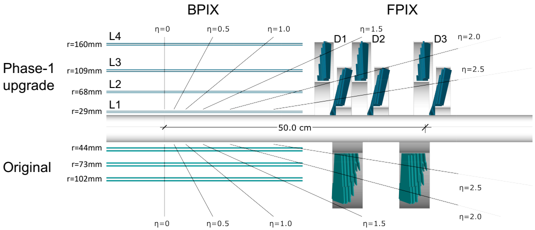
CMS Pixel Detector Upgrades and More

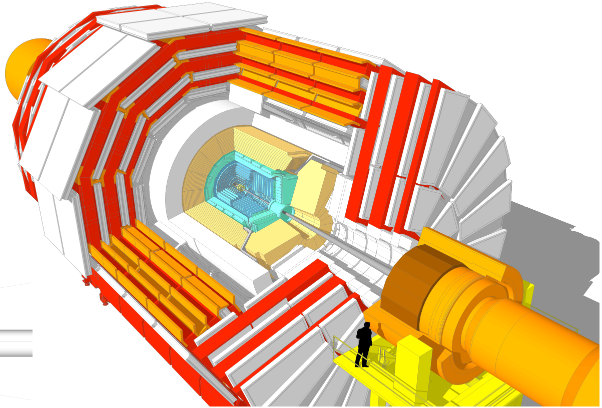
Erik Brücken

16.11.2021

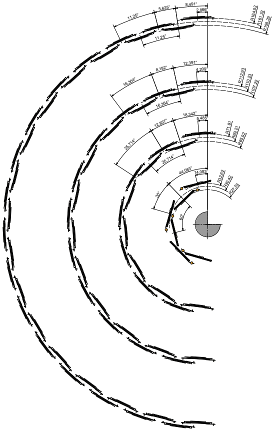
The CMS Pixel detector before LS2

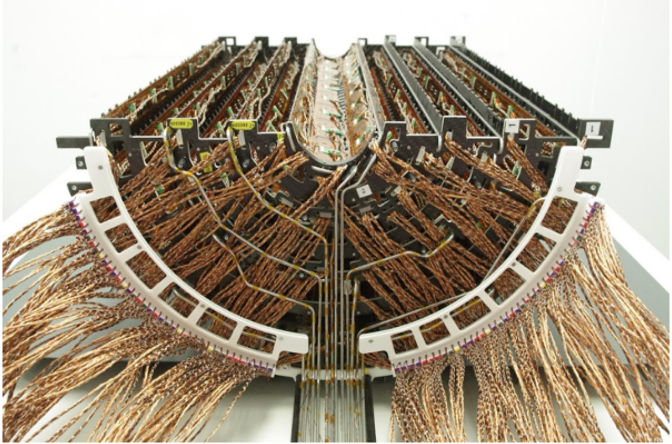
- Silicon Pixel Detect Detector is innermost part of CMS tracking detector.
- Closet detector to IP, facing harshest conditions.
- $\mathcal{L}$ (IP5) max $1.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Delivered in Run 2: $150\,\mathrm{fb}^{-1}$





Phase 1 upgrade version of BPIX

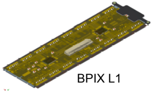




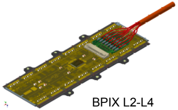
Phase 1 upgrade modules

Design

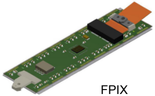
- Pixel sensors based on n-type silicon (300 μm).
- One module consists of 16 pixel sensors
- Each sensor contains $80 \times 52 = 4160$ pixels
- Hybrid detector design: Sensors flip-chip bonded to ReadOutChip (ROC).
- We use ROCs from PSI46 family.
- High density interconnect (HDI) clued onto sensor module.
- Three slightly different modules



