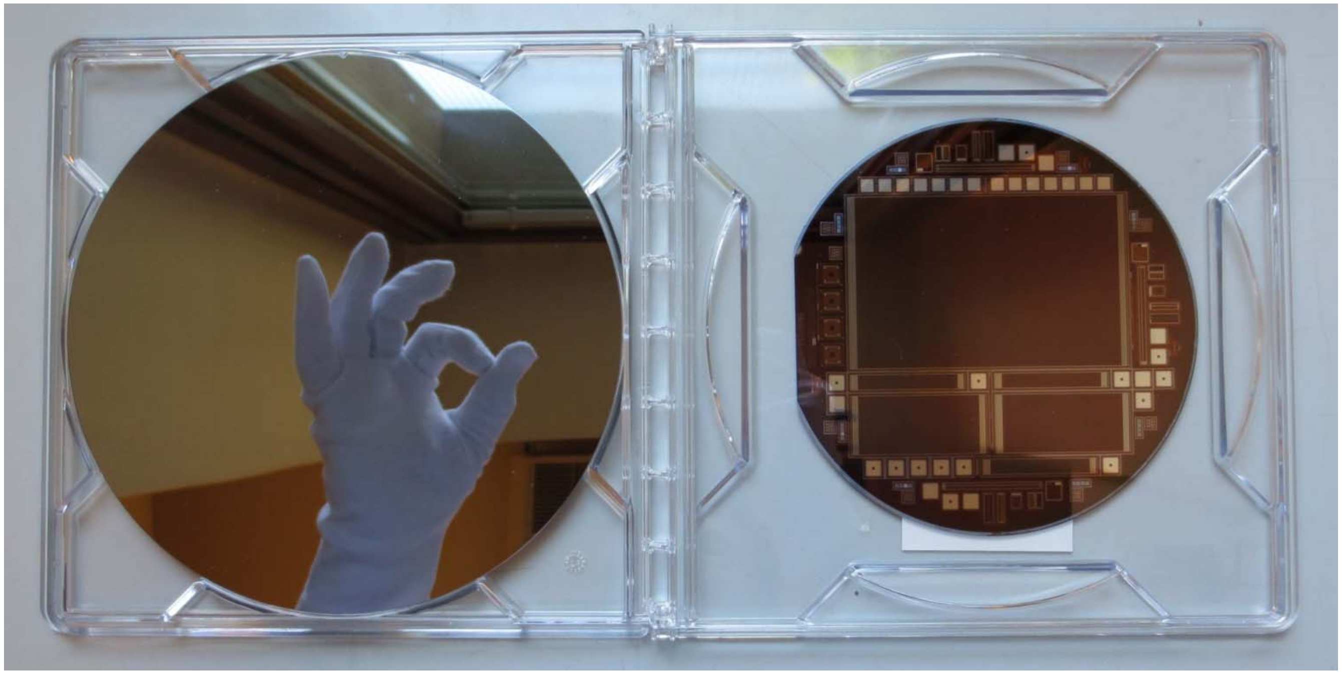


Silicon Sensor R&D for CMS Upgrade

Thomas Bergauer (HEPHY Vienna)

IPM Teheran

8 October 2013

Content

- Motivation
- Baseline Layouts for Phase 2 Upgrade
- Developments with alternative Vendors
- HPK campaign

The High Luminosity LHC and CMS

Upgrade of the LHC by 2022 to achieve **5x** the current design luminosity: **5×10^{34} $cm^{-2}s^{-1}$**

- Original LHC integrated luminosity: **~300 fb^{-1}**
- Integrated luminosity with upgrade: **~ 3000 fb^{-1}**

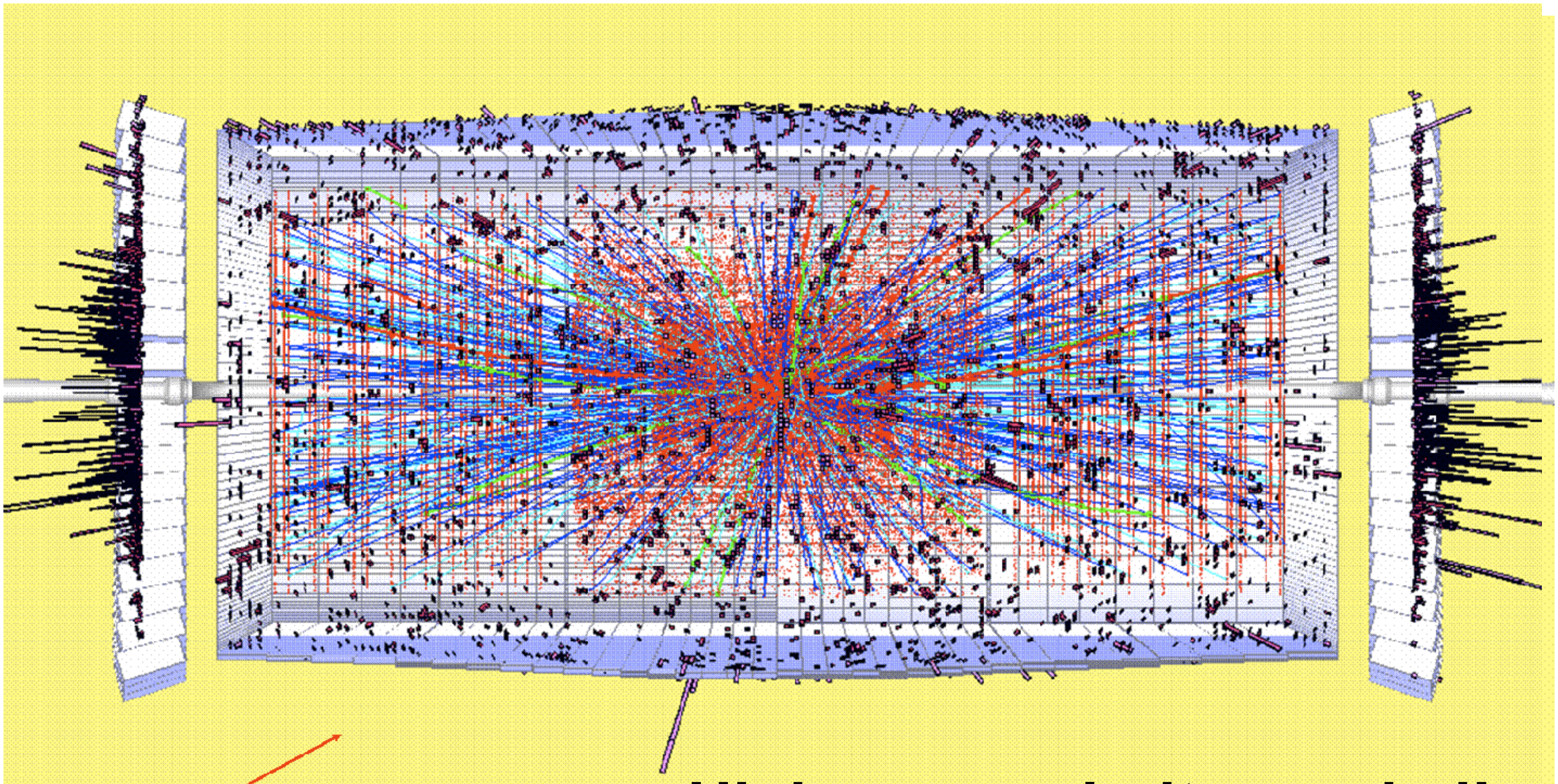
→Significant gain in collected events!

Current CMS Tracker was designed to operate for 10 years in LHC environment

- End of lifetime reached by ~2020

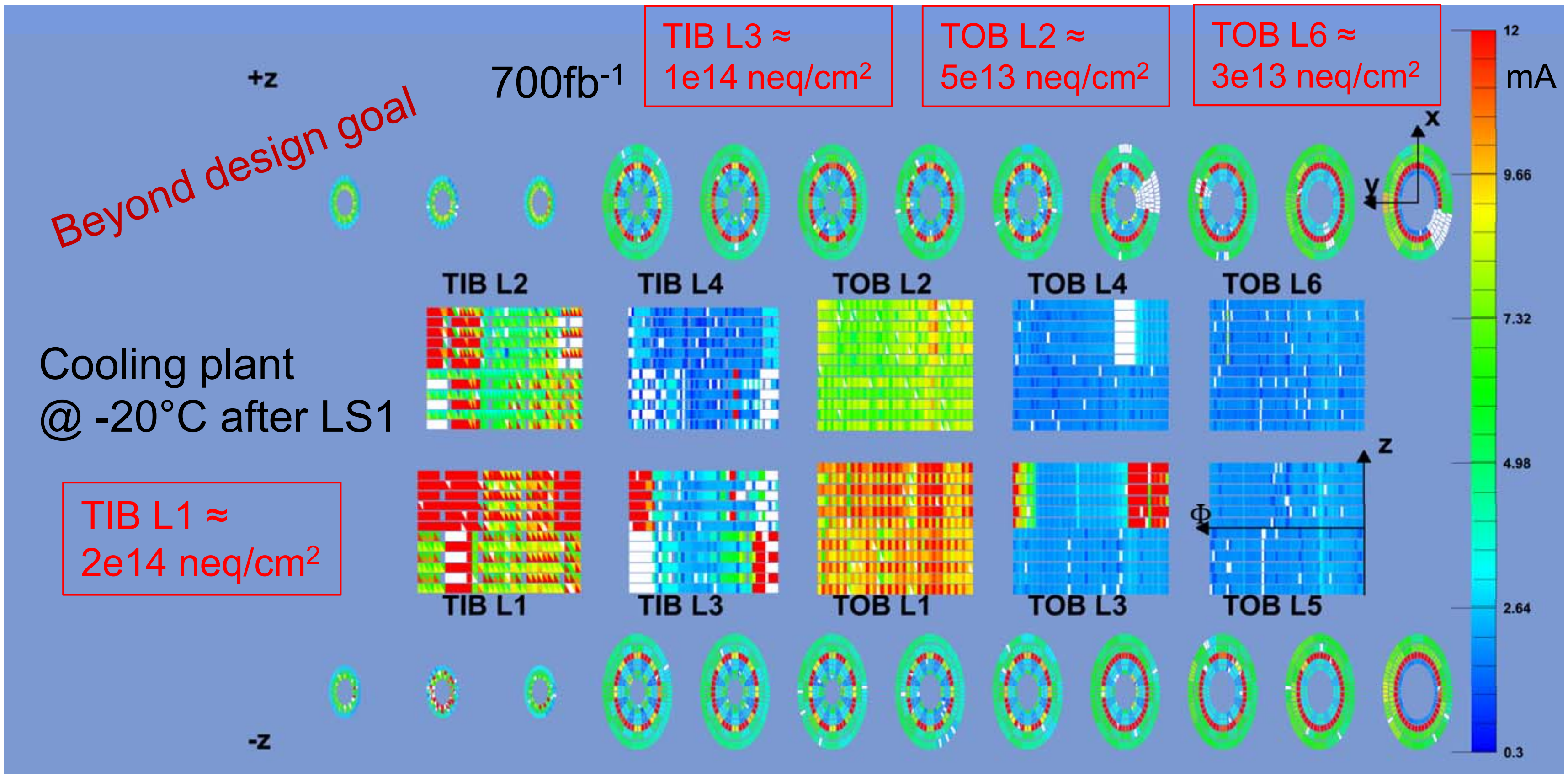
→ Replacement necessary to keep CMS running

Track Density at 10^{35} cm^{-2}s^{-1}



Higher granularity needed!

Leakage Current at 700fb^{-1}

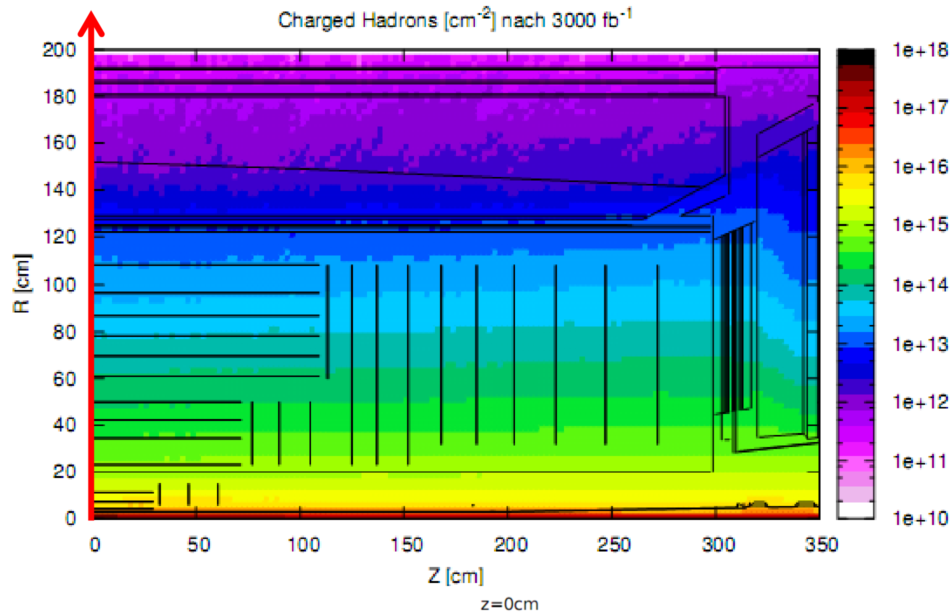


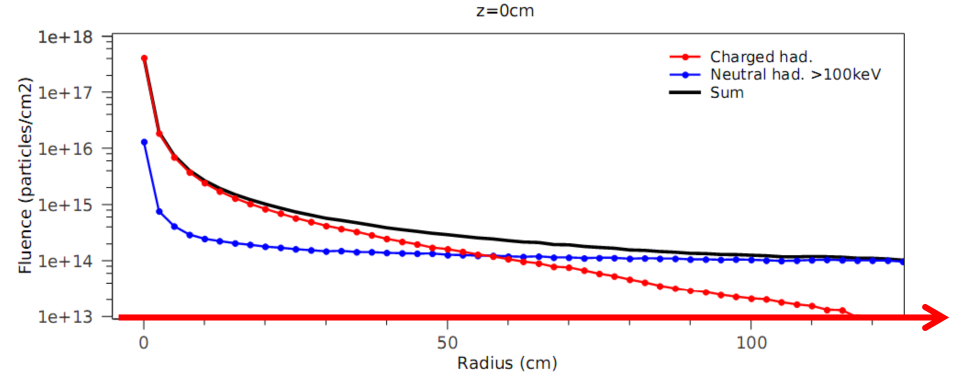
More radiation-hard sensors needed

Motivation

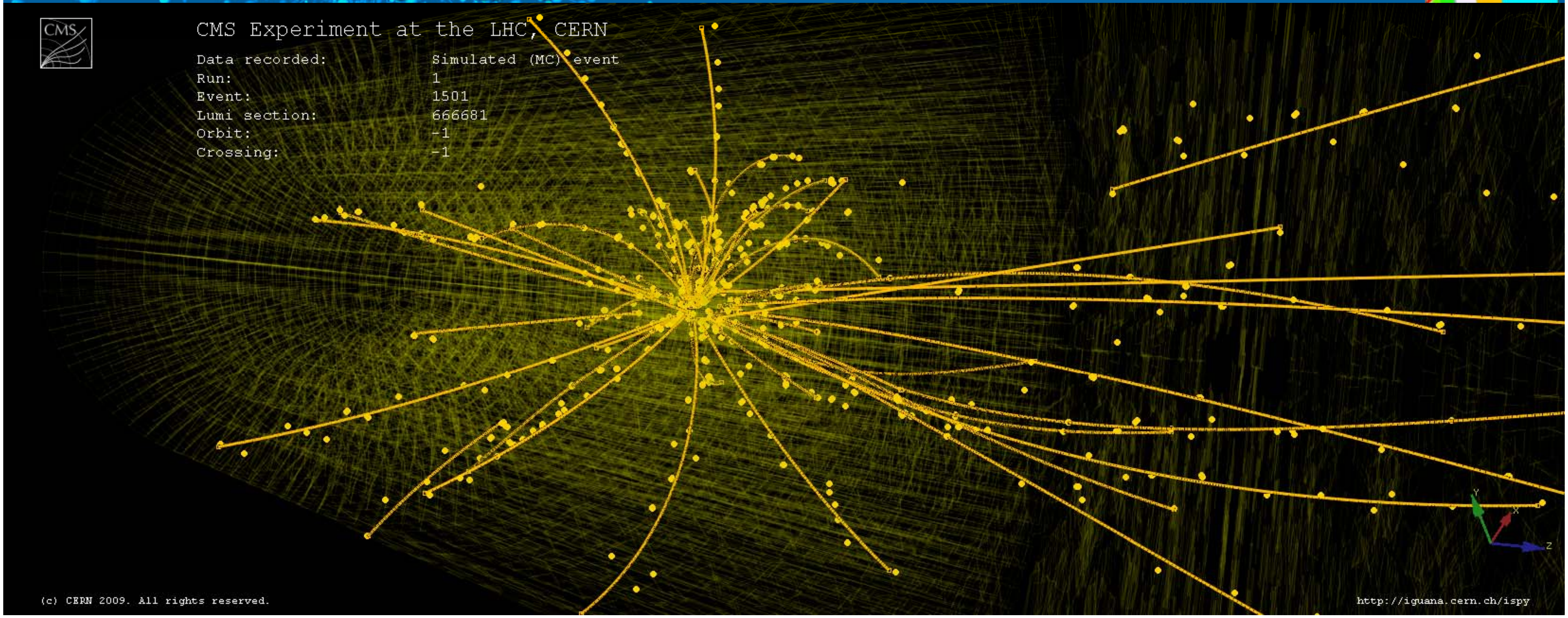
- High luminosity LHC
  - $L=10^{34}cm^{-2}s^{-1}$ to $L=5*10^{34}cm^{-2}s^{-1}$
- CMS Tracker performance affected by higher luminosity
- More radiation damage in silicon sensors
  - Higher leakage current
  - Higher depletion voltage
  - Lower signal (signal to noise)
- More protons per bunch
  - More tracks
  - Higher occupancy
- Phase II Upgrade of CMS Tracker
  - Campaign to find sensor baseline for the future CMS Tracker

Integrated Luminosity $L_{int}=3000fb^{-1}$



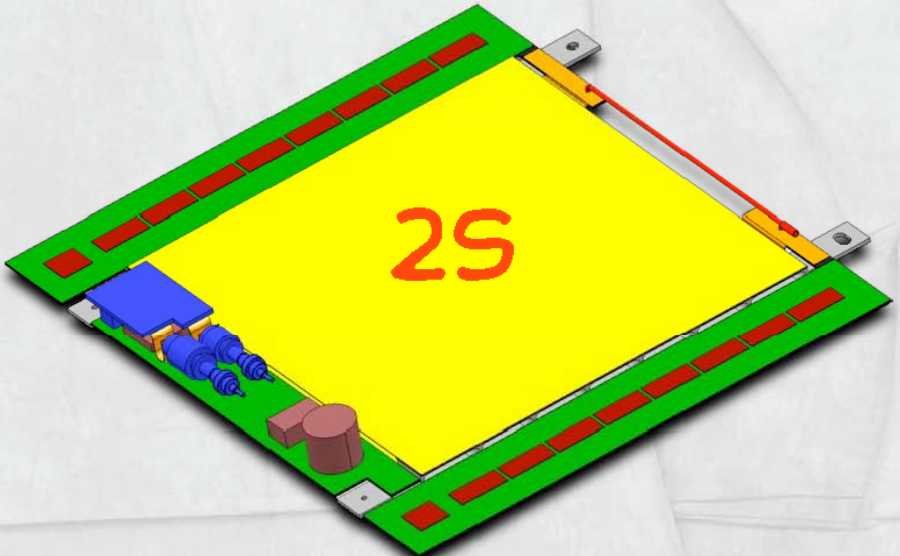


[S.Müller, phd thesis, KIT 2011]

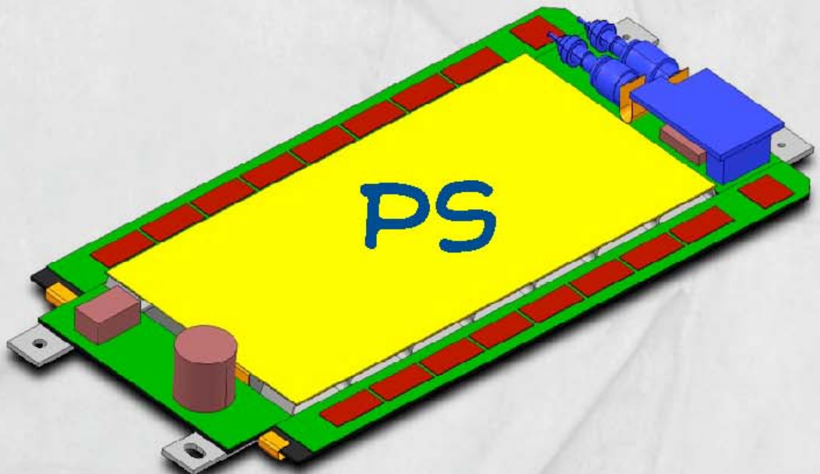


BASELINE LAYOUTS FOR TRACKER AFTER PHASE 2 UPGRADE

Current module design



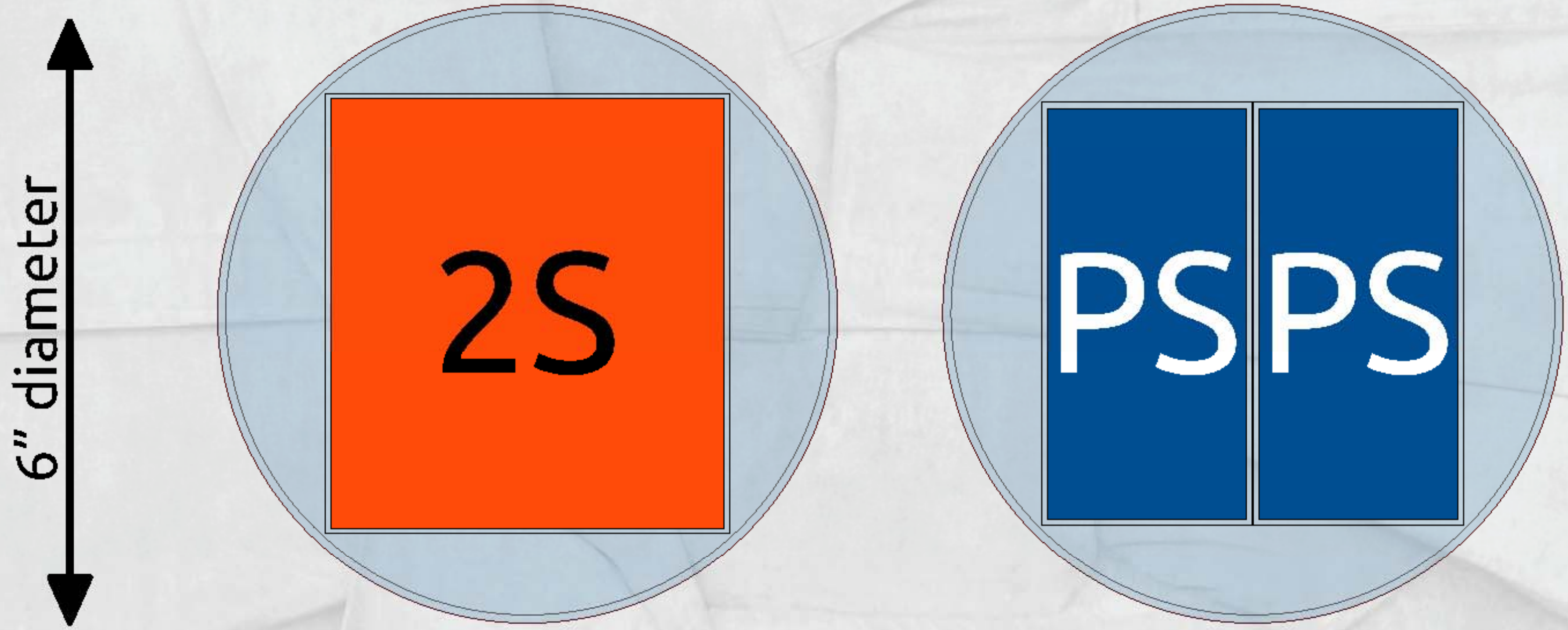
5 cm long strips (both sides)
90 µm pitch
P = 2.72 W
~ 92 cm^2 active area



