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The CMS Tracker Upgrade for Phase-2: Meeting the Challenges of the HL-LHC

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The High-Luminosity Large Hadron Collider (HL-LHC) will significantly increase the instantaneous luminosity of proton-proton collisions, pushing the CMS experiment into a regime of extreme radiation levels, high particle multiplicities, and unprecedented data rates. To maintain and extend the physics performance of the CMS detector under these conditions, a complete replacement of the tracking system is underway as part of the Phase-2 Upgrade. This paper presents the design, goals, and status of the Phase-2 CMS Tracker Upgrade, which includes entirely new silicon pixel and strip detectors with enhanced radiation hardness, finer granularity, and extended pseudorapidity coverage. The upgraded tracker will also feature on-detector data reduction through the use of real-time trigger information, an essential capability for sustaining low trigger thresholds at the HL-LHC. Special emphasis is placed on innovations in sensor technology, powering and cooling strategies, and the mechanical integration of large-scale modular components. We discuss the R&D, prototyping, and production progress, along with results from recent beam tests and system integration campaigns. The paper will also highlight key challenges in quality assurance, large-scale assembly, and pre-installation testing, as well as the timeline toward installation and commissioning.

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1. Introduction

The CERN LHC [1] will be upgraded to the HL-LHC [2] during Long Shutdown 3 (2026-2030). It will deliver an integrated luminosity of about 3000 fb^{-1} at a peak instantaneous luminosity of $7.5 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$, resulting in up to 200 proton–proton interactions per bunch crossing. Such operating conditions, far exceeding the current conditions, will impose unprecedented challenges in terms of radiation hardness, hit occupancy, and data throughput for all CMS detector [3] [4].

The present CMS tracker, designed for the LHC design luminosity of $1 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$, will reach the end of its operational lifetime by the conclusion of 2026, after acquiring an integrated luminosity greater than 500 fb^{-1}. Radiation damage will degrade the silicon sensors and front-end electronics, while the existing granularity will be insufficient to handle the hit rate increase. Moreover, the HL-LHC physics program would greatly benefit of broader angular coverage, and the tracker's readout architecture at the present time is incapable of contributing at the first level (L1) trigger. These consideration make a complete replacement of CMS tracker necessary, in the broader vision of Phase-2 CMS upgrade [5]

The Phase-2 Tracker upgrade, sketched in Fig. 1, consists of two main subsystems: the *Inner Tracker* (IT), based on hybrid pixel technology, which will provide coverage up to $|\eta| < 4$ and the *Outer Tracker* (OT) [6], composed of macro-pixel/strip (PS) and strip/strip (2S) modules, capable of forming track stubs for the L1 trigger.

Lightweight mechanical structures with evaporative CO_2 cooling, radiation-hard sensors, serial powering schemes, and high-bandwidth optical readout are key enabling technologies for this upgrade.

This paper summarizes the overall design and implementation of the CMS Phase-2 Tracker, with emphasis on the integration activities for both the IT and OT.

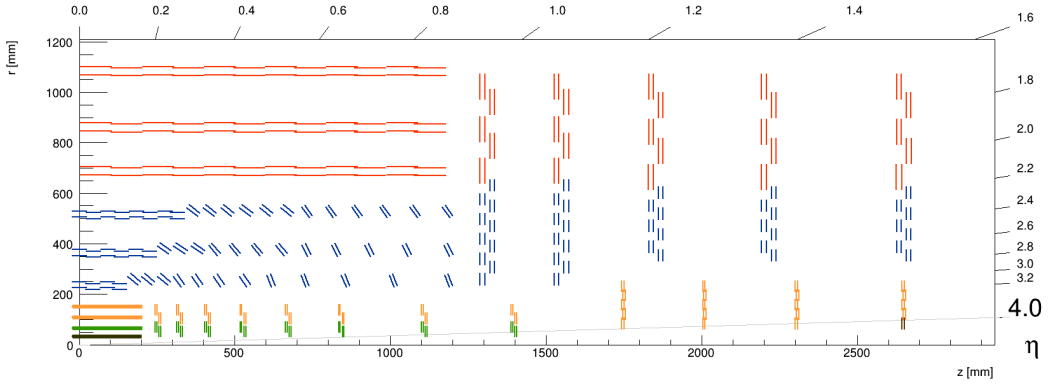

Figure 1: Sketch of one-quarter of the Phase-2 CMS tracking system in r-z view. In black, the 3D pixel modules, whilst in yellow planar pixel modules are shown. In the outer section, blue (red) lines represent PS (2S) modules.

2. Inner Tracker

The Inner Tracker will replace the current CMS pixel detector. It is composed of three subsystems: the Tracker Barrel Pixel (TBPX), consisting of four barrel layers, the Tracker Forward

Pixel (TFPX), consisting of 8 double discs on each side of the interaction point, and the Tracker Endcap Pixel (TEPX), consisting of 4 double discs per side.

