Charge collection efficiency study of neutron irradiated silicon pad detectors for the CMS High Granularity Calorimeter

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Outline

- **HGCAL**: Upgrade of ECAL/HCAL endcaps
- **Neutron irradiation campaign**: Samples, fluences & facilities

- **CCE study**: TCT-signal & simulation tuning
- **Results I**: $\text{CCE}(V, \Phi)$ of 300/200/120 $\mu$m sensors @ -30° C
  - $\text{CCE}(\Phi)$: Operating voltage @ HGCal
- **Results II**: Full depletion voltages

- **Conclusions**
HGCAL: Upgrade of ECAL/HCAL endcaps

- **Hexagonal 8” Si modules @ -30° C** → preserve MIP identification @ extreme fluences

- **Sensor tiling structure in 36 layers of Si-only cassettes**
  - 300/200 µm boundary
  - 200/120 µm sensor boundary

  - Higher η → 3.0: 10-fold > than tolerance of present system, Pileup: ~60 @ LHC → 140-200

Evaluate sensor performance for expected neutron fluences & operational conditions

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[1] CMS-TDR-17-007
TTU irradiation campaign: Samples, fluences & facilities
Neutron irradiations: RI & UCD samples

- **Radiation damage @ HGCAL mostly due to neutrons:**
  - 30 test samples irradiated @ Rhode Island (RINSC) & UC Davis (MNRC) reactors → crosscheck dosimetry & methods for LC-extracted $\Phi$ (see backup 1 – 2)
  - **Table:** Red - Rhode Island (RI), Black - UC Davis (UCD)

<table>
<thead>
<tr>
<th>Wafer size</th>
<th>Sensor type &amp; thickness</th>
<th>Target fluence $[n_{eq}/cm^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8”</td>
<td>300P</td>
<td>1 + 0 1 + 0 2 + 2</td>
</tr>
<tr>
<td>200P</td>
<td></td>
<td>1 + 0 1 + 1 0 + 1</td>
</tr>
<tr>
<td>Epi 120P</td>
<td></td>
<td>0 + 1</td>
</tr>
<tr>
<td>6”</td>
<td>300P</td>
<td>0 + 1 0 + 1 0 + 1</td>
</tr>
<tr>
<td>120P</td>
<td></td>
<td>1 + 0 1 + 0 1 + 2</td>
</tr>
<tr>
<td>300N</td>
<td>1 + 0 1 + 0 1 + 1</td>
<td></td>
</tr>
<tr>
<td>200N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120N</td>
<td></td>
<td>1 + 0 2 + 0 1 + 2</td>
</tr>
</tbody>
</table>

**Samples:**

- 300P: 300 µm thick n-on-p diode

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CCE study: TCT-signal & simulation tuning
**TCT-setup: Measured signal shape vs simulated**

- **Measured & TCAD simulated:** 300N diode
  - Particulars 440 ps, 11 µm wide IR-laser spot
  - V=500 V @ -30° C

- **Simulation input:**
  - Sensor parameters from measured CV/IV
  - $R_{bias}$ tuned for matching signal shape

- Closely reproduced transient signals & $Q_{coll}$
  → well understood/stable setup & samples

- **Irradiated:** CCE simulations w/ neutron defect model [2] @ -30° C (see backup 5)

Results I:

CCE(300/200/120 µm) @ -30° C
CCE(V) @ -30° C: 300N/P

- Solid (RI) & dashed (UCD) curves: TCAD simulated 300N/P
- Filled (RI) & hollow (UCD) markers: Measured 300N/P

Plot: IV-extracted Φ

- RI 6” & 8”:(1.05±0.05)e14, TCAD: 1.1e14
- RI 6”: (3.5±0.4)e14, TCAD: 3.9e14
- RI 6”: (5.4±0.4)e14, TCAD: 5.2e14
- UCD 6”: (6.1±0.5)e14, TCAD: 6e14
- UCD 8”: (6.1±0.5)e14, TCAD: 6.2e14

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CCE(Φ) @ -30° C, 600 – 800 V: 300N/P

