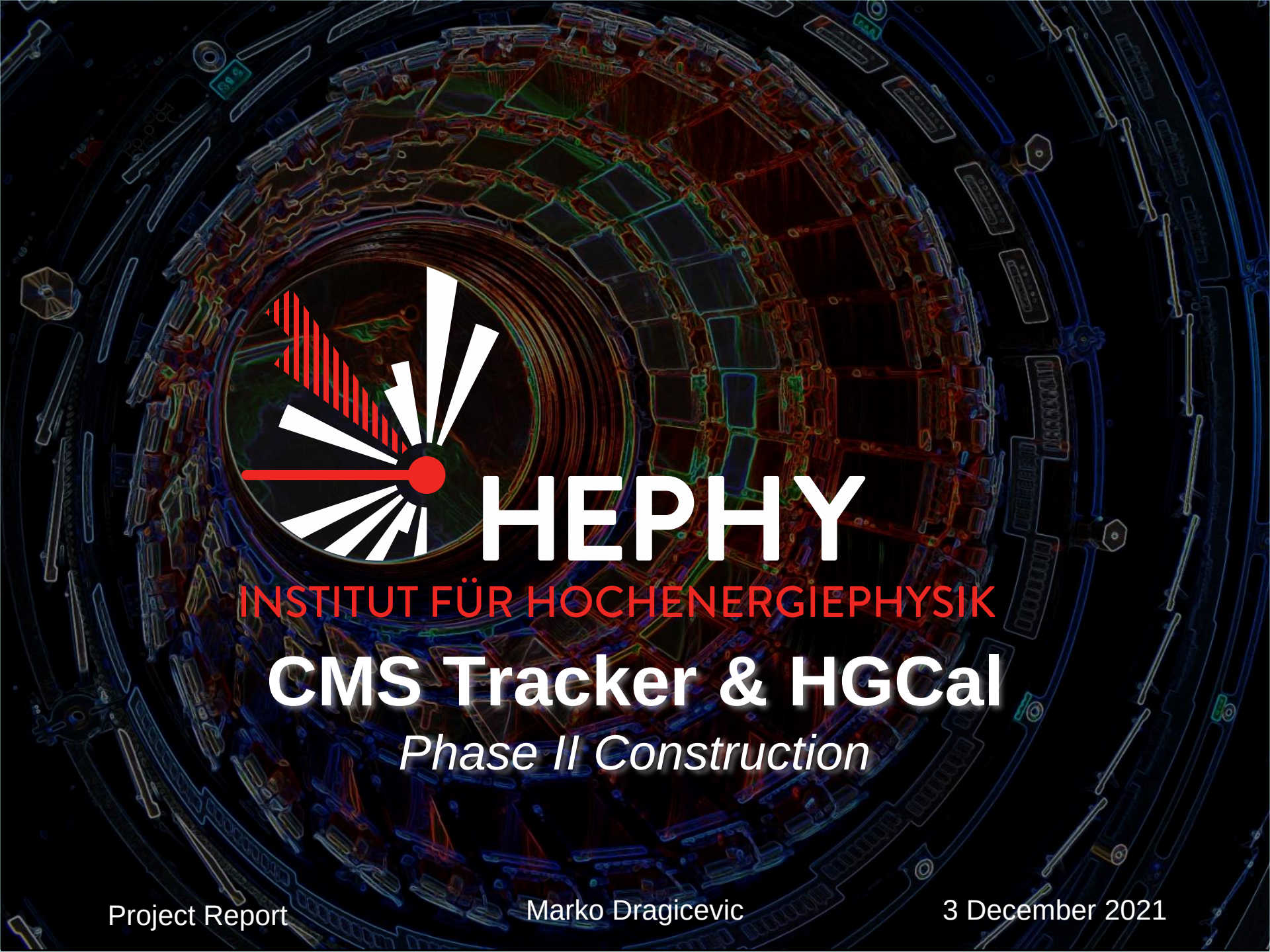


HEPHY

INSTITUT FÜR HOCHENERGIEPHYSIK

CMS Tracker & HGCal

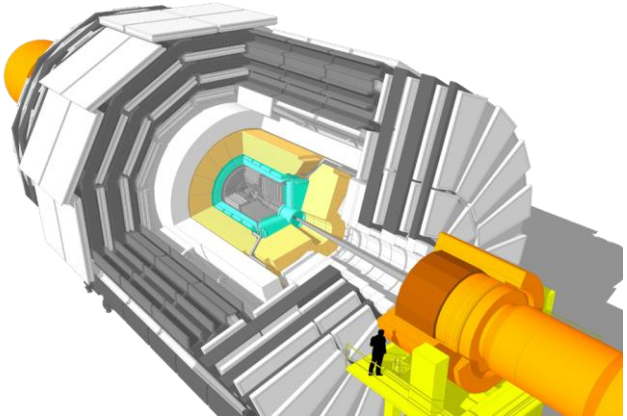
Phase II Construction

Project Report

Marko Dragicevic

3 December 2021

CMS Phase-II Upgrades



Long Shutdown 3 (LS3) scheduled for 2025-2027?!?

- LHC accelerator upgrade to High-Luminosity (HL)-LHC
- Upgrade of detectors necessary
  - Existing systems reach end of life (radiation damage)
  - Increase in luminosity at HL-LHC: 300 → 3000 fb^{-1}
- *Latest schedule with no COVID related delays*
  - *And experiments will not be ready by 2027 …*

CMS Phase-II Upgrades

Long Shutdown 3 (LS3) scheduled for 2025-2027?!?

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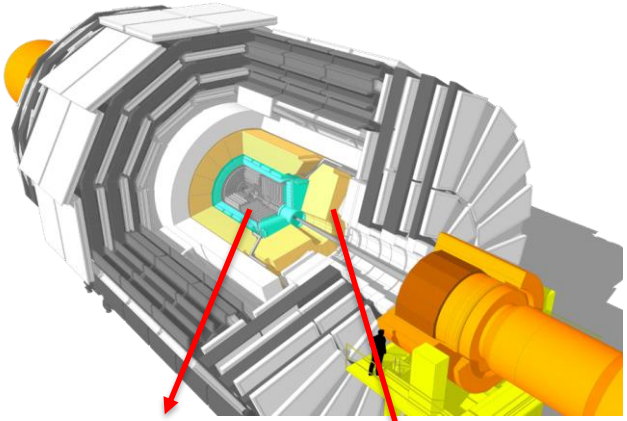
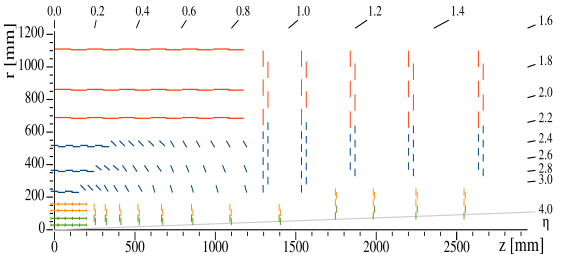


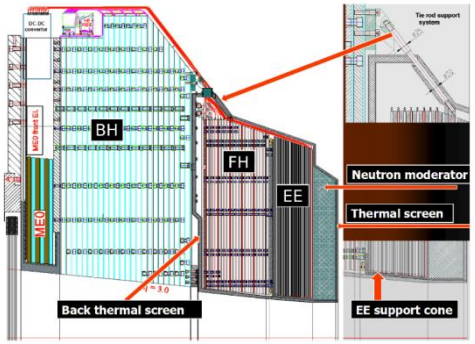


Layout of Phase II Tracker

Phase-II Upgrade of CMS (with HEPHY involvement):

- **CMS Tracker**
  → 200 m^2 Si Sensors needed
- **High Granularity Calorimeter**
  → 600 m^2 Si Sensors (8 inch)

Layout of Endcap Calorimeter



With our expertise in silicon sensors HEPHY plays a key role in *both* projects

- Simulations and design of sensors and test structures
- Electrical characterization of sensors and test structures
- Preparation, negotiations and QA of series production

→ Co-Convenors of both sensor development working groups

Staff

Active contributors today

- Staff Scientists
  - **Marko Dragicevic**
    - Convener: Outer Tracker Sensors WG
    - Tracker Resource Manager
  - **Thomas Bergauer**
    - Convener: HGCal Sensors WG
    - Also: Group Leader Detector Development (non-CMS)
- PhDs
  - ~~**Dominic Blöch:** Tracker SQC (ÖAW funded until Oct 2020)~~
  - ~~**Viktoria Hinger:** Tracker & HGCal PQC (FFG funded until Oct 2020)~~
  - ~~**Peter Paulitsch:** HGCal (FFG funded until mid 2021)~~
  - **Konstantinos Damanakis:** Sensor QA (ÖAW funded since Oct. 2020)
- PostDocs
  - ~~**Florian Pitters:** HGCal & Detector Development Left for paternity leave and to industry~~
  - **Moritz Wiehe:** HGCal Since mid August 2021
- Sensor QA team
  - Margit Oberegger
  - Andreas Bauer
  - Stefan Schultschik
  - Doris Wohlmuth July – October 2021
- Additional support
  - Wolfgang Brandner
  - Florian Buchsteiner

