Design and construction of the Inner Tracker for the CMS Phase-2 Upgrade

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on behalf of the CMS collaboration

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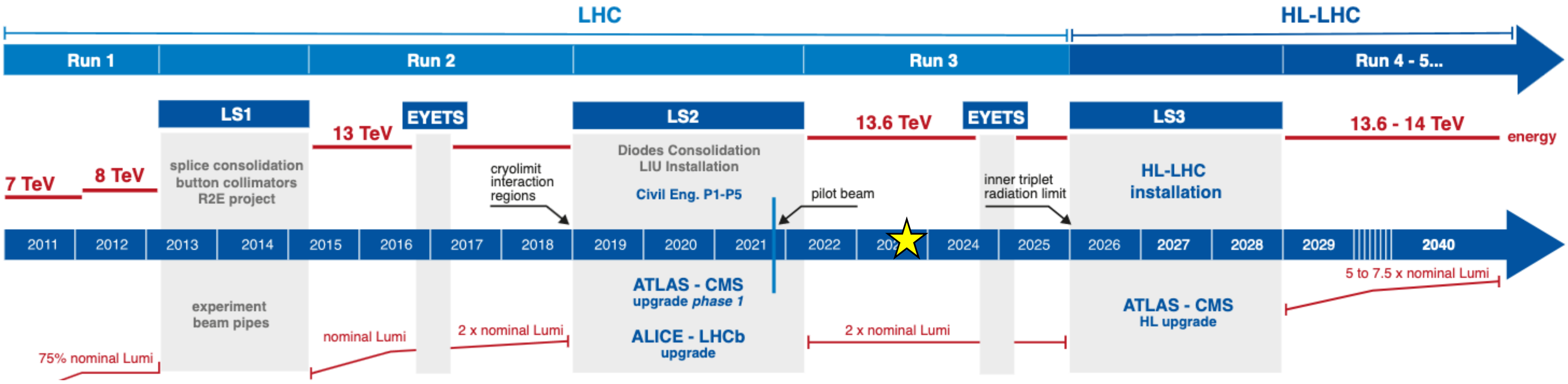
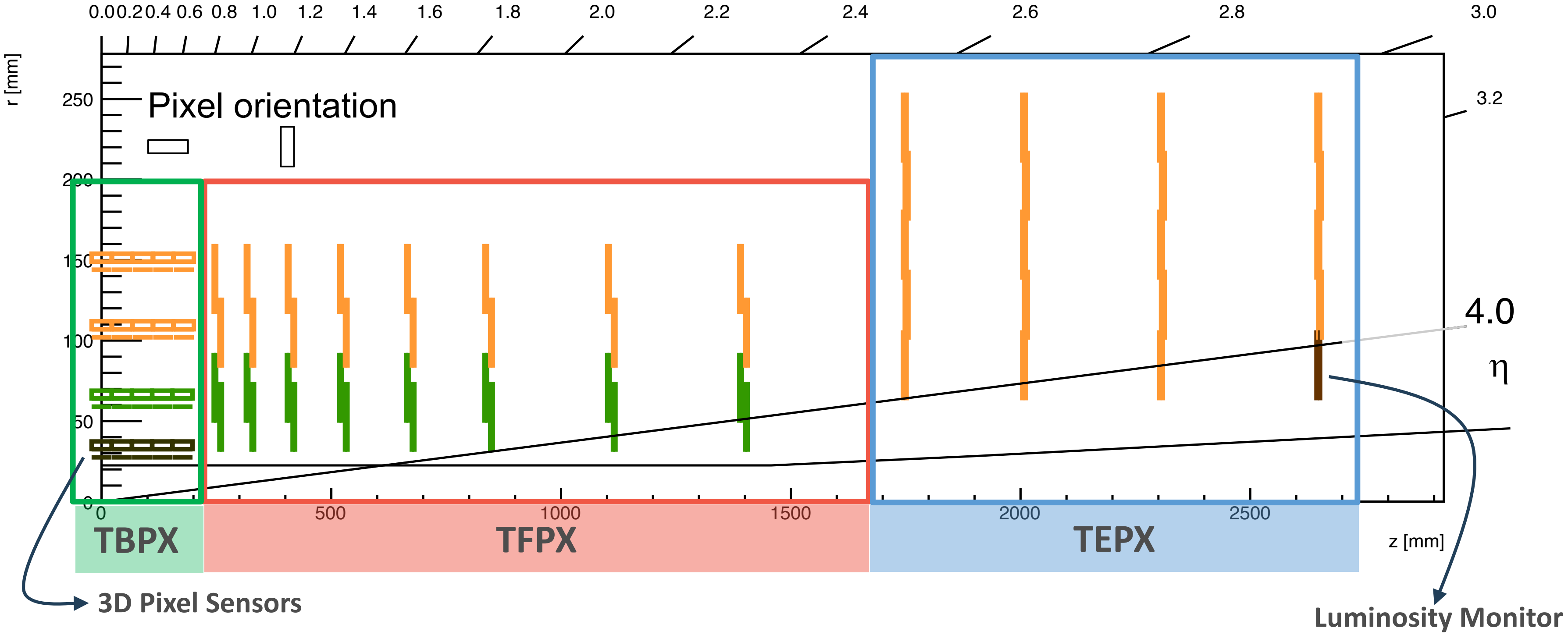
CMS Phase-2 Inner Tracker Upgrade

- HL-LHC will greatly expand the physics potential of CMS, but also bring severe experimental challenges
    - 3-4 x more pileup (up to 200 pp collisions per bunch crossing)
    - Hit rate up to 3.2 GHz/cm^2 in innermost layer
    - 3 x longer trigger latency (12.5 μs)
    - 10 x more radiation (TID up to 1.2 Grad, fluence of 2.3 x 10^{16} n_{eq}/cm^2)
- To maintain or even improve the tracking and vertexing performance with these conditions a new Inner Tracker (IT) will be built featuring
    - Increased granularity and resolution
    - Increased rate and radiation tolerance
    - Reduced material in the tracking volume
    - Increased acceptance in the forward region from $|\eta|<3$ to 4



