Contribution of INPP to the CMS Phase-2 Upgrade

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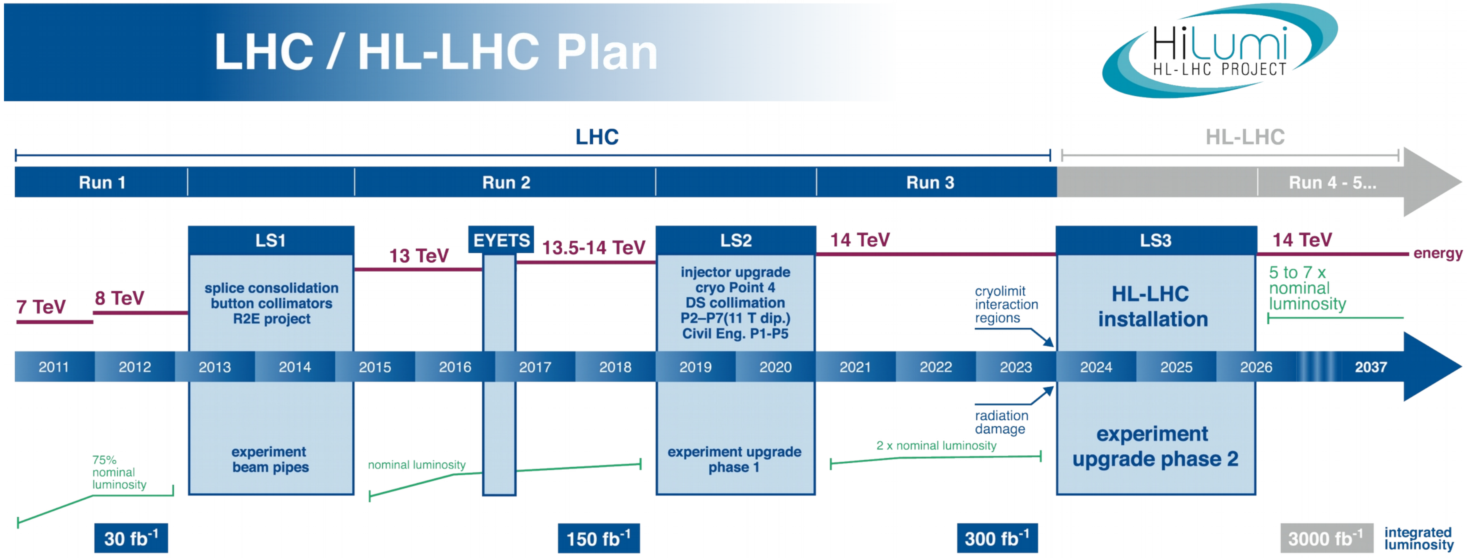
High Luminosity upgrade for the LHC: HL-LHC

- Phenomena with a very low probability of occurring require more data
- Increase the luminosity: from 300 fb^{-1} (2011-2023) to 3000 fb^{-1} (2026-2037)
- The goal for HL-LHC: Peak Luminosity: 5.0 (7.5) x 10^{34} cm^{-2} s^{1}; Integrated Luminosity over 10 years: 3000 (4000) fb^{-1}; PU: 150-200 at 25-50 ns bunch crossing
- HL-LHC will produce at least 15 million Higgs bosons per year, compared to around 3 million from the LHC in 2017

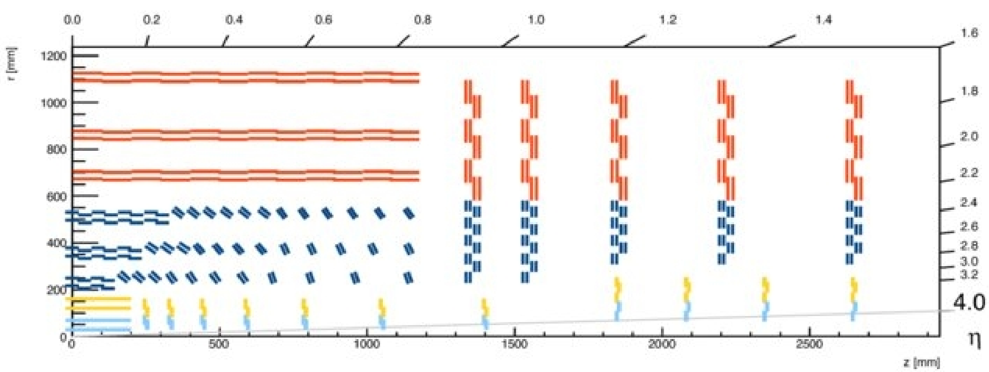


Phase-2 Upgrade of the CMS Tracker

- A 1 MeV neutron equivalent fluence of $2.3 \times 10^{16}\ n_{eq}/cm^2$ and a total ionizing dose (TID) of 12 MGy (1.2 Grad) expected at the center of CMS

- Due to high number of pile-up events and unprecedented radiation levels a major upgrade of the CMS experiment is needed, requiring
  - a higher radiation tolerance
  - an increased granularity
  - an improved two-track separation
  - a reduction of material in the tracking volume
  - a robust pattern recognition
  - high pT resolution
  - selective readout of OT at 40 MHz for L1 trigger

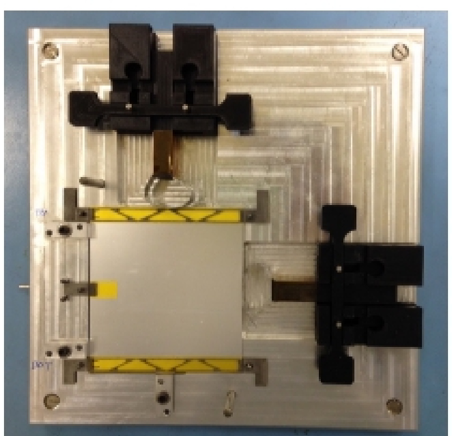
- The Phase-2 CMS tracker will consist of 1. an Inner Tracker (IT) based on silicon pixel modules and 2. an Outer Tracker (OT) made from silicon modules with strip and macro-pixel sensors

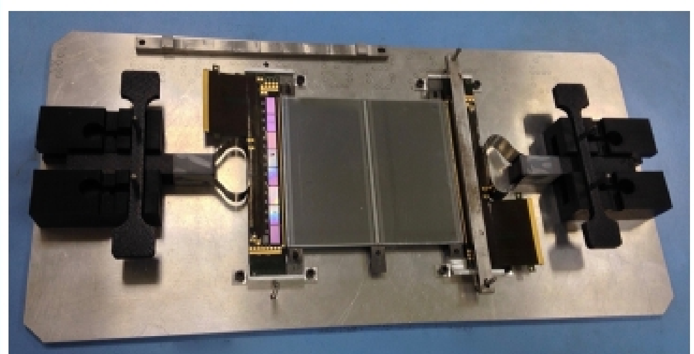


R-z view of a possible layout of the new CMS tracker foreseen for Phase 2. The inner part is composed of silicon pixel modules (yellow and light blue), while the outer part is composed of two different kind of silicon modules: PS modules (dark blue) and 2S modules (red).

The HPK Campaign

- A comprehensive R&D program is being carried out to identify suitable silicon materials for the OT → various test structures and sensors implemented on selected wafer materials
- Production by a single vendor: Hamamatsu Photonics K.K. (HPK)
- Devices: first electrical characterization → irradiation → second electrical characterization
- Attention paid to: charge collection (CC), noise behaviour, strip isolation, bias voltage needed to extract sufficient signal and leakage current 1. before and 2. after irradiation
- n-in-p (n-type implants in a p-type bulk) preferred: lower degradation of the signal with irradiation, no observation of non-Gaussian noise contribution (→ less fake hits)





The 2S module jigs used to glue the sensors to the Al-CF bridges (left) and to glue the front-end and service hybrids (not shown) to the sensor package (right).

