Grazing angle on 3D

with CNM-3D sensors bump-bonded to RD53A

The 38th RD50 Workshop
(online Workshop)

RD50

Jordi Duarte-Campderrós
on behalf of the CMS Collaboration
2021/06/23

EXCELENCIA MARÍA DE MAEZTU

IFCA Instituto de Física de Cantabria

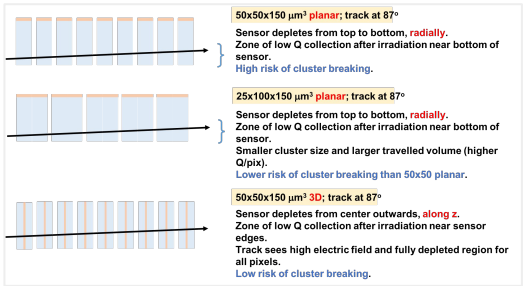
CSIC Consejo Superior de Investigaciones Científicas

UC Universidad de Cantabria

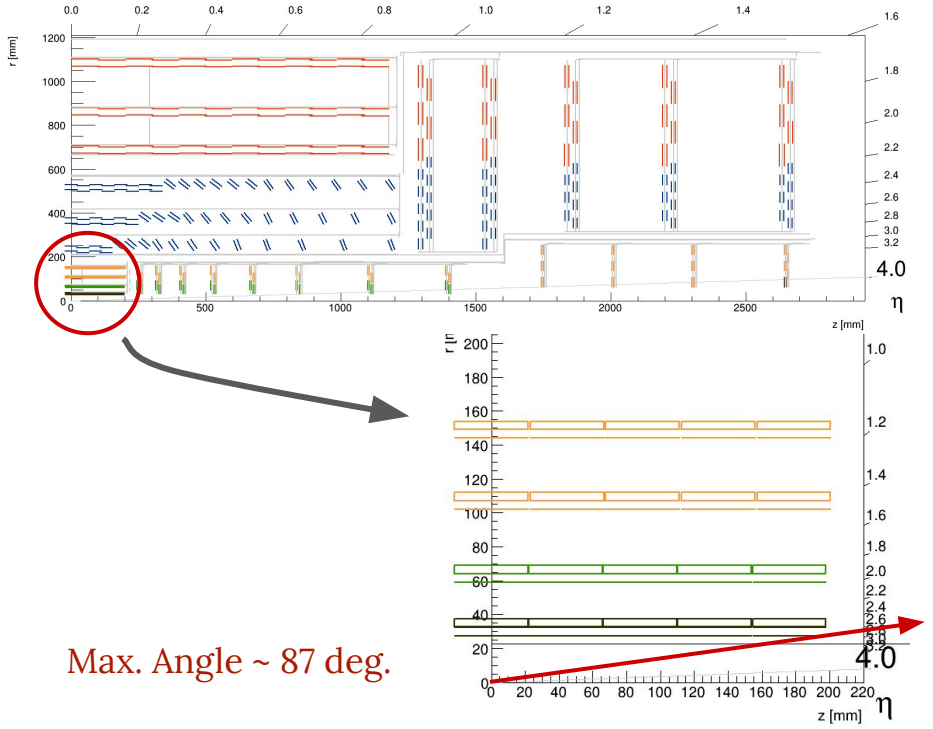
CMS Compact Muon Solenoid

Overview

- CMS Phase-2 Tracker
  https://cds.cern.ch/record/2116337/files/CERN-2015-005.pdf
- Study of cluster breaking for large incident tracks in 3D pixel
  - Layer-1 Barrel edge modules
- A priori: no cluster breaking expected in 3D sensors



https://cms-tklayout.web.cern.ch/cms-tklayout/layouts-work/repository-git-dev/OT800_IT702/layoutpixel.html

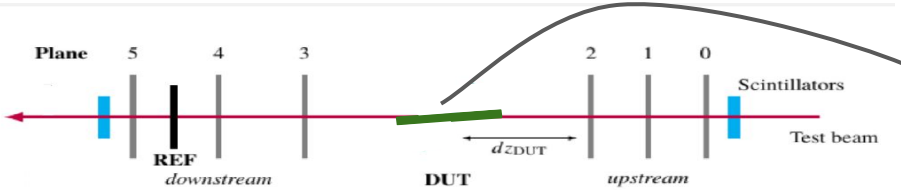


Max. Angle ~ 87 deg.

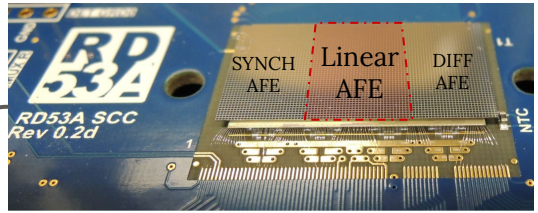
Test beam & Experimental Setup

- Test beam performed at DESY during Oct-Nov. 2019
  - Tested several 3D CNM sensors at shallow angle **with/without** bias

trying to “mimic” irradiation



AIDA-EUDET Telescopes
https://doi.org/10.1016/j.phpro.2012.02.434



RD53A: a demonstrator readout chip for HL-LHC upgrade of ATLAS and CMS
https://cds.cern.ch/record/2287593/files/%20RD53A_Manual_V3-42.pdf

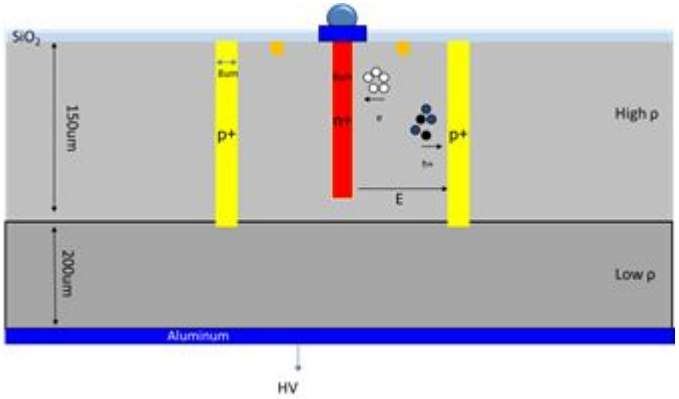
managed by

bdaq53
https://doi.org/10.1016/j.nima.2020.164721

Samples

- 3D sensors fabricated at CNM
  - Si-Si
  - 1E, no bias structure
  - 150 um thickness active, 350 um physical
  - 25x100 um2: **W331**, **W731**
  - 50x50 um2 : **W711**, **W719**

CENTRO NACIONAL DE MICROELECTRONICA IMB



Thresholds Tunning

W331: 349 DAC→ **1708** e^-
W731: 344 DAC→ **1448** e^-
W711: 360 DAC→ **2280** e^-
W719: 331 DAC → **772** e^-

