PROCEEDINGS OF SCIENCE

The Tracker End-cap Pixel detector for CMS Phase-2 upgrade

Riccardo Del Burgo *†
CMS Collaboration,
E-mail: riccardo.del.burgo@cern.ch

After the high-luminosity upgrade of the LHC (HL-LHC), the instantaneous luminosity will increase to unprecedented values of $5-7\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In order to cope with these conditions the whole CMS silicon tracker detector will be replaced. This presentation describes the Phase-2 upgrade of the inner pixel system. The new inner pixel detector will be composed of three sub-detectors: the barrel detector (TBPX) consisting of four concentric cylindrical layers, the forward detector (TFPX) consisting of eight small disks on each end, and the end-cap detector (TEPX) with four large disks on each end.

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*Speaker.
†on behalf of the CMS Collaboration.

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1. High Luminosity LHC

The Large Hadron Collider (LHC) is one of the largest scientific instruments ever built. To sustain and extend its discovery potential, the LHC will need a major upgrade in the 2020s. This will increase its luminosity (rate of collisions) by a factor of five beyond the original design value and the integrated luminosity (total number of collisions) by a factor of ten [1].
The number of simultaneous proton-proton collisions (pileup) happening during a single bunch crossing is proportional to the instantaneous luminosity. To limit the number of pileup events, it is foreseen to level the luminosity during an LHC fill, i.e. to operate at a constant luminosity below the maximum achievable value. About 140 pileup events on average are expected for an instantaneous luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, increasing to 200 pileup events in the ultimate luminosity scenario. The radiation level will be unprecedented. By design an integrated luminosity of $3000\,\mathrm{fb}^{-1}$, a 1 MeV neutron equivalent fluence of $2.3 \cdot 10^{16}\,\mathrm{neq/cm}^2$ and a total ionizing dose of 12 MGy (1.2 Grad) is expected at the centre of CMS experiment [2], where the innermost silicon pixel tracking layers will be installed.
The HL-LHC upgrade is accompanied by an upgrade programme of the CMS experiment, to maintain the excellent performance of the detector and allow us to fully profit from the HL-LHC capabilities, in spite of the challenging radiation levels and operating conditions.

