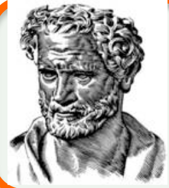


CMS Phase II Upgrade : Demokritos activities

NCSR 'Demokritos', Institute of Nuclear & Particle Physics

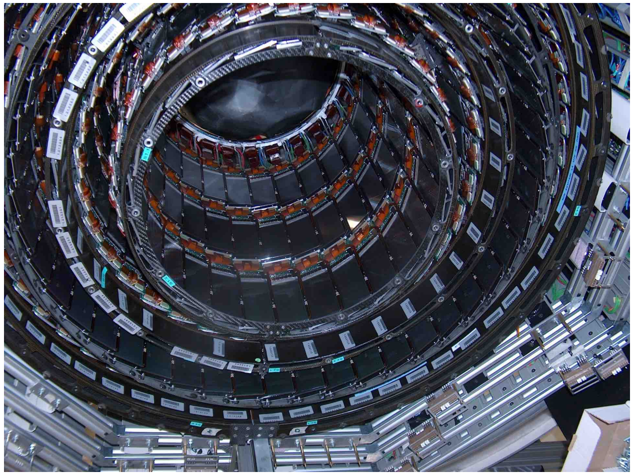
Staff
G. Anagnostou,
G. Daskalakis,
A. Kyriakis,
D. Loukas*

Ph.D. Students
P. Asenov
P. Assiouras
G. Paspalaki

CMS Students
A. Papadopoulos

Engineers
I. Kazas

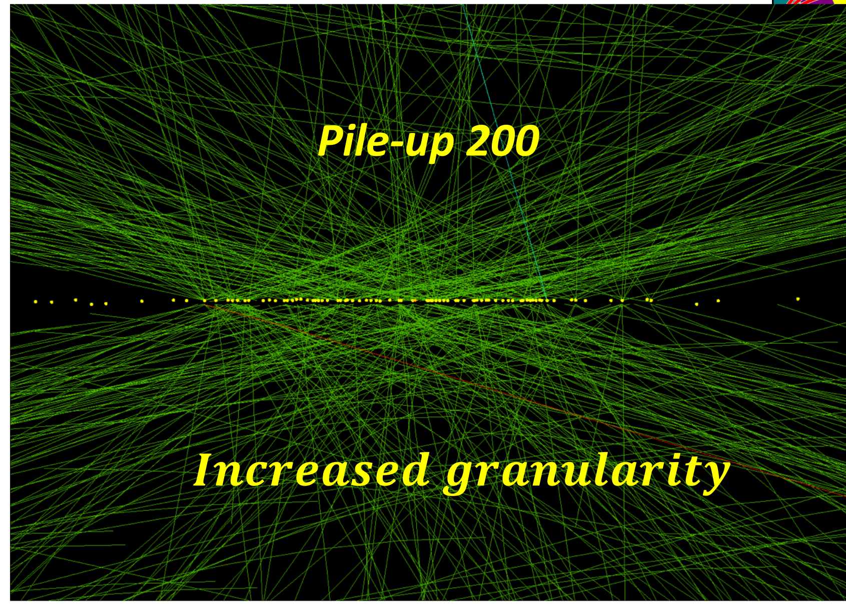
* Institution Team Leader



CMS Tracker Phase II Activities at NCSR DEMOKRITOS

- *Sensor & Process Quality Control for Outer Tracker*
- *Data Acquisition for the Pixel detector*
- *CMS Particle Telescope*

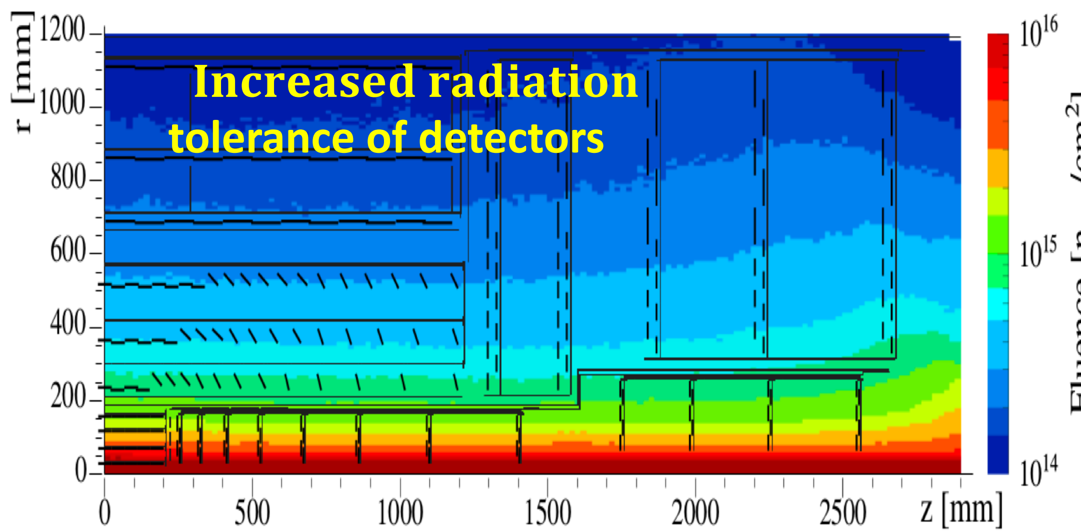
The CMS experiment at the HL – LHC



- *Instantaneous Lumi: up to 7 x $10^{34} cm^{-2} s^{-1}$*

- *Integrated Lumi: 3000 fb^{-1}*

  - *Radiation levels up to:*
  - *2 x $10^{16} n_{eq} cm^{-2}$*



CMS Phase II Upgrades

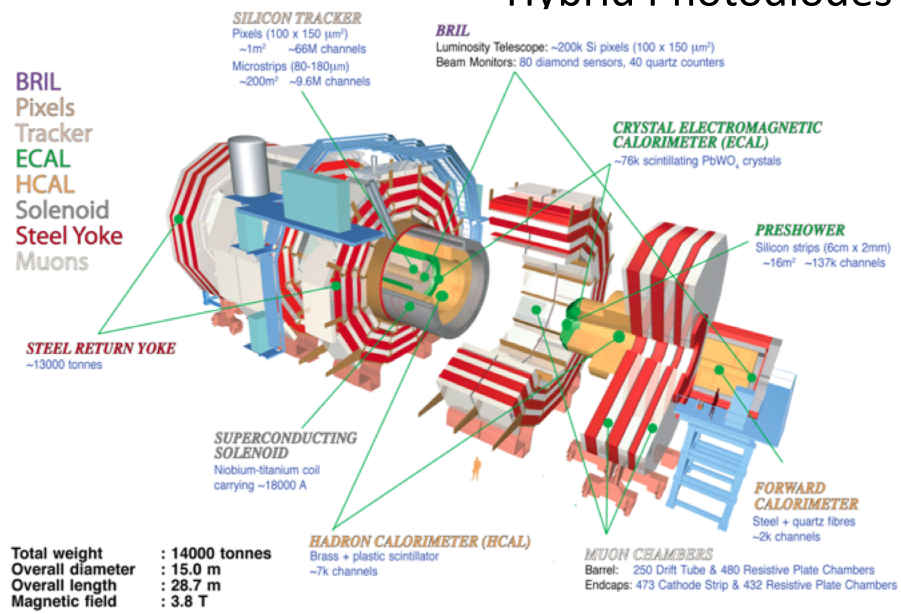
Barrel EM calorimeter
- new FE/BE electronics (increased time resol.)
- Lower operating temperature (8 deg.)

EndCap EM&Hadron Calorimeter
complete replacement
with HGCal

Hadron Calorimter
Hybrid Photodiodes (HPDs) -> SiPMs

Trigger HLT-DAQ
- Hardware Track info in L1
- L1 Trigger latency 12.5 μs
- HLT output 7.5 KHz

MIP Timing Detector
- 30 ps precision
- Just outside the Tracker
-LySo:Ce readout by SiPMs

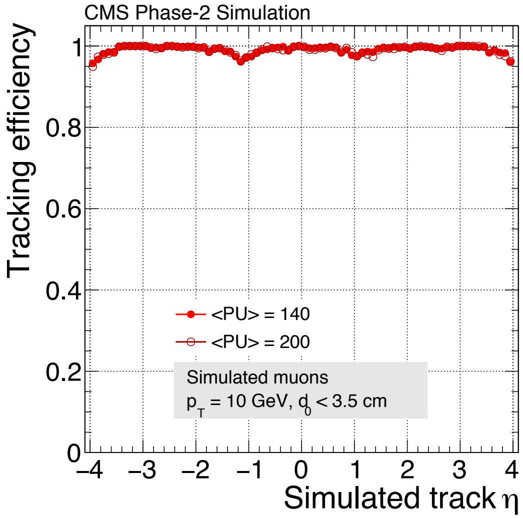


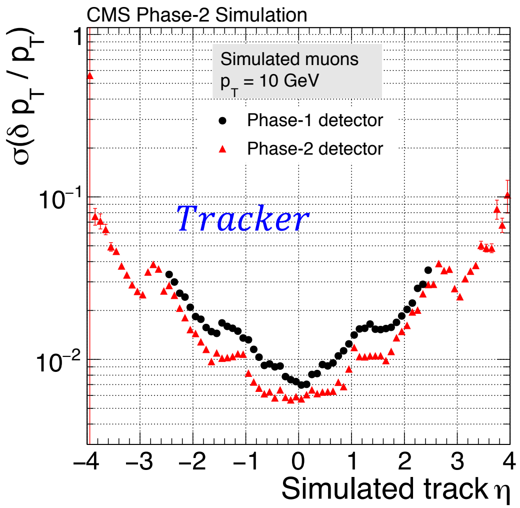
Beam radiation & luminosty
Common system & Infrastructure

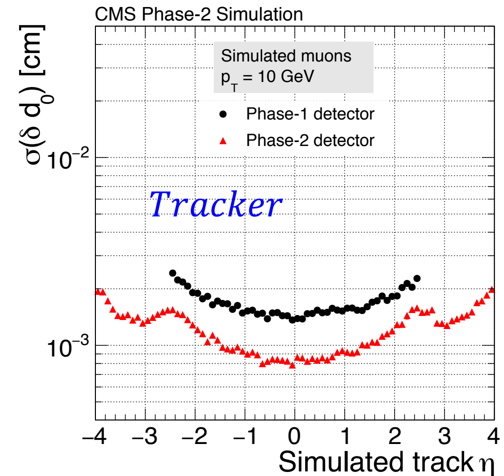
New Tracker
- Rad. tolerant - increased granularity
- 40 MHz selective readout in Outer Layer
- Extended coverage to η=4

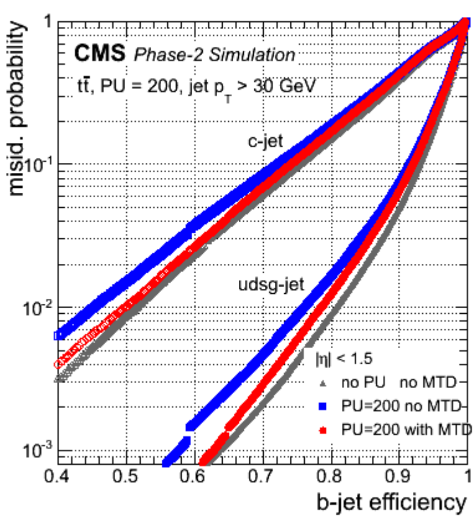
Muon System
- New DT & CSC FE-BE electronics
- Extended RPC coverage 1.6 < η < 3
- Muon tagging 2.4 < η <3

Highlights of expected performance









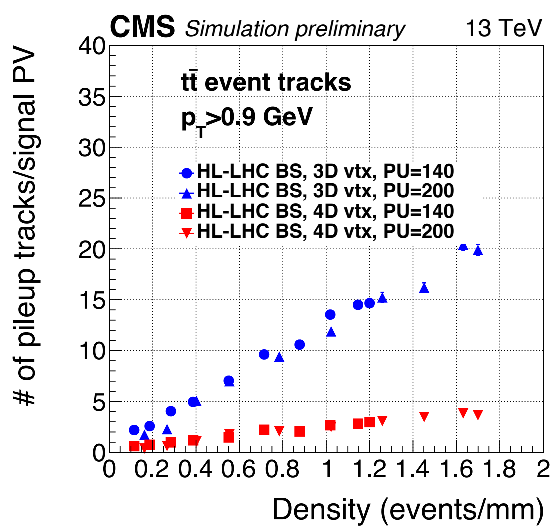


Table 1: The "floor" systematic uncertainties for the HL-LHC.

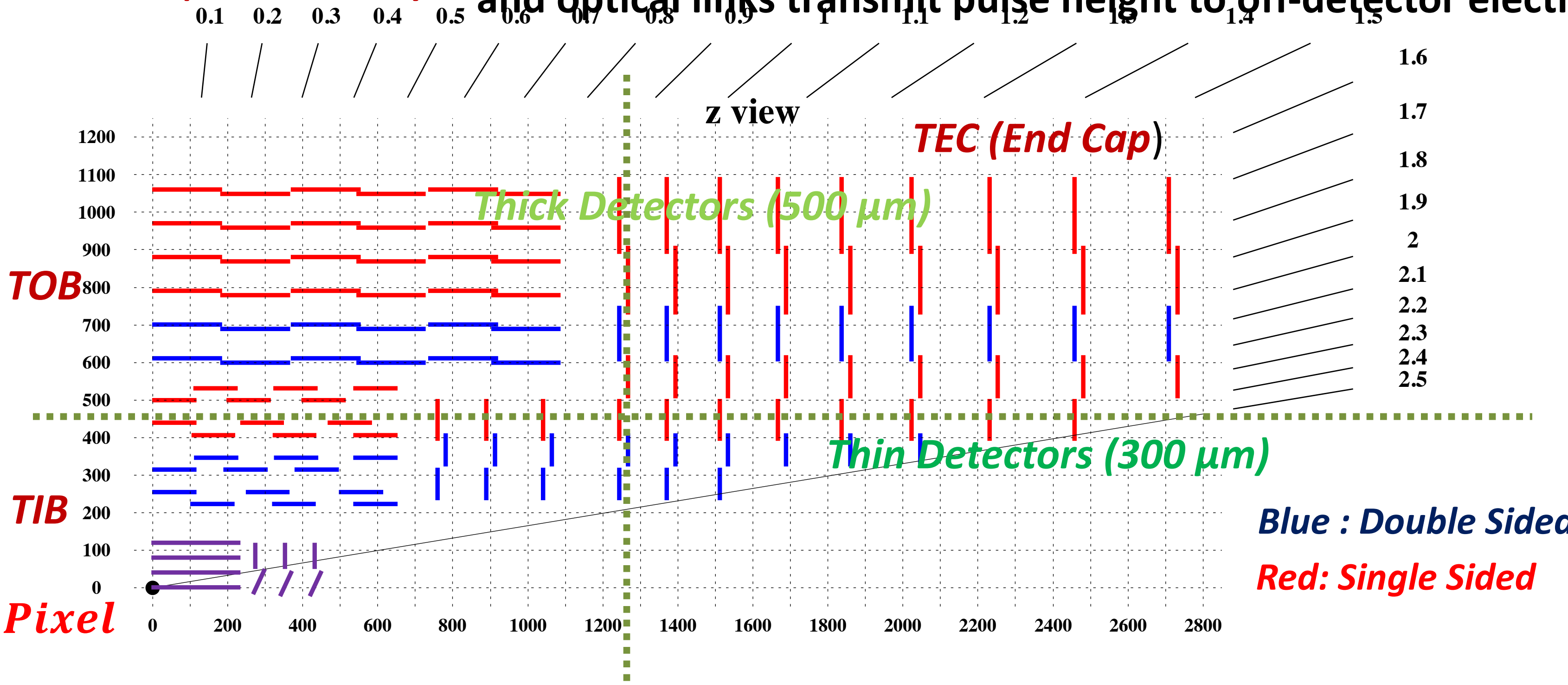
Uncertainty	Working point/ component	Value
Electron ID	All WPs, $p_T > 20\,\text{GeV}$	0.5%
	All WPs, $10 < p_T < 20\,\text{GeV}$	2.5%
Photon ID		2%
Muon ID	All WPs	0.5%
Tau ID	All WPs	2.5%
Jet energy scale	Total	1–2.5%
	Absolute scale	0.1–0.2%
	Relative scale	0.1–0.5%
	PU	0–2%
	Jet flavor	0.75%
Jet energy resolution		3–5% as a function of η
b-tagging	b jets (all WPs)	1%
	c jets (all WPs)	2%
	Light jets, loose WP	5%
	Light jets, medium WP	10%
	Light jets, tight WP	15%
	Subjet b tagging	1%
	Double c tagging	
p_T^{miss}	Propagate jet energy corrections uncertainties (must)	
	Propagate jet energy resolution uncertainties (recommended)	
	Vary unclustered energy by 10% (recommended)	
Integrated luminosity		1%

The Phase 0 CMS Tracker

TOB (Outer Barrel)

TIB (Inner Barrel)

All detectors are read out via analogue electronics and optical links transmit pulse height to off-detector electronics.