https://hilumilhc.web.cern.ch/sites/default/files/HL-LHC_Janvier2022.pdf

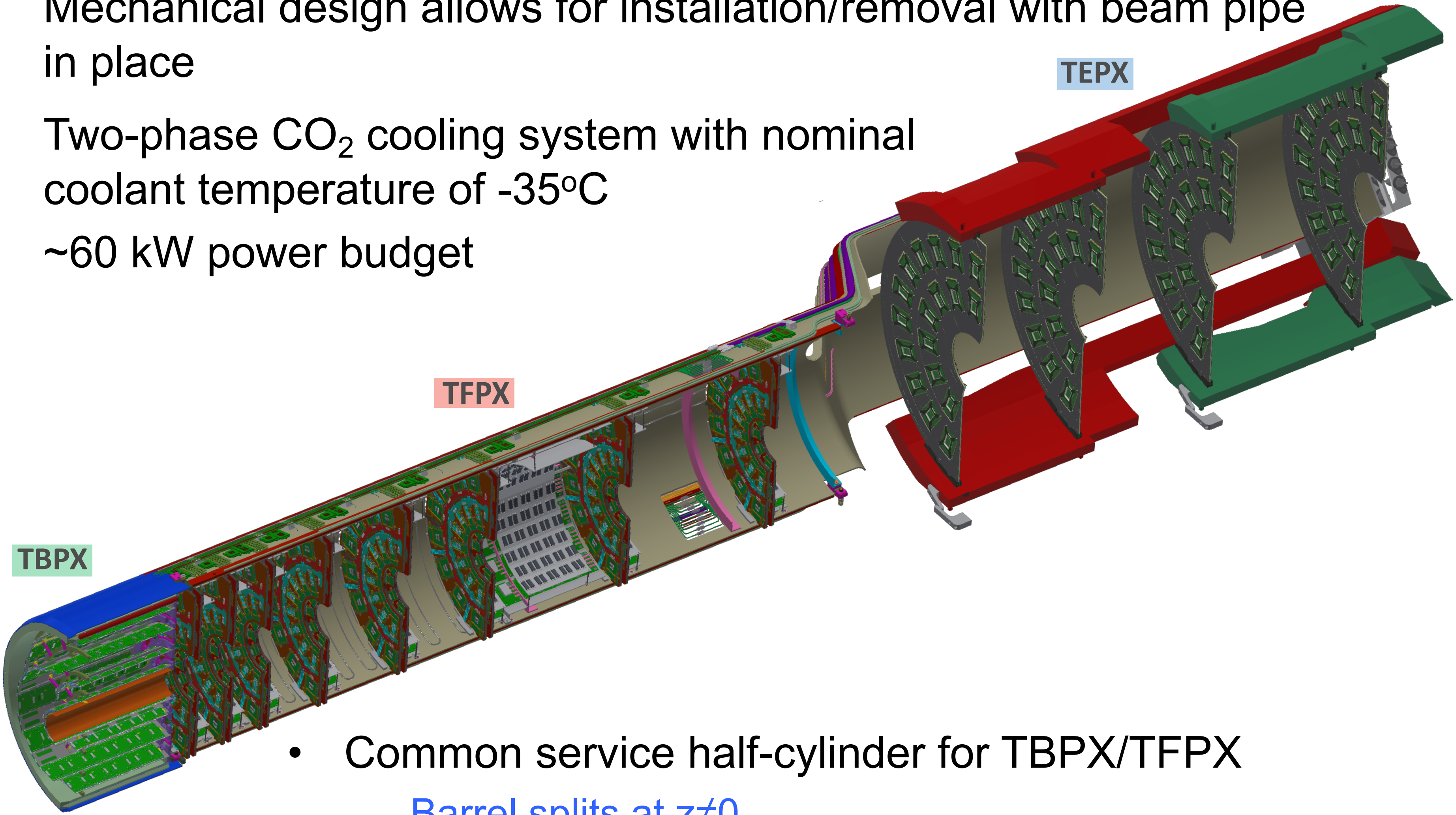
Inner Tracker Layout



- IT built from 3892 modules with either 1x2 or 2x2 readout chips (ROCs)
  - 2 billion pixels with size of 25x100μm^2
  - 3D Si sensors in innermost layer (L1), planar Si sensors elsewhere
- Three subsystems:
  - Tracker Barrel PiXel (TBPX), 4 layers
  - Tracker Forward PiXel (TFPX), 8 small double-disks on each side
  - Tracker Extended PiXel (TEPX), 4 large double-disks on each side

Inner Tracker System

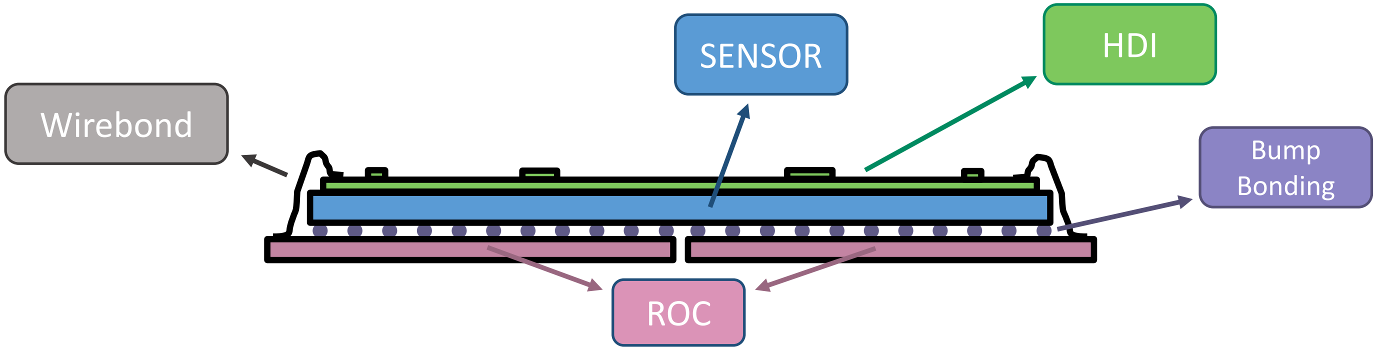
- Mechanical design allows for installation/removal with beam pipe in place
- Two-phase CO_2 cooling system with nominal coolant temperature of $-35^{o}C$
- ~60 kW power budget



- Common service half-cylinder for TBPX/TFPX
  - Barrel splits at z≠0
- TEPX split in two mechanical units to enable installation

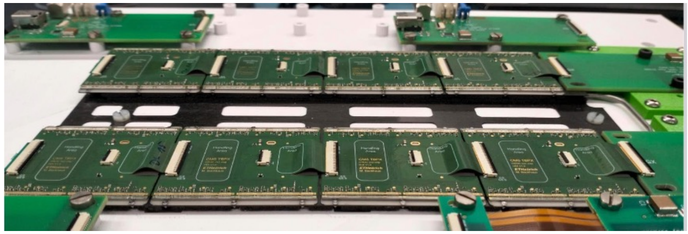
Inner Tracker Modules

- Simple design with ROC as only active electronics on the module
- Serial powering scheme with up to 11 modules per chain
- High Density Interconnect (HDI):
  - Flexible PCB containing only passive components
  - Contains return path for supply current
  - Careful design for low material budget
  - HV capable up to 1000V
- Different module flavors depending on module location (due to different layout of serial powering and mounting scheme)

