2021 Meeting of the Division of Particles and Fields of the American Physical Society (DPF21), 12 – 14 Jul 2021

Silicon sensors for the CMS HGCAL upgrade

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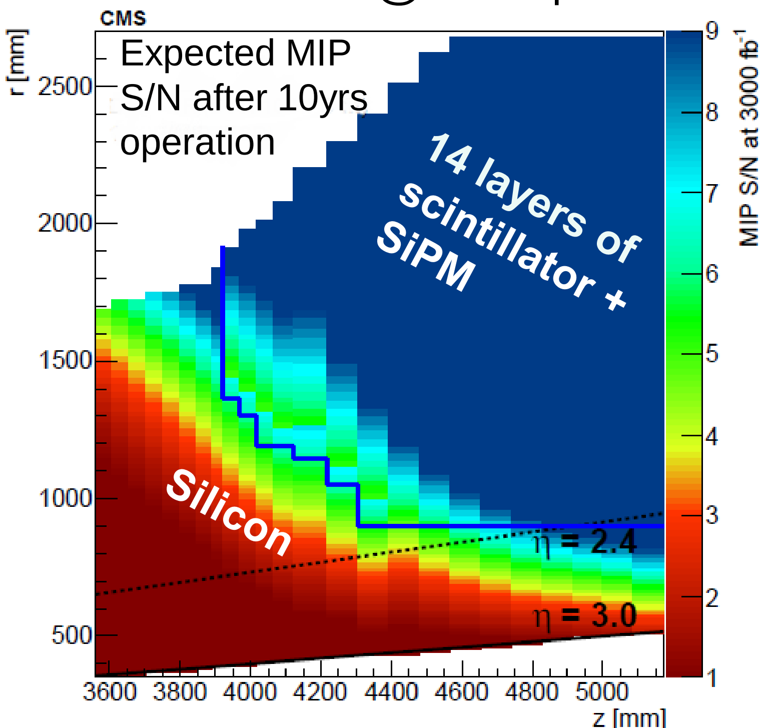
Outline

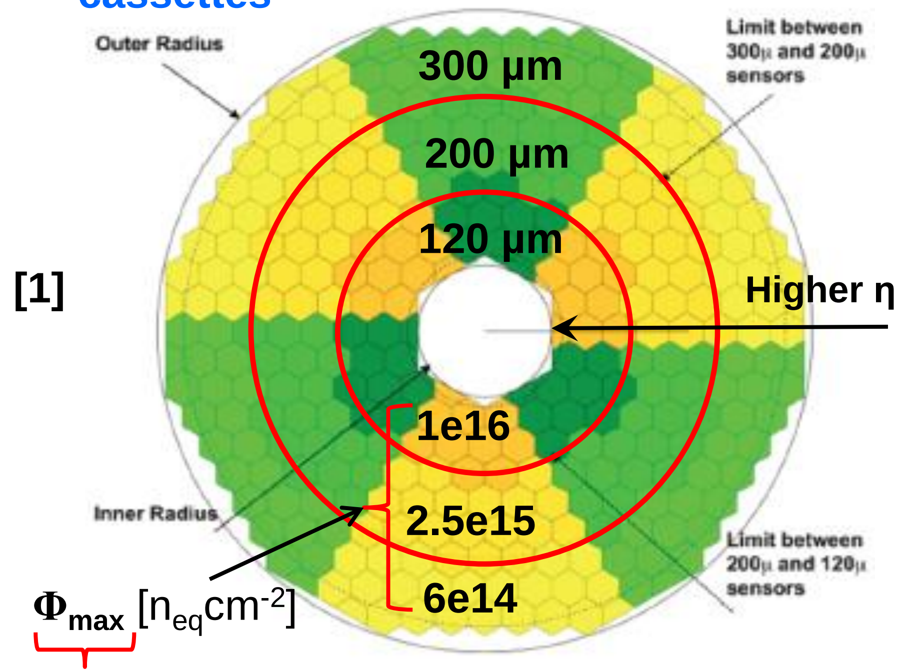
- **Introduction: HGCAL -** Upgrade of ECAL/HCAL endcaps
- **Status of sensor development**
- **Irradiation tests:**
    - Selected full sensor results
    - Selected test structure results
- **Plans towards full sensor production**
- **Summary**

HGCAL: Upgrade of ECAL/HCAL endcaps

HGCAL: Highly segmented calorimeter @ 1.5 ≤ η ≤ 3.0



Sensor tiling structure in 36 layers of Si-only cassettes



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

- **Fluence & Dose:** Backup 1

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

Evaluate sensor performance for expected neutron fluences & operational conditions

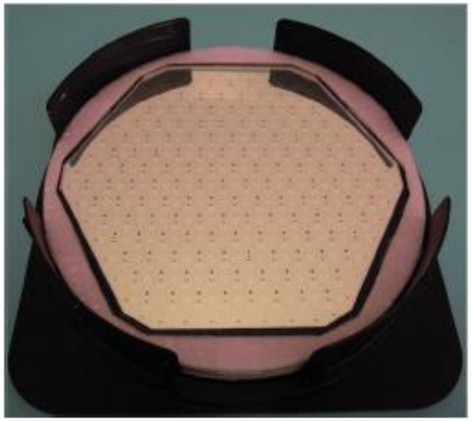
[1] CMS-TDR-17-007

HGCAL 8-inch sensor development: Status

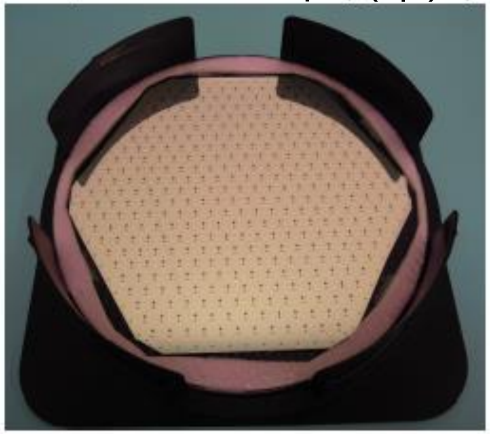
- **Hamamatsu Photonics K.K. (HPK) 6” → 8” sensors:** [2]
  - Established process → New production process
  - AC-coupled Float-zone (FZ) → DC-coupled FZ & epitaxial (epi) Si
  - Thick (STD & DD-diffused) → Thin (~1 μm) LD-backplane implant
  - Lower oxygen content in bulk → radiation hardness?

