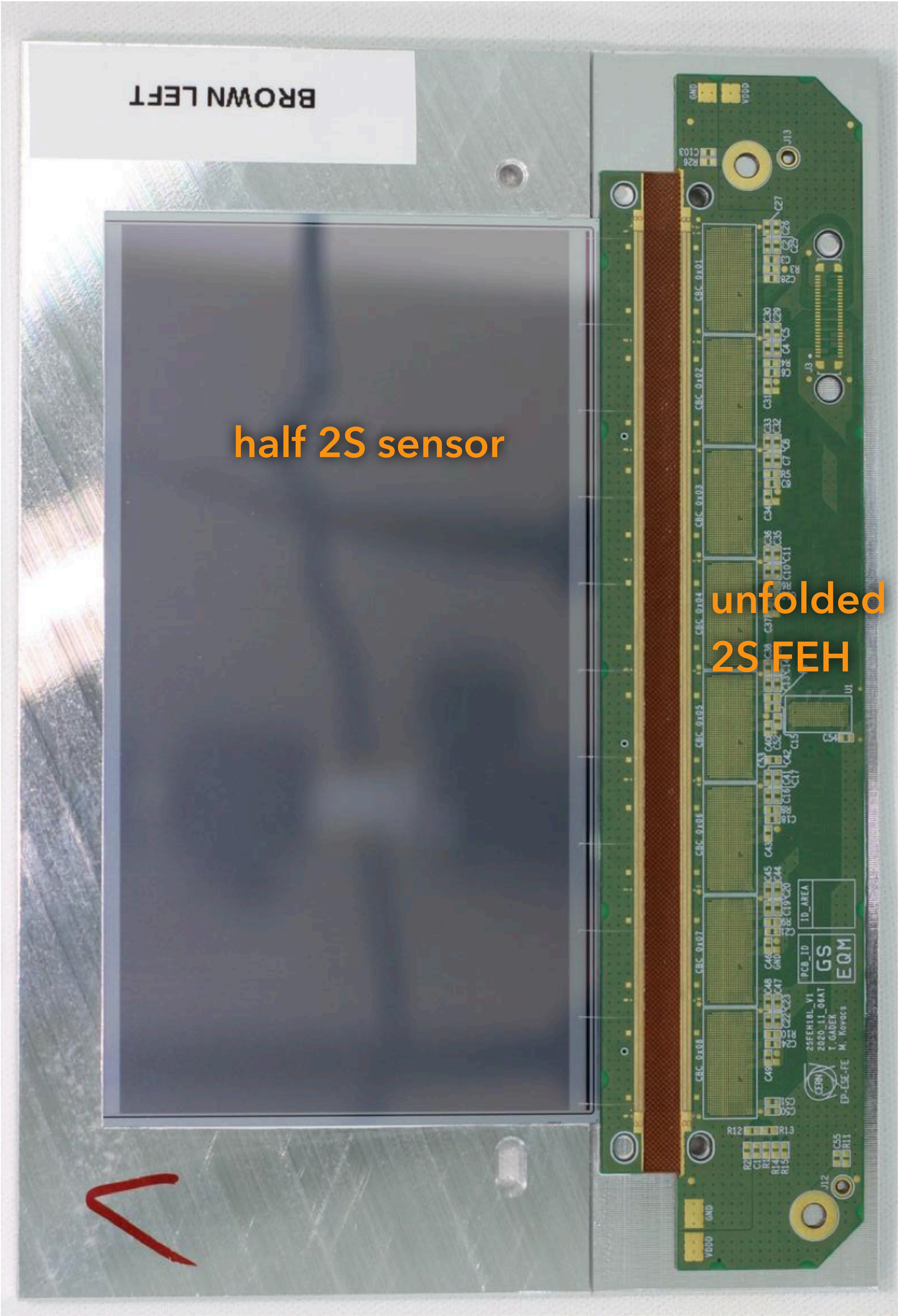


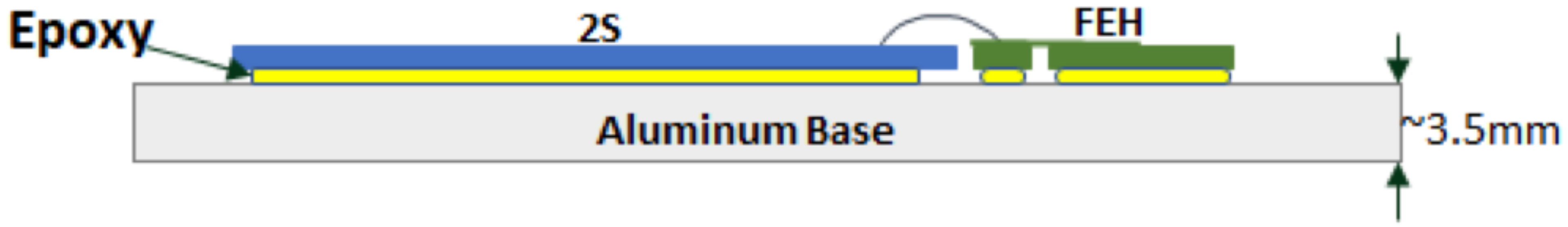
- Procurement and/or production of module components, assembly tooling and consumables is shared among assembly centers
  - Kapton isolators: FNAL
  - Al-CF bridges for 2S modules: Brown
  - CFRP base plate for PS modules: Perugia + Purdue and FNAL
  - Inserts for PS base plates: DESY
  - AlN spacers for PS modules: DESY
  - Adhesives: Perugia
  - Wirebond spools and wedges: Belgium

Tooling	Design	Production
2S sensor isolator & HV tail gluing fixture	KIT/Brussels/ Louvain	Brussels/Louvain for all 2S assembly lines
2S sensor gluing fixture	FNAL	FNAL for all 2S assembly lines
2S hybrid gluing fixture	KIT	KIT for all 2S assembly lines
2S module carrier	FNAL	FNAL + NISER
PSs sensor HV tail gluing fixture	DESY	DESY for all PS assembly lines
PS sensor gluing fixture	Bari/Perugia	individual
PS automated assembly	DESY	individual
PS module baseplate insert gluing fixture	DESY	DESY for all PS assembly lines
PS module baseplate isolator gluing fixture	Bari	Bari for all PS assembly lines
PS module hybrid gluing fixture	Brown	Brown for all PS assembly lines
PS module carrier	Brown	Brown + NISER
2S & PS wire bonding fixture	individual	individual
Module transport box	KIT	KIT + individual

Qualification of module assembly centers

- Qualification of module assembly centers split into three stages
- Stage 1: Clean room(s) and related infrastructure
  - dry air supply, storage capacity, etc.
  - ESD safety
  - all assembly centers have passed this stage
- Stage 2: Equipment
  - wire bonder, pull tester, glue dispenser, etc.
    - includes wirebonding qualification campaign with dedicated test samples
  - to be complete by start of pre-production
- Stage 3: Module assembly
  - availability of assembly tooling
  - description of the assembly work flows and how the target production throughput is established
  - training of personnel
  - production of functional modules
  - infrastructure and access to the construction database
  - to be completed by end of pre-production

