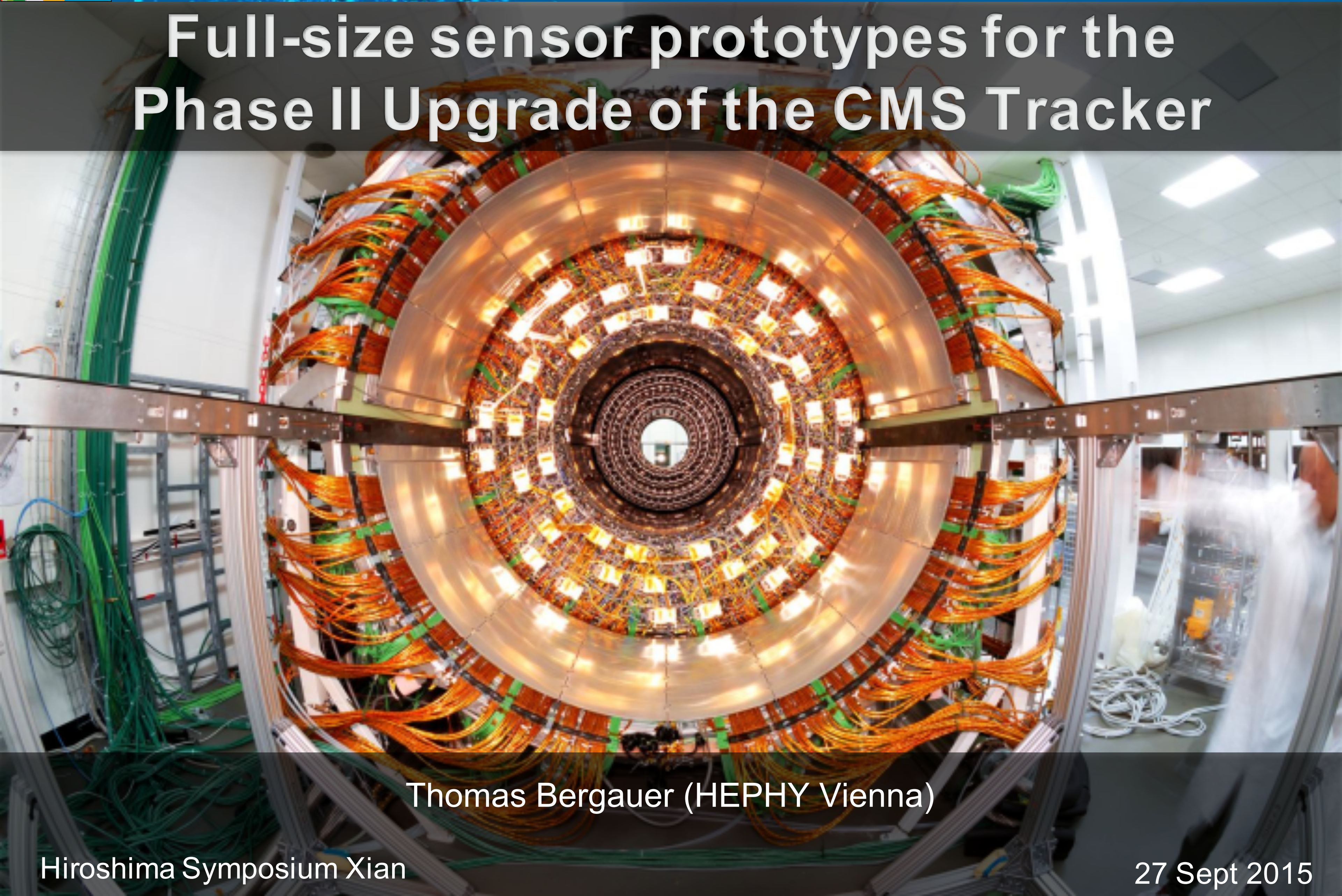
HEPHY
Institute of High Energy Physics

Full-size sensor prototypes for the Phase II Upgrade of the CMS Tracker



Thomas Bergauer (HEPHY Vienna)

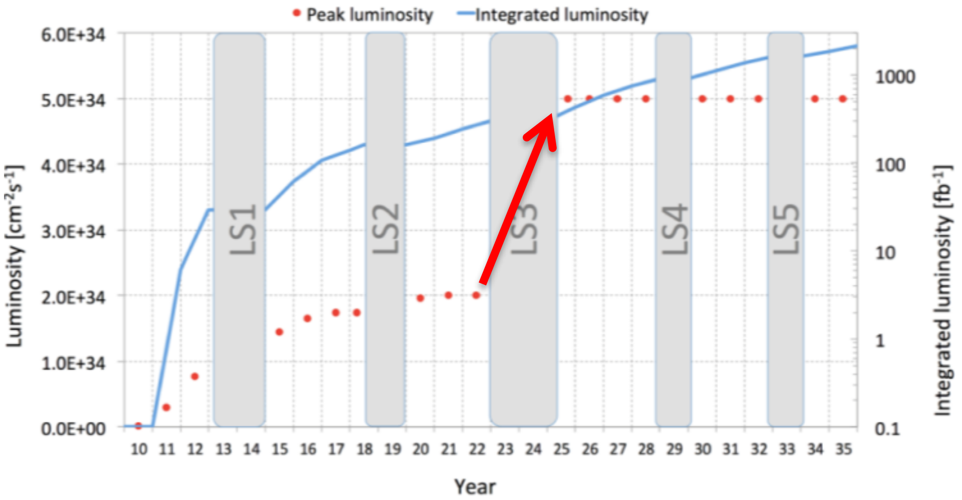
Hiroshima Symposium Xian

27 Sept 2015

The High Luminosity LHC and CMS

Upgrade of the LHC during LS3 (2023-25) to achieve **5x** the current design luminosity:
$5 \times 10^{34}\ cm^{-2}s^{-1}$

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

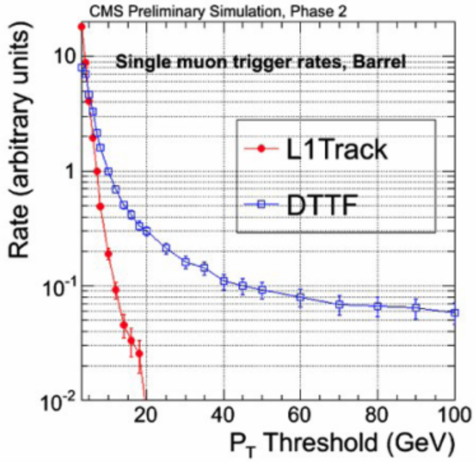


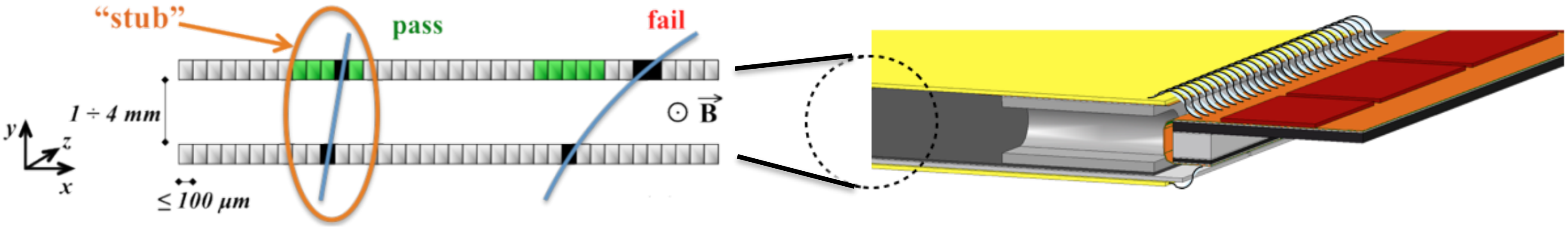
Challenges for CMS in HL-LHC Environment (after 2025):

- Higher density of tracks → Increase granularity of sensor elements
- Increase in radiation → Radiation hard components
- L1 Trigger needs input from tracker
  - Transmitting full tracker information at 40 MHz not possible
  - Data selection inside the tracker → p_T module concept

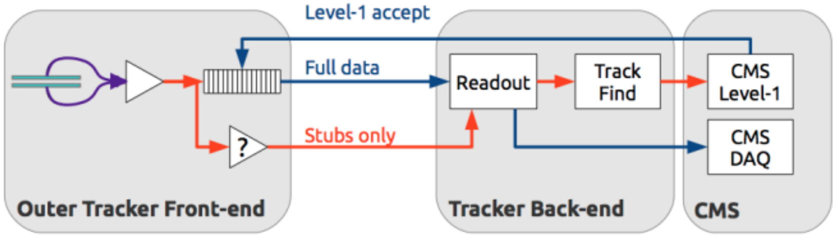
p_T-Module Concept

- Myon and calorimeter-based triggers will not be able to stand the rates due to PU and limited resolution
- Myons: no p_T threshold can limit the rate
  - due to strong magnetic field in the tracker high-p_T tracks can be discriminated



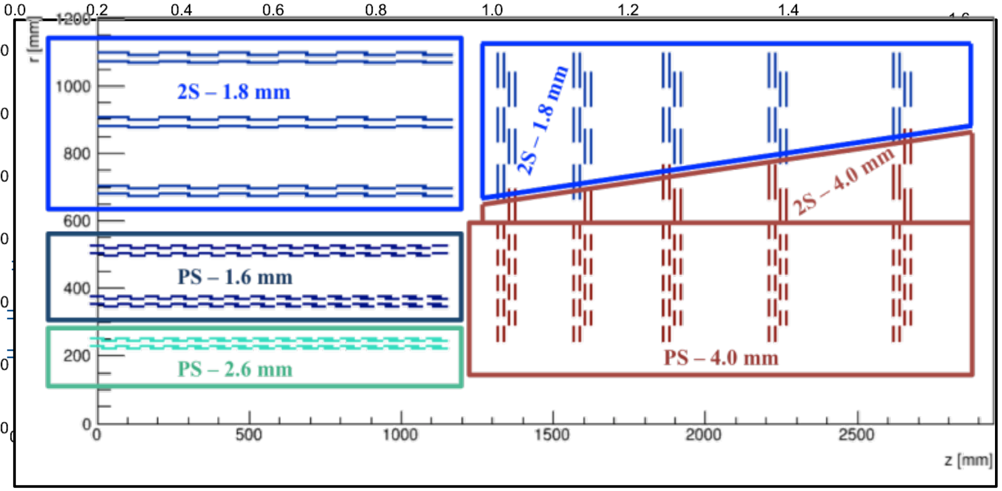


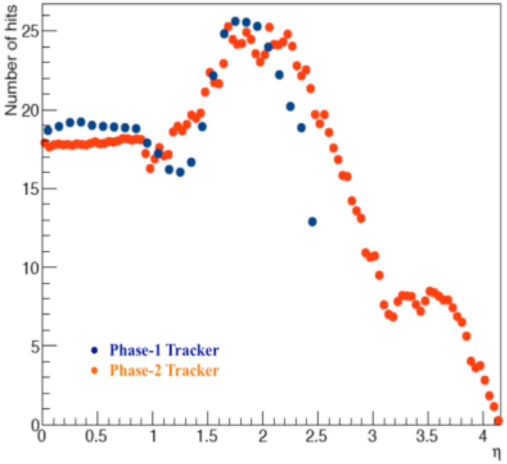
- Stubs will be processed in the back end to build L1A

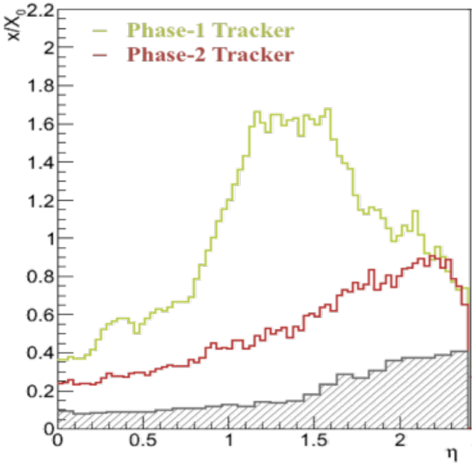


Tracker Layout Baseline

- **2 module types only,** both for barrel and end caps
  - **Pixel-Strip-(PS)-module** (r < 60 cm)
  - **2 Strip (2S) modules** (r > 60 cm)
- Sensor spacing optimised with 2 (2S) or 3 (PS) groups
- Similar number of hits vs. η
  - Extending coverage to |η|<4
- Lower material budget than existing tracker due to
  - CO_2 cooling
  - DC/DC powering
  - No dedicated control electronics