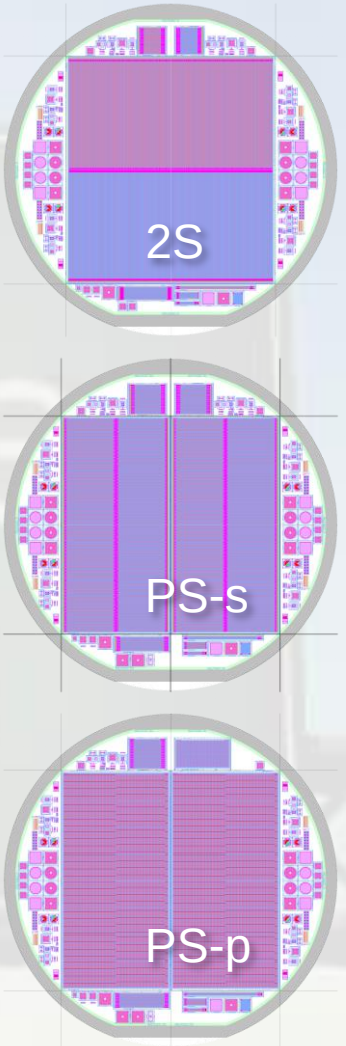
HEPHY in CMS Phase II

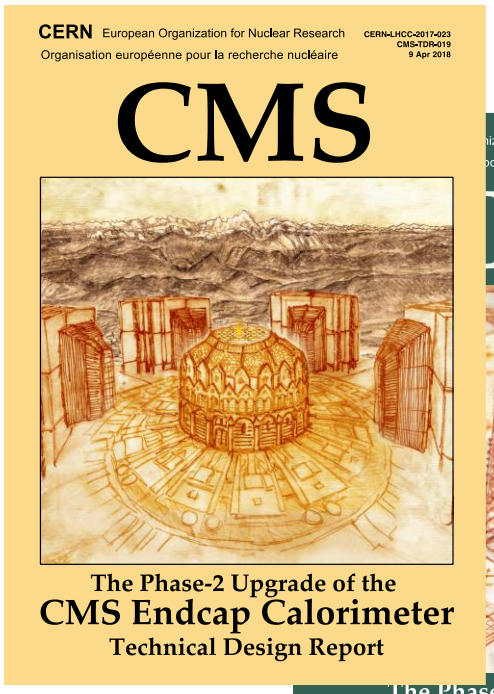
Note: In 2015, after long internal discussions and with the SAB, we decided to contribute to sensors only!

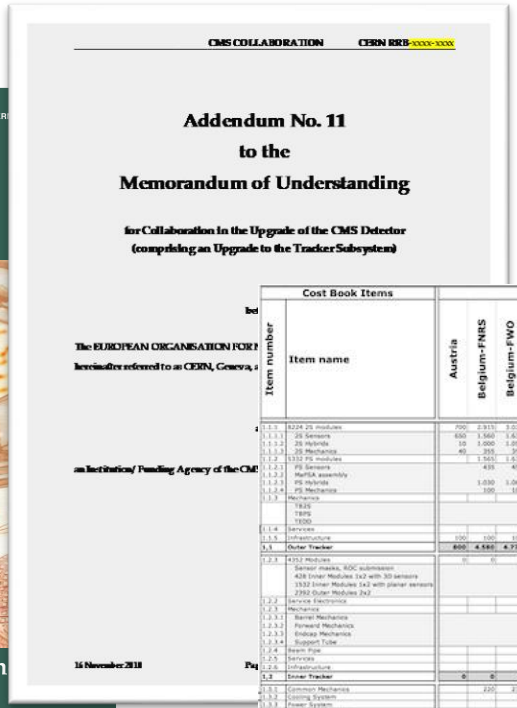
- HEPHY responsibilities in CMS Outer Tracker
  - **2010 – 2019:** *Participation in all development studies of the sensors*
    (Materials, thickness, radiation hardness, simulations, production process, design choices, etc.)
  - **2008 – 2018:** *Establishing alternative European sensor producer (Infineon)*
    - Stopped by Infineon in 2018 due to commercial reasons
  - **2019:** *Final design and wafer layout for all three sensor types*
    (PS-p pixel design from KIT)
  - **2014 – 2019:** *Conduction of the procurement process* (~18 MCHF)
  - **2019 – 2024:** *Definition and supervision of the Quality Assurance Campaign to produce ~ 29.000 sensors*
    - Process Quality Control (PQC) as major contribution from HEPHY
      (Viktoria Hingers PhD Thesis)

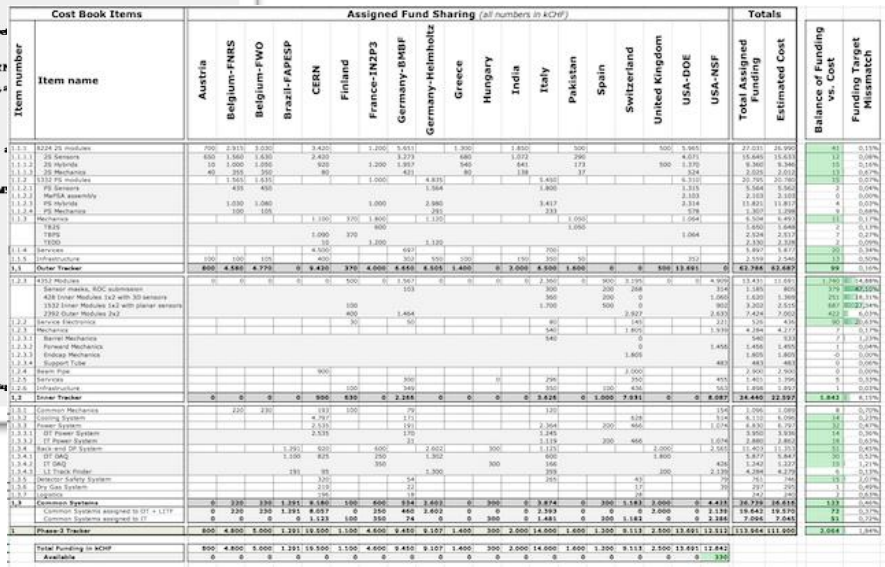
- HEPHY responsibilities in CMS HGCal
  - **2015 – 2018:** *Establishing alternative European sensor producer (Infineon)*
    - Initially our main interest to join HGCal
    - Infineon's 8" sensor technology was highly attractive for HGCal
    - Pushed HPK into developing 8" process for HGCal in parallel
  - **2018 – 2022:** *Development of radiation hard HGCal sensors with HPK*
    (Materials, thickness, radiation hardness, simulations, production process, design choices, etc.)
  - **2022 – 2024:** Participate in Quality Assurance campaign
    - Process Quality Control (PQC) as major contribution from HEPHY
      (Viktoria Hingers PhD Thesis)

- Managerial responsibilities
  - **Thomas Bergauer**
    - since 2016: Co-Convener of the HGCal Sensor WG
  - **Marko Dragicevic**
    - Since 2014: Co-Convener of the Tracker Sensor WG
    - Since 2017: Tracker Resource Manager



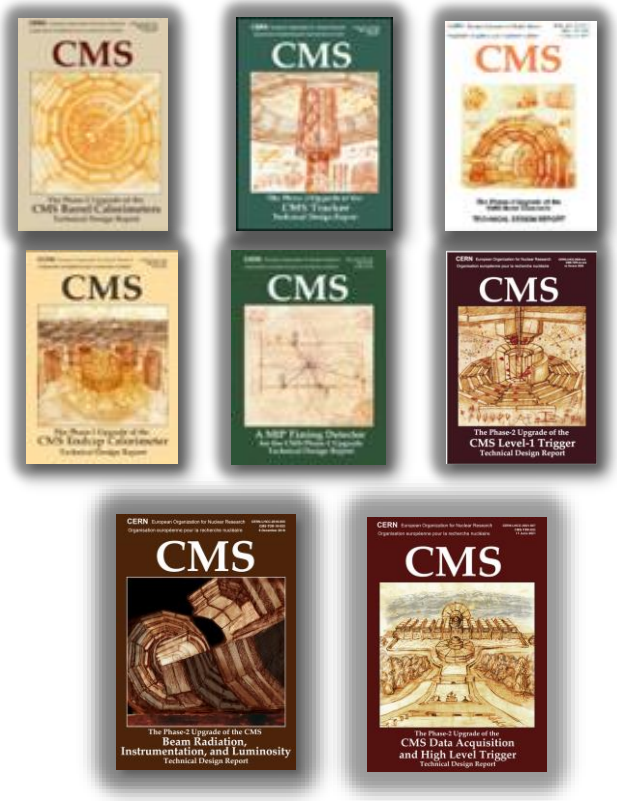






CMS PHASE II UPGRADE STATUS

- TDRs[1] for all major Phase 2 upgrades completed and reviewed by LHCC
  - Tracker since 2017
  - HGCal since 2018
- MoUs[2] defined and signatures still in progress
  - MTD, BRIL and DAQ/HLT outstanding
- Tracker has recently passed the EDR[3] for the Outer Tracker