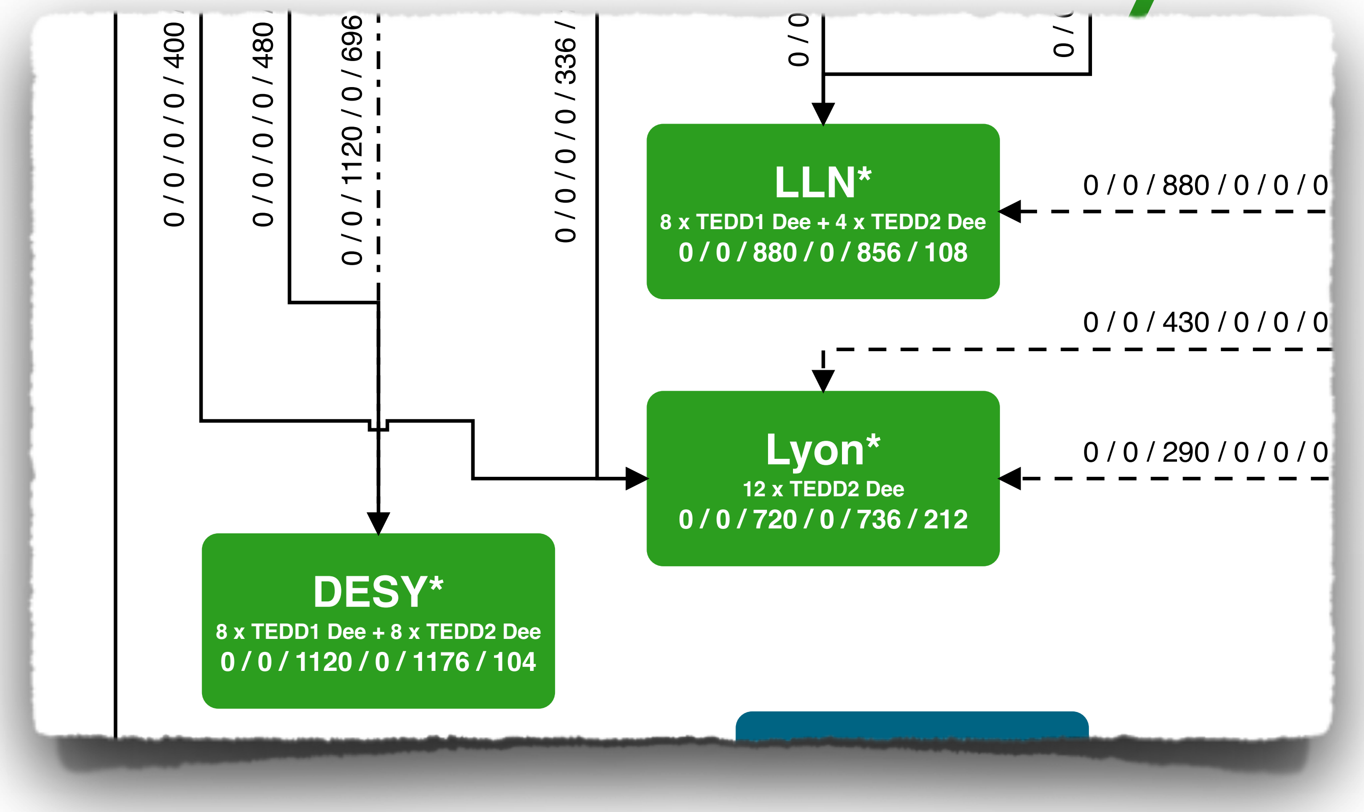


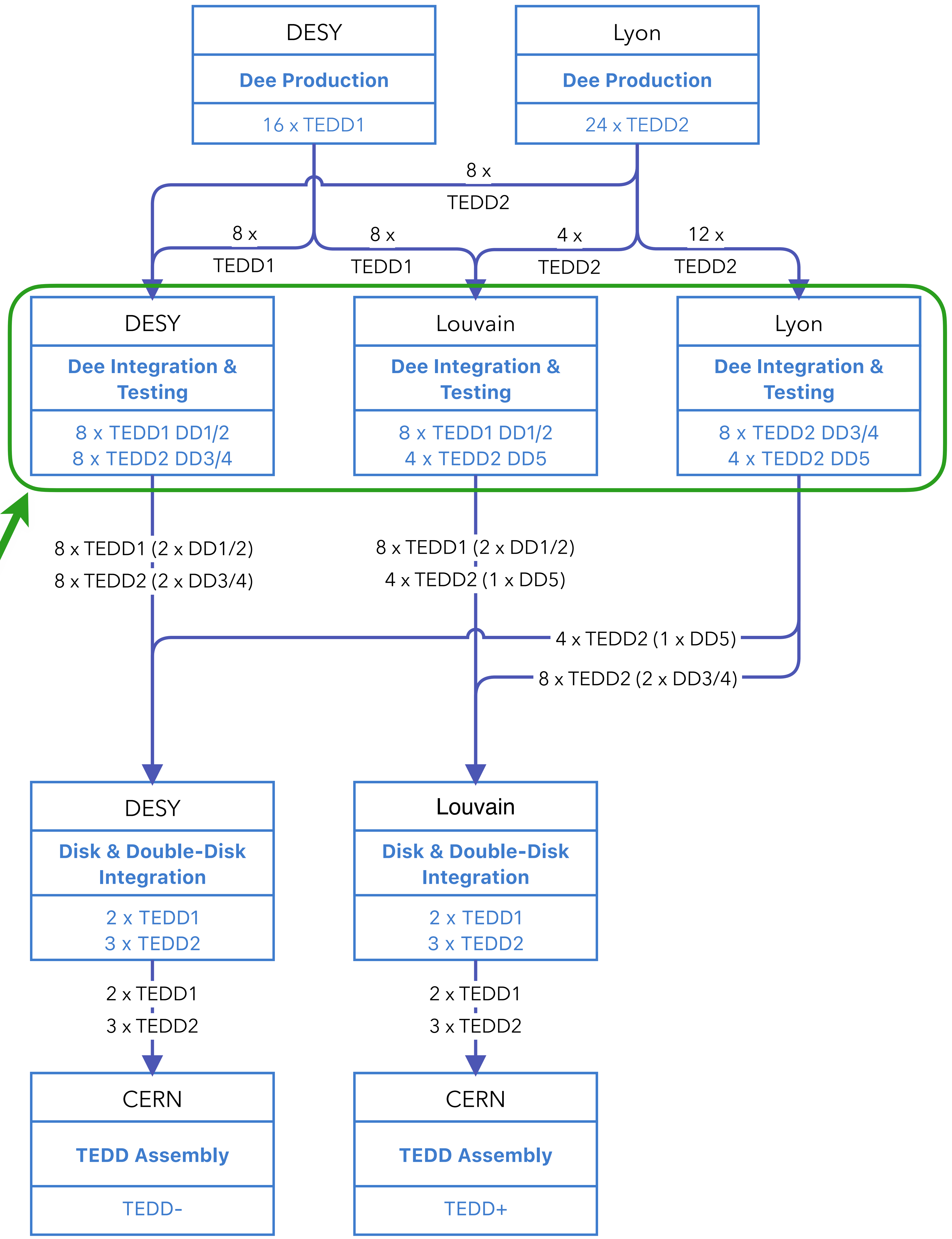


TEDD production

- Two end caps from three institutes is a challenge in itself…
- Responsibilities
  - Electrical and optical services: Louvain
  - Cooling services: DESY
  - Global mechanics: Lyon
  - Tooling for Double-Disk and TEDD integration: DESY

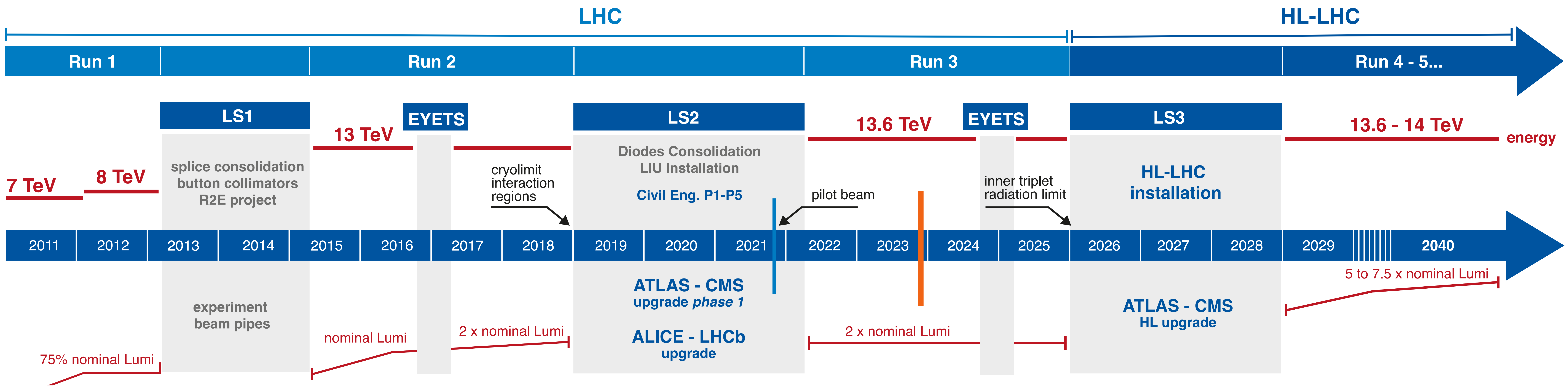
  - Dee production: Lyon & DESY
  - Dee Integration: Louvain, Lyon & DESY
  - Double-Disk integration: Louvain & DESY
    - Requires shipment of integrated Dees from Lyon to Louvain & DESY
    - Logistics model designed to minimize shipments and risk
  - TEDD integration at CERN: Louvain & DESY





Summary

- The CMS phase 2 outer tracker is an exciting but challenging project
- Many novel concepts and technologies are being used
  - On-module p_T discrimination
  - Reconstruction of the charged particle trajectory at trigger Level 1 (track trigger)
  - Tilted geometry in part of the outer tracker
- Currently transitioning from R&D to pre-production phase
  - Pre-production of sub-detector components has started
    - This week assembly of first DESY pre-production Dee started
  - Optimization and finalization of tooling is ongoing
    - Pre-production of modules will start by Q3/2024



Backup

Phase 2 CMS detector overview

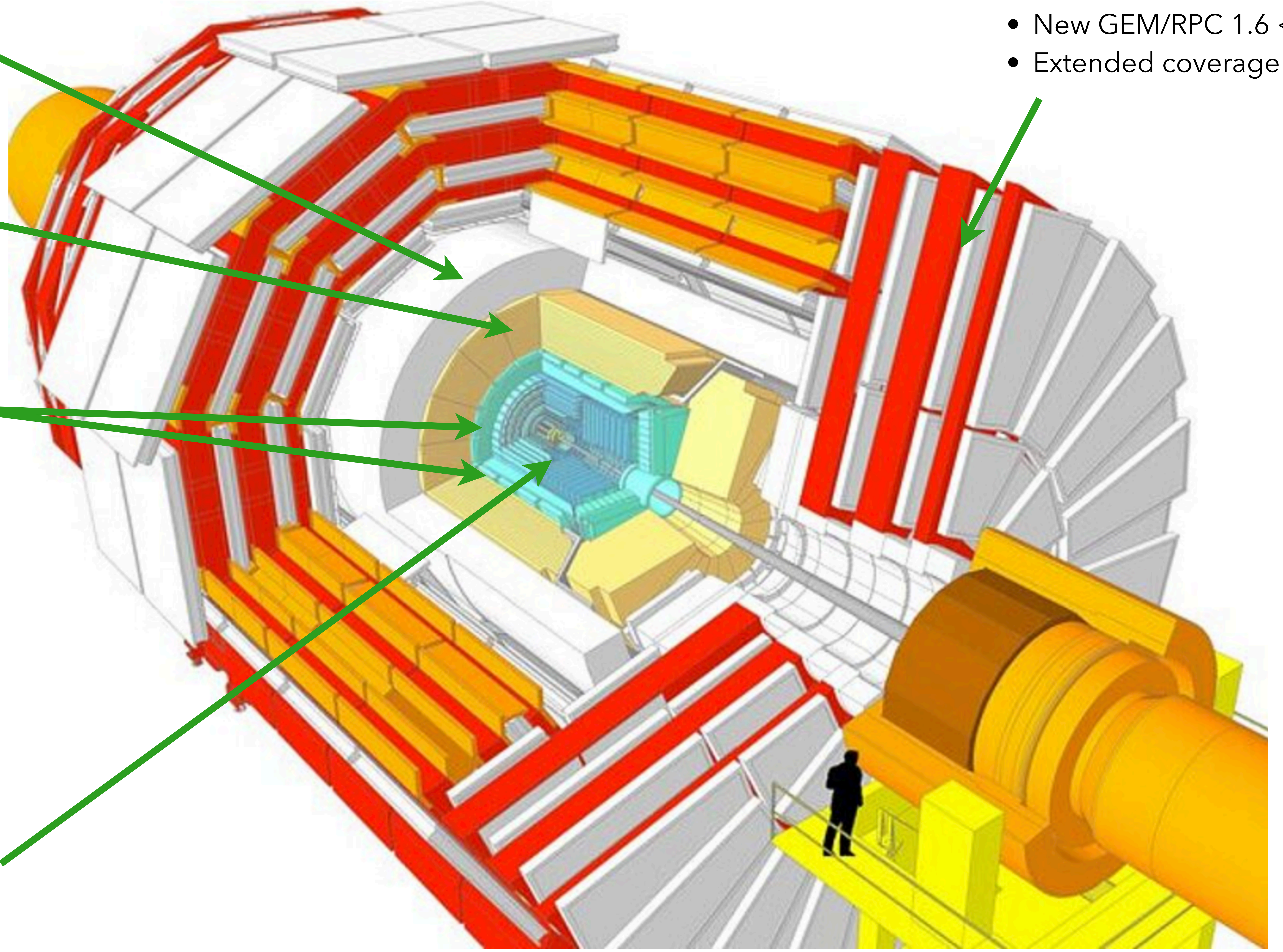
Endcap Calorimeter (HGCAL)
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Barrel Calorimeter
- ECAL crystal granularity readout at 40 MHz
- with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