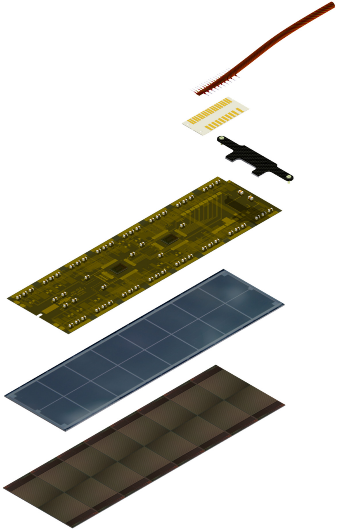
BPIX L1



BPIX L2-L4



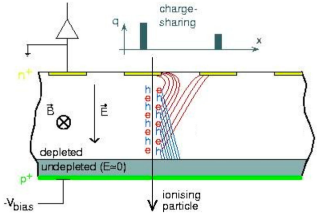
FPIX

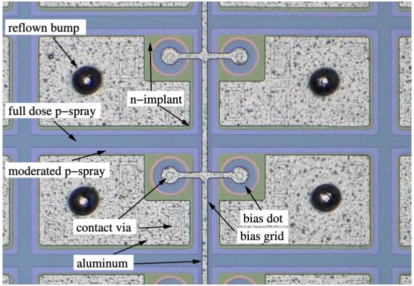


CMS Pixel Phase-1 upgrade sensor

Design

- Material: n-type float zone (FZ) silicon wafer (4-inch).
- Resistivity 3.7 kΩcm.
- Highly doped pixelated n^+ in n sensor design with uniform p doped back side.
- Pixel isolation via p-spray/p-stop structures.
- Bias grid with punch through bias dots.

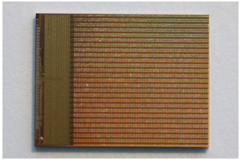


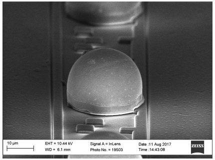


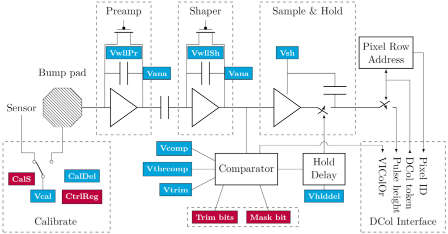
CMS Pixel Phase-1 upgrade ROC

Readout chip for prototypes

- CMOS ASIC developed by PSI for the pixel sensors of the CMS tracker.
- 4160 pixels (52×80) in $8 \times 7.6\,\mathrm{mm}^2$ active area.
- Photo counting capable.
- Full pulse processing per pixel.
- Charge threshold of $1.5\,\mathrm{ke}^-$, resolution $\sim 120\,\mathrm{e}^-$.
- Radiation hardness $> 2.5\,\mathrm{Mrad}$.
- Available with PbSn or (Indium bumps for low-T processing).
- Several versions available: PSI46dig for Layer 2-4, PROC600 for layer 1.







see: B. Meier 2011 JINST 6 C01011,

D. Hits & A. Starodumov 2015 JINST 10 C05029

CMS Pixel Phase-1 Layer-1 upgrade

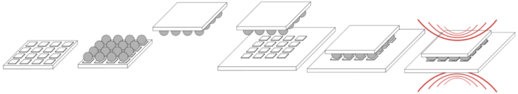
Why upgrade?

- Fluence of $\Phi \approx 3.0 \times 10^{15} n_{eq}/cm^2$ in layer 1 for 500 fb^{-1}. Operational limits require change at 250 fb^{-1}
- Ionizing Radiation causes displacements, vacancies, interstitials, etc.
- Radiation damages in sensor bulk and on surface causes:
  - Higher leakage currents $\Rightarrow$ electronic noise
  - Type inversion can occur in silicon bulk
  - Need higher depletion voltage for operation $\Rightarrow$ breakdown risk
  - Charge trapping.
- Overall signal quality reduced.

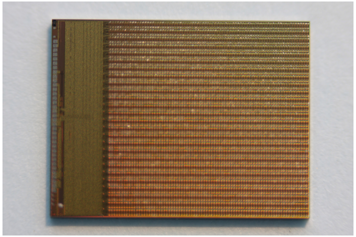
CMS Pixel Phase-1 Layer-1 upgrade modules

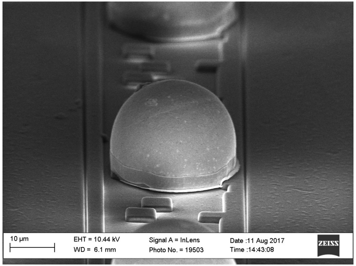
Our role in Finland

- Part of the production of 150 new layer 1 pixel modules.
- Wafers of modules and ROCs were received via PSI.
- Thinning (ROC) and dicing of wafers and bump bonding done by ADVACAM Oy.
- At HIP we tested the modules for basic functionalities, unit by unit.
- Emphasis on bump bonding and IV test as fast feedback to the producer.



