The Phase 2 upgrade of the CMS Outer Tracker

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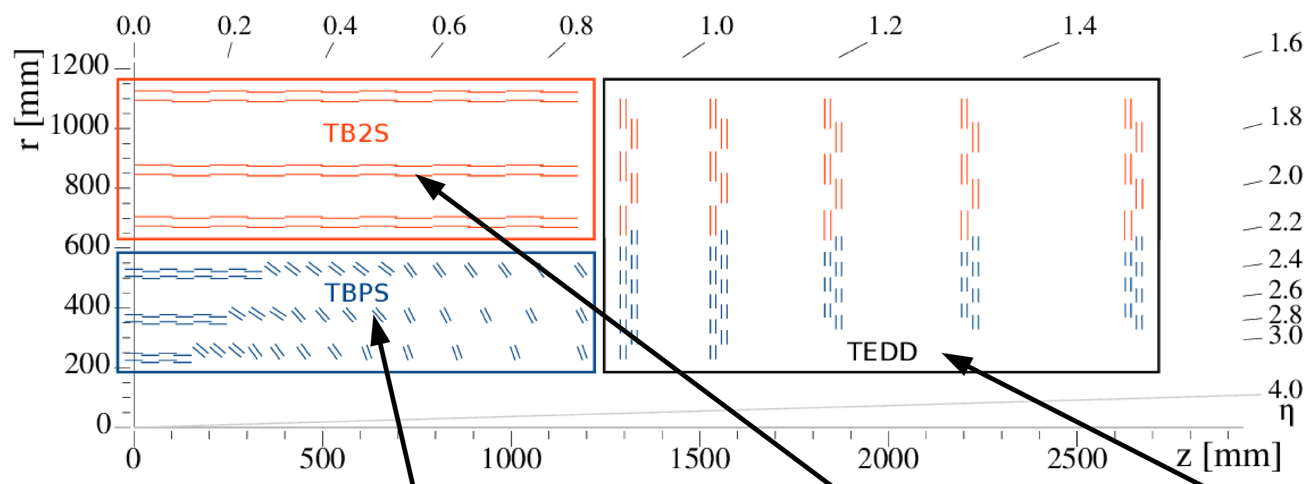
High Luminosity LHC starts colliding particles in 2029

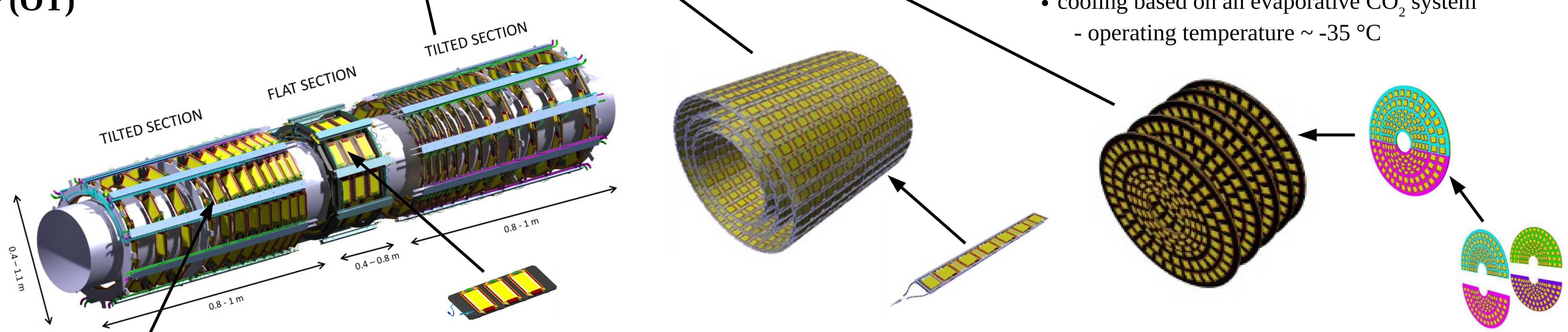
- 14 TeV center-of-mass energy, 25 ns bunch-crossing
- peak instantaneous luminosities up to 5-7.5 x 10^{34} $cm^{-2}s^{-1}$, pileup ~ 140-200
- 10 years of operation → 3000-4000 fb^{-1} integrated luminosity

CMS will replace its whole Tracker detector for the start of the new data taking phase (see the talk "The CMS tracker upgrade for HL-LHC" by Alessandro Rossi for details)