25x100 µm² 1E

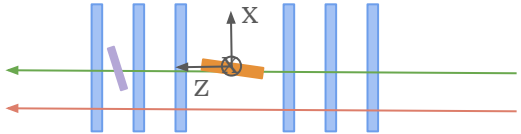
50x50 µm²

$$y(e^-) \sim 52.0\ [e^-/\mathrm{DAC}] - 16440\ [e^-]$$

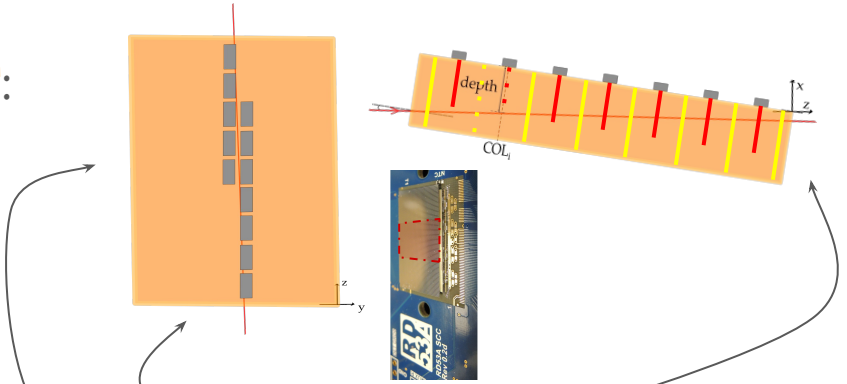
https://twiki.cern.ch/twiki/pub/RD53/RD53ATesting/LIN_AFE_guidelines.pdf

Grazing angle analysis

- In-time tracks:
  - Telescope reconstructed tracks, matching a hit in the REF plane



- In-time tracks defines a ROAD at the DUT:
  - Each **ROAD** associates activated pixels "close enough" to the road → cluster
    - 'Empty pixels' allowed

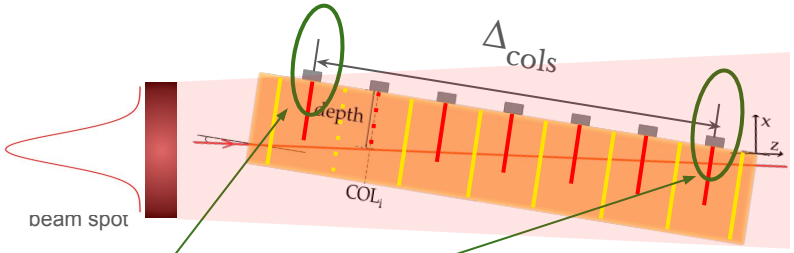


- Sensor acceptance:
  - 150 um thickness
  - height: 9.6 mm
  - RD53A AFE LIN region: 6.8 mm

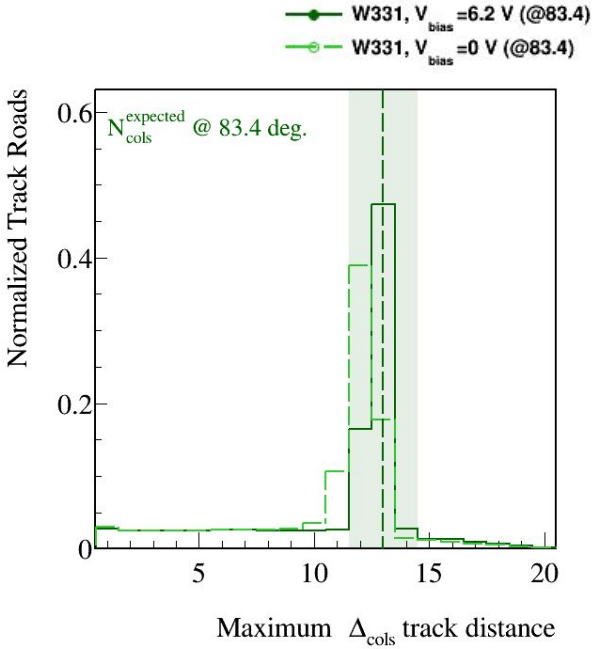
Highly "inspired" in D. Pitzl's (DESY) analysis code:
https://stash.desy.de/projects/RDA/repos/tele-scope/

Road track distance in the DUT: Δ_{cols}

- Maximum distance between columns associated to a track road



  - **First** and **Last** column activated defines the track distance in the DUT: Δ_{cols}
    - Beam size and angular profiles
      → Δ_{cols} distribution



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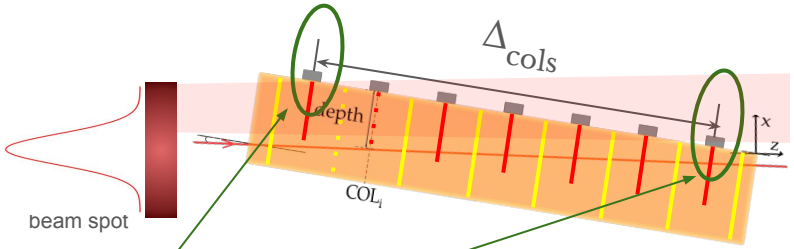

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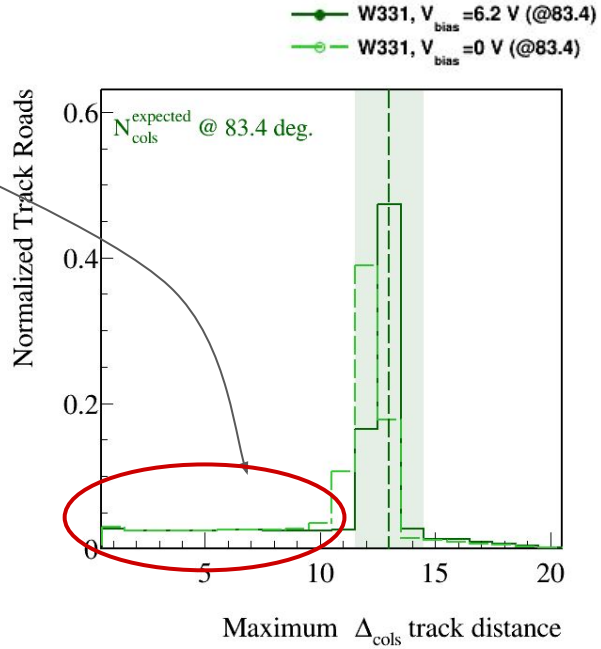

Road track distance in the DUT: Δ_{cols}

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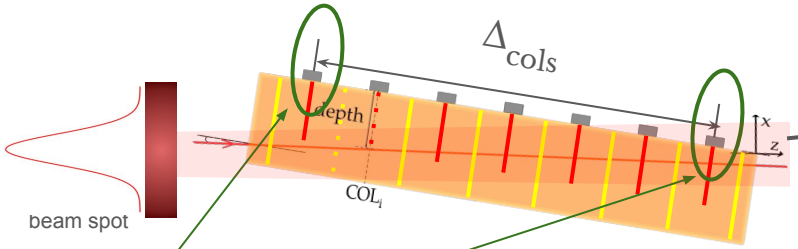
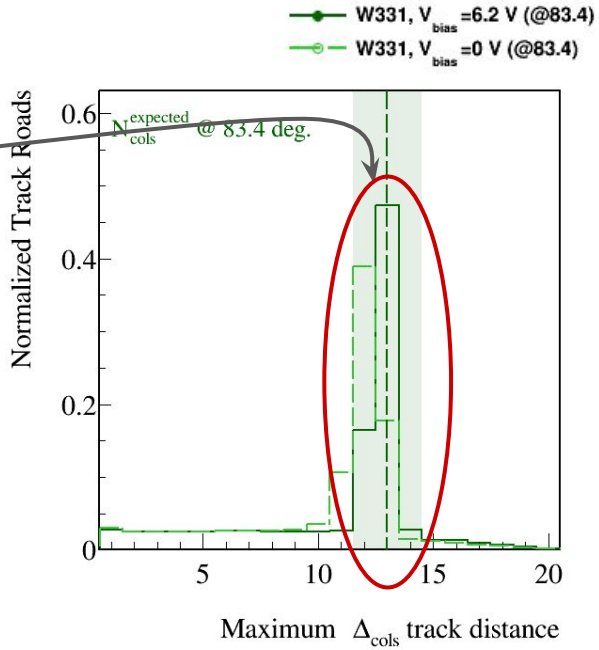
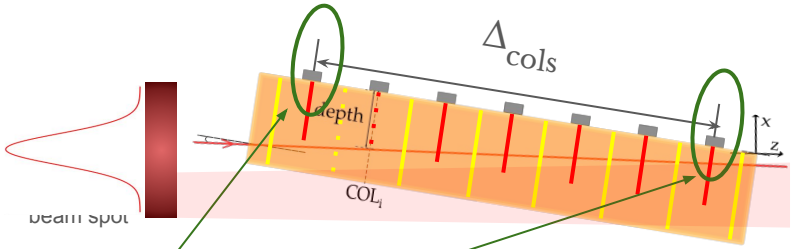