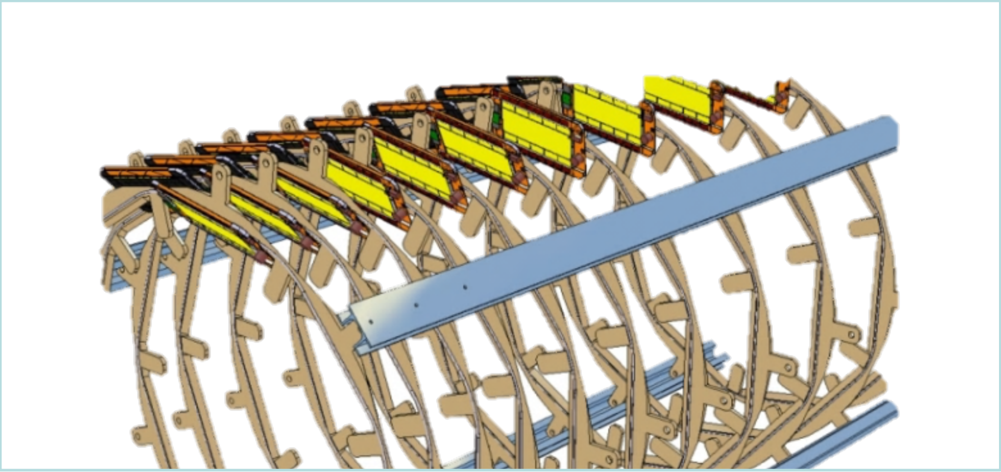


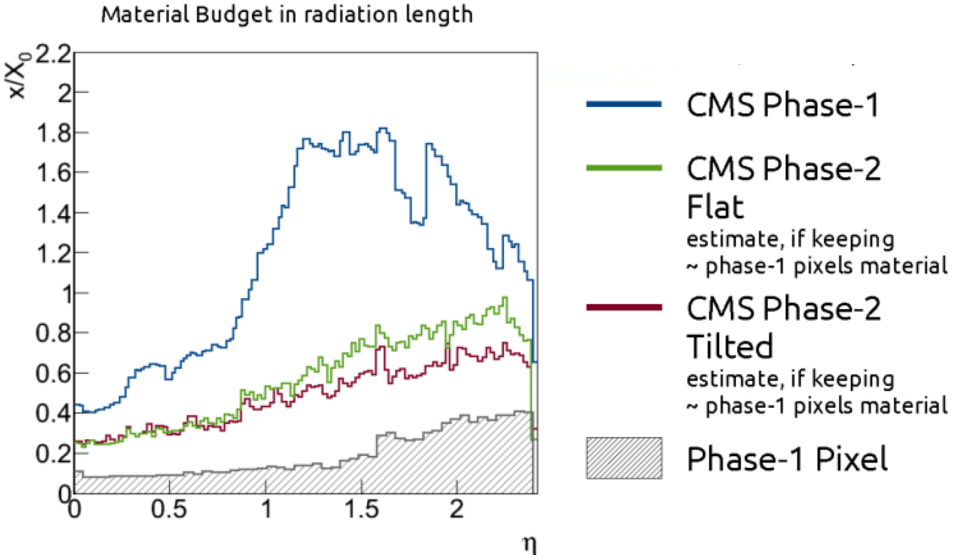


Layout Option: Tilted PS Barrel

PS modules in inner barrel tilted “towards” IP

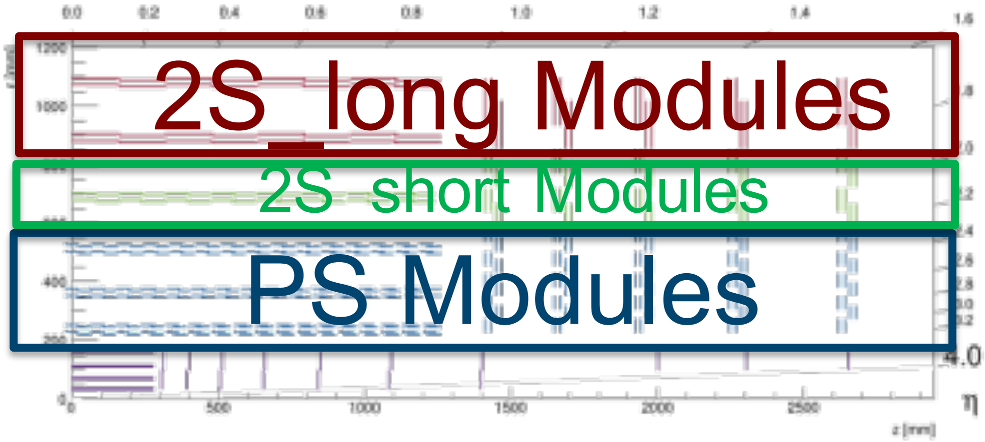
- Gives smooth transition from barrel to forward disks
- Reduction of number of modules/sensors
  - By 1800 PS modules
- Advantages
  - Reduction in material budget
  - Safes costs
- Disadvantages
  - More complicated mechanics
  - Significant increase of mechanical engineering required!

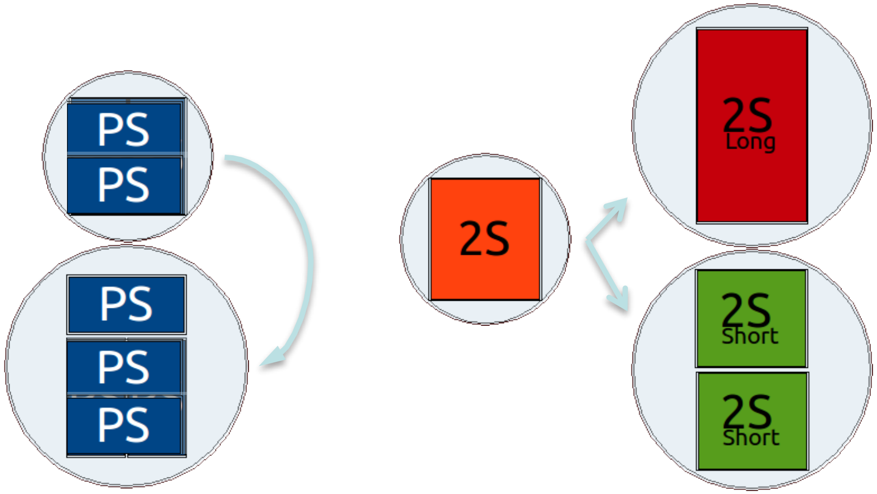




Layout Option: 8” Sensors

- Goal:
  - Cost reduction since costs per area on 8” is cheaper than on 6”
  - But keep electronics identical for 6” and 8”
- Changes:
  - 2→3 PS sensors per wafer
  - Elongate 2S sensor from 10 x 10 cm^2 to 10 x 15 cm^2: **2S long**
  - High occupancy in innermost 2S layer → Shorten sensor to 10 x 7.5 cm^2 and cut two from one wafer: **2S short**
- Break even if cost per wafer
  - 8” < 1.5 x 6”





Tracker Layout Baseline Numbers

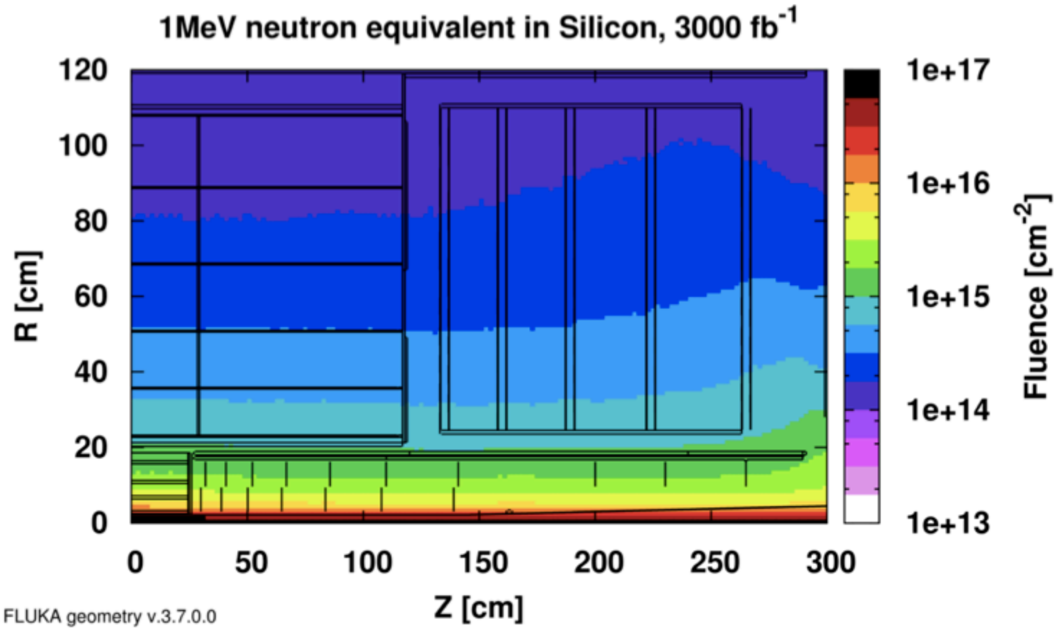
	Baseline Design			Tilted PS Barrel		
	6” design					
	2S	PS		2S	PS	
	(ac)	Strip (ac)	Pixel (dc)	(ac)	Strip (ac)	Pixel (dc)
N of modules	8424	7084	7084	8424	5204	5204
N of sensors	16848	7084	7084	16848	5204	5204
N of 6” wafers	16848	3542	3542	16848	2602	2602
6” wafers with spares	**19200**	**4000**	**4200**	**19200**	**3000**	**3150**

	8” design							
	2S_short	2S_long	PS		2S_short	2S_long	PS	
	(ac)	(ac)	Strip (ac)	Pixel (dc)	(ac)	(ac)	Strip (ac)	Pixel (dc)
N of modules	3696	3760	7084	7084	3696	3760	5204	5204
N of sensors	7392	7520	7084	7084	7392	7520	5204	5204
N of 8” wafers	3696	7520	2362	2362	3696	7520	1735	1735
8” wafers with spares	**4250**	**8650**	**2700**	**2850**	12900		**2000**	**2100**

RADIATION TOLERANT SILICON SENSORS

Irradiation Targets

radius	proton Φ_{eq} [cm^{-2}]	neutron Φ_{eq} [cm^{-2}]	total Φ_{eq} [cm^{-2}]
40 cm	$3 \cdot 10^{14}$	$4 \cdot 10^{14}$	$7 \cdot 10^{14}$
20 cm	$1 \cdot 10^{15}$	$5 \cdot 10^{14}$	$1.5 \cdot 10^{15}$

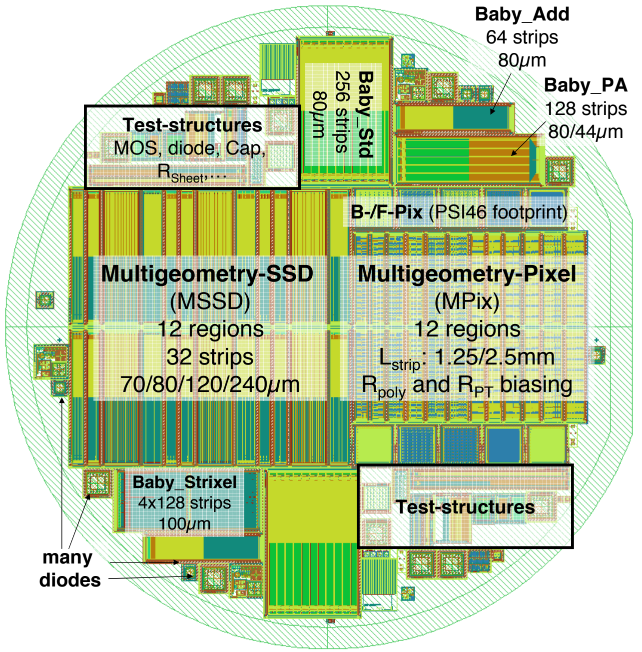


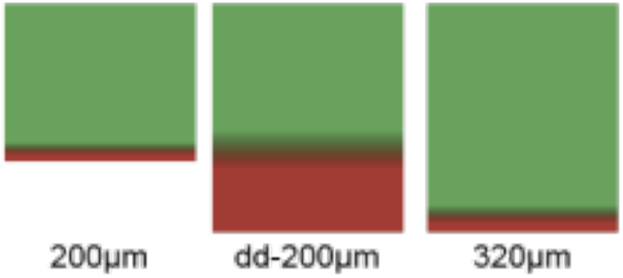
- Fluences target **20** and **40 cm radius** in the outer tracker after 3000 fb^{-1}
- Highest fluence for innermost layers of the outer tracker at **1.5 x 10^{15} $n_{eq}cm^{-2}$**

