The CMS Tracker for the High Luminosity LHC

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22-28 May 2022
La Biodola – Isola d’Elba (Italy)
LHC Schedule

- High Luminosity upgrade after LS3
- Peak Luminosity \( \sim 7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \)
- Expected Pile-up \( \sim 200 \)
- Higher rates and radiation dose wrt Run3
- Crab cavities
- (some) New Magnets (11T)
- Civil engineering:
  - New access shafts
  - New service tunnels
- ...and more!

### 2021 - 2028

<table>
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<tr>
<th>Year</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
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- **Long Shutdown 3 (LS3)**

### 2030 - 2038

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<th>2030</th>
<th>2031</th>
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- **Run 4**
- **LS4**
- **Run 5**

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**Legend:**
- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training
High Luminosity Requirements

- **Increased granularity**: In order to ensure efficient tracking performance with a high level of pileup
- **Reduced material in the tracking volume**: The exploitation of the high luminosity will greatly benefit from a lighter tracker
- **Contribution to the level-1 trigger**: The selection of interesting physics events at the first trigger stage becomes extremely challenging at high luminosity
- **Extended tracking acceptance**: The overall CMS physics capabilities will greatly benefit from an extended acceptance of the tracker
- **Radiation tolerance**: The upgraded tracker must be fully efficient up to a target integrated luminosity of 3000fb$^{-1}$
  - Outer layers “far away” from interaction point will see $>10^{14}$MeV neutron equivalent fluence
    - more than innermost strip tracker layers at 20 cm for today’s trackers after 10 years of LHC running
Why change the current Tracker

• Radiation damage at the end of Run3
  o A big part of current strip tracker will become completely in-operational due to either leakage current or full depletion voltage limitations at 1 ab\(^{-1}\)
  o Pixel detector need to handle a factor 6 higher hit rate (from 0.58 to 3.2GHz/cm\(^2\)) and need an higher granularity

• Full tracker replacement needed for HL-LHC program
Also a dedicated poster: *The CMS Pixel Detector for the High Luminosity LHC* - Antonio Cassese
Phase-2 CMS Inner Tracker

- **TBPX**: Tracker Barrel PiXel
  - 4 Layers, no crack at z=0

- **TFPX**: Tracker Forward PiXel
  - 8 small disks on each side

- **TEPX**: Tracker Endcap PiXel
  - 4 large disks on each side

Extended coverage up to $|\eta| = 4$

Innermost modules located at $r=2.75\text{cm}$ form the beamline
Modules

- Two types of Pixel Modules
  - 1x2 and 2x2 readout chip

- 3892 module plus spares (1156 1x2, 2736 2x2)
  - 2 Billion pixel (124 million in current detector)

- Read Out Chip (ROC) only active element on module

- Components:
Modules

- Two types of Pixel Modules
  - 1x2 and 2x2 readout chip
  - 3892 module plus spares (1156 1x2, 2736 2x2)
  - 2 Biolln pixel (124 million in current detector)
- Read Out Chip (ROC) only active element
- Components:
Sensors

- Intese R&D program carried out
  - Several report on posters:
    - *Characterization of irradiated passive CMOS sensors for tracking in HEP experiments* - Franz Glessgen
    - *Performance of highly irradiated FBK 3D and planar pixel detectors* - Rudy Ceccarelli
    - *Study of irradiated 3D pixel sensors from CNM* - Clara Lasaosa Garcia

- 25x100cm$^2$ pixel cells with 150µm active thickness

- 2 different technology will be adopted
  - n-in-p planar sensors
    - Bitten implant, no punch-through bias dot
    - Hit efficiency >99% after $2\times10^{16}$ n$_{eq}$/cm$^2$
  - 3D pixel sensors on Barrel layer1
    - Better power consumption
    - Stable hit resolution performances up to $10^{16}$ n$_{eq}$/cm$^2$
C-ROC

