The CMS Tracker Phase II Upgrade for the HL-LHC Era

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On behalf of the CMS Collaboration

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- The HL-LHC schedule
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The High Luminosity LHC (HL-LHC)

- **Around 2024 (during LS3), the LHC will be upgraded to the HL-LHC**
  - Increase in instantaneous luminosity by a factor of ~ 5
  - Expected int. luminosity of 3000 fb^{-1} to 4000 fb^{-1} after 10 years of operation
- **At the same time, the CMS experiment will be upgraded as well**
  - Muon chambers, ECAL and HCAL (especially front-end electronics)
  - Increase of L1 trigger rate and latency (750 kHz and 12.5 μs)
  - New silicon based endcap high granularity calorimeter (~ 600 m^2 of silicon)
  - **Complete replacement of the CMS tracker (pixel and strips)**

LHC						HL-LHC
Run 1	**LS1**	**Run 2**	**LS2**	**Run 3**	**LS3**	**Run 4 - 5 ...**
$L \approx 8 \cdot 10^{33}$ cm^{-2} s^{-1}		$L \approx 1.5 \cdot 10^{34}$ cm^{-2} s^{-1}		$L \approx 1.5 \cdot 10^{34}$ cm^{-2} s^{-1}		$L \approx 5 \cdot 10^{34}$ cm^{-2} s^{-1}
$\mathcal{L} \approx 30$ fb^{-1}		$\mathcal{L} < 300$ fb^{-1}		$\mathcal{L} \approx 300$ fb^{-1}		$\mathcal{L} \approx 3000\text{-}4000$ fb^{-1}
$\sqrt{s}$ = 7-8 TeV		$\sqrt{s}$ = 13-14 TeV		$\sqrt{s}$ = 14 TeV		$\sqrt{s}$ = 14 TeV
PU ≈ 25		PU ≈ 50		PU ≈ 50		PU ≈ 140 - 200

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	...

We are here

Why do we need an upgrade?

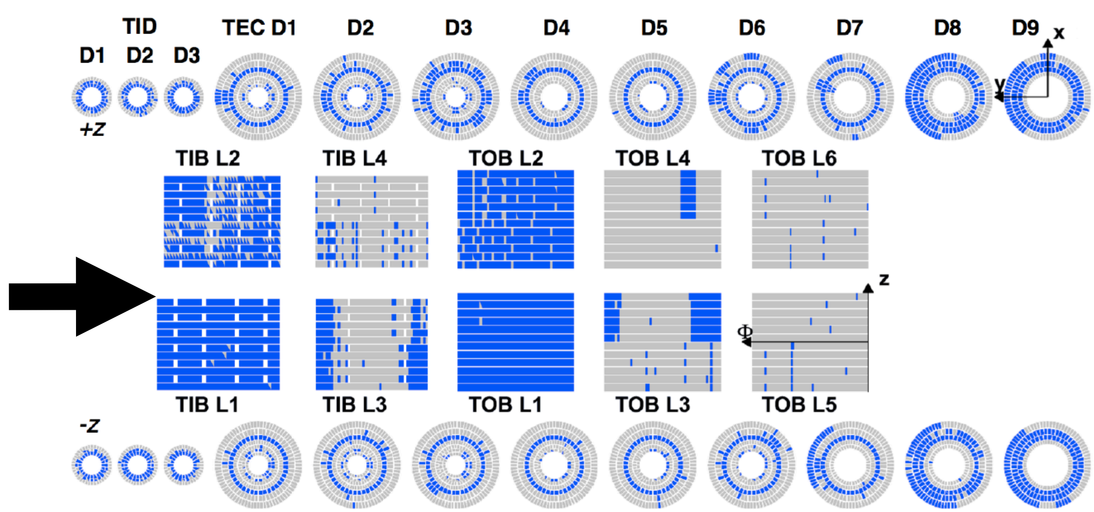
1. To fully exploit the high luminosity conditions
2. Design limitations of current tracker will be exceeded by far

	Design limitations of current Tracker	HL-LHC conditions
Pileup	20-30	140-200
int. lumi.	< 1000 fb^{-1}	3000-4000 fb^{-1}

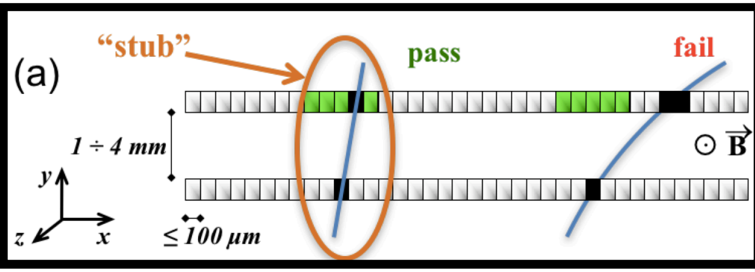
3. Radiation damage will lead to many non-functional modules

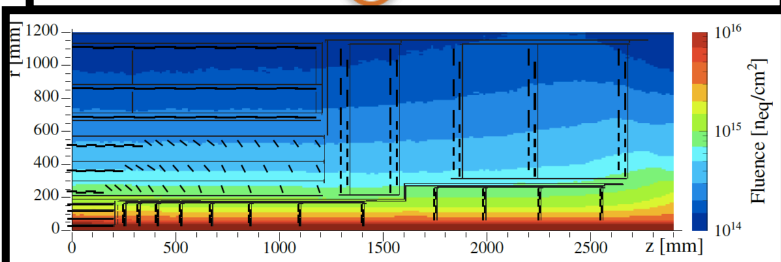
- ➢ Increased leakage current cannot be compensated by cooling anymore

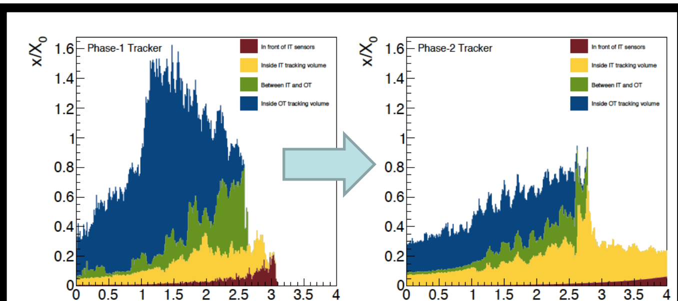
Simulation of non-functional modules of the current tracker (in blue) after 1000 fb^{-1} int. luminosity.

