14th “Trento” Workshop for Advanced Silicon Radiation Detectors, 25 – 27 Feb 2019

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


**Timo Peltola** [1] *On behalf of the CMS collaboration*

[1] *Texas Tech University, Department of Physics and Astronomy, Lubbock 79409, TX*

# Outline

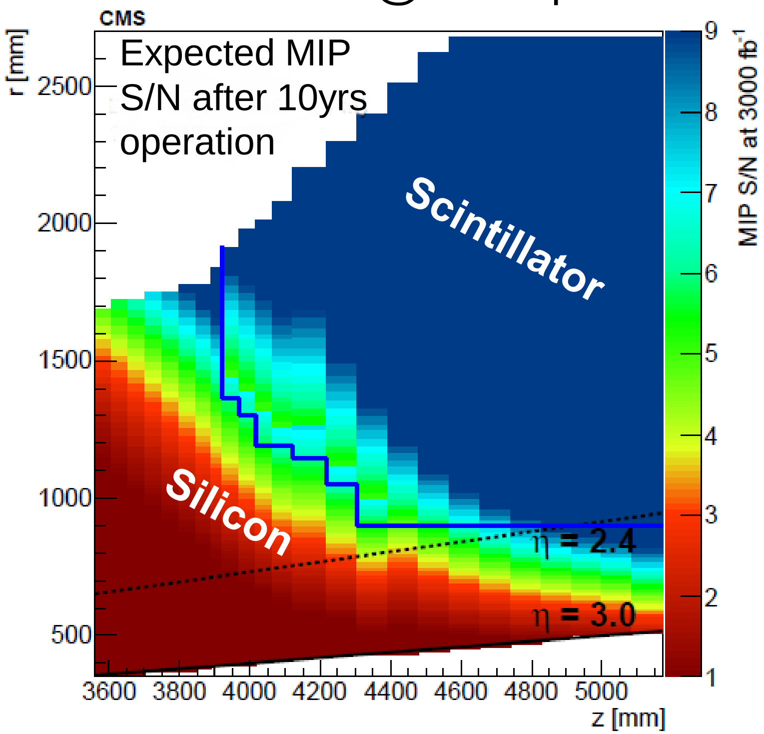
- **HGCAL:** Upgrade of ECAL/HCAL endcaps
- **Neutron irradiation campaign:** Samples, fluences & facilities

- **CCE study:** TCT-signal & simulation tuning
- **Results I:** CCE(V,Φ) of 300/200/120 µm sensors @ -30° C
  - **CCE(Φ):** Operating voltage @ HGCal
- **Results II:** Full depletion voltages

- **Conclusions**

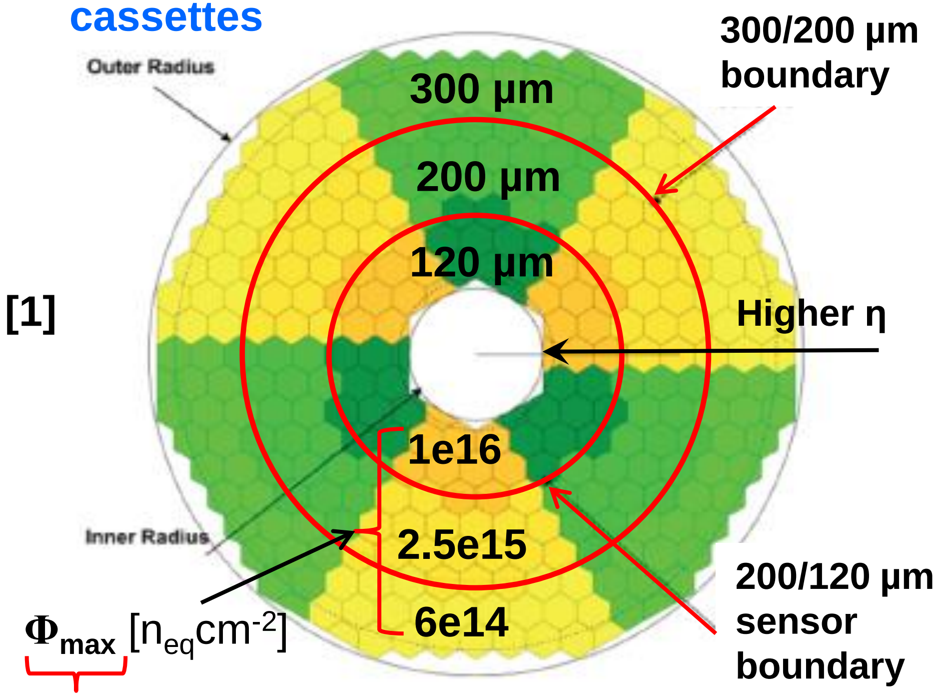
# HGCAL: Upgrade of ECAL/HCAL endcaps

**HGCAL:** Highly segmented calorimeter @ $1.5 \leq \eta \leq 3.0$




**Sensor tiling structure in 36 layers of Si-only cassettes**

[1]




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

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

**Evaluate sensor performance for expected neutron fluences & operational conditions**

[1] CMS-TDR-17-007

# **TTU irradiation campaign:** Samples, fluences & facilities

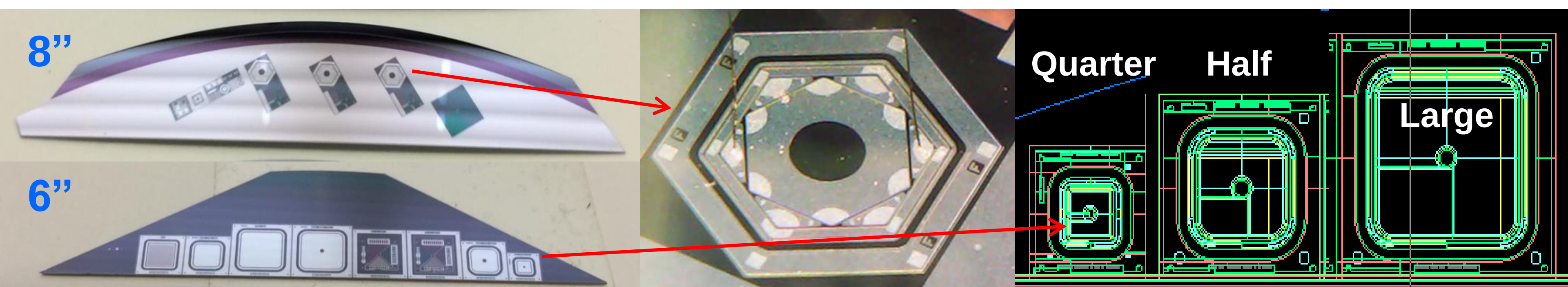
# **Neutron irradiations:** RI & UCD samples

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

**300P:** 300 µm thick n-on-p diode

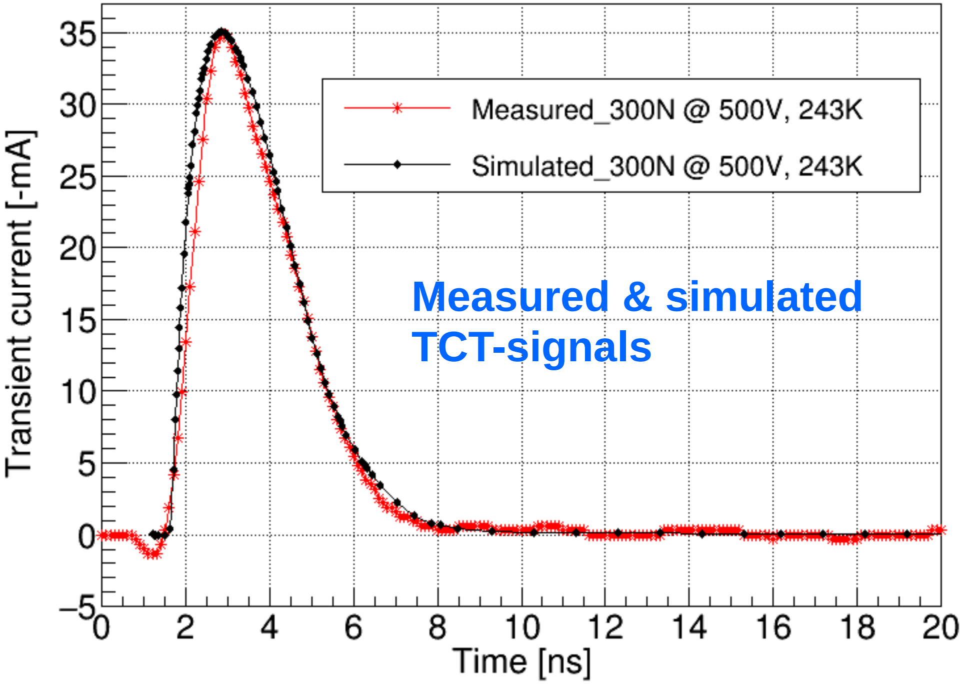
| Wafer size | Sensor type & thickness | **Target fluence** [$n_{eq}/cm^2$] | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1.5e14 | 5.0e14 | 7.5e14 | 1.5e15 | 3.8e15 | 1.0e16 |
| 8” | 300P | 1 + 0 | 1 + 0 | 2 + 2 | | | 0 + 1 |
| | 200P | | | | 1 + 0 | 1 + 1 | 0 + 1 |
| | Epi 120P | | | | | 0 + 1 | |
| 6” | 300P | | | | 0 + 1 | 0 + 1 | 0 + 1 |
| | 120P | | | | 1 + 0 | 1 + 0 | 1 + 2 |
| | 300N | 1 + 0 | 1 + 0 | 1 + 1 | | | |
| | 200N | | | | 1 + 0 | | |
| | 120N | | | | | 2 + 0 | 1 + 2 |