2.4 cm long strips + pixels
100 µm pitch
P = 5.01 W
~ 44 cm^2 active area

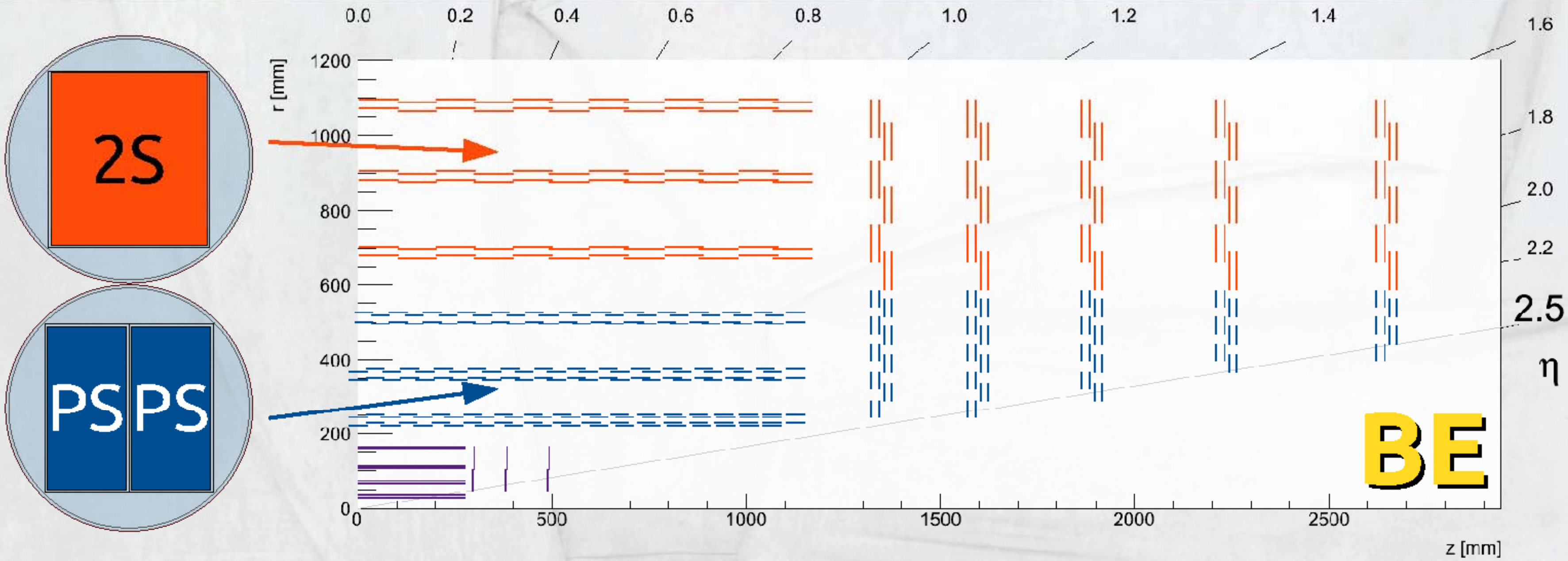
Current sensors on 6” wafers

Almost **square sensor**:
optimal use of the wafer

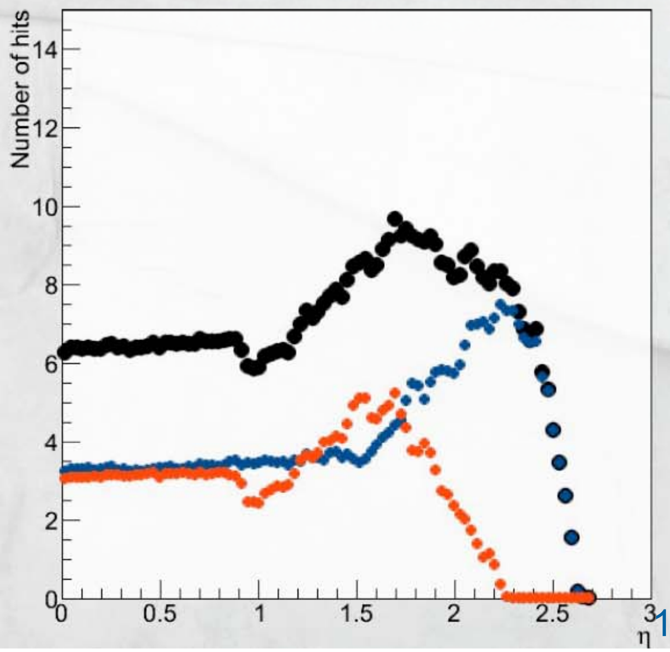


Smaller **PS sensors**
still fit into almost square surface

Barrel + End-cap baseline

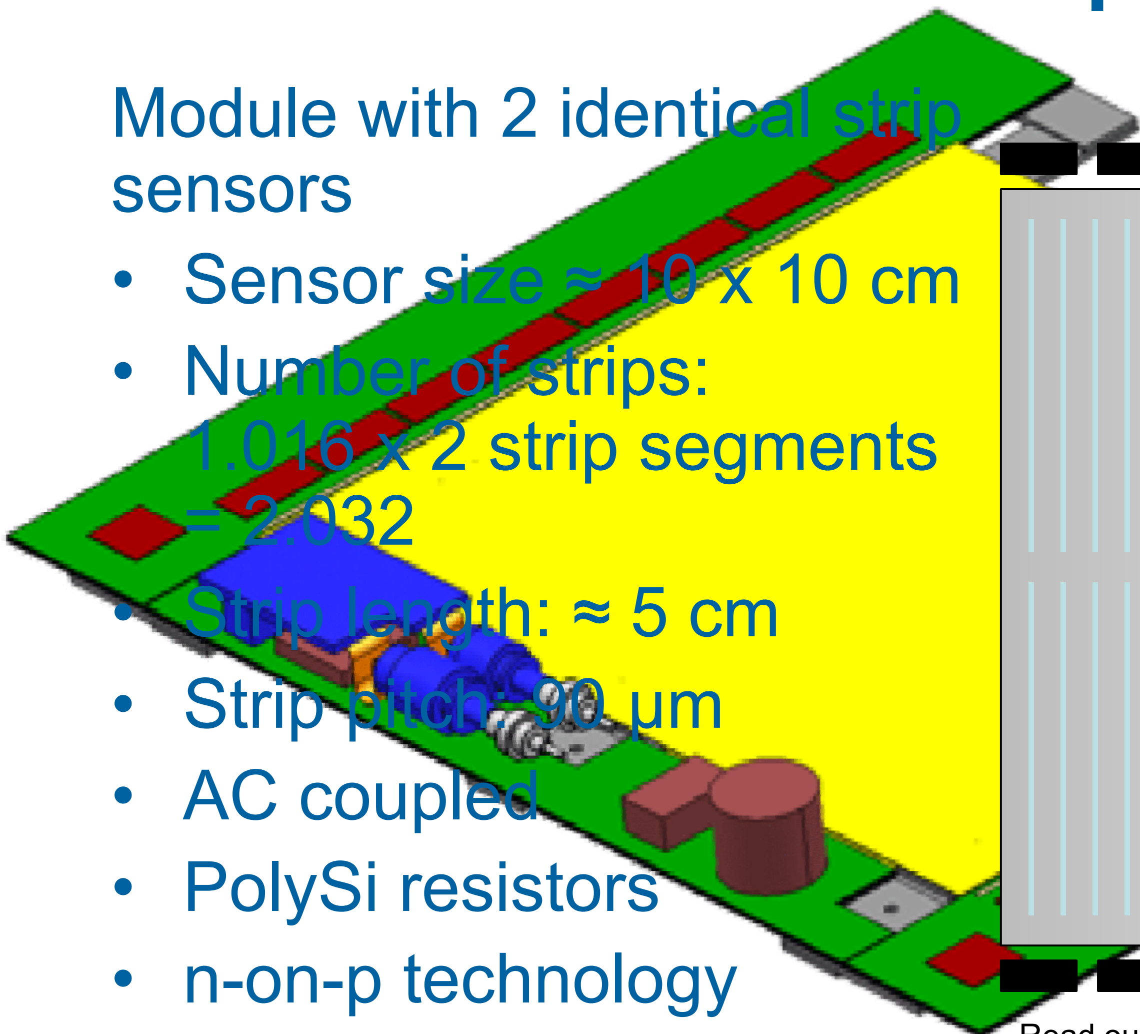


	2S	PS	Total
Modules	8'344	6'620	14'964
Sensors	16'688	13'240	29'928
Wafers	16'688	6'620	23'308
Power [kW] (FE+sensors)	22.7+3.1	33.2+2.9	55.9+6.0



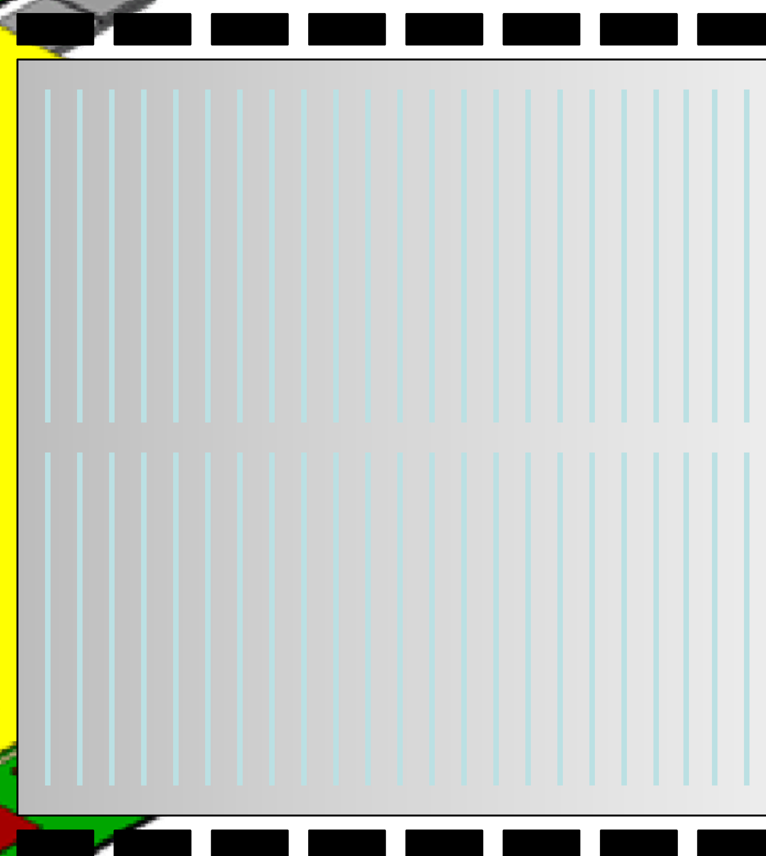
Baseline: 23'308 wafers needed

2S Module: Strip Sensor

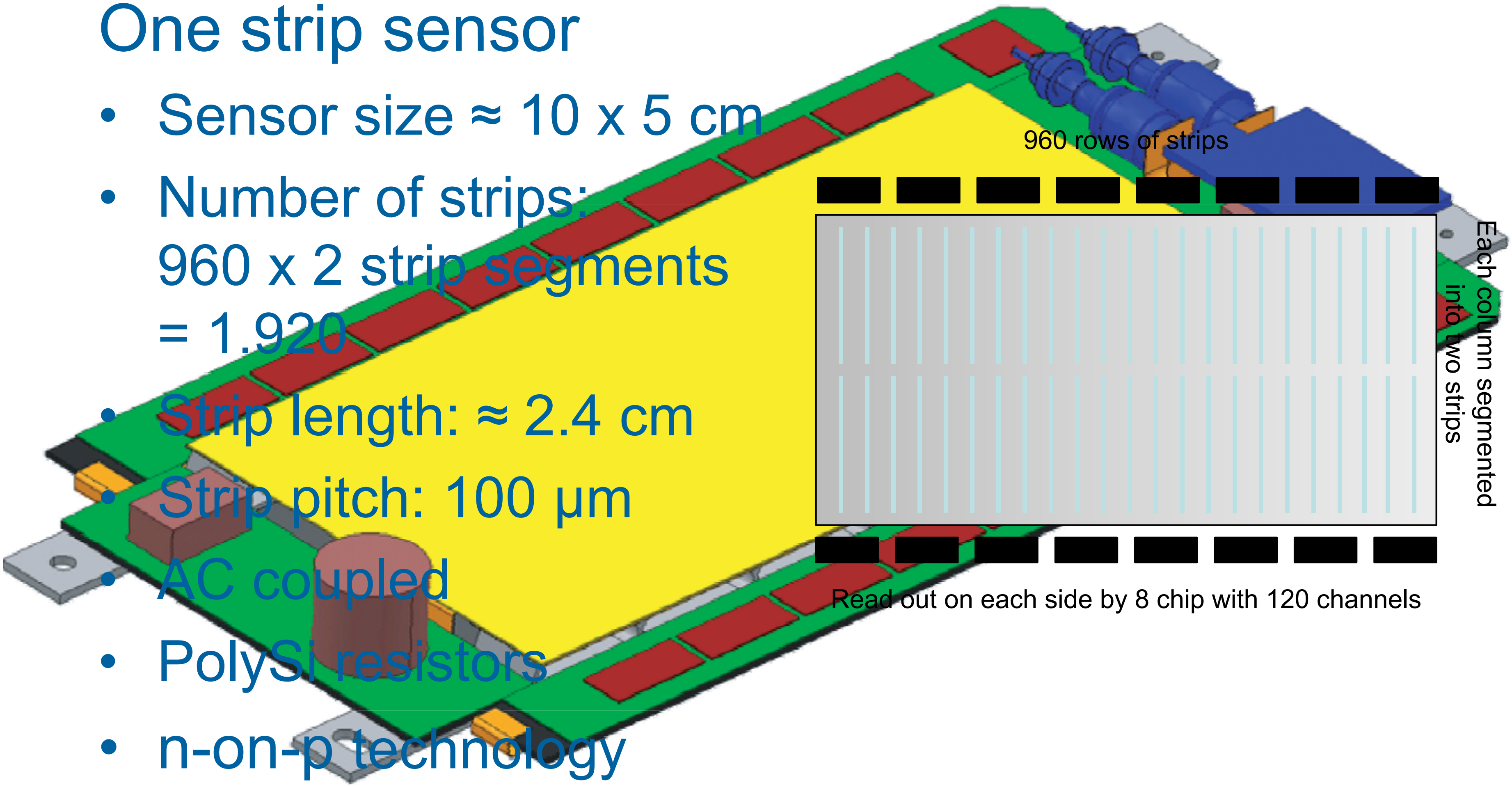


Module with 2 identical strip sensors

- Sensor size ≈ 10 x 10 cm
- Number of strips: 1.016 x 2 strip segments = 2.032
- Strip length: ≈ 5 cm
- Strip pitch: 90 µm
- AC coupled
- PolySi resistors
- n-on-p technology



PS Module: Strip Sensor



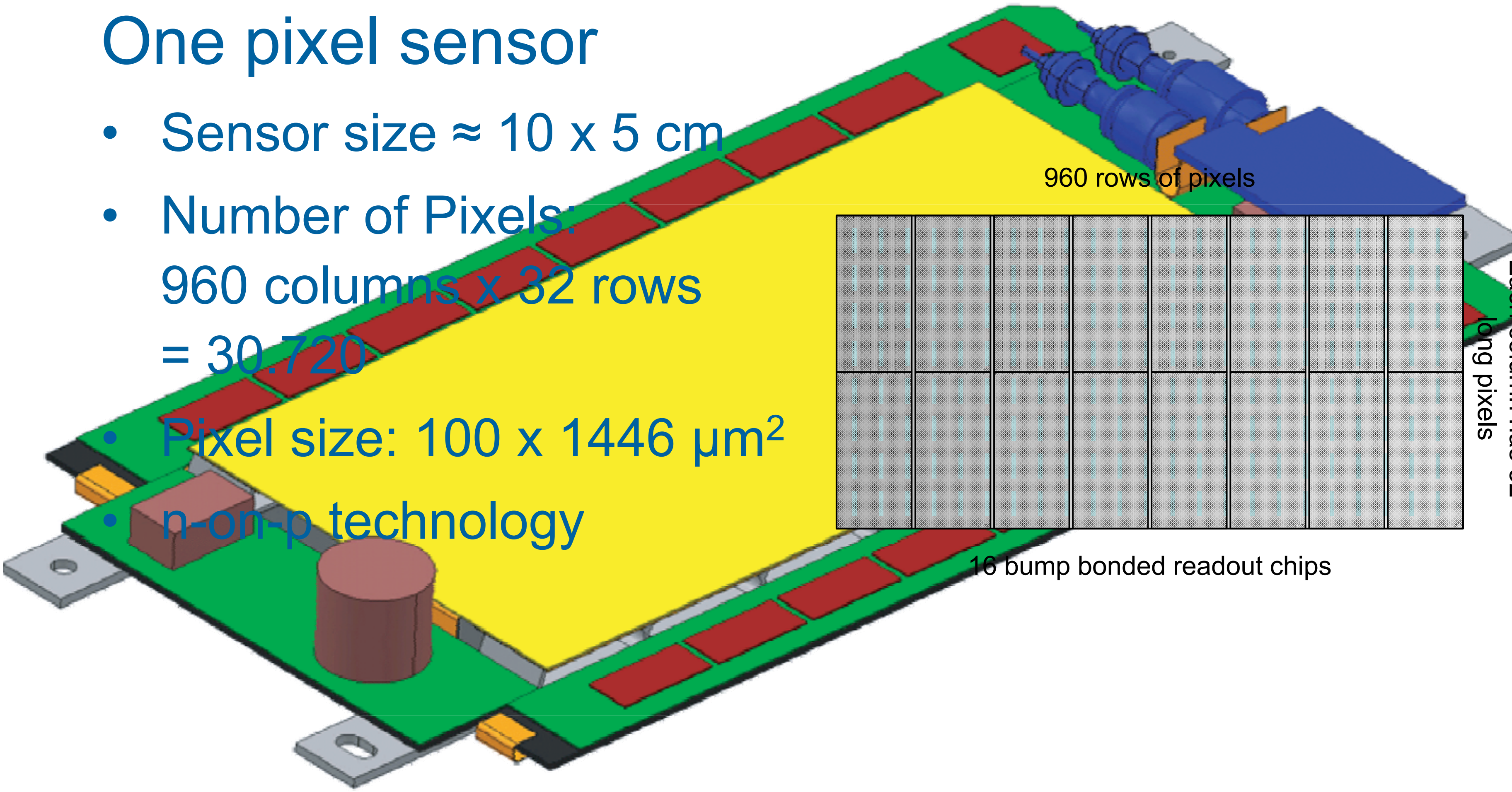
One strip sensor

- Sensor size ≈ 10 x 5 cm
- Number of strips:
  960 x 2 strip segments
  = 1.920
- Strip length: ≈ 2.4 cm
- Strip pitch: 100 µm
- AC coupled
- PolySi resistors
- n-on-p technology

PS Module: Pixel Sensor

One pixel sensor

- Sensor size ≈ 10 x 5 cm
- Number of Pixels:
  960 columns x 32 rows
  = 30.720
- Pixel size: 100 x 1446 μm^2
- n-on-p technology



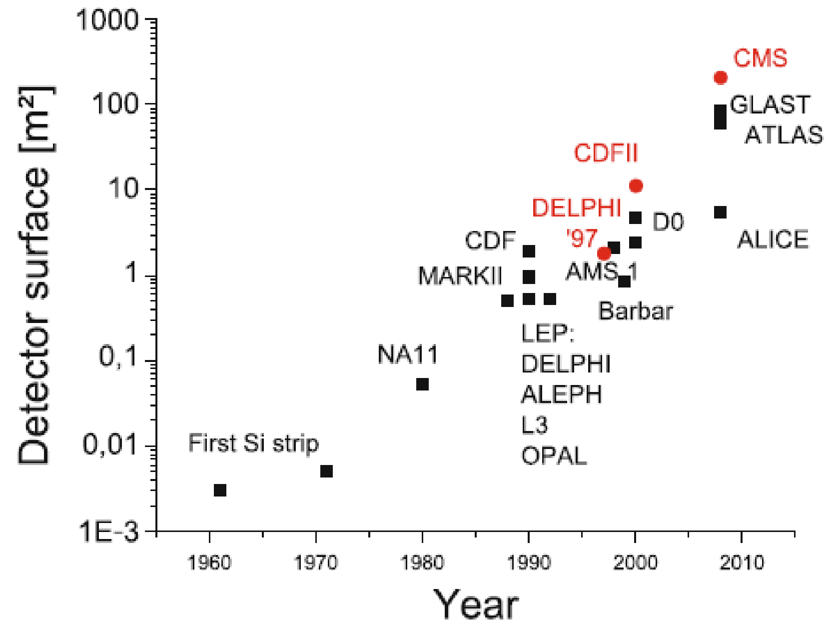
What has changed since the 90ies?

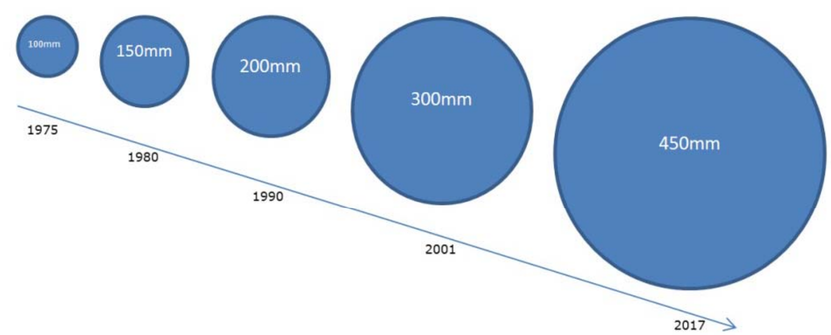
CMS Design was done ~1995

- Silicon surface
  - Today: Up to 200 m² (CMS)
  - Similar demand for upgrades of CMS and ATLAS
- Wafer Size
  - NA11 started with 2” and 3”
  - Today 6” (150 mm) is standard

→ **Introduced in the Industry in the 80ies!**

→ **Effort to bring silicon detector vendors to invest in 8” production technology.**

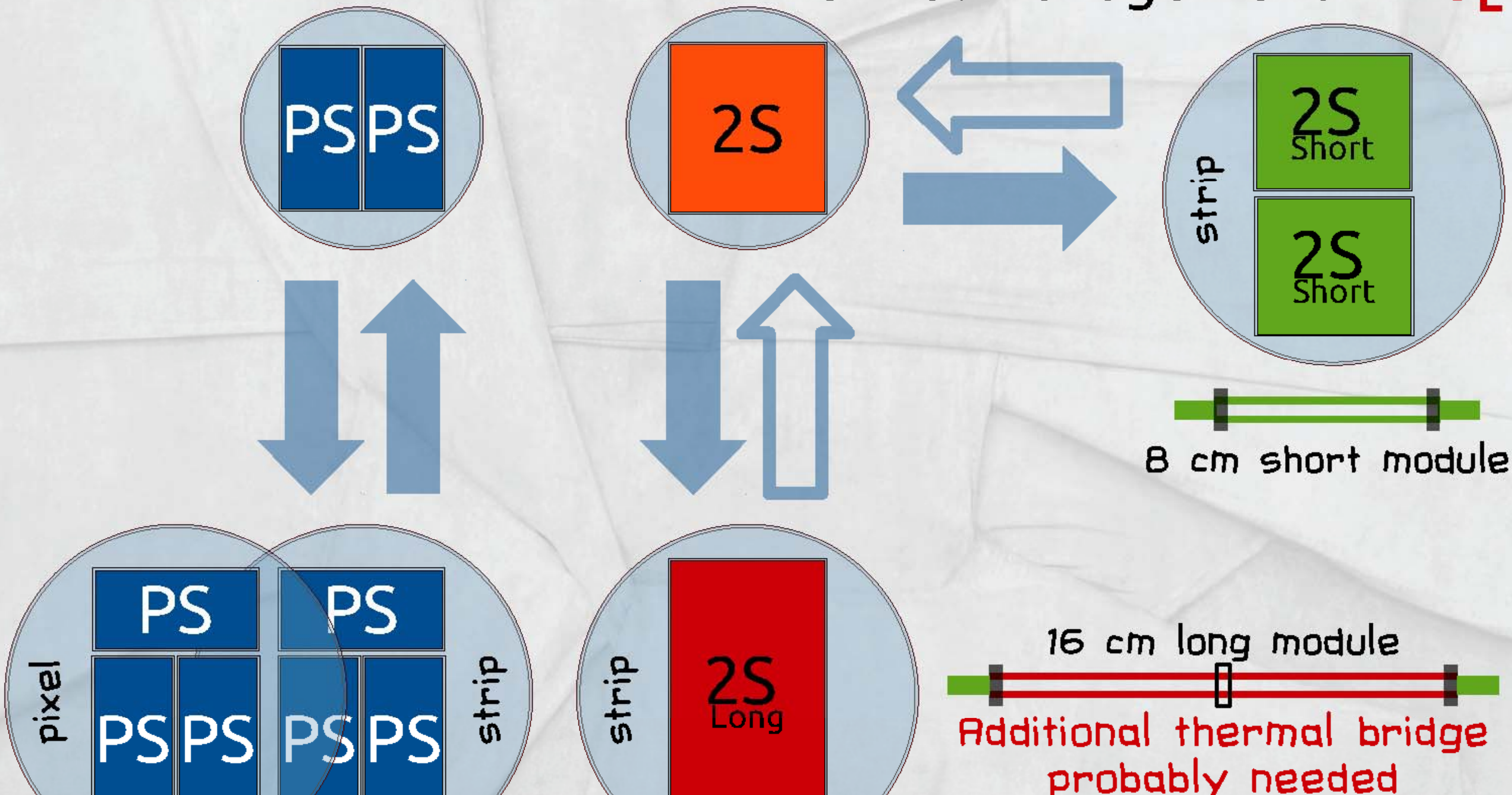




8" dedicated module design

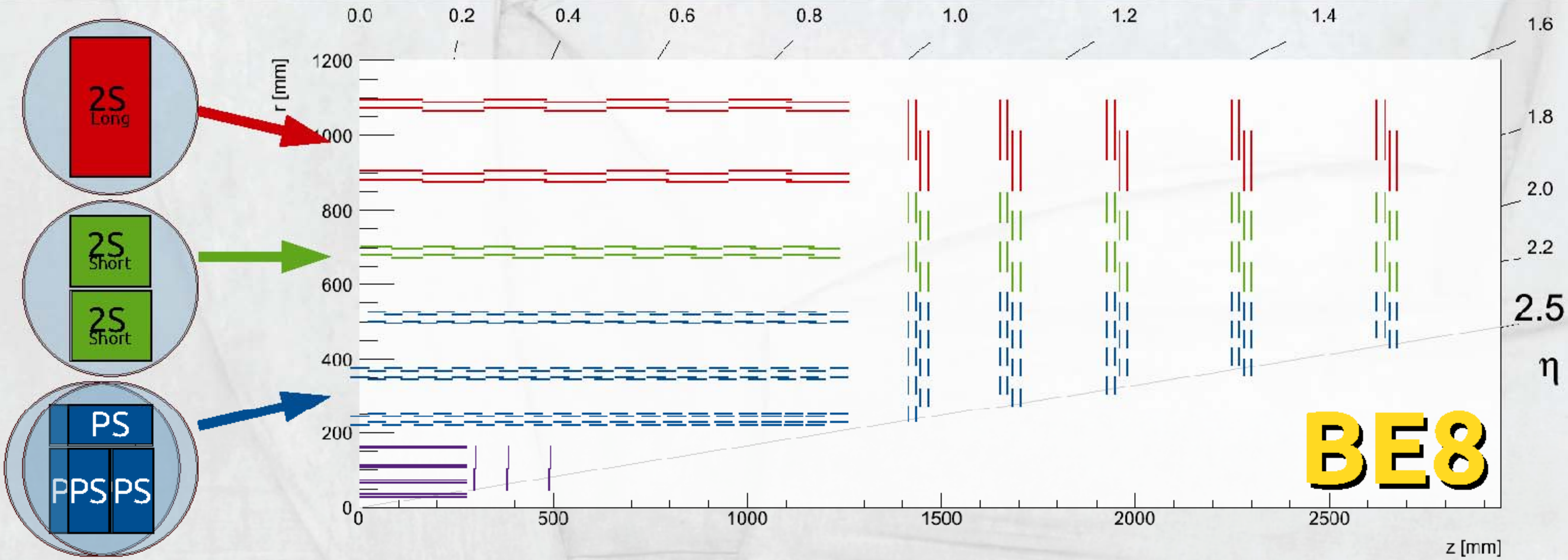
+ Good use of surface
+ Same electronics

– New (but similar) mechanics
– Two module designs for **2S**
– Thermal management in **$2S_L$**



(See talks by Andreas Mussgille and Lutz Feld earlier today)

Barrel+Endcap 8” wafers



	$2S_L$	$2S_S$	PS	Total
Modules	3'680	3'696	6'846	14'222
Sensors	7'360	7'392	6'846 strip 6'846 pixel	28'444
Wafers	**7'360**	**3'696**	**2'282 strip** **2'282 pixel**	**15'620**
Power [kW] (FE+sensors)	10.0+2.0	10.0+1.4	34.3+3.1	54.4+6.4

