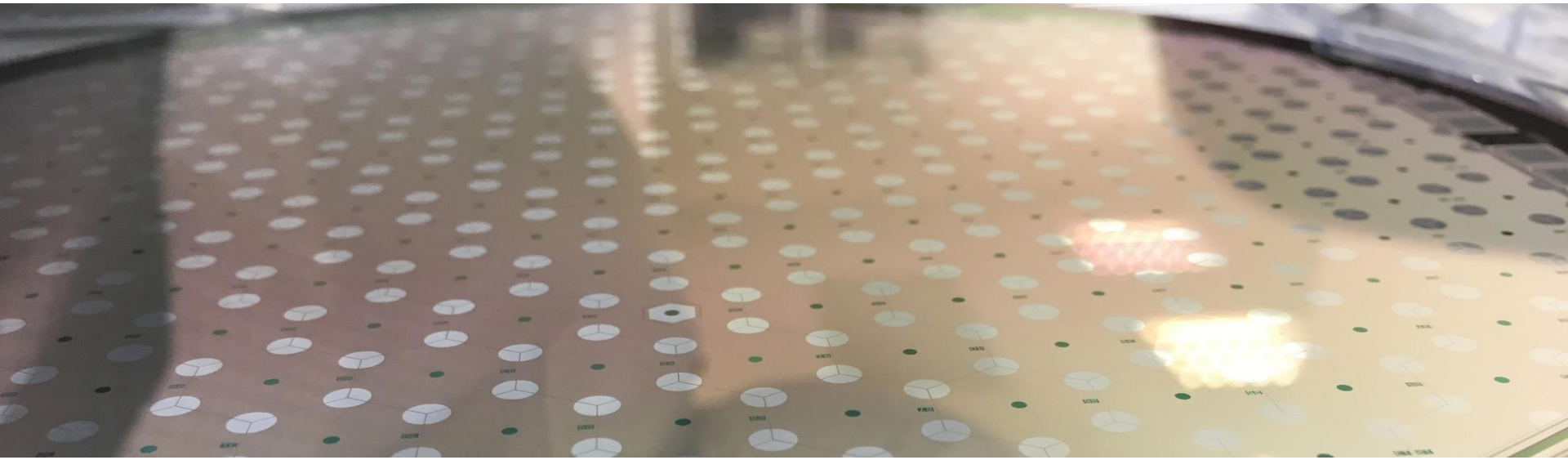


HGCal General Meeting during CMS Week

Status Si Sensors

Thomas Bergauer

9. April 2019

Contents

- **Sensor Procurement**
  - From Market Survey to Invitation to Tender
  - Prototype orders 2019/2020
  - Sensor Designs
- **Status Sensor Testing**
  - Setups for series production
  - Bad cells after repeated probe card measurements
  - Noise studies, Test Structures
- **Irradiations**
  - What happened so far on 6”
  - 8” planning

SENSOR PROCUREMENT

Common CMS/ATLAS Market survey for Tracker Sensors initiated in 2016

Enabling factors:

- Strip sensors for ATLAS and CMS are very similar
- Different specifications are not so significant for the production

Advantages:

- Shows the combined demand of the largest projects of the coming years to interested companies
- We can share qualification work among the two collaborations

HGCal Status:

- HGCal was not approved at that time and so a very large fraction of sensor production is not reflected in this MS
- HGCal is also participating in the results of the first step(s) of this MS

CMS/ATLAS Market Survey Procedure

Each interested company has to successfully pass a three step qualification procedure to be eligible to receive the Invitation to Tender!

- **Step 1:** Companies need to return the ***"Technical Questionnaire"*** document where the responses need to fulfil the requirements set in the "*Qualification Criteria"* document **(2016)**
- **Step 2:** Companies need to provide samples free of charge of functional devices of e.g. previous project **(2017)**
  - **ATLAS and CMS qualified samples produced by Infineon as 8" proof-of-principle**
- **Step 3**: CMS/ATLAS orders (and remunerates) a batch of prototype sensors according to CMS layout and specs **(2018)**
  - **ATLAS and CMS ordered close-to-final prototypes as described in the TDRs**
- **Step 4:** Invitation to Tender for procurement of series production **(2019)**

Companies qualified

- **Step 1:** HPK (JP), Infineon (EU), Novati (US)
- **Step 2:** HPK, Infineon
  - Novati was sold several times (initially Tezzaron, later Nhanced, Ziptronix, Skorpios) and facility was no longer available, plus quality issues
- **Step 3:** HPK
  - On 11 July 2018, IFX decided to withdraw from participating in HEP projects

- → Only Hamamatsu left for Invitation to Tender

Consequences on Infineon's decision

- **HPK is the only qualified vendor of sensors for CMS Tracker, CMS HGCal and ATLAS ITk**
  - More than 46.000 x 6" and 30.000 x 8" wafers over ~3 years

- To ensure that HPK can prepare for this large production:
  - A committee was formed with participation from all projects and CERN procurement
  - HPK was informed of the situation
  - A high-level management meeting at Hamamatsu was held (including CERN DR and ATLAS/CMS SPs)
  - A timeline was defined for the Invitation to Tender which will lead to the contracts for the series production

Procurement timeline

	ATLAS Strip sensors	CMS Strip sensors	CMS HGCAL
Finalisation of draft IT documents and related documents* (by both Procurement and Technical officers)	17 March 2019	17 March 2019	17 March 2019
Specification Committee date	25 March 2019	25 March 2019	27 March 2019
Dispatch of IT documents	3 April 2019	3 April 2019	**3 April 2019**
Submission deadline	26 April 2019	26 April 2019	**26 April 2019**
Submission of FC paper	-	29 April 2019	29 April 2019
Peers review meeting for FC	-	9 May 2019	9 May 2019
FC meeting	-	18/19 June 2019	18/19 June 2019
Frame contract signature	June 2019	As of end June 2019	As of end June 2019
Delivery of pre-production and production units	As per contract and release orders	As per contract and release orders	As per contract and release orders

* Technical specification and annexes, Tender Form (and technical questionnaire, if any), Risk Matrix, memo of MS results, draft contract, General Conditions of CERN Contracts, General Conditions of CERN Invitations to Tender.

Delivery Schedule for Series production

Prototypes (HGC)
Pre-Series (HGC)
Pre-Production
Production

2019/2/27 HPK Proposal

				Q1'19	Q2'19	Q3'19	Q4'19	Q1'20	Q2'20	Q3'20	Q4'20	Q1'21	Q2'21	Q3'21	Q4'21	Q1'22	Q2'22	Q3'22	Q4'22	Q1'23	Q2'23	Q3'23	Q4'23		Production	Pre	Sum
ATLAS tender																											
ATLAS order																											
ATLAS Short Barrel	strip	1				159	159		0	0	0	0	0	0	0	0	0	100	860	860	860	860	860		4400	318	4718
ATLAS Long Barrel	strip	1				159	159		840	840	840	840	840	840	840	840	840	740	0	0	0	0	0		8300	318	8618
ATLAS Ring0	strip	1				23	23		60	60	60	60	60	60	60	60	60	60	60	60	60	60	60		900	46	946
ATLAS Ring1	strip	1				23	23		60	60	60	60	60	60	60	60	60	60	60	60	60	60	60		900	46	946
ATLAS Ring2	strip	1				23	23		60	60	60	60	60	60	60	60	60	60	60	60	60	60	60		900	46	946
ATLAS Ring3	strip	1				45	45		120	120	120	120	120	120	120	120	120	120	120	120	120	120	120		1800	90	1890
ATLAS Ring4	strip	1				45	45		120	120	120	120	120	120	120	120	120	120	120	120	120	120	120		1800	90	1890
ATLAS Ring5	strip	1				45	45		120	120	120	120	120	120	120	120	120	120	120	120	120	120	120		1800	90	1890
Sum						522	522		1380	1380	1380	1380	1380	1380	1380	1380	1380	1380	1400	1400	1400	1400	1400		20800	1044	21844
CMS OT tender																											
CMS OT order																											
CMS OT 2S	strip	1					80	200	370	1170	1170	1170	1170	1170	1170	1170	1170	1170	1170	1170	1170	1170	1190		16400	650	17050
CMS OT PS-s	strip	2					42	65	80	210	210	210	210	210	210	210	210	210	210	210	210	210	200		2930	187	3117
CMS OT PS-p	pixel	2					50	83	100	255	255	255	255	255	255	255	255	255	255	255	255	255	215		3530	233	3763
Sum							172	348	550	1635	1635	1635	1635	1635	1635	1635	1635	1635	1635	1635	1635	1635	1605		22860	1070	23930
CMS HGC tender																											
CMS HGC order																											
CMS HGC 300um	PAD	1			14	14		90	90	90		188	562	1425	1425	1425	1425	1425	1425	1425	1425	1425	1425		14250	750	15000
CMS HGC 200um	PAD	1			14	14		64	64	64		112	338	855	855	855	855	855	855	855	855	855	855		8550	450	9000
CMS HGC 120um	PAD	1			16	16		40	40	40		50	150	380	380	380	380	380	380	380	380	380	380		3800	200	4000
Sum					44	44		194	194	194		350	1050	2660	2660	2660	2660	2660	2660	2660	2660	2660	2660		28670	1400	28000

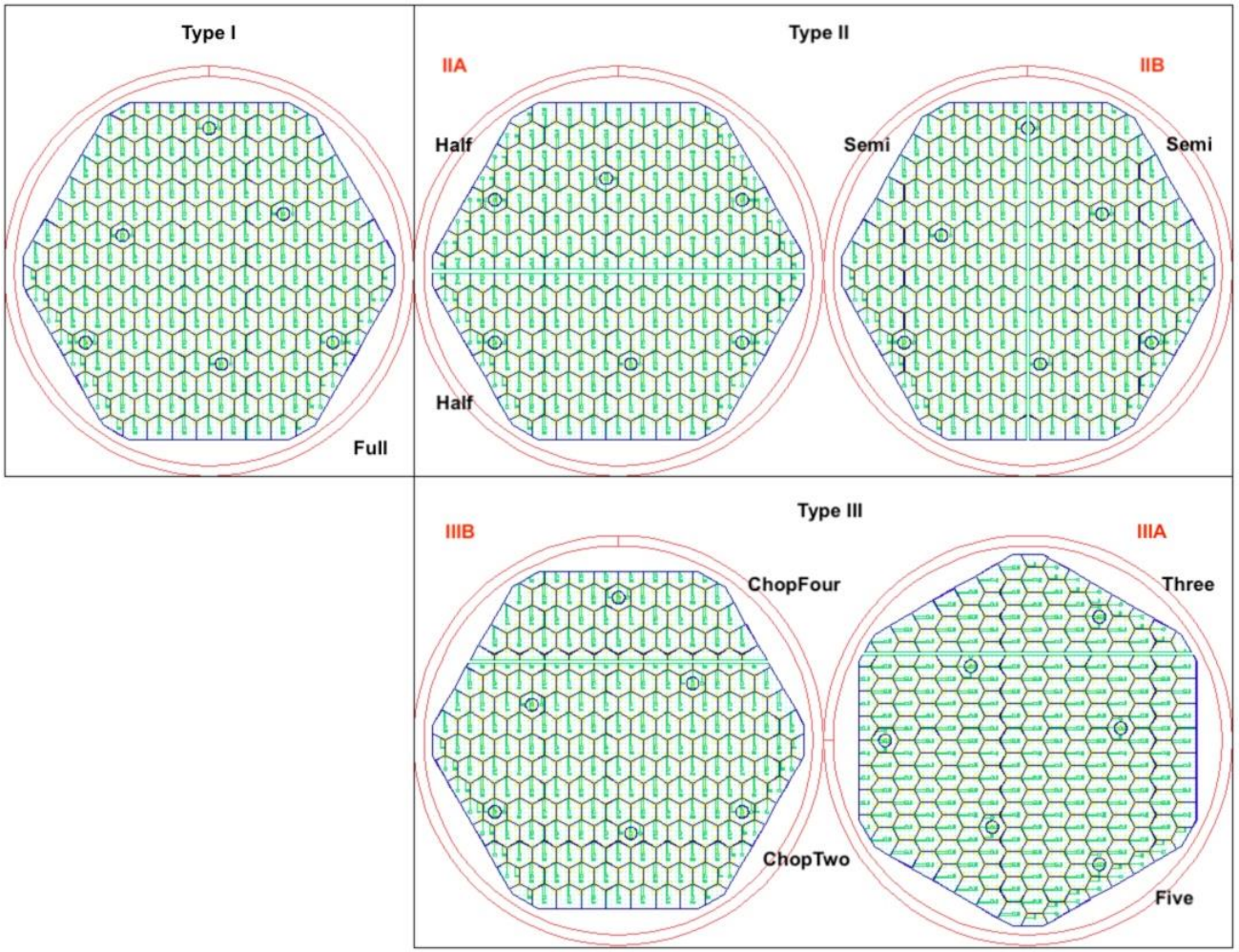
Tendering Package

Contains

- Technical Specifications
  - See next slides
- Tender Form where bidder needs to quote prices for each requested component
  - See right table
  - We are also asking for separate NRE costs and options
- Options:
  - 100um instead of 120um Epi-Sensors
  - Separate partial wafers

