The CMS Tracker Upgrade for the High Luminosity LHC

Martin Delcourt
on behalf of the Compact Muon Solenoid collaboration

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39th International Conference on High Energy Physics
The LHC will be upgraded in 2024 for a High-Luminosity phase

Great opportunity for physics but challenge for experiments

- High instantaneous luminosity
- High integrated luminosity
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Introduction

- To maintain the detector’s outstanding performance, its tracker (among others) will be upgraded

- The new tracker will need to:
  - **Be radiation tolerant**
    Total radiation dose 10x higher
  - **Have a higher granularity**
    Keep channel occupancy at percent level
  - **Reduce its material budget**
    Improves tracking performance
  - **Participate to Level-1 trigger**
    Necessary to stay effective
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Plan of the talk:

- Inner Tracker Upgrade
- Outer Tracker Upgrade
- New layout and expected performances
- L1 tracking

Sketch of one quarter of the current (phase 1) CMS tracking system.

Pixel detector, single sided and double sided strip modules.
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Inner tracker

- Radiation tolerance is key for the inner tracker
  - Up to 1.2 Grad and $2.3 \times 10^{16} \text{n}_{eq}/\text{cm}^2$ for 3000 fb$^{-1}$
  - Possibility of replacement if needed

- Two n-in-p type sensors are being considered
  - Thin (100-150 µm) planar sensors
  - 3D sensors, higher radiation tolerant but more expensive

→ Would be limited to highest fluence regions

Planar sensor

Charge (electrons)

Number of entries

$10^3$

$2 \times 10^3$

$1 \times 10^3$

$0$

Charge (electrons $\times 10^3$)

$30$

$25$

$20$

$15$

$10$

$5$

$0$

Fit: Landau + Gaussian

$\chi^2 / \text{ndf} = 1080 / 286$

Width (e$^-)$ $422.1 \pm 4.2$

MPV (e$^-)$ $5722 \pm 7.4$

Noise (e$^-)$ $1387 \pm 7.8$

p$^+$ irrad to $1.2 \times 10^{15} \text{n}_{eq}/\text{cm}^2$

$V_{bias} = 300 \text{V}$

Temperature $= -20 ^\circ \text{C}$

3D sensor

Charge (electrons $\times 10^3$)

Number of entries

500

400

300

200

100

$0$

$10$

$20$

$30$

$40$

$50$

$60$

MPV $= 16 \text{k electrons}$

$25 \times 100 \times 230 \ \mu\text{m}^3$

p$^+$ irrad to $5.7 \times 10^{16} \text{n}_{eq}/\text{cm}^2$

$V_{bias} = 180 \text{V}$

Temperature $= -25 ^\circ \text{C}$

120 GeV $\pi^+/p^+$ beam
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Inner tracker

• To keep a low occupancy in the inner tracker, smaller pixels are considered.
  - 50x50 µm or 25x100 µm (6 x smaller than now)

• **Pixel Read Out Chip (PROC)** will have to be radiation hard and cope with a hit rate up to 3 GHz/cm²
  - Being developed within RD53 (CMS-ATLAS collaboration)

• Two different flavours, **one** or **two** rows of two PROCs (~16.4x22.0 mm²)
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Outer tracker

- For L1 triggering, data has to be sent for every bunch crossing
  - Full data would exceed bandwidth
  - **Data reduction is needed at detector level**
    2GeV cut → data reduction of 10x to 100x

- High transverse momentum tracks can be selected by correlating hits on two sensors
  - "Stubs" read-out at 40MHz
  - **Full data** read-out if triggered (~750kHz)
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Outer tracker

- Outer tracker modules:
  - Planar n-in-p, 200µm thick sensors
  - Binary read-out chips
  - Zero-suppression and data aggregation at module level

- **2S** strip modules
  - 2x1016 strips ~5cm x 90µm
  - 2x1016 strips ~5cm x 90µm

- **Pixel** strip modules
  - 2x960 strips ~2.4cm x 100µm
  - 32x960 macro-pixels ~1.5mm x 100µm
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Outer tracker

- Prototypes are being tested and characterized in beam
  - **Stubs are correctly produced** (p_T emulated by rotating module in beam)
  - High efficiency
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Current layout

