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Mechanical Design and Integration of the CMS Phase-2 Tracker

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The mechanical design of the CMS Phase-2 Tracker addresses the stringent requirements imposed by the High Luminosity LHC environment, including stability under high radiation and thermal loads, a minimal material budget, and precise alignment across large detector volumes. This article describes the engineering challenges and the mechanical solutions implemented in both the Inner Tracker and the Outer Tracker. Key topics include the design of support structures, thermal management systems, carbon-fibre composite components, and the modularity that enables efficient assembly and maintenance. The integration strategy, from substructures to the fully assembled Tracker, is presented together with results from mechanical qualification tests, thermal cycling, and alignment validation, demonstrating the readiness of the Phase-2 Tracker for High Luminosity LHC operation.

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1. Background and motivation

1.1 CMS and HL-LHC

The Compact Muon Solenoid (CMS) [1] is a particle detector that is built around a huge solenoid magnet. This takes the form of a cylindrical coil of superconducting cable, cooled at −268.5 °C, that generates a magnetic field of 4 Tesla, about 100 000 times that of the Earth.
Detectors consist of layers of material that exploit the different properties of particles to catch and measure the energy and momentum of each one.
The experiment is built 100 meters underground, it is a combination of very massive and very light detectors working at different temperatures, it requires high stability and precision in dimensionally large objects. It is also composed of tons of services (like cables, fibres and pipes).
Operation of the accelerator started in 2009 and now the CMS detector needs to be substantially upgraded during Long Shutdown 3 (LS3) to exploit the increase in luminosity provided by the High Luminosity-LHC (HL-LHC). This upgrade is referred to as the CMS Phase-2 Upgrade [2, 3].

1.2 Tracker and upgrade

Particles emerging from collisions first meet a tracker, based on silicon sensors, that charts the positions where the particles cross the sensors, allowing us to measure their momentum.
The measurement of the momentum of particles is crucial in helping us to build up a picture of what happens at the heart of the collision. One method of calculating the momentum of a particle is to track its path through a magnetic field; the more curved the path, the less momentum the particle had. The tracker can reconstruct the paths of high-energy muons, electrons, and charged hadrons.

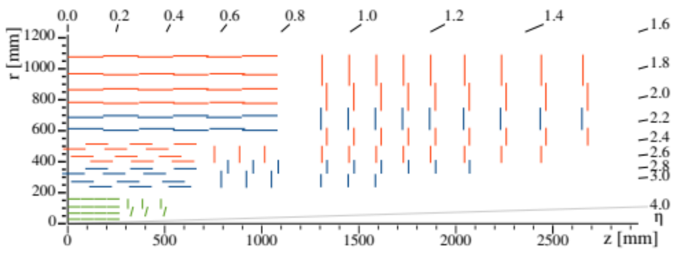

Figure 1: Sketch of one quarter of the Phase-1 CMS tracking system in r-z view.

Before the start of the HL-LHC both the strip tracker and the Phase-1 pixel detector will have to be replaced due to significant damage and performance degradation they would suffer during operation at the HL-LHC.
The completely new Tracker will use new module types capable of selecting high momentum tracks (>2−3 GeV). The high-powered electronics will be cooled down at −35°C thanks to a CO_2 based two-phase cooling system.

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The Phase-2 tracker will consist of an Inner Tracker (IT) based on silicon pixel modules and an Outer Tracker (OT) made from silicon modules with strip and macro-pixel sensors.

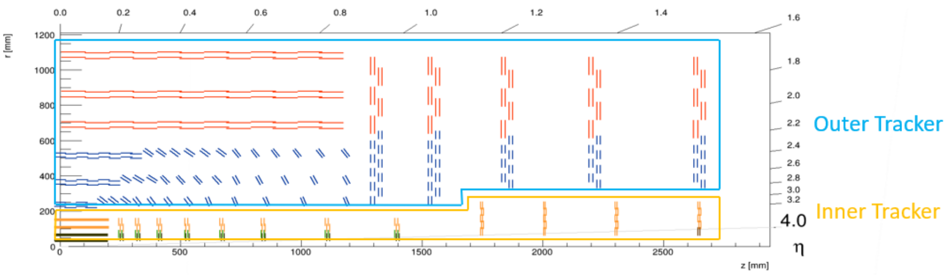

Figure 2: Sketch of one quarter of the tracker layout in r-z view.

The main requirements for the tracker upgrade are the following: radiation tolerance, increased granularity, improved two-track separation, robust pattern recognition, extended tracking acceptance and reduced material in the tracking volume. The exploitation of the high luminosity will greatly benefit from a lighter tracker. The performance of the current tracker is affected by the amount of material, which also influences the performance of the calorimeters and of the overall event reconstruction in CMS. This low material aspect has mainly defined the future structures of the Tracker.