Pos.	Sensor Description	Thick	Nb of sensors (a)	Total NRE (b)	Sensors production unit price (c)	Total price (d) = (a) * (c) + (b)
Type I – One sensor per wafer						
1	Type I - Full sensors	300	12000	.....	.....	.....
2	Type I - Full sensors	200	9600	.....	.....	.....
3	Type I - Full sensors	120	4000	.....	.....	.....
Type II – Two half sensors per wafer						
4	Type IIA - Half sensors (2/wafer)	300	1320	.....	.....	.....
5	Type IIA - Half sensors (2/wafer)	200	160	.....	.....	.....
6	Type IIA - Half sensors (2/wafer)	120	160	.....	.....	.....
7	Type IIB - Semi sensors (2/wafer)	300	800	.....	.....	.....
8	Type IIB - Semi sensors (2/wafer)	200	40	.....	.....	.....
9	Type IIB - Semi sensors (2/wafer)	120	360	.....	.....	.....
Type III – Two different sensors per wafer						
10	Type IIIA – Five (largest sensor)	300	1100	.....	.....	.....
11	Type IIIA – Three (remaining part)		1100	.....	.....	.....
12	Type IIIA - Five (largest sensor)	200	140	.....	.....	.....
13	Type IIIA – Three (remaining part)		140	.....	.....	.....
14	Type IIIA – Five (largest sensor)	120	60	.....	.....	.....
15	Type IIIA – Three (remaining part)		60	.....	.....	.....
16	Type IIIB – ChopTwo (largest sensor)	300	60	.....	.....	.....
17	Type IIIB – ChopFour (remaining part)		60	.....	.....	.....
18	Type IIIB – ChopTwo (largest sensor)	120	360	.....	.....	.....
19	Type IIIB – ChopFour (remaining part)		360	.....	.....	.....

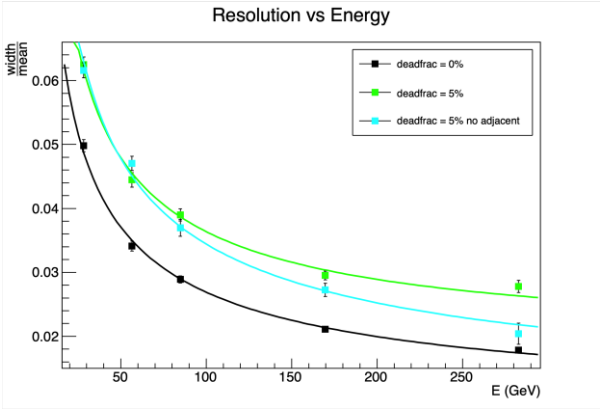
Sensor Layout Variants



(Key) Technical Specifications

- **Sensor breakdown voltage V_{break} > 800V, I_{800} < 2.5 x I_{600}**
- **Current @600V I_{600} (at 20°C):** ≤ 100 nA/pad
- **Current @600V (at 20°C):** ≤ 100 µA integrated over the sensor and guard rings
- Sensors must withstand standard handing procedures such as placement on probe stations and lamination to support circuit boards without developing additional bad cells.
- **Allowed number of bad pads:**
  - ≤ 8 for full-sized sensors
  - ≤ 4 for half and semi
  - ≤ 6 for choptwo and five types
  - ≤ 2 for chopfour and three types
  - Not more than two adjacent bad pads

Software tool needed to test measurement results against these specs (Hexplot?)



Sarah Eno, Sara Nabili, Chris Papageorgakis (UMD)
https://indico.cern.ch/event/808789/#1-simulation-of-bad-cells-frac

Prototype orders 2019/2020

Shape:				full	full	full	full	partials	partials	partials
Thickness:				300	200	120E	120E	300	200	120
Layout:			Sum	192	192	192	432	??	??	??
Use of sensor:	Aim	Sensor Delivery Dates								
				14	14	12				
SKIROC 2cms	module qual	*in hand*	0	*6*	*6*	*6*				
HGROC DV1	module test & evaluation	Jul.19	6	*6*	*6*		6			
Sensor QC	SQC qualification	Jul.19	18	6	6	*2*	6			
Irradiation	Irradiation		6	2	2		2			
	MAC qualification	Sep.19	30	10	10		10			
	cassette test & evaluation	Okt.19	30	10	10		10			
Prototypes		Sub Total 2019	90	40	40	*2*	34	0	0	0
						36				
Irradiation	irradiation	Feb.20	50	14	18		18			
HGROC DV2	module test & evaluation	Mär.20	18	6	6		6			
	MAC qualification	Apr.20	30	10	10		10			
	cassette test & evaluation	Jun.20	***213***	93	54		18	38	6	4
Pre-Series		Sub Total 2020	311	123	88	0	52	38	6	4
						52				
Prod HGCROC	module test & evaluation	Mär.21	18	6	6		6			
	MAC qualification	Apr.21	30	10	10		10			
	cassette test & evaluation	Jun.21	***426***	186	108		36	76	12	8
Final pre-series		Sub Total 2021	474	202	124	0	52	76	12	8
						52				
			875	**365**	**252**	**2**	**138**	**114**	**18**	**12**
						140				

Prototypes 2019

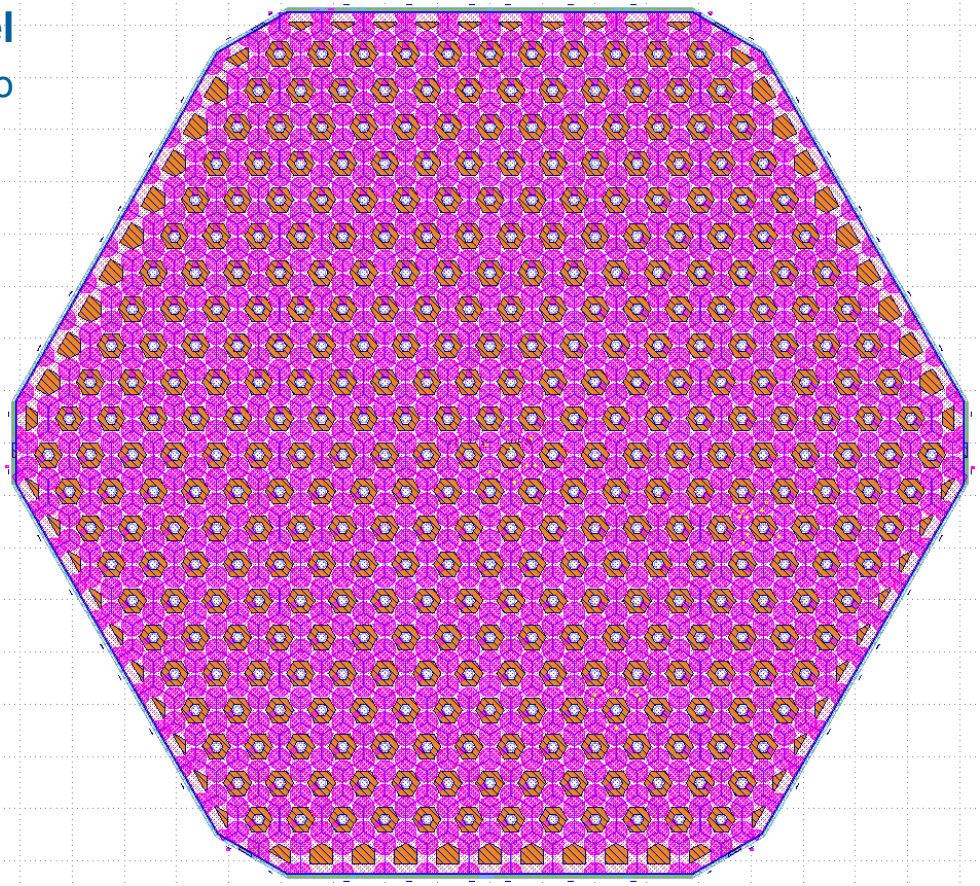
- DAI entered into EDH
  - Order still not placed
  - Long signature run for 340kCHF from non CERN-MS
- Key features of order:
  - 200 / 300 um Sensors (28pcs each)
    - Update of 2 masks to implement scratch pads
  - 120µm sensors (22pcs): New 432-cell sensor design

Order Lines

Item	Quantity	Description
1	1	**Masks set and NRE costs** Non-recurring engineering (SSD) Country of origin: **JAPAN (JP)**, Del Goods already delivered: **No**, Ser Budget Codes: **T660002 (70.0%)**
2	28	**200 um working Si sensors** hexagonal Si sensors on 8-inch v Country of origin: **JAPAN (JP)**, Del Goods already delivered: **No**, Lea Budget Codes: **T660002 (70.0%)**
3	28	**300 um working Si sensors** hexagonal Si sensors on 8-inch v Country of origin: **JAPAN (JP)**, Del Goods already delivered: **No**, Lea Budget Codes: **T660002 (70.0%)**
4	1	**Masks set and NRE costs** Non-recurrent engineering (SSD) Country of origin: **JAPAN (JP)**, Del Goods already delivered: **No**, Ser Budget Codes: **T660002 (70.0%)**
5	12	**120 um working Si sensors** hexagonal Si sensors on 8-inch v Country of origin: **JAPAN (JP)**, Del Goods already delivered: **No**, Lea Budget Codes: **T660002 (70.0%)**
6	20	**120 um working Si sensors** hexagonal Si sensors on 8-inch v Country of origin: **JAPAN (JP)**, Del Goods already delivered: **No**, Lea Budget Codes: **T660002 (70.0%)**

New 432-cell sensor design

- **Sensor design finished to ~80% level**
  - Follows “max_wafer” layout [1] similar to 192-cell sensor
- **Implemented already:**
  - Cell and overall sensor dimensions defined
  - Guard + edge ring
- **To be done/verified:**
  - Corner & calibration cells
  - Numbering / labeling /Scratch pads
  - **Thicker inner guard ring to allow pogo-pin connection (biggest changes) *)**
  - **Decision on p-stop*)**
  - **Alignment marks*)**
  - **Test structures*)**



*) input from measurements/others needed

[1] All parameters:
https://docs.google.com/spreadsheets/d/1B67SSaqeN8b72-4JqnazcWX577o51CuqV9GUH-siibE

STATUS SENSOR TESTING

For Prototypes

Center	Probe stations	Switch/ Probe card	Laser for TCT/CCE
CERN	• Manual 6/8“ available • (Automatic 6/8“ w/ cold chuck ordered)	yes	ordered
FNAL	• Automatic 6/8“ w/ cold chuck • 7-needle probecard with laser for CCE		yes
HEPHY	• Manual 6“ w/cold chuck • Automatic 6/8“ w/cold chuck • Probe card setup for Test structures & 2 others	yes	yes
TTU	• Manual setups	yes	yes
FSU	Manual 6“ retrofitted with 8“	yes	

During Series production

Sensor testing will be performed at/by:

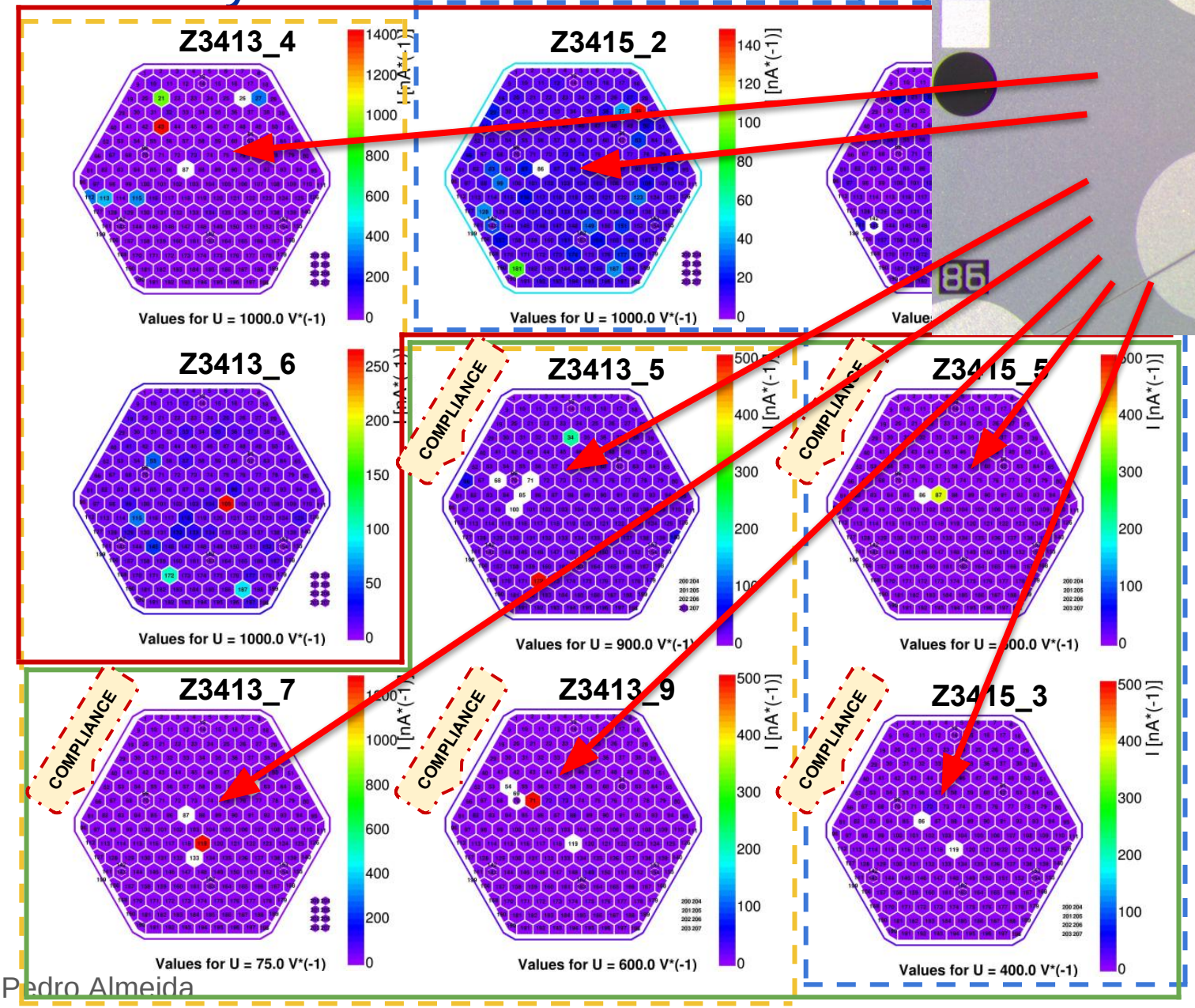
- **Vendor (HPK)**: 100%
- **By CMS** at different labs on sample test level (1-2%)
  - At dedicated ”sensor test centers” (tbd?)
  - At **Module Assembly Centers (MACs)** as part of incoming inspection (t.b.d.)
- On **test structures** (PQC)
- At dedicated ”expert centers” for Irradiations tests during production

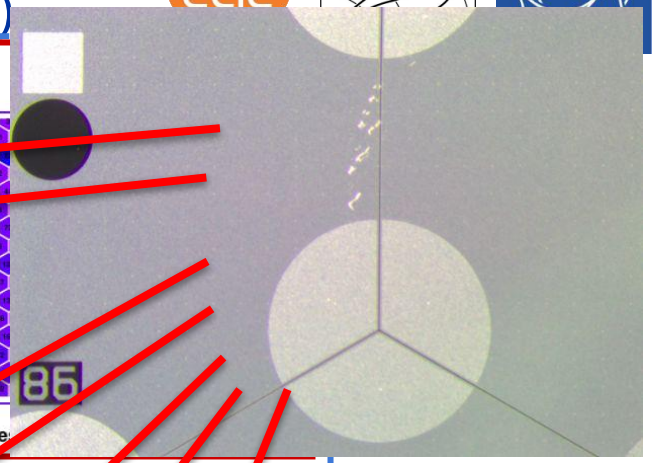
Manpower for logistics at CERN needed!!

*) Interest expressed by all three centers

MAC	SQC	PQC
Texas Tech	Texas Tech.	Brown
CMU	Florida State	Brown
Taipeh	Taipeh*)	Vienna
Beijing	Beijing*)	Vienna
Mumbai	Mumbai*)	Vienna

Summary of Measurements - IV (1st)





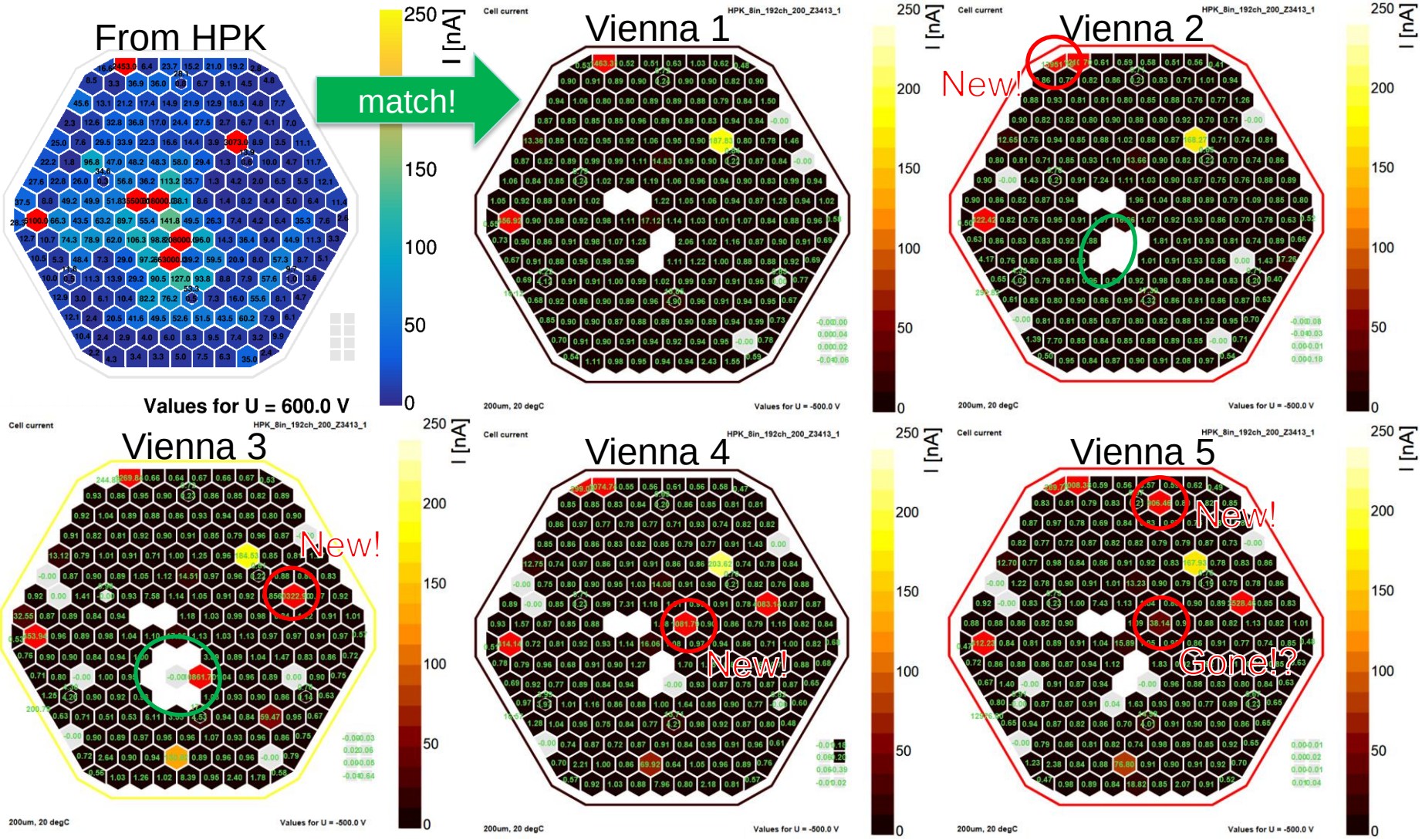
300 µm

200 µm

Individual p-stop

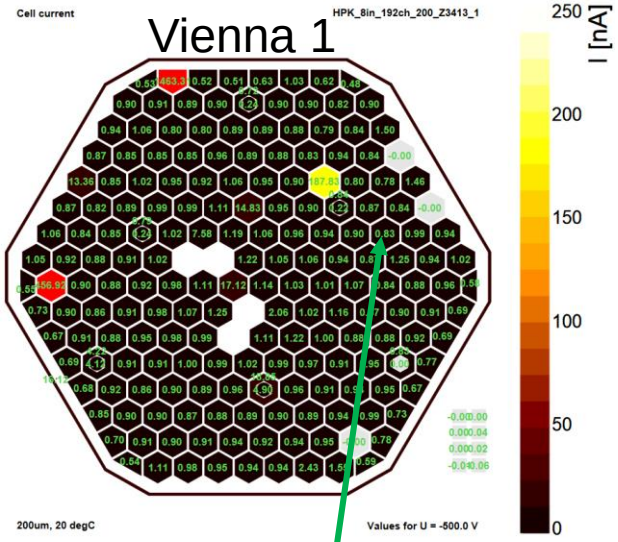
Common p-stop

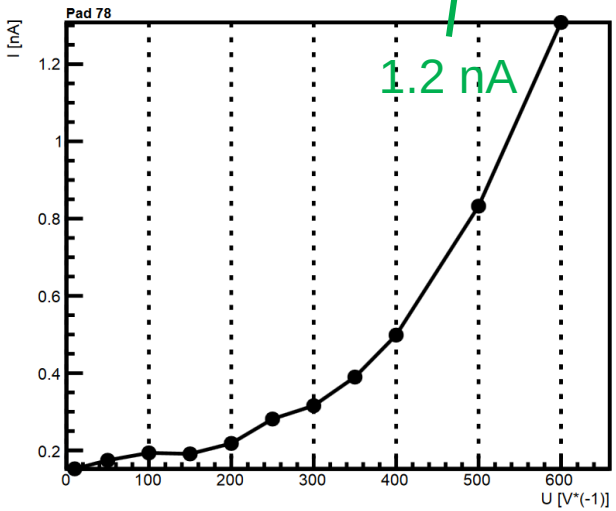
Repeated measurements with handling



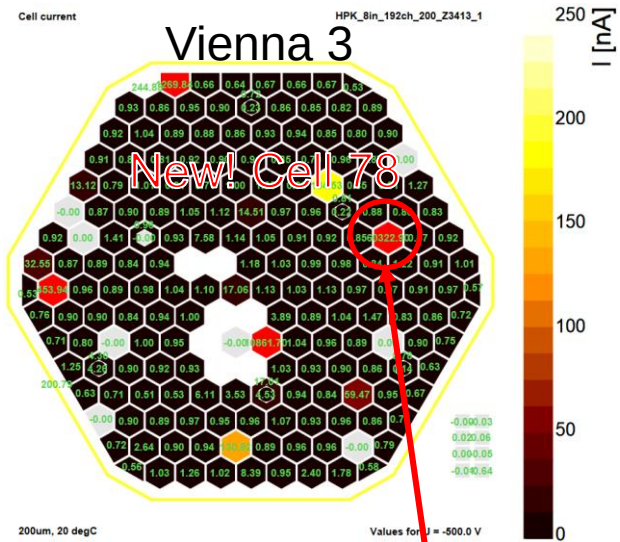
- HPK_8in_192ch_200_Z3413_1
- Measurements 2 and 3: bad contact on breakdown cell, current shows up in neighbors. Those are not additional breakdowns!

