The Phase-2 Upgrade of the CMS Outer Tracker

European Physical Society Conference on High Energy Physics 2021, 27.07.2021

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GEFÖRDERT VOM

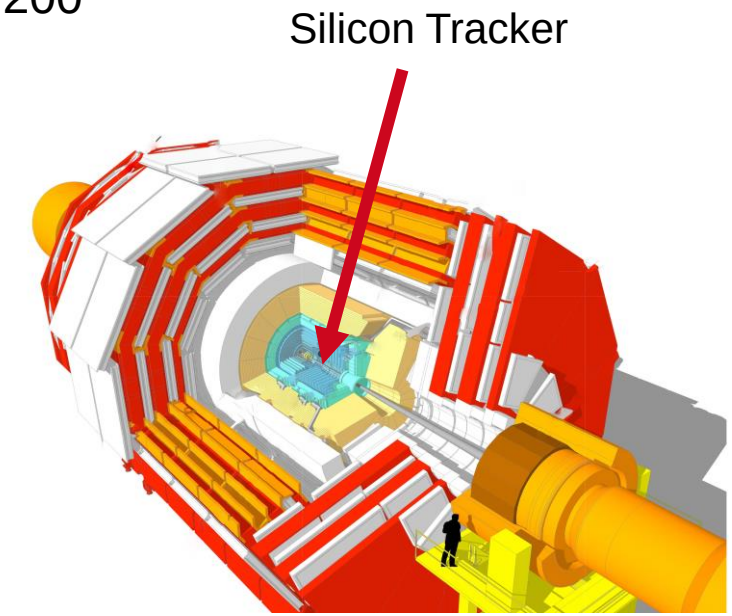
Bundesministerium
für Bildung
und Forschung

Motivation

High-Luminosity LHC upgrade (HL-LHC): luminosity up to 5-7×10^{34} $cm^{-2}s^{-1}$

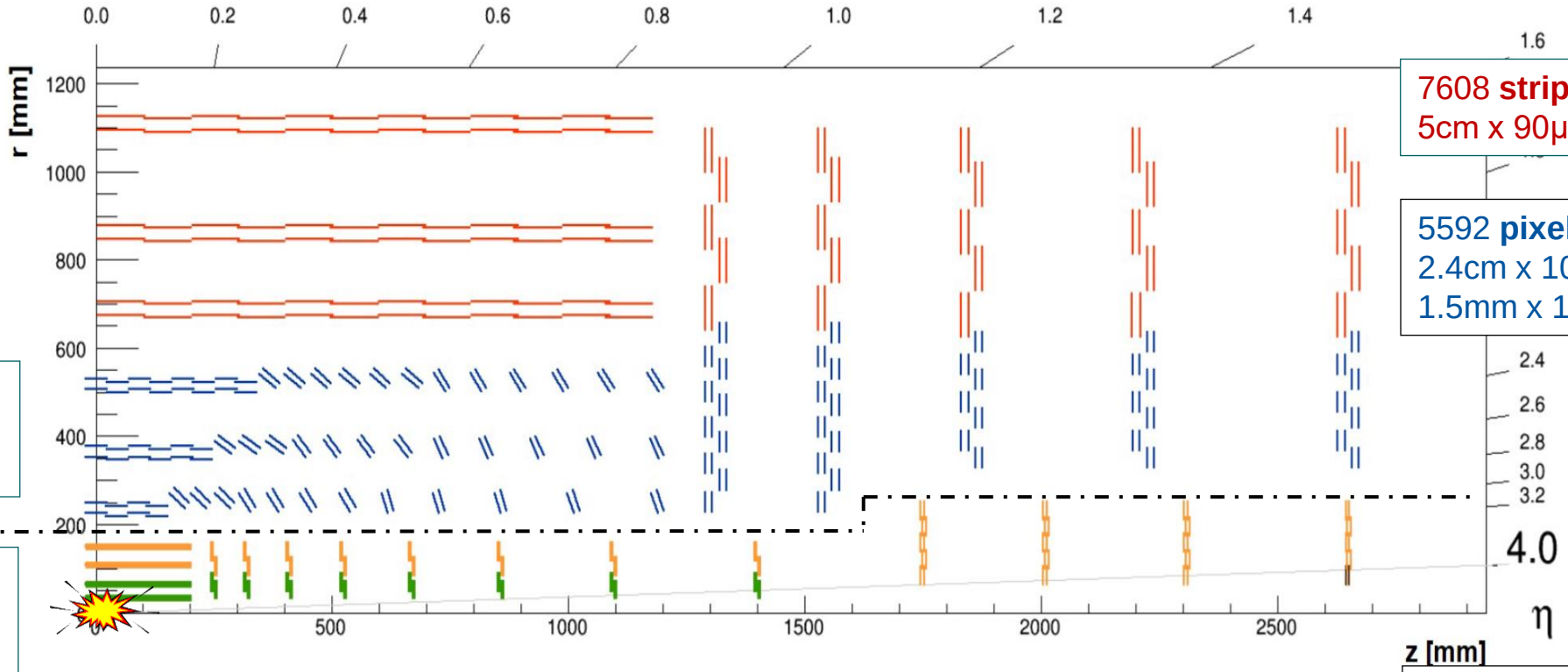
Requirement for the CMS tracker: Maintain or improve tracking performance with 200 simultaneous interactions (pile-up)

