Characterization of planar and 3D pixel sensors for the inner tracker of the CMS experiment

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CMS inner tracker upgrade

2025-2026: CMS plans the upgrade of the inner pixel detector

- Luminosity levelled at 7.5×10^{34} cm^{-2} s^{-1}
- Pile-up: $\langle\mu\rangle = 200$
- Integrated luminosity: 4000 fb^{-1}

Compared to Phase I

x10 more / event

x10 more data!

To maintain the same performance:

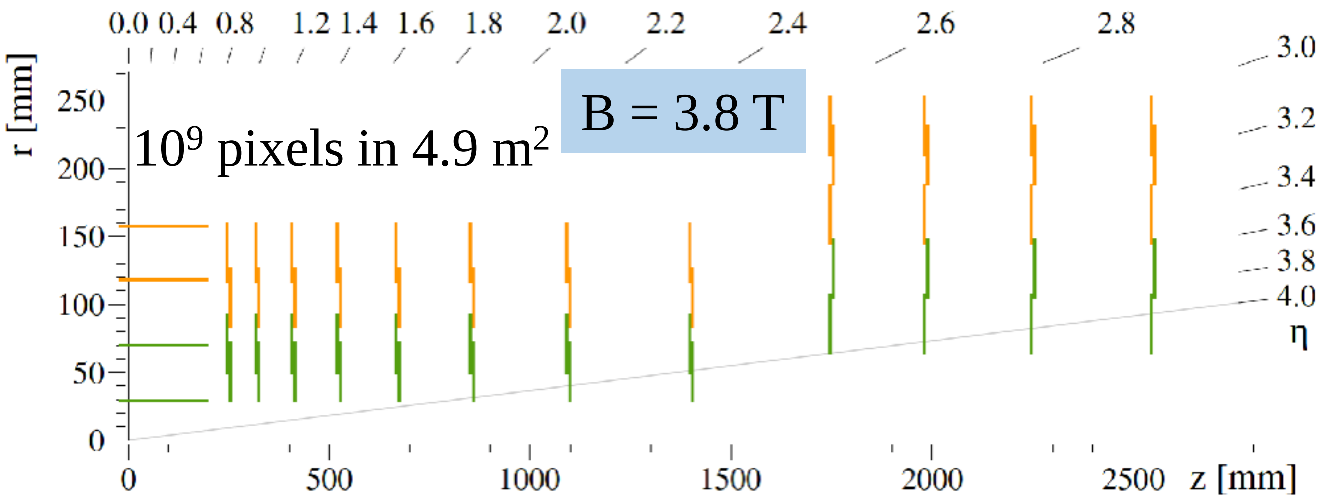
- maintain same occupancy ($< 10^{-4}$)

  pixel area factor 6 smaller

- radiation tolerance up to:

  dose = 10 MGy

  fluence = 2.3×10^{16} cm^{-2}



CMS inner tracker requirements

Beginning of lifetime:

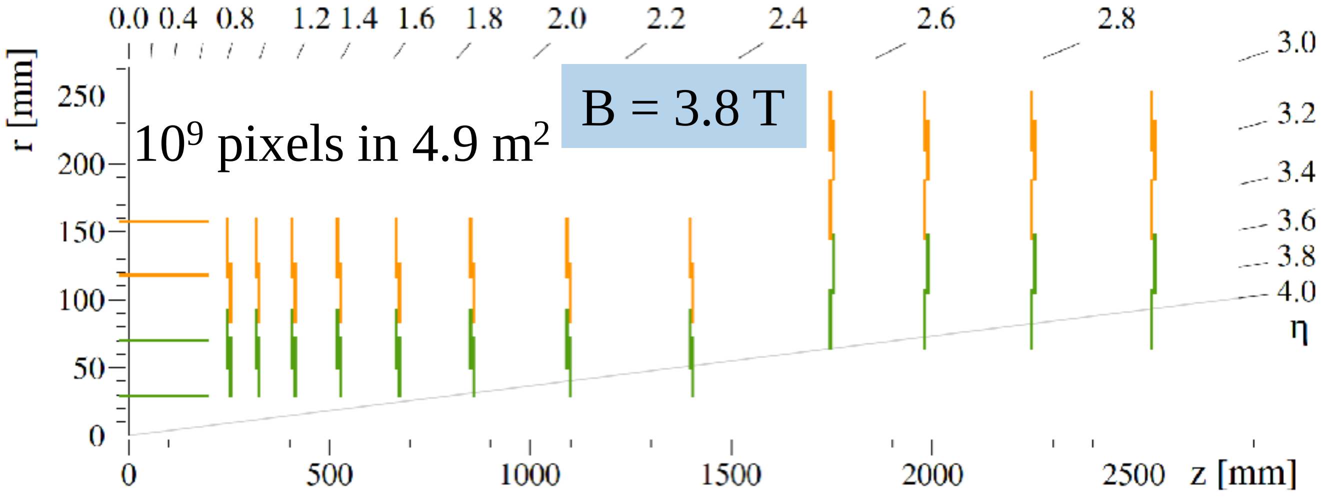
- Single hit reconstruction efficiency $\epsilon_{hit} > 99\ \%$
- Best single point resolution $\sigma_{hit} \ll \text{pitch} / \sqrt{12}$

End of lifetime:

- L1: $\epsilon_{hit} > 98\ \%$
  L2-L4: $\epsilon_{hit} > 99\ \%$ for $V_{bias} < 800$ V

- Leakage current < 10 nA/pixel
  (readout chip specs)

- No thermal runaway ($T_{CO2} = -33\ ^{o}C$)



CMS inner tracker sensor design

Beginning of lifetime:

- Single hit reconstruction efficiency $\epsilon_{hit} > 99$ %
- Best single point resolution $\sigma_{hit} \ll$ pitch / $\sqrt{12}$

End of lifetime:

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- Leakage current < 10 nA/pixel
  (readout chip specs)
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Detector choice:

- Hybrid silicon-chip
- Substrate: p-type
- Active thickness: 150 µm
- Pixel pitch: 50x50 μm^2 or 25x100 μm^2
- L1: 3D or planar
  L2-L4: planar
- Breakdown planar: > 300 V (non-irrad.)
- Breakdown planar: > 800 V (end of life)
- Breakdown 3D: > V_{depl} + 20 V

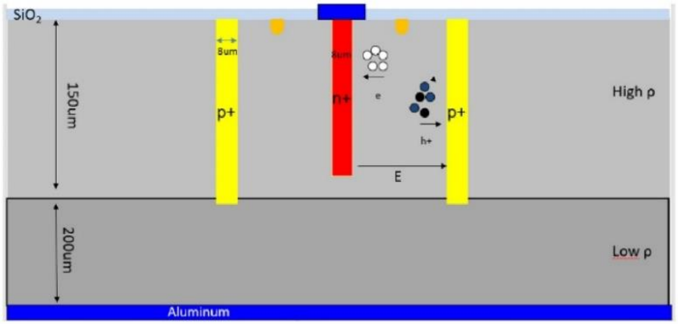
Outline of this talk

- Sensor design
  3D and planar sensors

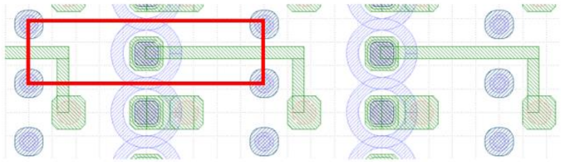
- Results of characterizations
  before & after protons irradiation