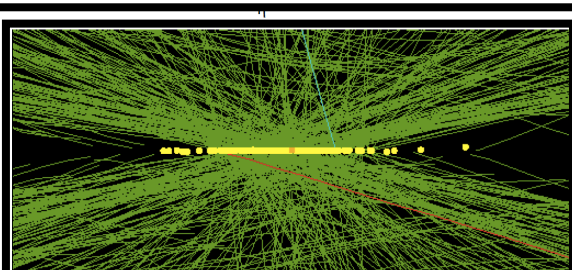


Requirements for the Tracker upgrade





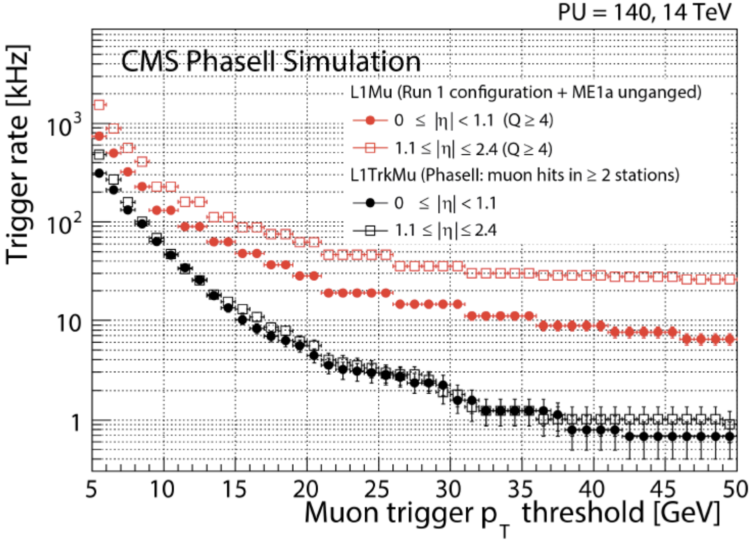


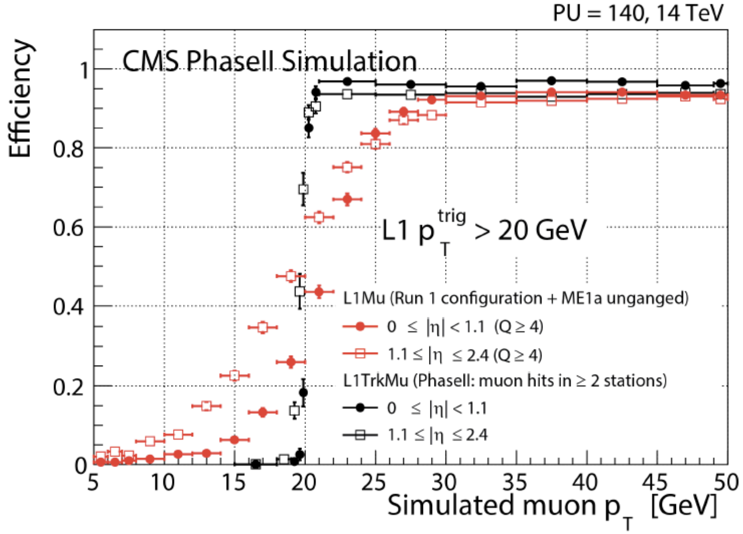


1. **Maintain physics performance**
   - Introduce track trigger concept
2. **Increased radiation hardness**
   - Efficient operation up to:
     - $2.3 \times 10^{16}\ n_{eq}/cm^2$ → Pixel
     - $1 \times 10^{15}\ n_{eq}/cm^2$ → Strips
3. **Reduced material budget**
4. **Extended tracking acceptance**
   - $|\eta| = 2.4$ → $|\eta| = 4$
5. **Increased granularity**
   - Keep channel occupancy < 1 %

Motivation of the track trigger concept

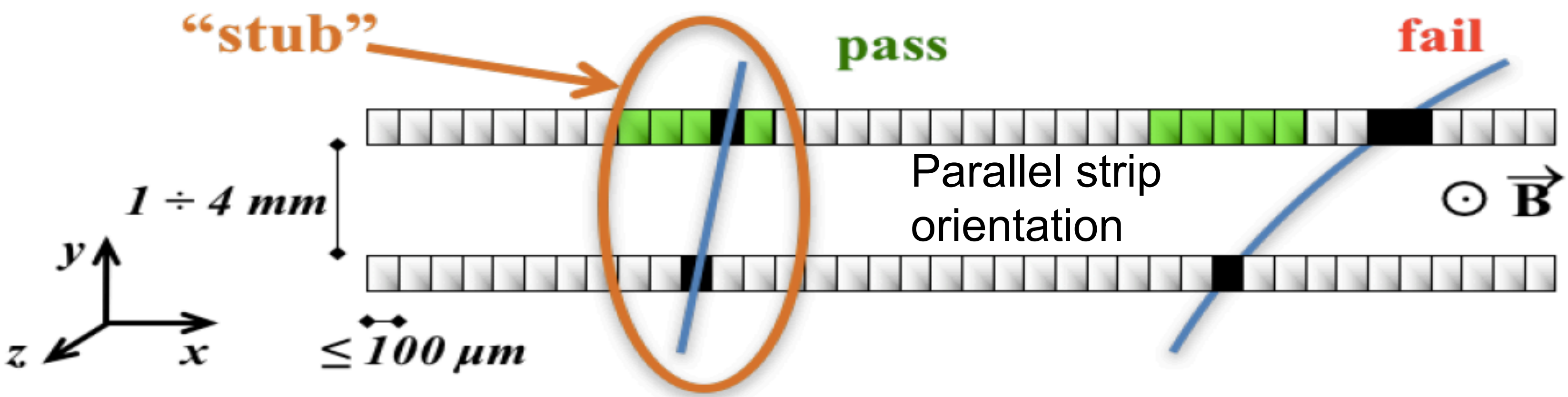
- The current CMS L1 trigger rate is limited to **100 kHz**
  - ➢ HL-LHC rates of e, μ and jets exceed this limitation by far!
- <u>How to maintain physics performance?</u>
  - Drastic increase of trigger p_T thresholds
    - ➢ Unacceptable restriction of physics performance
  - Increase L1 trigger rate to **750 kHz**
    - ➢ Alone not sufficient
  - **Filter p_T at module level**





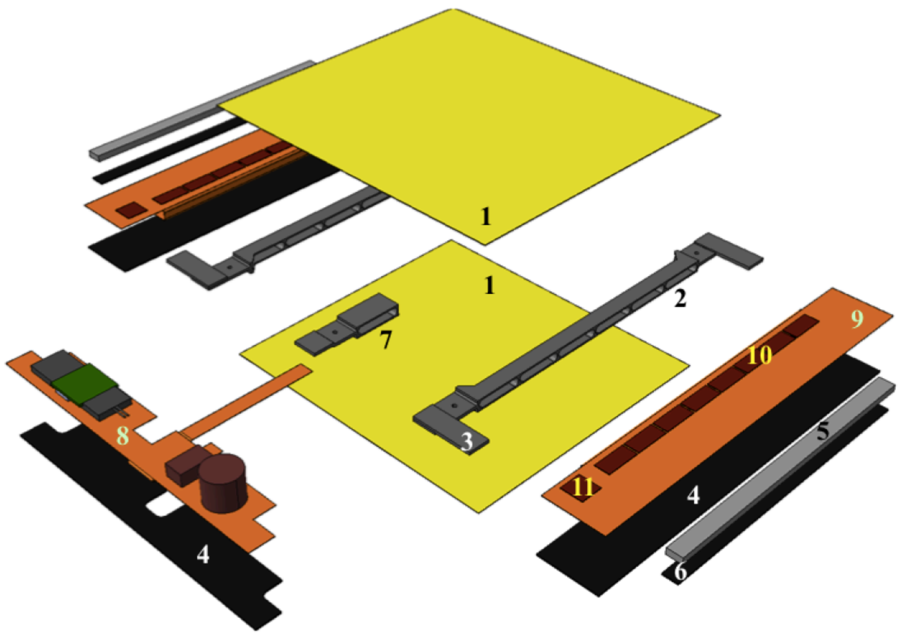
Concept of p_T discrimination at module level