- 8x higher pile-up: 25 → 200
- 8x higher hit-rate: up to 3.2 GHz/cm^2 (innermost pixel layer)
- 7.5x higher trigger rate: 100 kHz → 750 kHz
- 4x longer trigger latency: 3.2 µs → 12.8 µs
- 10x larger lifetime radiation dose: 300 fb^{-1} → 3000 fb^{-1}



→ A new silicon tracker will be installed in CMS in Long Shutdown 3 (2025-2027)

Layout of the CMS Phase-2 Tracker



7608 **strip-strip modules** (2S)
5cm x 90µm strips

5592 **pixel-strip modules** (PS)
2.4cm x 100µm strips
1.5mm x 100µm macro-pixels

Outer Tracker (OT)
- 190 m^2
- 213M channels

Inner Tracker (OT)
- 5 m^2
- 1.9G channels

3892 pixel modules
100µm x 25µm pixels
1 x 2 and 2 x 2chips

- Acceptance up to $|\eta| = 4$ (IT)

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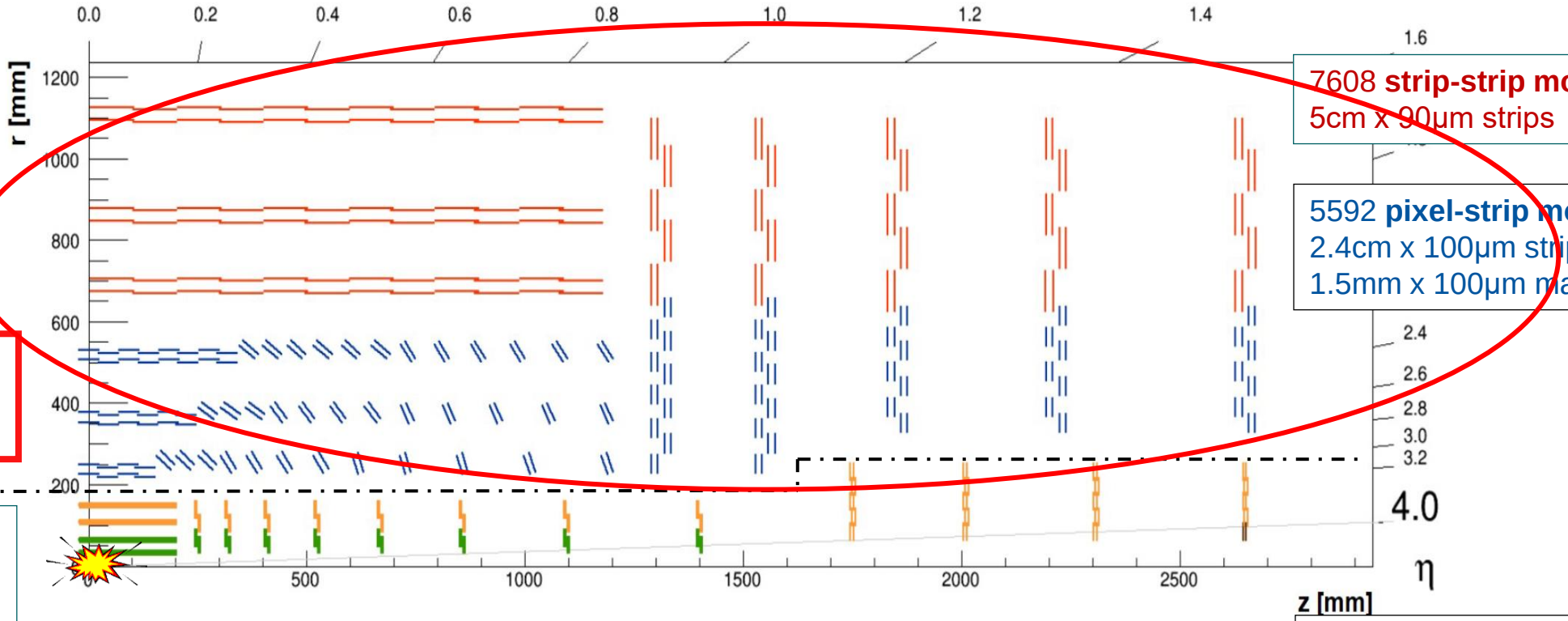

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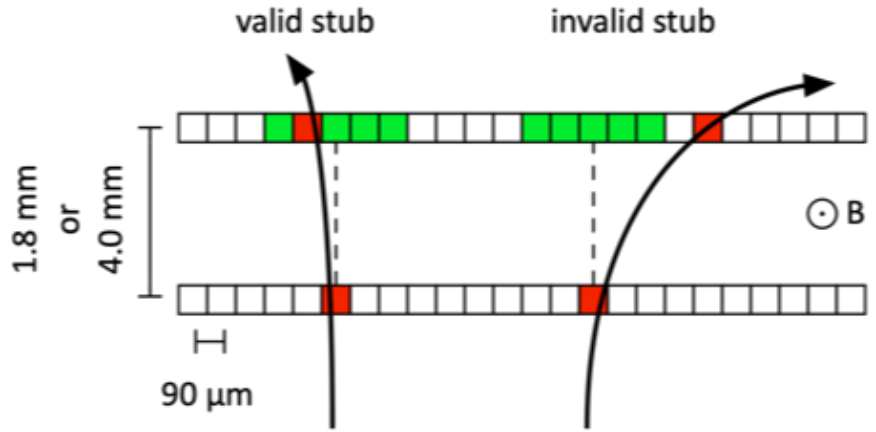
- Acceptance up to $|\eta| = 4$ (IT)
- OT: 6 cylindrical layers in the barrel and 5 discs in the endcap
- Tilted geometry in inner barrel
- Contribution to Level-1 trigger (OT)