Sensor design

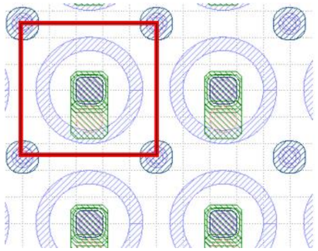
3D sensors from Fondazione Bruno Kessler (FBK) and CNM



- Substrate: p-type
- Active thickness: 150 μm

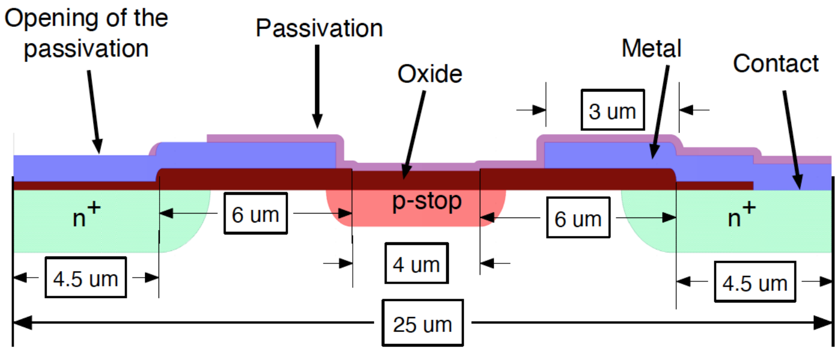


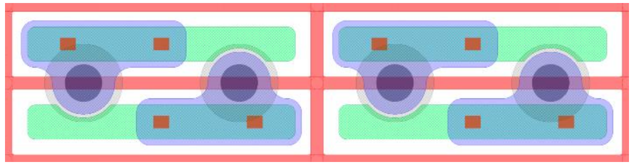
$25 \times 100\ \mu m^2$, CNM



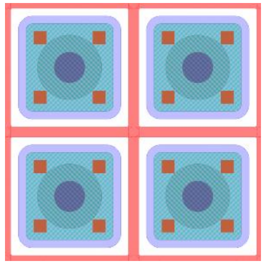
$50 \times 50\ \mu m^2$, CNM

Planar sensors from HPK and FBK





$25 \times 100\ \mu m^2$, HPK



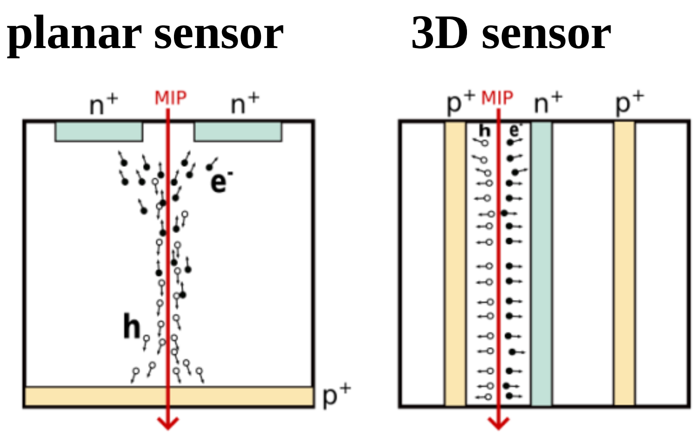
$50 \times 50\ \mu m^2$, HPK

Several variants of sensors design produced at various vendors

In the following only most promising designs for CMS upgrades presented (more info here)

Features of 3D sensors

- Charge carrier drift decoupled from electron-hole pair generation
  - Number of e-h pairs determined by sensor thickness, CMS: 150 µm
  - Electric field and drift distance determined by distances of columns
  - Reduced effect of charge carrier trapping →radiation hardness
  - Low operating voltages →less power, more thermal runaway margin

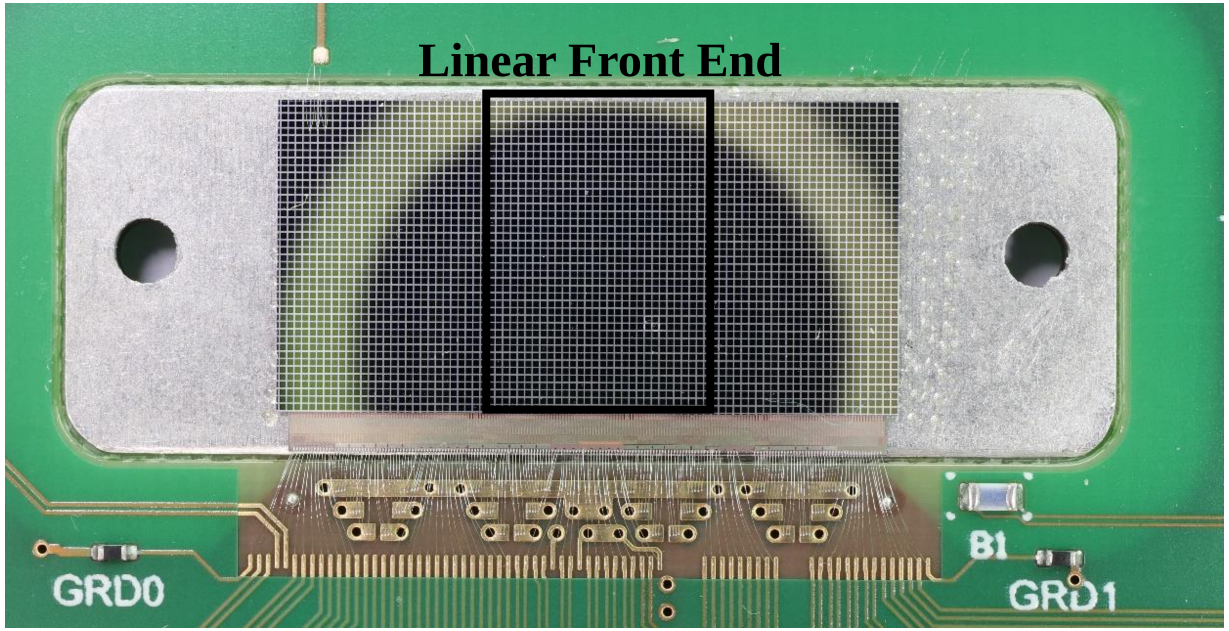


- Complicated production process
  - Production yield for large sensors is an issue
  - CMS maintains the option of having 2-chip modules with two 3D sensors

Pixel modules

All sensors are bonded to **RD53A Chips***

- Linear Front End (LFE)
- 4-bit digitisation of the charge (ToT unit)
- Adjustable online threshold
- 50x50 μm² pixels, 77k / chip
  (final CMS full size chip: 144k / chip)
- 65 nm CMOS technology (TSMC),
  radiation hard design, serial powering