New pixel telescopes

- Control of the developed sensors and its readout electronics through beam tests is necessary to examine the behavior of silicon sensors in real conditions
- A telescope is an array of highly segmented detectors that can reconstruct with high accuracy particle tracks
- A new detector under development (usually named Detector Under Test, DUT) can be tested for channel efficiency, cluster size, cross talk between adjacent channels etc.
- Comparison: Existing telescopes used by CMS (AIDA) use a Monolithic Active Pixel Sensor chip with an integration time of 115.2 μs or 8.68 kHz readout frequency
- Integration time in Phase II tracker modules (and other HL-LHC sensors) is 25 ns → 40 MHz (x4600 the today's CMS telescopes readout frequency)
- We cannot test Phase-II modules at nominal rates with the old telescopes exploited by CMS → That's why new telescopes are being developed (e.g. CHROMIE – CMS High Rate telescOpe MachInE at CERN, CHROMini at IPHC-Strasbourg)

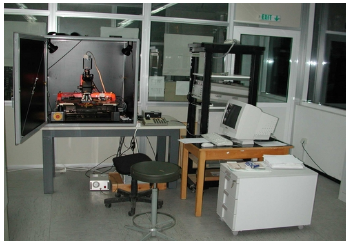
Activities of the DIL group

- The members of DIL (Detector Instrumentation Laboratory) at INPP (Institute of Nuclear and Particle Physics) - "Demokritos" are actively involved in the Phase-2 Tracker Upgrade:
  - electrical characterization of silicon sensors
  - the readout electronics and data acquisition development for the CMS pixel detector
  - study of new high-rate telescopes (CHROMIE, CHROMini) for the upcoming beam tests on the new tracker modules (tracking algorithms, simulations, participation in beam tests)
  - DQM (Data Quality Monitoring) shifts

The current configuration of our lab

Laboratory (120 m^2) with temperature and humidity control (constantly at RH~40%, θ = 23 °C ± 1 °C), storage desiccator with humidity control

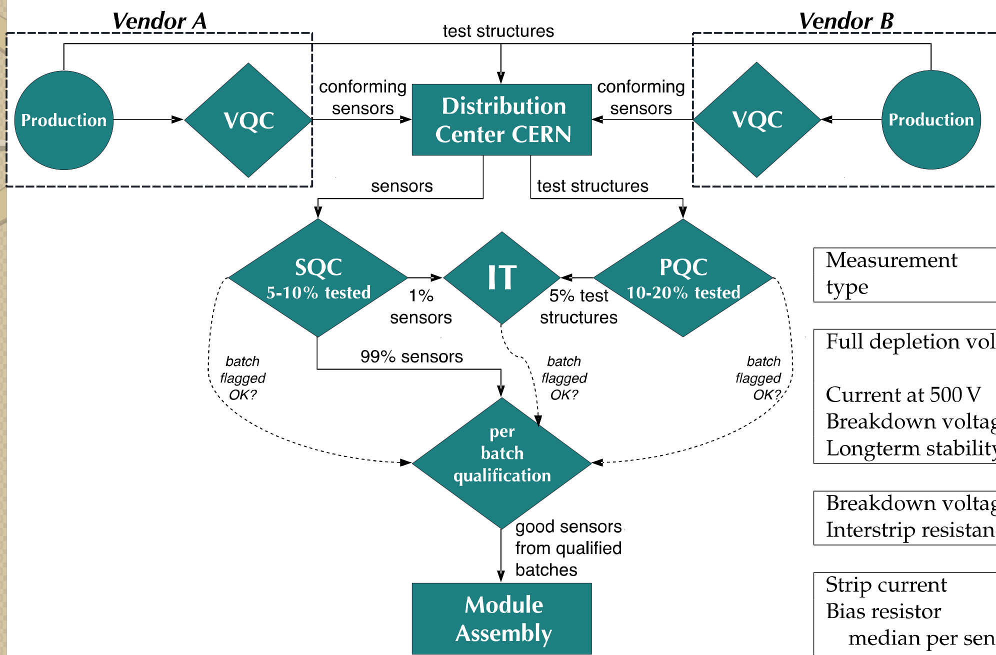
Probe Station: Karl Suss PA 200
CV: HP4092A
IV: Keithley 6517A
The whole setups is controlled by a LabView program

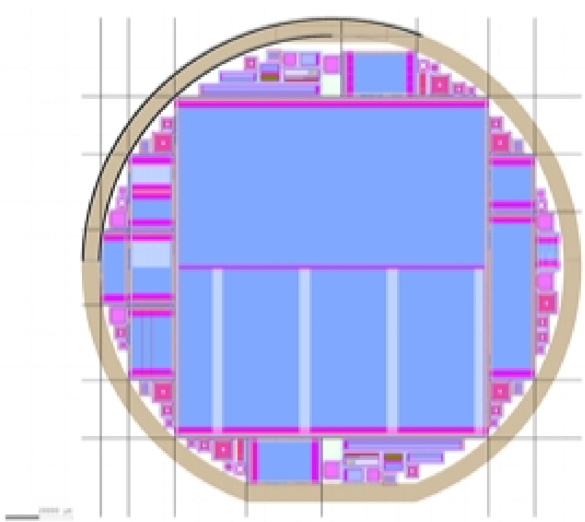


Delvotec 5430 Wire Bonder

Climate Test Chamber (Weiss WKS 3-180/40/5)

Sensor and Process Quality Control





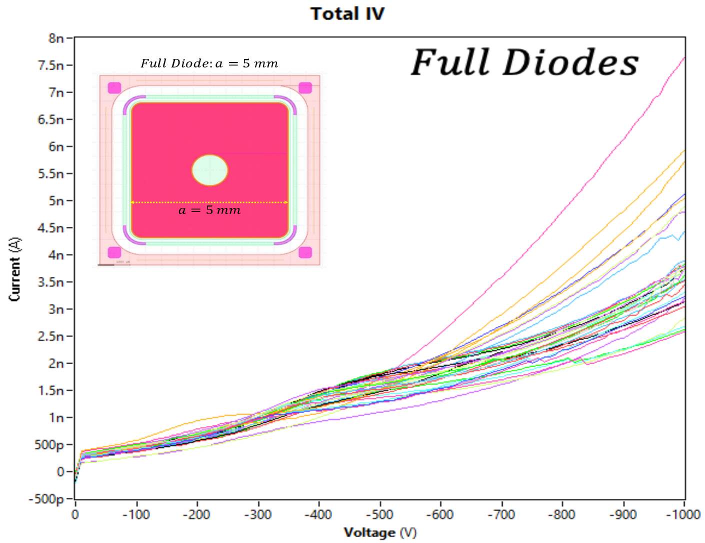
Measurement type	Acceptance value/window	Measured at VQC	SQC	PQC	IT
Global measurements (2S, PS-s, and PS-p)					
Full depletion voltage	$V_{fd} < 150$ V for 200 μm	✓	✓	✓	✓
	$V_{fd} < 300$ V for 300 μm	✓	✓	✓	✓
Current at 500 V	$I_{500} \leq 2\,\mathrm{nA/mm^3}$	✓	✓	✓	✓
Breakdown voltage	$V_{break} >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

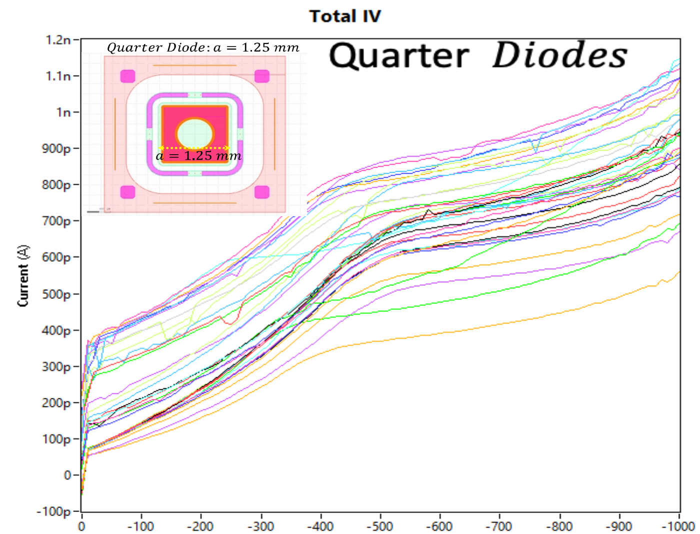
[1] Only for a smaller sample of sensors, approximately 1% of the full quantity.