Sensor Technology : *p-in-n*

Design occupancy : *1-2%*

Outer cell size : *~20cm x 100-200μm*

Inner cell side : *~10 cm x 80 cm*

Pixel cell size: *100 μm² x 150 μm² (66M)*

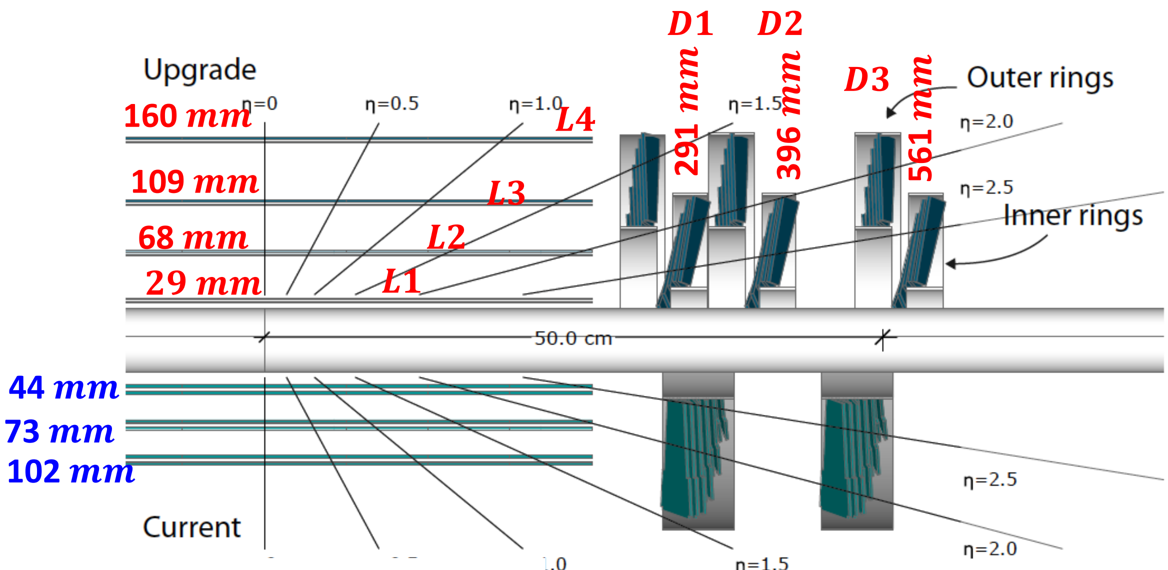
Operation : *-15 °C*

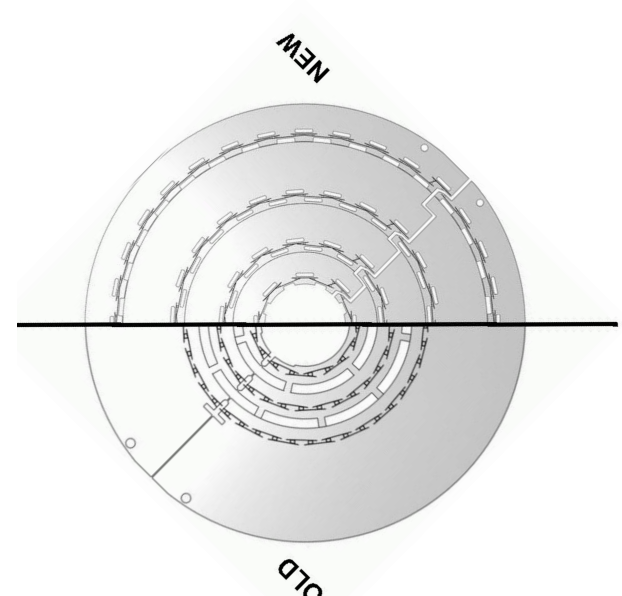
Signal / noise: *~20 (above 10 after radiation)*

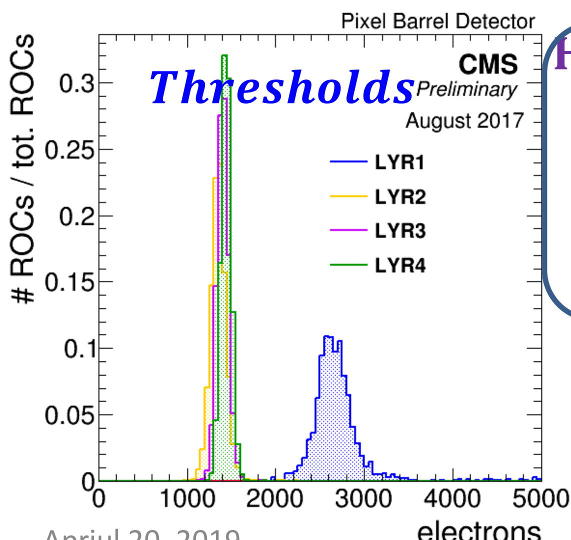
Radiation tolerance: *~1.5 x 10^{14} n_{eq}/cm^2*

The CMS Phase 1 Pixel

The Phase 0 pixel replaced during LHC winter shutdown 2016/2017







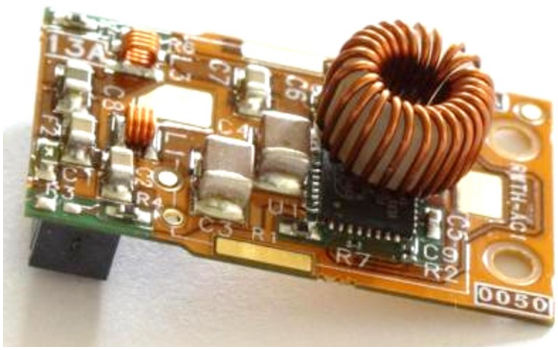
Higher than expected noise in PROC600 plus some synchronisation problems

PROC600 redesign

Allows for luminosities up to $2.5 \times 10^{34}\ cm^{-2}s^{-1}$ and pilup 120 at BX 25 ns

120 MRad in outer layers, 480 Mrad in L1 for 300 fb^{-1}

The DC – DC Case …



Based on the FEAST2 ASIC developed by the CERN EP – ESE group

"After one year of CMS PIXEL 1 operation 35% of the DC-DC converters were found by a damage mechanism that… did not prevent them to work correctly"*

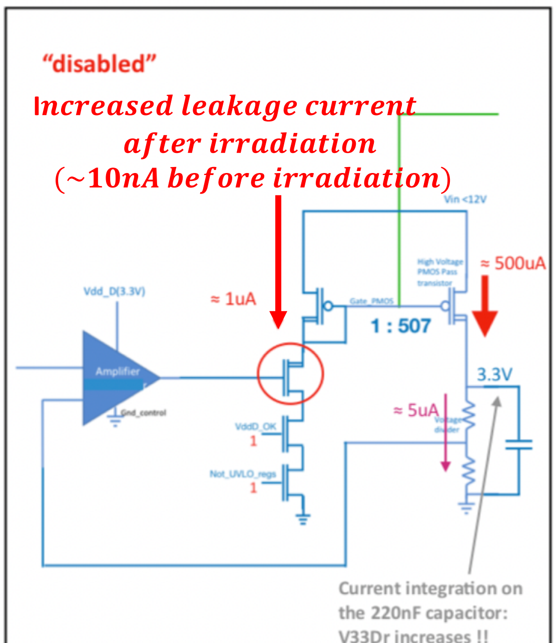
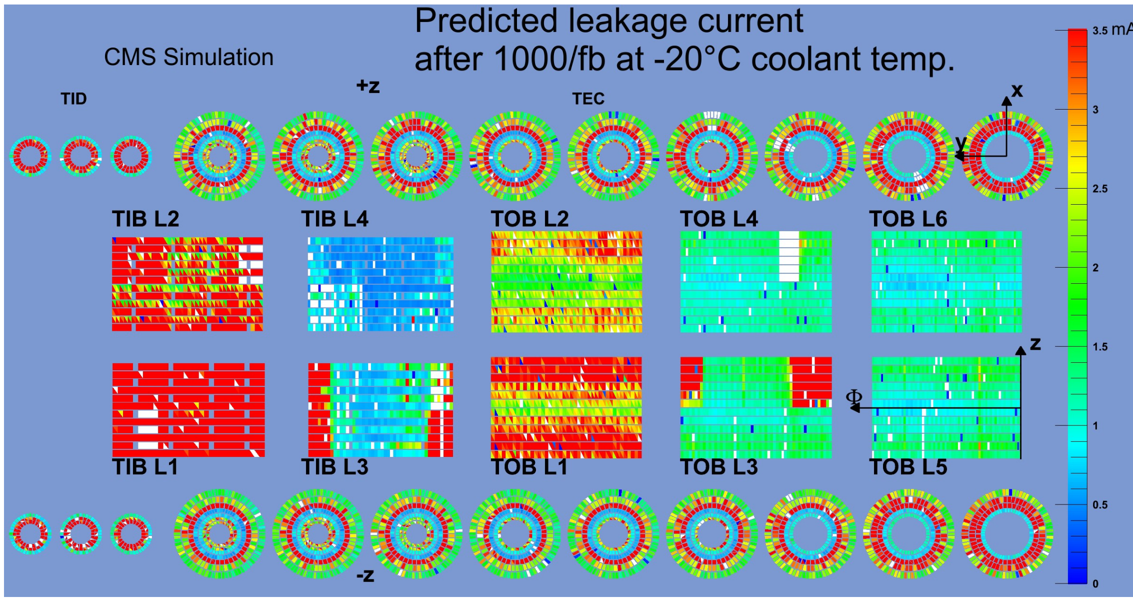


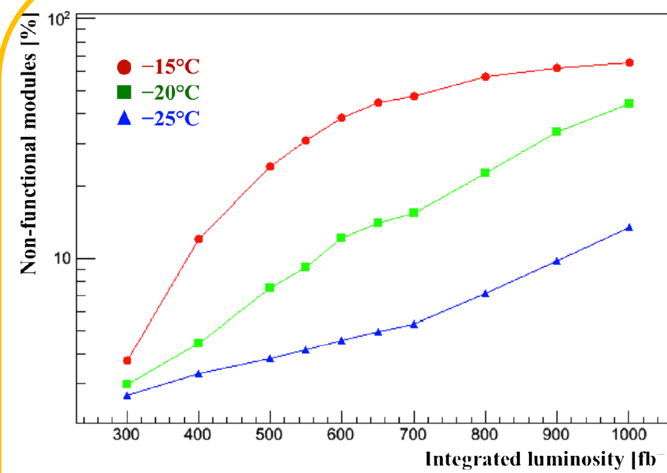
Figure by F. Faccio (CERN)

The problem is believed to be due to a transistor that develops a radiation induced leakage current, which is amplified by a current mirror by a factor of about 500 driving a 3.3 V capacitor to 12 V.

