The CMS Outer Tracker Detector for HL-LHC

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Outline

module designs

introduction

thermal performance

support structures

module prototyping
Introduction - Tracker Layout

- layout with 6 barrel layers and 5 end cap double-disks
  - pixelated modules at $r < 60$ cm - stack of pixel and strip sensor (PS)
  - stack of two strip sensors at $r > 60$ cm (2S)
Introduction - Module Concept

• modules will have on-board pT discrimination
  • signals from two closely spaced sensors are correlated
  • exploit strong magnetic field for local pT measurement
  • local rejection of low-pT tracks to minimise data volume

1.6 - 4.0 mm

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• detector modules provide Level-1 and readout data at the same time
  • the whole tracker sends trigger data ("stubs") at each bunch crossing (40 MHz)
  • readout data up to 750 kHz

• "stubs" are used to form Level-1 tracks

• cooling via evaporative CO2
  • sensors at ~ -20 °C

• integrated at module level:
  • low power giga-bit transceiver (LP-GBT) as data link
  • powering via DC-DC conversion

• two different module types
  • different sensor spacings are treated as 'variants'
  • requires optimisation of only two designs

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Diagram:

- **Outer Tracker Front-end**
  - Full data < 750 kHz
  - Stubs only 40 MHz

- **Tracker Back-end**
  - Readout
  - Track Finder

- **CMS**
  - CMS Level-1
  - CMS DAQ

**Flow**:
- Level-1 accept
- Full data
- Stubs only 40 MHz
- 40 MHz
Introduction - Module Concept

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  - local rejection of low-pT tracks to minimise data volume
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Talk by Jacobo Konigsberg

[Diagram of CMS Tracker Back-end, Outer Tracker Front-end, and CMS DAQ connections showing Level-1 accept, Full data < 750 kHz, Stubs only 40 MHz, Readout, Track Finder, and CMS Level-1.]
Introduction - Module Configuration

- layout with 6 barrel layers and 5 end cap double-disks
  - pixelated modules at $r < 60$ cm - stack of pixel and strip sensor (PS)
  - stack of two strip sensors at $r > 60$ cm (2S)
- PS modules
  - sensor spacings: 1.6 mm, 2.6 mm and 4 mm
- 2S modules
  - sensor spacings: 1.8 mm and 4 mm
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  - sensor spacings: 1.8 mm and 4 mm

<table>
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<tr>
<th></th>
<th>barrel</th>
<th>end caps</th>
<th>tracker</th>
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<td>4464</td>
<td>2824</td>
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<td>4.0 mm 2S Module</td>
<td>936</td>
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<td>1.6 mm PS Module</td>
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<td>2.6 mm PS Module</td>
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<td>4.0 mm PS Module</td>
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<td>6256</td>
<td>13520</td>
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Design of the 2S Module

- sensors are supported by AlCF bridges
  - AlCF = carbon fibre reenforced aluminum
  - good CTE match to silicon: 3.6 ppm/K vs. 4 ppm/K
  - coated with Parylene for HV insulation (more on this on a later slide)

- five cooling contacts per module
  - extra AlCF stumped bridge introduced for thermal management
  - heat load from service hybrid (~2W)
  - inserts on support structure are used for cooling and positioning

1.8 mm variant is shown

CBC
- CMS Binary Chip
- correlates signals from both sensors
- 1800 mW (total)

opto package 800 mW

power converter 1300 mW

10 cm x 10 cm

Al-CF support bridges

hybrid

concentrator 2 x 200 mW
Design of the 2S Module

- Five cooling contacts per module
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- CMS Binary Chip
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- Opto package
- Power converter
- Al-CF support bridges
- 10 cm x 10 cm

- 1800 mW (total)
- Concentrator
- 2 x 200 mW

- Al-CF = carbon fibre reinforced aluminum
- Good CTE match to silicon: 3.6 ppm/K vs. 4 ppm/K
- Coated with Parylene for HV insulation