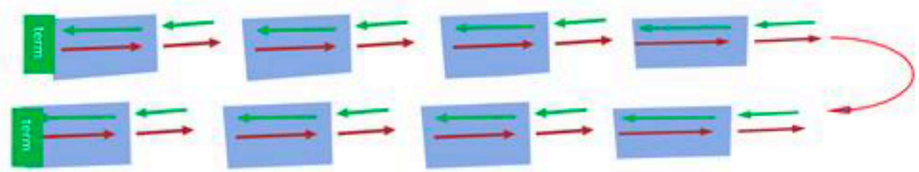


Inner Tracker Modules

Ladders in TBPX

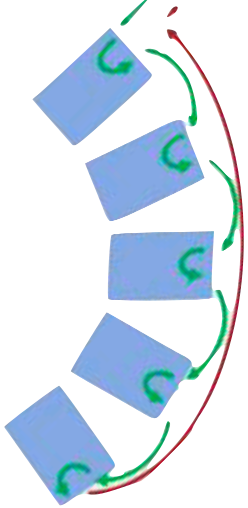


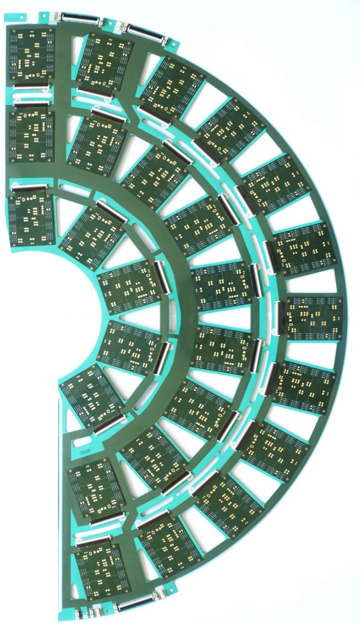
SP current path



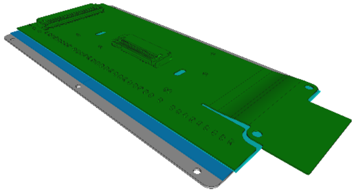
Half-disks in TFPX/TEPX

SP current path

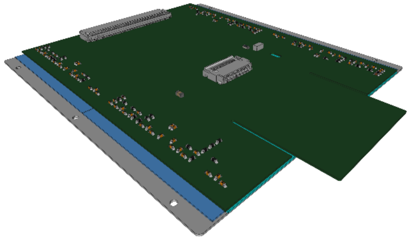




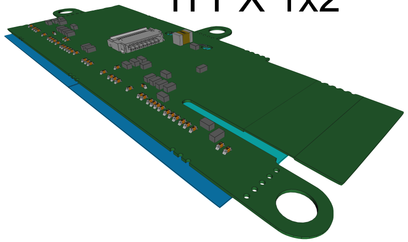
TBPX 1x2



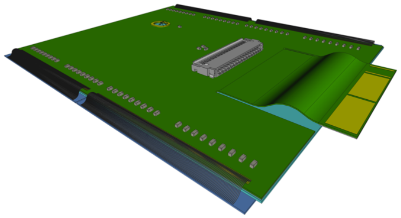
TBPX 2x2



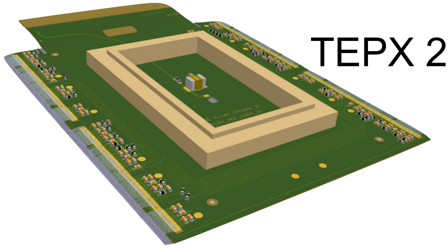
TFPX 1x2



TFPX 2x2

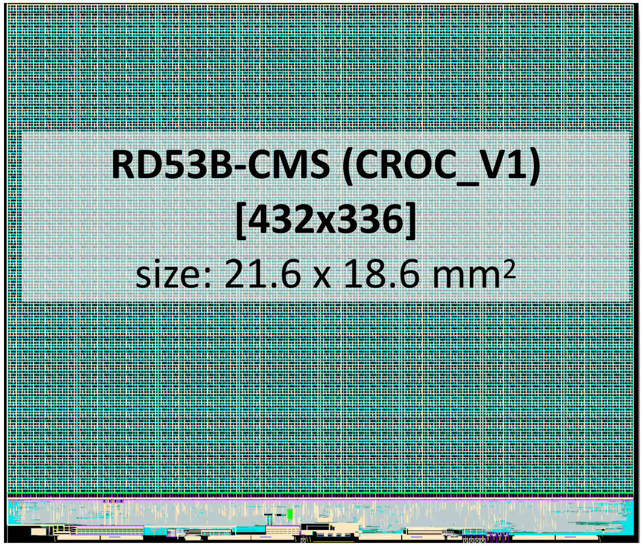


TEPX 2x2

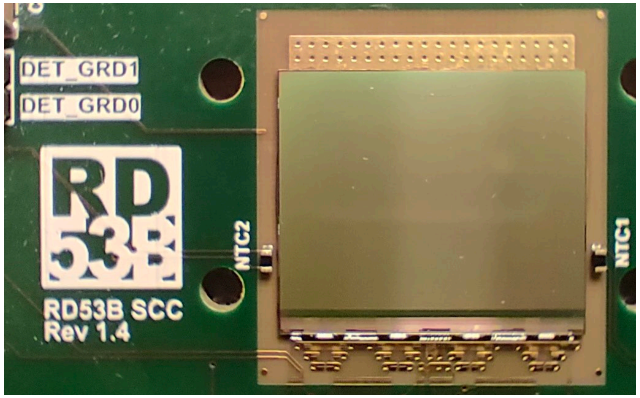


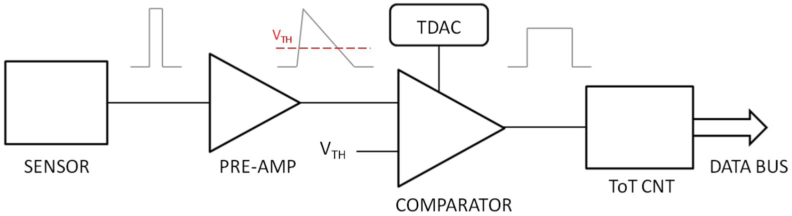
CMS Readout Chip (CROC)

- CROC 65nm CMOS ASIC developed by joint ATLAS-CMS RD53 collaboration
- Full size prototype thoroughly tested and validated, final version submitted
- 50x50 μm^2 cell size
- 3.5 GHz/cm^2 hit rate
- Radiation tolerance up to 1 Grad
- Linear analog front-end design
  - Low, adjustable threshold < 1000 e^-
  - Adjustable feedback to cope with large sensor leakage currents
- 4-bit digital readout with time-over-threshold (ToT) counter
- Up to 4x1.28 Gbps output links (configurable)

