CMS Tracker Upgrade:
Requirements and Layout

Stefano Mersi
On behalf of the CMS Collaboration
19 March 2014
ACES 2014
<table>
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New outer tracker & new pixel
### Total tracker replacement

**Pixel & strip replacement: aim at LS3**

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<th>Upgrade Details</th>
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| Survive $\int L \, dt = 3000 \text{ fb}^{-1}$ | **Radiation hardness**
| Higher L1A rate $\rightarrow > 500 \text{ kHz}$ | **Operating cold** (-20°C)
| Resolve $<\mu>/140 \rightarrow 200$ | **Bandwidth!**
| Latency $\rightarrow > 10 \mu s$ | **Higher granularity**
| Ensure **experiment lifetime** | **Larger front-end buffers**
| **Improve tracking** at high pT | **Redundancy** for Outer Tracker
| **Improve tracking** at low pT | Possible **extraction** for Pixels
| Reduce secondary interactions | **Increase granularity**
| Increase forward acceptance | **Reduce material**
| Improve CMS trigger | Mostly through **pixel layout**
| | **Provide tracking to Level-1**
| | 40 MHz output for L1
The challenge

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

LESS power/material

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

MORE power/material

Higher granularity
Bandwidth!

Less layers
Outer Tracker

Challenging requirements:
- Trigger readout (40 MHz)
- Power (=material!)
- Track finding @L1
- ...

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!

EXP. \( p_T \) cut 2.14 GeV/c
FIT \( p_T \) cut 2.17 GeV/c
FIT \( \sigma(p_T \text{ cut}) \) 0.1 GeV/c
Module design
Concept: integration at the module level

**Binary readout: CBC**
provides hit-matching (already working prototype)

**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

Hybrid is the key element for module integration
Functional prototypes in hand!
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
- Pixels: 1.5 mm × 100 μm
- P = 5.0 W
- ~ 44 cm² active area
  For r > 20 cm
Module design
Only two module types

**2 Strip sensors**
- Strips: 5 cm × 90 μm
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- $\sim 44 \text{ cm}^2$ active area
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See 11:10 CMS Strips Readout
David Mark Raymond
Module design
Only two module types

2 Strip sensors
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Coarse z information

See 11:10 CMS Strips Readout
David Mark Raymond

See 11:30 CMS Pixel-Strip Project
Kostas Kloukinas
Module design
Concept: integration at the module level

• **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
  - System very simple and elegant (… light!)
    - Almost no electrical connectivity in the tracking volume
    - The module is a self-contained system

The chosen implementation brings many more advantages than drawbacks
Uniform cut
Possible, with tuning

Monte-Carlo CMS Preliminary

Barrel muon efficiency

Need to tune sensor spacings and hit matching windows are required to maintain uniform $p_T$ cut
2S modules

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

4.0 mm version
- Silicon sensor
- Bridge
- Flex PCB hybrid
- 500um CF support
- Foam spacer
- 200um CF stiffener

1.8 mm version
- Silicon sensor
- Bridge
- Flex PCB hybrid
- 500um CF support
- CF stiffener

Mersi - ACES 2014
CMS Tracker Upgrade
layout and requirements
PS modules

Flex hybrid:
- Technology leap
- Key element for 2-sensor design
Providing tracks for trigger

Readout architecture

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 – CMS Level-1 trigger
Providing tracks for trigger
Readout architecture

See 14:20 CMS Views for the Off-Detector Track Trigger Electronics
Ted Liu

Completely new system component
new sub-project

@ 40 MHz – Bunch crossing
@ ~ 500 kHz – CMS Level-1 trigger
Pixel detector

Challenging requirements:
- Radiation hardness
- Readout bandwidth
- Power (=material!)
- Contribution to trigger?
Pixels: radiation hardness

Sensors and front-ends

- Sensors: $\Phi$ up to $2 \times 10^{16}$ neq cm$^{-2}$ @ r=5 cm

With current CMS pixel @600V
CCE = 50% at $10^{16}$ neq cm$^{-2}$
• Sensors: $\Phi$ up to $2 \times 10^{16} \text{ neq cm}^{-2} @ r=5 \text{ cm}$
  - Thin planar
  - 3D
  - Resolution? Smaller pixels:
    • $100 \times 25 \mu\text{m}^2$
    • $50 \times 50 \mu\text{m}^2$
Pixels: radiation hardness
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- Front-end: up to 10 MGy
  - ROC Chip 65 nm CMOS
    - One chip, footprint compatible with both pixel geometries
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• Front-end: up to 10 MGy
  - ROC Chip 65 nm CMOS
    • One chip, footprint compatible with both pixel geometries
    • Same chip compatible also with 100x100 $\mu$m$^2$ pixels
  - Radiation hardness? Other electronics?
**Pixels: radiation hardness**

