American Physical Society April Meeting
2022, Apr 9 – 12

Radiation hardness study of HGCAL v1-prototype Si sensors

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

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

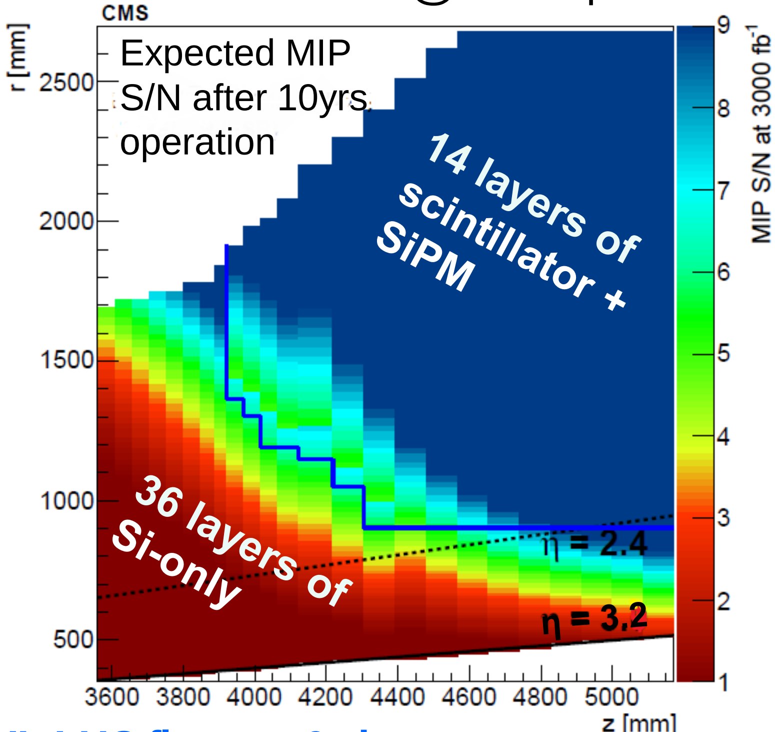
Outline

- **Introduction: HGCAL -** Upgrade of ECAL/HCAL endcaps
- **HGCAL 8-inch sensors:** R&D Status
- **Reactor (RINSC) irradiation tests of v1-prototypes:**
  - **Evolution of bulk properties:**
    - Leakage currents (I_{leak})
    - Full depletion voltages (V_{fd})
  - **Surface effects:**
    - Channel stability before/after irradiation
    - Inter-pad capacitances (C_{int})
- **Summary**

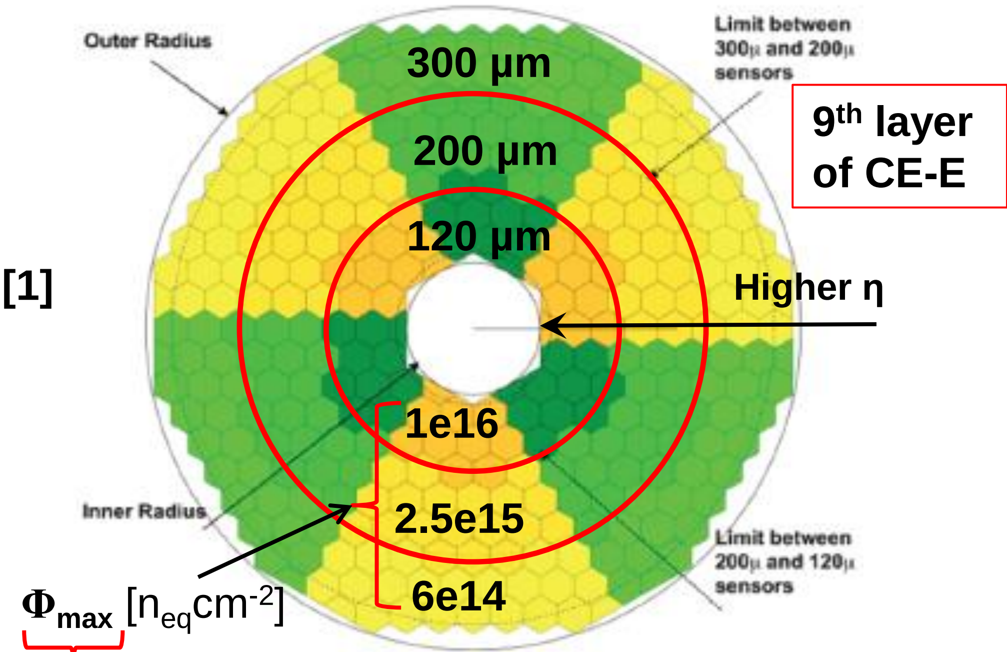
RINSC = Rhode Island Nuclear Science Center

HGCAL: Upgrade of ECAL/HCAL endcaps

- **HGCAL:** Highly segmented calorimeter @ 1.5 ≤ η ≤ 3.2



[1]



- **HL-LHC fluence & dose:** Backup 1

η → 3.2: 10-fold > than tolerance of present system, Pileup: ~60 @ LHC → >140

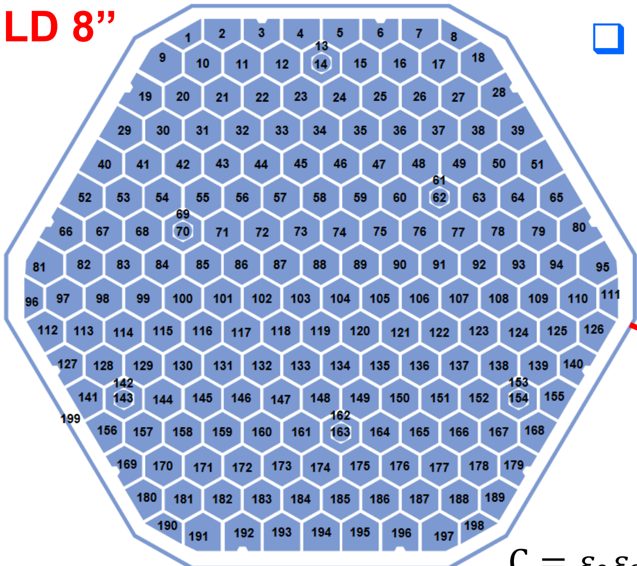
- **Hexagonal 8" Si-modules @ -30° C & 600-800 V** → maintain MIP identification @ extreme fluences

[1] CERN-LHCC-2017-023; CMS-TDR-019

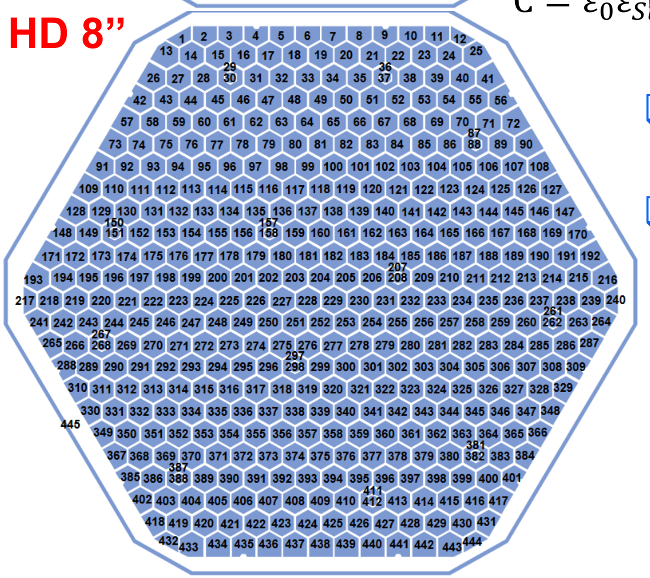
CE-E=electromagnetic calorimeter
HL-LHC=High Luminosity LHC

HGCAL 8-inch sensors: R&D Status

LD 8''

