Results on 3D Pixel Sensors for the CMS Inner Tracker Upgrade at the High Luminosity LHC

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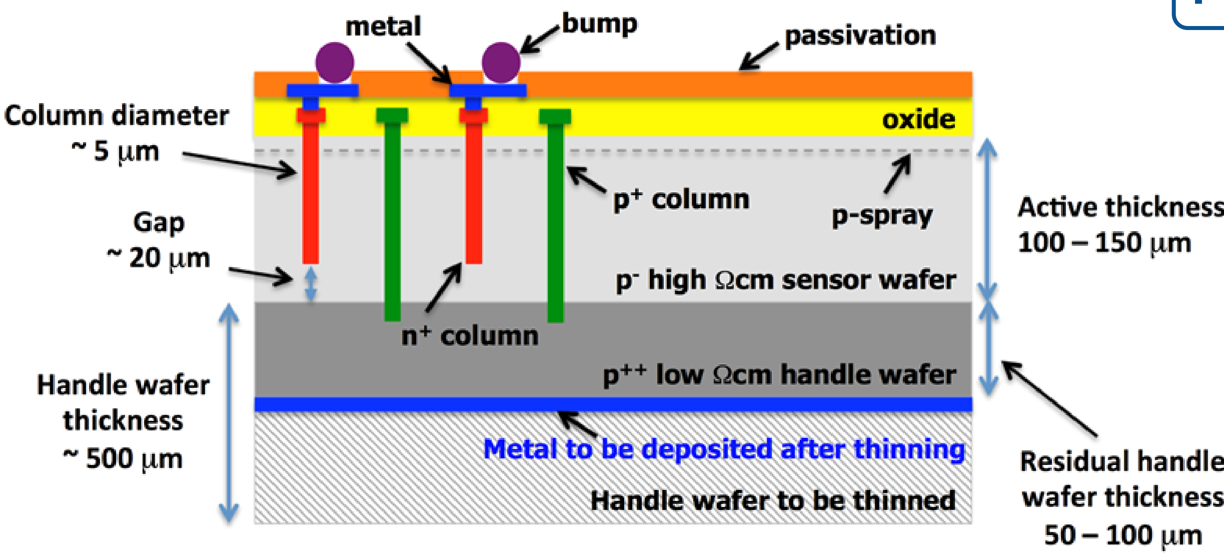
on behalf of the CMS Tracker Group

"Trento" Workshop on Advanced Silicon Radiation Detectors Physics
17th-19th February 2020
Vienna - Austria

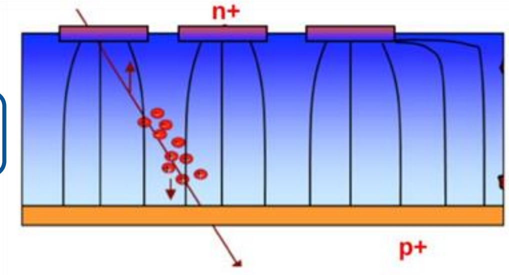
Introduction

- I will not talk about details of CMS Inner Tracker: there are excellent talks on the subject at this workshop!
  - ✓ Jory Sonneveld talk (17th Feb 2020, 12:55): "The CMS Pixel Detector for the High Luminosity LHC" https://indico.cern.ch/event/813597/contributions/3727821/
  - ✓ Corrinne Mills talk (17th Feb 2020, 15:15): "Performance of highly irradiated pixel sensors for the CMS HL-LHC upgrade" https://indico.cern.ch/event/813597/contributions/3727828/
  - ✓ Finn Feindt talk (17th Feb 2020, 15:55): "Test Beam Characterization of Planar Pixel Sensors for the CMS Phase 2 Upgrade" https://indico.cern.ch/event/813597/contributions/3727834/
  - ✓ Jordi Duarte Campderros talk (19th Feb 2020, 10:00): "Study of 3D pixel sensors after non-uniform proton irradiation" https://indico.cern.ch/event/813597/contributions/3727824/
  - ✓ Roberto Seidita talk (19th Feb 2020, 16:00): "Serial powering at CMS silicon tracker detector for High Luminosity Upgrade" https://indico.cern.ch/event/813597/contributions/3727820/