Radiation tolerant sensor materials

CMS performed an extensive irradiation and measurement campaign:

- Total of 164 wafers
- Wafer layout with 34 different structures
  - Small strip and pixel sensors
  - Dedicated test structures
- Produced by Hamamatsu on
  - FZ: 200 and 320 µm thickness
  - ddFZ*: 120 and 200 µm active thickness
  - MCz: 200 µm thickness
  - Epi: 50 and 100 µm thickness
- Each material processed with
  - p-on-n
  - n-on-p (pspray)
  - n-on-p (pstop)



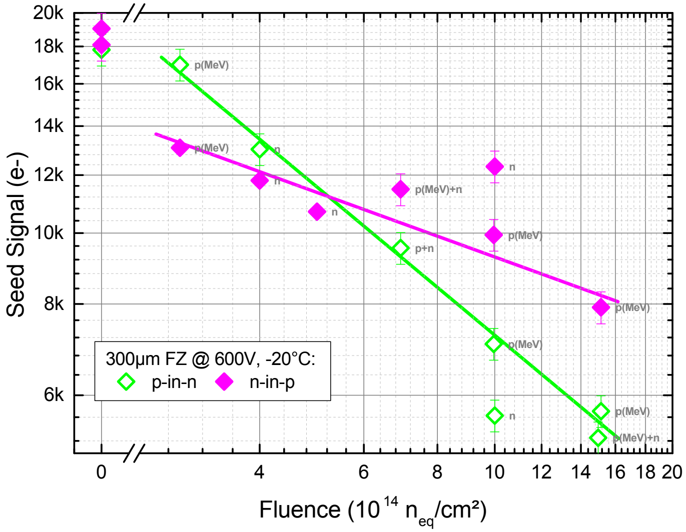


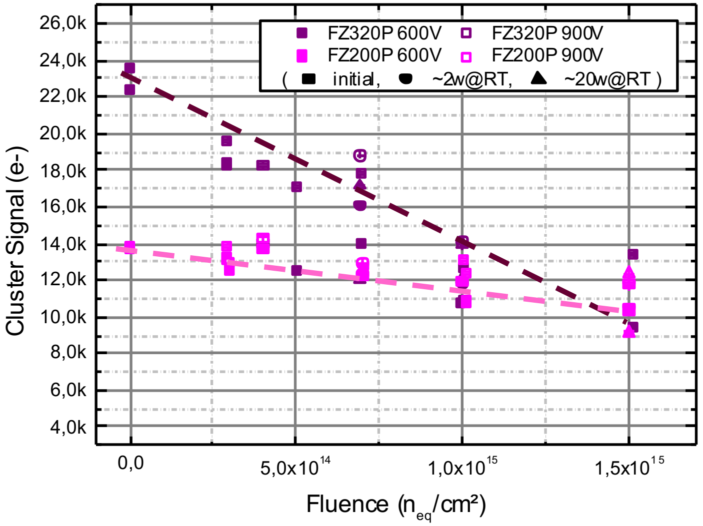
* ddFZ = deep diffused FZ

Collected Charge

- N-type sensors (hole collection) show higher signal degradation than p-type

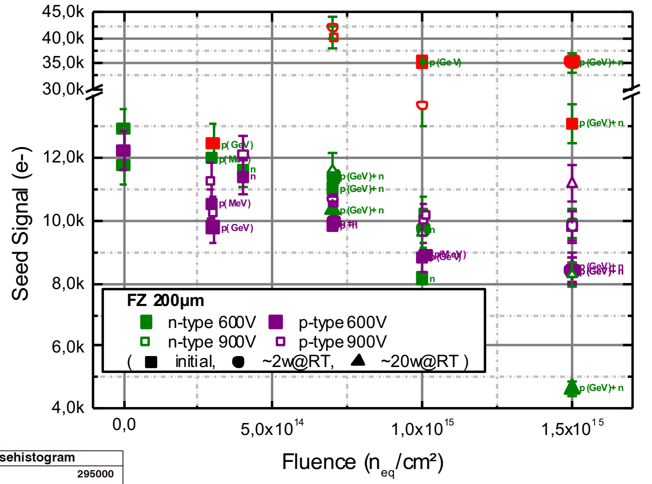
- Beyond ~$10^{15} n_{eq}cm^{-2}$ 200 µm of active silicon show a similar signal to 300 µm



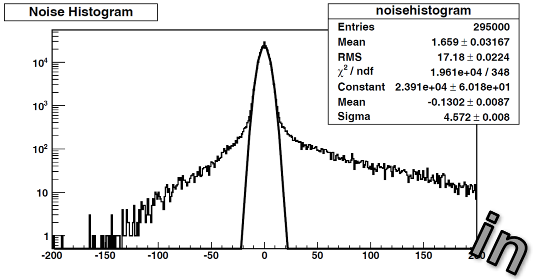


Random Ghost Hits (RGH)

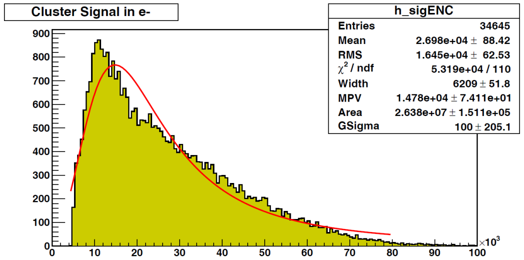
- Very high charge collected in highly irradiated n-type silicon
  - Not originating from charge created by a particle
- Not observed in p-type silicon on R&D study (“HPK campaign”)



- Adds non-Gaussian noise which act as hits
- Simulations suggest an increase of electric field maxima with N_{ox} at strip edges for p-in-n sensors
  - For p-type sensors the maxima goes down with an increase in N_{ox}



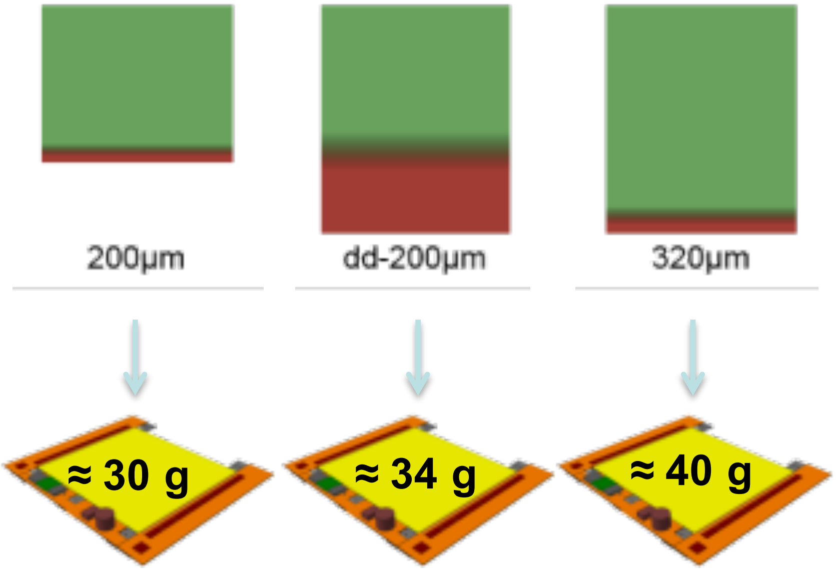
RGH rate = 3%

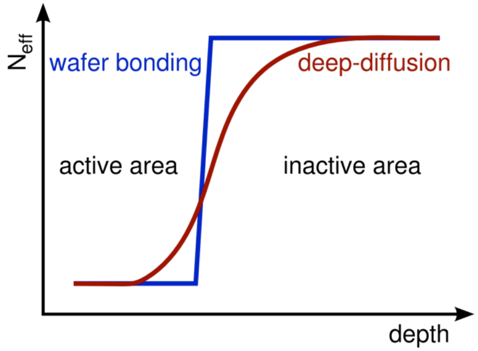


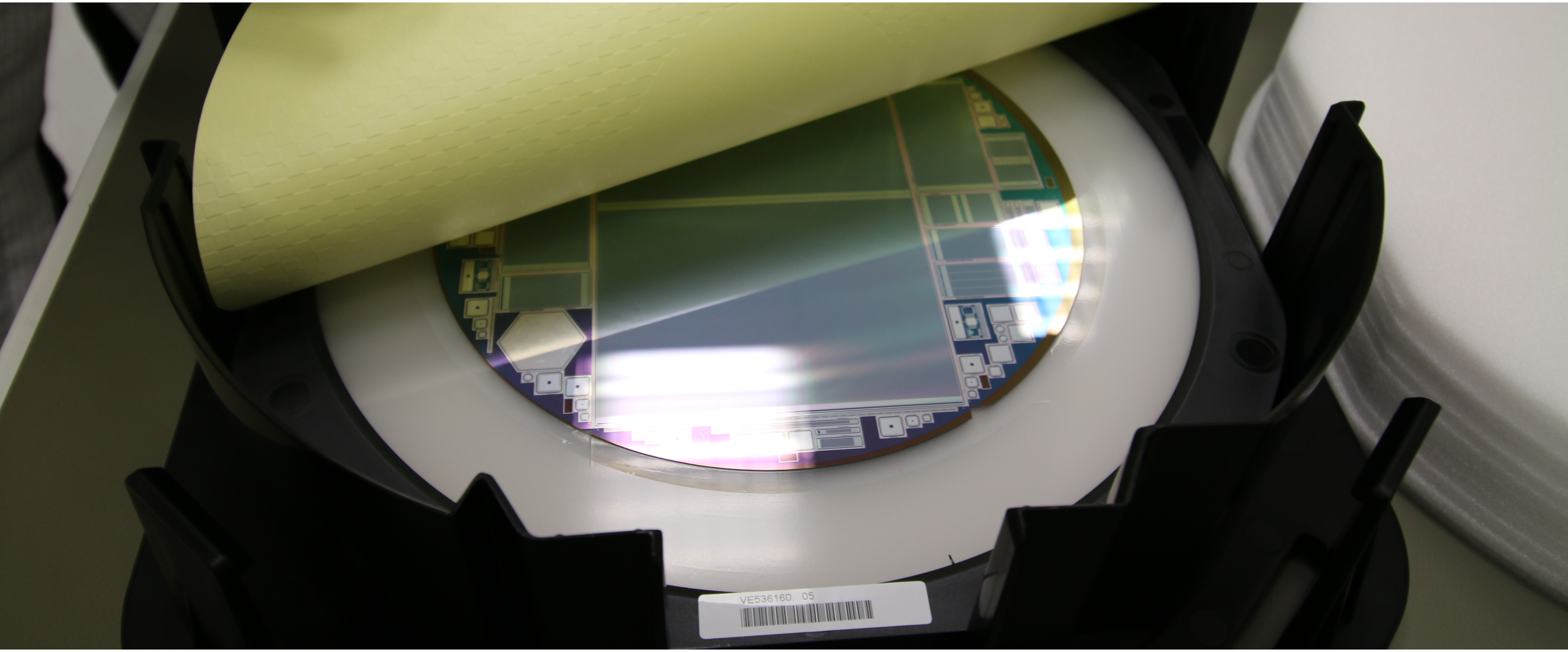
Presented by Martin Printz in previous session

Baseline for the Phase II Outer Tracker

- **P-type materials (n-on-p) are the baseline**
  - Slower signal degradation
  - No Random Ghost Hits (RGH)
- **200 µm active thickness** is preferred
  - Collected charge similar to 300 µm after high fluences
  - Lower dark current
- **200 µm physical thickness** is preferred
  - Less material
- **mCZ is preferred**
  - No change in the V_{depl} with annealing
- **p-stop and also p-spray** show sufficient strip isolation after high fluences