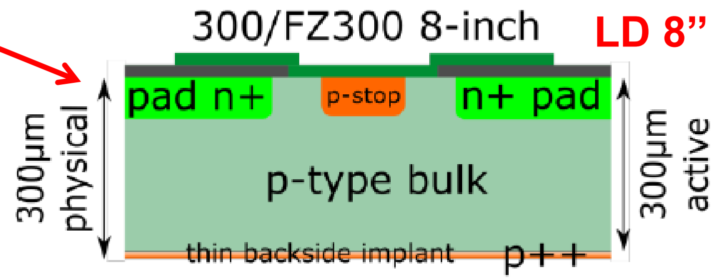


HD 8''



- **2 types of Hamamatsu Photonics K.K. (HPK) 8-in sensors:**
  - **Low-density (LD) sensor:** 198 chs, A ≈ 1.25 cm^2, t_{active}= $t_{physical}$ = 300 & 200 µm (FZ)
  - **High-density (HD) sensor:** 444 chs, A = 0.55 cm^2, t_{active}=120 µm, $t_{physical}$ = 300 µm (epitaxial)

$$C = \varepsilon_0 \varepsilon_{Si} \frac{A}{d}$$

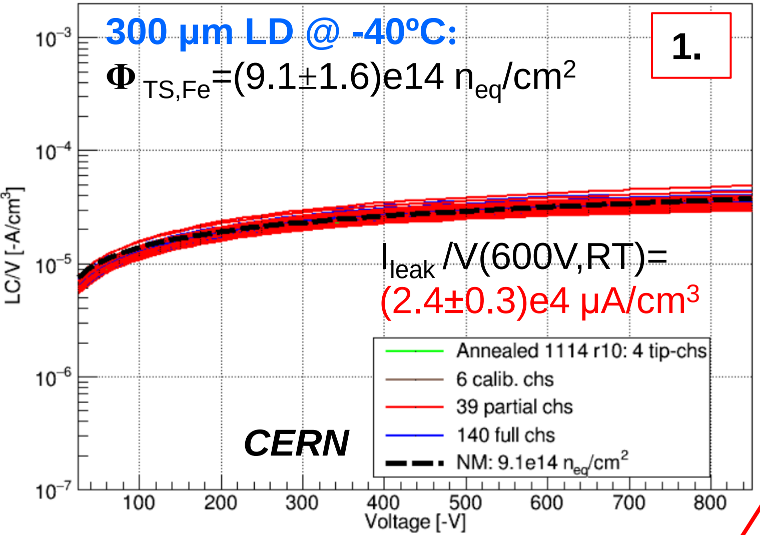


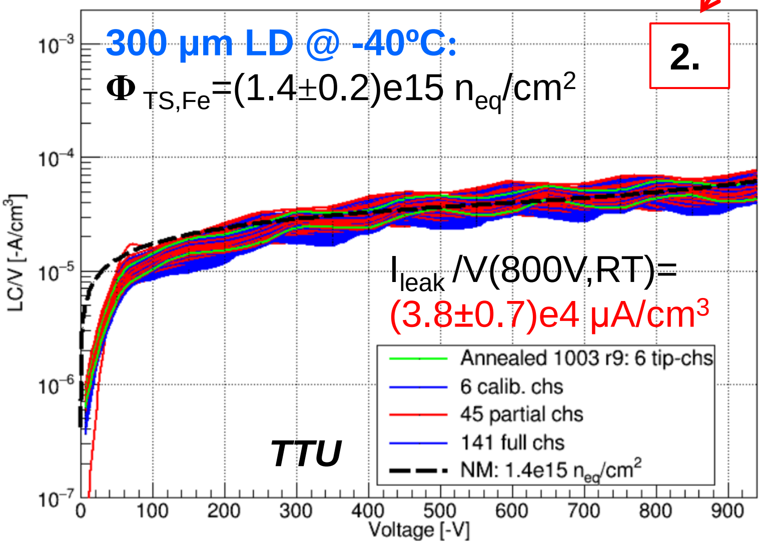
- **Sensor info & production timeline:** Backups 1-3

- **Production param. tuning:** Series of protypes (v1, v2,…) w/ process splits (oxide quality, p-stop type/doping,…)
- **Radiation hardness studies:**
  - Irradiations of 42 v1 8'' LD/HD-sensors for 6 Φ_{target} = 6.5e14 - 1e16 n_{eq}/cm^2 completed @ RINSC May 2021 (backups 4-6) → differences btw/ proc. splits?
  - 2nd RINSC irradiation campaign of V2-prototypes underway in Spring 2022

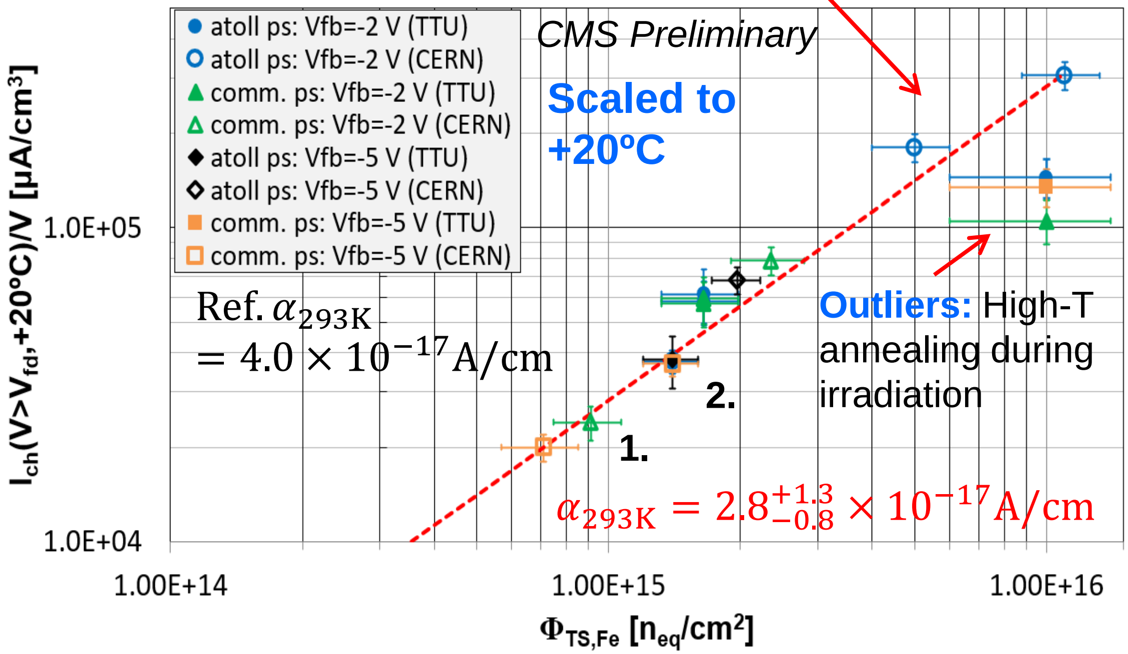
Irradiated 8” v1-sensors: Bulk properties

8" v1-sensors @ RINSC: Selected IV-results





- **CERN & TTU:** T-controlled multi-ch setups for CV/IV of irradiated 8" sensors
- **Neutron defect model (NM):** Input $\Phi_{TS,Fe}$ from RINSC D0-diodes (TS) & Fe-foils → full-sensor I_{leak}/V @ -40ºC reproduced by TCAD in lower part of Φ-range
- **Current-related damage rate α [2]:** ~0.7 of ref. α(RT) → reasonable confidence in TS/Fe-foil fluence estimates