Main Design Diver: Use of Tracking Information at Level 1 Trigger

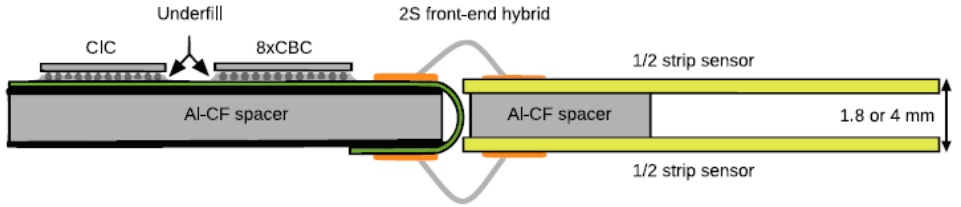
- Today: Level 1 trigger uses data from the muon system & calorimeter only
- The Phase-2 OT will contribute to the L1 trigger

  → Mitigate effects of pile-up



- Readout of whole tracker at 40 MHz not possible → data reduction at frontend needed:
- Modules made of two closely spaced sensors
- Frontend electronic compares hit patterns, which depend on bending in 3.8T magnetic field

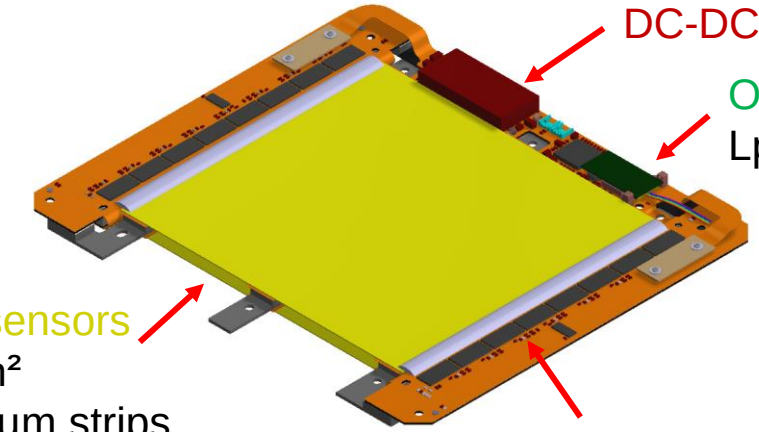
  → Select tracks with p_T > 2-3 GeV (“stubs”)



- Stubs sent to the backend at 40 MHz → L1 trigger decision
- Whole detector read out in case of L1-Trigger accept (≈ 750 kHz)

Phase-2 CMS Outer Tracker: Module Design

2S Module



DC-DC converters

Optical transceiver
LpGBT

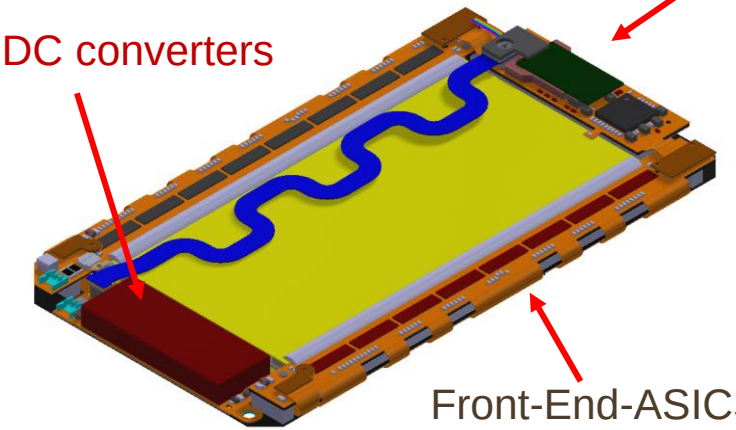
Two strip sensors
≈10x10 cm²
5 cm x 90 µm strips

Front-End-ASICS
8x CBC3 ASIC per side
1x Concentrator (CIC) ASIC per side

PS Module

Optical transceiver

DC-DC converters



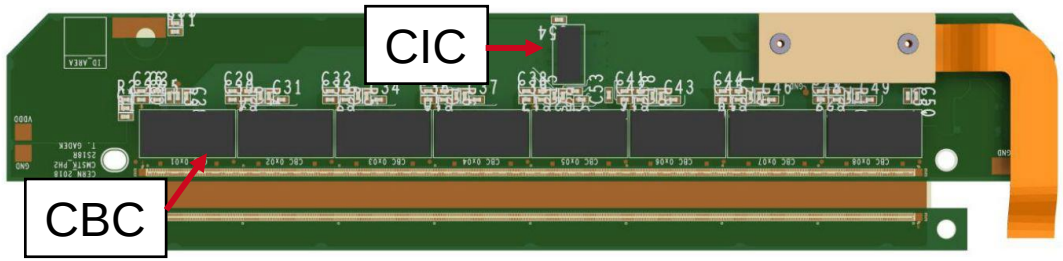
Front-End-ASICS
8x SSA ASIC per side
1x Concentrator per side