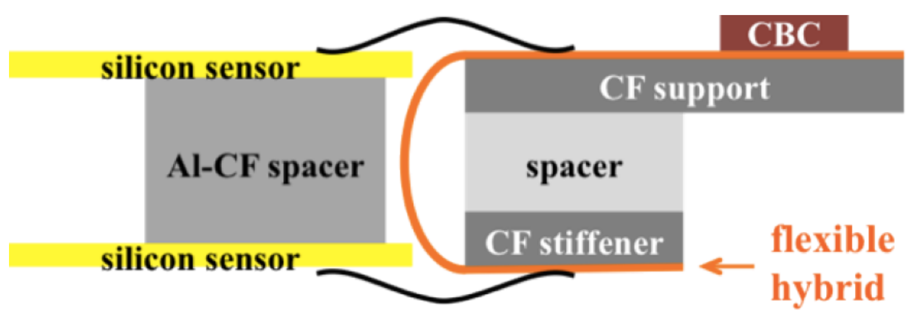
- Two stacked and closely spaced silicon sensors housed in one module
- **Correlating the hit positions on both sensors enables p_T discrimination**
  - ➢ Different curvatures for different particle transverse momenta
- Selection of p_T by adjusting hit matching window (variable) and sensor spacing (fixed)
  - ➢ p_T threshold of 2 GeV → data reduction of **one order of magnitude**
- Hit pairs corresponding to particles having a **p_T > 2 GeV** are called "**stubs**"
  - ➢ Transmitted at 40 MHz bunch crossing frequency to L1 trigger



p_T modules: 2S module

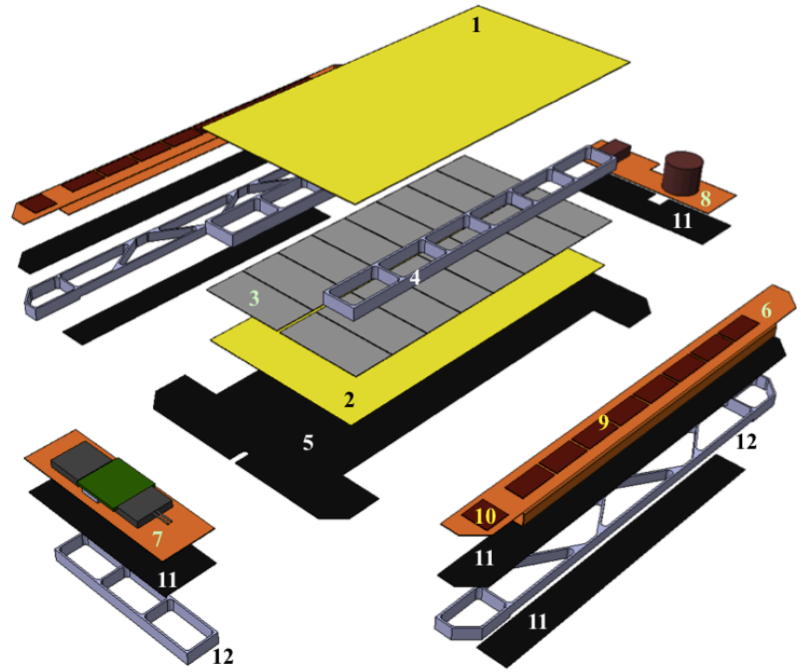
- **Two stacked silicon strip sensors with parallel strip orientation** [pic. #1]
  - Strips are segmented at the center
  - 127 × 8 × 2 (2032) AC-coupled strips per sensor
  - Strip dimensions:
    - 5 cm long, 90 µm pitch
  - Sensor size: 10 cm × 10 cm
- **Front-end electronics:**
  - CMS Binary Chip (CBC), 16 chips per module [pic. #10]
    - ➢ Readout and hit correlation
  - Concentrator ASIC (CIC) [pic. #11]
    - ➢ Buffer, aggregate and format data of CBC
  - DC/DC converter [pic. #8]
  - Low-power gigabit data transceiver (LpGBT) [pic. #8]

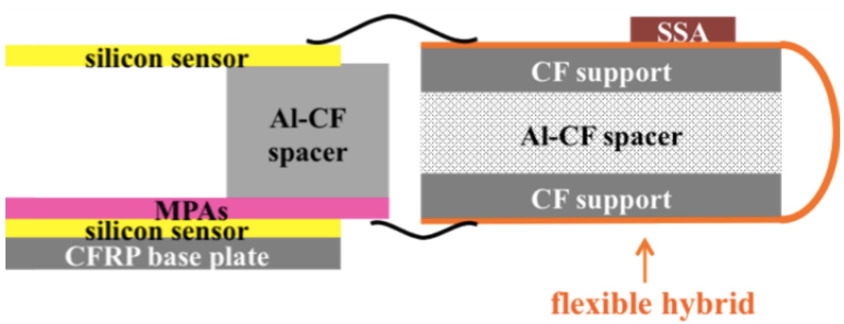




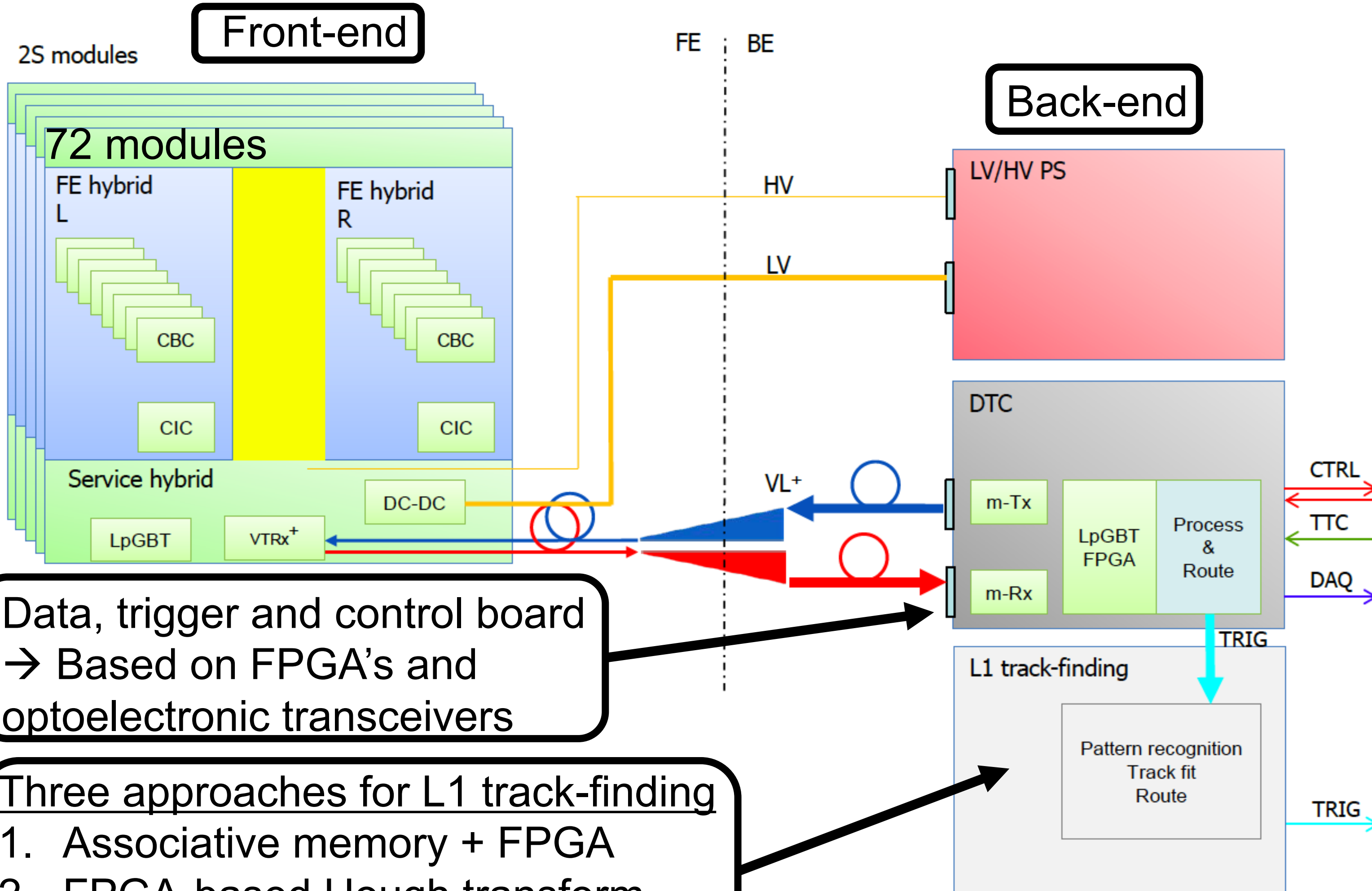
p_T modules: PS module

- **One silicon strip sensor (PS-s) and one silicon macro pixel sensor (PS-p) stacked** [pic. #1, #2]
  - AC-coupled PS-s: 2.4 cm x 100 µm
  - DC-coupled PS-p: 1.5 mm x 100 µm
- **Front-end electronics:**
  - PS-s readout → Short Strip ASIC (SSA)
  - PS-p readout → Macro Pixel ASIC (MPA)
    - ➢ Bump bonded to PS-p
    - ➢ Performs hit correlation
    - ➢ Cooling via carbon fibre reinforced polymer (CFRP) base plate [pic. #5]
  - Concentrator ASIC (CIC) [pic. #10]
    - ➢ Buffer, aggregate and format data
  - DC/DC converter [pic. #8]
  - Low-power gigabit data transceiver (LpGBT) [pic. #7]