* Report: Failure of FEAST2.1-based modules in the CMS pixel detector systems (physics run 2017)

Limitations of Current CMS Tracker





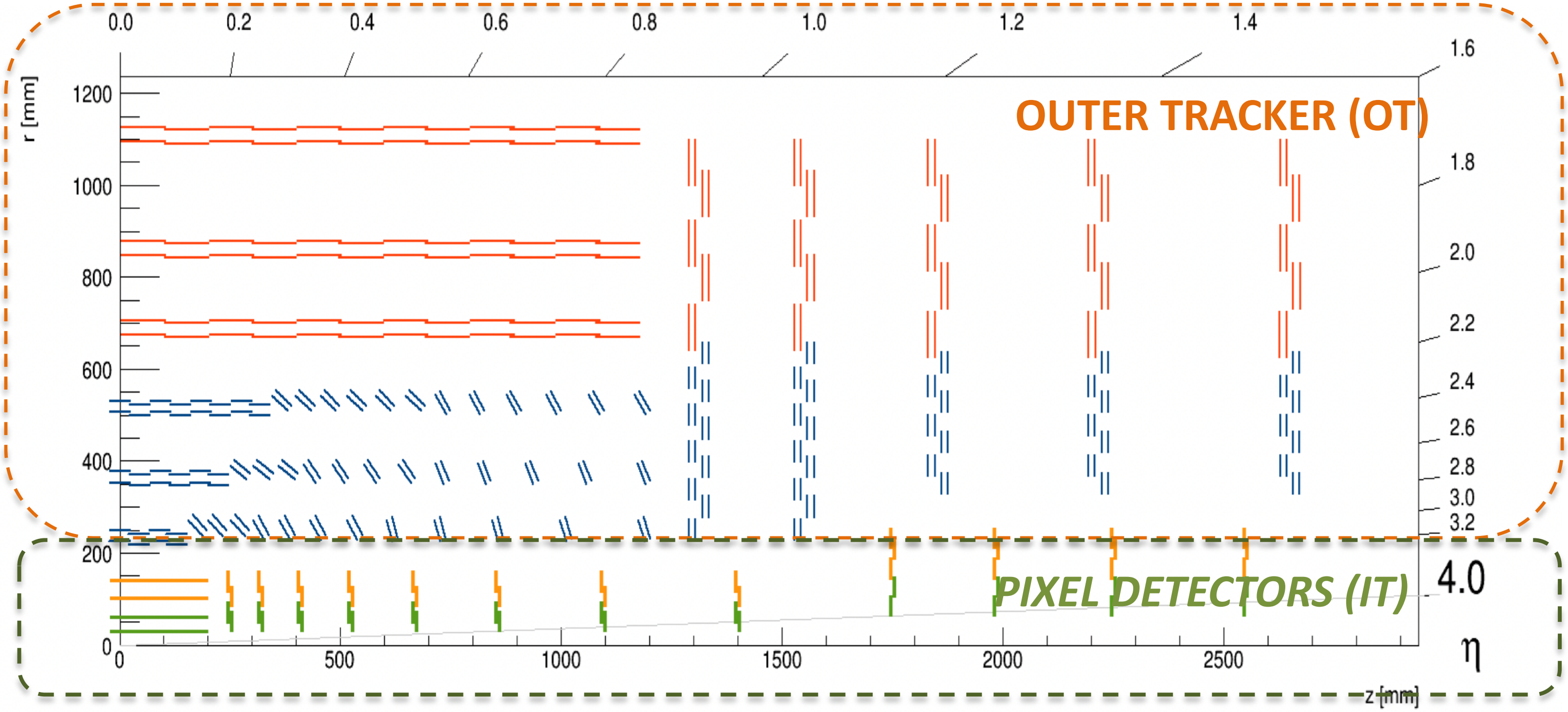
Expected fraction of non-functional modules in the Outer Tracker as a function of integrated luminosity

Total Tracker Replacement

Total Tracker Replacement

Radiation Tolerance up to $\int L dt = 3000\ fb^{-1}$	Flip from p_on_n sensors to n_on_p
Pile Up 140-200 , Occupancy < 1 %	Increase granularity
Longer Latency : from 3.2 μs to 12.5 μς	Increase front end buffer depth
Increase forward acceptance	Mostly through pixel extension
Improve CMS Trigger	Provide tracking info to L1
Improve resolution at low P_t	Reduce material
Improve resolution at high P_t	Increase granularity

Phase II Tracker layout



Red: Strip-Strip (2S) modules   *Blue: Pixel-Strip (PS) modules*   *Green: pixel*

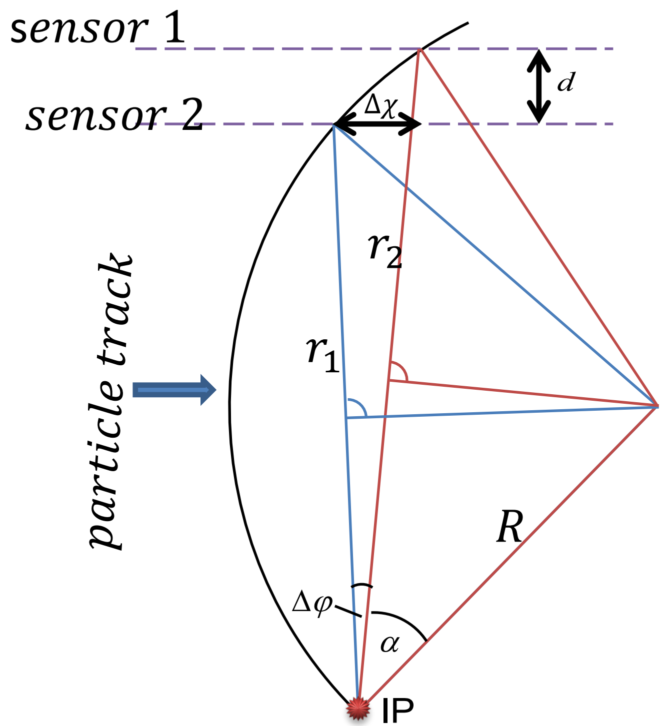
200 μm thick sensors

Outer Tracker based on 2 type modules only

2S strip-strip double-layers
~8400 modules
~34M channels
~155m^2

PS strip-strixel double-layers
~7000 modules
~230M channels
~62m^2

Principle of Pt Measurement in OT



Typical Values:

$$r_1 \approx r_2 \approx r \approx 0.5\ m$$

$$d \approx r_2 - r_1 \approx 1\ mm$$

$$\Delta\varphi \approx \frac{\Delta x}{r}$$

$$cos\Delta\varphi \approx 1 \quad sin\Delta\varphi \cong \Delta\varphi$$

$$p_t[GeV] \approx 0.57\frac{d}{\Delta\varphi} = 0.57\frac{dr}{\Delta\varphi}$$

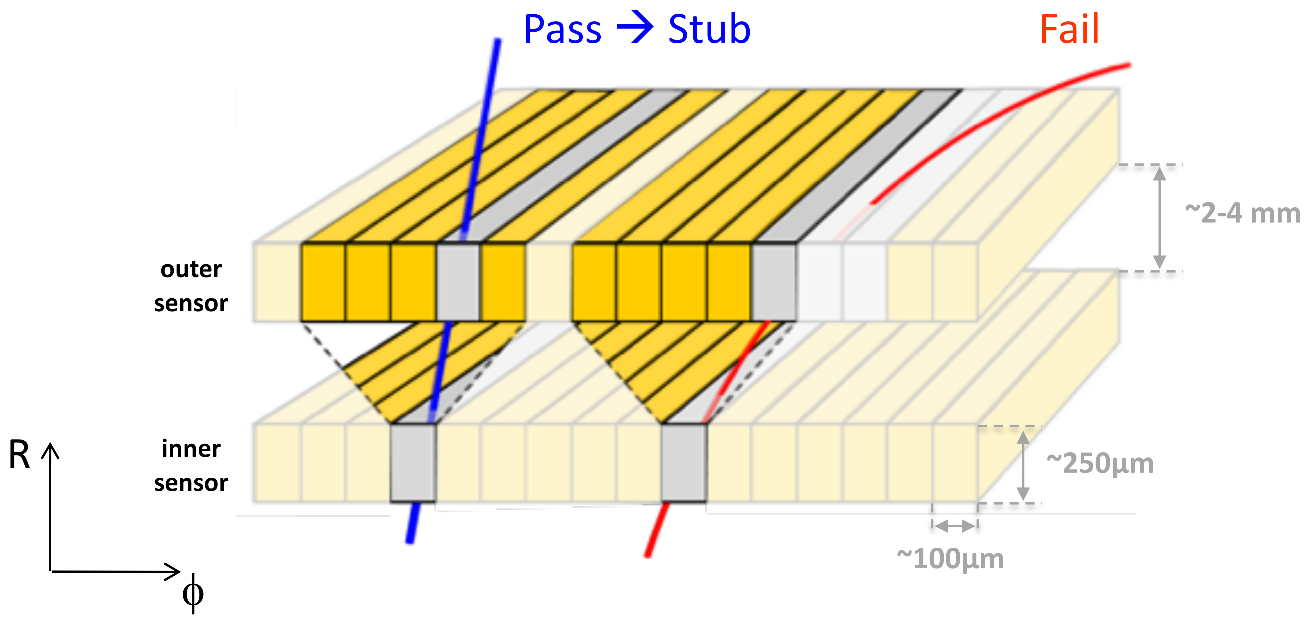
$$\frac{\delta p_t}{p_t} = \frac{p_t[GeV]}{0.57rd} \cdot \delta(\Delta x)$$

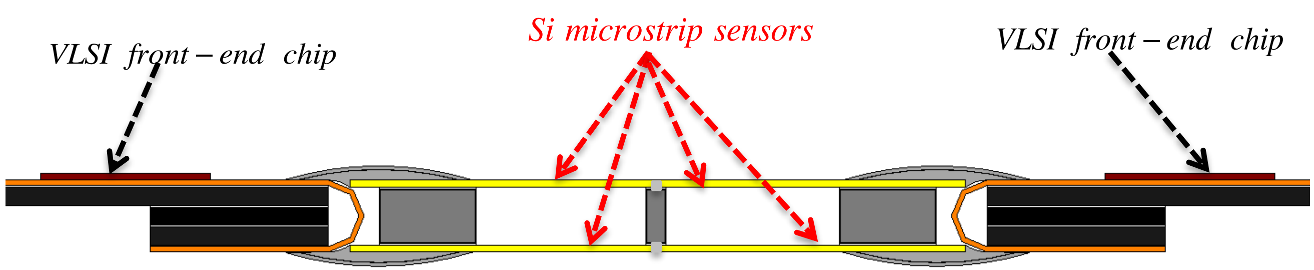
$for\ B = 3.T, in\ natural\ units:$

$$p_t[GeV] \approx 0.57\frac{\sqrt{r_1^2 + r_2^2 - 2r_1r_2cos\Delta\varphi}}{sin\Delta\varphi}$$

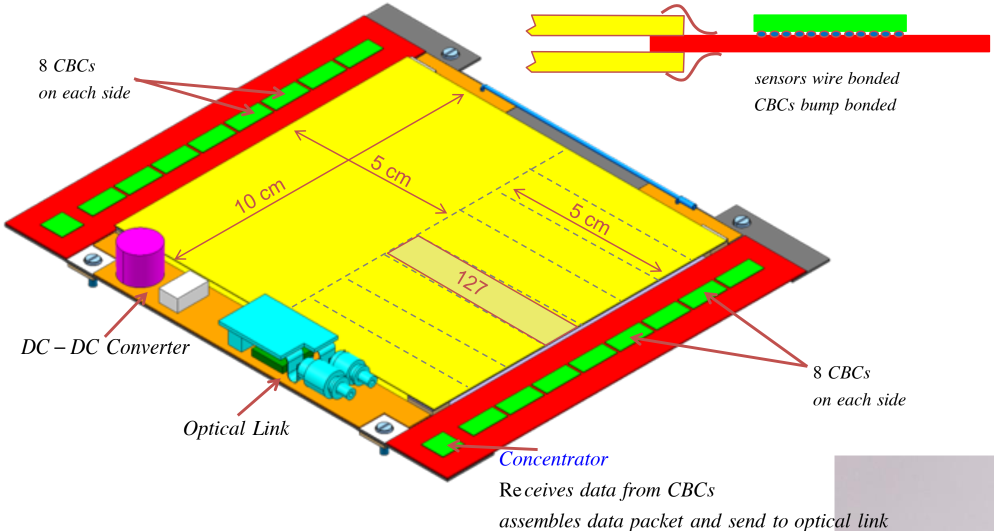
concept by Lutz Feld

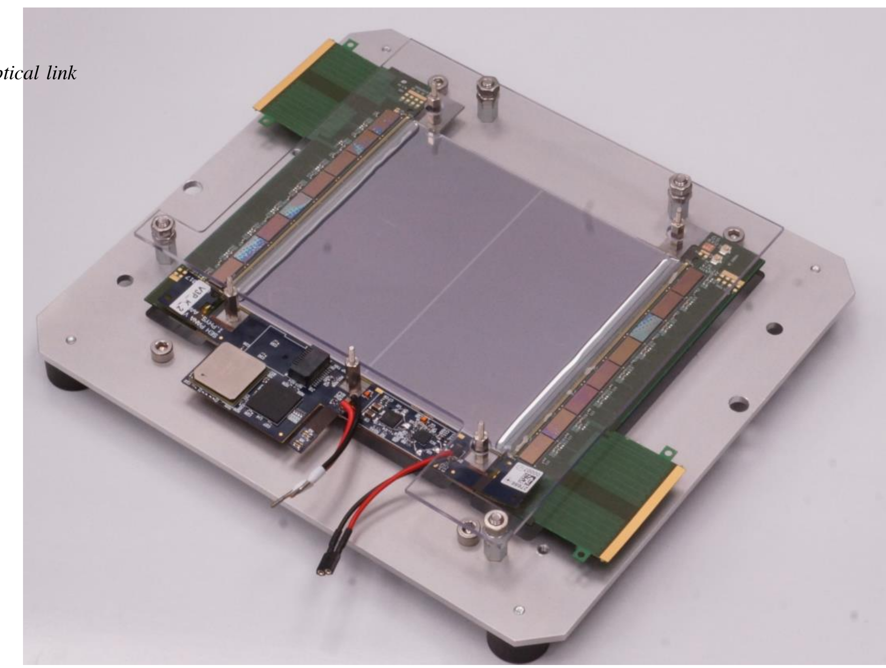
Principle of Pt Measurement in OT



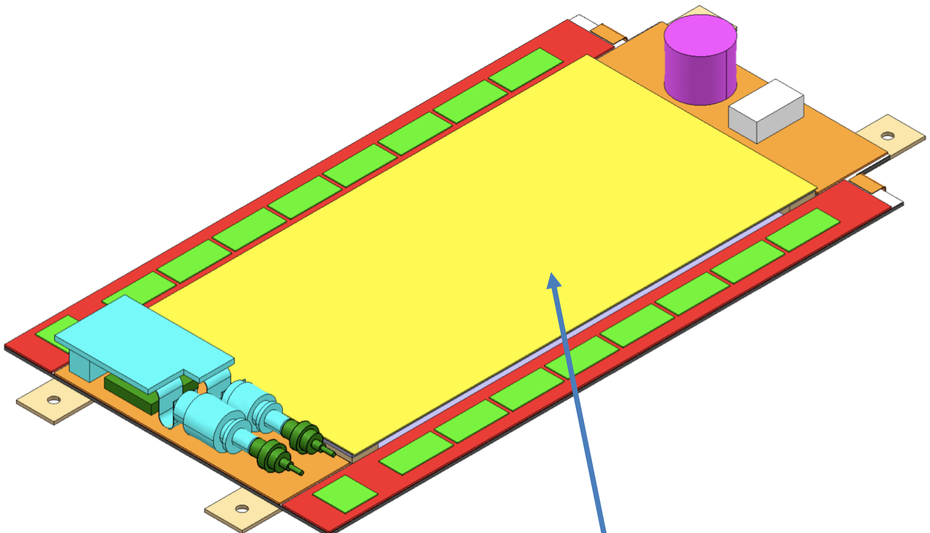


The 2S Module : Two Strips (2S)