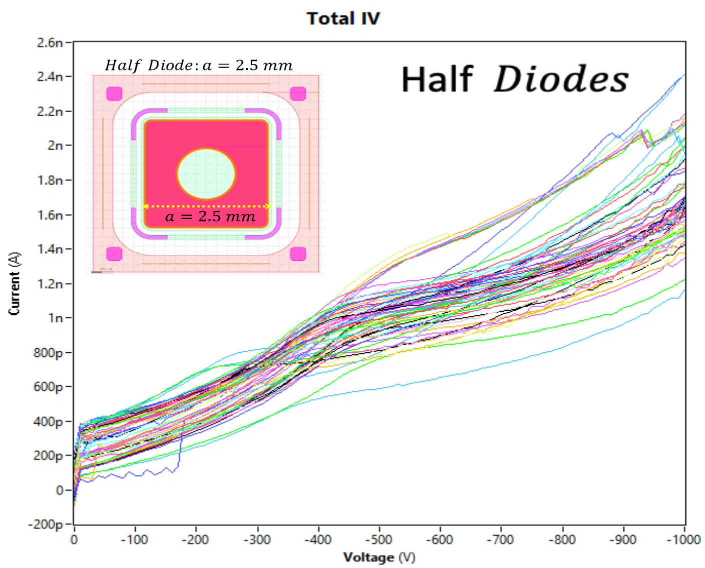
IV profiling of diodes

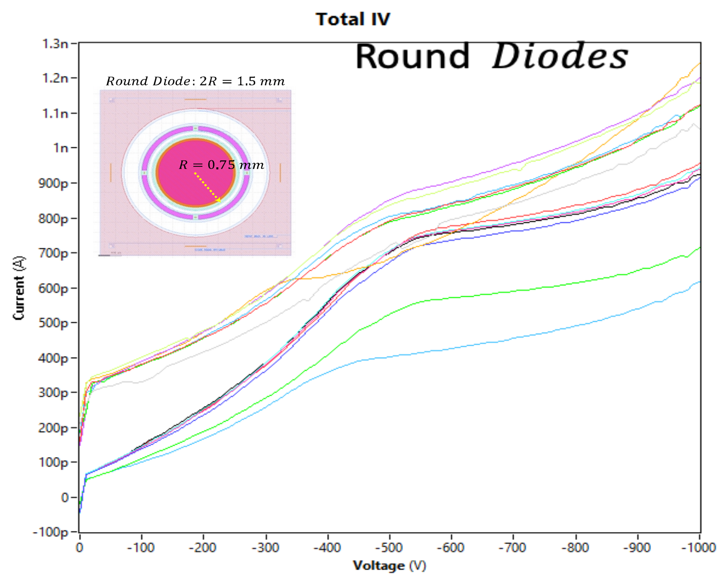
VPX28442 batch (Thinned 240 µm): IV for all Diodes →

Estimation of order of magnitude of leakage current → low currents



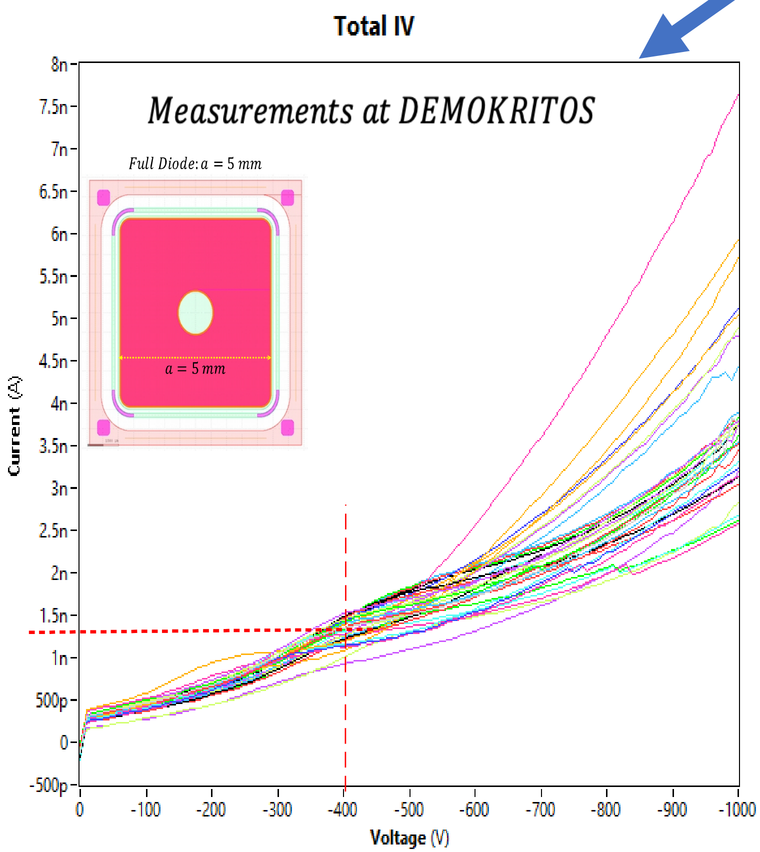




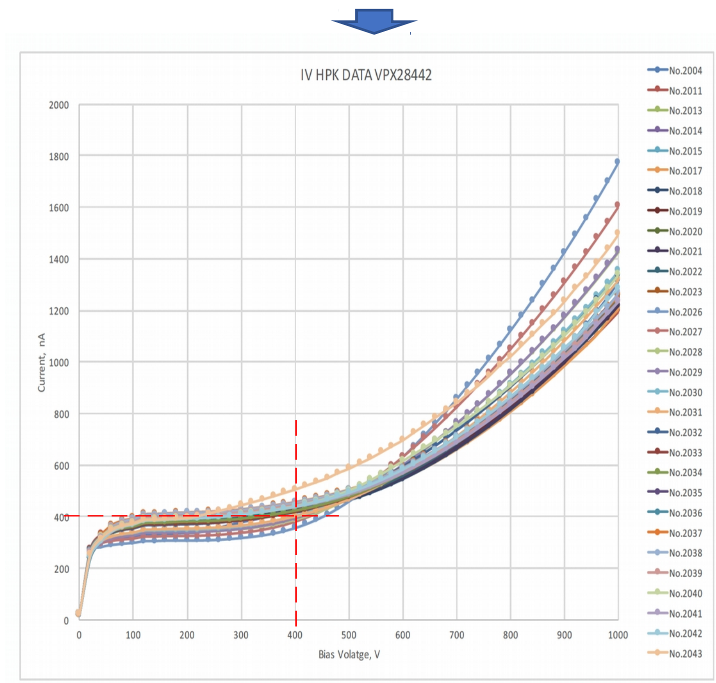


IV comparison: Full diodes at "Demokritos" vs. 2S sensors at Rochester

VPX28442 batch Thinned 240 μm: IVs for Full Diodes



VPX28442 2S Sensors



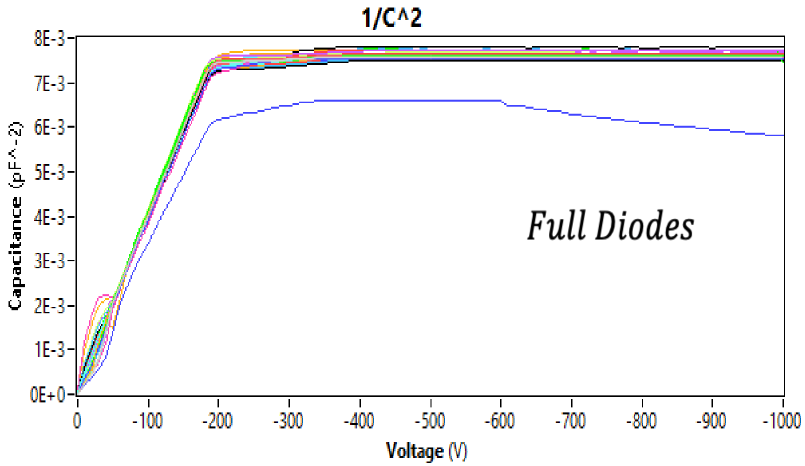
- Coarse Comparison:

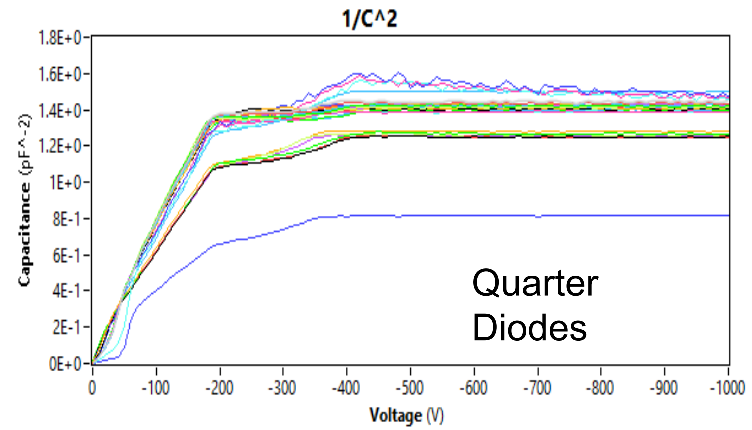
$$\frac{area_{2S}}{area_{Full\ Diode}} \approx 4\times 10^2 \qquad \frac{leakage\ current_{2S}}{leakage\ current_{Full\ Diode}} \approx 3\times 10^2$$

