The CMS Tracker Upgrade for the High-Luminosity LHC

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on behalf of the CMS Collaboration
The HL-LHC scenario

- Goal: collect 3000/fb (optionally 4000/fb) in about 10 years of operations (2026-2039) with a peak luminosity of \(7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}\)
  - Increase of \(\mathcal{L}_{\text{inst}}\) => at 25 ns BX, 200 pileup vertices and \(O(10^4)\) tracks per event
  - Increase of \(\int \mathcal{L}_{\text{inst}} \, dt\) => unprecedented hostile radiation environment

- Expected fluence up to \(2.3 \times 10^{16} \text{ 1-MeV } n_{\text{eq}} /\text{cm}^2\) or TID 12 MGy
  - NB: \(\approx 0.6 \times 10^{14} \text{ 1-MeV } n_{\text{eq}} /\text{cm}^2\) fluence as at \(r=20\) cm in current Tracker after 200/fb
<table>
<thead>
<tr>
<th>REQUIREMENT</th>
<th>IMPLEMENTATION</th>
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<tbody>
<tr>
<td>Contribute to L1 trigger</td>
<td>Measure $p_T &gt; 2$ GeV tracks at 40 MHz</td>
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<td>Compatible with the upgraded CMS L1 trigger</td>
<td>Large readout bandwidth and deep front end buffers</td>
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<tr>
<td>● 750 kHz L1 accept trigger rate</td>
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<td>● 12.5 $\mu$s L1 accept latency</td>
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<td>Robust two track separation in high energy jet</td>
<td>High granularity</td>
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<td></td>
<td>● 0.1% occupancy in the Inner Tracker</td>
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<td>● 1% occupancy in the Outer Tracker</td>
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<td>Efficient pileup mitigation</td>
<td>Extended coverage up to $</td>
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<tr>
<td>Improve tracking performance/momentum resolution measurement</td>
<td>Low material budget</td>
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<td>Radiation tolerance up to 3000/fb</td>
<td>● Operations at -20 °C</td>
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<td></td>
<td>● Rad-hard sensors and ASIC</td>
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<td></td>
<td>● Option of replacing the innermost layer of barrel pixel at half the nominal dose</td>
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The CMS Tracker for HL-LHC

- **Outer Tracker**: main detector for retaining the L1 trigger thresholds low enough to be fully efficient for the electroweak physics
  - **PS**: (macro)pixel-strip modules
  - **2S**: strip-strip modules

- **Inner Tracker**: main detector for pattern recognition
  - **1x2 chip (hybrid)pixel modules**
  - **2x2 chip (hybrid)pixel modules**
- TBPX: 4 barrel layers (4+5 modules/ladder) no projective gap at $|\eta|=0$
- TFPX: 8x2 small discs (4 rings/disc)
- TEPX: 4x2 large discs (5 rings/disc)

**Design guidelines:**
- Simple mechanics (no turbines or tilted modules)
- Two types of module only: 1x2 or 2x2 chips
- Fully accessible for maintenance and repair

- Silicon surface 4.9 m$^2$ and 2x10$^9$ channels
IT sensors

- Small pixel cells (1/6 of the pixel cell of the current CMS pixel detector) with two possible aspect ratios (25x100 μm$^2$ and 50x50 μm$^2$) both compatible with the same bond pad pattern

Technology:
- Planar n-in-p sensors (baseline)
  - Efficient charge collection after irradiation
    - Thin (100-150 μm active thickness)
    - High bias (800-1000V) => spark protection between the ROC and the sensor

- 3D sensors (option for the innermost modules)
  - Low bias (150 V) required for efficient charge collection after irradiation
  - Larger cell capacitance (up to 50 fF)

Final choice on cell aspect ratio and sensor technology still to be taken
IT readout chip

- ROC developed by CERN/RD53 collaboration
  - Radiation tolerant (TID 12 MGy)
  - High hit (3.2 GHz/cm²) and trigger rate (4x1.28 Gb/s output links)
  - Low threshold (1000e)

- First prototype (RD53A) delivered in 2018 for qualification
  - ½ size of the final chip
  - 3 different architectures for the analog FE, all working
  - Fully functional after 5 MGy
**IT ROC on a test bench**

- Hit rate capability measured in the lab with an X-ray source (isolated hits)

![RD53A Measurement vs. simulation](image)

- Simulation reproduces the separate contributions of hit losses due to the digital buffer and to the dead time
- ROC expected to meet the design specs (99% efficiency at 3.5 GHz/cm²) with clustered hits

**Measured hit losses at 3.75 μs latency (dead time)**

**Measured hit losses at 12.5 μs latency (digital buffer overflow)**
### IT single ROC+sensor assemblies

- Intense beam-test campaign on RD53A+irradiated sensor assemblies

- Example of results: efficiency maps for
  - 3D sensors (FBK, 130 μm thickness) irradiated up to $1 \times 10^{16}$ 1-MeV n$_{eq}$/cm$^2$
  - beam test at CERN H6, 120 GeV proton beam at normal incidence