Outer Tracker electronics



Timing, trigger and control

On reception of L1 trigger (750 kHz)

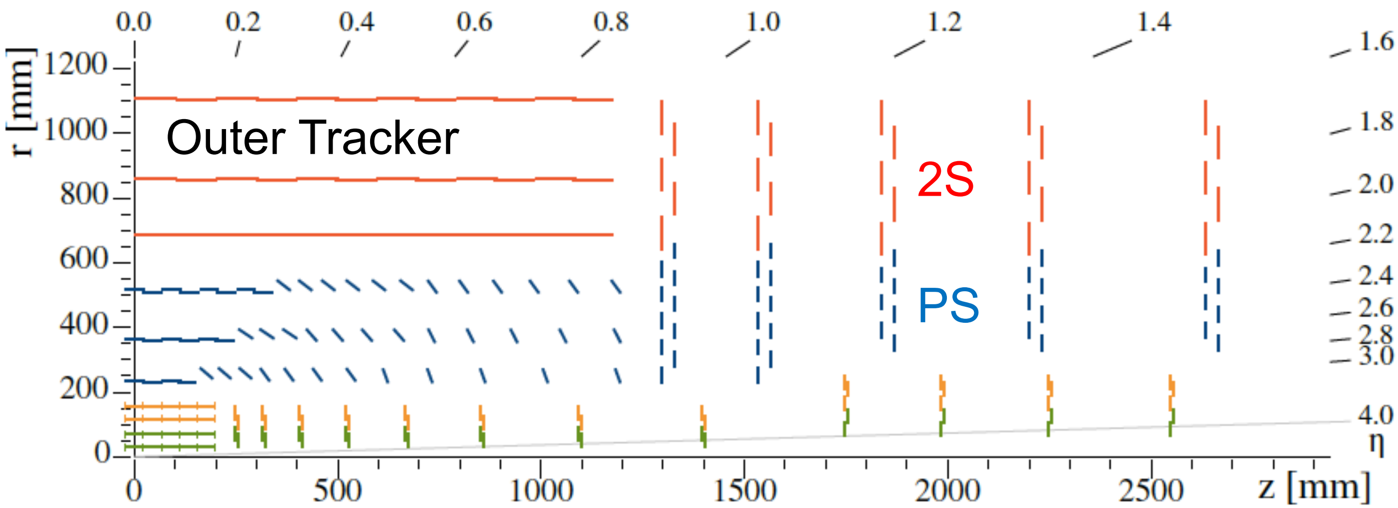
Data to L1 trigger (40 MHz)

Data, trigger and control board
→ Based on FPGA's and optoelectronic transceivers

Three approaches for L1 track-finding
1. Associative memory + FPGA
2. FPGA-based Hough transform
3. FPGA-based tracklet

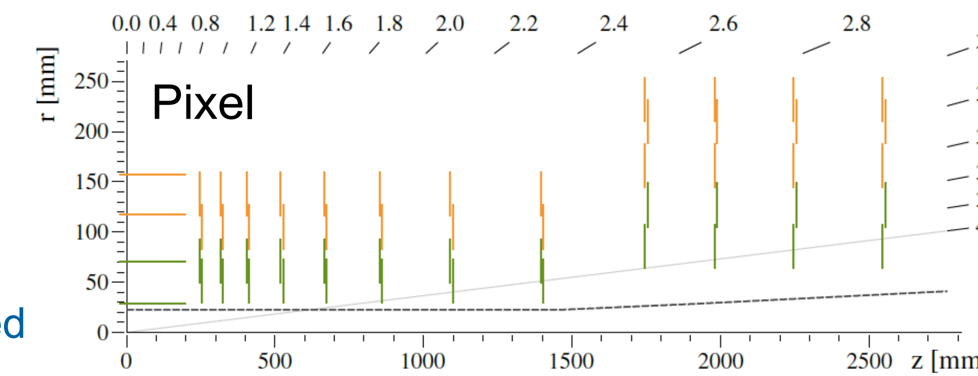
See talk by Tom James (tomorrow)

Phase II Tracker layout



- **2S modules**
  - 7680 pcs.
  - Sensor spacing
    - 1.8 mm
    - 4.0 mm
- **PS modules**
  - 5616 pcs.
  - Sensor spacing
    - 1.6 mm
    - 2.6 mm
    - 4.0 mm

- Extended coverage up to $|\eta| = 4$
- **Tilted layout for the PS barrel modules**
  - ➢ Reduces geometrical stub finding inefficiency at large incident angles
  - ➢ Cost and material reduction
    - ~ 1300 PS modules less needed
  - ➢ Drawback: More complicated mechanics



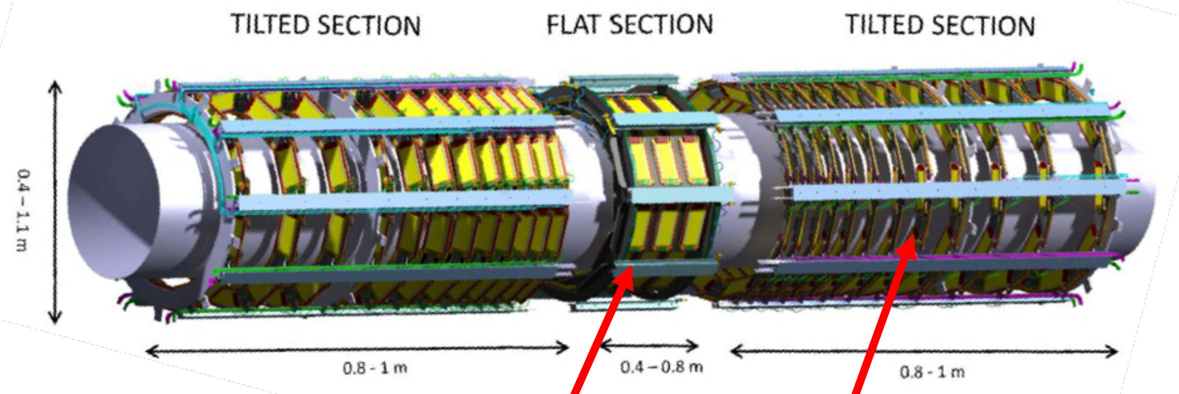
Two readout chip modules: 1960 pcs.

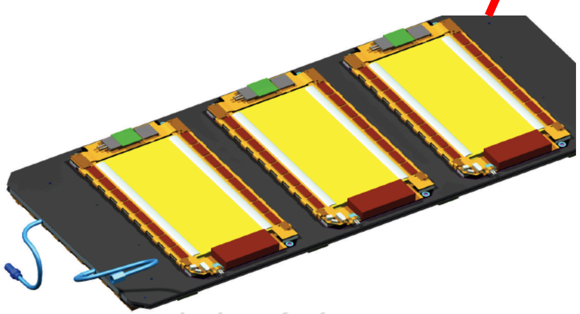
Four readout chip modules: 2392 pcs.