**Samples:**



# **CCE study:** TCT-signal & simulation tuning

# **TCT-setup:** Measured signal shape vs simulated



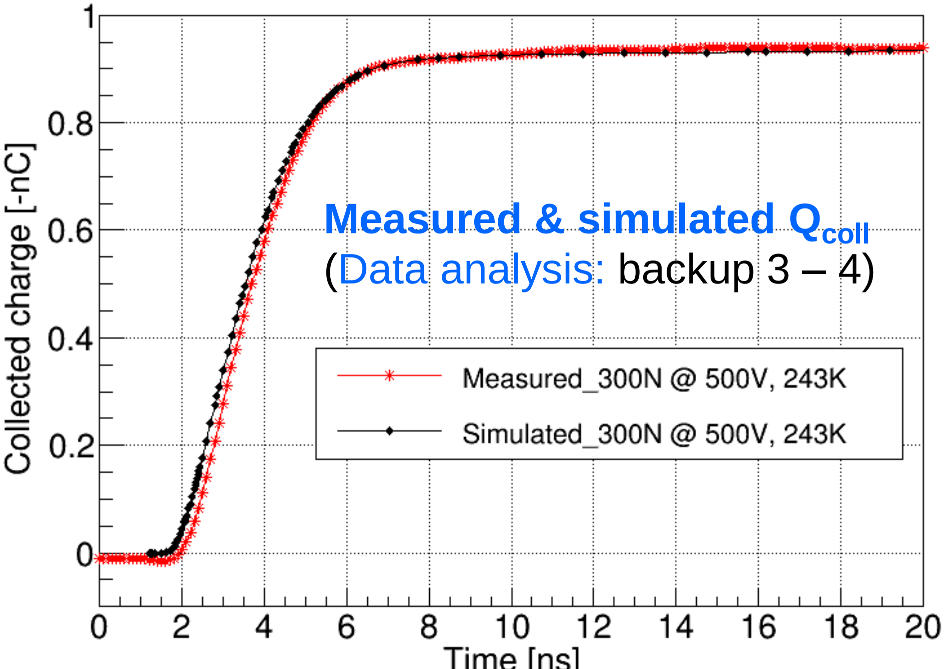

- Closely reproduced transient signals & $Q_{coll}$

→ **well understood/stable setup & samples**

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

[2] R. Eber, PhD Thesis, KIT (2013)