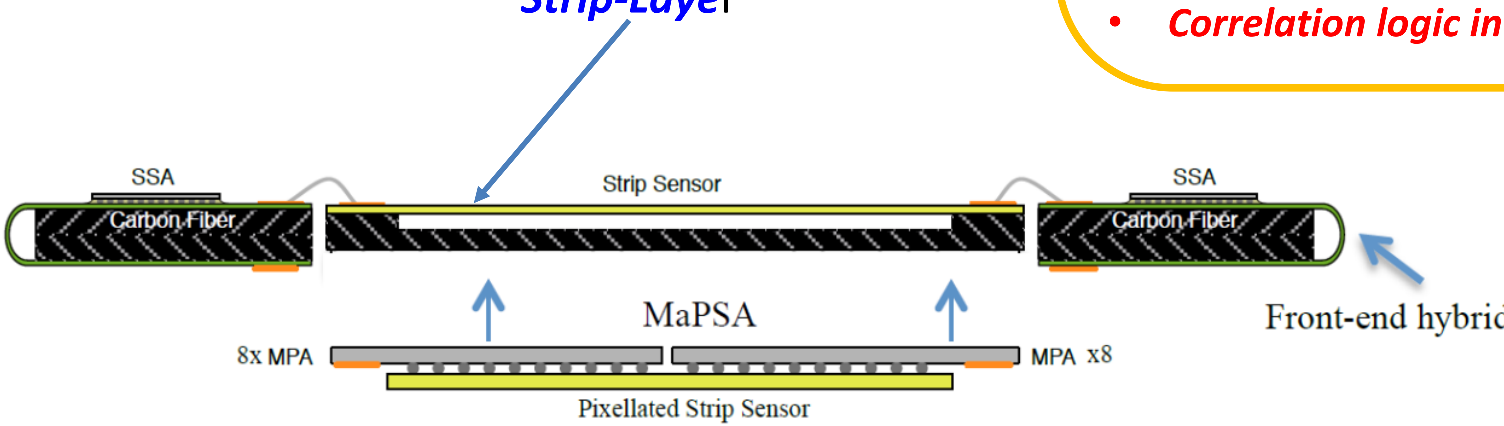


The PS Module: Strip-Pixel (StriXel)

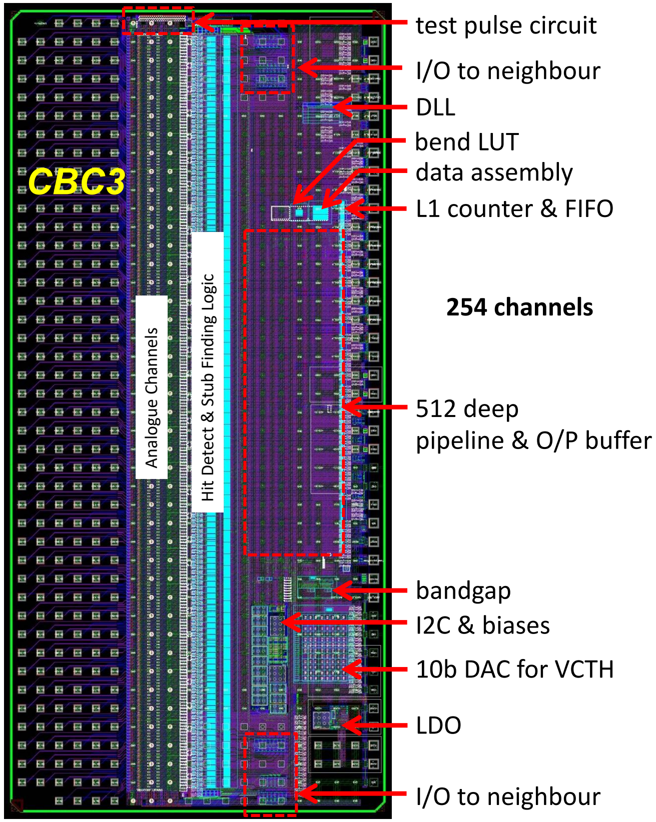


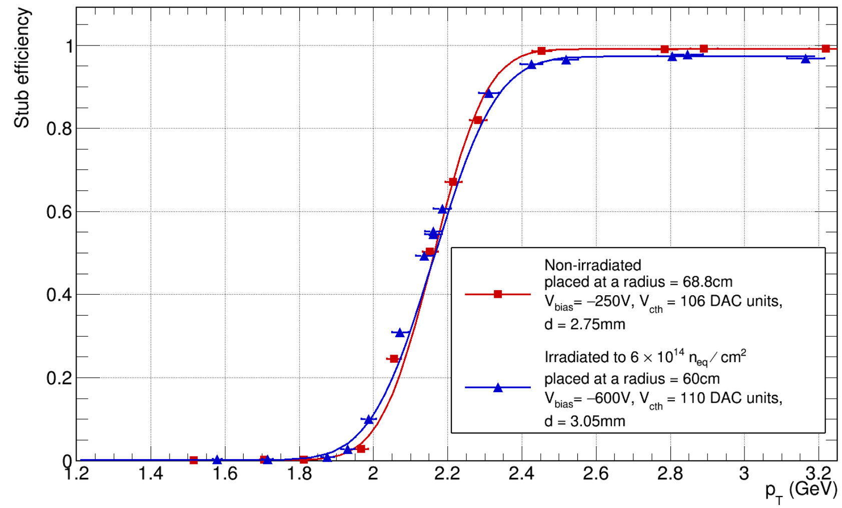
Sensors
- *Top sensor: Strips*
- *2x25 mm, 100 µm pitch*
- *Bottom sensor: Long Pixels*
- *100 µm x 1500 µm*
- *5 x 10 cm^2 overall sensor size*
- *Provide z coordinate*

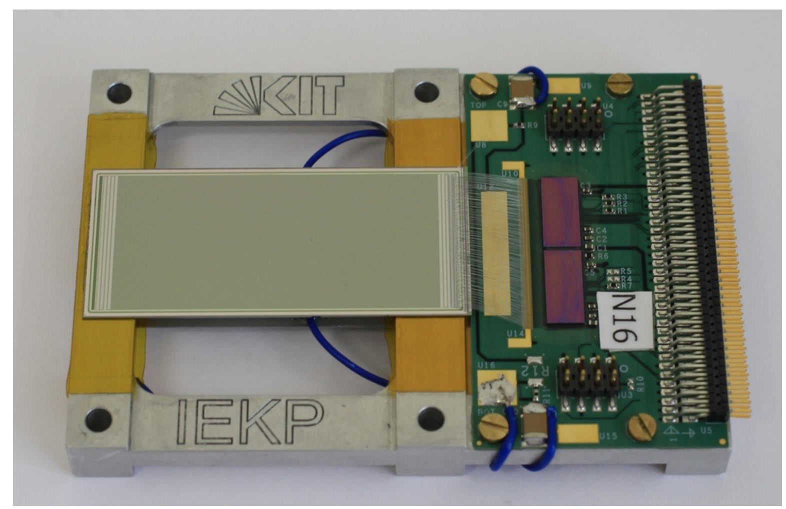
Readouts
- *Top : wirebond to hybrid*
- *Bottom: Pixel chips*
- *Correlation logic in pixel chips*

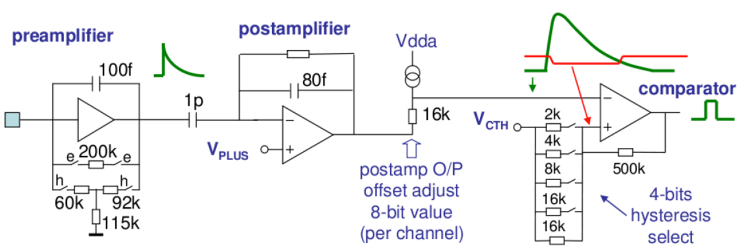


Beam Test of 2S P_t mini-modules









Silicon Sensors for the CMS Phase II OT

Unique provider : Hamamatsu !

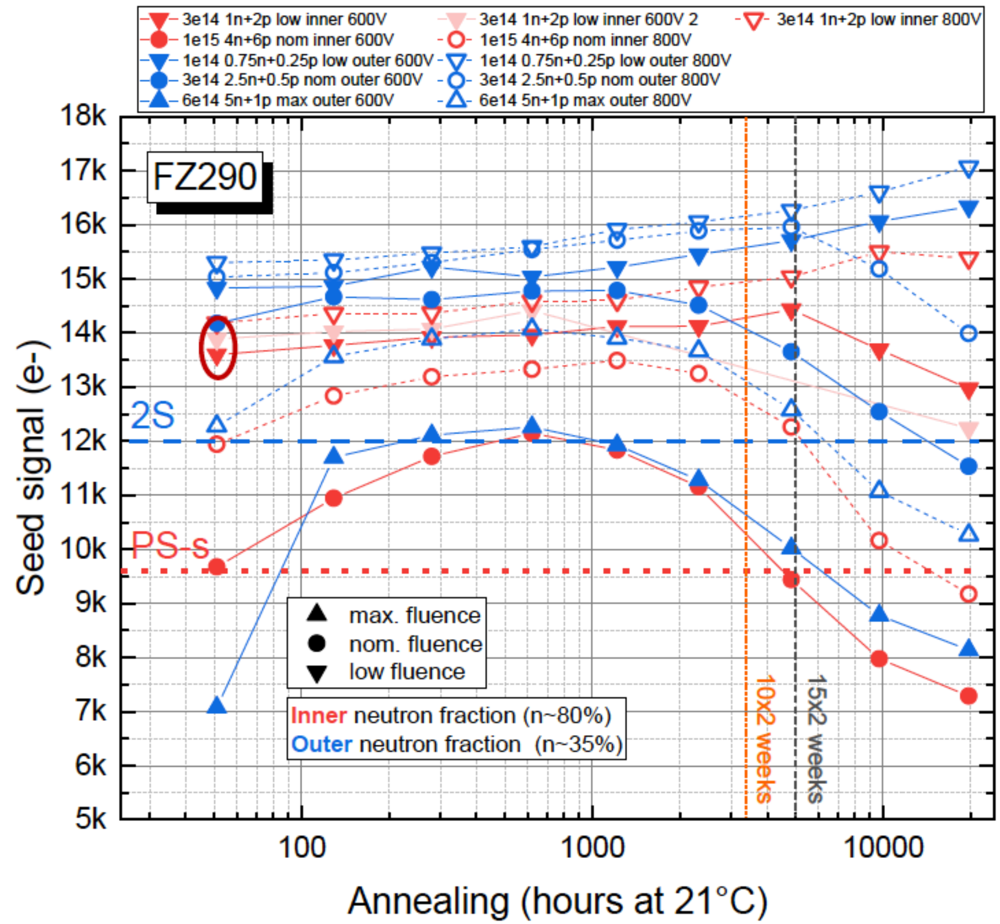
We are examining two options:

- FZ290 µm thick sensors
- FZ240 µm thinned sensors

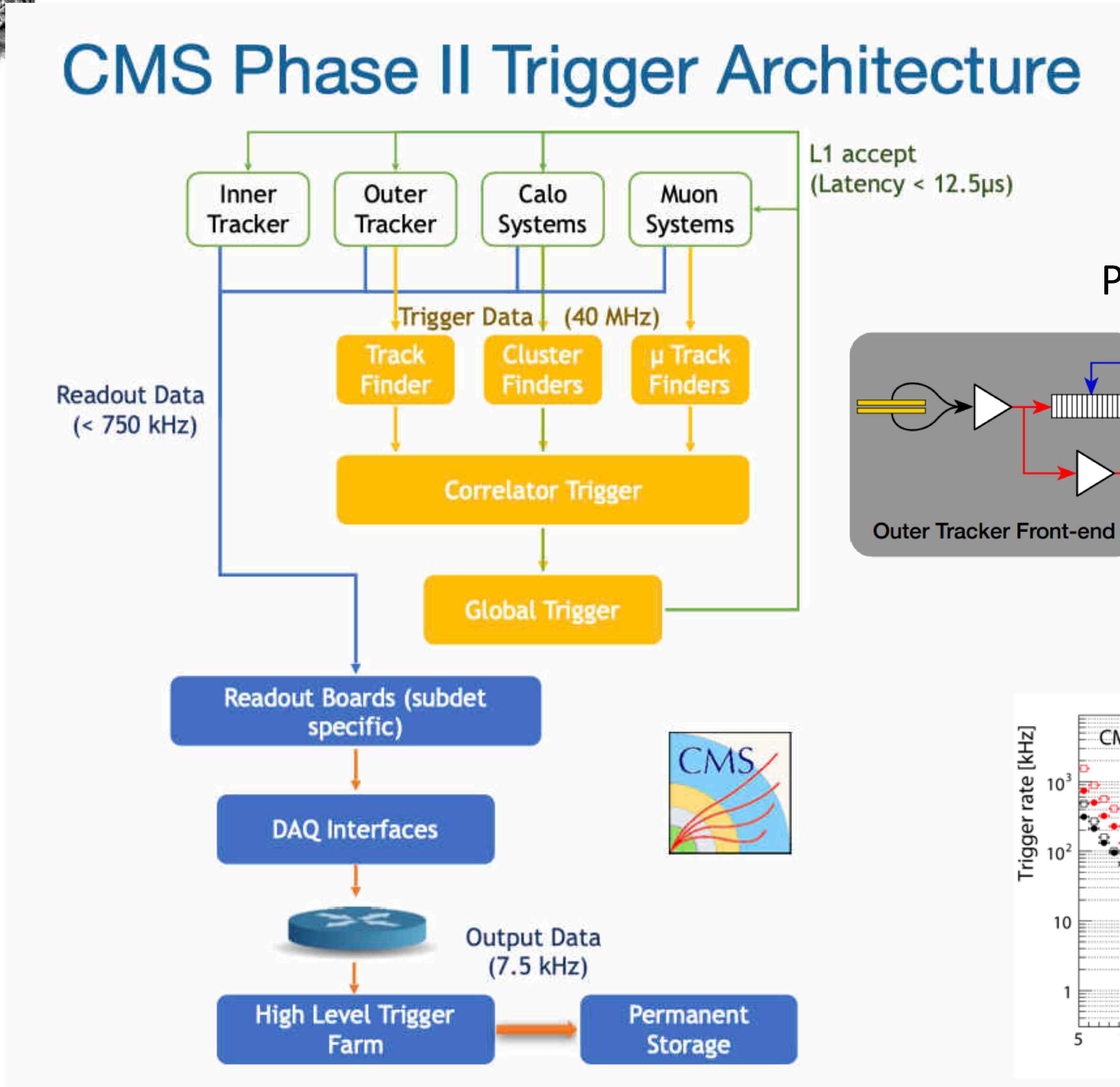
Decision to be taken by
end of summer 2019

- FZ290 material irradiated with neutrons and 23MeV protons
- Annealing study performed for most fluences:

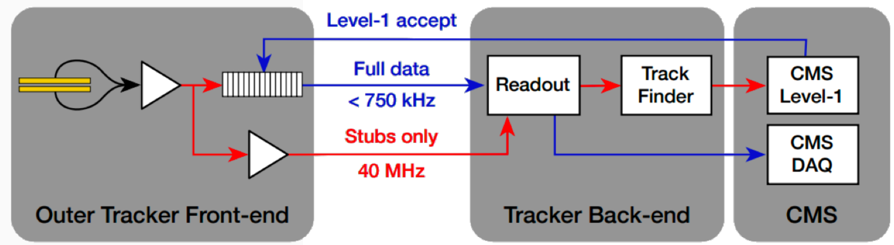
Set	Neutrons $10^{14} n_{eq}/cm^2$	Protons $10^{14} n_{eq}/cm^2$	Total $10^{14} n_{eq}/cm^2$	Fraction F_n/F_{tot}	Dose 23MeV kGy
Low outer	0.75	0.25	1	75%	37.5
Low inner	1	2	3	33%	300
Nom. outer	2.5	0.5	**3**	83%	75
Nom. inner	4	6	**10**	40%	900
Max outer	5	1	6	83%	150
Max inner	5	10	15	33%	1500