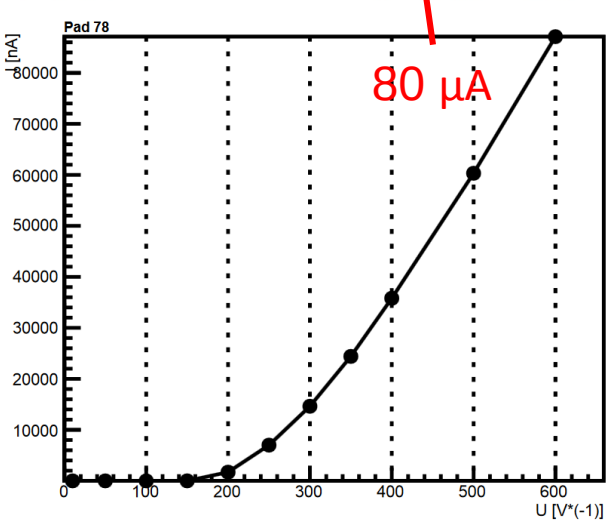
Closer look…





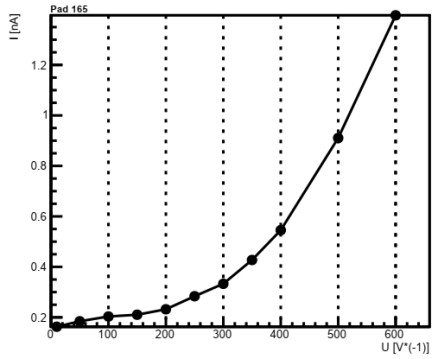
Typical behavior of all cells of this sensor

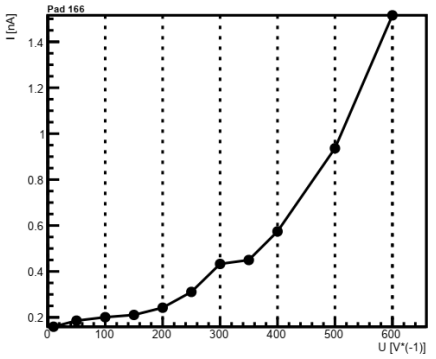


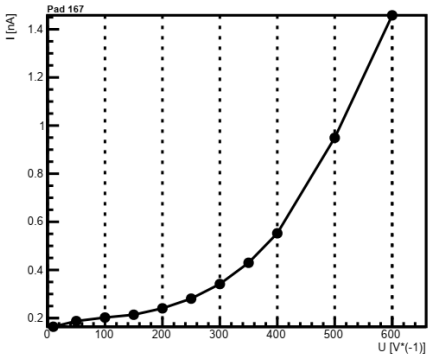


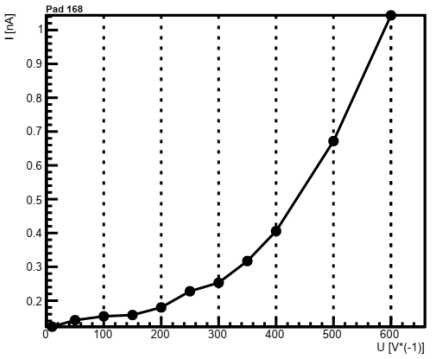
Similar shape but current orders of magnitude higher