- **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

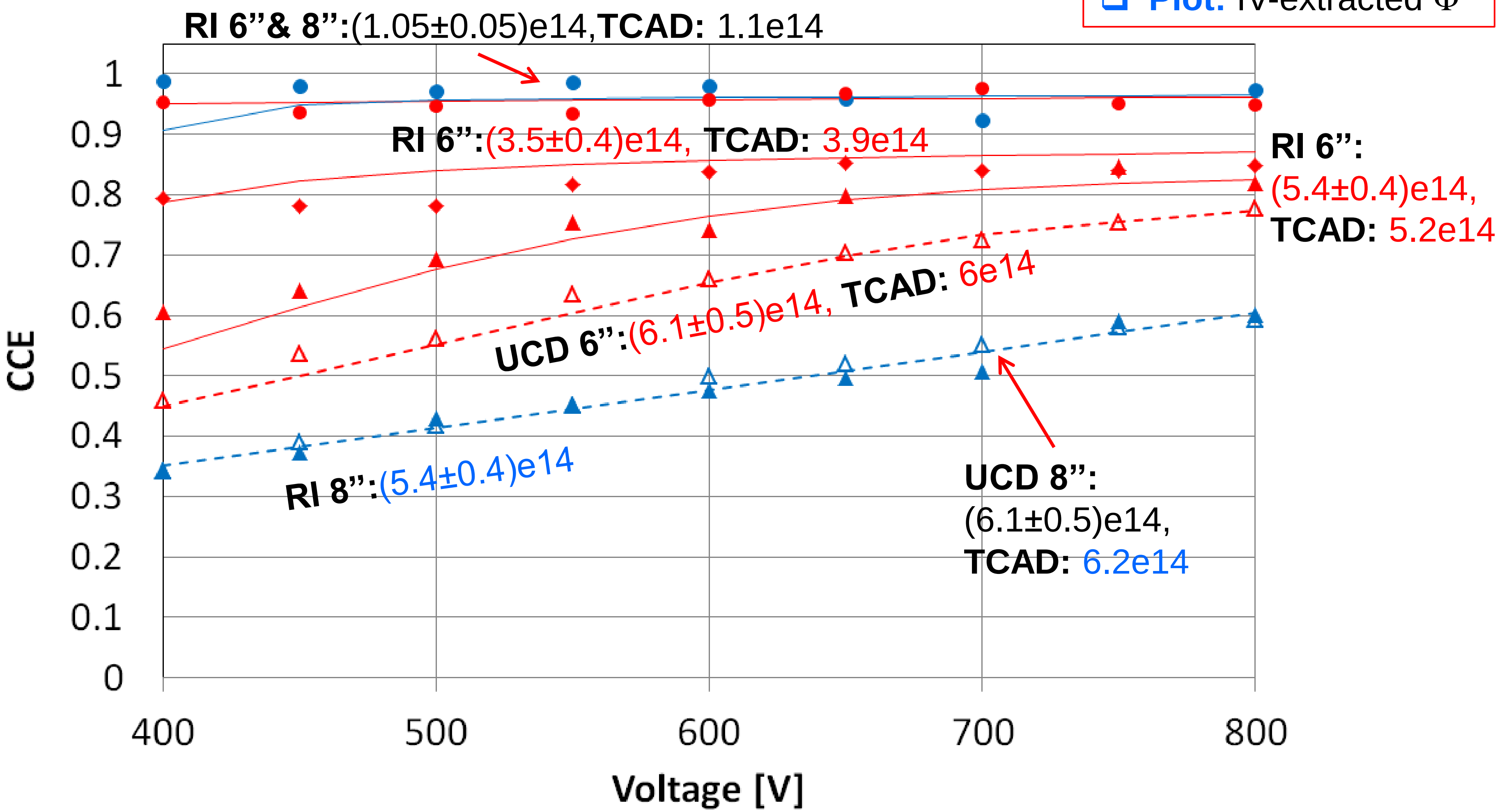


# **Results I:** CCE(300/200/120 µm) @ -30° C

# CCE(V) @ -30° C: 300N/P

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

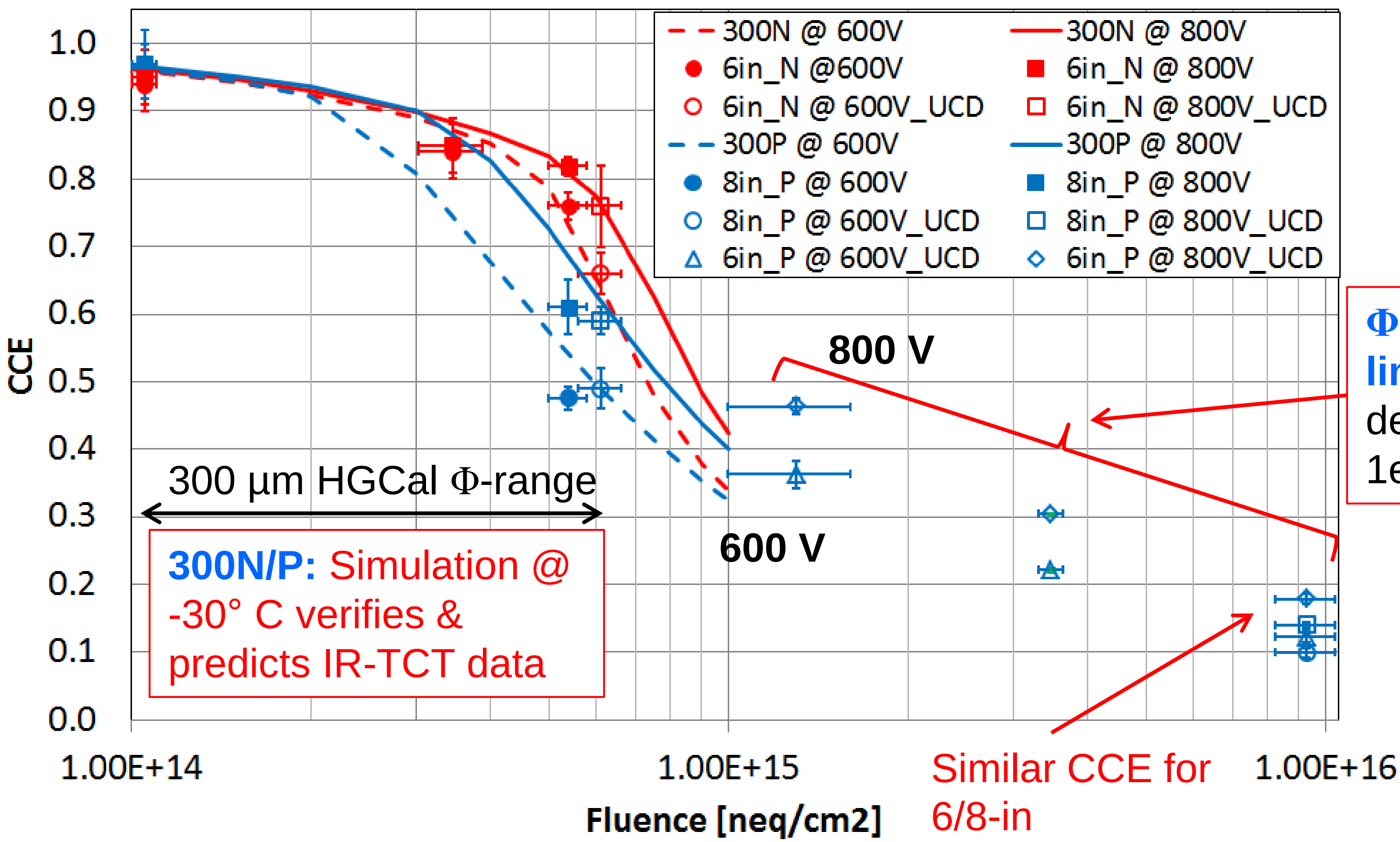
- **Plot:** IV-extracted Φ



# 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 $\Phi_{eff}$

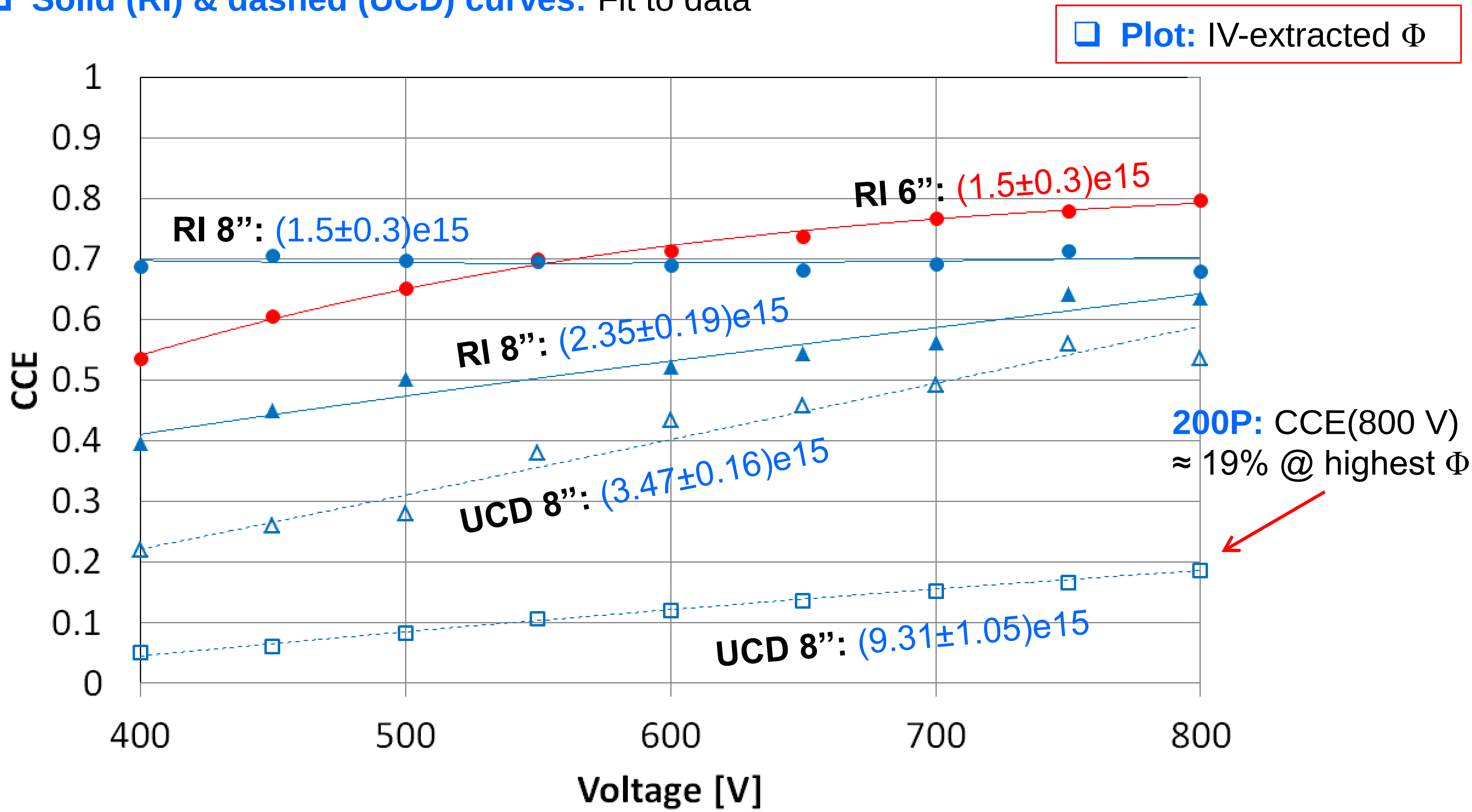
- **300N/P:** >10% benefit from operating @ $V_{max}$ for high Φ(HGCal)




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

# CCE(V) @ -30° C: 200N/P

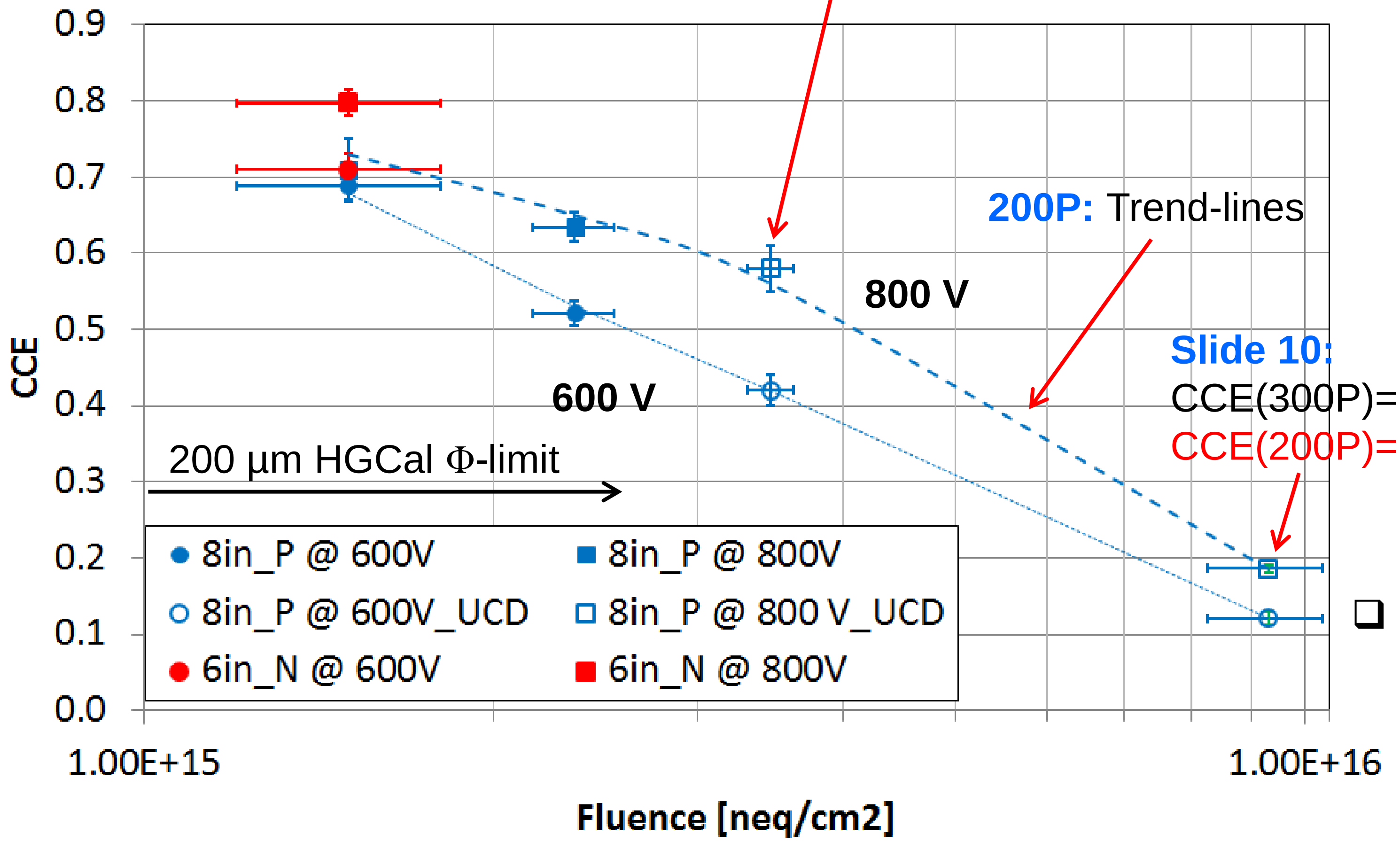
- **Filled (RI) & hollow (UCD) markers:** Measured 200N/P
- **Solid (RI) & dashed (UCD) curves:** Fit to data



