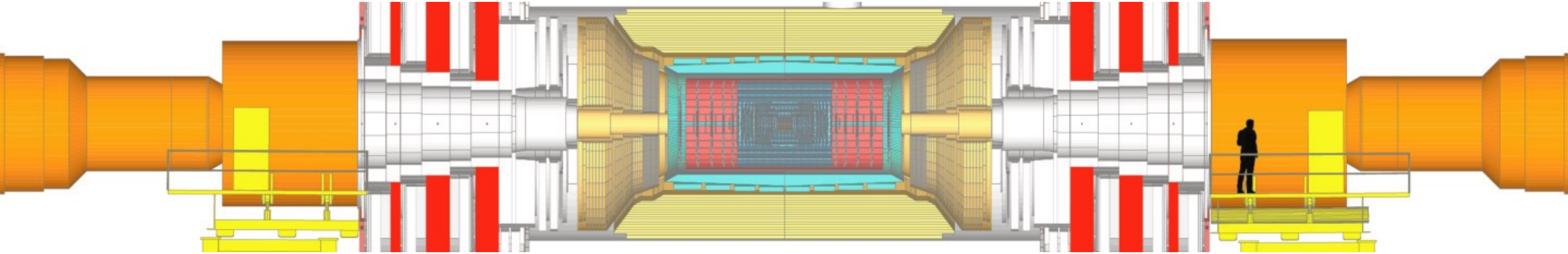
CMS Phase-2 Tracker Upgrade



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17th Terascale Detector Workshop
20th of March, 2025

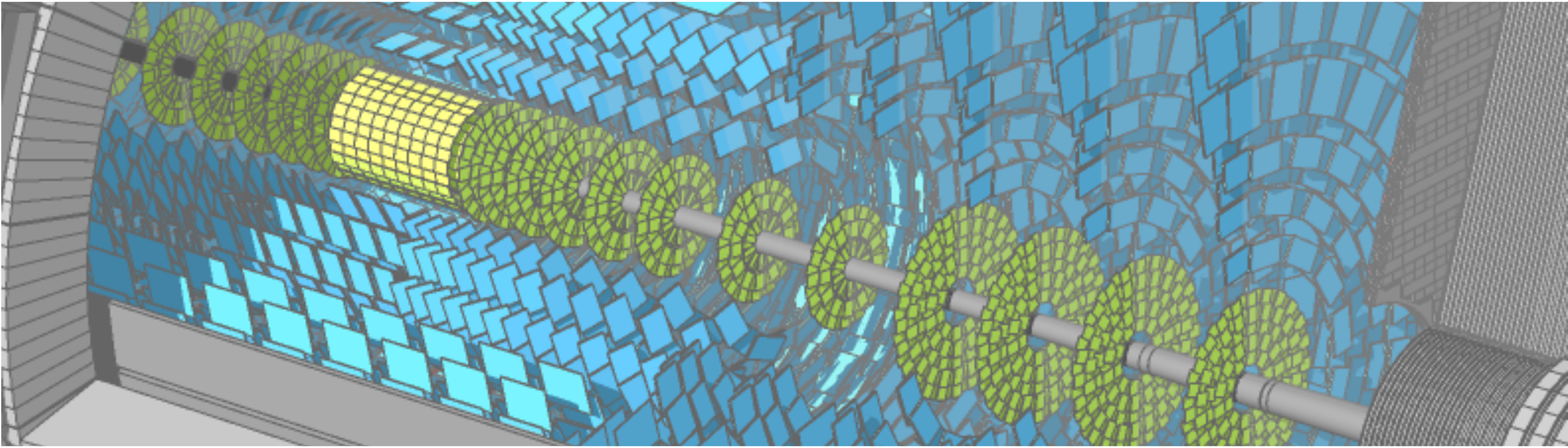
Outline

- **Tracker upgrade overview**
- **Outer Tracker**
  - Design and status of components, modules, structures
- **Inner Tracker**
  - Design and status of components, modules, structures
- **Integration**
- **LpGBT strategy**
- **Schedule and concerns**
- **German contributions**
- **Conclusion and outlook**

CMS tracker basics:

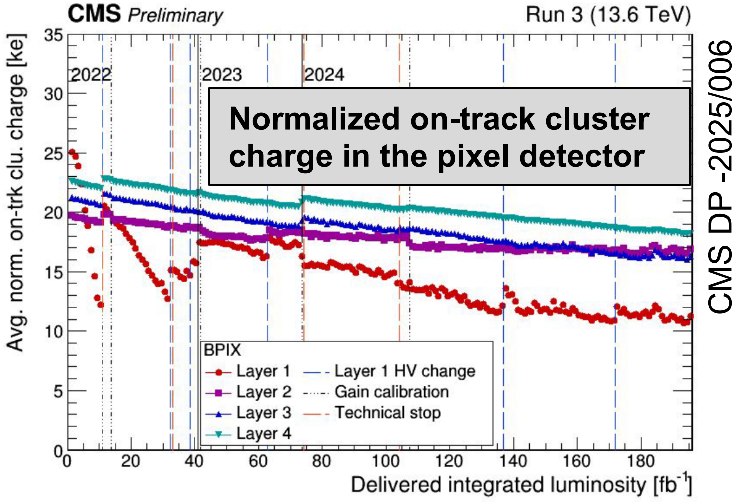
- 73 institutes, from 17 countries
- ~1100 people
- must operate an aging detector
- must maintain best possible performance
- must finish a very substantial upgrade

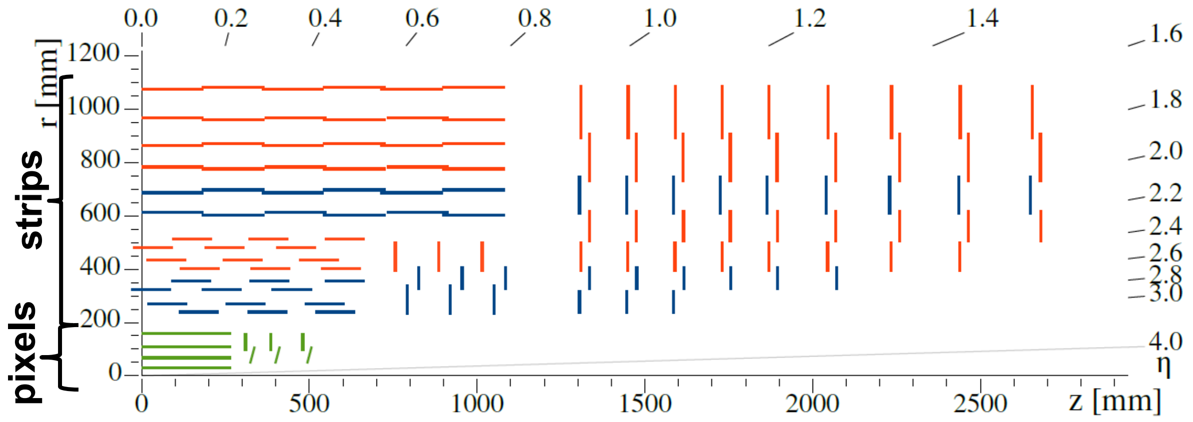
Overview



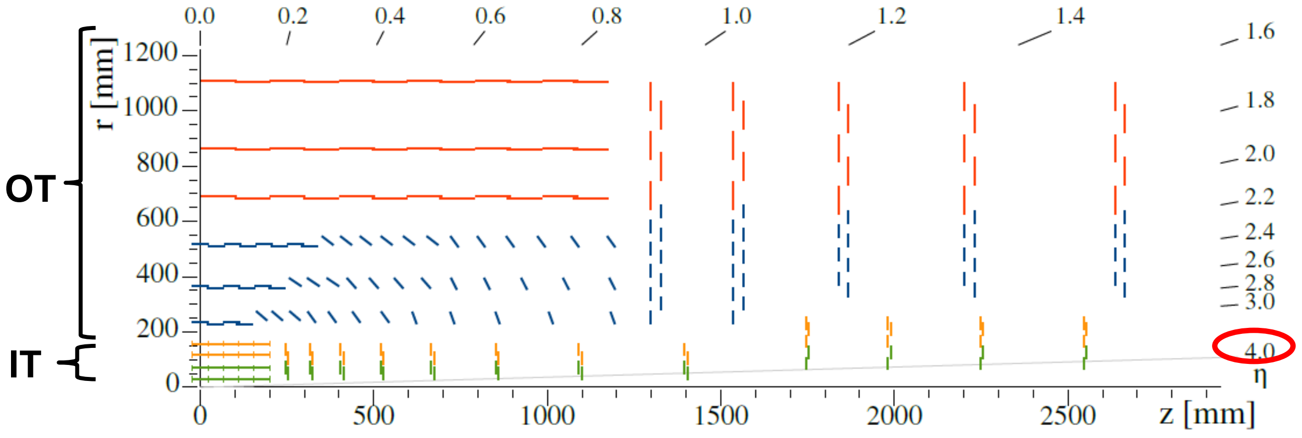
Tracker Upgrade Overview

- **After Run 3 the tracker will have reached the end of its lifetime (~500 fb^{-1})**
  - Outer Tracker (OT) replaces original silicon strip tracker
  - Inner Tracker (IT) replaces Phase-1 silicon pixel detector (installed in 2017)
- **Main improvements:**
  - Capable to deal with hit, track and data rates expected for 7.5 x 10^{34} $cm^{-2}s^{-1}$
  - Radiation-tolerance up to 1.9 x 10^{16} n_{eq}/cm^2 and TID of ~1 Grad (IT Layer 1) [with replacements in LS4]
  - Extended forward pixel detector, tracking acceptance increased from |η| = 2.5 to 4.0
  - Simplified layout in OT, less layers, reduced material due to improved service routing and inclined modules
  - New: contribution of OT to Level-1 trigger



