THE CMS OUTER TRACKER UPGRADE FOR THE HIGH LUMINOSITY LHC

V. Mariani for the CMS Collaboration
The LHC Schedule

- High Luminosity LHC is expected to start after LS3:
  - Peak luminosity up to $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  - Expected integrated luminosity $\sim 3000$ fb$^{-1}$
  - PU up to 200 interactions per bunch crossing
- Higher radiation doses for detector

We are here
An intense upgrade programme is foreseen for the whole experiment

**New design and technology are required to fully exploit the HL-LHC scenario!**
The current CMS tracker was designed to operate up to an integrated luminosity of 500 fb$^{-1}$, and an average PU of < 50. It could not operate in HL-LHC scenario due to either leakage current or full depletion voltage limitations at 1 ab$^{-1}$ => a new tracker detector is needed for CMS

Requirements:
- High granularity
- Reduced material budget
- **Contribution to the L1 trigger**
- Extended acceptance
- Radiation tolerance
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Outer layers “far away” 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
THE NEW CMS TRACKER DETECTOR

Current tracker (phase 1)

Phase 2 tracker
The new CMS Tracker detector

- The OT coverage will be up to $\eta \sim 2.5$ -> global tracking up to $\eta \sim 4$ thanks to IT
- Tilted barrel geometry for better trigger performances and reduction of the number of modules
- **pT modules** will be used with two different type of technologies: macro-pixels and micro-strips
THE CONCEPT OF $p_T$ MODULES

- The target L1 rate ~ 750 kHz with a trigger latency of 12.5 µs
- Keep data rate under control in high luminosity && large PU scenario is challenging

Tracks will be used in the L1 decision

Since most of the tracks have low $p_T$ the idea is to perform a selection on track $p_T$ at module level to reduce the L1 tracking input size
The concept of $p_T$ modules

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The new modules will be capable rejecting signal from particles below a certain $p_T$ threshold $\Rightarrow$ $p_T$ modules

Two single-sided closely-spaced sensors read out by a common set of front-end ASICs that correlate the signals and select the hit pairs $\Rightarrow$ stub

Different sensor spacing for different detector region and tunable correlation windows

With a 2GeV threshold, a data reduction by an order of magnitude is achieved enabling stub readout at 40MHz
**OUTER TRACKER MODULES**

**PS module**
1 macro pixel + 1 micro strip sensor

3 different spacing: 1.6mm, 2.6mm & 4mm
Strip sensor with 2.5 cm x 100µm strips
Pixel sensor with 1.5 mm x 100µm pixels
Sensor dimension are 5 cm x 10 cm:
two column of 960 strips + 32x960 pixels

**2S module**
2 micro strip sensors

2 different spacing: 1.8mm & 4mm
Both micro strip sensors with 5cm x 90µm strips
Sensor dimension are 10cm x 10cm:
two column of 1016 strips
Module houses both frontend and service hybrids

- Service hybrid(s) has:
  - IpGBT = low powering Gigabyte Transceiver
  - VTRx+ = versatile Link Plus Transceiver
  - DCDC converters

- Frontend hybrids have readout chip and data concentrator

- 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
**OUTER TRACKER MODULES – READOUT**

**PS Module ASICS**
- PS modules readout by MPA and SSA chips
- Short Strip ASIC (SSA)
  - Reads strip data
- Macro-pixel ASIC (MPA)
  - Reads macro-pixel data
- MPA receives the clusters from SSA and forms stubs.

**2S Module ASICs**
- 2S modules readout by CMS Binary Chip (CBC)
- Both sensors read out by same chip
- 254 channels per chip

**Common ASIC**
- Data from the CBC/MPA are formatted by Concentrator Integrated Circuit (CIC) chips.
- 2CIC chips per module
- Packs data for 8 bunch crossings
- Priority to Trigger data.
OUTER TRACKER SENSORS

- Silicon sensors will be produced by Hamamatsu
  - n-in-p sensors

- Extensive irradiation and characterization campaign was undertaken to study the different sensor choices
  - FZ290: 290 µm active thickness (Same material as current tracker)
  - FZth240: 240 µm active thickness -> thinned material with physical ~ active thickness

Signal measurements:
- FZth240 barely reaches 2S limit
- FZ290 is well above

Signal measurements:
- FZth240 only just above PS-s limit
- FZ290 is well above
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There is not a clear benefit of FZth240 over the standard FZ290. FZ290 show excellent performance under the foreseen operation conditions.