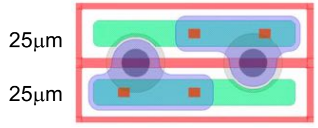


RD53B-CMS (CROC_V1)
[432x336]
size: 21.6 x 18.6 mm^2



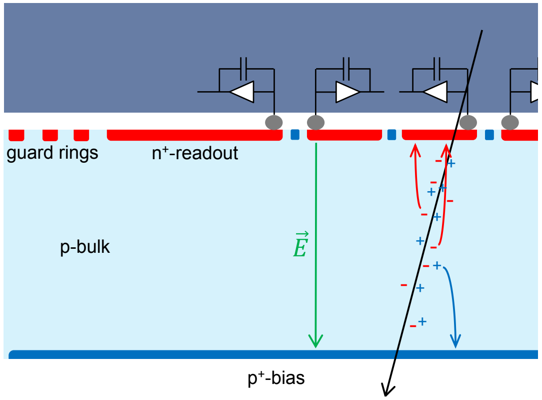


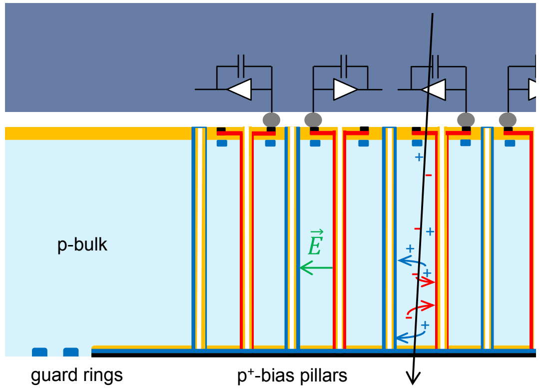
Sensors



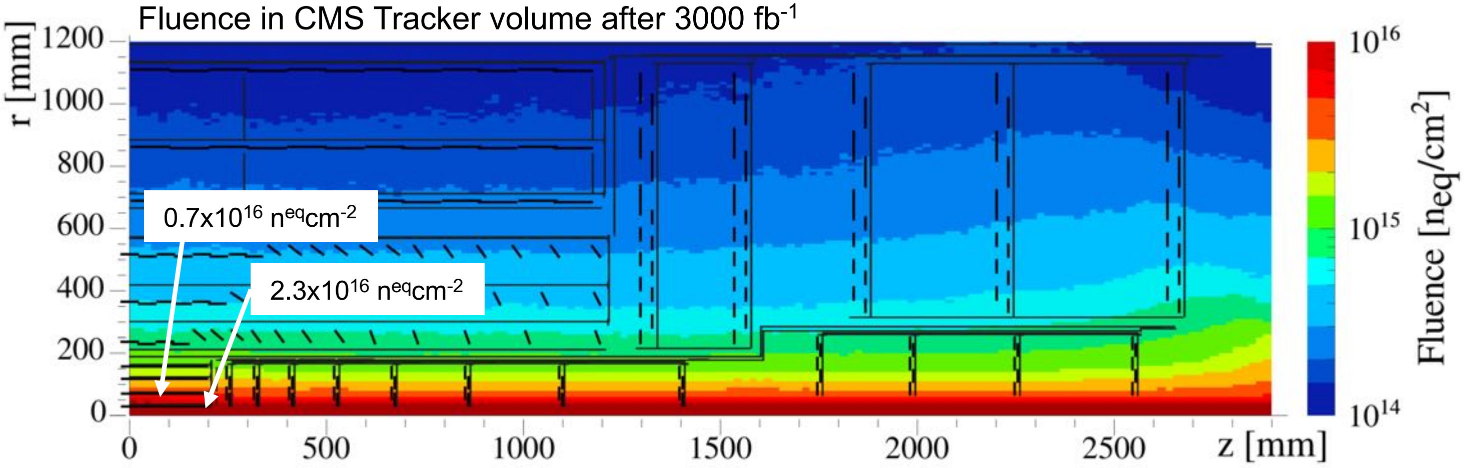
Bitten implant design

- Planar Si sensors (150 μm thickness, n-in-p)
  - Less production steps due to single-sided processing, but Parylene coating needed for edge isolation
  - 11 ke⁻ of charge for MIP
  - Higher radiation tolerance due to reduced thickness (and reduced bias voltage)
- 3D Si sensors in L1
  - Lower leakage current, necessary for safe margin to thermal runaway after irradiation (ϕ=1.5x10^{16} n$_{eq}$cm^{-2})
  - Replacement of TBPX L1 and TFPX R1 foreseen



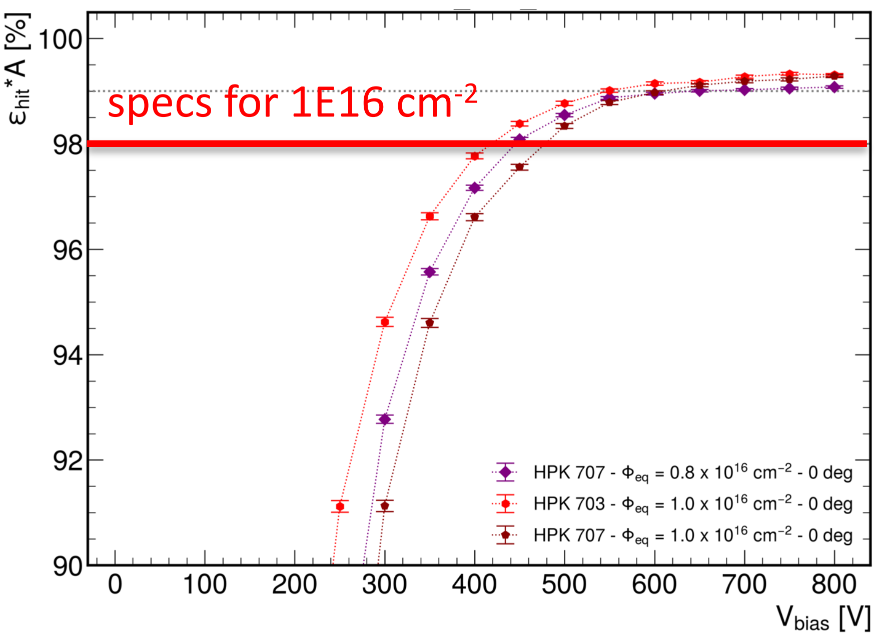


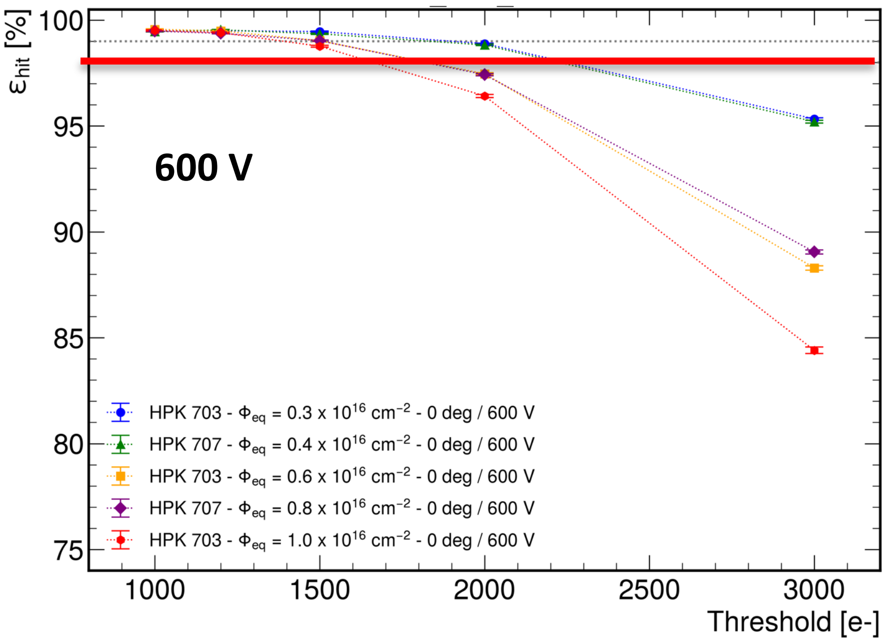
Fluence in CMS Tracker volume after 3000 fb^{-1}



Hit efficiency

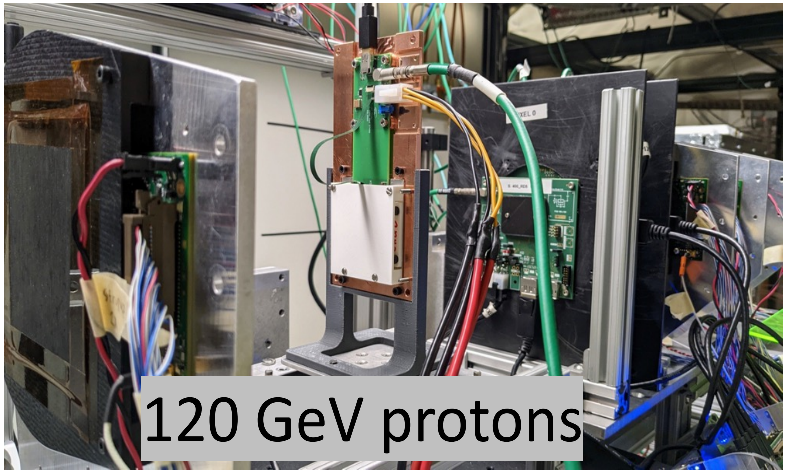
- Single-chip assemblies with planar sensors irradiated up to $\phi=1\times10^{16}\ n_{eq}cm^{-2}$ at CERN PS (23 GeV protons)
- Performance in terms of hit efficiency, noise and resolution measured in test beam at DESY
- Excellent performance with hit efficiency > 98% and <1% noisy pixels
- Resolution better than binary resolution even at highest fluence



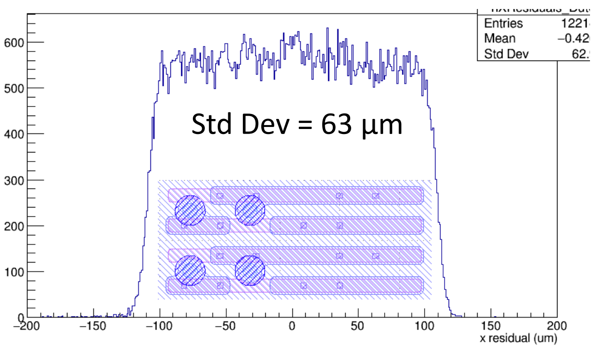


Validation of full module

- TBPX 2x2 module in FNAL testbeam
- Excellent performance confirmed
- Studied larger cells in inter-CROC regions (columns of 225x25 µm^2) → residuals as expected
- Analysis of data of irradiated modules underway