Outer Tracker mechanics – inner layers

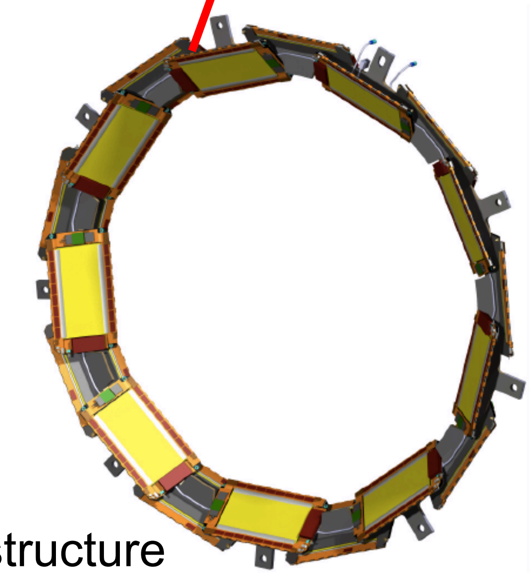
- **PS modules tilted towards the interaction point**
  - Tilt angles: 47° to 74°
- **Modules of flat section supported by plank structures**
  - Foam core with carbon fibre skins
  - Cooling pipe in mid of the plank
  - Phase change thermal interface material for thermal connection of modules
- **Tilted modules placed on ring structures (carbon fibre foam sandwich)**
  - High conductivity carbon fibre / epoxy laminate used to attach modules to support ring

Innermost layer of outer tracker





Plank structure

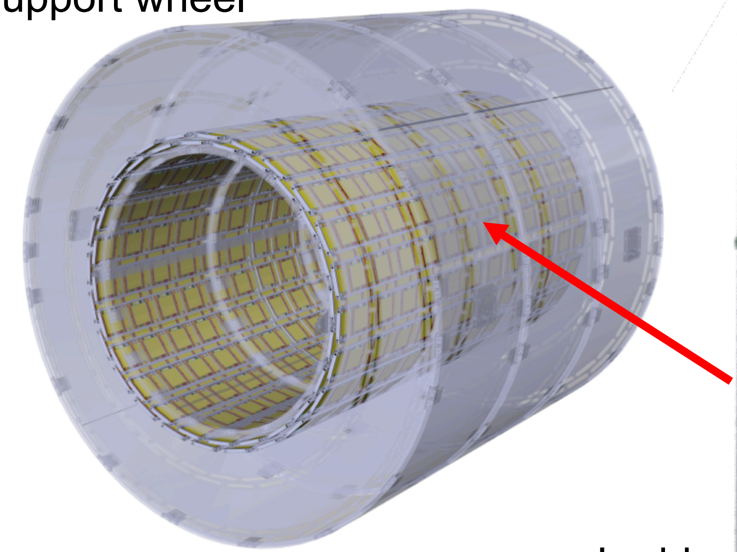


Ring structure

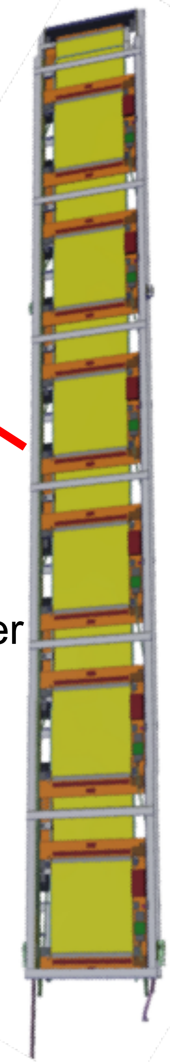
Outer Tracker mechanics – outer layers

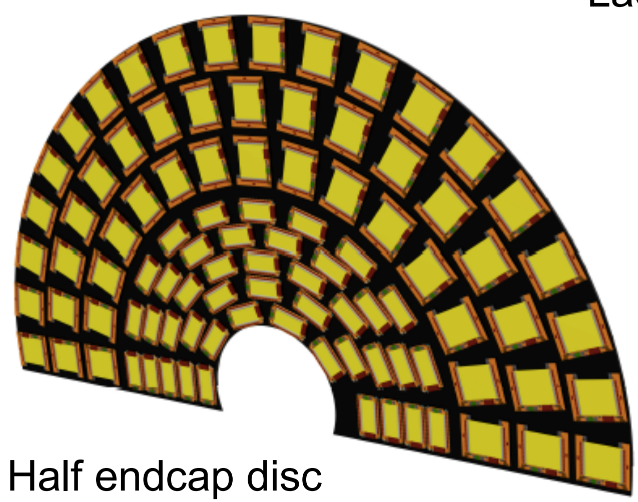
- **Barrel mechanics**
  - 2S modules mounted on ladders (12 modules per ladder)
    - Made out of carbon fibre C-shaped profiles
    - Cooling pipes transits full length of ladder
    - Ladders are supported by wheel
      - Essentially a copy of the wheel used for the current tracker
- **Endcap discs**
  - Split in half discs → two are grouped to form a double disc
  - Lower radii → PS modules
  - Higher radii → 2S modules
  - Cooling pipes run inside the sandwich structure of the discs

Support wheel



Ladder

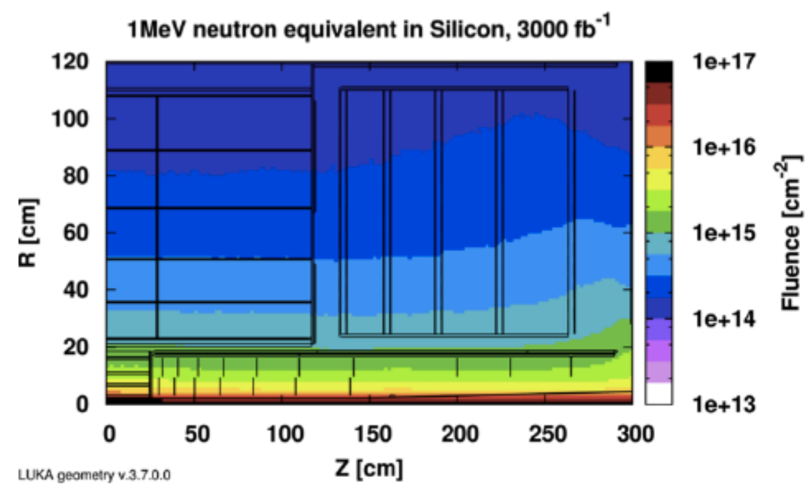


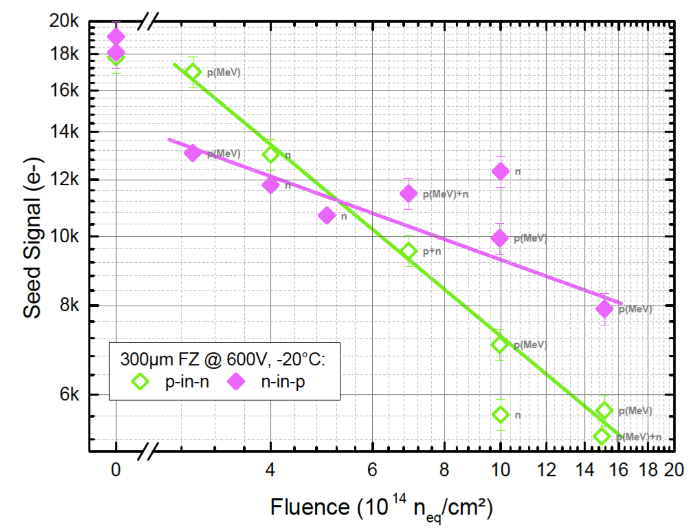


Half endcap disc

Radiation hard sensor material for the outer Tracker

- A large campaign to was carried out to find the optimal sensor material (HPK campaign)
  - ➢ **Constraint:** Should withstand fluences of up to **1×10^{15} n_{eq}/cm^2**
- **Outcomes**:
  1. Float-zone as well as magnetic Czochralski are suited
  2. n-in-p sensors show higher signal than p-in-n sensors after irradiation
  3. Non Gaussian noise observed for p-in-n sensors
  4. Thin sensors preferred
     - Better annealing behavior
     - Higher signal after irradiation
     - Less current after irradiation