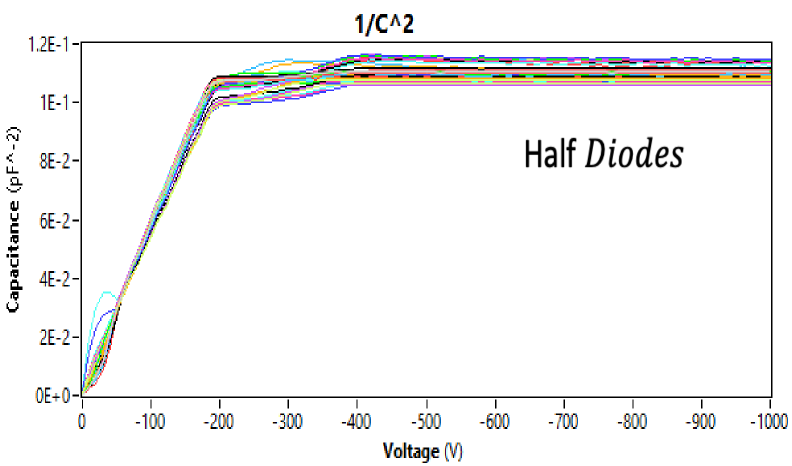
CV profiling of diodes

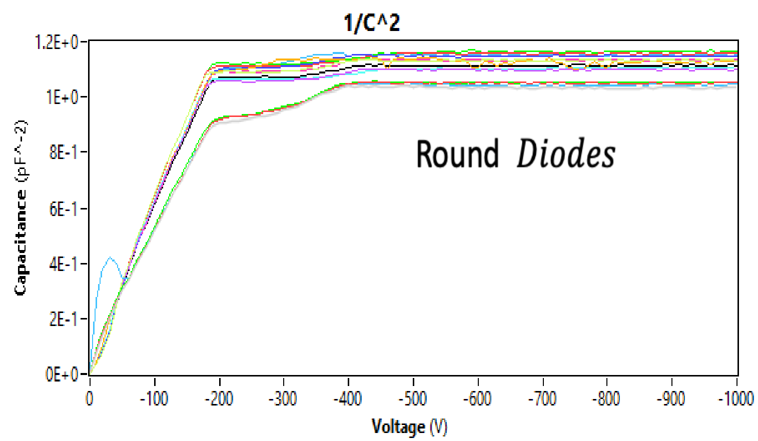
VPX28442 batch (Thinned 240 μm): 1/C²-V for all Diodes →

Estimation of depletion voltage

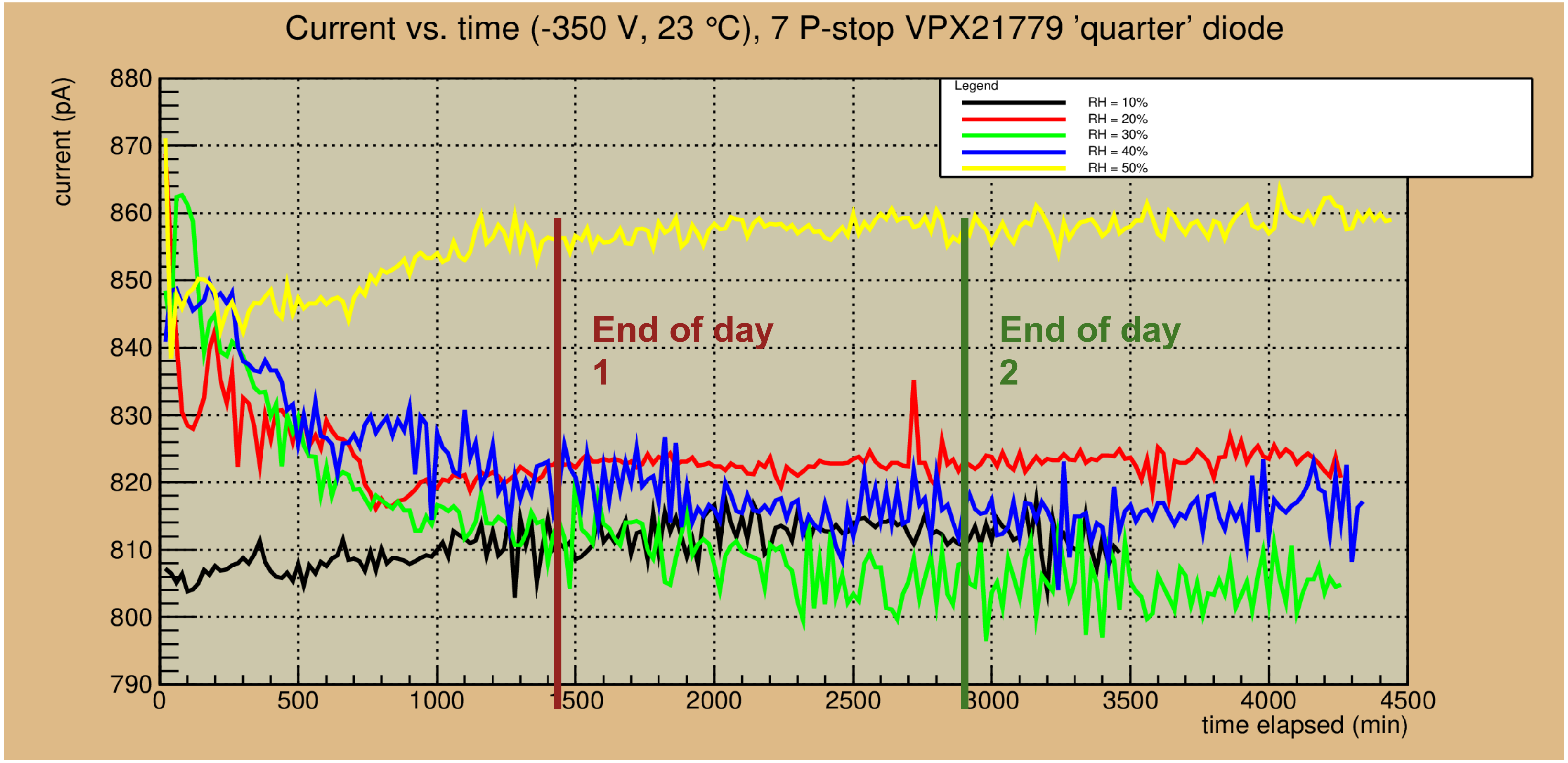








Climate tests on a diode



Measurements have been taken every 20 min. At high relative humidity it takes ~1 day for the system to stabilize, however for RH = 10% stabilization occurred immediately. That's why we stopped the RH = 10% measurement after the second day.

The firmware in the FPGA of the Pixel Front-end Readout Chip

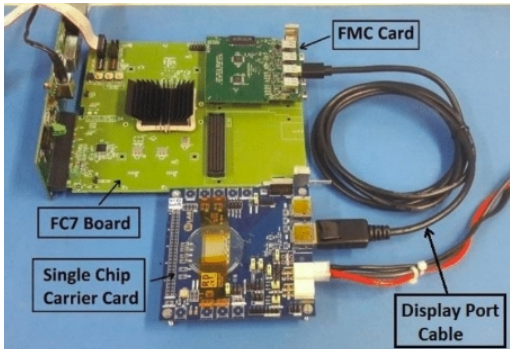
- Contribution to the development of the firmware for the Inner Tracker μDTC, which is the CMS DAQ testing and development platform for the RD53A chip

- The firmware:
  - controls the operation and the data readout sequence of the chip
  - handles incoming Timing Trigger and Control (TTC) commands from external Triggering Logic Units (TLU)

- Communication with RD53A (the pixel readout integrated circuit) achieved using a custom serial protocol which provides commands and clocking to the chip over a single differential input, at a speed of 160 Mbps

