The CMS Pixel Detector Upgrade and R&D Developments for the High Luminosity LHC

Rudy Ceccarelli
on behalf of the CMS Tracker Group

INFN Firenze

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High Luminosity LHC

- HL-LHC will be installed between 2024 and 2026
- Phase 2 of LHC will start in 2026
- Luminosity will reach $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Collect up to 4500 fb$^{-1}$ in 10 years
- The CMS detector will be upgraded
  - Expected up to 200 pileup vertices
  - Hit rate up to 3.2 GHz cm$^{-2}$
  - 750 kHz L1 trigger rate
  - 12.5 μs latency time
The Tracker Upgrade

✓ The CMS Tracker will be completely replaced
✓ Composed by two sections → Inner (this talk) and Outer (see J. De Clercq talk)
The Inner Tracker Upgrade

Requirements

1. High granularity
2. Radiation resistance
3. Low material budget
4. Large acceptance

- ✓ Good two tracks separation → Needed in jet reconstruction
- ✓ Robust pattern recognition → Needed for high pileup conditions

New pixel sensors and front-end electronics

New Inner Tracker layout
The Inner Tracker Layout

- “Simple” mechanical structure
- Simple installation and removal for potential replacement of parts
- 4.9 m² of pixel surface & $2 \times 10^9$ channels
- Inner layer at 30 mm from beam line

Tracker Barrel Pixel (TBPX) (4 layers)
Tracker Forward Pixel (TFPX) (8 disks per side)
Tracker Endcap Pixel (TEPX) (4 disks per side)

2736 2 × 2 pixel modules
1156 1 × 2 pixel modules
Unprecedented radiation levels

After 10 years of operations, in the innermost layer:

12 MGy

2.3 \times 10^{16} \ n_{eq} \ cm^{-2}
TBPX Mechanics

- Four cylindrical layers
- Split in two parts along $z \rightarrow 4$ or $5$ modules per layer
- No projective gap at $|\eta| = 0$
- Carbon fiber support structures
- CO$_2$ cooling in order to operate modules below $-20\, ^\circ C$
- Cooling pipes below chip hotspots
TFPX & TEPX Mechanics

✓ TFPX is composed by eight planar double disks per end
✓ Each disk is composed of two dees
✓ Front → rings 2 & 4
✓ Back → rings 1 & 3
✓ Modules are arranged in both sides of a dee
✓ TEPX has a similar structure
The Pixel Modules

✓ Simple design, mechanical and cooling constraints
✓ ReadOut Chip (ROC) is the only active electronics
✓ Two flavours → 1 × 2 and 2 × 2 ROCs
✓ High Density Interconnect (HDI) flexible circuit
  ✓ Decoupling caps and connectors on HDI
  ✓ Sensors bump-bonded to the ROC
  ✓ Sensors glued to the HDI
  ✓ ROC wire-bonded to the HDI
✓ Spark protections

“Quad” Module FBK planar sensor
Serial Powering

High occupancy → Small pixels & large bandwidth → High supply current

- Future CMS Inner Tracker will require 50 kW on-detector power
- Direct powering requires too much material
- DC/DC converters are cumbersome and not radiation resistant enough for the Inner Tracker
- Serial powering solution is being developed
  - Up to 10 pixel detector modules serially powered
  - Up to four chips per module powered in parallel
  - Radiation hardness and low material budget
Serial Powering

- Constant current, independent of actual load
- shuntLDO → combination of a shunt and a regulator
- 2 × 2.0 A shuntLDOs present on ROC (analog and digital)
- Any extra current not used by loads enters the shunt
- Local ground is different inside a chain (not trivial HV distribution scheme)

CERN CMS & ATLAS serial powering collaboration
Planar Pixel Sensors

✓ Planar pixel *n*-in-*p* sensors R&D (HPK, FBK)
✓ Good charge collection efficiency on irradiated sensors
✓ Low active thickness

✓ Pixel size reduced by a factor 6 from 100 \(\times\) 150 \(\mu\text{m}^2\)
✓ Two pixel cells under study → 25 \(\times\) 100 \(\mu\text{m}^2\) or 50 \(\times\) 50 \(\mu\text{m}^2\)
✓ Various pixel design configurations
  ✓ Isolation → p-stop or p-spray
  ✓ Sensor test bias scheme → punch trough or temporary metal