  - **First** and **Last** column activated defines the track distance in the DUT: Δ_{cols}
    - Beam size and angular profiles
      → Δ_{cols} distribution

Road track distance in the DUT: Δ_{cols}

- Maximum distance between columns associated to a track road



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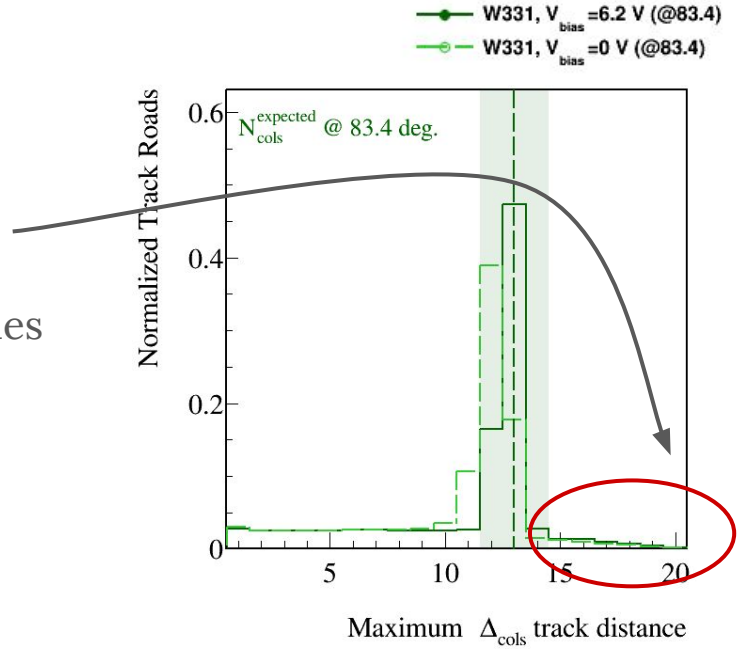
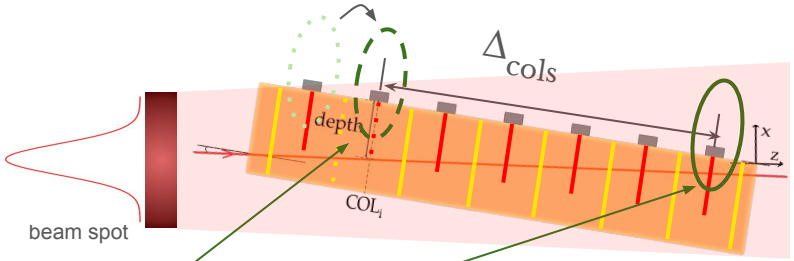
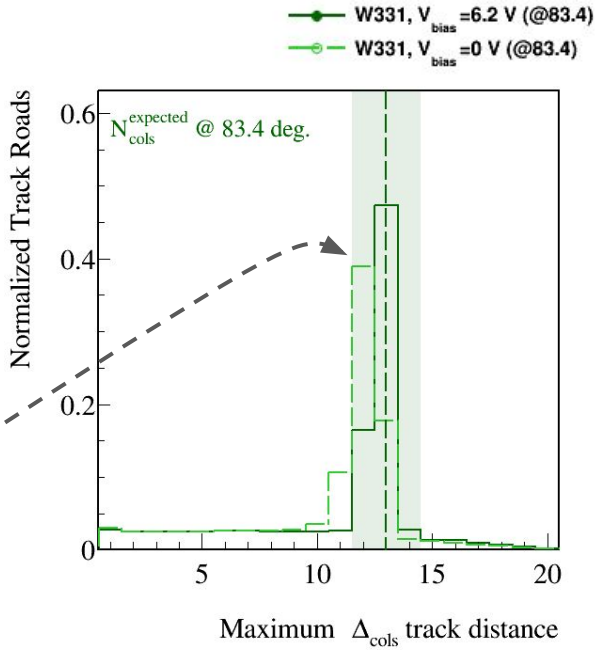


Road track distance in the DUT: Δ_{cols}

- Maximum distance between columns associated to a track road



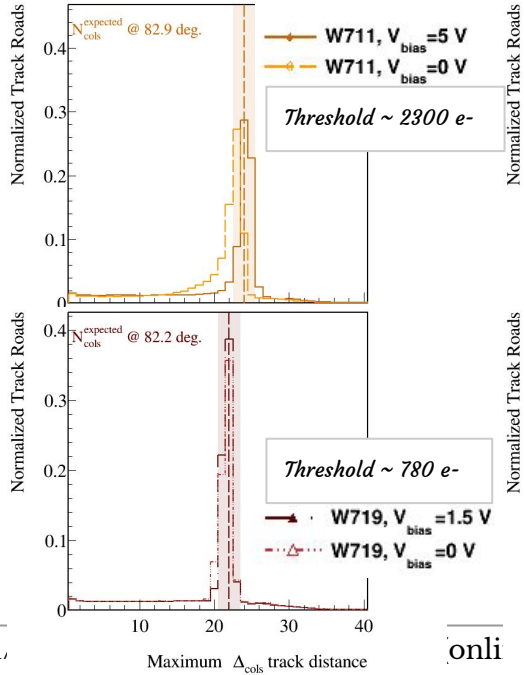
  - **First** and **Last** column activated defines the track distance in the DUT: Δ_{cols}
    - Not fully depleted sensors:
      → lower distance than expected given the mean incident angle



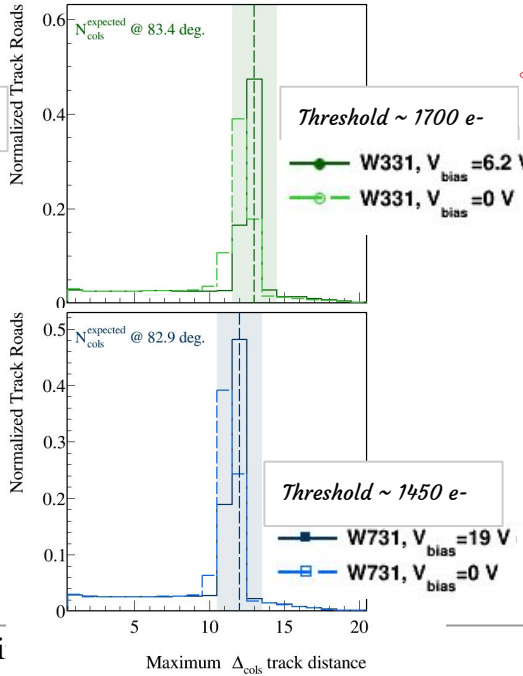
Δ_{cols} measurement

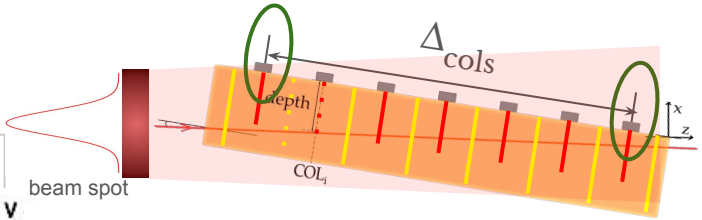
- Maximum distance between columns associated to a track road

