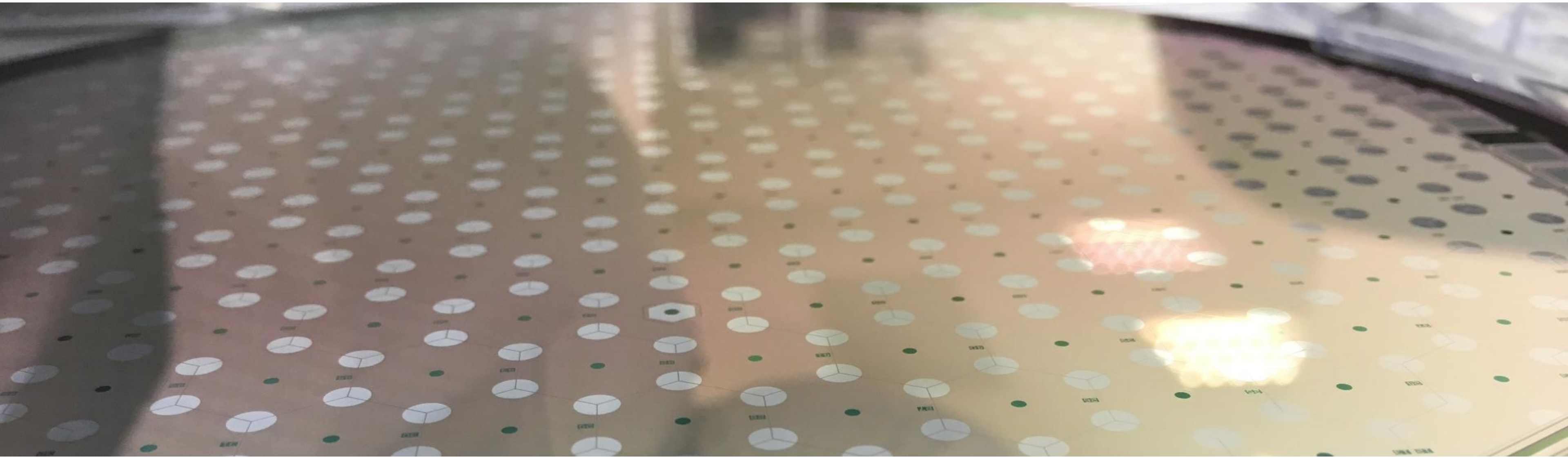


Trento Meeting 2018 Munich

Silicon Sensors of the CMS High Granularity Calorimeter

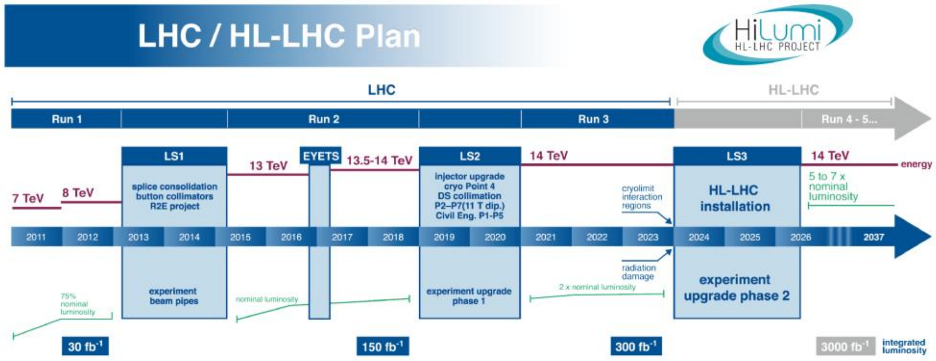
Thomas Bergauer
On behalf the CMS collaboration

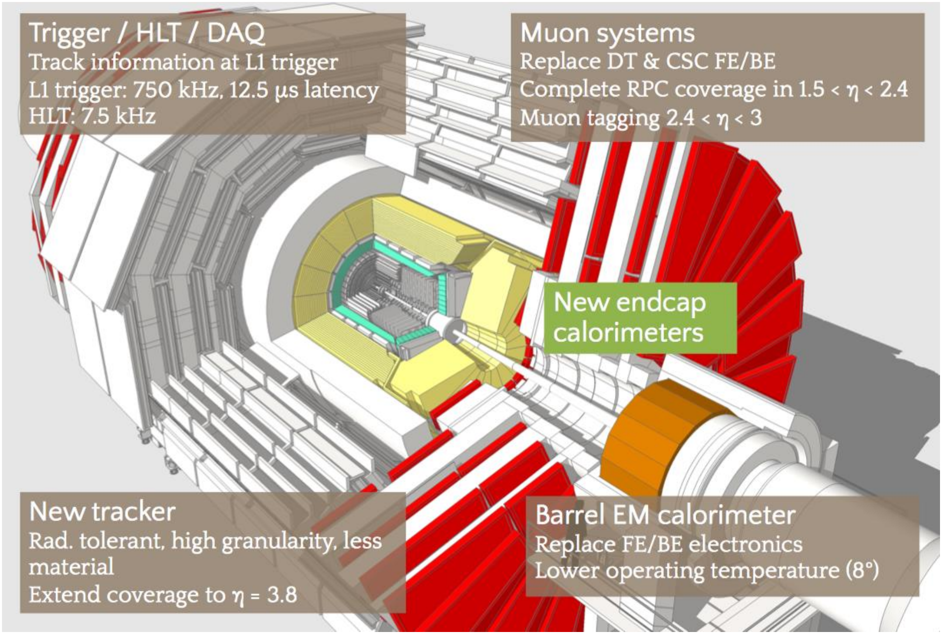
20 Feb 2018

CMS Phase-II Upgrade

- CMS Phase 2 upgrade during LS-3 (around 2024-2026) for HL-LHC Phase
  - 5-7 times higher instantaneous luminosity
  - 10x integrated luminosity (3000 fb^{-1})

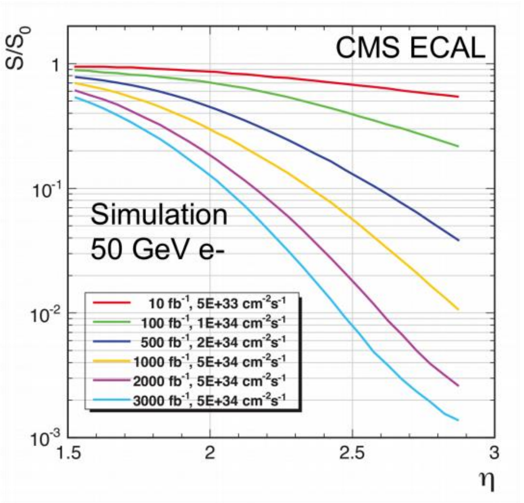
- A major challenge for detector design
  - New tracker, trigger, muon and calorimeters





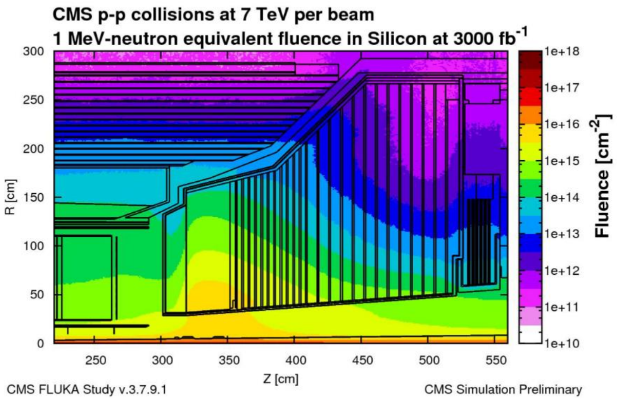
Current CMS Calorimeters:

- Designed for integrated luminosity of maximal 500 fb^{-1}
- Electromagnetic: $PbWO_4$ crystals
- Hadronic: plastic scintillators



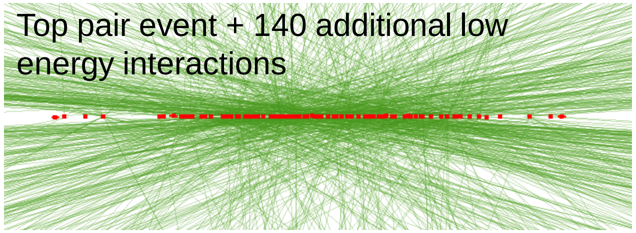
Environment of CMS Endcap at HL-LHC:

- Fluences of up to 10^{16} n_{eq}/cm^2
- doses of up to 1.5 MGy
- Pile-up of up to 200 collisions/crossing



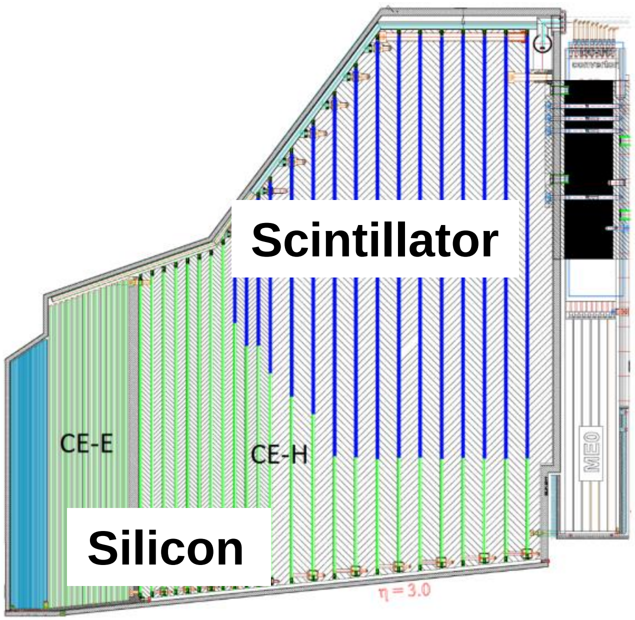
→ Only silicon detectors are

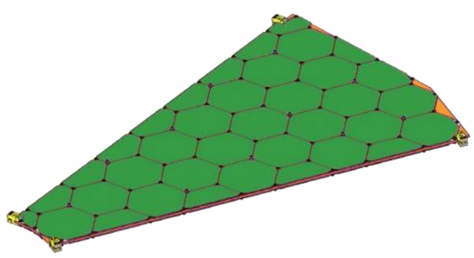
- radiation tolerant enough
- Fast enough to mitigate pile-ups
- Fine segmented to allow high granularity
- affordable

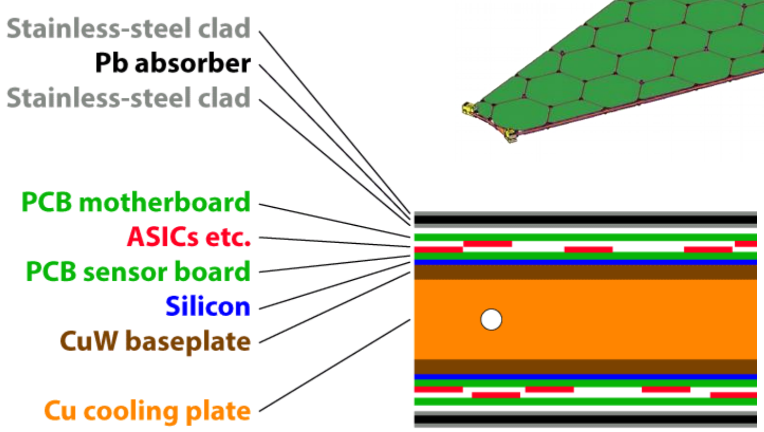


CMS is planning to build a High Granularity Calorimeter for Phase-II at HL-LHC

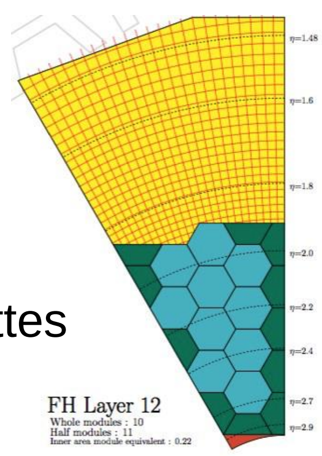
- Covering 1.5 < η < 3.0
- Features unprecedented transverse and longitudinal segmentation
  - Silicon in high radiation areas
  - Scintillating tiles in the low-radiation region of CE-H (Mixed Silicon-Scintillator cassettes)