- **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)



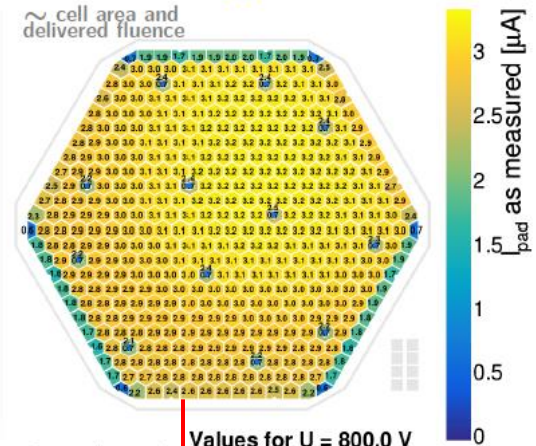
[2] E. Sicking, CMS Phase II Upgrade Project Review, May 10, 2021.

- **Additional sensor info:** Backup 1

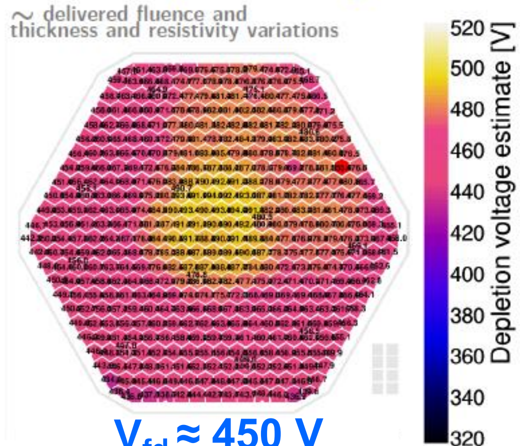
Selected results I: Full 8"-sensors @ RINSC

- **120 µm HD-epi sensor @ Φ_{target}=1e16 n_{eq}/cm^2** [2]

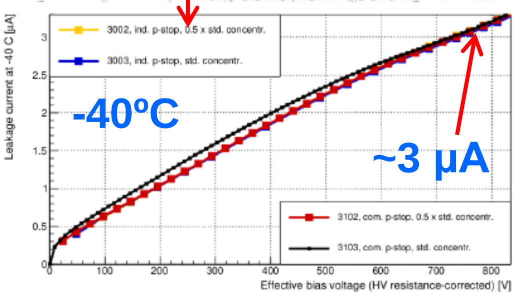
Leakage current



Depletion voltage



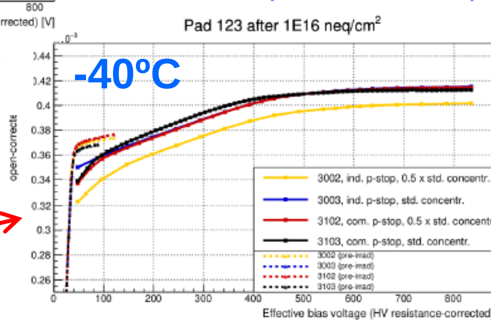
V_{fd} ≈ 450 V



CMS Preliminary

Cell CV results (4 process splits)

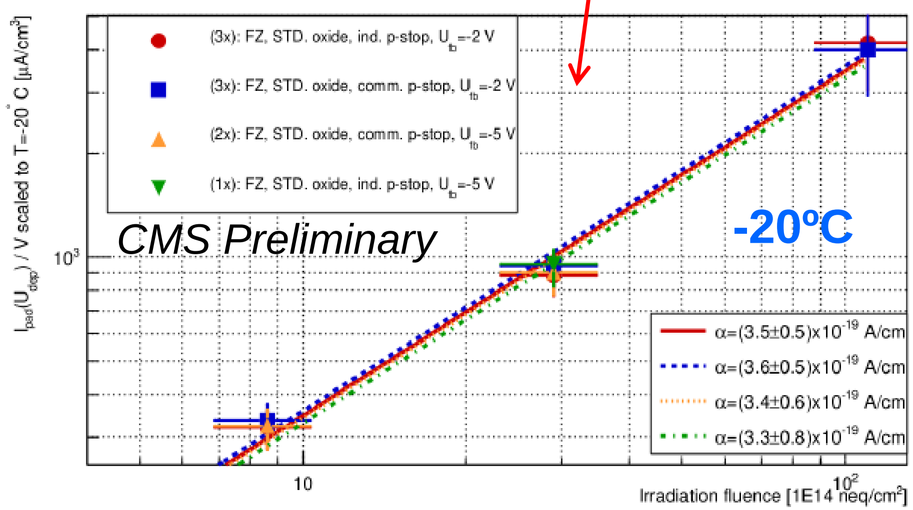
Cell IV results (4 process splits)



Pad 123

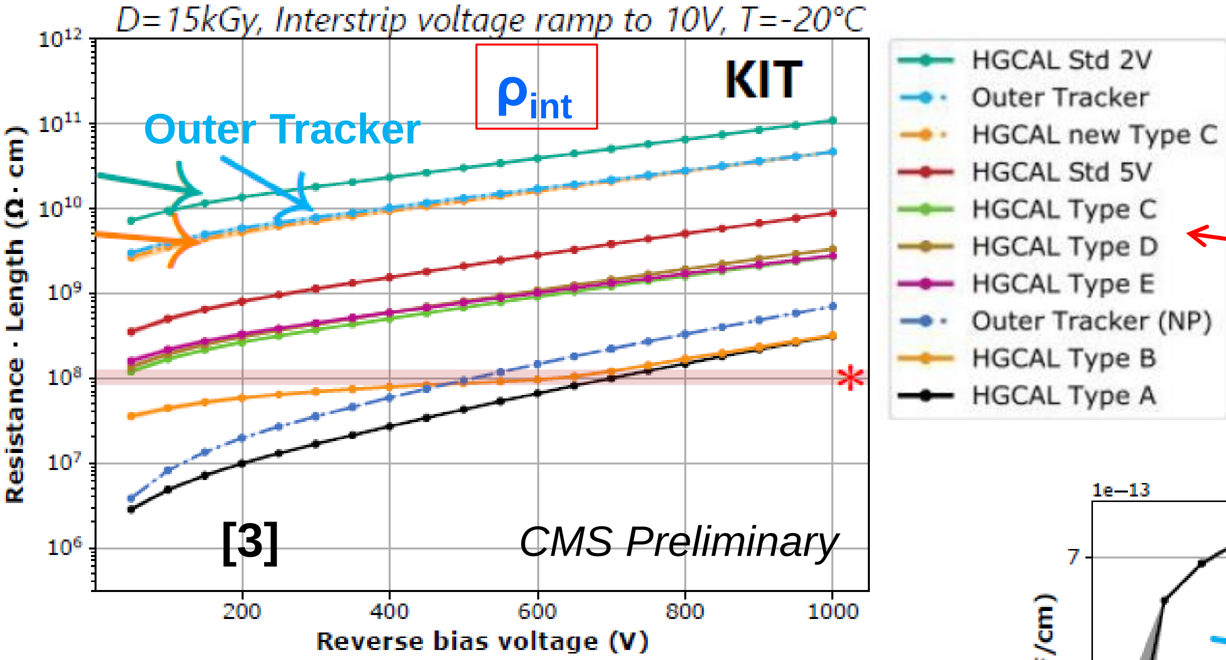
Process split comparison:
Similar for CV/IV