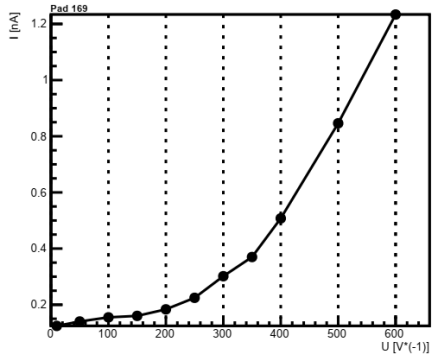
Examples of healthy cells

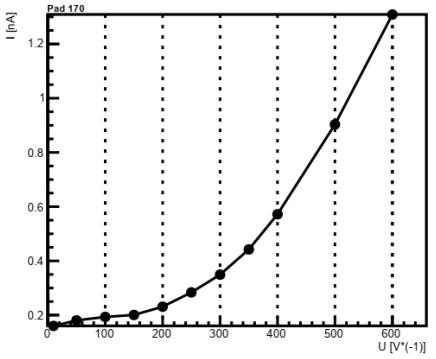


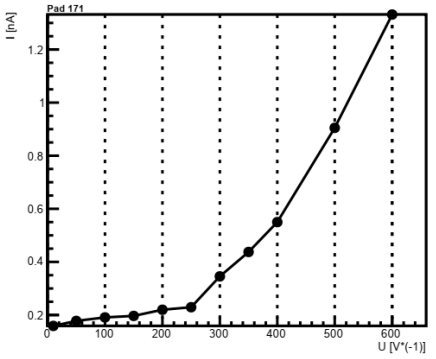


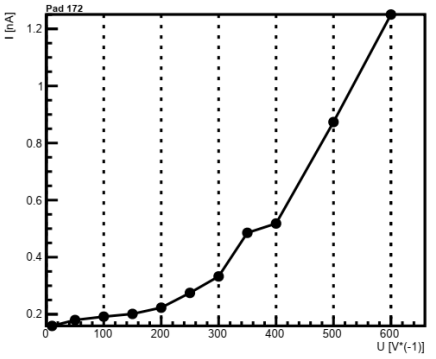


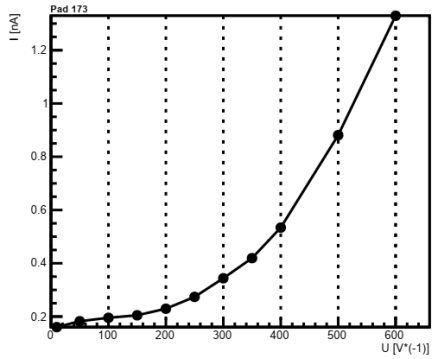


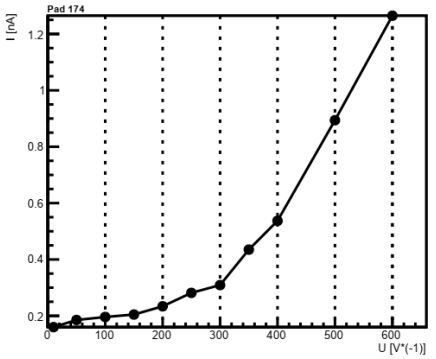


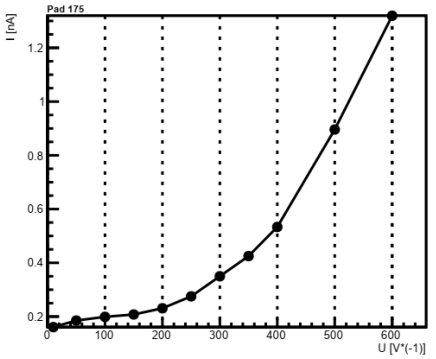


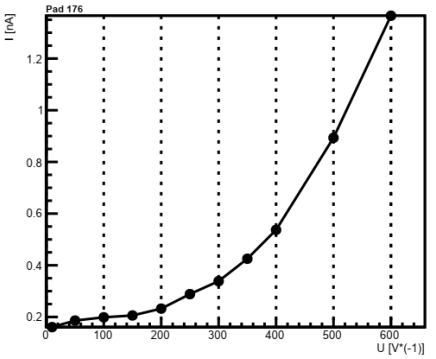




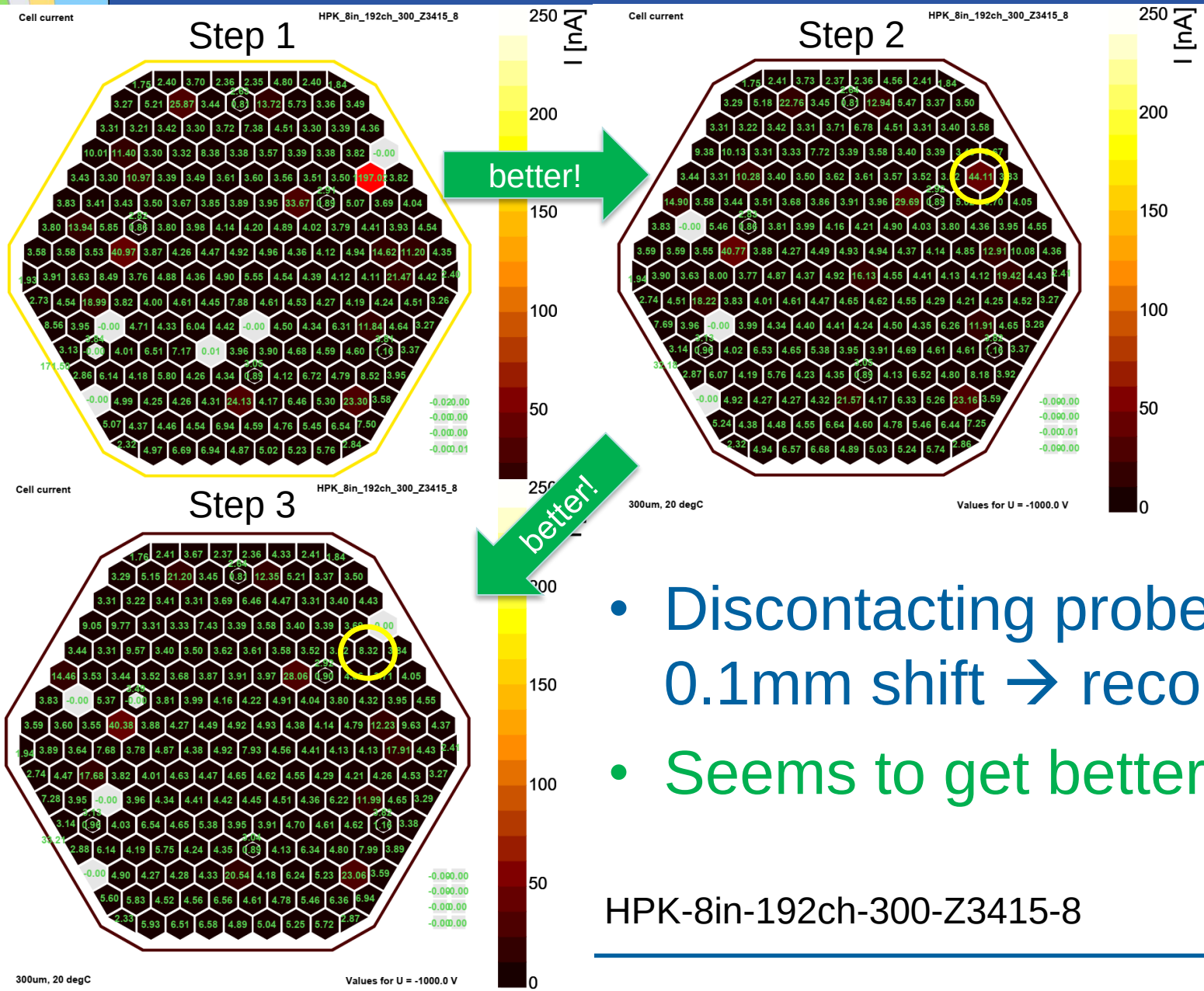








Recontact w/o handling



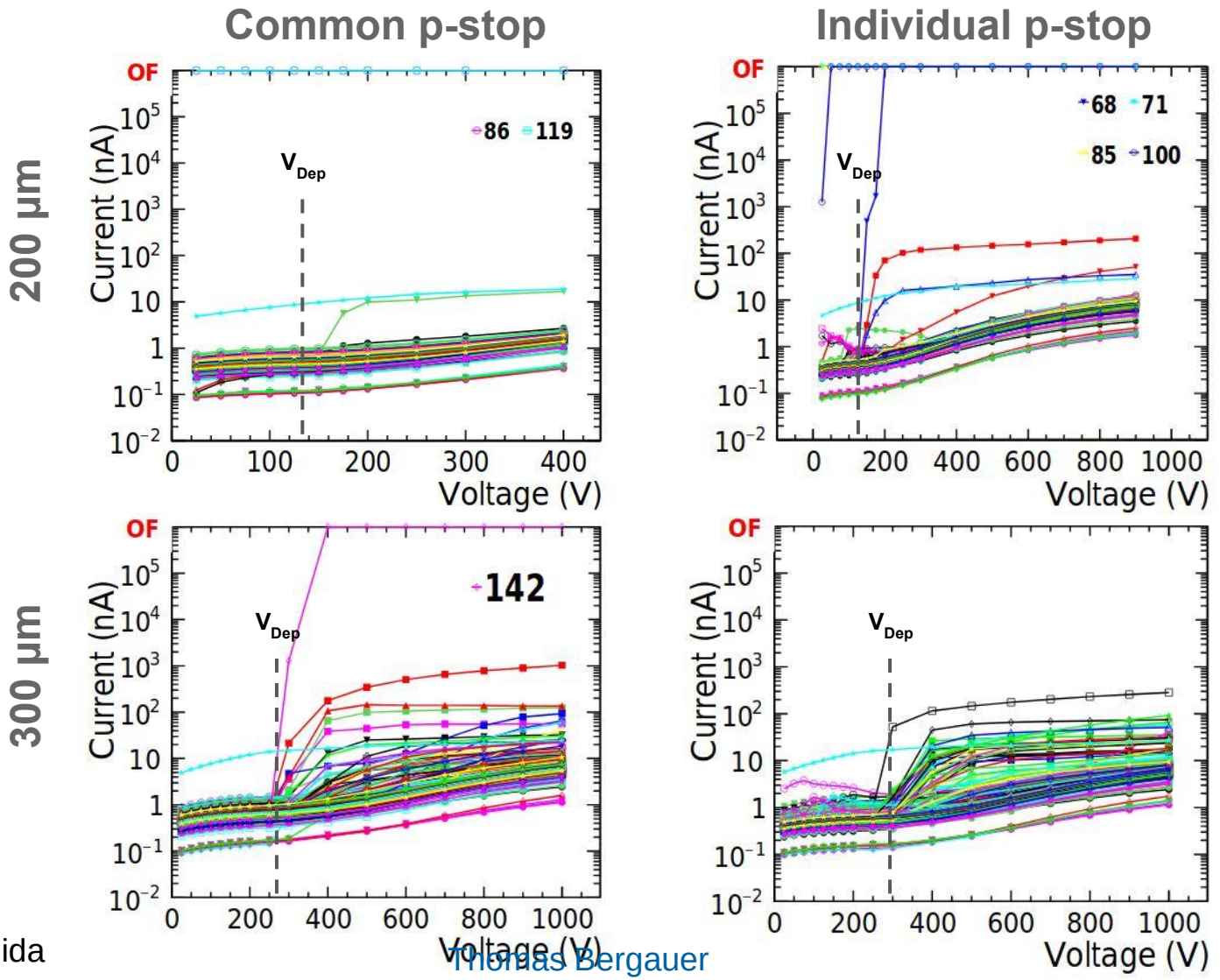
By Thomas Brezovsky

- Discontacting probecard → 0.1mm shift → recontact
- Seems to get better!

HPK-8in-192ch-300-Z3415-8

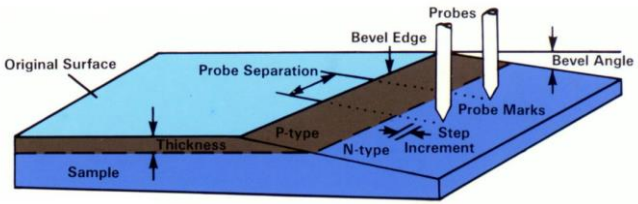
Current Step @ V_{Dep}

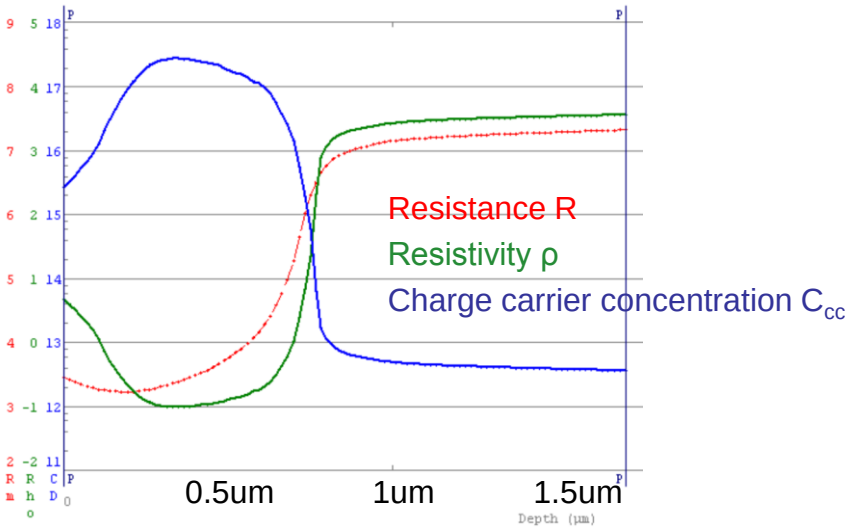
Not only the breakthroughs happen at depletion voltage, but the leakage current also tends to suddenly increase. Backside damage? or p-stop?



Backside doping profile

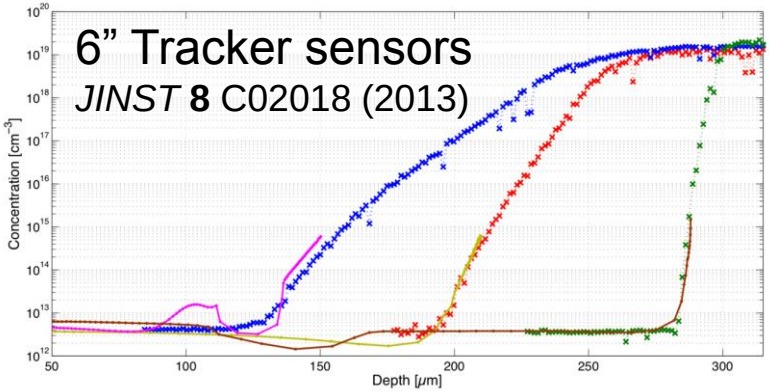
- SRP (spreading resistance profiling) performed to determine backside doping concentration and profile





Results for 8" HGCal sensors:
- Backside doping depth ~ 0.7 µm!
- Low doping concentration ~ $5*10^{17}$ / cm³

For comparision 6" FZ290/200/120 Using deep diffusion:

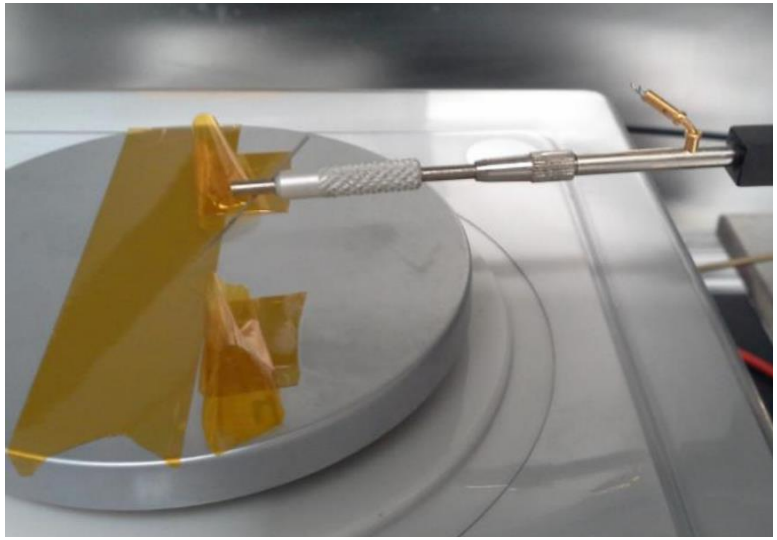


Results for 6" CMS tracker sensors:
- **Deep diffusion process**
- Backside doping depth >20 µm
- High doping concentration ~ 10^{19} / cm³

Scratch tests

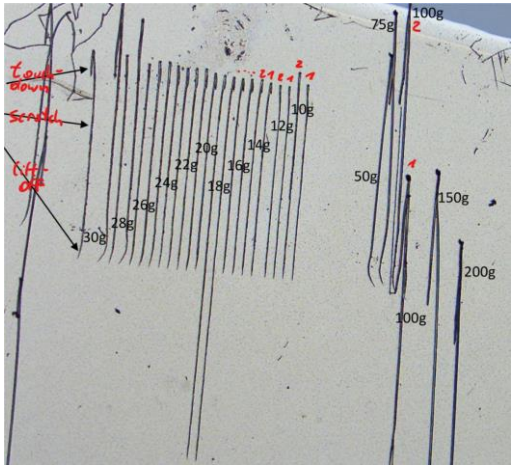
- Introduce scratches on backside using probe tip while sensor/structure rests on an electronic scale to measure the “weight”
  - Performed on full sensors (slide 14) and diodes (slide 15-17)

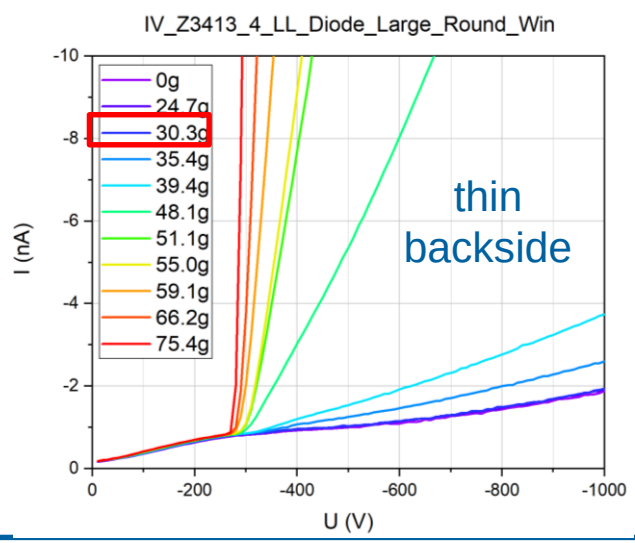
- Setup:
  - Kern precision scale 572-30, reproducibility 0,001 g
  - Cascade positioner with tungsten carbide needle
    - D=0.5 mm, alpha=10°
    - 50 µm tip diameter
    - 60° angle to surface

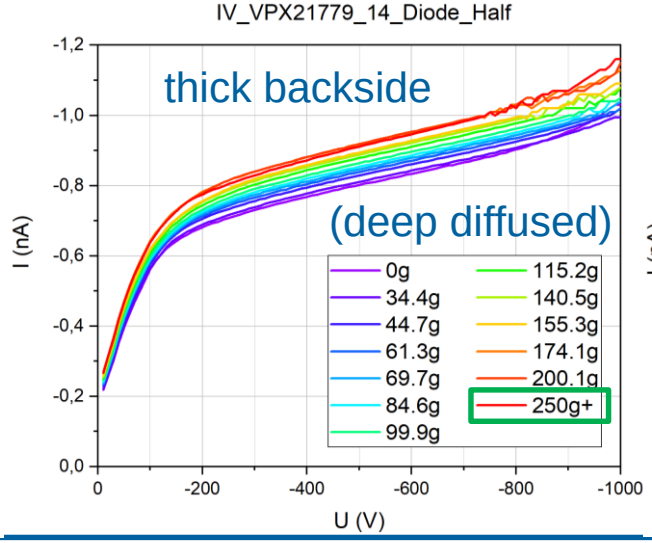


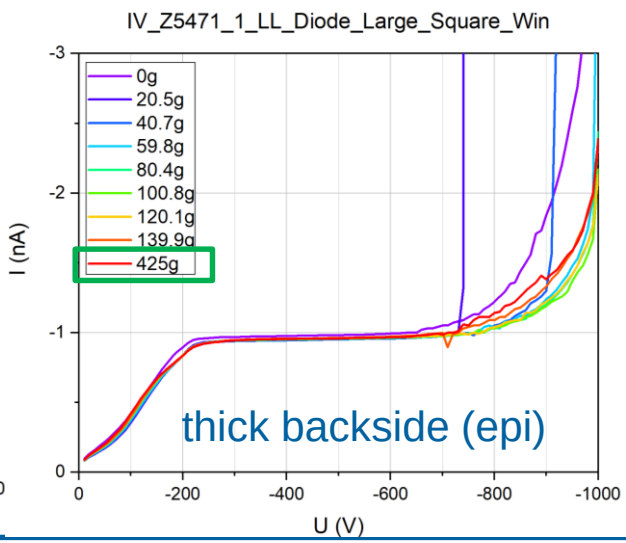
Scratch tests

- Perform scratches with Tungsten carbide pro needle in probe station on scale and measure IV
  - Thin backside: breakdowns start at 30 g needle weight at full depletion voltage
  - Thick (deep diffused) backside: No breakdown up to 250 g
  - Thick (epi) backside: No breakdown