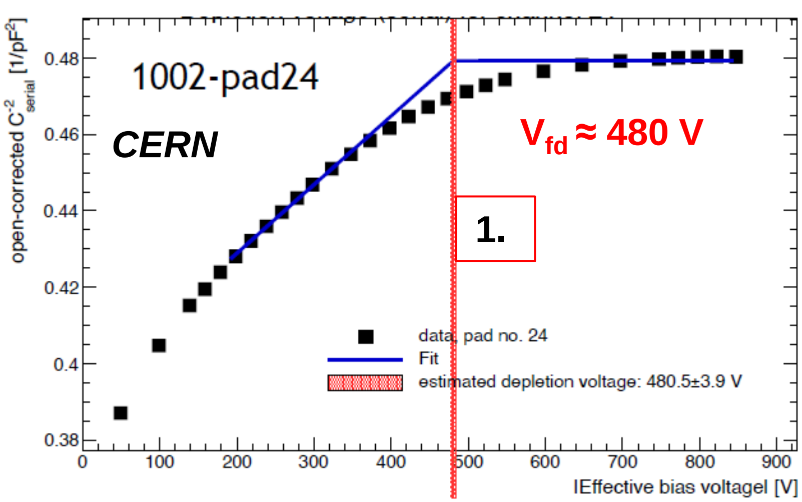


- ARRAY-setup: Backup 7
- NM: Backup 8

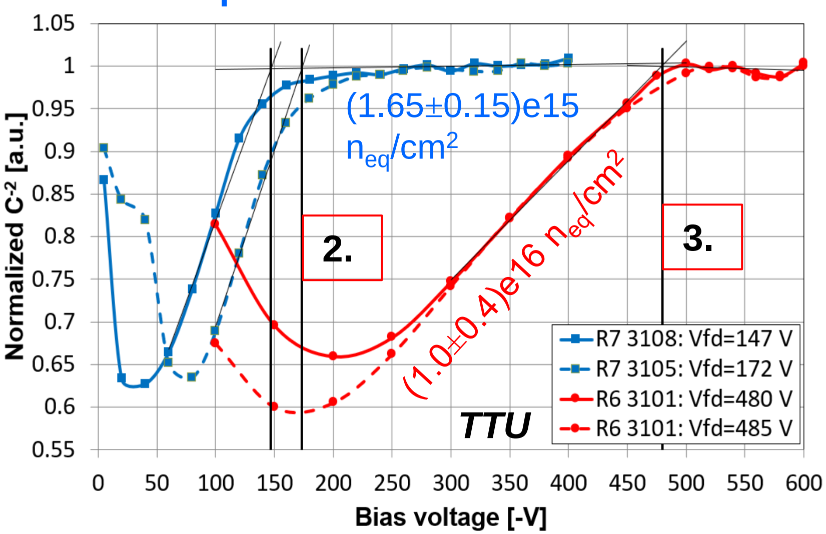
[2] M. Moll, PhD Thesis, UH (1999).

8" v1-sensors @ RINSC: Selected V_{fd}-results

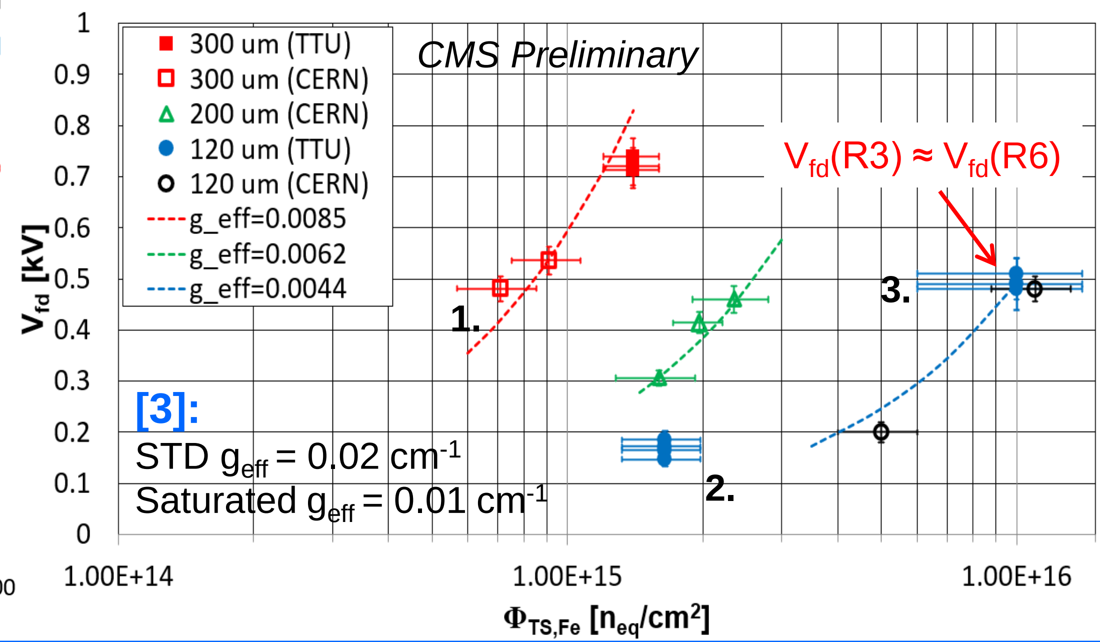
- **300 µm LD:** $\Phi_{TS,Fe}$=(7.1±0.5)e14 n_{eq}/cm^2



- **120 µm HD-sensors:**



- **After standard annealing:** All V_{fd} < 800 V (HGCAL upper V-limit)
  - V_{fd} > 600 V only for highest $\Phi_{TS,Fe}$ 300-µm sensors (beyond 300 µm Φ_{max})
- **Analytical V_{fd} [3]:** Models observed V_{fd} only w/ g_{eff}-values below saturated (0.01 cm⁻¹), expected for high-Φ
  - Φ-scaling by factor ~2.8/4 (α-ratio) moves highest g_{eff} btw/ saturated & STD

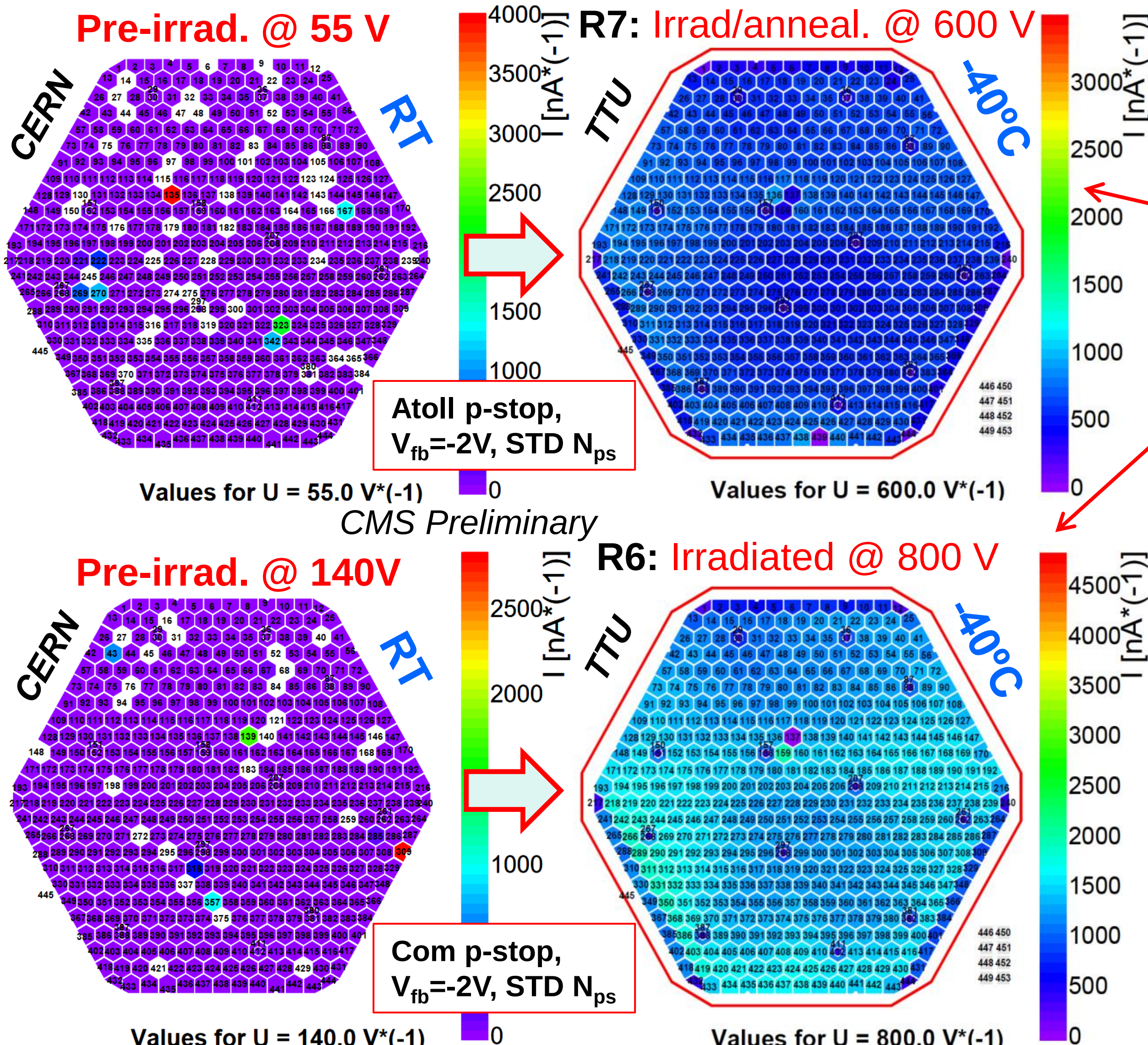


[3] N. Cartiglia, H.F.W. Sadrozinski & A. Seiden, *PoS* VERTEX2018 (2019) 029.