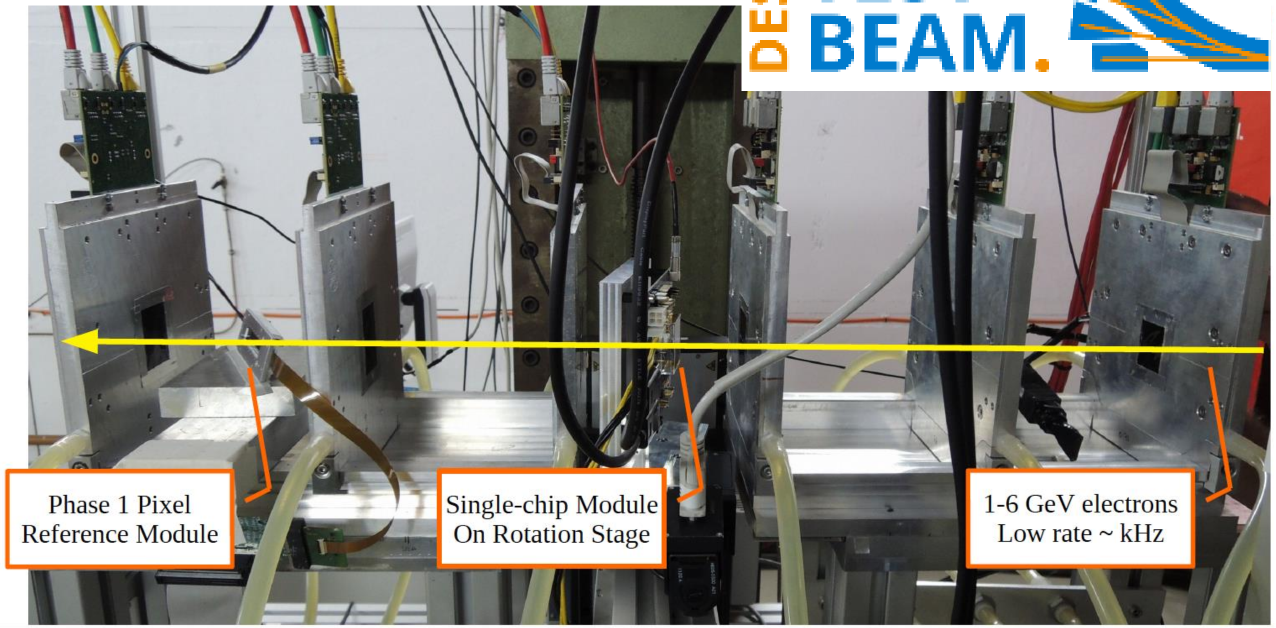


Single Chip Module

***Common development for ATLAS and CMS within RD53 collaboration**

Characterization procedure

- Lab measurements: I-V, C-V
- Test beam measurement:
    - Hit efficiency w.r.t telescope tracks
    - Single hit resolution, at various angles



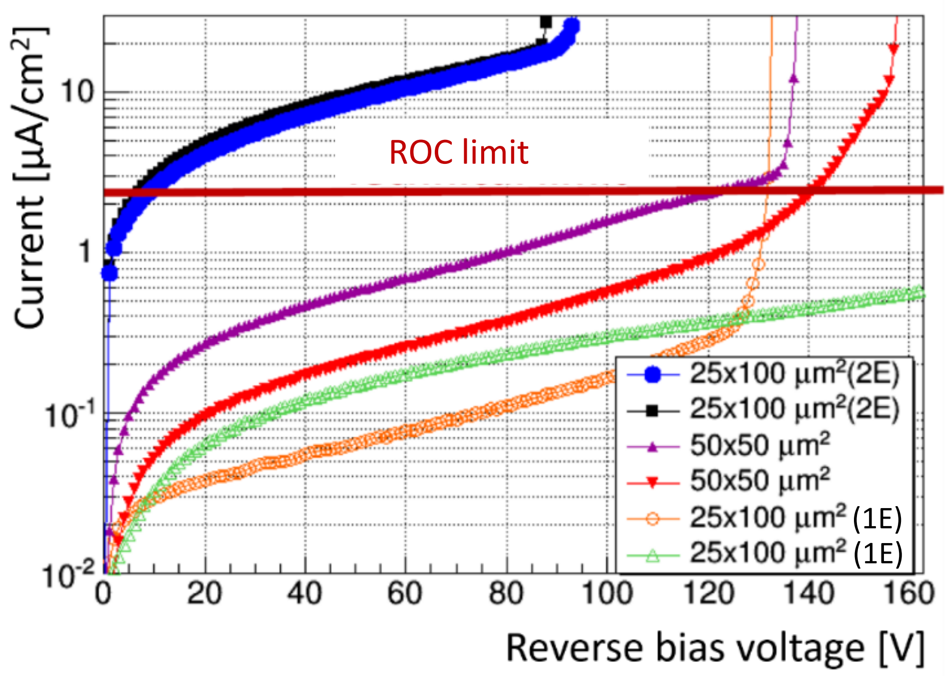
- Irradiated modules are tested inside a cooling box at $\mathbf{T_{chiller} \approx -35\ ^{o}C}$

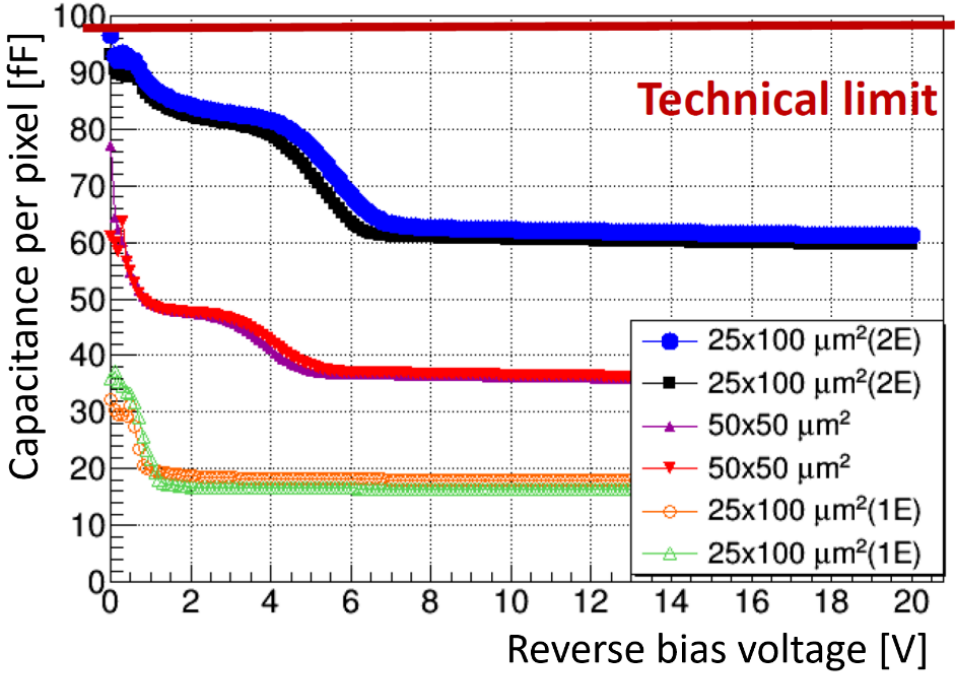
- Irradiations:
  24 GeV protons at Proton Irradiation Facility (PS-IRRAD)
  23 MeV protons at Karlsruhe Institute of Technology (KIT)