Requirements fot the Phase 2 Outer Tracker (OT)

- increased radiation hardness
  - 10^{15} n_{eq}/cm^2 expected fluence in the inner layers
- higher granularity, better track separation
- reduced material budget
- compatibility with higher data rates and longer trigger latency of 12.5 µs
- provide tracking information to the L1 trigger



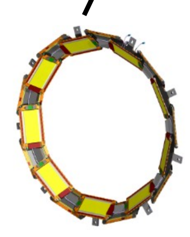


CMS Phase 2 OT layouts and mechanics

- built from semiconductive silicon modules
  - 7608 2S modules +5592 PS modules
  - 190 m² total silicon area, with 213 million channels
- barrel section with six cylindrical layers
  + two endcaps with five layers of double-sided disks at the two ends of the barrel
- lightweight mechanical support structure made from carbon fiber
- cooling based on an evaporative CO_2 system
  - operating temperature ~ -35 °C

p_T modules

- stand-alone units, connected directly to the detector back-end electronics
- made from two silicon sensors separated by a few millimeters and read out by common front-end electronics
- chosen sensor technology: Float Zone n-in-p type silicon with 290 µm active thickness [2]
- 2 types of modules: 2S and PS, both with different sensor spacings
- modules are assembled manually at several CMS institutes
- required precision:
  - distance perpendicular to the strips of Δx < 50 µm
  - distance along the strips of Δy < 100 µm
  - tilt angle between the strips (strips and macro-pixels) smaller than 400 µrad (800 µrad) for the 2S (PS) modules



TBPS

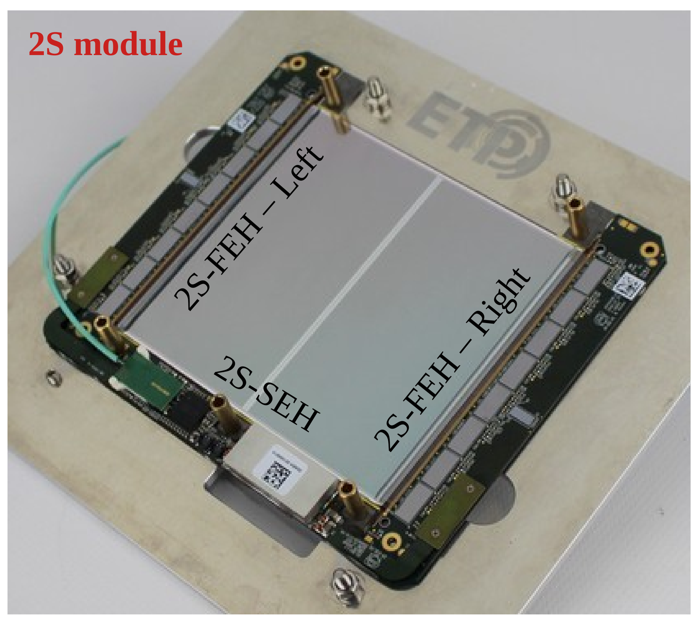
- three inner layers of the barrel, built from PS modules
- in the flat section modules are mounted on planks oriented along the beam axis
- in the tilted section modules are mounted on rings

TB2S

- three outer layers of the barrel, built from 2S modules
- modules are mounted on ladders oriented along the beam axis

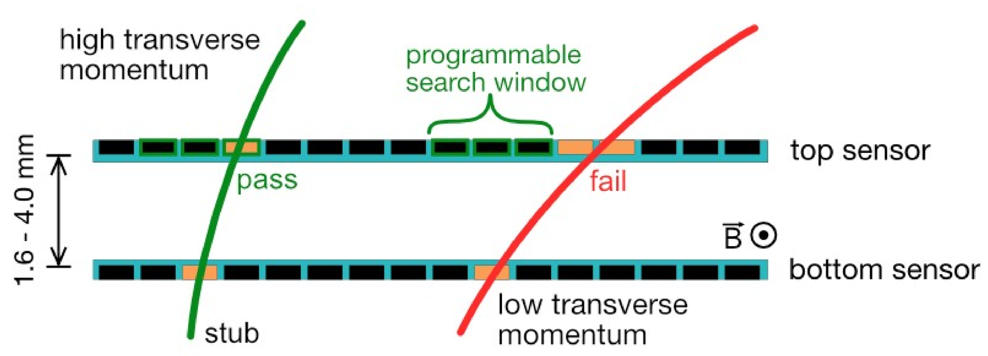
TEDD

- in the endcaps, modules are mounted on half-disks, four half-disks form one detector layer
- PS modules at r < 60 cm
- 2S modules at r > 60 cm



Contribution to the L1 trigger

Modules are able to provide tracking information to the first trigger level by measuring the transverse momentum of the tracks and sending out self-selected information at every bunch-crossing (40 MHz).