g_{eff} = acceptor creation coefficient

Irradiated 8” v1-sensors: Surface effects

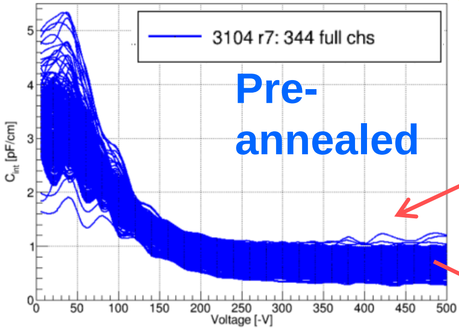
I_{leak} channel-maps: Before/after irradiation



- **Irradiation round 7:**
  - $\Phi_{TS,Fe}$=(1.65±0.15)e15 n_{eq}/cm^2
  - Annealed 80 min @ 60ºC
- **Irradiation round 6:**
  - $\Phi_{TS,Fe}$= (1.0±0.4)e16 n_{eq}/cm^2
- **Masking level:** I_{leak} > 5 μA (white chs)
- **I_{leak} stability:** Benefit from irradiation for proc. splits w/ low N_{ox} (V_{fb}= -2V) & high p-stop doping (STD N_{ps})
  → E-field moderation w/ accumulation of N_{ox} @ Si/SiO_2-interface (TCAD simulation: backup 9)

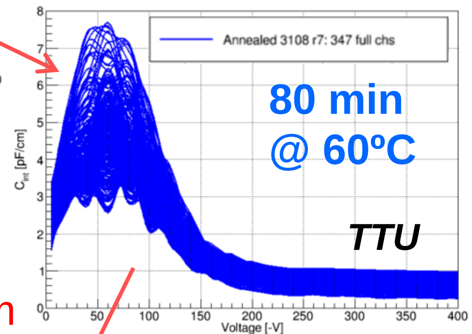
V_{fb}=Flat-band voltage
TCAD=Technology Computer-Aided Design

C_{int}: Proc. splits/location from core



HD: $\Phi_{TS,Fe}$ = (1.65±0.15)e15 n_{eq}/cm^2

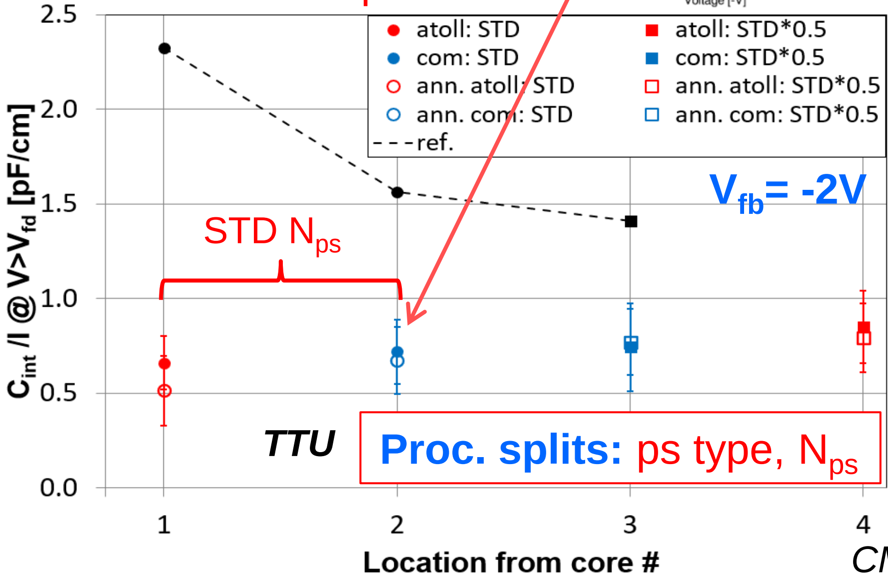
C_{int} @ 400 V= 0.72±0.17 pF/cm



$$C_{int} = C_{corr} - C_{bulk},$$

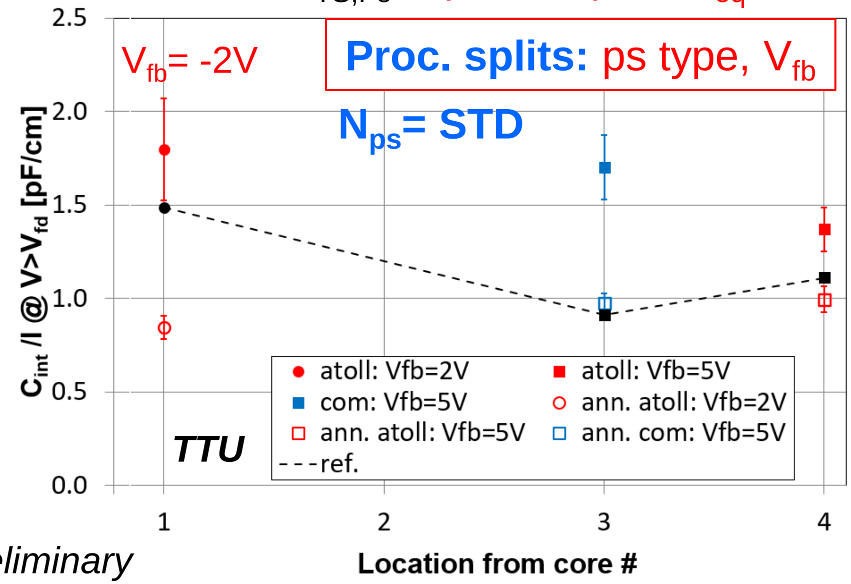
$$C_{bulk} = \varepsilon_0 \varepsilon_{Si} \frac{A}{d}$$

C_{int} @ 400 V = 0.67±0.18 pF/cm



- **Reactor irradiations:** Stack of 4 sensors placed in puck on core-wall
- **After standard annealing:**
  - **HD-sensors:** Weak effect to C_{int}
  - **LD-sensors:** Signicantly reduced C_{int}
  - **HD & LD:** No clear position or proc. split dependence
- **Ref. C_{int}(CERN):** Benefit from irradiation/ annealing for both HD & LD-sensors