CMS will use FZ290 sensors for the entire Outer Tracker.
Phase 0/1 → Phase 2

Material budget much reduced wrt Phase0/1 detector despite an increase in the number of channels thanks to:
- Fewer layers
- Lighter material
- Optimised service routine
- CO2 cooling
- Inclined geometry
OUTER TRACKER: TILTED GEOMETRY

Stubs generation works only if the charged particle cross the two sensors on the same half of the same module.

This is not true for (flat) barrel peripheral modules → Tilt peripheral barrel modules introduced for this reason.

Sizable reduction on the number of modules needed → From ~15k (flat) to ~13k (tilted)
PERFORMANCES: PHASE 1 VS PHASE 2

Comparing tracking efficiency and track parameters resolution between Phase 1 and Phase 2 tracker an improvement is shown thanks to higher granularity and less material.

Significant extension at higher $\eta$
Comparing two different scenario of high PU: \( <\text{PU}> = 200 \) and \( <\text{PU}> = 140 \) in terms of tracking efficiency and fake rate.

Almost the same tracking efficiency between the two scenario but the fake rate increase by a factor 1.5 – 2 at higher \( <\text{PU}> \) value.
CONCLUSION

- The Phase2 upgrade of the CMS tracker is an important project to ensure efficient performance of the CMS detector in the HL-LHC era.

- Designed to operate even at high pileup environment ~200 keeping excellent performances despite the challenging radiation level foreseen.

- Participate in L1 trigger decisions
  - Tracks above 2 GeV as L1 primitives at 40MHz

- Improvements result in the tracker being more performant and yet more lightweight compared to its predecessor

- Advanced layout and integration studies

**Looking forward to Phase 2!**
BACKUP
UPGRADE FOR LHC:

- Reduction of $\beta^*$ -> Crab cavities that rotates the bunches overlapping perfectly at the collision point.
- New and more powerful magnets to collimate the beam
- Civil engineering started in 2018 for new access points and service tunnels
- ...
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
## Outer Tracker Modules

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<th>Module type and variant</th>
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<th>TB2S</th>
<th>TEDD</th>
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**Outer Tracker Modules – Prototypes**

Fully functional PS module prototypes produced

- MaPSA-light module: 6 MPA chips bump bonded to PSp sensors with 48 channel readout channels each
- PS micro module: two MaPSA-light module stacked.
- MPA and SSA communication being checked on a test bench.
- Functional hybrid expected by 2020
- Single MaPSA module - beam test studies performed.

Fully functional 2S module prototypes produced

- Mini-modules with 2 X CBC2 and CBC3 readout.
- Full size module with 16 CBC readout (both CBC2 and 3 readout).
- Irradiated mini module with CBC2 readout.
- Studies at beam tests with both mini and full sized modules.
DTC (Data, Trigger and Control) boards readout and control module
- ACTA standard

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
Sensor irradiated with neutron only at JSI
- CBC3 readout chip
- 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/cm$^2$ 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
Tilted geometry
POWERING AND COOLING

Large area + High Granularity

-> High Power budget:
Outer tracker ~ 100 kW

-> Parallel powering with on-module conversion

Powerful cooling system:
- (4+1) x 50W cooling plants
- based on two-phase CO2 cooling system (-30°C set point)
- small pipes
IV after the irradiation -> FZ290 structures show a better behavior than thinned sensors.
HIGHLIGHTS FROM THE TEST BEAM

Bending of charged particles inside the magnetic field emulated by rotating the modules w.r.t beam direction.

- Stub efficiency measured as a function of emulated $p_T$.
- The modules demonstrate the power to discriminate tracks with $p_T < 2$ GeV
- The difference in the turn-on threshold for the irradiated module compared to non-irradiated one is due to different sensor spacing.
- No significant loss of efficiency even after irradiation.

- Stub efficiency measured as a function of emulated $p_T$ for different correlation window ($\Delta x$ in units of macro-pixel)
- Discriminating power for tracks below $p_T < 2$ GeV

The concept of $p_T$ discrimination works!