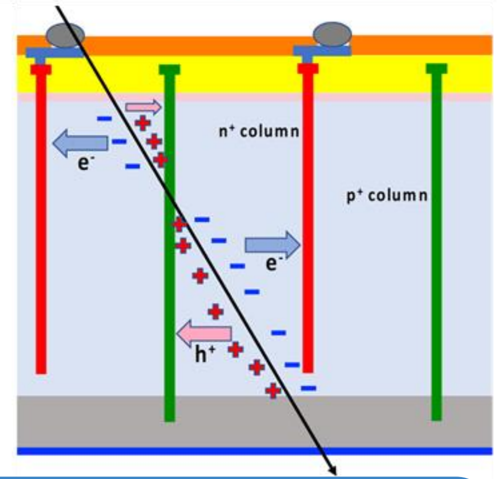
3D pixel sensors



Planar

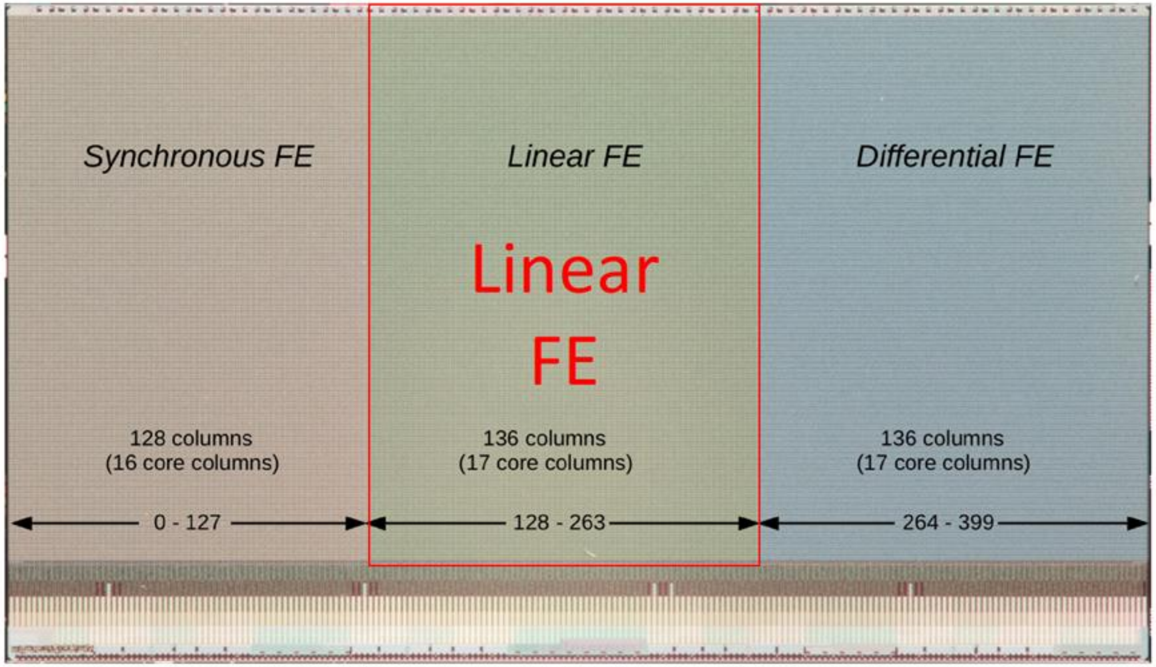


3D



- **3D pixel R&D (FBK & CNM)**
- **In 3D sensors the drift path is perpendicular to the active depth**
  - **Short drift** distance → ~ 30 ÷ 50 μm (3D) vs 100 ÷ 150 μm (Planar)
- **Many advantages with respect to planar sensors:**
  - **Smaller bias voltage** needed to deplete the sensor (5 V before and ~ 150 V after irradiation)
  - **Less trapping** in irradiated sensors (shorter drift distance!)
  - Slim edges, i.e. **smaller dead zones**
  - **Same charge** produced
- **Promising candidates for the high radiation environment of the inner layers and rings**