# CCE(Φ) @ -30° C, 600 – 800 V: 200N/P

- **Filled (RI) & hollow (UCD) markers:** Measured 200N & 200P

**(3.47±0.16)e15:** ~16% benefit from operating @ $V_{max}$ → CCE(800V) ≈ 60%



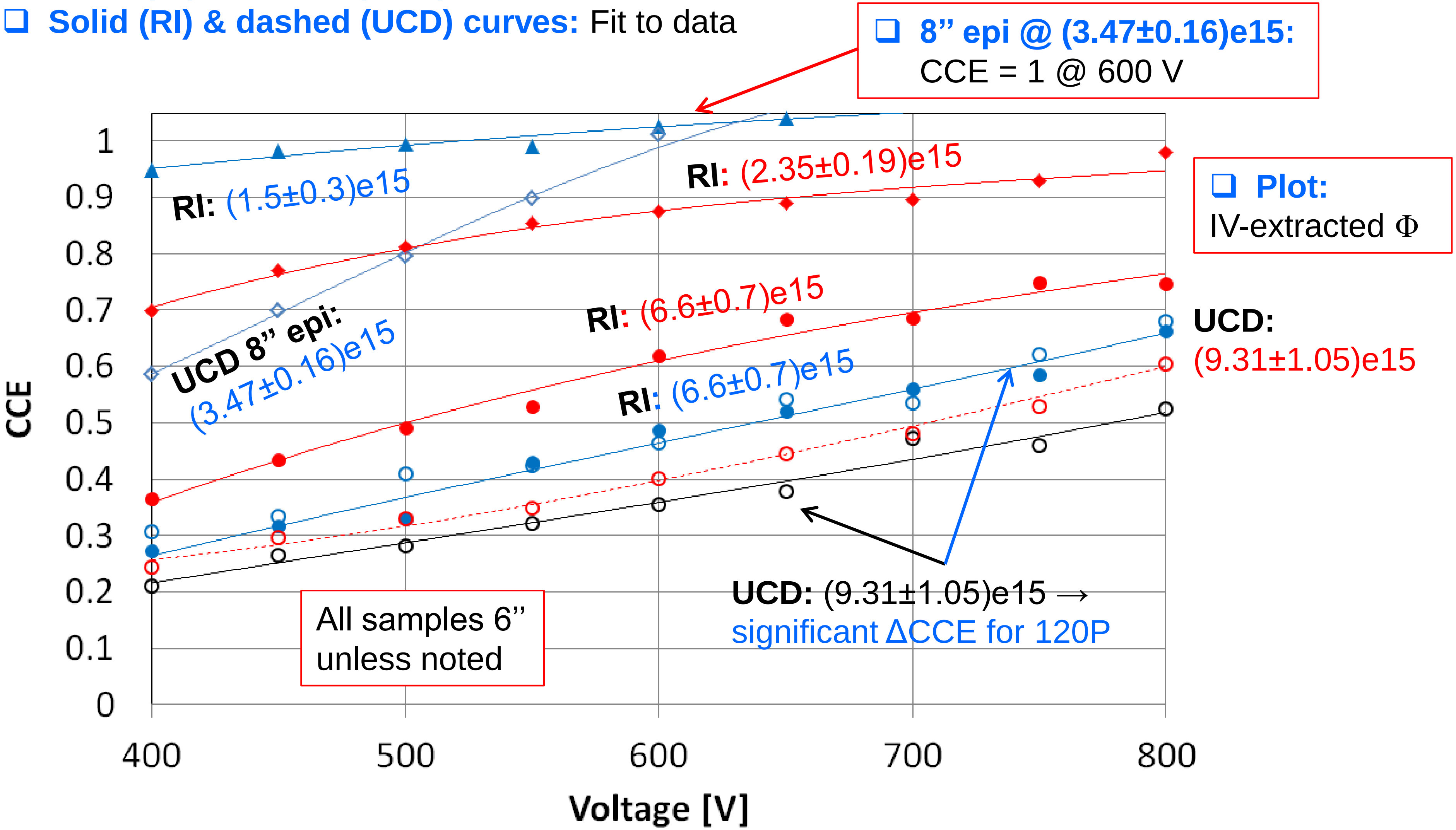

**200P:** Trend-lines

**Slide 10:**
CCE(300P)=(16.0±0.9)%
CCE(200P)=(18.6±0.5)%

- Verification by CCE vs $V_{fd}$: backup 6

# CCE(V) @ -30° C: 120N/P

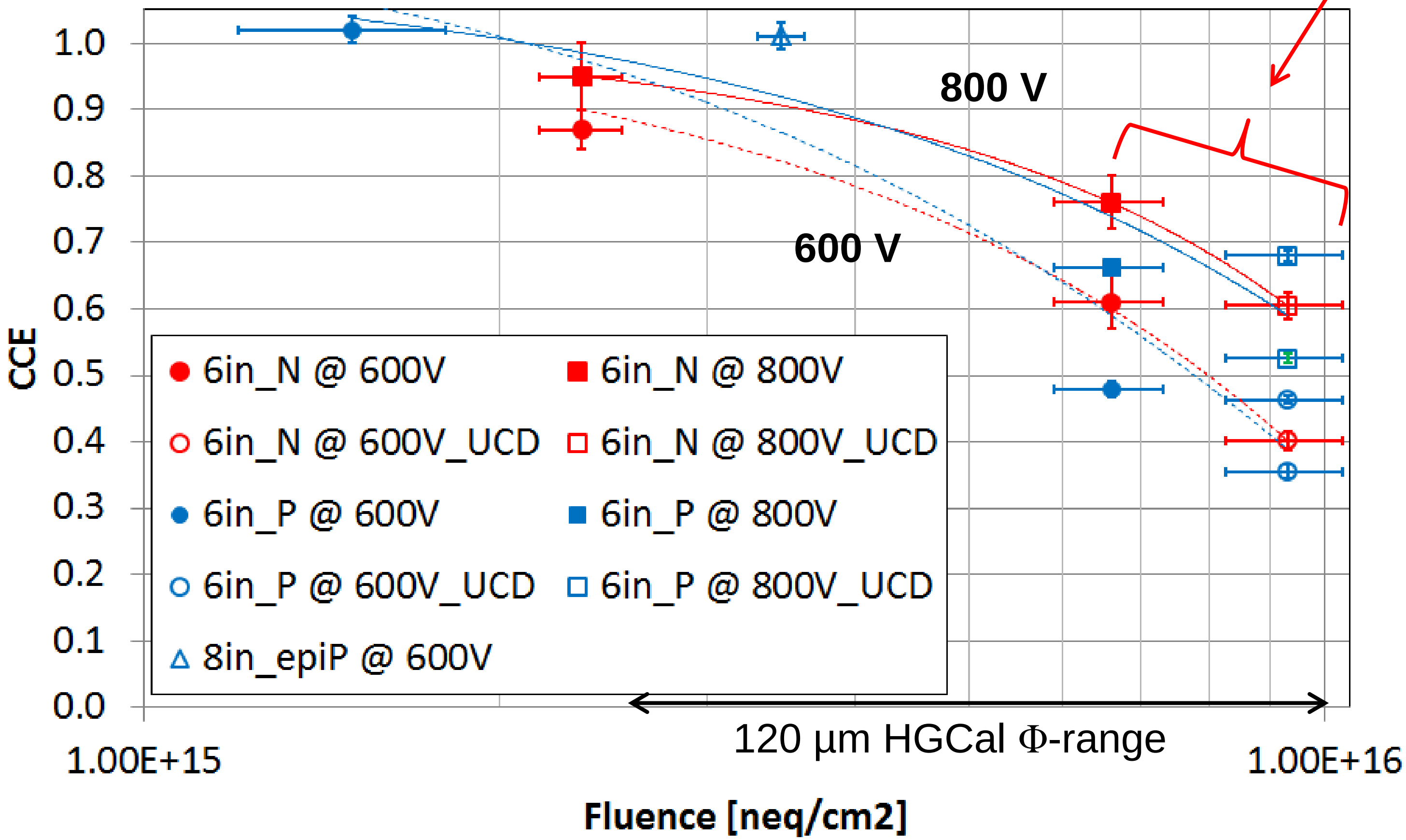
- **Filled (RI) & hollow (UCD) markers:** Measured 120N/P
- **Solid (RI) & dashed (UCD) curves:** Fit to data



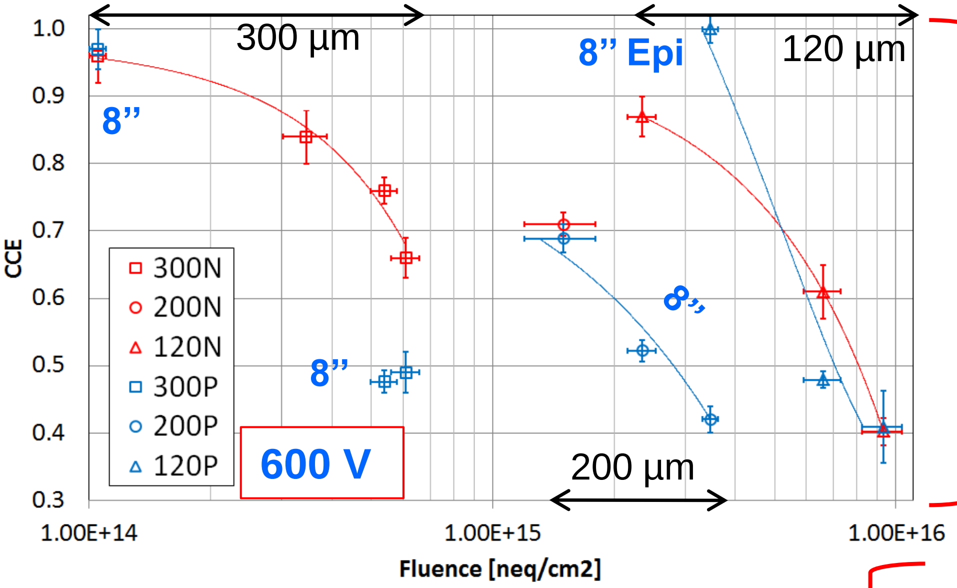
# CCE(Φ) @ -30° C, 600 – 800 V: 120N/P

- **Filled (RI) & hollow (UCD) markers:** Measured 120N/P
- **Solid (800 V) & dashed (600 V) curves:** Fit to data

- **120N/P:** CCE starts degrading 3.5e15 < Φ < 6.7e15 $n_{eq}/cm^2$
  - (15 – 20)% benefit from operating @ $V_{max}$ for high Φ

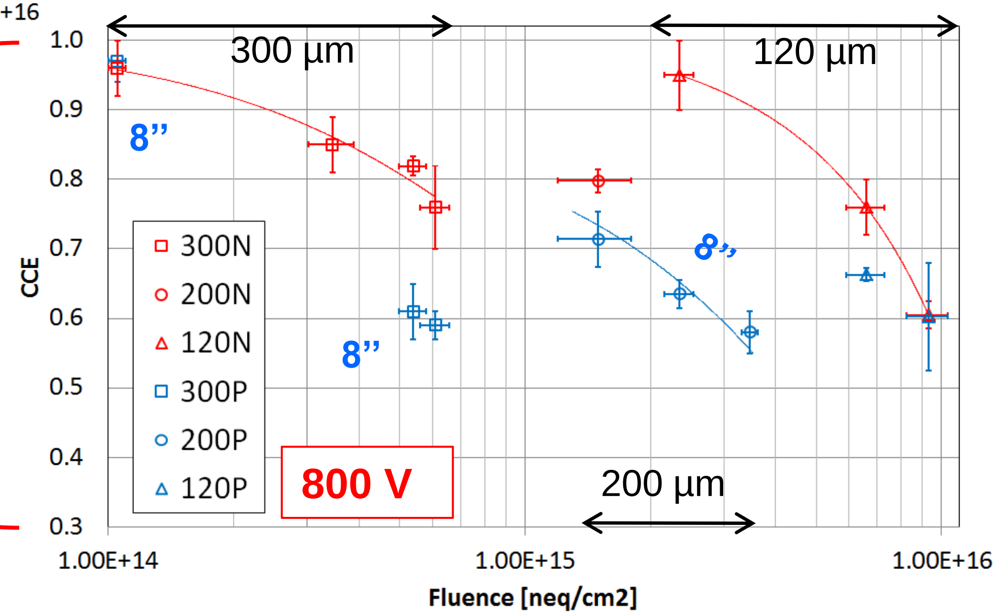


# CCE(Φ): Operating voltage @ HGCal




- **Assumed acceptance limit:** CCE = 60%
- **600 V for operating V:**
  - **300N:** For all Φ
  - **300P:** Not for highest Φ
  - **200N/P:** Up to ~2e15
  - **120N:** Up to ~7e15
  - **120P:** Up to < 6e15

- **800 V for operating V:**
  - **300N/P:** For all Φ
  - **200P:** For all Φ
  - **120N/P:** For all Φ