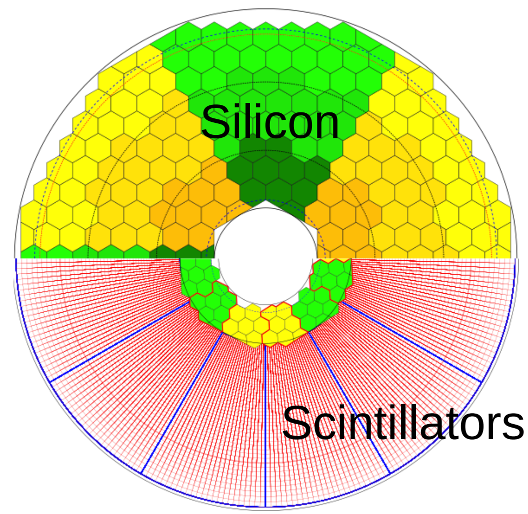






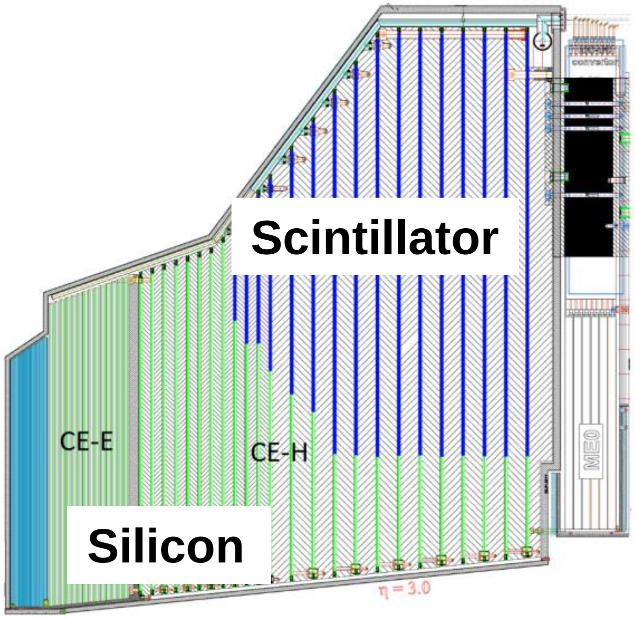
Cassettes



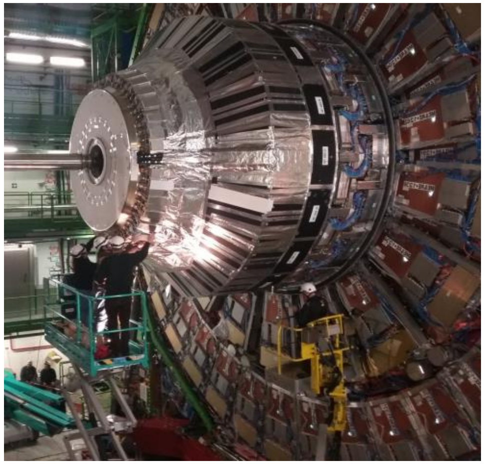


CMS High Granularity Calorimeter

	CE-E	CE-H (Si)	CE-H (Si + Scint)
Active	Silicon sensors		Scintillators
Absorber	Lead	Stainless steel	
Depth	$26X_0$ / 1.7λ	9λ	
Layers	28	8	16
Weight	23t	205t	



	Silicon sensors	Scintillators
Area	**600 m²**	500 m²
# Modules	25,000	2500
Channels Size	0.5-1 cm²	4-30 cm²
# Channels	6 Mio	400k
Op. temperature	-30° C	-30° C

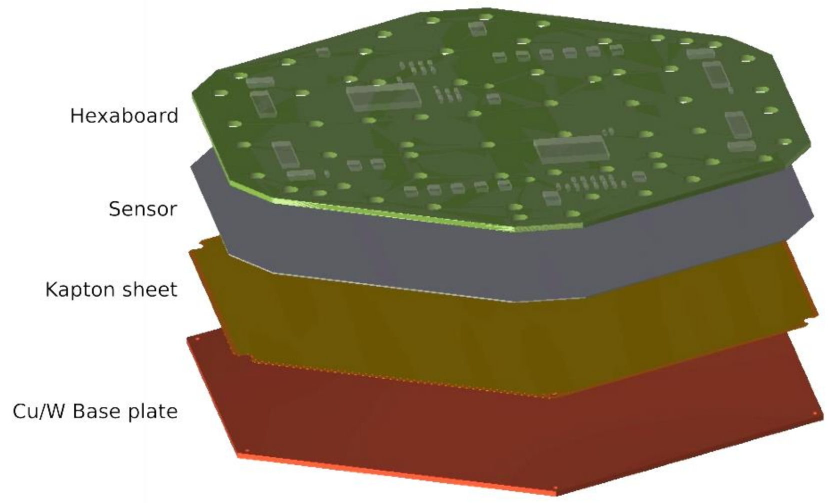


Si Detector Modules

Silicon detector module is of hexagonal shape and is a stack of:

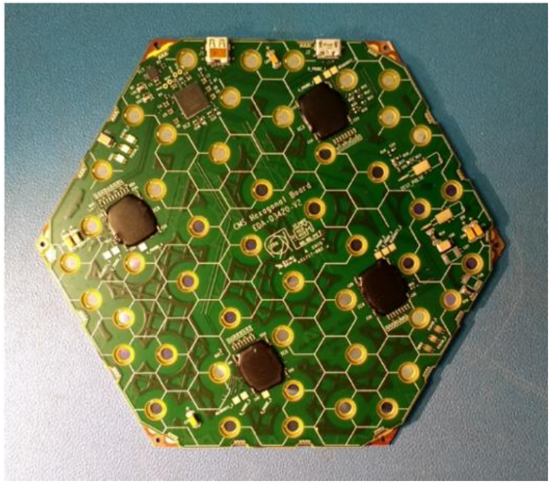
- PCB: "hexaboard": contains FE ASICs and connects to Si sensor via wire-bonds through holes
- Hexagonal Si-Sensor
- Kapton sheet for HV isolation
- Copper/Tungsten Base plate

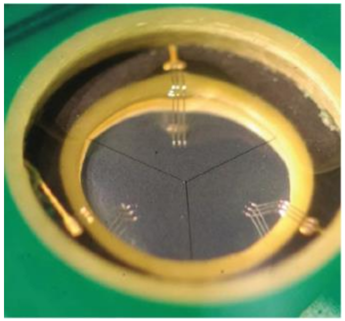
The whole module sits on a copper cooling plate with CO_2 cooling channels



Additional components:

- 2nd PCB (not shown): Motherboard for powering, data concentration, trigger generation and bi-directional communication
- Trigger/data transfer: low-power GBT links (lpGBT)





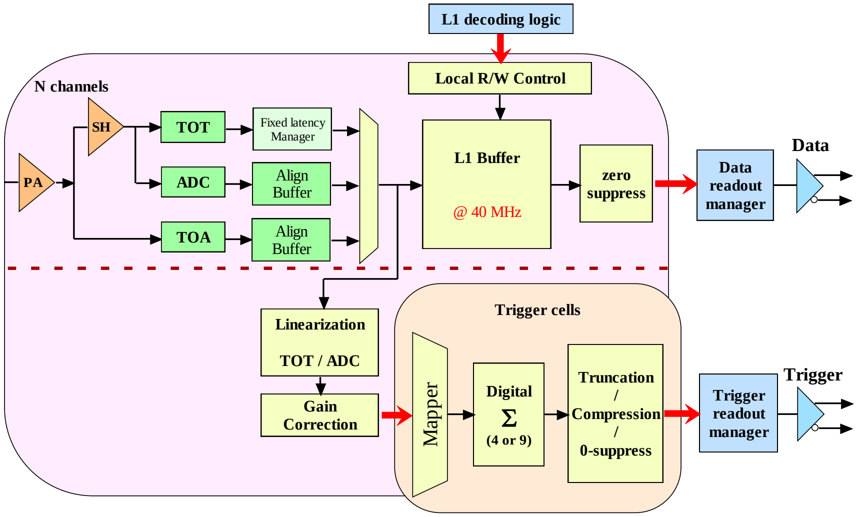
Front-End ASIC

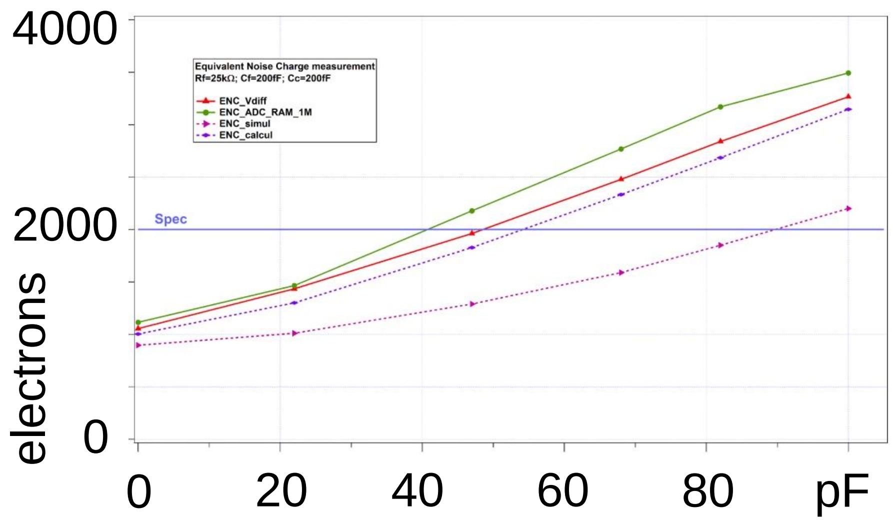
Current FE chip prototype is called HGROCv1, *submitted in July 2017, recently received*

- Based on SKIROC of CALICE
- 32 channels (final version -> 72+2+4)
- Dual polarity (p-type and n-type sensors)
- Low noise: 2000 e$^-$ @ 50pF
- Dark current compensation
  - DAC is sinking up 20 µA (channel wise)
  - Input protection diodes limiting input voltage to <1V: sinking mA

“Three chips in one”:

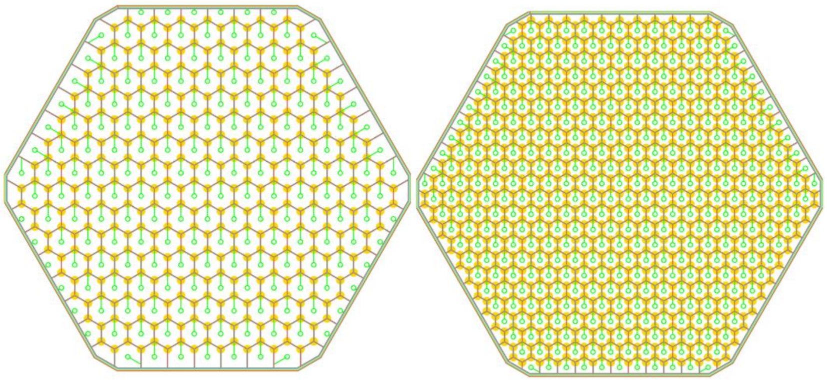
- ADC: Charge 0–100 fC [11 bits]
- Time over Threshold: 0.1–10 pC [12 bits]
- Time of Arrival with 25 ps resolution > 50 fC [12 bits]





