CMS Tracker Upgrade:
Requirements and Layout

Stefano Mersi
On behalf of the CMS Collaboration
5 July 2014
ICHEP 2014 – Detector RD and Performance
## LHC broad schedule

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase-1</th>
<th>Phase-2</th>
<th>Phase-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{CM} ) [TeV]</td>
<td>( \leq 8 )</td>
<td>( \leq 13 )</td>
<td>( \leq 13? )</td>
</tr>
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<td>( L ) ([\text{cm}^{-2} \text{s}^{-1}])</td>
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<td>( \leq 50 )</td>
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<td>( \int L dt ) ([\text{fb}^{-1}])</td>
<td>( \leq 120 )</td>
<td>( &lt; 500 )</td>
<td>( \leq 3000 )</td>
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**New CMS phase-1 pixel detector**

installed during extended winter shut-down
**LHC broad schedule**

<table>
<thead>
<tr>
<th>Phase-2</th>
<th>LS 1</th>
<th>LS 2</th>
<th>LS 3</th>
</tr>
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<tbody>
<tr>
<td>E(_{\text{CM}}) [TeV]</td>
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<td>L [cm(^{-2}) s(^{-1})]</td>
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<td>PU</td>
<td>(~ 21)</td>
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<td>(\int L dt) [fb(^{-1})]</td>
<td>(~ 30)</td>
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High-Luminosity LHC
Limitations of current tracker

Cannot push the detector (much) beyond design lifetime of 500 fb\(^{-1}\) and specifications PU \(\approx 20\)

Pixel:
Pile-up!
- 2-track resolution
- efficiency

Outer tracker:
Radiation damage
- leakage current
- double-sided not cooled
- Huge impact on tracking performance

Predicted leakage current after 1000/fb at -20°C coolant temp.
Limitations of current tracker

Cannot push the detector (much) beyond design lifetime of 500 fb⁻¹ and specifications PU ≈ 20

Pixel:
- Pile-up!
  - 2-track resolution
  - efficiency

Outer tracker:
- Radiation damage
  - leakage current
- double-sided not cooled
- Huge impact on tracking performance

After installation
At 1000 fb⁻¹ & PU=140
Total tracker replacement

- Radiation tolerance up to $\int L \, dt = 3000 \text{ fb}^{-1}$
- Pile up $140 \rightarrow 200$ Occupancy $< \%$
- Longer latency $\rightarrow > 10 \mu s$
- Higher L1A rate $\rightarrow > 0.5 \sim 1 \text{ MHz}$
- Improve resolution at high $p_T$
- Improve two-track separation
- Improve resolution at low $p_T$
- Reduce secondary interactions
- Increase tracking robustness
- Increase forward acceptance
- Improve CMS trigger

- Radiation hardness
  - Operating cold (-20°C)
  - Pixel replacement possible
- Increase granularity
- Larger front-end buffers
- Bandwidth!
- Increase granularity
- Reduce material
- Mostly through outer tracker design
- Mostly through pixel layout
- Provide tracking to Level-1
  - 40 MHz output for L1
Material vs. data rate

Material amount is limiting current tracker's performance: reduce material

LESS power/material

MORE power/material

New technologies
- DC-DC converters
- CO₂ cooling
- Low-power GBT
- Front-ends

Higher granularity
Higher radiation
Bandwidth!

Less layers in outer tracker
Tracker Layout

Outer Tracker

Pixel detector
Pixel detector

Challenging requirements:
- Radiation tolerance
- Readout bandwidth
- Power (=material!)
Pixel sensors radiation

Hadron fluence after 3000 fb\(^{-1}\)
- $2 \times 10^{16}$ n\(_{eq}\) cm\(^{-2}\) @ $r=3$ cm
- $3 \times 10^{15}$ n\(_{eq}\) cm\(^{-2}\) @ $r=11$ cm
Phase 2 Upgrade of the CMS Tracker
Mersi – ICHEP 2014

Pixel sensors technology

Studies ongoing to qualify technology:

Baseline

- **Thin planar** (<150 μm) suitable for outer regions and possibly also inner
  - n-in-n → n-in-p
  - ~ 4'000 e⁻ @ 800V 1.3×10¹⁶ n_{eq} cm⁻²
- **Epitaxial strip sensor** test beam results available (not public yet)
  - 3D might be suitable for inner regions
  - ~ 7'000 e⁻ @ 150V 5×10¹⁵ n_{eq} cm⁻²
  - lower Vbias, shorter charge drift

Evolution of other R&D lines also followed (HV-CMOS, diamond, MAPs)


Final choice will be based on:
Performance
Radiation tolerance
Cost & yield
Pixel electronics front-end

- RD53 collaboration
  19 institutes – CMS+ATLAS

- Resolution: small pixel size
  100×25 & 50×50 μm²
  - Improved resolution & 2-track separation (jets)
  - Outer layers can be larger pixels, using same chip 100×100 and 50×200 μm²

- Technology
  - ROC Chip 65 nm CMOS
  - Hit rate up to 2 GHz/cm²

- Radiation tolerance
  - 1 Grad dose!
  - ROC up to 10x LHC
  - Other electronics?
**Phase 2 Upgrade of the CMS Tracker**

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**Pixel electronics services**

**Bandwidth**

Phase-1

- Rate → 400 MHz/cm²
- L1 rate 100 kHz

HL-LHC

- Rate → 2 GHz/cm²
- L1 rate 500 kHz (1 MHz)

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Optical on-board readout not possible:
- Rad-hardness
- Material/space

=> **Electrical links to opto links**

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Even more difficult to keep material budget under control
Pixel electronics powering

Target: $O(0.5)$ W/cm$^2$

Traditional inductor-based on-board DC/DC not possible:

Possible options:

- Serial powering
- More complex schemes
  - Inductor-based
  - Switched-capacitor converters
Outer Tracker

Challenging requirements:

Trigger readout (40 MHz)

Power (=material!)

Track finding @L1

...
Outer tracker sensors

- Hadron fluence: up to $1.5 \times 10^{15} \text{n}_{\text{eq}} \text{cm}^{-2}$

- **Large investigation** based on Hamamatsu test samples (oxygen-rich*), with a combination of:
  - p-in-n, n-in-p implant
  - Float-zone, Magnetic Czochralski, Epi substrate
  - 300, 200, 100, 50 μm active thickness

- Conclusion:
  - **Cold operation** (-20 °C) is needed at the highest dose
  - n-in-p substantially higher radiation tolerance (p-spray or p-stop isolation both working)
  - 200 μm sensors have lower current and same signal as 300 μm at highest dose
  - Annealing does not significantly impact charge collection, especially for Magnetic Czochralski

* [O] > 8×10^{16} \text{cm}^{-3}
Outer tracker front-ends

Need to ship hits off detector

Ship all hits @ 40 MHz? No

- Bandwidth needed: off by 1 order of magnitude (order of 10 Gbps per module)
- Track reconstruction ~ impossible

Solution: ship only high-pT hits (stubs)

- Threshold of ~ 2 GeV
- Data reduction of one order of magnitude or more

Modules with pT discrimination (“pT modules”)

Thanks to CMS 3.8 T magnetic field!

Same electronics reads two sensors

EXP. $p_T$ cut 2.14 GeV/c
FIT $p_T$ cut 2.17 GeV/c
FIT $\sigma(p_T$ cut) 0.1 GeV/c

preliminary beam test Dec ‘13
$p_T$ faked by tilting detector under test
Providing tracks for trigger

Level-1 “stubs” are processed in the back-end
Form Level-1 tracks, pT above ~ 2 GeV, contributing to CMS Level-1 trigger

@ 40 MHz – Bunch crossing
@ 500 kHz (1 MHz) – CMS Level-1 trigger
Module design

Integration at the module level

Binary readout: CBC
provides hit-matching
(functional prototypes!)