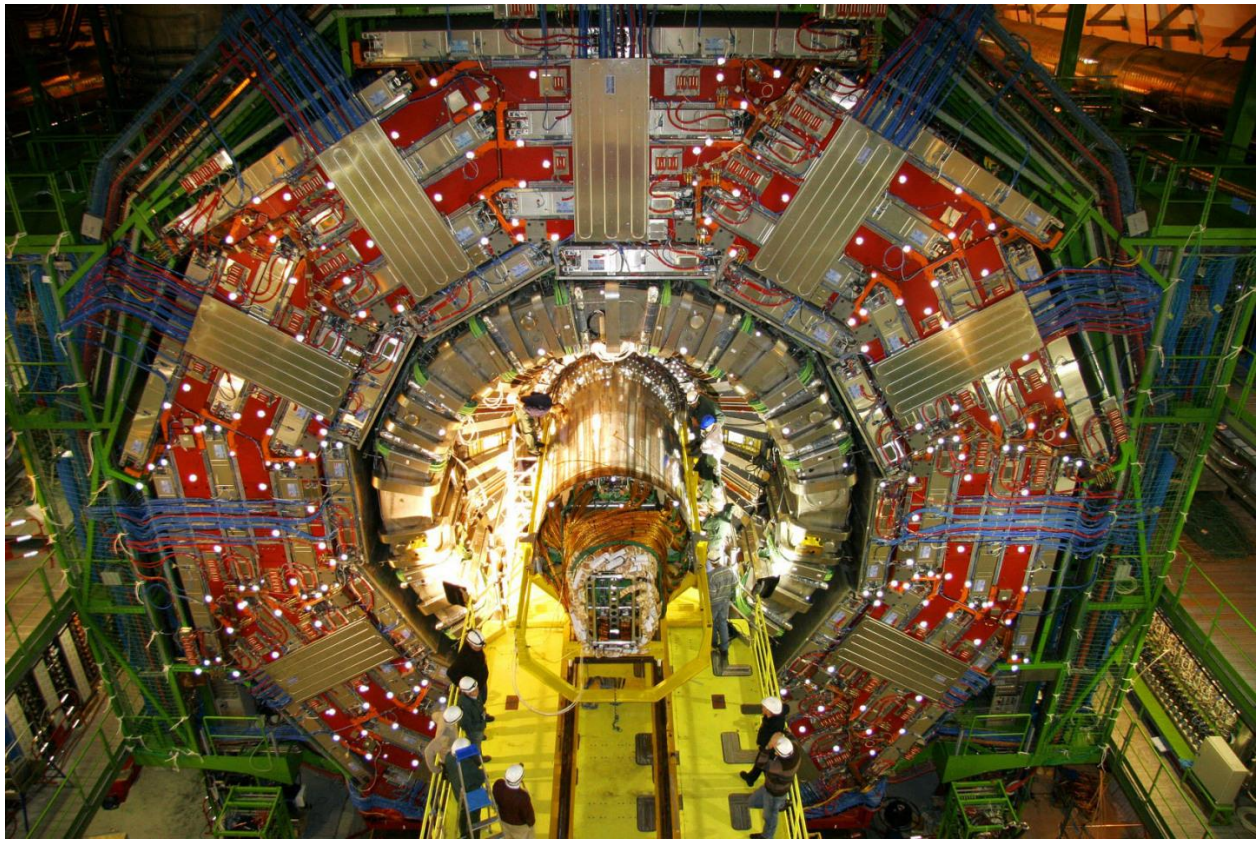


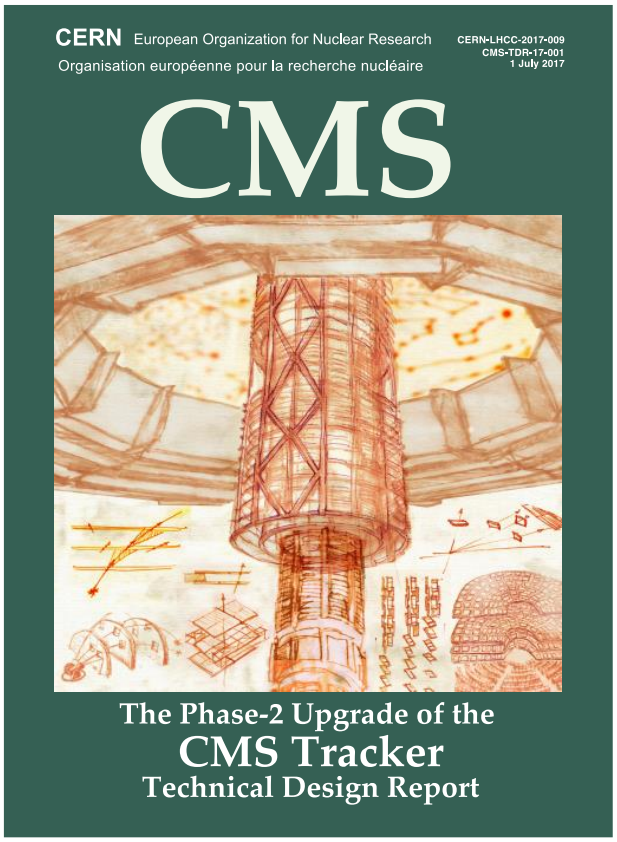
[1] Technical Design Report – Comprehensive description and motivation of the detector design with some details not yet fixed

[2] Memorandum of Understanding - defining technical and financial responsibilities of each Funding Agency in the construction of a subdetector

3 Engineering Design Review - CMS internal review to authorise the construction of significant parts of the detector

Phase-2 Upgrade MoU Addenda Signatory Progress					
Concerning	No.	Addendum	Last signed MoU Addendum received on 19/11/2021	Out of	Remaining
Common Fund	10	CERN-MoU-2017-060	30	56	26
Tracker	11	CERN-MoU-2019-006	13	22	9
Barrel Calorimeter	12	CERN-MoU-2019-007	5	8	3
Muons	13	CERN-MoU-2019-008	10	22	12
HGCal	14	CERN-MoU-2019-009	11	23	12
MoU Extension	15	CERN-MoU-2019-036	29	55	26
L1-Trigger	16	CERN-MoU-2020-319	3	12	9
Totals			101	198	97





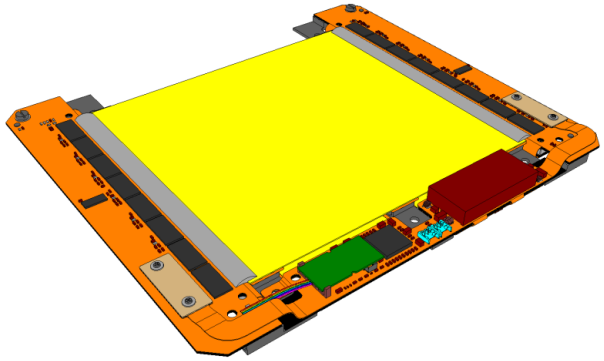
OUTER TRACKER

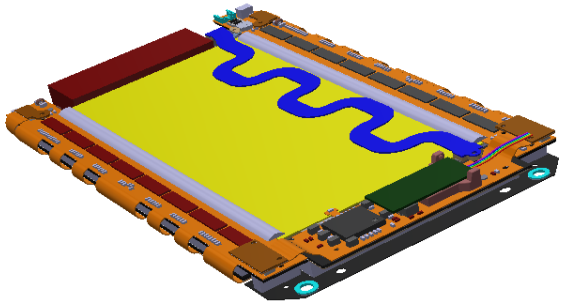
Reminder HL-LHC tracking

- Challenges for HL-LHC tracking
  - Harsh radiation environment up to
    - IT max.: 3.5 x 10^{16} n_{eq}/cm^{-2}, 1.9 Grad
    - OT max.: 1.1 x 10^{15} n_{eq}/cm^{-2}, 77 Mrad
  - High pileup
    - Increase granularity for sufficient two track separation
  - L1 Trigger needs tracking information
    - Tracker needs to provide data to L1 Trigger at every BX
    - Transmitting full information at every BX not possible, data reduction is required
- Goal: Keep performance of existing system in HL-LHC environment for 3000 fb^{-1} (ultimate 4000 fb^{-1})

CMS Tracker Solution

- Fully integrated modules
  - Just add services (HV, LV, CO_2 cooling, readout and control links, mechanical mounting)
  - Filtering on high p_t tracks on module
- Just two types of modules used everywhere
  - Barrel and endcaps!
  - 2 and 3 different flavours (sensor spacing)

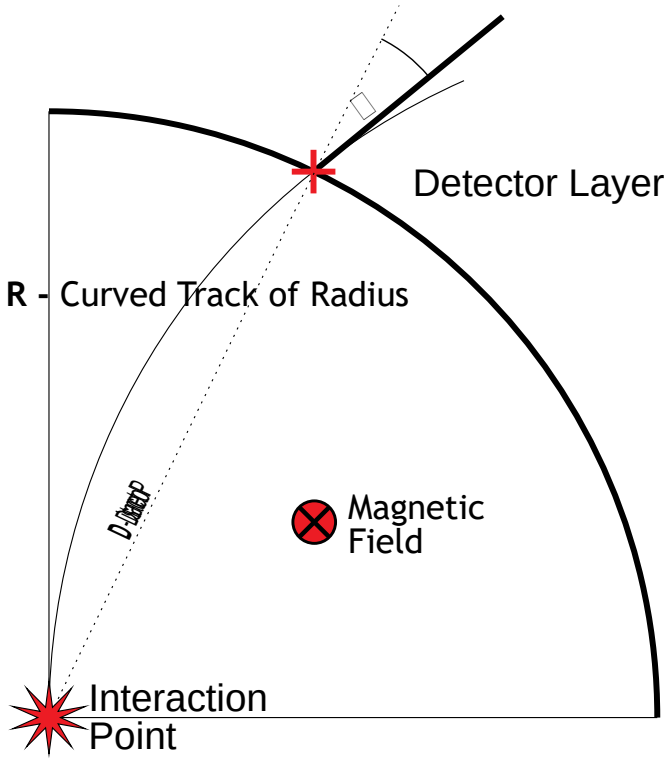


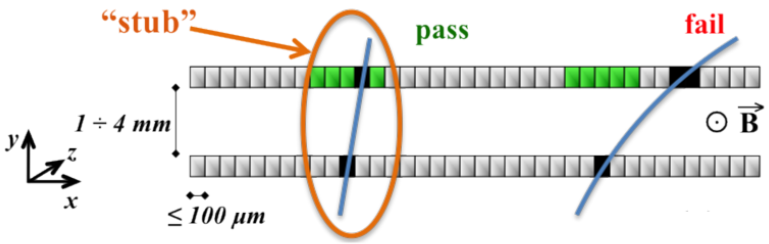


Data filtering

On-module data reduction by only sending hits from particles with a transverse momentum $\mathbf{p_t}$ of **> a few GeV/c**

- At given magnetic field the track **curvature** depends on the **particle's $\mathbf{p_t}$**
- **Different curvature** results in **different incident angles** at a given radius
- Estimate **incident angle** from **hit displacement** over a short distance
  → two parallel sensor planes