Many thanks to the DESY test beam support team

Results before irradiation: I-V

3D sensors from FBK and CNM

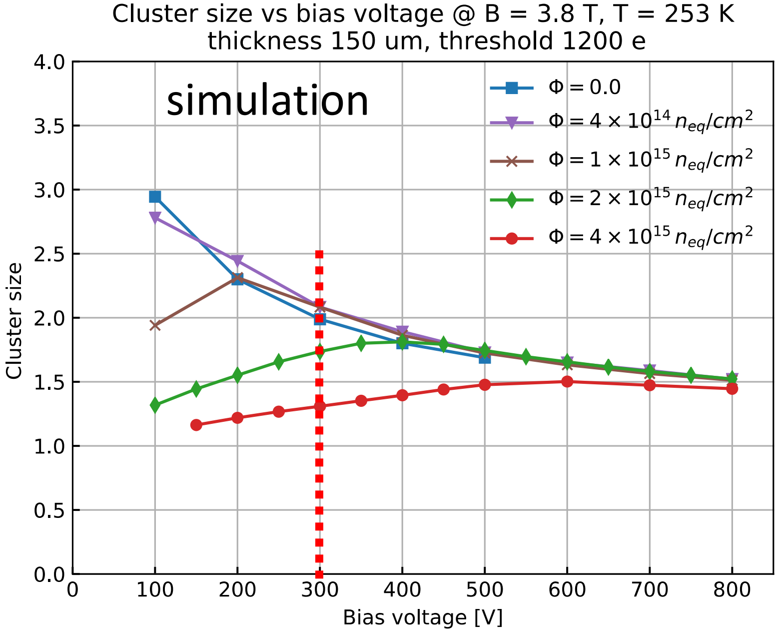


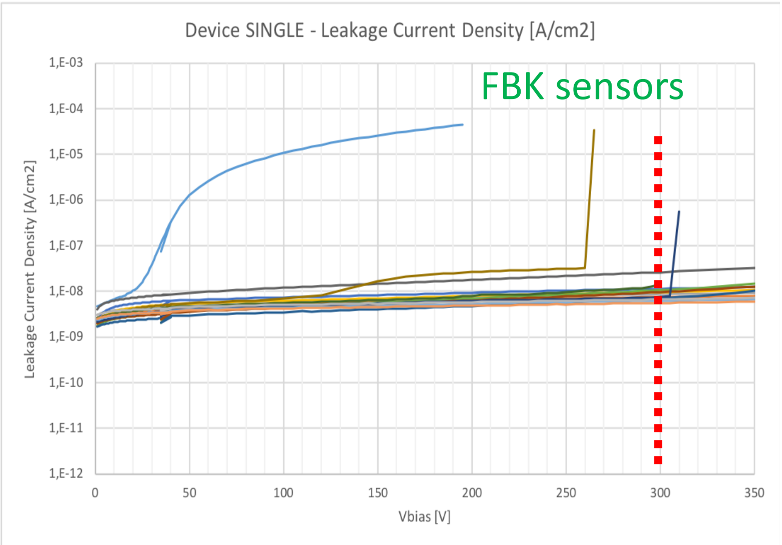


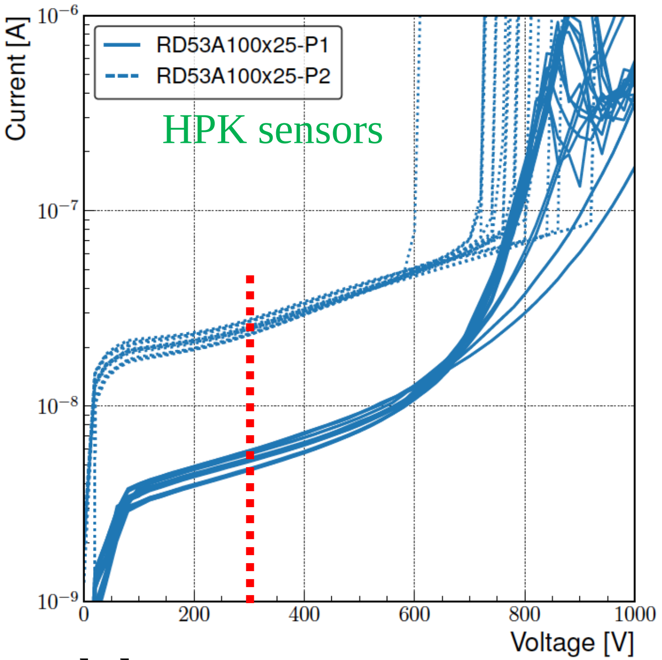
- Comparison of leakage current for three designs
- Full depletion is reached at 2-5 V for all designs (C-V)
- $25 \times 100\ \mu m^2$(2E, 2 Electrode) excluded: exceeds ROC technical limit

Results before irradiation: I-V

Planar sensors from HPK and FBK





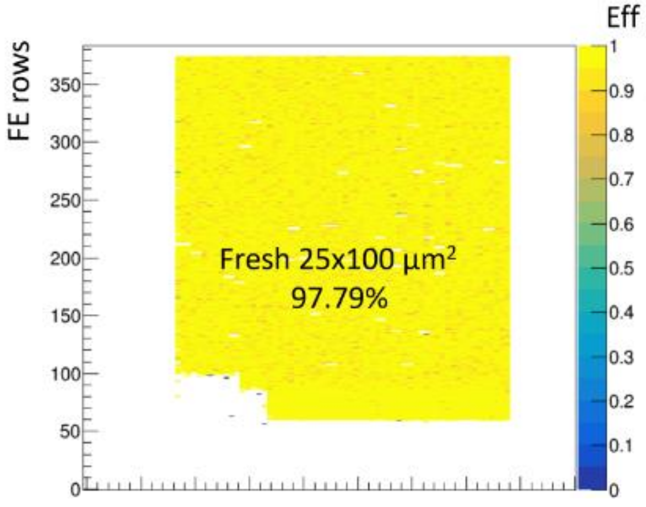


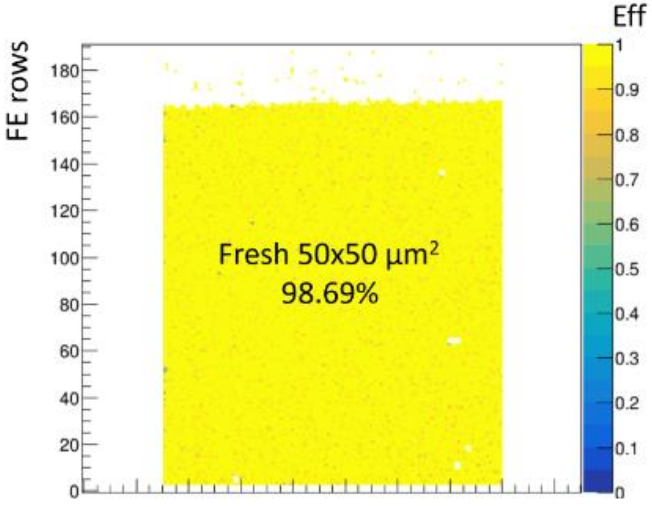
- **High voltage stability for Φ_{eq} = 0-1x10^{15} cm^{-2}:** At least 300 V required for optimal resolution
- All HPK sensors breakdown at > 300 V
- For FBK sensors only minor rejections