CO₂ cooling
already used in Phase-1
mass-efficient cooling

Data link:
Low-power GigaBit Transceiver
lpGBT currently under development
integrated at module level

DC/DC converter
already used in Phase-1
10 V lines: lower current, lower material
Module design

Only two module types

**2 Strip sensors**
- **Strips:** 5 cm × 90 μm
- **P:** 2.7 W
- ~ 92 cm² active area
  - For r > 40 cm

**Pixel + Strip sensors**
- **Strips:** 2.5 cm × 100 μm
- **MacroPixels:** 1.5 mm × 100 μm
- **P:** 5.0 W
- ~ 44 cm² active area
  - For r > 20 cm

Coarse z information

accurate z information
**Front-end interconnection**

**Flex hybrid:**
- Technology leap
- Key element for 2-sensor design
Module prototypes

2xCBC functional module:
- 2 chips (instead of 8)
- Electrical readout (instead of optical)
- No data concentration
- Rigid hybrid
+ Stub-finding logic
+ Nominal noise and thresholds

8xCBC prototype:
+ 2x8 chips
- Electrical readout (instead of optical)
- No data concentration
+ Flex-hybrid
+ Stub-finding logic
  Just produced

Prototype readout format **defined**
Data concentrator will be produced later fitting both PS and 2S modules
Mechanics

Just a taste of it...
End-cap mechanics: 2S & PS

Double disks
Barrel mechanics: 2S
Barrel mechanics: PS
Barrel mechanics: PS
Barrel mechanics: PS
Barrel mechanics: 2S alternative
Layout

and expected performance estimates
Phase 2 Upgrade of the CMS Tracker

Tracker Layout

Lower density
**2S modules** outside
(~8400 modules)

**PS modules** middle
z info in trigger
θ info in trigger
(~7100 modules)

**Pixel modules** inside
accurate impact parameter resolution & forward coverage

More detailed model

No detailed model: using Phase-I detector layout w/ more disks in the forward
Sensor spacing in the Outer Tracker was tuned to have as much as possible a uniform pT cut (around 2 GeV/c).

Further tuning is performed by adjusting the hit-matching windows.
Uniform cut

Need to tune sensor spacings and hit matching windows are required to maintain uniform $p_T$ cut

Muon Efficiency vs $p_T$ [GeV/c] for different spacings ($\rho$):
- $\rho = 22.7$ cm
- $\rho = 35.6$ cm
- $\rho = 50.6$ cm
- $\rho = 68.4$ cm
- $\rho = 88.6$ cm
- $\rho = 107.8$ cm

[@construction] [@front-ends]
• **×4 granularity** in strip sensors
• +3 layers of **MacroPixel sensors**
  - Unambiguous **3D coordinates** helps track finding in high pile-up
• Up to **10 points** available for track-trigger up to $\eta=2.5$
  - Comparable to current tracker's coverage, **but at L1**
Phase 2 Upgrade of the CMS Tracker

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Layout of current baseline

- **×4 granularity** in strip sensors
- +3 layers of **MacroPixel sensors**
  - Unambiguous **3D coordinates** helps track finding in high pile-up
- Up to **10 points** available for track-trigger up to \( \eta = 2.5 \)
  - Comparable to current tracker's coverage, **but at L1**
- Hit coverage up to \( \eta \approx 4 \) in full readout (after L1 Accept)
Tracker material budget

Number of hits in full readout

Material Budget in radiation length

CMS Preliminary Simulation

CMS Phase-1

CMS Phase-2

estimate, using phase-1 pixels material

~ phase-1 pixels material

Phase-1 Pixel
Tracking resolution

Single μ resolution $p_T=10$ GeV/c
Transverse momentum resolution

- Current CMS (CMS simulation)
- Upgrade (tkLayout estimate)