MIP Timing Detector
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

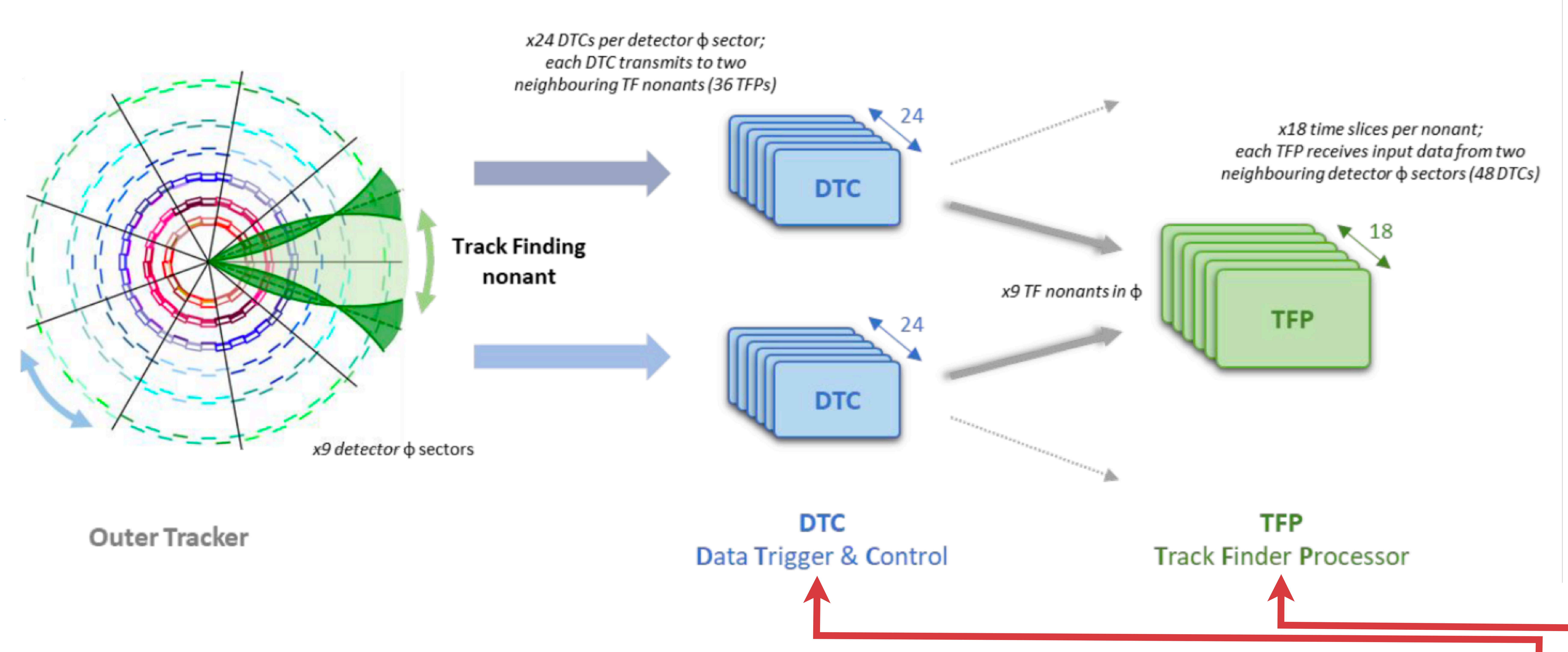
L1 Trigger HLT/DAQ
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- Latency within 12.5 μs
- 40 MHz data scouting

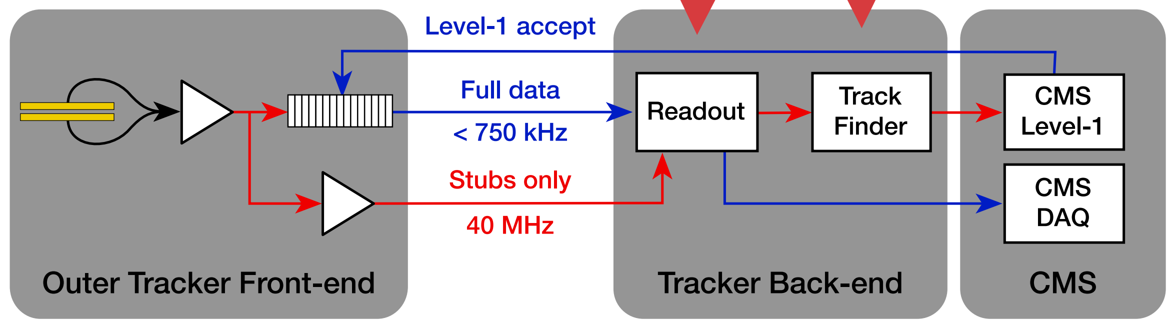
Tracker
- Increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 4$



Muon Systems
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

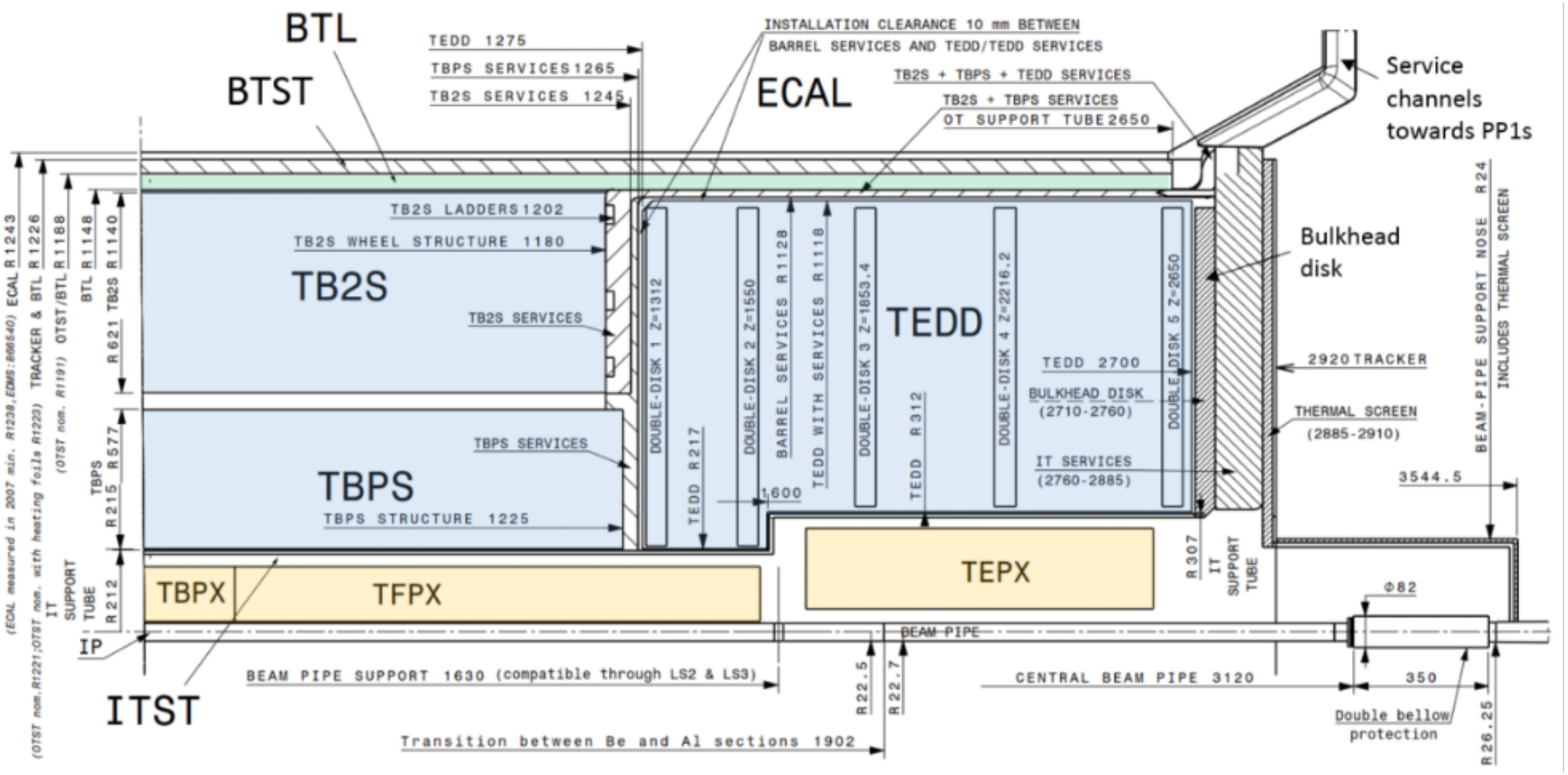
Back-end





- Tracker is split into nine detector and track finding ϕ-sectors (nonants)
  - track finding nonants are offset by 20° wrt. read-out nonants
- Data from each detector sector with $|\eta| < 2.4$ are distributed to 24 Data Trigger & Control boards (DTC)
- From each DTC data are transferred to two neighboring Track Finding Processors (TFP) with an 18-fold time multiplexing
  - Each TFP receives an event every 450 ns (18 x 25 ns)