Ratio: 1.05

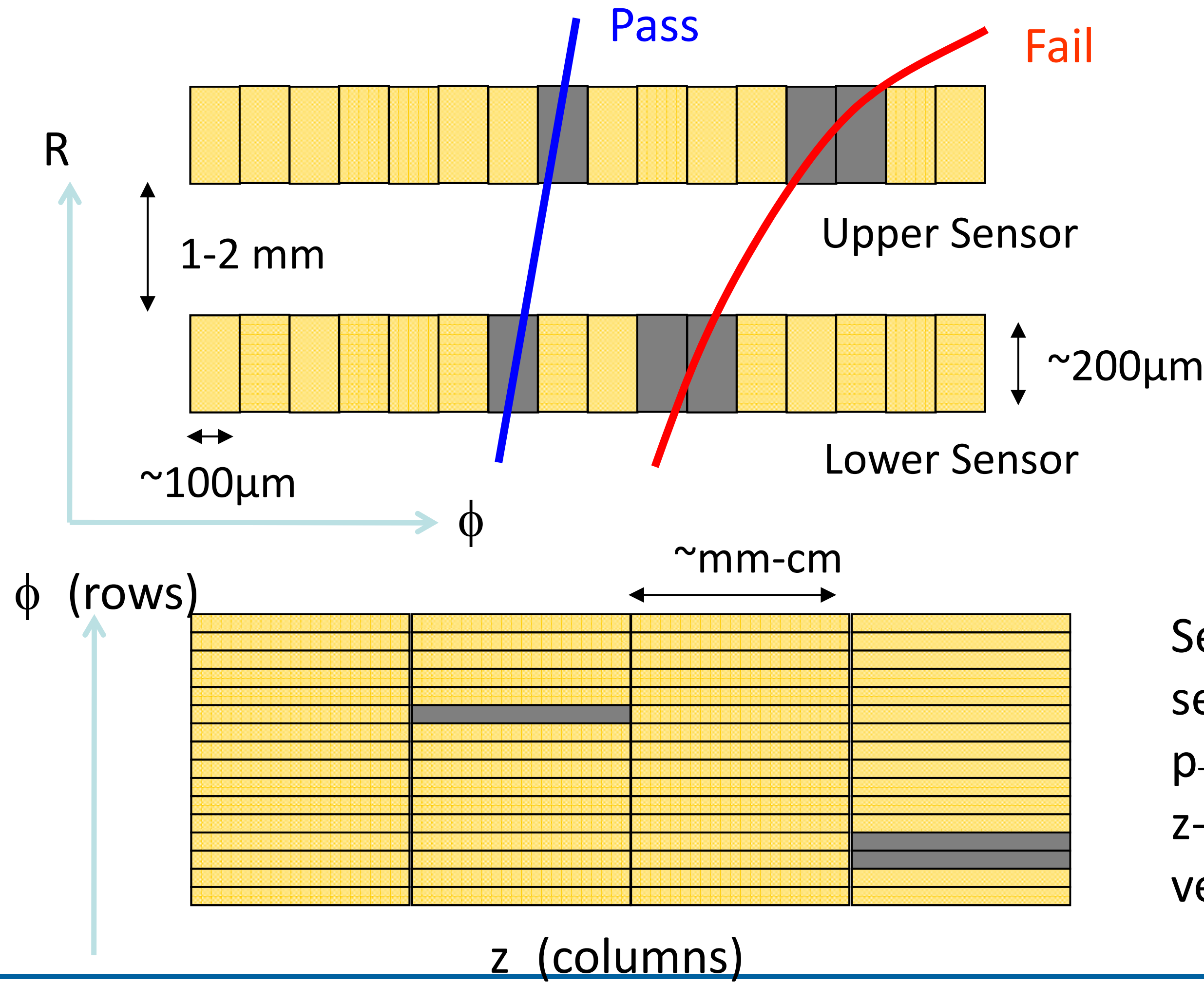
Reasonably large gain

Ratio: 1.49

23'308 wafers
(6” baseline)

Basic trigger module concept

- Compare binary pattern of hit pixels on upper and lower sensors



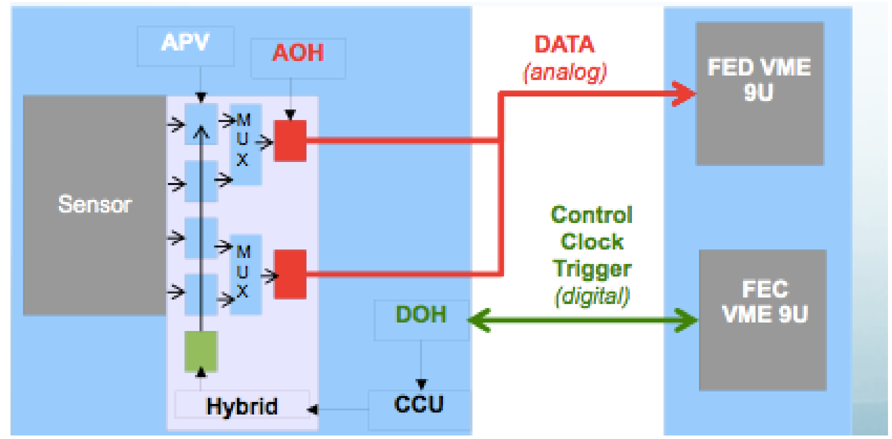
High p_T tracks can be identified if hits lie within a search window in R-ϕ (rows) in second layer

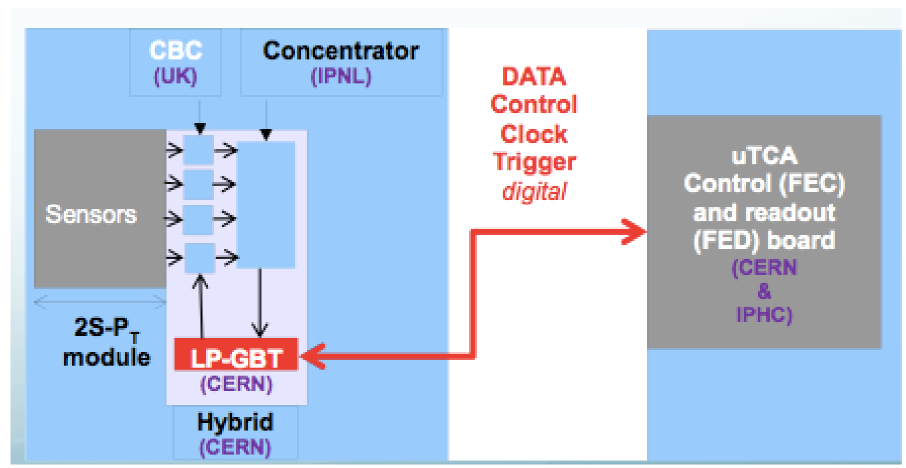
Sensor separation and search window determines p_T cut
z-segmentation determines vertex capability

New readout scheme

Digital readout instead of analog one

- Channel fires if signal above threshold
- Seed channel becomes more important
- No center of gravity to improve position resolution
- Power reduction by ~10 per channel

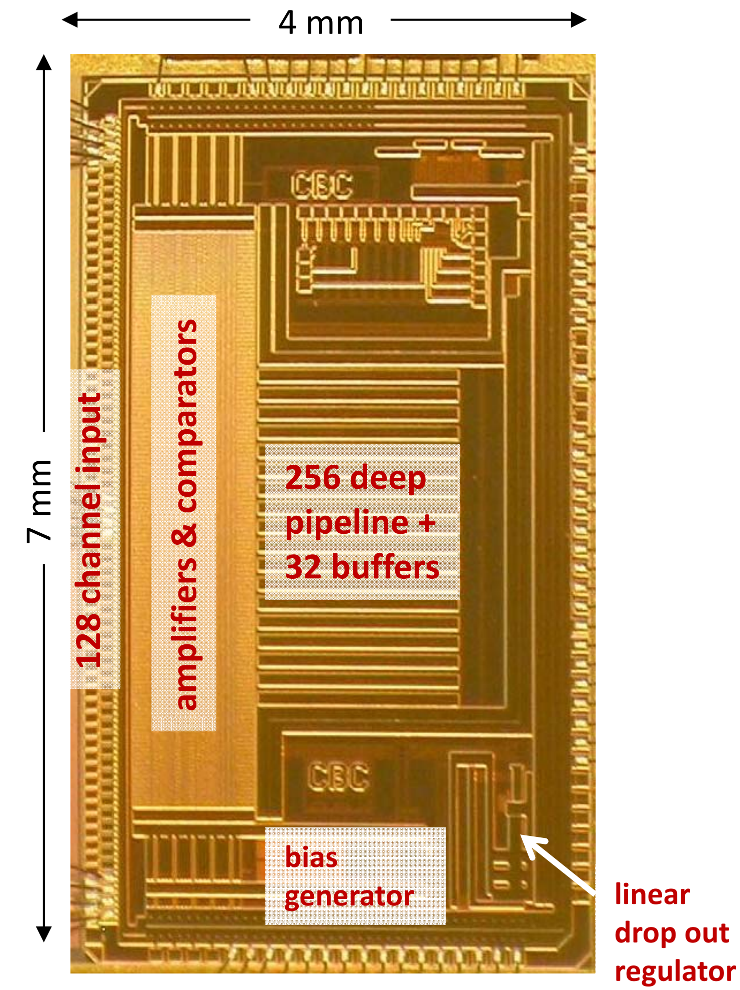




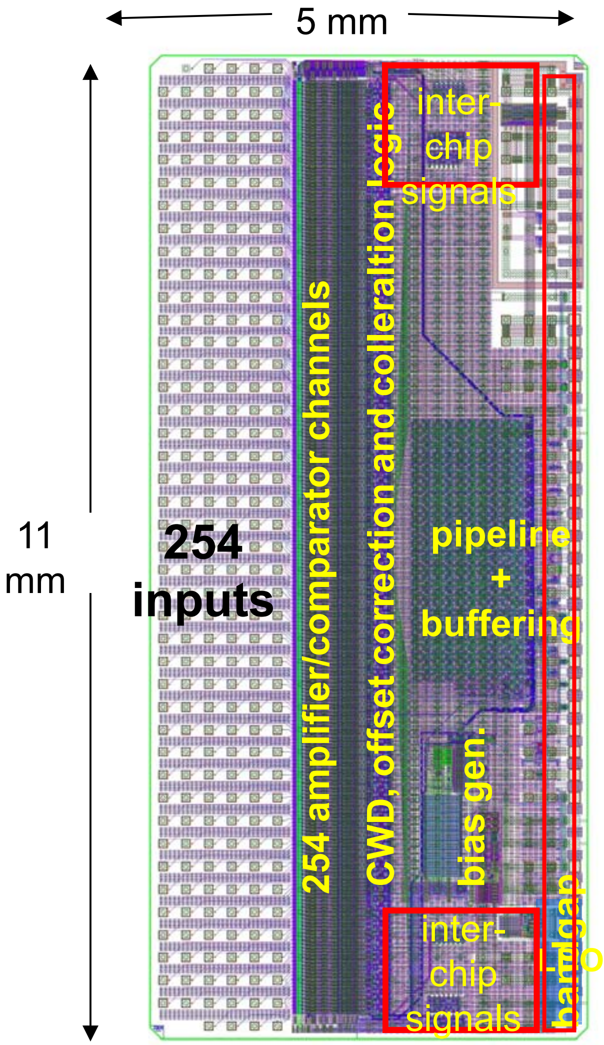
CBC1 readout chip

Development of a new readout chip

- IBM 130nm CMOS process
- binary, unsparsified architecture
  - retains chip and system simplicity
  - but no pulse height data
- designed for ~2.5 - 5cm µstrips < ~ 10 pF
- 128 channels, 50 μm pitch wire-bond
- either polarity input signal
- **not contributing** to L1 trigger
- powering test features:
  - 2.5 -> 1.2 DC-DC converter
  - LDO regulator (1.2 -> 1.1) feeds analogue FE
- fast (SLVS) and slow (I2C) control interfaces



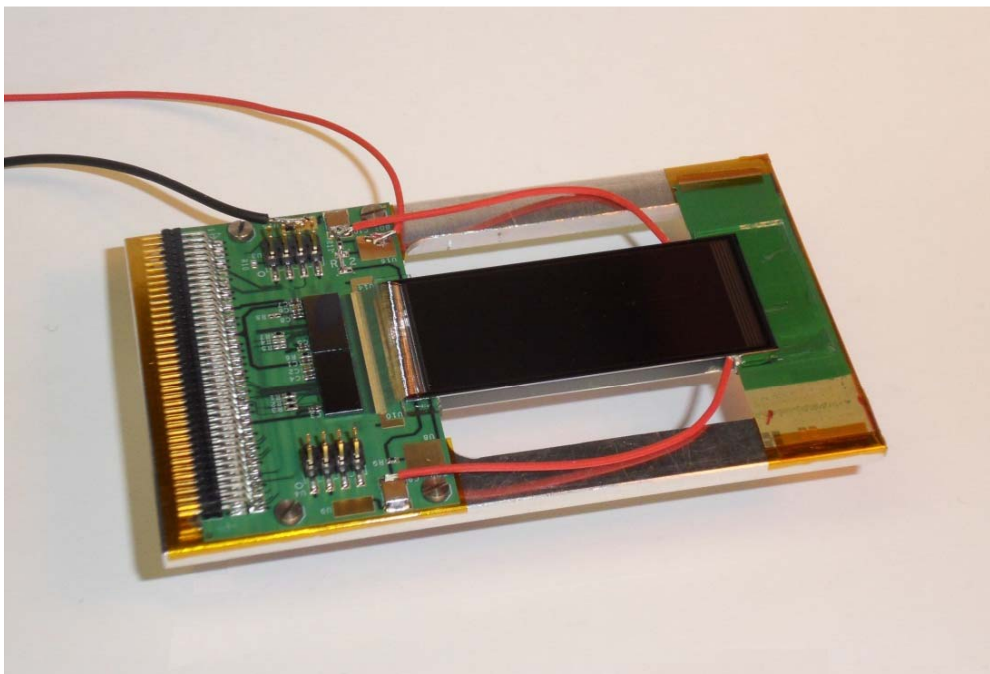
CBC -> CBC2: New features



- 250µm pitch C4 layout
  - aim for commercially assembled module
  - some gains in bond inductance
  - back edge wire-bond pads for wafer probe
- 254 channels for 127 + 127 strips
- correlation logic for stub formation
  - between top & bottom strips
  - vetoes wide clusters
- Test pulse
  - no time to implement on CBC
  - & other minor circuit improvements
- received Jan 2013 – fully functional

2S mini-module

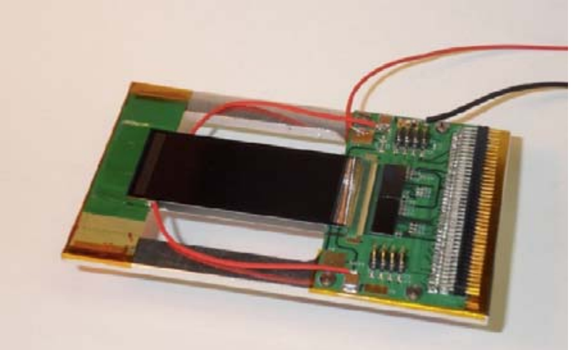
- Three prototypes assembled using CBC2 chips and two Infineon baby sensors
  - Now under test in lab
  - Beamtest scheduled for week of 25 November



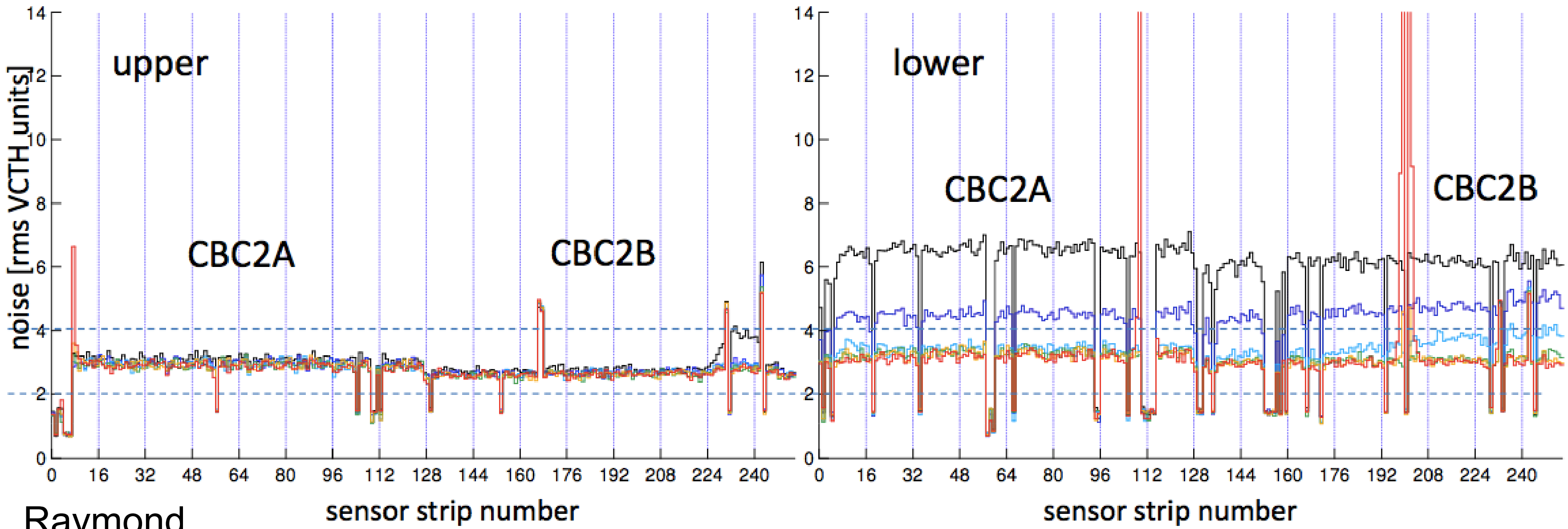
A. Honma

Noise Issues on CBC2 mini-module

- 4 STS sensors (batch 1) have been used to build two CBC2 mini-modules
- For both modules the lower sensor needs higher bias



Vbias: 20 - 400 V



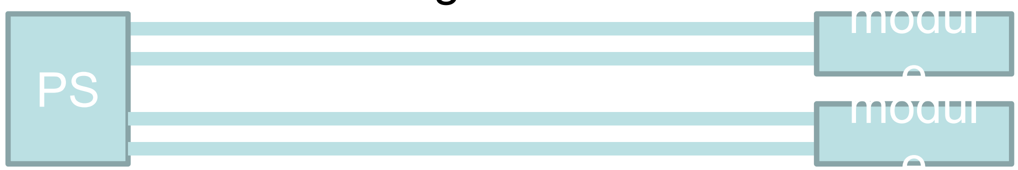
M. Raymond

CBC chip road map

2011	**CBC1** - analogue front end in 130nm - wirebonded - binary logic - L1 triggered readout only, non-sparsified	
2012–2013	**CBC2** - C4 bump-bonded - full hit correlation logic - L1 triggered non-sparsified readout, fast trigger OR	
2014–2015	**CBC** - full readout architecture defined - final data format - additional correlation logic	**2S prototype module studies**
2016–2017	**CBC4** - optimisation - final version	**2S final module studies** **start production**

Power Distribution Options

Conventional Powering



- well established
- excessive cable losses

→ supply power at higher voltage i.e. lower current
→ cable loss $P_{loss}=R\cdot I^2$ is reduced by factor r^2!

DC-DC Powering r=conversion ratio

- system design is kept simple and close to current systems
- only one new component
- switching noise is a concern

Serial Powering r=number of modules in chain

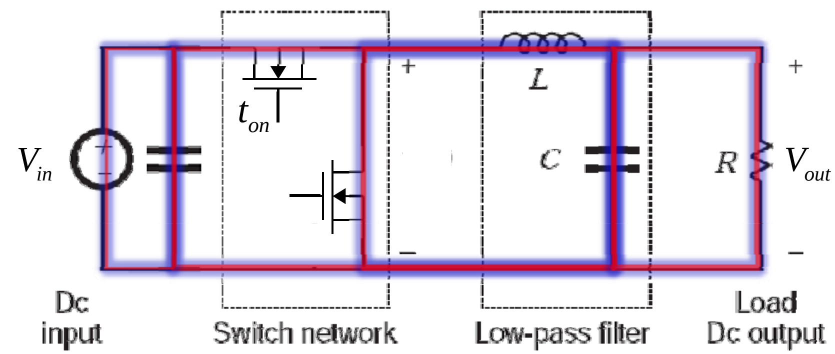
- no switching
- each module has different ground potential
- modules in a chain are coupled, need safety features

DC-DC Powering: Buck Converters

operation principle

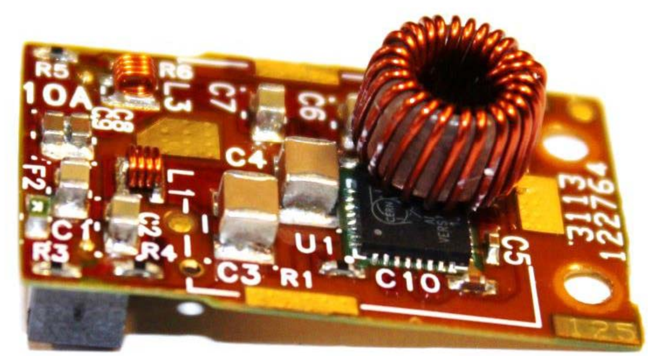
output voltage is regulated via feed-back loop by adjustment of duty cycle $D = \frac{t_{on}}{T}$:

$\boxed{V_{out} = D \cdot V_{in}}$ for lossless converter



main parameters

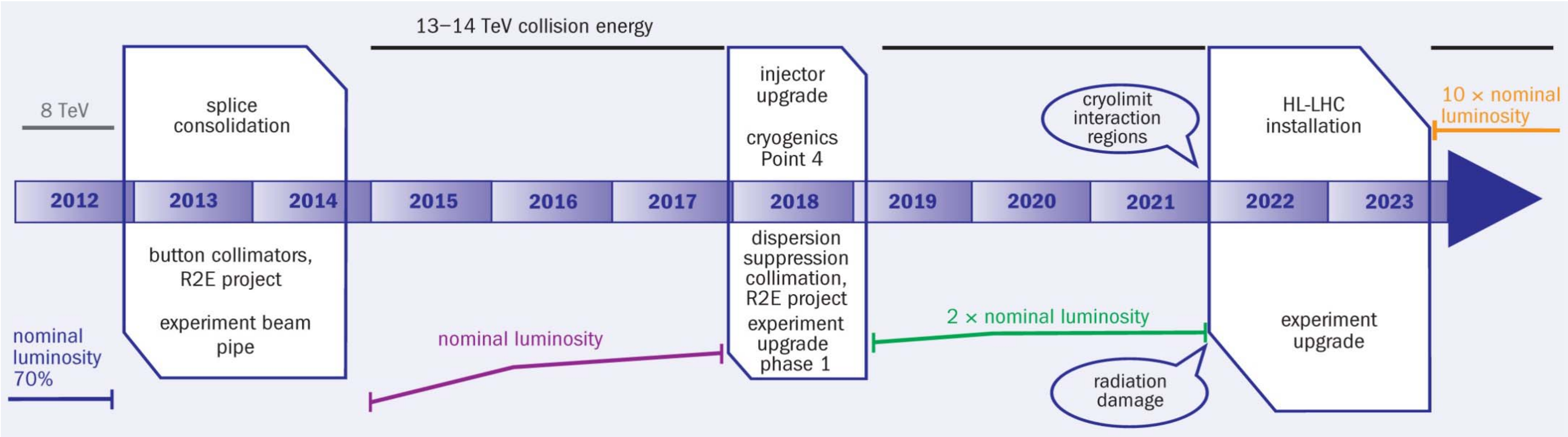
conversion ration	$r = \frac{V_{in}}{V_{out}} = 2 \ldots 10$
switching frequency	$f = 1 \ldots 4$ MHz
efficiency	$\eta = \frac{P_{out}}{P_{in}} = 60 \ldots 90\%$
current ripple at inductor	$\Delta I_L = \frac{V_{out}(1-D)}{L\ f}$