The mechanical concept of the Phase-2 Tracker follows the same principles as the current CMS Tracker. The system will be constructed and assembled in surface facilities and subsequently installed into CMS in the following sequence: Outer Tracker (OT), then central beampipe and Inner Tracker (IT).

Both the central beampipe and the IT are supported by the OT. The IT is designed to be removable without extracting the beampipe, allowing maintenance or replacement during Extended Technical Stops. In contrast, the OT is intended to remain installed for the entire duration of its operational lifetime.

The different sub-detectors, made all around the world thanks to the collaboration, are represented in the following figure:

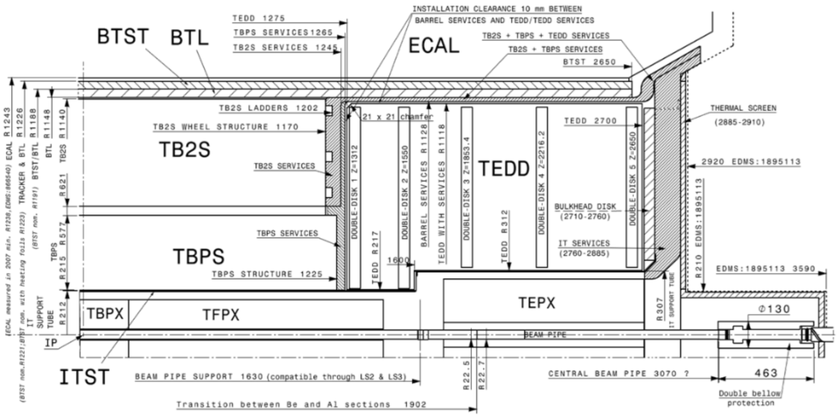

Figure 3: Sub-detectors names and their envelopes for CMS-Tracker Phase 2 upgrade

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2. Outer Tracker

The Outer Tracker is equipped with pT modules that provide the L1 track-trigger functionality by correlating hits in two closely spaced sensors. In 2S modules, this correlation is obtained from two strip sensors with parallel strip orientations. Since the strips run parallel to the z axis in the barrel and are nearly radial in the endcap regions, this configuration does not provide stereo information and therefore does not yield a direct measurement of the z (or r) coordinate.
To meet the requirements on pT discrimination and spatial resolution, two types of pT modules are deployed in the Outer Tracker: 2S modules, consisting of a pair of strip sensors, and PS modules, combining a strip sensor with a macro-pixel sensor, providing improved resolution in the z (or r) coordinate.
To support all those modules reliable structures are necessary for different subdetectors shapes. And all the sub-detectors are supported by a single structural tube capable of carrying seven tons of delicate components.

2.1. BTST

The BTST (BTL-Tracker Support Tube) is a cylindrical structure measuring 5.3 meters in length and 2.5 meters in diameter, identical in dimensions to the current Tracker Support Tube (TST). Its total mass is approximately 450 kg.
The BTST is constructed from a 30 mm thick carbon fibre sandwich structure, featuring M16 threaded inserts along its edges. Inside the tube, two fully carbon-fibre rails are installed at the 3 o'clock and 9 o'clock positions to support detector installation.
The structure was manufactured in the United States and initially tested at Purdue University, where both 3D scanning and load tests were conducted. It was subsequently delivered to CERN in November 2024.
The BTST serves as the mechanical interface between the Tracker and the surrounding Electromagnetic Calorimeter (ECAL). To prevent condensation and mitigate thermal effects resulting from the cooled Tracker, approximately 40 m^2 of heating foils were bonded to the tube's outer surface.
During the final stages of the heating foil installation, macroscopic defects were detected and quantified. A year-long campaign of investigation, measurement, and repair was carried out to ensure the readiness and reliability of the structure.
All Tracker subdetector integrations will take place at CERN, within the Tracker Integration Facility (TIF), a cleanroom environment specifically dedicated to this purpose. During the integration phase, both cold tests and power tests will be performed inside the facility, which has been refurbished to include CO_2 cooling capabilities.
The first subdetector to be installed inside the BTST will be the Tracker Barrel with 2S Modules (TB2S). All subsequent subdetectors will follow according to the integration schedule established by the Tracker project team.