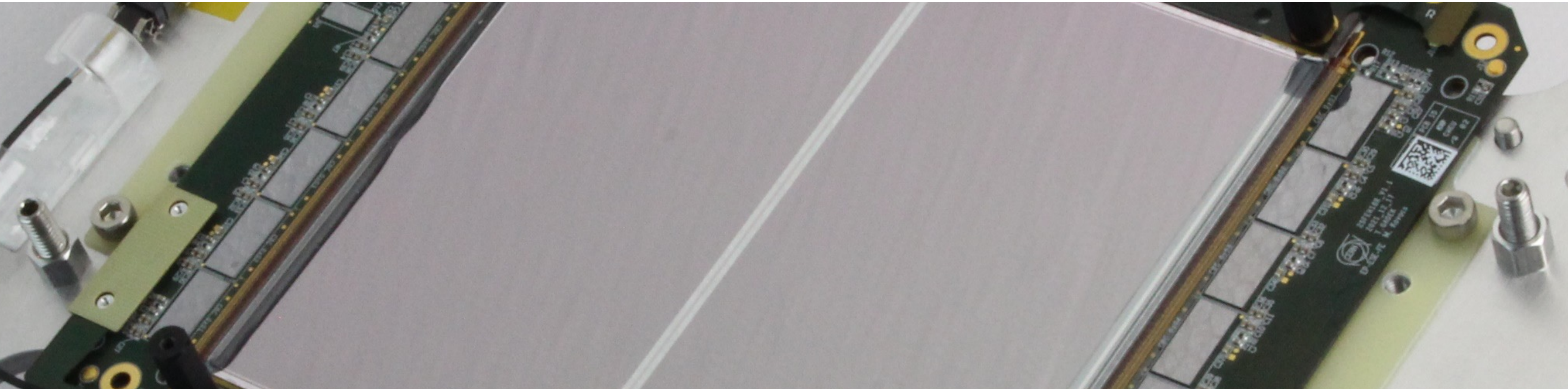


Present tracker layout



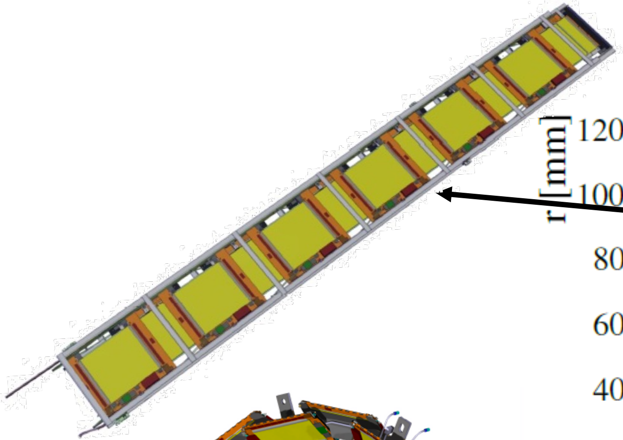
Phase-2 tracker layout

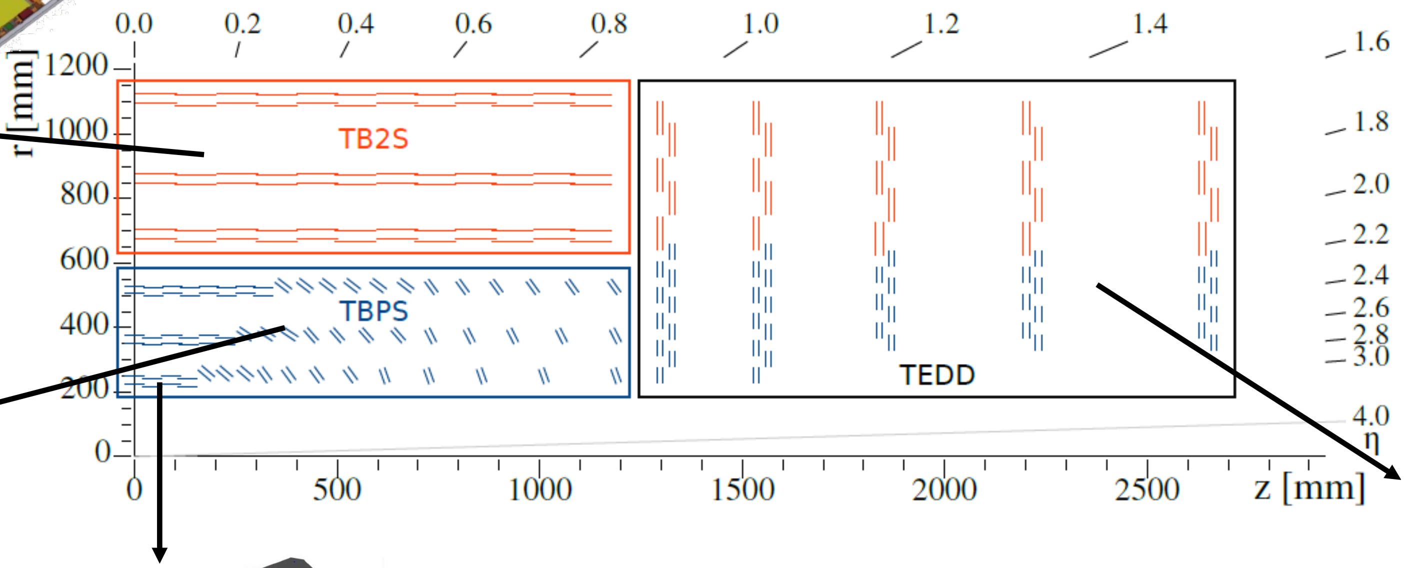
Outer Tracker (OT)

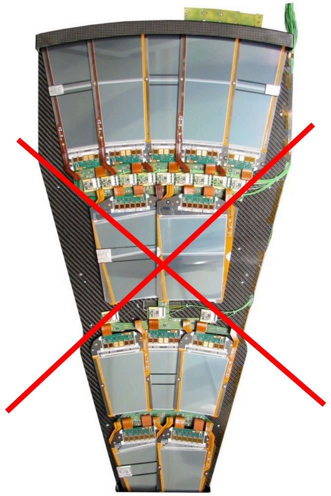


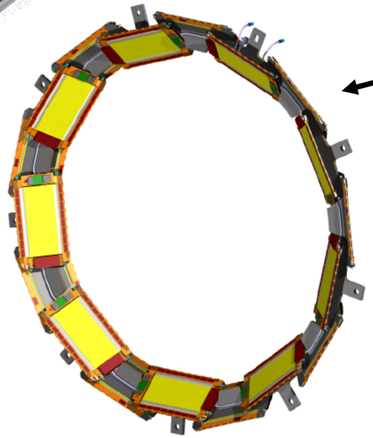
OT Overview

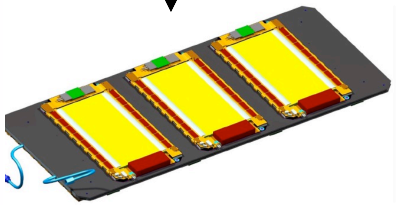
- **190m² of silicon and 213M channels (was: 200m² and 9.3M)**
- **r > 60cm: modules with 2 strip sensors (2S); r < 60cm: modules with 1 strip and 1 macro-pixel sensor (PS)**
- **OT is separated into 3 sub-detectors**
  - TB2S – tracker barrel with 2S modules: 2S modules on ladders
  - (flat/tilted) TBPS – tracker barrel with PS modules: PS modules on planks and rings
  - TEDD – tracker endcap double-discs: dees (D's) with 2S and PS modules

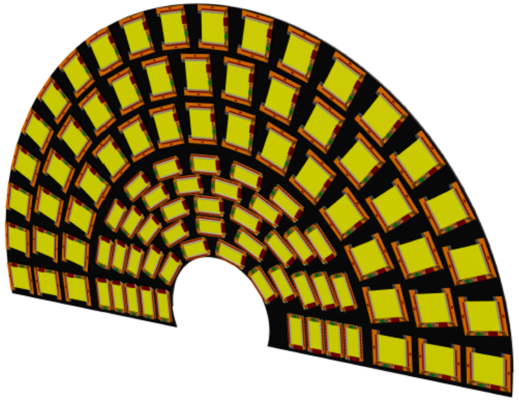








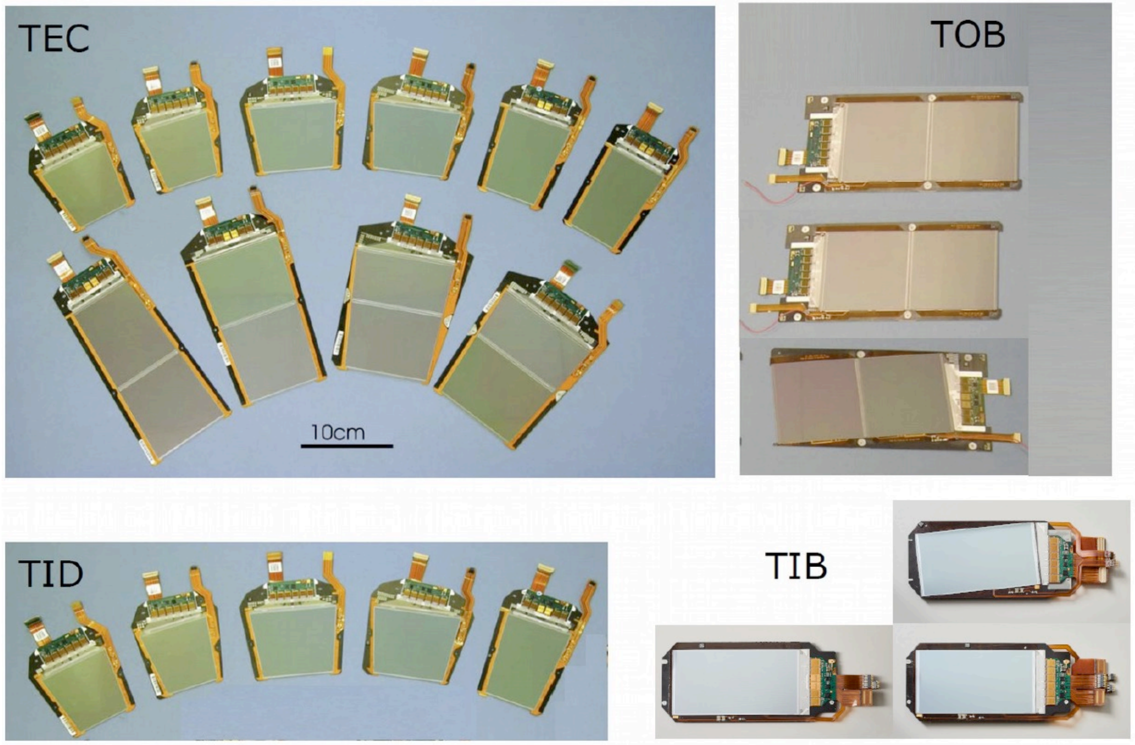


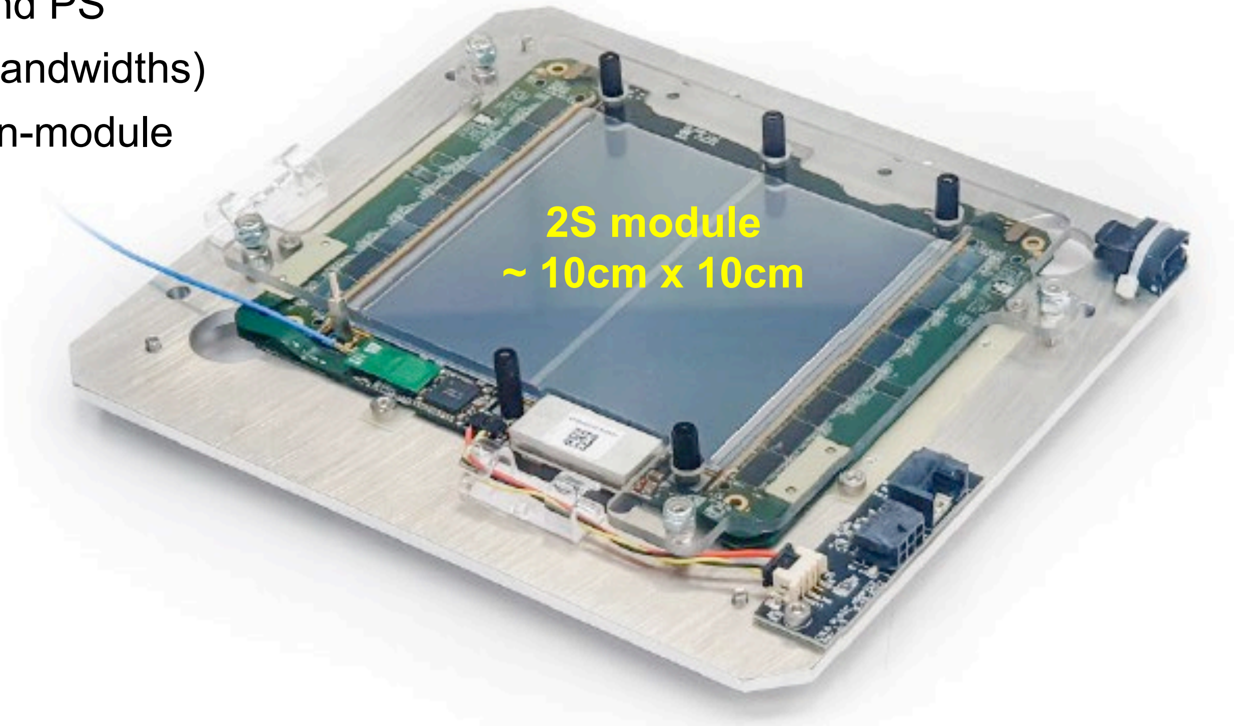


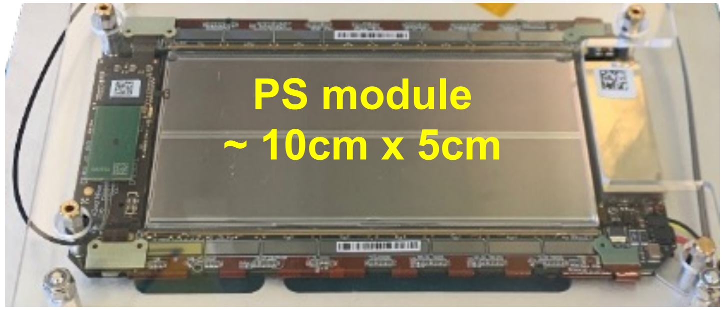
OT Modules

- Module design driven by two factors: avoid zoo of modules, and L1 track finder
- All modules rectangular, two (pretty different) main types: 2S and PS
- In total 9 variants (5 sensor spacings, 5 or 6 cooling points, 2 bandwidths)
- Powering (DC-DC converters) and opto-electrical conversion on-module