• ASIC based on CMOS 65nm technology (CERN RD53 project)
  o Radiation tolerant up to 1 Grad
  o Strongly protected against SEU effects
  o Low power consumption < 1 W/cm²
    • At CMS Level1 trigger rate of 750 kHz
  o Serial powering via on-chip shunt-LDO regulators (1 for analog, 1 for digital sections)

• CMS flavor of RD53 ROC : C-ROC
  o First wafer level test performed
    • All details on poster: Wafer level test of the readout chip of the CMS Inner Tracker for HL-LHC - Michael Grippo
  o Full size ASIC: 432x336 channels
  o Analog FE linear architecture
  o 4 bit digital readout with selectable 6-to-4-bit dual slope ToT mapping for charge compression (elongated clusters, heavy ionizing particles)
Read out architecture

- Comunication electronics hosted on dedicated board:
  - Portcards optoelectronic service card
- Portcard houses 3x IpGBTs and VTRx+ links, powered via cascaded DC-DC converters
- Up to 6 electrical up-links at 1.28 Gb/s $\rightarrow$ module to IpGBT
  - Rates reduction achieved with data formatting
- One electrical down-link at 160 Mb/s $\rightarrow$ IpGBT to module
  - clock, trigger, commands, configuration data to modules
- 28 Data Trigger Control boards required for inner tracker
Powering scheme

- Supply the needed 50 kW with a limited mass of the power cables → SERIAL POWERING
  - Modules grouped in 500 serial power chains, up to 12 modules in a chain
    - Modules powered in series, chips within each module powered in parallel
    - A shunt-LDO (SLDO) on each chip provides voltage regulation for each chip while maintaining a constant current
  - Chips in a module in parallel (4A for 1x2 modules, 8A for 2x2 modules)
  - Sensor bias following the serial power chains with single return line
  - Single power supply module: current source (SP), HV for sensor (0-800V), LV for portcards and pre-heaters required by CO2 cooling
Mechanical Structure

- Light Carbon Fiber structures with embedded cooling pipes
- Disks with flat geometry (unlike turbine in current detector)
- Improved fiber routing which reduces radiation induced attenuation
- Cooling based on evaporative CO\(_2\) (T=-35°C) distributed in 1.8 mm outer diameter stainless steel pipes (168 cooling loops)
OUTER TRACKER
Phase-2 CMS Outer Tracker

- **TBPS**: Tracker Barrel with PS modules
- **TB2S**: Tracker Barrel with 2S modules
- **TEDD**: Tracker Endcap Double Disk
Phase-2 CMS Outer Tracker

- Outer Tracker coverage up to $\eta \sim 2.5$
  - Tracking up to $\eta \sim 4$ thanks to InnerTracker

- Two different type of technology: micro-strips and macro-pixels

- Tilted barrel geometry
  - Better trigger performances
  - Reduction on number of modules
Tracks for L1 Trigger

- HL-LHC will deliver an high instantaneous luminosity with a high PileUp
  - It’s fundamental to be more selective at L1 trigger in order to keep data rate under control

- Include Tracks on L1 decision

- Most of charged particles have low $p_T$

- Perform a $p_T$ selection at readout level in order to reduce the L1 tracking input data size

- pT Modules

  - Two silicon sensors with small spacing in a module
  - Flex hybrid in order to get data from both sensors to one ASIC → Select track «stubs»
  - Different sensor spacing for different detector region
  - Tunable correlation windows

- Track Trigger

  - Associate track to stubs from OT layers and extract $p_T$ measurement
  - Trigger events based on track $p_T$ at L1
Phase-2 Tracker Modules

- Two type of modules:
  - 2S Modules
    - 2 different spacing: 1.8mm & 4mm
    - 2 micro strip sensors with 5cm x 90μm strips
    - Sensor dimension are 10cm x 10cm
      - two column of 1016 strips
  - PS Modules
    - 3 different spacing: 1.6mm & 2.6mm & 4mm
    - One strip sensor: 2.5cm x 100μm strips
    - One macro Pixel sensor: 1.5mm x 100μm pixels
    - Sensor dimension 5cm x 10 cm
      - two column of 960 strips
      - 32x960 pixels
Phase-2 Tracker Modules