- Irradiations of 42 8'' LD/HD-sensors for 6 Φ_{target}=6.5e14 - 1e16 n_{eq}/cm^2 completed @ RINSC May 2021 (see backups 2-4)
- **α-factor:** Agreement within factor 2 → reasonable confidence in RINSC fluence estimates



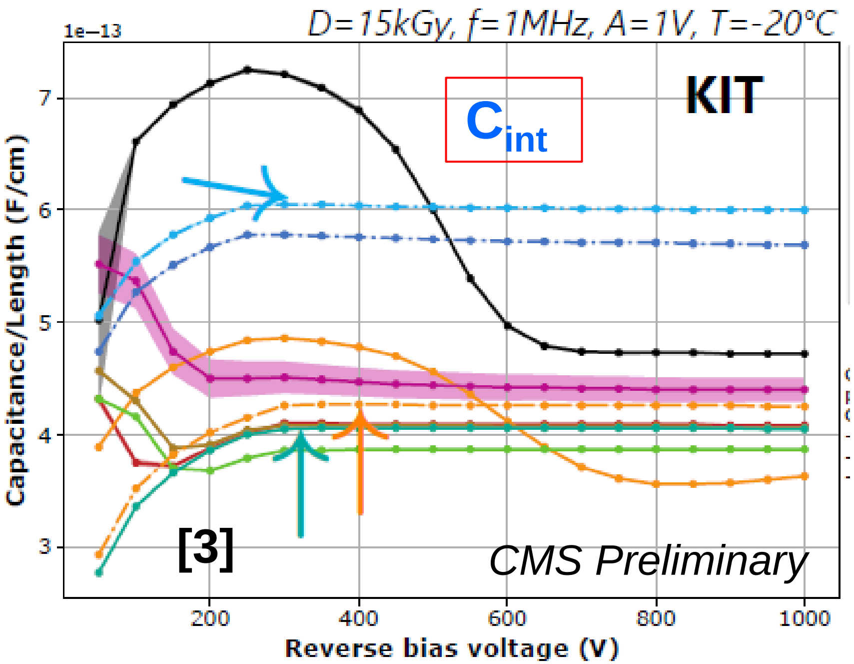
- **Probe card (PC)-setup:** Backup 5

Selected results II: 8"-wafer test structures I



- **X-ray irradiated (D=15 kGy) strip-sensors from HGCAL wafers**:
  - Process splits **std** & **New Type C** (V_{fb}=-2V): High $\rho_{int} \rightarrow$ **high pad isolation**
  - Measured pad isolation reproducible by TCAD (see backup 6)

- **Std** & **New Type C** also have low & stable $C_{int} \rightarrow$ **low cross-talk** → focus on V_{fb}=-2V oxide splits

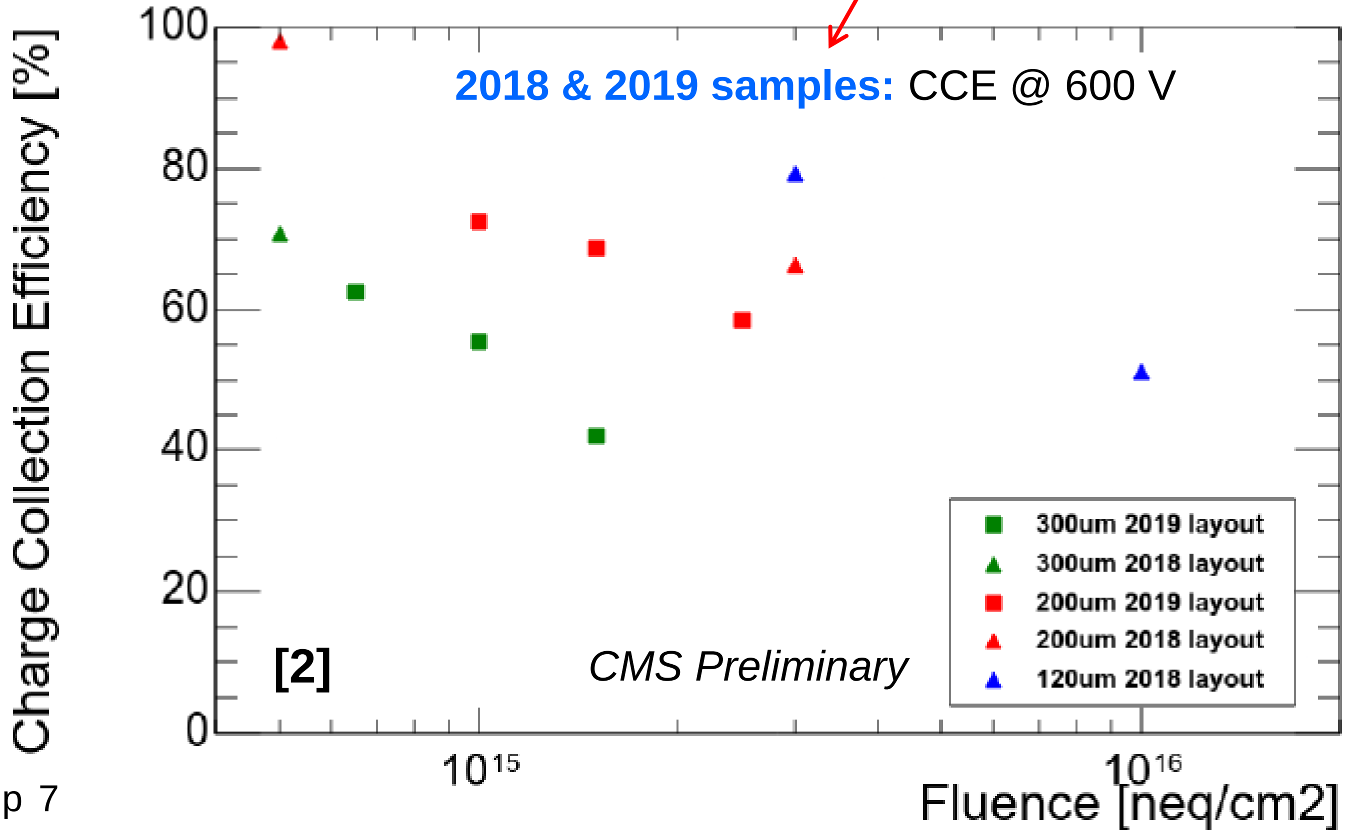


TCAD=Technology Computer-Aided Design

[3] J.-O. Müller-Gosewisch, Si Sensors WG meeting, 03/23/2021.