Hexagonal Silicon Sensors

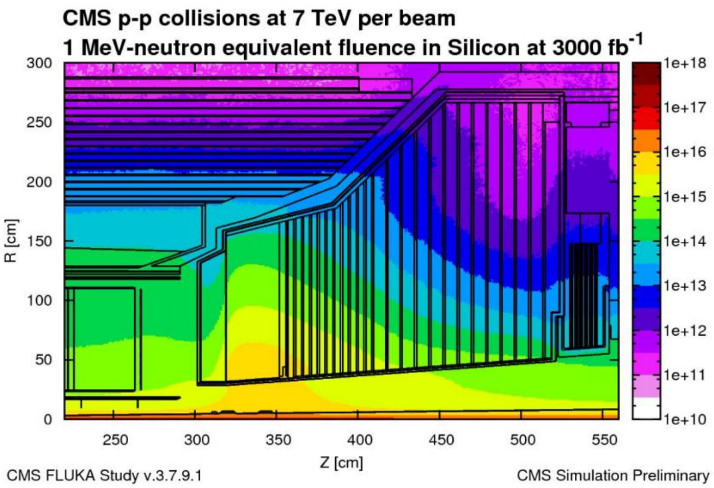
- Hexagonal sensor geometry as largest tile-able polygon
  - maximize use of circular wafer
  - Minimize ratio of periphery to surface area
  - Truncated tips ("mouse-bites") used for module mounting → Further increase use of wafer surface
- Each sensor consists of individual pads (cells)
- Three thicknesses based on radiation and occupancy considerations

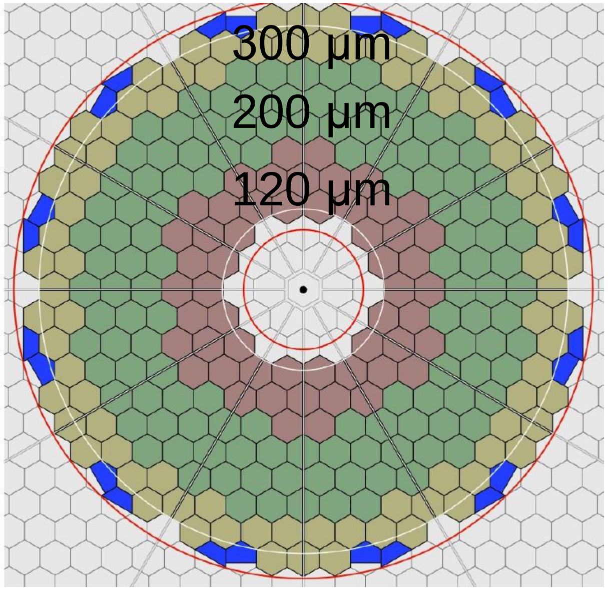


Thickness [μm]	# cells	Cell size [cm²]	Cell C [pF]	Bulk polarity	Expected Fluence [E15 n cm^{-2}]	# wafers (8 inch)	# partial 8 inch wafers
300	192	1.18	45	p (n)	0.1-0.5	13164	1284
200	192	1.18	65	p	0.5-2.5	8712	144
120	432	0.52	50	p	2-7	3000	324
					Total:	**24876**	**1752**

Radiation Hardness

- Fluence is n-dominated w.r.t. charged hadrons (90%/10%)
- Deployment of thinner sensors in the higher fluence regions of the calorimeter
  - improved charge collection
  - reduced leakage current
- Typical signals in calorimeter much higher than MIPs
  - MIP sensitivity needed for energy calibration (e.g. isolated muons)



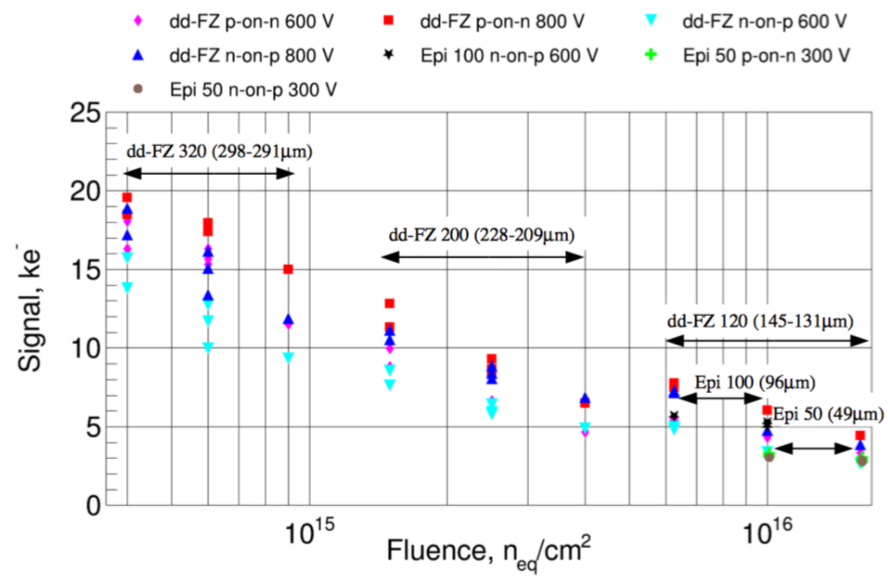


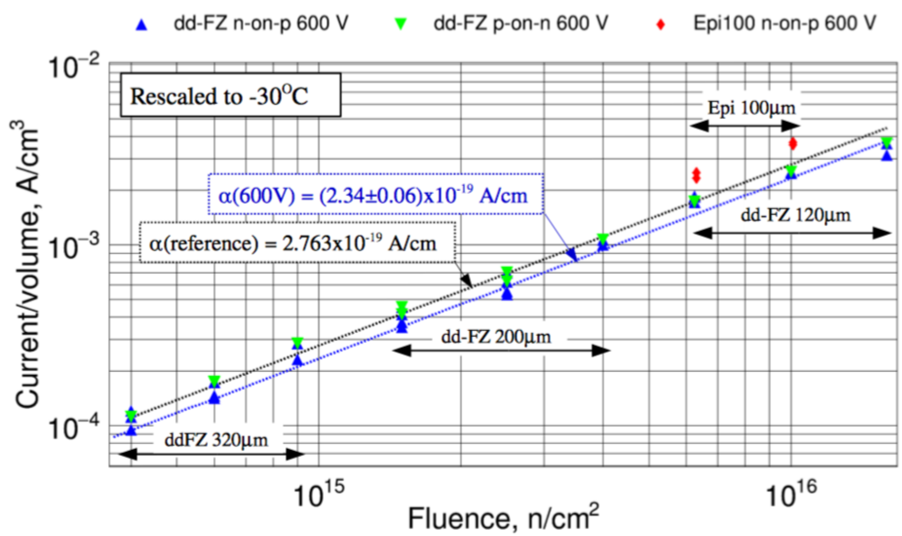
Radiation Hardness

Radiation hardness study performed on different materials

- Deep-diffused FZ and Epitaxial of different thicknesses
- Need to operate at -30° C to keep dark current below limit given by power supplies (10mA)
- N-type sensors would give 20% more signal, but….

P-type@600V Thickness [µm]	Signal for MIP before Irrad. [ke^-]	Signal for MIP after irrad [ke^-]
300 dd-FZ	22	10
200 dd-FZ	15	6
120 epi	9	5



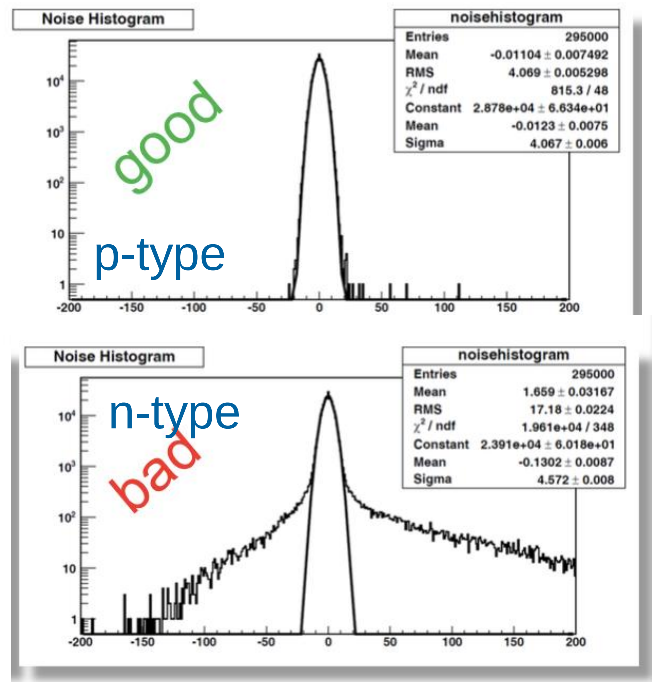


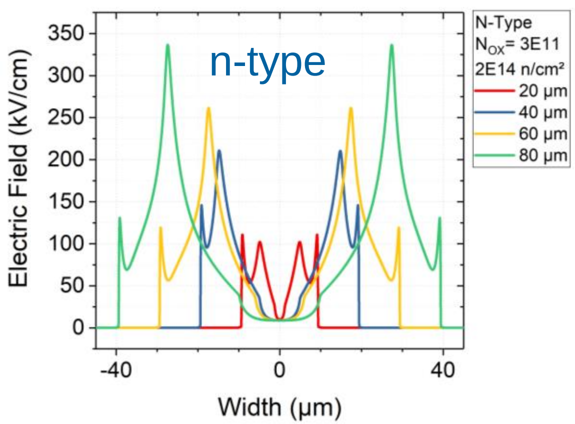
Feasibility of n-type FZ material

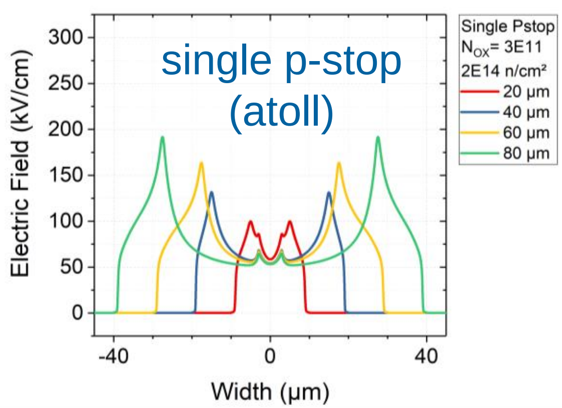
- Studies of CMS Tracker revealed non-Gaussian noise caused by micro-discharges due to high electric field
  - CCE after irradiation similar to p-type
- TCAD Study performed to study electric field of n-type vs. p-type sensors (for two different p-stop designs)
  - ➢ Electric fields in **N-type** is **higher** than the corresponding **P-type** ones
  - ➢ **Higher** Pad distance leads to **higher** electric field peaks (for all types)

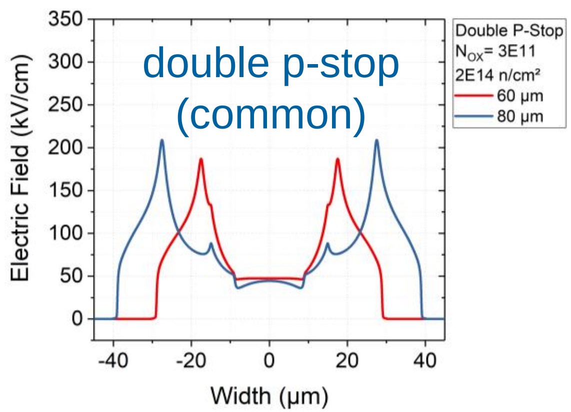
➢ **Biggest advantage of n-type: 20-30% cost saving**