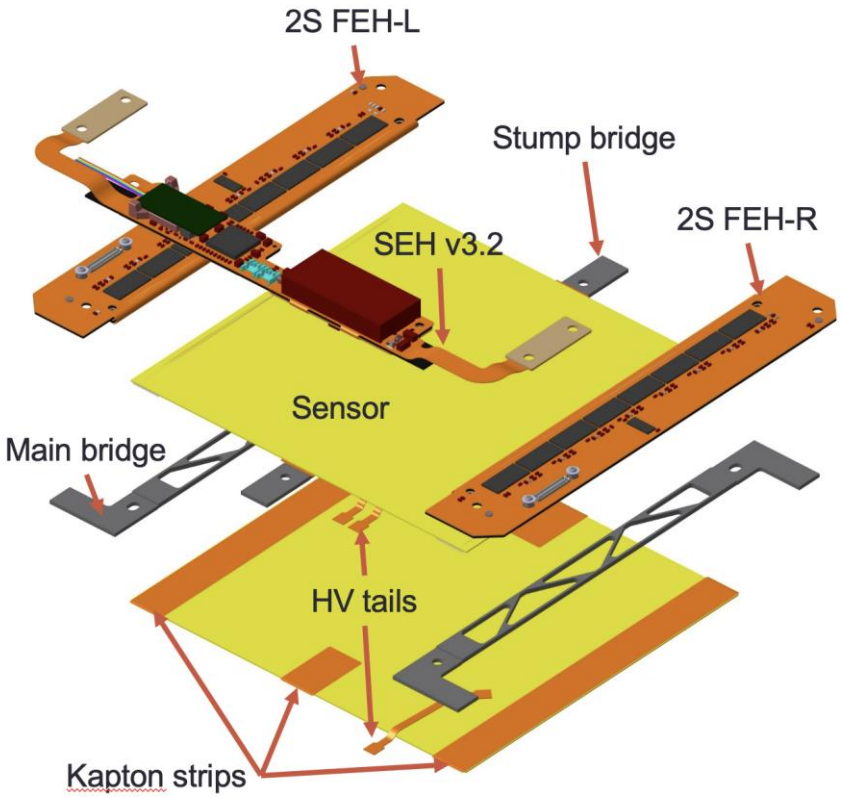




The p_t Module Concepts

The 2S Module

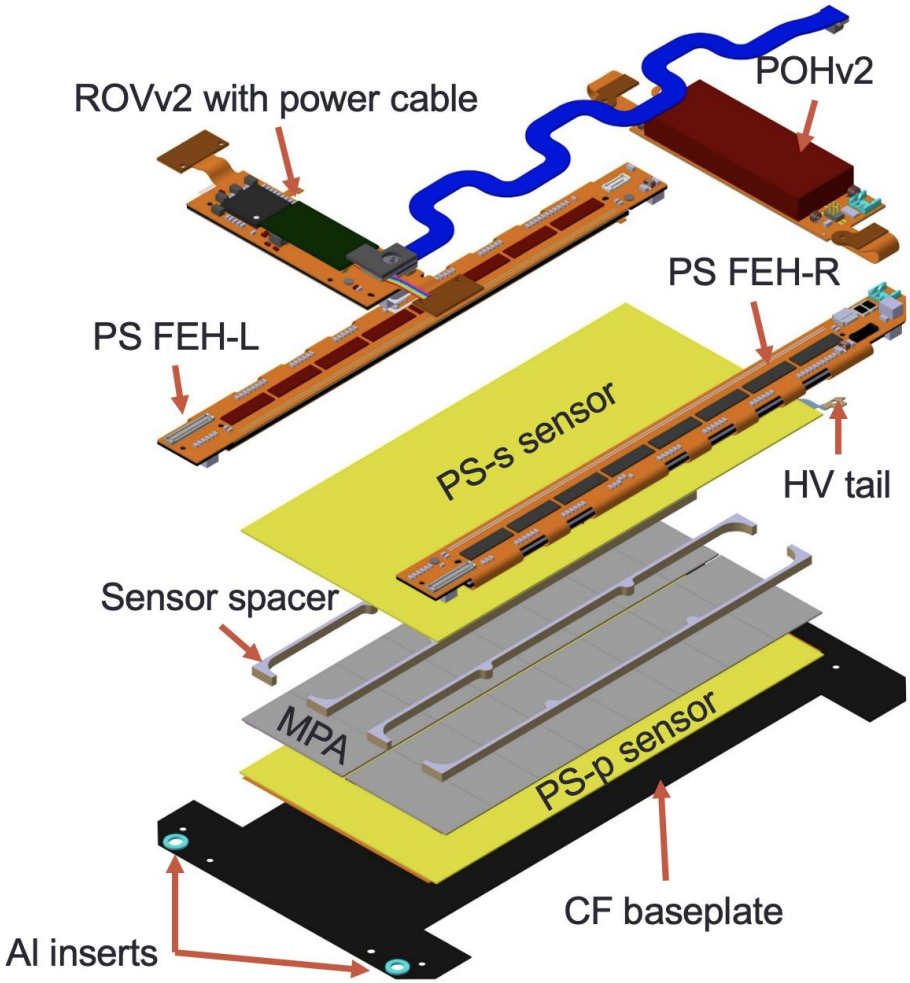
- **2** x **S**trip sensors: **2S sensor**
  - Size: 10 x 10 cm^2
  - Pitch: 90 µm
  - Length: 5 cm
  - No. of strips per sensor: 2x1016
- 2 x 8 **C**MS **B**inary **C**hips: **CBC**
  - 2x127 channels per chip
  - Bump bonded to flexible hybrid
  - Connects to top and bottom sensors
  - Interchip communication via hybrid
- **C**oncentrator AS**IC**: **CIC**
  - collects data from 8 CBCs (half module)
- Low Power GigaBit Transceiver ***lpGBT + VTRx+***
  - Bandwidth: 5 Gb/s
- 2-stage DCDC powering
  - 12 V to
    - 2.5 V (opto)
    - 1.25 V (ASICS)



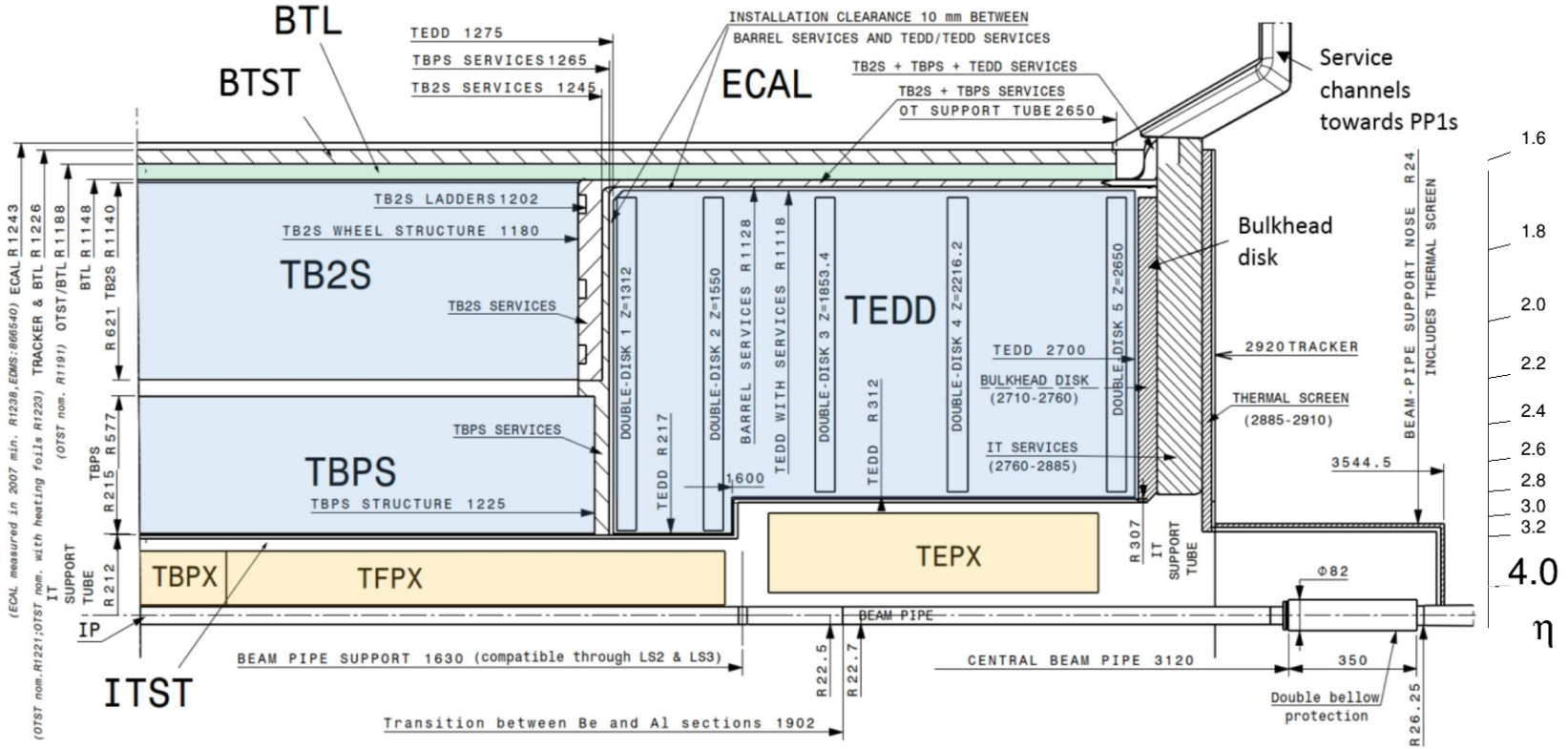
The p_t Module Concepts

The PS Module

- MacroPixel sensor: **PS-p sensor**
  - Size: 5 x 10 cm^2
  - Pitch: 100 µm
  - Length: 1.5 mm
  - No. of pixels: 32x960
- Strip sensors: **PS-s sensor**
  - Size: 5 x 10 cm^2
  - Pitch: 100 µm
  - Length: 2.5 cm
  - No. of strips: 2x960
- 2 x 8 Short Strip ASIC: **SSA**
  - 120 channels per chip
  - Sends hits to MPA
  - Bump bonded to flexible hybrid
- 16 MacroPixel ASIC: **MPA**
  - 120 x 16 pixels per chip
  - Bump bonded to MacroPixel sensor
  - Includes correlation logic
- Concentrator ASIC: **CIC**
  - collects data from 8 MPAs
- Low Power GigaBit Transceiver ***lpGBT + VTRx+***
  - Bandwidth: 5 or 10 Gb/s
- 2 stage DCDC powering
  - 12 V to
    - 2.5 V (opto)
    - 1.25 V (ASICS)
    - 1.05 V (MPA digital)