For details, check the talk "Level-1 Track Finding at CMS for the HL-LHC" by Riu Zou

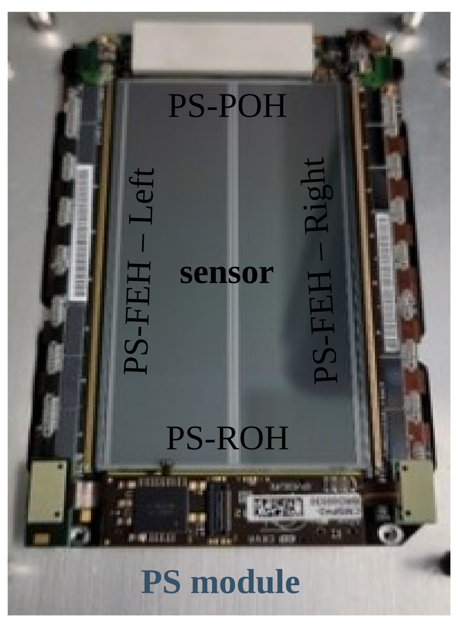
- charged particles bend in the magnetic field of the CMS detector with a transverse momentum dependent radius and generate signals in both sensors when passing through a module
- hits from the bottom and top sensors are matched → if they are within a pre-defined window, they will be combined to form a "stub" (short track segment)
- stub information is sent out to the back-end track finder system at every bunch crossing from each modules
- back-end performs track finding in two steps: pattern recognition and track fitting

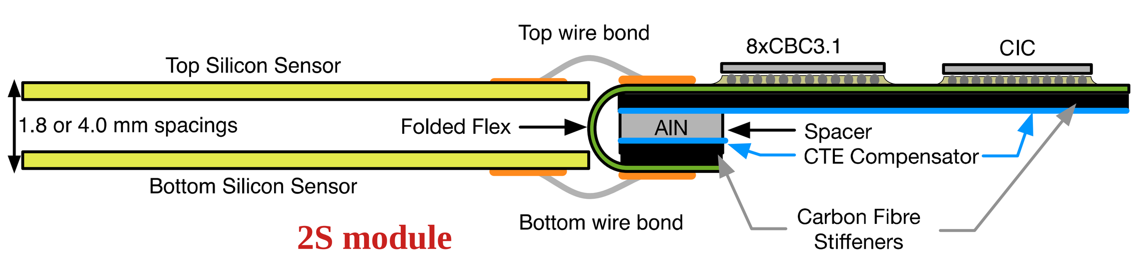
PS modules

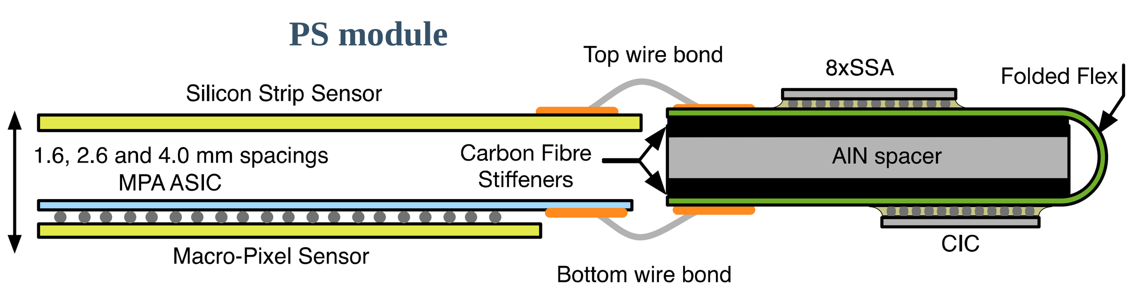
- one micro-strip sensor
  - 2 columns of 960 strips
  - single cell size: 2.5 cm x 100 µm
- one macro-pixel sensor
  - 32 x 960 pixels
  - single cell size: 1.5 mm x 100 µm
- 16 MPA chips, bump-bonded to the bottom side of the macro-pixel sensor
- two front-end hybrids (PSFEH) on the two sides, wire-bonded to the sensors
- separate electronics for powering (PSPOH) and read-out (PSROH) to achive smaller module size

