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The CMS Experiment Tracker Upgrade for High Luminosity LHC(*)

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Summary. — The High Luminosity Large Hadron Collider (HL-LHC) at CERN is expected to collide protons at a centre-of-mass energy of 14 TeV and to reach an unprecedented peak instantaneous luminosity of $5-7.5\times10^{34}\,\mathrm{cm^{-2}s^{-1}}$ with an average number of pileup events of 140-200. This will allow the CMS experiments to collect integrated luminosities up to 3000-4500 fb^{-1} during the project lifetime. To cope with this extreme scenario, the CMS detector will be substantially upgraded before starting the HL-LHC, a plan known as CMS Phase-2 upgrade. The entire CMS silicon tracker detector will be replaced and the new detector will feature increased radiation hardness, finer granularity, longer trigger latency and higher data rate capability. The new tracker will consist of two main subdetectors: the Inner Tracker, containing pixel modules, and the Outer Tracker, consisting of strip and macro-pixel modules. In this paper the Phase-2 upgrade of the CMS tracker is reviewed.

1. – The CMS Tracker Upgrade

The CMS experiment [1] will be significantly upgraded for LHC Phase-2, in order to operate in the conditions of High Luminosity LHC (HL-LHC). In particular, because of the higher radiation levels, the radiation hardness of the detectors has to be improved. Moreover, the higher pileup and the consequent increased track density require higher detector granularity, to reduce the occupancy, and increased bandwidth, to read out the higher data rates.

The current CMS tracker will be completely replaced [2]: it will consist of two subsystems, the Inner Tracker (IT), containing pixel modules, and the Outer Tracker (OT), containing strip and macro-pixel modules. The Inner Tracker will be made of four layers in the barrel and twelve discs per side in the endcaps. It will cover the region closer to the beam pipe: the innermost layer will be at only 30 mm from the beam line. The Outer Tracker will be made of six layers in the barrel and five discs per side in the endcaps.

In fig. 1 a schematic view of the new tracker is shown. The number of layers was optimized to ensure robust tracking, so that the performances are unaffected when one detecting layer is lost in some parts of the rapidity acceptance.

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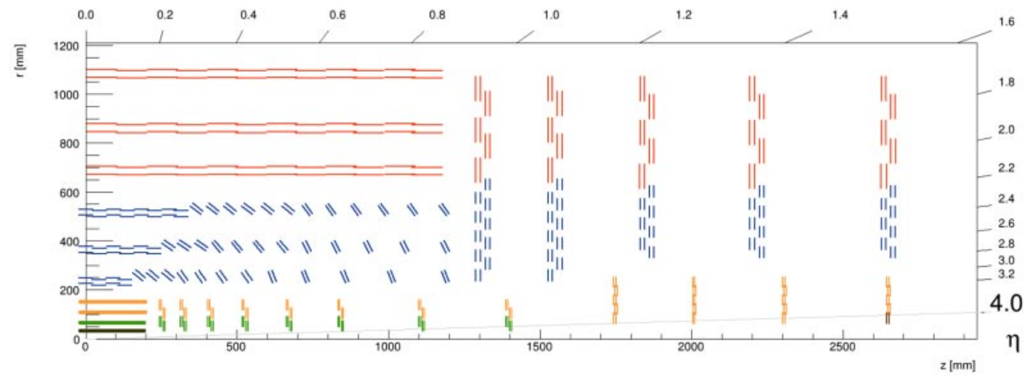

Fig. 1. – Schematic view of a quarter of the tracker in the $r-z$ plane. The Inner Tracker is depicted by green and yellow lines, corresponding to modules with two and four ROCs respectively; the black line represent 3D pixel sensors. The Outer Tracker is depicted by blue and red lines, corresponding to modules with a strip sensor and a macro-pixel sensor, and modules with two strip sensors, respectively.

The requirements of the new tracker can be summarized as follows. First of all, the new tracker must have a high radiation tolerance, for an integrated luminosity up to $4500\,\mathrm{fb}^{-1}$. For the Outer Tracker, this requirement needs to be fulfilled without the possibility of replacement, since the detectors will not be easily accessible. However, it will be possible to extract the Inner Tracker and replace modules, for example, radiation damaged modules.

A finer granularity in needed in order to keep the occupancy of the order of 10^{-3} in the IT and 10^{-2} in the OT. This is necessary to ensure efficient tracking performance with the high pileup expected during Phase-2.

The material will be significantly reduced in the new tracker. Indeed the performance of the present tracker is limited by the amount of material, which also impacts the calorimeters.