Tracker Layout



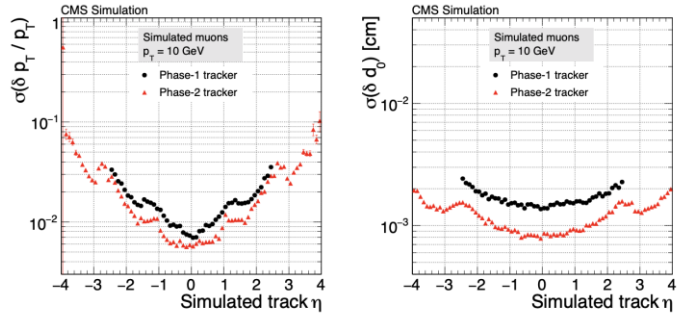


Figure 6.12: Relative resolution of the transverse momentum (left) and resolution of the transverse impact parameter (right) as a function of the pseudorapidity for the Phase-1 (black dots) and the upgraded (red triangles) tracker, using single isolated muons with a transverse momentum of 10 GeV.

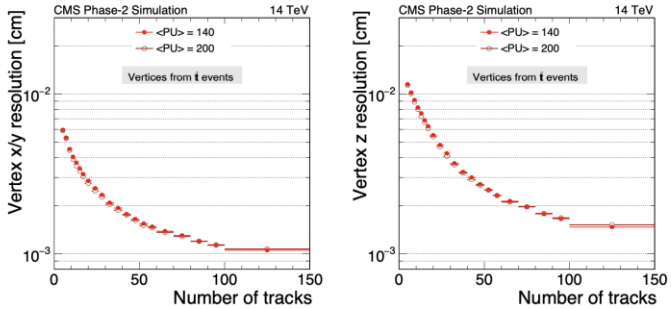
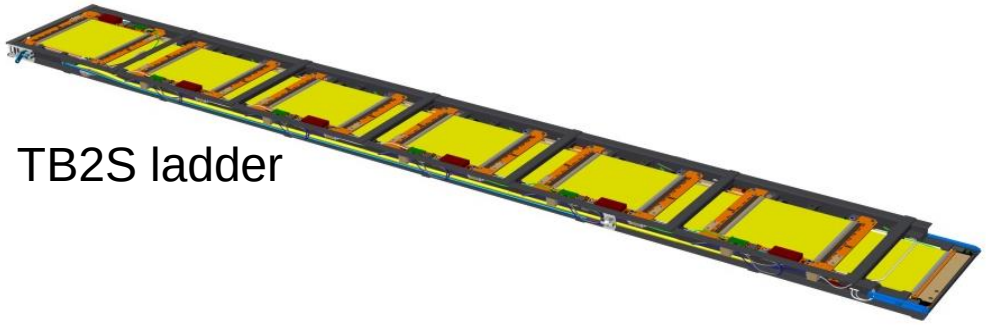
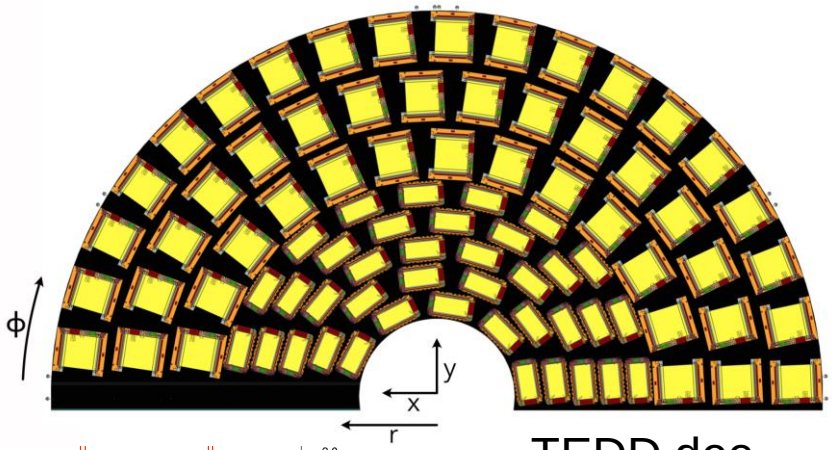


Figure 6.13: Vertex position resolution in x and y (left) and z (right) as a function of the number of tracks associated to the vertex, for $t\bar{t}$ events with 140 pileup events (full circles) and 200 pileup events (open circles).