LD: $\Phi_{TS,Fe}$ = (1.4±0.2)e15 n_{eq}/cm^2



CMS Preliminary

Atoll p-stop=Individual p-stop for each pad

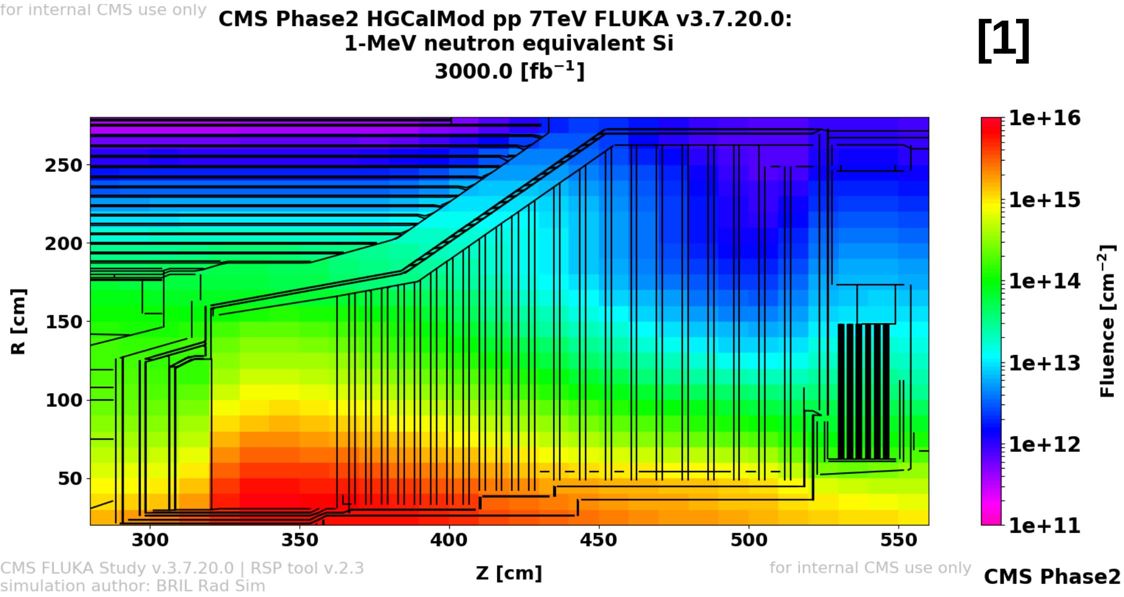
Summary

- Reactor irradiations of 42 8-in v1-protype LD/HD-sensors for six target fluences from 6.5e14 to 1e16 n_{eq}/cm^2 was successfully conducted at RINSC 2020/2021 → v2-protype irradiation campaign underway in Spring 2022

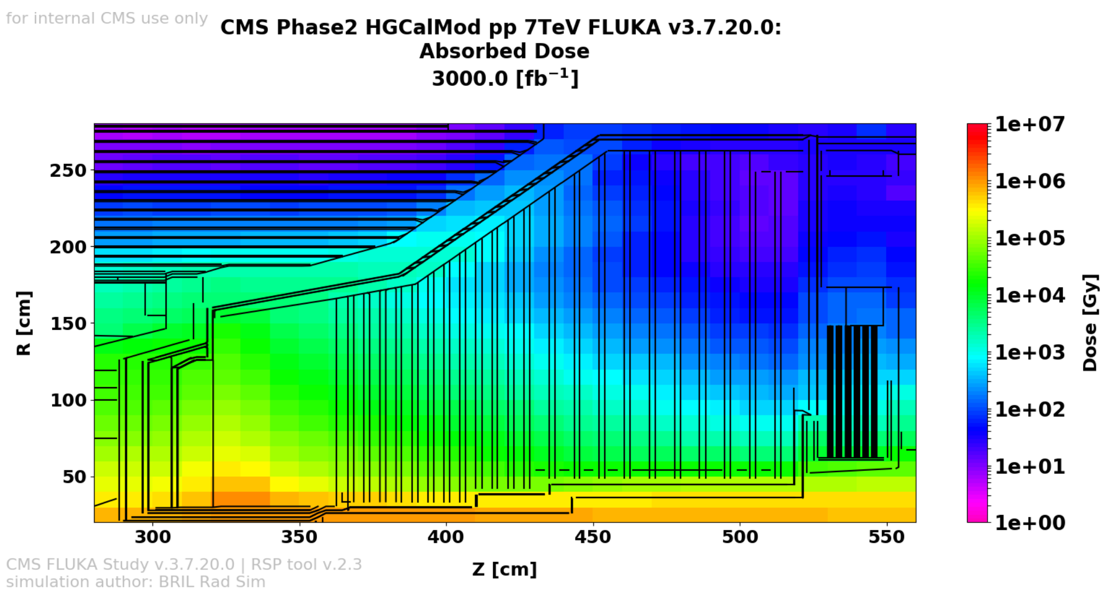
- **I_{leak} results:**
  - **α-factor extracted from I_{leak}/V of 8-in sensors:** ~0.7 of ref. α(RT) → reasonable confidence in TS/Fe-foil fluence estimates
  - **Lower part of studied fluence range:** Full sensor I_{leak}/V results supported by TCAD simulations w/ $\Phi_{TS,Fe}$ as input for neutron defect model
- **V_{fd} results:**
  - All V_{fd} < 600 V (HGCAL $V_{default}$) within ea. thicknesses Φ-range → I_{leak}-results indicate 200 & 120 μm sensors did not reach highest expected lifetime Φ
  - Rounds 6 & 3 (Φ_{target}=1e16 n_{eq}/cm^2) V_{fd} in close agreement, while >2-fold lower I_{leak}/V in R6 → substantial Δ(annealing) during irrad.? → 'reverse annealing'
- **V1 process splits:**
  - $I_{leak,ch}$ stability benefits from irradiation (N_{ox} accumulation) for low V_{fb} w/ high p-stop peak doping (independent of p-stop type) → reproducible by TCAD
  - Similar C_{int} btw/ irradiated proc. splits after annealing @ V > V_{fd} → C_{int} displays lower values to ref. after irradiation/annealing (preliminary)

Back-up 1: Fluence & Dose in HGCAL @ 3 ab^{-1}

[1]



- **HGCAL:** ~27,000 hexagonal 8-inch silicon modules → ~6M channels w/ area of 620 m^2
  - Hexagonal sensor shape to maximize usable area of circular wafers while remaining tileable
  - **8” wafers:** Reduced # of modules to 6” wafers in trackers

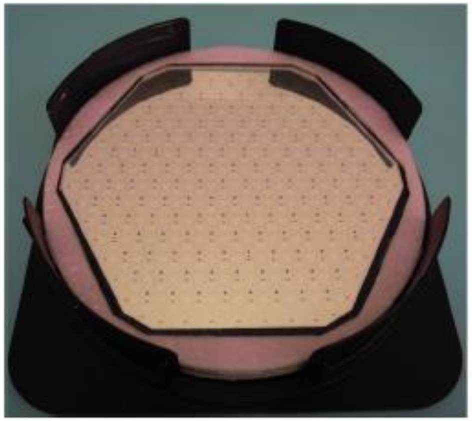


Back-up 2: HGCAL 8-inch sensor development

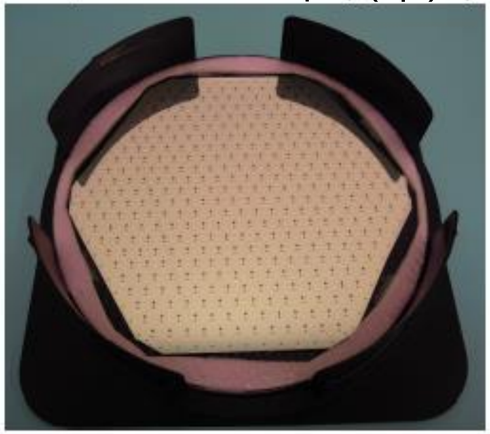
- **Hamamatsu Photonics K.K. (HPK) 6” → 8” sensors [4]:**
  - Established process → New production process
  - AC-coupled Float-zone (FZ) → DC-coupled FZ & epitaxial (epi) Si
  - Thick (STD & DD-diffused) → Thin (~1 μm) LD-backplane implant
  - Lower oxygen content in bulk → radiation hardness?

- **Sensor qualification milestones:**
  - **2018:** R&D – 25 LD-stepper sensors
  - **2019:** Prototypes – 42 LD-full lithography sensors (Version 0)
  - **2020:** 56 LD & 32 HD sensors (V1)
    - Front side biasing for backside damage mitigation
    - Process splits to find best production param. (oxide quality, p-stop concentration,…)
    - Full radiation hardness study (neutron, X-ray)
  - **Aug-Sep 2021:** 72 LD & 44 HD sensors (V2)
    - Design upgrades for improved HV-stability
    - Best process param. from V1 results
  - **Fall 2021:** Multi-geom. wafers for partial sensors

Low-density (LD) sensor (V1):
~200 chs, A≈1.2 cm^2,
active t≈300 & 200 μm (FZ)



High-density (HD) sensor (V1):
~450 chs, A≈0.55 cm^2,
active t≈120 μm (epi)



[4] E. Brondolin, ***JINST*** 15 (2020) C05068.