Selected results III: 8”-wafer test structures II

- **Charge collection of JSI-neutron irradiated test-diodes:** IR-TCT @ -20ºC (CERN, SSD group) → compatible w/ published results [1,4]
  - TCT of full sensors underway w/ 7-needle PCs



- **TCT-setup:** Backup 7
- **7-needle probe card:** Backup 8

[4] N. Akchurin et al., ***JINST*** 15 (2020) P09031.

Toward full sensor production: Timeline

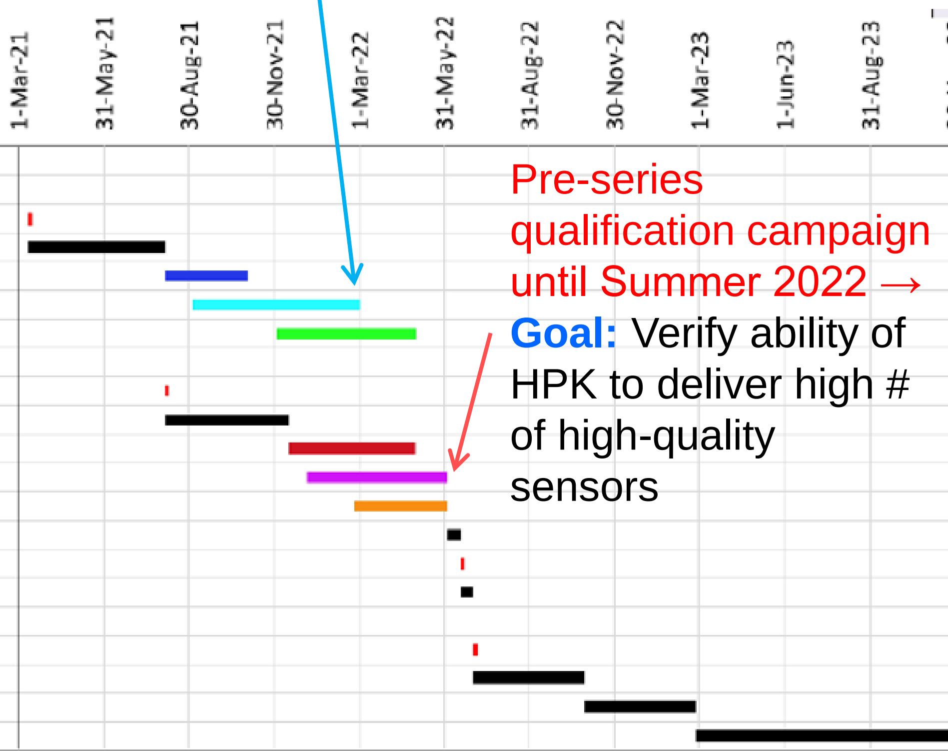
Type	Vfb	P-stop layout	P-stop conc.	Oxide quality	Quantity per thickness
A	-5V	com	std	STD (for reference)	4
B	-2V	com	std	Masking method (for reference)	8
C	~-2V	com	std	Thermal condition change	8
		ind			8
D	~-2V	com	std	New combination of B and C	8

- ❑ **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 (testing schedule: backup 9)

- ❑ **Pre-series:** Approval from analysis of probe-card data of HPK V2-full wafers + HPK-internal pilot run → validate high mass production yield & testing

[2]

FULL SENSORS		
2nd prototypes		
ok for HPK prototypes a: optimise process	11-Mar-21	11-Mar-21
production lead time	11-Mar-21	5-Aug-21
prototypes delivery	5-Aug-21	3-Nov-21
prototype tests and irradiations	4-Sep-21	3-Mar-22
assemble and test modules	3-Dec-21	2-May-22
Preseries		
ok for preseries	5-Aug-21	5-Aug-21
production lead time	5-Aug-21	16-Dec-21
delivery of pre-series	16-Dec-21	30-Apr-22
sample tests, review of results	5-Jan-22	4-Jun-22
assemble and test modules	24-Feb-22	3-Jun-22
PRR Preparation	4-Jun-22	18-Jun-22
PRR	18-Jun-22	18-Jun-22
PRR follow-up	18-Jun-22	2-Jul-22
Preproduction		
ok fo preproduction	2-Jul-22	2-Jul-22
production lead time	2-Jul-22	29-Oct-22
delivery of pre-production	29-Oct-22	26-Feb-23
Production	26-Feb-23	16-May-25



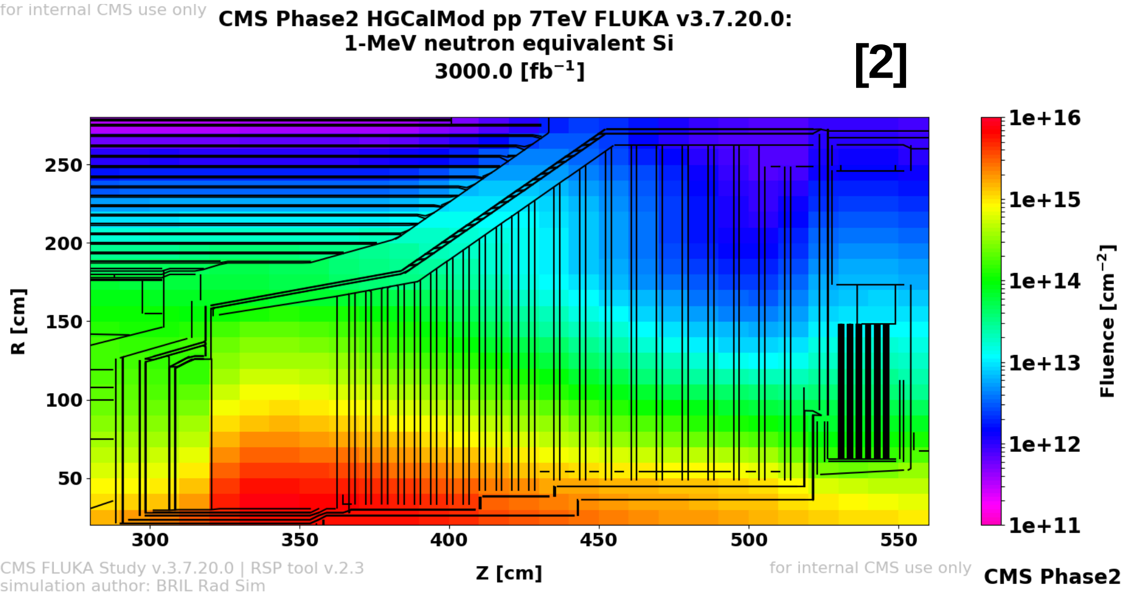
Pre-series qualification campaign until Summer 2022 →