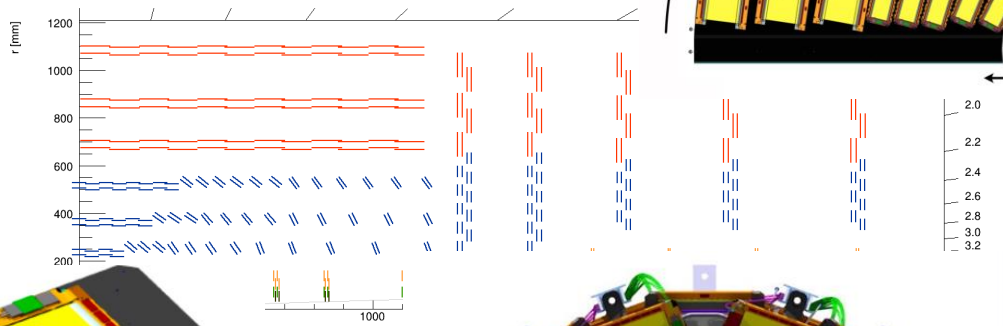
Mechanics

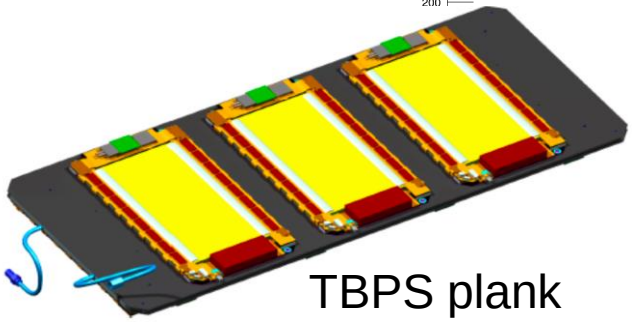


TB2S ladder

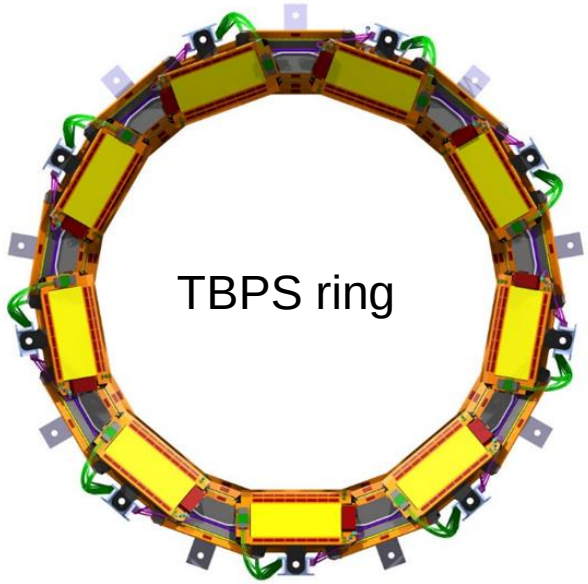


TEDD dee





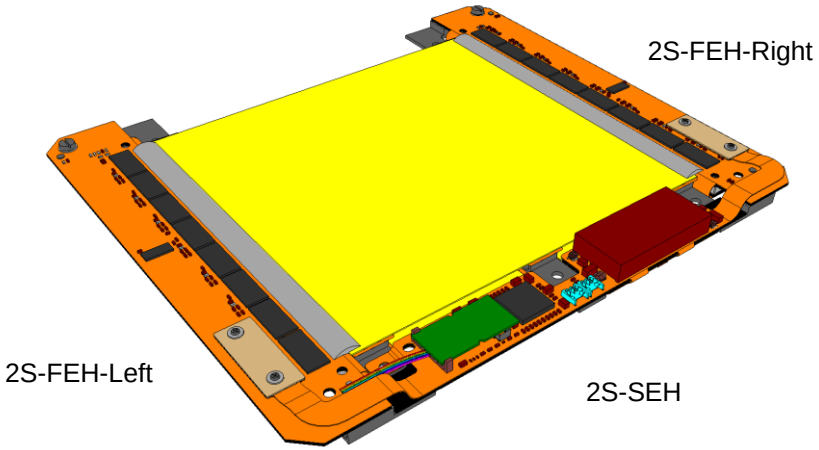
TBPS plank



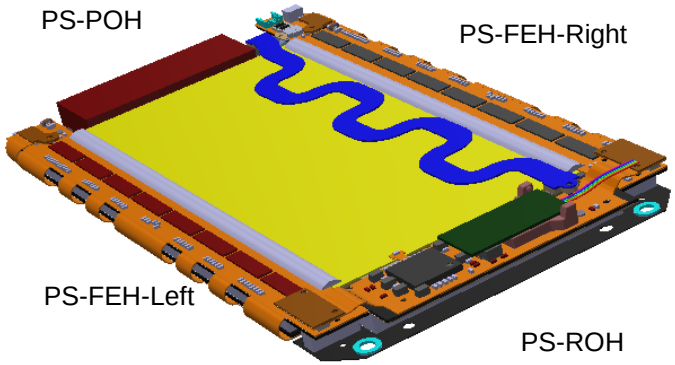
TBPS ring

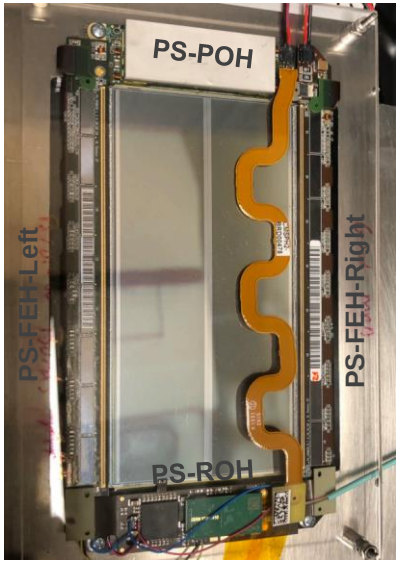
Modules

2S Module



PS Module





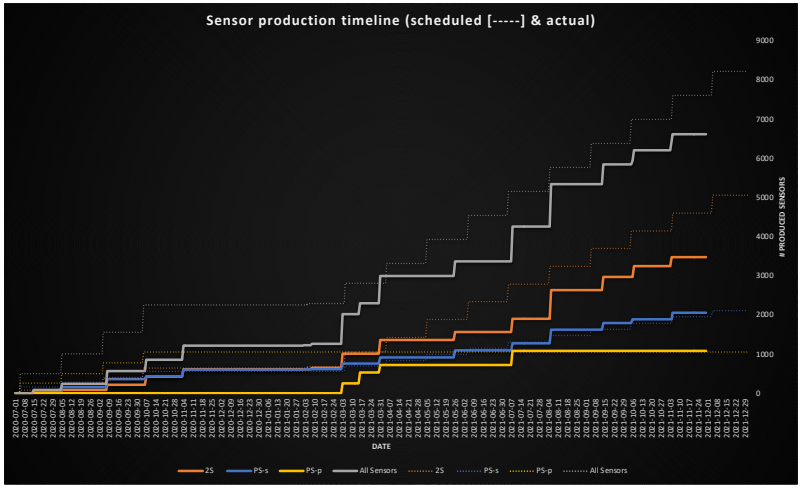
Construction Status

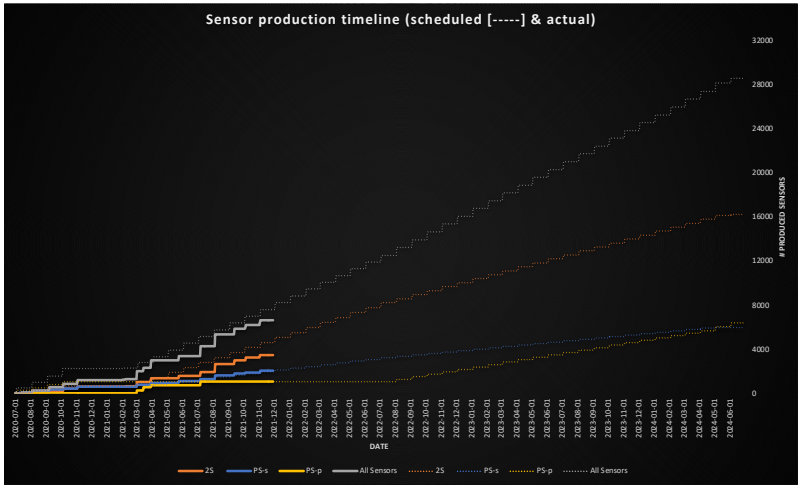
- Outer Tracker in transition to construction
  - Engineering Design Review (EDR) held on 14 – 15 October https://indico.cern.ch/event/1064838
    - Authorised global production start for Outer Tracker
      - Specifically Hybrids, MaPSA and mechanics
  - Procurement Readiness Reviews (PRRs) already done for
    - Sensors (2019/20)
    - Raw composite materials CFRP, CF-foam, AlCF (2020)
    - CBC production (2020)
    - MPA, SSA and CIC design and engineering run (2021)
  - Some components already in production since 2020
    - Sensors and CBC
- Production of modules will start next year

SENSOR PRODUCTION (AT HEPHY)

Production Status

- Sensor **production** (deliveries) started **summer 2020**
  - Campaign started within COVID-19 pandemic
  - Lockdowns had significant effects on all centres
  - But all institutes pulled through
  - Several problems identified during pre-production and now corrected
- Projected end date for production is **mid 2024**
  - Almost 24.000 x 6” wafers
  - 16900 x 2S + 3100 x PS-s + 3750 x PS-p
- Today:
  - > 5000 wafers (> 20%) delivered
  - > 1200 sensors IV tested
  - > 500 sensors fully tested
  - > 3000 halfmoons tested



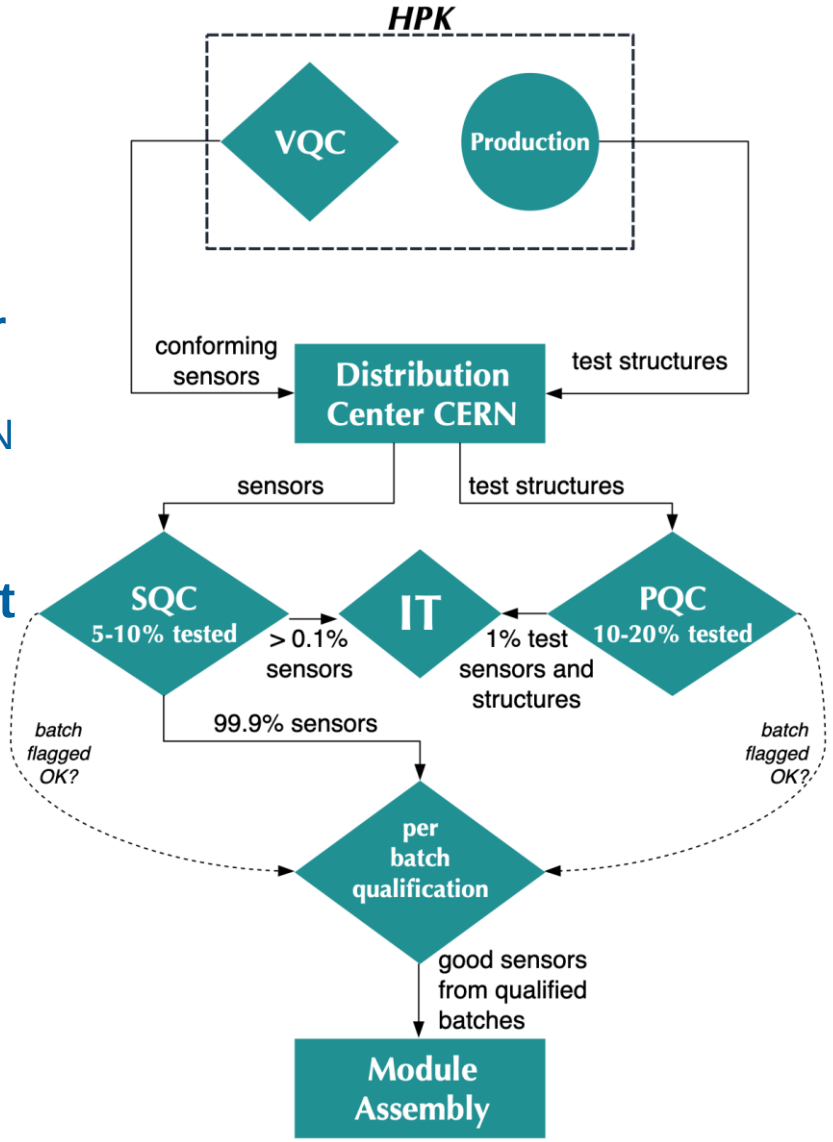


Quality Assurance

- Four tier quality control system
  - **VQC** - *Vendor Quality Control*
  - **SQC** - *Sensor Quality Control*
  - **PQC** - *Process Quality Control*
  - **IT** - *Irradiation Tests*
- **All sensors** characterised by **producer**
  - Results recorded in DB for each sensor
  - Only conforming sensors are sent to CERN
- Acceptance using **sample measurements** at SQC, PQC and IT
- Production and QA monitored by **expert panel**