50x50



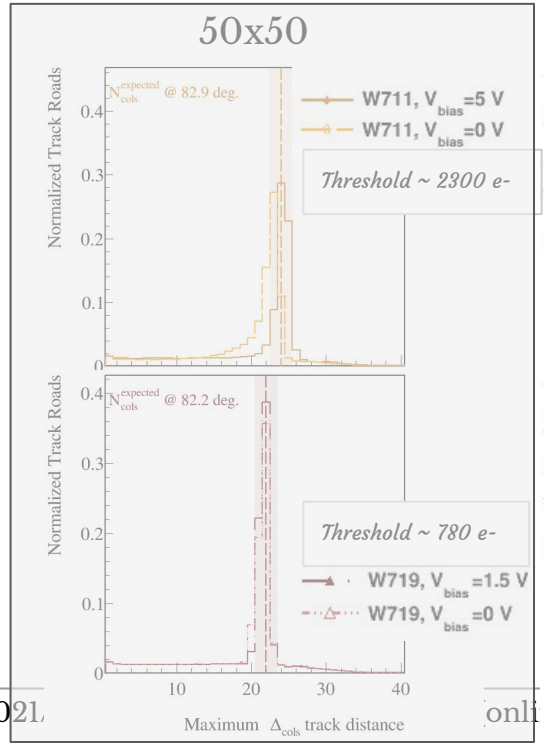
25x100

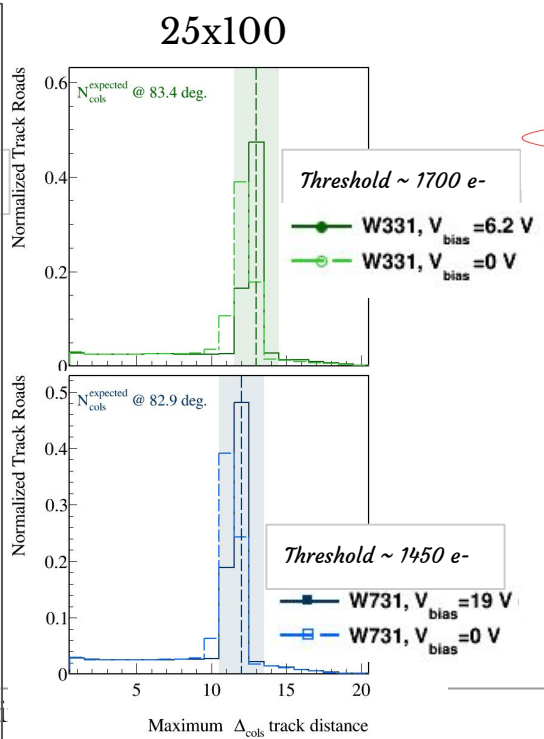


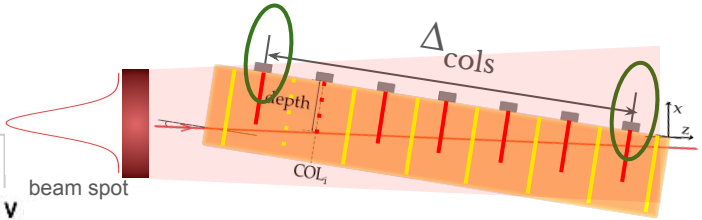


Δ_{cols} measurement

- Maximum distance between columns associated to a track road



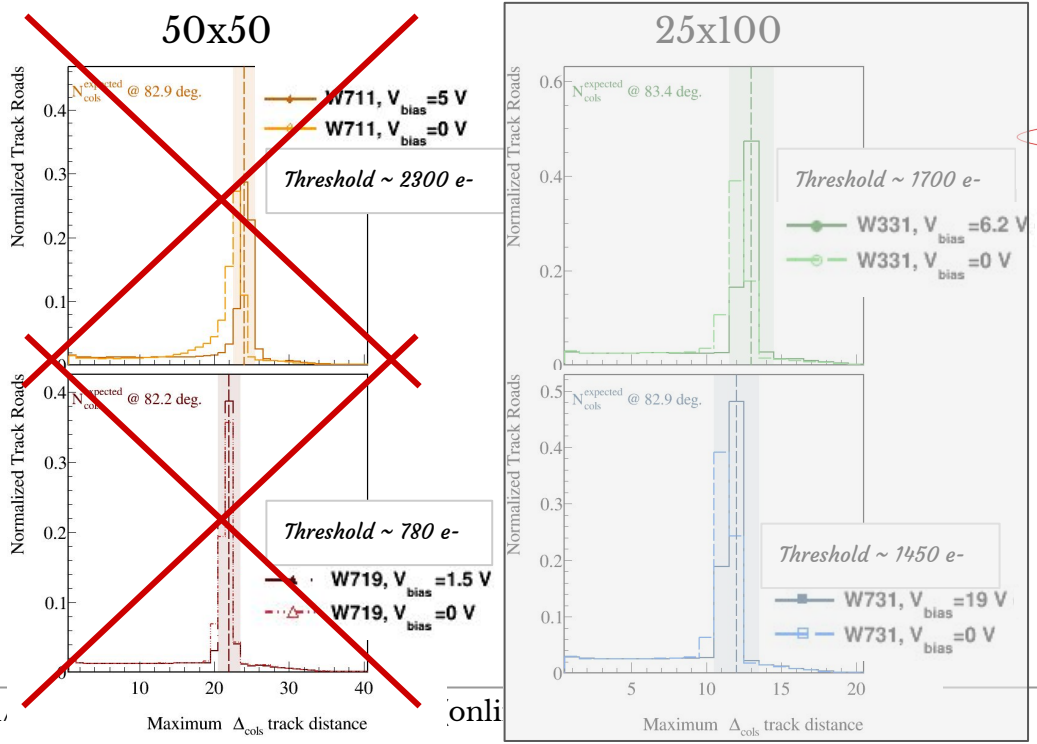


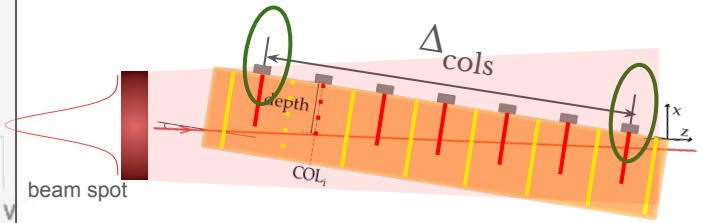


- 25x100:
  - As expected, smaller $<\Delta_{cols}>$ for unbiased sensors
    → **hit lost** in the edges of the track

Δ_{cols} measurement

- Maximum distance between columns associated to a track road



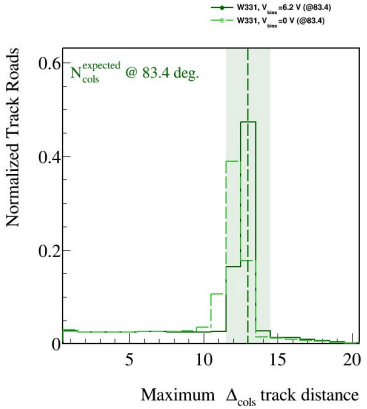


- 50x50:
  - W711: Unbiased-biased runs were taken different incident angles
  - W719: No difference between unbiased-biased Δ_{cols} → Probably not biased

Track incident angle

- Measured $\Delta_{\text{cols}} \pm 1$ for fully depleted sensor
  → Average incident angle:

$$\alpha = arctan\left(\frac{\text{thickness}}{\langle\Delta_{\text{cols}}\rangle \cdot \text{pitch}}\right)$$



- Sensor alignment with telescope tracks
  → Minimize residuals, and residuals dependences between activated pixels and telescope in-time tracks

Track incident angle estimation

Δ_{cols} method

- 25x100:
  - **W331:** 13 ± 1 → **83.5 ± 0.5** deg.
  - **W731:** 12 ± 1 → **82.9 ± 0.5** deg.