- **Solid (800 V) & dashed (600 V) curves:** TCAD simulated 300N/P
- **Filled (RI) & hollow (UCD) markers:** Measured 300N/P
- **V_{default}(HGCal) = 600 V → V_{max}(HGCal) = 800 V**
- **Fluences:** IV-extracted Φ_{eff}

- **300N/P:** >10% benefit from operating @ V_{max} for high Φ(HGCal)

**Φ > 300N/P HGCal-limit:** Data to extend defect model from 1e15 → 1e16 n_{eq}/cm^2

**300N/P:** Simulation @ -30° C verifies & predicts IR-TCT data

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CCE(V) @ -30° C: 200N/P

- Filled (RI) & hollow (UCD) markers: Measured 200N/P
- Solid (RI) & dashed (UCD) curves: Fit to data

Plot: IV-extracted Φ

- **RI 8\"":** $(1.5\pm0.3)e^{15}$
- **UCD 8\"":** $(3.47\pm0.16)e^{15}$
- **RI 6\"":** $(1.5\pm0.3)e^{15}$
- **UCD 8\"":** $(9.31\pm1.05)e^{15}$

- **200P: CCE(800 V)**
  - $\approx 19\%$ @ highest Φ
Filled (RI) & hollow (UCD) markers: Measured 200N & 200P

(3.47±0.16)e15: ~16% benefit from operating @ V_max → CCE(800V) ≈ 60%

Verification by CCE vs V_{fd}: backup 6
CCE(V) @ -30° C: 120N/P

- Filled (RI) & hollow (UCD) markers: Measured 120N/P
- Solid (RI) & dashed (UCD) curves: Fit to data

- 8” epi @ (3.47±0.16)e15: CCE = 1 @ 600 V

- Plot: IV-extracted Φ

- UCD: (9.31±1.05)e15
  - All samples 6” unless noted
  - significant ΔCCE for 120P

- RI: (1.5±0.3)e15
- UCD 8” epi: (3.47±0.16)e15
- RI: (6.6±0.7)e15
- UCD: (9.31±1.05)e15
- RI: (2.35±0.19)e15

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Filled (RI) & hollow (UCD) markers: Measured 120N/P

Solid (800 V) & dashed (600 V) curves: Fit to data

- 120N/P: CCE starts degrading $3.5 \times 10^{15} < \Phi < 6.7 \times 10^{15}$ neq/cm$^2$
  - (15 – 20)% benefit from operating @ $V_{\text{max}}$ for high $\Phi$

$CCE(\Phi) @ -30^\circ \text{C}, 600 – 800 \text{ V}: 120\text{N/P}$
CCE(\(\Phi\)): Operating voltage @ HGCal

- Assumed acceptance limit: CCE = 60%

- 600 V for operating V:
  - 300N: For all \(\Phi\)
  - 300P: Not for highest \(\Phi\)
  - 200N/P: Up to \(\sim2\times10^{15}\)
  - 120N: Up to \(\sim7\times10^{15}\)
  - 120P: Up to \(<6\times10^{15}\)

- 800 V for operating V:
  - 300N/P: For all \(\Phi\)
  - 200P: For all \(\Phi\)
  - 120N/P: For all \(\Phi\)

- CCE(\(\Phi\)) comparison w/ published study: backup 7
Results II: Full depletion voltages
**$V_{fd}(\Phi)$**: 300N/P (meas vs sim) & 120/200N/P

- **300N/P**: Measured vs simulated
  - 800V
  - 600V

- **300N**: Measured and simulated within error margins
  - Not fully depleted @ 600 V for $\Phi > 5 \times 10^{14} \text{ n}_\text{eq}/\text{cm}^2$

- **300P**: Simulated within error margins, except @ highest $\Phi$ $\Delta V_{fd} = 7.5$
  - No $V_{fd}$ @ 600 V for $\Phi > 3 \times 10^{14} \text{ n}_\text{eq}/\text{cm}^2$
  - No $V_{fd}$ @ 800 V for $\Phi > 4 \times 10^{14} \text{ n}_\text{eq}/\text{cm}^2$