Phase-0 modules

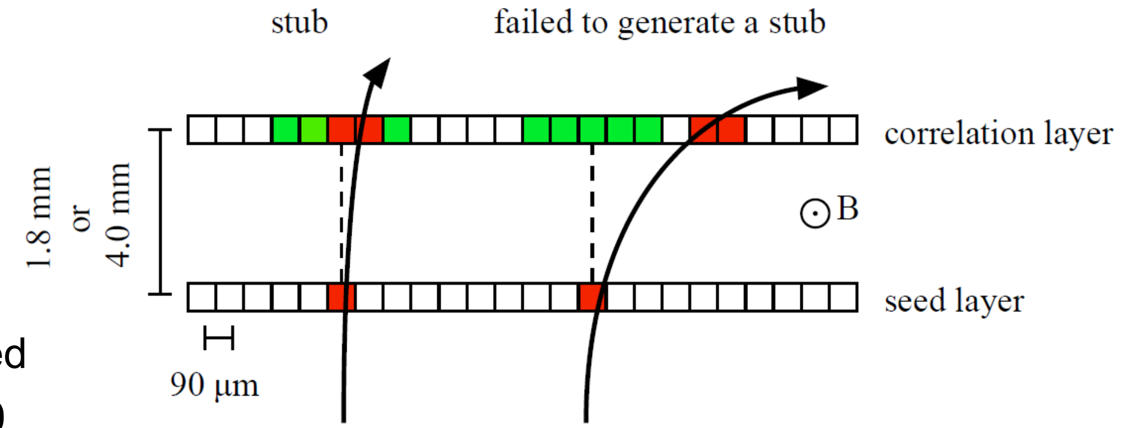






L1 Track Finder Concept

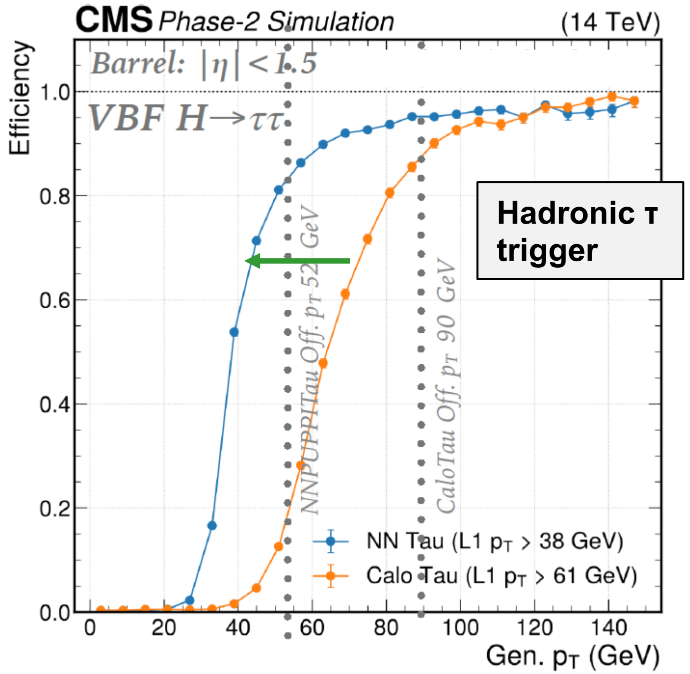
- Presently muon system and calorimeters used in L1 trigger, tracker data only used in High-Level Trigger
- Bandwidth insufficient to read out all tracker data at 40MHz
- Tracks are bent in the 3.8T B field according to their p_T
- Comparing hit patterns in closely spaced sensor layers, tracks with p_T above a (programmable) threshold can be identified
- With threshold of p_T > 2 GeV, data volume reduced by factor ~10



- Excellent z resolution due to macro-pixels (1.5mm length) in PS layers

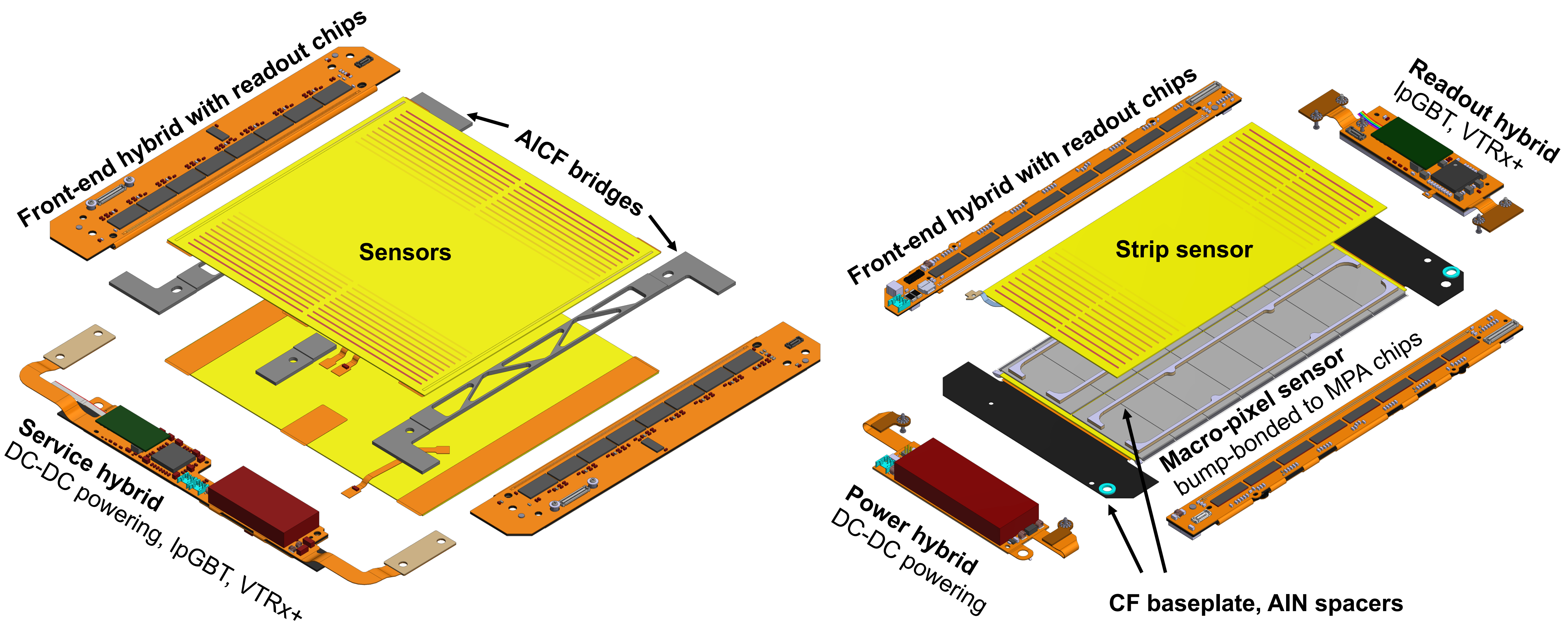
→ **Substantial enhancement of trigger capabilities:**

- vertex identification
- pileup mitigation
- track isolation
- b-tagging
- particle flow
- displaced objects from long-lived particles



OT Module Design

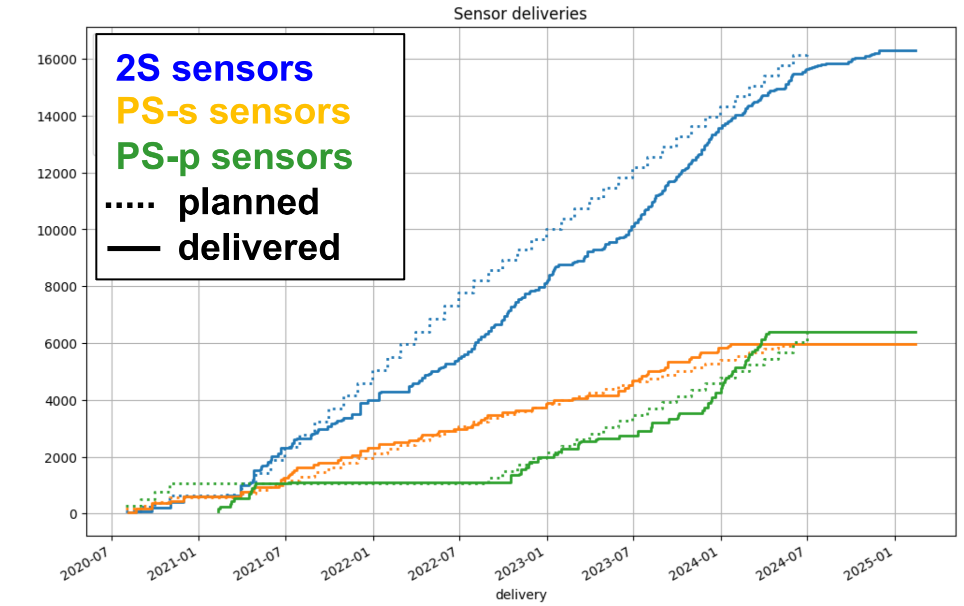
- **7608 x 2S modules** (1.8 and 4.0mm sensor spacing), **5592 x PS modules** (1.6, 2.6, 4.0mm sensor spacing)



Status of Sensors and Readout ASICs

Silicon sensors (3 types, 26.4k needed):

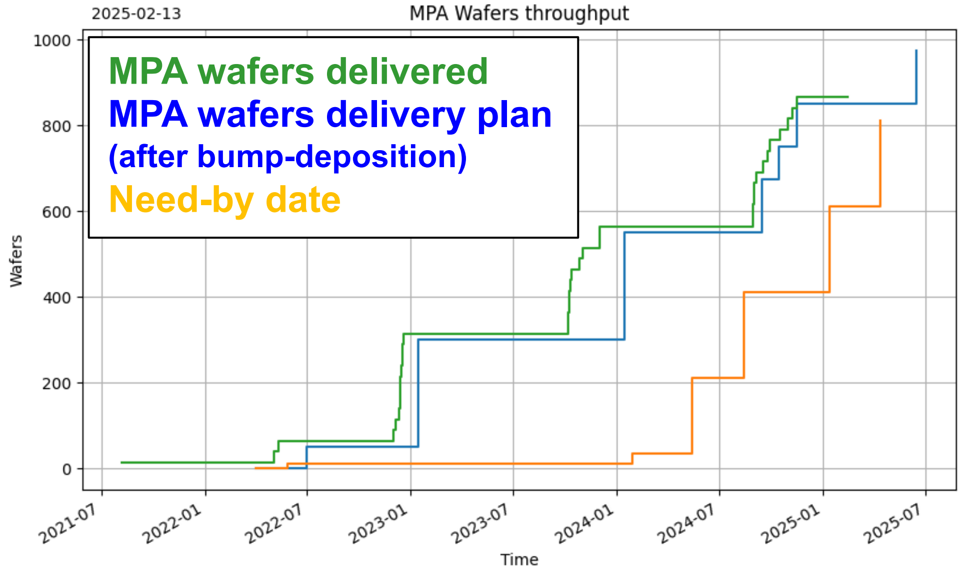
- n-in-p type, 320/290µm physical/active thickness:
  2S (5.0cm x 90µm), PS-s (2.4cm x 100µm), PS-p (1.5mm x 100µm)
- Production at HPK finished in January 2025



Readout ASICs (4 types, 327k needed):

- 2S readout: CMS Binary Chip (GF, 130nm) – production finished
- PS readout:
  - Macro-pixel ASIC (TSMC, 65nm): ~90% of wafers done
  - Short-strip ASIC (TSMC, 65nm)
- 2S+PS: Concentrator IC (TSMC, 65nm)

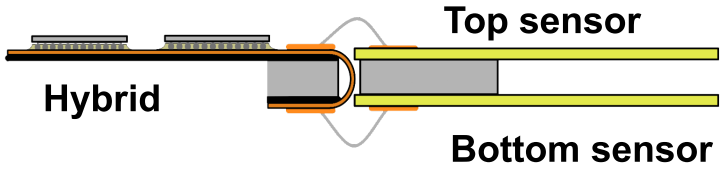
} ~60% of wafers done



Status of Hybrids

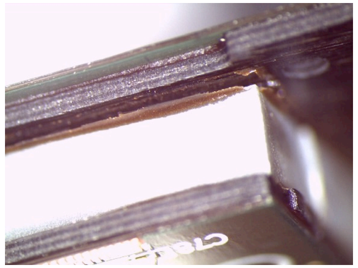
Highly complex readout and service hybrids (5 types, 18 variants, 45k needed):

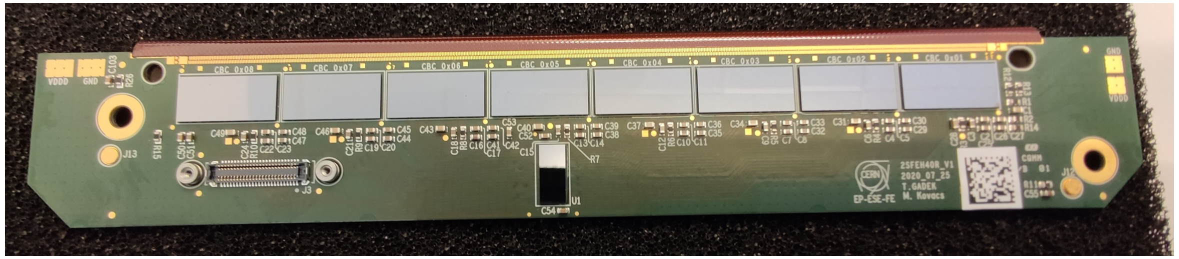
- High line density; wire-bonding and bump-bonding; fold-over; stiffeners & spacers
- Manufacturer is Valtronic, with flex producer Dyconex as sub-contractor