Angle error: Δ_{cols} ± 1 propagation

Alignment method

- 25x100:
  - **W331:** **83.2 ± 0.5** deg.
  - **W731:** **82.6 ± 0.5** deg.

Angle error: 1-sigma variation on residuals

Track maximum distance estimation

Δ_{cols} method

- 25x100:
  - **W331:** **13 ± 1** → 83.5 ± 0.5 deg.
  - **W731:** **12 ± 1** → 82.9 ± 0.5 deg.

Angle error: Δ_{cols} ± 1 propagation

Alignment method

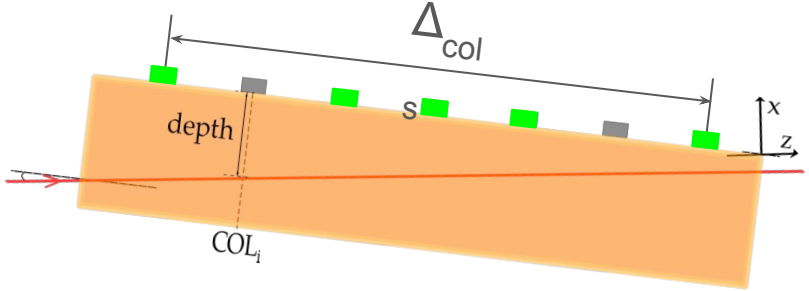
- 25x100:
  - **W331:** 83.2 ± 0.5 deg. → **13 ± 1**
  - **W731:** 82.6 ± 0.5 deg. → **12 ± 1**

Angle error: 1-sigma variation on residuals

$$\Delta_{\text{cols}} = \frac{\text{thickness}}{\tan(\alpha) \cdot \text{pitch}}$$

Cluster breaking estimator

- Maximum number of hits (columns) in a road: $\langle \Delta_{\text{cols}} \rangle$
- Measured hits (columns) associated to a road: N_{obs}



- $\frac{N_{\text{obs}}}{\Delta_{\text{cols}}}$ will account for lost hits in between the edges
  → **cluster breaking**
- Lost hits in the edges: can be estimated by comparing $\langle \Delta_{\text{cols}} \rangle$ obtained with alignment method

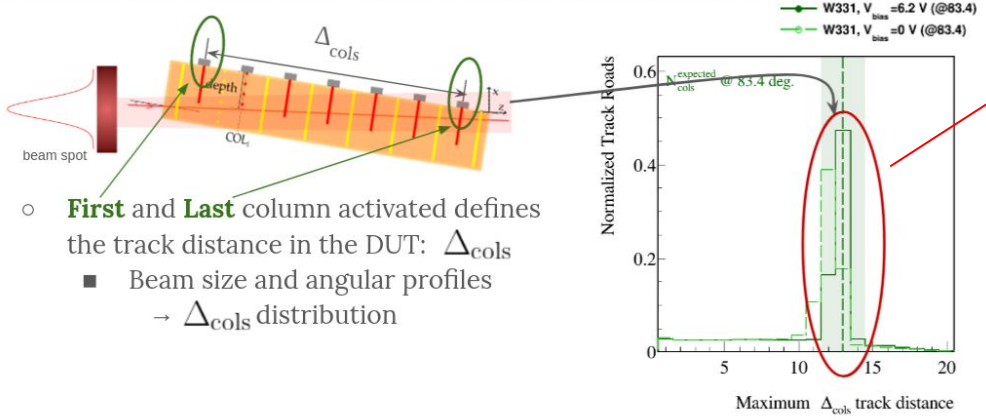
Breaking cluster frequency:

$$\left\langle \frac{N_{\text{cols}}}{\Delta_{\text{cols}}} \right\rangle = \sum_i \left\langle \frac{N_{\text{cols}}}{\Delta_{\text{cols}}} \right\rangle_i \cdot w_i$$

Cluster breaking estimator

Road track distance in the DUT: Δ_{cols}

- Maximum distance between columns associated to a track road

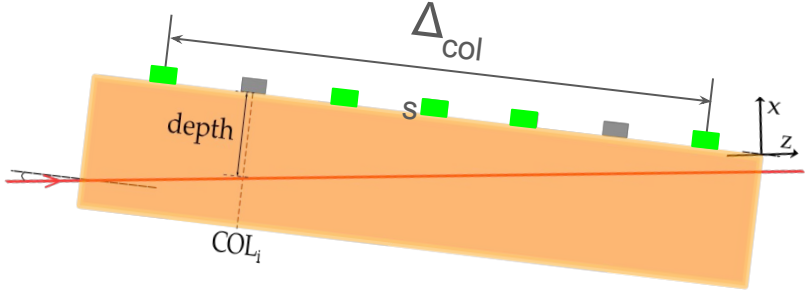


  - **First** and **Last** column activated defines the track distance in the DUT: Δ_{cols}
    - Beam size and angular profiles → Δ_{cols} distribution

- Select tracks roads with expected distance given the estimated incident angle α : Δ^{α}_{cols}
  - select beam spot core tracks

Cluster breaking estimator

- Maximum number of hits (columns) in a road: $\langle \Delta_{\text{cols}} \rangle$
- Measured hits (columns) associated to a road: N_{obs}



- $\frac{N_{\text{obs}}}{\Delta_{\text{cols}}}$ will account for lost hits in between the edges
  → **cluster breaking**
- Lost hits in the edges: can be estimated by comparing $\langle \Delta_{\text{cols}} \rangle$ obtained with alignment method

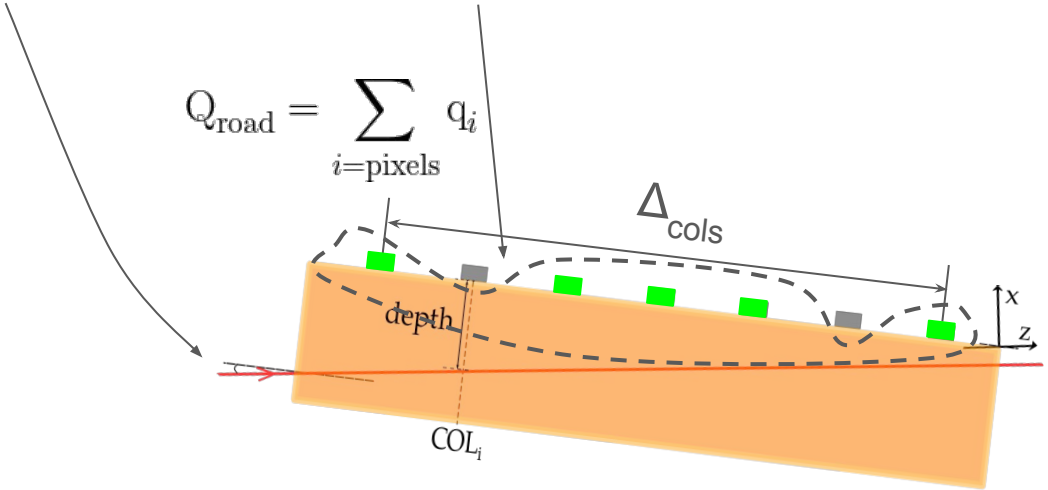
Breaking cluster frequency:

$$\left\langle \frac{N_{\text{cols}}}{\Delta_{\text{cols}}} \right\rangle = \sum_{i=\Delta^{\alpha}_{\text{cols}} \pm 1} \left\langle \frac{N_{\text{cols}}}{\Delta_{\text{cols}}} \right\rangle_i \cdot w_i$$