Results before irradiation: Efficiency

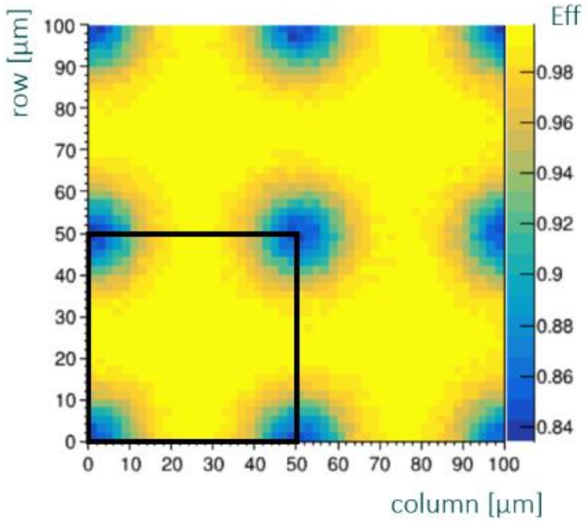
3D sensors from CNM

- Vertical beam incidence, room T
- Online threshold ≈ 1000 e⁻





In-pixel efficiency map



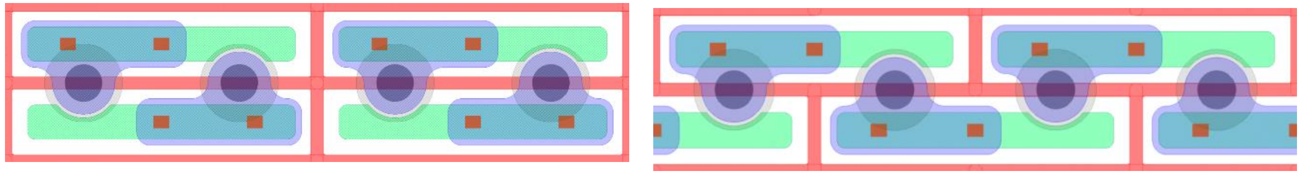
- Overall ϵ_{hit} < 99 % for vertical incidence
- Effect less prominent at non-zero angles
- All 3D results already published at [Alonso, A. Garcia, et al.]

… due to large inefficiency in the p+ implant columns for vertical incidence
➔ worst case scenario

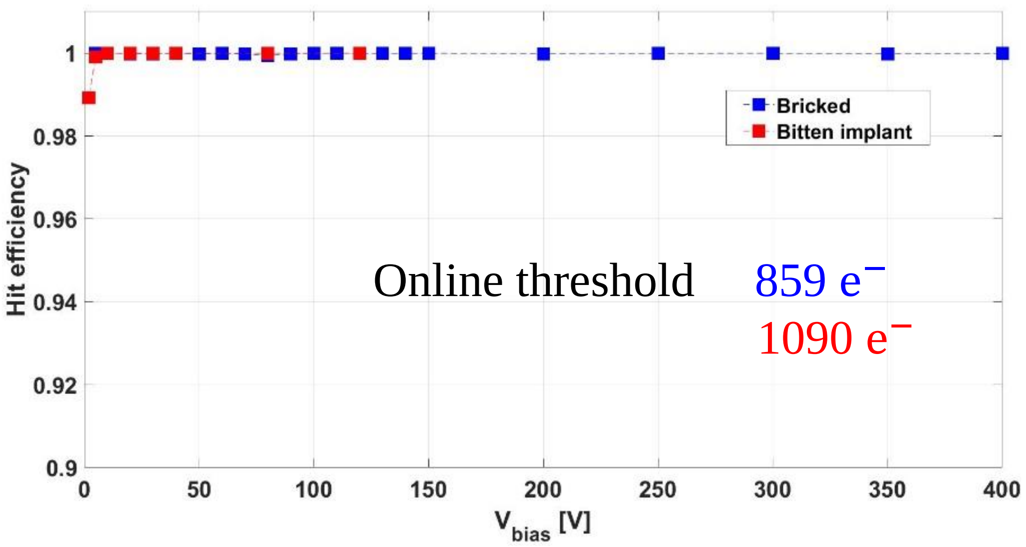
Results before irradiation: Efficiency

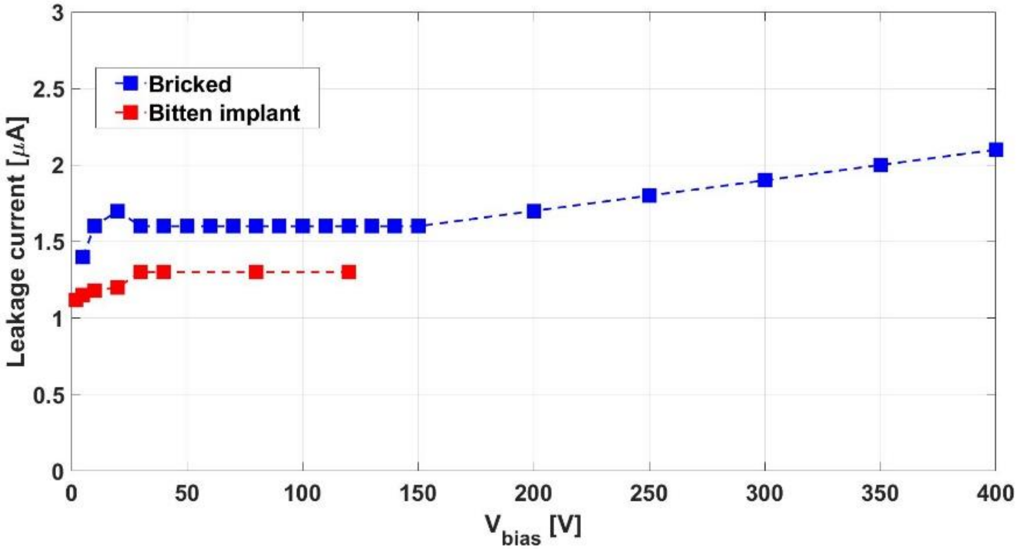
Planar sensors from HPK

- Vertical beam incidence, room T
- Online threshold ≈ 1000 e⁻



Bitten implant Bricked design



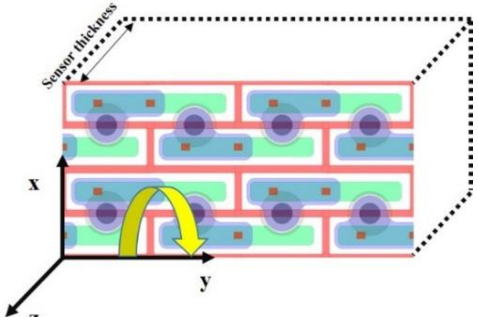


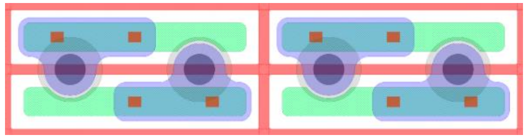
- $\epsilon_{hit} > 99$ % for $V_{bias} > 5$ V
- No sign of breakdown up to 400 V