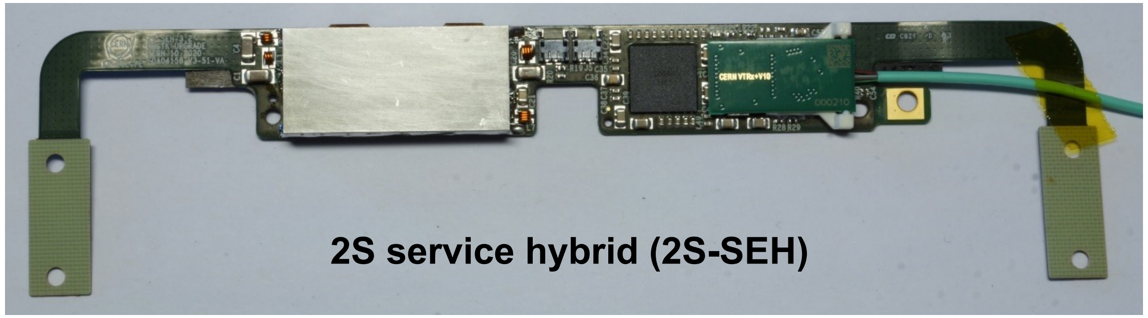
Production status:

- Pre-production completed October 24, ~1400 hybrids of all types received
- Production launched mid last year, so far ~1100 hybrids received
  - Flex production in full swing, assembly lacking behind
- Many technical issues solved over the years, but still improving on two fronts:
  - Contamination of bond pads: continuous struggle, tackled by training, cleaning, relaxing of specs
  - Improvement of glue joints in PS-FEHs: systematic tests with two alternative methods ongoing
- QC also challenging: visual inspection and functional cold test on 100% of hybrids





2S front-end hybrid (2S-FEH)

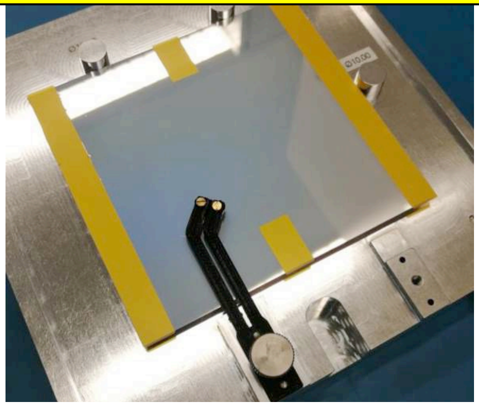


2S service hybrid (2S-SEH)

Module Assembly Procedure

- Manual assembly procedure, using several dedicated precision assembly jigs
- Many steps, glueing, curing, wire-bonding, burn-in (10 cycles, -35°C) etc. → assembly of a module takes 10 days
- In steady-state, all steps done every day (pipelining)
- QC on leakage current, mechanical precision, wire-bond quality, number of dead/noisy channels

Kapton isolator & HV tail gluing



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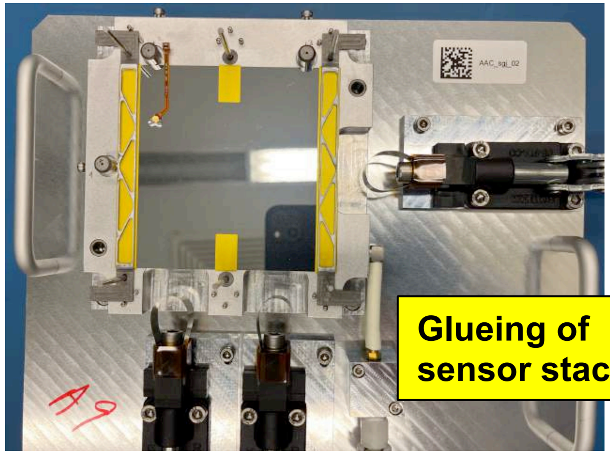

Glueing of sensor stack

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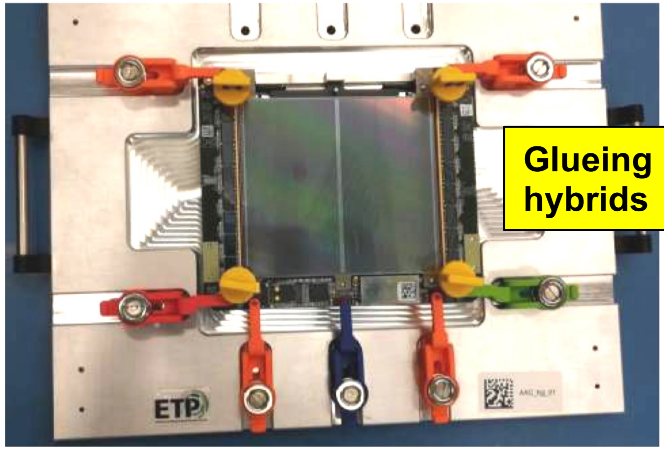
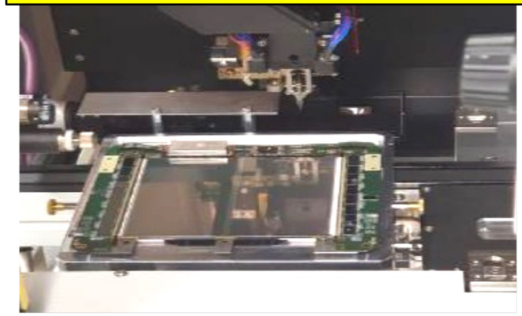


Glueing of hybrids

Wire-bonding, encapsulation



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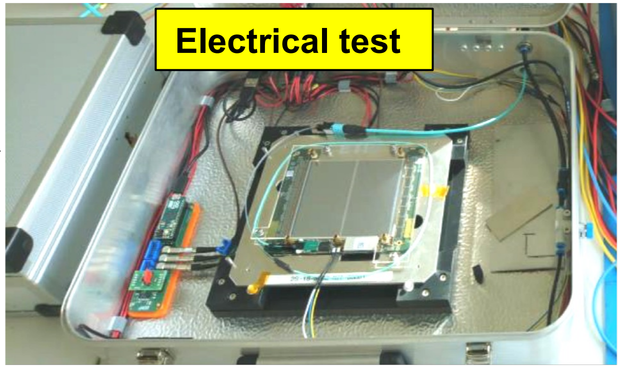
Electrical test



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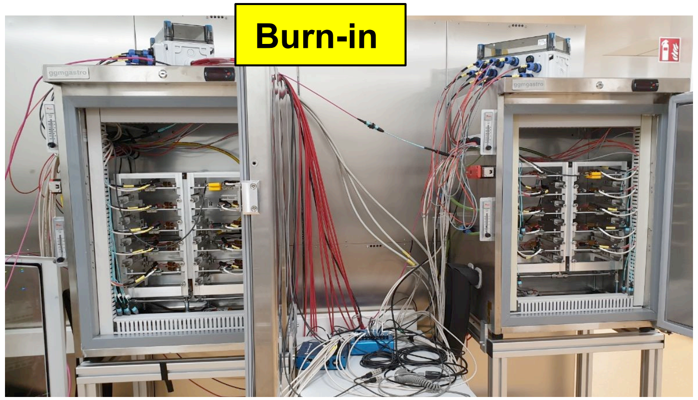
Burn-in

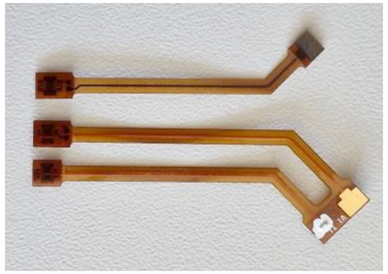


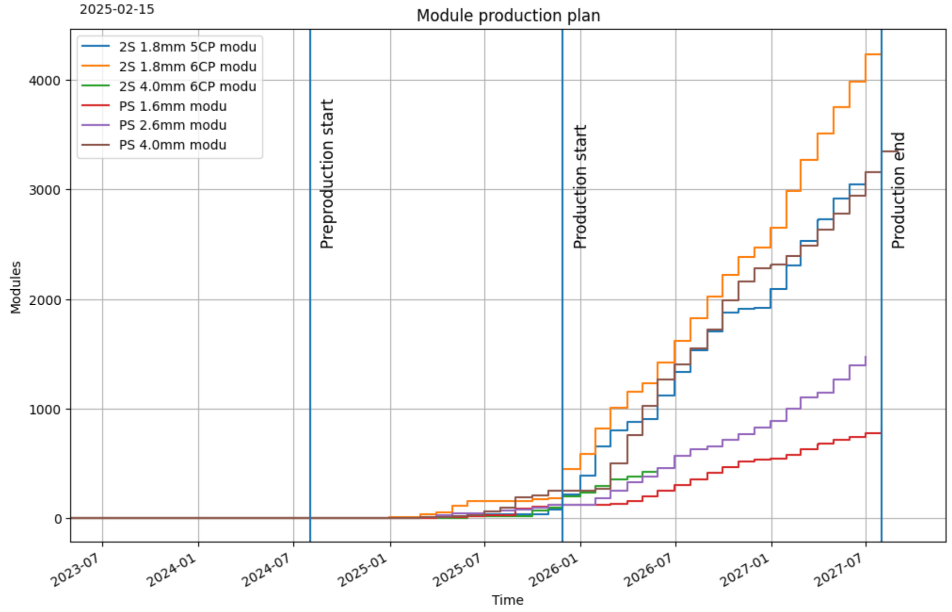
Module Production Status and Plan

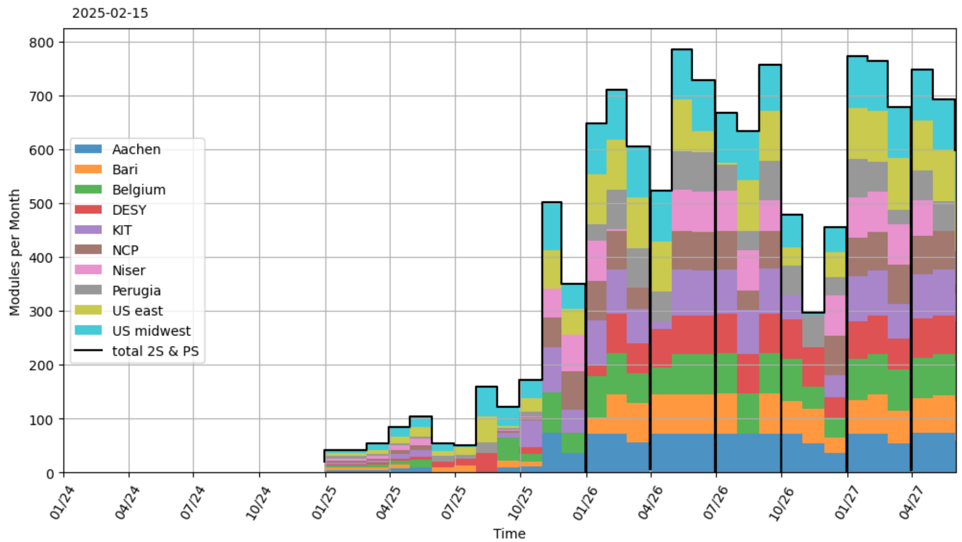
- **Module production is shared between 10 assembly centers**
  - Aachen (2S), Belgium (2S), KIT (2S), NCP (2S), Niser (2S)
    Bari (PS), DESY (PS), Perugia (PS), US East (PS, 2S), US Midwest (PS, 2S)
  - Between 1000 and 2000 modules per center
  - Typical peak throughput of 4 modules per day (not yet proven)

- **We are presently in module pre-production (5% of modules)**
  - Ramping up in small steps:
    - each center had to assemble 5 good modules (~done)
    - now “pipeline test“: 7 modules, with one module started every day → need to do all steps on day-7
    - then at least 2 modules in parallel
  - So far ~50 pre-production modules built

- **Fighting to overcome limitations:**
  - parts (recently: 2S high voltage pigtails)
  - jigs (quantity and quality, e.g. rework for PS)