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  - 2 different spacing: 1.8mm & 4mm
  - 2 micro strip sensors with 5cm x 90μm strips
  - Sensor dimension are 10cm x 10cm
  - Two columns of 1016 strips
  - ~30k pixels

- PS Modules
  - 3 different spacing: 1.6mm & 2.6mm & 4mm
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  - Sensor dimension 5cm x 10cm
  - Two columns of 960 strips

First prototypes (with almost final chips and hybrids) assembled this year → now it’s time to test and test and test…
Modules Service Systems

- Module houses both frontend and service hybrids

- Service hybrid(s) has:
  - IpGBT
    - Low Power Gigabit Transceiver
  - VTRx+
    - Versatile Link Plus Transceiver
  - DCDC converters

- Frontend hybrids have readout chip and data concentrator
Modules Service Systems

- Module houses both frontend and service hybrids

Each module is a functional unit individually connected to:
- backend power system
- DTC (Data, Trigger and Control) system via Optical link
- no token control rings
- no intermediate power grouping

- Frontend hybrids have readout chip and data concentrator
Modules ReadOut

- **2S Module ASICS**
  - CMS Binary Chip (CBC) for readout and stub finding for L1
    - both sensors read out by same chip
    - Detailed description on poster: *Studies of the CBC3.1 readout ASIC for CMS 2S-modules* – Kirika Uchida – Geoff Hall
  - 254 channels per chip
    - 127 from each sensor
    - Implemented in 130 nm technology

- **PS Module ASICS**
  - Macro-Pixel ASIC (MPA) and Short-strip ASIC (SSA) for readout of sensors
  - Stub finding performed by MPA
    - SSA sends cluster and L1 information to MPA to enable match in space and time
  - Both chips done in 65 nm technology

- **Common ASIC:**
  - CIC concentrator chip
    - Receives L1 information and readout data
  - “Data hub” to service hybrid
  - Done in 65 nm technology
Backend

- **DTC (Data, Trigger and Control)** boards readout and control module
  - ACTA standard
  - Details on poster: *The DAQPATH readout system of the Serenity boards for the CMS Phase-II Upgrade* – Paolo Prosperi

- Bi-directional optical links
  - **2.56 Gb/s DTC → Module**
    - clock, trigger, fast-commands and programming
  - **5.12 or 10.24 Gb/s Module → DTC**
    - L1 and DAQ data

- L1 data at 40 MHz
- DAQ data (after L1) at 750 kHz
Powering & Cooling

- Large Area + High Granularity

High Power Budget: Outer Tracker ~100kW

Parallel Powering with on-module conversion

Powerful cooling system:
- (4+1) x 50W cooling plants
- based on two-phase CO\textsubscript{2} cooling system (-35°C set point)
- small pipes
Material Budget

- Material budget much reduced wrt Phase0/1 detector despite an increase in the number of channels

- DCDC converters
- Fewer layers
- Lighter materials
- Optimized service routing
- CO2 cooling
- Inclined geometry
Performances: Phase-1 vs Phase-2

- Track parameters resolution of Phase-2 tracker improve wrt Phase-1
  - Higher granularity and less material
- Significant extension at higher $\eta$

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22-28 May 2022

15TH PISA MEETING ON ADVANCED DETECTORS
Performances: High PileUp

- High tracking efficiency (~90%) also at 200PU
  - Fake rate below 2(4)% at 140(200)PU

- Dip around $\pm 1.2\eta$ due to Barrel/endcap transition in Inner Tracker
  - Due to TDR geometry, reduced by a factor $\sim 2$ with optimized geometry
Conclusions

• Ambitious upgrade project underway for the CMS Outer Tracker for the HL-LHC running
  o Designed to maintain or improve tracking performance compared to current system even in the presence of up to 200 pile-up events
  o Tracks above 2 GeV as L1 primitives at 40MHz