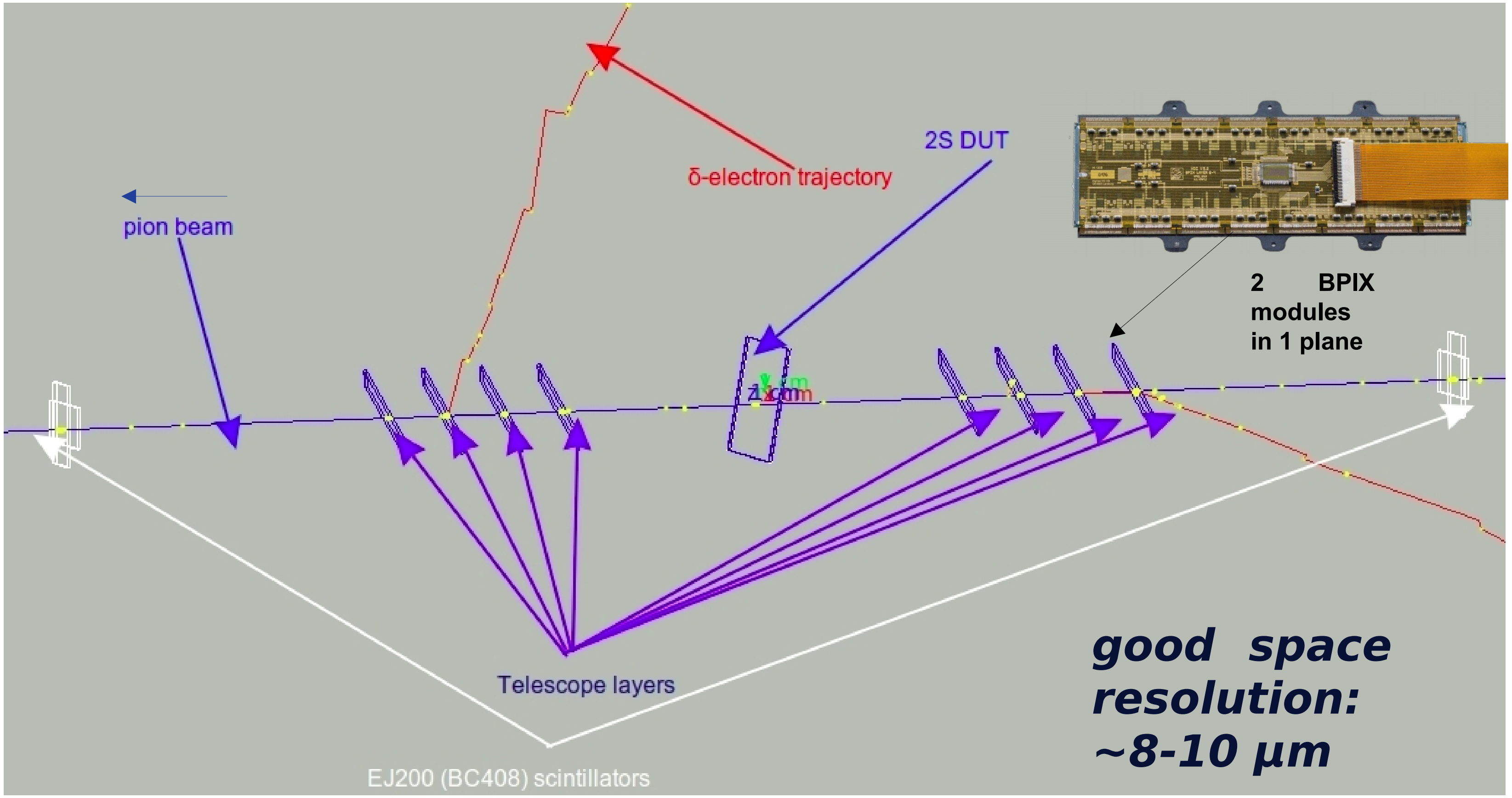
- Readout data coming out from the chip encoded using the "Aurora protocol" (a Xilinx-specific serial protocol running at 1.28 Gbps)

- Calibration procedures for the ASICs will be performed by the firmware → to reduce the execution speed in comparison to the software-based procedures.



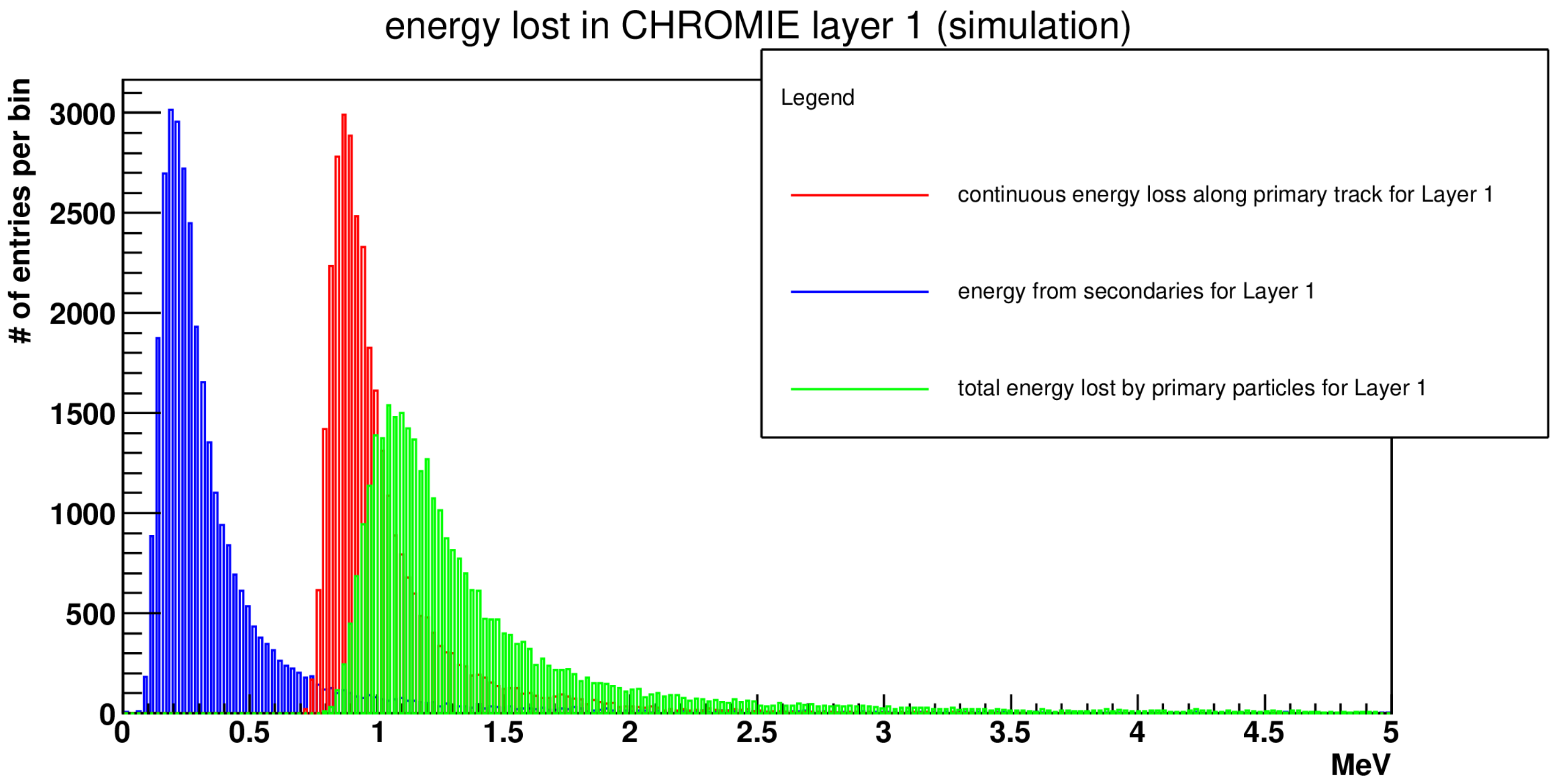
Test bench system at "Demokritos" for the firmware development of the CMS Phase-II Pixel front-end chip

A Geant4 visualization of the CHROMIE geometry



pos_zBPIX12 = (17.3 + 5.0 + 5.0 + 5.0) cm; pos_zBPIX34 = (17.3 + 5.0 + 5.0) cm;
pos_zBPIX56 = (17.3 + 5.0) cm; pos_zBPIX78 = 17.3 cm; pos_zBPIX910 = -17.3 cm;
pos_zBPIX1112 = -(17.3 + 5.0) cm; pos_zBPIX1314 = -(17.3 + 5.0 + 5.0) cm;
pos_zBPIX1516 = -(17.3 + 5.0 + 5.0 + 5.0) cm;
InterArmDeltaZ = 350.0 mm; InterPlaneDeltaZ = 50.0 mm;
DistanceScintillator1 = 27.5 cm; DistanceScintillator2 = 27.5 cm;

Energy lost by 120 GeV π^+ in CHROMIE Layer 1 (simulation)



