Summary of CMS 3D pixel sensors R&D

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Outline

• 3D vs planar technology
• 3D detectors @ CERN LHC
• CMS 3D sensors
• Pre-irradiation laboratory tests
• Pre-irradiation beam test results ➔ PRELIMINARY
• Irradiation
• Post-irradiation laboratory results
• Post-irradiation beam test results ➔ PRELIMINARY
• Summary & outlook
3D technology

• p+ and n+ electrodes are arrays of columns penetrating into the bulk
  – Lateral depletion
  – Charge collection is sideways

• Superior radiation hardness due to shorter electrode spacing
  – Short carrier drift distance
  – Faster charge collection
  – Lower depletion voltage
  – Lower charge trapping probability

• Higher noise, complex, non-standard technology
3D @ CERN LHC

3Ds are promising tracking detector candidates for future upgrades at LHC

25% of ATLAS IBL will be 3D sensors at phase I upgrade in 2015

- New rad-hard sensor candidates for the HL-LHC CMS vertex detector ($L = 10^{35} \text{cm}^{-2}\text{s}^{-1}$)
- Equivalent dose $\sim 10^{16} \text{n}_{eq}/\text{cm}^2$ @ $r = 5$ cm
- Current CMS pixel detector can collect 50% charge at the fluence of $\sim 1 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ at $\geq 600$V
  (doi:10.1016/j.nima.2010.03.157)

- HPS (near beam proton spectrometer - under approval for CMS)
  Crucial requirement for this application: radiation hardness and active edges
CMS 3D sensors (200 µm thick)

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3D detector assembly

• 3D sensors bump-bonded to CMS PSI46v2 readout chip
  – At IZM for SINTEF 3Ds (PbSn)
  – At SELEX for FBK 3Ds (In)
  – At IZM for CNM 3Ds (PbSn)
• CMS sensor dimensions 52(col)x80(row) (100 µm x 150 µm)
• Wire bonding and assembly done at Purdue, FNAL, and Torino

Lab testing:
• ROC calibration
• Leakage current
• Noise
• Radioactive source testing
CMS 3D sensor assembly

Plaquette assembly

Testboard assembly
Lab: IV @ 21 °C

**SINTEF 3D**

- 2E Vbreakdown ~120 V
- 4E Vbreakdown ~100 V

**FBK 3D (ATLAS09 batch)**

- All 1E type
- Vbreakdown ~45 V

**CNM 3D**

- Vbreakdown ~100 V

**FBK 3D (ATLAS08 batch)**

- Vbreakdown 25-40 V

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Lab: noise measurements @ 21 °C

SINTEF 3D

Unable to measure 4E noise at $V_{\text{bias}} < 40\text{V}$

- Higher number of electrodes, larger capacitance $\rightarrow$ large noise
- CMS planar sensor noise 100-150 electrons

FBK 3D (ATLAS08 batch)

- 1E type

FBK 3D (ATLAS09 batch)

All 1E type
Lab: charge collection with source @ 21 °C

- Sr-90 source: 1 mCi, $E_\beta = 0.546$ MeV
- Random trigger used

Slight difference between measured and simulated collected charges:
- combined effect of charge sharing and readout chip threshold (~3.9 ke-)
- Lower chip gain calibration due to high noise of 3D sensors
- wafer thickness uncertainty (200±20)mm
Fermilab testbeam setup

- Four 2x3 and four 2x4 CMS pixel modules rotated at 25° w.r.t. beam to improve tracking resolution
- Pixel pitch: 100 μm along the rotated axis (150 μm in the other direction)
- Alignment done with a software developed at Milano Bicocca
- Telescope resolution on DUT: 6 μm
Beam test: pre-irradiation

**Hitmap**

**CNM 3D, 1E**

$V_{bias} = -15V$, 0° tilt

- **FBK 3D, 1E**
- **FBK 3D, 2E**

**FBK 3D, 1E**

$V_{bias} = -15V$, 20° tilt

**FBK 3D, 2E**

$V_{bias} = -5V$, 20° tilt

**Efficiency**

- **93.4% efficiency**
- **98.5% efficiency**
- **94.6% efficiency**

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Beam tests: pre-irradiation

FBK (ATLAS09 batch, slim edge), 1E

Charge collection

$V_{\text{bias}}$: $-20$ V
$\text{MPV}: 17 \text{ ke-}$
$200 \pm 20 \text{ } \mu\text{m}$

Efficiency vs bias

Efficiency vs tilt

$V_{\text{bias}} = -20$ V

Residuals for 2 pixel clusters

Spatial resolution

$s_x = 14.4$ mm
$s_y = 12.8$ mm
Irradiation

• Irradiation at the Los Alamos Neutron Science Center (LANSCE) with 800 MeV protons/cm$^2$
  – Fluences: 5E14, 1E15, and 5E15 p/cm$^2$ (FBK)
  – Fluences: 1E15, and 5E15 p/cm$^2$ (SINTEF)
  – Fluences: 1E14, 3E14, 5E14, and 1E15 p/cm$^2$ (CNM)
• Post-irradiation lab (@ Purdue) and beam tests (@ FNAL) performed for SINTEF and FBK 3D sensors
  – CNM sensors only tested in testbeams
• All readout chips work after irradiation
  – Except SINTEF case: 1 out of 6 ROCs worked
• Post-irradiation lab measurements carried out in the thermal chamber running at -20 °C
  – sensor temp estimated by an IR camera to be -7 °C

