CMS Pixel detector development for the HL-LHC

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HSTD11
OIST, Okinawa, Japan
CMS Technical Proposal & Scope Document (Q2/Q3 2015)

Installation of phase-I Pixels

Tracker TDR (Q4 2017)

Time for development

EDR date

Construction
THE PHASE II PIXEL UPGRADE

High-Luminosity LHC:
• Luminosity of $5-7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, up to 200 events/25 ns bunch crossing
• Maintain occupancy at the permille level and increase the spatial resolution
  ➡ Pixel size $\sim 25 \times 100 \text{µm}^2$ or $50 \times 50 \text{µm}^2$ (currently $100 \times 150 \text{µm}^2$)

Pixel layout:

Pixel detector (25 cm $> R > 3$ cm):
• 4 barrel layers à la phase I
• 12+12 discs (|$\eta$| up to 4)

Radiation tolerance for the 1st pixel layer after 3000 fb$^{-1}$:
• $\Phi_{eq} \approx 2.3 \times 10^{16} \text{cm}^{-2}$, dose $\approx 12 \text{MGy}$

3D or planar pixel sensors for the 1st layer?
• R&D in parallel. Both options described and costed in TDR.
Simple mechanics:
- No turbines/blades in TFPX/TEPX

Only 2 module types:
- 1x2 and 2x2

Step in the pixel envelope:
- To allow installation of central section with beam pipe in place

In total ~ 4.9 m² of Si, > 4300 modules
Thin, small pitch planar pixel sensors:
- HPK submission (n⁺-p): Lead by UHH
- INFN - FBK R&D program, together with ATLAS (see talk from M. Meschini at HSTD10 (2015))
  - 6” n⁺-p, > 3 kΩ·cm, direct wafer bond
  - 100 µm and 130 µm active thickness
  - p-spray isolation
  - temporary metal for sensor testing
  - active edge / slim edge designs

3D silicon pixel sensors:
- CNM Barcelona
- INFN - FBK R&D program, together with ATLAS (see talk from M. Meschini at HSTD10 (2015))

No fine pitch, radiation hard readout chip available in time for the TDR
- ROC4Sens (PSI R&D chip available since summer 2017)
- RD53A (prototype chip for phase 2, end of 2017)
Sensor order:
- 35 wafer 6” n⁺-p FZ
  - 10 wafer with **150 µm thickness** (FTH150)
  - 20 wafer with **150 µm + 50 µm handle wafer** (FDB150)
  - 5 wafer with **150 µm deep diffused** (FDD150)
- Resistivity: 1 kΩ·cm - 5 kΩ·cm
- Isolation: 25 with **p-stop** (P) and 10 with **p-spray** (Y)
- Biasing schema: **none**, common **punch-through**, **polysilicon resistor**
- Backside grid for laser test

Bump-bonding at IZM:
- 8 wafers (2xFDB150P, 2xFTH150P, 2xFDD150P, 2xFTH150Y) have been processed
- 140 **ROC4Sens** modules (64 module + some test structures received)
ROC for small pitch sensor development from PSI:

- 50 x 50 µm² staggered bump bond pattern
- 155 columns x 160 row → 24800 pixels
- Size: 9.80x7.80 mm²
- Based on PSI46 (IBM 250 nm)
- Simple operation:
  - no DACs or other programming
  - no discriminator, threshold adjustment and trimming
  - small number of signals required
- Analog pulse height is read out
- Suitable for test beams and source measurements with asynchronous hits (no synchronous sampling with external clock)
- Radiation hardness > 5 MGy (expected)
- Readout based on CMS PIXEL-DTB
p-stop designs:
• 8 variants for 100x25 μm²
  - no bias (default), 2 x common punch through, 2 x poly Si
  - +1 sensor for routing testing
  - +1 sensor bricked
  - +1 sensor to test limits
• 9 variants for 50x50 μm²
  - no bias (default)
  - open p-stop
  - 3 x common punch through
  - 2 x poly Si
  - +1 sensor bricked
  - +1 sensor to test limits

p-spray designs:
• Similar variants to p-stop

Measurement program will guide design of final sensor!
**FIRST DATA FROM DESY TEST BEAM**

**DESY test beam**
- Electron / positron synchrotron
- Radius $r = 46.6$ m
- Injector for DORIS and PETRA
- And for beam test measurements
- Beam on carbon fiber targets  
  ➡ Bremsstrahlung
- Bremsstrahlung on copper target  
  ➡ electron / positron beam
- Energies from 1 to 6 GeV
- Peak rates around 10 kHz
- Beamline 21
- Setups:
  - EUDET telescope DATURA
  - 3 CMS pixel modules in “Three-master” configuration
  - Edge on configuration
**SETUP**

R4S with sensor on carrier PCB

Adapter PCB from PSI

**Three-master:**
- Support frame for 3 planes
- 20 mm spacing
- Allows reco of tracks with stand alone DAQ / no sync to external device
- Turn angle from 0° to 30°
- With cooling (not used so far)
- Changing sensors takes ~30 min

Design / production by C. Muhl (DESY)
SETUP

Three-master in telescope
HIT MAP

run 434, plane C

- Module 114
- FTH150P-R4S100x25-P4
- 5.6 GeV
- Bias voltage: 120V
- At room temperature
- No bump bond defects
- Profile due to collimator and/or scintillator
PH vs Vcal with Fermi fit