Finally, an extended tracking acceptance is needed in order to have efficient tracking up to $|\eta| = 4$. The physics capabilities of CMS will greatly benefit from the extended acceptance, both in the tracker and in the calorimeters.

2. – The Inner Tracker

The Inner Tracker consists of a barrel part with four layers (Tracker Barrel Pixel Detector, TBPX), eight small double-discs per side (Tracker Forward Pixel Detector, TFPX) and four large double-discs per side (Endcap Pixel Detector, TEPX).

In the TBPX the pixel modules will be arranged in "ladders" along the z axis. In the TFPX and TEPX the modules will be arranged in concentric rings.

In fig. 2 the three subsystems are visible inside the supporting structure, which is referred to as service cylinder since it hosts the services required by the modules (power supply cables, readout connections, and cooling pipes). The Inner Tracker will have a total pixel surface of approximately $4.9\,\mathrm{m}^2$ and 2×10^9 channels, from almost 4000 pixel modules.

In order to increase the granularity with respect to Phase-1, the new pixel pitch will be $25 \times 100\,\mu\mathrm{m}^2$ (with the long side pointing along z in the barrel and along r in the

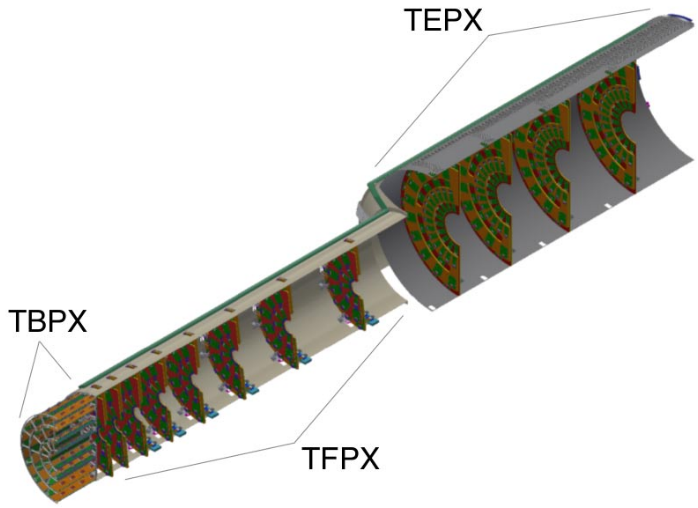

Fig. 2. – Sectional view of a quarter of the Inner Tracker, showing TBPX, TFPX, TEPX, and the service cylinder.

endcaps), while the present tracker is made of $100 \times 150\,\mu\text{m}^2$ pixels. Moreover, the active thickness will be reduced from 285 μm (Phase-1) to $150\,\mu$m (Phase-2), and the silicon sensors will be n-in-p instead of n-in-n.

Two types of pixel sensor technologies will be used in the Inner Tracker: traditional planar pixel sensors, where the electrodes are parallel to the sensor surface, and 3D pixel sensors, where the electrodes are orthogonal to the sensor surface [3]. The latter feature a higher radiation resistance thanks to a reduced drift distance, therefore they will be installed in the innermost tracker layer.

The CROC is the new CMS pixel ReadOut Chip (ROC) [4], developed by the RD53 collaboration, a joint CMS and ATLAS effort to develop the pixel electronics for the HL-LHC experiment upgrades. The CROC is designed in 65 nm CMOS technology and features 1.5×10^5 pixel channels with an area of $50 \times 50\ \mu\text{m}^2$.

A pixel module is made of a pixel sensor, several ROCs, and a thin, high density flex

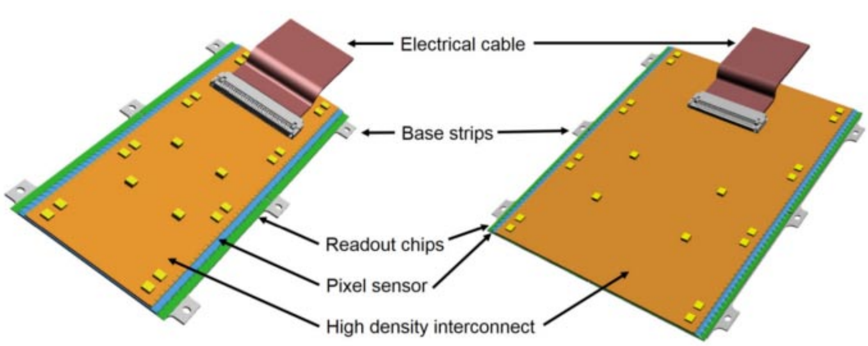

Fig. 3. – Schematic sketch of the 1×2 pixel module (left) and the 2×2 pixel modules (right).