Goal: Verify ability of HPK to deliver high # of high-quality sensors

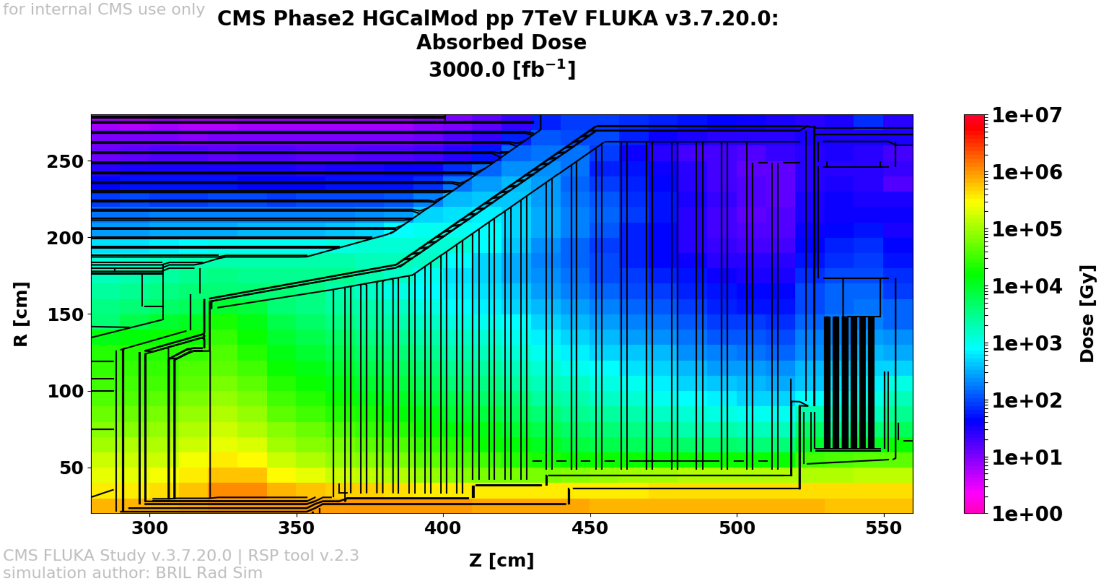
Summary

- **8" sensor qualification & irradiation campaign has been largely successful**
  - **Initial issues:** low yield, high number of process splits
  - **Identified mitigation techniques for yield:** Improved sensor handling @ HPK, sensor design optimization
  - Identified 2 process variants w/ excellent oxide quality & interpad characteristics
  - Reactor irradiations of 42 8'' LD/HD-sensors for six target fluences from 6.5e14 to 1e16 n_{eq}/cm^2 was successfully conducted at RINSC
    - The test results are positive, bulk radiation damage effects meet expectations & surface damage effects consistent w/ 6" experience
    - Radiation hardness of 8" bulk found to be better to 6"
- **Multi-geometry wafer designs**
  - Submitted designs in December 2020 → expect first deliveries in fall 2021
- **Steps towards mass production**
  - First V2 prototypes due in fall '21, validated by spring '22
  - V2 intended as basis for pre-series, expected to be validated by summer '22 → choose good production process candidate based on V2 prototypes
  - HPK-internal pilot run & pre-series lay ground for mass production

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



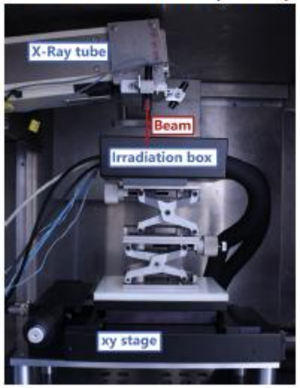
- **HGCAL:** ~27,000 hexagonal 8-inch silicon modules → ~6M channels w/ area of 620 m^2
- Hexagonal sensor shape to maximize usable area of circular wafers while remaining tile-able
- **8" wafers:** Reduced # of modules to 6" wafers in trackers



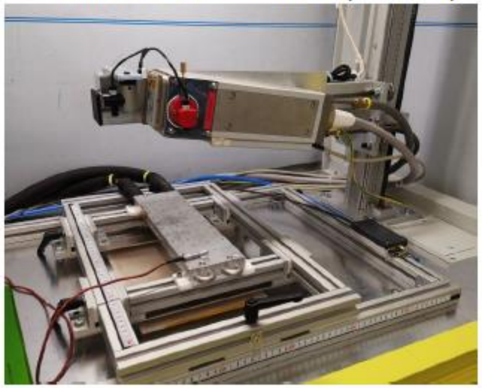
Back-up 2: Irradiation facilities

- **Neutrons:**
  - **Full 8" sensors:** RINSC/BU → only facility for full 8" sensors
  - **Test structures** (diodes, strips,…): JSI Ljubljana (SLO) & RINSC **[2]**
- **X-rays:**
  - **Test structures** (MOS, GCD, strips,…): KIT, INFN & CERN

X-ray facility (KIT)

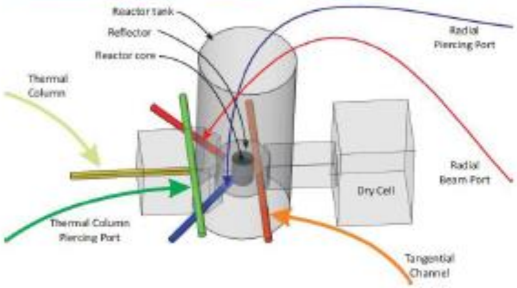


ObeliX X-ray facility (CERN)

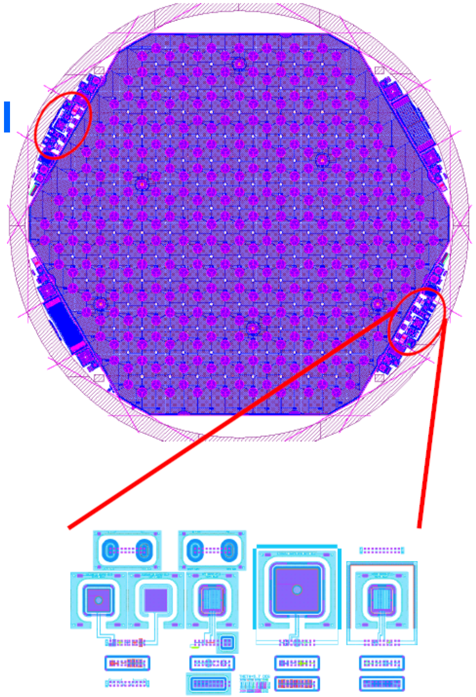


RINSC core

JSI TRIGA reactor, Ljubljana



- **8" wafer w/ full sensor & test structures [5]**



[5] M. Babeluk, Si Sensors WG meeting, Jun 22, 2021.