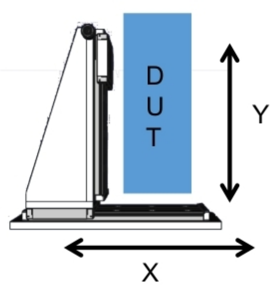
The future mini-telescope (CHROMini) at IPHC

- Shutdown of CERN facilities → 25 MeV proton beam line at IPHC-Strasbourg, high intensities (up to 100 nA → 10^{12} protons/second), rate can be adjusted to 40 MHz (nominal LHC rate)

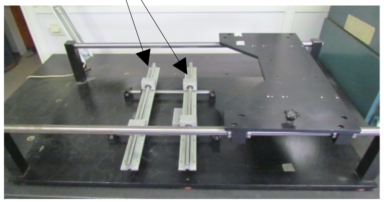
- A mini-telescope adapted to the 25 MeV proton beam is being designed and constructed for the new beam line at IPHC, as simulation studies showed that the project is feasible and can be used for tracking → a reduced version of CHROMIE with only two planes due to attenuation of 25 MeV protons in Si

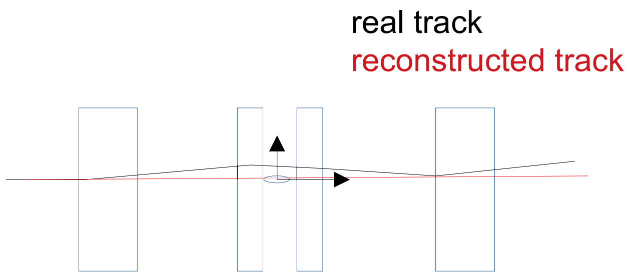
- Design:
  - Two CMS pixel Phase-I module planes,
  - Modules sandwiching the DUT on shifting (on trail) planes to accommodate different sizes of DUT
  - Pixel modules positioned at ~+/- 1 cm from the DUT
  - DUT on a x-y table, with 15 cm x 15 cm shifts
  - Box for cooling under investigation
  - LV and HV power supplies, FC7 cards available

- First beam test expected in July 2019

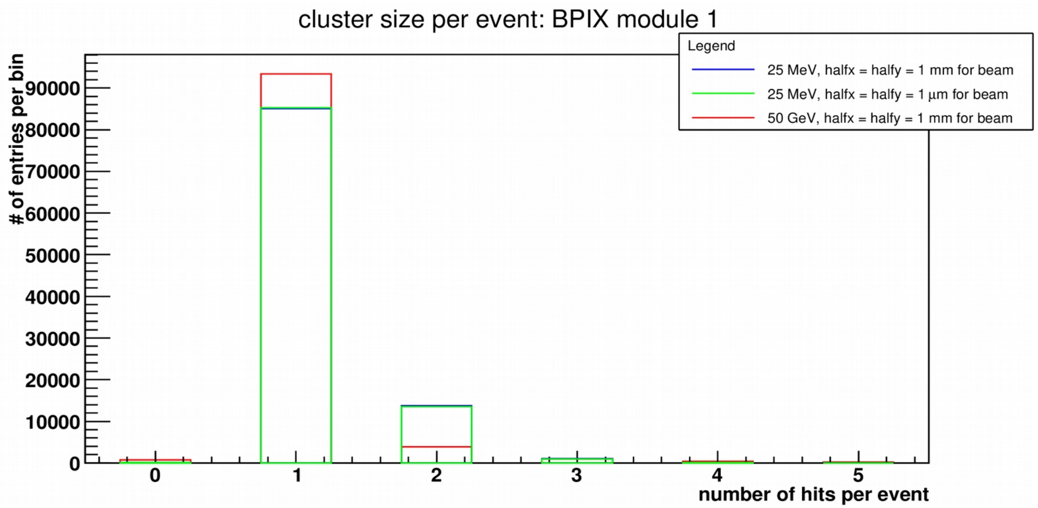


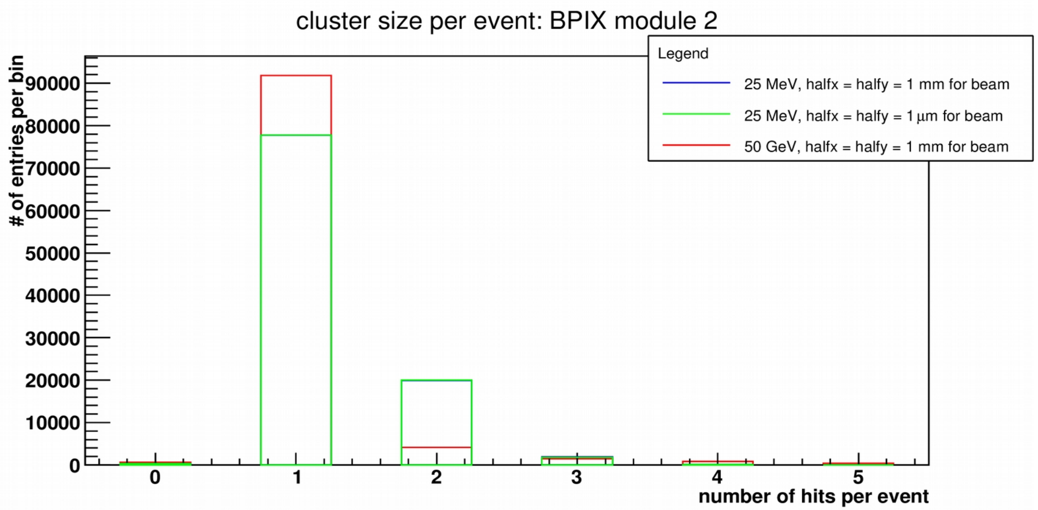
2 Phase-I pixel modules will be placed here





Cluster size in pixel modules (simulation)





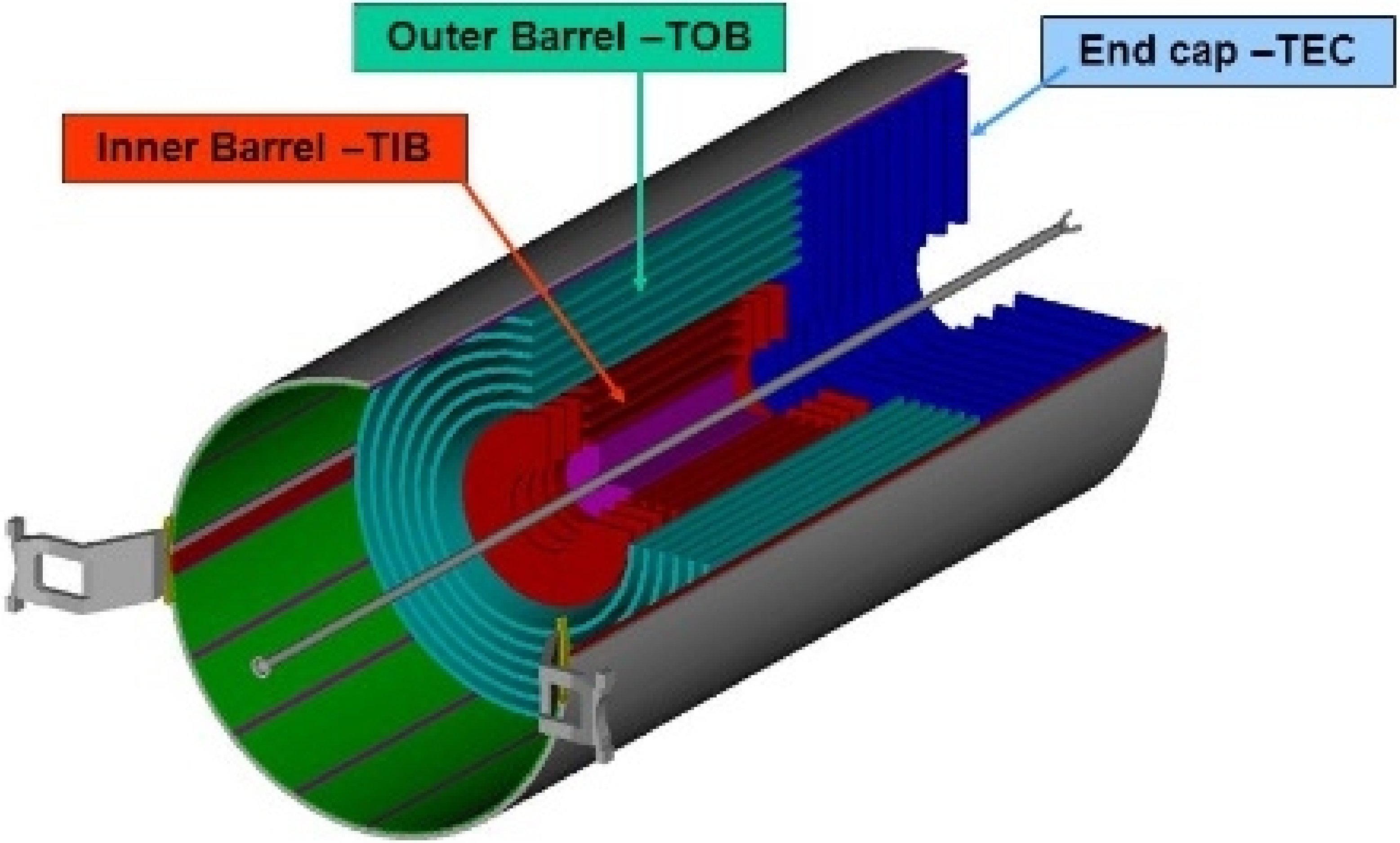
- 1 BPIX module in front of the DUT and 1 BPIX module behind the DUT (1 cm distance between the edge surfaces of each sensor and the nearest BPIX module)
- BPIX module: 66.6 mm X 25 mm X 460 µm; Pixel size: 150 µm X 100 µm
- 100000 events