2S modules

- two silicon micro-strip sensors
  - each with 2 columns of 1016 strips
  - single cell size: 5 cm x 90 µm
- two front-end hybrid (2SFEH) electronics on the two sides of the sensors, wire-bonded to the strips
- one service hybrid (2SSEH) responsible for powering, controlling, and data-transfer







Hybrid electronics for the OT modules

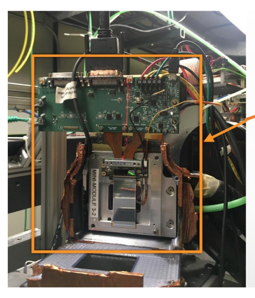
Front-end hybrids (FEH)

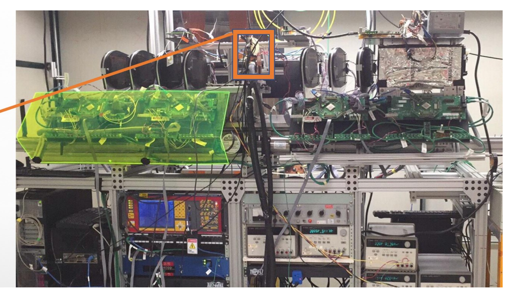
- 4-layer, high density flexible circuits, laminated to carbon-fibre stiffener and folded back to allow wire-bonding to the top and bottom side sensors
- Al-N spacers to adjust the thickness of the hybrid to the module spacing
- CTE compensators to eliminate the bow (only needed for the 2S)
- custom ASIC readout chips, flip-chip soldered directly to the hybrid and underfilled
  - 8 x CBC3 chips for the 2S and 8 x SSA chips for the PS modules + 1 CIC for both

Service electronics

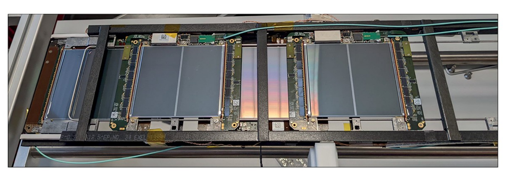
- responsible for powering, controlling, and data-transfer
- merge data from both FEHs and send it out via a single optical fibre to the backend system
- powering scheme using DC-DC converters → keep power losses and voltage drops at acceptable level

Prototyping of the p_T modules





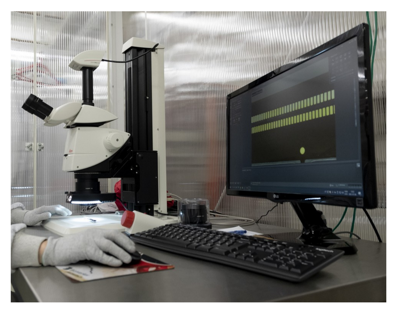
- module prototyping had been ongoing for many years
- functional modules with the required accuracy have been assembled
- prototype modules have been studied at various test beam facilities (CERN, DESY, Fermilab) and the full readout chain has been exercised in test setups [3-5]
  - stub finding mechanism proven to work as expected, no significant drop in the performance with irradiated sensors
  - validated the funcionality of the ASICs and the design of the hybrid electronics
- sub-detector mechanical structure prototypes have been built and equipped with modules



The prototyping phase of the module components is finished.
Production of sensors and hybrid electronics for the Phase 2 Outer Tracker has been already started.

Quality assurance (QA) and quality control (QC) during the production

- large number of modules (>13000) have to be built manually in the next years with high accuracy
- modules will operate under extreme environmental conditions, without the possibility for repair or replace due to their inaccessable location → QA is a crucial part of the production
- several assembly centers → common set of tooling and procedures to guarantee similar quality
- every components are going to be tested before assembly
  - sensors are tested by the manufacturer and inspected also at the Quality Control Centers [6]
  - hybrid electronics
    - tested by the manufacturer, including a passive thermal cycling and a quick electrical test
    - visual inspection of all hybrids at CERN and Wigner RCP
    - functional test of a subset of hybrids at CERN, INFN Catania and INFN Genova
- each module will undergo a final test before assembled onto the detector support structure



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