2.2. TB2S

The TB2S detector, positioned at the centre of the BTST, consists primarily of a 2-meter-long cylindrical structure comprising six cylinders and four disks. The structure is entirely made of carbon-fibre composite materials with plastic inserts and has an approximate mass of 300 kg.
(500 kg including the sensors).
Four support feet are mounted on the outer surface to enable a sliding installation inside the BTST. Additionally, two internal rails are integrated within the TB2S to allow the installation of the inner subdetector (TBPS). All mechanical components are manufactured, quality controlled, and tested

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by companies in France and Italy. The final mechanical assembly will take place at the Institut Pluridisciplinaire Hubert Curien (IPHC) in Strasbourg, prior to module integration at CERN.

A total of 4,416 2S Modules will be installed on the TB2S. These modules are mounted on supporting structures called ladders. Each ladder consists of a carbon-fibre frame with an embedded titanium cooling pipe, providing both mechanical support and thermal management, while ensuring precise module positioning within the detector wheel.
The ladder structure is assembled in a high-precision metallic jig. The components are positioned on the jig, and a low viscosity epoxy adhesive is applied to the joints. The adhesive is cured at room temperature to avoid deformations caused by the difference in thermal expansion of the metallic jig and the carbon fibre components.

For the upgrade, 368 ladders (each carrying 12 modules) are required, they are distributed in 3 concentric layers inside the wheel. Ladder assembly is performed in Pakistan, and the first fully module-populated ladders were delivered to CERN in 2024, where they are currently undergoing cosmic-ray testing.

2.3. TBPS

The TBPS comprises 2,872 PS modules distributed across three concentric layers. Each layer is divided into one central section and two end sections.
In the central section, the modules are arranged horizontally in a barrel configuration and are supported by flat plank structures. In the end sections, the modules are tilted, with the outer (larger radius) edge of each module positioned at a lower $|z|$ compared to the inner edge. The tilt angles vary from 47° to 72°, depending on the layer and radial position. The full mass of the TBPS subdetector is around 300 kg.

The planks of the flat central section are of sandwich construction, consisting of a foam core enclosed between two carbon-fibre skins. A cooling pipe runs along the mid-plane of each plank, extending the full length before looping back in a U-shape. The pipe is embedded within carbon foam, which serves as a heat spreader, enhancing the thermal connection between the modules and the cooling circuit.
The planks structures and assemblies are made and tested at Fermilab (US).

In the tilted end sections of the TBPS, the modules are mounted on ring structures made of carbon-fibre/foam sandwich panels. Half of the modules are installed on the front face of each ring, and the other half on the back face. Each side of the ring features a circular cooling pipe. The modules are attached to the support rings using cooling plates made from high-conductivity carbon-fibre/epoxy laminates. Machined aluminium/carbon-fibre composite components provide the thermal and mechanical connections between the cooling plates and the cooling pipes. The key feature lies in the matching of the coefficients of thermal expansion (CTE) between the materials. Each individual ring is fully manufactured at CERN in a dedicated workshop. After production, every ring undergoes a comprehensive quality-control test campaign, including 3D metrology scanning, mass and stiffness measurements, as well as pressure, leak, and thermal tests.

A phase-change thermal interface material (TIM) is used to ensure efficient thermal contact between the modules and the plank or ring surfaces. These thermal joints can be disassembled by heating the assembly to approximately +50 °C, at which temperature the interface material softens and allows for safe detachment.

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The TBPS (Tracker Barrel with PS Modules) will be installed immediately after the TB2S. It will be inserted from the BTST side and positioned inside the TB2S, remaining centred within the BTST.

2.4. TEDD

The TEDD (Tracker Endcap Double-Discs) system uses the same 2S and PS modules deployed in the barrel sections of the Outer Tracker. The modules are mounted on 10 mm thick discs, which, for assembly reasons, are divided into half-discs, or "dees." Two dees form a full disc, and two discs are grouped to create a double-disc, which constitutes a hermetic detector plane.
In total, ten double-disc units will be produced, five per endcap.

The cooling pipes run within the sandwich structure of each dee. The thermal interface differs for the PS and 2S modules:
In the PS module regions (low-radius areas), carbon-foam blocks are inserted to provide thermal conduction between the dee skins and the cooling pipe. The PS modules are therefore attached directly to cooled surfaces of the dee.
In the 2S module regions (larger radii), aluminium inserts provide the thermal connection to the cooling pipes. These inserts protrude slightly from the dee surface, serving simultaneously as precision mounting points for the 2S modules.
Where no thermal connection is required, lightweight polyetherimide foam is used to reduce mass. To achieve the required planarity, the various foam sections are machined to uniform thicknesses. During assembly, the module-support inserts are positioned using a precision alignment table. After the dee is glued, the inserts on both sides are machined to their final dimensions, ensuring accurate module support and guiding surfaces.