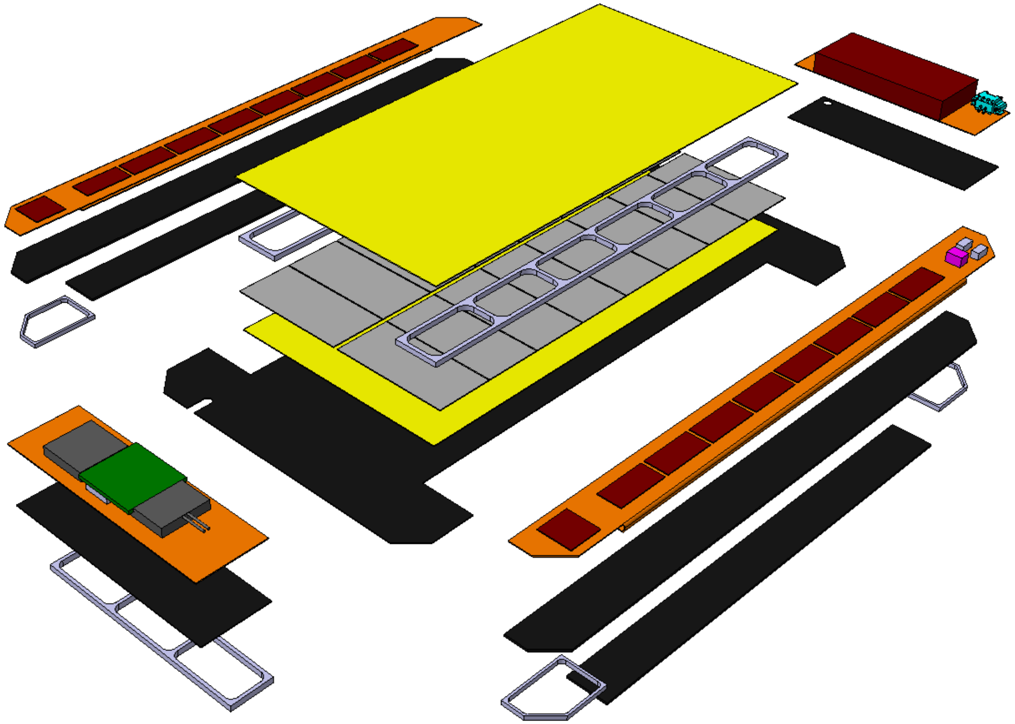


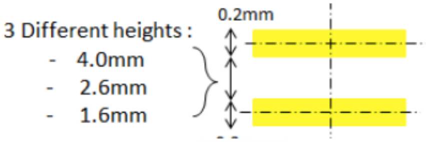
PROTOTYPING

PS Module

- 5 x 10 cm^2 hybrid module consisting of
  - **one strip sensor** (PS-s) ; 2 x 960 strips of 25mm at p=100um
  - **one pixelated layer** of 32 x 960 pixels with 1446µm and p=100µm consisting of PS-p sensor with bump-bonded chips
- Readout:
  - Strips: 2x8 Short Strip ASIC (**SSA**),
  - Pixels read out by 16 MacroPixel ASIC: **MPA**

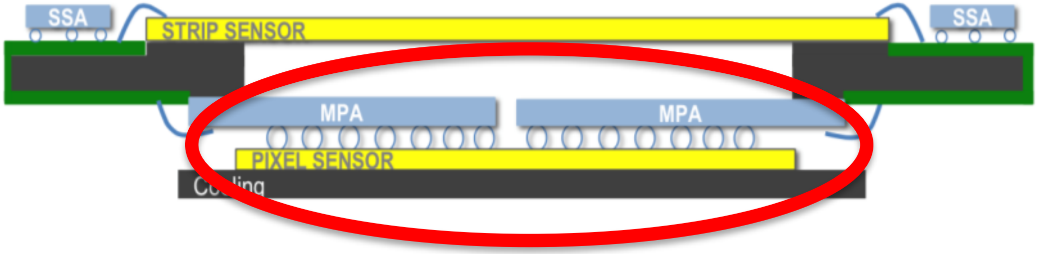
  - SSA processes strip sensor signals at BX frequency
  - MPA processes signals from each pixel and correlates hits from pixel sensor with data received from SSA and
  - builds stubs (p_T>2GeV/c)

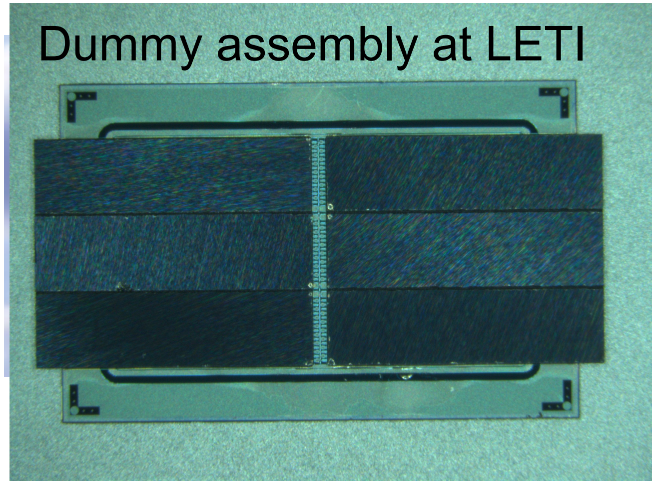




MaPSA-light: Prototypes for PS Module

- We concentrate on pixel part: **M**acro**P**ixel**S**ub**A**ssembly – light
  - **Scaled down** version of the pixel part of the PS module



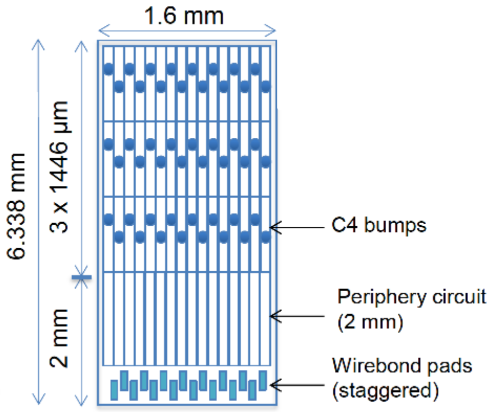

Dummy assembly at LETI

Main Purpose

- Demonstrate and understand the technical aspects of the PS module assembly and design, evaluate flip chip bump bonding, sensor development
  - joint effort of electronics and sensor groups towards PS modules

Current status

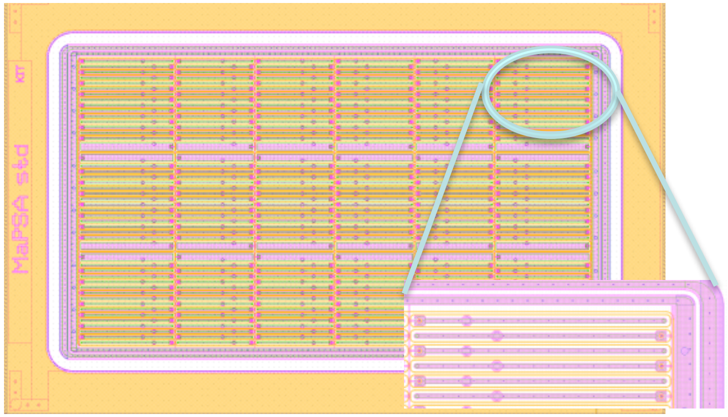
- MPA-light chips and sensors exist
- Few bare sensor wafers were diced and evaluated
- Assembly (Bump Bonding) in progress at 3 companies (Novapack, AEMTEC, LETI)

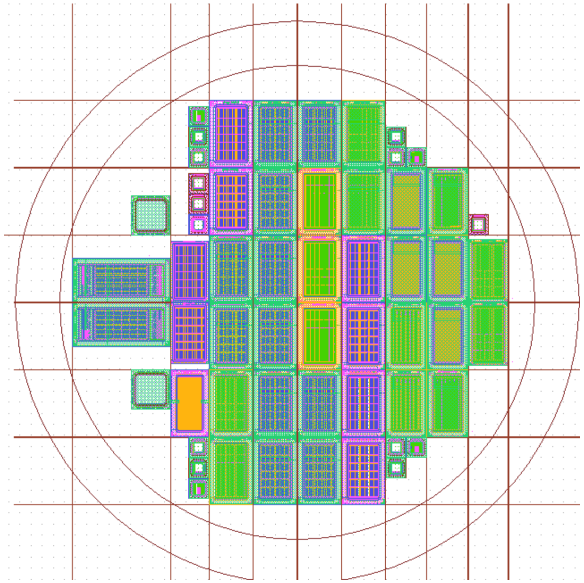


MaPSA-light “pixel” sensor

Wafer/Sensor details:

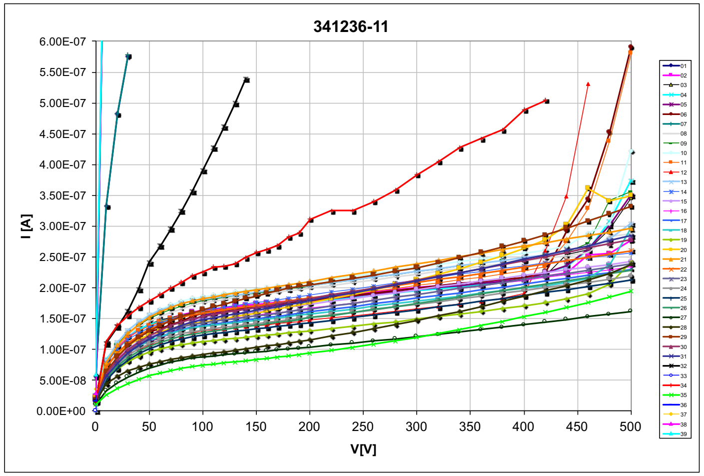
- Substrate p-type FZ, 4-8 kΩcm, wafer thickness 200µm
- 288 “long pixels” (100 x ~1500 µm)
- P-stop and p-spray isolation
  - different P-stop peak concentrations (1E16-1E17) and implant depths (1.5µm-2.5µm) tested
- Biasing via punch through structure, DC coupling to readout ASIC (MPA)
- Wafer layout contains 12 MaPSA-std plus variations with different distances and other tests (spark protection, i.e. “inverted MaPSA” concept)
- 4” Wafers were ordered at CiS (Germany)
  - First batch delivered end of March (10 of 14 wafers)
  - Problems during production (delays, bad wafer material, scratched sensors, humidity dependence, significant losses during production)
  - Later batches significantly better

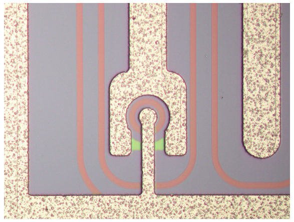


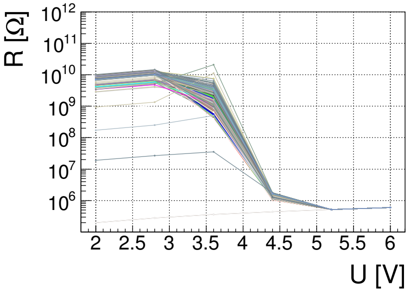


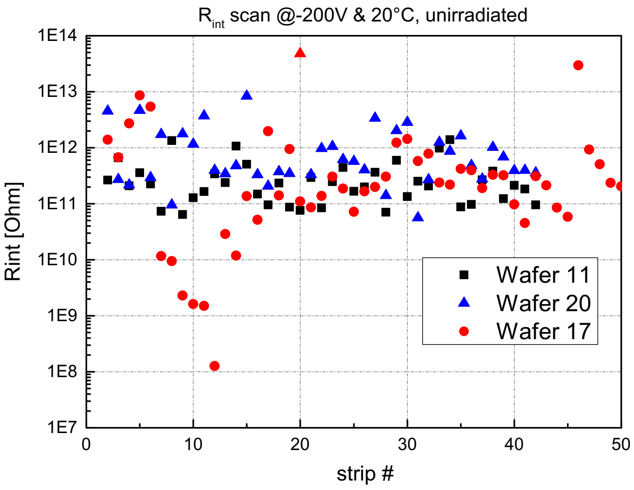
MaPSA-light sensor results

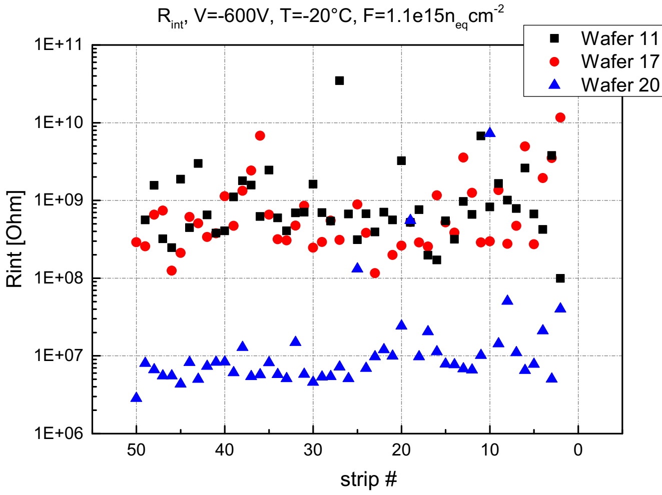
- Three wafers from first batch were diced and sensors were under investigation at HEPHY and KIT
- Sensor concept works
  - Punch through
  - Maintain high inter-strip resistance vs. irradiation
  - Measurements suffer from problems of first batch (e.g. systematic scratches)