Results before irradiation: Resolution

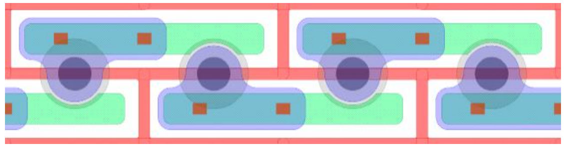
Planar sensors from HPK

- $V_{bias} = 120$ V, T ≈ 20 °C
- Online threshold ≈ 850 e^-

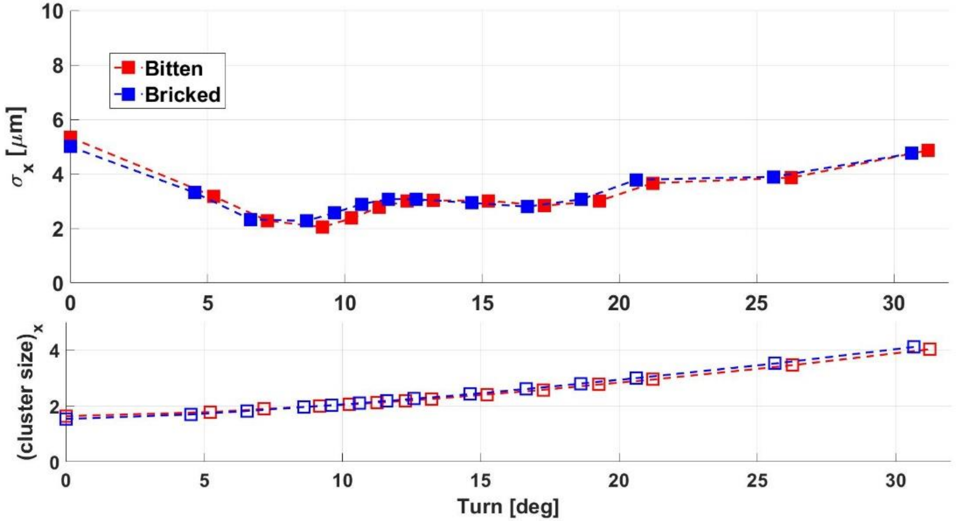


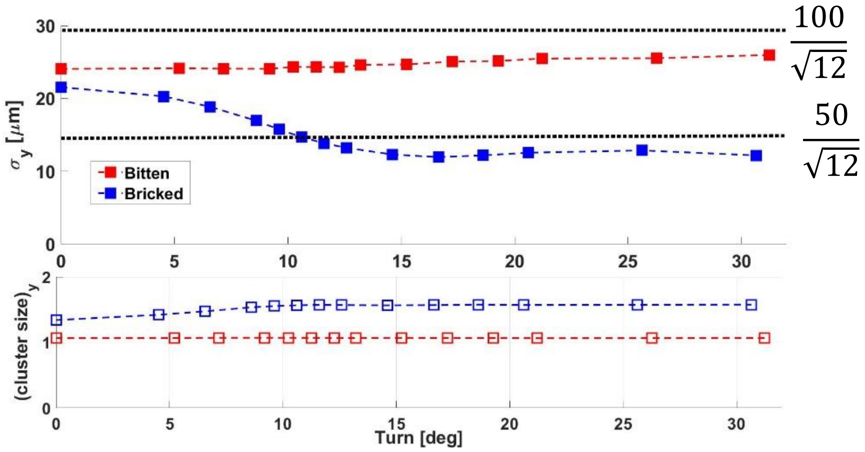


Bitten implant



Bricked design





- Both designs reach $\sigma_{hit} \approx$ 2 µm at (cluster size)$_x$ = 2
- Optimal angle consistent with: $\tan\theta = \frac{pitch}{d} = 9.6^{o}$

- Bricked design: resolution improves with turn angle
- Effective pitch of the bricked design is 50 µm.

Conclusion before irradiation

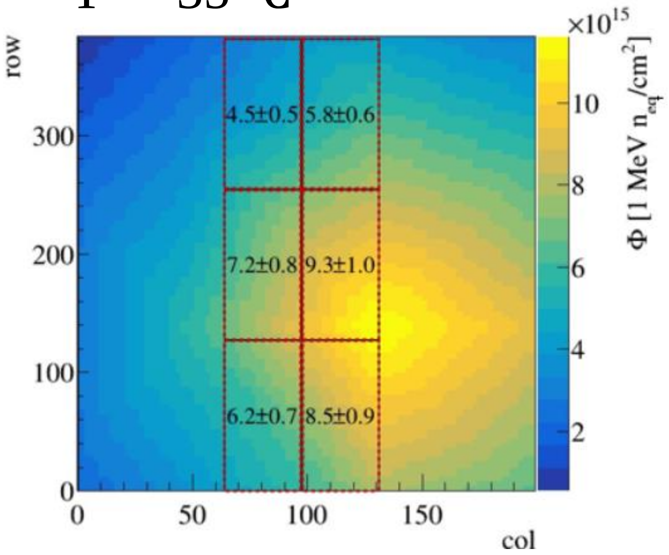
- Various 3D and planar sensors designs have been produced and tested
- The selected designs fulfill the requirements before irradiation

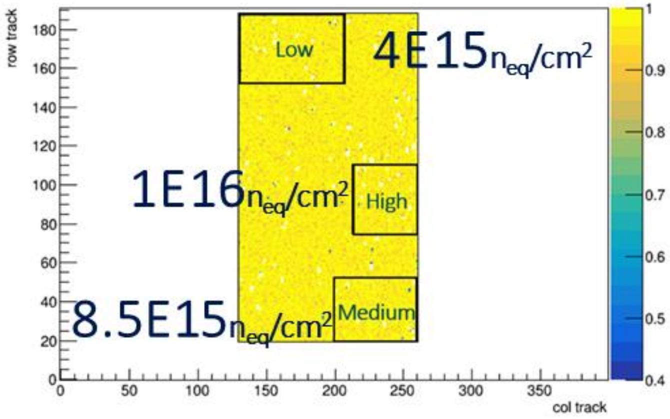
- For planar $\sigma_{hit} \approx 2\ \mu m$ is reached at optimal angle with 25 µm pixels
- The bricked design has ~2x better resolution in the 100 µm pixel direction

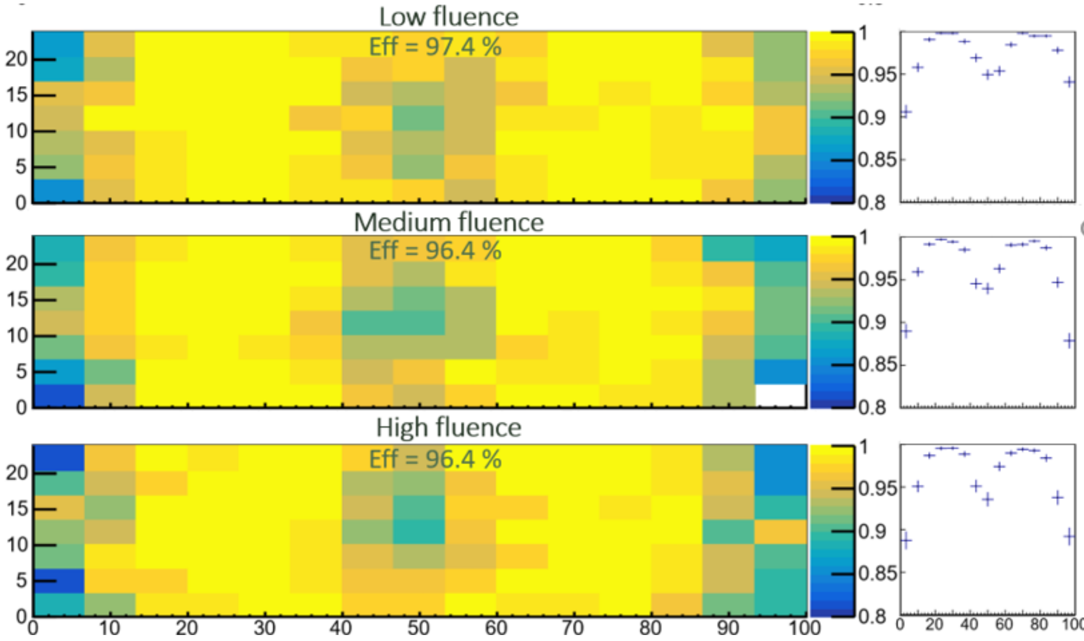
Results after irradiation: Efficiency

3D sensors from CNM

- Non-homogeneous sensor irradiation due to beam profile
- T = -35 °C







- Overall $\epsilon_{hit} \approx$ 96-97 % for vertical incidence
- Angular scan could not yet be performed

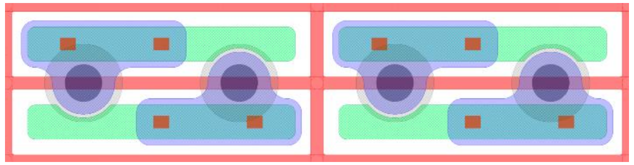
… due to large inefficiency in the p+ implant columns for vertical incidence
➔ worse case scenario

- All 3D results already published at Alonso, A. Garcia, et al.