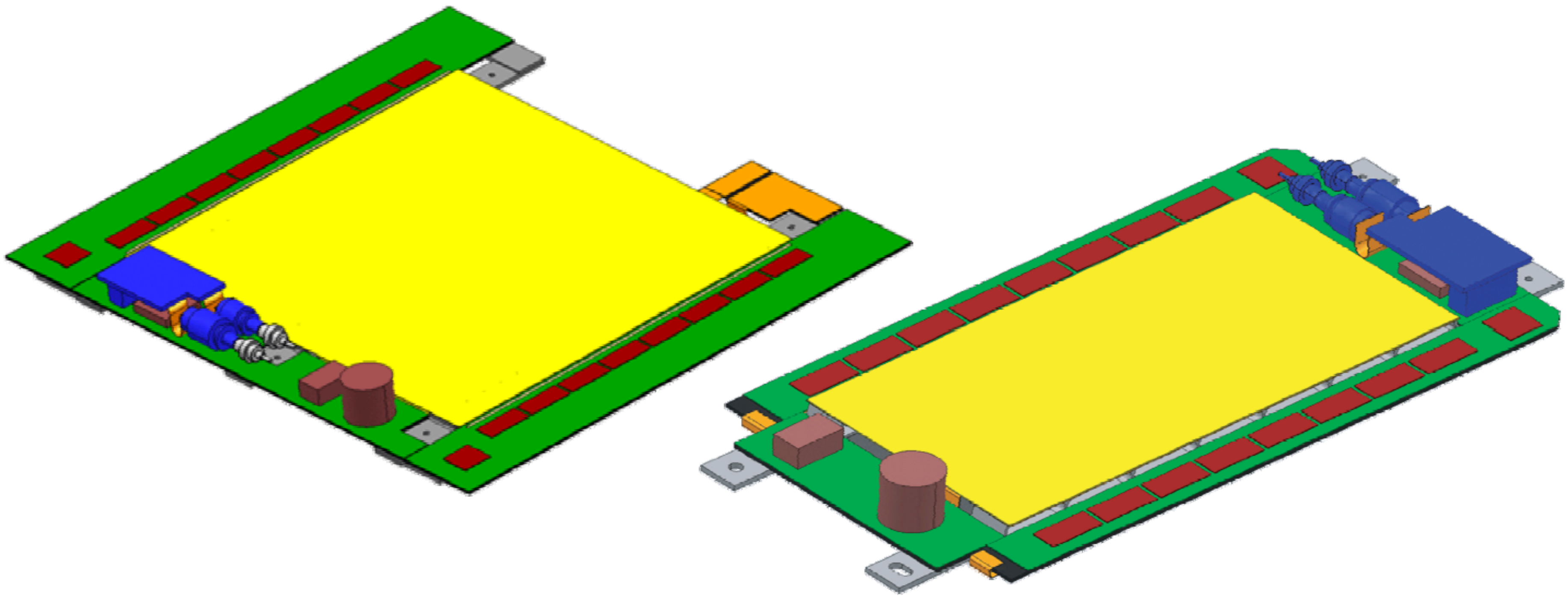
custom development necesssary

- radiation hard ASIC
- air core inductor for operation in magnetic field

Timeline for Sensor Procurement

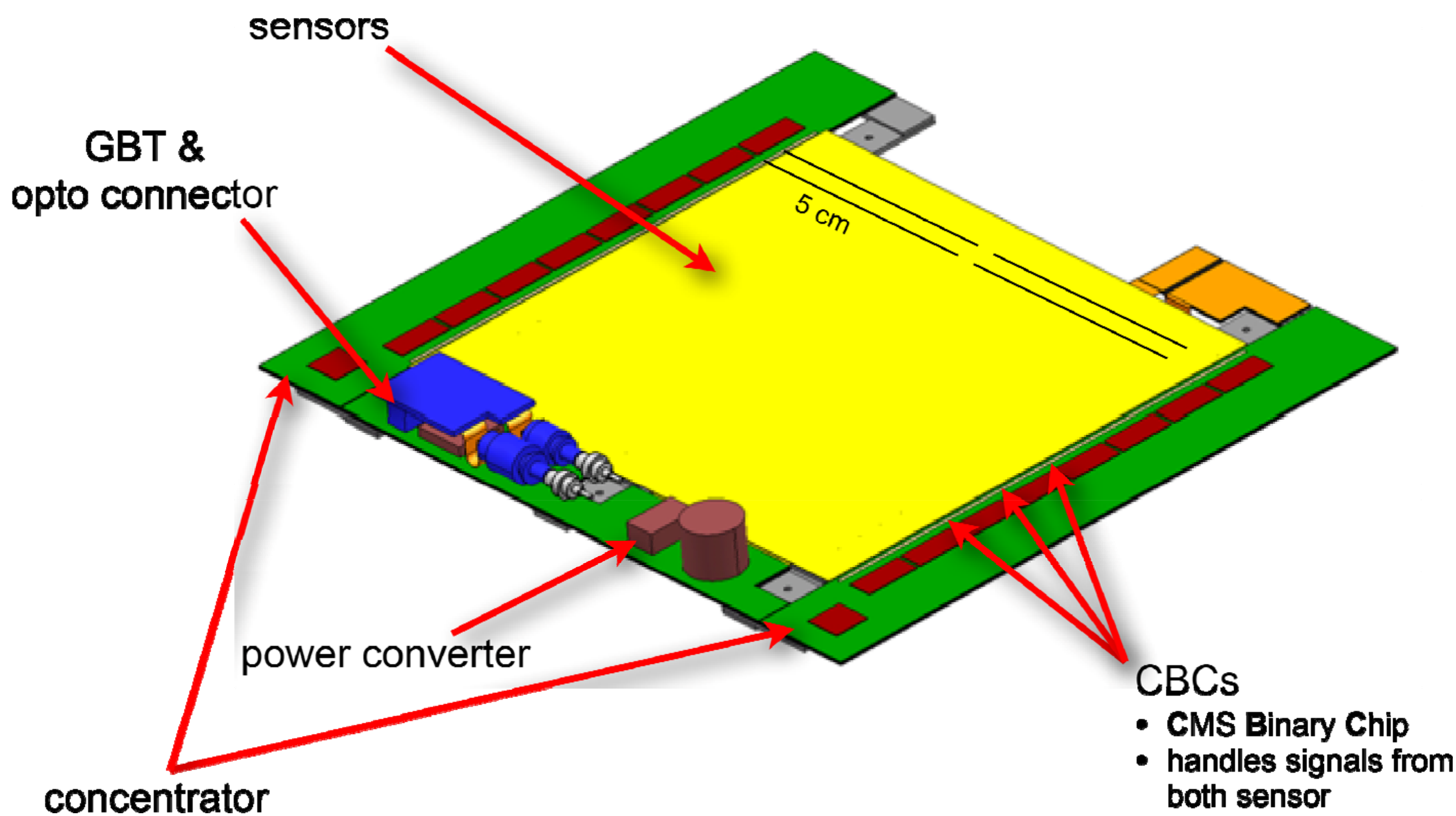


- Tentative sensor procurement timeline:
  - Mid 2014: Market survey
  - Then define detailed specs with qualified vendors
  - 2016: Tender
  - 2016 - 2017: Preproduction
  - 2017 – 2018: Production

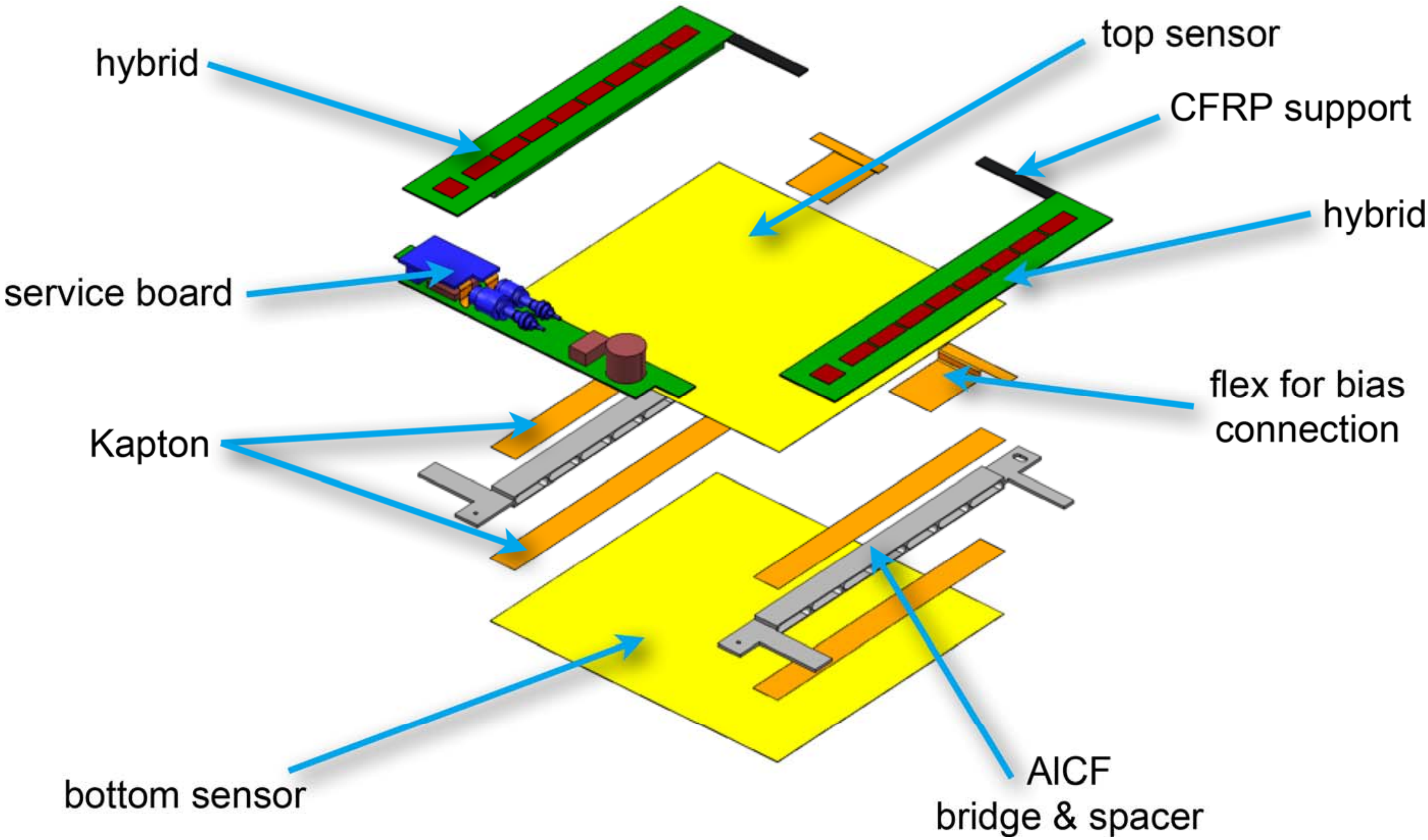


BASELINE MODULE DESIGNS

2S Module

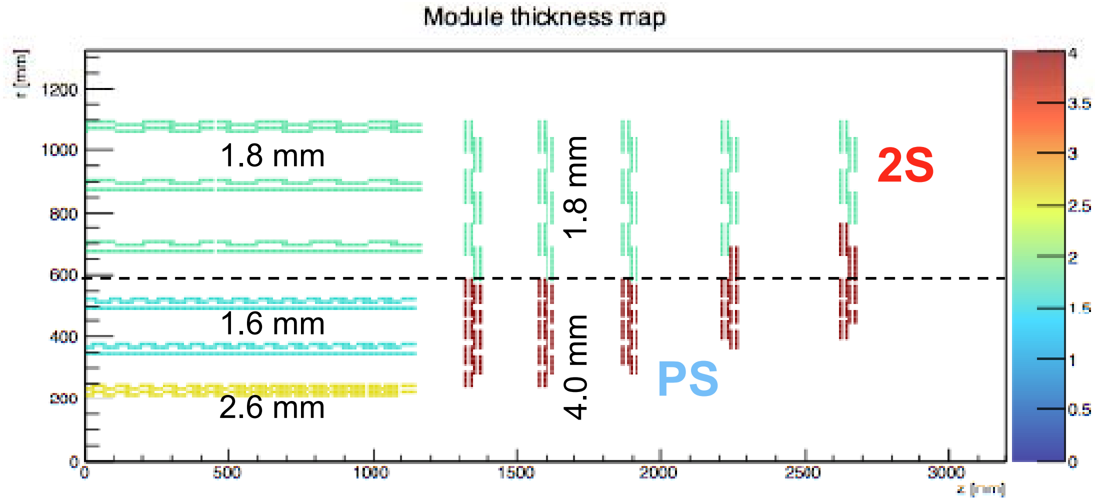

sensors
GBT &
opto connector
5 cm
power converter
CBCs
• CMS Binary Chip
• handles signals from both sensor
concentrator

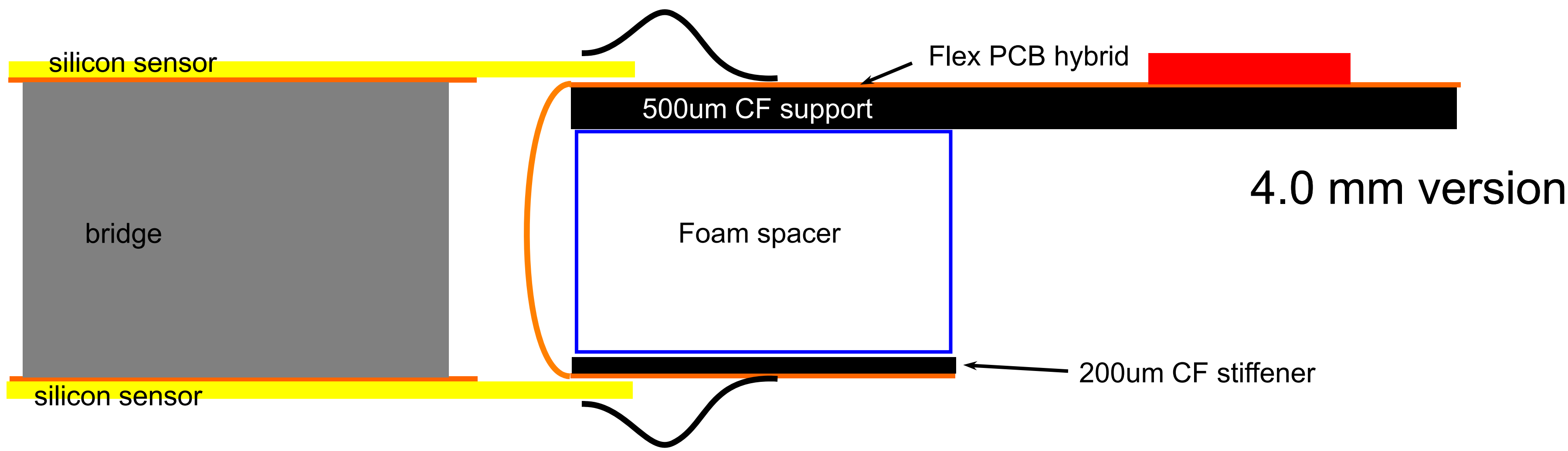
2S Module


hybrid
top sensor
CFRP support
hybrid
service board
flex for bias
connection
Kapton
bottom sensor
AlCF
bridge & spacer

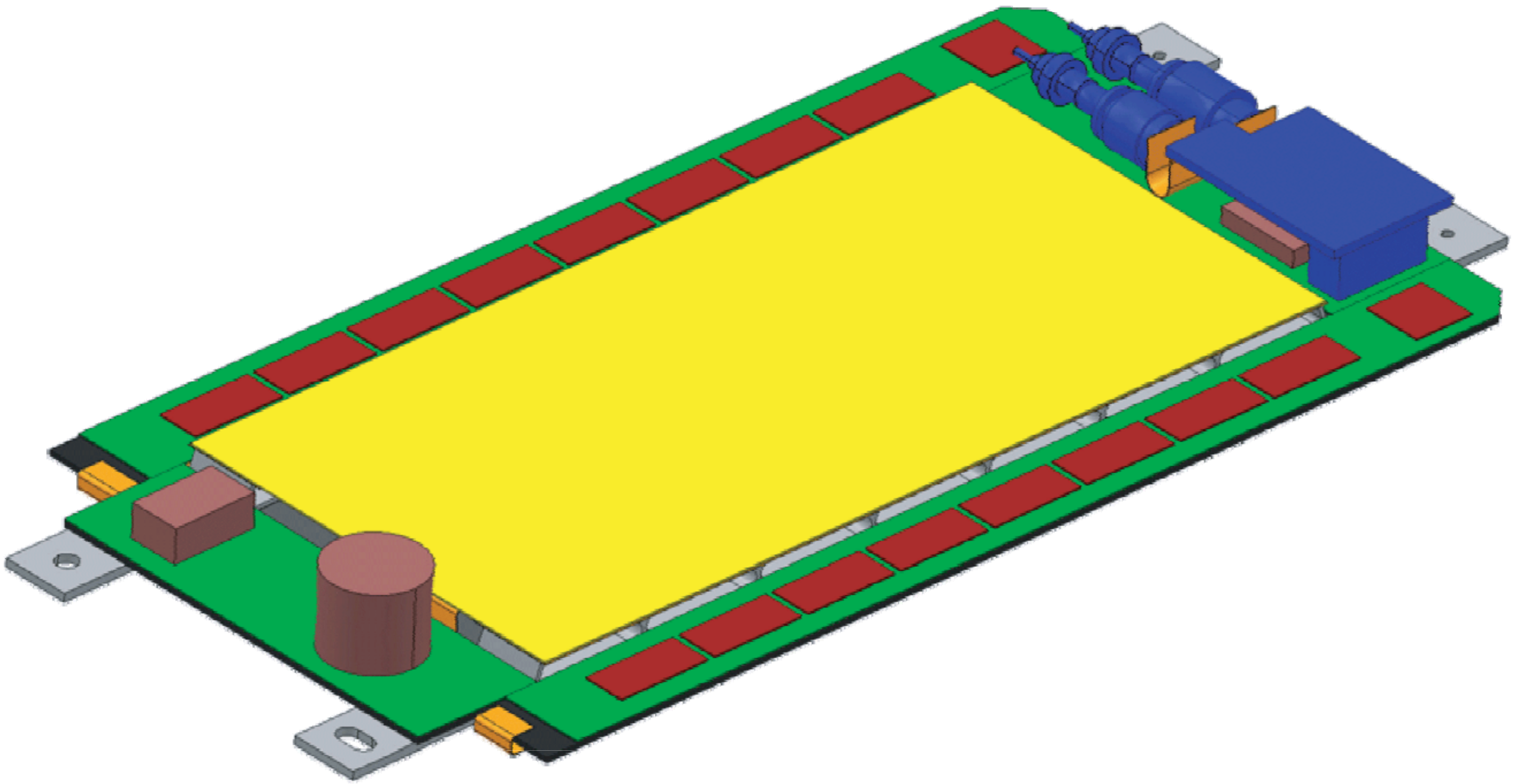
2S Module - Flexible Hybrid Option

- 2 sensors have different distances depending on position
- How to connect second (bottom) sensor?

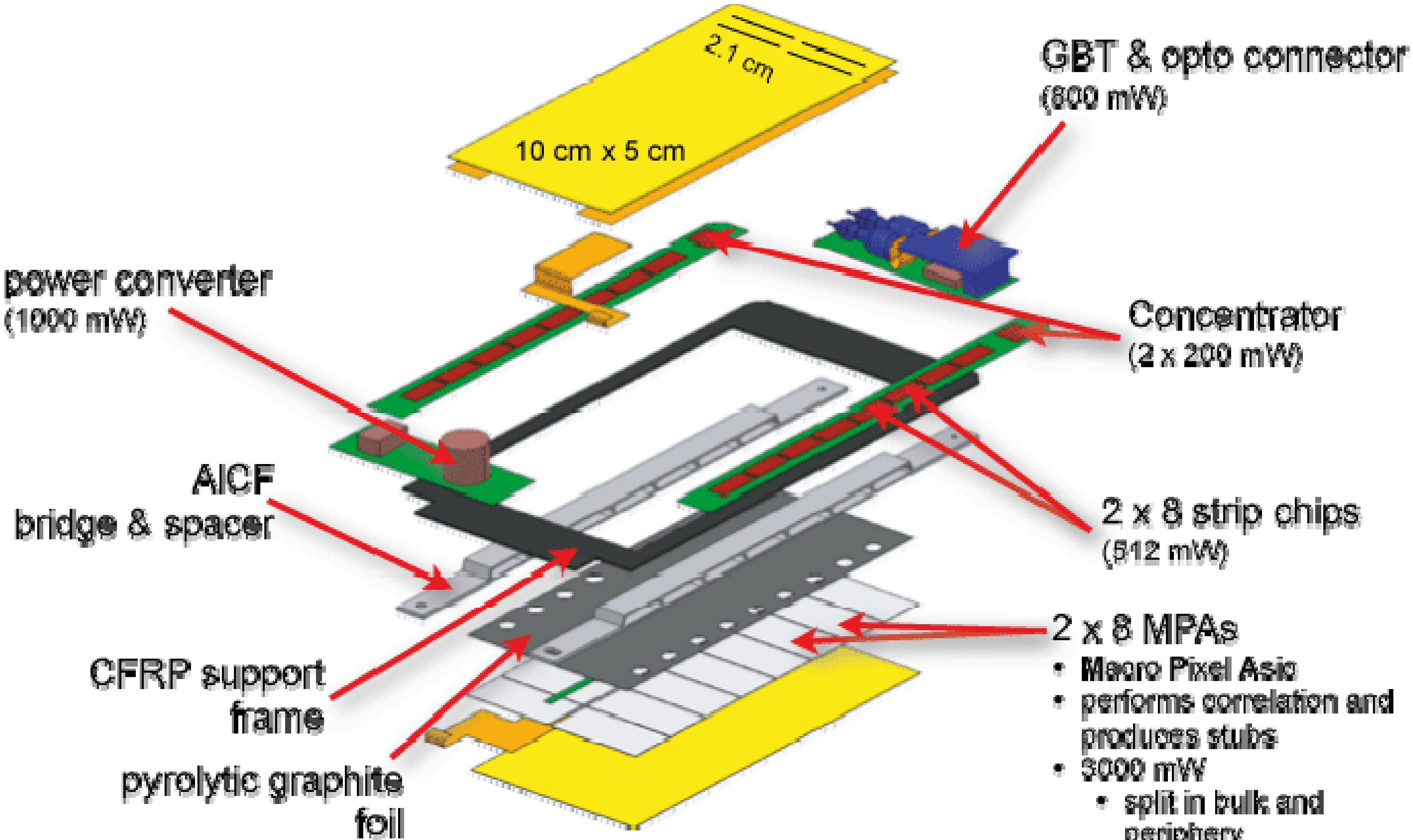




PS Module



PS Module


2.1 cm
10 cm x 5 cm
GBT & opto connector
(800 mW)
power converter
(1000 mW)
Concentrator
(2 x 200 mW)
AlCF
bridge & spacer
2 x 8 strip chips
(512 mW)
2 x 8 MPAs
• Macro Pixel Asic
• performs correlation and produces stubs
• 3000 mW
• split in bulk and periphery
CFRP support frame
pyrolytic graphite foil

DEVELOPMENTS WITH ALTERNATIVE VENDORS

Producers for Silicon Detectors

- Small scale R&D production:
  - Many institutes and companies are able to produce a few 10-100 wafers per year
  - 6 inch is usually available at many sites
  - The sensors differ in a broad spectra of quality and price
- Large scale commercial production:
  - Currently only one company is able to produce a few 1.000 – 10.000 high quality wafers per year
- Possible new producer: **Infineon**
  - Production on thinned 8 inch wafers could be possible

→ Dual or multi-source strategy would be preferable

SINTEF
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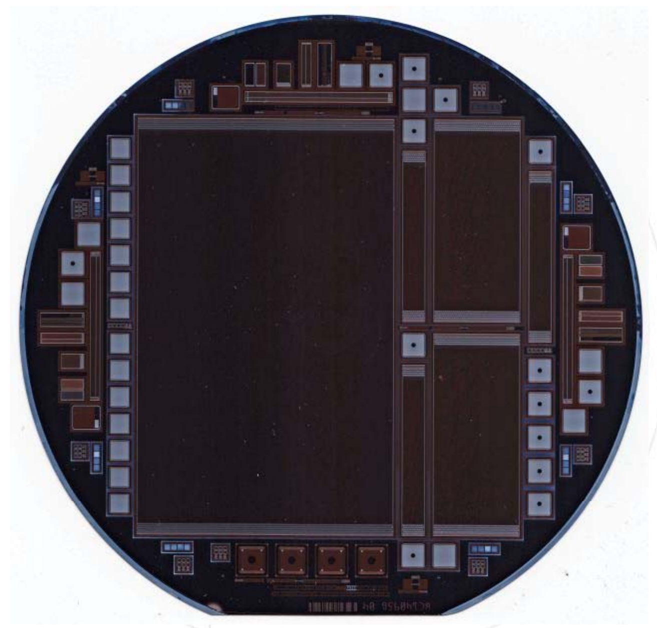
IMB
CANBERRA
VTT
CiS
Forschungsinstitut für Mikrosensorik und Photovoltaik GmbH
HAMAMATSU
PHOTON IS OUR BUSINESS

Production of Sensors at Infineon

- End of 2009: Started intense **discussion on technical details**
- Beginning of 2011: **First milestone**
  - Reached a general **understanding of the production process**
  - HEPHY started **design of the masks**
  - Infineon started the generation of the **detailed production plan**
- 24 August 2011: **Final mask design finished!**
- October 2011: **Production start**
  - Full production at Infineon was accompanied by HEPHY diploma student
- 29 February 2012: **Production finished**
- 2 April 2012: **Wafers arrive in Vienna** (via CERN)
- October 2012: **Beam tests and Irradiation**
  - **Beam tests** at the SPS accelerator at CERN
  - Gamma Irradiation at SCK-CEN Mol, Belgium

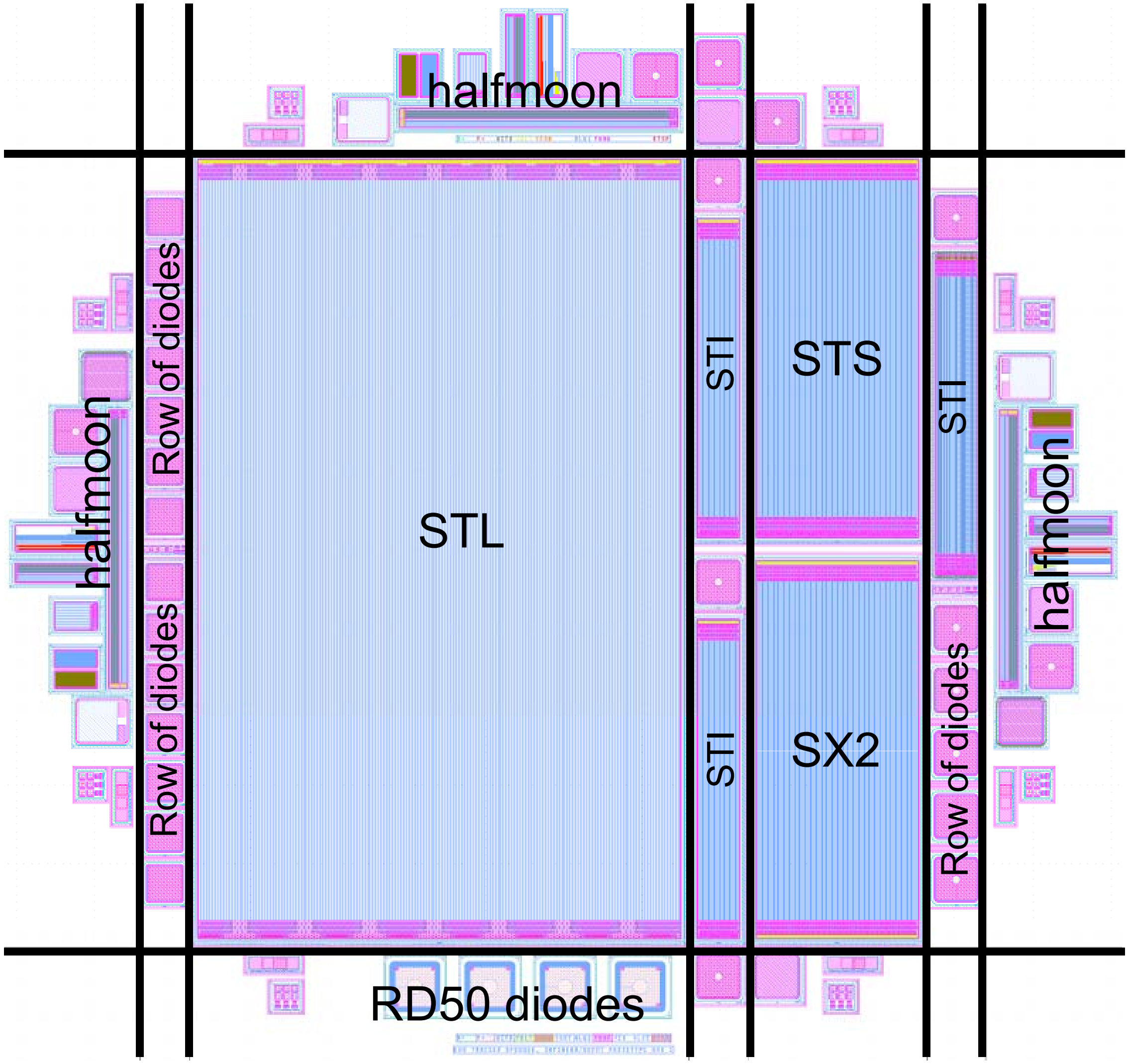


HEPHY Institute of High Energy Physics

infineon

Layout of Batch 1 and 2

- Large Sensor: STL
- Small Sensor: STS
- Strixel Sensor: SX2
- Irradiation Sensor: STI
- CMS halfmoons (Test structures)
- Large number of diodes and MOS
- SIMS fields