taken from UCDavis website





CMS Pixel Phase-1 Layer-1 upgrade modules :: QA in HKI

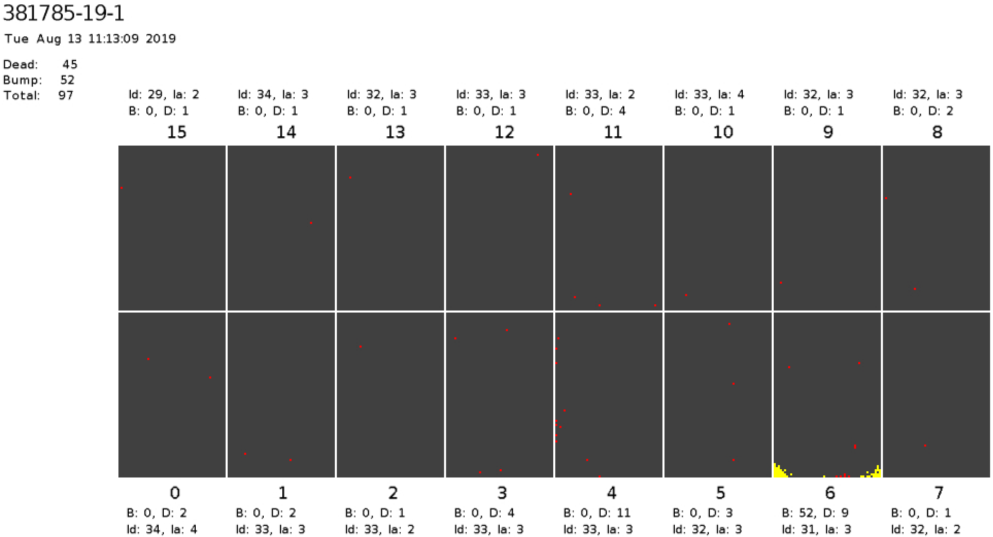
Criteria for bare modules after bump bonding

- Leakage current at -150 V $< 2\,\mu$A: grade A; $< 10\,\mu$A: grade B; otherwise: grade C.
- Slope of leakage current I(-150 V)/I(-100 V) < 2: grade A; otherwise grade B.
- ROCs needs to be alive and configurable.
- Pixel and bump bonding test.
- For worst ROC in module $< 1\%$ defects: grade A; $< 4\%$ defects: grade B, otherwise grade C.

The bump bonding test

- Test pulse send via capacitively coupled test pad to each pixel. Signal readout via metal bump. Received signal is compared to test pulse.

CMS Phase-1 Layer-1 upgrade modules :: QA in HKI



CMS Phase-1 Layer-1 upgrade modules :: QA in HKI

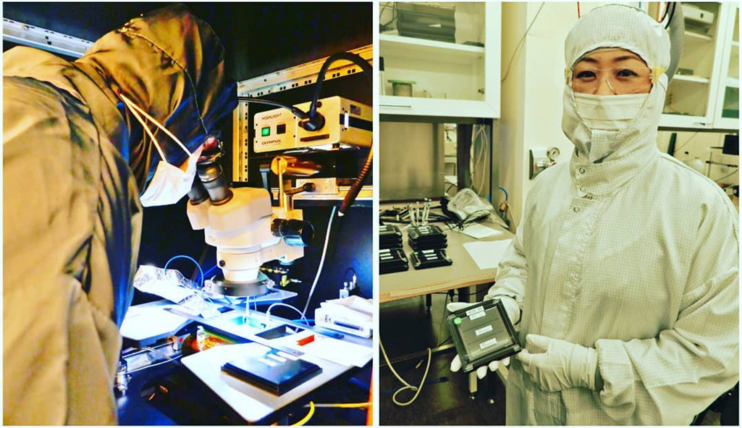


Figure: Setting up QA process for detector module in probestation at HIP Detector Laboratory cleanroom (left), flip-chip bonding expert showing ready detector modules (right).