$\Delta^{\alpha}_{\text{cols}}$: expected distance given an incident angle α

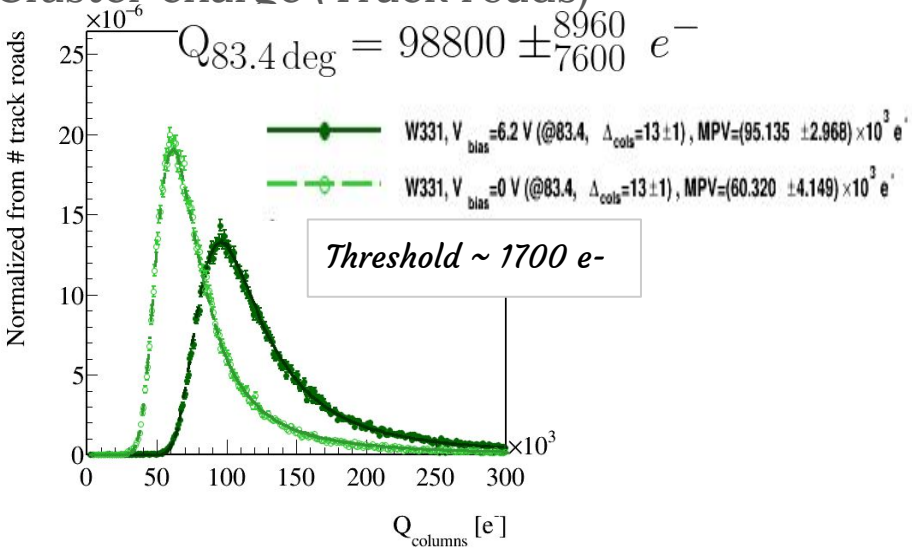
Deposited charge

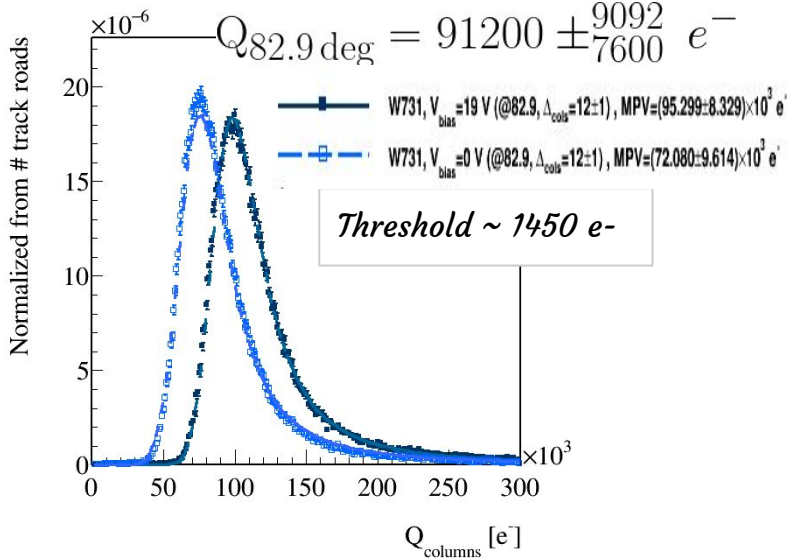
- Track road → associate pixels



Deposited charge: 25x100

- Cluster charge (Track roads)



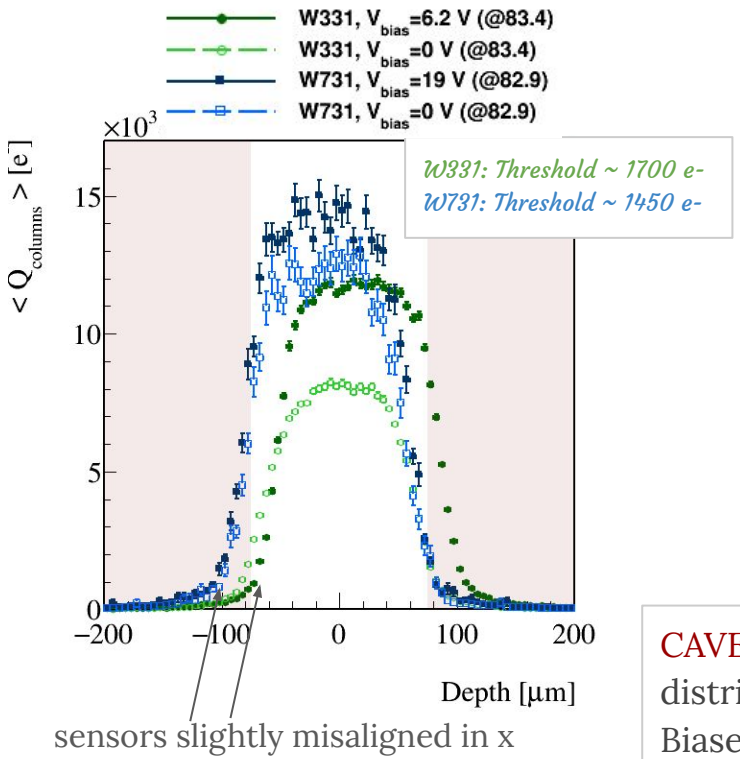


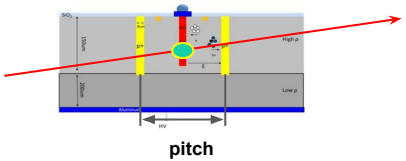
- Charge measured compatible with expectation
- Around 40% charge lost without bias

- Charge measured compatible with expectation
- Around 25% charge lost without bias

- Threshold for W331 larger than for W731 → larger 'charge lost' in W331 (unbiased vs. biased)

Deposited charge vs depth





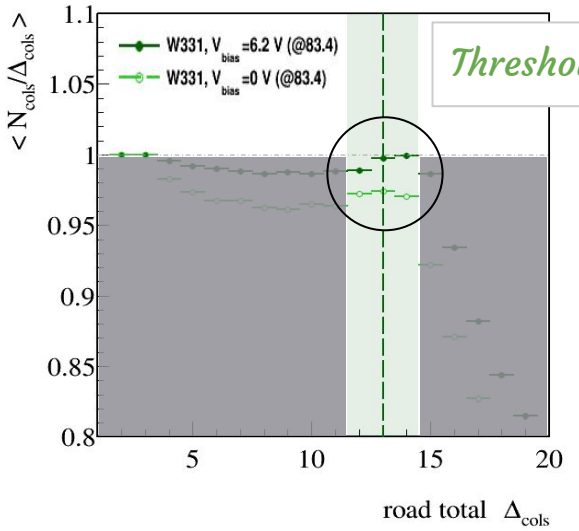
- **Grazing angle at 3D pixel sensors**: deposited charge per pixel is **independent of the track depth**
  - **Homogenous charge collection** along the whole thickness, even without bias