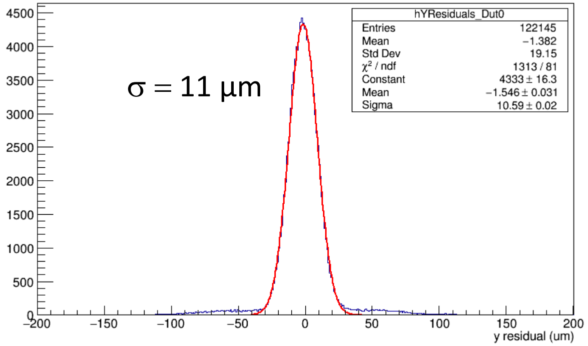

120 GeV protons

x residuals (225 µm side)

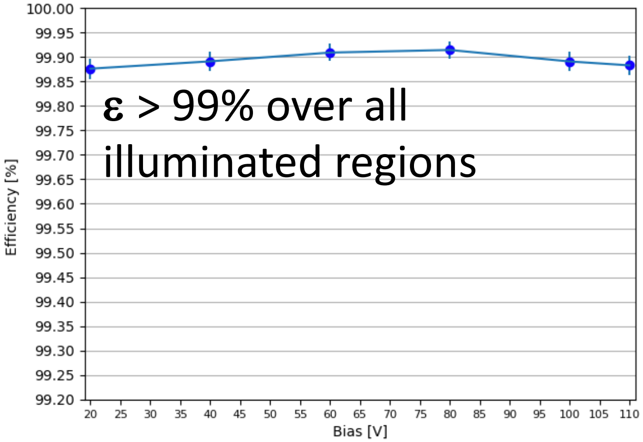


Std Dev = 63 µm

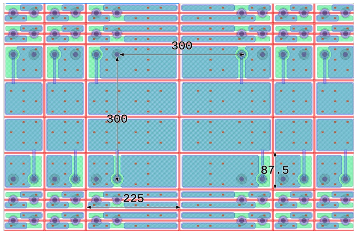
y residuals (25 µm side)



σ = 11 µm

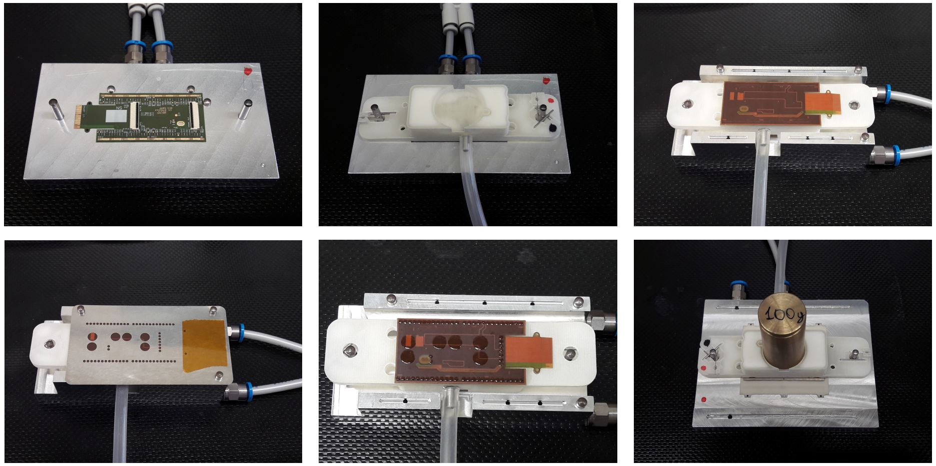


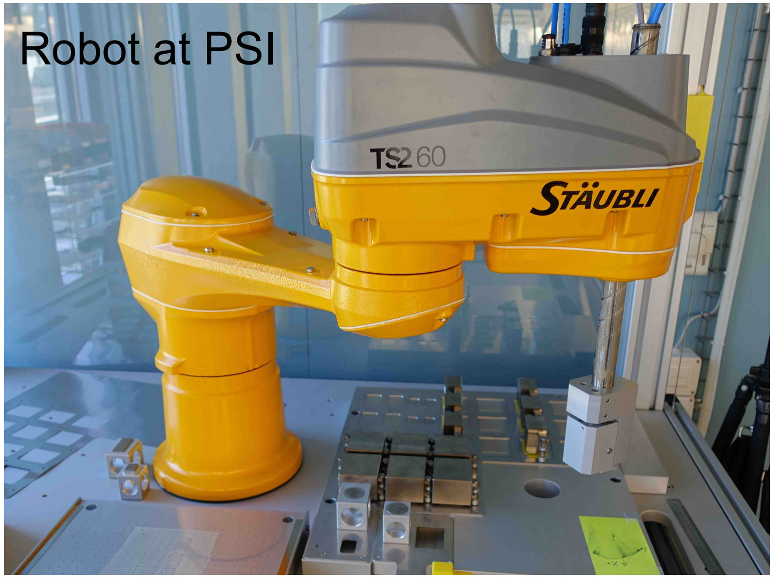
ε > 99% over all illuminated regions



Module Production

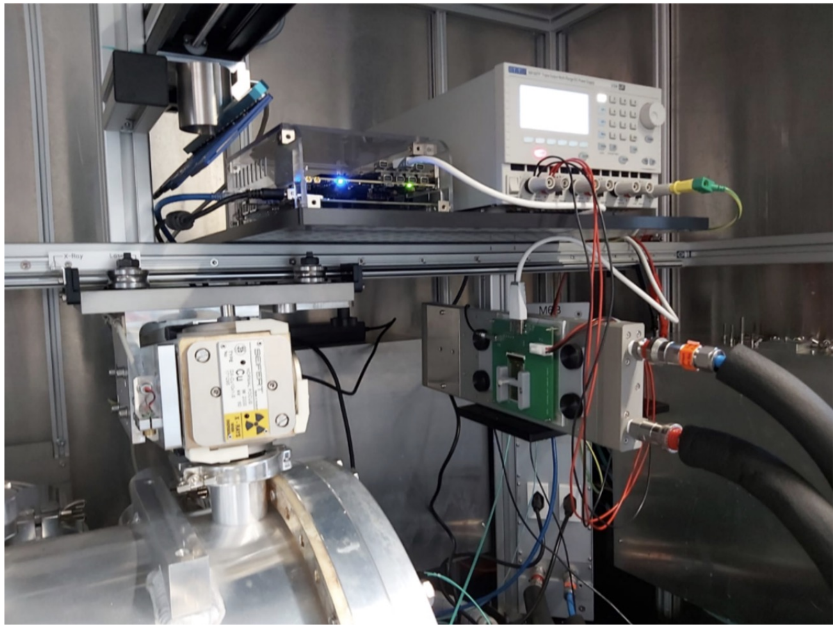
- Module production and testing done in 12 different centers in Europe (TBPX/TEPX) and USA (TFPX)
  - 3 vendors qualified for hybridization
- 6000 modules to be built (3892 to be installed)
  - Expect maximum throughput of 300 modules per month
  - Production will start in summer 2024
- Prototype modules built in different centers, demonstrated assembly accuracy in the range of 10-20μm
- Assembly by jigs (TBPX) or more automated procedures using gantry (TFPX) or robotic arm (TEPX)




Robot at PSI

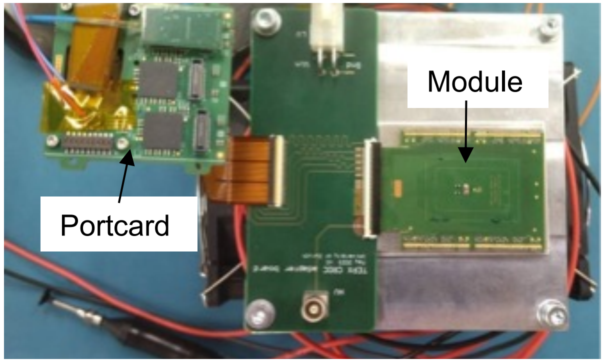
Module Testing

- Quick module functionality test after assembly, including optical inspection
- Full module qualification after coating
  - IV curves
  - ROC and pixel functionality
  - Bump-bonding
  - Thermal cycling
  - High-rate x-ray tests and x-ray calibration for subset of modules
- Coldbox to test up to 8 modules at a time