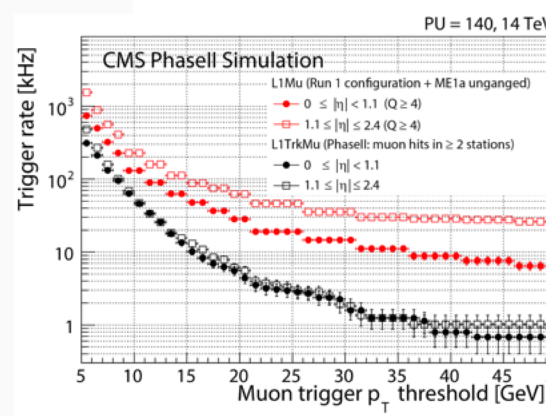


Outer Tracker in L1 Trigger



Phase II Tracker





PHASE II UPGRADE OF THE CMS SILICON TRACKER

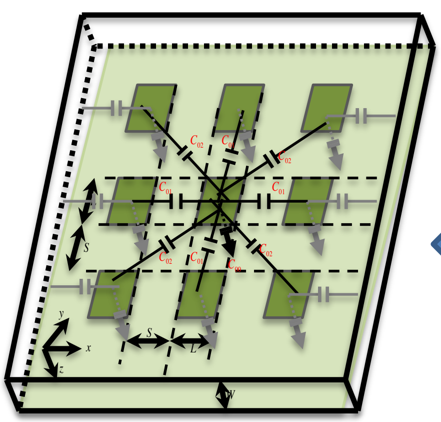
Activities of the Demokritos Group

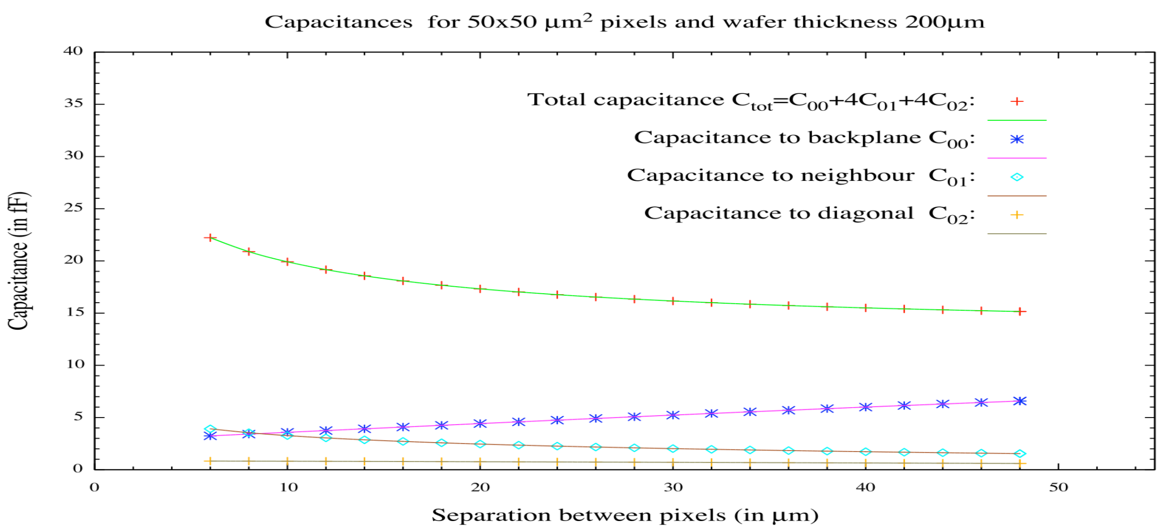
- ***Simulations***
- ***Electronics***
- ***Sensors***
- ***Beam Tests***

Simulations

✓ ***3D Simulation of silicon & pixel capacitances****

Fast calculation by a technique that reduces the 3D Laplace equation to a 2D problem:
Discretization of the two dimensions that are parallel to the junction while keeping the vertical dimension continuous.

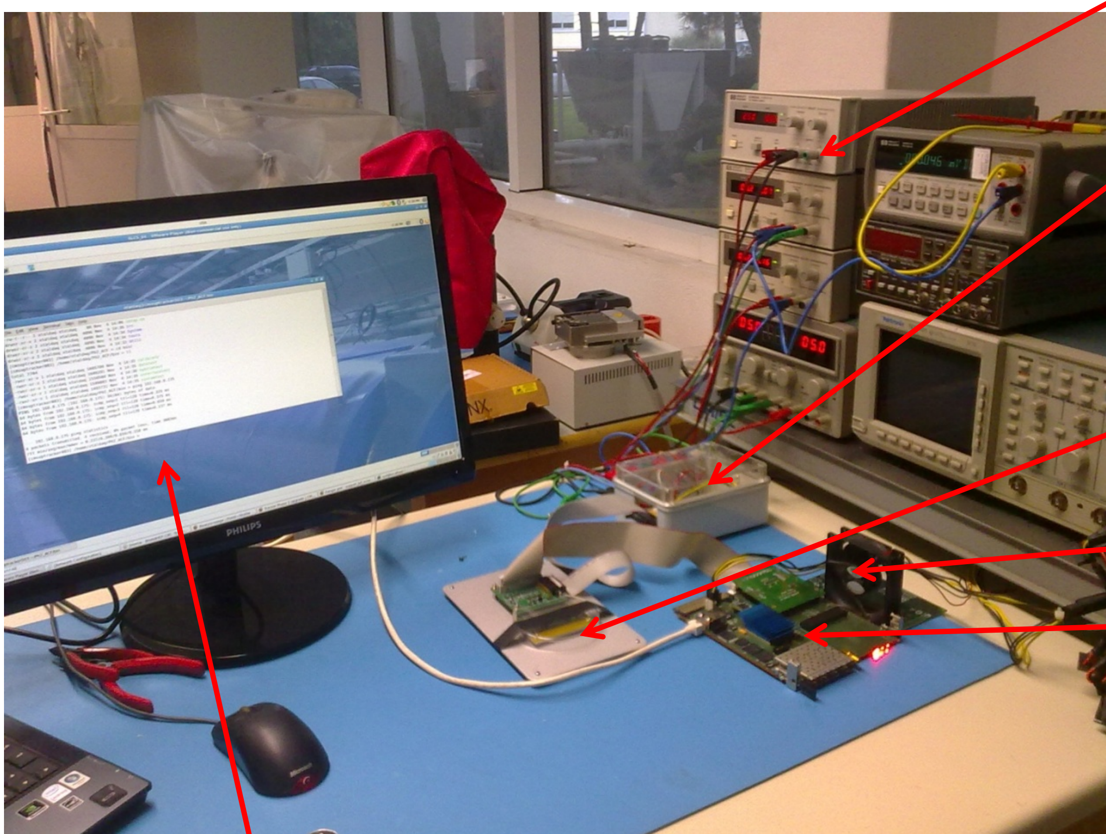


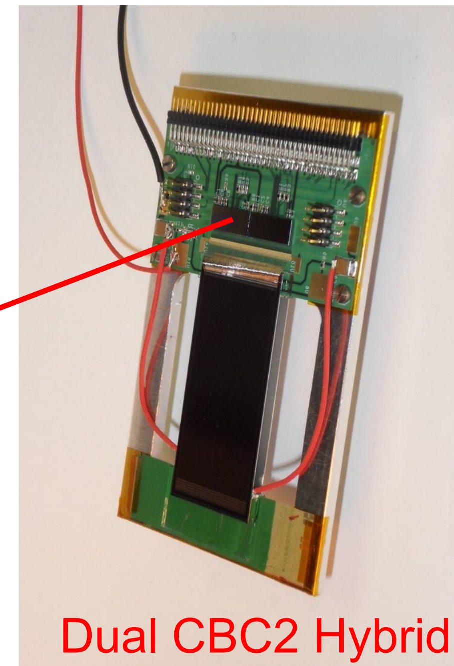


For details see*: ***S. Kavadias, K. Misiakos and D. Loukas IEEE Trans. Nucl. Sci., vol 41, no 2, p. 397, 1994*

Electronics Test System

- ✓ ***Test setup for evaluation of the CBC2 VLSI Chip***

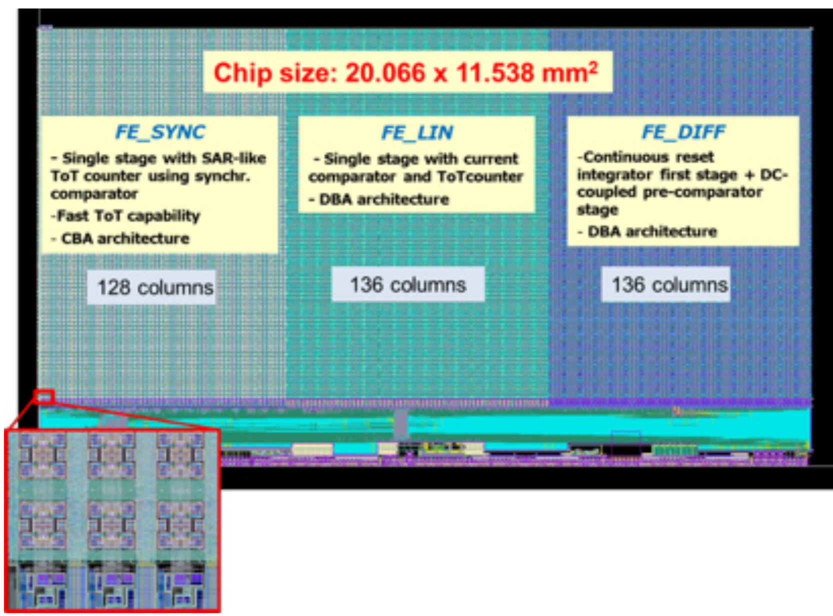


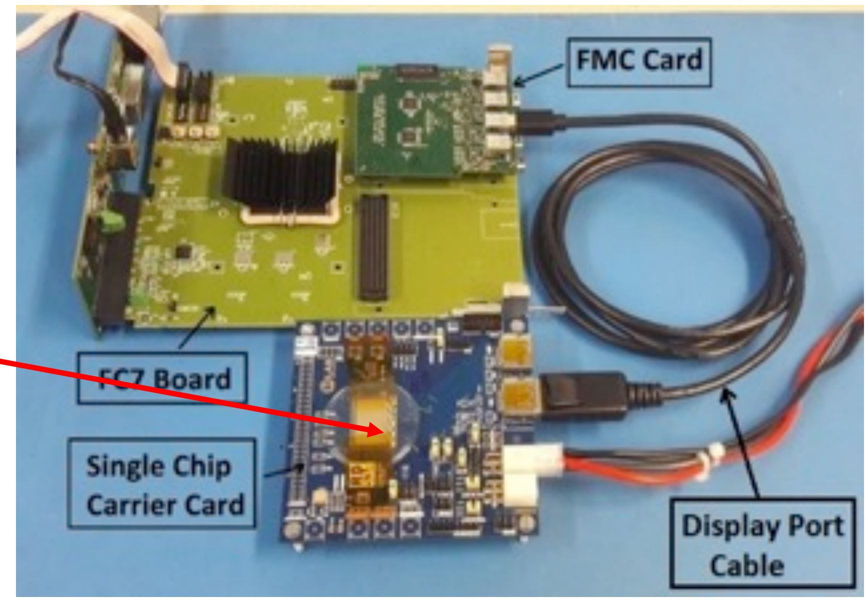


Electronics Test System

DEMOKRITOS” is contributing to the development of the firmware for the Inner Tracker µDTC, which is the CMS DAQ testing and development platform for the RD53A chip.