CMS Pixel Phase-1 Layer-1 upgrade summary

- Critical update for maintaining high quality CMS data during Run 3.
- Modules were successfully flip-chip bonded by Advacam Oy.
- QA after flip-chip bonding done in Helsinki Detector Laboratory clean rooms.
- Detector modules were sent to Paul Scherrer Institute, Switzerland, for full module assembly.
- Of 154 tested modules: 139 class A, 2 class B, 3 class C, 10 unclassified.
- All over yield $\sim 90\,\%$
- Full detector now installed and in preparation process for Run 3.

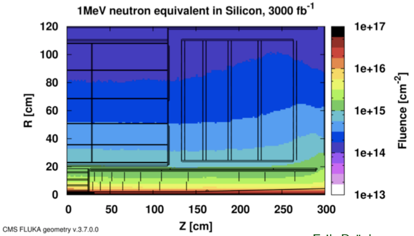
In progress: The Phase 2 upgrade of the CMS tracker

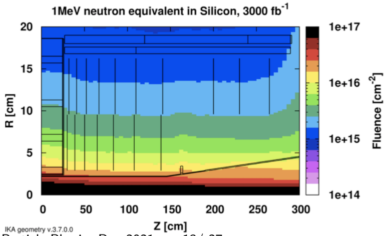
Challenges in HL-LHC

- Pile-up increases substantially to $\sim$200
- Luminosity increase up to $\mathcal{L} \approx 7.5 \times 10^{34}$ cm^{-2} s^{-1}, $\mathcal{L}_{\text{int}} \approx 3000\text{fb}^{-1}$

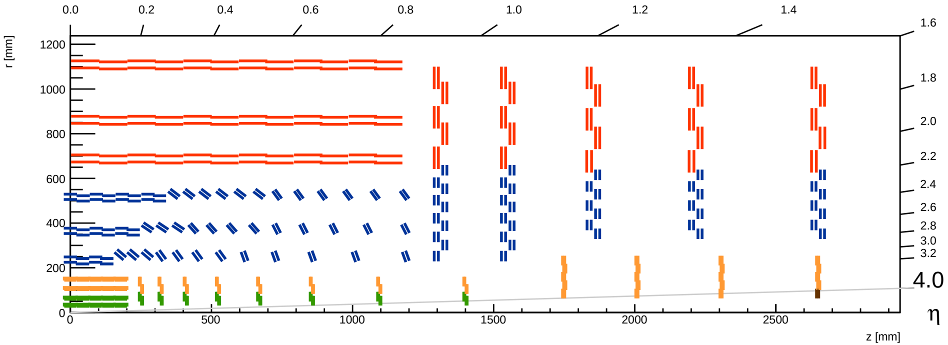
Tracker requirements

- High granularity to reduce occupancy
- Reduction of material budget to improve tracking performance
- Radiation hardness





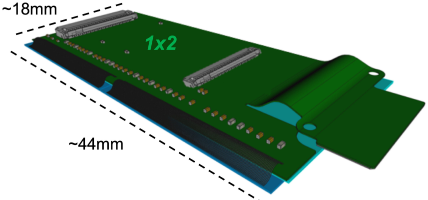
CMS Phase 2 tracker

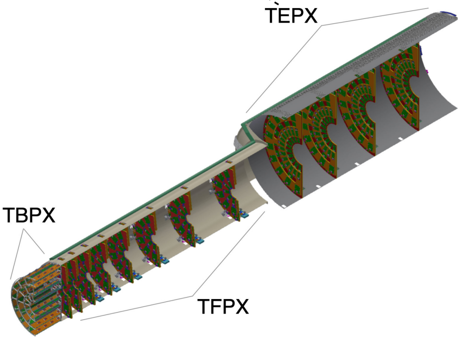


- Important differences to phase 1 tracker: re-arrangements of layers, inclined outer tracker modules, better forward coverage, higher granularity, etc.

CMS Phase 2 inner tracker modules

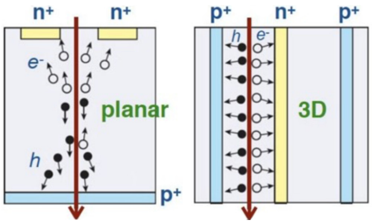
- Detector modules consist of bump bonded ROC sensor units with glued HDI on sensor side.
- HDI electrically connected by wire bonds.
- HDI without active electronics.
- Foreseen to have 2 type of modules, 1×2 and 2×2.
- Small 1×2 modules will be used in inner 2 layers of the barrel (TBPX) and the disks (TFPX, TEPX). Larger 2×2 modules for the outer layers.