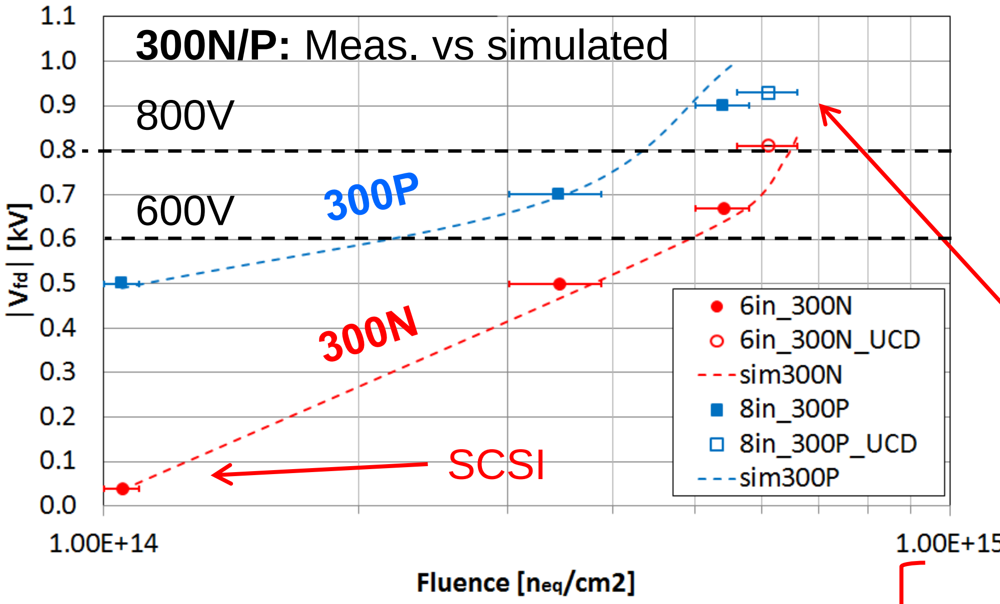



- CCE(Φ) comparison w/ published study: backup 7

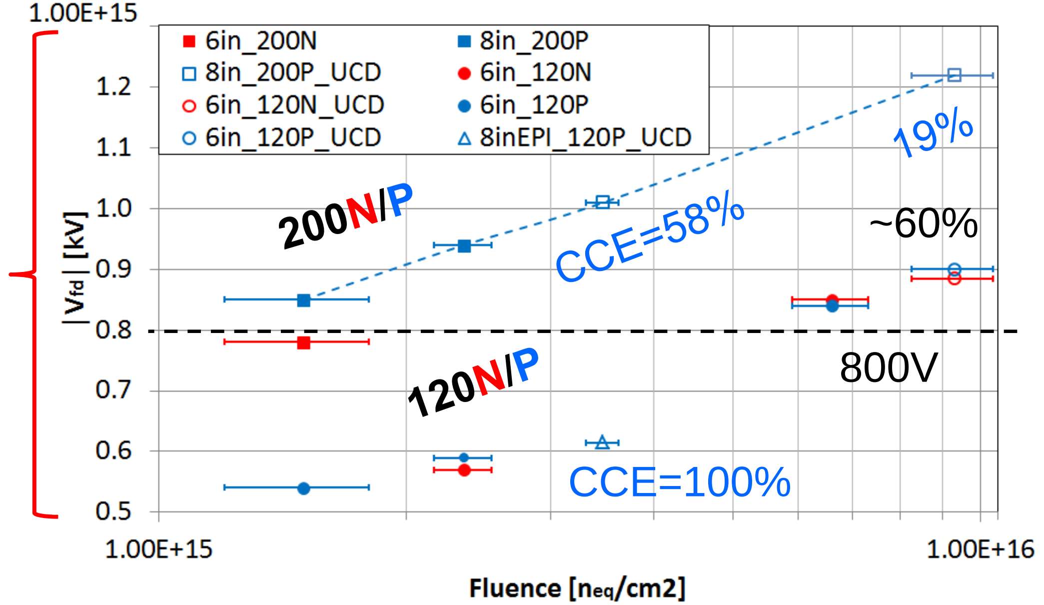
# **Results II:**
# Full depletion voltages

# $V_{fd}(\Phi)$: 300N/P(meas vs sim) & 120/200N/P

- **Measured $V_{fd}(\Phi)$:** IV-extracted Φ
- **300N:** Simulated within error margins
  - Not fully depleted @ 600 V for Φ > 5e14 $n_{eq}/cm^2$
- **300P:** Simulated within error margins, except @ highest Φ $\Delta V_{fd}$ = 7.5%
  - No $V_{fd}$ @ 600 V for Φ > 3e14 $n_{eq}/cm^2$
  - No $V_{fd}$ @ 800 V for Φ > 4e14 $n_{eq}/cm^2$




- **200P:** Not fully depleted @ 800 V for HGCal Φ-range
- **120N/P:** Not fully depleted @ 800 V for Φ > 6e15 $n_{eq}/cm^2$ → **no charge multiplication @ highest Φ**



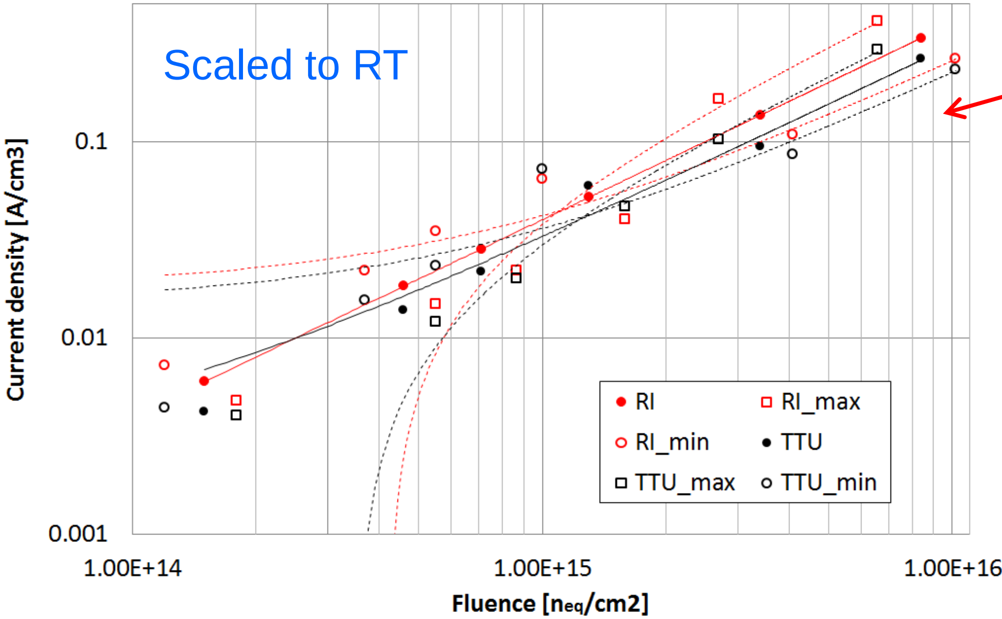
# Conclusions

- **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 @ $V_{max}$ @ high $\Phi$(HGCal)
    - **N vs P:** 300N performs better after ~4e14 $n_{eq}/cm^2$ → CCE ≥ 60% @ $V_{default}$ for HGCal $\Phi$-range
  - **200P:** 16% benefit from operating @ $V_{max}$ @ ~3.5e15
    - **200P vs 300P @ ~1e16:** Similar CCE due to ~equal depletion region
  - **120N/P @ ~1e16:** 20% benefit from operating @ $V_{max}$
    - No clear difference observed between polarities
  - **300N/P, 200P & 120N/P:** CCE ≥ 60% @ $V_{max}$ for HGCal $\Phi$-ranges
  - **$V_{fd}(\Phi)$:** Low $V_{fd}$ due to SCSI reason for higher CCE on 300N
    - 200P not fully depleted even @ $V_{max}$ for HGCal $\Phi$-range

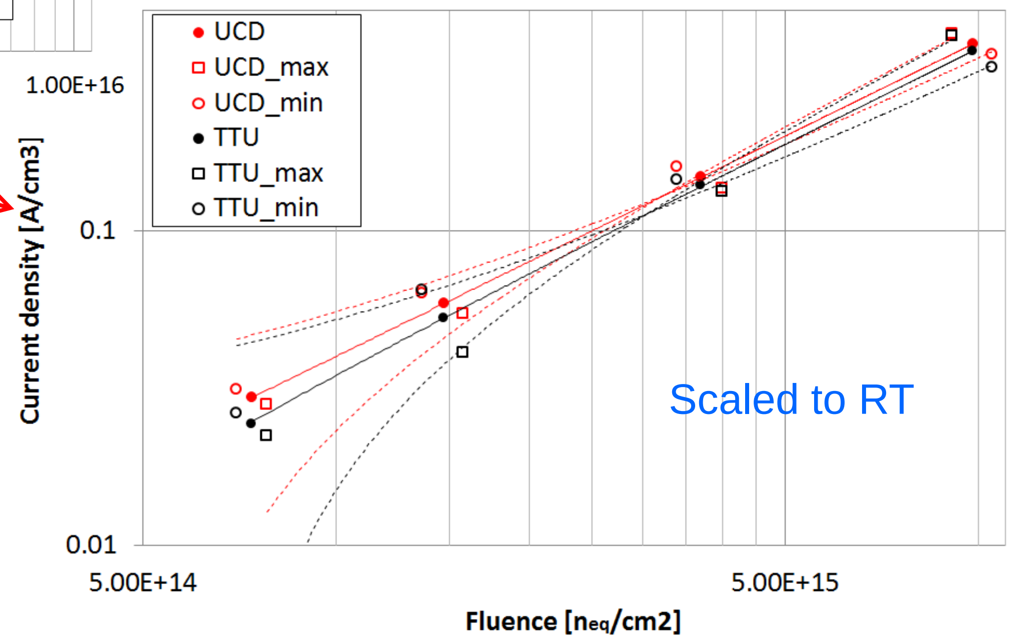
- **TCAD tuning w/ sensor & IR-TCT parameters:** Reproduced transient signals → minimized error sources for neutron irradiation modeling → extend defect model to 1e16 $n_{eq}/cm^2$ w/ measured CCE, LC & $V_{fd}$ @ extreme fluences

# **Back-up 1:** Facility crosscheck: α-factor




- **α-factor for Rhode Island dosimetry Φ:**
  - **Expected: α(RT)= $4.0^{+2.6}_{-1.6}$ e-17 A/cm**
  - **IV-extracted @ TTU:** **α(RT)= $3.1^{+1.5}_{-1.0}$ e-17 A/cm**