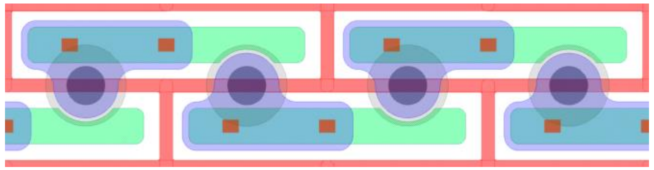
Results after irradiation: Efficiency

Planar sensors from HPK

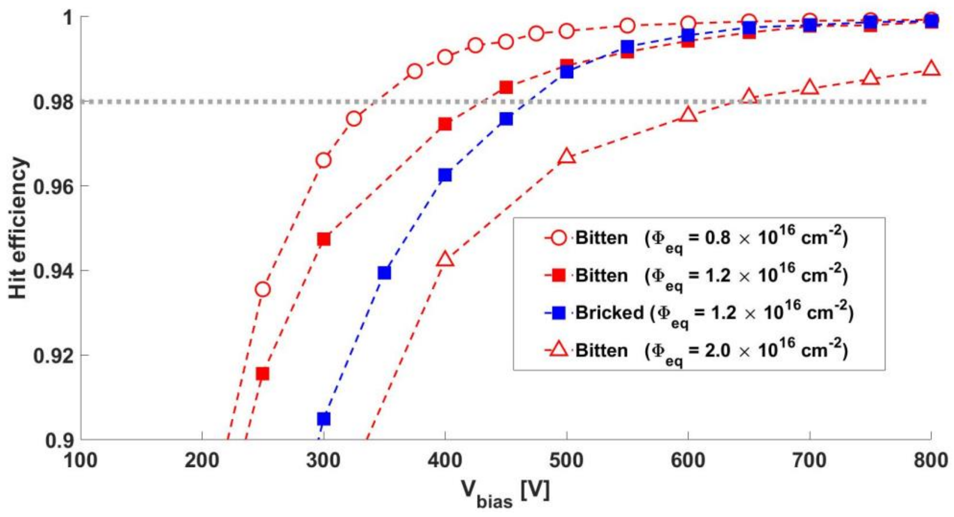
- Vertical beam incidence, T = -27 °C / -35 °C
- Online threshold ≈ 1100 − 1200 e^-

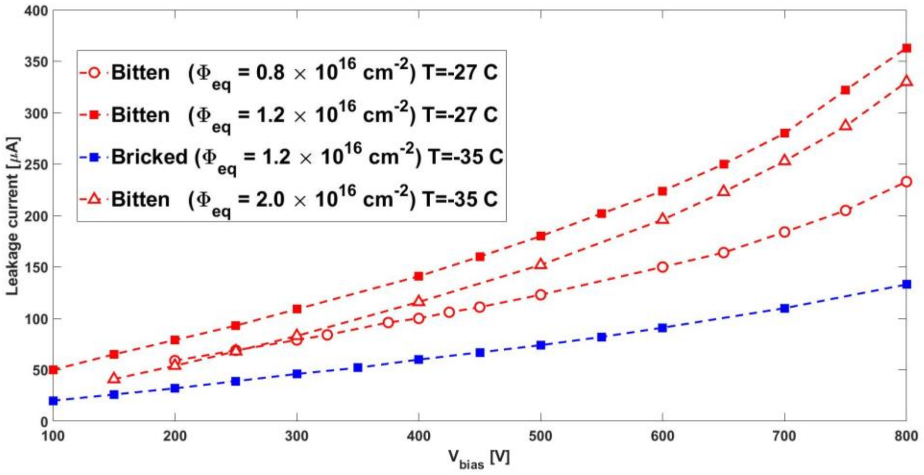


Bitten implant



Bricked design



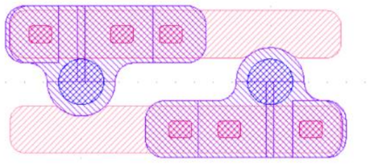


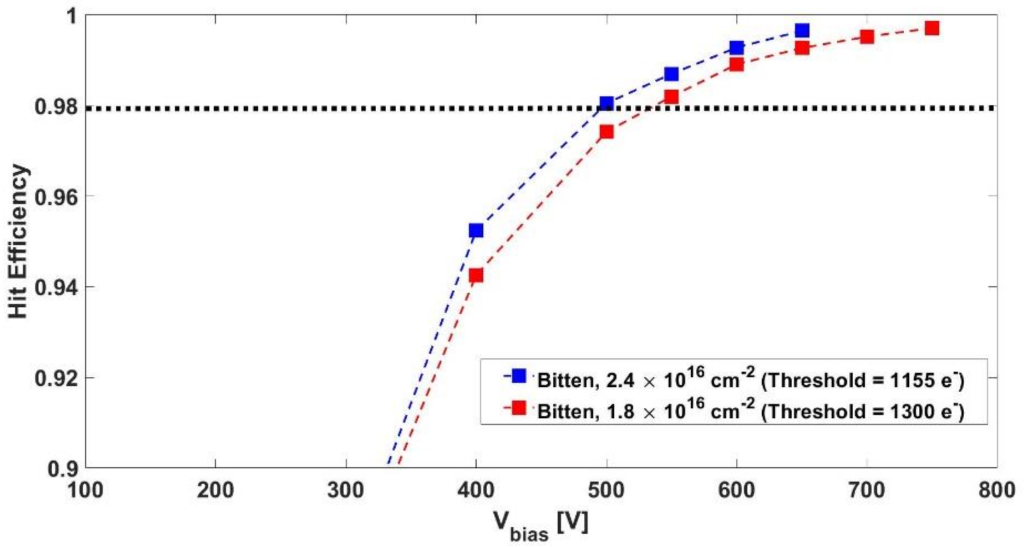
- All modules reach $\epsilon_{hit} > 98\%$ for $V_{bias} < 800$ V
- The leakage current ≪ 10 nA/pixel (total 750 μA)