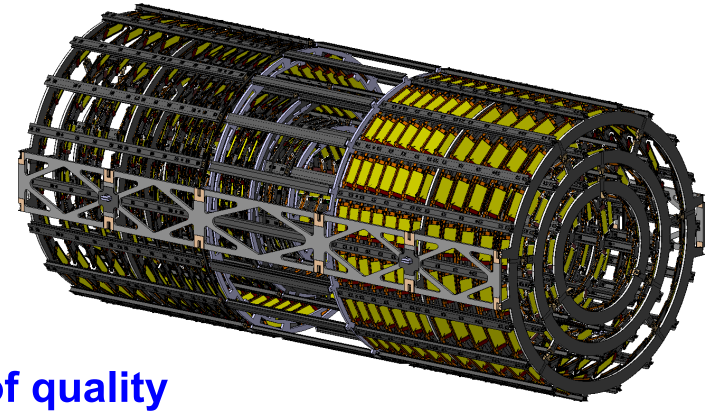




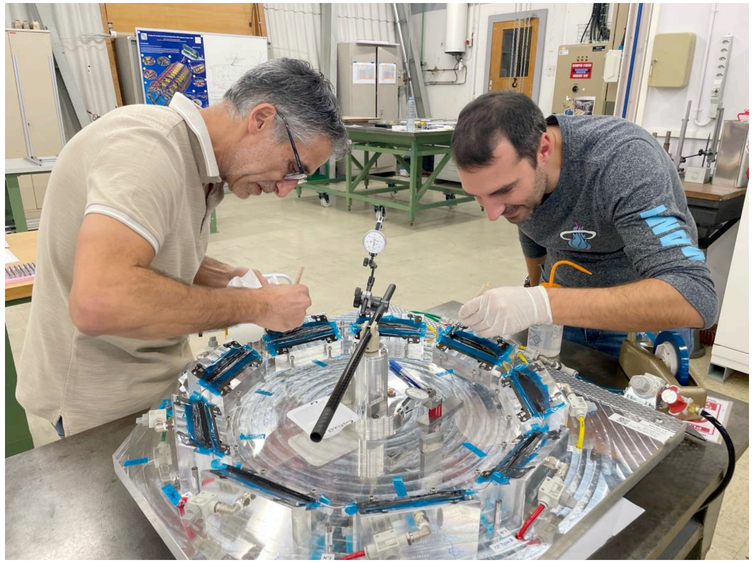


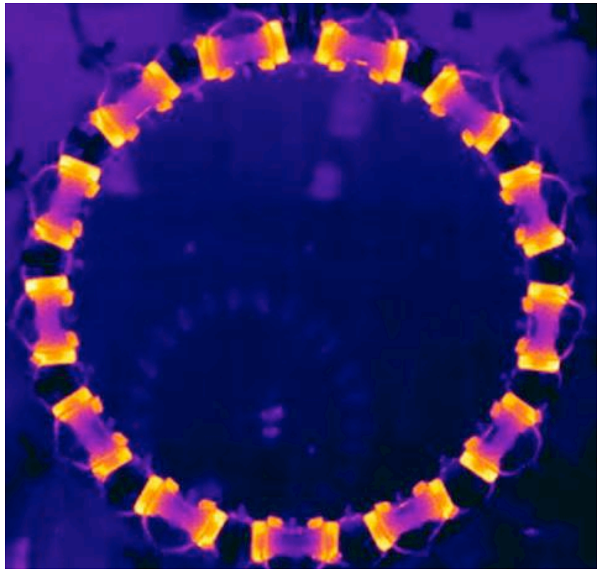
Production of Mechanical Structures

- **Tilted TBPS needs 72 rings of 22 types (3 layers, various tilt angles, cooling pipe details)**
  - Rings are produced “in-house“, at CERN
  - Target throughput of 1 ring per week reached
  - QC: dimensions, mass, stiffness, pressure test, grounding, thermal performance
  - ~40% of rings already produced
  - Integration tests of modules on rings about to start in Pisa



- **Planks, dees, ladders are in pre-production: still small numbers, careful checks of quality**



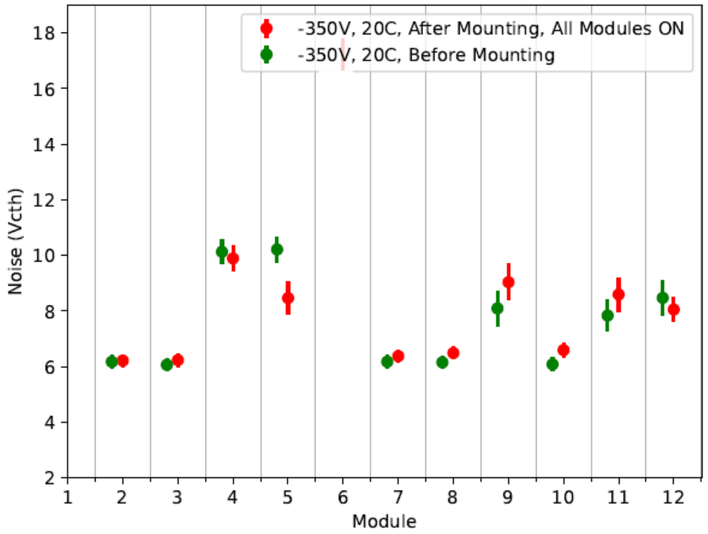


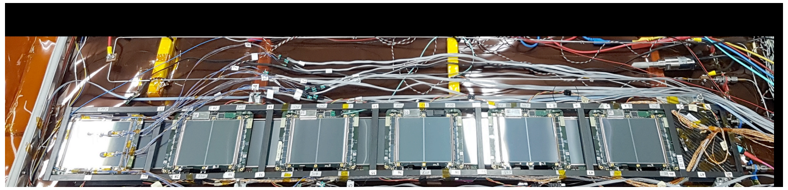
Module Integration

- **Integration tests on ladders and dees done, on planks ongoing**
  - Mechanical tests (thermal interface material for PS modules), noise tests, thermal tests
- **No real surprises, e.g. module noise not increased compared to single module readout**
- **Module integration hampered by lack of modules, in particular final ones (LpGBT V2, see later)**

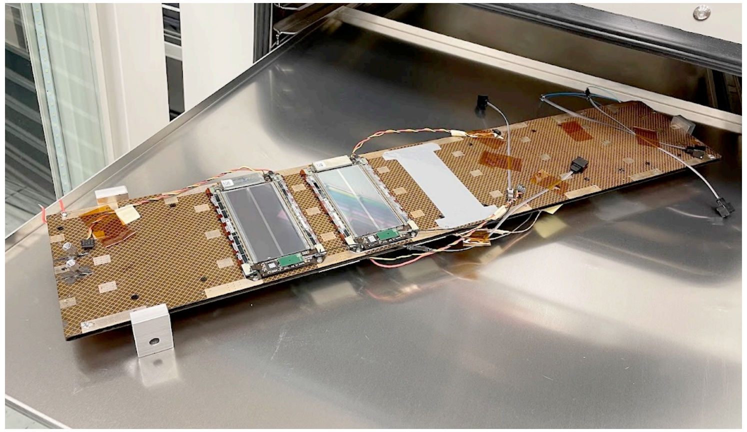
Dee integration test / DESY (later: DESY, Louvain, Lyon)

Ladder integration test / CERN (later: Strasbourg, Niser)

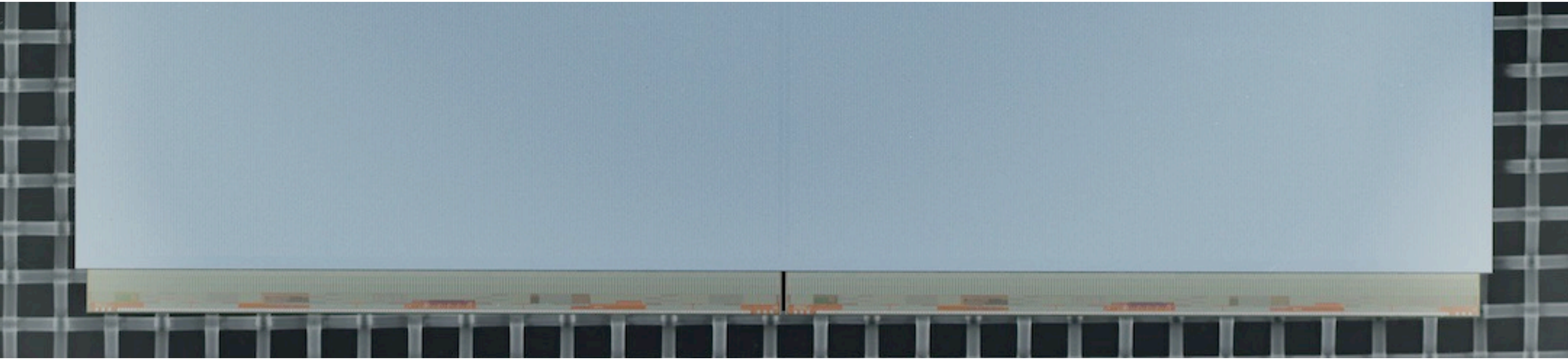




Plank integration test / FNAL (later: FNAL)

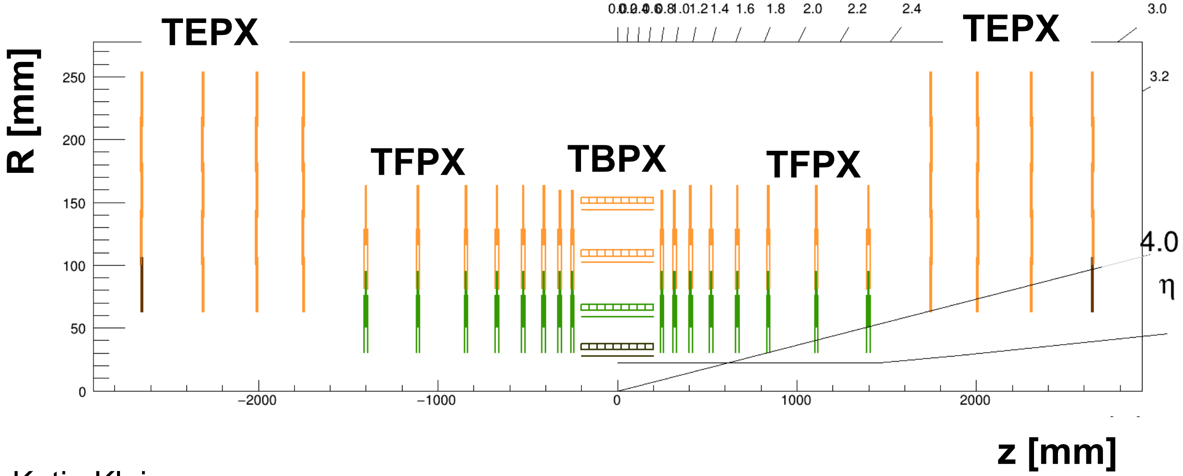


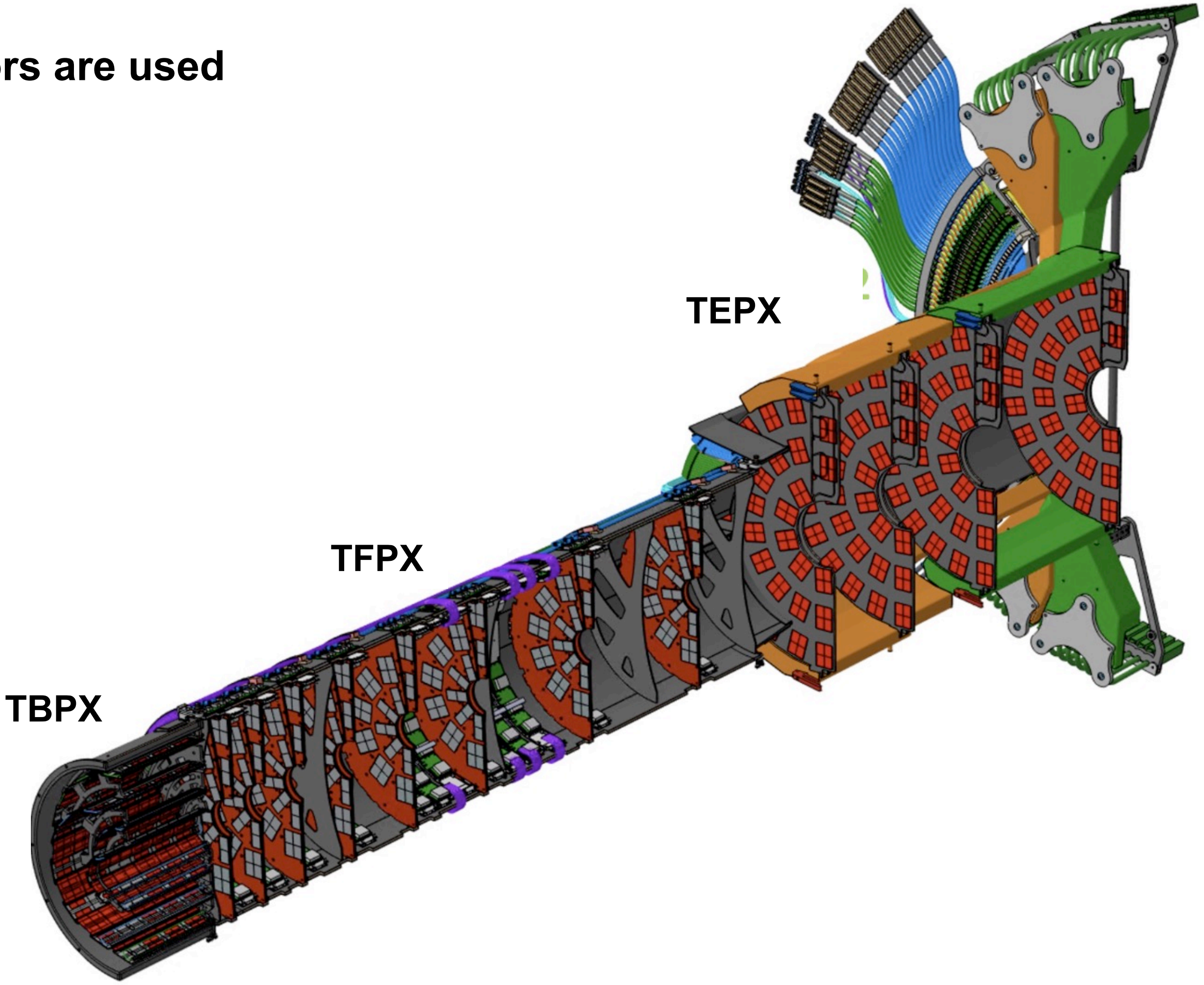
Inner Tracker (IT)