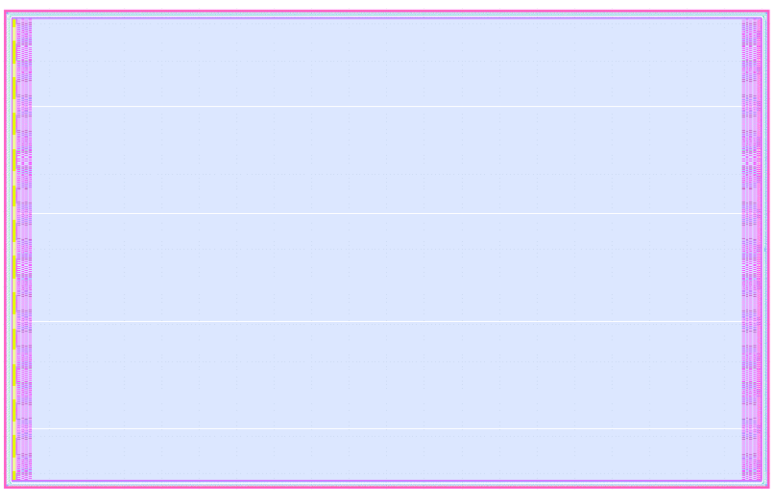
Main Device Properties

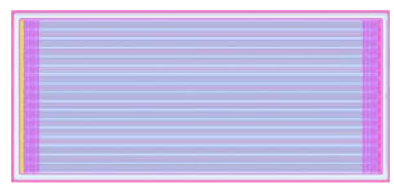
Sensor STL

- 120 µm pitch
- 20 µm strip implant width
- Size: 64 x 102 mm
- 512 strips (4xAPV)

Sensor STS, SX2 and STI

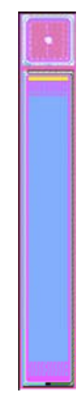
- 80 µm pitch
- 20 µm strip implant width
- STS and SX2:
  - Size: 23 x 50 mm
  - 256 strips (2xAPV)
- STI: 64 strips, 42.4 x 7 mm





STS

SX2: Strixel

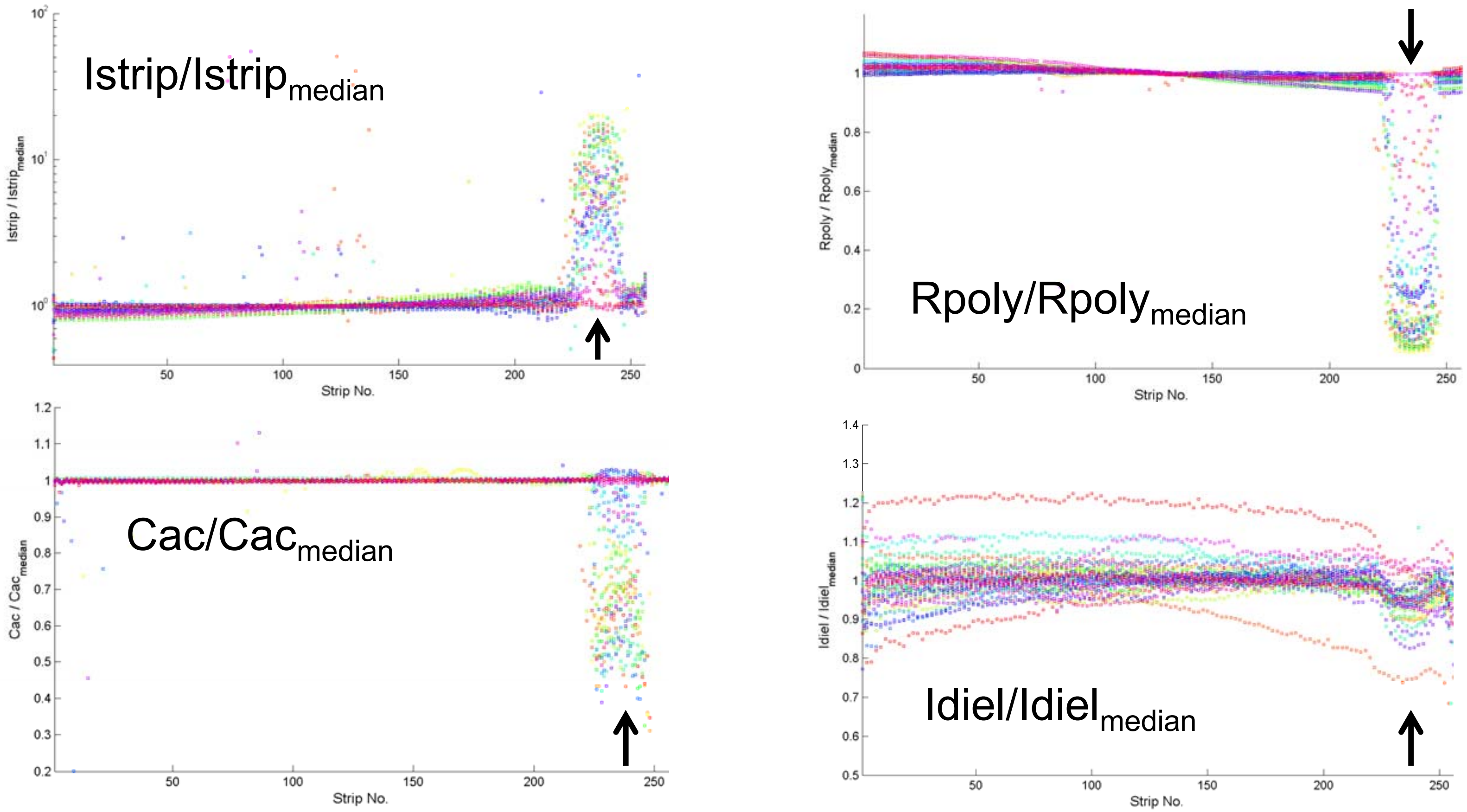


STI

Batch 1 Defective Strips (STS Sensor)

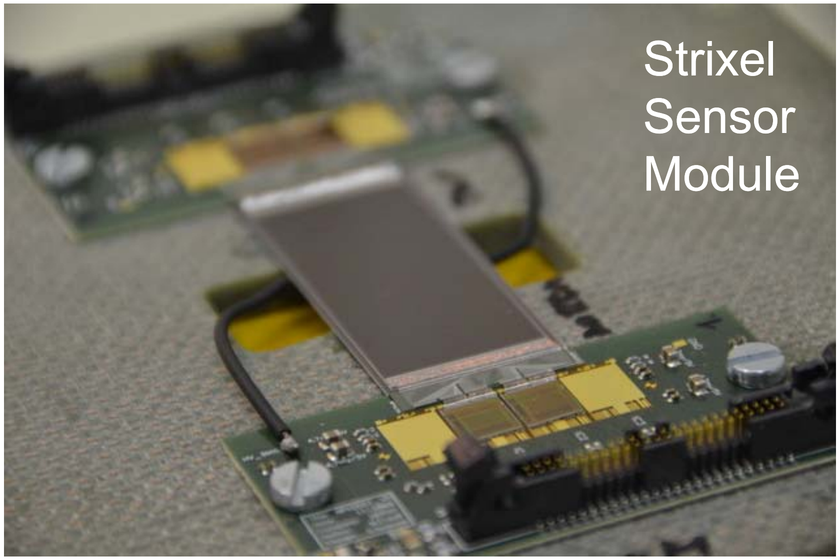
- Accumulation of anomalous strips around strip no. *222-248*

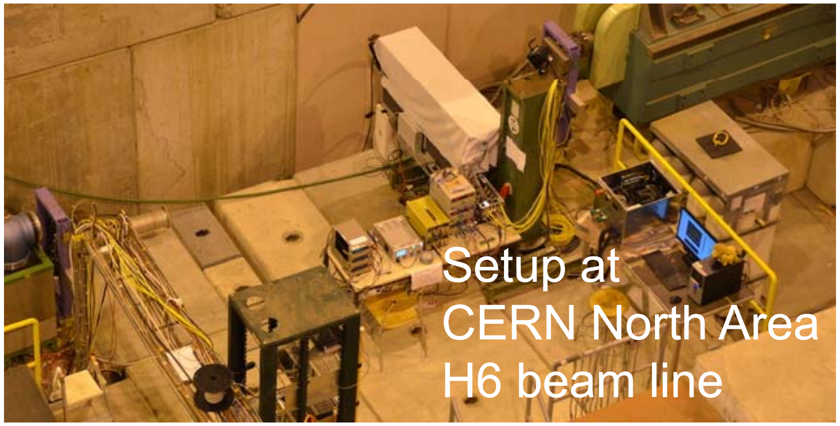
– all split groups affected



Beam Test at CERN‘s SPS

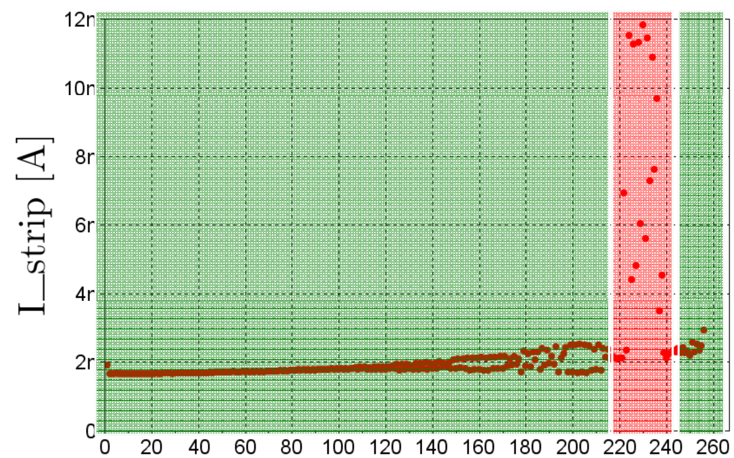
- 120 GeV/c hadrons (mostly pions) in H6 area of NA hall
- 4 detector modules build
  - 2 baby sensors
  - 2 strixel sensors
- Readout chips (APV25) same as in the CMS Tracker
- Readout system is a prototype for the Belle II Experiment
- Detector modules were
  - Tested at CERN
  - Gamma irradiated at CNK-CEN Mol
  - Tested again at CERN

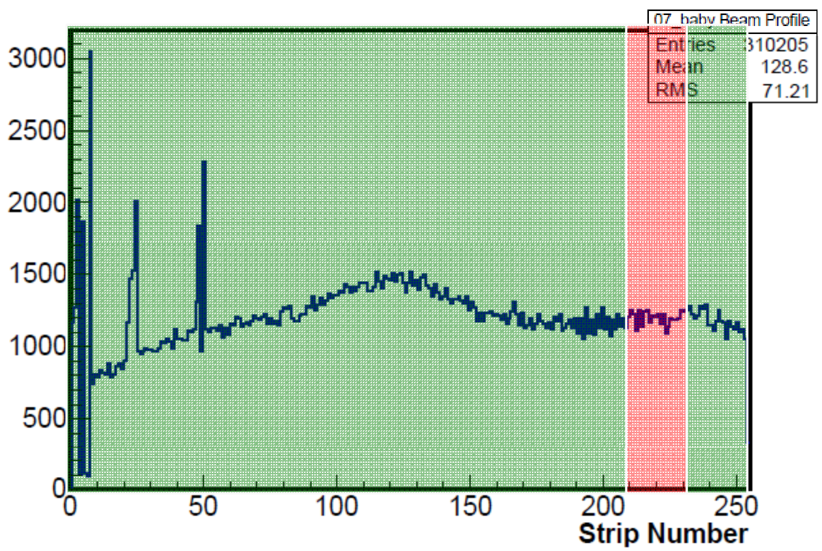


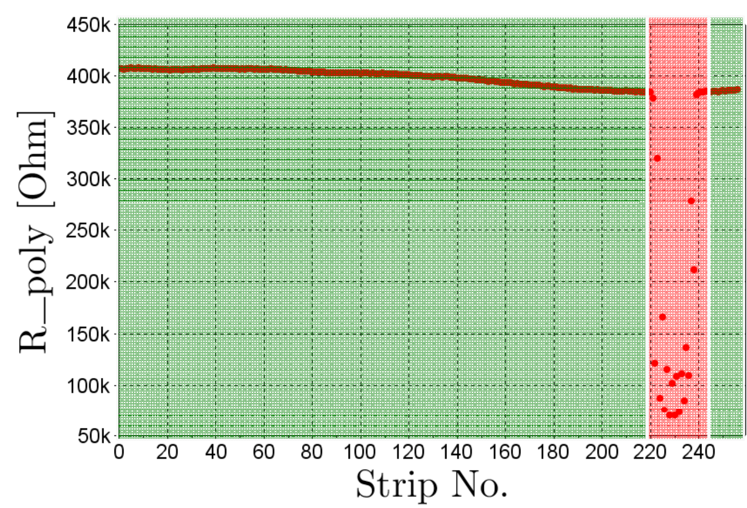


1. Results of Beam Test: Sensor Sections

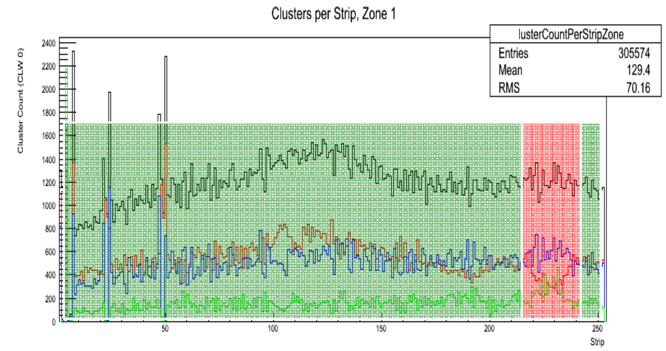
- The bad strip area does not stand out clearly in beam profile and seems to be fully efficient
- For a more detailed analysis the sensor has been divided into two sections:
    - One good section (green)
    - One bad section (red, strip no. 222 – 238)



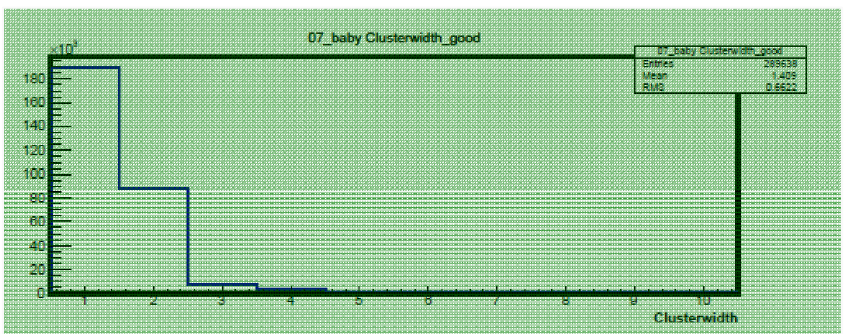


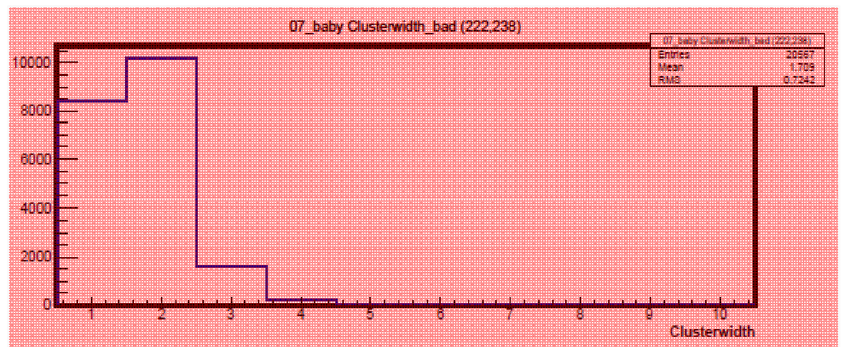


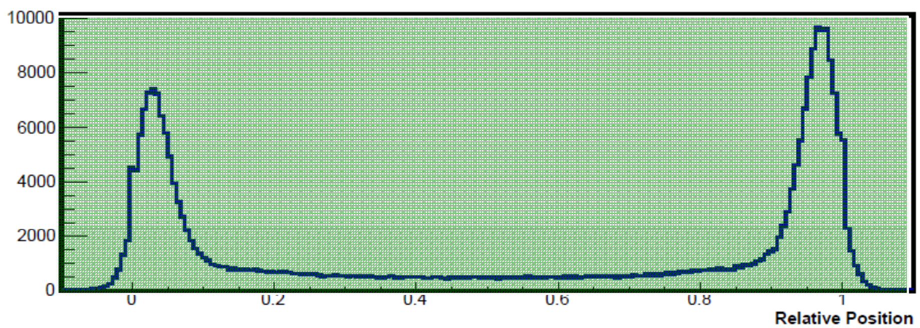
1. Results of Beam Test: Different Sections

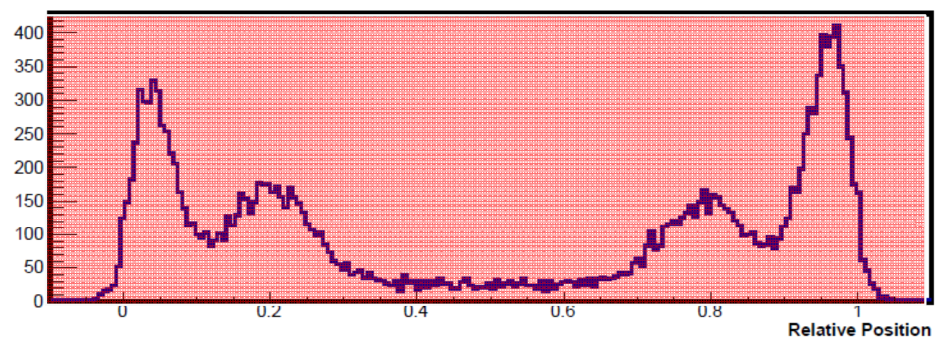


- The results indicate problems with the strip isolation at the “bad area”
  - Clusters are wider in “bad section”
  - The eta distribution indicates an anomalous charge sharing between the strips



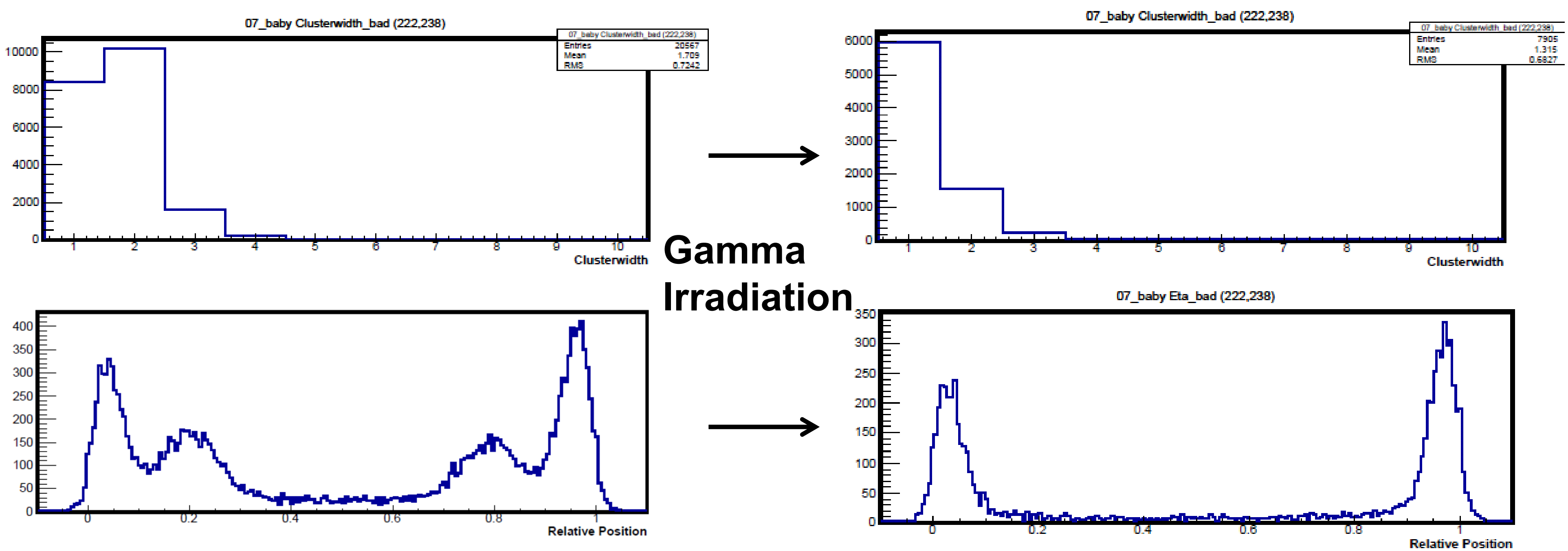






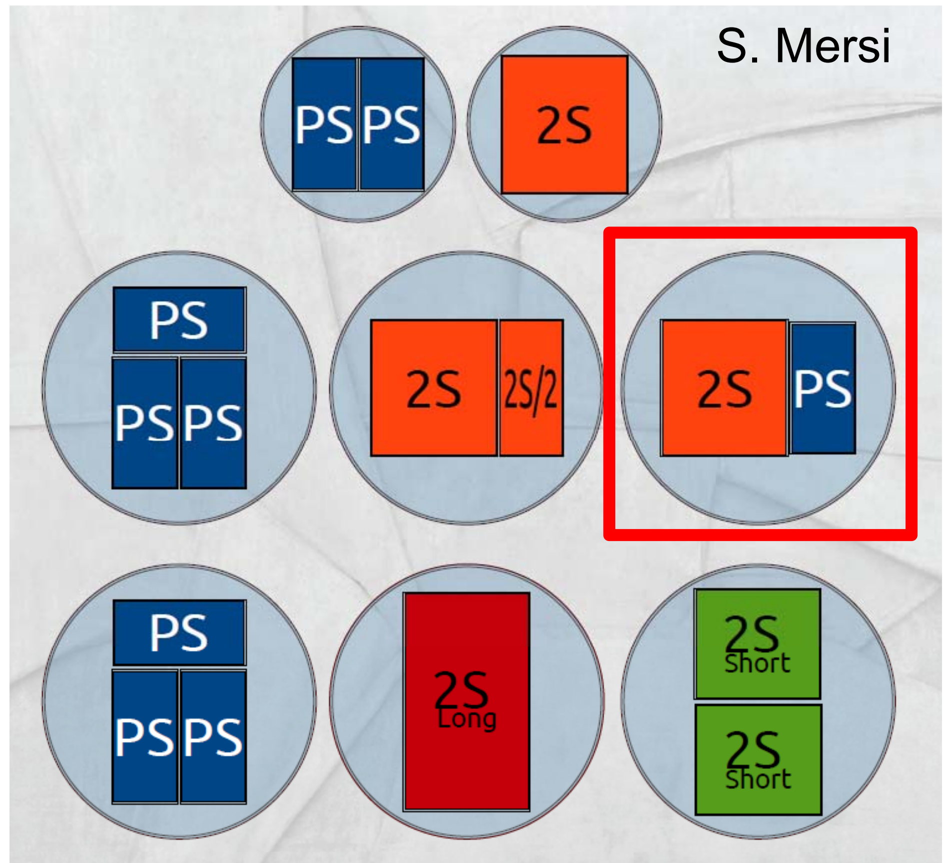
1. **Results of Beam Test:** Gamma Irradiation

- The modules have been gamma irradiation and tested again
- The gamma irradiation mainly effects the silicon oxide layer on the sensor surface
- Gamma irradiation seems to cure the problem, which fits well to the assumption of accumulated charge inside the silicon oxide



Proposals for 8“ Sensors

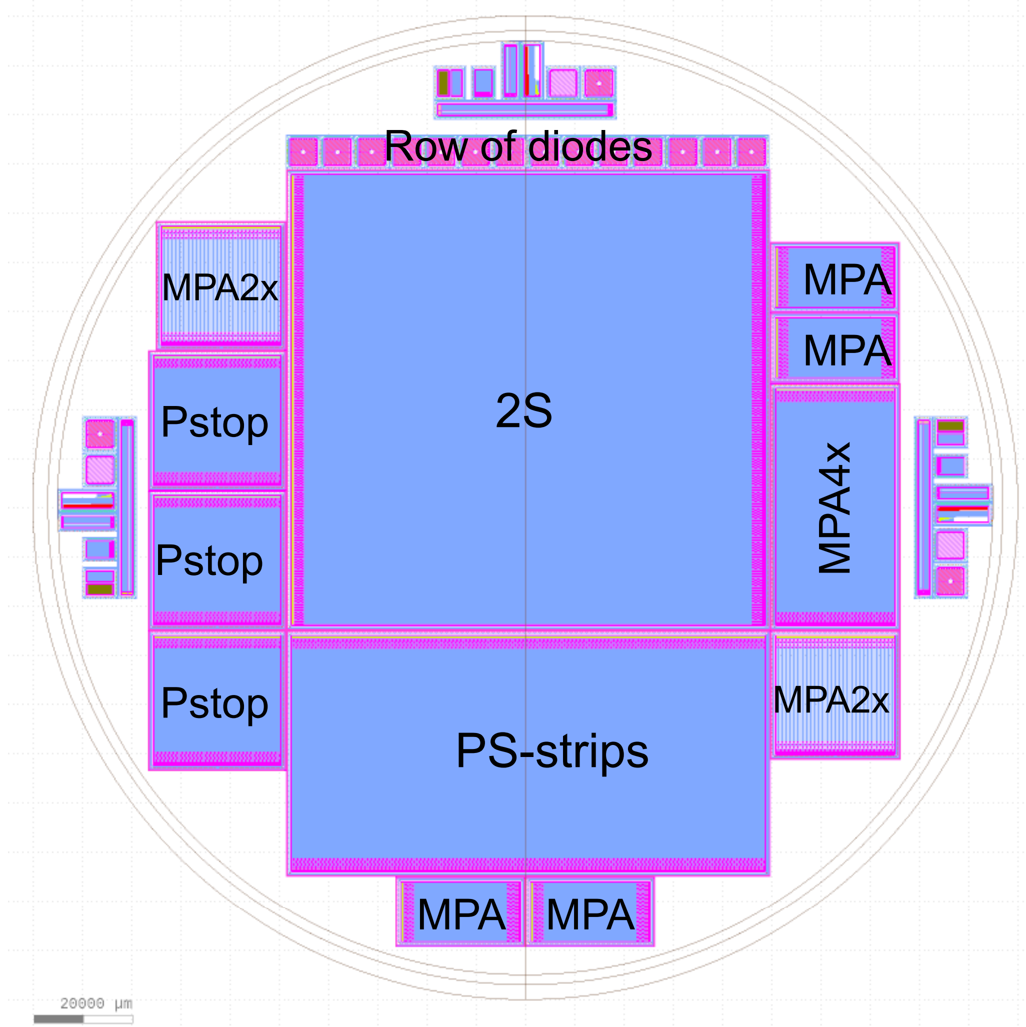
- Top-down approach driven by tkLayout
  - Long-term prospective for building an optimal tracker
- Compatibility with 6“ implies that we do not use 8“ area optimal
  - But better suitable for existing module designs
- Now (2013/14) we need a layout which is suitable for
  - Building module prototypes (2S and PS)
  - Evaluate 8“ production (n-on-p)
  - P-stop studies



„PS“ means „PS-strips“ (and not „PS-pixel“)

8” Wafer Layout Proposal

- Wafer size: 200 mm
- Clearance zone 5 mm default around fiducial area
  - 3 mm absolute minimum if necessary
- 8” Wafer do not have a flat only a very small notch (not shown)
- Layout not yet taking alignment marks and vendor test structures into account
  - Have to sit on fixed places