- **200P**: Not fully depleted @ 800 V for HGCal $\Phi$-range

- **120N/P**: Not fully depleted @ 800 V for $\Phi > 6 \times 10^{15} \text{ n}_\text{eq}/\text{cm}^2$ → **no charge multiplication @ highest $\Phi$**

**Note**: Measured $V_{fd}(\Phi)$: IV-extracted $\Phi$
Conclusions

- **CCE study of irradiated test diodes w/ IR-TCT:** Completed for 11 8-inch & 17 6-inch samples @ HGCal operational conditions

- **CCE results @ -30° C, 600 V & 800 V:**
  - **300N/P:** Simulation verifies/predicts IR-TCT data
    - >10% benefit from operating @ $V_{\text{max}}$ @ high $\Phi(\text{HGCal})$
    - N vs P: 300N performs better after $\sim 4e14 \ n_{eq}/cm^2 \rightarrow \text{CCE} \geq 60\% \ @ \ V_{\text{default}}$
      for HGCal $\Phi$-range
  - **200P:** 16% benefit from operating @ $V_{\text{max}}$ @ $\sim 3.5e15$
    - 200P vs 300P @ $\sim 1e16$: Similar CCE due to $\sim$equal depletion region
  - **120N/P @ $\sim 1e16$:** 20% benefit from operating @ $V_{\text{max}}$
    - No clear difference observed between polarities
  - **300N/P, 200P & 120N/P:** CCE $\geq 60\% \ @ \ V_{\text{max}}$ for HGCal $\Phi$-ranges
  - $V_{\text{fd}}(\Phi)$: Low $V_{\text{fd}}$ due to SCSI reason for higher CCE on 300N
    - 200P not fully depleted even @ $V_{\text{max}}$ for HGCal $\Phi$-range

- **TCAD tuning w/ sensor & IR-TCT parameters:** Reproduced transient signals $\rightarrow$ minimized error sources for neutron irradiation modeling $\rightarrow$ extend defect model to $1e16 \ n_{eq}/cm^2 \ w/ \ measured \ CCE, \ LC \ & \ V_{\text{fd}} @ \ extreme \ fluences$
Back-up 1: Facility crosscheck: $\alpha$-factor

- **$\alpha$-factor for Rhode Island dosimetry $\Phi$:**
  - Expected: $\alpha(\text{RT}) = 4.0 \times 10^{-17} \text{ A/cm}$
  - $\Phi$: $\alpha(\text{RT}) = 4.0 \times 10^{-17} \text{ A/cm} + 2.6$

- **IV-extracted @ TTU:**
  - $\alpha(\text{RT}) = 3.1 \times 10^{-17} \text{ A/cm}$
  - $\Phi$: $\alpha(\text{RT}) = 3.1 \times 10^{-17} \text{ A/cm} + 1.5$

- **$\alpha$-factor for UC Davis dosimetry $\Phi$:**
  - Expected: $\alpha(\text{RT}) = 4.0 \times 10^{-17} \text{ A/cm}$
  - $\Phi$: $\alpha(\text{RT}) = 4.0 \times 10^{-17} \text{ A/cm} + 0.8$

- **IV-extracted @ TTU:**
  - $\alpha(\text{RT}) = 3.1 \times 10^{-17} \text{ A/cm}$
  - $\Phi$: $\alpha(\text{RT}) = 3.1 \times 10^{-17} \text{ A/cm} + 1.0$

UCD dosimetry verified by IV-extracted $\Phi$
Back-up 2: LC/Vol - Before/after annealing

- Annealing 80min @ (59.9±0.6)° C
- Before annealing: Black dashed curves
  - IV-extracted: ΔΦ(1e16) ≈ 11%, ΔΦ(1.5e15) ≈ 20%, ΔΦ(7.5e14) ≈ 7%
- Before/after annealing:
  - 120N 1e16: ΔΦ ≈ -3%
  - 200N 1.5e15: ΔΦ ≈ -3%
  - 300P 7.5e14: ΔΦ ≈ -5.6%