RD53 chip

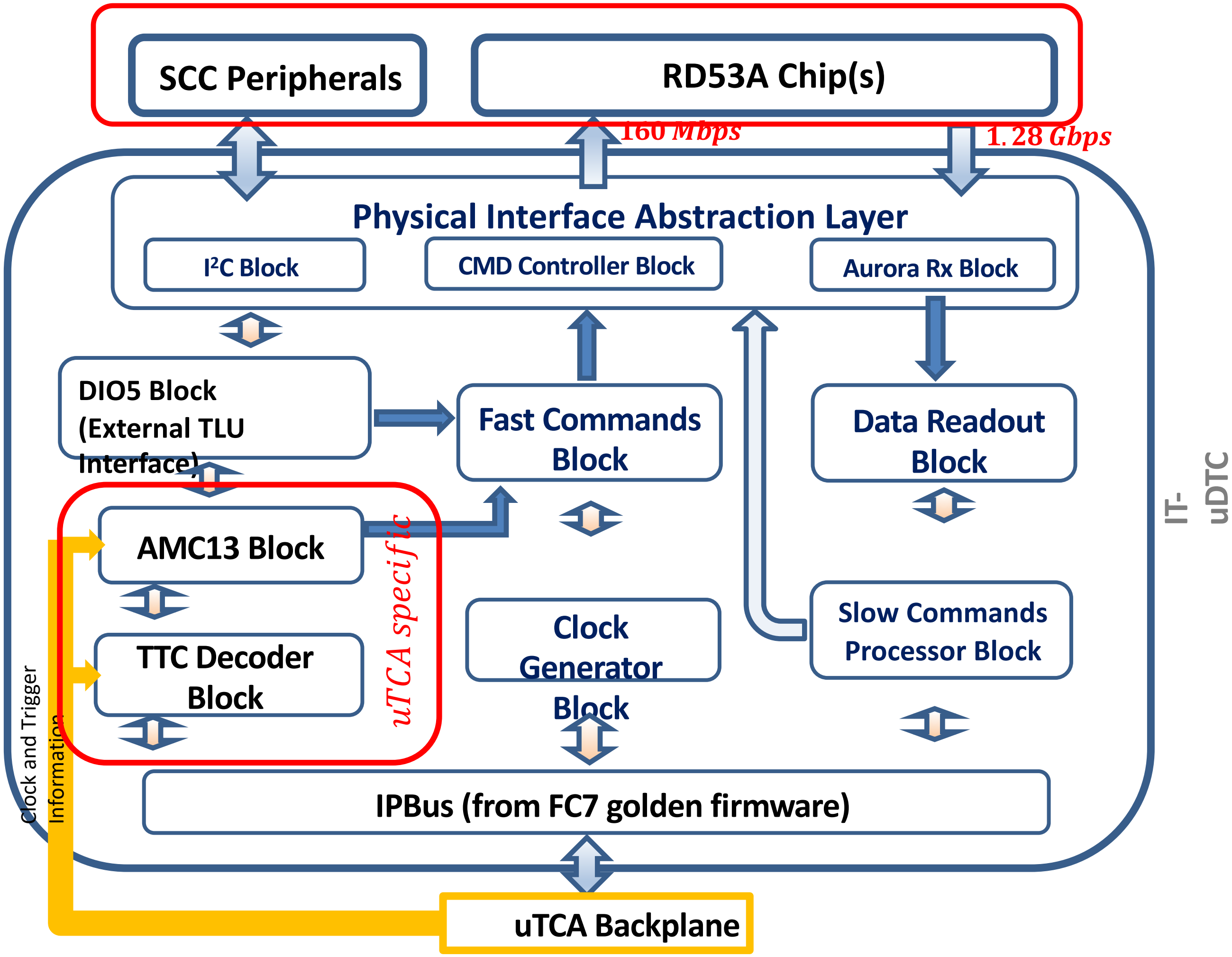




Test Bench system at Demokritos

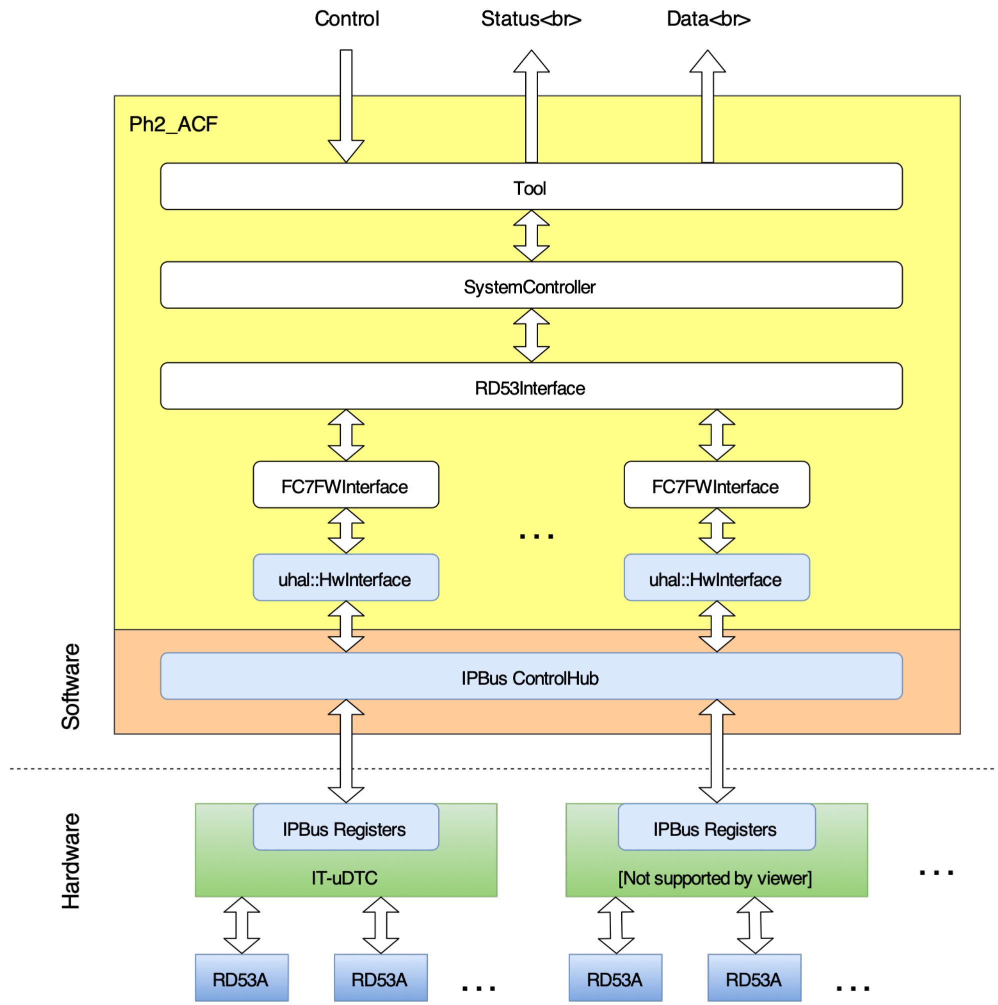
Electronics Test System

Phase II Pixel CMS Firmware



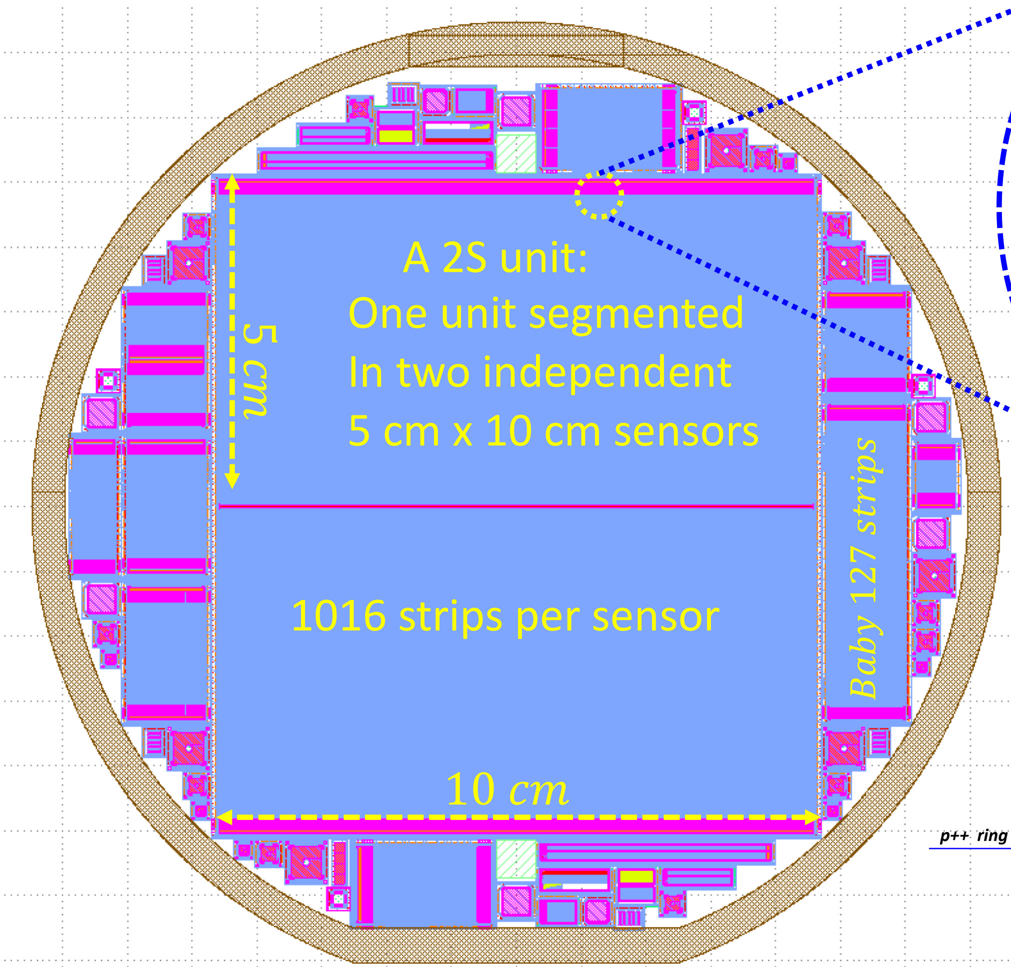
Electronics Test System

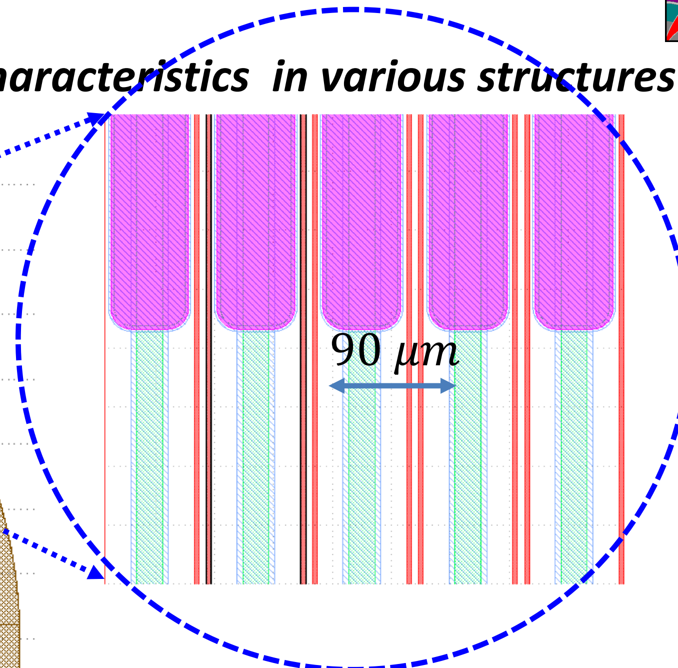
Phase II Pixel CMS Midlleware

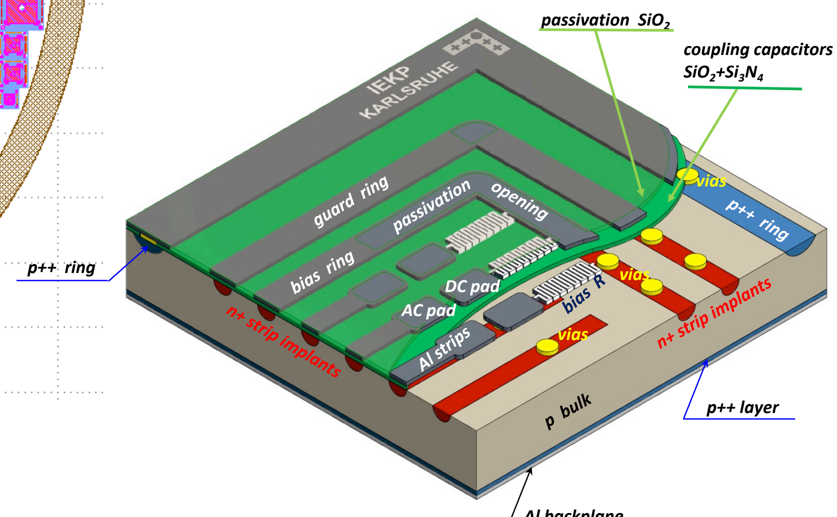


2S Sensors

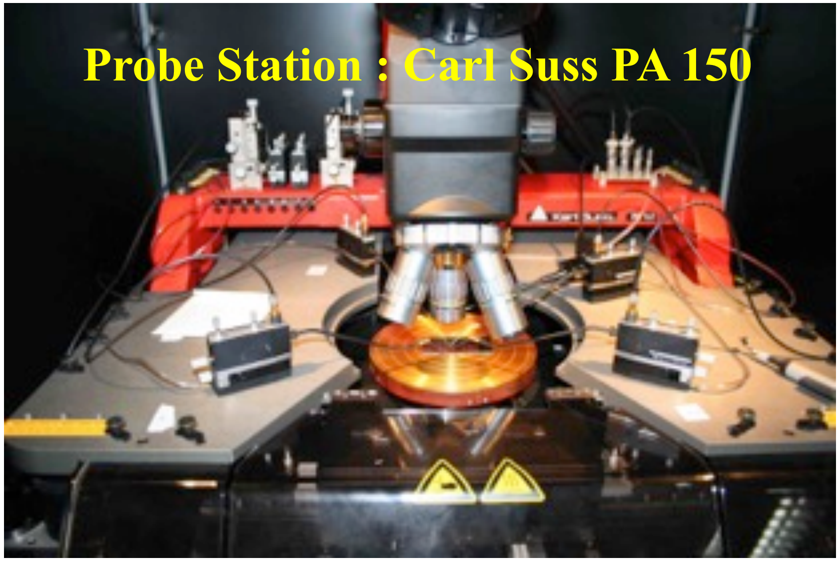
Systematic Measurements of Electrical Characteristics in various structures

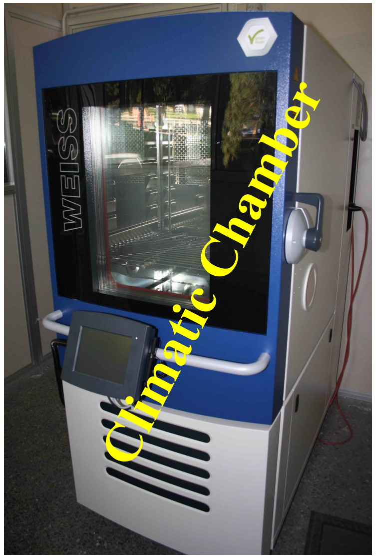




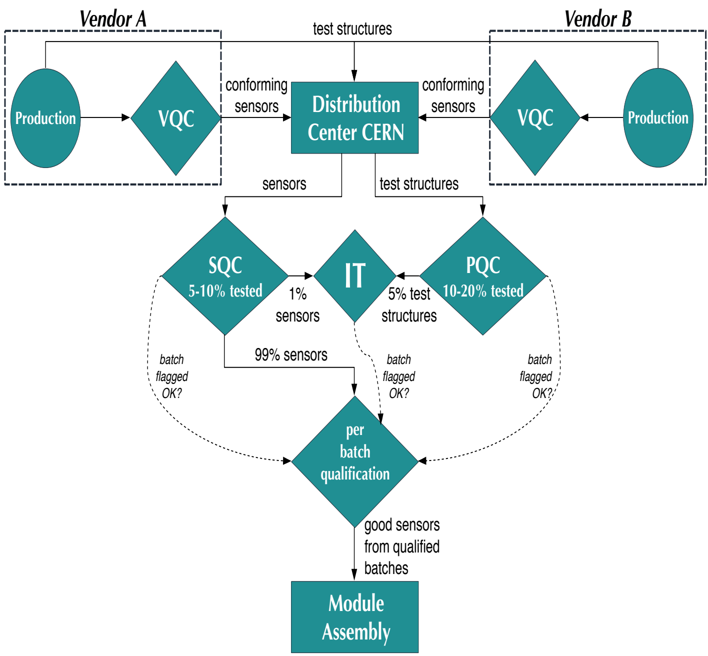


Sensor Quality & Process Quality Control





Sensor Quality & Process Quality Control



Flow of sensors and test structure control during the quality assurance program

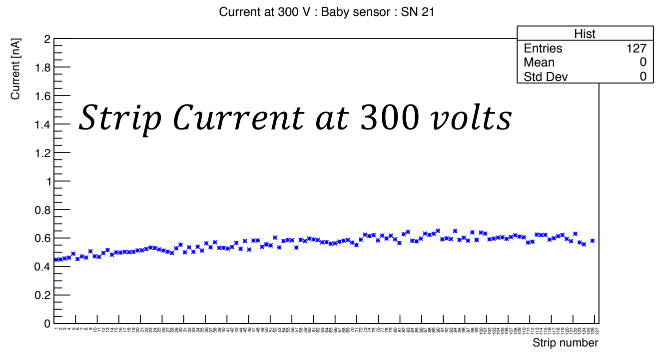
Table of electrical specifications for the sensors