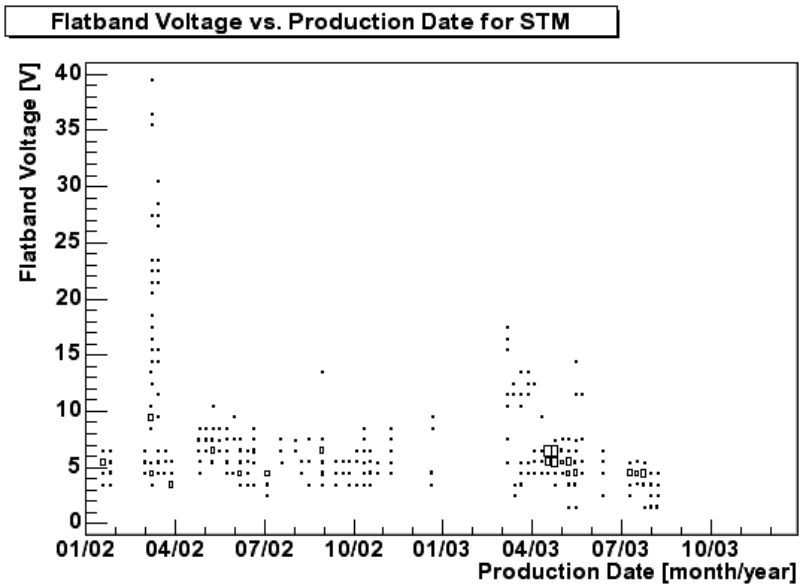
Noise Measurements

- CERN re-started tests with hexaboard+pogo-pin probecard
  - Substantial improvements on noise. Details during the sensors meeting this afternoon
- If measurement results are fully understood CLIC LCD group could visit HEPHY to get the system running and for measuring a first batch of the irradiated sensors

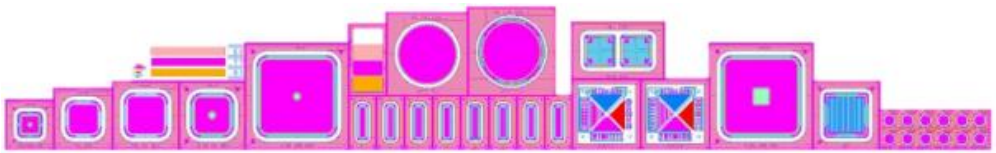
Test Structures

Usefulness of test structures must not be underestimated:

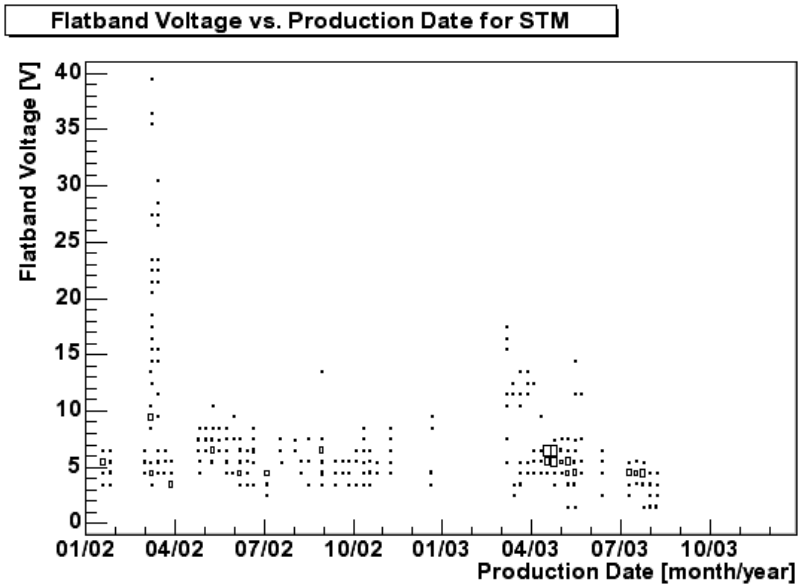
- Quick measurement
- Helped to identify several severe problems during CMS Tracker production
  - E.g. C_{int} scales with increase of fatband voltage of MOS



Current HGCal implementation:

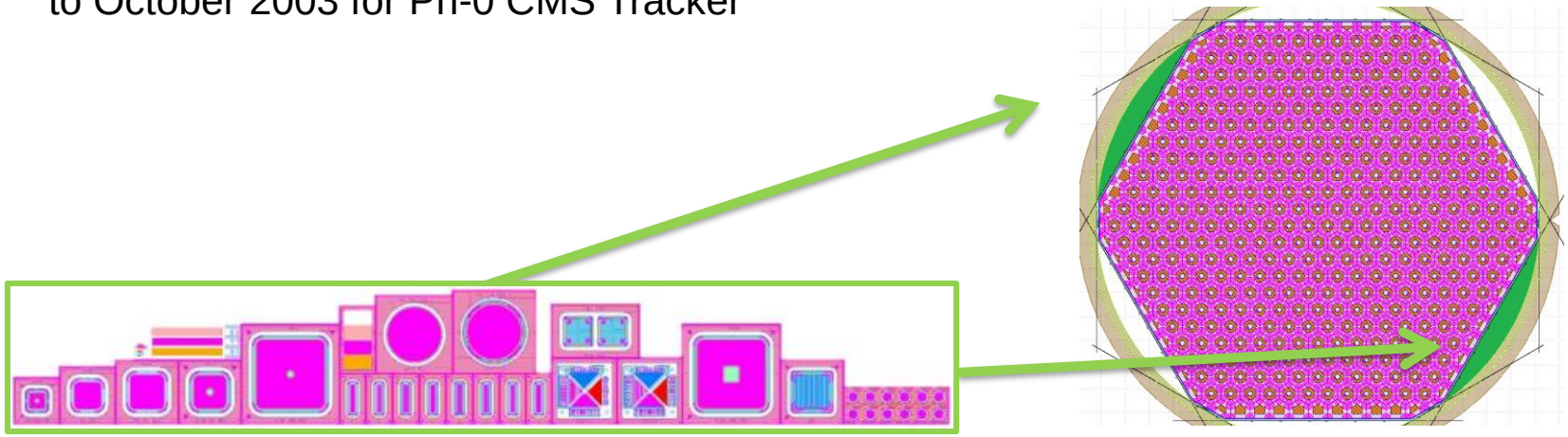


Test Structures



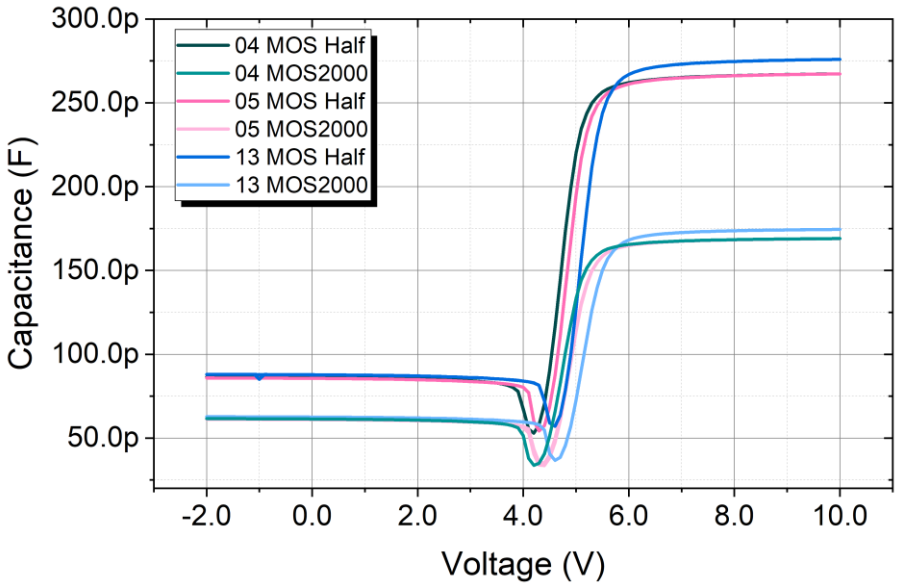
Evolution of flat-band voltage from January 2002 to October 2003 for Ph-0 CMS Tracker

- Usefulness of test structures must not be underestimated
  - Helped to identify several severe problems during CMS Tracker production