2. CMS Phase-2 Tracker upgrade

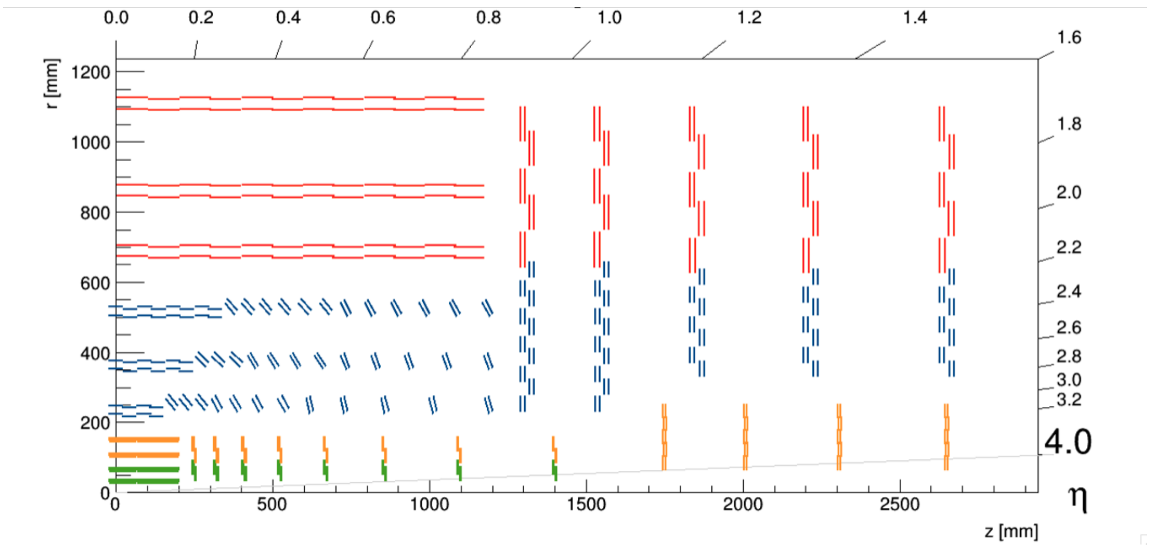

Figure 1: Sketch of one quarter of the Phase-2 CMS tracking system in r-z view. The pixel detector is shown in green/yellow, while single-sided and double-sided strip modules are depicted as red and blue segments, respectively.

The entire silicon tracking system, presently consisting of pixel and strip detectors, will be replaced. A sketch of one quarter of the Phase-2 CMS tracking system in *r*-*z* view is shown in Fig.(1). The Outer Tracker (OT) layout is shown in red/blue while the Inner Tracker (IT) layout in green/yellow. The new tracker will feature increased forward acceptance, increased radiation hardness, higher granularity, and compatibility with higher data rates and a longer trigger latency. CMS trigger consists of two levels, the Level 1 trigger (L1) and the High Level Trigger (HLT). In addition, the tracker will provide tracking information to the Level 1 trigger, information presently only available at the HLT. This will allow the trigger rates to be kept at a sustainable level without sacrificing physics potential. The Phase-2 Inner Tracker is based on silicon pixel modules and the Outer Tracker is composed of silicon modules with strip and macro-pixel sensors. The main requirements for the tracker upgrade can be summarised as follows.

- Radiation tolerance. The upgraded tracker must be fully efficient up to a target integrated luminosity of $3000\,\mathrm{fb}^{-1}$, with an appropriate margin of the order of 50%. For the Inner Tracker, where pixel detector modules are deployed, it is envisaged to keep the present concept of accessibility, allowing us to extract the Inner Tracker during scheduled LHC end of year technical stops and offering the option to replace modules and other elements as they accumulate substantial radiation damage.

- Increased granularity. In order to ensure efficient tracking performance with a high level of pileup, the channel occupancy must be kept at around or below the per cent level (per mille level) in the Outer Tracker (Inner Tracker), which requires a high channel density. Target values of 140 and 200 collisions per bunch crossing are used to benchmark the performance of the detector.

- Improved two-track separation. The present tracker has limited track finding performance in highly energetic jets, due to hit merging in the pixel detector. In order to optimally exploit the large amounts of collision data that will be taken during high luminosity operation, two-track separation needs to be improved.

In the central region, the four layers of the Inner Tracker are the key for the pixel-based track seeding, which ensures good track finding performance with affordable computing time down to very low transverse momentum. Preliminary studies indicate that with the same number of layers as in the Phase-1 detector good performance is preserved also at the expected HL-LHC pileup levels, thanks to the smaller pixel size. In the forward part, the number of detection layers deployed ensures an optimal coverage up to $|\eta| < 4.0$ providing robust performance over the whole rapidity acceptance.

3. The Inner Tracker and the Phase-2 pixel module

Three different sub-detectors will form the Inner Tracker: the barrel pixel (TEPX), the forward pixel (TFPX), and the end-cap pixel (TEPX). With reference to Fig.(1), the TBPX includes four barrel layers, while the TFPX includes the first eight small diameter disks, and the TEPX will comprise the last four big diameter disks on each side of the interaction point along z. The acceptance extends to $|\eta| = 4$.
The design of the Inner Tracker will allow to replace degraded parts over an extended year-end technical stop, which includes the possibility to extract and insert the detector without removing the CMS beam pipe. This is achieved by inserting the detector on inclined rails, necessitating a step in the radial boundary between the Outer Tracker and the Inner Tracker.