Less material

Clear improvement expected in the whole $p_T$ range
### Upgrade overview

<table>
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<th>Upgrade</th>
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<td>~200 m²</td>
<td>~220 m²</td>
</tr>
<tr>
<td>Silicon</td>
<td>Silicon</td>
</tr>
<tr>
<td>9.3 M</td>
<td>47.8 M</td>
</tr>
<tr>
<td>Strips</td>
<td>Strips</td>
</tr>
<tr>
<td>0</td>
<td>217 M</td>
</tr>
<tr>
<td>MacroPixels</td>
<td>MacroPixels</td>
</tr>
<tr>
<td>15'148 Modules</td>
<td>15'508 Modules</td>
</tr>
<tr>
<td>40 MHz</td>
<td>readout rate*</td>
</tr>
<tr>
<td>100 kHz readout rate</td>
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</table>

### Pixel

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<td>4.6 m²</td>
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<tr>
<td>Silicon</td>
<td>Silicon</td>
</tr>
<tr>
<td>66 M</td>
<td>O(1) G?</td>
</tr>
<tr>
<td>Pixels</td>
<td>Pixels</td>
</tr>
<tr>
<td>1440 Modules</td>
<td>??</td>
</tr>
<tr>
<td>0.5~1 MHz</td>
<td>readout rate</td>
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* only high-pt hits read-out
L₁-tracking
Providing tracks for trigger

Extreme challenge: reconstruct $O(100)$ tracks at 40 MHz

**Track-finding** step approach being studied

@ **40 MHz** – Bunch crossing
@ **500 kHz (1 MHz)** – CMS Level-1 trigger
**L1-tracking 3 strands of R&D**

Extreme challenge: reconstruct $O(100)$ tracks from $\sim 15000$ stubs at 40 MHz

**Track finding** step is performed here (main step)

### Table: Trackfinding & Triggering

<table>
<thead>
<tr>
<th></th>
<th>1st pass</th>
<th>2nd pass</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardware</strong></td>
<td>Dedicated</td>
<td>FPGA</td>
</tr>
<tr>
<td><strong>Stubs</strong></td>
<td></td>
<td>FPGA</td>
</tr>
<tr>
<td><strong>Method</strong></td>
<td>Pattern match ($10^8$)</td>
<td>Projective binning</td>
</tr>
<tr>
<td><strong>Generates</strong></td>
<td>Patterns</td>
<td>Track candidates</td>
</tr>
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<td><strong>Primitives</strong></td>
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<td>Tracklets</td>
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<td><strong>Track candidates</strong></td>
<td></td>
<td>Tracklets + stubs</td>
</tr>
<tr>
<td><strong>Method(s)</strong></td>
<td>PCA or Hough transform or Retina</td>
<td>Under study</td>
</tr>
<tr>
<td><strong>Generates</strong></td>
<td>L1-Tracks</td>
<td>L1-Tracks</td>
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</tbody>
</table>

<table>
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<tr>
<th><strong>Sectors</strong></th>
<th>$48 = 8 \times 6$ (φ×η)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time MUX</strong></td>
<td>$24 \times (BX)$</td>
</tr>
</tbody>
</table>

- Tracklet finding
- Hardware: Dedicated FPGA
- Time: Multiplexed Trigger
- Tracklet algorithm: Stubs

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*Note: BX stands for bunch crossings.*
A good track parameter resolutions is obtained in L1-tracking simulations (tracklet algorithm shown here)
Track trigger will reduce rates through:
- High momentum resolution of leptons - sharp thresholds
- Isolation for e/γ/μ/τ - reduce background
- Association of particles to same primary or secondary vertex - reduce combinatorial effect of PU in multi-particle/jet triggers

Gain ~ 10 for lepton triggers - will allow maintaining low trigger thresholds
Summary & Outlook

- **Outer Tracker** design is advanced
  - 2S module prototypes in hand
  - PS prototype structures will be available soon
  - Mechanics/cooling studied in detail

- **Pixel** detector is being defined, more challenging
  - Electronics development: RD53
  - Radiation damage: sensors + electronics
  - Material, layout, power, bandwidth