Sub-detectors and envelopes



DESY Deliverables

modules

- 1120 4.0 mm PS modules
- Burn-in test of modules
  - 1120 DESY PS and 800 RWTH Aachen 2S modules

local supports

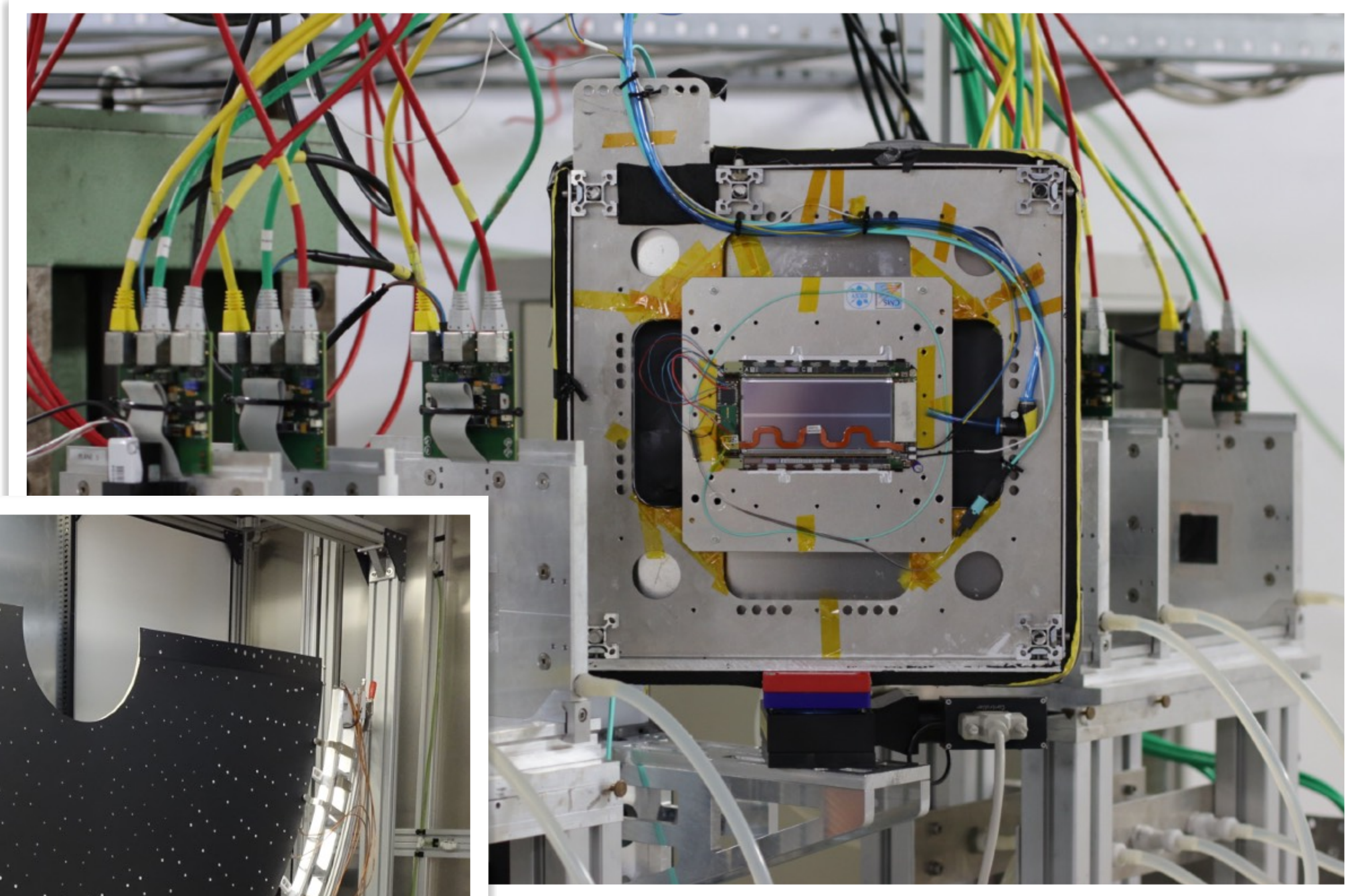