The measurement of the luminosity will be integrated as additional functionality in the four large double-discs forming the high z extension.
Thin silicon sensors of thickness 150 μm segmented into pixel sizes of $25 \times 100\,\mu\text{m}^2$ or $50 \times 50\,\mu\text{m}^2$, are expected to exhibit the required radiation tolerance and to deliver the desired performance in terms of detector resolution, occupancy, and two-track separation. For the first layer of TBPX 3D sensors are under consideration because of their resistance to radiation damage. Consequently a readout chip with a small cell size and low detection threshold is required. ATLAS and CMS are carrying out a common development in the framework of RD53 to design a pixel chip with $2500\,\mu$m cell size, in 65 nm CMOS technology [3]. With such a configuration the detector resolution is much more robust with respect to radiation damage than the present detector. The pixel module comprises a pixel sensor, several PROCs (Pixel Read Out Chip(s)), a flex circuit, and a mechanical support. Sensors are bump bonded to the readout chips. A thin, high-density flex circuit, also referred to as high density interconnect (HDI), is glued onto the sensor and wire bonded to the PROCs. It ships the data out, provides clock, trigger and control signals, as well as power distribution for the PROCs, and hosts all other passive and active components.
In the case of the TBPX and TFPX, low mass electrical cables connect the pixel modules to the global readout, control and powering systems, while TEPX opted for a different solution which will be described in the following sections.
Heat generated on the module is removed via a layer of thermally conductive carbon foam to CO_2 cooling pipes, keeping the pixel chips and sensors at an operating temperature of about -35° C. The modules have support strips glued to the back side of the PROCs. These strips should feature high thermal conductivity, and aluminium nitride is being considered. The entire Phase-2 pixel detector design is based on a PROC whose active dimensions are $16.4 \times 22.0\,\text{mm}^2$. Only two types of modules are foreseen, differing exclusively in the sensor surface and number of readout chips. Modules with two chips and four chips, arranged as two by two, are foreseen, referred to as 1×2 and 2×2 modules. The two module types are respectively shown in green (1 × 2) and yellow (2 × 2) in Fig.(1). The 1×2 and 2×2 modules are used to equip TBPX and TFPX, while only the 2×2 modules are employed in TEPX. These rectangular modules are arranged in the cylindrical geometry of the barrel and in the disc-like geometry of the end-caps with appropriate overlaps of the active areas.

4. TEPX mechanical design and disk structure

The TEPX mechanical structure is a product of the past experience in building, testing, commissioning and operating the Phase-0 and Phase-1 pixel detectors. Each of the eight disks that composes TEPX are split in two halves, the Double-Dees. Each Double-Dee is composed of a front Dee and a rear Dee, mounted back to back on a sandwich structure. Only two different Dee designs are required for the construction of the current TEPX design. Each Double-Dee will host 44 modules for a total of 1408 modules for the full TEPX detector.
Fig. (2) shows the different layers inside a Double-Dee. In the center sits a Airex core with graphite/TPG heat sinks and a titanium cooling loop. Two $400\,\mu$m thick PCB layers will be glued on each side. These layers will connect the modules to the readout electronic and provide power. This solution allows to have one connector per module and avoid using cables. The last two layers

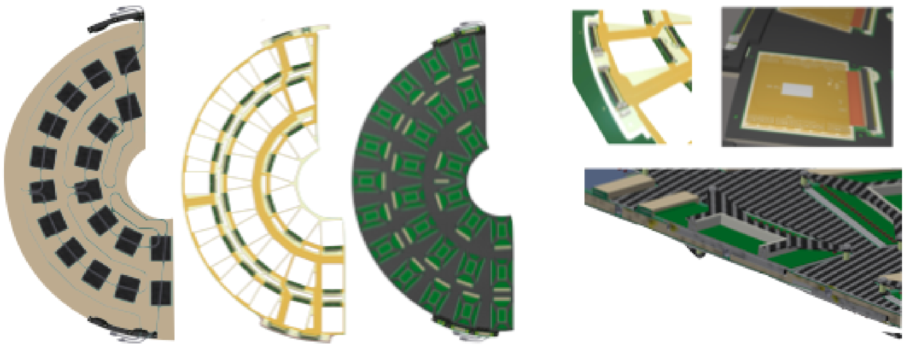

Figure 2: Different layers and details of the Double-Dee structure. From left to right: the Airex core with the single cooling loop and the heat sinks, The 400 μm thick PCB layer which connects the modules to the readout electronics, power and the stiffening carbon fibre layer. First figure on the top right: detail of the PCB Molex connector. Second figure on the top right: detail of the HDI and the flex cable connecting the module to PCB. Bottom right: cross-section of the Double-Dee.