M. Printz (KIT) for CMS Tracker





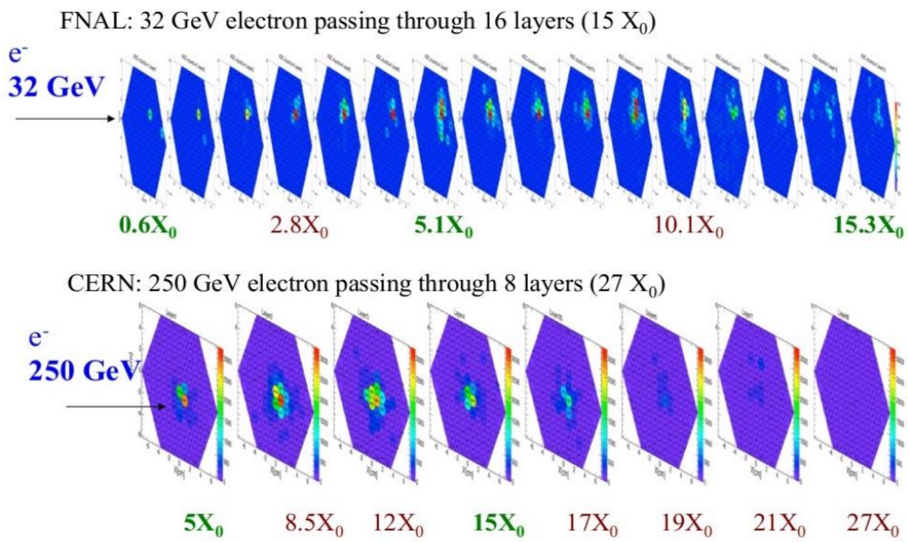




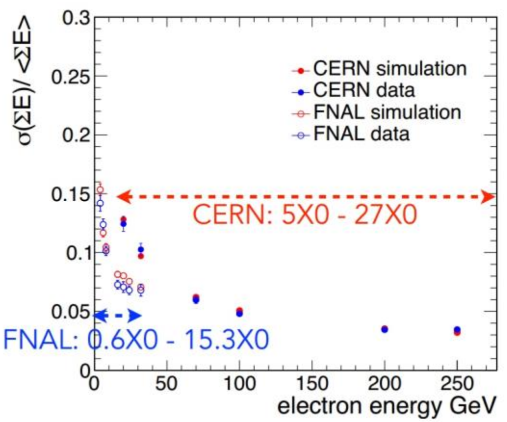
Testbeams with 6” sensors

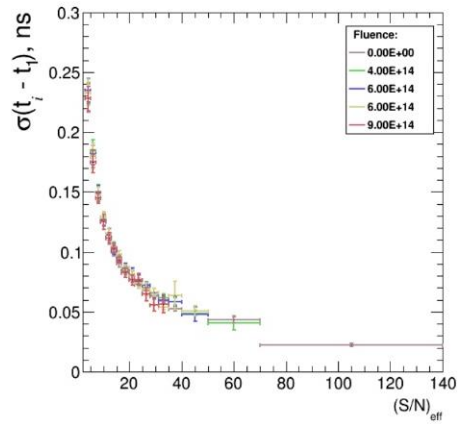
Beam tests at FNAL and CERN performed with modules built on TP geometry (6” sensors) to study

- Longitudinal and transverse shower shapes
- Energy, position, time resolution



- Achieved resolution for:
  - Energy: below ~7%, for e energy > 50 GeV
  - Position: below ~ 2mm, for e energy > 50 GeV
  - Time: ~ 20 ps





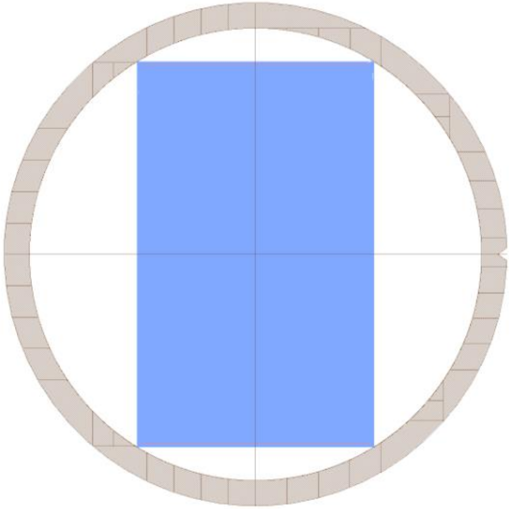
6” vs. 8” sensors

- HGCal Technical Proposal (TP) was based on 6 inch sensors (2015)
- Recent advancements allowed us to define 8-inch sensors as baseline for Technical Design Report (TDR) submitted at the end of 2017

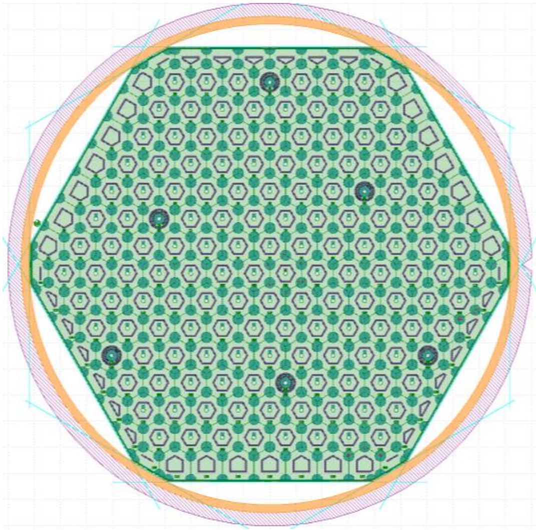
- Advantages of larger sensors:
  - Simplifies module mechanics by larger sensors/modules
  - Affordable only if maximal wafer area is used

- Disadvantages:
  - Precision of full-mask photolithography a bit worse than for 6” (no standard procedure)
  - **Deep diffused Float zone wafer material is not available on 8-inch**

Rectangular sensor



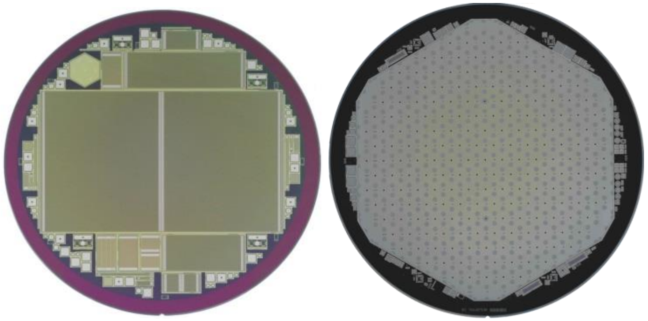
8” HGC Layout



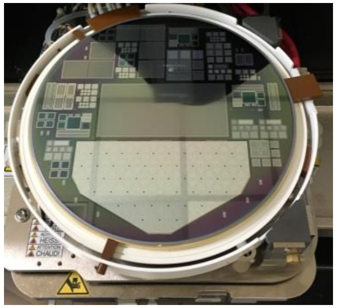
Realistic 8” Sensor Vendors

- **Hamamatsu (HPK)** was the only one high-quality high-volume producer for 6” sensors
  - They are well advanced in porting this technology to 8” production lines
  - **Two demonstrator batches on 8” produced**

- HEPHY Vienna is working with **Infineon (IFX)** to establish them as vendor for HEP Sensors
  - 6” (n/p-type) and 8” (p-type) production performed for the CMS tracker
  - **HGC sensor prototypes in 8” p-type**



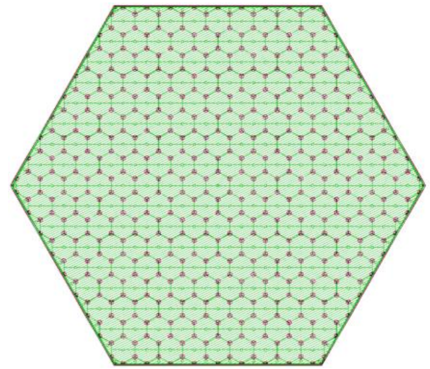
- US-Grant to **Novati/Tezzaron/Nhanced** to develop HEP sensors on 8 inches

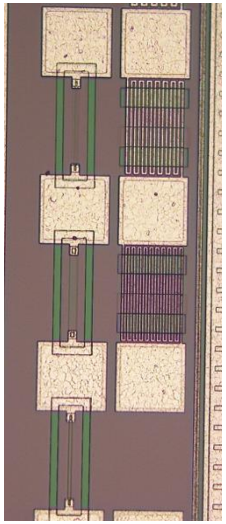


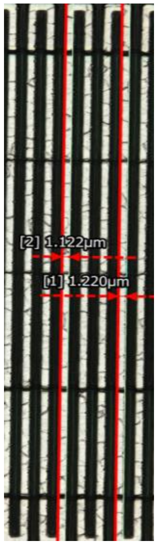
First HPK 8-inch p-Type HGC Sensors

- **HPK used stepper technology for first "demonstrator" run on 8-inch**
  - Small masks used to consecutively expose small squares on wafer,
  - results in excellent lithography (sub-µm structures)
  - Some disadvantages: no pad numbers, limitations in layout
- First batch:
  - Different process splits to evaluate best parameters
  - Reason for defective cells thought to be understood by HPK

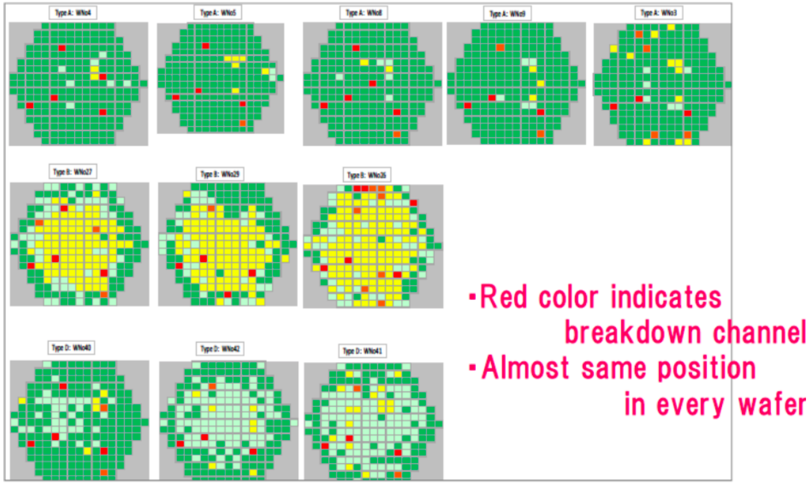
- **Stepper technique will not be used for mass production**
  - Full-wafer lithography equipment for 8 inches currently being purchased by HPK
  - **First delivery of real 8" prototypes in Q2/2018**







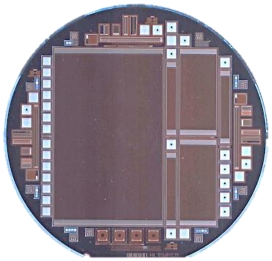
1st batch:



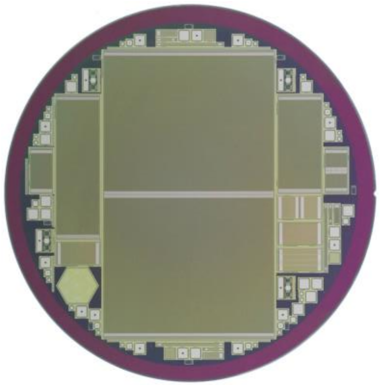
Sensor development with Infineon

- We are collaborating with them since a couple of years to develop Si sensors for HEP
  - 2012-2014: production of 6” p-on-n sensors
  - 2015-2017: production of first Si strip sensors on 8-inch FZ p-type wafers
  - 2016/17 onwards: production of Si pad sensors for HGCal
- Quality constantly improving
  - One remaining problem: premature IV breakdowns, scaling with sensor size
  - Addressed now by thicker backside implantation