Back-up 3: RINSC irradiation rounds 1 – 4

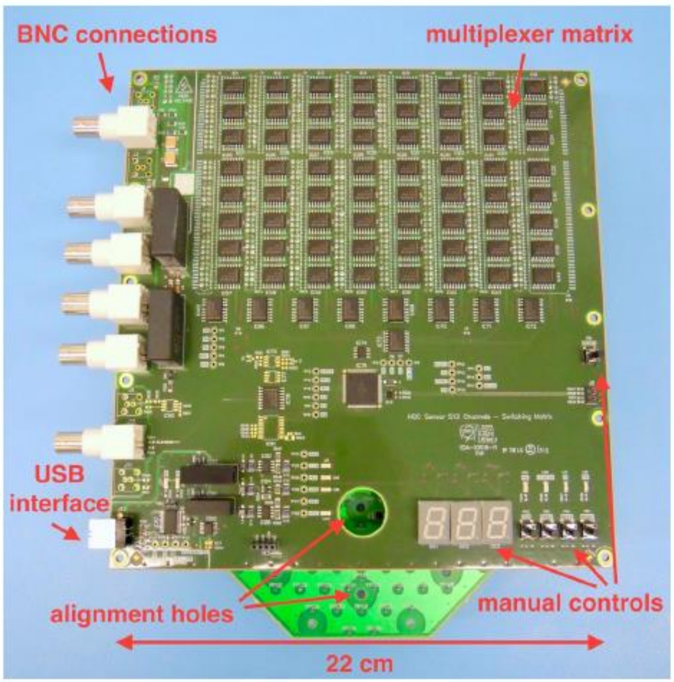
Irrad. round	Target fluence [neq/cm2]	Sensor ID	P-Stop	Thick-ness	Flat band volt.	Oxide quality	P- Stop conc.	Proc.	Status (wafer location from core)	Current location	date at RINSC (one per week)
1	6.50E+14	1004	ind.	300	-5V	STD	STD	FZ	Irradiated (3rd)	CERN	August 26
1	6.50E+14	1002	ind.	300	-2V	STD	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

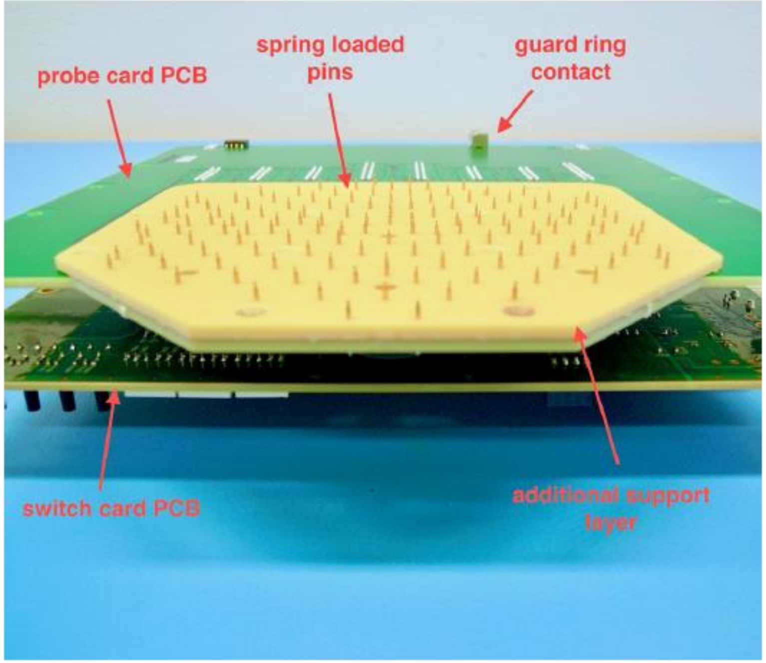
Back-up 4: RINSC irradiation rounds 5 – 11

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

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

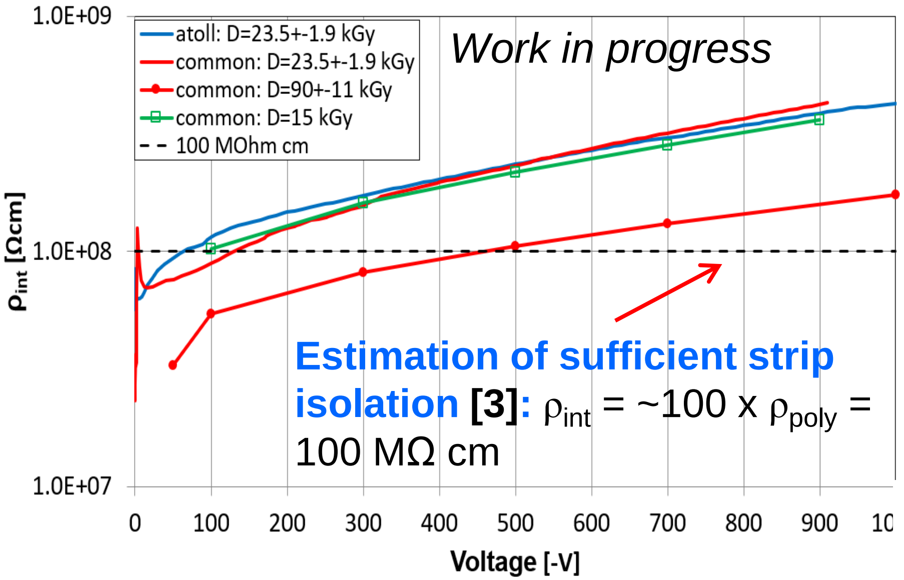




[2,6]