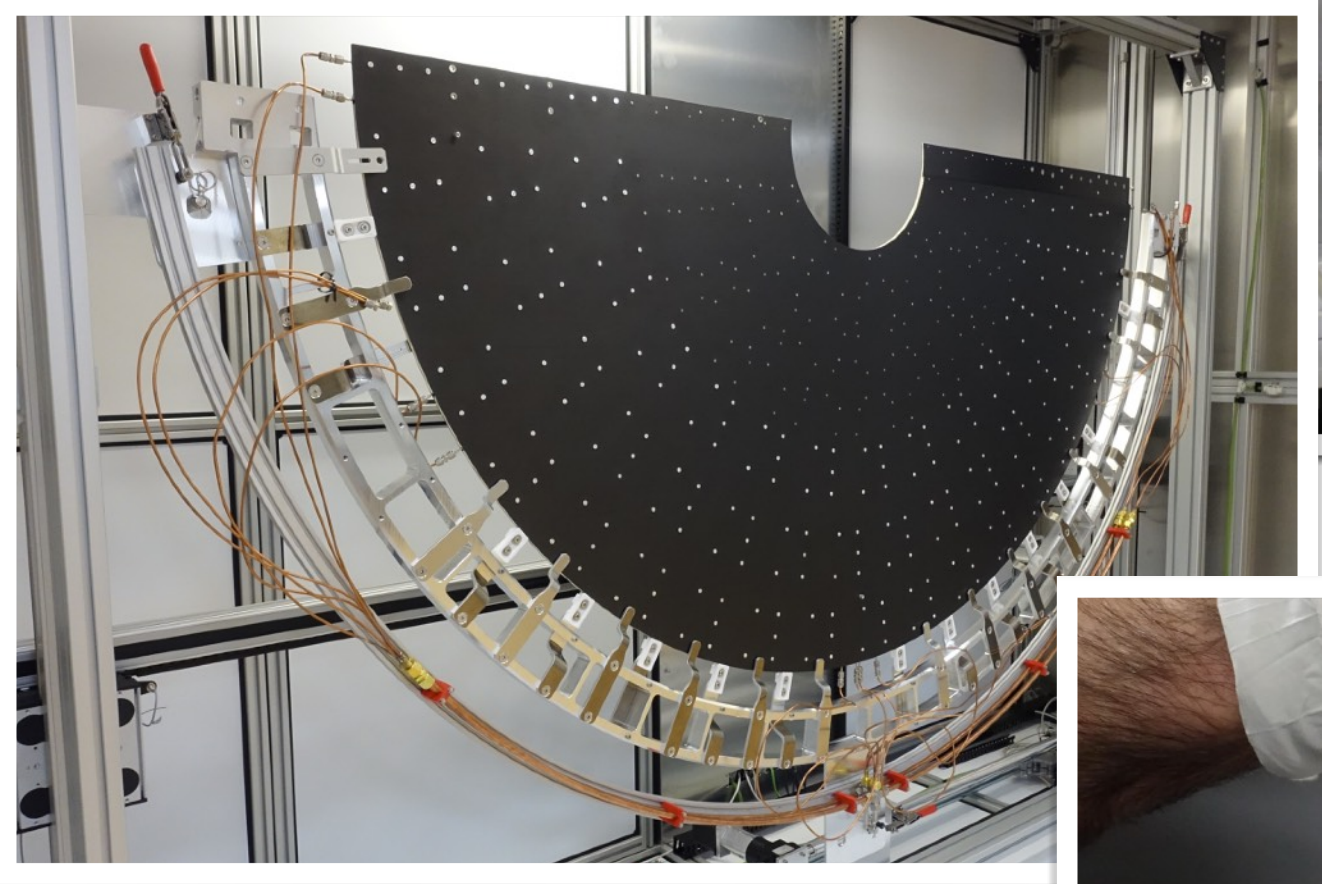
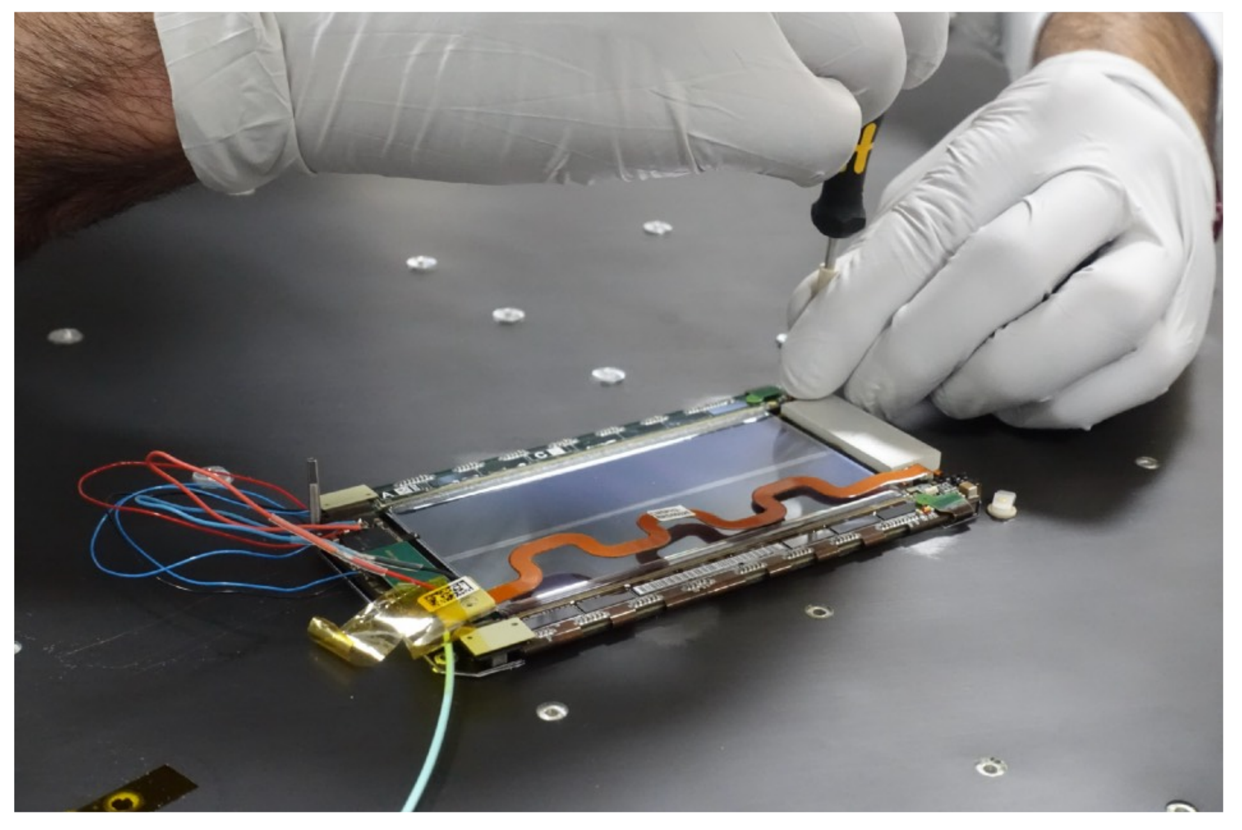
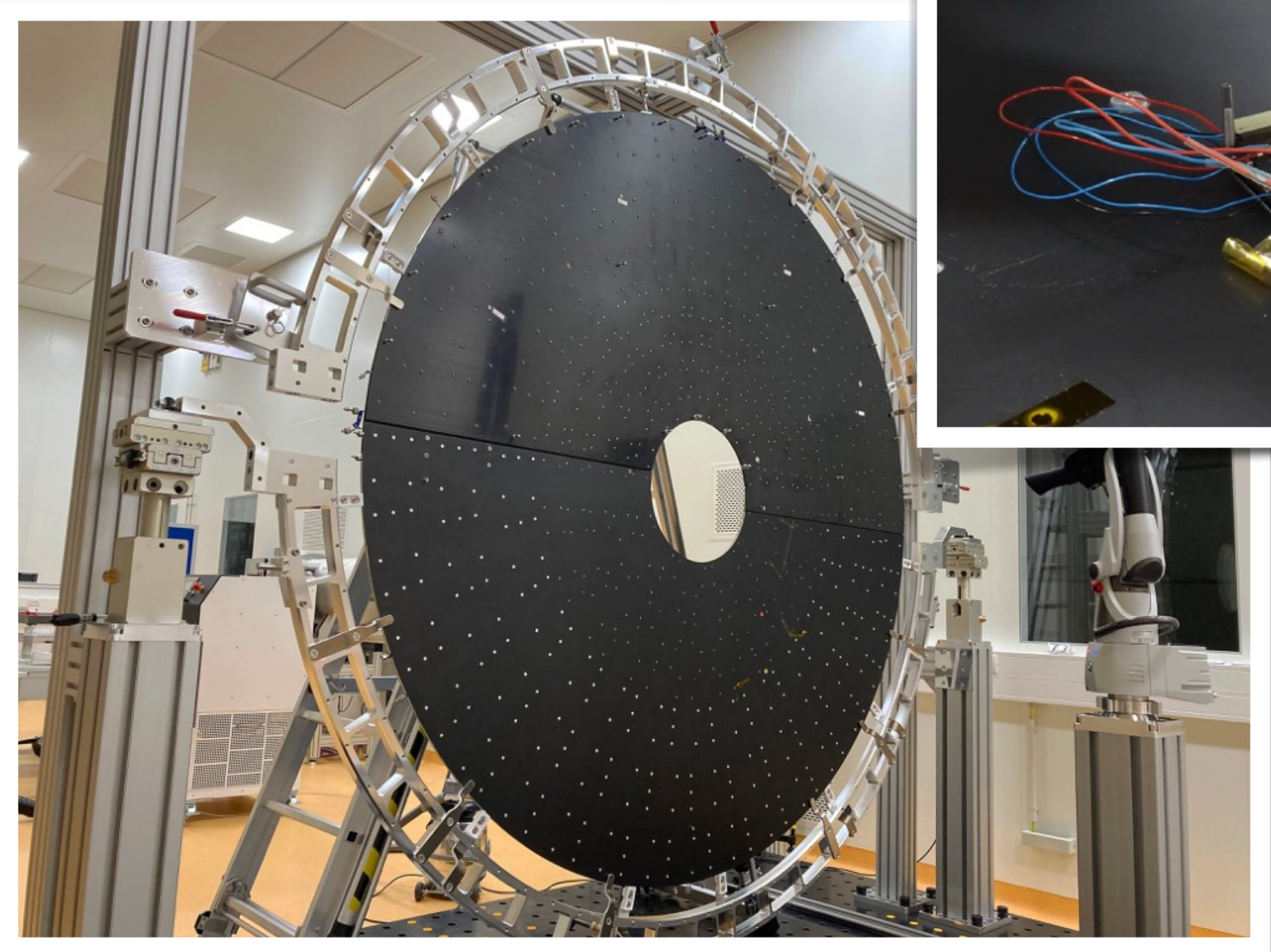
- 16 TEDD1 Dees
  - production in industry supervised by DESY