Test of Silicon for radiation hardess

HPK CAMPAIGN

CMS Strategy

- Most of the volume of a future Tracker will be equipped with planar silicon sensors
  - We have started a **survey of available silicon materials** to probe their individual limits
  - **One wafer layout** has been developed and the various materials are processed with this mask by the same producer, which allows well defined comparisons
  - We investigate the properties of **several layout options for strip, strixel and pixel sensors**
  - A well defined **measurement plan** has been worked out and participating institutes have been inter-calibrated to guarantee comparable measurements
  - For the test wafers a producer was chosen, that can provide the large quantity and high quality we need → "**HPK campaign**"
  - Measurements are complemented by **device simulations**

HPK Campaign Overview

We investigate 3 processes (on all materials):

- **p-on-n:** p-strips in n-bulk
- **n-on-p, p-stop:** n-strips in p-bulk with p-stop isolation
- **n-on-p, p-spray:** n-strips in p-bulk with p-spray isolation

Different base (substrate) materials:

- Floatzone (FZ)
- Magnetic Czrochalski (mCZ)
- Epitaxial (EPI)

- Different thicknesses of substrate material ranging from 70 to 320 μm

HPK campaign – Materials

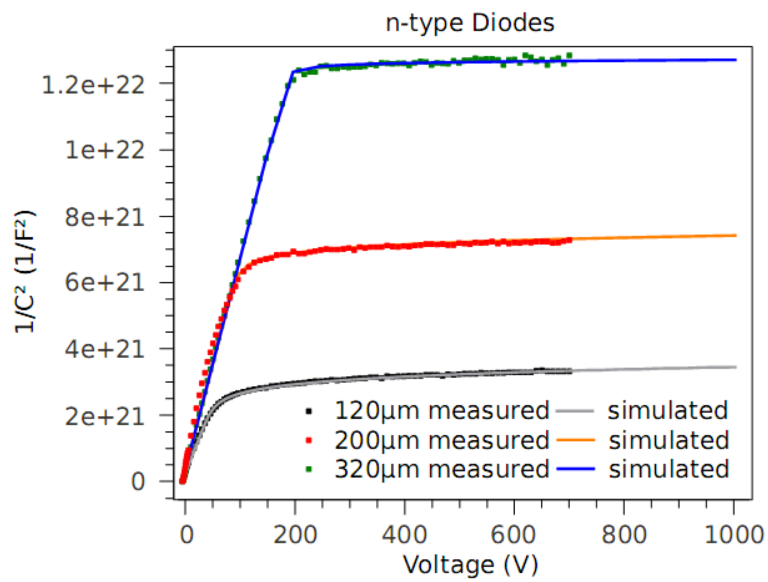
- Initially ordered production of 126 wafers delivered completely
- Part of thin FZ wafers came "deep diffused" showing some features, which makes a comparison with physical MCz difficult
- "Deep diffused" wafers are about 20% cheaper than 200µm thin wafers!
- Additional material ordered later (2nd metal and PTH200

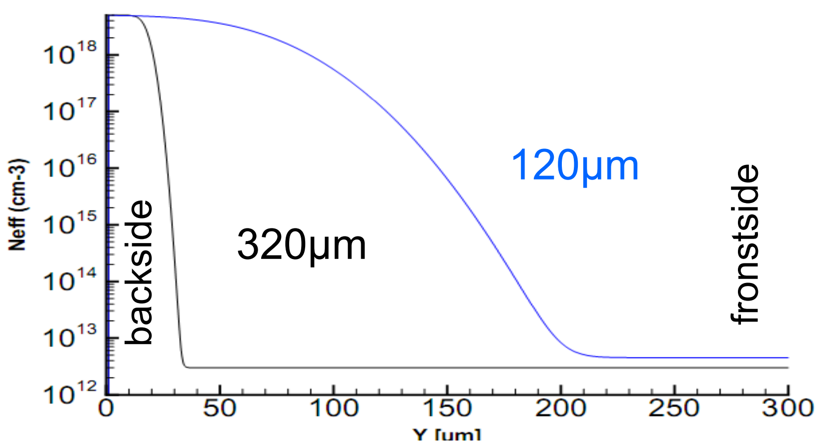
	n-type	p-type (p-stop)	p-type (p-spray)
FZ320	6 / 6	6 / 6	6 / 6
FZ200 deep diff.	6 / 6	6 / 6	6 / 6
FZ120 deep diff.	6 / 6	6 / 6	6 / 6
MCz200 physical	6 / 6	6 / 6	6 / 6
Epi100	2 / 6	6 / 6	6 / 6
Epi70	4 / 0	-	-
Epi50	6 / 6	6 / 6	6 / 6
FZ200 deep diff. & 2.metal	6 / 6	6 / 6	6 / 6
FZ200 physical	0 / 6	0 / 6	0 / 4
FZ120 on carrier	0 / 6	0 / 6	0 / 4

	physical thickness		deep diffusion		carrier wafer		
active thickness	320µ	200µ	200µ	120µ	120µ	100µ	50µ
FZ	X	X	X	X	X		
MCz		X					
Epi						X	X

Deep diffusion

- Deep diffusion (process)
  - Reduction of active volume of 320µm thick wafers but not of material budget
  - High concentration of dopants is diffused deep into the wafer
  - Smooth change of doping concentration
- Compared to wafer bonding is cheaper

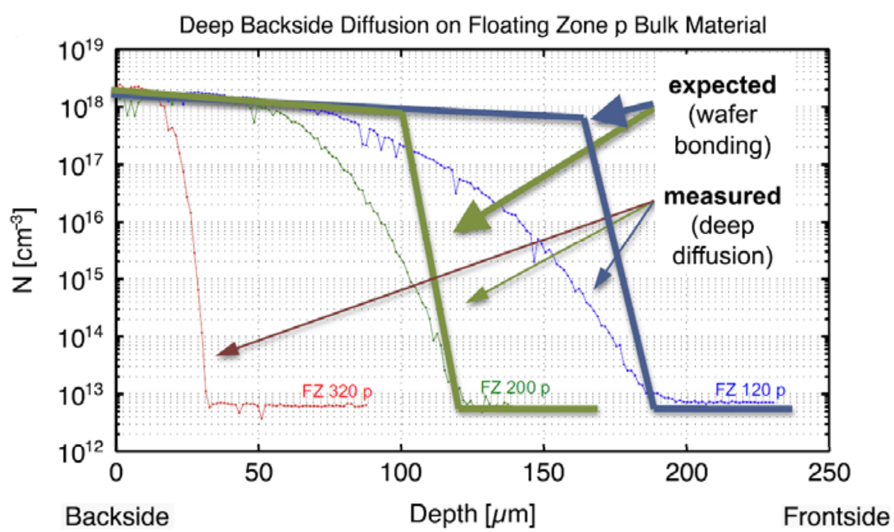


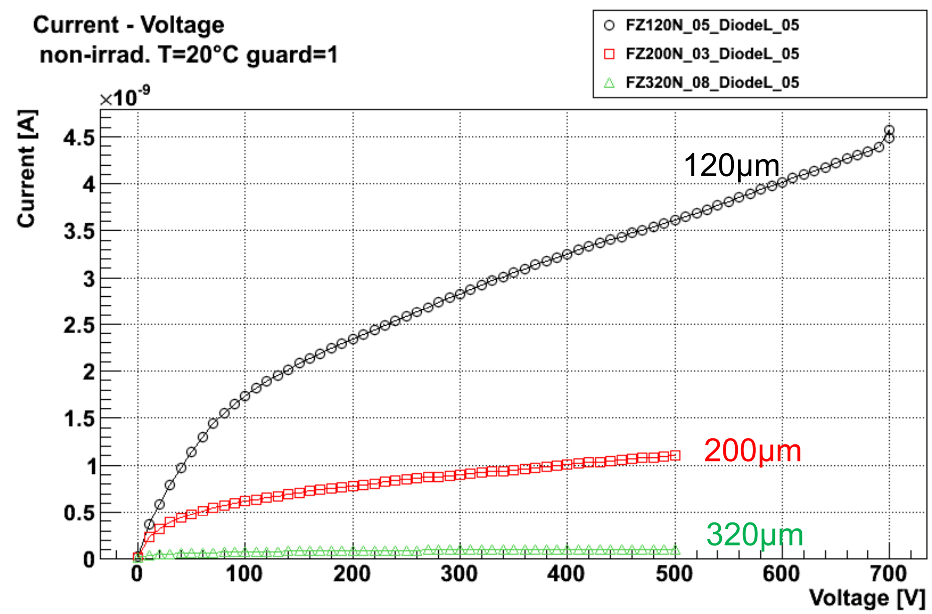


- Deep diffusion doping profile can be introduced into the simulation
- Simulation can be fitted to measurement results
- Excellent agreement between simulated and measured CV curves

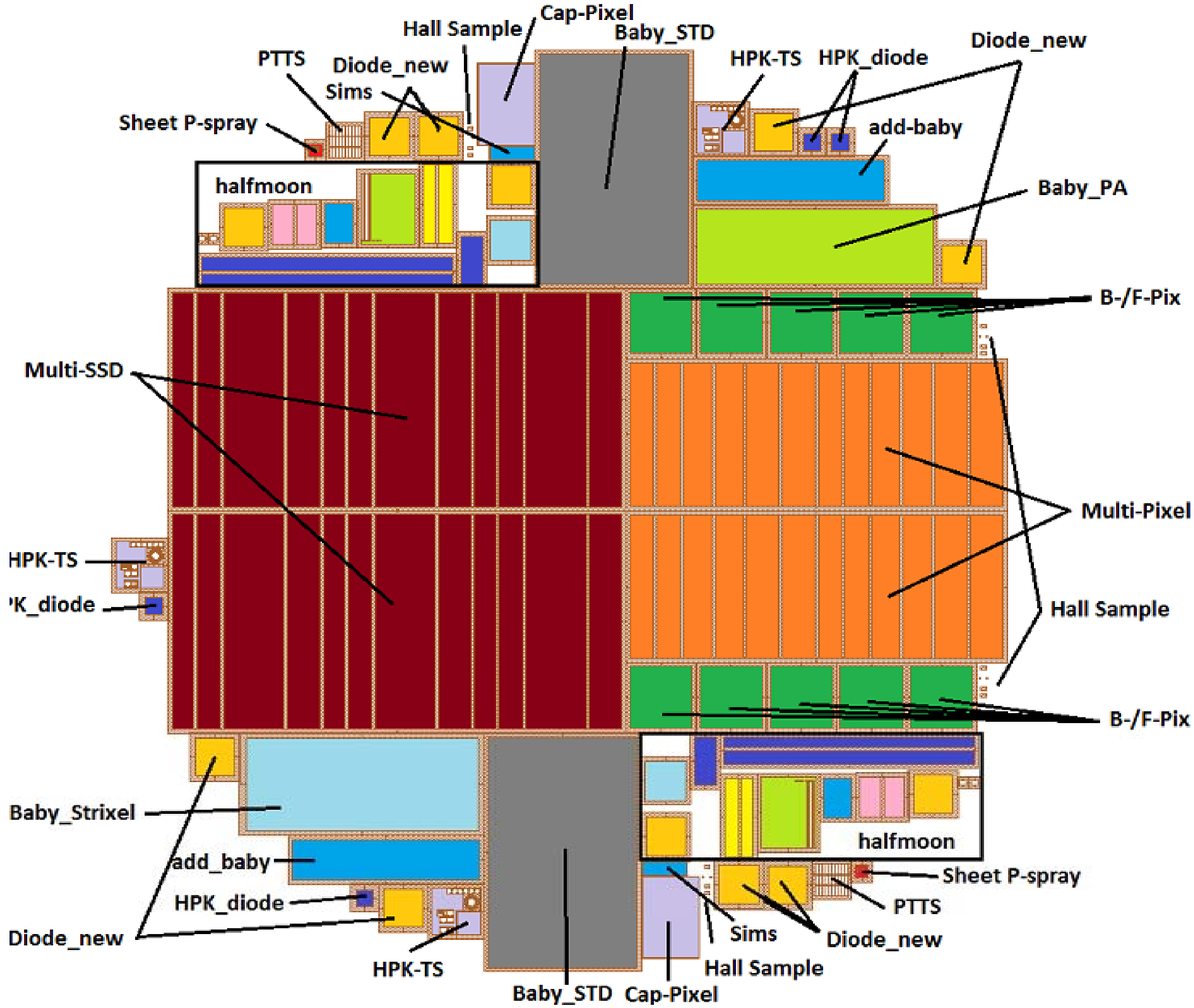
Investigation of "deep diffused" material

- Unusual behaviour of thin "deep diffused" material
- Well seen in IV and CV of diodes
- Thin diodes show non-abrupt depletion behaviour
- Volume generated currents are higher than in thick diodes
  - But currents are still very low (<1.5µA/cm³ @ 500V)!



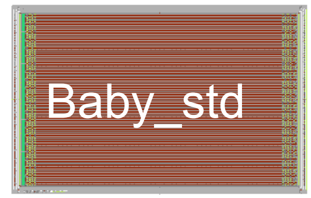


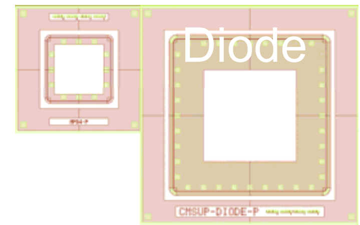
HPK campaign wafer layout

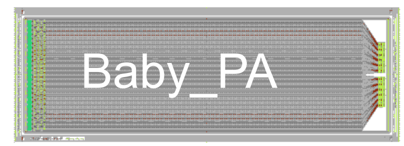


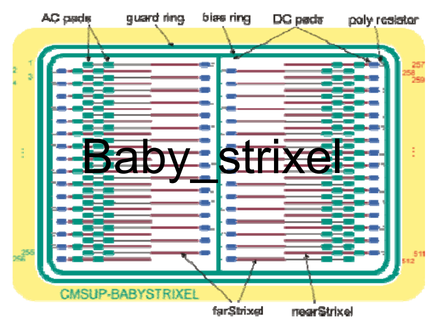
Structures and goals

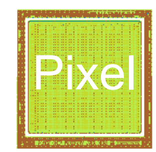
- Diodes
  - Material characterization and add. annealing studies
  - Measure IV, CV, CCE, TCT, DLTS, TSC, photo cond., …
- Mini sensor I (Baby_std)
  - Material characterization, charge collection
  - Measure IV, CV, strip para., CCE, e-TCT
- Mini sensor II (Add_Baby)
  - Material characterization using different radiation sources
  - Measure IV, CV, Lorentz angle
- Sensor with integrated PA (Baby_PA)
  - Layout study: spare glass PA
  - Measure strip capacitances, CC, signal coupling
- Sensor with short strips and edge read-out (Baby_strixel)
  - Layout study: read-out lines from inner strip to outer edge
  - Measure strip capacitances, CC, signal coupling
- Test structure field (TS)
  - Process qualification
  - Measure many things incl. SIMS, SRP, SEM, …
- Pixel
  - Real size pixel sensor for CMS ROC footprint
  - Measure IV, efficiency, σ
- Multi-geometry strip (30mm) sensor (MSSD)
  - Layout study: strip width and pitch variations
  - Measure CV, IV, Cint, S/N, σ
- Multi-geometry pixel (1.25mm/2.5mm) sensor (MPix)
  - Layout study: pixel length and pitch variations
  - Measure CV, IV, Cint, R_{poly}/R_{PT}, S/N, σ

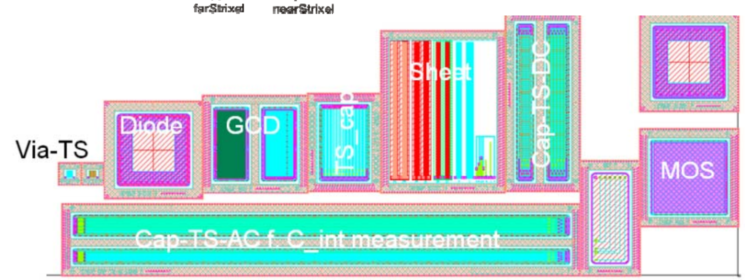




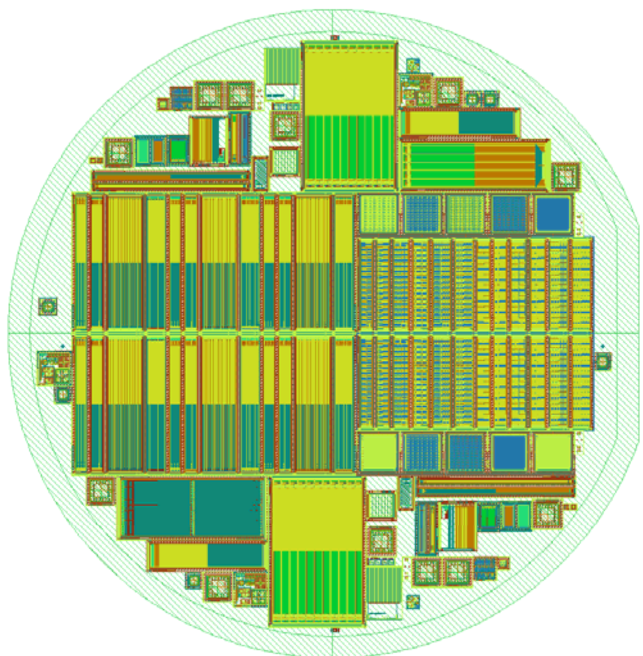








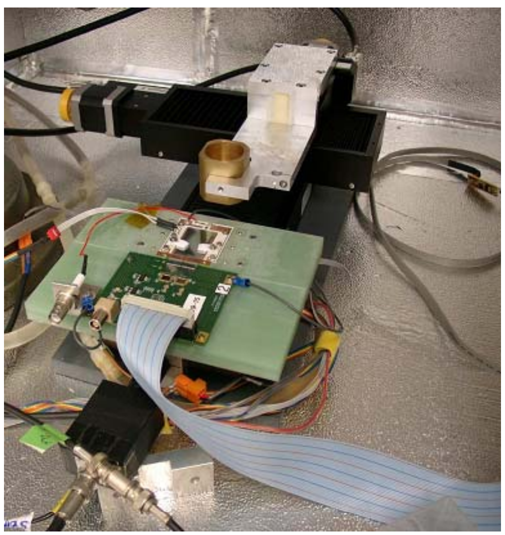
17 institutes currently involved in HPK campaign



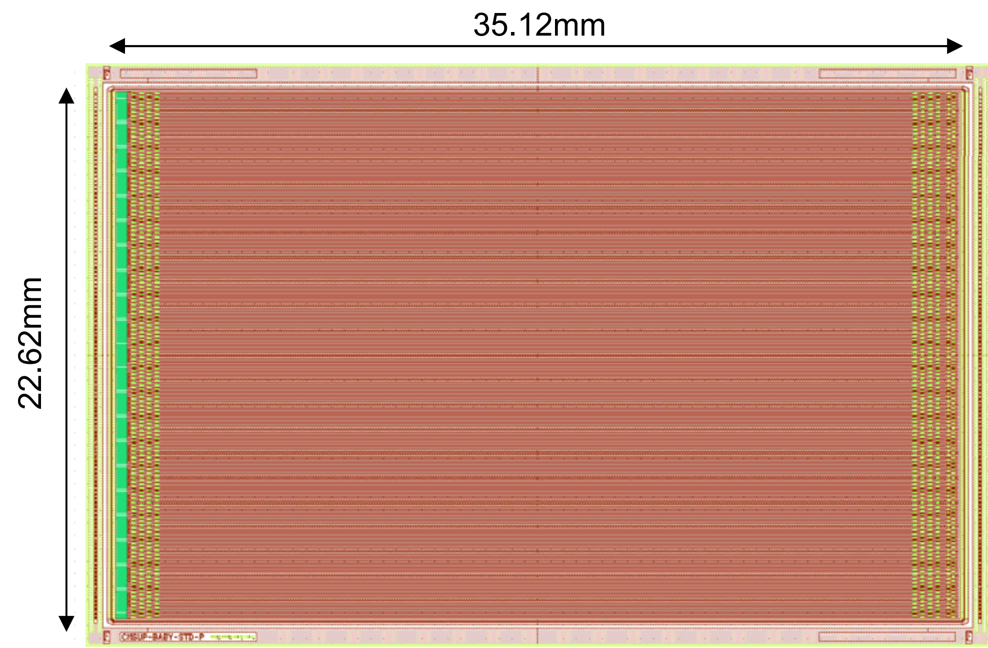
Size of logos has **no** meaning!!!

Baby_std

- A “standard” mini strip sensor with 256 strips and 80μm pitch
- Evaluation of all electrical parameters
- Measurement of charge collection with beta-source and LHC-like read-out system
- Edge-TCT can provide E-field and charge collection vs. thickness profile on sub-set

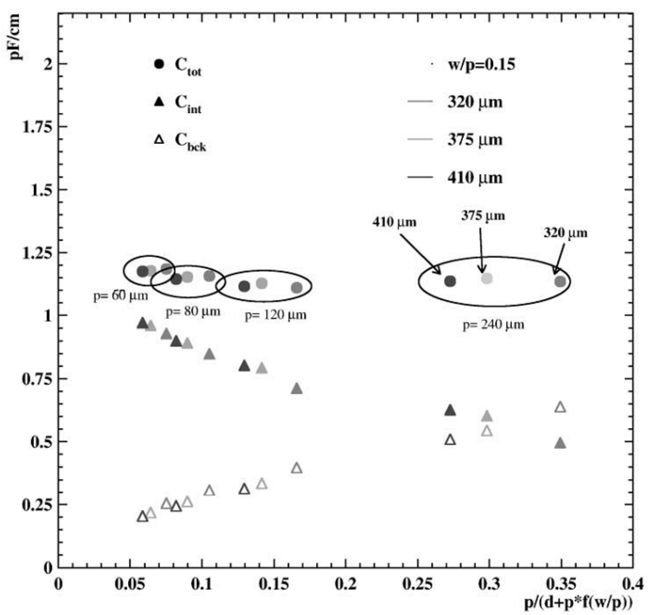


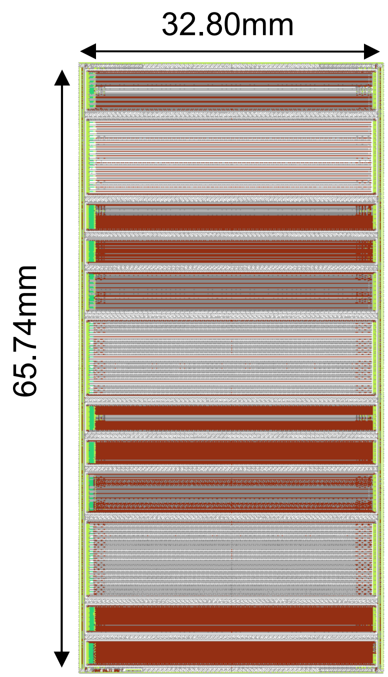
ALiBaVa setup at KIT



Multi-SSD

- Contains 12 regions with different strip sensor layouts
- This is a replica of the famous test-structure, which brought us the conclusion that the total strip capacitance is a function of w/p only (demonstrated for 0.2<p/d<0.8 and 0.1<w/p<0.6) [CMS Note 2000/011]





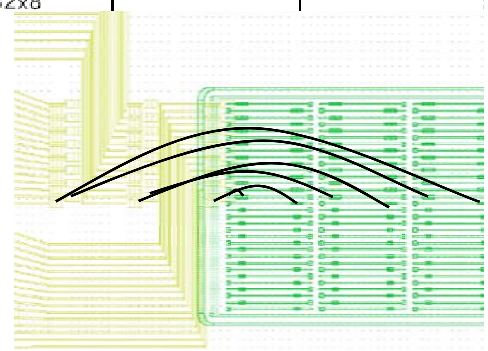
REGION No.-PITCH	P	WP	WAL	D	E	L
1-120	120	18	26	60	60	3820
2-240	240	36	44	120	60	7660
5-120	120	24	32	60	60	3820
6-240	240	48	56	120	60	7660
9-120	120	36	44	60	60	3820
10-240	240	72	80	120	60	7660

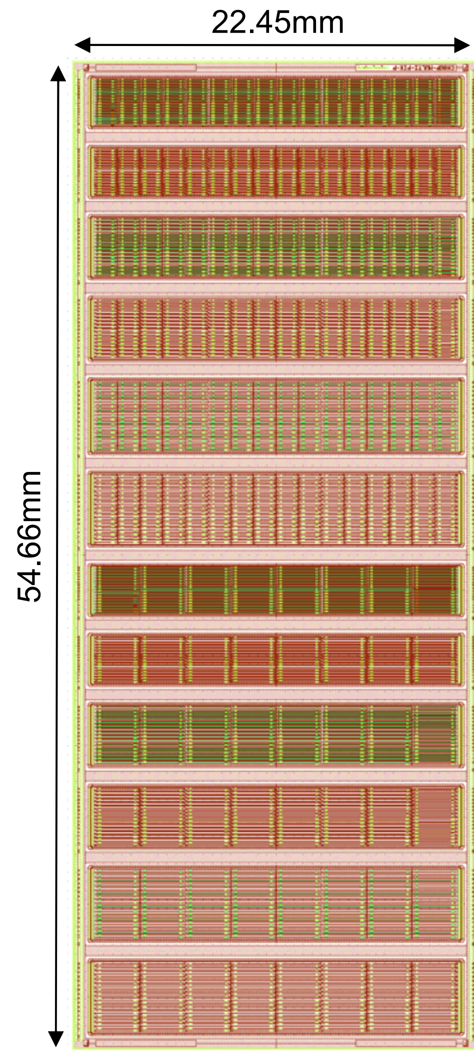
REGION No.-PITCH	P	WP	WAL	D	E	L
3-80	80	12	20	60	60	2580
4-60	60	9	17	50	50	1940
7-80	80	16	24	60	60	2580
8-60	60	12	20	50	50	1940
11-80	80	24	32	60	60	2580
12-60	60	18	26	50	50	1940

Multi-Pixel

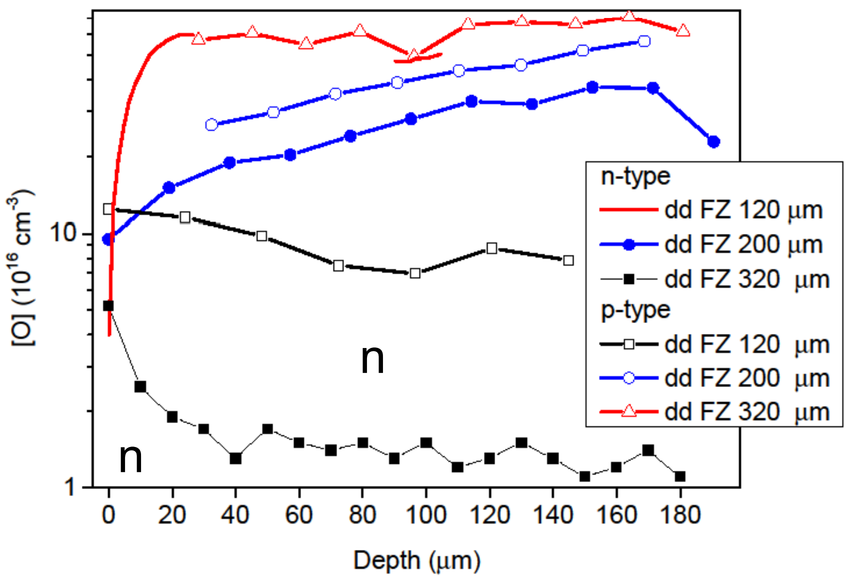
- Contains 12 regions with different pixel/strixel layouts
- Pixel size in the regime of pixellated p_T layers
- Study inter-pixel capacitances and different biasing schemes
- Special PA to read-out with APV25 in beam test