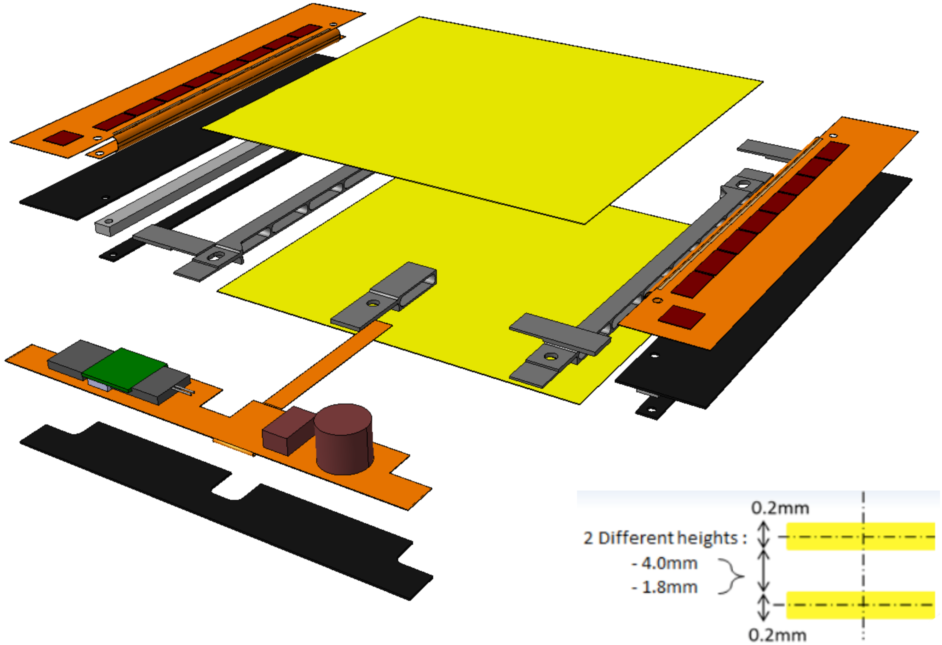


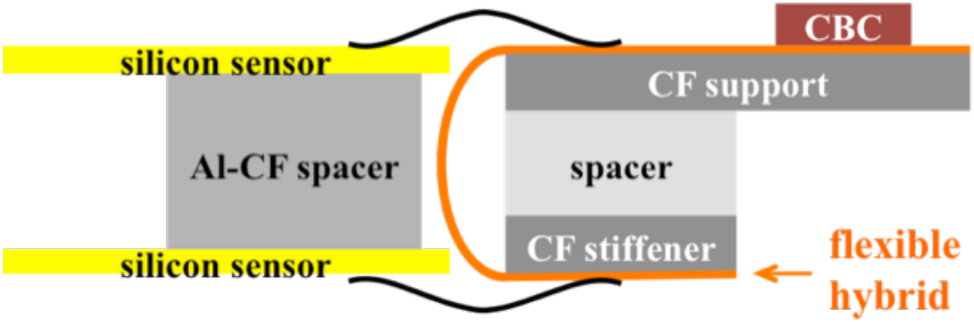




2S Module

- **2** x **S**trip sensors: **2S sensor**
  - Size: 10 x 10 cm^2
  - Pitch: 90 µm
  - Strip length: 5 cm
  - No. of strips per sensor: 2x1016
- 2 x 8 **C**MS **B**inary **C**hips: **CBC**
  - 2x127 channels per chip
  - Bump bonded to flexible hybrid
  - Connects to top and bottom sensors
  - Interchip communication via hybrid
- **C**oncentrator AS**IC**: **CIC**
  - collects data from 8 CBCs (half module)
- Service Hybrid:
  - Low Power Gigabit Transceiver
  - 2-stage DC/DC powering





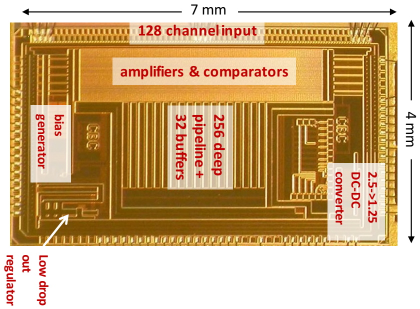
CBC: the 2S readout chip

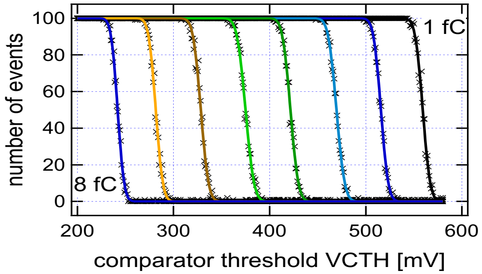
Binary architecture

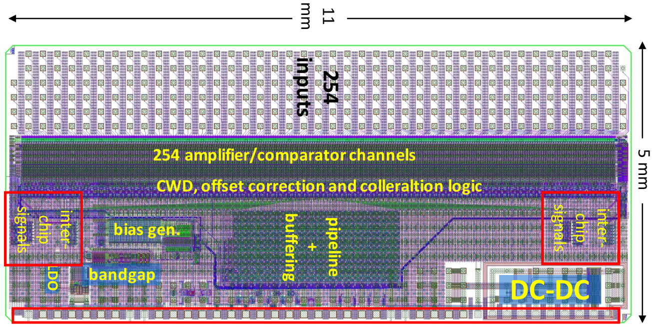
- retains chip and system simplicity
- but no pulse height data

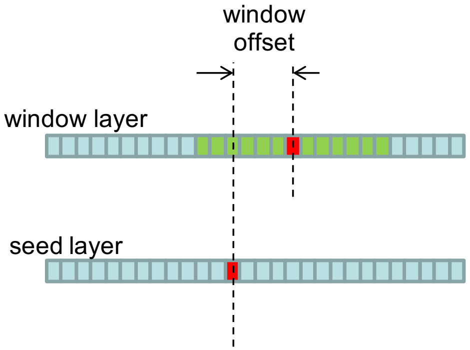
Versions:

- CBC1 (2012-)
  - IBM 130nm CMOS process
  - 128 channels, 50 µm pitch wire-bond pads
  - either polarity input signal (n- and p-substrate sensors)
  - noise: ~ 800 eRMS for 5pF input capacitance:
  - total power: < 300 µW/channel
- **CBC2** (2013-)
  - 254 channels for 127 + 127 strips
  - correlation logic for stub formation
  - C4 bump-bonding to hybrid PCB
- CBC3 (2016-)
  - Should be final chip
  - n-on-p polarity only
  - For AC sensors only (no current compensation)
  - Designed for final trigger rate & latency
  - <450 µW/Channel



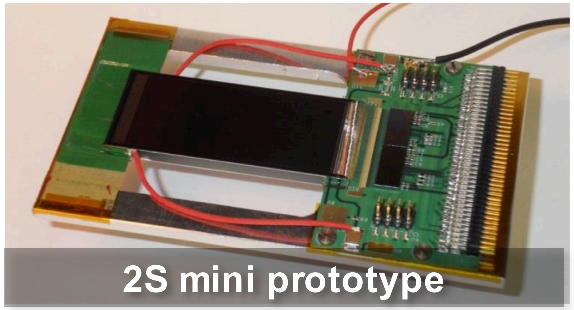




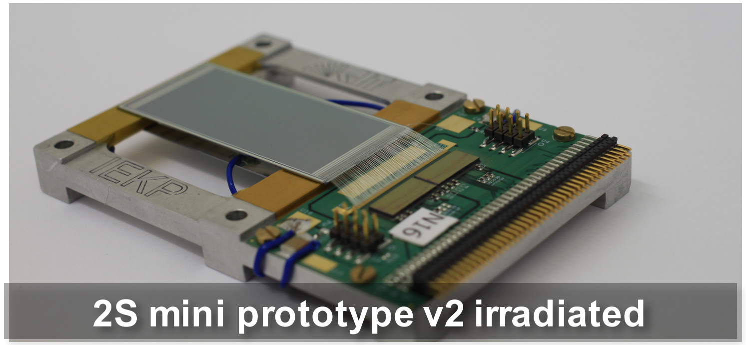


2S prototype modules

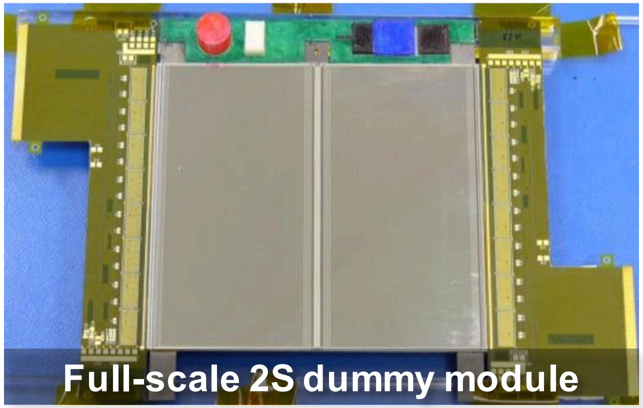
- First mini 2S prototype modules were built in 2013
  - Two 5 x 2.3 cm^2 sensors with 256 strips from Infineon or CNM
  - 2 x CBC2 readout chips bumped to hybrid
- Beam test at DESY in 2013 and SPS in 2015 (with irradiated modules)
  - Demonstrate stub finding efficiency
  - Show performance of irradiated module
- Full-scale dummy modules built for assembly studies
  - Prototype readout hybrids without chip
  - Inactive dummy sensors



2S mini prototype

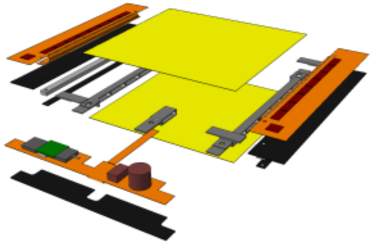


2S mini prototype v2 irradiated



Full-scale 2S dummy module

Baseline Design 2S Sensor



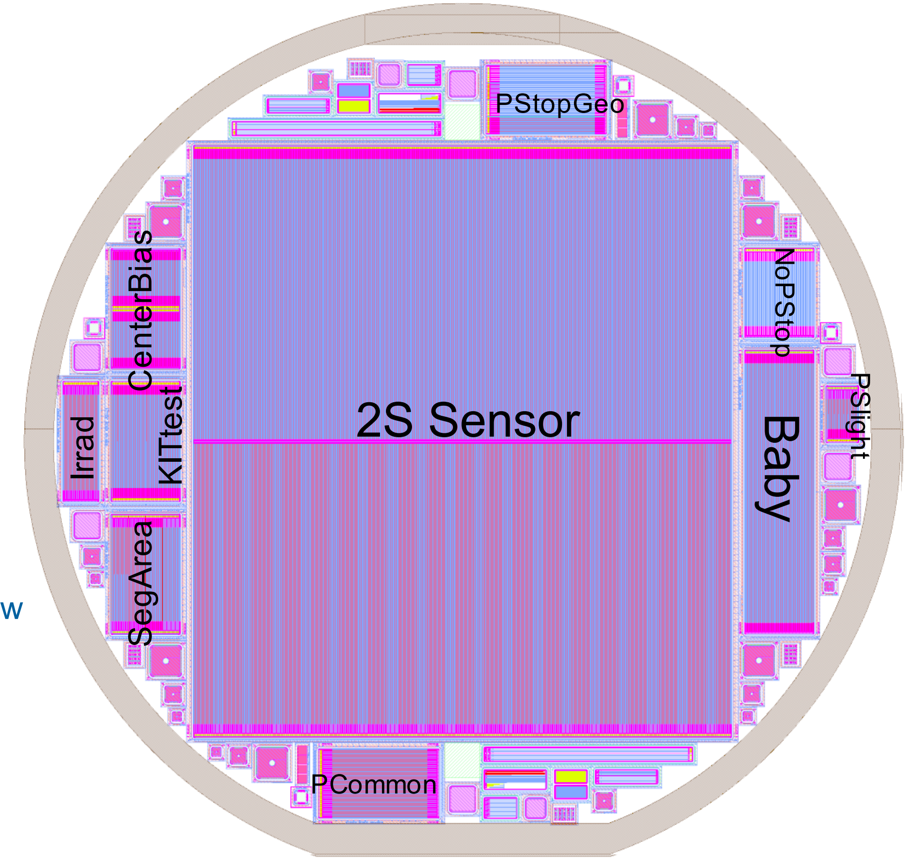
- **Wafer**
  - Wafer diameter *(6" wafer)*: **150 mm**
  - Forbidden margin 5 mm -> **140 mm usable**