- CNN (CMS Converter NC): predicts high activity regions

Flexible hybrid is glued on CFRP stiffeners and folded around a spacer
- Bond pads on hybrid are on the same level as the bond pads on the sensor
- Requires different spacer thicknesses and hybrid variants
- Flex hybrid is in contact with sensor to allow for bond wire encapsulation

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2S Module 4.0 mm vs 1.8 mm

- one module design
- two module variants: 1.8 mm & 4.0 mm

- only a minimum amount of components change
  - AICF sensor spacers
  - hybrid spacer
  - length of hybrid fold-over region
  - service hybrid
2S Module 4.0 mm vs 1.8 mm

- sensors after 3000 fb⁻¹: 572 mW each (@ -20°C)
- total power: 5444 mW
- 320 μm physical sensor thickness
- 200 μm active sensor thickness
- thermal runaway at
  - 1.8 mm: -24.3 °C
  - 4.0 mm: -26.3 °C

- five cooling contacts per module
Module Assembly Requirements

- straight trajectories do not cross the same strip on the sensors of a module
  - offset can be corrected for in the stub finding logic of the chip
  - programmable in steps of 0.5 strips
- a tilt of one sensor with respect to the other introduces a variation of the offset along the strip that cannot be corrected for
- to minimise the effect on the resolution the requirement on the assembly precision is $t < 40 \, \mu m$
2S Module Assembly Jig

basic steps:
1. gluing of bridges to top sensor
2. gluing of bottom sensor to top sensor package
3. gluing of hybrids to module
4. wire-bonding of top and bottom sides
1st Working 2S Modules

- two working modules were built at nearly the same time
  - using the developed assembly procedures and jigs
- module successfully tested in beam test
- sensor to sensor alignment measured in Aachen
  - 14 / 1 μrad (27 / 13 μrad rms)
  - goal is < 400 μrad
Design of the PS Module

- sensors are supported by AICF bridges
- initially same cooling concept as in 2S module
  - four cooling contacts at end of bridges
  - power density of PS module is too high for this cooling concept
- PS module needs large-area thermal contact

Module is built on top of a CFRP base plate
- MPAs and sensors are cooled through base plate
- concentrator IC located on bottom of folded hybrid

MPA
- Macro Pixel Asic
  - pixel size: 1400 x 100 µm
  - correlates signals from both sensors
  - 3000 mW (total)

SSA
- Single Strip Asic
  - handles signals from strip sensor
  - transfers data to pixel chip
  - 500 mW (total)

CFRP base plate
- 9.4 cm x 4.6 cm
- 4.0 mm variant is shown

Power converter
- ~2000 mW

Opto package
- 800 mW

Hybrid

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Design of the PS Module

4.0 mm variant is shown

- power converter ~2000 mW
- hybrid
- opto package 800 mW
- CFRP base plate

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• large number of bond wires between read-out hybrid and opto hybrid requires opto hybrid to be at the same level as read-out hybrid

• heat load from power converter and size of package requires power converter to be at level of base plate
Design of the PS Module

- A large number of bond wires between read-out hybrid and opto hybrid requires opto hybrid to be at the same level as read-out hybrid.
- Heat load from power converter and size of package requires power converter to be at level of base plate.

**MPA**
- Macro Pixel Asic
- Pixel size: 1400 x 100 µm
- Correlates signals from both sensors
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**SSA**
- Single Strip Asic
- Handles signals from strip sensor
- Transfers data to pixel chip
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**CFRP base plate**

**opto package**
- 800 mW

**hybrid**

4.0 mm variant is shown
PS Module 4.0 mm vs 2.6 mm vs. 1.6 mm

- flexible hybrid is folded on the outside
  - increased area for routing of connections

- four parts change between 1.6 mm, 2.6 mm and 4.0 mm variant
  - AlCF sensor spacers
  - opto spacer
  - hybrid spacer
  - length of hybrid fold-over region
PS Module Assembly Jigs