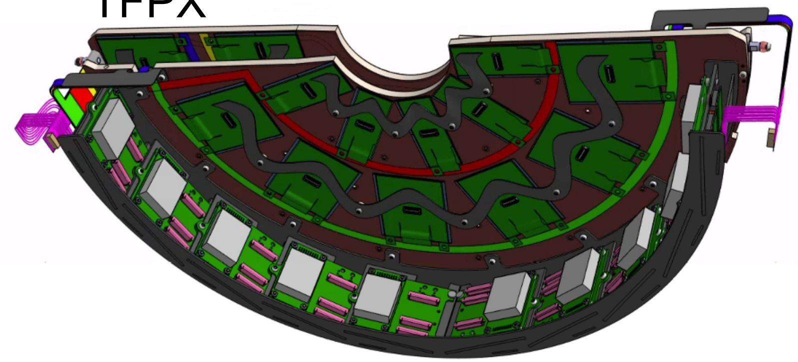


Readout system

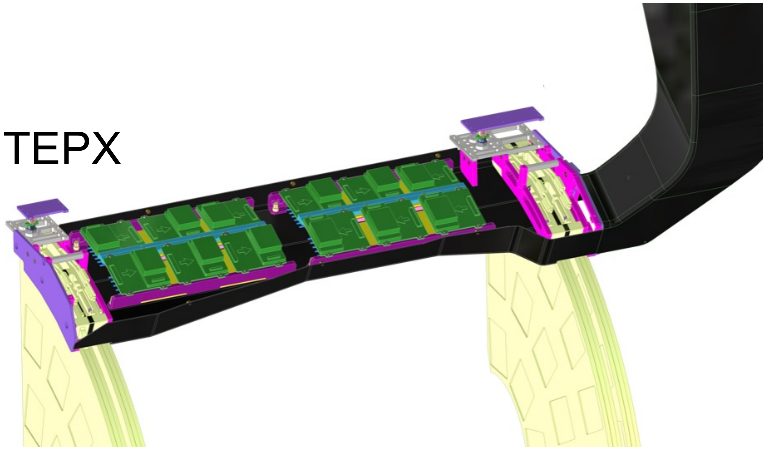
- Up to 6 electrical up-links at 1.28 Gbps per module to lpGBT
- One electrical down-link at 160 Mbps per module for clock, trigger and commands
- Auxiliary electronics and opto-converters hosted on 680 portcards located on cartridges (TBPX/TFPX) or supplies (TEPX)
- DAQ made from 28 Data Trigger Control (DTC) boards