Back-up 3: Full sensor production – Timeline status

Type	Vfb	P-stop layout	P-stop conc.	Oxide quality	Quantity per thickness
A	-5V	com	std	STD (for reference)	4
B	-2V	com	std	Masking method (for reference)	8
C	~-2V	com	std	Thermal condition change	8
		ind			8
D	~-2V	com	std	New combination of B and C	8

(by E. Sicking, CMS Phase II Upgrade Project Review, May 10, 2021.)

Year	2022					
Quarter	Q2'22			Q3'22		
Month (shipping date !)	Apr	May	June	July	Aug	Sept
S15591-01 (FULL 300LD)	20	40	59	59		
- Delivered (per month)						
- Cummulated	20	60	119	178		
- Cummulated						
S15591-02 (FULL 200LD)	20	20	23	23		
- Delivered (per month)						
- Cummulated	20	40	63	86		
- Cummulated						
S15591-XX (FULL 200HD)						
- Delivered (per month)						
- Cummulated						
- Cummulated						
S15591-03 (FULL 120HD)	20	20	18	18		
- Delivered (per month)						
- Cummulated	20	40	58	76		
- Cummulated						

(by E. Sicking, R. Yohay, HGCAL General Meetings Spring 22: Si Sensors Meeting, Mar 29, 2022.)

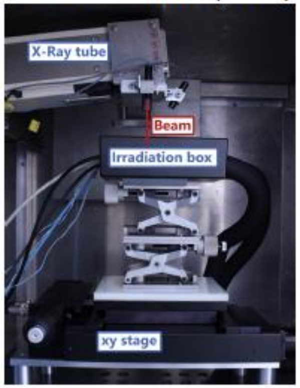
- **V2 prototypes:** Process splits
  - 4 oxide quality splits (C & D most promising)
  - 36 sensors/thickness = 108 sensors
  - Start of deliveries: Aug 2021 → qualification campaign until Spring 2022

- **Pre-series:** Approval from analysis of probe-card data of HPK V2-full wafers + HPK-internal pilot run → validate high mass production yield & testing
  - 340 sensors
  - Pre-series qualification campaign until Summer 2022 → **Goal:** Verify ability of HPK to deliver high # of high-quality sensors

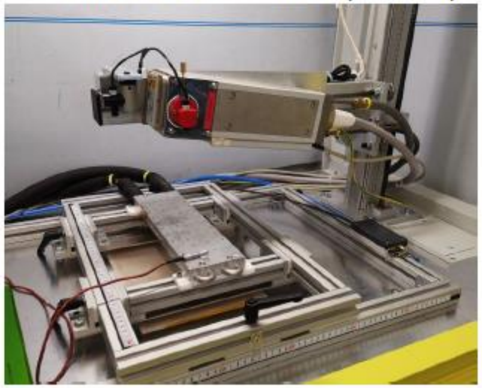
Back-up 4: Irradiation facilities

- **Neutrons:**
  - **Full 8" sensors:** RINSC/BU → only facility for full 8" sensors
  - **Test structures** (diodes, strips,…)**:** JSI Ljubljana (SLO) & RINSC
- **X-rays:**
  - **Test structures** (MOS, GCD, strips,…)**:** KIT, INFN & CERN

X-ray facility (KIT)

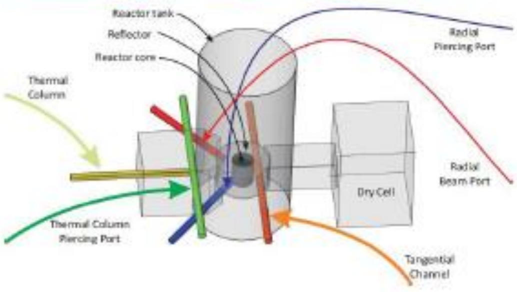


ObeliX X-ray facility (CERN)



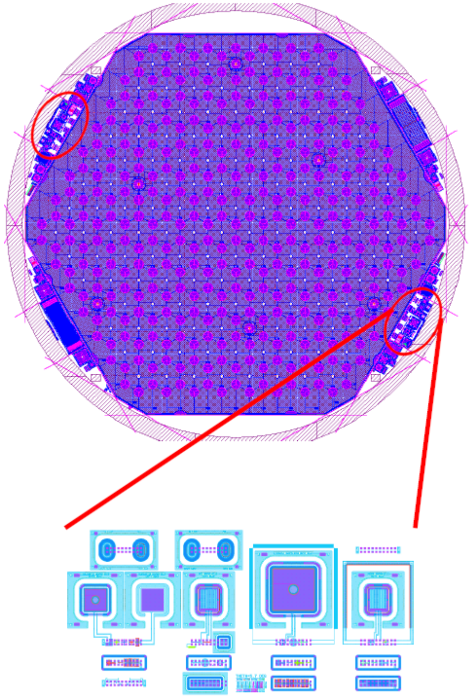
RINSC core

JSI TRIGA reactor, Ljubljana



- **8" wafer w/ full sensor & test structures**

(by M. Babeluk, Si Sensors WG meeting, Jun 22, 2021)



Back-up 5: RINSC irradiation rounds 1 – 4

Irrad. round	Target fluence [neq/cm2]	Sensor ID	P-Stop	Thick-ness	Flat band volt.	Oxide quality	P- Stop conc.	Proc.	Status (wafer location from core)	Current location	date at RINSC (one per week)
1	6.50E+14	1004	ind.	300	-5V	STD	STD	FZ	Irradiated (3rd)	CERN	August 26
1	6.50E+14	1002	ind.	300	-2V	STD	STD	FZ	Irradiated (4th)	CERN	August 26
1	6.50E+14	1101	com.	300	-5V	STD	STD	FZ	Irradiated (2nd)	CERN	August 26
1	6.50E+14	1102	com.	300	-2V	STD	STD	FZ	Irradiated (1st)	CERN	August 26
2	2.50E+15	2001	ind.	200	-5V	STD	STD	FZ	Broken during extraction	-	Septemer 22
2	2.50E+15	2013	ind.	200	-2V	STD	STD	FZ	Broken during extraction	-	Septemer 22
2	2.50E+15	2101	com.	200	-5V	STD	STD	FZ	Broken during extraction	-	Septemer 22
2	2.50E+15	2104	com.	200	-2V	STD	STD	FZ	Broken during extraction	-	Septemer 22
3	1.00E+16	3002	ind.	120	-2V	STD	STD*0.5	epi	Irradiated (2nd)	CERN	October 20
3	1.00E+16	3003	ind.	120	-2V	STD	STD	epi	Irradiated (1st)	CERN	October 20
3	1.00E+16	3102	com.	120	-2V	STD	STD*0.5	epi	Irradiated (3rd)	CERN	October 20
3	1.00E+16	3103	com.	120	-2V	STD	STD	epi	Irradiated (4th)	CERN	October 20
4	2.50E+15	2109 (marked 2019)	com.	200	-5V	Type B	STD	FZ	Irradiated (4th)	CERN	January 21
4	2.50E+15	2110	com.	200	-5V	Type C	STD	FZ	Irradiated (3rd)	CERN	January 21
4	2.50E+15	2111	com.	200	-5V	Type D	STD	FZ	Irradiated (2nd)	CERN	January 21
4	2.50E+15	2112	com.	200	-5V	Type E	STD	FZ	Irradiated (1st)	CERN	January 21