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

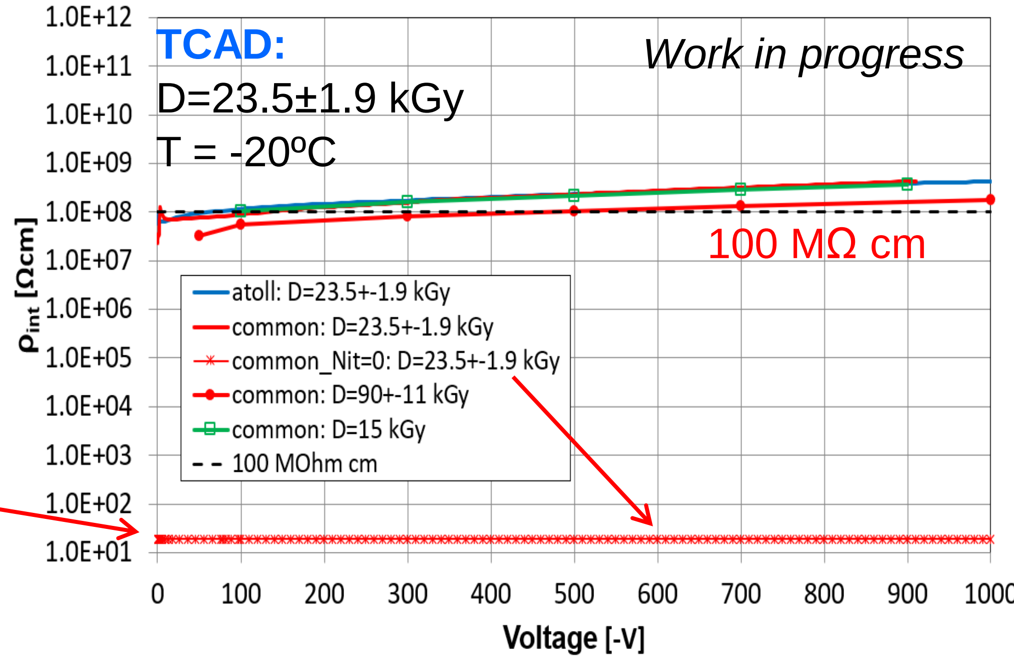
Back-up 6: TCAD simulated ρ_{int} - N_f & $N_{it,don,acc}$



- Reactor-irradiated MOS CV-curves reproduced by TCAD only by including N_f & both $N_{it,don,acc}$ @ Si/SiO_2-interface
- **N_{it} param. for D=23.5±1.9 kGy, f=4 kHz & N_f = 1.0e12 cm^{-2}:**

Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Density [cm^{-2}]
Deep donor	E_V + 0.65	1e-15	1e-15	2.3e12
Deep acceptor	E_C - 0.60	1e-15	1e-15	2.6e12

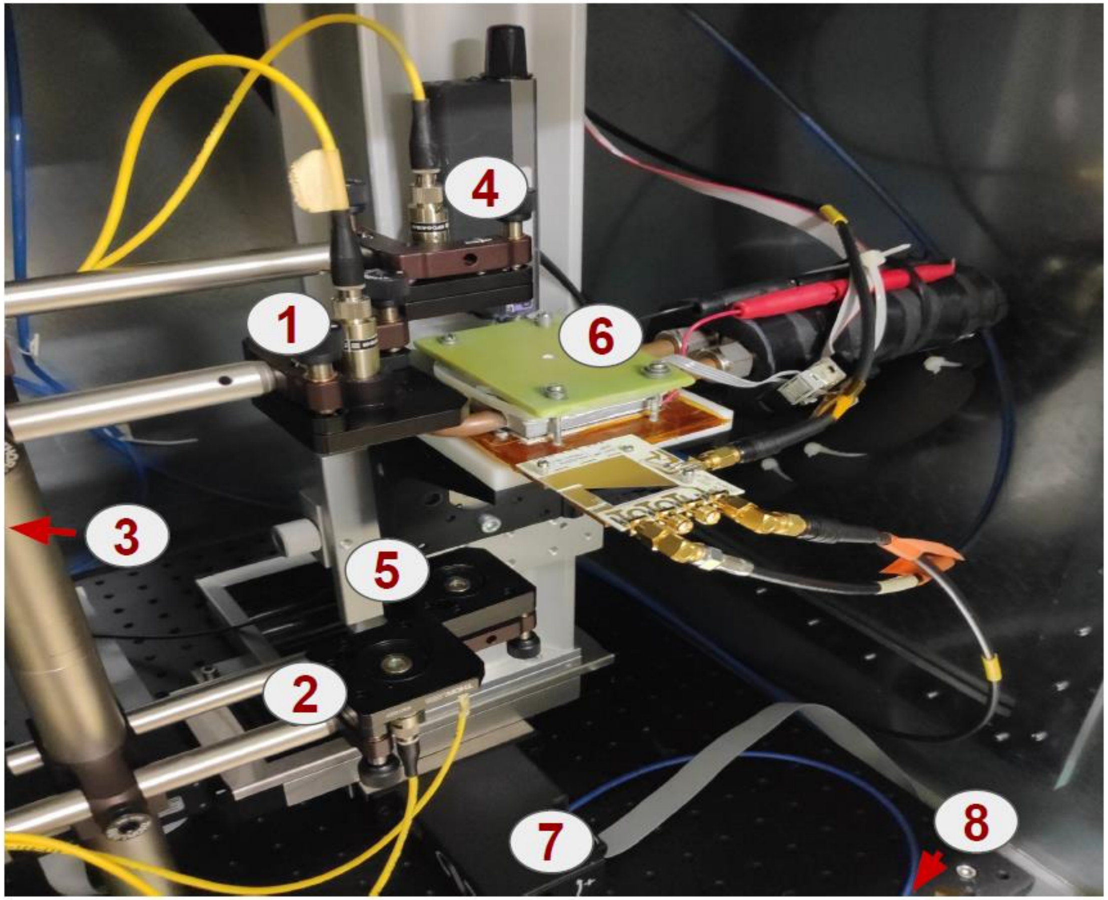
- Apply model to ρ_{int}-simulations @ similar conditions to measured ρ_{int} on slide 6 & for HGCAL p-stop param. → similar values btw/ measured & TCAD
- ρ_{int} decreases w/ increased dose
- Sufficient isolation due to N_{it}, not isolation implants



N_f=fixed oxide charge density,
$N_{it,don,acc}$=donor/acceptor-type interface trap density

SSD TCT+ setup **[7]**

1. IR top laser
2. IR bottom laser
3. IR edge laser
4. Red top laser
5. Red bottom
6. Sample holder with cooling system (chiller + peltier)
7. x,y,z stage
8. Pre-amplifier (CIVIDEC)

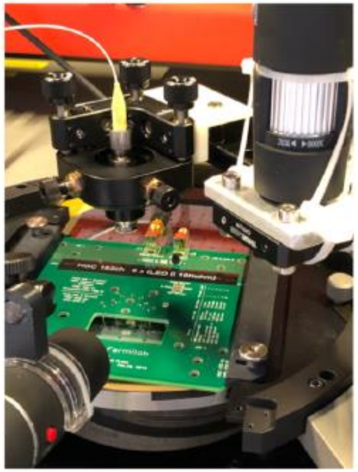


[7] P. Almeida, Si Sensors WG meeting Jun 15, 2021.