integrated local supports

- 16 integrated Dees
  - in collaboration with KIT and RWTH Aachen
  - 4/5 of one end-cap

end-cap

- 5 integrated Double-Disks
- 1 integrated TEDD
  - assembly and services done at CERN in close collaboration with UC Louvain and IP2I Lyon

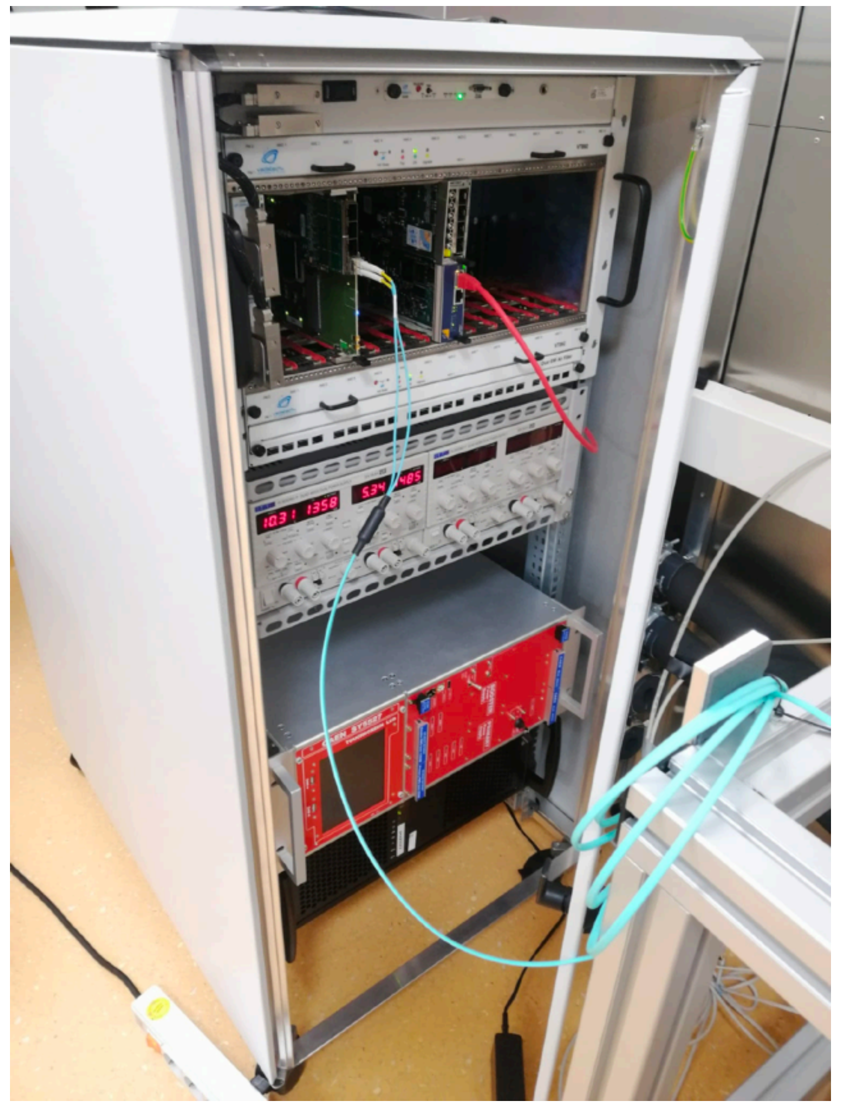
Burn-in setup

Chiller

- Unistat Hubber Pilot One

Controller Board

- Interface between the temperature and dew point sensors and the DAQ software

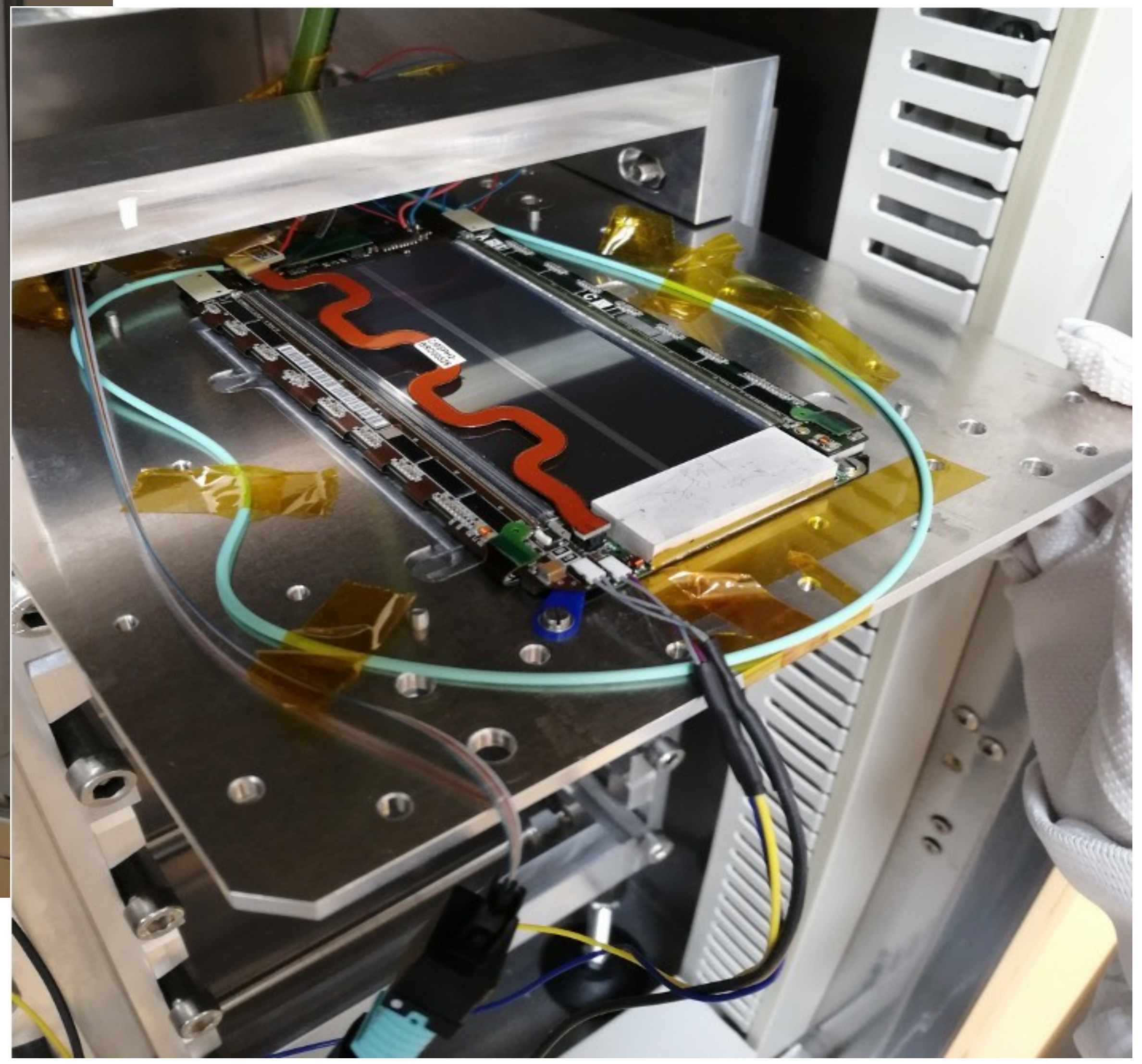


Rack

- Power supplies
- Read-out system
  - FC7: FPGA-based circuit board

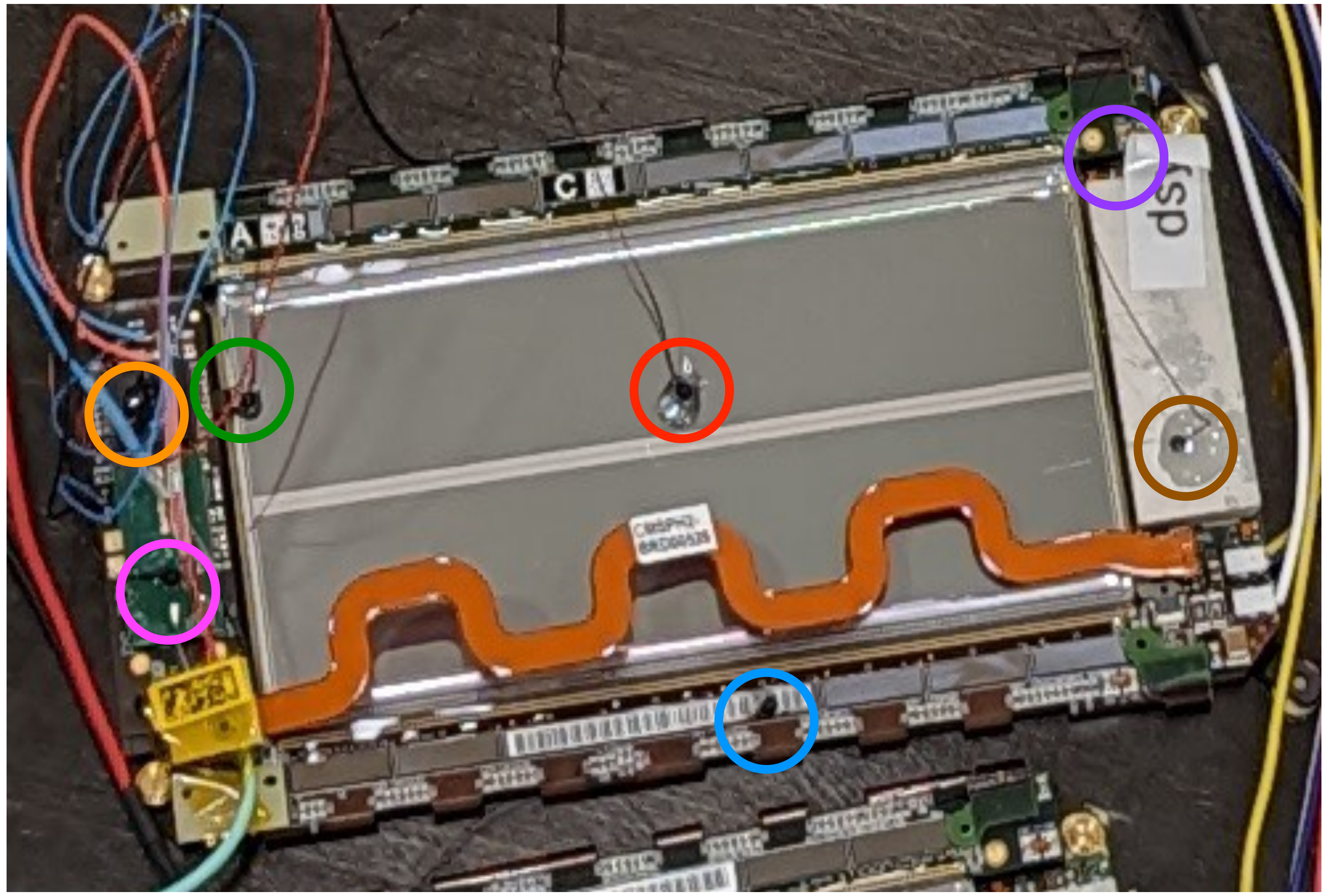
Passive cooling unit

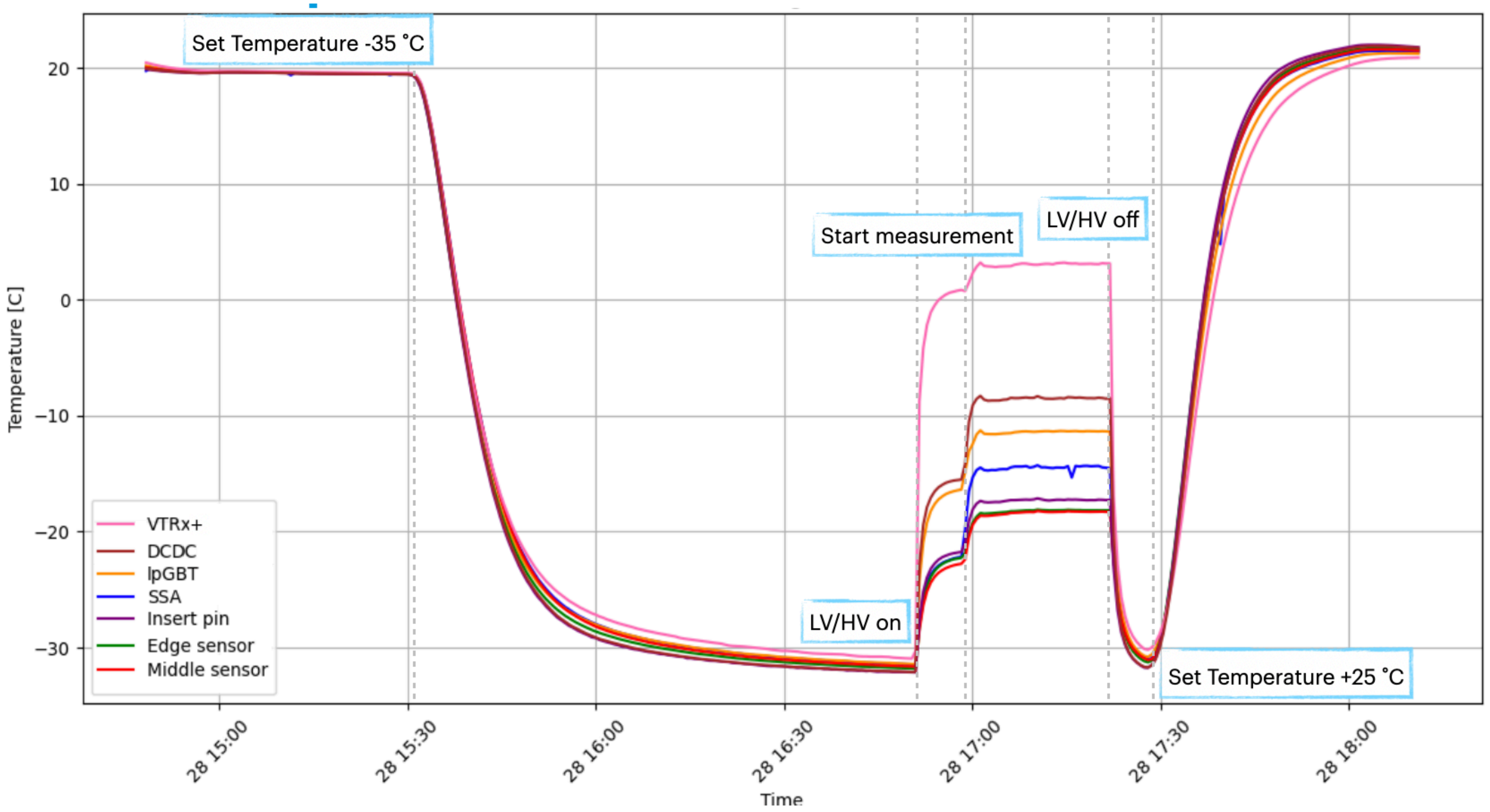
- Carrier plate support
- Cooling pipes connected to the chiller
- Temperature sensors