- **2S Sensor Layout**
  - Strips: **2032** (2 x 8 x 127)
  - Strip Pitch: **90 µmm,** Width/Pitch: **~ 0.25**

- **2S Sensor size**
  - Sensor width: **94.183 mm**
  - Sensor length: **102.7 mm**

- **And more …**
  - Test sensors to evaluate design options
  - Test structures (Diodes, MOS, Sheet, Van-der-Pauw Cross-Bridge-Kelvin-Resistors, etc …)

- Ordered from both, HPK and Infineon



2S Sensor Production at HPK

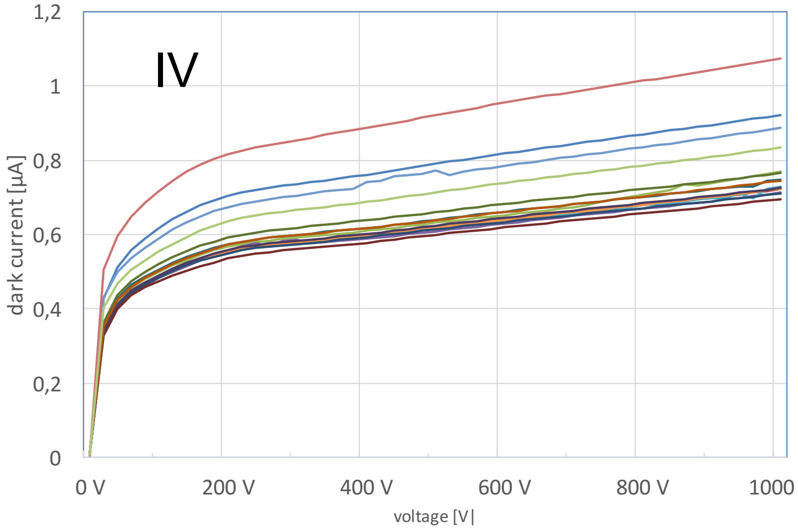
- Material: p-substrate
  - mCZ with 320 µm physical thickness
  - ddFZ with 240 µm active thickness (dd, 320µm physical)
- Both p-stop and p-spray strip isolation

Status:

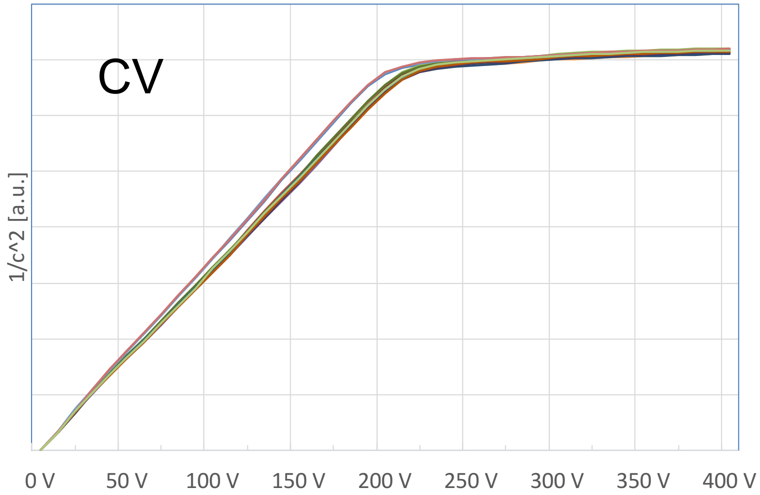
- ddFZ production finished by HPK
  - Quality looks very good as judged from HPK measurements
  - 5 pinholes on 15 sensors (30,480 strips in total) → 0.16 per mille
  - Sensors arrived at CERN last week
- mCZ to be done

Next steps:

- Electrical tests within CMS institutes (HEPHY, KIT, Rochester,…)
- Build full-scale 2S module for beam test in November

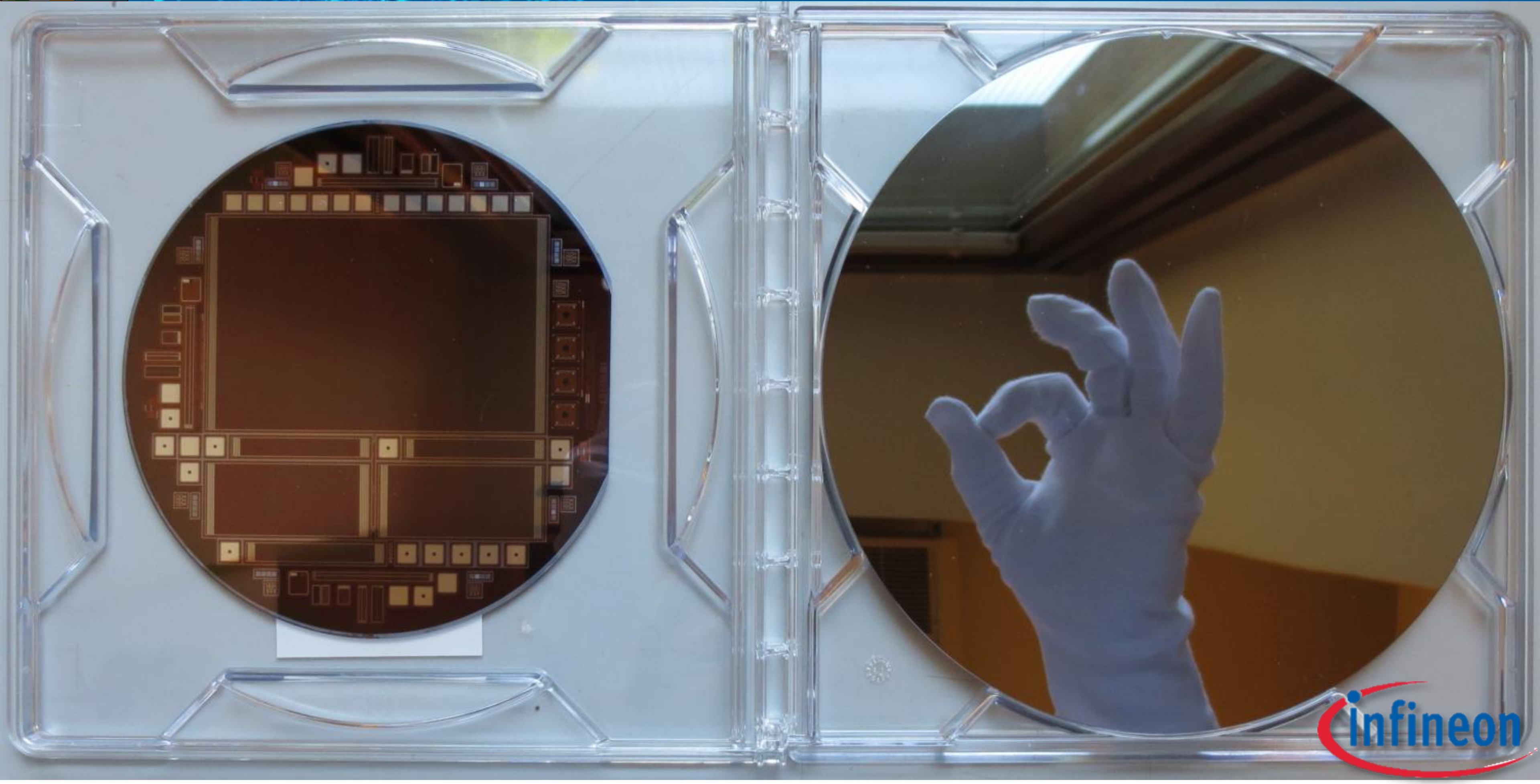


Measurement by HPK



Measurement by HPK

8” Prototypes



8” SENSORS FROM INFINEON

Company profile Infineon

- Infineon is one of the major players in the semiconductor business
  - 35,000 employees worldwide
- Main target markets
  - Automotive, Power, Chip Card
- Villach (Austria): R&D and "frontend" production
  - 3,300 employees (1,200 in R&D)
  - Production in clean room of class 1 with 20,000 m² area


Infineon@Villach (Austria)

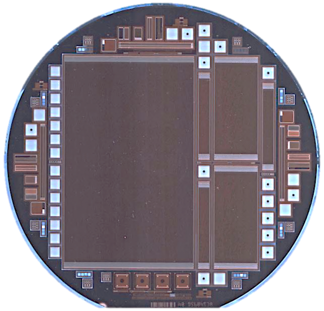
Timeline of collaboration with Infineon

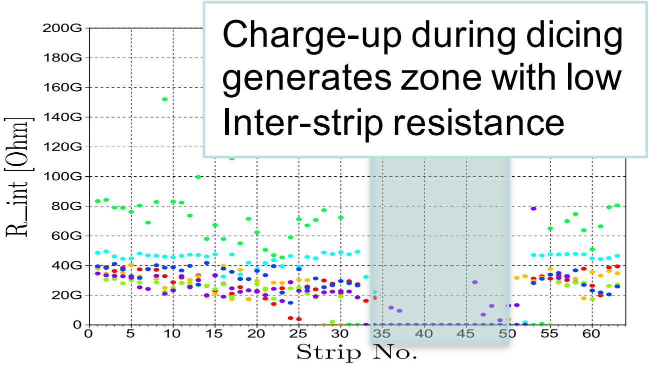
- 2009: Project started between HEPHY and Infineon
- 2012: First production of 6" p-on-n sensors
  - Goal: re-produce the same sensors CMS tracker is using now
  - Several batches in 5 different runs with good quality, but some issues, eventually tracked down to charge-ups

- Since 2014:
  - Working on 8" process for CMS Tk Phase II Upgrade
  - First production finished just 2 weeks ago → see next slides

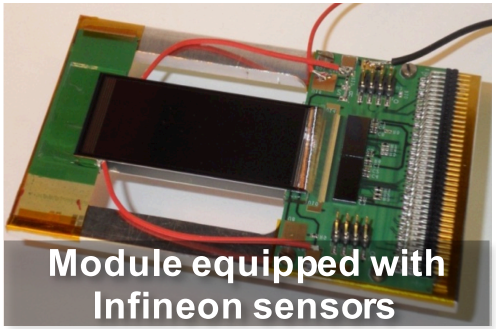
- Since 2015: Development of sensors for CMS High-granularity calorimeter
  - Order for Prototypes under discussion
  - Total demand: 600 m^2

6" p-on-n Wafers:





Charge-up during dicing generates zone with low Inter-strip resistance



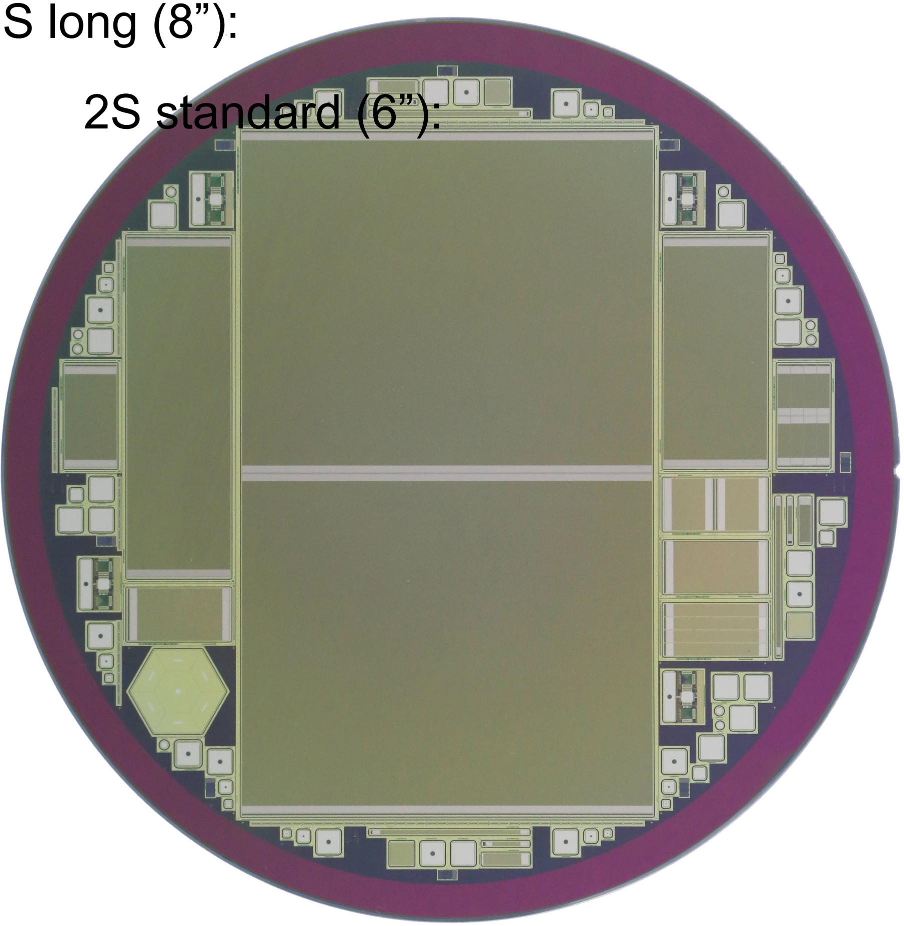
Module equipped with Infineon sensors

2S Sensor (8" version)