Test structure measurements

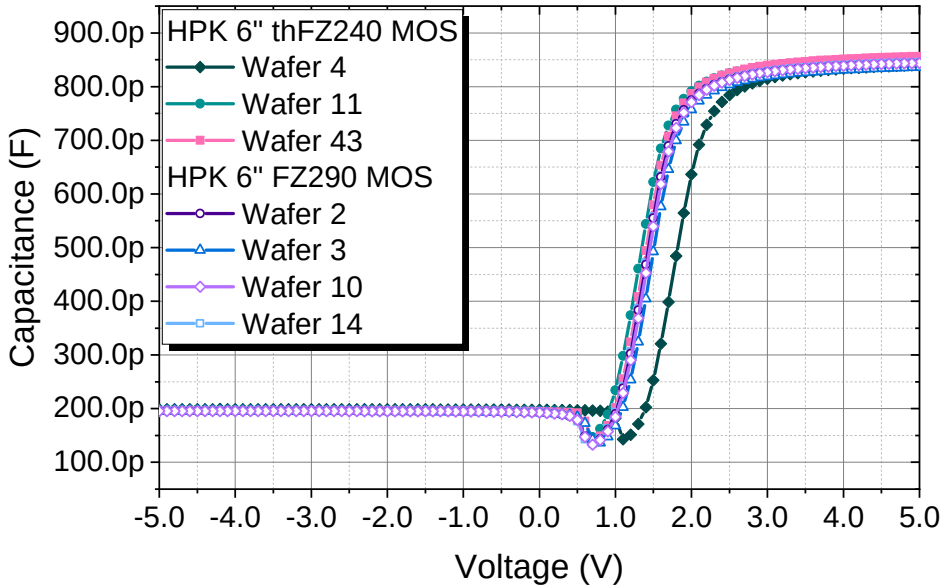
CMS HGCal 8“



→ **V_{fb} ~ 5.2 – 5.6 V**

→ t_{ox} ~ 700 – 750 nm

CMS Tracker 6“



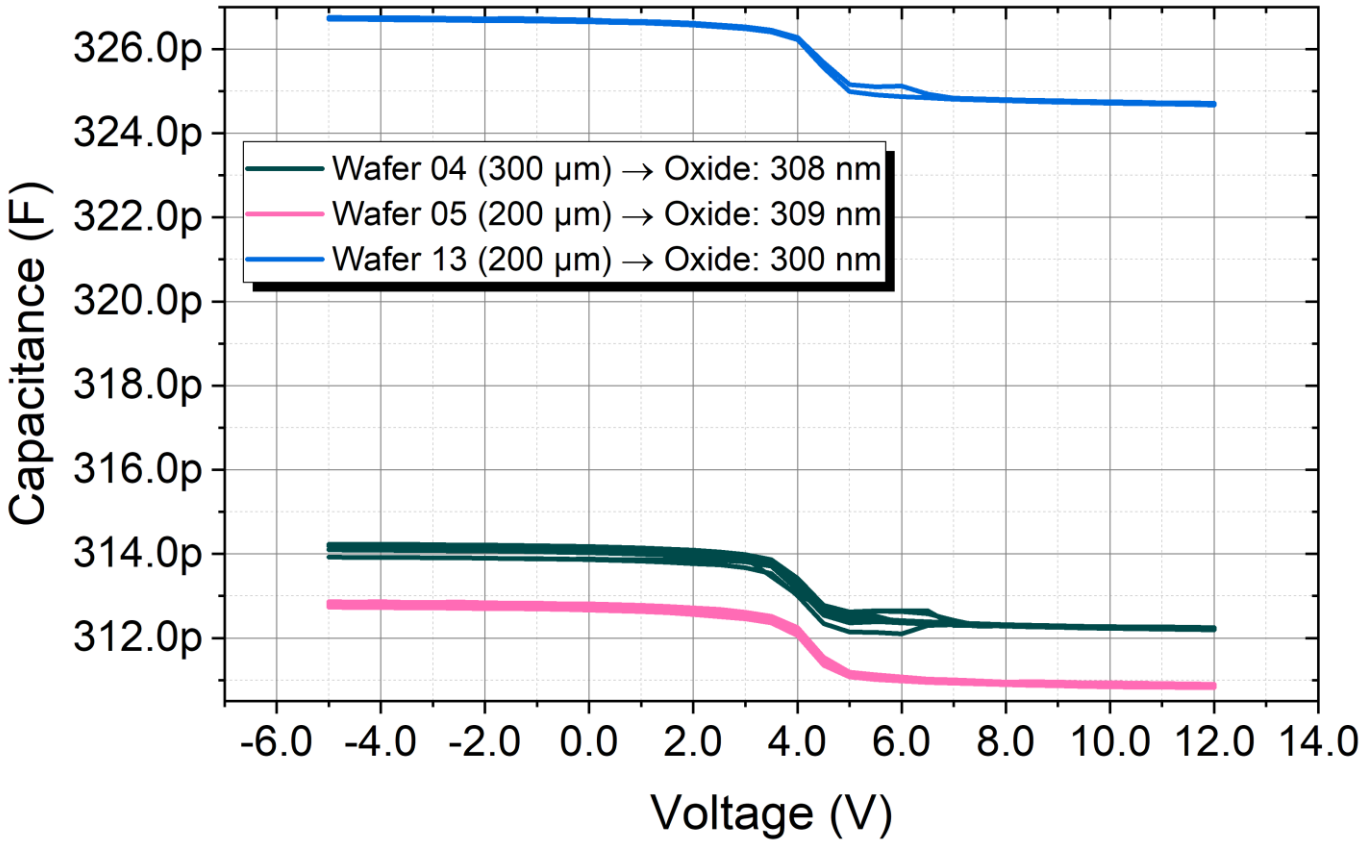
→ V_{fb} ~ 1.5 – 2 V

→ t_{ox} ~ 705 nm

- Flatband voltage is a measure of oxide charges. Much higher for 8” than for 6” → **different behavior after irradiation expected**

Test structure measurements

forward bias → CV → oxide thickness (thin oxide)

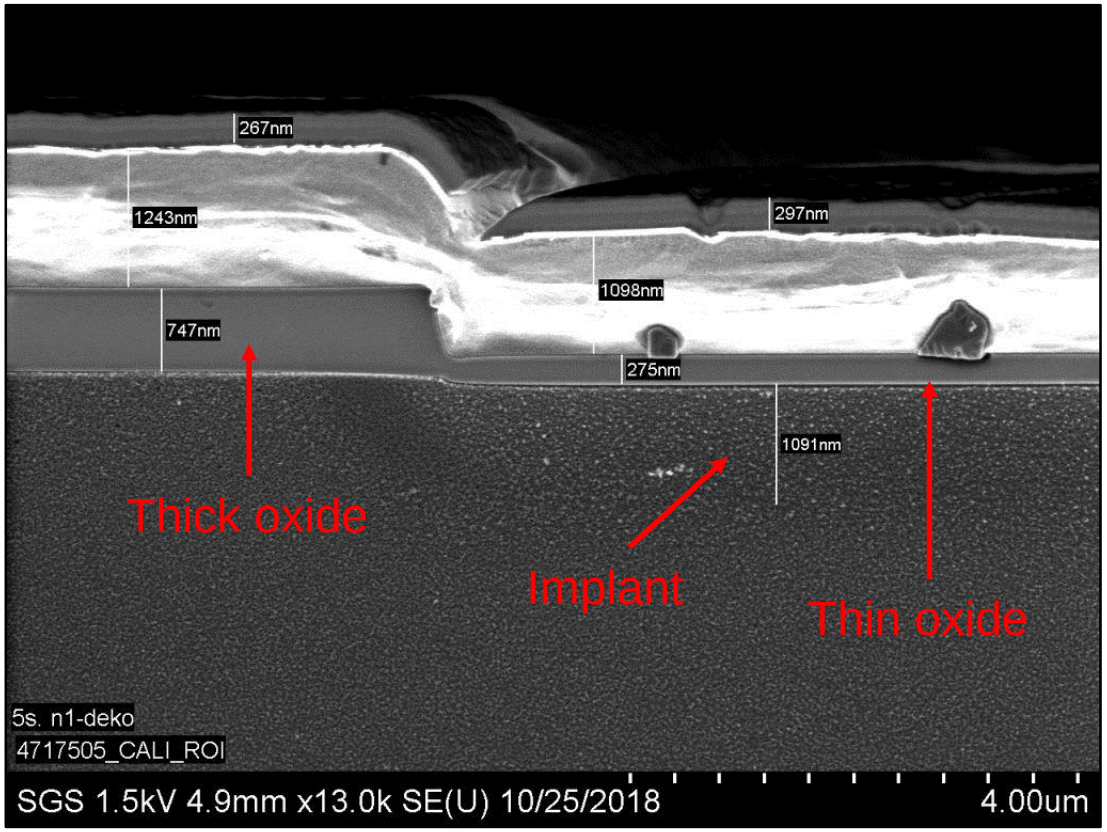


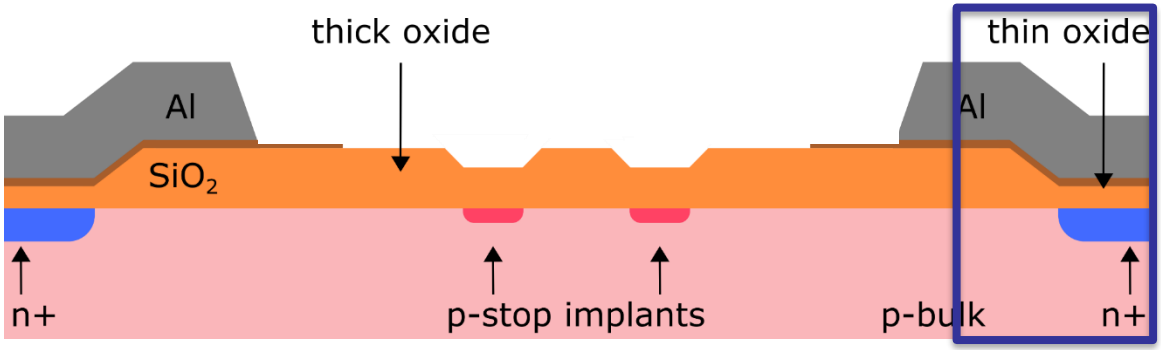
→ V_{fb} ~ 2.9 – 3.7 V

Test structure measurements

Electron Microscopy

- Passivation: 267-297 nm
- Metal: 1098-1243 nm
- **Oxide:**
  - **thin 275 nm**
  - **thick 747 nm**
- Implant: 1091 nm

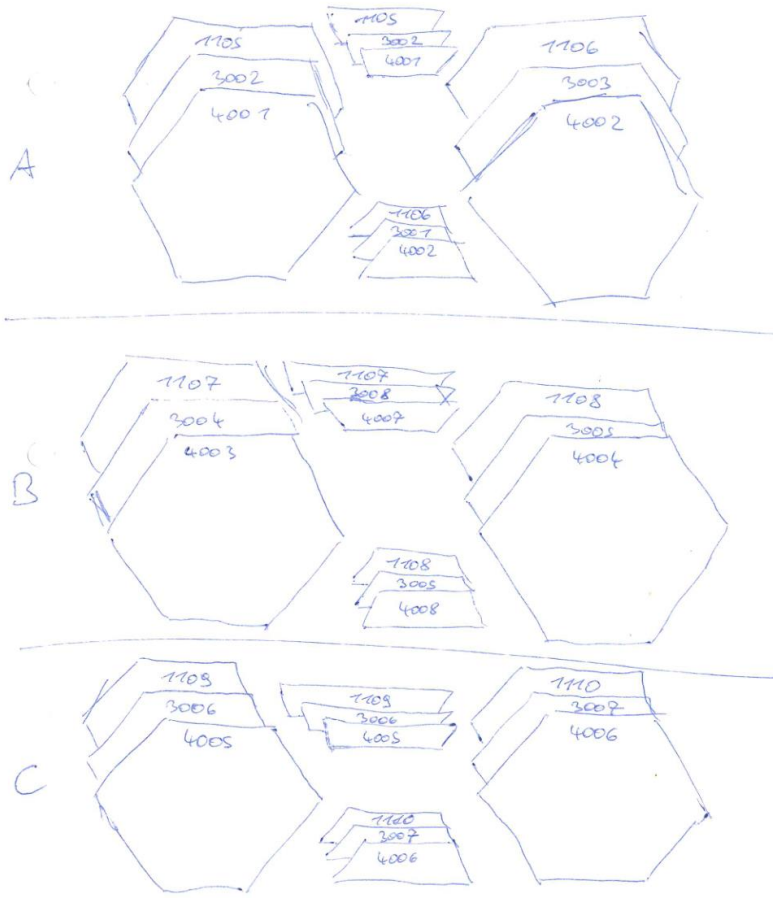




Courtesy of Viktoria Hinger

IRRADIATIONS

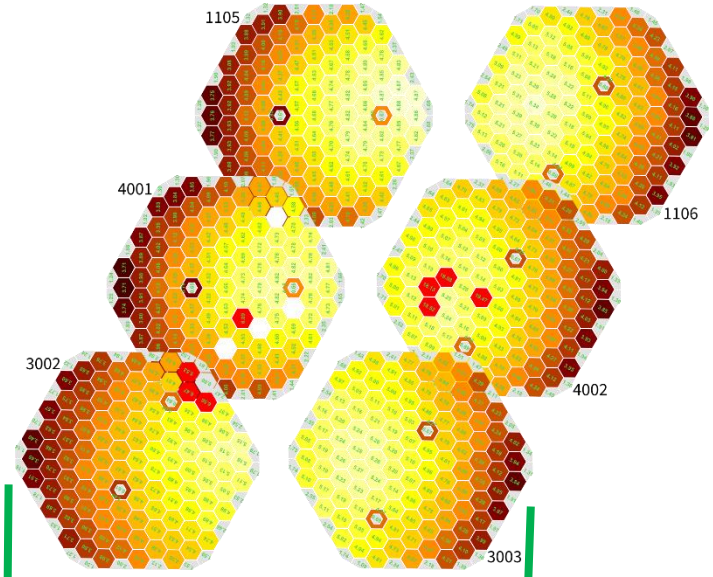
Irradiated 6” sensors

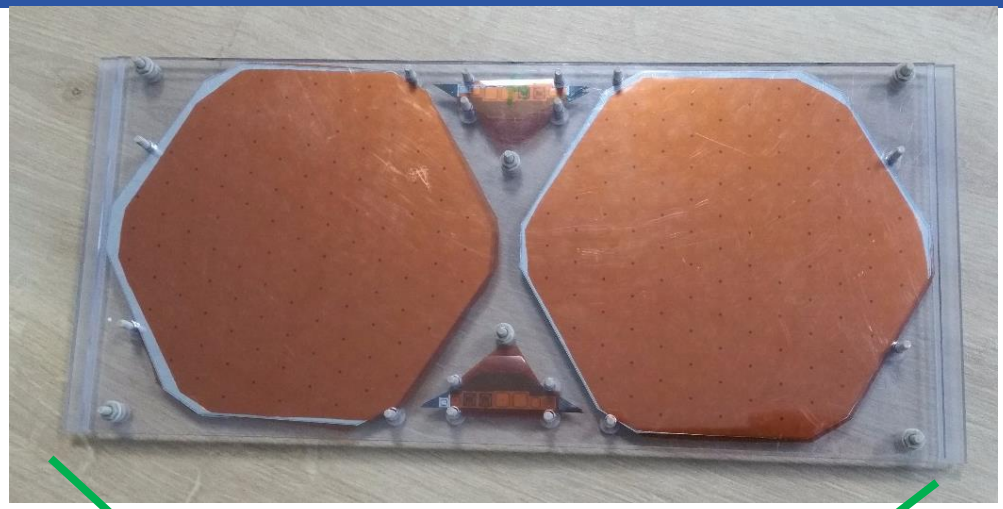


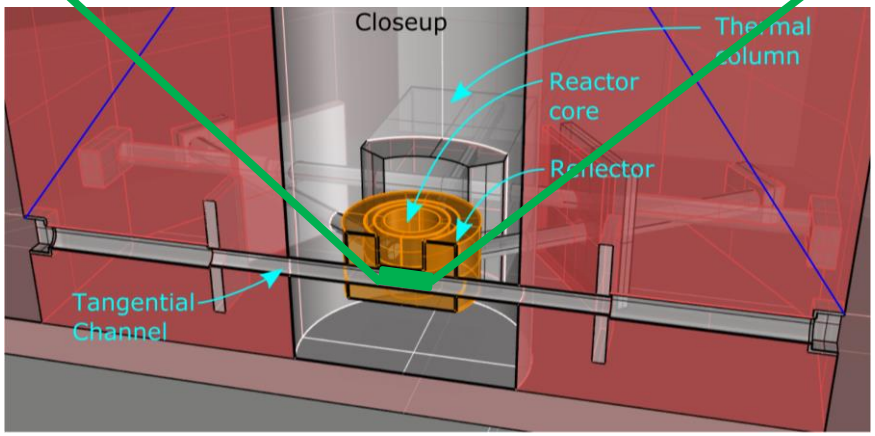
18 sensors irradiated at JSI Ljubljana in 2018