are stiffening carbon layers. Each module is inserted in position. The HDI is placed on top and will connect to a single molex connector. An X-shaped carbon fibre holder will hold the module in position. Connectors at the top and bottom of each Dee will connect signals, power and HV.

5. Mechanical design and insertion

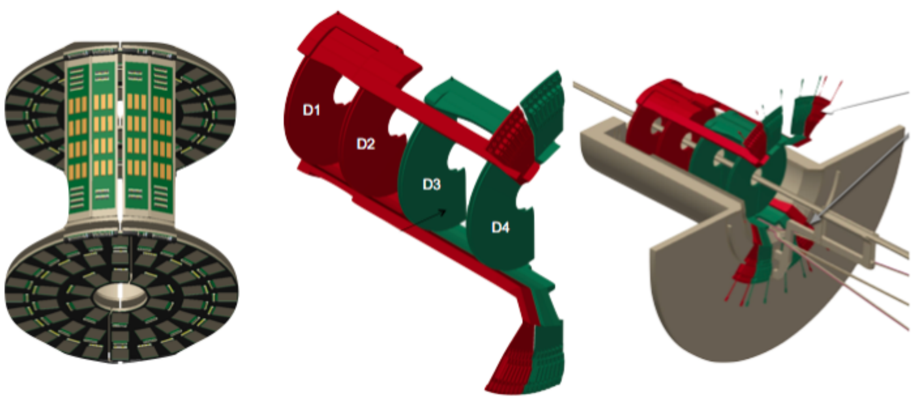

Figure 3: Left: Readout electronics arrangement at the top (bottom) of the half quadrant. Center: TEPX quadrant. The two halves are independent because of space constraint during the installation. Right: Rendering of two quadrants after installation in CMS
TBPX

The mechanical design of the TEPX is driven by the limited space available during the final detector insertion. Four Double-Dees will be arranged in a quadrant as shown in Fig.3, center. The incoming and outgoing signal from and to the modules will be converted from electrical to optical signal using Low Power GigaBit Transceiver (lpGBT) with a bandwidth of 10 Gb/s. They will be hosted on the top and the bottom of the quadrant. Each Double-Dee uses 24 lpGBT, for a total of 384 for the full TEPX detector. The lpGBTs will be placed at the top and bottom of the quadrant. The two halves of each quadrant are independent because of space constraint during the installation.

6. Summary

The CMS Phase-2 pixel detector consisting of the TBPX, TFPX and TEPX sub-systems will be installed during the long shutdown in the years 2024- 2025. It will operate for the next ten years collecting an integrated luminosity of $3000\,\mathrm{fb}^{-1}$, with an ultimate goal of $4000\,\mathrm{fb}^{-1}$. The TEPX will extend the tracking coverage up to $|\eta| < 4.0$ expanding the acceptance region of the CMS detector. This will allow a better reconstruction in the high η region which is important for many analysis. The design of the mechanics will allow easy access to the detector in case the CMS collaboration will decide to replace the innermost modules that could suffer more from the radiation damage.

References

[1] *The Phase-2 Upgrade of the CMS Tracker*, *CERN-LHCC-2017-009. CMS-TDR-014* [2017].

[2] *The CMS experiment at the CERN LHC*, *JINST 3 (2008) S08004* [2008].

[3] *Production chip combined requirements for ATLAS and CMS*, *CERN-RD53-PUB-19-001* [2018].