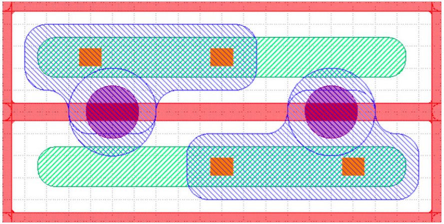


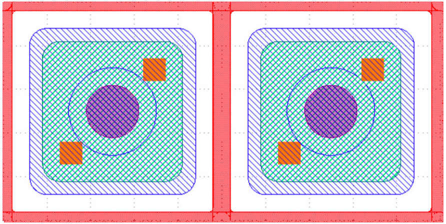


CMS Phase 2 tracker sensor options

- Thin (150μm) n-in-p Si sensors.
- Planar sensors baseline
- 3D option for inner layer (more radiation hard but more expensive)
- Pixel size 25$\times$100μm or/and 50$\times$50μm.
- Decision of technology very soon.

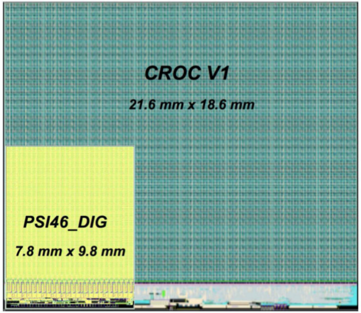




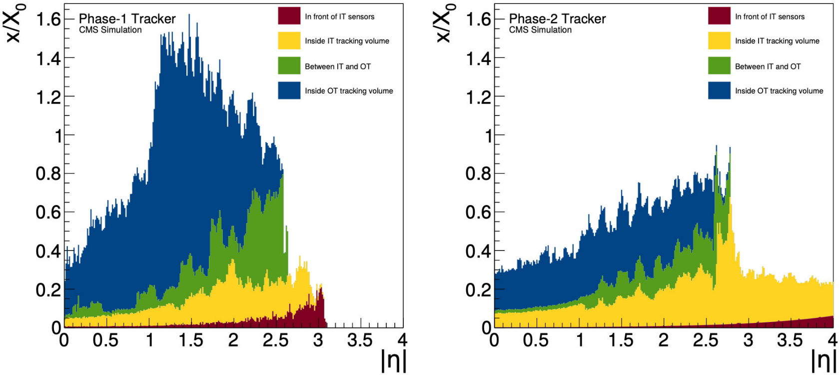


CMS Phase 2 pixel readout chip

- New readout chip developed within the CERN RD53 collaboration.
- ASIC based on 65 nm technology.
- CMS uses RD53B-CMS flavor called CROC
- Cell size of $50 \times 50\,\mu m^2$
- Number of pixels 432×336.
- Radiation hard (tested up to 1GRad).
- Power consumption low ($\sim$ 1W/cm^2).



CMS Phase 2 tracker material budget



- Significant improvements compared to present tracker due to e.g. lighter materials, less layers, inclined modules of outer tracker, etc.

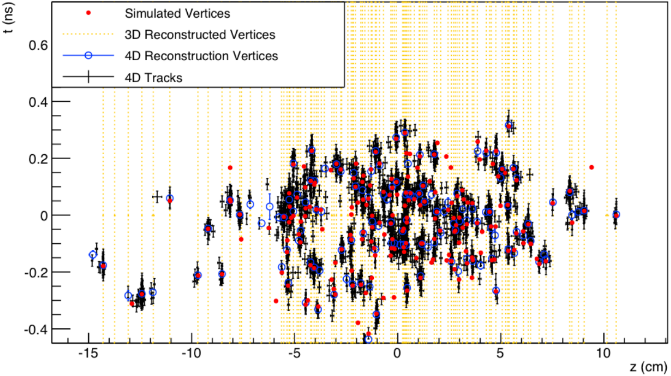
Finnish contributions to the CMS Phase 2 tracker upgrade

- Building of 250 inner tracker modules.
- Testing and calibration of all 500 modules paid by Finland.
- Module production center at CERN currently in building up phase in collaboration with Rudjer Boscovic Institute (Croatia).
- First pre-production modules foreseen for mid-2022.
- Mechanical design of the Outer Tracker.