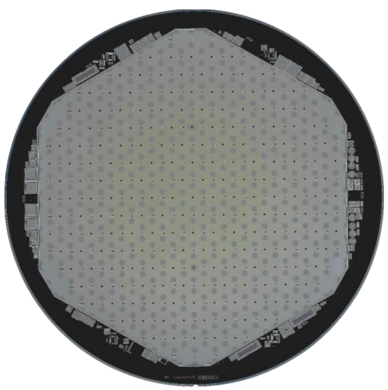
6” n-type strips



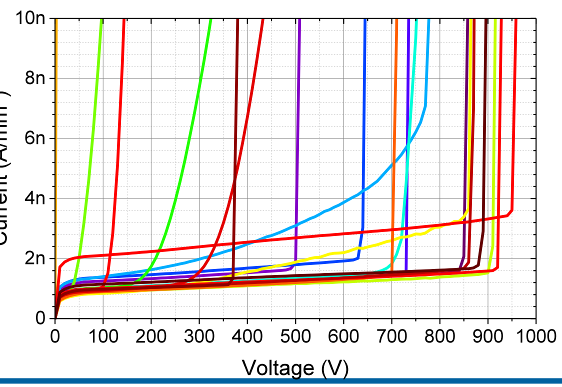
8” p-type strips

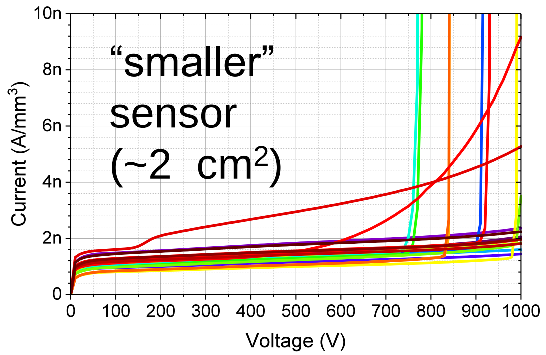


8” p-type pads



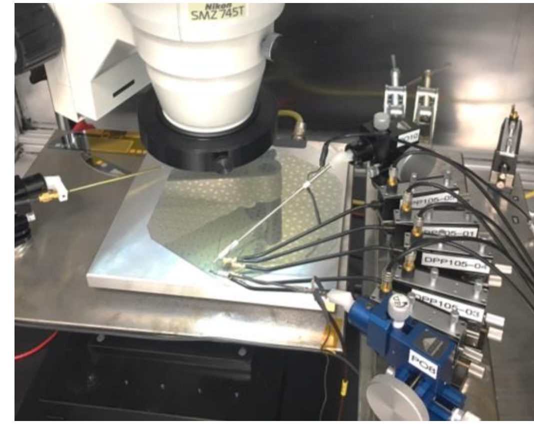
Baby sensor ($11.6 cm^2$)

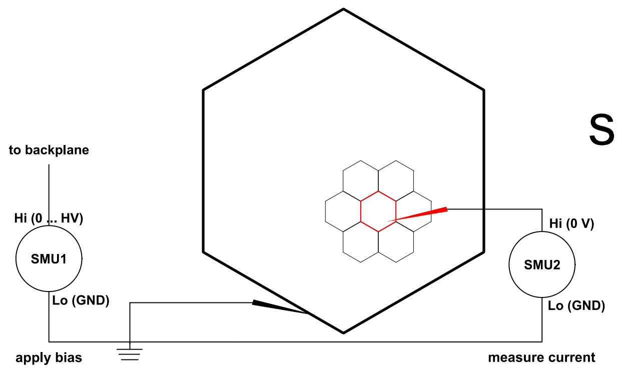




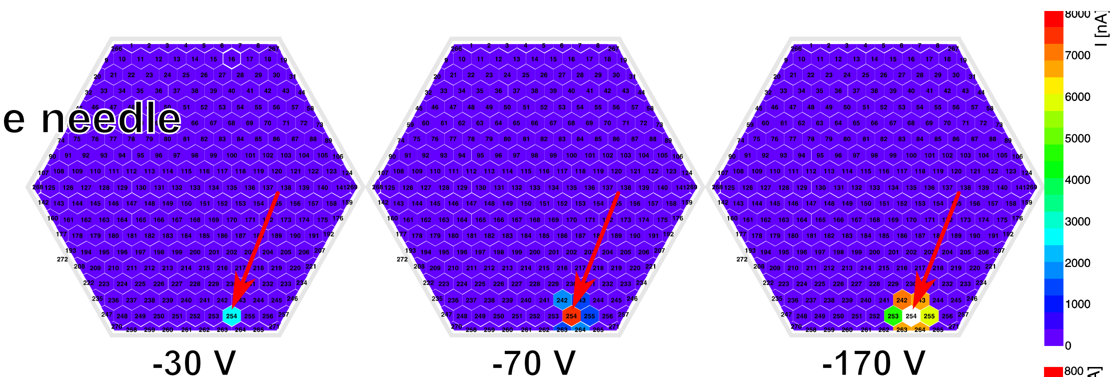
Sensor Characterization

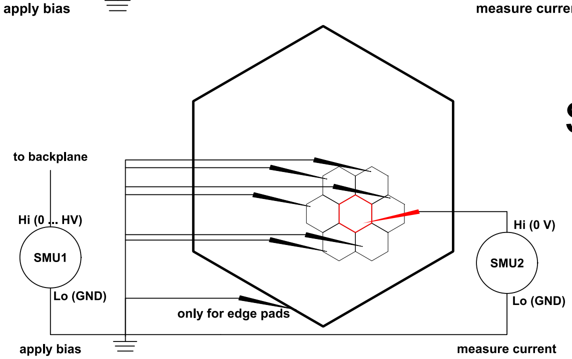
- Sensor is a bunch of parallel diodes without any biasing structure
- Simple IV measurements show influence of leaky cell to neighbors
- **Only 7-needle measurements give precise results** (only if neighbor cells are not in breakdown)



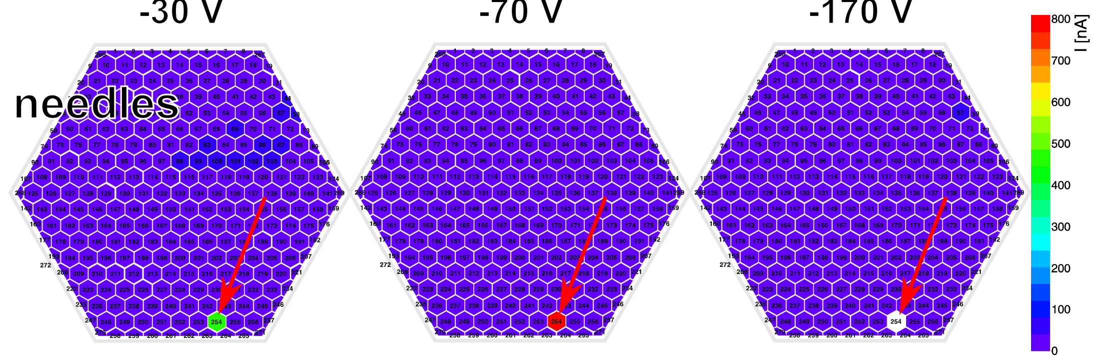


Single needle





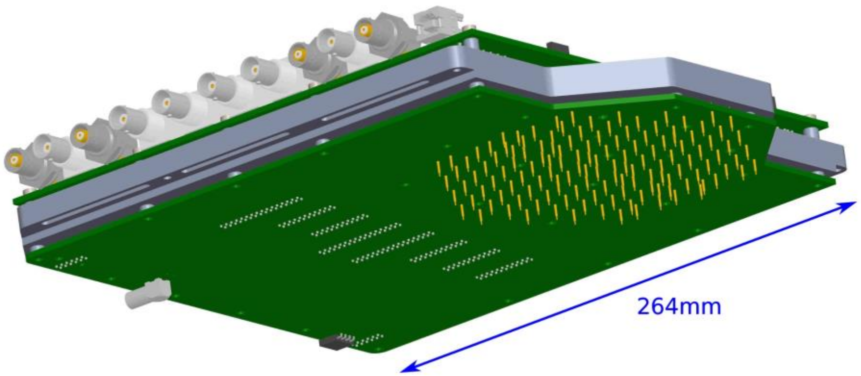
Seven needles



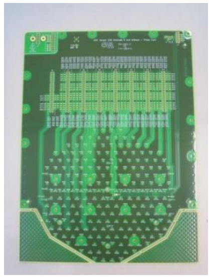
Contacting all cells in Parallel: Full Probe card

- Switching & Probe cards allow testing each pad while other pads are biased
- Flexible design: can be adapted to different sizes and geometries
  - **”upper” switching card** houses multiplexers and microprocessor
  - **“lower” probe cards** equipped with “pogo-pins” (spring loaded contacts) to match actual sensor geometry

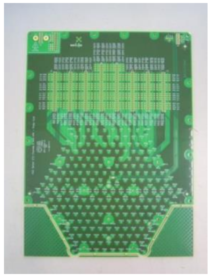
- Will allow also coupling to readout (e.g. to test noise of irradiated sensors)



Switching card



IFX 8”

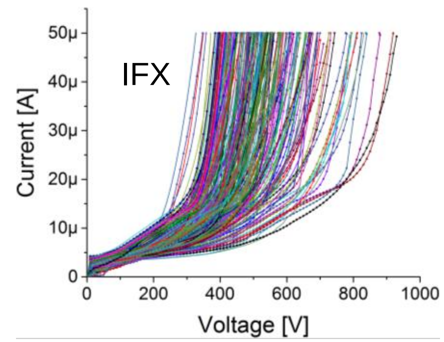


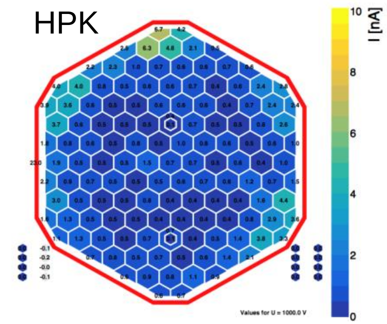
HPK 8”

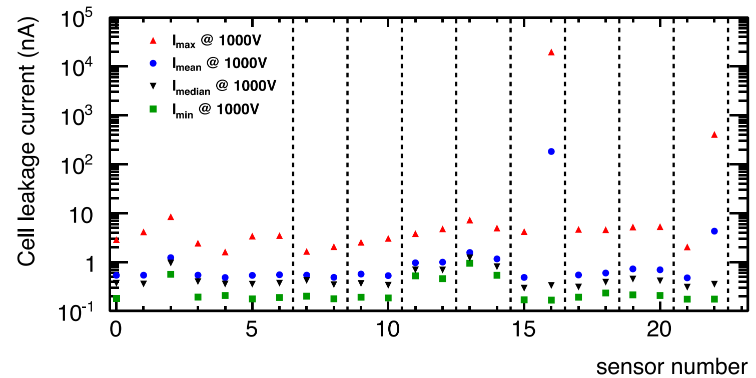
Performance of Switching/Probe card system

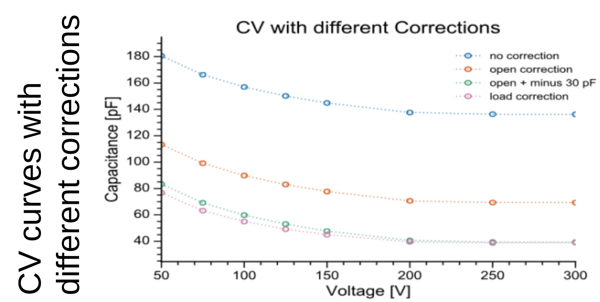
- Testing procedure:
  - IV curve: 11 voltage steps up to 1000V
  - CV curve: 15 voltage steps up to 300V

  Performed for all cells for each voltage step, then voltage is ramped to next step
- Probe card has been used to characterize ~90 HPK sensors for test beams
- Complicated network of parasitic impedances
  - Need open, short AND load correction of LCR meter to obtain an almost correct CV curve
  - We are working on better CV measurement to precisely determine active thickness