→ Effort lead by HEPHY and KIT

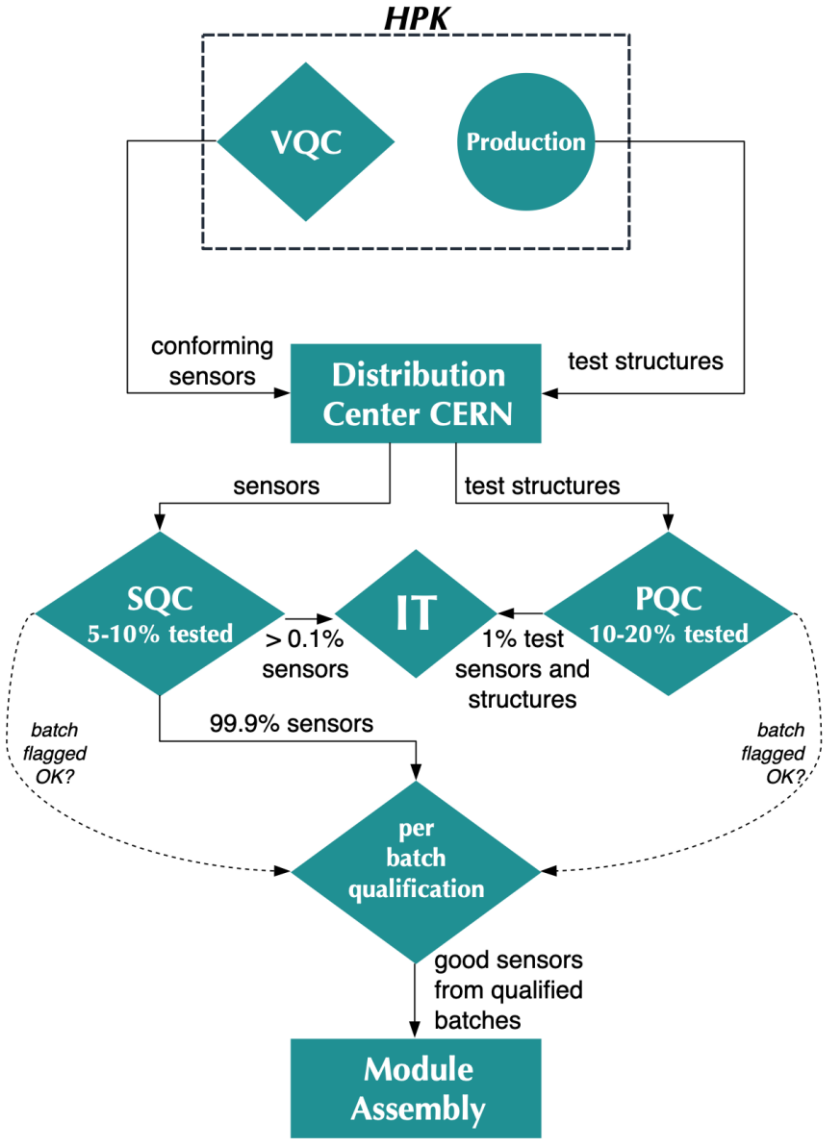
- Participants
  - Europe: Demokritos, Perugia,
  - US: Brown, Rochester
  - Asia: Delhi, NCP Pakistan



Quality Assurance

HEPHY's responsibilities

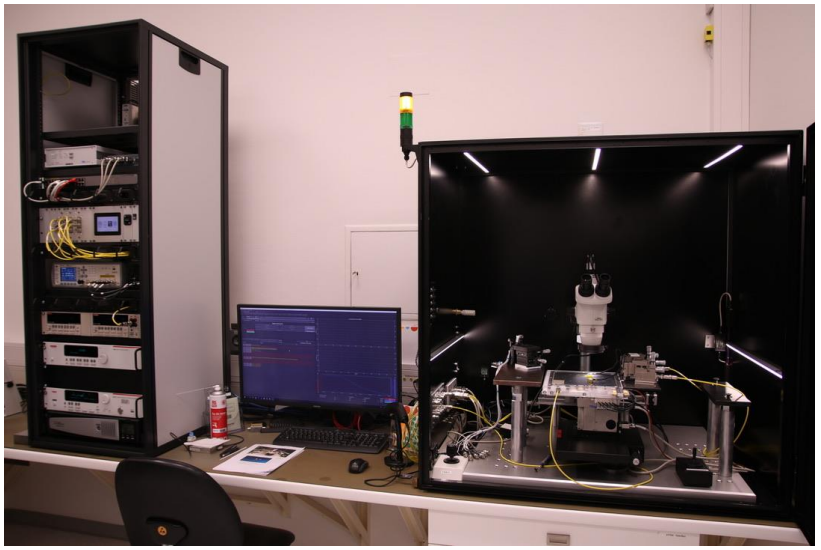
- Managerial tasks
  - Overall planning
  - Co-convener of weekly acceptance meetings (OTSEPP)
  - Contact to Tracker and CMS
  - Contact to Vendor (HPK)
- Sensor Quality Control (SQC)
  - Responsible for testing 25% of the production
- Process Quality Control (PQC)
  - Test structures, characterisation methods and setups developed at HEPHY
  - Responsible for testing 25% of the production



SENSOR QUALITY CONTROL
SQC AT HEPHY

SQC: Tracker

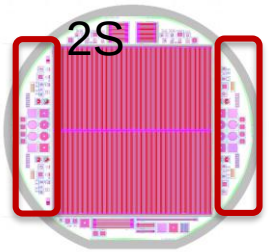
- **SQC** – **S**ensor **Q**uality **C**ontrol:
  fully characterise strip sensors
- Existing semiautomatic probe station **completely refurbished**
  - Fully custom made at HEPHY
  - Complex mechanical and electrical setup with precise environmental control and monitoring
  - Can automatically characterise ~2000 strips in 4-8 hours
- **Custom software** to control setup implemented in **Python**
  - Written by PhD Student (D. Blöch)
  - Important first step to phase out proprietary LabVIEW control
  - Plan to be replaced by more reliable Python tool implemented and maintained by Bernhard Arnold
    - Based on existing software tools by Bernhard for other setups like PQC
- Setup in operation **every day** to test one or two sensors
  - Mainly operated and maintained by Kostas and Stephan
  - Fully characterize at least 3 sensors per batch of ~40, one batch per week
- In addition, **longterm tests** are performed in our **climate chamber**
  - Including more detailed studies on humidity and temperature behaviour
- **After initial difficulties, HEPHY SQC is now among the fastest and most reliable!**

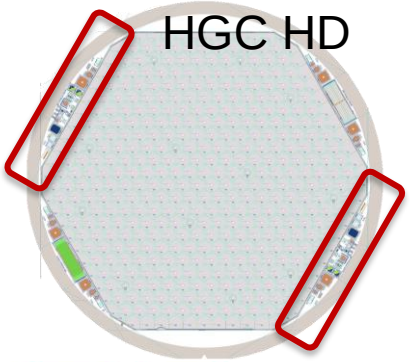


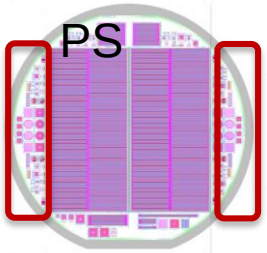
PROCESS QUALITY CONTROL
PQC AT HEPHY

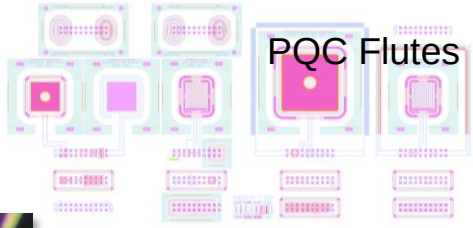
PQC: Tracker & HGCal

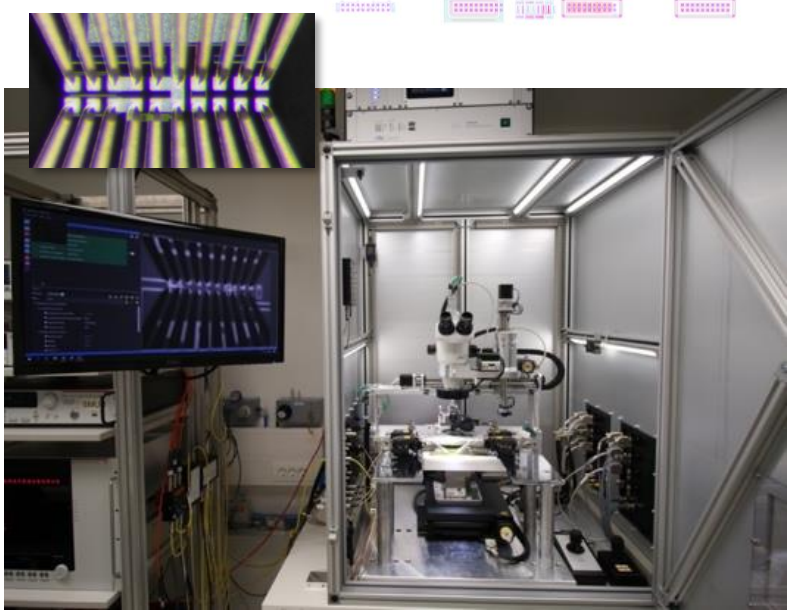
- **PQC** - **P**rocess **Q**uality **C**ontrol: Use **test structures** to asses the **quality and stability** of the production process
  - 6” AC coupled (Tracker 2S and PS-s)
  - 6” DC coupled (Tracker PS-p)
  - 8” DC coupled (HGCal)
- **Identical** set of test structures on **all wafers**
- Use **standardised pattern** of 20 connection pads: **flute**
  - Connect using standardised probe cards
  - Use switching to access all structures on one flute
  - Automatic movement to next flute