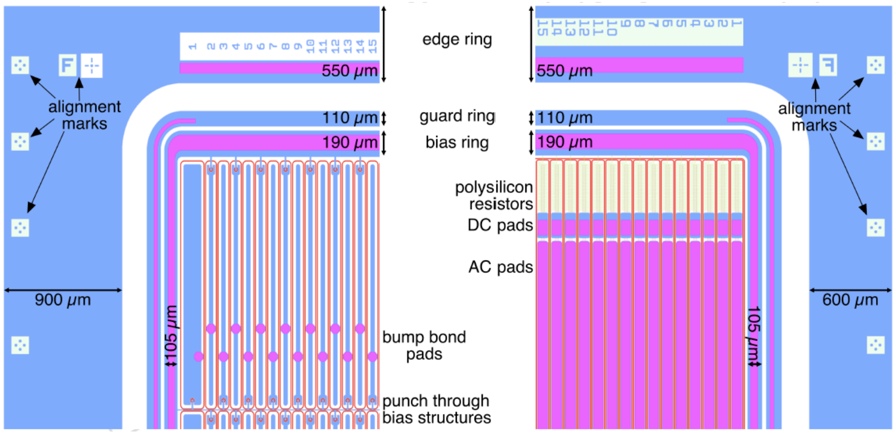


➡ CMS will use **thin** (200 – 240 µm) **n-in-p** sensors for the outer Tracker

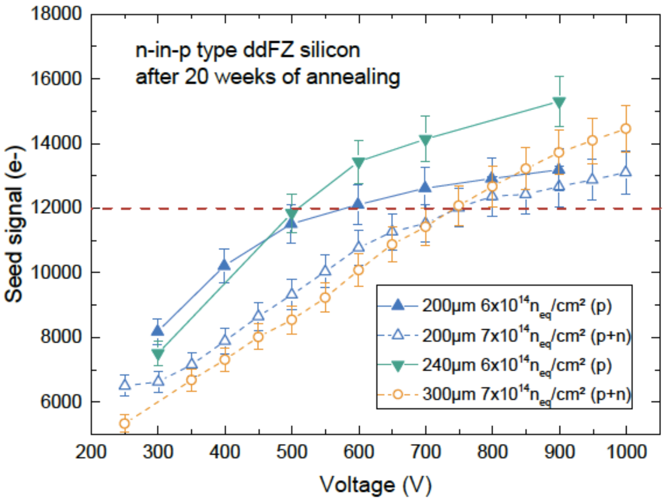
Outer tracker sensor prototyping

- **Sensor layouts nearly finalized**
- **Still under investigation:**
  - Design optimizations for PS-p sensors
  - Modified biasing scheme for 2S sensors (bias rail at the sensors center)
  - **Deep diffused** base material
    - ➢ Backside implant deeply diffused into the bulk → active volume < physical volume
- Several prototype batches have been produced and characterized
  - ➢ **2S sensors:** Multiple batches of two vendors
  - ➢ **PS-p sensors:** One prototype batch containing small versions of the actual sensor (PS-p light)
  - ➢ **PS-s sensors:** Prototype batch expected by the end of this year
- **So far, radiation hardness could be confirmed**

PS-p layout | 2S layout

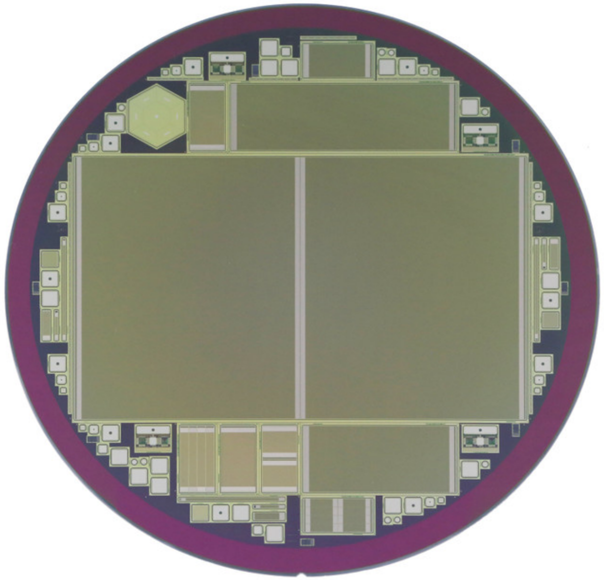


1-1.5 expected fluence of 2S sensors



Outer Tracker sensor procurement

- **CMS started a market survey which is currently ongoing**
- ➢ **Joint effort of CMS and ATLAS**
  - **Structured in three steps**
    1. Technical questionnaire
    2. Provide "sensor like" samples
    3. Prototype run with tight specifications
- **Aim:** Find at least **two vendors**
  - ➢ Redundancy and pricing benefits
  - ➢ 50 % of sensors produced by each vendor
    - Both capable of producing all sensors
- **Current status: Between step 2 and 3**
  - Three possible vendors already identified
    - HPK (Japan), Infineon (Austria) and Novati (U.S.)