Dee production is shared among DESY (Germany), Lyon (France), and Louvain (Belgium). The final integration of the dees into complete TEDD units will take place at TIF.

Each TEDD unit has a mass of approximately 600 kg. Once assembled, each unit will be installed at the edge of the BTST as a single package. The two TEDD units are identical.
Once the two TEDD units are in place, the Inner Tracker Support Tube can be installed.

2.5. ITST

The Inner Tracker Support Tube (ITST) is constructed from a high-stiffness carbon-fibre composite and is divided into five sections to facilitate assembly.
Once installed, however, the ITST forms a continuous shell structure, acting as a physical barrier between the IT and OT volumes.
The ITST incorporates installation and support rails at the 6 o'clock and 12 o'clock positions, enabling the insertion and alignment of the IT and its associated services.
The IT subsections are equipped with small, high-precision support wheels that allow them to be guided along the ITST rails during installation.
The ITST weighs less than 80 kg and is fully assembled and tested at Purdue University, the first ITST sub-sections have already been produced.

The integration of the ITST will take place at the very beginning of the TBPS integration. It will be positioned on the TBPS assembly tooling as the inner structural element, onto which all TBPS layers, both tilted and flat, will be sequentially assembled from Layer 1 to Layer 3.

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2.6. Outer Tracker Integration

To complete the full Outer Tracker (OT), two bulkheads—carbon-fibre sandwich panels—are inserted at both ends of the BTST, acting as OT closing caps and IT services supports.
Once fully assembled and tested, the OT is transported to LHC Point 5 (CMS), lowered through the main shaft into the experimental cavern, and installed into the CMS detector using a new insertion tool. This tool differs from the one used for the previous Tracker installation due to the significantly increased mass of the Phase-2 Tracker: The Barrel Timing Layer (BTL), which is installed inside the BTST and has a mass of roughly 2 tons, is a new component that was not part of the previous installation. The new insertion system was tested and validated in 2024.
In the cavern, the OT is aligned with respect to the CMS survey reference system. Alignment targets mounted on the Inner Tracker guide rails serve as references, ensuring that the IT support rails are centred as symmetrically as possible around the expected LHC beam position.
Following alignment, the OT is secured to the barrel HCAL via four metallic bolted brackets. OT installation is then completed by connecting all cables and cooling pipes to the service lines previously installed on YB0, followed by functional testing of each service. This is concluded with full checkout and commissioning of the OT, including cosmic-ray test runs.

3. Inner Tracker

The Phase-2 Inner Tracker is designed to maintain or enhance tracking and vertexing performance under the high-pileup conditions expected at the HL-LHC. Its design incorporates the capability to replace degraded components, particularly the modules of the first barrel layer, should this become necessary over the detector's lifetime. In addition, the electronics components located on the service cylinders will remain accessible for maintenance or replacement.

3.1. Inner Tracker Mechanics

The Inner Tracker consists of three distinct subsystems: TBPX (Tracker Barrel Pixel) a four-layer barrel detector, TFPX (Tracker Forward Pixel) a forward detector featuring eight double-discs per side, TEPX (Tracker Endcap Pixel) two endcaps, each comprising four double-discs.
Carbon-fibre service cylinders provide the primary structural support for all pixel detector elements, including the barrel layers and the discs. These cylinders also carry the electronics, cables, CO_2 cooling tubes, and monitoring devices.
In total, 756 pixel modules will be mounted on TBPX, 1,728 on TFPX, and 1,408 on TEPX.
The service cylinders are manufactured in two halves to allow installation around the central beampipe. A −35 °C two-phase CO_2 cooling system, identical to that used in the Outer Tracker, is employed to manage the high-power dissipation of the new pixel modules and to mitigate the effects of radiation damage accumulated over time.
The mechanical design of the Inner Tracker emphasises minimising material in the central $|z|$ region, to reduce multiple scattering and optimise tracking and vertexing performance.

3.2. Inner Tracker integration in CMS

Firstly, the central beampipe will be installed, connected to the endcap beampipes, and baked out prior to the installation of the Inner Tracker (IT).
Then, the IT is installed in eight subsections, each of which is fully tested beforehand in the surface laboratories, either in the TIF or at the CMS experimental site. The alignment of the beampipe and the IT is then repeated in the CMS cavern using the survey reference network, with the aim of positioning the system precisely around the expected LHC beam trajectory.
The target final positioning accuracy of the IT with respect to the beam is ±1 mm.

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[3] CMS Collaboration, *Development of the CMS detector for the CERN LHC Run 3*, JINST 19 (2024) P05064.

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