- jigs are currently being designed
- test assemblies are carried out at Brown

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• The two sensor edges (top / bottom) are parallel to 30 μm over the 10 cm length of sensor.
• module is built on top of a CFRP base plate
• base plate serves as a large-area thermal interface between module and support structure
4.0 mm PS Module - FEA Geometry

- 2 x 8 MPA: 3000 mW
- 2 x 8 SSA: 500 mW
- 2 CIC: 400 mW
- LP-GBT: 500 mW
- opto package: 300 mW
- power converter: 2000 mW
- 320 μm physical sensor thickness
- 200 μm active sensor thickness

- sensors after 3000 fb⁻¹: 646 mW each (@ -20°C)
- total power: 7994 mW
- heat transfer coefficient into CO2: 5000 W/m²/K
- geometry of tilted barrel option is similar to end cap geometry
• thermal runaway at
  • 1.6 mm: -12 °C
  • 2.6 mm: -20 °C
  • 4.0 mm: -22 °C
• thermal runaway temperature is defined by strip sensor
Tracker Mechanics

![Graph showing Tracker Mechanics](image)

- Tracker Barrel 2S (TB2S)
- Tracker Endcap Double-Disks (TEDD)
- Tracker Barrel PS (TBPS)

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Support Wheel with
- 372 Ladders
- 4464 Module

One Ladder supports and cools 12 2S 1.8mm Modules

Ladders installed from the two ends of the wheel with overlap a Z=0
• consist of pre-assembles tilted and flat sections
• longitudinal profiles join the sections of one layer and provide for services routing paths
• modules are mounted on planks (flat section) and rings (tilted sections)
• each end cap consists of five double-disks
• each double-disk consists of two double-dees (+ and -)
• modules are mounted on front and back sides of dees
  • overlap in phi established within dee (green/blue and red/black)
  • overlap in radius established within double-disk
TEDD Mechanics

- Cooling pipes are routed in sectors - petal like
- Pipe sectors run at two different levels
  - $z = 0$ is center of dee, $t$ (10 mm) is thickness of dee
  - Facings are at $z = -t/2$ (-5 mm) and $z = +t/2$ (+5 mm)
  - Pipes run at $z = -t/4$ (-2.5 mm) and $z = +t/4$ (+2.5 mm)
  - Bending of pipes only in two dimensions instead of three
- Sectors overlap which gives enough space for pipe routing
  - Pipes routed in 2D only (inside dee)
Dee Prototyping

- small (35 cm x 40 cm) part of a dee with all features
  - transition between PS and 2S regions
  - edge of dee
  - two small cooling sectors
- goal is to study assembly sequence, scaleability to real object and to understand potential show-stoppers
Dee Prototype Precision

- results presented are for a first version of the prototype
- assembly precision is within specifications
- discovered some drawbacks in the assembly procedure and tooling
  - will be solved for the second prototype

Thickness: **10.51 mm** (expected 10.3 mm)
Parallelism (front / back): **95 μm**
Flatness: **62 μm**

2S Cooling Inserts (10 measurements)
average distance to nominal position: **22.1 μm**
standard deviation: **23.8 μm**

PS Positioning Pins (6 measurements)
average distance to nominal position: **29.2 μm**
standard deviation: **14.3 μm**
Dee Prototype - Thermal Tests

• prototype connected to conventional cooling system
• check thermal interface between C-foam and facing
• looks promising as a diagnostics tool, but work in progress
• designs of both 2S and PS modules are well understood
  • fine-tuning is ongoing
  • few details still have to be worked out
  • thermal performance as estimated from FEA look promising
  • FEA results to be checked by measurements

• 2S module assembly procedure and jigs are further developed and improved
  • achieved assembly precision is within the requirements

• design of PS module assembly jig makes good progress
  • maximise similarities with 2S module jig design

• good progress in the design of the sub-detector support structures
  • no show-stoppers seen so far

• prototyping of support structures has started to prove manufacturing techniques and thermal performance
2S Module Integration in End Cap