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<tr>
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<th>25x100 μm$^2$ (1E)</th>
<th>50x50 μm$^2$ (1E)</th>
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<tbody>
<tr>
<td>Before irradiation</td>
<td>97.3 % (HV=3 V)</td>
<td>98.6% (HV=15 V)</td>
</tr>
<tr>
<td>After irradiation target fluence $1 \times 10^{16}$ 1-MeV n$_{eq}$/cm$^2$</td>
<td>96.6% (HV=120 V)</td>
<td>97.5% (HV=150 V)</td>
</tr>
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IT modules and powering scheme

- **Two main concepts:**
  - Only two types of modules (1x2 and 2x2 chips) with a simple design
  - Serial powering to reduce power loss in the cable with an acceptable cable mass

Extra complexity in the design:

- Low Drop Out regulator integrated in the ROC to convert the input current into a constant input voltage (1.2V)
- 2 (4) chips in one module connected in parallel => shunt on-chip to absorb the extra current in case of a failure of a chip
- 2 ShuntLDO per chip (analog + digital domain): ROC and module cooling circuit designed for an efficient cooling of the hotspots

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Sensor
ROC
High Density Interconnect
No extra ASICs

\[\text{Power Supply} \sim 1.5V \cdot n\]

\[n \sim 8-12\]
Outer Tracker: pT module concept

- Exploit the high B-field (3.8 T) of the CMS solenoid
- Modules made of two silicon sensors with a small spacing (from 1.6 mm up to 4 mm)
- Flex hybrid to route data from both sensors to one ASIC which performs cluster correlation between top/bottom sensor in a programmable search window
  Correlated clusters from high pT tracks => “stubs”
- Stubs are readout at each BX (40 MHz) and sent to L1 track finder

No other aggregator cards between the module and the back-end

OT modules are self-contained units
OT intelligent layout

- Tilted barrel geometry fully efficient for inclined track stubs otherwise crossing top/bottom sensors in different modules
- Sensor spacing optimized in the different regions to guarantee efficient turn-on curves for stubs from pT=2 GeV tracks
OT modules

- **Two types of modules:**
  - 2S: 2 sensors with 2 rows of 5cm x 90μm AC coupled strips
  - PS: 1 sensor with 2 rows of 2.4cm x 100μm AC coupled strips
    1 sensor with 1.5mm x 100μm DC coupled macro-pixels

- **Modules are self-contained units:**
  - Front-End Hybrid: readout and concentrator ASICs
  - Service Hybrid: DC-DC converter + data-link
  - Sensors
  - Al-CF spacer

- Correct stub finding poses stringent requirements on the accuracy of the mechanical assembly (max rotation in 2S modules: Δφ<400 μrad)
OT sensors

- OT has a binary readout electronics

The figure-of-merit is the charge collected on a single seed-channel

- **Strip**: ENC is 1000e for CBC chip (2S module), 700e for SSA chip (PS-s module)
  - Thin sensors (200-240 μm) operated at nominal bias (600V) provide enough charge after irradiation even at 1.5x the expected fluence (10% more charge in 240 μm sensors)
  - Charge on seed-strip is stable vs. annealing time for thin sensors
- **Macro-pixel**: ENC is 200e for MPA (PS-p module) => less stringent requirements
  Thin sensors (200 μm) sufficient
Data from 72 OT modules are sent to 1 DTC board which unpacks the stubs and converts the information from local to global coordinates.

Track Finder Processor receives data sliced in space and time (time-multiplexing: 1 event for 1 TFP node) and performs pattern recognition and track finding using commercially available FPGAs.

Two different approaches for pattern recognition and track fitting developed and verified in real life on two TFP hardware demonstrators => latency below the 4 μs spec (time budget for L1 track finding) for both.

More details in Tom James's talk on Thursday.
Material budget

- Huge effort to limit the amount of passive material despite the huge power required (IT: 50 kW, OT: 100 kW)
  - optimized layout (reduced number of layers/discs and better orientation of the modules)
  - optimized powering scheme (serial powering in IT, DC-DC converters in OT)
  - optimized routing of the services from the early stages of the design of the detector
  - choice of evaporative CO$_2$ cooling (small diameter/low mass pipes)
Design tracking performance

- Guarantee fully efficient tracking in high pileup conditions with resolution on offline track parameters as good or better than the current tracker and on extended η range.
Summary

- The upgraded CMS Tracker for HL-LHC will be a key ingredient for the CMS physics program after 2026
- In all the critical areas the project is moving from the R&D phase to the construction of demonstrators fully functional in the extreme conditions of HL-LHC
- Numbers of the project are huge (3892 IT modules + 13296 modules in OT)

Challenges ahead of us
- large scale/high quality production of the components
- extreme care in system and integration aspects
EXTRA SLIDES
HL-LHC and CMS Tracker upgrade timeline

[Diagram showing a timeline and plan for LHC / HL-LHC phases with specific milestones and timelines.]
IT modules and powering scheme

- Pixel-by-pixel difference of the noise between parallel powering and serial powering (4 RD53A chips) => no deterioration when operating in chain
- Distribution of the HV ground for modules in the same chain under investigation