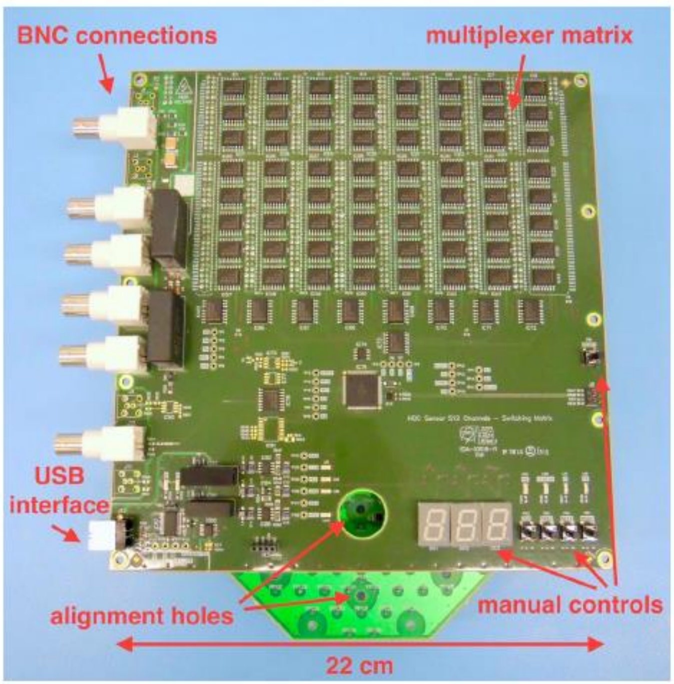
Back-up 6: RINSC irradiation rounds 5 – 11

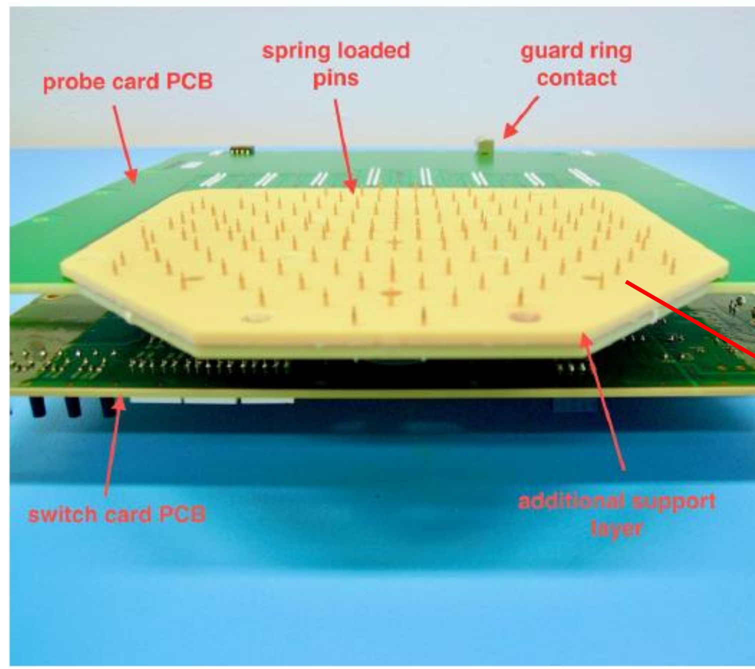
5	2.50E+15	2004	ind.	200	-5V	STD	STD	FZ	Irradiated (2nd)	CERN	January 28
5	2.50E+15	2002	ind.	200	-2V	STD	STD	FZ	Irradiated (1st)	CERN	January 28
5	2.50E+15	2105	com.	200	-5V	STD	STD	FZ	Irradiated (4th)	CERN	January 28
5	2.50E+15	2114	com.	200	-2V	STD	STD	FZ	Irradiated (3rd)	CERN	January 28
6	1.00E+16	3001	ind.	120	-5V	STD	STD	epi	Irradiated (1st)	TTU	February 4
6	1.00E+16	3101	com.	120	-5V	STD	STD	epi	Irradiated (2nd)	TTU	February 4
6	1.00E+16	3007	ind.	120	-2V	STD	STD	epi	Irradiated (3rd)	TTU	February 4
6	1.00E+16	3107	com.	120	-2V	STD	STD	epi	Irradiated (4th)	TTU	February 4
7	2.50E+15	3008	ind.	120	-2V	STD	STD	epi	Irradiated (1st)	TTU	February 11
7	2.50E+15	3108 (marked 3104)	com.	120	-2V	STD	STD	epi	Irradiated (2nd)	TTU	February 11
7	2.50E+15	3005	ind.	120	-2V	STD	STD*0.5	epi	Irradiated (4th)	TTU	February 11
7	2.50E+15	3105	com.	120	-2V	STD	STD*0.5	epi	Irradiated (3rd)	TTU	February 11
8	5.00E+15	3009	ind.	120	-2V	STD	STD	epi	Irradiated (1st)	CERN	March 11
8	5.00E+15	3010	ind.	120	-2V	STD	STD	epi	Irradiated (2nd)	CERN	March 11
8	5.00E+15	3109	com.	120	-2V	STD	STD	epi	Irradiated (3rd)	CERN	March 11
8	5.00E+15	3110	com.	120	-2V	STD	STD	epi	Irradiated (4th)	CERN	March 11
9	1.50E+15	1003	ind.	300	-2V	STD	STD	FZ	Irradiated (1st)	TTU	March 1
9	1.50E+15	1113	com.	300	-2V	STD	STD	STD	Irradiated (2nd)	TTU	March 1
9	1.50E+15	N0541 WNo.17	ind.	300	-5V	STD	STD	STD	Irradiated (4th)	TTU	March 1
9	1.50E+15	1105	com.	300	-5V	STD	STD	FZ	Irradiated (3rd)	TTU	March 1
10	1.00E+15	1013	ind.	300	-2V	STD	STD	FZ	Irradiated (2nd)	CERN	April 15
10	1.00E+15	1114	com.	300	-2V	STD	STD	FZ	Irradiated (1st)	CERN	April 15
10	1.00E+15	N0538 WNo.3	ind.	300	-5V	STD	STD	FZ	Irradiated (3rd)	CERN	April 15
10	1.00E+15	N0538 WNo.25	com.	300	-2V?	New type C	STD	FZ	Irradiated (4th)	CERN	April 15
11	2.50E+15	N0541 WNo.4	ind.	200	-5V	STD	STD	FZ	Irradiated	CERN	May 6
11	2.50E+15	N0538 WNo.10	ind.	200	-2V?	New type C	STD	FZ	Irradiated	CERN	May 6

Back-up 7: Full sensor CV/IV – ARRAY system

ARRAY system: Overview

- ARRAY: switching mAtRix pRobe cArd sYstem
- Dual card setup to automatically measure CV and IV of individual cells
  - Switch card: contains all the active components and electronics (multiplexers, switches, etc.)
  - Probe card: routes the switchcard channels to the sensor cells using spring loaded pins



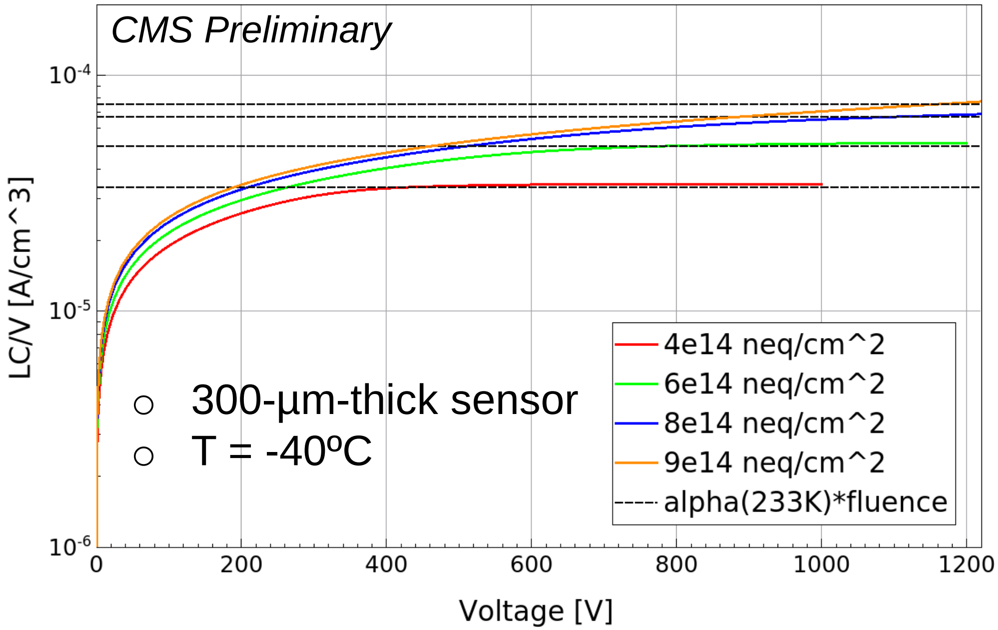


[5]

[5] E. Brondolin et al., ***NIM A*** 940 (2019) 168-173.