• Improvements result in the tracker being more performant and yet more light-weight compared to its predecessor

• Advanced layout and integration studies

• First fully equipped modules prototype in 2022

• ...a long way toward HL-LHC!
Backup
Inner Tracker insertion

- Two ladder of each Barrel Pixel layer skewed in \( r\phi \)
  - This will allow the detector insertion and removal without any action on the beam pipe
Mechanics

- **TBPS**
  - Flat Part: planks
  - Tilted Part: rings

- **TB2S**
  - Ladder support structure

- **TEDD**
  - Building block: DEE (half disk)
  - Double-Disk to be hermetic also with rectangular modules

<table>
<thead>
<tr>
<th>Module type and variant</th>
<th>TBPS</th>
<th>TB2S</th>
<th>TEDD</th>
<th>Total per variant</th>
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<td>4464</td>
<td>5960</td>
<td>13296</td>
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Sensors

- Silicon sensors will be produced by Hamamatsu
  - n-in-p sensors
    - Showed better behavior after irradiation
- HPK lost confidence in deep diffused material as substrate for mass production
  - baseline for TDR
- Options left:
  - standard material: 320µm physical and 290µm active (FZ290)
    - same material as in the current tracker
  - thinned material with physical ~ active thickness (thFZ240)
    - same substrate as FZ290, but backside ground down to desired thickness, followed by polishing
    - more expensive
• Irradiation campaign to study the sensors behavior and perform a technology choice:
  o Take nominal expected max. fluences for outer (2S) and inner (PS) regions after 3000 fb⁻¹
  o Consider the approximate mixture of neutrons and charged hadrons

• Expected max. 2S fluence after 3000 fb⁻¹
• Signal measurements:
  • thFZ240 barely reaches 2S limit
  • FZ290 is well above

• Expected max. PS fluence after 3000 fb⁻¹
• Signal measurements:
  • thFZ240 only just above PS-s limit
  • FZ290 comfortably above with 800V
Sensors

• Irradiation campaign to study the sensors behavior and perform a technology choice:
  o Take nominal expected max. fluences for outer (2S) and inner (PS) regions after 3000fb⁻¹
  o Consider the hadrons mixture:
    • There is not a clear benefit of thFZ240 over the standard FZ290
    • FZ290 show excellent performance under the foreseen operation conditions

CMS will use FZ290 sensors for the entire Outer Tracker

• Expected max. 2S fluence after 3000fb⁻¹
• Signal measurements:
  • thFZ240 barely reaches 2S limit
  • FZ290 is well above

• Expected max. PS fluence after 3000fb⁻¹
• Signal measurements:
  • thFZ240 only just above PS-s limit
  • FZ290 comfortably above with 800V
Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module.

This is not true for (flat) barrel peripherical modules.

\[ \rightarrow \] (increasingly) Tilt peripherical barrel modules.
Tilted Barrel Geometry

• Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module

• This is not true for (flat) barrel peripherical modules

→ (increasingly) Tilt peripherical barrel modules

• Sizable reduction on the number of modules needed

→ From ~15k (flat) to ~13k (tilted)
Some highlights from beam tests

- Different module prototypes tested in particle beam
  - 2S
    - Full size module and mini-module has been tested
    - No services and no data Concentrator
    - Stubs finding capabilities tested
      - Magnetic bending «simulated» with module rotation
  - PS
    - Single sensor (pixel) with MPA readout
      - No stub info
    - MPA+SSA intercommunication was tested on bench
Irradiated Sensors at Beam Test

- Sensor irradiated with neutron only at JSI
- CBC3 readout chip (almost final)
- Charge collection reflected in hit efficiency as a function of threshold
  - FZ290 can tolerate higher thresholds
  - Only after long annealing (200 days) at ultimate $5 \times 10^{14}$ neq/cm² both materials are comparable
- dark noise occupancy was measured:
  - lower than $10^{-5}$ while expected hit occupancy is $\sim 10^{-2}$
  - Scale with annealing (current) and not with thickness