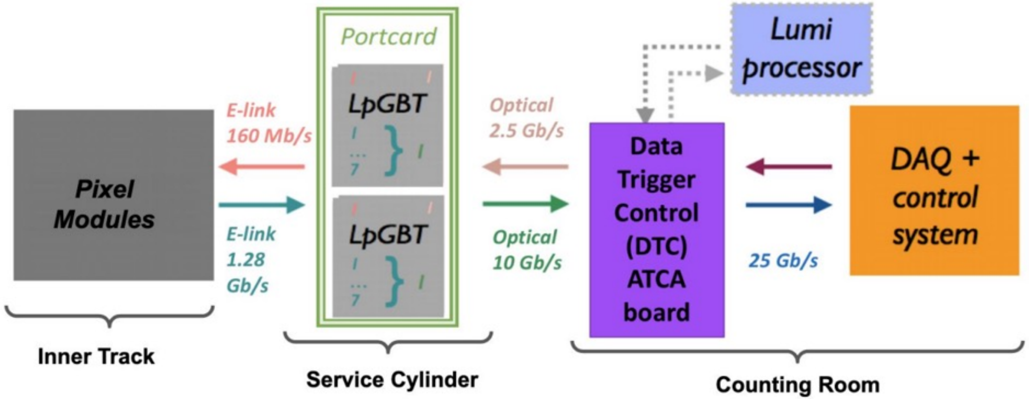


TFPX

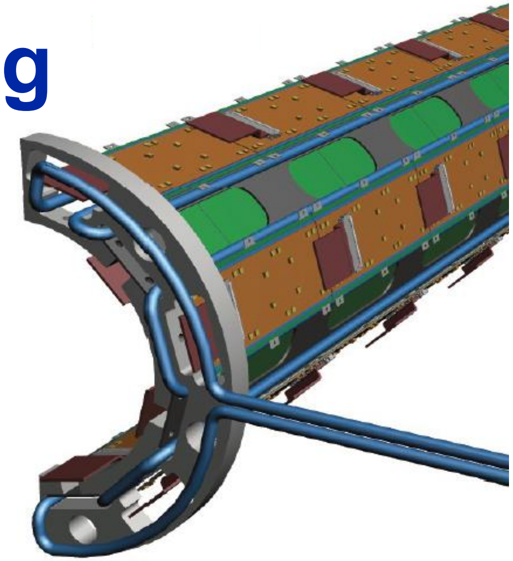


TEPX

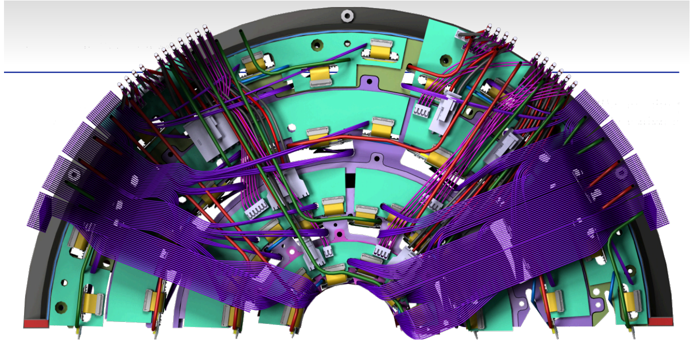


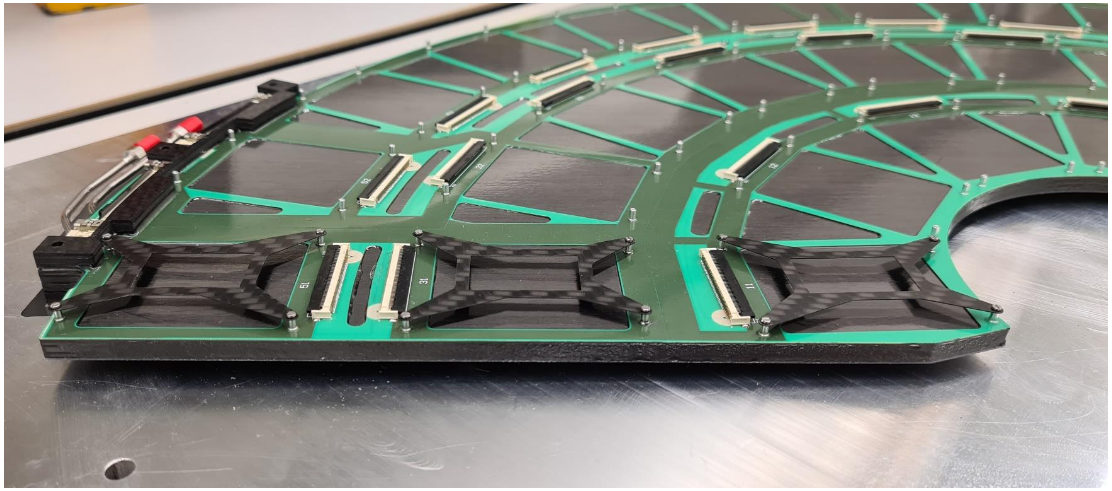


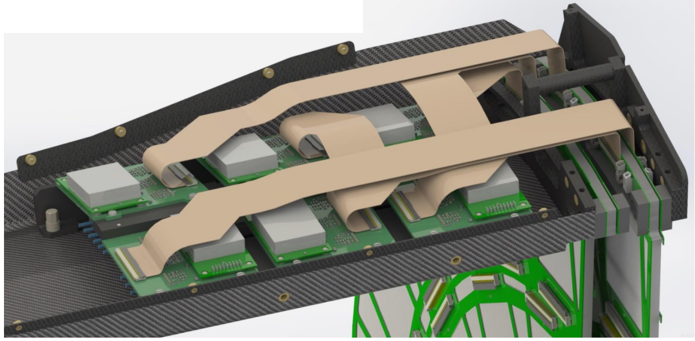
Mechanical support and cabling



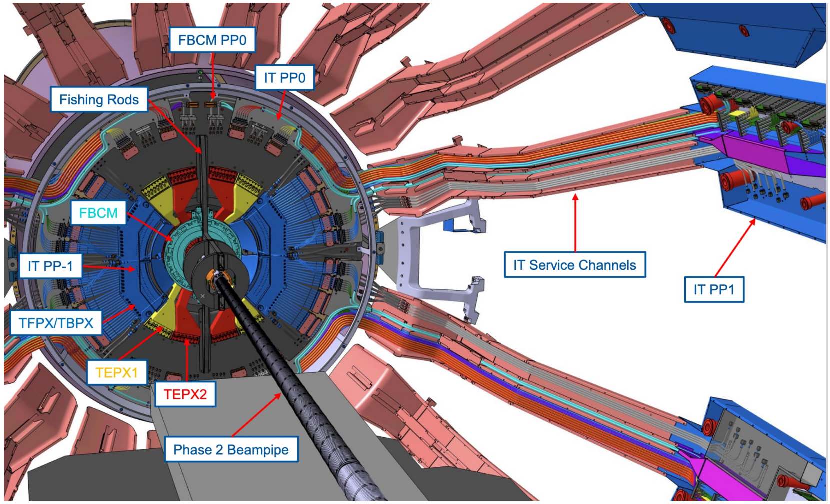
- Light Carbon Fiber structures with embedded thin-walled Titanium cooling pipes
- TBPX made from ladders of 4 or 5 modules, complex elink routing at enflange to portcards
- Disks with flat geometry, elinks routed through disk PCB, flex cables connect to portcards

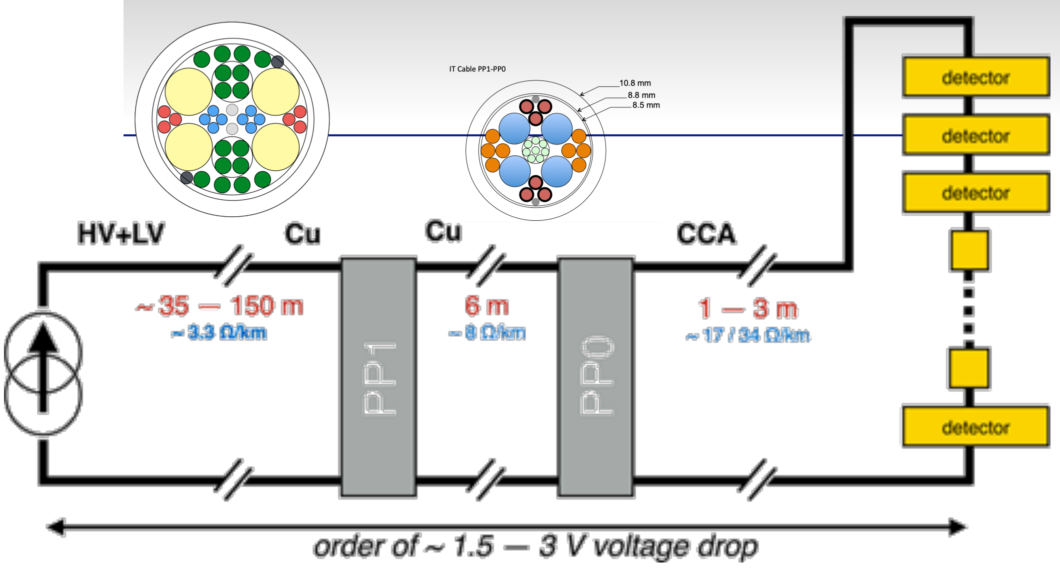






Power system

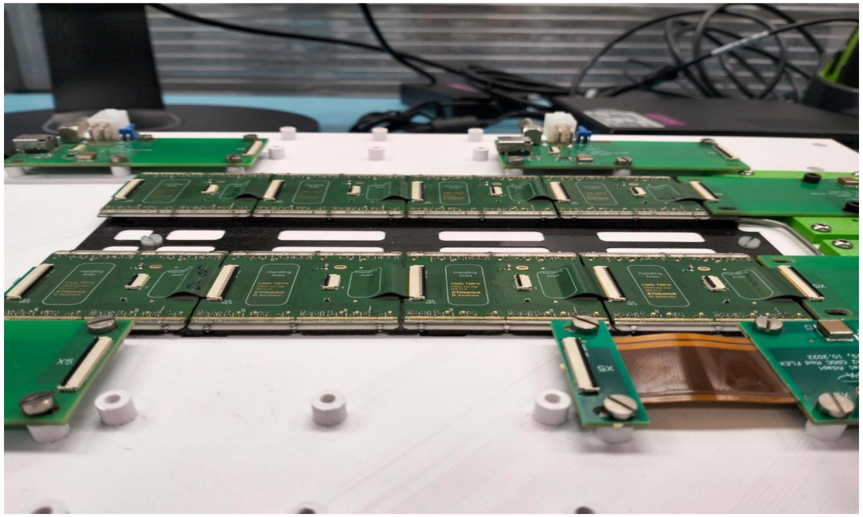


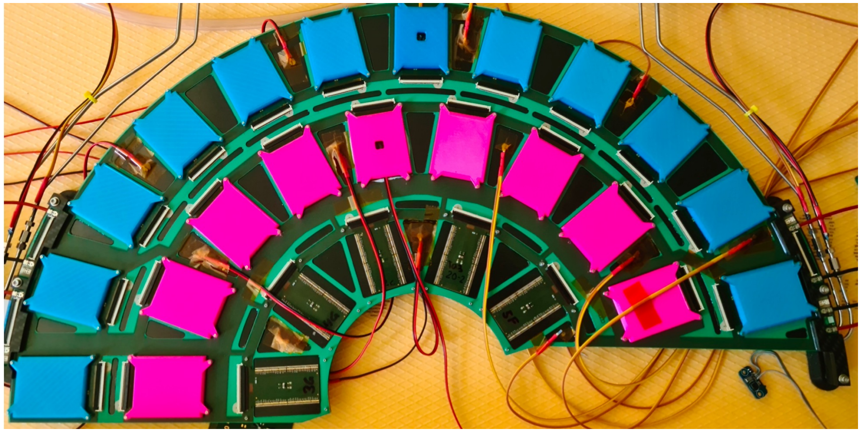


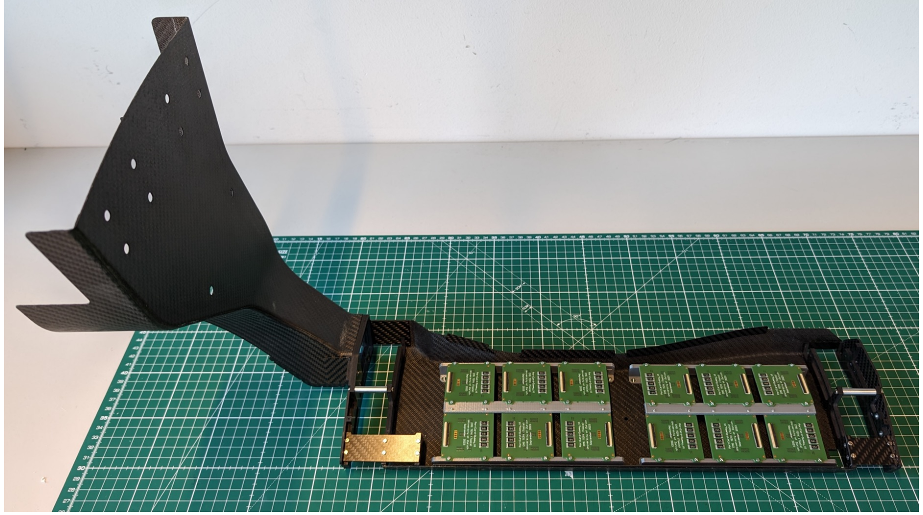
- Serial powering used to supply ~60kW
- 500 SP chains (164@4A, 336@8A) with 5-11 modules per chain
- ROCs within modules powered in parallel
- HV distributed in parallel to modules
- DCDC converters on portcards for optoelectronics and lpGBT
- Preheaters for each cooling loop
- Power supply within experimental cavern