RD53: the inner tracker readout chip



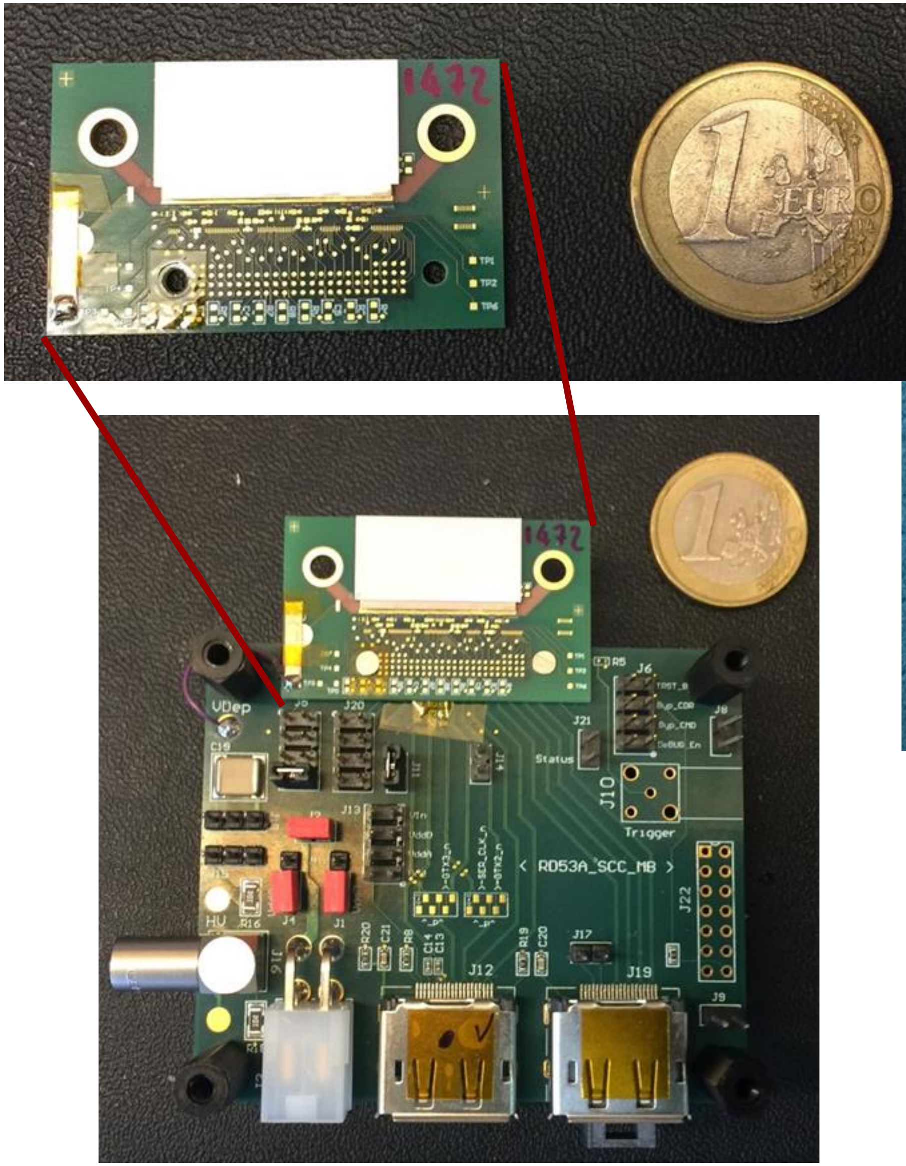
RD53A first prototype of ROC

- ½ total size (**50×50 μm² cell**, 65 CMOS nm technology)
- Used for **R&D**
- 3 analog Front-Ends (Synchronous, **Linear**, Differential)
- Time over Threshold counter to measure charge (4 bits); caveat **ToT as charge unit**
- CMS choice: **Linear F.E.**
- **Low threshold and noise**, **radiation hard** (proven up to at least **5 MGy**)
- **All results presented here obtained using Linear F.E. (central section)**

Test beam setup @DESY in 2019

- **Beam:** 5.2 GeV electrons
- **Telescope:** Mimosa
  - 3 planes before DUT (Device Under Test)
  - 3 planes after DUT
  - Spatial resolution up to ~3.8 μm, depends on telescope and geometry configuration
- **Single Chip Modules on beam:**
  - Two FBK mask aligner fresh 3D sensors
    - 130 μm active thickness
    - One 50×50 μm^2, One 25×100 μm^2 pitch
    - Bump bonded at IZM (Germany)
  - One FBK stepper fresh 3D sensor
    - 150 μm active thickness
    - 50×50 μm^2 pitch
    - Indium bump bonded at Leonardo (Italy)
  - One FBK irradiated 3D sensor
    - 130 μm active thickness
    - 50×50 μm^2 pitch
    - Irradiated @CERN
    - Nominal fluence 1×10^{16} $n_{eq}cm^{-2}$