- **α-factor for UC Davis dosimetry Φ:**
  - **Expected: α(RT)= $4.0^{+0.8}_{-0.7}$ e-17 A/cm**
  - **IV-extracted @ TTU:** **α(RT)= $3.8^{+1.0}_{-0.8}$ e-17 A/cm**

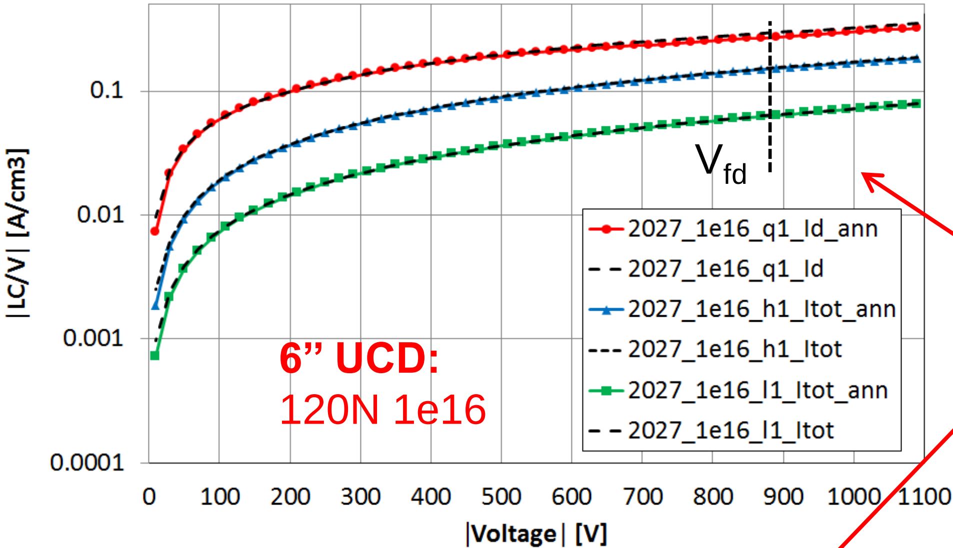


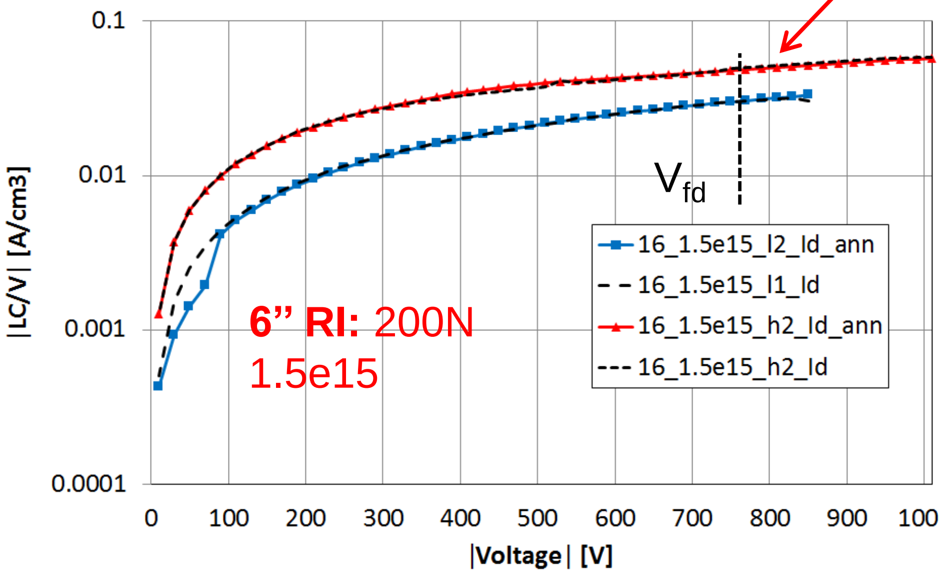

**UCD dosimetry verified by IV-extracted Φ**

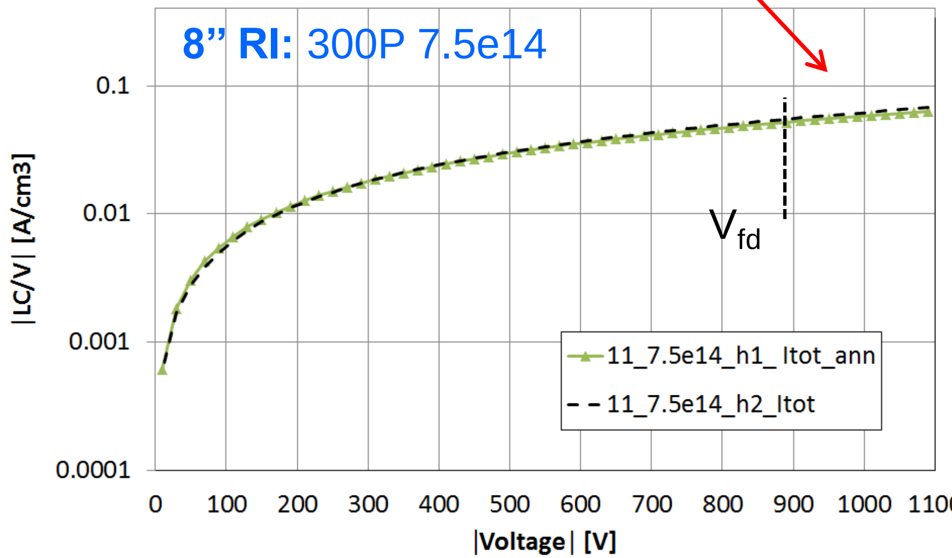
# **Back-up 2**: LC/Vol - Before/after annealing

- 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**



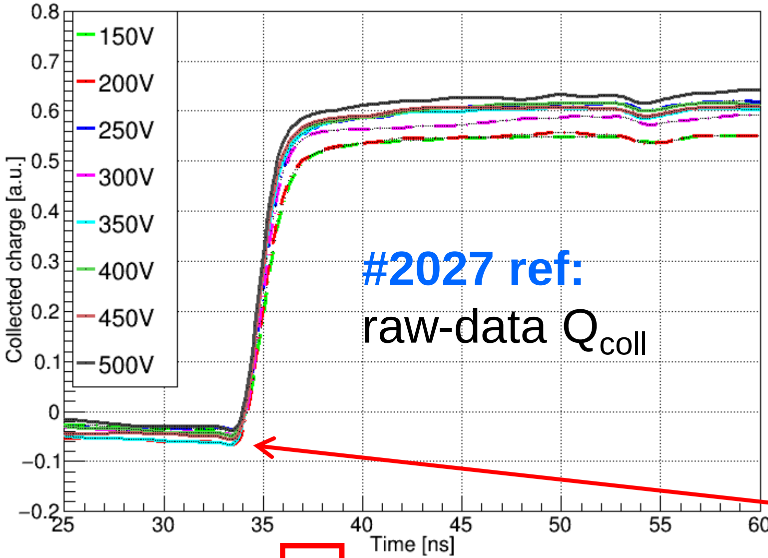



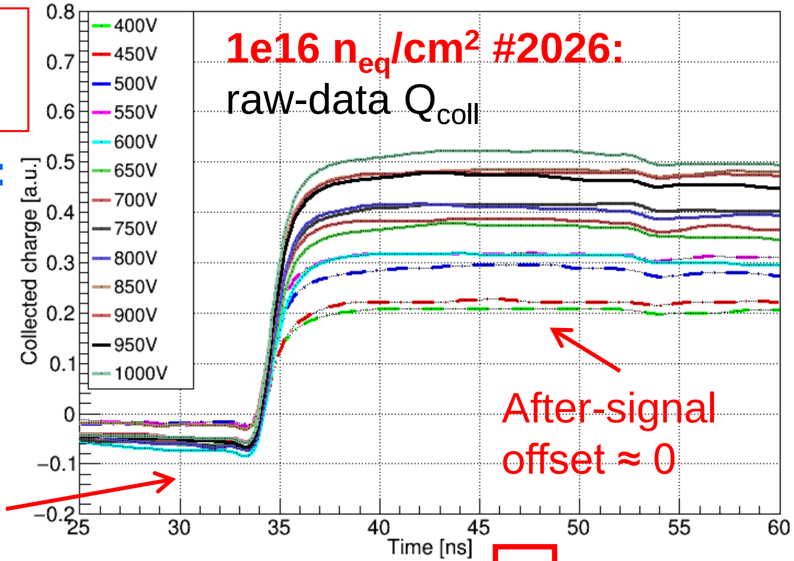



# **Back-up 3:** CCE(p-on-n) - Offset-corrected $Q_{coll}$

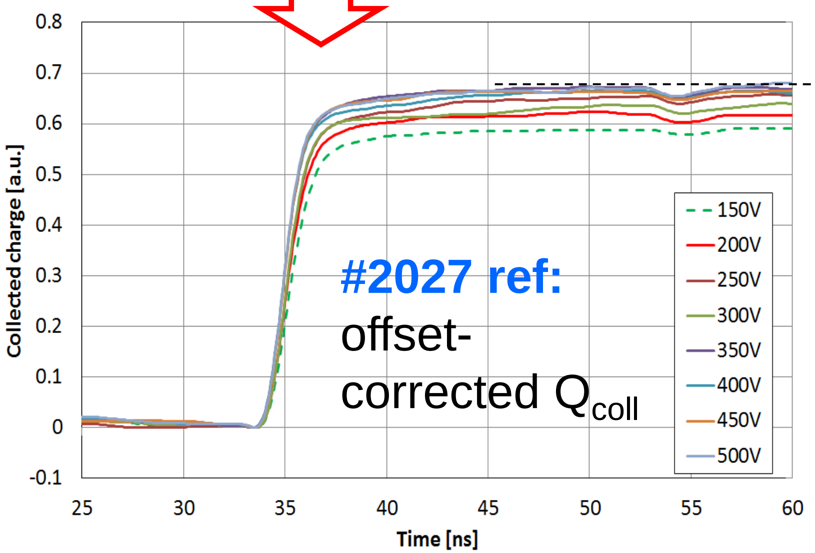
**#2027/2026:**
120 µm p-on-n

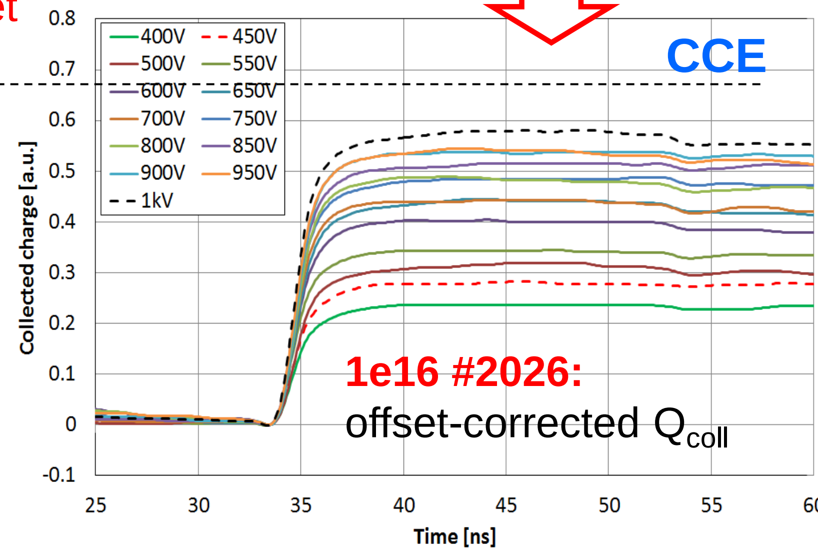
- **Fixed param:**
  - T= -(30.2 – 30.0)° C
  - DAC=62.8%