- **Performance** improvements
  - “Regular” tracking improved, particle interactions reduced
  - L1-tracking will greatly improve CMS physics reach
Thank you!
# Total tracker replacement

| Radiation tolerance up to $\int L \, dt = 3000 \text{ fb}^{-1}$ | Radiation hardness  
Operating cold (-20°C)  
Pixel replacement possible |
|---|---|
| Pile up $140 \rightarrow 200$  
Occupancy $< \%$ | Increase granularity |
| Longer latency $\rightarrow > 10 \text{ \mu s}$ | Larger front-end **buffers** |
| Higher L1A rate $\rightarrow > 0.5 \sim 1 \text{ MHz}$ | **Bandwidth!** |
| **Improve resolution at high $p_T$**  
**Improve two-track separation** | **Increase granularity** |
| **Improve resolution at low $p_T$**  
Reduce secondary interactions | **Reduce material** |
| Increase tracking robustness | Mostly through **outer tracker design** |
| Increase forward acceptance | Mostly through **pixel layout** |
| Improve CMS trigger | **Provide tracking to Level-1**  
$40 \text{ MHz output for L1}$ |
L1-tracking potential resolution

Potential resolution using all stub info
Challenge for L1-track finding:
finding precise tracking information

Single $\mu$ $p_T=2$ GeV/c
Single $\mu$ $p_T=10$ GeV/c
Single $\mu$ $p_T=100$ GeV/c
Module design

- **Two sensors per module**
  - Mass-effective way of collecting two coordinates
  - Help for pattern recognition (also for HLT)

- **Large bandwidth needed**
  - One link per module
    - Contribution to power: moderate
    - Almost no electrical connectivity in tracking volume
    - The module is a self-contained system

The chosen implementation brings many more advantages than drawbacks
L1-tracking

- Extreme challenge: reconstruct O(100) tracks at 40 MHz
- Three strands of R&D:
  - Associative Memories
    - Fast candidate finding (pre-computed hit patterns)
      - As soon as the hits are loaded in the memory, all the patterns are found: $T \propto n_{\text{hits}}$
    - Segmented: 6x along $\eta$ and 8x along $\phi$ (with overlaps)
    - $\sim$100M reference patterns needed ($\sim$2M per segment)
    - Precise fitting on candidates in a second step (being studied)
  - Tracklet algorithm (FPGA)
    - Conventional road-search
    - Primitives: combination of compatible stubs (tracklets)
      - Segmented: 6x along $z$ and 28x along $\phi$, then recombined before next step:
    - $\chi^2$ fit on compatible tracklets (no segmentation)
  - Time Multiplexed Trigger (FPGA)
    - Data streamed into (but not limited to) FPGA based processors over many BX (~24)
    - Candidate finding using projective binning, precise fitting in a second step (under study)
    - Primitives: stubs
    - Also segmented: 5x along $\phi$ (with overlaps), but regional processors operate independently

Example of 8x segmentation along $\phi$
Overlaps to find $p_T > 2$ GeV/c
Integrated fluence

CMS Preliminary Simulation
2012 FLUKA geometry

CMS protons 7TeV per beam
1 MeV-n-eq in Si at 3000 fb\(^{-1}\)

FLUKA nominal geometry 1.0.0.0
**Conclusion**

- DCDC modules are moving to production now
- They can be provided to all HEP detector systems (and they will be made available for several years)
  - Radiation tolerance limited **only** by displacement damage effects to 5-8e14 n/cm²
- For CMS and ATLAS trackers:
  - an upgrade is possible making the DCDC tolerant to at least 5e15 n/cm²
  - optimisation of the module can be made to considerably reduce contribution to material budget
**Pixel chip radiation damage**

**Courtesy of RD53**: Preliminary studies show pmos devices significant parameter change above $O(10^8)$ Rad. Target for $3000 \text{ fb}^{-1}$ for first layers is $10^9$ rad

![Graph showing transconductance factor variation versus dose level](image)