- Different incident angles: explains different charge in biased runs
- Different thresholds: explains different relative difference between bias-unbiased

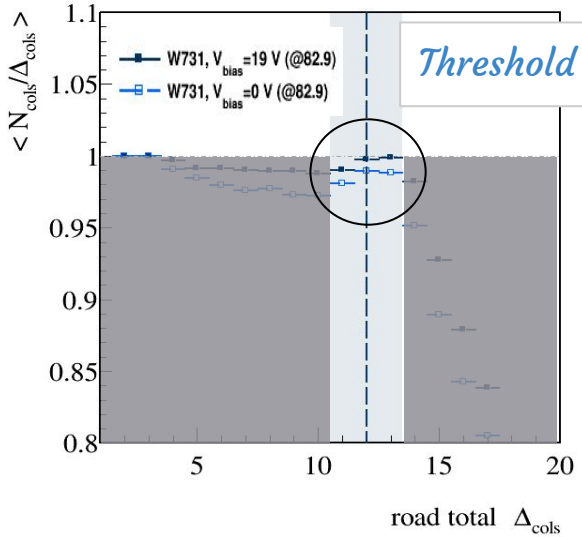
CAVEAT: Mean charge distributions, not MPV! Biased to larger values

Cluster breaking frequency: 25x100

$$\left\langle \frac{N_{cols}}{\Delta_{cols}} \right\rangle = \sum_{i=\Delta^{\alpha}_{cols}\pm 1} \left\langle \frac{N_{cols}}{\Delta_{cols}} \right\rangle_i \cdot w_i$$



Threshold ~ 1700 e-



Threshold ~ 1450 e-

"High" V_{bias} $\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{6.2\,V}_{W331} = 99.8 \pm 0.5\ \%$

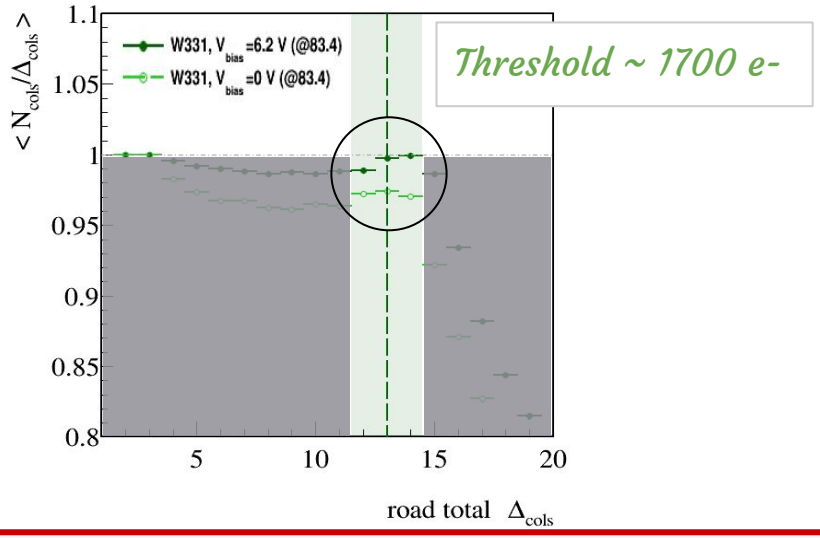
No V_{bias} $\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{0\,V}_{W331} = 97.3 \pm 0.2\ \%$

$\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{19\,V}_{W731} = 99.8 \pm 0.4\ \%$

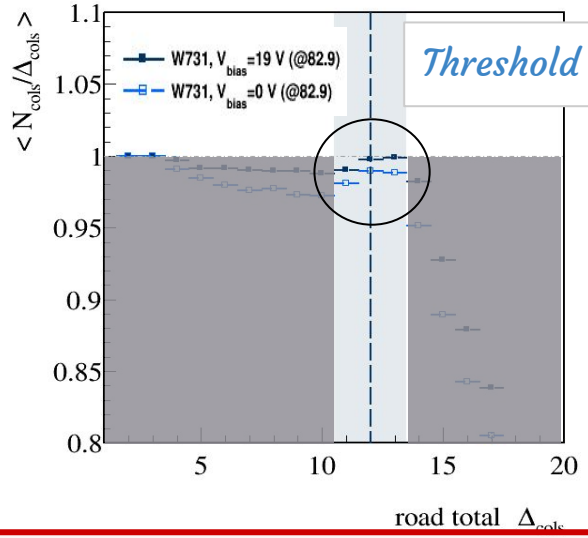
$\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{0\,V}_{W731} = 98.8 \pm 0.5\ \%$

Cluster breaking frequency: 25x100

$$\left\langle \frac{N_{cols}}{\Delta_{cols}} \right\rangle = \sum_{i=\Delta^{\alpha}_{cols}\pm 1} \left\langle \frac{N_{cols}}{\Delta_{cols}} \right\rangle_i \cdot w_i$$



Threshold ~ 1700 e-



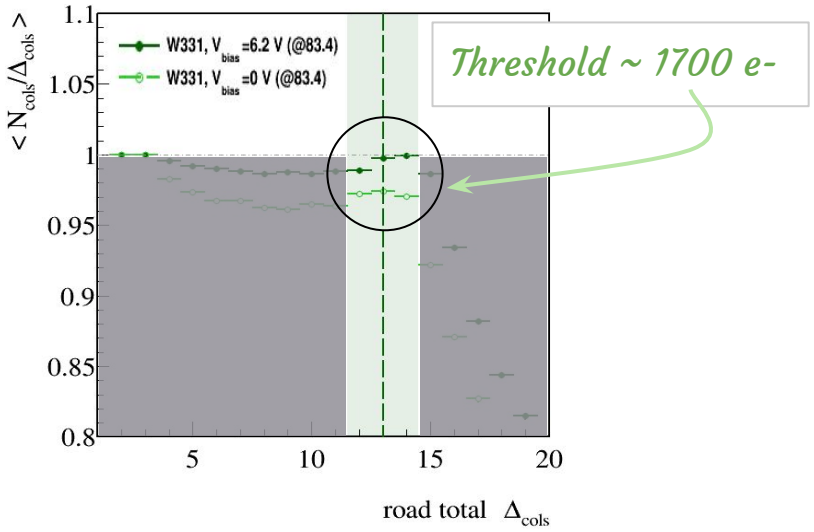
Threshold ~ 1450 e-

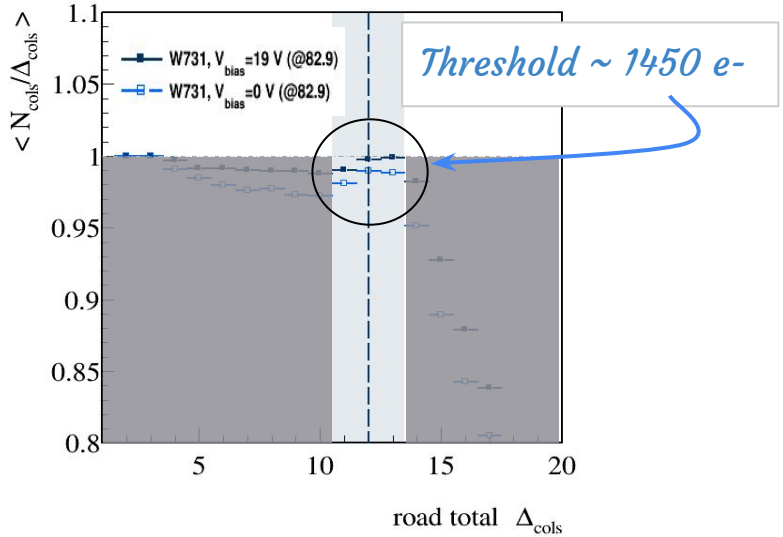
"High" V_{bias} $\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{6.2\,V}_{W331} = 99.8 \pm 0.5\ \%$ $\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{19\,V}_{W731} = 99.8 \pm 0.4\ \%$