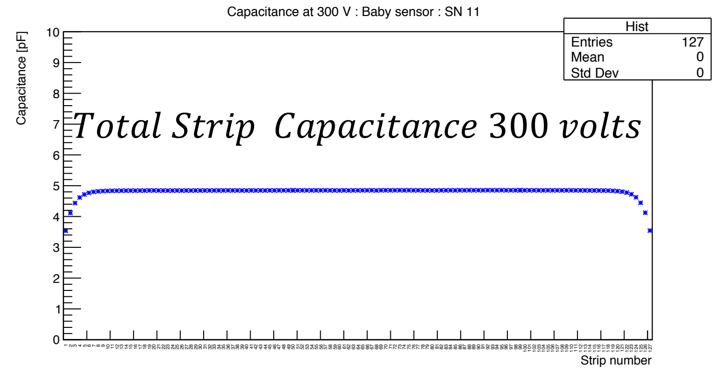
Measurement type	Acceptance value/window	Measured at VQC	SQC	PQC	IT
Global measurements (2S, PS-s, and PS-p)					
Full depletion voltage	$V_{fd} < 150\,V$ for $200\,\mu m$	✓	✓	✓	✓
	$V_{fd} < 300\,V$ for $300\,\mu m$	✓	✓	✓	✓
Current at 500 V	$I_{500} \leq 2\,nA/mm^3$	✓	✓	✓	✓
Breakdown voltage	$V_{break} > 700\,V$, $I_{700} < 3\times I_{500}$	✓	✓	✓	✓
Longterm stability	$\lvert\Delta I_{500}/I_{500}\rvert < 30\%$ for 48 hours	-	✓[1]	-	-
Measurements after irradiation (2S, PS-s, and PS-p)					
Breakdown voltage	$V_{break} > 1000\,V$, $I_{1000} < 4\times I_{700}$	-	-	-	✓
Interstrip resistance	$R_{int} > 100\,M\Omega cm$	-	-	-	✓
Strip measurements (2S and PS-s)					
Strip current	$I_{strip} \leq 2\,nA/cm$	✓	✓	-	✓
Bias resistor					
median per sensor	$median(R_{poly}) = 1.5 \pm 0.3\,M\Omega$	✓	✓	✓	-
per strip	$R_{poly} = median(R_{poly}) \pm 5\%$	✓	✓	-	-
Coupling capacitance	$C_{ac} > 1.2\,pF/(cm\,\mu m)$	✓	✓	✓	-
Interstrip resistance	$R_{int} > 10\,G\Omega cm$	-	✓[1]	✓	✓
Interstrip capacitance	$C_{int} < 1\,pF/cm$	-	✓[1]	✓	✓
Pinhole check	$I_{diel} < 1\,nA$ at $10\,V$	✓	✓	-	-
Number of bad strips incl. open/shorted strips	$N_{bs} < 0.5\%$	✓	✓	-	-
Macro-pixel measurements (PS-p)					
Pixel current	$I_{pixel} \leq 300\,pA/cm$	-	-	✓	-
Interpixel resistance	$R_{int} > 1\,G\Omega cm$	-	-	✓	-
Number of bad pixels	$N_{bp} < 0.2\%$	-	-	-	-
Measurements on dedicated teststructures					
Strip/pixel implant resistivity	$R_{strip} < 250\,\Omega/square$	-	-	✓	-
Strip/pixel alu resistivity	$R_{alu} < 25\,m\Omega/square$	-	-	✓	-
Dielectric breakdown	$V_{diel} > 150\,V$, $I_{diel} < 10\,nA$ at $150\,V$	-	-	✓	-

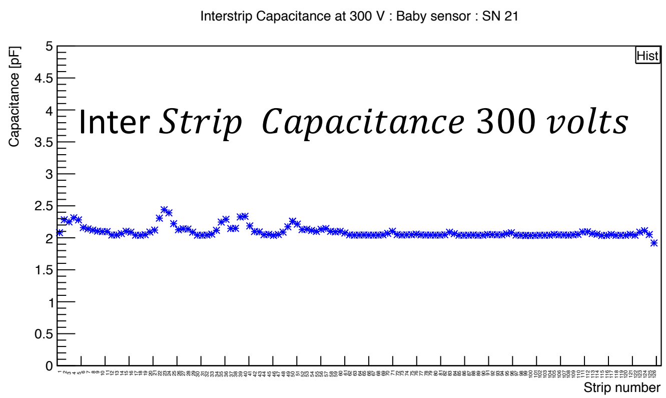
[1] Only for a smaller sample of sensors, approximately 1% of the full quantity.

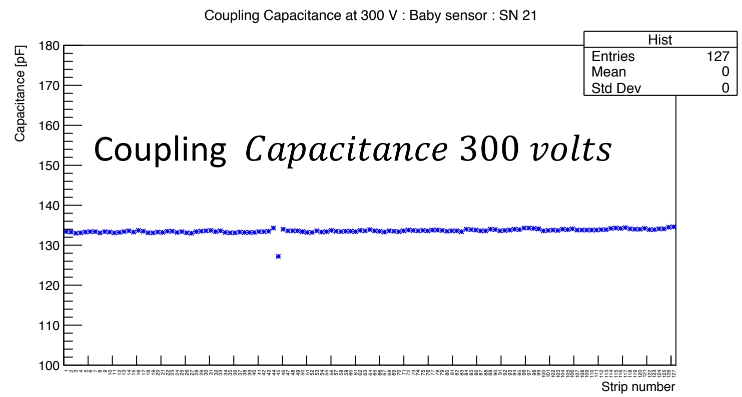
SCQ: Automatic Measurements

Baby Sensors









2S with reduced number of 127 strips.

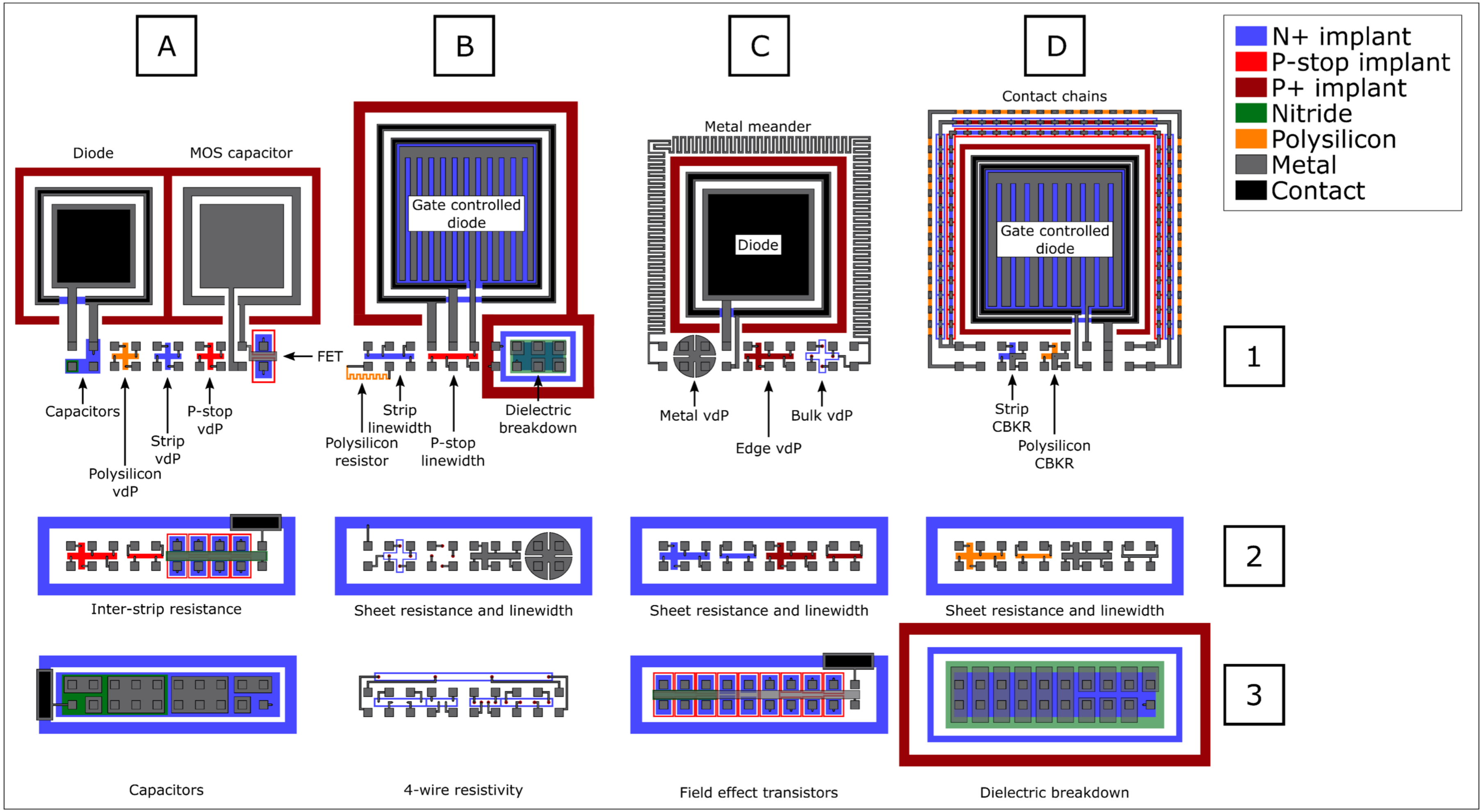
PROCESS PARAMETERS

Parameter	Measured with
Bulk resistivity	Diode, van-der-Pauw, 4-wire
Oxide quality	MOS, GCD, capacitors with implant
Interstrip resistance	FET, van-der-Pauw
Sheet resistances	Meander, van-der-Pauw, linewidth
Contact quality	CBKR, contact chain, diode
Carrier lifetimes	GCD, diode, pulsed MOS
Dielectric strength	Dielectric breakdown

By Viktoria Hinger

Process Quality Control

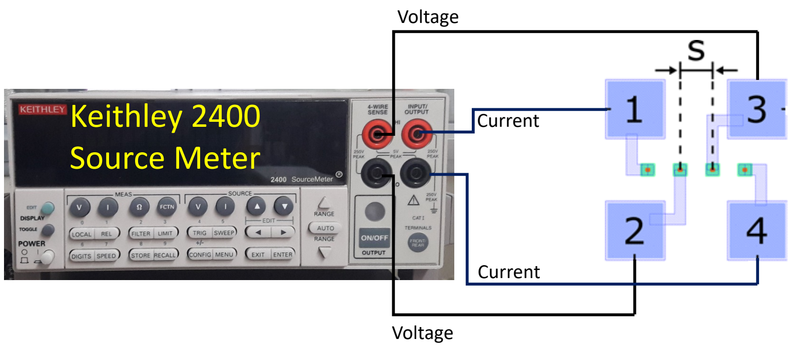
Flute test structures

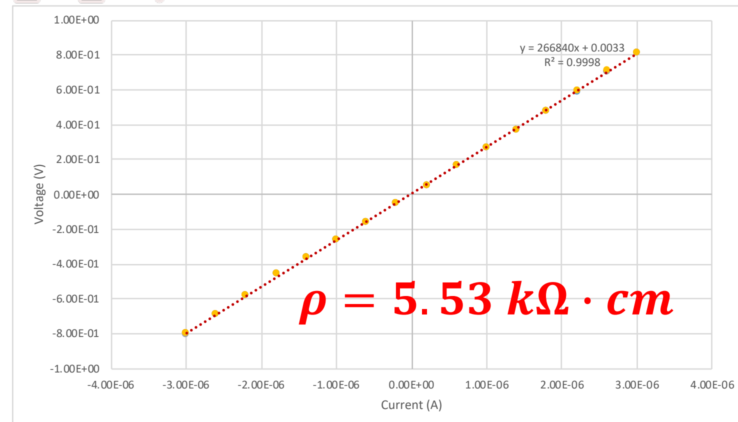


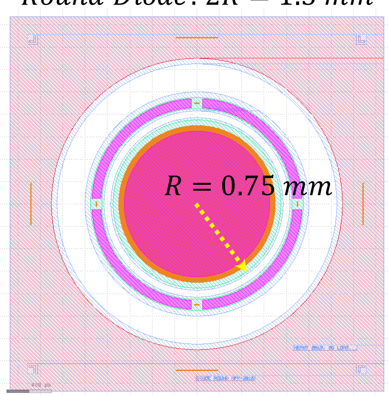
Process Quality Control

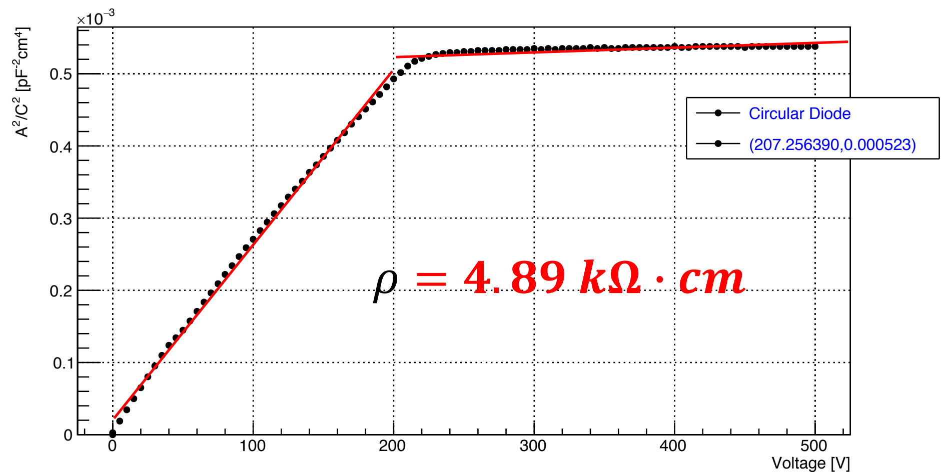
4-Point Resistivity Measurements

(Infineon VE711408_08_16)









A Geant4 Study of Residuals and Hit Multiplicity in Silicon Strip Sensors for the CMS Phase-II Upgrade

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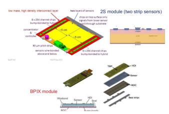
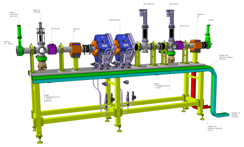
b) Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France



1. Overview

- Upgrade of the LHC to the HL-LHC: up to 3000 fb^{-1} integrated luminosity [1]
- New silicon tracking devices, improved radiation hardness
- Test beams: study the performance of silicon sensors, also under irradiation
- A new beam line at cyclotron CYRCÉ (mid 2019, 25 MeV protons) at IPHC-Strasbourg: testing CMS tracker modules (performances and the DAQ system) with high rates of particles and for large energy depositions [2]
- Studying the new setup is critical: performing a Geant4 simulation of the interaction between a 25 MeV proton beam and the silicon sensors [3], [4]

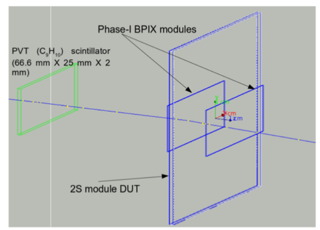


2. The New CYRCÉ Beamline

- Energy (fixed): 16-25 MeV; dispersion: ΔE = 100 keV
- Particle: Protons
- Intensities: max 10^{12} p/s, min 10^2 p/s
- Time micro-structure: 11.75 ns → 85.085 MHz, just about twice the nominal LHC bunch collision rate = 40 MHz [2]; a "kicker" could be used to have exactly 85.085 MHz/2.