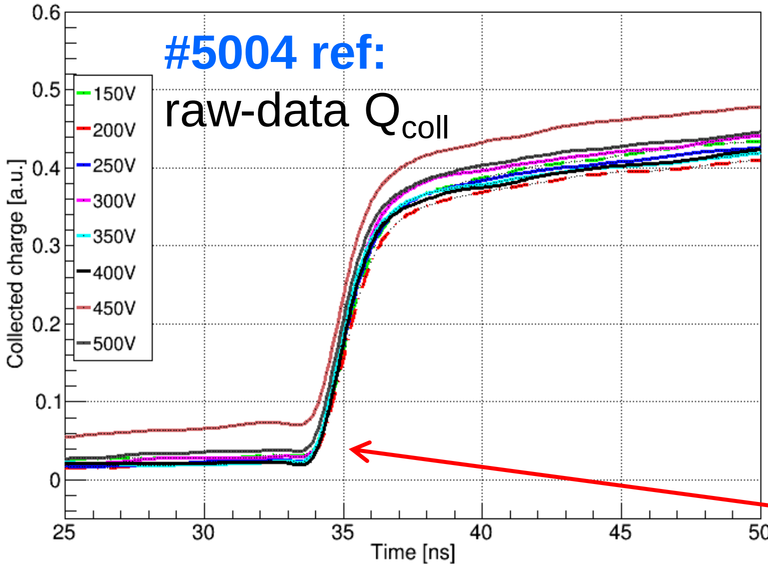




Pre-signal negative offset



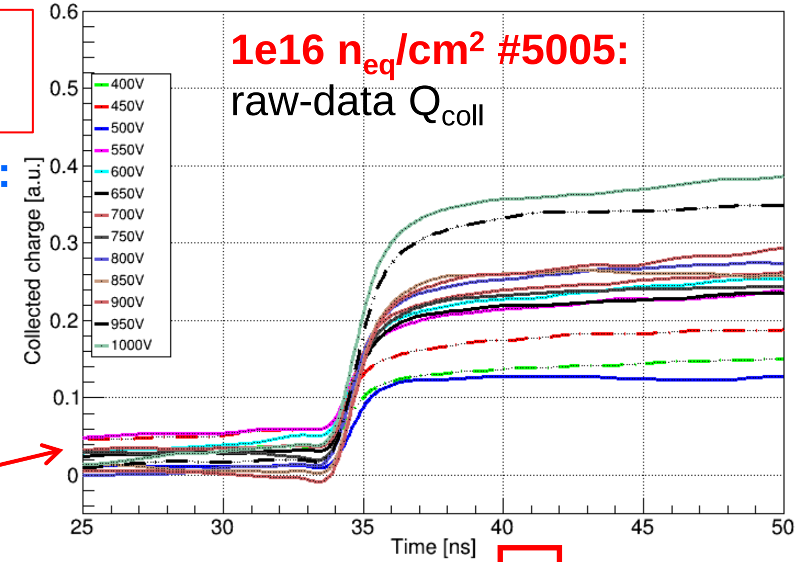



# Back-up 4: CCE(n-on-p) - Offset-corrected $Q_{coll}$

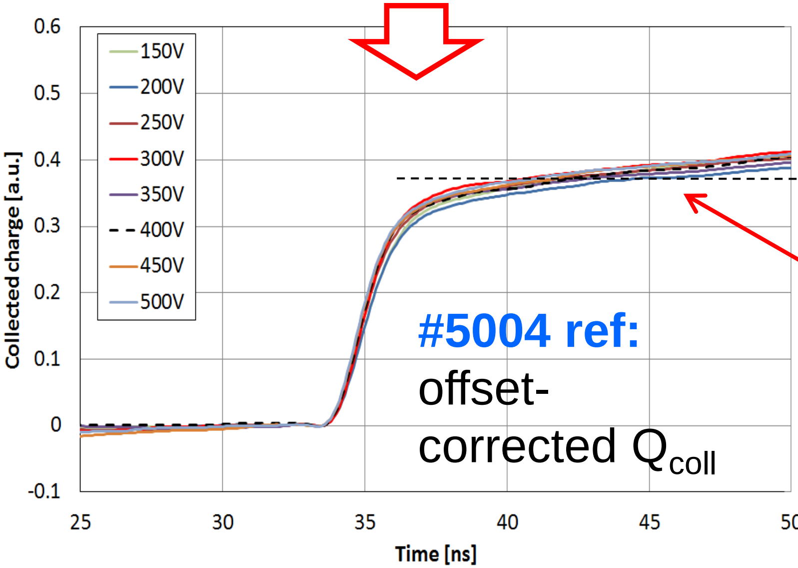



**#5004/5005:**
120 µm n-on-p

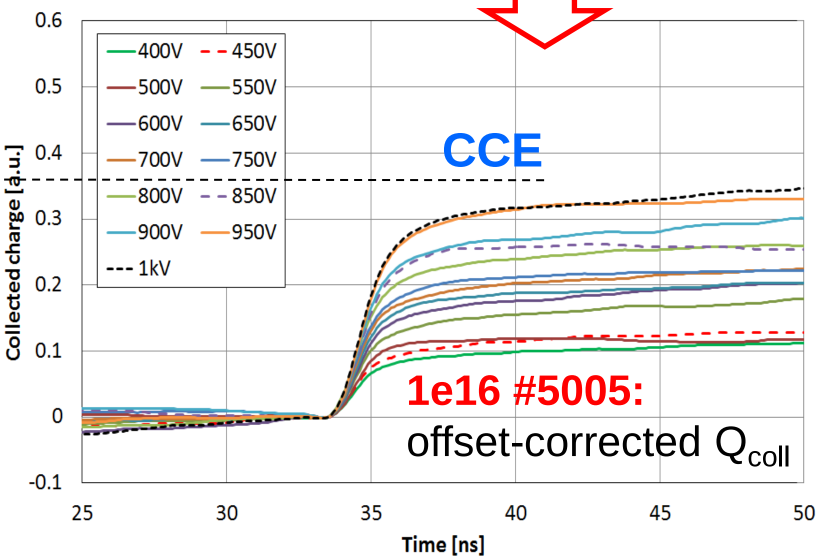
- **Fixed param:**
- T= -(30.2 – 30.1)° C
- DAC=64%




Pre-signal positive offset

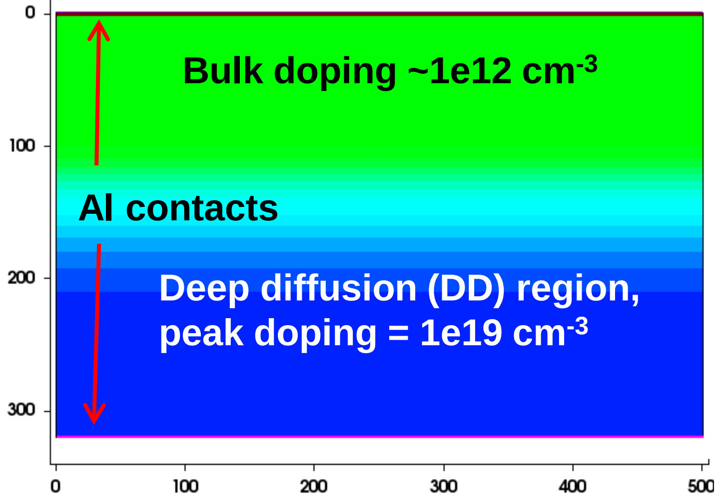



After-signal positive offset → extract $Q_{coll}$ @ early t



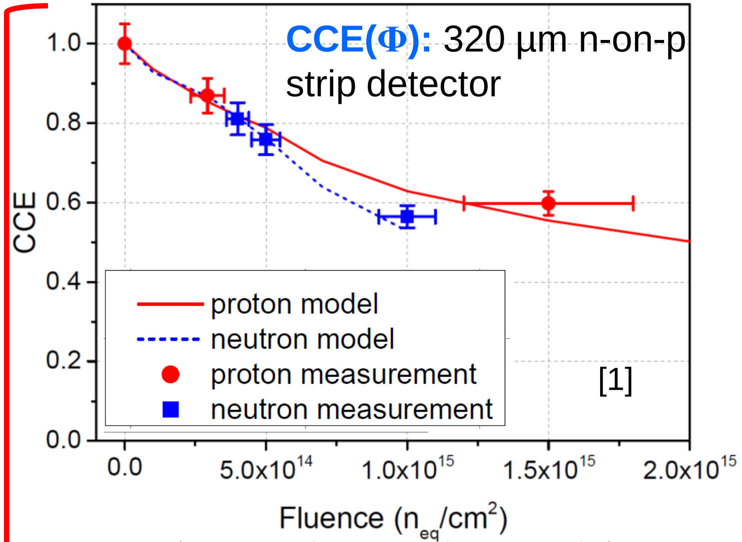
# **Back-up 5:** TCAD: 2D-structure & defect model