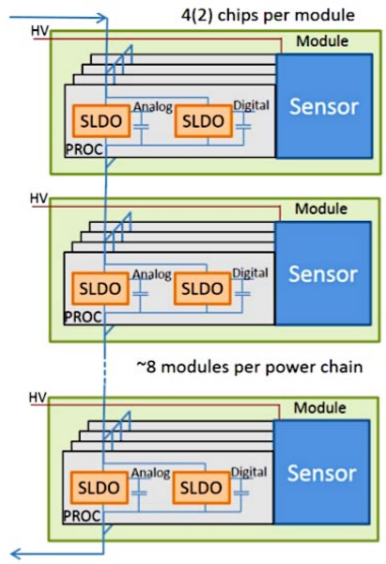

Fig. 4. – Serial power distribution with the ROCs in parallel on each module and modules connected in series.

circuit, referred to as High Density Interconnect (HDI). Sensors are bump bonded to the ROCs and glued to the HDI. The ROCs are then wire bonded to the HDI. The HDI provides clock trigger and control signals, as well as the power distribution, while also shipping the data out.

Two types of modules are foreseen, differing only on the active pixel area and the number of ROCs: modules with two ROCs (1×2 modules) and with four ROCs (2×2 modules). The 1×2 modules will be placed in the innermost regions, while the 2×2 modules will be placed in the outer layers, as shown in fig. 1. In fig. 3 a sketch of the two types of modules is shown.

The cooling system will keep the modules at a stable temperature of about -20 °C.

Hits data are stored by ROCs during the $12.5\,\mu$s trigger latency. Triggered data events are then extracted from the ROCs, compressed, and sent to differential digital lines (E-links), at 1.28 Gb/s. The number of E-links per module is configurable $(1-6)$ in order to have sufficient bandwidth in the innermost layers. In the outer layers, where the hit rates are lower, event data from all chips of a module are merged into a single E-link.

The Data AcQuisition (DAQ) system is located too far from the detectors to be compliant with an electrical transmission protocol. Therefore, opto-conversion modules, based on the LpGBT (Low-power Gigabit Transceiver) chip set, merge data from up to seven E-links into 10 Gb/s optical links for transmission to the off-detector DAQ system. Clock, trigger, real-time commands, and configuration data are received by the LpGBTs on the opto-conversion modules via 2.5 Gb/s optical down links and sent to the pixel chips via one 160 Mb/s E-link per pixel module.

The 2.5 Gb/s and the 10 Gb/s optical links to and from the Inner Tracker will be connected to the CMS DAQ system, using a DAQ interface module. The DAQ interface of the Inner Tracker consists of a Data, Trigger, Control board (DTC), which communicates with the on-detector electronics via the LpGBT optical links. The DTC is planned to accommodate 72 pairs of LpGBT optical up and down links. A crate with six pixel DTC modules can accommodate the readout and control of a quarter of the Inner Tracker; there will be a total of four crates with 24 DTC modules and 1728 optical link pairs.

The Phase-2 ROC necessitates a modern low density CMOS technology with low supply voltage (about 1.2 V), which however requires a high current level (about 2 A), corresponding to a power consumption of about $0.5\,\mathrm{W/cm^2}$. A direct powering scheme would require large cross-section power cables, which would dramatically increase the passive material in the tracker. An alternative approach, based on the present pixel tracker, is based on DC-DC converters. However, these are affected by two problems. In the first place, they are not radiation resistant enough for the Inner Tracker environment. In the second place, they are large and heavy objects that are difficult to place inside the tracker, while also adding significant passive material near the collision point. While this scheme is indeed used in the Outer Tracker, since it is far less affected by these problems, the Inner Tracker has opted for a direct powering scheme instead [5].

The Inner Tracker is organized in chains of up to ten modules, with the ROCs of each module connected in parallel, as shown in fig. 4. The ROC includes a highly specialized circuit that combines the functionality of a current shunt and a Low-DropOut (LDO) regulator, referred to as Shunt-LDO (SLDO) The SLDO ensures that power and current consumption are kept constant, independent of hit and trigger rates. Moreover, the SLDO is designed to ensure appropriate current sharing between multiple chips, powered in parallel. Thanks to this scheme, the serial chain presents itself as a constant load to the power supplies: the SLDO manages the ROC power consumption variations.

The production of pixel sensors has already started and will continue in 2024. CROC chips will be produced during 2024 and the first pixel modules will be assembled in late 2024.