Strip sensors (top)
≈5x10 cm²
2.4 cm x 100 µm strips

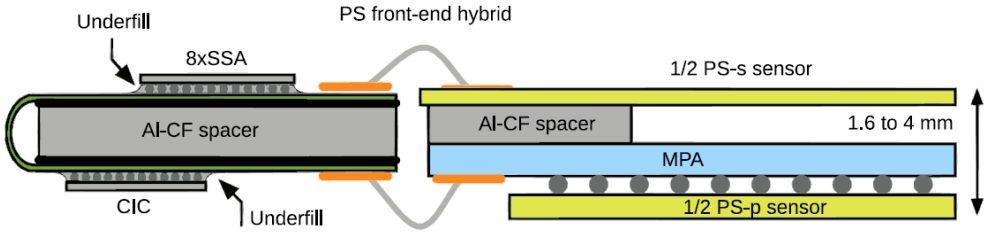
Macro-pixel sensor (bottom)
1.5 mm x 100 µm macro-pixels
Bump-bonded to MPA readout ASICs

Outer Tracker: Frontend Electronics

2S Module



PS Module



CMS Binary Chip (CBC):

- Binary readout at 320 MHz
- 254 channels (127 top sensor + 127 bottom sensor)
- Correlation logic builds the stubs
- 8 Chips per half-sensor
- Final version in mass production

Concentrator Integrated Circuit (CIC):

- Receives data from all chips, performs sparsification
- Communication with the backend via LpGBT ASIC
- Submission of CIC2.1 imminent

Short Strip ASIC (SSA):

- 120 channels
- 8 SSA read out half top sensor
- Data sent to MPA via fold-over
- SSA2.1 ready for submission

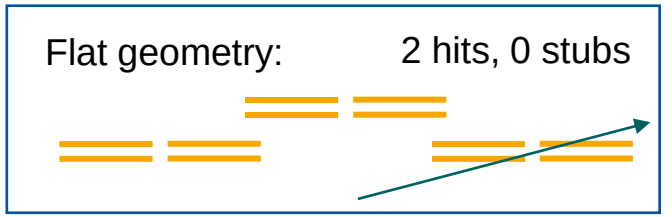
Macro-Pixel ASIC (MPA)

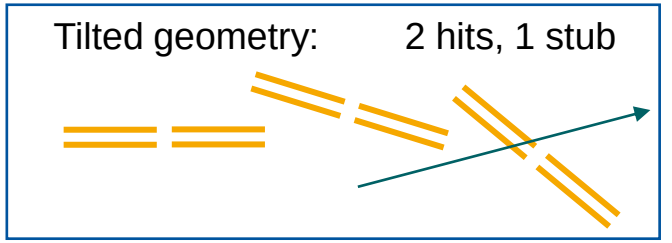
- 1888 channels
- 16 MPAs bump-bonded to bottom sensor
- Correlation logic builds the stubs

Mechanics & Cooling

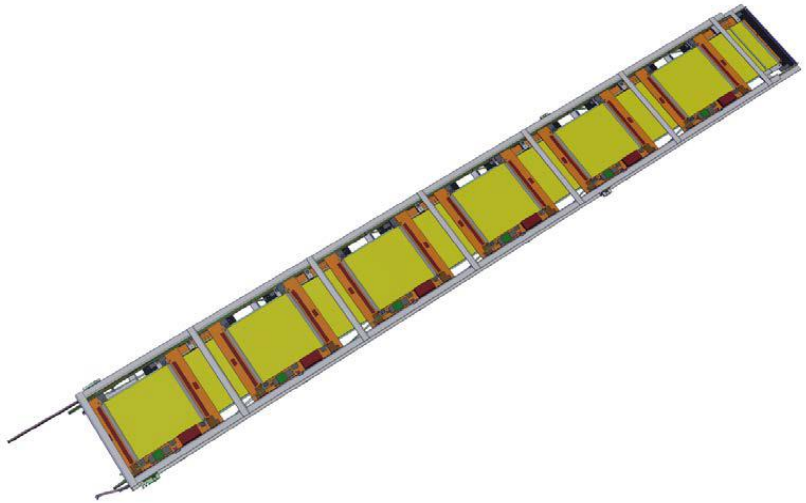
Modules are mounted on carbon fiber & foam support structures:

- Barrel: ladders and planks oriented along the beam axis
  - Innovative tilted barrel section: increases stub efficiency at high $|\eta|$, reduces material budget
- Endcap: modules are mounted on double-disks perpendicular to the beam axis
- Low-mass two-phase CO_2 cooling at -35 °C