- Dew point sensor
- Magnetic interlock
- Dry air supply



Temperature studies in burn-in setup

- Studies performed during commissioning for understanding the temperature distribution on a module
  - seven thermistors attached to module at various positions



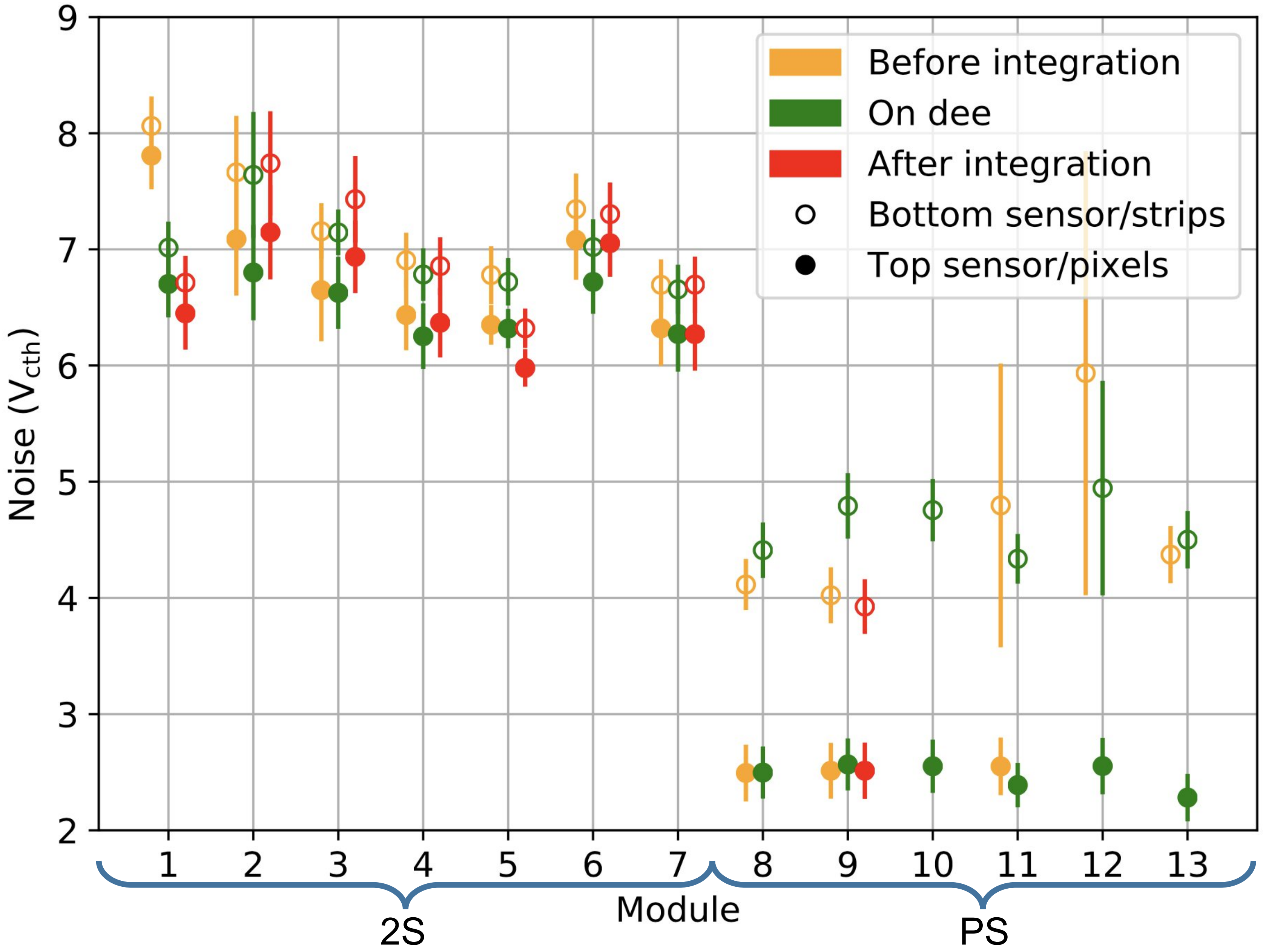


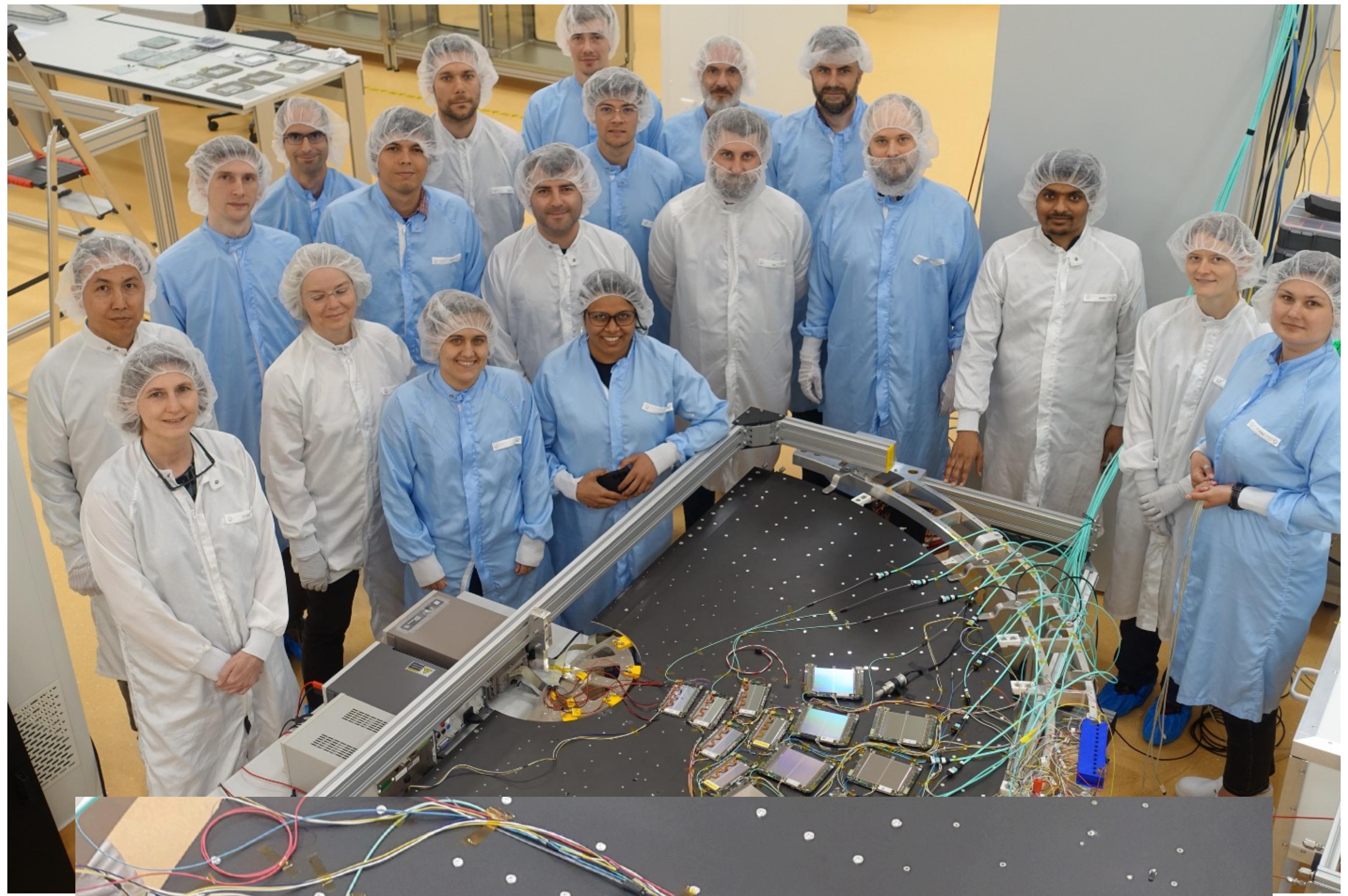
S1: on top of the optical link module (VTRx+), located in the Readout Hybrid
S2: on top of the DCDC converter in the Power Hybrid
S3: on the low-power Gigabit Transceiver (lpGBT), located in the Readout Hybrid
S4: on one of the Front-End Hybrids
S5: next to one of the insert pins
S6: in the edge of the the Strip sensor, next to temperature sensor in the hybrid
S7: in the middle of the Strip sensor