- Wafer:
  - Wafer diameter *(8" wafer)*: **200 mm**
  - Resistivity ~ 7 kΩcm, n-on-p float zone, orientation <100>
  - **200 µm physical thickness** → V_{fd}~60V
- Main Sensor
  - Same as the 6" version but elongated
  - Size: **94.183 x 153.4 mm²**
- Split groups for first batch (25 pcs)
  - P-stop / p-spray
  - implant/p-stop depth and concentration
  - Different R_poly doping

2S long (8"):

2S standard (6"):



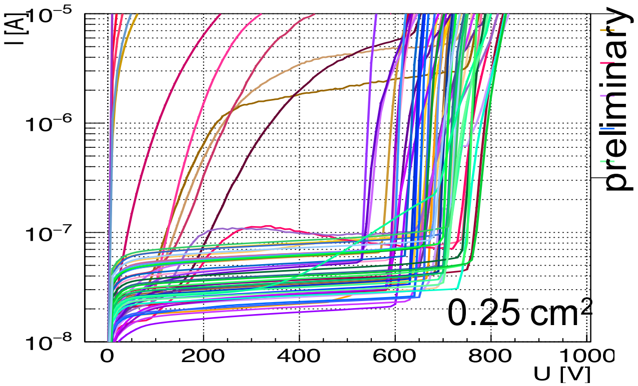
First batch produced without any losses at Infineon and is now in Vienna for electrical tests since two weeks!

First results of Infineon 8” 2S Sensor

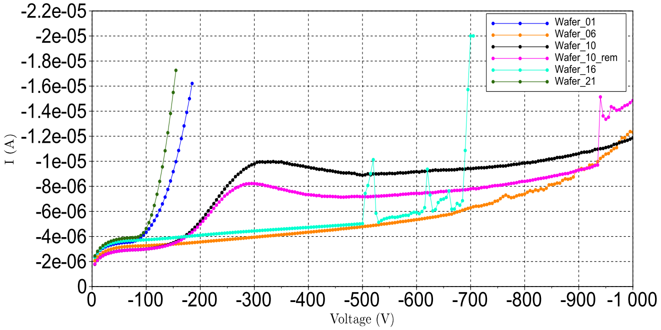
- IV on diodes (5x5 mm^2) mostly stable up to 700V
- IV on full sensor ~4μA @ 100V (144 cm^2),
- CV: full depletion of main sensor at ~70V as expected
- Strip-scans of 2S_long sensors from 5 wafers show **no pinholes** (out of 10k strips)

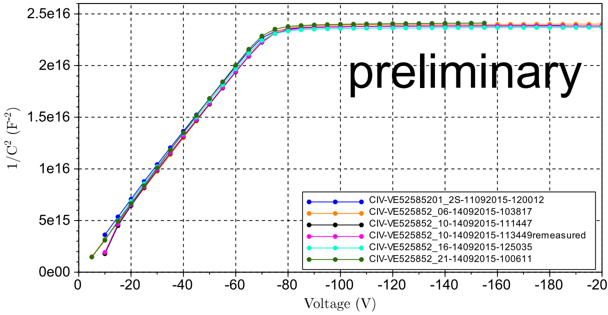
- Next steps:
  - In-depth electrical characterization of all structures
  - Build full-size 2S_long module for beam test scheduled for this November
  - Irradiation studies

Diodes (0.25cm^2):



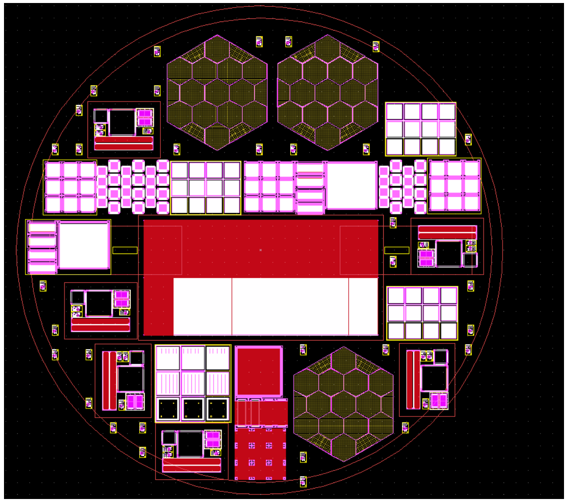
Sensor (144 cm^2):





Novati Project

- Some time ago Novati/Tezzaron expressed interest in and capability for a fabrication of **8” sensor wafers**.
  - Project driven by US groups (FNAL, SLAC, Brown, et al.)
  - Fab has 12,000 wafers/month capacity
- Wafer material P-type, >5kohm cm <100>
- SLAC provided reference process flow (DC-coupling)
- Split groups:
  - 3 full-thickness wafers (725micron)
  - 3 thinned to **500 microns** after top processing
  - 4 p-stop plus p-spray, 2 p-stop only (one broken)
- Future steps (Underway with US SBIR funds):
  - Phase 1: Si-Si or SOI stack for thin wafers
  - Phase 2: include poly-silicon resistors and AC coupling with full CMS prototype wafers

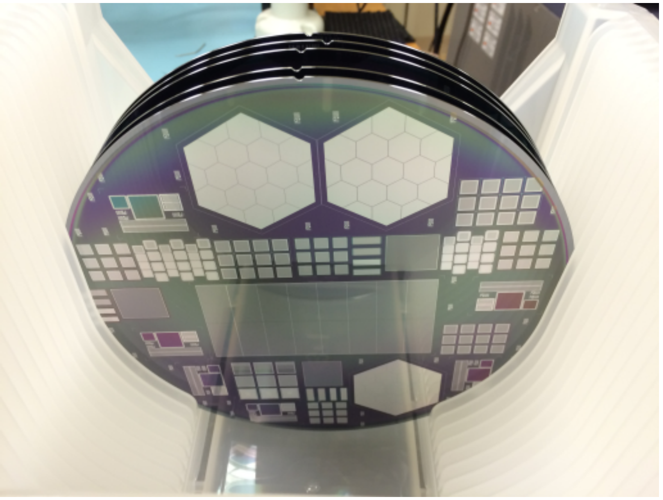


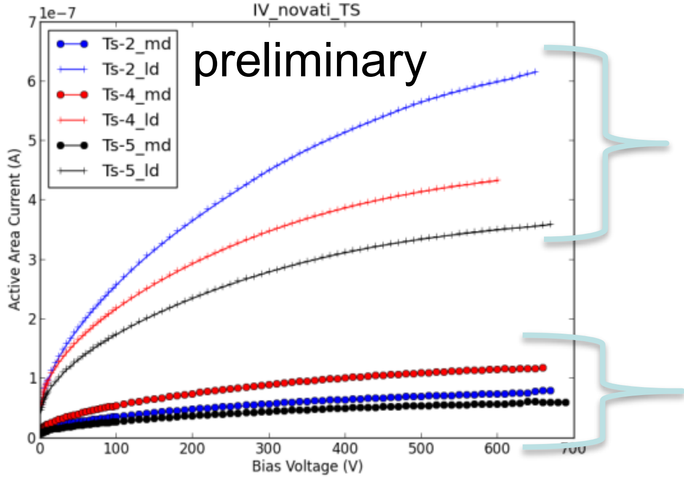
Layout contains:

- CMS strip structures
- CMS HGC structures
- CMS Pixel structure
- SLAC/ATLAS pixel structures
- Argonne Lab x-ray structure
- Test structures

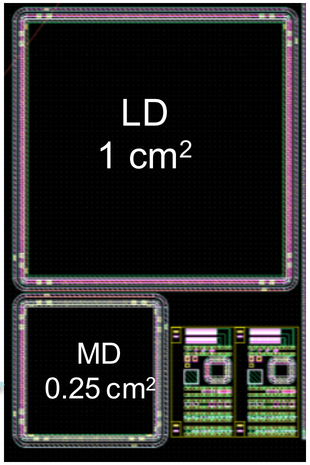
First Novati Measurement results

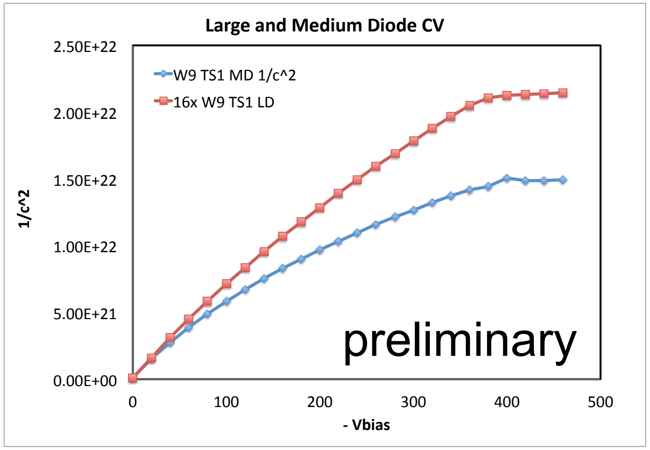
- Final masks beginning of January, Fab-out mid April 2015
  - 3 pcs. with725µm
  - 2 pcs. with 500µm (one broken)
- Initial tests on full wafers have been performed by Fermilab and Brown University
  - IV of Diodes (725 micron p stop + p spray)
  - CV curve show depletion at ~400 V -> resistivity ~ 6 kΩcm (500µm thickness)
  - MOS structures, inter-strip resistance, Charge collection





preliminary





preliminary

Summary

- CMS Outer Tracker for HL-LHC (Phase II Upgrade) will contribute to L1 trigger
  - All modules will provide p_T cut information
  - 2 Sensor types for whole tracker only: PS (pixel-strip) modules and 2S (two strip sensor) modules
- Tracker layout baseline defined in Technical Proposal for CMS Phase-II Upgrade (released June 2015)
  - Two alternatives/options exist: *titled PS barrel* and *Layout with 8” Sensors*
- Sensor baseline is p-substrate, 200um (active) thickness, FZ or mCZ

- Prototypes have been produced and are currently being tested
  - PS-p light sensors from CiS for testing pixel-chip-assemblies (MaPSA-light)
  - 2S_standard sensors from HPK
  - 2S_long sensor on 8” wafers with 200µm thickness from Infineon
  - Test run with Novati at 8”

- Full scale 2S modules (with HPK sensors) and 2S_long modules (with Infineon sensors) will be tested in Nov 2015 beam test