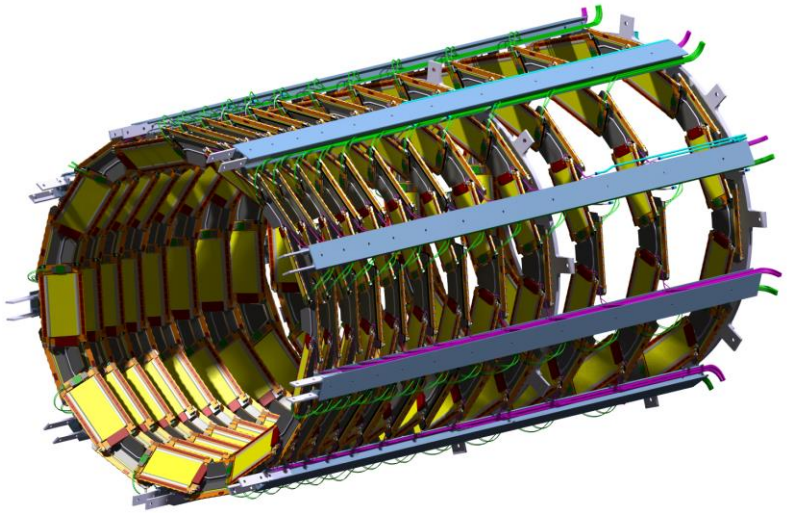




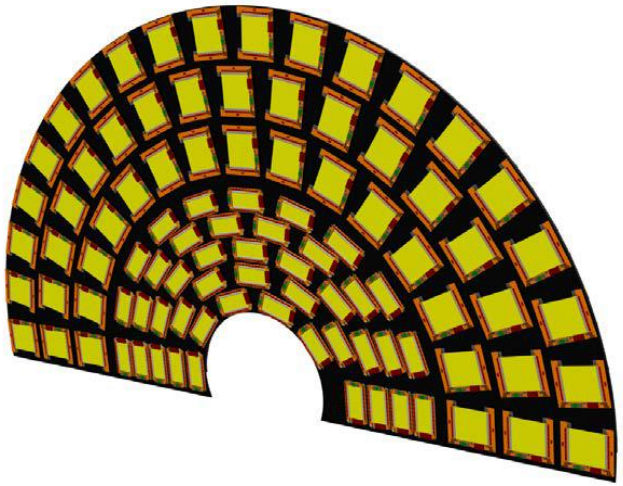
2S ladder



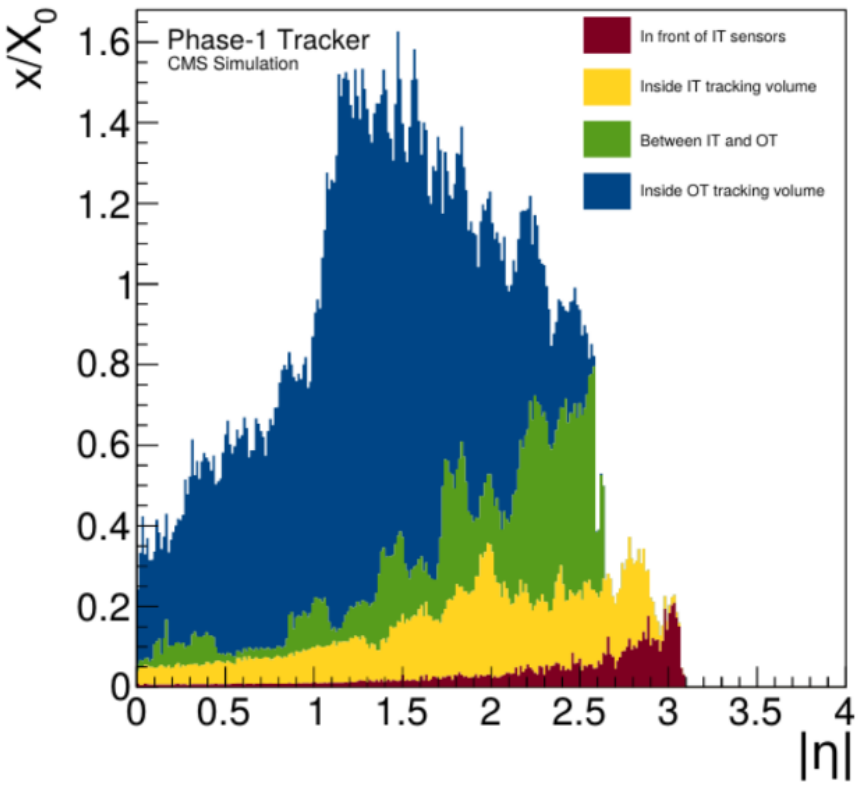
Tilted barrel section



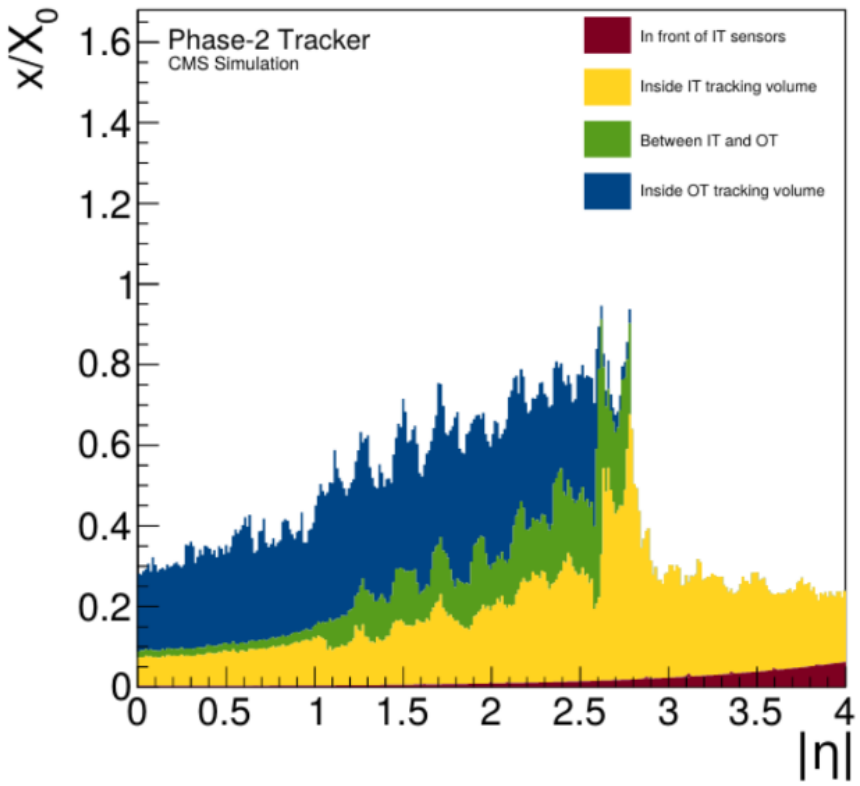
Endcap “dee”