**Sensors and front-ends**

- **Sensors:** \( \Phi \) up to \( 2 \times 10^{16} \) neq cm\(^{-2} \) @ \( r=5 \) cm
  - Thin planar
  - 3D
  - Resolution? Smaller pixels:
    - \( 100 \times 25 \) \( \mu \)m\(^2\)
    - \( 50 \times 50 \) \( \mu \)m\(^2\)

- **Front-end:** up to 10 MGy
  - ROC Chip 65 nm CMOS
    - One chip, footprint compatible with both pixel geometries
    - Same chip compatible also with 200x200 \( \mu \)m\(^2\) pixels
  - Radiation hardness? Other electronics?

See 11:50 [RD53](#)  
*Jorgen Christiansen*
**Pixels: readout bandwidth**

Huge increase w.r.t. present system

- **Present system**
  - Rate → 200 MHz/cm²
  - L1 rate 100 kHz

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

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

- **Electrical links to opto links**

Even more difficult to keep material budget under control.

Out of main acceptance?
Pixel: powering

Mantra: power => material

• Target: O(0.5) W/cm²
• Traditional inductor-based on-board DC/DC not possible:
  - Rad-hardness
  - Material/space
• Possible options:

Serial powering

More complex schemes

Switched-capacitor converters

Inductor-based
Layout and expected performance
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
• **×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 η=2.5
  – Comparable to current tracker's coverage, **but at L1**
• **×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 $\eta\approx4$ at L1A
## Upgrade overview

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<th>Upgrade</th>
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<tr>
<td><strong>Outer</strong></td>
<td></td>
</tr>
<tr>
<td>~200 m² Silicon</td>
<td>~220 m² Silicon</td>
</tr>
<tr>
<td>9.3 M Strips</td>
<td>47.8 M Strips</td>
</tr>
<tr>
<td>0 MacroPixels</td>
<td>217 M MacroPixels</td>
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<tr>
<td>15'148 Modules</td>
<td>15'508 Modules</td>
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<tr>
<td>100 kHz readout rate</td>
<td>40 MHz readout rate*</td>
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<td></td>
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<td><strong>Pixel</strong></td>
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<tr>
<td>~1 m² Silicon</td>
<td>4.6 m² Silicon</td>
</tr>
<tr>
<td>66 M Pixels</td>
<td>O(1) G? Pixels</td>
</tr>
<tr>
<td>1440 Modules</td>
<td>?? Modules</td>
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<td>100 kHz readout rate</td>
<td>&gt;500 kHz readout rate</td>
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* only high-pt hits read-out
Tracker material budget

Material Budget in radiation length

CMS Preliminary

- CMS Phase-1
- CMS Phase-2

estimate, if keeping
~ phase-1 pixels material

Phase-1 Pixel
Tracking resolution
pT resolution of single muons

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Clear improvement expected in the whole pT range
Track-trigger resolution
Potential \( p_T \) resolution using all stub info

Challenge for L1-track finding:
finding precise tracking information

See 14:20  CMS Views for the Off-Detector Track Trigger Electronics
Ted Liu
Thank you!
### Total tracker replacement

**Pixel & strip replacement: aim at LS3**

- **Survive** $\int L \, dt = 3000 \text{ fb}^{-1}$
- **Higher L1A rate** $\rightarrow > 500 \text{ kHz}$
- **Resolve** $<\mu> = 140 \rightarrow 200$
- **Latency** $\rightarrow > 10 \mu s$
- **Ensure** experiment lifetime
- **Improve tracking** at high pT
- **Improve tracking** at low pT
  - Reduce secondary interactions
- **Increase forward acceptance**
- **Improve CMS trigger**

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Module design
Only two module types

Hit correlation in different chips

**Cms Binary Chip (CBC)**
- strip readout
- + correlation

**MacroPixel ASIC (MPA):**
- pixel readout
- + correlation

**Readout only**
- wire bonds
- bump bonds
Working hypothesis:

- Each sector independent
- Overlap regions function of
  - Luminous region $\Delta z$
  - Minimum $p_T$ cut
sensor spacing
must be tuned along with search windows

![Graph showing sensor spacing](image-url)
2S modules

Flex hybrid:
- Technology leap
- Key element for 2-sensor design
Radiation map

CMS Preliminary Simulation
2012 FLUKA geometry

CMS protons 7TeV per beam
Dose at 3000.0 [fb⁻¹]

Dose [Gy]

FLUKA nominal geometry 1.0.0.0
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Layout and requirements