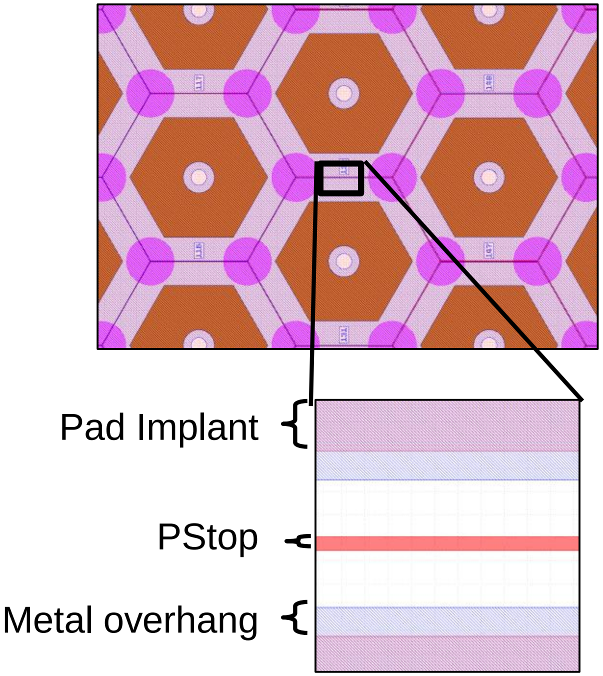


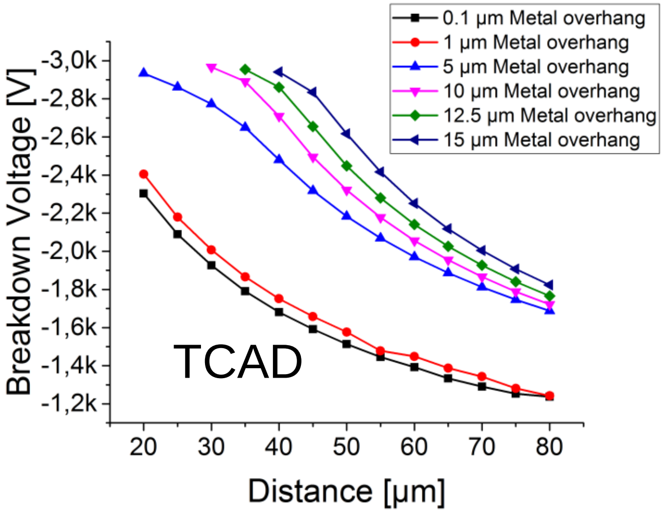


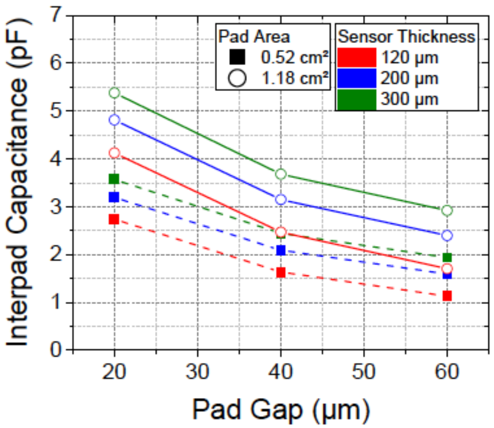


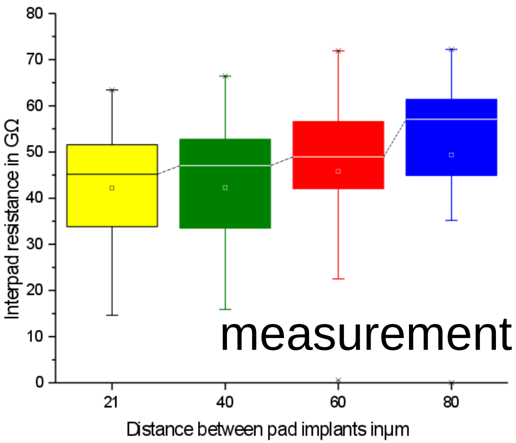
Sensor Layout Optimization

- Inter-cell gap is main parameter for design optimization
- Studied by TCAD simulations and measurements
  - Prototype sensors equipped with 4 quadrants of different pad distance (20, 40, 60, 80 µm) and p-stop geometry (atoll vs. common)
- Results: higher breakdown voltage for smaller pad distance
  - In contradiction to inter-pad isolation performance and capacitances (better for larger distances)







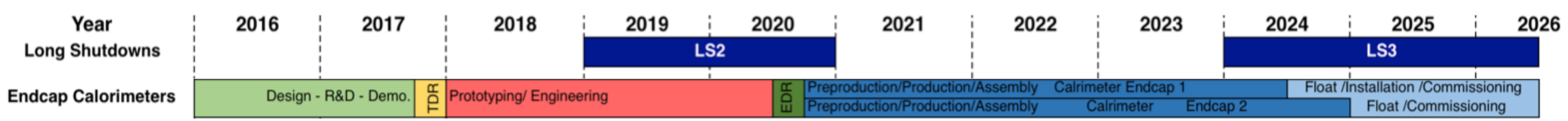


Summary & Outlook

- High Granularity Calorimeter (HGCal) is the upgrade of the endcap calorimeters of CMS
  - Based on prior work of CALICE and SiD/ILC
  - Consists of silicon sensors and scintillators as active elements

- Will be the largest Si-based particle detector by factor of three (600 m^2 active silicon area)
  - Move to 8-inch sensors is a significant cost saving and complexity reduction
    - Planar 300µm and 200µm thick sensors, epitaxial 120µm
  - Three vendors potentially capable of production: Hamamatsu, Infineon, Novati

- Basic design of the detector has been validated
  - Must be shown for 8-inch technology as well, despite tight timescale