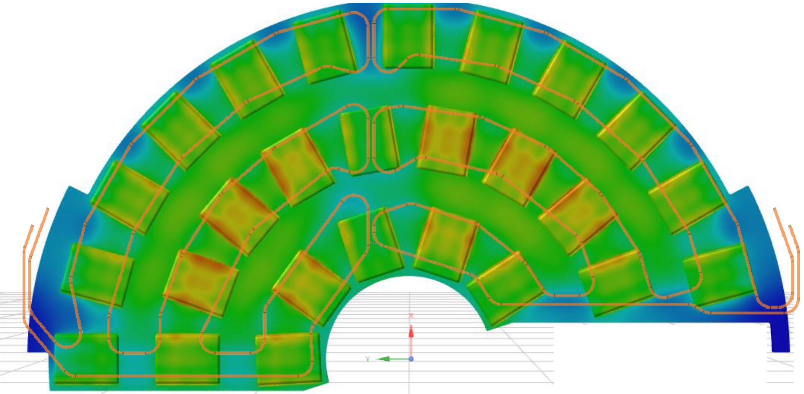
System test

- System tests of all IT subsystems ongoing to gain experience in operation
- Qualify electrical and optical links
- Investigate performance of SP chains and thermal behavior
- Establish testing and calibration procedures for detector integration





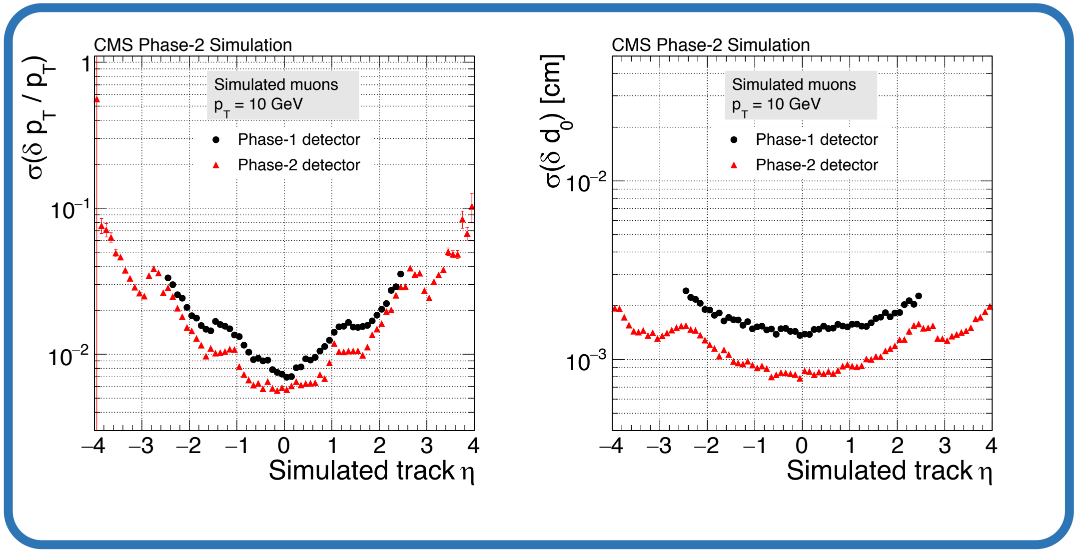




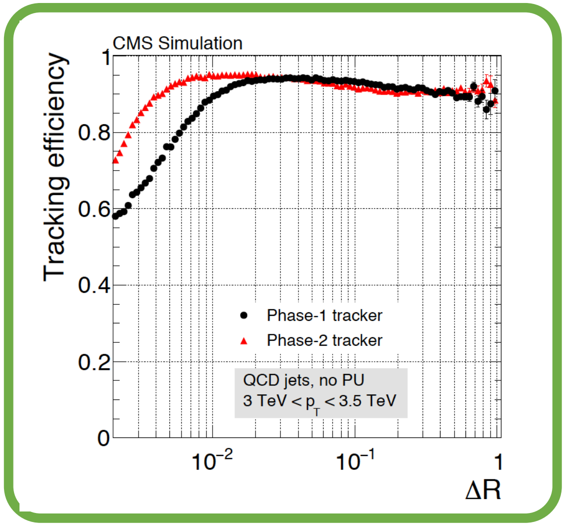
Expected performance

- Improvements on all physics observables even at highest pileup thanks to increased granularity with smaller pixels

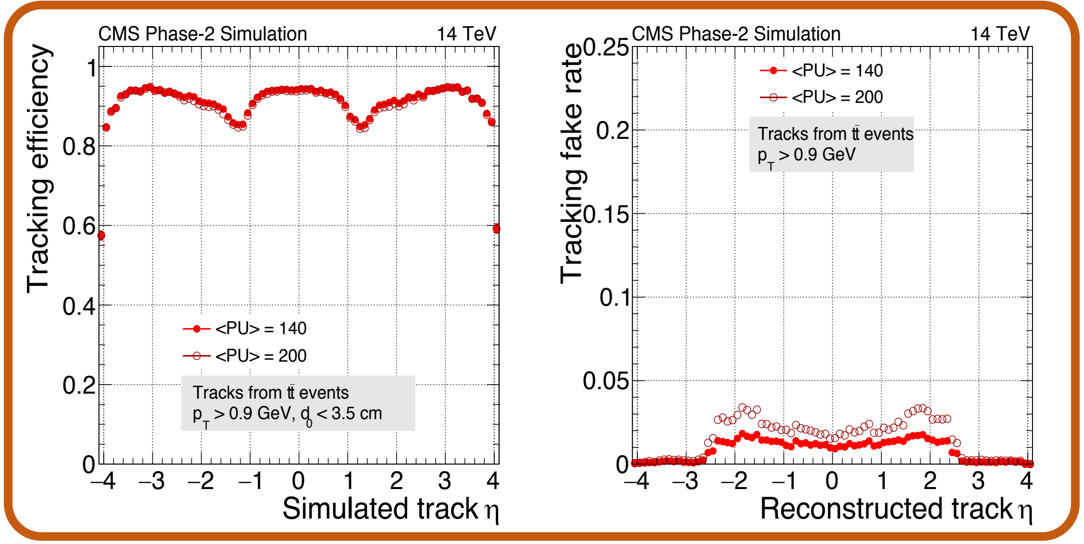
Improved resolution



Improved efficiency in high pT jets



Robust track finding performance



Summary

- Phase-1 CMS pixel detector will be replaced by Phase-2 Inner Tracker system for operation at HL-LHC
- Highlight in the design of the Phase-2 IT is increased granularity and extended acceptance in the forward region from $|\eta|<3$ to 4
- Performance of all module components has been validated, CROC and sensors in fabrication, module production will start in summer 2024
- Prototypes of all components (serial powering, readout electronics, modules) available and being tested in system tests
- CMS Phase-2 is a challenging project with lots of activities in detector construction ahead of us

THANK YOU