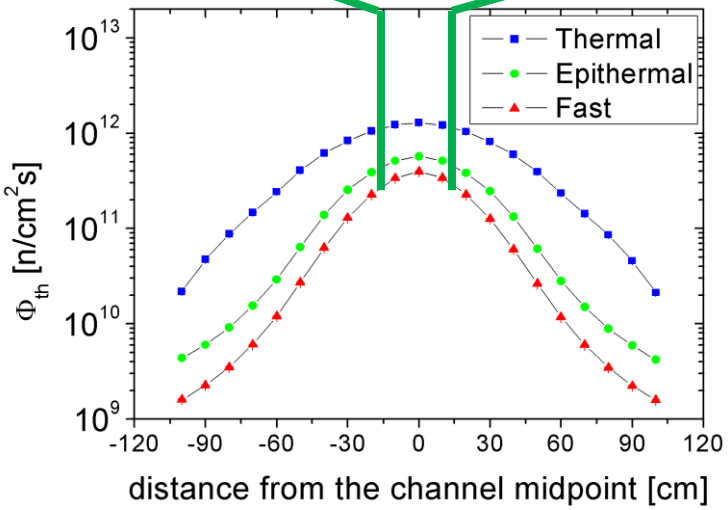
- 3 Fluences:
  - A: 1.5e14 n_{eq}/cm^2
  - B: 5e14 n_{eq}/cm^2
  - C: 7.5e14 n_{eq}/cm^2
- 6 sensors for each fluence (only 300µm thickness):
  - 2 x N-substrate
  - 2 x P-substrate comm. p-stop
  - 2 x P-substrate indiv. p-stop

Inhomogeneous irradiation



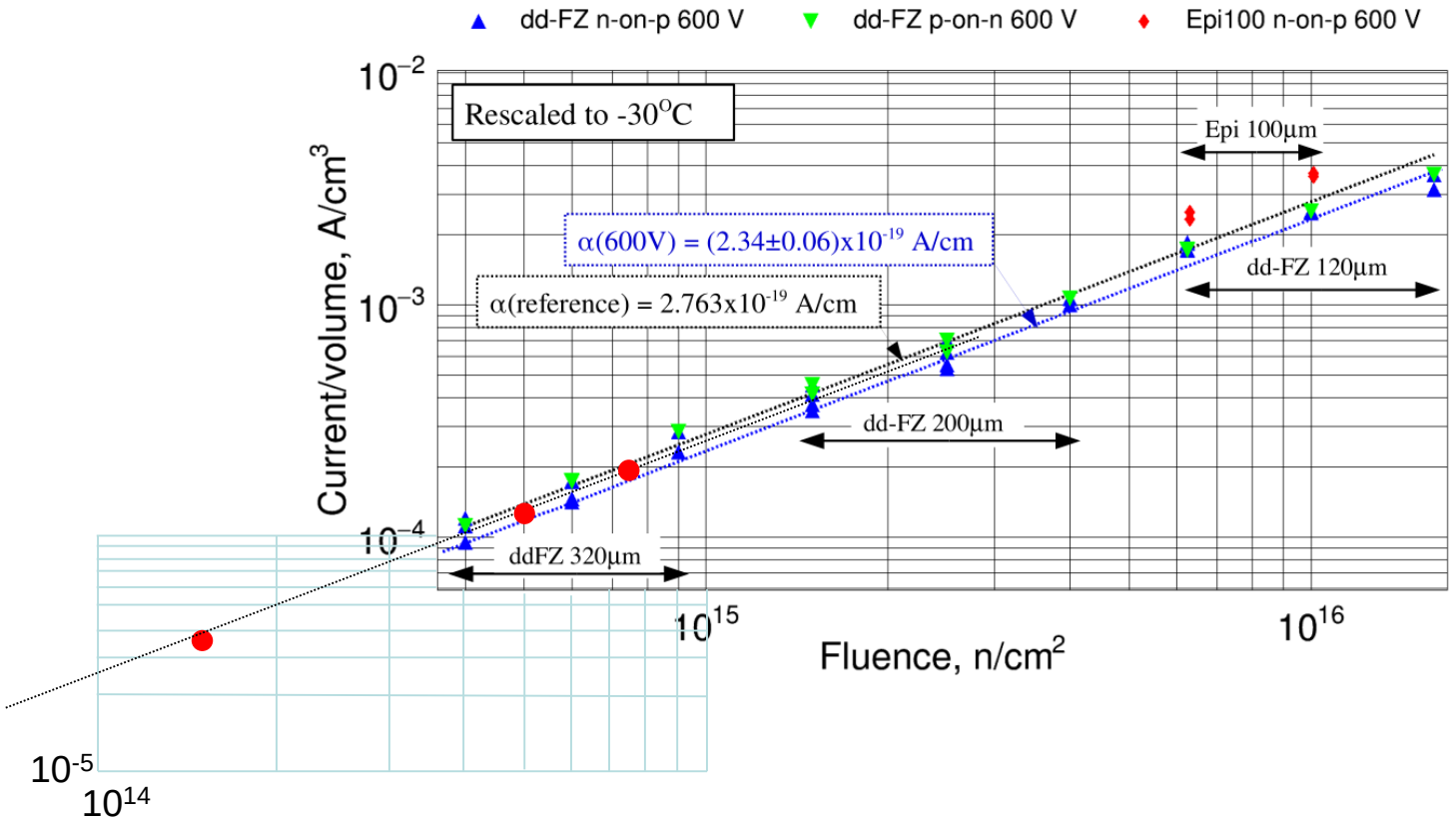






- Current gradient across the sensor
- The sensors are large enough to see the (known) fluence gradient

TDR sensor current



- Measured data is the typical SMU current at -1000 V
- Rescaled to -30 degC, and normalized for volume
- Consistent with TDR values

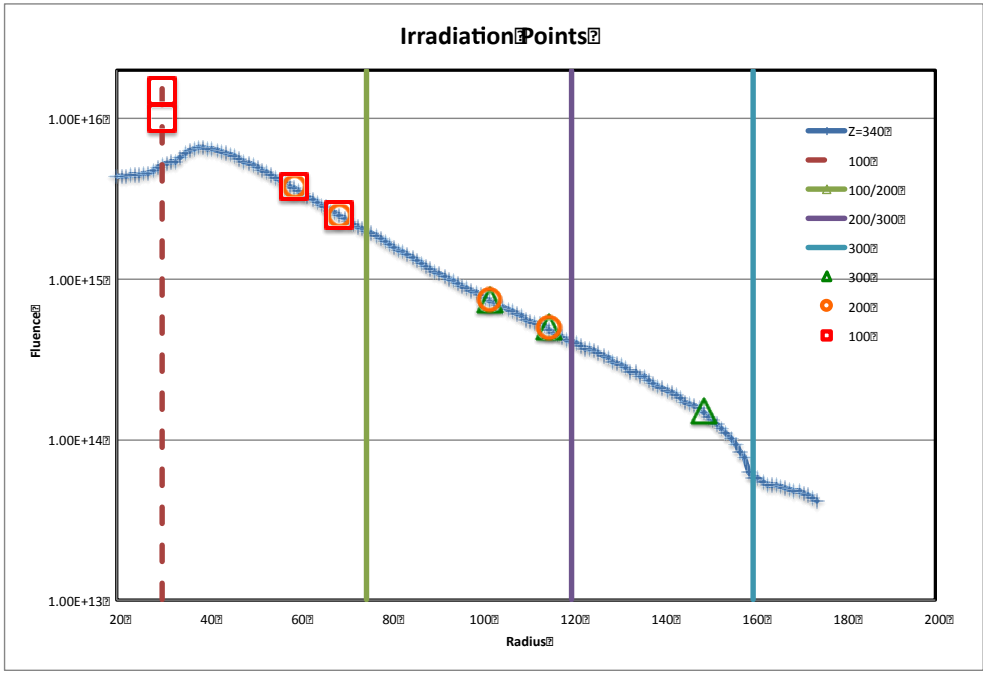
Breakdown, Inter-pad Capacitance not representative for 8”

8“ Irradiation

- Focus on p-substrate
- 300, 200, 120 thickness
  - Possibly 100µm epi if attractive in terms of costs

Thickness		Expected dose range
300	micron	1E14-5E14
200		5E14-2.5E15
120		2.5E15-1E16

- points at the low dosage, 1.5x the low dosage, the high dosage, and 1.5x the high dosage.
- We may migrate some low dose sensors to subsequent higher dose. This complicates logistics a bit



8“ Irradiation

- The RINSC (Rhode Island Nuclear Reactor Center) 8” port has been commissioned and is calibrated to ~15-20% by Brown
- Sensors are encased in wooden holder and placed in an acrylic cylinder
  - Cylinder lifetime and machining is a limiting factor - trying to find 8” peek rod
  - Move machining to FNAL or buy machined parts?
- There was an issue with gold activation in the HPK 6” sensors
- 8” runs will have to be scheduled with the reactor staff
  - 6-6.5 week interval is reasonable. Planned schedule:

Exposure Plan (RINC) & FNAL							
test	Date	Exposure	Location	Thickness	Devices		
Initial 8" tests	6/1/19	1.50E+14	RINC	300	HPK 8" TS	HPK 8" 300 micron	
				200	Infineon prototype	Nhanced SiSi TS	Nhanced SiSi wafer
	7/1/19	1.50E+14	FNAL	300	HPK 8" TS		
				200	HPK 8" TS		
8" 5E14	7/16/19	5.00E+14	RINC	300	HPK 8" TS	HPK 8" sensor	
				200	HPK 8" TS	HPK 8" sensor	Nhanced SiSi
		5.00E+14	FNAL	300	HPK 8" TS	HPK 8" sensor	
8" 7.5E14	8/31/19	7.50E+14	RINC	300	HPK 8" TS	HPK 8" sensor	
				200	HPK 8" TS	HPK 8" sensor	
8" 2.5E15	10/15/19	2.50E+15	RINC	200	HPK 8" TS	HPK 8" sensor	
				120	HPK 8" TS	HPK 8" sensor	
8" 2.5E15		2.50E+15	FNAL	200	HPK 8" TS	HPK 8" sensor	
				120	HPK 8" TS	HPK 8" sensor	
8" 3.75E15	11/30/19	3.75E+15	RINC	200	HPK 8" TS	HPK 8" sensor	
				120	HPK 8" TS	HPK 8" sensor	
8"1e16	1/14/20	1.00E+16	RINC	120	HPK 8" TS	HPK 8" sensor	

Summary

- Invitation to Tender documents sent to HPK
  - HPK time to 28 April to respond with costs
- 2019 sensor order (almost) placed for 28+28+22 sensors (300/200/120)
  - For sensor irradiation campaign, MAC prototyping and cassette test & evaluation
  - 432 cell design due
- Sensor testing
  - Unknown reason of failing cells on repeated tests
  - Logistics for series production to be worked out
  - Test structure layout/ideas to be worked out in synergy with CMS Tracker
- 8“ Irradiation scheduled for 2 half of 2019
  - Irradiation on 6“ not representative because of higher oxide charges
  - We need to assign responsibilities on tasks (noise tests, pre/post tests of 8” irrads,…)