Each subsystem is built from hybrid pixel modules consisting of a silicon sensor bump-bonded to a readout ASIC and wire-bonded to a high-density interconnect that provides power, command, and data transmission. Most layers employ 150 μm thick n-in-p planar sensors, while the innermost TBPX layer uses radiation-hard 3D sensors to sustain fluences up to 1×10^{16} n_{eq}/cm^2.

The readout ASIC, named *CROC*, is implemented in 65 nm CMOS technology and has been developed within the RD53 collaboration [7]. It provides radiation tolerance up to 0.5 Grad and operates with low noise and power consumption. The analog front-end features a linear time-over-threshold (ToT) response and supports a trigger rate of up to 750 kHz. Each CROC transmits data through differential electrical links (e-links) at 1.28 Gb/s and receives control commands via a 160 Mb/s downlink.

The CROC interfaces with the data acquisition chain through the low-power Gigabit Transceiver (*lpGBT*) [8], mounted on a dedicated service board called the *portcard*. Each portcard hosts three lpGBTs and three Versatile Link Plus (*VTRx+*) [9] optical transceivers, providing 2.5 Gb/s downlink and 10.24 Gb/s uplink bandwidth to the backend board.

Modules are mounted on lightweight carbon-fibre structures with evaporative CO_2 cooling and serial powering, reaching temperatures down to $-35°C$. This allows removing roughly 50 kW of heat dissipated by the front-end electronics, keeping the sensors and ASICs within the operational temperature margin. The serial powering, with an integrated Shunt-LDO voltage regulator on the module ensuring stable operation across long power chains (up to 12 modules), reducing the material budget.

The modular design allows replacement or testing at the subsystem level while maintaining compactness and uniformity of performance.

2.1 Integration and System Test

Integration of the Inner Tracker subsystems is performed at multiple assembly centers using dedicated tooling: precision jigs for TBPX, automated gantry systems for TFPX, and robotic arms for TEPX. Each mechanical element, such as ladders and half-disks, is assembled with pre-tested modules and services, followed by metrology and leak verification of the embedded CO_2 cooling loops. After mechanical integration, a complete sequence of quality control and validation steps is carried out to ensure full functionality before system-level testing.

Quality control includes IV-curve measurements and functionality verification using the `Ph2_ACF` [10] framework. Modules undergo threshold tuning, noise and pedestal scans, and injection-capacitance calibration, while optical link integrity is verified through bias–modulation and eye-diagram scans of the lpGBT and VTRx+. Thermal cycling and stress tests ensure stable performance over repeated operation cycles. All results obtained from these procedures are automatically stored in the `Panthera` [11], a web-based platform to store, analyze, and grade test results for traceability.

Modules are then mounted on the final support structures, equipped with final power, readout, and cooling components. Four setups with final integration structures have been assembled for testing purposes up to now (TBPX L2 and L3/4, TFPX and TEPX disks), in order to run thermal, mechanical and powering tests. These are the structures on which the final DAQ chain will be tested.

3. Outer Tracker

The Outer Tracker will provide precise tracking and a crucial contribution to the L1 trigger through on-detector transverse momentum (p_T) discrimination. It covers the radial range from 20 cm to 110 cm and is built from two types of hybrid modules, the 2S and PS modules, arranged in six barrel layers and five endcap double-disks per side. Each module consists of two silicon sensors read out by a common set of ASICs via a flex hybrid. Given the known magnetic field and the fixed spacing between the two sensors, the module can locally correlate hits in a tunable correlation window, thus applying a p_T threshold and selecting high-momentum particles and forming *stubs* that are transmitted at the 40 MHz bunch-crossing rate to the L1 trigger logic. Tilted layers are present in the three innemorst layers of the barrel (200—600 mm), to allow for better precision in p_T measure and track reconstruction. Upon receiving an L1 accept, the module transmits the full cluster data through the hit stream at an expected rate of 750 kHz.

Two module geometries are used:

- **2S modules:** Two strip sensors, each $10\times10\,\mathrm{cm}^2$, with 90 μm pitch and spacings of 1.8 or 4 mm depending on the detector region.
- **PS modules:** A combination of one strip sensor (100 μm pitch) and one macro-pixel sensor (100 μm pitch), each $5\times10\,\mathrm{cm}^2$ with spacings of 1.6, 2.6, or 4 mm.

Recent test beams have confirmed that the p_T modules maintain full hit efficiency and signal-to-noise ratio even after irradiation above the expected end-of-life fluence of the HL-LHC.

3.1 Integration and System Test

The integration of the Outer Tracker follows a well-defined workflow that begins with module assembly in dedicated regional centers and continues through staged qualification and large-scale tests at CERN. Each integration step includes mechanical, electrical, and thermal validation to ensure consistent quality across all production sites.