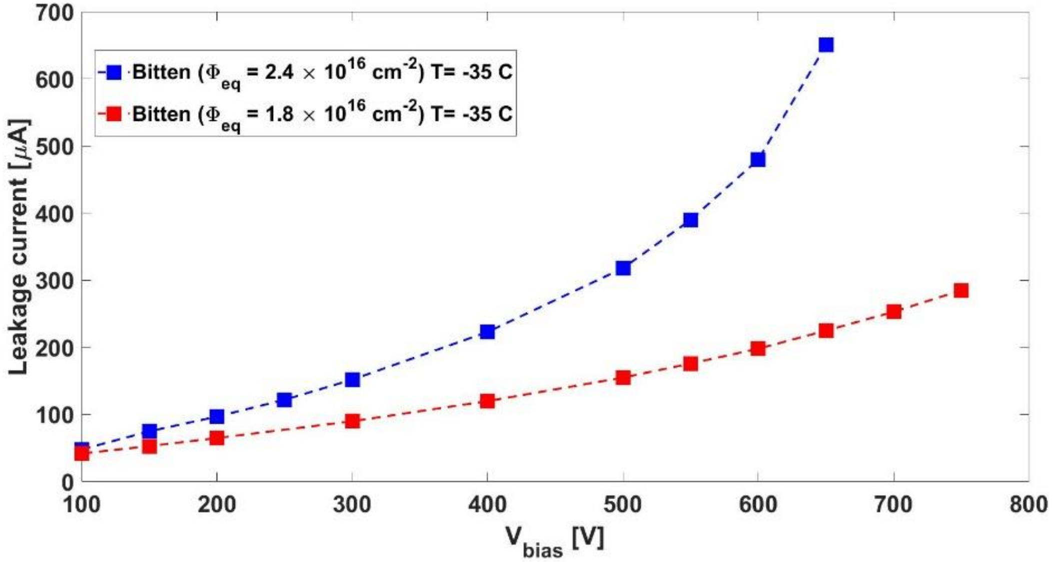
Results after irradiation: Efficiency

- Vertical beam incidence, T = -35 ℃
- Online threshold ≈ 1155 e^-, 1300 e^-

Planar sensors from FBK





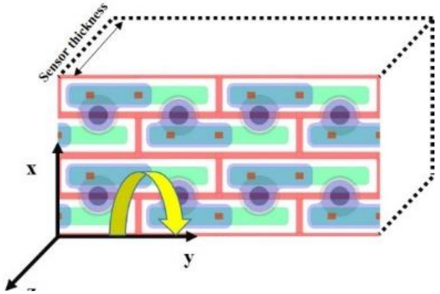


- Also at highest fluence $\epsilon_{hit} > 98\%$ for $V_{bias} < 800$ V
- NB: Higher fluence data have higher ϵ_{hit} due to lower threshold

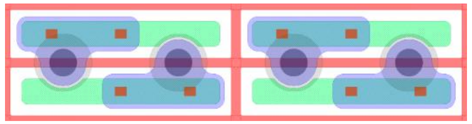
The leakage current < 10 nA/pixel (total 750 μA)

Results after irradiation: Resolution

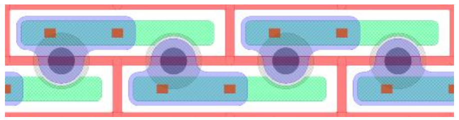
- V_{bias} = 800 V, T ≈ -35 °C
- Online threshold ≈ 1200 e^{-}



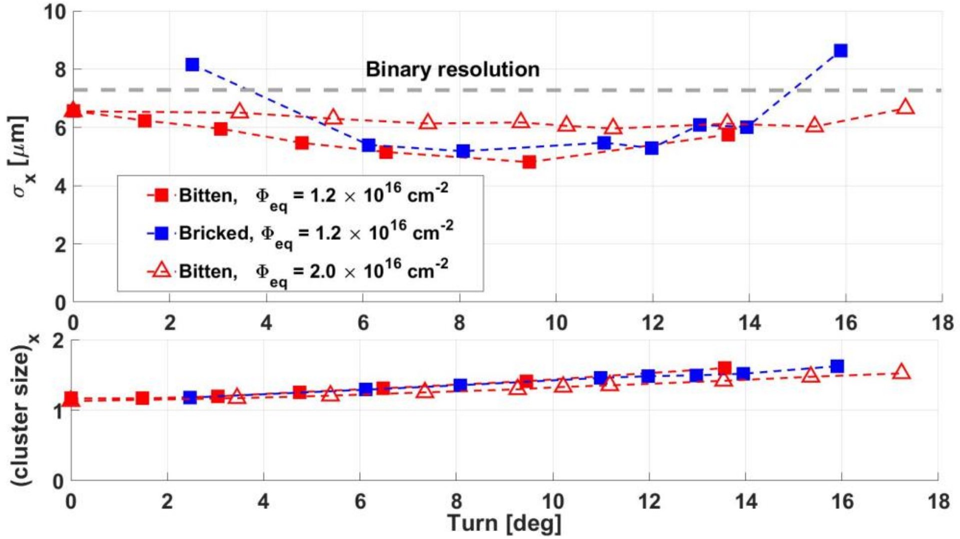
Planar sensors from HPK

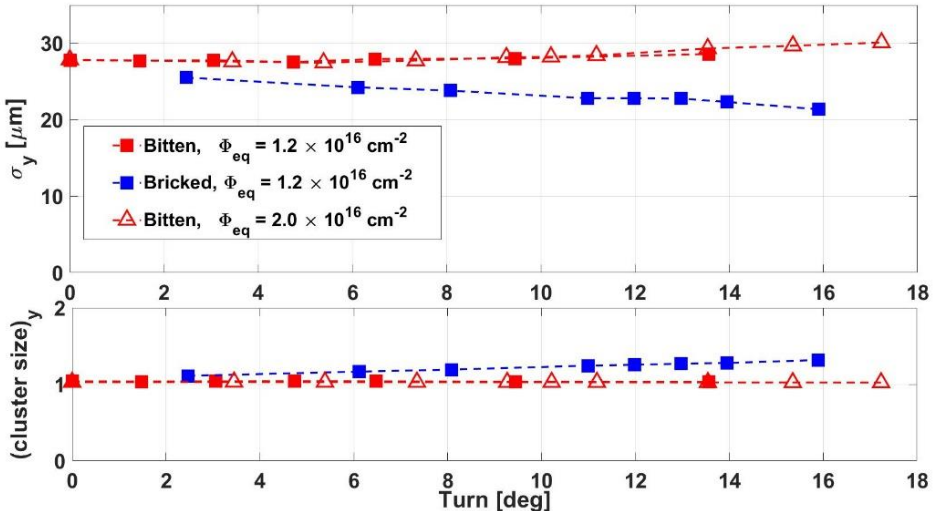


Bitten implant



Bricked design





- (Cluster size)$_x$ always < 2, resolution better than binary resolution
- Optimal angle consistent with: $\tan\theta = \frac{pitch}{d} = 9.6^{o}$

- Bricked design: resolution improves with turn angle
- Worse performance than before irradiation

Conclusion after irradiation

- Further investigations of 3D are ongoing to reach the highest fluence

- Planar sensors remain > 99% efficient after $\Phi_{eq} = 2.4 \times 10^{16}$ cm^{-2}
- The resolution is still below the binary level (pitch / $\sqrt{12}$)
- The bricked design maintains better resolution in the 100 µm pixel direction

Planar sensor designs are qualified for operation in the CMS Pixel Phase II upgrade

BACKUP

12th International Conference on POSITION SENSITIVE DETECTORS

Hosted by UNIVERSITY OF BIRMINGHAM

Bias scan results
Irradiated modules, HPK

CMS

Measurement conditions:

- Temperature: -35 °C
- Online threshold 1308 e^-, 1253 e^-
- $V_{\mathrm{bias}} = 100\ \mathrm{V} - 800\ \mathrm{V}$
- Angle of incident: 0°

Observations:

- Tuning the same module at a lower threshold, increases the h
- The difference is more significant at lower bias voltages
- $V_{98\%}$ is shifted by ≈50 V by decreasing the threshold

Conclusion:

- At high fluences, the hit efficiency of the module is highly sensitive to the threshold of the readout chip