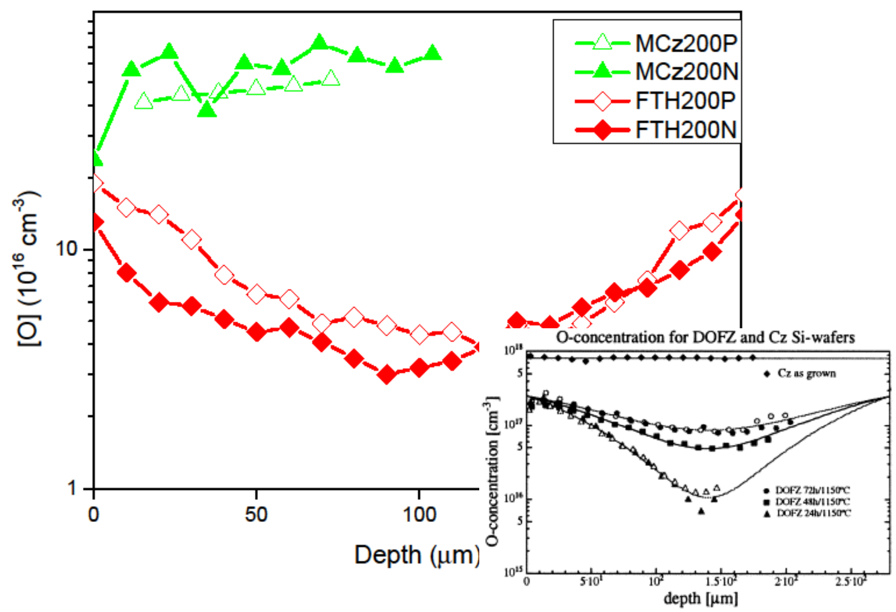
	PIXEL Length	Pitch	bias type	No. of pixels	Pixel size (um)	Lateral P-P gap
1	1250	80	Poly	32x16	20x1160	60
2			PT	32x16		
3		100	Poly	32x16	25x1160	75
4			PT	32x16		
5		120	Poly	32x16	30x1160	90
6			PT	32x16		
7	2500	80	Poly	32x8	20x2410	60
8			PT	32x8		
9		100	Poly	32x8	25x2410	75
10			PT	32x8		
11		120	Poly	32x8	30x2410	90
12			PT	32x8		





Oxygen Content





- Deep diffused material: Higher [O] when active thickness lower
- [O] in p typically larger than n
- 120 dd extremely high!
- New: FTH and dd320n

- [O] FTH lower than MCZ but higher than typical FZ, more like DOFZ
- For reference: Standard FZ: <3x16^{16}, DOFZ*: 1x10^{17}

*Diffusion 72h at 1150°C

Irradiation fluences

- Need to understand damage by neutron, charged hadron and mixed particle irradiation
- Fluences chosen for conditions at various radii
- Annealing steps chosen to cover initial short term and long term annealing

Step	1	2	3	4	5	6	7
Temp. / °C	60	60	60	60	80	80	80
Time / min	20	20	40	76	15	30	60
$\sum t@60°C$ / min	20	40	80	156*	312	624	1248
$\sum t@20°C$ / d	4.5	8.1	15.6	31.8	92.8	243	496

* 156min at 60°C ~ 15min at 80°C

Radius	Protons	Neutrons	Ratio p/n	Total	Material
40cm	2,5	4	0,63	6,5	≥ 200µm
20cm	10	5	2,00	15,0	all
15cm	15	6	2,50	21,0	all
10cm	30	8	3,75	38,0	all
5cm	130	12	10,83	142,0	< 200µm

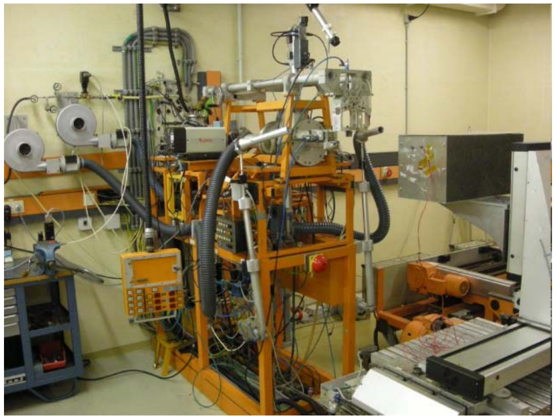
In 10^{14} Neq cm^{-2}

Overview of fluences (in$10^{14} N_{eq} cm^{-2}$) for different radial positions

Radius/cm	Protons	Neutrons	total
40	3	4	7
20	10	5	15

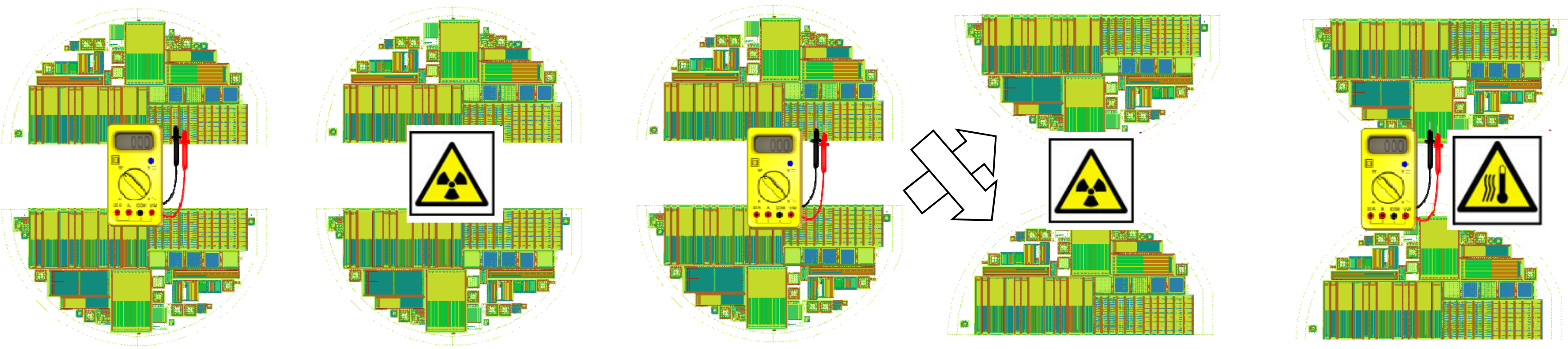
Irradiation sequence

- Initial measurements of all parts
- Irradiation with n/p
- Short annealing 10min @ 60°C
- Measurement of devices
- Irradiation with p/n
- Short annealing 10min @ 60°C
- Measurement of devices for several annealing steps

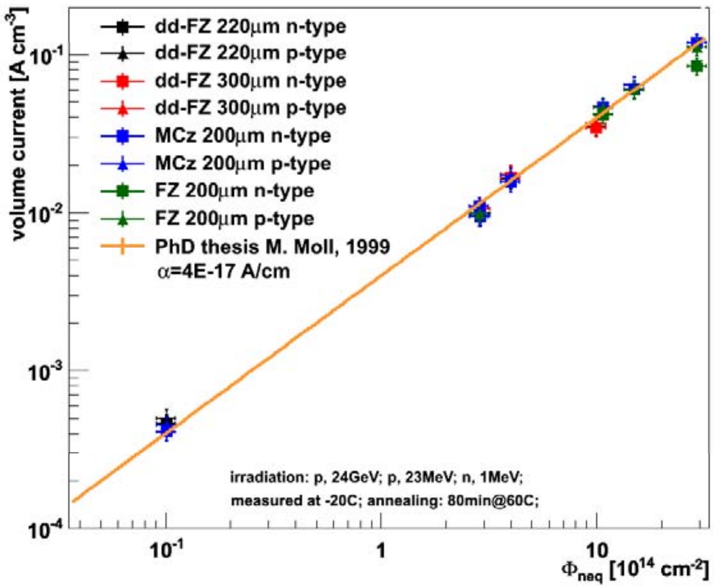


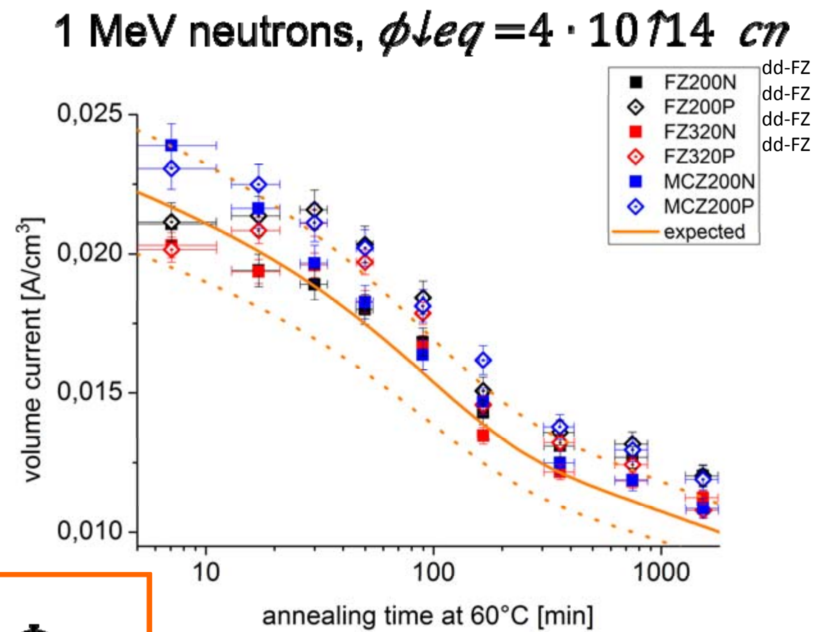
Proton cyclotron, KIT

TRIGA reactor, Ljuljana



Volume Current





$$\frac{\Delta I}{V} = \alpha \Phi_{eq}$$

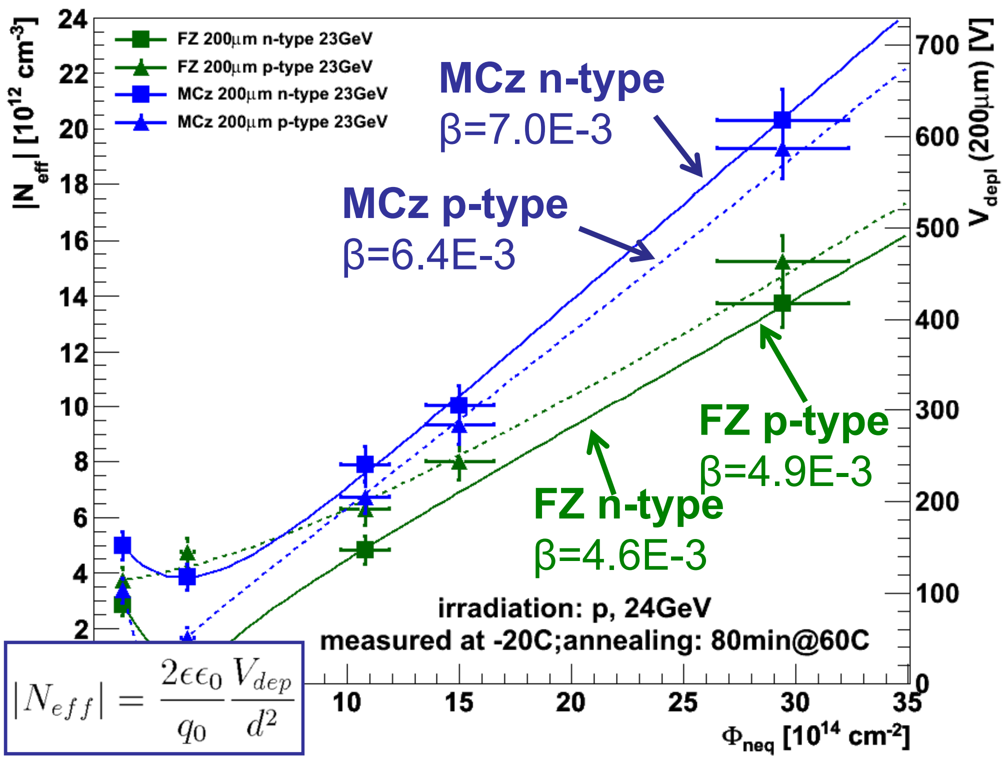
- Current drops after annealing (expected)

- Volume current scales with fluence:
- Scaling parameter independent of Si material, oxygen concentration
- Scaling parameter agrees with previous measurements

→ Current/ fluences understood
→ Independent of material
→ Independent of polarity

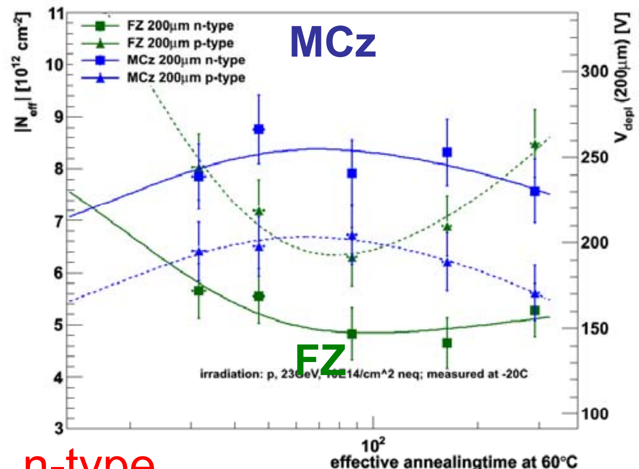
Depletion Voltage: 23 GeV p

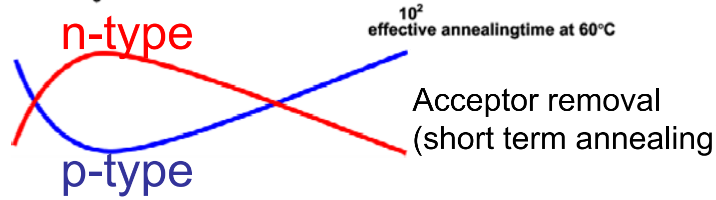
Irradiated with 23 GeV protons (PS)



$$|N_{eff}| = \frac{2\epsilon\epsilon_0}{q_0}\frac{V_{dep}}{d^2}$$

Annealing→Info about type inversion

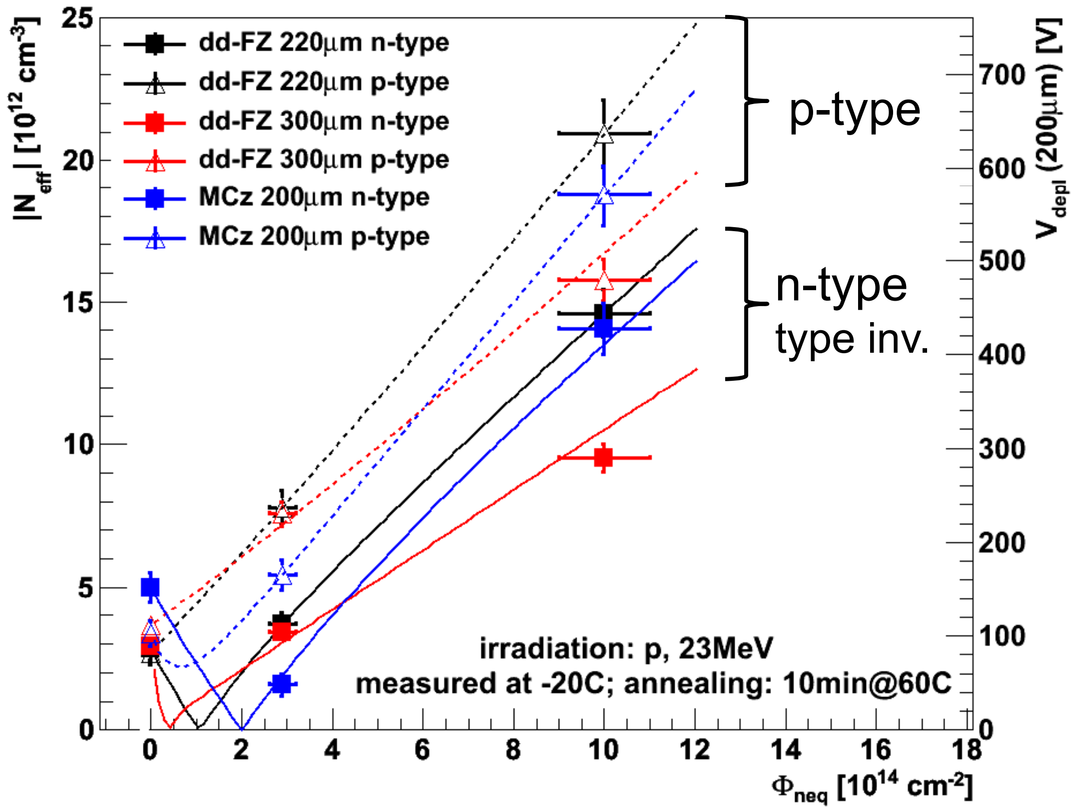




Type inversion	FZ	MCZ
N-type	✔	-
P-type	-	✔

Depletion voltage under 600V at highest Φ (200µm)
Introduction rate smaller for FZ than for MCz

Depletion Voltage: 23 MeV p

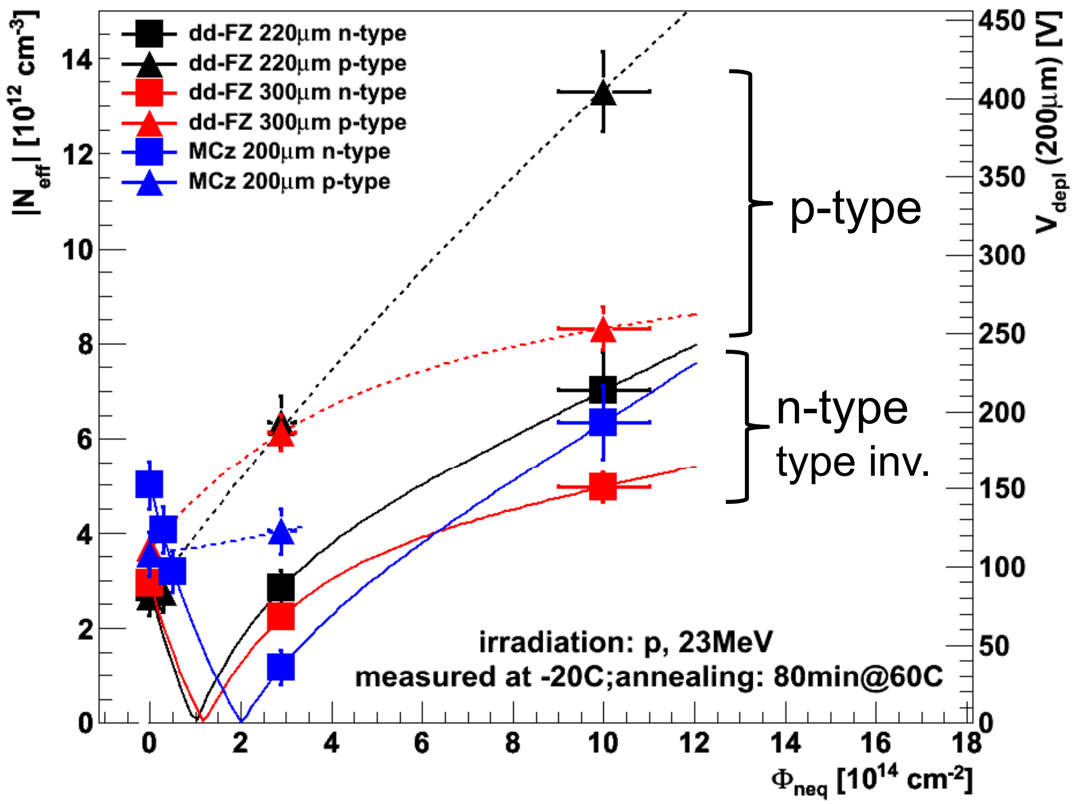


Different picture compared to GeV irradiation:

Type inversion	dd-FZ	MCZ
N-type	✔	✔
P-type	-	-

Lower depletion voltage for n-type due to type inversion

23 MeV p after 80min@60°C



Different picture compared to GeV irradiation:

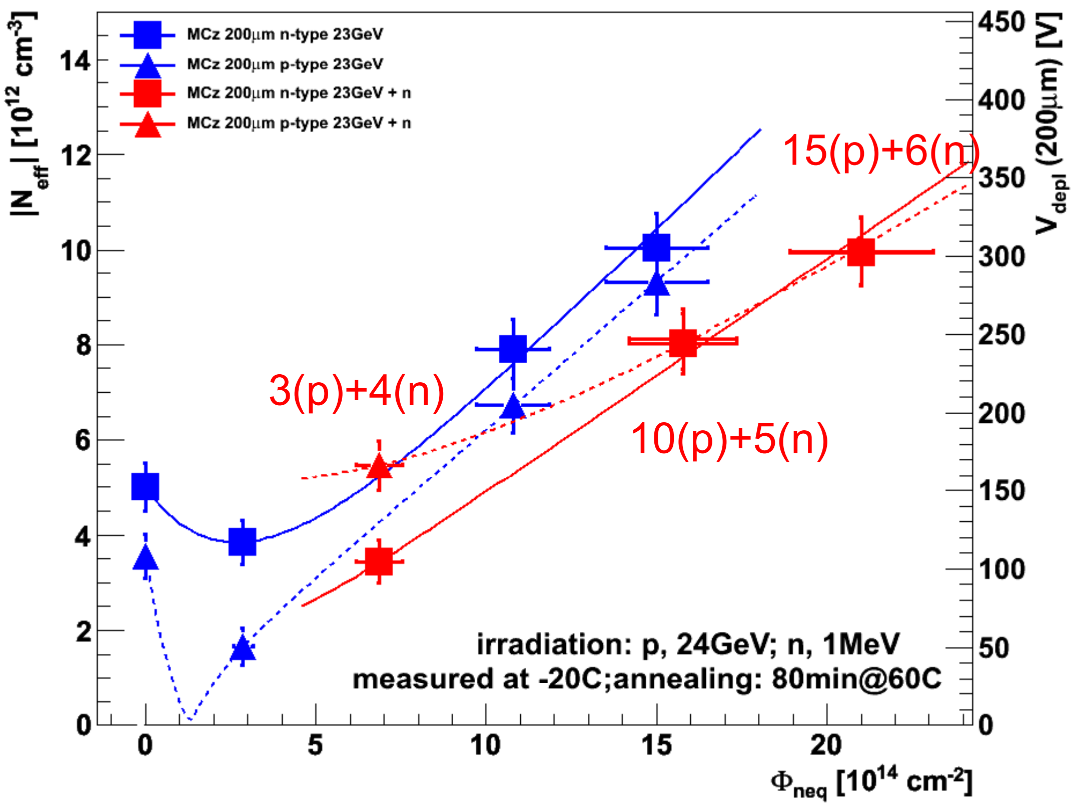
Type inversion	dd-FZ	MCZ
N-type	✔	✔
P-type	-	-

Annealing reduces V_{dep} significantly, especially at high Φ

Lower depletion voltage for n-type due to type inversion

Compensation in MCZ

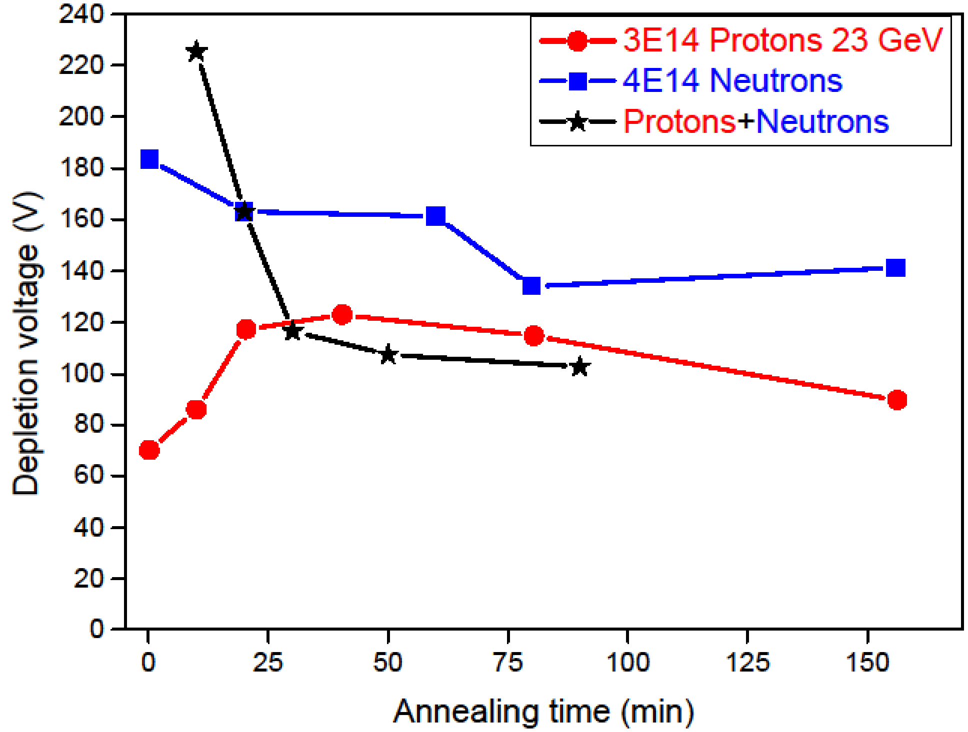
- N_{eff} influenced by interplay of particle type (n-p), proton energy, [O] and annealing
- Compensation of GeV protons and neutrons in [O]-rich material (MCZ)



Compensation in MCZ seen for both polarities.