Sketch of one quarter of the *current* (phase 1) CMS tracking system
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New layout

Sketch of one quarter of the phase 2 CMS tracking system

- Tilted barrel to optimize stub efficiency
- Reduction of material budget
- Extended eta coverage from to $|\eta| \leq 4$
  - Increases forward acceptance
  - Mitigates pile-up effects in forward region
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Expected performances

- Full Monte-Carlo simulation

- Significant improvement expected in \( p_T \) and \( d_0 \) resolution

- 90% tracking efficiency for tracks from \( \text{tt} \) events with < 2% fake rate

- Work in progress!
  - Geometry is being optimized
  - Efficiency at \(|\eta| \sim 1.2\) is being addressed
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L1 track finding

- Tracking at L1 is a challenging task
  - Tracks need to be produced within ~ 5µs
  - Two different all-FPGA solutions are considered

- Tracklet approach
  - “Tracklets” formed from stubs in adjacent layers
  - Extrapolate to tracks, minimize chi² (linearised chi² fit)
  - Remove duplicates

- Hough transform approach
  - Select track candidate through Hough transform
  - Minimize chi² (Kalman Filter)
  - Remove duplicate
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L1 track finding

- Demonstrators were set-up for both approaches
  - Simulated event used as input
  - Similar results obtained
  - Tracks produced within timing constraints

- Work being done to merge approaches
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Summary

• The phase-2 tracker upgrade is necessary in order to maintain the detector performance

• The new design will allow to keep tracking performance under a high pile-up and radiation environment

• Tracks will be sent to the CMS level-1 trigger at 40 MHz

• Design is well advanced
  - many prototypes have been produced and tested
  - the upgrade concepts have been validated
  - mechanics, integration and installation concepts well advanced

• Final prototyping and EDR are awaiting us!
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Backup – Why do we need a track trigger?
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Backup – Hough transform
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Backup – Tilted barrel stub efficiency
Figure 11.4: Schematics of the 2PACL cooling system concept as used in the CMS pixel Phase-1 upgrade.
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Backup – Mechanical view
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Backup – Read out

Pixel region: 2x2 (1x4 or 4x4)
Pixel core: 8x8 pixels
Pixel array: 22x16.4mm² = 144k pixels of 50x50um²

SLDO
DAC
DAC
Config
Config
region proc
B-ID tag
B-ID
Trigger match
Link Int.

Compress
Format
Readout Interface

ECC: End Of Column 22mm

25 modules
FE hybrid L
FE hybrid R

HV
LV
LV/HV PS
CTRL
TTC
DAQ

FE
BE
m-Tx
m-Rx
LPGBT
FPGA
Process & Route

L1 track-finding

Pattern recognition
Track fit
Result
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Backup - Outer tracker sensor irradiation

**Graphs:**
- **Graph 1:**
  - Title: n-in-p type ddFZ silicon after 20 weeks of annealing
  - X-axis: Voltage (V)
  - Y-axis: Seed signal (e⁻)
  - Data points:
    - 200µm 6x10⁶ n⁺/cm² (p)
    - 200µm 7x10⁶ n⁺/cm² (p+p)
    - 240µm 6x10⁶ n⁺/cm² (p)
    - 300µm 7x10⁶ n⁺/cm² (p+p)

- **Graph 2:**
  - Title: n-in-p type ddFZ silicon after 20 weeks of annealing
  - X-axis: Voltage (V)
  - Y-axis: Seed signal (e⁻)
  - Data points:
    - 200µm 1.5x10⁷ n⁺/cm² (p+p)
    - 240µm 1.0x10⁷ n⁺/cm² (p)
    - 300µm 1.0x10⁷ n⁺/cm² (n)

**Additional Graph:**
- Title: Stub efficiency
  - X-axis: p_T (GeV)
  - Y-axis: Stub efficiency
  - Data points:
    - Non-irradiated placed at a radius = 68.8cm
    - Irradiated to 6x10⁶ n⁺/cm² placed at a radius = 60cm
    - Irradiated to 6x10⁶ n⁺/cm² placed at a radius = 60cm
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Backup - Outer tracker beam test