Module assembly is performed in multiple centers equipped with automated bonding, encapsulation, and metrology stations. During this process, a first-level quality control is carried out to verify connectivity, leakage current, and mechanical tolerances. After assembly, modules undergo electrical functionality tests and IV-curve characterization to verify proper operation of the front-end ASICs. A subsequent functional test, performed using the `Ph2_ACF` framework, verifies the integrity of the electrical connections between chips and measures noise and threshold distributions. At this stage, the test results are uploaded to the production database, and a grade is assigned to each module to ensure consistent quality assurance across production sites. Thermal cycling of modules is performed over 48 full temperature cycles between +20°C and −35°C, with intermediate functional checks validating long-term electrical stability and mechanical robustness.

Following these qualification, modules are sent to integration centers where they are mounted on higher-level structures such as 2S ladders and PS rings for the barrel, and 2S+PS double-disks for the endcaps. Following additional qualifications, integrated structures are transported to CERN where they are further combined into sub-systems (TB2S, TBPS, TEDD), and finally installed in the tracker support tube. Before their final installation, the sub-systems are tested in realistic

operating condition, using the complete data acquisition chain, described briefly in Sec. 4 final power distribution, CO_2 cooling manifolds.

In parallel with the integration of the sub-systems, which will proceed in a well-defined sequence, a permanent setup has been deployed at CERN to reproduce the full DAQ environment, including synchronization, event building, and monitoring, providing end-to-end validation from the detector response to data acquisition. This `cosmic rack` hosts up to six 2S ladders and includes an external scintillator-based trigger system. This will allow us to test the full data acquisition chain with final hardware: starting from stub acquisition, matching with other information to build an high level trigger, and retrieval the full hit information from modules. After that, offline reconstruction is planned, and match between the tracks reconstructed offline and online. The `cosmic rack` setup will also allow us to test the interoperability of different sequences during data taking, and tune the procedures to minimize data taking losses once the detector is installed.

4. Operation and Integration Data Acquisition Chain

The data acquisition and control system of the Phase-2 Tracker is based on the *Data, Trigger and Control* (DTC) boards: an Advanced Telecommunications Computing Architecture (ATCA) board, used in two architecture flavors, called Serenity [12] and Apollo [13]. Both boards feature a Zynq System-on-Module, FPGAs and numerous optical links to support high data rates.

On the software side, the system is handled by the *ShepHerd* [14] online software framework, a common software architecture developed jointly by the L1 Trigger and Tracker groups. It provides unified configuration, calibration, and monitoring of both Tracker subsystems through a hierarchical and modular control design.

The *ShepHerd* [14] online software framework is composed of three layers:

- **Run Control:** The top-level orchestration layer responsible for configuring and synchronizing the tracker operation with the CMS central DAQ.
- **Shep:** The off-detector supervisor, one instance per subsystem, providing network APIs and web interfaces for detector experts.
- **Herd:** The on-detector controller running on the DTC, which executes low-level operations via dedicated subsystem plugins.

The tracker-dedicated plugin responsible for the configuration and calibration of the CMS Tracker relies on the `tk-fe-daq` [15] library, which provides all the necessary tools for configuration, calibration, and monitoring required for stable operation. The `tk-fe-daq` library offers the functionalities to configure front-end ASICs and readout chains for both Inner and Outer Tracker modules, to perform module calibrations (e.g. threshold tuning, gain equalization, and pedestal scans), and to support automatic recovery from Single Event Upsets through reconfiguration. It also provides interfaces for monitoring module currents, voltages, and temperatures, logging them to a conditions database, managing data-taking mode transitions, and verifying data integrity—capabilities that are implemented and orchestrated at the plugin level. The framework is being developed with the goal of running on the System-on-Module available on the DTC board, in order to make the system scalable by design.

5. Conclusion

The CMS Phase-2 Tracker will fully replace the current tracking detector to meet the demanding conditions of the High-Luminosity LHC. It integrates two complementary subsystems: the Inner Tracker, composed of hybrid pixel modules optimized for radiation tolerance and precision tracking up to $|\eta| < 4$, and the Outer Tracker, featuring p_T-sensitive modules that enable on-detector track stub formation for the L1 trigger. Both systems employ radiation-hard electronics, serial powering, and lightweight CO_2-cooled mechanical structures to minimize material and ensure reliable long-term operation.

Large-scale integration and system tests have validated the electrical, thermal, and data transmission performance of the tracker elements, confirming compliance with design requirements. Final testing campaigns, including full readout with production-grade DAQ hardware and cosmic-rays setups, are ongoing and will extend to multi-subsystem integration before installation. With module production and infrastructure commissioning well underway, the CMS Tracker upgrade is on track to deliver robust performance throughout the HL-LHC program.

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