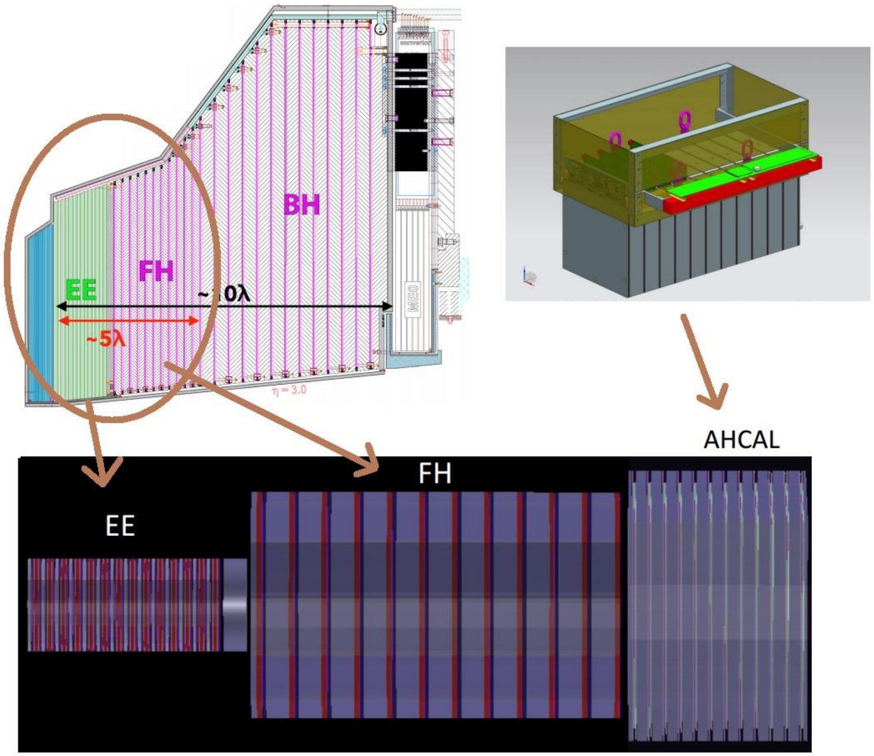


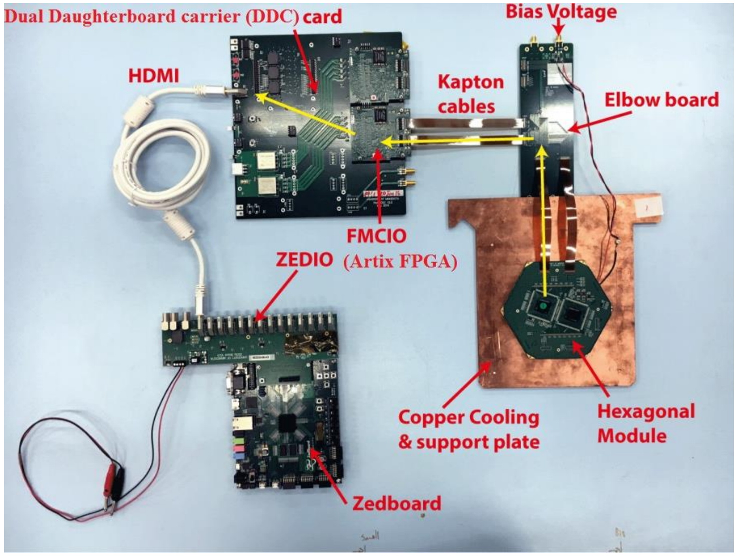
THE END

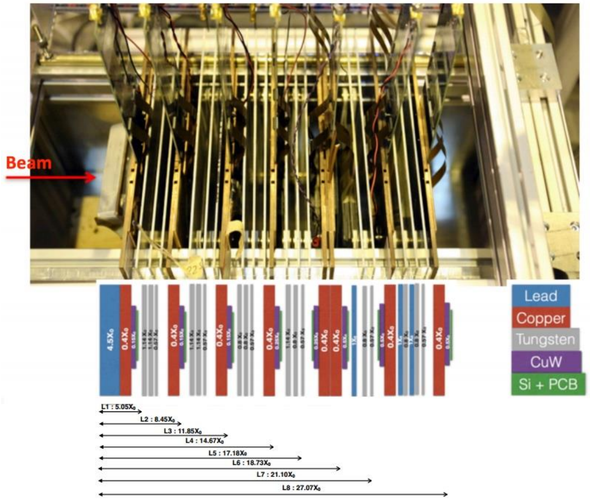
Various slides follow

Testbeams with 6” sensors

Aim to test full EE+FH+BH - like setup

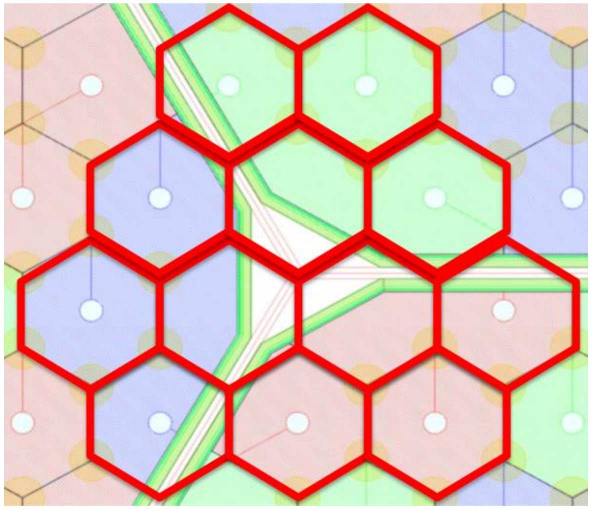


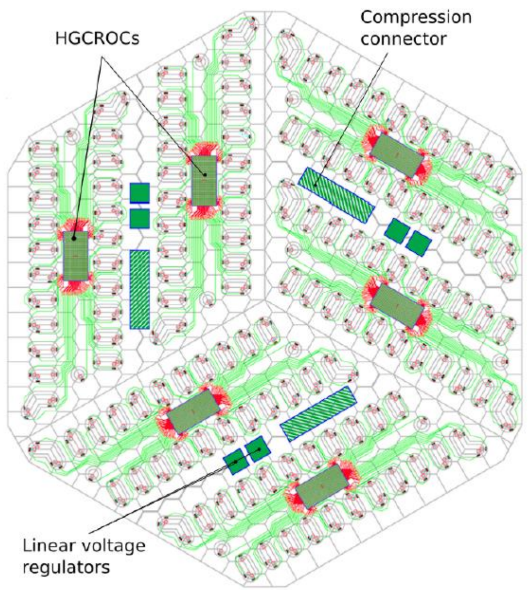


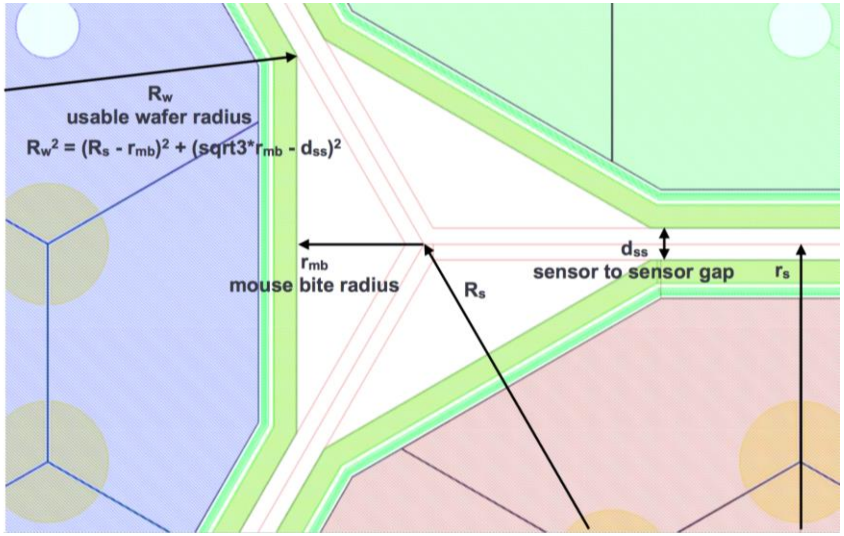


Continous Pitch

- A geometry which repeats the hexagonal cell pitch across modules is used
  - optimized for trigger cell geometry





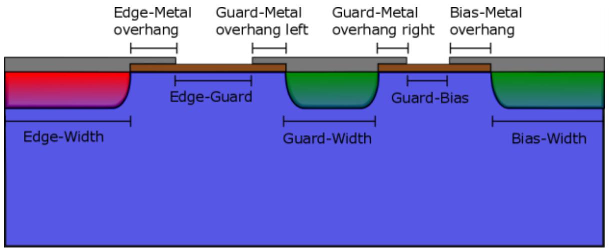


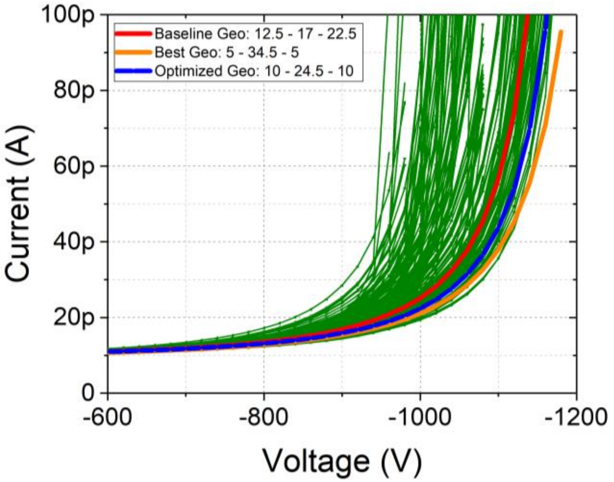
Layout Optimization

Periphery Simulation

- Synopsis TCAD 2D
- Dimensions between edge implant, floating and grounded guard ring varied
- It turned out that „old“ design was already very good

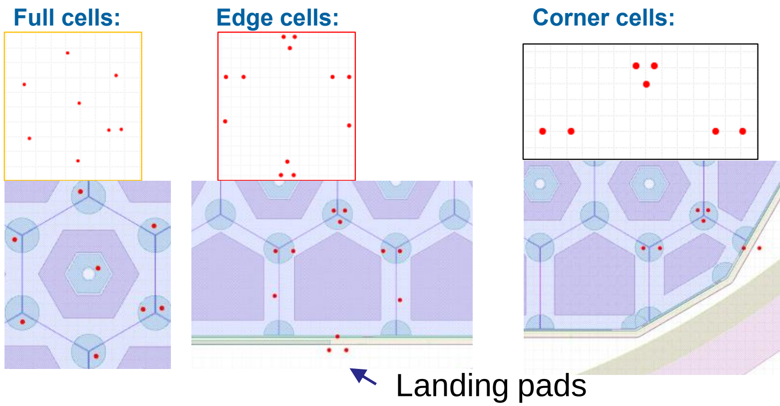
HGC Periphery (µm)	Edge-Width	Edge-MO	Edge-Guard	Guard-MO left	Guard-Width	Guard-MO right	Guard-Bias	Bias-MO	Bias-Width
IFX_V1	502	50	119.5	32.5	18	12.5	17	22.5	131.5
New Geo	400	50	119.5	40	18	10	24.5	10	131.5





Simplifying testing at vendors

- proposing layout for small „probe cards“ to allow 7-needle testing
- Even for edge and border cells
- Need to have „landing pads“ in otherwise unused region of wafer



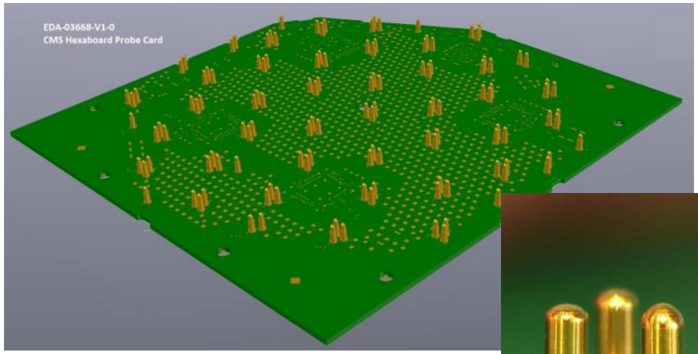
Hexaboard probe card

Purpose: Signal/Noise tests of bare (irradiated) sensors without the need of module assembly of irradiated sensors or irradiation of whole module

- Aim: understand noise behavior of irradiated sensors (n-type/p-type)

- Replace wire-bonds by pogo pins
- Added holes for laser on cell center and inter-cell regions
- Status: Design finished, should be ready in ~2 months from now
- To be installed in CERN probe station

- Possible collaboration of new „system test" group with sensors group



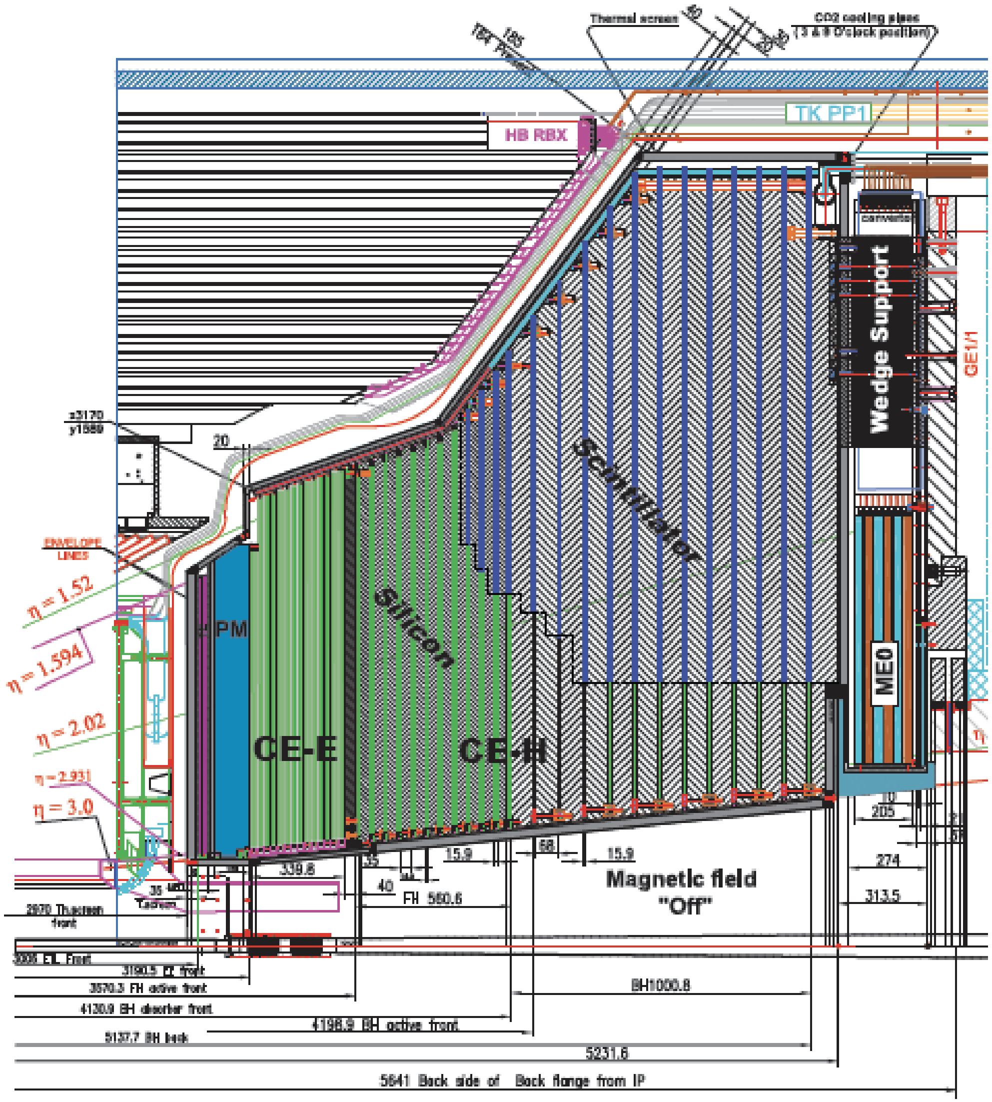
Details on Sensor Variants

CE-E: ECAL

Active thickness (μm)	300	200	120
Area (m^2)	245	181	72
Largest lifetime dose (Mrad)	3	20	100
Largest lifetime fluence (n_{eq}/cm^2)	0.5×10^{15}	2.5×10^{15}	7×10^{15}
Largest outer radius (cm)	≈180	≈100	≈70
Smallest inner radius (cm)	≈100	≈70	≈35
Cell size (cm^2)	1.18	1.18	0.52
Initial S/N for MIP	11	6	4.5
Smallest S/N(MIP) after 3000 fb^{-1}	4.7	2.3	2.2

CE-H: HCAL

Sensor thickness	Scintillator 3 mm	Si 300 μm	Si 200 μm
Area (m^2)	480	71	15
Largest lifetime dose (Mrad)	<0.3	30	100
Largest lifetime fluence (n_{eq}/cm^2)	8×10^{13}	5×10^{14}	2.5×10^{15}
Largest outer radius (cm)	≈235	≈160	≈100
Smallest inner radius (cm)	≈90	≈80	≈45
Cell size (cm^2)	2×2 to 5.5×5.5	1.18	1.18
Initial S/N for a MIP	≫5	11	6
Smallest S/N(MIP) after 3000 fb^{-1}	5	4.7	2.3