Back-up 8: 7-needle probe card - Full sensor CC/noise

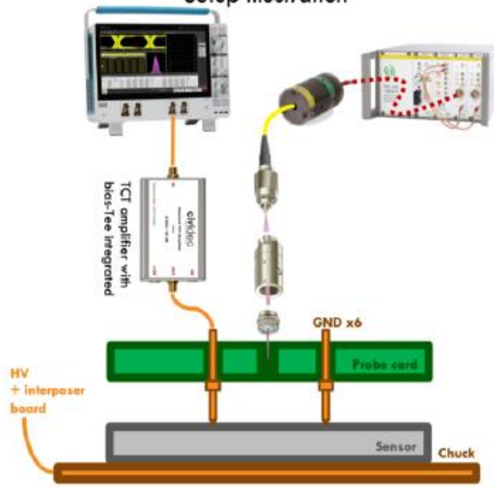
FNAL board

Setup in probe-station

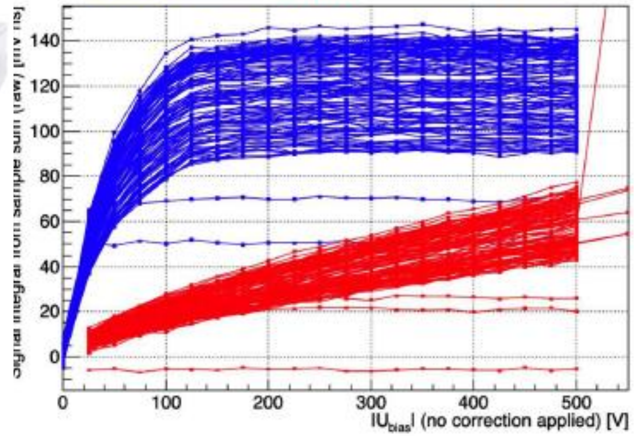


Setup illustration

[2]

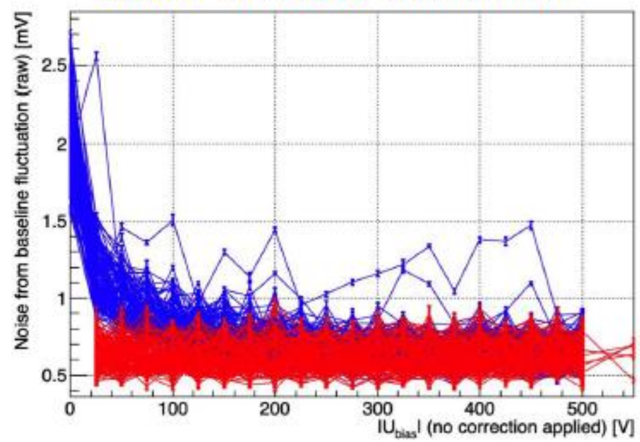


Integrated charge
before and after irradiation



- 7-needle TCT measurements for all cells with regular neighbours as function of bias voltage
- First results on charge collection efficiency measurements with 300 μm full sensors irradiated to 6.5e14 n_{eq}/cm^2 (80 min annealing at 60ºC)
- Status: Debugging of origin of signal fluctuation from cell to cell (differences in passivation, reflection, etc.)

Baseline fluctuation (noise)
before and after irradiation



Back-up 9: V2 validation – Testing schedule

Activity			Weeks																													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
MOS X-ray	MOS+GCD x-ray irradiation, 3 splits * 2 samples/split, reduced annealing	FZ	2	0	2	2	2	2	2	2	2																					
		epi				2	0	2	2	2	2	2	2	2	2																	
		Analysis														2	2															
Mini-strip X-ray	HGCAL-like mini-strip x-ray irradiation, 3 splits * 2 samples/split, reduced annealing	Setup	2	2	2	2	2	2																								
		FZ								2	0	2	2	2	2	2	2	2														
		epi											2	0	2	2	2	2	2	2	2	2										
		Analysis																					2	2								
Mini-strip neutron	HGCAL-like mini-strip neutron irradiation, 6 fluences * 3 splits/fluence * 2 samples/split, 2000m annealing with 7 measurements		2	2	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2												
Diode neutron	Diode neutron irradiation, 6 fluences * 3 splits/fluence * 2 diodes/split, 590m annealing with 5 measurements							2	2	0	0	0	0	0	2	2	2	2	2	2												
Full sensor neutron	Φ = 1.5e15 n_eq/cm^2, 300 µm, 3 sensors		0	1	0	1	0	0	1	1																						
	Φ = 1.5e15 n_eq/cm^2, 300 µm, 3 sensors			0	1	0	1	0	0	1	1																					
	Φ = 2e15 n_eq/cm^2, 300 µm, 3 sensors				0	1	0	1	0	0	1	1																				
	Φ = 2e15 n_eq/cm^2, 300 µm, 3 sensors					0	1	0	1	0	0	1	1																			
	Φ = 4e15 n_eq/cm^2, 200 µm, 3 sensors						0	1	0	1	0	0	1	1																		
	Φ = 4e15 n_eq/cm^2, 200 µm, 3 sensors							0	1	0	1	0	0	1	1																	
	Φ = 5.5e15 n_eq/cm^2, 200 µm, 3 sensors								0	1	0	1	0	0	0	1	1															
	Φ = 5.5e15 n_eq/cm^2, 200 µm, 3 sensors									0	1	0	1	0	0	0	1	1														
	Φ = 10e15 n_eq/cm^2, 120 µm, 3 sensors										0	1	0	1	0	0	0	0	1	1												
	Φ = 10e15 n_eq/cm^2, 120 µm, 3 sensors											0	1	0	1	0	0	0	0	1	1											
	Φ = 14e15 n_eq/cm^2, 120 µm, 3 sensors												0	1	0	1	0	0	0	0	0	1	1									
	Φ = 14e15 n_eq/cm^2, 120 µm, 3 sensors													0	1	0	1	0	0	0	0	0	1	1								
	Req'd. FTE		6	5	5	8	6	10	9	12	10	10	12	10	13	12	13	9	7	8	3	3	4	3								

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- 20–37 weeks available for acceptance and irradiation testing
- Fewer test structure annealing measurements w.r.t. V1 prototypes: confirmation of V1 results, not repetition of entire V1 study
- Full sensor irradiation fluences correspond to maximum expected at 3 and 4.5 ab^{-1}
- Personnel spread across institutes
- Contingency available to accommodate delays or serialize activities