M. Menouni, CPPM

Underlying mechanism under study
Pixel Columns: <512 pixels x 50um

Pixel Rows: e.g. <512 pixels x 50um

Pixel cell 50um x 50um

Pixel region: e.g. 2x2 or 4x4

Pixel column

Pixel chip with <512 x 512 pixels of 50um x 50um

RD53 ROC architecture

Courtesy of RD53
Phase 2 Upgrade of the CMS Tracker
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Data from 1-4 neighbour ROCs

Data to data merging ROC

Pixel array

Data merging and distribution

1-8 E-link coders and cable drivers

Coding

Serializer

PLL

1.2 Gb/s
Twisted pair

cables ≤ 2 m

8 E-link rec.

Cable Equalizer

LP-GBT

10 G Ser.

10 Gb/s
Optical
HPK test wafers

Phase 2 Upgrade of the CMS Tracker
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<tr>
<th>Radius (cm)</th>
<th>Protons (10^4) neq cm(^{-2})</th>
<th>Neutrons (10^4) neq cm(^{-2})</th>
<th>Ratio p/n</th>
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<tbody>
<tr>
<td>60</td>
<td>3</td>
<td>4</td>
<td>0.75</td>
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<tr>
<td>20</td>
<td>10</td>
<td>5</td>
<td>2.0</td>
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<tr>
<td>15</td>
<td>15</td>
<td>21</td>
<td>2.5</td>
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</table>
Stub find in barrel & end-cap

(a) "stub" pass fail

(b) \[ \Delta z = \Delta R / \tan \varphi \]

(c) \[ l \leq 4 \text{ mm} \]

\[ \leq 100 \mu m \]
Charge collection vs. fluence for 600 V at −20°C after short annealing (50 h to 250 h) at room temperature, for sensor thickness of 300 μm. Lines are drawn to guide the eye.
Charge collection vs. fluence for 600 V at -20°C after short annealing (50 h to 250 h) at room temperature, for sensor thickness of 200 μm. Lines are drawn to guide the eye.
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- **Consolidation**: Improvement of tracker thermal and humidity insulation: running colder (-20°C achieved, -15°C target)
- **Preparation for Phase-1**: New beam pipe
  - Pixel slice test installation

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(You are here)
## LHC broad schedule

<table>
<thead>
<tr>
<th>$E_{\text{CM}}$ [TeV]</th>
<th>8</th>
<th>13</th>
<th>13?</th>
<th>13?</th>
<th>≈ 5 × 10^{34}</th>
</tr>
</thead>
<tbody>
<tr>
<td>L [cm^{-2} s^{-1}]</td>
<td>7 × 10^{33}</td>
<td>≤ 2 × 10^{34}</td>
<td>≤ 2.5 × 10^{34}</td>
<td>≤ 140</td>
<td></td>
</tr>
<tr>
<td>PU</td>
<td>~ 21</td>
<td>≤ 50</td>
<td>≤ 70</td>
<td>≤ 3000</td>
<td></td>
</tr>
</tbody>
</table>
| $\int L \, dt$ [fb^{-1}] | ~ 30 | ≤ 120 | < 500 | |}

**Phase-2**

- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2026

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**High-Luminosity LHC**
Stubs expected (OT)
Hits expected (OT)
Phase 2 Upgrade of the CMS Tracker
Mersi – ICHEP 2014

2S readout & control
2s Front-end data flow

One of the schemes under study.
Data flow not completely frozen yet, but this likely to be "very similar to" final

CBC

@ 160 Mb/s each CBC

2b DAO 10b TRIG

CIC L

@ 160 Mb/s

2b DAO 8b TRIG

FE-Hybrid L

Service-Hybrid

10b + 10b

@ 160 Mb/s

LP-GBT

CBC

@ 160 Mb/s each CBC

10b DAO 2b TRIG

CIC R

@ 160 Mb/s

8b DAO 2b TRIG

FE-Hybrid R
Hadron fluence after 3000 fb$^{-1}$

- $2 \times 10^{16}$ n$_{eq}$ cm$^{-2}$ @ $r = 3$ cm
- $3 \times 10^{15}$ n$_{eq}$ cm$^{-2}$ @ $r = 11$ cm