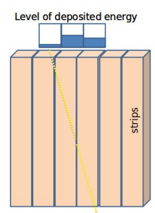
3. Simulated Geometry and Physics Processes

- 2S module DUT and Phase-I BPIX modules as part of the telescope [1]
- 25 MeV proton beam in z-direction. Origin: Center of World. Scintillator: z = -10 cm. Particle gun: (-1, 0, -20) cm
- Run: 100000 events
- Physics processes included in the simulation: 1) Ionizations, 2)Bremsstrahlung, 3) Pair production, 4) Annihilation, 5)Photoelectric effect, 6) γ production, 7) Compton scattering, 8) Rayleigh scattering, 9) Klein-Nishina model for the differential cross section [4]

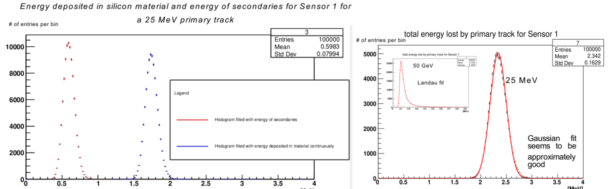


4. Energy Deposition in Silicon Sensors

- Energy lost by primary protons: a) deposited energy in the material of the detectors; b) kinetic energy of secondary (newly created by physics processes) particles
- 25 MeV protons: stopped by about 3 mm of silicon (as expected from Bethe formula [5]) and deposit large amounts of energy [6]
- Goal: To collect info regarding the deposited energy per sensor of DUT/pixel module
- 5σ noise threshold: at 5000 e^- for 2S strips and at 1000 e^- for pixels
- For each event: stored energy in each strip/pixel, respectively, calculated; when dividing this energy by the energy required for a single electron-hole production in silicon (= 3.67 eV) charge collected in each strip/pixel (measured in electrons) obtained
- If this charge exceeds the threshold of 5000/1000 electrons, for a strip/pixel respectively, we consider that we have got a hit in the examined strip/pixel in the current event



Energy deposited in silicon material and energy of secondaries for Sensor 1 for a 25 MeV primary track

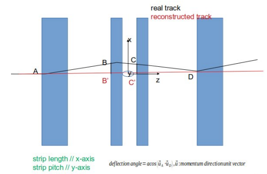


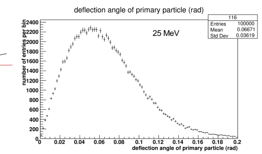
Left: Energy stored in the volume of Sensor 1 from the passage of a proton (blue) and the amount of energy transformed to kinetic energy of newly produced secondaries due to the physics processes (red). Right: The sum of the above energies is equal to the total energy lost by the primary proton. A comparison is made between the 25 MeV beam of the beam line at IPHC and an MIP beam of 50 GeV protons (inset). On all the vertical axes: Number of entries for a run of 100000 events.

5. Multiple Scattering of Protons

- A, B, C, D points defined as entrance points of primary protons in the first pixel module, the first 2S sensor, the second 2S sensor and the second pixel module, respectively; they all lie on the front surfaces of each compnent in the way of the beam
- Geant4 returns the real (extrapolated) entrance positions
- An attempt made to perform a local reconstruction: the reconstructed entrance points correspond to those that could be measured in reality
- Simplifications made in the calculation of reconstructed entrance points to estimate the detector residuals

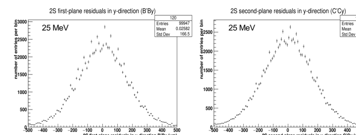
This work has received financial support by the Hellenic Foundation for Research & Innovation.





6. Estimation of the Resolution of 2S Sensors

- Impact points Q_{pixel} = A, D; Q_{strip} = B, C, where A, B, C, D defined above
- Weight w_{pi} for each pixel with a hit = charge collected in the current pixel over the total charge collected in all pixels of the current module that have counted a hit in the current event; weight w_s for each strip with a hit = 1 over the total number of strips of the current sensor that have counted a hit in the current event (no charge info from CMS Binary Chip)
- N_{pixels}: the total number of pixels with a hit in the current module, P_{pi}: the geometric center of the front surface (in the way of the beam) of the i-th pixel that has counted a hit; N_{strips}: the total number of strips with a hit in the current sensor, P_{si}: the geometric center of the front surface (in the way of the beam) of the i-th strip that has counted a hit

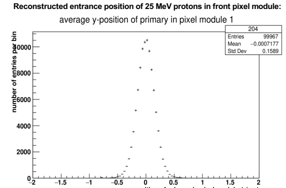


$$A, D = Q_{pixel} = \frac{1}{N_{pixels}} \sum^{N_{pixels}} w_{pi} P_{pi}$$

$$B, C = Q_{strip} = \frac{1}{N_{strips}} \sum^{N_{strips}} P_{si}$$

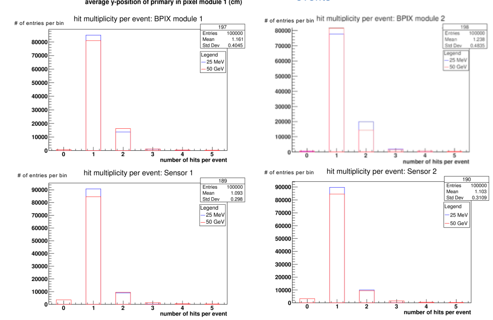
y-residuals' distribution is a superposition of two effects: discrete positions due to the signal from the strips (B and C positions), and continuous positions from the track extrapolation through the DUT (B' and C' positions). Multiple scattering accounting for the differences between B/C and B'/C', respectively.

Reconstructed entrance position of 25 MeV protons in front pixel module:



7. Hit Multiplicities of Simulation Components

- Hit multiplicity = the number of strips/pixels per sensor/module, respectively, with a hit in a single event (→ cluster size for strips)
- For each of the sensors of the 2S module and the pixel modules of the telescope: hit multiplicity computed for a run of 100000 events



8. Outlook

- Small deflection angle in the proposed telescope system (< 0.3 rad) for 25 MeV protons
- Similar hit multiplicities for sensors regardless of energy
- A novel simulation algorithm for the estimation of multiple scattering angles, residuals and energy deposition per strip/pixel for any test beam system and telescope containing pixel and strip sensors

References
[1] CMS collaboration, 2017 The phase-2 upgrade of the CMS tracker, CERN-LHCC-2017-009, CERN, Geneva Switzerland, [CMS-TDR-17-001]
[2] P. Marchand, A. Ouadi, M. Pellicioli, D. Brasse. Cyrcé, un cyclotron pour la recherche et l'enseignement en Alsace. L'Actualité Chimique, 2014, 386, 9-14.
[3] S. Agostinelli et. al., Geant4: A simulation toolkit, Nucl. Instrum. Meth. A, vol. 506, no. 3, pp. 250-303, 2003.
[4] Allison, John et al., Geant4 developments and applications - IEEE Trans.Nucl.Sci. 53 (2006) 270 SLAC-PUB-11870
[5] H. Bethe und J. Ashkin in "Experimental Nuclear Physics, ed. E. Segré, J. Wiley, New York, 1953, p. 253

Historic Data Quality Monitor

- The Historic Data Quality Monitor (HDQM) of the CMS experiment is a framework developed by the Tracker group of the CMS collaboration that permits a web-based monitoring of the time evolution of interesting quantities (i.e. signal to noise ratio, cluster size) in the Tracker Silicon micro-strip and pixel.

- The tool run smoothly during 2018 data taking period and was documented as an internal note and also presented in CHEP2018, Sofia Bulgaria

Available on CMS information server **CMS IN -2018/004**

CMS Internal Note

The content of this note is intended for CMS internal use and distribution only

14 December 2017 (v5, 23 May 2018)

Historic Data Quality Monitor (HDQM) Tool for the CMS Tracker

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[a] Fermi National Accelarator Laboratory (USA), [b] National Taiwan University (TW), [c] National University of Sciences and Technology (PK), [d] Universitaet Zuerich (CH), [e] Nat. Cent. for Sci. Res. Demokritos (GR), [f] Universita e INFN, Perugia (IT)

Abstract

Monitoring the time evolution of sensitive quantities is fundamental to LHC experiments. It permits keeping control on data quality during LHC running and also effectively checking the influence on data of any detector calibration performed during the year. The Historic Data Quality Monitor (HDQM) of the CMS experiment is a framework developed by the Tracker group of the CMS collaboration that permits a web-based monitoring of the evolution of measurements (S/N ratio, cluster size) in the Tracker Silicon micro-strip and pixel detectors. The framework provides a way to build and deploy trend plots based on two steps of actions. In the first step data are retrieved from the offline DQM data base periodically via a cron scheduled job and a list of datasets is produced. In the second step, the web interface dynamically and interactively produces the trend plots from the datasets. The overall organization of the tool will be presented along with its internal structure and representative examples. Finally the skeleton for the flexible implementation of the HDQM in the other sub-detectors of the CMS experiments will be described.

Available on CMS information server **CMS CR -2018/285**

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

17 October 2018 (v3, 29 October 2018)

A Historic Data Quality Monitor (HDQM) tool for the CMS Tracker Detector

Aristotelis Kyriakis for the CMS Collaboration

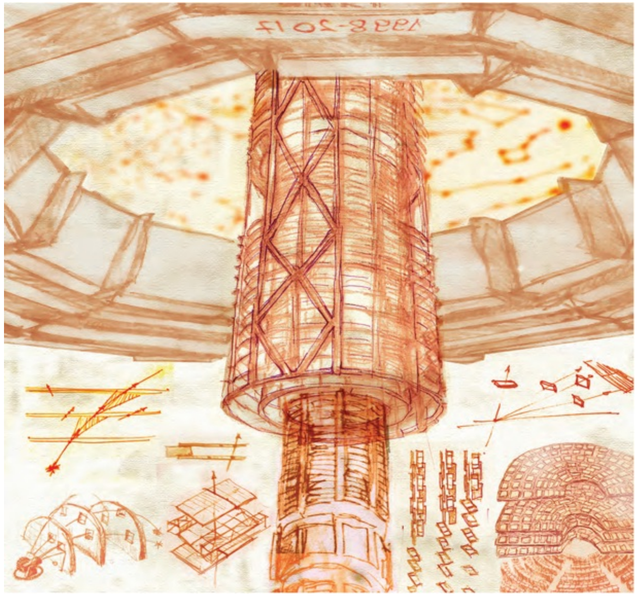
Abstract

Monitoring the time evolution of data related observables is important for the successful operation of the LHC experiments. It permits keeping control on data quality during LHC running and also effectively checking the influence on data of any detector calibration performed during the year. The Historic Data Quality Monitor (HDQM) of the CMS experiment is a framework developed by the Tracker group of the CMS collaboration that permits a web-based monitoring of the time evolution of interesting quantities (i.e. signal to noise ratio, cluster size) in the Tracker Silicon micro-strip and pixel.

Greek Core Contribution

The Phase II CMS Tracker Upgrade :

- ***10 years of R&D***
- ***Over 100 MCHF core cost***
- ***1.4 M CHF foreseen Greek contribution***



Backups

Tracker Material Budget

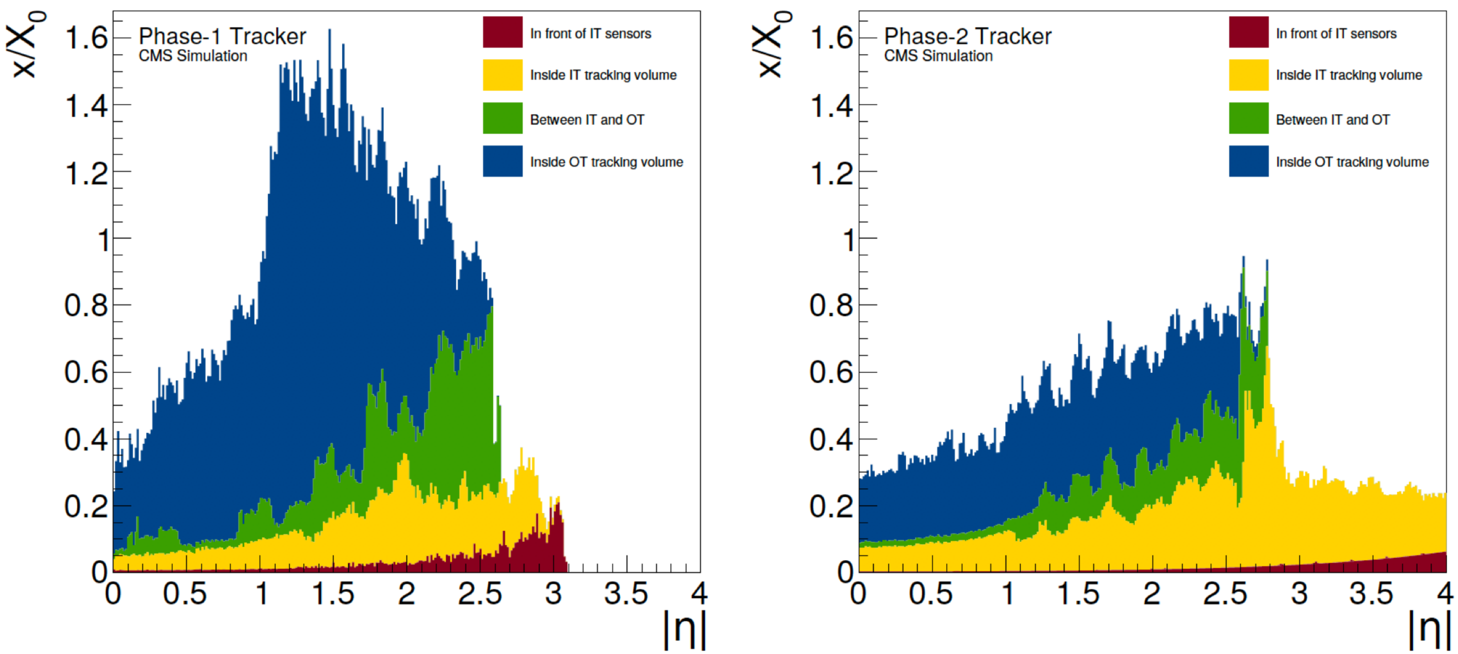


Figure 6.2: Material budget inside the tracking volume estimated in units of radiation lengths, comparing the Phase-1 (left) and the Phase-2 (right) detectors. The material in front of the Inner Tracker sensors is shown in brown, that inside the Inner Tracker tracking volume in yellow, that between IT and OT sensors in green, and that inside the Outer Tracker tracking volume in blue. The histograms are stacked.