- Gain calibration:
  - Pulse height vs test pulse
- Fit by Fermi function
  - 4 parameters
  - Good, not perfect
  - Restricted range (Landau peak is at PH-ped = 180 ADC)
  - For every pixel

\[ PH = p_3 + \frac{p_2}{1 + \exp(-u)}, \quad u = \frac{V - p_0}{p_1} \]
CLUSTER CHARGE

run 449, module 110, turn 10°

<table>
<thead>
<tr>
<th>clqB3</th>
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</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
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<tr>
<td>peak</td>
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<td>sigma</td>
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<tr>
<td>area</td>
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<tr>
<td>smear</td>
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</tbody>
</table>

- Module 110
- FTH150P-R4S100x25-P2
- 5.6 GeV
- Bias voltage: 120V
- At room temperature
- Turn angle 10°
- Charge of clusters on tracks
- Offline threshold at 1.4 ke
- Fermi gain calibration
- Scaled to get peak at 11 ke
- Fit by Landau⊗Gauss
**TRIPLET RESIDUALS**

run 449, module 110, turn 10°

- Module 110
- FTH150P-R4S100x25-P2
- 5.6 GeV
- Bias voltage: 120V
- Turn angle 10°
- Landau peak clusters (8 ke < Q₀ < 16 ke)
- Triplet residuals:

\[ \Delta x = x_B - \frac{x_A + x_C}{2} \]

- Plane B residual width = 4.2 µm in 25 µm direction (fit Student t)
- Unfolding other planes and multiple scattering: 2.7 µm (binary 7.2 µm)
- Using PCB with cutout: 2.0 µm after unfolding
HIT EFFICIENCY

R4S50x50-P1:

run 31168, module 117, turn 0°

Efficiency = \( \frac{N(\text{Hit})}{N(\text{Track})} \)

- Track definition:
  - Get upstream and downstream triplets
  - Match triplets using tight 0.1 mm cut
  - Demand REF-link; tight 0.1 mm cut
  - Demand 0.6 isolation at REF

- Hit definition (hit on track):
  - Take Track
  - Demand DUT-link; loose 0.3 mm cut

- Fiducial region 0.2 mm to sensor edge

⇒ Flat at 99.99% over 15 hours
IN-PIXEL CHARGE COLLECTION

Small vs large bias dot for normal incidence

R4S50x50-P3

run 31393, module 102, turn 0°

Large bias dot (d = 25 µm) leads to large area with low cluster charge

R4S50x50-P9

Design suggested by Y. Unno

run 31315, module 142, turn 0°
IN-PIXEL CHARGE COLLECTION

Reduced bias dot: cluster charge

run 31315, module 142, turn 0°

- Module 142
- FTH150P-R4S50x50-P9
- Bias voltage: 120V
Cluster size vs. track impact point

R4S50x50-P1

R4S50x50-P2

R4S50x50-P3

- Bias voltage: 120V
- Normal incidence
- 5.6 GeV
- Using beam telescope

- Cluster size determined by diffusion and field distribution
- Bias scans for further investigations
Hit map
run 31126, module 106, turn 0°

- Bias voltage: 120V
- First 15 columns are noisy
- Lower 20 and upper 20 rows no signal
- Only central band of rows is efficient

Cluster charge
run 31126, module 106, turn 0°

- Bias voltage: 120V
- Cluster on track
- Peak at 5 ke
- Expected 11 ke from sensor thickness

➡ Further investigations needed! Uniformity of resistors?
Resolution studies@DESY test beam (5.6 GeV)

CNM, Barcelona
Double sided 3D process
50x50 µm²
BB at IZM to ROC4Sens

Preliminary

Binary resolution
HPK SUBMISSION: SPARKING

Options for spark protection:
• BCB on sensor, on chip or on both
• Parylene

First attempt at IZM:
• BCB on sensor only (frame only)
  ➡ Sparking at approx. 490 V observed (Paschen’s Law gives for a gap of 25 µm: 495 V)

ROC4Sens has additional test pads close to the sensor (not in PROC600/PSI49)
➡ Next iteration with BCB on sensor and chip
New pixel detector for HL-LHC:
- Extend forward coverage up to $|\eta| = 4$
- Small pixel, thin, rad. hard sensors
- RD53: Development of radiation hard, small pixel size ROC in 65 nm technology

R&D programs with in CMS:
- Thin, small pitch planar pixel sensors
  - HPK submission, INFN/FBK
- 3D pixel sensors
  - INFN/FPK, CNM Barcelona

HPK submission:
- First thin sensors of 50x50 $\mu m^2$ and 100x25 $\mu m^2$ pixel size successfully bump bonded to novel PSI chip
- First test beam results with ROC4Sens are very promising
  - Resolution for 100x25 $\mu m^2$: $2.0 \mu m$ after unfolding
  - Efficiency > 99.99% before irradiation
  - Sensors with poly silicon bias shows some problems
- Irradiated modules expected back from CERN during these days
➡ Many studies ahead of us to guide final design of sensors
- Bump bonding of RD53A and tests will be started beginning of next year
Backup