- 4.0 mm 2S module only installed in end caps
- previous designs of 1.8 mm and 4.0 mm 2S modules were not compatible from an integration point of view
  - cooling contacts were not at the same levels which would have required different insert lengths in the end caps (extra mass)
- current design: cooling contacts are at the same level wrt. to the bottom sensor
  - required new AICF bridge design and service hybrid with tails
• assembly-friendly view
• read-out hybrids are already folded around their spacers
  • done in industry
Sensor Power Generation

- a silicon sensor is essentially a reverse biased diode
- leakage current produces heat

\[ P = U_{bias} \cdot I_{leakage} \]

\[ V = 200 \, \mu m \cdot 9.87 \, cm \cdot 4.92 \, cm = 0.9712 \, cm^3 \]

\[ \Phi_{eq} = 1.5 \cdot 10^{15} \, \text{n}_{eq}/\text{cm}^2 \]

\[ \alpha = 4.0 \cdot 10^{-17} \, A/cm \]

\[ I_{leakage}^{RT} = V \cdot \phi \cdot \alpha = 0.9712 \, cm^3 \cdot 1.5 \cdot 10^{15} \, \text{n}_{eq}/\text{cm}^2 \cdot 4.0 \cdot 10^{-17} \, A/cm = 58 \, mA \]

- leakage current is a function of temperature \[ I \propto (kT)^2 \exp \left( -\frac{1.21 \, eV}{kT} \right) \]

- in this example \( I = 0.99 \, mA \) at -20 °C
- for a bias voltage of 600 V the heat produced by the sensor is 593 mW
- in FEA (ANSYS) sensor can be treated as a resistor with a voltage applied
- temperature dependence of heat generation is modelled via temperature dependent resistivity of FEA sensor material
Sensor Power Generation

![Tracker Layout and Fluence Distribution](image)

### Expected Fluence for 3000 fb-1

- **neq/cm²**

### Fluence Distribution per Module Type and Variant

- 2.6mm PS
- 1.6mm PS
- 4.0mm PS
- 1.8mm 2S Endcap
- 1.8mm 2S Barrel
- 4.0mm 2S

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Sensor Power Generation

• use maximum nominal fluence for a given module type to estimate sensor power dissipation
  • 1.6 mm PS module: $5.96 \times 10^{14} \text{ neq/cm}^2$
  • 2.6 mm PS module: $1.12 \times 10^{15} \text{ neq/cm}^2$
  • 4.0 mm PS module: $1.06 \times 10^{15} \text{ neq/cm}^2$
  • 1.8 mm 2S module endcap: $2.94 \times 10^{14} \text{ neq/cm}^2$
  • 1.8 mm 2S module barrel: $2.61 \times 10^{14} \text{ neq/cm}^2$
  • 4.0 mm 2S module: $4.55 \times 10^{14} \text{ neq/cm}^2$
  • 30% for uncertainties in FLUKA simulation and 20% for possible geometry changes are added to the extracted maximum fluences

• damage constant is $3.44 \times 10^{-17} \text{ A/cm}$
  • running scenario: 2 weeks annealing at RT per year
  • 15% is added to damage constant take strip effects into account

• fluence, damage constant, bias voltage are used to model sensor power generation in FEA

• temperature dependence of leakage current is modelled in FEA to estimate thermal runaway behaviour of module
Cooling plate in high-conductivity carbon-fibres