Compensation for n-type MCZ: Annealing

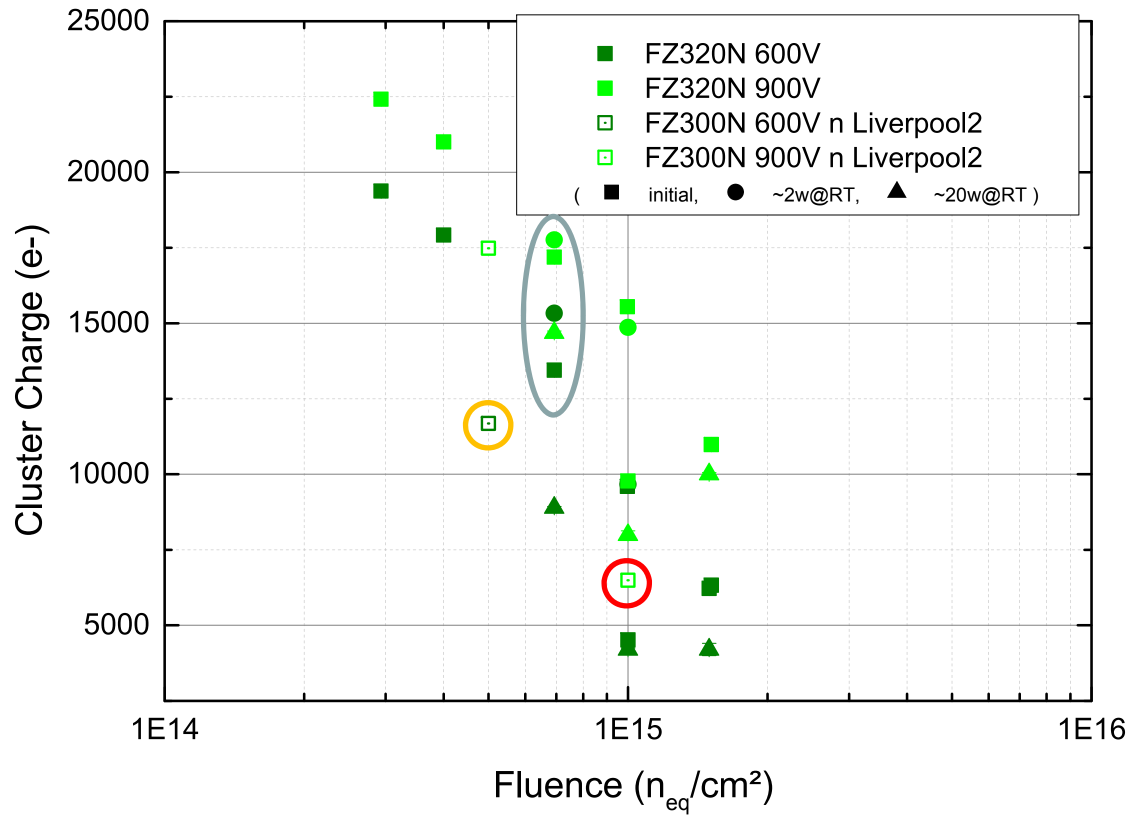
- After protons only: n-type annealing, no type inversion
- After neutrons only: negative slope →type inversion
- Depletion voltage after mixed irradiation less than the sum for proton and neutron irradiation, strong function of annealing
- Complicated picture →Need to add Hamburg model for neutrons and protons



Depletion voltage after mixed irradiation lower than sum of individual depletion voltages. Dramatic annealing effect!

Charge Collection – n-Type 300µm Strip Sensors

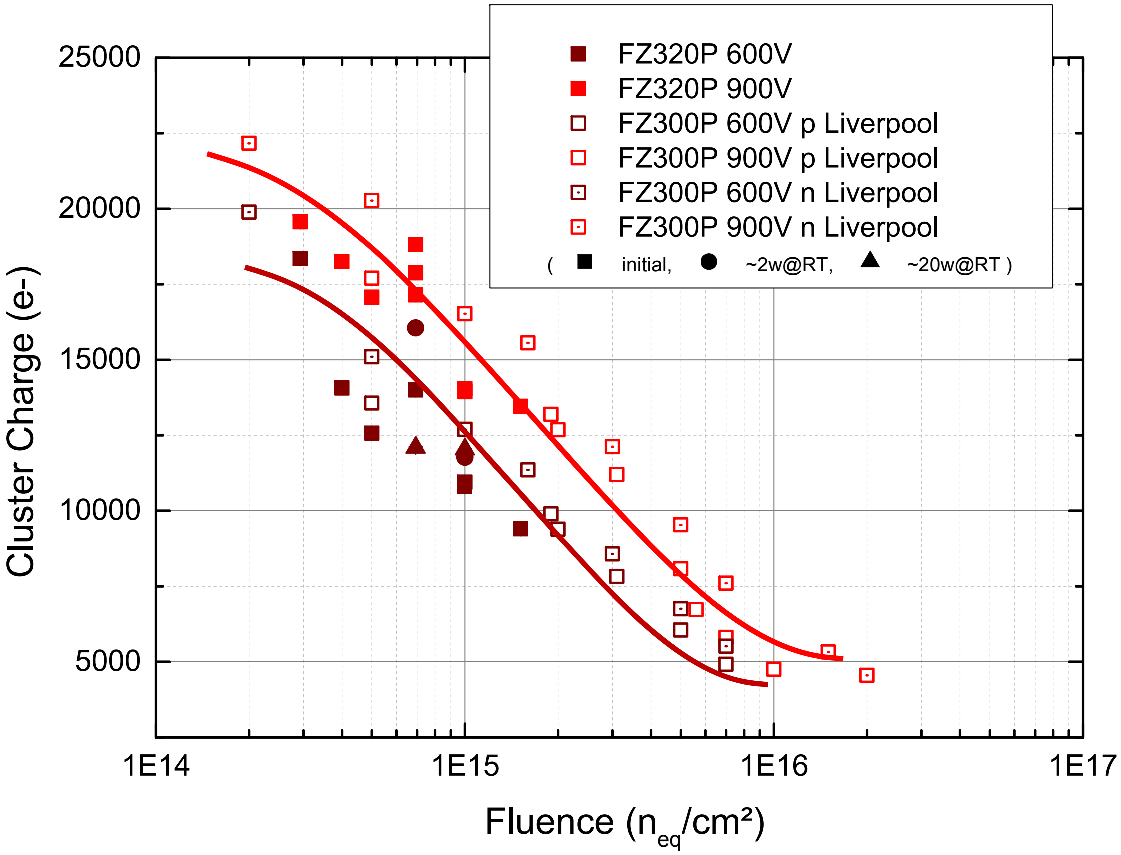
- Charge collection measured with Sr90 at -20°C with 600V and 900V bias on small strip sensors using read-out chips with short int. time:
  - SCT128 for Liverpool/ATLAS
  - Beetle for Karlsruhe/CMS
- Few years ago Liverpool measured huge drop in signal for p-in-n sensors even at 900V → concentrate on p-type development within RD50
- New measurements show much higher signal now
  - sensors from different vendor
  - severe drop in signal after long annealing
- From these measurements: 320µm p-in-n strip sensors could still be used up to 7e14n_{eq}/cm² avoiding long annealing



Liverpool2: PoS(VERTEX 2008)036

Charge Collection – p-Type 300µm Strip Sensors

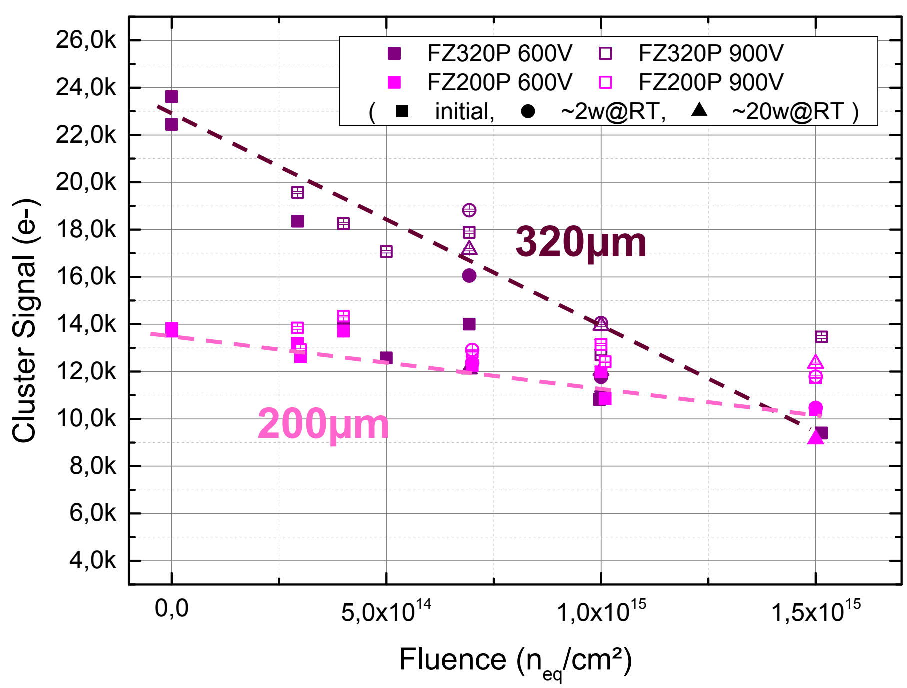
- Charge collection measured with Sr90 at -20°C with 600V and 900V bias
- Liverpool (SCT128A) and Karlsruhe (Beetle) results show reasonable agreement
- p-type strip sensors show uniform drop like exponential decay,
  - e.g. for 600V in the range of $F=(1e14-1e16)n_{eq}/cm^2$:

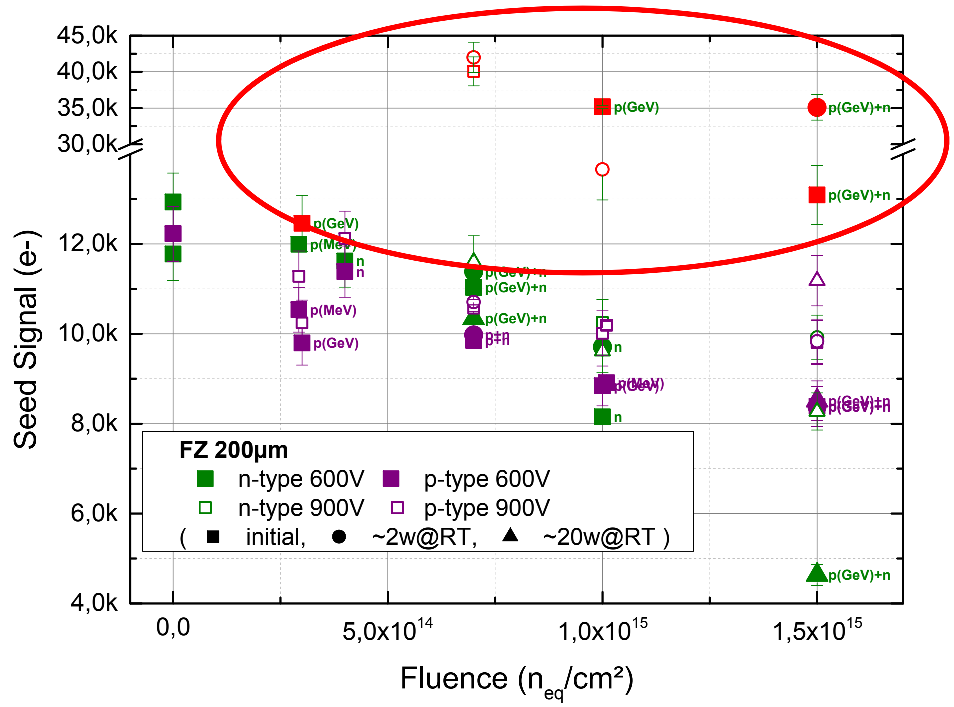


Liverpool: NIM A 636 (2011) S56-S61

Charge Collection – 200µm FZ

- 200µm strip sensors allow to reduce the material budget and keep CC at same level as 320µm at high fluence
- But for **p-in-n** sensors CMS saw many devices showing large signal and **large noise**

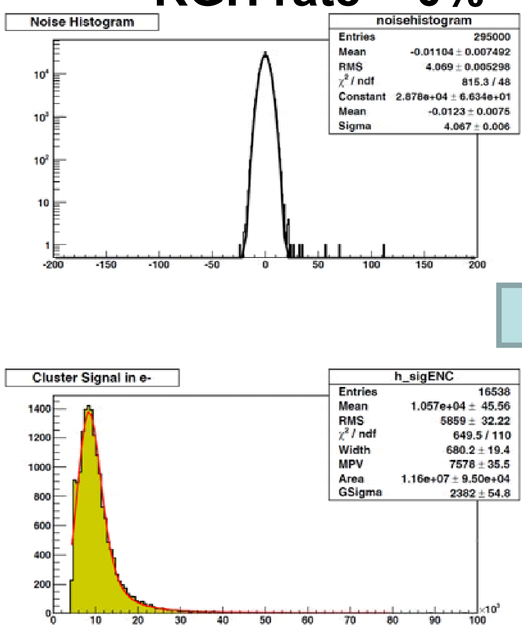




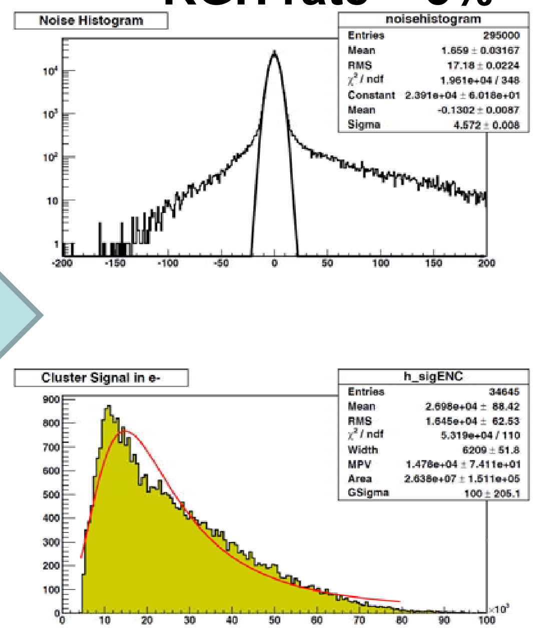
Noise – Random Ghost Hits

- CMS has observed **non-Gaussian noise** for **irradiated p-in-n** sensors for a significant fraction of the phase space (fluence, bias voltage, annealing)
- This results in randomly distributed hits, with **no** particle passing the sensors
  → **Random Ghost Hits** (RGH)
- A RGH rate was defined by counting all signals >5σ and dividing by #strips and #events
  - resulting number is an occupancy of RGHs or fakes
  - more than 1% fake occupancy is considered bad

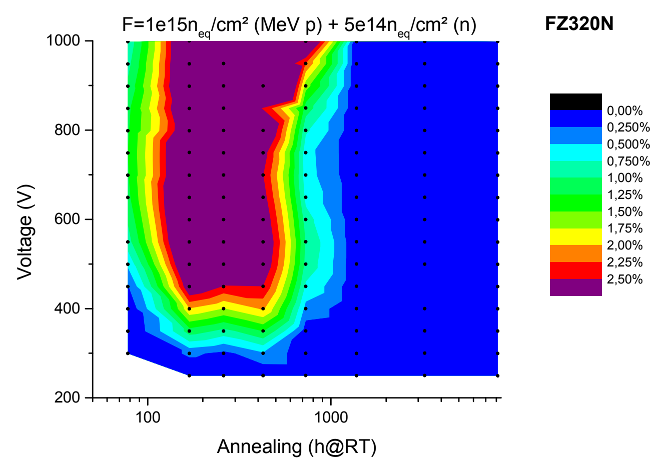
RGH rate = 0%



RGH rate = 3%

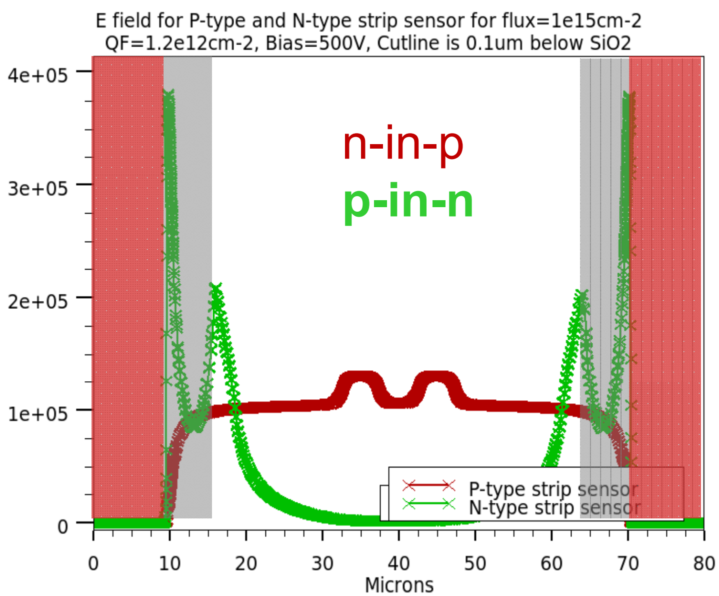


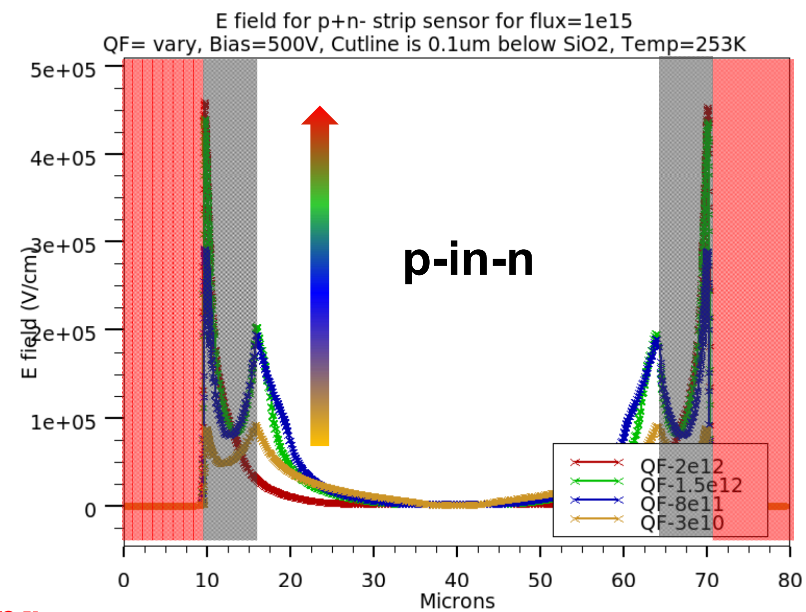
Since the effect was not always visible, the phase space was scanned



Device Simulation – Electric fields

- T-CAD simulations show **higher electric fields** at the strip edges **for irrad. n-in-p sensors** than for p-type sensors with same geometry (except p-stop)
  - This would explain why p-in-n sensors are more likely to discharge or break-down locally
- Increasing oxide charge…
  - **increases** max. electric fields in **p-in-n**
  - **reduces** max. electric fields in **n-in-p**
  - This would explain why RGHs are reduced for neutron irradiation with less ionization

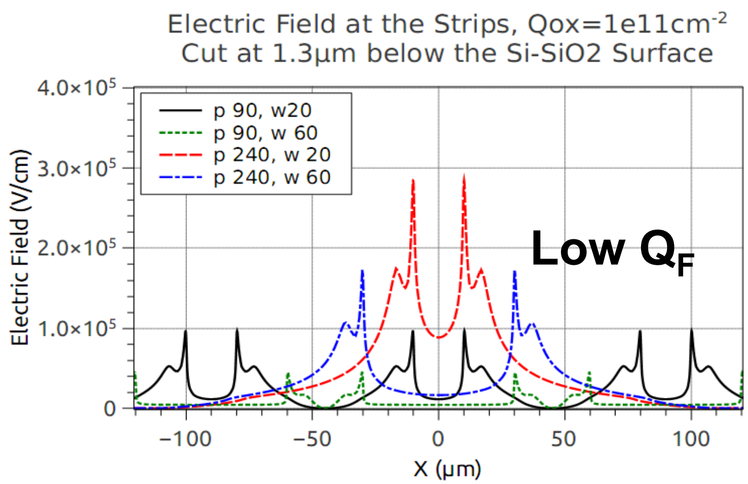




$F=1\times10^{15}cm^{-2}$; $Q_F = 1.2\times10^{12}cm^{-2}$;
U = 500 V; 5-trap model (Silvaco)

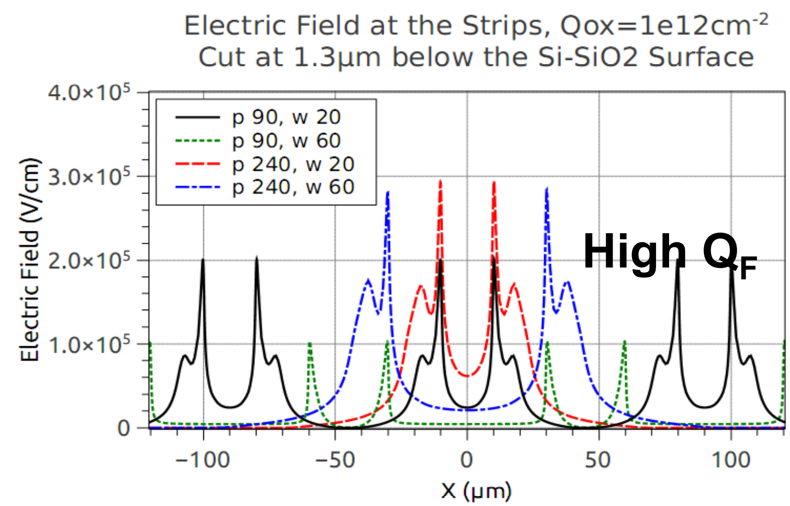
strip doping
aluminum

Device Simulation – Geometry Dependence

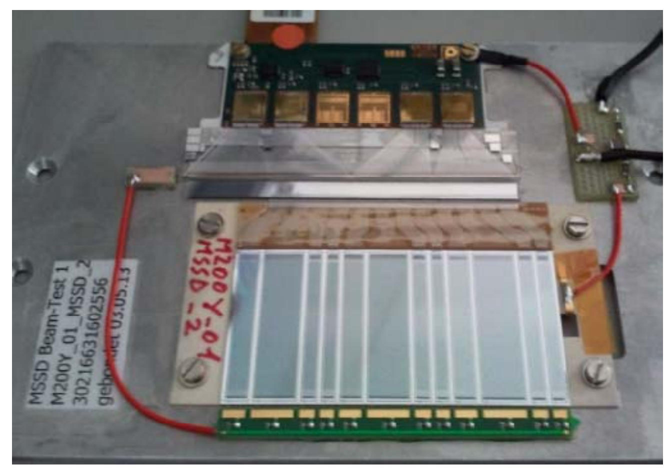


$F=1e15 n_{eq}/cm^2$

U=1000V

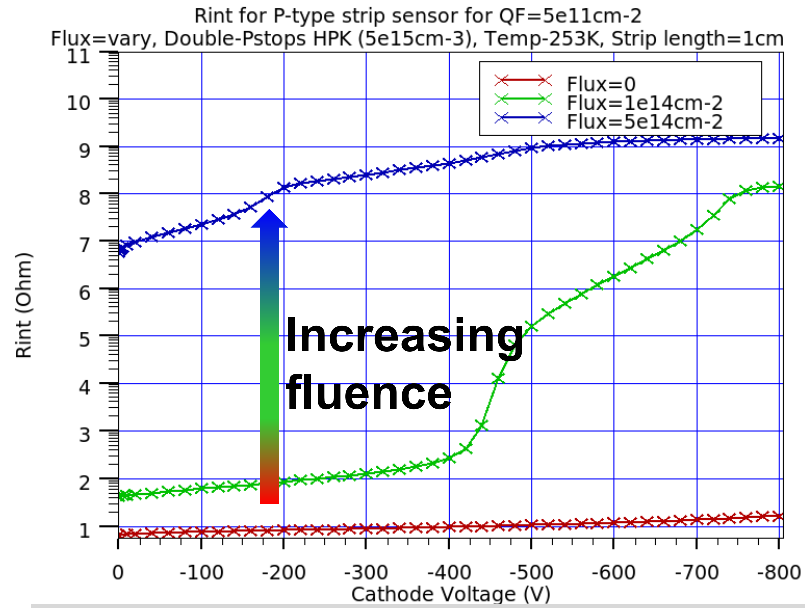


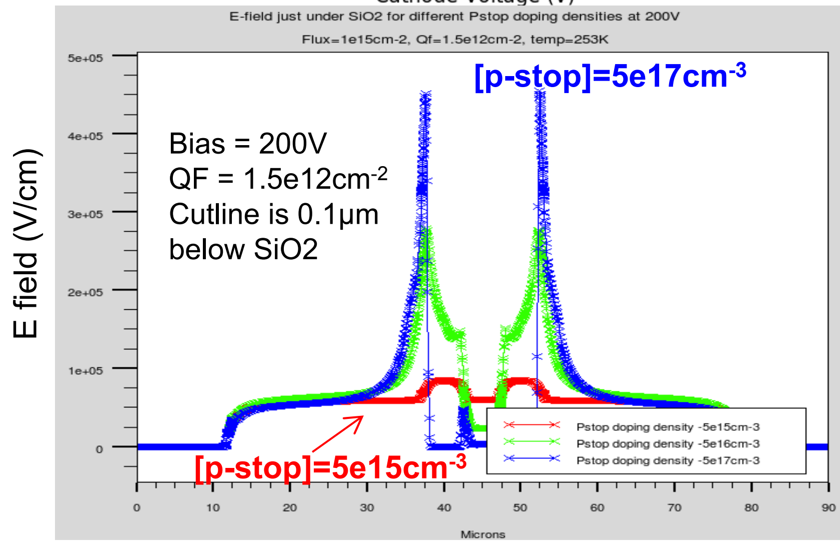
- Simulations indicate that **large pitch** and **narrow strip width** leads to **higher max. electric fields** at the strip edges
- This was investigated on a special multi-geometry strip sensor with 12 regions implementing various pitches and w/p ratios



Strip isolation

- Before irradiation:
  - p-spray need tuning of conc. to guarantee isolation, but avoid high fields at strip edges
  - p-stop needs a minimum conc., but electric fields not much affected
- After irradiation:
  - Trapping and generation of space charge around strips automatically isolates the strips!
    - Increasing bulk damage for given oxide charge increases Rint!
  - Now, p-stop conc. critical! Simulation suggests to avoid very high p-stop concentration





SUMMARY

Summary on HPK Campaign

- HPK Campaign to identify the best material for Phase-2 tracker
  - 126 Wafers
  - FZ, mCZ, EPI and p-on-n, n-on-p with p-stop and p-spray processing technique and different thicknesses
- Conclusions of the HPK campaign
  - n-on-p and p-on-n almost equally suitable (but only because of high O concentration in FZ material)
  - Oxygen concentration important to measure/know
  - Random Ghost Hits in p-on-n due to high field at strip edge
  - Conclusion: N-on-p will be the baseline
  - Cost estimates given by vendors show that mCZ is not cheaper than FZ
    - Most cerntainly will use float zone (FZ) substrate material
  - NIEL Hypothesis not fully applicable in highly irradiation regime (double junction)

Summary on Phase-2 Tracker

- Phase 2 Upgrade in 2020-2022 during LS3
- Completely new tracker based on double-sensor modules
  - Each module will be able to provide input to L1 trigger by measuring curvature of track (derive momentum)
  - 2S and PS module, 2S module design well advanced
  - Digital readout using CBC chip (CBC2 available) and MPA chip
- Work with alternative sensor vendors (Infineon) to have alternatives to HPK
  - Will reduce silicon costs
  - 8-inch wafers will provide even better cost ratios (only if enlarged area is fully used)