  - General Particle Source (GPS):
  - sigma = 100 keV
  - position = (-1, 0, -20) cm
  - type: beam
  - shape: ellipsoid
  - halfx = halfy = 1 mm, halfz = 0.5 cm

The plots basically show the number of pixels with a hit in the current module in the current event.

Backup

The CMS Tracker



Hamamatsu test structures

After each new batch of test structures has been produced at HPK, “Demokritos” receives a part of them along with the other PQC (Process Quality Control) Centers for the Upgrade of the OT.

VPX28442 batch (Thinned 240 μm): Test Structures at NCSR “Demokritos”

Structure	Type	Lot No.	Serial No	Total Quantity
1 : D 1PS 2GR etc (Upper)	S10938-8524	VPX28442	2018, 2019, 2020, 2021, 2022, 2023, 2026	7
12 : D 1PS 2GR (lower)	S10938-8524	VPX28442	2018, 2019, 2020, 2021, 2022, 2023, 2026	7
6 : VDP Flute etc (Upper Right)	S10938-8524	VPX28442	2018, 2019, 2020, 2021, 2022, 2023, 2026	7
3 : VDP Flute etc (Upper Left)	S10938-8524	VPX28442	2014, 2015, 2017	3
11 : VDP Flute etc (Lower Right)	S10938-8524	VPX28442	2014, 2015, 2017	3
7 : VDP Flute etc (Lower Left)	S10938-8524	VPX28442	2014, 2015, 2017	3
20 : SIMS etc (Right)	S10938-8524	VPX28442	2018, 2019, 2020, 2021, 2022, 2023, 2026	7
15 : SIMS etc (Left)	S10938-8524	VPX28442	2018, 2019, 2020, 2021, 2022, 2023, 2026	7
18 : HMSet (Right)	S10938-8524	VPX28442	2018, 2019, 2020, 2021, 2022, 2023, 2026	7
17 : HMSet (Left)	S10938-8524	VPX28442	2018, 2019, 2020, 2021, 2022, 2023, 2026	7
14 : MOS&Diode	S10938-8524	VPX28442	2018, 2019, 2020, 2021, 2022, 2023, 2026	7
2 : Sensor PS light etc	S10938-8524	VPX28442	2018, 2019, 2020, 2021, 2022, 2023, 2026	7
			Total	**72**

After an optical inspection (to detect scratches), IV and CV measurements are performed on diodes; breakdown voltage is calculated.

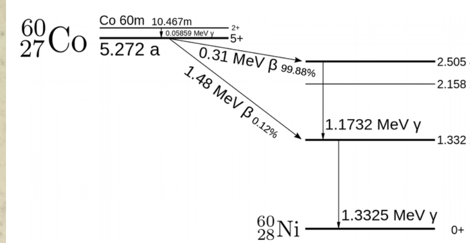
Irradiation of diodes

We used a cobalt-60 (^{60}Co) source to irradiate 5 test structures with half and quarter diodes for ~1 day with a dose rate of ~3-4 kGy/day (depending on the position of each diode in the cobalt source irradiation volume). During this period we were performing the dose rate calculation using Harwell PMMA Red 4034 Perspex Dosimeters.

After irradiation we performed an IV measurement on all diodes and for all of them observed a breakdown.

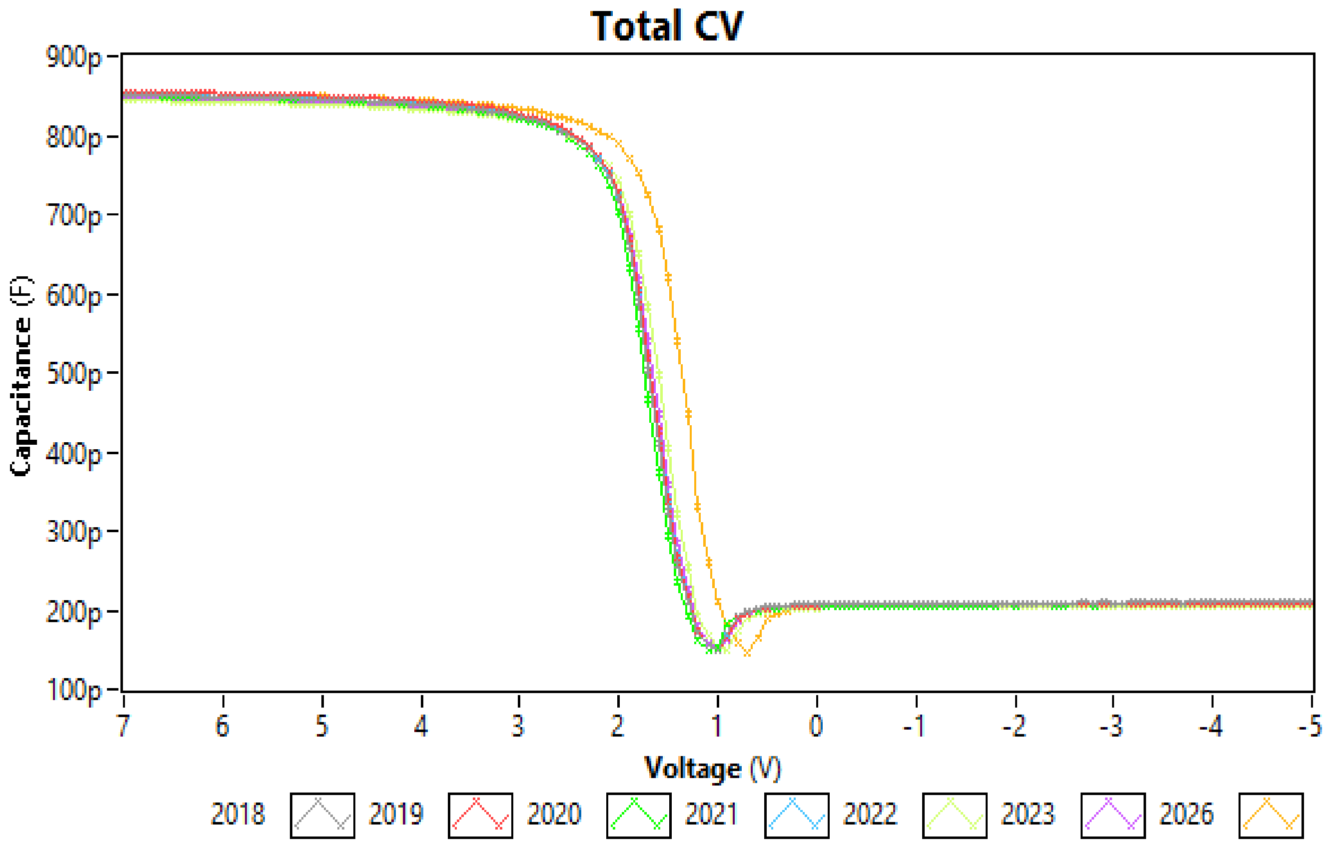
Minimum breakdown voltage for a half diode: -450 V.

Minimum breakdown voltage for a quarter diode: -580 V.