Test beam setup @DESY in 2019



- Sensors bump-bonded to RD53A
- Mounted on RICE cards
- BDAQ (https://gitlab.cern.ch/silab/bdaq53)
- Irradiated sensor kept inside a cooling box:
  - Stable temperature of -27°C
  - Telescope resolution worsen (~ 10 μm)

Modules: data taking and results

FRESH

- Two HV bias point:
  - 6 V (minimum allowed by PS)
  - 30 V
- All modules tuned to ~900 e^- threshold

IRRADIATED

- Bias scan
  - > 20V
  - < 150 V
- Tuned to 1100 e^- threshold

- Low voltage powering via RD53A LDO integrated circuit
- "Reference" hit efficiency measured for perpendicular tracks (effect of columnar electrodes)
- Cluster size studies and angle scan for spatial resolution measurements
- 24 V of bias voltage range with same performances guarantees a good behaviour with SP*

Module	Leakage Current @Bias Voltage Measured @ DESY TB, T = 45°C	Efficiency (Orthogonal Tracks)
3D Mask Aligner - 50x50 μm^2	150 nA @6 V - 250 nA @30 V	> 99%
3D Mask Aligner - 25x100 μm^2	130 nA @6 V - 190 nA @30 V	> 99%
3D Stepper - 50x50 μm^2	6.5 µA @6 V - 16.5 µA @ 30 V	> 99%
3D irradiated - 50x50 μm^2	120 µA @ 120 V	98.8% @146 V

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*See Roberto Seidita's talk (19th Feb 2020, 16:00): "Serial powering at CMS silicon tracker detector for High Luminosity Upgrade" https://indico.cern.ch/event/813597/contributions/3727820/

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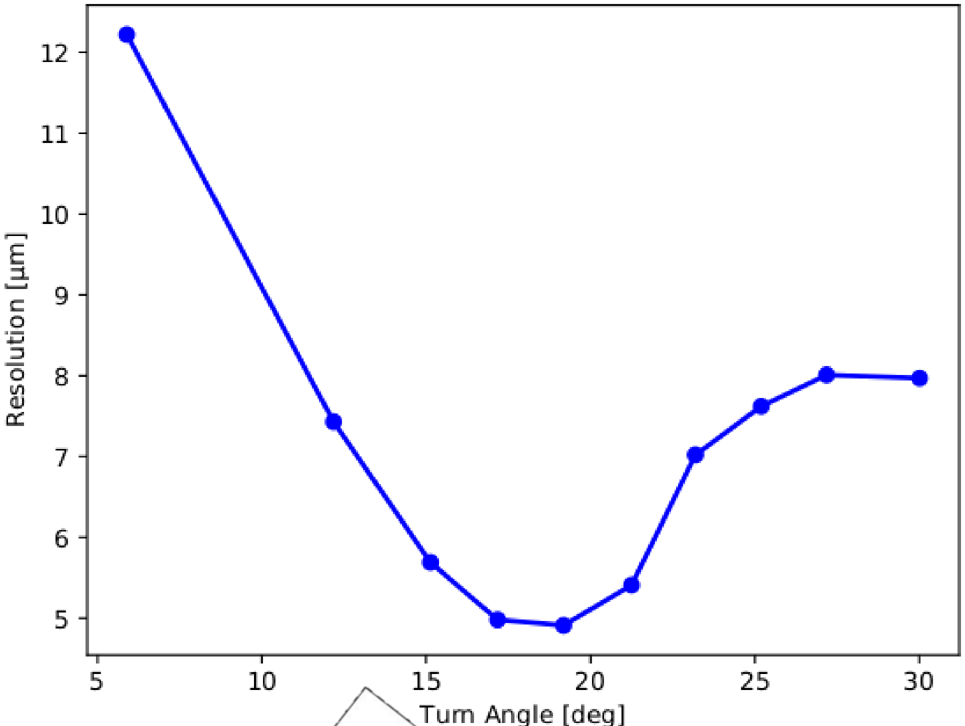
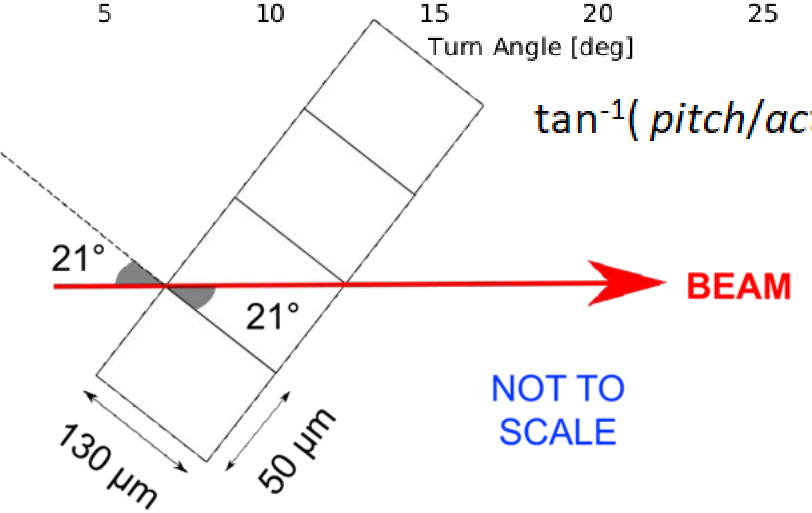
Resolution vs Turning angle: 50×50 μm²