- **No appreciable cluster breaking** when fully depleted

Cluster breaking frequency: 25x100

$$\left\langle \frac{N_{cols}}{\Delta_{cols}} \right\rangle = \sum_{i=\Delta^{\alpha}_{cols}\pm 1} \left\langle \frac{N_{cols}}{\Delta_{cols}} \right\rangle_i \cdot w_i$$

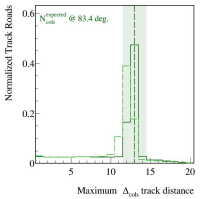




- Cluster breaking frequency **lower than 2-3%** when unbiased

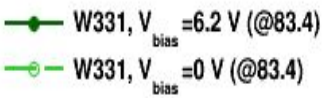
No V_{bias} $\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{0\,V}_{W331} = 97.3 \pm 0.2\ \%$ $\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{0\,V}_{W731} = 98.8 \pm 0.5\ \%$

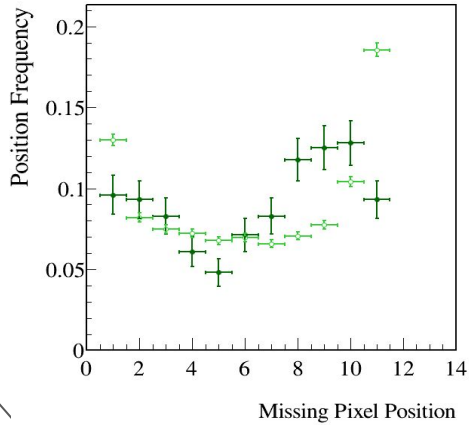
Missing pixel position

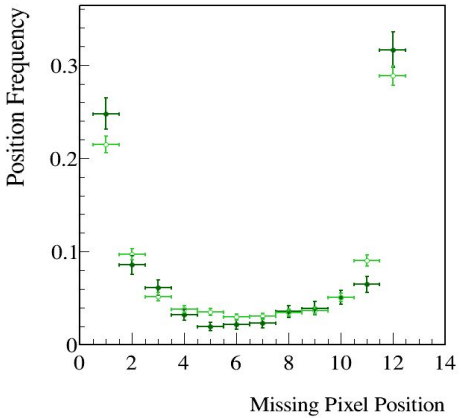


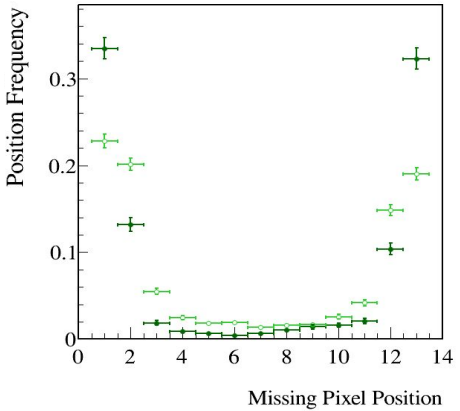
$$\langle \Delta_{cols} \rangle = 13 \pm 1$$

Threshold ~ 1700 e-





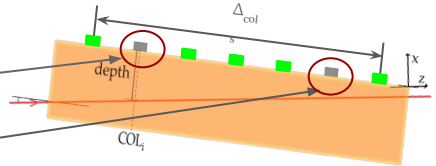




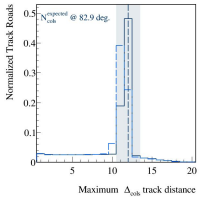
$$\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{6.2\,V}_{W331} = 99.8 \pm 0.5\ \%$$

$$\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{0\,V}_{W331} = 97.3 \pm 0.2\ \%$$

- Very low frequency of missing hits
  - in such cases, just 1 pixel lost (usually)
- Missing pixels localized at the edges
  - Low electric field region and/or not enough distance travelled

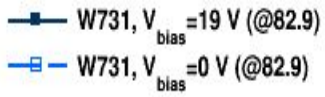


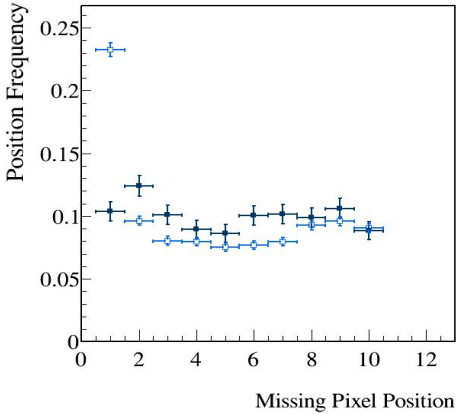
Missing pixel position

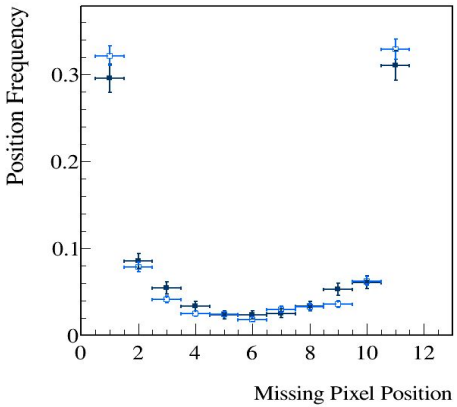


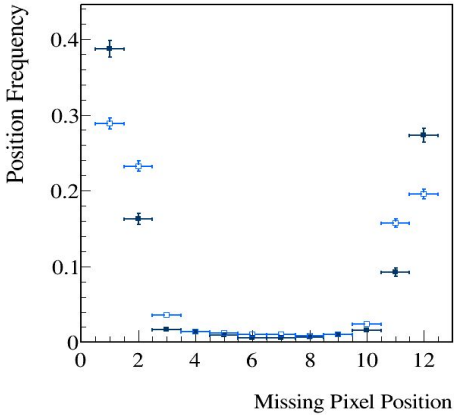
$$\langle \Delta_{\text{cols}} \rangle = 12 \pm 1$$

Threshold ~ 1450 e-





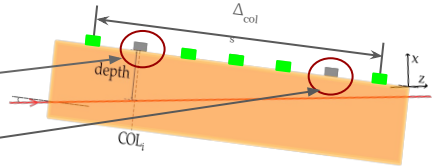




$$\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{19\,V}_{W731} = 99.8 \pm 0.4\,\%$$

$$\left\langle \frac{N_{obs}}{\Delta_{cols}} \right\rangle^{0\,V}_{W731} = 98.8 \pm 0.5\,\%$$

- Very low frequency of missing hits
  - in such cases, just 1 pixel lost (usually)
- Missing pixels localized at the edges
  - Low electric field region and/or not enough distance travelled



Summary & Conclusions

- No evidence of cluster breaking on fresh 3D for large clusters (produced by particles with large incident angle)
  - Cluster reconstruction in **FRESH 3D sensors are not affected by cluster breaking**
  - No Biased (irrad-like): Cluster reconstruction lower than 2-3% cluster breaking frequency (for 25x100)
    - Missing hits localized at the edges
- Homogeneous charge collection, independent of the track depth