Material Budget



Upgrade

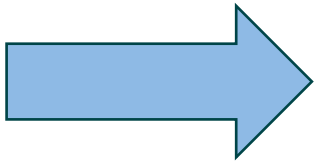


- Material budget of the Phase-2 OT significantly reduced compared to the current strip tracker
  - CO_2 cooling
  - DC-DC conversion based powering
  - Better routing of services
  - More lightweight support structure, tilted barrel region

Phase-2 CMS Outer Tracker: Powering

- Upgraded tracker will need more power at lower supply voltages
  - Higher granularity, more complex electronics
  - Smaller feature size electronics: 250 nm → 130 nm, 65 nm

Phase-0 CMS Tracker
Direct powering
- 9.3 M channels
- Front-end power ≈ 33 kW
- ≈ 34 kW loss in cables



Phase-2 Outer Tracker
DC-DC conversion based powering
- 213 M channels
- Front-end power ≈ 85 kW

→ Currents will increase substantially (CMS outer tracker: factor 4-5)
→ Cable losses would rise quadratically: $\mathbf{P_{loss}} = \boldsymbol{R} \cdot \boldsymbol{I}^2$
→ New powering scheme using DC-DC converters

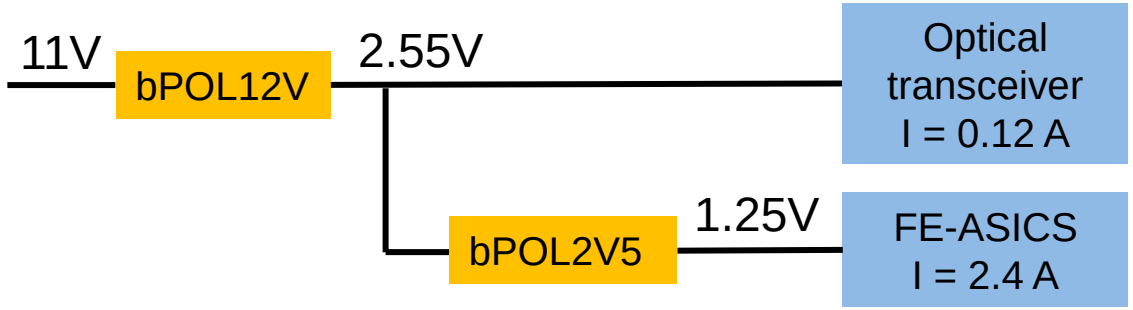
Phase-2 CMS Outer Tracker: Powering

- Two-stage DC-DC conversion powering
  - Currents reduced by ≈ conversion ratio r
  - Cable losses reduced by r^2
- DC-DC converters located on the modules

→ First time that converters will be used at point of load

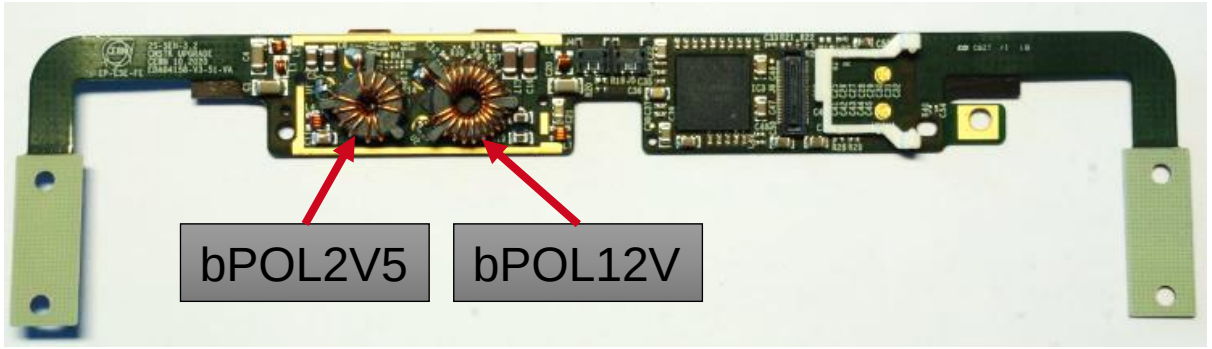
→ Switching noise is a concern!