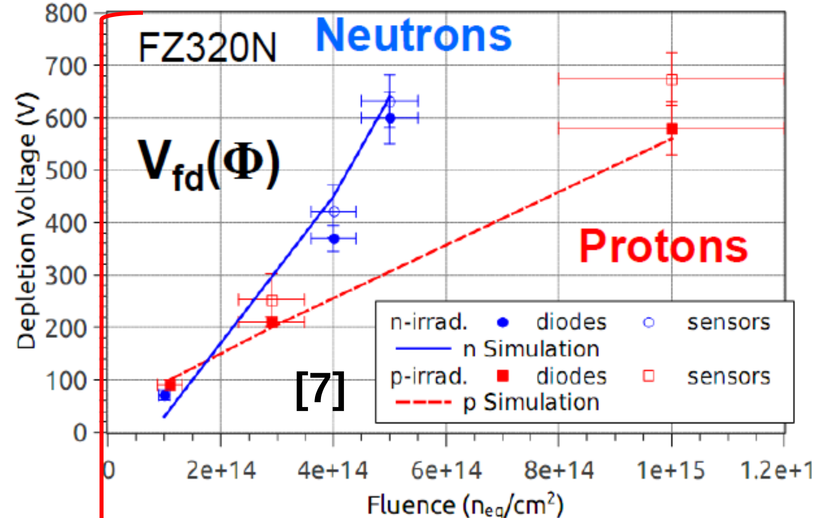
Back-up 8: TCAD[6] - Neutron defect model

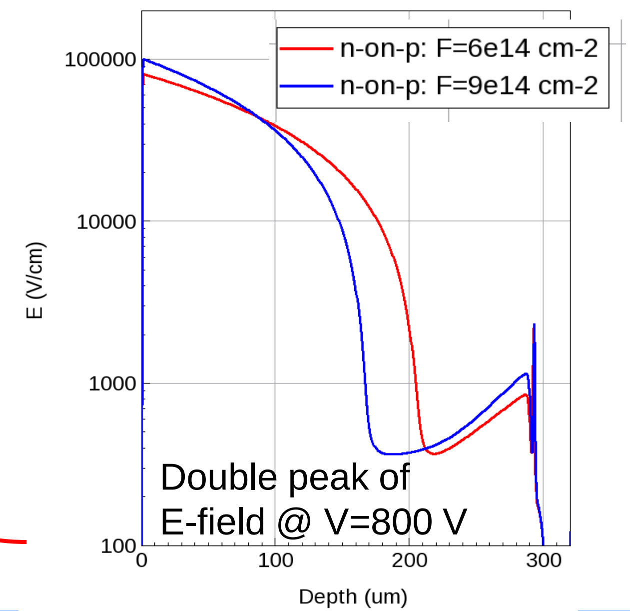
- **LC/V:** Analytical vs neutron defect model simulated



- CMS Neutron defect model parameters, Φ_{eq} =1e14 ~1e15 cm^{-2} @ T = 253 K [7]:

Type of defect	**Level** [eV]	$\boldsymbol{\sigma_e}$ [cm^2]	$\boldsymbol{\sigma_h}$ [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



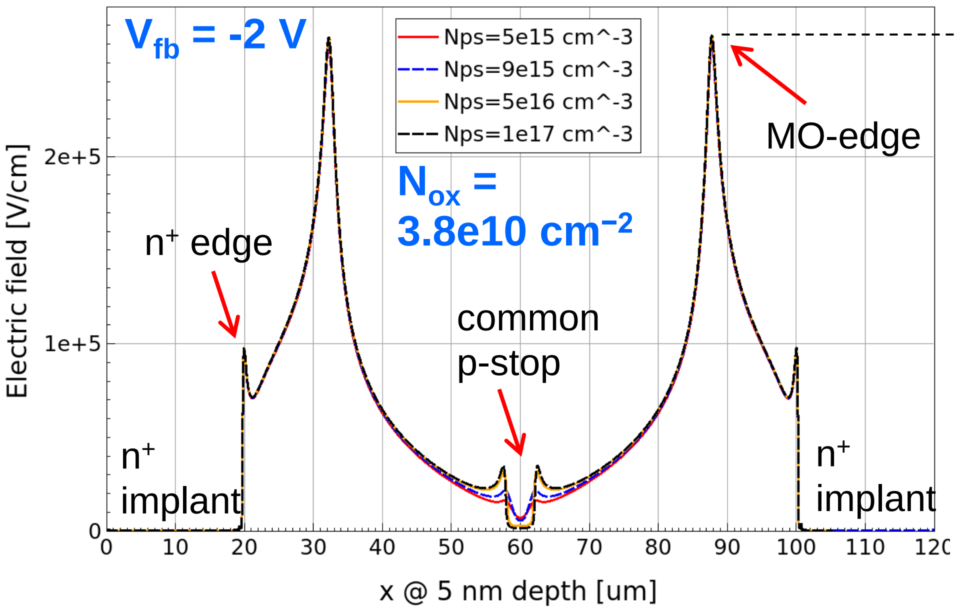


[6] Sentaurus TCAD, http://www.synopsys.com.
[7] R. Eber, PhD Thesis, KIT (2013).

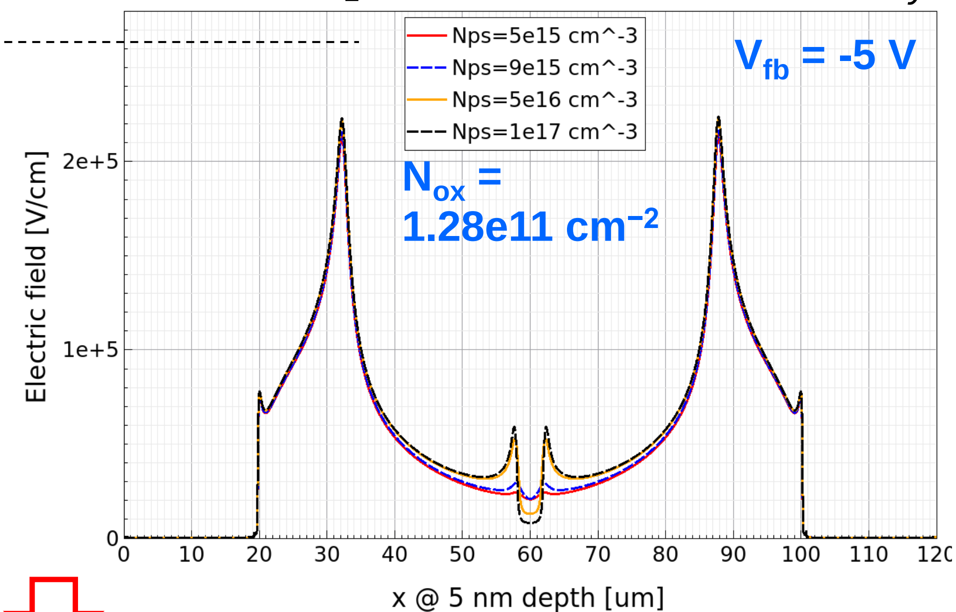
Back-up 9: TCAD - E-field evolution w/ N_{ox}

- **V_{fb} = -2 V:** $N_{ox} \approx 3.8e10\ cm^{-2}$
- **V_{fb} = -5 V:** $N_{ox} \approx 1.28e11\ cm^{-2}$
- **TCAD:** T = 293 K, V = -800 V
  - **N_{ox} & N_{ps}:** varied
  - **E-field cut:** 5 nm below Si/SiO_2 -interface

CMS Preliminary



CMS Preliminary



- **2 V vs 5 V:** E_{max} drops by ~20% w/ higher N_{ox} → reduced breakdown probability w/ N_{ox} accumulation

MO=Metal over-hang