Phase-change glue as interface to the module

Fiber direction, small CTE

± Aluminium
± CTE

TBPS
### TIM Handling

<table>
<thead>
<tr>
<th>Material</th>
<th>removal of first cover foil</th>
<th>stickness to glass</th>
<th>removal of second cover foil</th>
<th>number of trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>T777</td>
<td>very easy / easy / well</td>
<td>3 x well</td>
<td>2 x ok, tearing / well</td>
<td>2 / 2 / 1</td>
</tr>
<tr>
<td>T725</td>
<td>ok / easy / well / very easy</td>
<td>4 x well</td>
<td>4 x ok, tearing</td>
<td>2 / 1 / 1 / 1</td>
</tr>
<tr>
<td>T557</td>
<td>3 x easy / well</td>
<td>4 x well</td>
<td>4 x ok, some tearing</td>
<td>2 / 1 / 1 / 1</td>
</tr>
<tr>
<td>MPC315</td>
<td>easy / easy / well / very easy</td>
<td>well / well / well / well</td>
<td>ok / well / well / well</td>
<td>1 / 1 / 1 / 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>softness of TIM after reheating</th>
<th>separability of glass plates</th>
<th>removal of TIM</th>
<th>residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>T777</td>
<td>very soft / very soft / gum</td>
<td>2 x hard / easy</td>
<td>very easy / very easy / ok</td>
<td>3 x no</td>
</tr>
<tr>
<td>T725</td>
<td>quite soft / very soft / gum / very soft</td>
<td>2 x easy / 2 x very easy</td>
<td>3 x hard / 1 x very hard</td>
<td>4 x sticky</td>
</tr>
<tr>
<td>T557</td>
<td>3 x soft / gum</td>
<td>2 x hard / 2 x easy</td>
<td>3 x ok / smeary</td>
<td>2 x sticky / 2 x no</td>
</tr>
<tr>
<td>MPC315</td>
<td>really soft / soft / plasticine / soft</td>
<td>easy / easy / easy / easy</td>
<td>very very easy / easy / easy / very easy</td>
<td>no / no / no / no</td>
</tr>
</tbody>
</table>

- handling-wise ranking is as follows
  1. MPC315
  2. T557
  3. T777
  4. T725

- handling becomes more tricky with rough surfaces (Al, CFRP)
TIM Results

- filled boxes: sample a
- filled circles: sample b
- data points are spread around actual irradiation values for better visibility
- some samples were measured several times for cross checks
- individual results are shown on the next slides
TIM Comparison

Specifications

<table>
<thead>
<tr>
<th>Material</th>
<th>thermal impedance [K cm²/W]</th>
<th>pressure [psi]</th>
<th>pressure [kPa]</th>
<th>force per 4 cm² [N]</th>
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<tbody>
<tr>
<td>MPC315</td>
<td>0.208</td>
<td>40</td>
<td>276</td>
<td>110.4</td>
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<tr>
<td>T725</td>
<td>0.71</td>
<td>10</td>
<td>69</td>
<td>27.6</td>
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<tr>
<td>T557</td>
<td>0.13</td>
<td>10</td>
<td>69</td>
<td>27.6</td>
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<td>0.13</td>
<td>10</td>
<td>69</td>
<td>27.6</td>
</tr>
</tbody>
</table>

- thermal impedances quoted in material specifications (circles) were confirmed by measurements (filled circles)
  - reference sample for MPC 315 was produced with 10 psi pressure
  - first reference sample for T777 showed significant difference to specs - handling and production issues
- for T725, T777 and T557 the standard samples (no pressure; filled boxes) are not even close to the specifications
  - T series materials rely on pressure during baking
- for MPC 315 the standard sample is close to the specifications
  - thermal performance of material is not very sensitive to the pressure applied during baking
CVD Carbon Foam

- high thermal conductivity at low density
  - thermal conductivity: 10 W/m/K - 75 W/m/K
  - density: 0.09 g/cm$^3$ - 0.35 g/cm$^3$

- thermal impedance of contact between foam and pipe / CFRP / … depends on amount of glue
  - glue is mostly pushed into the foam and increases contact area
  - not enough glue: large thermal impedance
  - not much glue: excess mass
• thermal impedance as a function of glue thickness was investigated
  • thermal impedance reaches a minimum at around 250 μm glue thickness
Ultrasonic Testing

- feasibility studies of ultrasonic measurements as diagnostic tool
  - check glue joints, especially thermal interface between C-foam and facing
- still learning on test samples with dedicated imperfections
  - grooves in airex and C-foam
  - oil and water spots
  - unbonded areas of sizes 3 mm x 3 mm, 5 mm x 5 mm and 10 mm x 10 mm