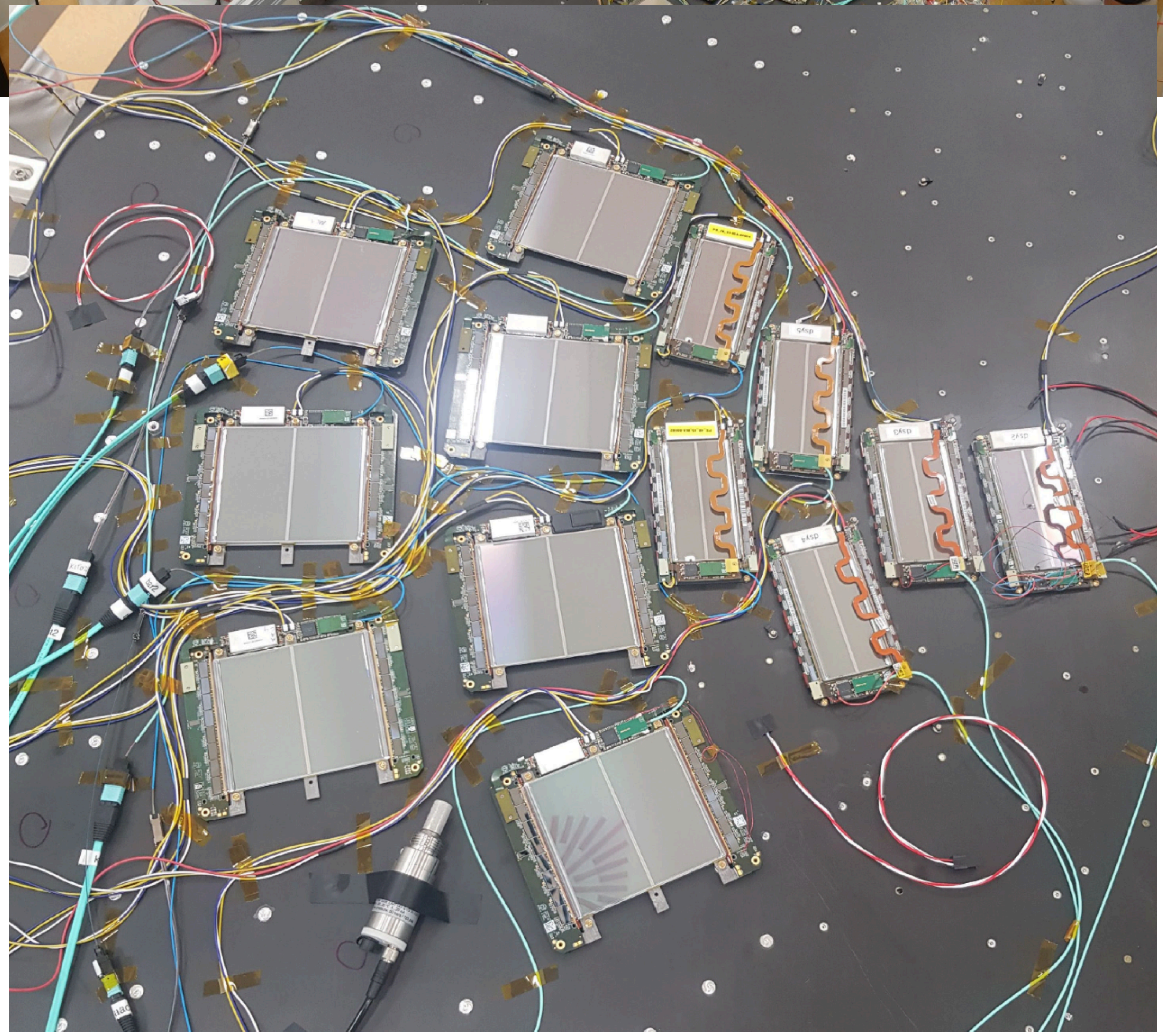
- Cool-down ramp to be optimized
- Second setup is currently being set up
  - both setups will be operated in parallel
- Planned tests with kick-off modules
  - test at extreme temperature
  - full burn-in test for 24 hours

Dee integration

- Dee integration exercise took place in June at DESY
  - Participants from Aachen, Karlsruhe, Louvain, Lyon and Bari
- 7 2S (5x KIT, 2x Aachen) and 6 PS modules (2x Bari, 4x DESY) mounted on prototype Dee and operated in parallel
- Electrical and optical services routed according to final routing developed at Louvain
- Valuable lessons learned for future integration
- Test will be repeated with kick-off modules and first pre-production Dees

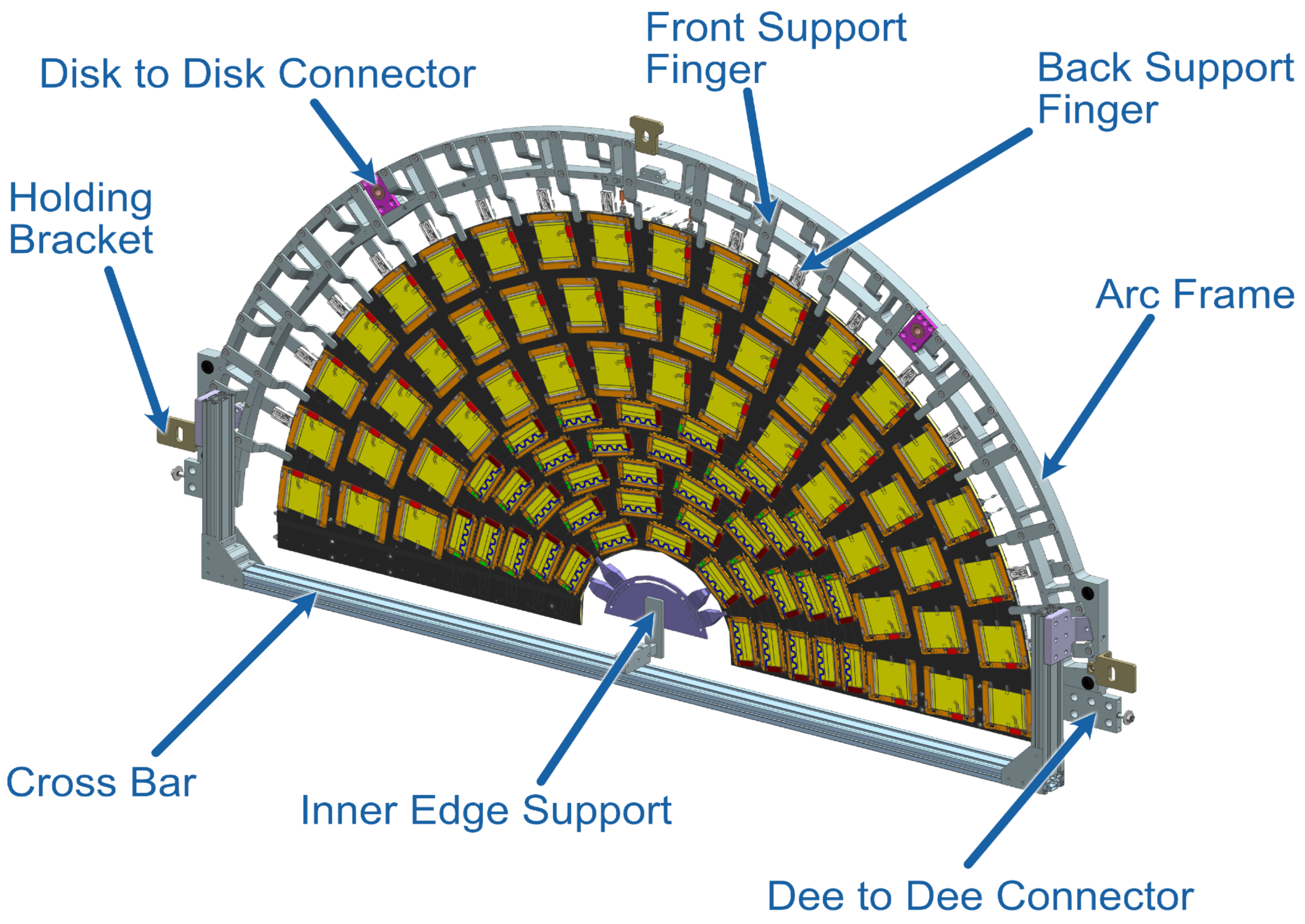






Dee tooling

- All 36 remaining Arc frames were delivered
- Cross bars and inner edge supports are partially available
- A few misc. parts still in production but expected soon
- Distribution to Lyon and Louvain once all parts are available
  - towards the end of the year



TEDD integration - inner rotation tool

- For installation of TEDD services load has to be transferred from outer radius (arc frames) to inner bore
- A cylinder in the shape of the TEDD inner bore can slide along an axle and be locked to it
- Pneumatic cylinders press against the inner edge inserts
  - Cylinders have a brake that is normally engaged
- Prototype rotation tool has been assembled
  - TEDD1 part equipped for one DD
  - Weight ring simulates the TEDD
- Insertion and removal is fairly complex and needs to be exercised thoroughly
- Tests of procedure are ongoing now