Example: 2S Module

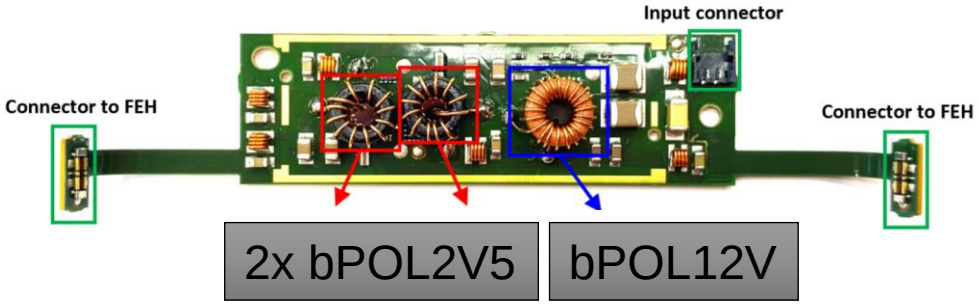


- Final prototypes of service hybrids (2S), and power hybrids (PS) with early versions of bPOL12V & bPOL2V5 available:
  → No significant increase of noise due to DC-DC converters observed

2S Service Hybrid



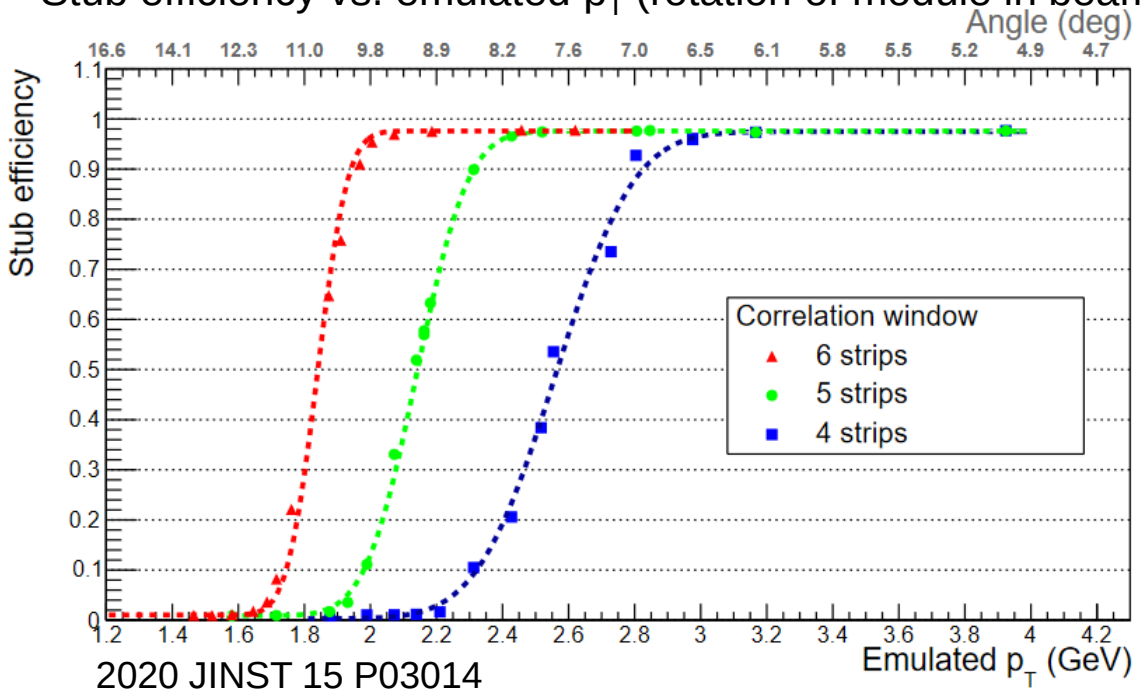
PS Power Hybrid



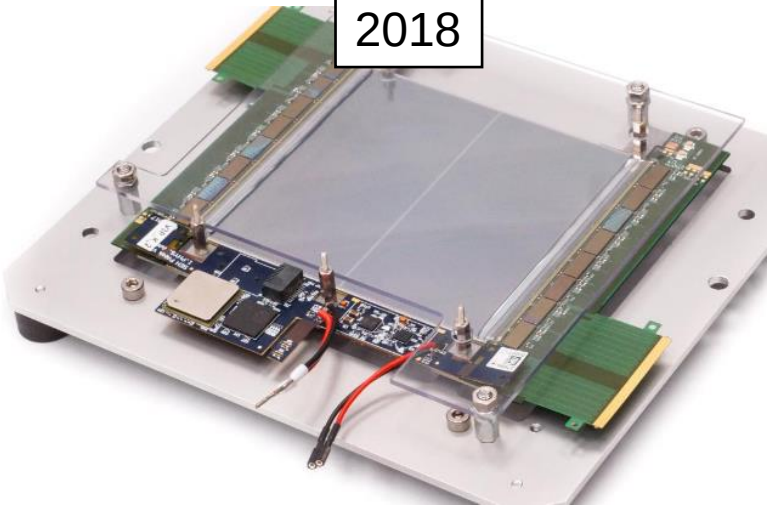
Prototyping

- More than 30 functional prototype modules have been built
- Final readout chain available
- First modules with final prototype components built this year
  - Several beam tests, performance as expected
  - Magnet test just finished