IT Overview

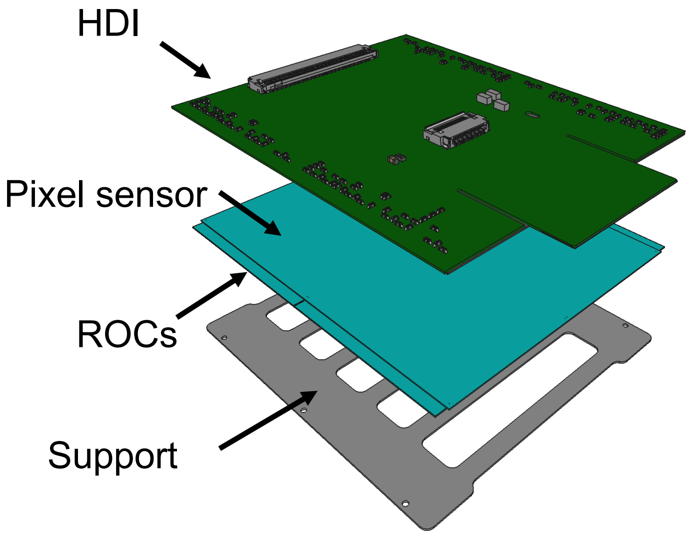
- **5m² of silicon and 1.9G channels (was: 1.9m² and 124M)**
- **Modules with 1 x 2 and 2 x 2 readout chips**
- **Planar sensors except for barrel layer 1, where 3D sensors are used**
- **IT is separated into 3 sub-detectors**
  - TBPX – tracker barrel pixel detector, with ladders
  - TFPX – tracker forward pixel detector, with dees
  - TEPX – tracker endcap pixel detector, with dees
- **Split into 4 quarters, extractable during EYETS**

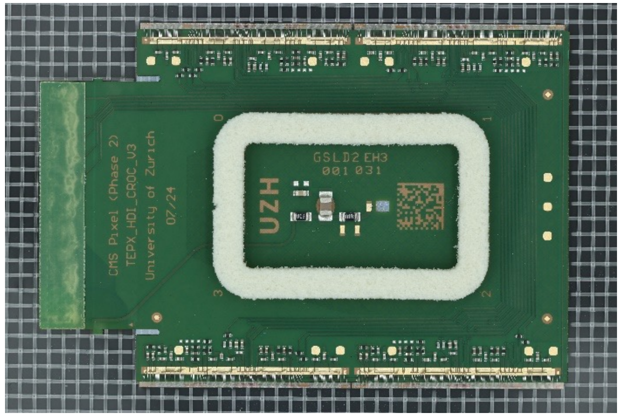




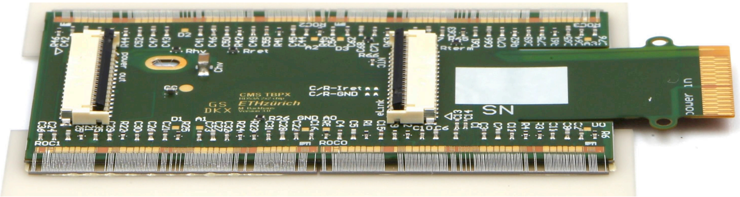
Pixel Modules

- **Hybrid pixel modules (2 types, 9 variants, 4212 modules in total)**
  - Bare module = readout chips (ROCs) bump-bonded to sensor
  - High Density Interconnect = PCB, wire-bonded to chips
  - Mechanical support for mounting, differing between sub-detectors
    - BPIX: AlN cooling plate, 250µm thin
    - TEPX: Airex frame
    - TFPX: none
  - Parylene coating of complete module, to avoid HV sparks
- **Combination of manual work and automation using gantries**
- **Production of 1 module takes 6 weeks (incl. parylene coating in industry)**



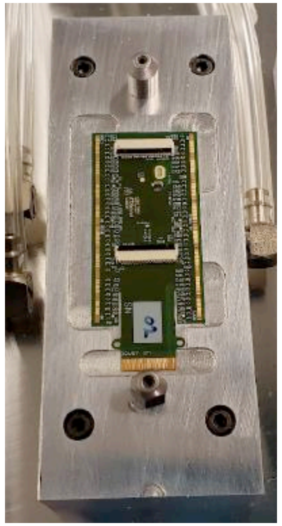


TEPX 2x2 module



TFPX 1x2 module

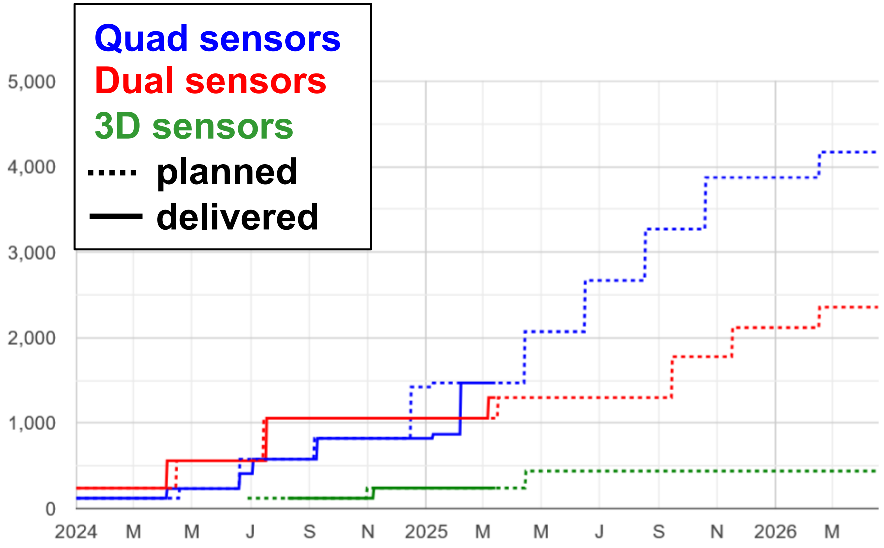
TEPX robot



TFPX jig

Status of Sensors and Readout ASIC

n-in-p type, 150μm active thickness, 25 x 100 μm² cell size
(was: 50 x 100 μm²)

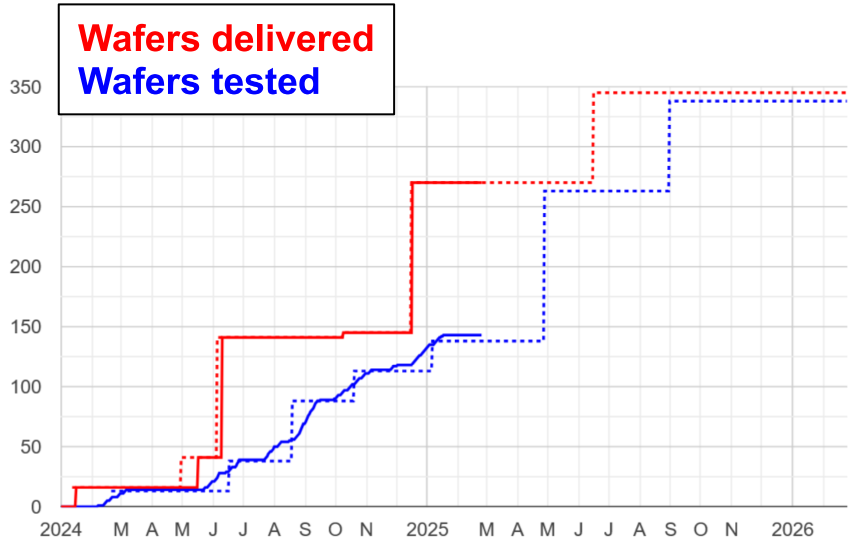


Planar silicon sensors (HPK, 2 types, 3996 needed):

- 55% of 2 x 1 (duals) delivered
- 35% of 2 x 2 (quads) delivered

3D silicon sensors (FBK, 1 type, 212 needed):

- 55% delivered
- These are "1 x 1", i.e. two sensors used per 2 x 1 module



Readout ASIC (1 type, 13 896 needed):

- C-ROC = CMS version of RD53 chip (TSMC, 65nm)
  - Analogue front-end = "linear"
- 78% of wafers delivered

Status of Hybridization

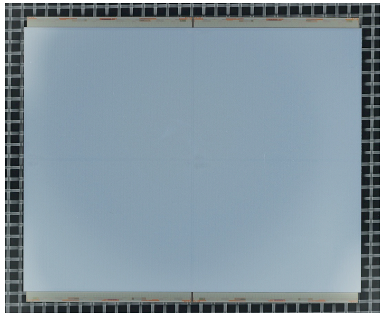
Hybridization = bump-bonding of readout chips to sensor

- Sensor under-bump metallization and dicing
- C-ROC wafer bump deposition, thinning, dicing
- flip-chip bump-bonding

→ "bare module"

Baseline sharing plan:

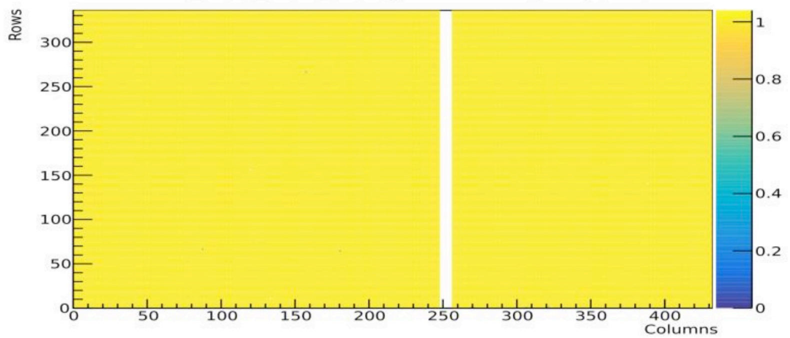
	Quads	Duals	3D
IZM	50%		
Advafab	50%	20%	100%
Micross		80%	



Three companies involved:

- Micross (US), Advafab (Finland), IZM (Berlin)
  - C-ROC wafer processing for Micross & Advafab now at Winstek

Example of a broken core column

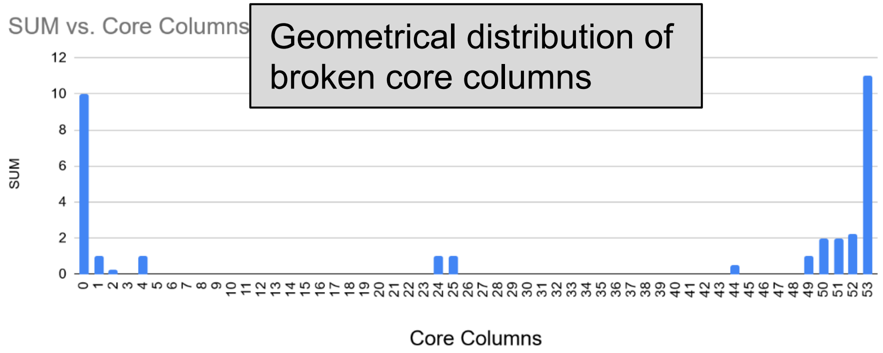


Long prototyping phase, not without problems:

- Scratches, bad IV, clusters of bad pixels (bowing)
- Broken core columns – related to dicing?
- Low throughput

} strongly vendor-dependent

Geometrical distribution of broken core columns



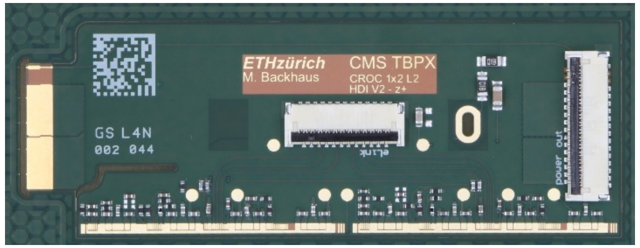
Pre-production ongoing:

- >200 bare modules already received and under study
- Production Readiness Review for Micross & Advafab in March, IZM later

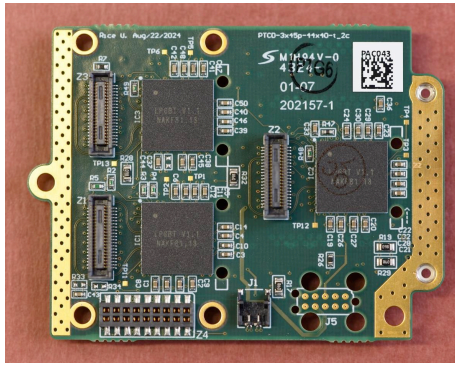
Electronic Aspects

- **HDI = PCBs for readout and power distribution (8 types, 4212 needed)**
  - Pre-production ongoing and first pre-production modules with final HDIs built
    - TBPX L1 & L2 +z production already completed
- **Portcards with LpGBTs and DC-DC power board: pre-production ongoing**
- **Serial powering of chains of 5-11 modules, with all chips of a module in parallel**
  - TEPX system test with disk PCBs: low noise, as standalone and independent of position

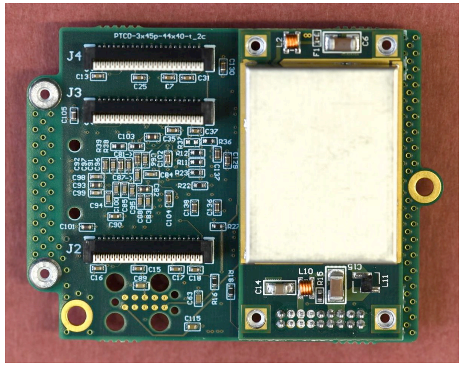
TBPX L2 HDI



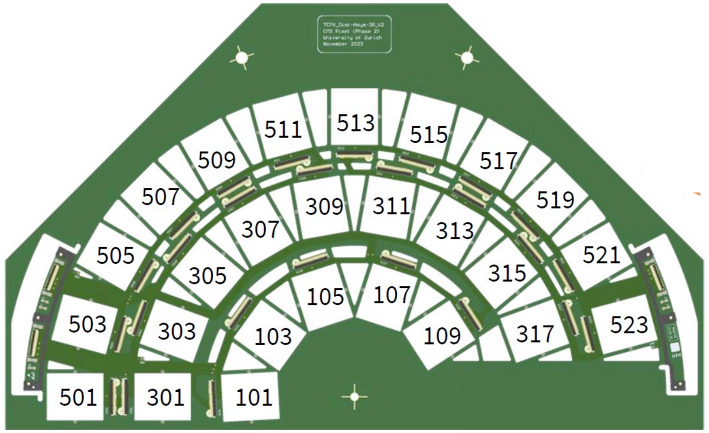
Portcard top side

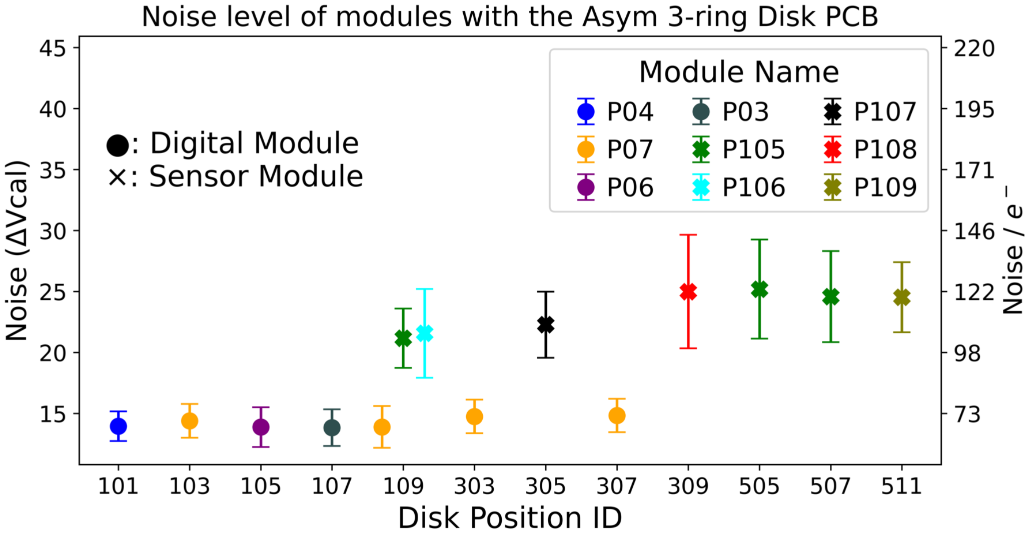


Portcard bottom side with DC-DC board



TEPX disk PCB





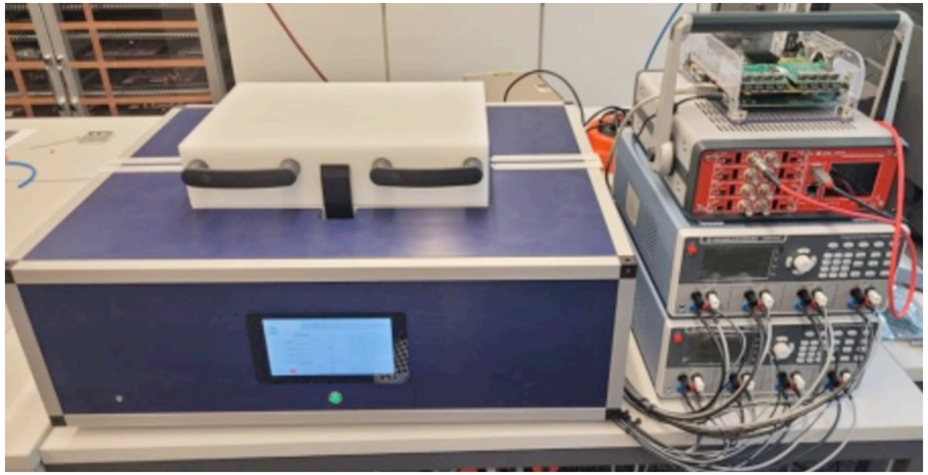
Module Production Status and Plan

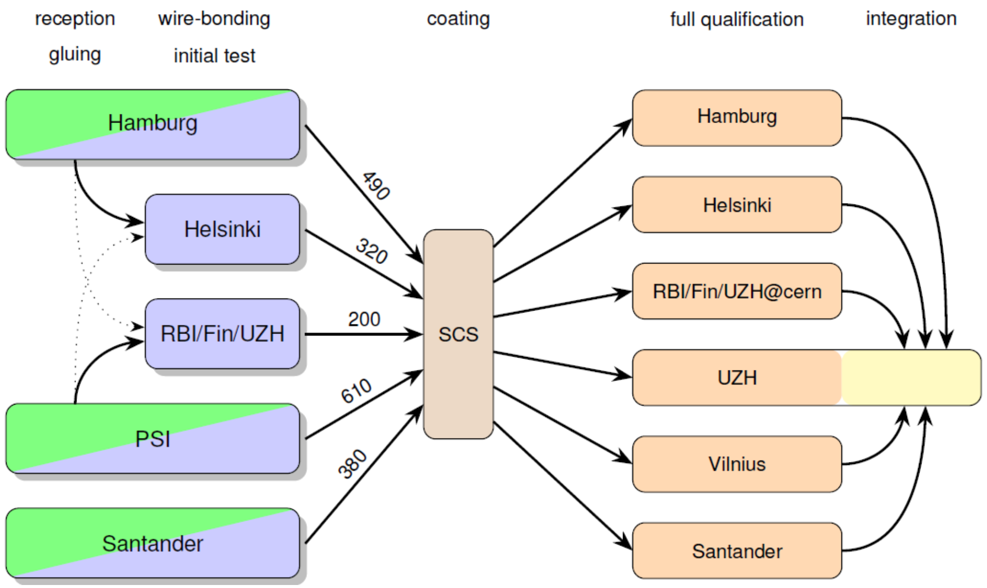
- **Module production is shared between 11 assembly centers**
  - **TBPX**: ETH Zurich, Florence
    TFPX: Boston, Catholic Univ. of America, Nebraska–Lincoln, Purdue
    TEPX: Hamburg University, Helsinki, IFCA Santander, PSI, Ruđer Bošković
    - Plus others for testing only: Ohio State, Univ. of Illinois, Vilnius
  - Between 200 and 800 modules per center

- **More than 60 full modules built so far**
  - Both with C-ROC V1 and V2, few with final HDIs
  - Experience of centers varies a lot: between 0-1 and > 20 modules

- **We are entering pre-production (5% of modules)**
  - Finalizing assembly jigs and cold boxes for module testing
  - Finalizing software and GUIs for testing, preparing data base

- **Peak throughput of 10 to 25 modules per week and center**
  - Factor 2-3 above need, but not yet proven



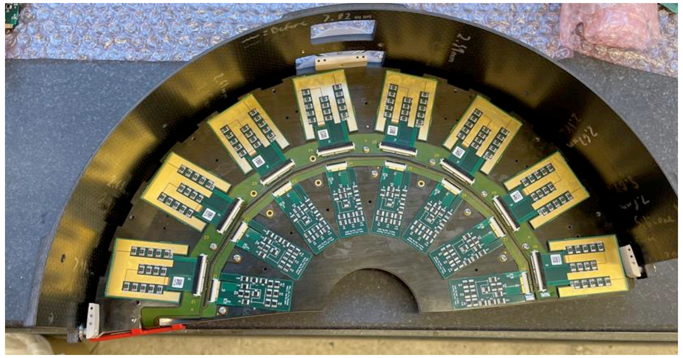


TEPX module flow

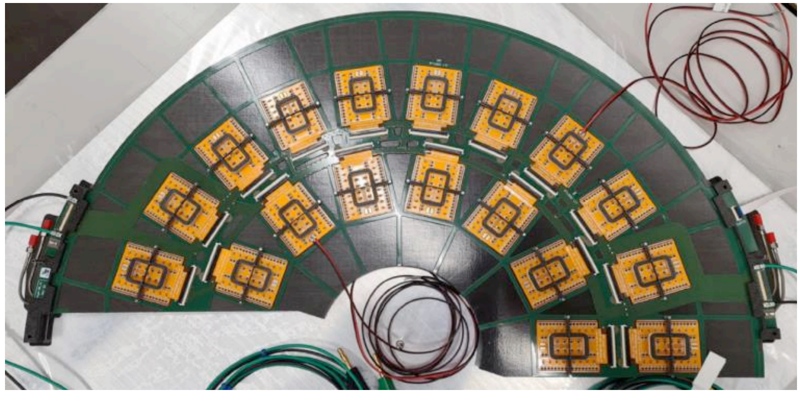
Mechanical Structures

- **Building final prototypes of all TBPX layers and TFPX & TEPX dees**
- **Validation ongoing**
  - Thermal tests with dummy and real modules
  - Electrical system tests
  - Metrology, validation of assembly methods and tooling
- **Production of pipes and mechanical parts has started**
- **Assembly of first BPIX quarter mechanics Q4/2025**