The Minimum ionizing particle Timing Detector (MTD)

Motivation

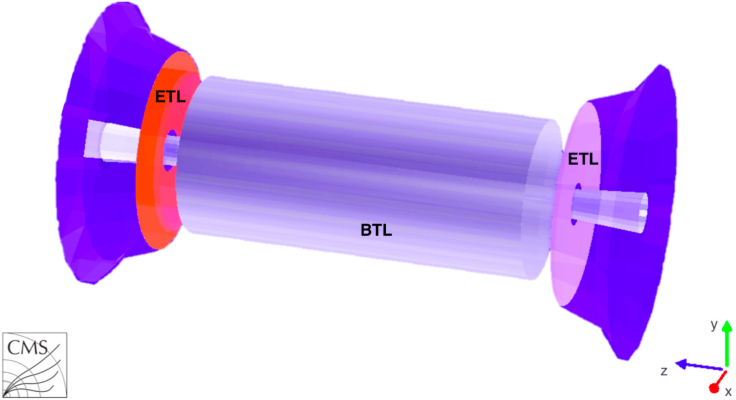
- In High Luminosity LHC we aim for $\mathcal{L} \approx 5.0 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ meaning we get huge pile-up (up to 200 interactions per bunch crossing).
- Idea: timing detector to help separating collisions (aim for $\sim 30\,\text{ps}$ t-resolution).



MTD overview

Layout

- MTD consists of the Barrel Timing Layer (BTL) and the Encap Timing Layer (ETL).
- Position between tracker and calorimeter.



MTD overview

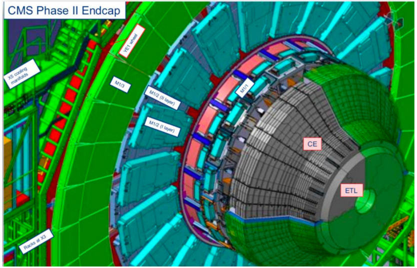
- BTL (LYSO + SiPM) has larger surface area, faces lower radiation dose and uses mature readout technology.
- ETL (LGAD) is exposed to larger radiation dose. Synergies with ATLAS in terms of R&D. Flexible installation schedule.

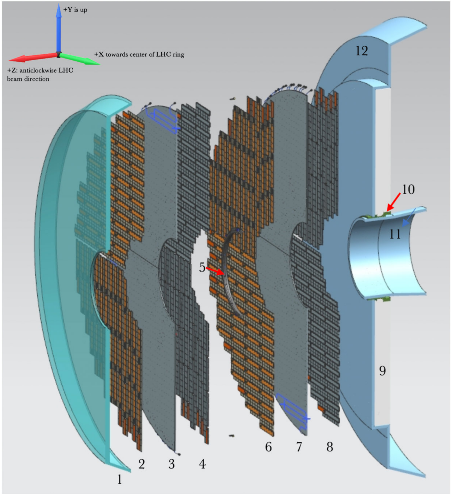
	Barrel (LYSO:Ce + SiPM)	EndCap (LGAD)
Region	$\|\eta\| < 1.5$	$1.6 < \|\eta\| < 3.0$
Surface area	$36.5\,\mathrm{m}^2$	$12\,\mathrm{m}^2$
Power consumption	$0.5\,\mathrm{kW/m}^2$	$1.8\,\mathrm{kW/m}^2$
Radiation dose	$2 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$	$2 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$
Installation date	2022	2024

MTD :: ETL

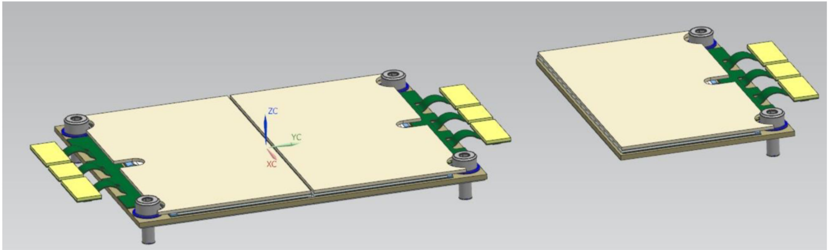
Position and design

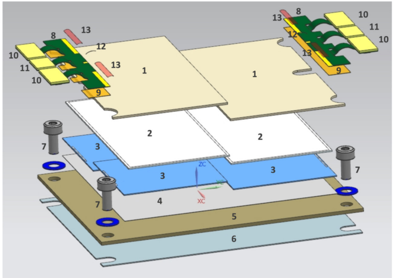
- ETL consist of 2 double sided disks of LGAD modules.
- Mounted on CMS endcap nose.