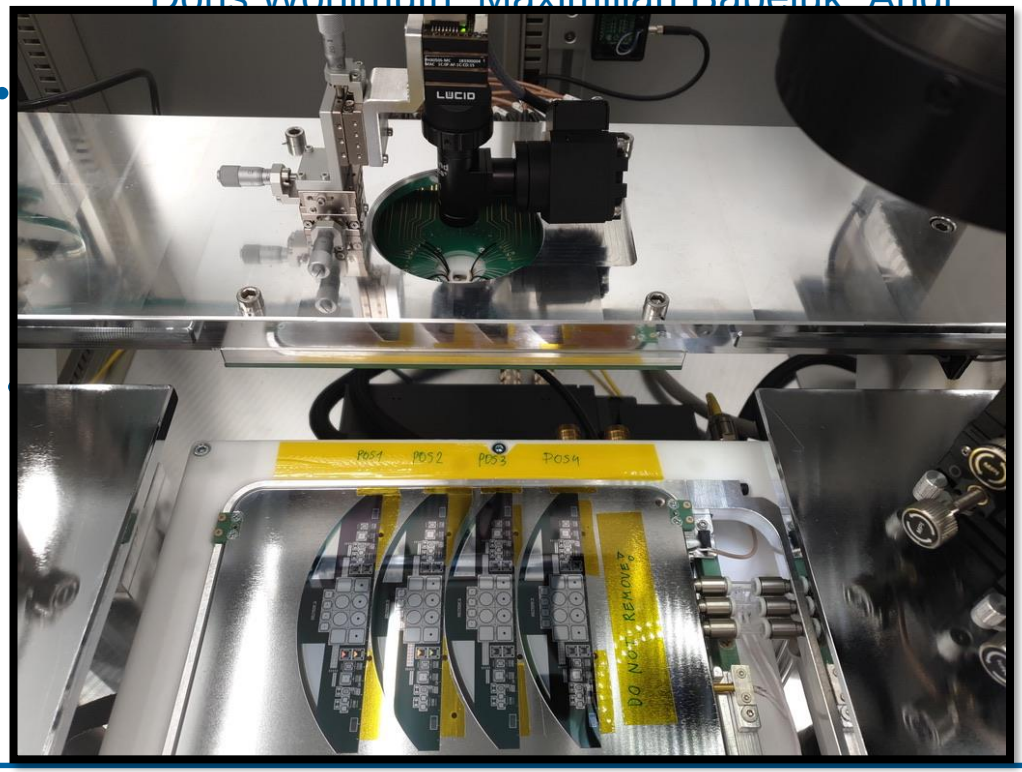


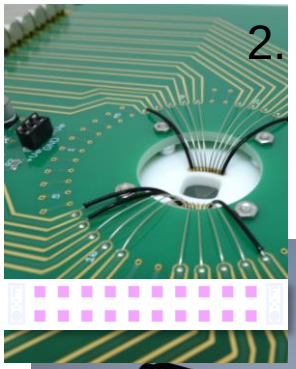


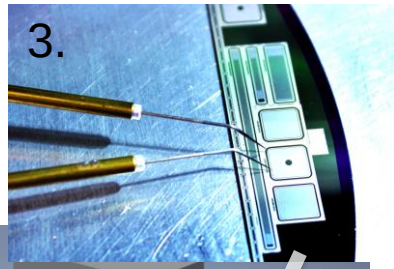


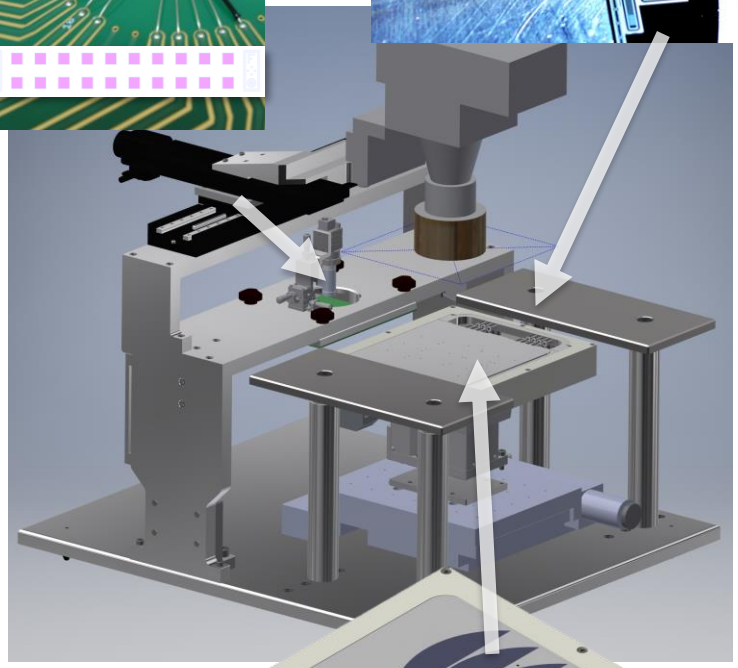
PQC: Tracker & HGCal

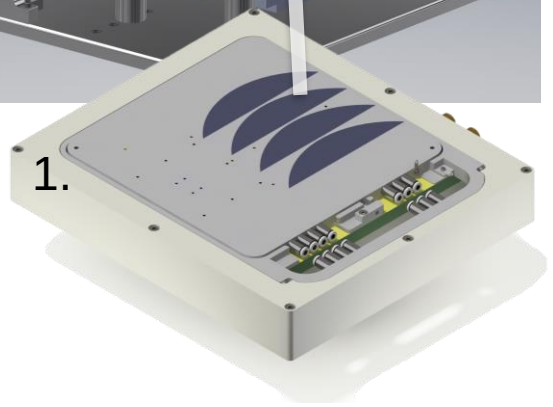
- New **versatile semiautomatic** probe station
  - Built from scratch in 2019
  - Excellent support for design and manufacturing from HEPHY machine shop
  - Commissioning in 2020 difficult due to lockdowns
  - Now reliable working thanks a lot of effort: Doris Wohlmuth, Maximilian Babeluk, Andi





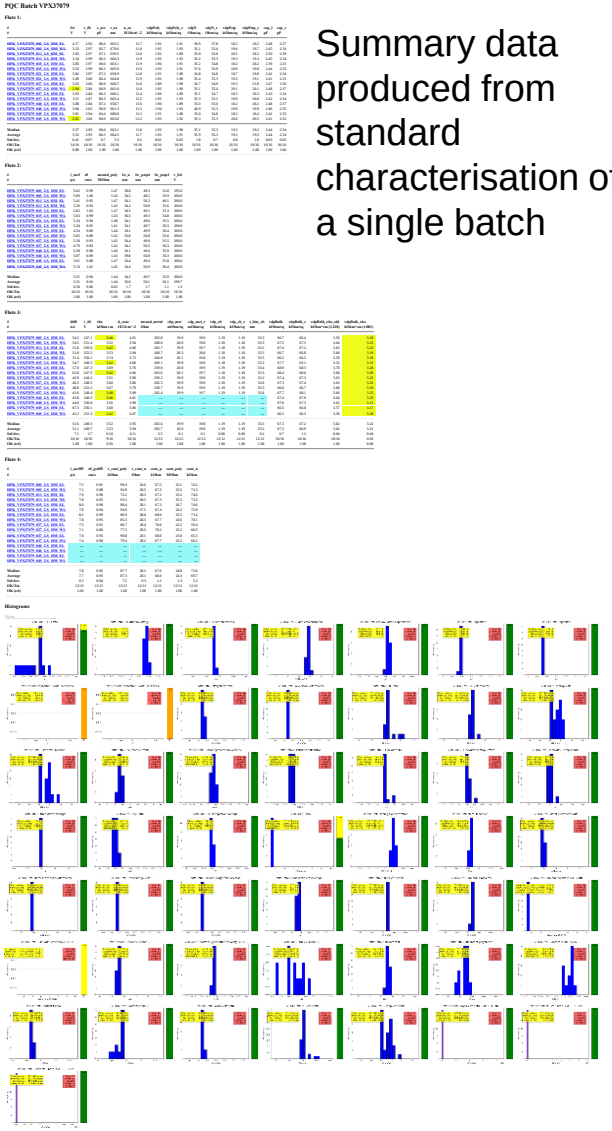






PQC: Tracker & HGCal

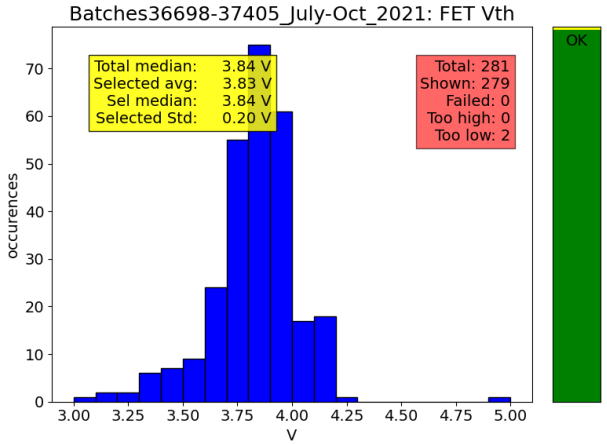
- PQC is providing **quick** and **detailed** check of process stability
  - First batches of sensor characterized within a week of delivery
  - Completed within a month
  - SQC usually lags behind a few weeks
- For each batch of ~40 wafers we perform **several 100 of measurements**
- All four Tracker PQC centers produce **consistent** results, **reliably** and **quickly**
- Also used to **understand** and **qualify** the **process** used for the future **HGCal production**

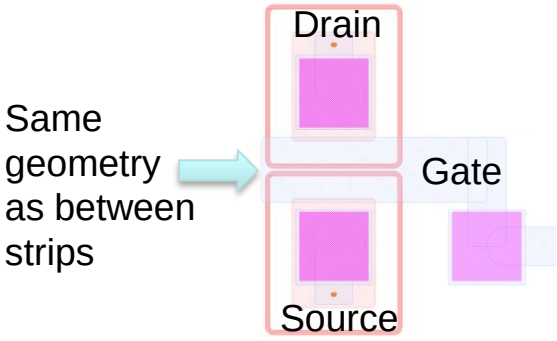


Summary data produced from standard characterisation of a single batch

PQC: Example

- Some exemplary results from http://heros.local.hephy.at/pqc-results/INCOMING/analysis_Batches36698-37405_July-Oct_2021/results.html
- Doris **analysed all measurements** she performed between **July to October**
  - 281 Halfmoons characterised
  - Analysis done by script developed by Maximilian
- Example: **Threshold voltage** of a **FET** using inter-strip geometry inside channel
  - Representative and sensitive to strip isolation
- Perfect batches show values **around 3.8 V** with a healthy **~gaussian distribution**
- Some **weak batches** (not shown here) have < 2 V
  - But do not yet compromise strip isolation → FET threshold V is more sensitive
  - HPK informed and can take countermeasures





Summary for Tracker

- **Outer Tracker construction** started and will be **in full swing** (module production) by end of 2022
- **Sensor production** ongoing **since 2020** with **HEPHY leading** the QA effort
- **High quality** of sensors delivered by HPK as **demonstrated and assured** by our measurements
- More **detailed** - and scientificly interesting - **investigations** starting now (not shown here)

→ *Now to Moritz with an update on HGCal*

THANKS FOR YOUR ATTENTION!