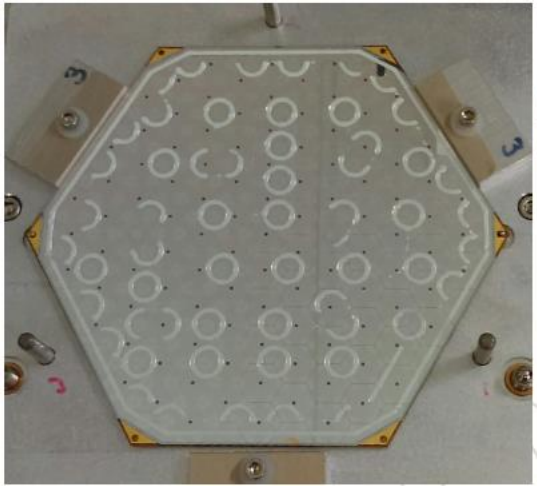
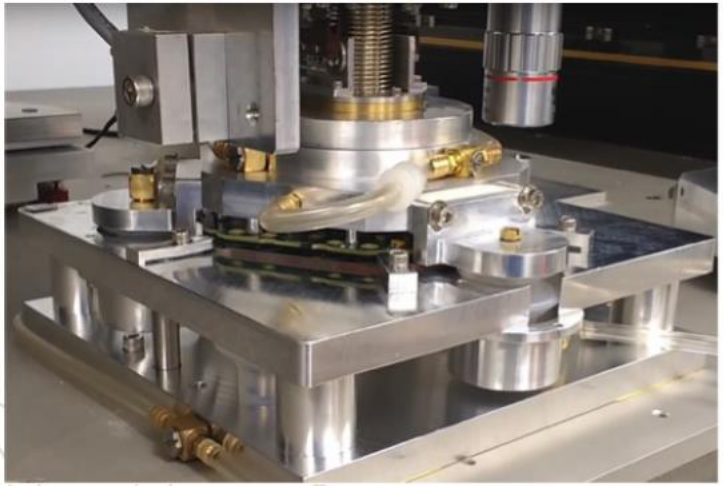


- SKIROC2: ASIC used by CALICE in the SiW ECAL
  - Dedicated 64 channel Si-detector readout ASIC, SiGe 350 nm
- SKIROC2cms: *submitted and received in Q1/2016*
  - Modification for test beams with CMS-like running conditions
  - 40 MHz clock and sampling, Gain + ToA + ToT
- Test Vehicle 1: *submitted in May 2016, received in August 2016*
  - First HGCROC test vehicle in CMOS 130 nm architecture
  - Dedicated to preamplifier studies
- Test Vehicle 2: *submitted in December 2016, received in May 2017*
  - Dedicated to analog channel study for TDR
- HGCROCv1: *submitted in July 2017, recently received*
  - All analog and mixed blocks; many simplified digital blocks

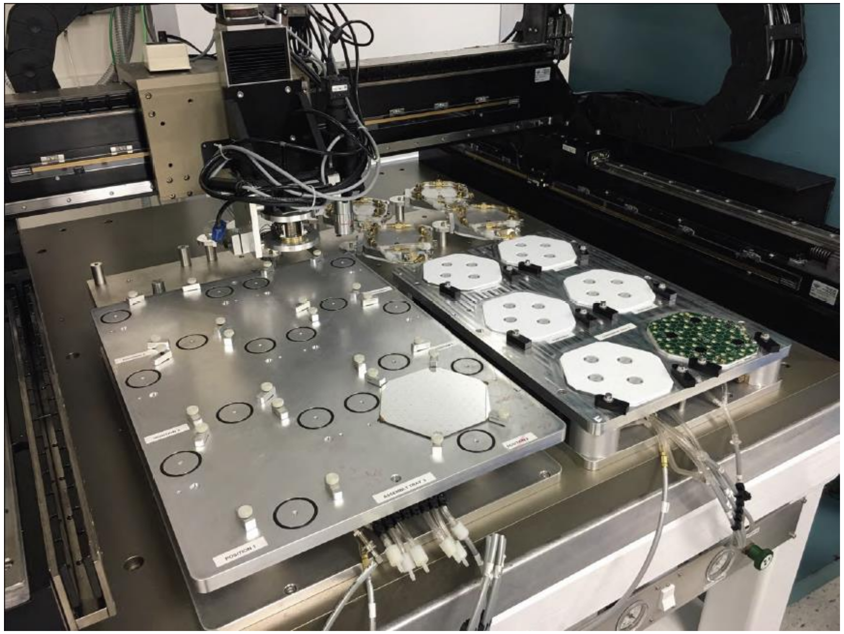
➡ **Final HGCROC submission by mid 2019!**

72 (+2 +4) channels, i.e. 3/6 chips per sensor

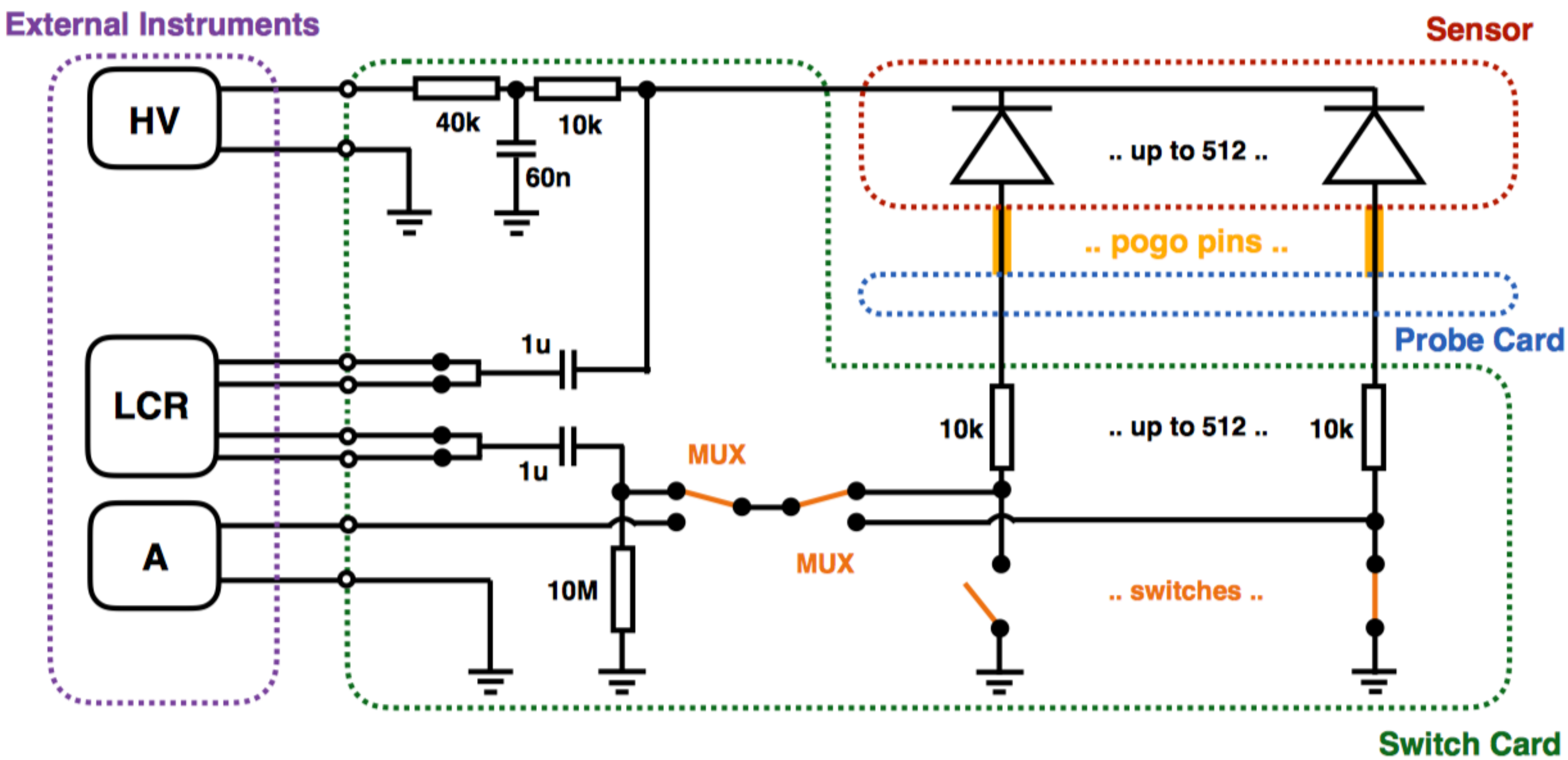
Automated Module Assembly

- 6"modules
  - 6 pick-up tools for PCBs, 6 for Sensors
  - 2 Portable assembly trays
  - 2 Portable component staging trays
- Enables 12 glue steps per day
  - Complete 6 modules/day, Start 6 others to be finished the next day
  - Kapton preassembly rate 6/day



Switchcard Schematics



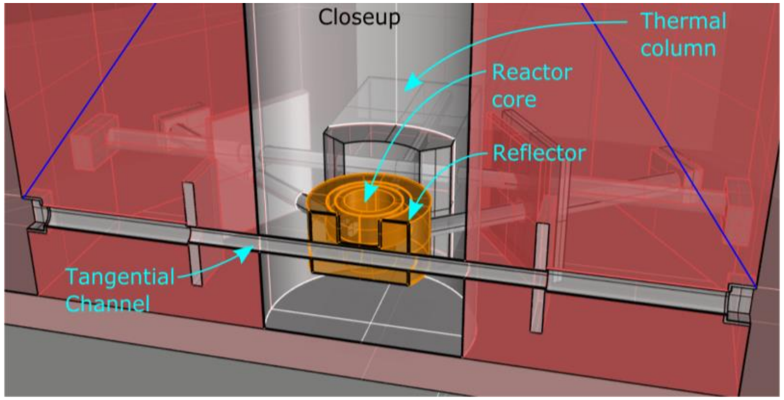
6” Irradiation @ Ljubljana

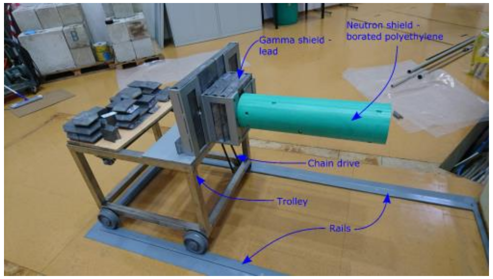
Triga Mark III reactor at JSI Ljubljana recently upgraded for irradiation of large objects

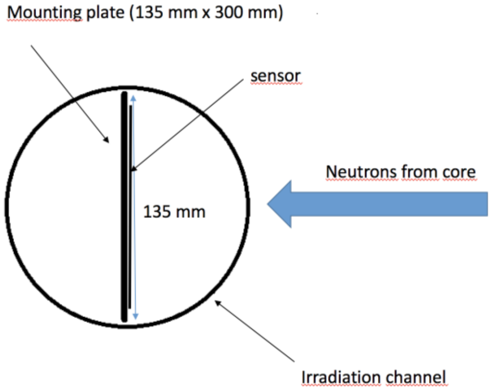
- Funding by AIDA-2020
- 6” HPK sensors just fit (verified)
- Fluences: 1E14, 5E14 and 1E15 (further steps to be negotiated)
- Sensor should have some protection (plastic bag, thin box) and fixed to this plate
- Can be shipped there anytime, returned 4-6 weeks later

- Need to agree on samples, e.g.
  - 3 pcs. n-type
  - 3 pcs. p-type (atoll)
  - 3 pcs. p-type (common)

  (all 300um thickness)







8” Irradiations @ US

Setups:

- Rhode Island reactor (RINSC)
  - close to Brown Univ.
  - Foil dosimetry for spectrum determination
  - 6/8 inches beam port
  - Annealing study performed
- FSU protons (Tandem Van-der-Graaf)
  - Diode samples irradiated
  - Samples tested in dark box (no probe station?)
- Texas Tech: IV/CV
  - IV/CV performed on cold chuck