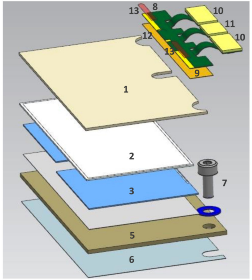


MTD :: ETL module design





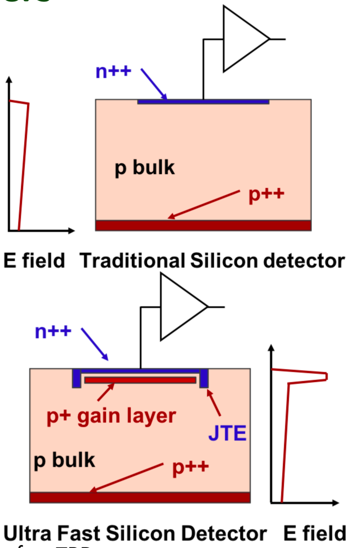
1: AlN module cover
2: LGAD sensor
3: ETL ASIC
4: Mounting film
5: AlN carrier
6: Mounting film
7: Mounting screw
8: Front-end hybrid
9: Adhesive film
10: Readout connector
11: High voltage connector
12: LGAD bias voltage wirebond
13: ETROC wirebonds



MTD :: ETL sensors

LGADs

- MTD-ETL based on Low Gain Avalanche Diode (LGAD) technology.
- Planar silicon sensors of 50 μm thickness.
- Avalanches or charge multiplication due to high electric field ($\sim 300\,\mathrm{kV/cm}$).
- Field generated by high doped layer (p++) of $N_\mathrm{d} \approx 10^{16}\mathrm{cm}^{-3}$.
- R&D Structures manufactured by:
  Fondazione Bruno Kessler (FBK) - Italy
  Hamamatsu Photonics K.K. (HPK) - Japan
  Microelectronic National Center (CNM) - Spain

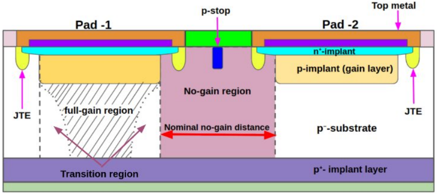


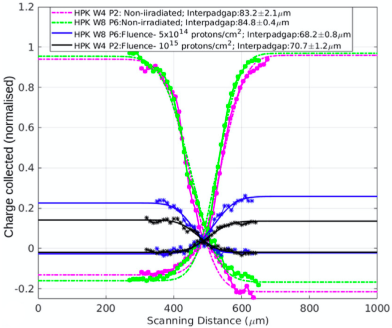
taken from TDR

MTD :: ETL :: Finnish activities

R&D

- Find sensor for optimal timing resolution:
  $\sigma_t^2 \sim \sigma_{\text{jitter}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{distortion}}^2$
  $\Rightarrow$Small capacitance and high signal strength reduce jitter and Landau noise.
- Also important the geometrical coverage
  $\rightarrow$ study of interpad inactive region.
  $\rightarrow$ high fill-factor (active / geometrical area) increases number of two hit tracks.
  $\rightarrow$ using transient current technique to measure fill-factor[1].
- Radiation tolerance
  $\rightarrow$ study of long term stability, acceptor removal problem, etc.





[1]see S. Bharthuar et al., Study of interpad-gap of HPK 3.1 production LGADs with TCT, NIM A 979 (2020) 164494

Finnish contributions to CMS upgrade :: Summary

Pixel phase-1 layer-1 upgrade

- Upgrade finished and detector installed, waiting for Run 3.

Phase 2 tracker upgrade

- Currently preparing premises in CERN clean room for the Pixel Phase-2 production (furniture, equipment).
- Next year we start commissioning the production center and pre-production will start.
- Phase-2 pixel module production will start in late 2023.

MTD-ETL

- Ongoing testing of LGAD sensors.
- Participation in pre-production and production (at HIP detector laboratory).