CV profiling of MOS

VPX28442 batch Thinned 240 µm: Rectangular MOS capacitors



Waiting time: 500 ms
Step Size: 100 mV
AC frequency: 10 kHz
Amplitude: 250 mV
Range: (-7 – 5) V (polarity of probes reversed)

DAQ development for the Pixel Front-end Readout Chip

- Contribution to the development of the firmware for the Inner Tracker µDTC, which is the CMS DAQ testing and development platform for the RD53A chip

- The hardware of the system consists of:
  - an FPGA Mezzanine Card (FMC) carrier board (the so called FC7 board)
  - up to two FMC cards to communicate with the chips
  - up to eight Single Chip Carrier (SCC) cards, hosting one chip each

- The system can operate either 1. in a µTCA crate, with several FC7 boards connected, or 2. in a desktop mode, where one FC7 board is connected to the host PC via Ethernet cable

- FC7 board: developed at CERN, hosts a Kintex-7 Field Programmable Gate Array (FPGA) from Xilinx (firmware implemented in VHDL)

- FMC card: also custom made and one card can communicate with up to 4 chips using Low Voltage Differential Signals (LVDS) transferred via Display Port (DP) cables

- The stack for the DAQ chain consists of:
  - the software in the host-PC (implemented in C++, containing the user code to control the testing sequence and the middleware, which handles the low-level communication between the user code and the FPGA)
  - the firmware in the FPGA

Purpose of DQM

- Execution of the live monitoring applications and visualization tool (DQM GUI) on the DQM cluster

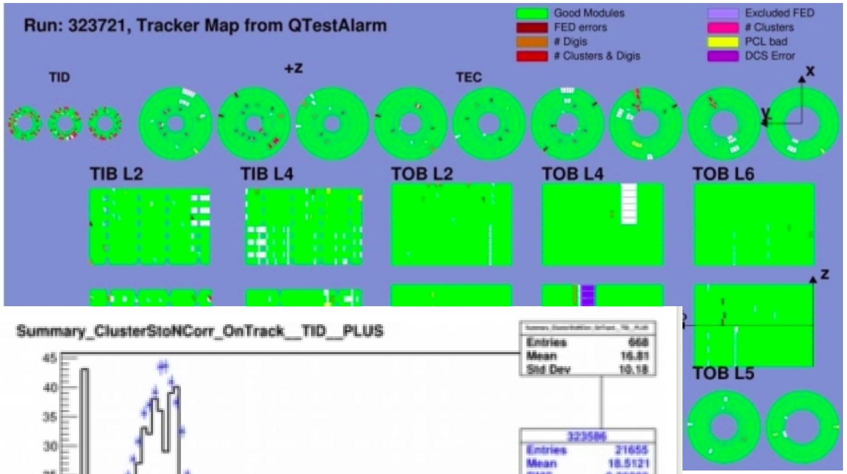
- The goal of the online Data Quality Monitoring is to spot problems in the CMS detector while it is runnin

- The goal of the **offline Data Quality Monitoring and Data Certification** is to determine which data can be used for data analysis

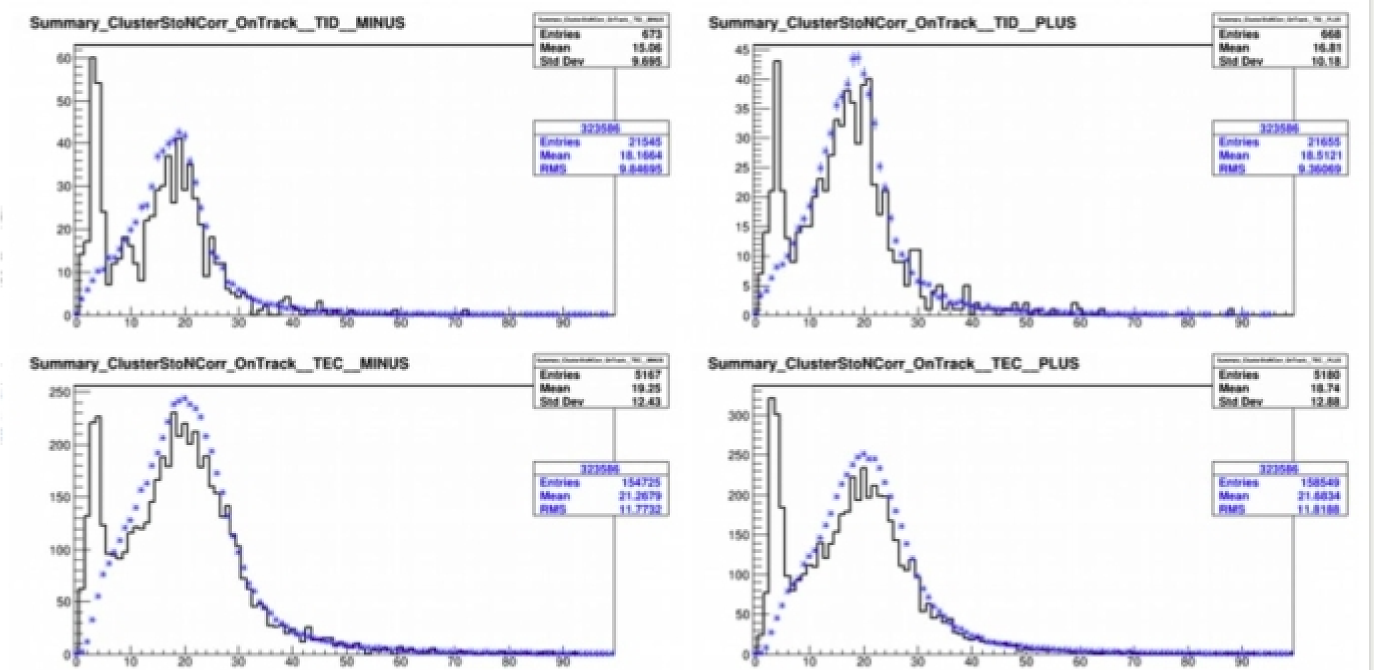
- Silicon strips, Phase-I pixels and Tracking checked by Offline shifters and Offline crew.

Example of a validation of a run

- A high noise level seen in TID and TEC+7/8, producing a high amount of low-p_T tracks with low cluster S/N

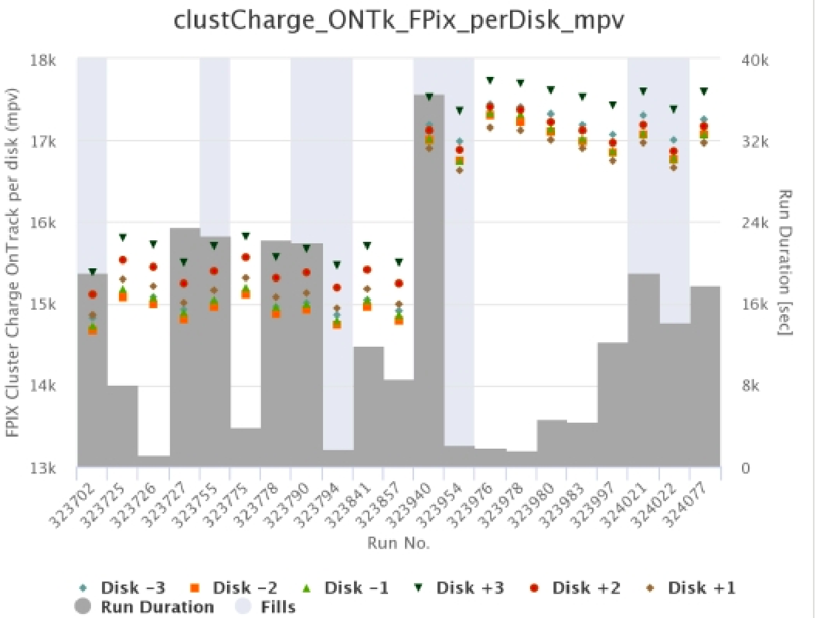


- Certified as bad



Shift on Pixel Cluster Charge

- FPix: charge decreases when instantaneous luminosity decreases
- Increasing of cluster size when instantaneous luminosity decreases (the same thing was observed in the barrel)



BPIX (barrel pixel) modules

Sensor silicon area 18.6x66.6mm^2
Number of ROCs=2x8
Pixel size 100x150um^2 (size twice as wide at chip boarders)
Number of pixels 80x52
Sensor active area 16.2x64.8mm^2 since
2*(80*0.1mm+0.1mm)=16.2mm
8*(52*0.15mm+2*0.15mm)=64.8mm