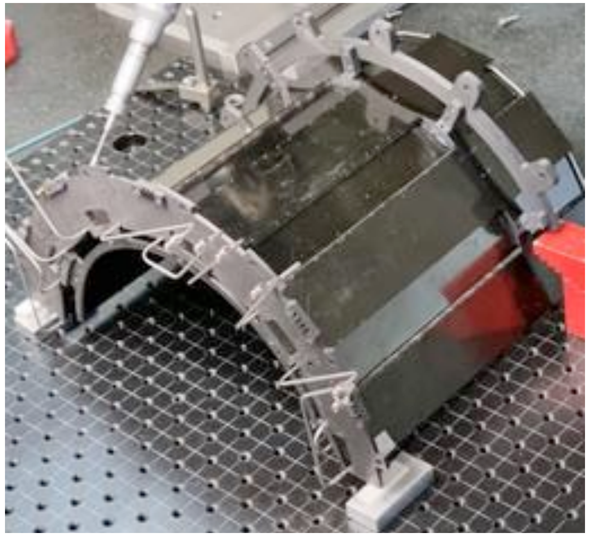
TFPX dee system test



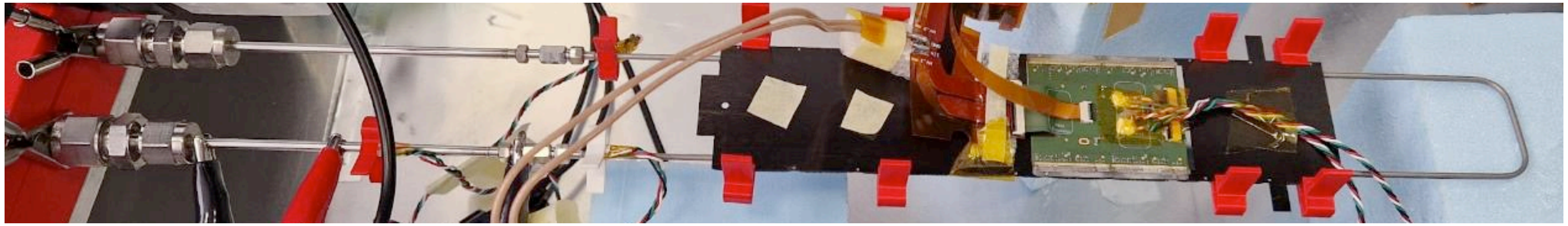
TEPX dee with dummy modules



L3 prototype on assembly tool



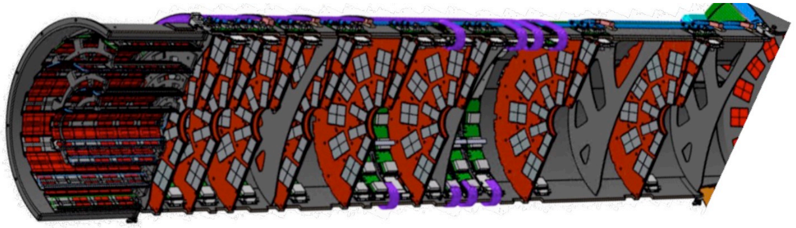
TBPX thermal test with real modules

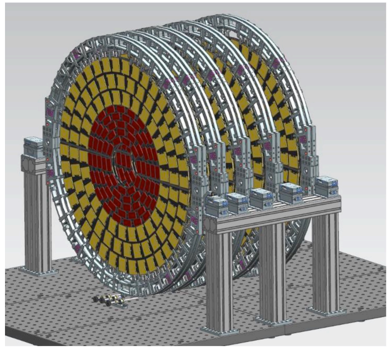


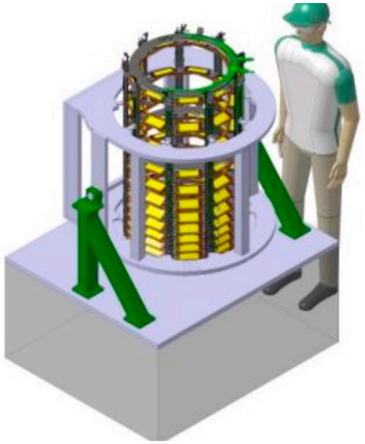
Common Aspects

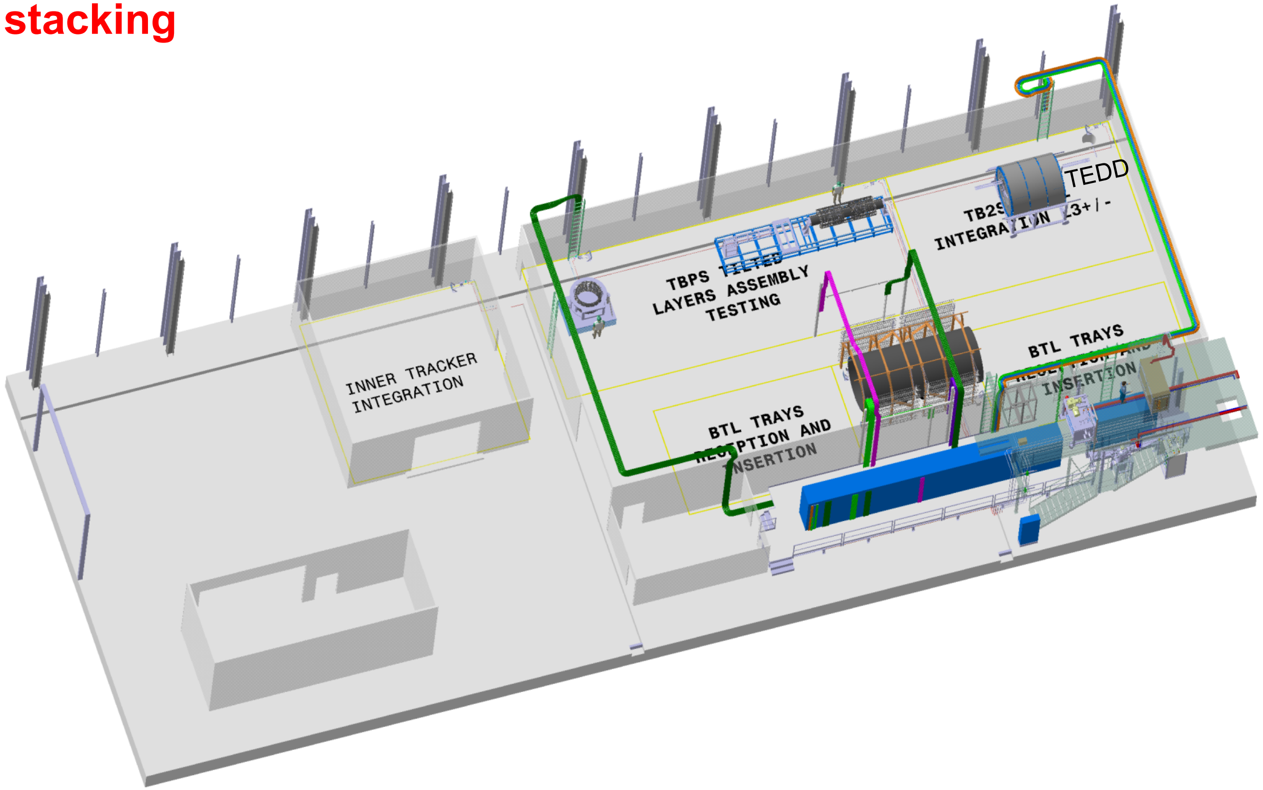
Tracker Integration

- **Tracker will be integrated in the Tracker Integration Facility, B186, Meyrin site**
  - Double-discs and rings are formed into super-structures (cylinders, endcaps)
  - Ladders are inserted into the TB2S wheel structure
  - TBPX layers and TFPX dees are assembled into quarters
- **TIF is being prepared (infrastructure, scaffolding, DAQ ...)**
  - BTL-Tracker Support Tube (BTST) already present
- **Integration starts in Q4/2025, with TBPS ring stacking**





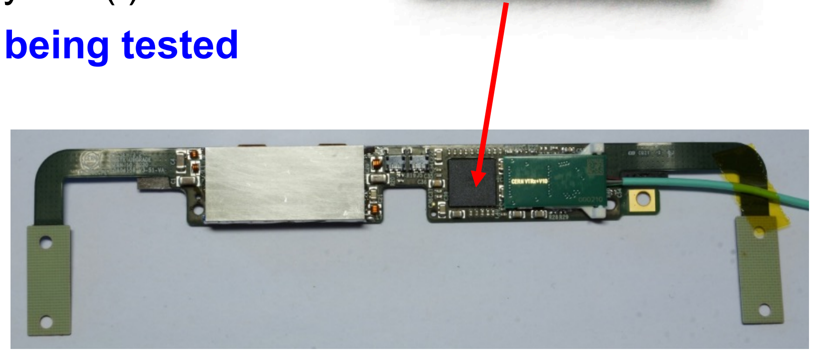




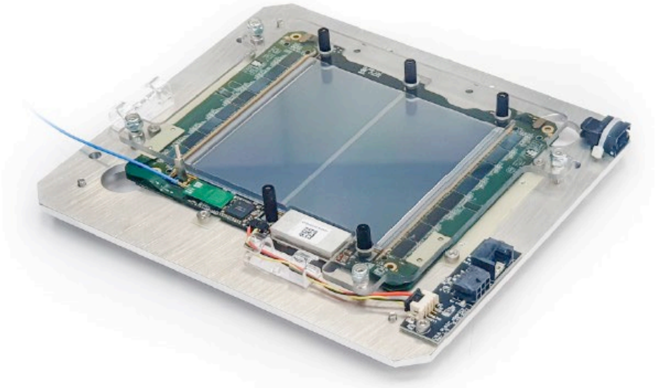
LpGBT Strategy

- **LpGBT = Low power Giga-Bit Transceiver, basically a bi-directional serializer**
  - Complex ASIC developed by CERN and used in ~all Phase-2 upgrades

- **Two bugs found in V1 mid last year**
  - “Stuck at power-up“, affects ~1% of chips but population changes with TID
  - “Equalizer attenuation issue“, affected percentage depends on TID, ~70% for PS layer 1 (!)
- **Bugs understood, fixed, new version V2 submitted, produced, packaged, and now being tested**
  - First 2080 samples delivered to tracker beginning of March



- **Tracker strategy is to minimize use of V1**
- **IT uses LpGBT on portcards – prototypes with V1, production with V2**
- **OT uses LpGBT on every module, on Service and Readout Hybrids**
  - ~800 SEHs (10%) and ~300 ROHs (5%) with V1 already produced!
    - Production of both types stopped in October
  - Module pre-production not stopped: SEH and ROH not glued – swap with V2 hybrids later
  - Fate of V1 hybrids / modules not fully clear yet, also financial impact



Schedule and Concerns

- **With the new LS3 schedule, we have presently 22 weeks of float for the OT and 50 weeks for IT**

- **Critical path for OT: hybrids → module production → integration**
- **Critical path for IT: TBPX mechanics → integration**

- **(My) 3 biggest concerns for OT:**
  - Ramp-up of hybrid production at company too slow
  - Module production throughput not yet proven
  - Integration throughput not yet proven

- **(My) 3 biggest concerns for IT:**
  - Technical issues could turn out to be more problematic than thought: core column issue, parylene coating
  - Hybridization throughput not yet proven
  - Module production throughput not yet proven

German Contributions

5 institutes: Uni Hamburg (IT), Aachen-1B, Aachen-3B, KIT, DESY (all OT)

- Leading contributions to **sensor design, production and testing** (IT+OT, Uni HH, KIT)
- Leading contributions to **OT hybrids and modules** (Aachen, KIT, DESY)
- Leading contributions to **system tests, cooling tests, beam tests, magnet tests, integration tests** (IT+OT, all)
- Production of **~500 pixel modules** (Uni HH)
- Production of **~1000+2000 OT 2S modules** (Aachen, KIT) and **~1300 PS modules** (DESY)
- Integration of **16 dees** (out of 40), assembly into **5 double-discs** (DESY)
- Tracker Phase-2 Technical Design Report (main editor K.K., many individual contributions)
- ......

Tracker Phase-2:

- **IT Sensor WG**: Georg Steinbrück
- **OT Sensor WG**: Alexander Dierlamm
- **OT Hybrids WG**: KK
- **OT Modules WG**: Andreas Mussgiller
- **OT System Test WG**: Alexander Dierlamm
- **OT modules QC manager**: Oliver Pooth
- **Data base WG**: Stefan Maier

Tracker general:

- **Deputy Project Manager**: KK
- **Tracker Editorial Board chair**: Erik Butz
- **Deputy Tracker Operations Coordinator**: Erik Butz
- **DPG Coordinator**: Henriette Petersen

[previous Tracker Project Managers: Frank Hartmann, Erik Butz]

Conclusions & Outlook

- Many interesting topics not covered: DAQ, Track Finder, power system, Long Shutdown 3 ... sorry.
- **No show-stoppers, all designs finished**
- **Broadly speaking, OT is in production, IT is in pre-production**
  - OT float not comfortable → next months are critical to achieve production ramp up
  - IT float ok, but project less advanced and issues can still pop up
- **As soon as parts will be flowing, we will enter a new regime!**