Negligible effect from annealing to IV-extracted Φ

6” UCD: 120N 1e16

6” RI: 200N 1.5e15

8” RI: 300P 7.5e14
Back-up 3: CCE(p-on-n) - Offset-corrected $Q_{coll}$

#2027/2026:
- 120 µm p-on-n

Fixed param:
- $T = -(30.2 - 30.0)° C$
- DAC=62.8%

#2027 ref:
- raw-data $Q_{coll}$

#2027 ref:
- offset-corrected $Q_{coll}$

1e16 $n_{eq}/cm^2$ #2026:
- raw-data $Q_{coll}$

Pre-signal negative offset

After-signal offset ≈ 0

CCE

1e16 #2026:
- offset-corrected $Q_{coll}$
Fixed param:

- $T = -(30.2 \text{ – } 30.1) \degree C$
- DAC = 64%

Pre-signal positive offset

After-signal positive offset

→ extract $Q_{coll}$ @ early $t$
**2D-structure:** 6-inch sample deep diffused doping profile for 320 µm physical & 200 µm active thickness

- Bulk doping ~1e12 cm⁻³
- Deep diffusion (DD) region, peak doping = 1e19 cm⁻³

**CMS Neutron defect model parameters, \( \Phi_{eq} = 1e14 \sim 1e15 \text{ cm}^{-2} @ T = 253 \text{ K} [2]:**

<table>
<thead>
<tr>
<th>Type of defect</th>
<th>Level [eV]</th>
<th>( \sigma_e ) [cm²]</th>
<th>( \sigma_h ) [cm²]</th>
<th>Concentration [cm⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>( E_C - 0.525 )</td>
<td>1.2e-14</td>
<td>1.2e-14</td>
<td>1.55*( \Phi )</td>
</tr>
<tr>
<td>Donor</td>
<td>( E_V + 0.48 )</td>
<td>1.2e-14</td>
<td>1.2e-14</td>
<td>1.395*( \Phi )</td>
</tr>
</tbody>
</table>


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**Back-up 5: TCAD: 2D-structure & defect model**

**CCE(\( \Phi \)):** 320 µm n-on-p strip detector

**Double peak of E-field @ V=800 V**

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Back-up 6: 300P vs 200P - $\Phi \approx 1 \times 10^{16}$ n$_{eq}$/cm$^2$

$CCE = \sqrt{\frac{V}{V_{fd}}} \left(1 - e^{-\frac{t_{dr}}{\tau_{eff}}} \right)$

Equal $\Phi$ & $V \rightarrow \tau_{eff1} = \tau_{eff2}, \ t_{dr1} \approx t_{dr2}$

$$\frac{CCE_{200}}{CCE_{300}} = \sqrt{\frac{V_{fd300}}{V_{fd200}}}$$

$R(CCE) = 1.17 \pm 0.07 = 1.39 \pm 0.15 = R(V_{fd})$

$V_{fd} \approx 2.4$ kV

200P vs 300P @ 1e16:
- 300P: $\Delta CCE = 6\%$, $\Delta V_{fd} = 8\%$
- 200P: $\Delta CCE = 3\%$, $\Delta V_{fd} = 7\%$

$V_{fd}$ results in line w/ observed CCEs

Back-up 7: CCE(Φ) – TTU vs published study

- **Published 2017 CCE study** [1,4]: Filled markers for CCE @ -20° C
  - 6-inch dd-FZ test diodes
- **TTU**: Hollow markers for CCE @ -30° C
  - **p-on-n**: 6-inch dd-FZ test diodes
  - **n-on-p**: 8-inch std-FZ & 6-inch dd-FZ test diodes
  - **CCE(Φ)**: IV-extracted Φ\text{eff}
  - **Simulated**: Dashed curves

- **Published & TTU**: 300N better to 300P
- **Published**: 120N better to 120P @ high Φ
- **TTU**: 8” 200P better to 6” 200N/P @ 600 V & to 6” 200P @ 800 V & high Φ
  - **120N/P**: Similar performance @ highest Φ