THE END

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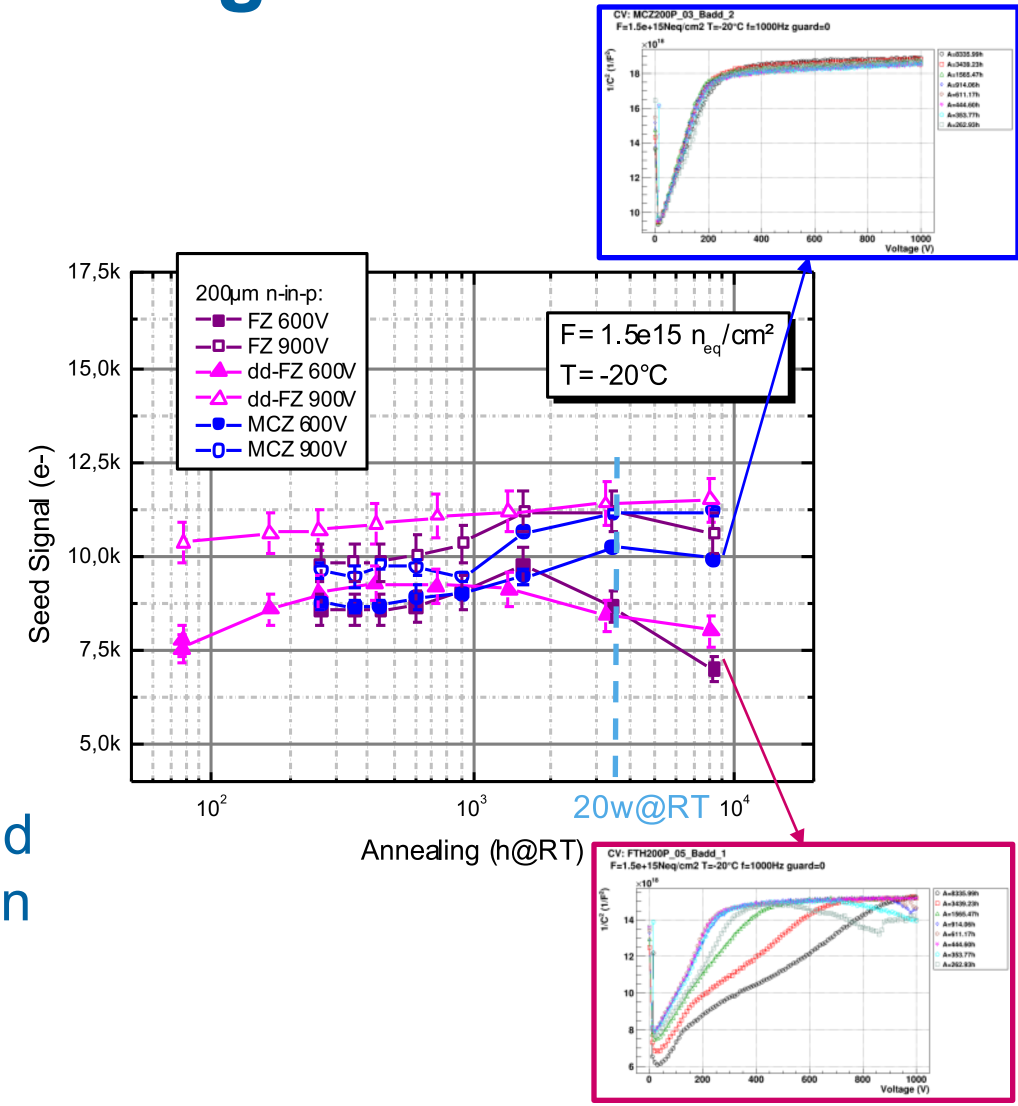
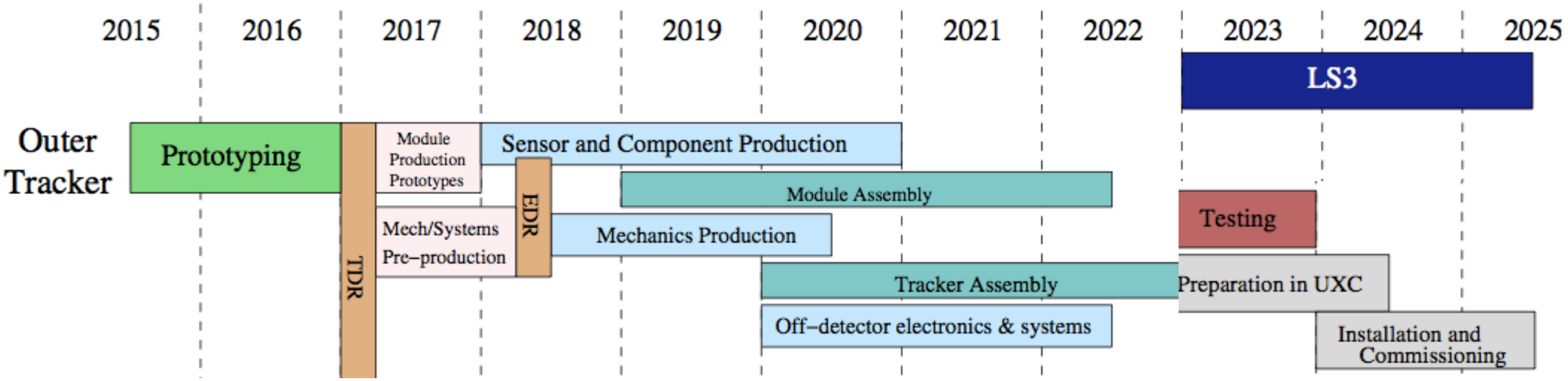
BACKUP

Annealing

- Charge collected in 200 µm sensors stays relatively constant up to 20 weeks at room temperature (RT)
  - Thick sensors show more pronounced loss
- mCZ shows no loss (even gain) after 20w@RT
  - Full depletion voltage stays constant
- Annealing in mCZ would decrease leakage current (and therefore noise) with no loss in signal



Timeline and Procurement Procedures

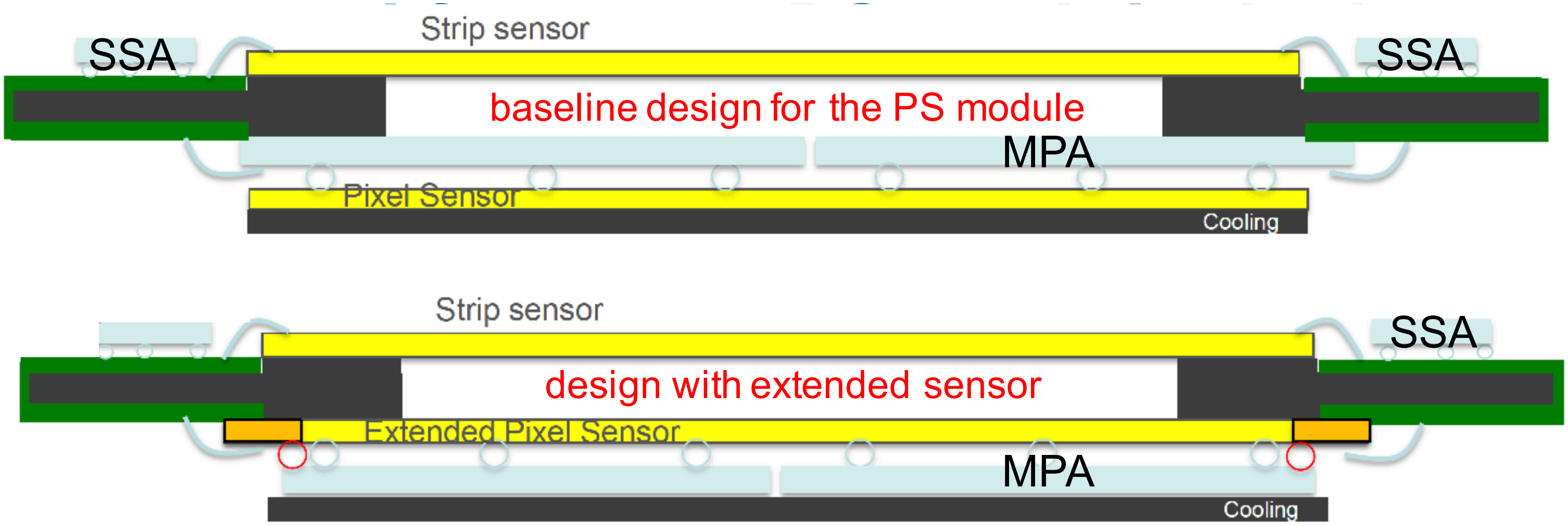


CERN procurement rules follow three steps: a) Market Survey (MS), b) Invitation to Tender, c) awarding the contract

Common MS for planar strip sensor of ATLAS and CMS!

- Tender (and procurement) will be **separate**
- MS will be open for the **next 2-3 years**
  → up until the invitation to tender
- **Share workload** in qualifying vendors
  - Expect fruitful exchange of expertise

Inverted MaPSA concept



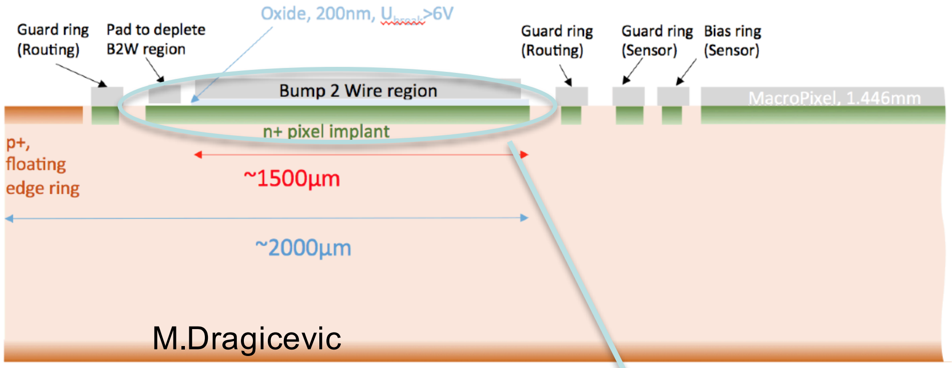
G.Blanchot

- -> connection between chip and the hybrid via on sensor routing (next slide)

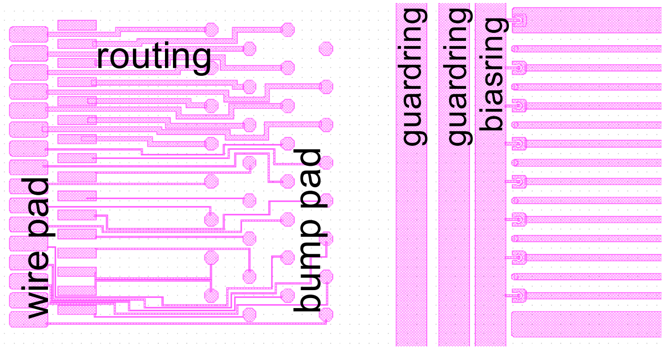
pro	contra
only bump bonding in MPA design	digital IO through sensor periphery
better cooling of MPA	larger sensor and temperature gradient

Inverted MaPSA sensor design

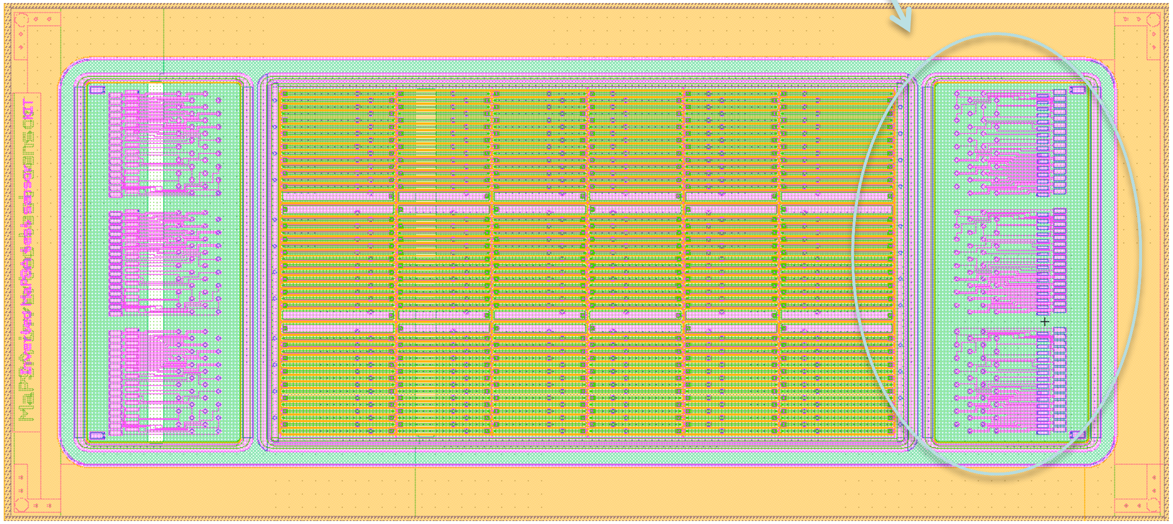
- I/Os of MPA pass on silicon (sensor periphery)
- periphery isolated from active area
- use of first metal only
- n+ pad under routing in order to isolate B2W region from HV



M.Dragicevic



B2W region



design of the inverted MaPSA light sensor