800 MeV proton to 1 MeV neutron equivalent conversion factor is 0.7
**Lab: post-irradiation IV @ -20 °C**

**SINTEF 3D**

- **4E_B2-10_1** ($\Phi = 1E15$ neq/cm²) @ -20 °C
- **4E_B2-10_1** ($\Phi = 0$ neq/cm²) @ 21 °C

**FBK 3D**

- **1E_2_W8** ($\Phi = 1E15$ p/cm²)
- **2E_9_W8** ($\Phi = 1E15$ p/cm²)
- **4E_14_W8** ($\Phi = 1E15$ p/cm²)
- **1E_1_W8** ($\Phi = 5E15$ p/cm²)
- **1E_1_W8** ($\Phi = 0$ p/cm²)
- **2E_9_W8** ($\Phi = 0$ p/cm²)
- **4E_14_W8** ($\Phi = 0$ p/cm²)

- SINTEF 3D breakdown improved by 15V
- FBK 3D breakdown improved by less than 10V in average

- FBK ATLAS08 sensors have process related problems
  - high leakage current
  - early breakdown
- Current increased after irradiation
- Problems of ATLAS08 understood and improved in later batches (ATLAS09 and ATLAS10)

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Lab: post-irradiation noise

**SINTEF 3D**

- SINTEF 3D noise degraded by less than 50 electrons
  - but only one sensor
- FBK 3D noise after irradiation
  - almost no change in 4E
  - 30 e- in 2E
  - 30 e- (50 e-) in 1E with 1E15 (5E15)

Pre-irradiation noises measured: 20 °C
Post-irradiation noises measured: -20 °C

**FBK 3D**

- Pre-irradiation noises measured: 20 °C
- Post-irradiation noises measured: -20 °C

E. Alagoz, 3D workshop @ CERN, 11/16/2012, Geneva, CH
Lab: post-irradiation charge collection @ -20 °C

- Sr-90 source: 1 mCi, $E_\beta = 0.546$ MeV
- Random trigger used

Signal **LOSS in FBK 3D (@ -30V, 3900 electrons threshold):**
- 1E 43% after 1E15 p/cm$^2$ (0.7E15 n$_{eq}$/cm$^2$)
- 1E 50% after 5E15 p/cm$^2$ (3.5E15 n$_{eq}$/cm$^2$)
- 2E 14% after 1E15 p/cm$^2$ (0.7E15 n$_{eq}$/cm$^2$)
- 4E 14% after 1E15 p/cm$^2$ (0.7E15 n$_{eq}$/cm$^2$)

**CMS pixel 50% after 1E15 n$_{eq}$/cm2 at 600V**

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SINTEF (200 µm thick)

Winner is 2E ➔
Beam test: post-irradiation

- Measured at -20 °C
- No tilt (0° degree) wrt beam
- Electrodes are less sensitive: observed lower efficiency in electrode regions
- Post-irradiation simulations ongoing to understand post-irrad sensor efficiencies
Beam test: post-irradiation

- Track efficiency decreases after irradiation. 1E sensors more affected
- Efficiency increases with bias, due to larger electric field in the bulk, up to breakdown where it falls off
- Not all sensors tested up to breakdown

### Efficiency at maximum bias

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Pre-irradiation</th>
<th>Post-irradiation</th>
<th>Fluence [$n_{eq}/cm^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1E_1</td>
<td>97.7</td>
<td>37.9</td>
<td>$3.5 \times 10^{15}$</td>
</tr>
<tr>
<td>1E_2</td>
<td>81.1</td>
<td>59.2</td>
<td>$0.7 \times 10^{15}$</td>
</tr>
<tr>
<td>2E</td>
<td>97.1</td>
<td>91.1</td>
<td>$0.7 \times 10^{15}$</td>
</tr>
</tbody>
</table>
Summary & outlook

- 3D sensors have several features outperform planar sensors
- Sensors received from SINTEF (Norway), FBK (Ital), and CNM (Spain)-
- Breakdown voltage: SINTEF > 100V, CNM > 100V, and FBK < 40V
- 3D sensors have higher noises vs CMS planar sensors
- Pre-irradiation beam test results show efficiencies higher than 90%
- Irradiated fluences are between 1E14 and 3.5x10^{15} n_{eq}/cm^2 (800 MeV protons)
- Placed in testbeam at FNAL in October (April) 2011 (2012) before (after) irradiation
  - > 90% tracking efficiency before irradiation
  - Low tracking efficiency after irradiation due
    - High readout threshold
    - Low electric field (lower post-irradiation breakdown voltage)
  - Good charge collection after heavy irradiation wrt planar
  - 2E configuration outperforms 1E and 4E after irradiation
  - Signal loss in FBK 3Ds is lower (14%) for sensors with more than 1 electrodes
- Expecting 3Ds from SINTEF without support wafer; and 1E, 2E, 3E, and 4E sensors from FBK ATLAS10 batch
- Ongoing simulation to develop understanding FBK beam test results
- Next irradiation fluences will go up to 1E16 n_{eq}/cm^2
3DC

Czech Technical University, Fermilab, Purdue University, INFN Torino, SINTEF, SLAC, University of Hawaii, University of Manchester
BACKUP SLIDES
Noise test

Single pixel SCurve

Noise measurement of FBK 1E type 3D sensor

2D noise map

Noise distribution

Error function fit

Gaussian fit

Higher noise due to long pixel on the sensor edges