Phase 1

| 285 \(\mu\text{m}\) |

Phase 2

| 100 \(\mu\text{m}\) - 150 \(\mu\text{m}\) |

50 \(\times\) 50 \(\mu\text{m}^2\)

25 \(\times\) 100 \(\mu\text{m}^2\)
✓ 3D pixel sensors R&D (FBK, CNM)
✓ In 3D sensors the drift path is perpendicular to the active depth
✓ Many advantages with respect to planar sensors
  ✓ Smaller bias voltage needed to deplete the sensor
  ✓ Lower probability of charge trapping in irradiated sensors
  ✓ Same charge produced
✓ Promising candidates for the high radiation environment of the inner layers and rings
RD53 ROC goals (see L. Demaria talk):

- Radiation hard (up to 5 MGy)
- Low thresholds and noise
- 65 nm technology & 50 × 50 μm² pixel size
- RD53A prototype (~½ size of the final chip) used for R&D
- Three analog front-ends (Synchronous, Linear, Differential)
- Good performance of all front-ends
- Compatible for the capacitance of both planar and 3D sensors (50 fF per channel)
- Planar and 3D sensors already tested with RD53A at test beams (CERN, DESY, FNAL)
- Sensors + ROC assemblies are compliant with half layer 1 and layer 2 radiation levels
  (See J. Schwandt and S. Gennai talks)
Readout chain

✓ DAQ interface
✓ 28 Data Trigger Control (DTC) boards required for the IT
✓ Communicates with on-detector electronics via low-power Gigabit Transceiver (LpGBT) optical links
✓ E-links connecting modules with LpGBTs which are placed in service cylinder (tolerable radiation levels)

✓ Up-links
✓ Data from L1 accept, monitoring info to DAQ and control system
✓ Up to 6 electrical up-links @1.28 Gb/s per module to LpGBT

✓ Down-links
✓ Clock, trigger, commands, configuration data to modules
✓ One electrical down-link @160 Mb/s per module from LpGBT
Performances

Material Budget

- **Phase-2 Tracker**
  - In front of IT sensors
  - Inside IT tracking volume
  - Between IT and OT
  - Inside OT tracking volume

- **LHC**

- **HL-LHC**

**Improved $p_T$ resolution**

**Improved $d_0$ resolution**

**Improved tracking in the jet core**

**Track reconstruction efficiency**

**CMS Simulation**

Simulated muons $p_T = 10$ GeV

- Phase-1 tracker
- Phase-2 tracker

**CMS Simulation**

Simulated muons $p_T = 10$ GeV

- Phase-1 tracker
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**14 TeV**

- Track from 1 event
  - $p_T > 0.9$ GeV, $|\eta| < 3.5$ cm

**QCD jets, no PU**

- $3$ TeV $< p_T < 3.5$ TeV
The CMS Inner Tracker Upgrade is extremely challenging

RD53A chip used for sensors R&D: studies of irradiated 3D and planar pixel sensors at test beams ongoing

25 × 100 μm² or 50 × 50 μm² and 3D/planar options still open

Final CMS pixel chip should be submitted in 2020

System level validation of serial powering, mechanics, cooling

Industry-like modules production

Thank you!
Backup
The CMS Detector

Superconducting Coil, 3.8 Tesla

CALORIMETERS
ECAL 76k scintillating PbWO4 crystals
HCAL Plastic scintillator/brass sandwich

IRON YOKE

TRACKER Pixels
Silicon Microstrips
210 m² of silicon sensors
9.6 M channels

MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)

Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m

2900 scientists from 182 Institutes from 38 countries

MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
The CMS Detector Upgrade

The CMS Detector Upgrade

CALORIMETERS

ECAL Barrel
Replace FE electronics

New Endcap Calorimeters
Radiation tolerant - high granularity
Investigate coverage up to $\eta = 4$

MIP TIMING LAYERS
Barrel: LYSO + SIPM
Endcaps: Low Gain Avalanche Diode

NEW TRACKER
Radiation tolerant - high granularity - less material
Tracks in hardware trigger (L1)
Coverage up to $\eta = 4$

TRIGGER/DAQ
L1 (hardware) with tracks and rate ~750kHz
Latency $\geq 10$ $\mu$s
HLT output up to 10 kHz

MUON
Replace DT FE electronics
Complete RPC coverage in forward region (new GEM/RPC technology)
Investigate Muon-tagging up to $\eta = 4$