Prototype wafer of Infineon

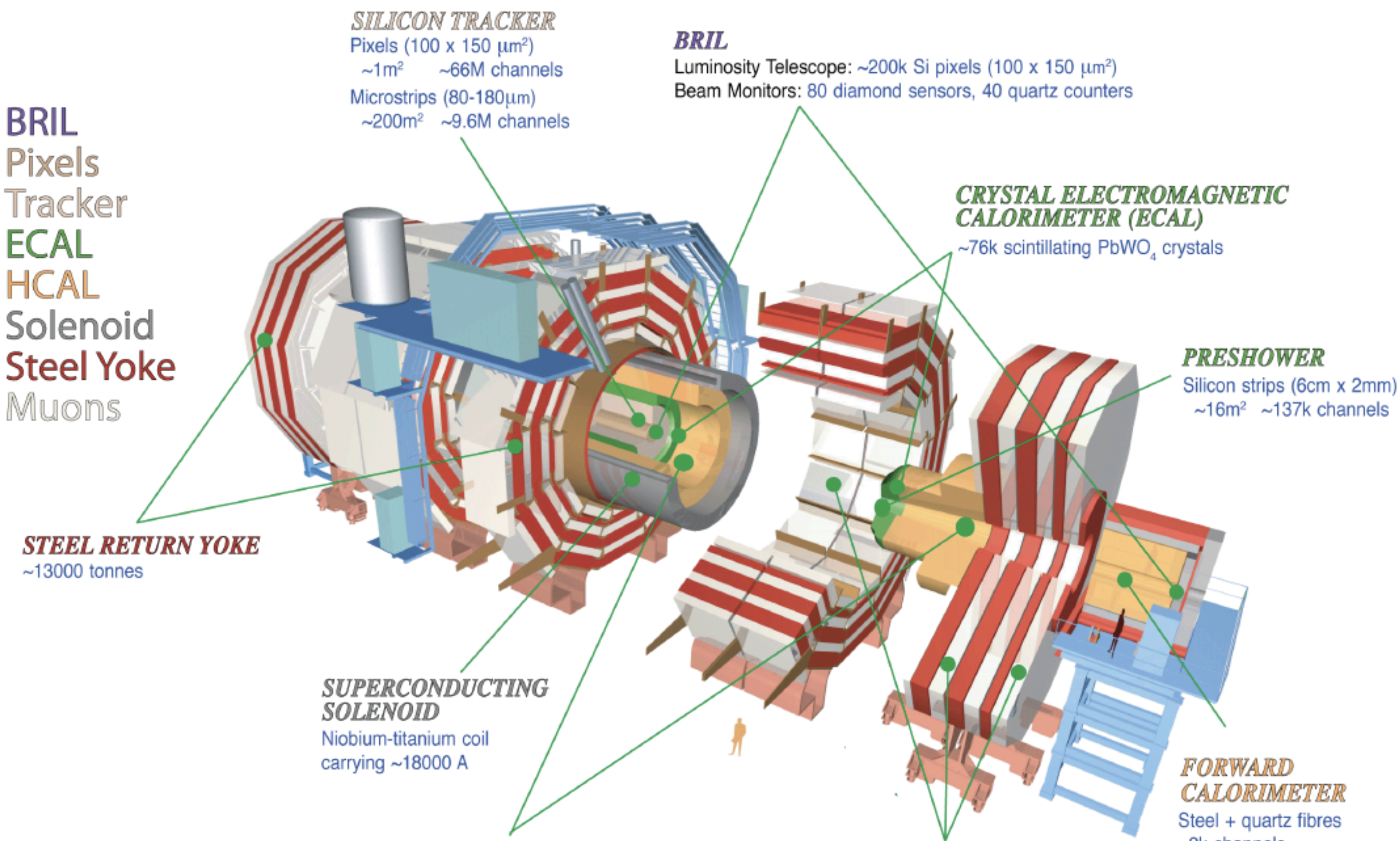
Summary

- The R&D for the Phase II Tracker is already very advanced
  - Sensors, module design, electronics, layout, mechanics, etc.
- However, there is still a lot of work to do
- Technical proposal already published in 2015

Technical design report (TDR) of the CMS Tracker Phase II upgrade is expected to be published in autumn this year!

Backup

The present CMS detector

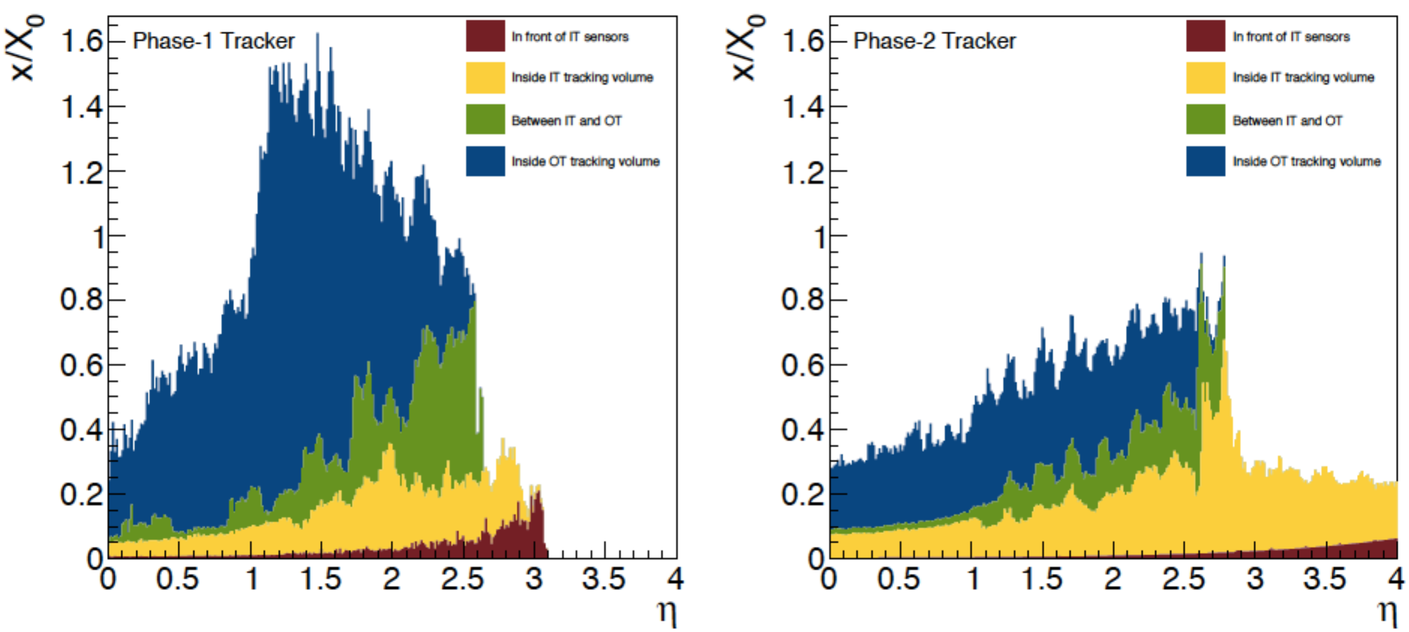


Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Material budget

- Material budget simulated using tkLayout software
  - Developed in context of the Phase II upgrade
- **Significant reduction of material budget**
  - Especially for $|\eta| > 1.5$

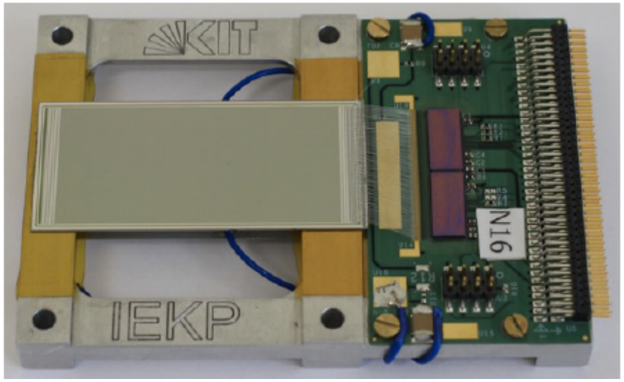
Present Tracker　　　　Phase II Tracker



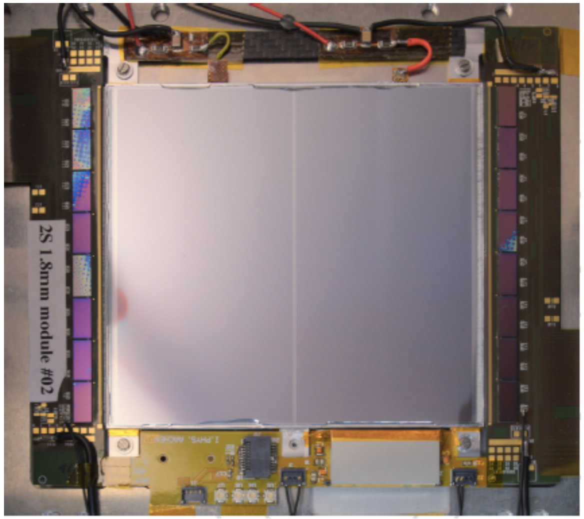
2S prototype modules

- Prototyping started with 2S mini module
  - Only one sensor readout by 2 CBCs
- Full scale 2S module prototype built and tested at the SPS at CERN
  - Two stacked full scale 2S sensors
  - 2×8 CBC chips (generation 2)
  - Without CIC, LpGBT and DC/DC converter