3. – The Outer Tracker

In order to limit the data sent to the L1 trigger at every bunch crossing, the tracker will make a self-selection of interesting events. This is achieved by using detectors that are capable of rejecting signals from particles below a certain p_T threshold, referred to as "p_T modules". As shown in fig. 5, p_T modules are made of two closely-spaced silicon strip sensors read out by a common set of front-end Application Specific Integrated Circuits (ASICs), which correlate the signals in the two sensors and select the hit pairs, referred to as "stubs". Tracks from charged particles are bent in the transverse plane by the 3.8 T field of the CMS magnet, with the bending angle depending on the p_T of the particle. Stubs that are geometrically compatible with tracks above a certain p_T threshold ($2-3$ GeV) are selected and sent to the L1 trigger at every bunch crossing. All other hits are stored in the pipelines waiting for the L1 trigger response. The resolution of p_T modules depends on the distance from the interaction point, therefore they are only used in the Outer Tracker.

There are two type of p_T modules: 2S modules, with two strip sensors, and PS modules, with a strip and a macro-pixel sensor. The strips in the 2S modules have a length of about 5 cm, while those in the PS modules are about 2.4 cm long. Both module types have a pitch of about $100\,\mu$m. In PS modules one of the two sensors is segmented into macro-pixels with a length of about 1.5 mm, providing the z (r) coordinate measurement in the barrel (endcaps).

The PS modules will be installed in the first three layers of the Outer Tracker while the

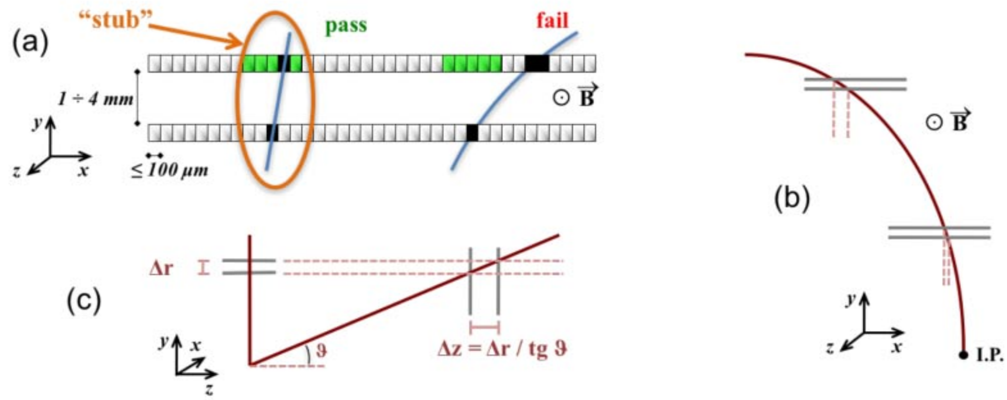

Fig. 5. – Illustration of the p_T module concept. Correlation of signals in closely-spaced sensors enables rejection of low p_T particles. The channels shown in green represent the selection window to define an accepted stub (a). The same p_T corresponds to a larger distance between the two signals at large radii for a given sensor spacing (b). For the endcap discs, a larger spacing between the sensors is needed to achieve the same discriminating power as in the barrel at the same radius (c).

2S modules will be installed in the outermost three layers. In the endcaps, the modules are arranged in rings on disc-like structures, with the rings at low radii, equipped with PS modules, while 2S modules are used at larger radii.

The readout electronics require Low Voltage (LV), in the range of $1-2$ V, and high current powering, provided by Power Supplies Units (PSU) installed outside the CMS experiment. A direct powering scheme requires too much material in the tracker, therefore a powering scheme based on a Point of Load (PoL) conversion was chosen for the Outer Tracker. In each module, a DC-DC converter generates the necessary voltage from an intermediate voltage ($10-12$ V) provided from the PSUs. Considering also the High Voltage (HV) necessary to bias the silicon sensors, which follows a direct powering scheme instead, the Outer Tracker requires a power of roughly 90 kW. Thanks to the PoL conversion, the passive material associated with the power supply cables is greatly reduced. The power dissipated from the Phase-2 tracker is removed by a CO_2 cooling system.

Both 2S and PS modules are currently being assembled and tested.

REFERENCES

[1] The CMS Collaboration, *JINST*, **3** (2008) S08004.
[2] The CMS Collaboration, *The Phase-2 Upgrade of the CMS Tracker*, CERN-LHCC-2017-009 (2017).
[3] Dalla Betta G. F. *et al.*, *PoS*, **Vertex 2016** (2016) 028.
[4] Christiansen J. and Garcia-Sciveres M., *RD Collaboration proposal: Development of pixel readout integrated circuits for extreme rate and radiation*, CERN-LHCC-2013-008 (2013).
[5] Ta D. B. *et al.*, *Nucl. Instrum. Methods A*, **557** (2006) 445.