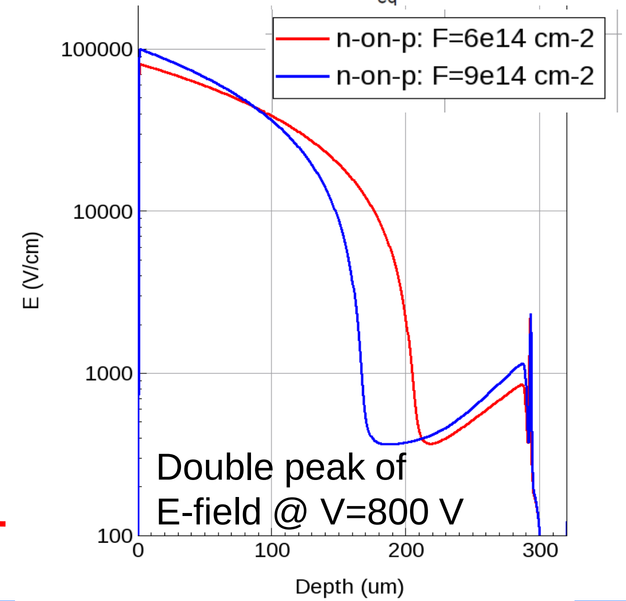
- **2D-structure:** 6-inch sample deep diffused doping profile for 320 μm physical & 200 μm active thickness




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

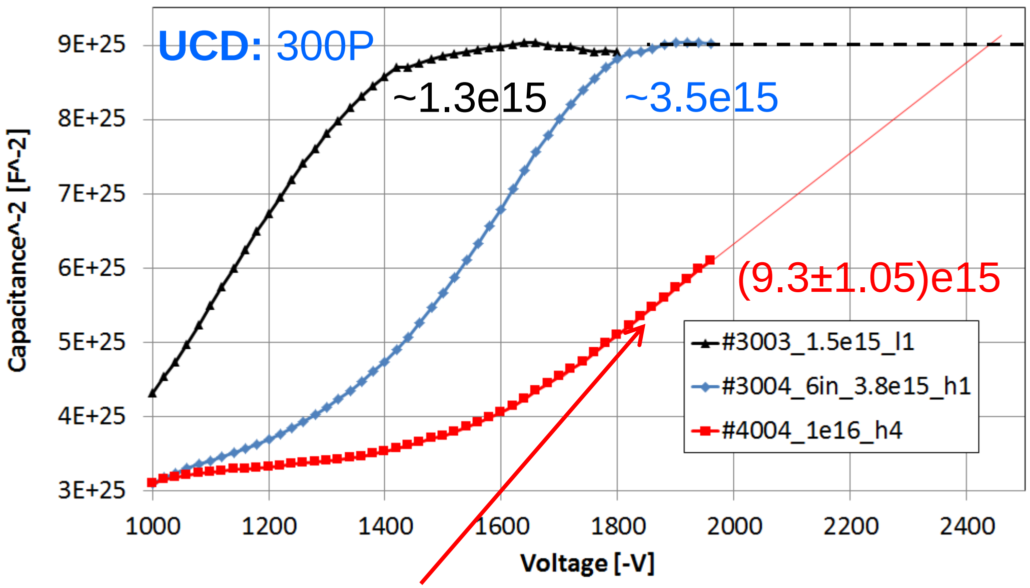
| Type of defect | Level [eV] | $\sigma_e$ [cm$^2$] | $\sigma_h$ [cm$^2$] | Concentration [cm$^{-3}$] |
|---|---|---|---|---|
| Acceptor | $E_C$ - 0.525 | 1.2e-14 | 1.2e-14 | 1.55*Φ |
| Donor | $E_V$ + 0.48 | 1.2e-14 | 1.2e-14 | 1.395*Φ |




[2] R. Eber, PhD Thesis, KIT, 2013

# **Back-up 6:** 300P vs 200P - $\Phi \approx 1e16\ n_{eq}/cm^2$

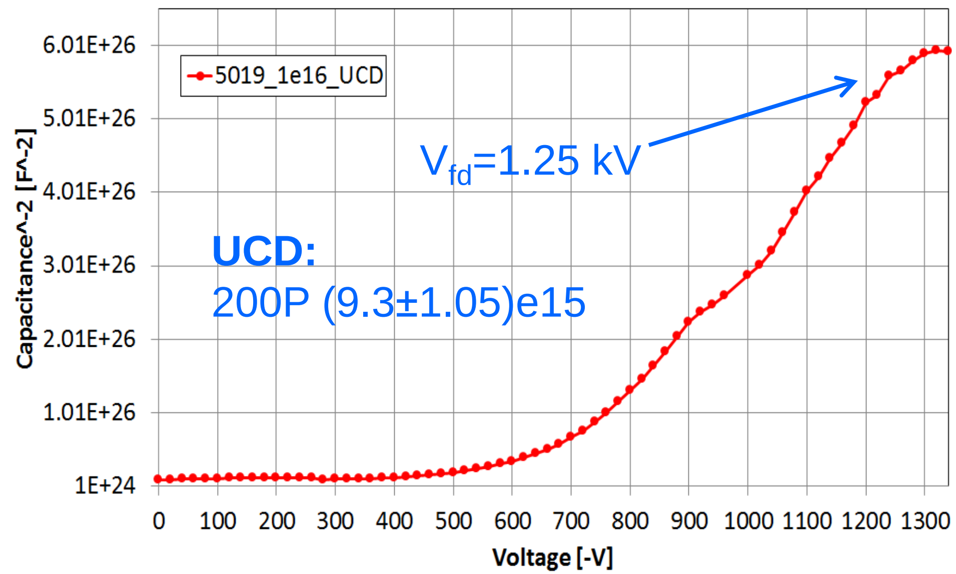



$$CCE = \sqrt{\frac{V}{V_{fd}}\frac{\tau_{eff}}{t_{dr}}\left(1 - e^{-\frac{t_{dr}}{\tau_{eff}}}\right)}$$ [3]

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

⇒ $$\underbrace{\frac{CCE_{200}}{CCE_{300}}}_{R(CCE)} = \underbrace{\sqrt{\frac{V_{fd300}}{V_{fd200}}}}_{R(V_{fd})}$$

Linear fit extrapolation: $V_{fd} \approx 2.4$ kV



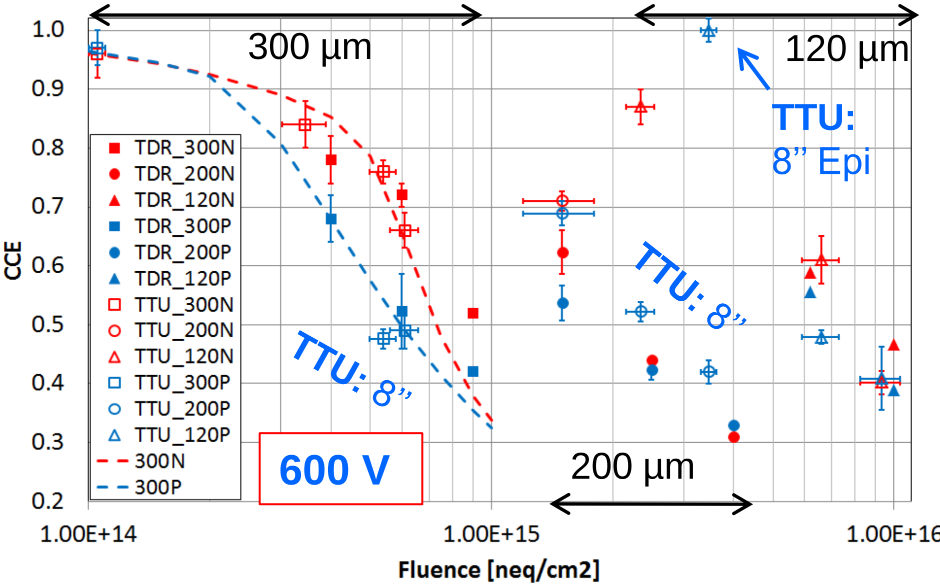

- **200P vs 300P @ 1e16:**
  - **300P:** $\Delta$CCE=6%, $\Delta V_{fd}$=8%
  - **200P:** $\Delta$CCE=3%, $\Delta V_{fd}$=7%

→ R(CCE) = 1.17±0.07 = 1.39±0.15 = $R(V_{fd})$

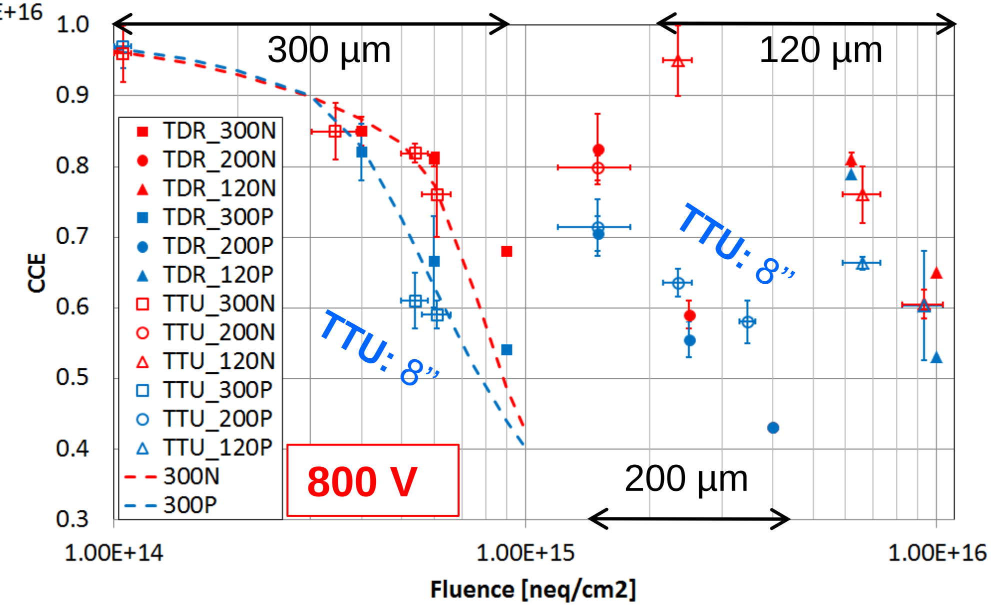
→ $V_{fd}$ results in line w/ observed CCEs


[3] Z. Li, *JINST* **4** P03011 (2009).

# 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 $\Phi_{eff}$
  - **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

[4] E. Currás et al., *JINST* **12** C02056 (2017).