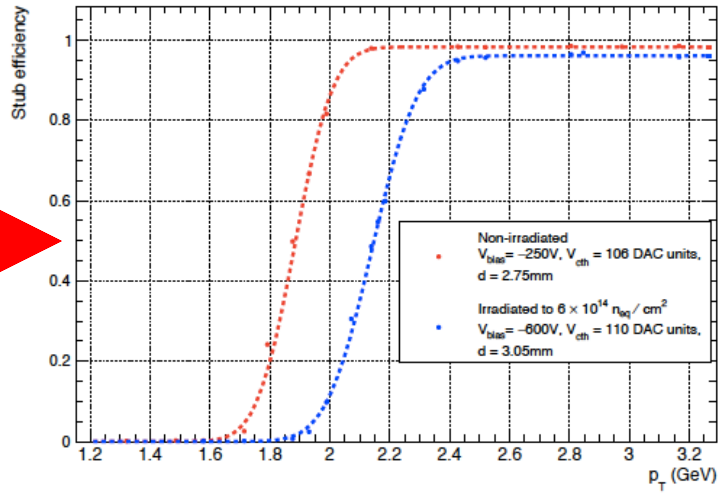
2S mini module



Full scale 2S prototype module

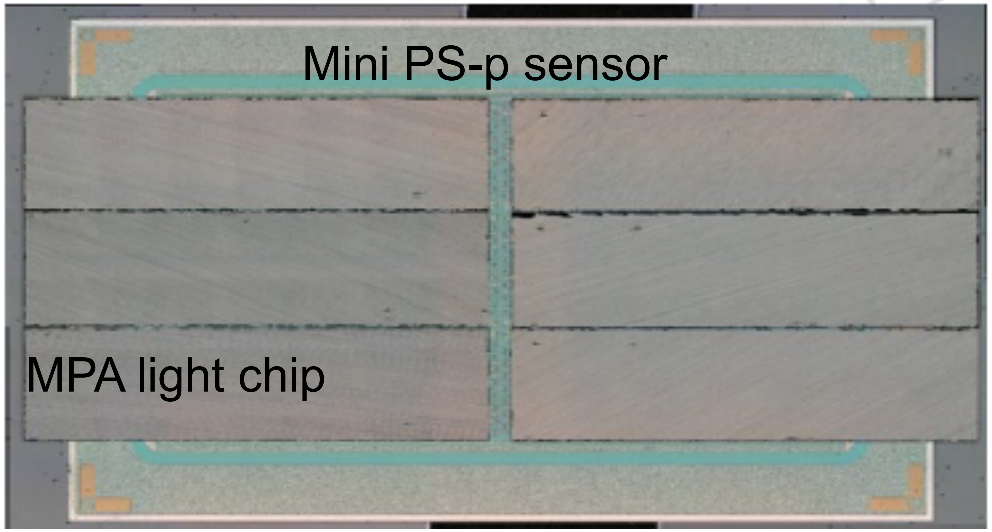


Stub reconstruction efficiency for unirradiated (red) and irradiated module (blue)

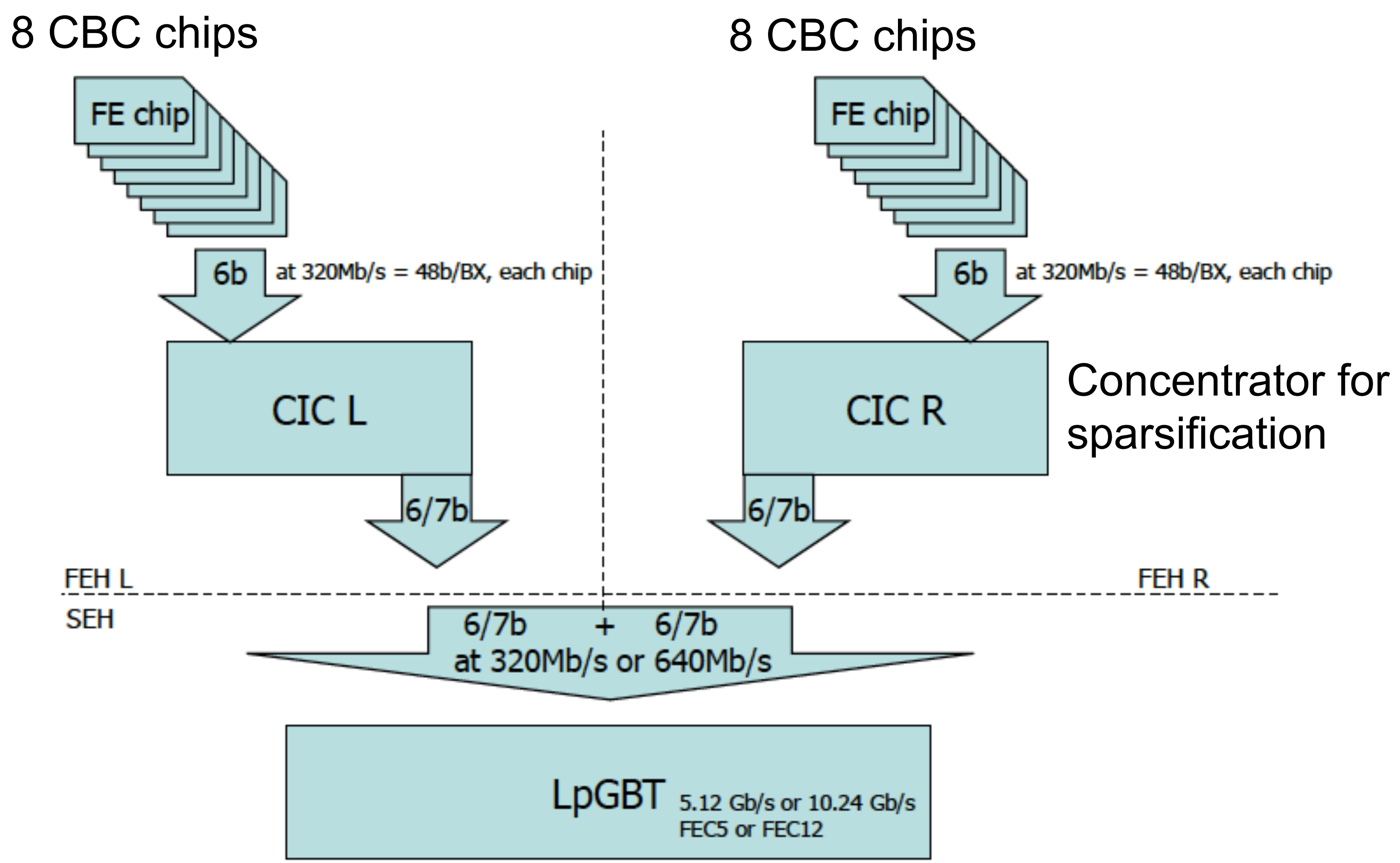


PS prototype modules

- Mini module (MaPSA light) build and tested
  - Small version of PS-p sensor
    - 288 macro pixels
  - Readout by 6 MPA light prototype chips
  - Without stacked PS-s sensor



Outer Tracker front-end electronics (2S modules)



L1 track finding approaches

1. **FPGA-based Hough transform**
   - Stub with defined (r, φ) represents a line in Hough space (φ, q/p_T)
   - Set of stubs corresponding to a high p_T track form intersecting lines in Hough space
   - Intersection point defines parameters of track
2. **FPGA-based tracklet**
   - Tracklet: Pairs of stubs in adjacent layers
     - Must be consistent with $p_T > 2$ GeV
     - Performed in parallel for multiple pairs of layers
   - Helix parameters used to project trajectories to other layers
   - Linearized χ^2 fit determines final track parameters
3. **Associative Memory (AM) + FPGA**
   1. Find low resolution tracks candidates “roads” using AM based pattern recognition
      - Highly parallel pattern comparison in AM
   2. Final track reconstruction realized in FPGA
      - Reduced combinatorics due to previous step