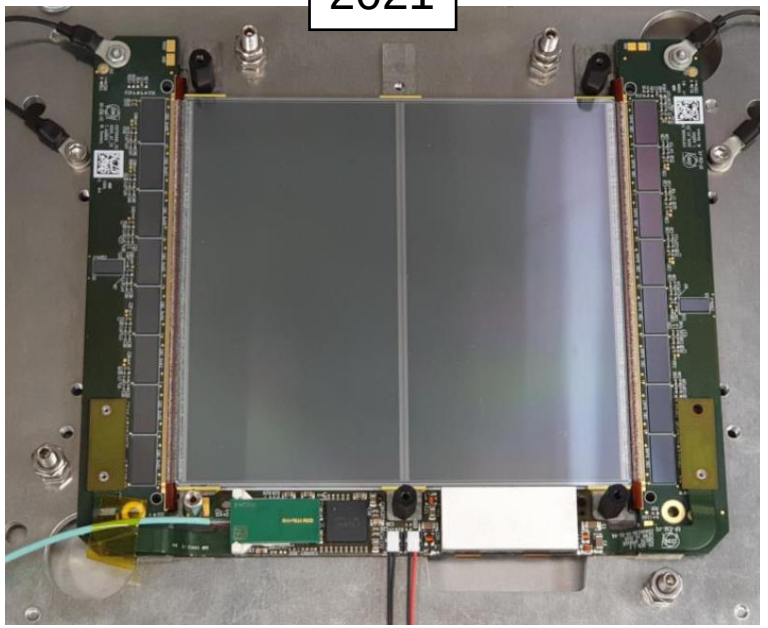
Stub efficiency vs. emulated p_T (rotation of module in beam)



2018



2021



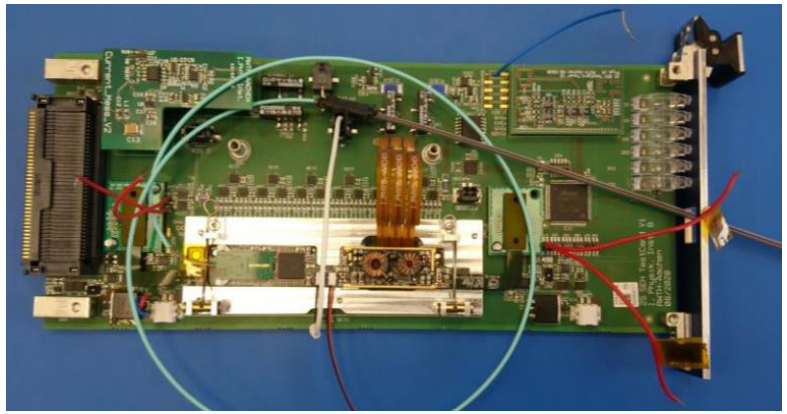
Testing

- 2 years of series production foreseen
  - 1000 - 2000 modules per site

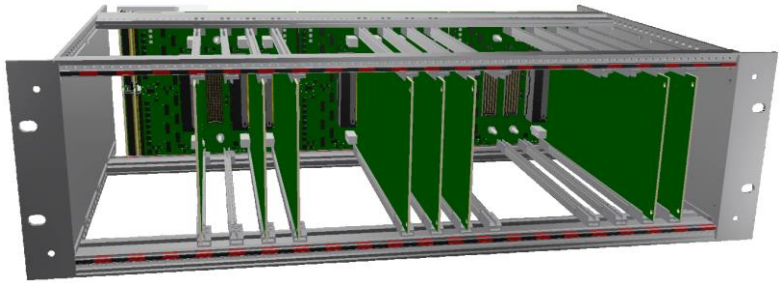
- Several test systems have been developed, ensuring high module quality

- Final commissioning of the test systems is ongoing, mass production will start this year

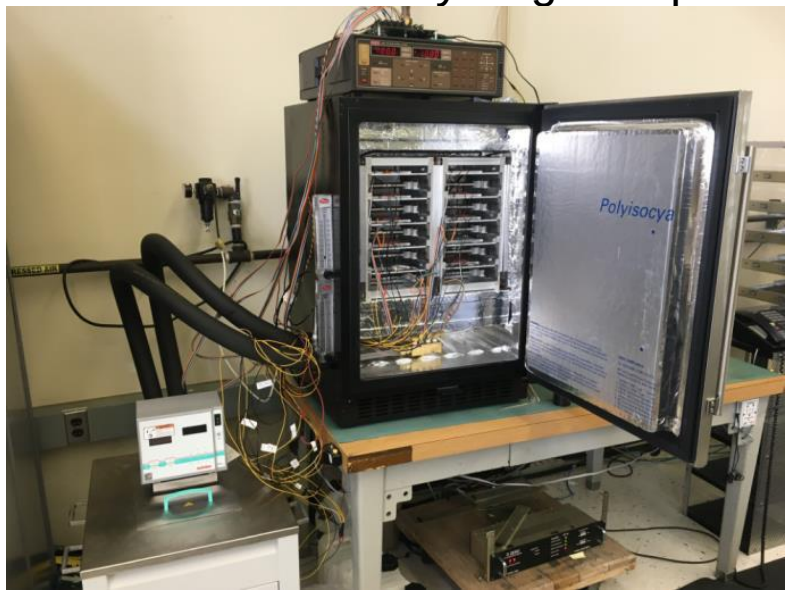
2S-SEH Testcard



Crate System for Hybrid Testing



Module Thermal Cycling Setup



Conclusions

- Phase-2 upgrade of the CMS silicon tracker is an important project to ensure a good performance of the CMS detector after the HL-LHC upgrade
- Delivering tracking information for the L1 trigger requires an innovative detector design
- The Phase-2 tracker will have a better performance than the current tracker under much harsher conditions
- Project is progressing well and so far on track for installation in LS3 (2025 – 2027)