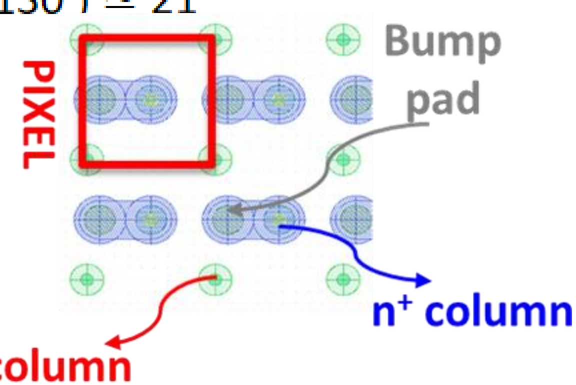
- Telescope resolution (σ_{tele}) subtracted in quadrature from DUT residual using both triplets
- σ_{tele} goes from 3.8 μm to 6.2 μm (depends on telescope configuration, mainly distance between first and second MIMOSA triplets)
- Best σ_{DUT}~5 μm @ ~19° (expected value compatible)
- In most of the angular range σ_{DUT} is 8 μm or better



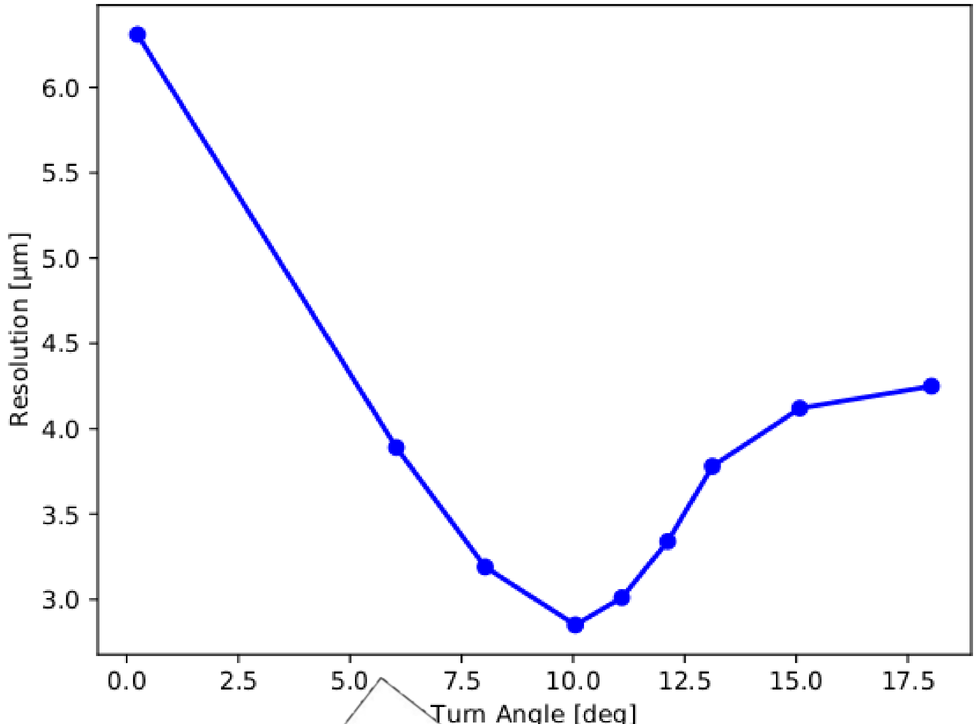
$\tan^{-1}(\textit{pitch/active\_thickness}) = \tan^{-1}(50/130) \simeq 21°$

Cluster size = 2

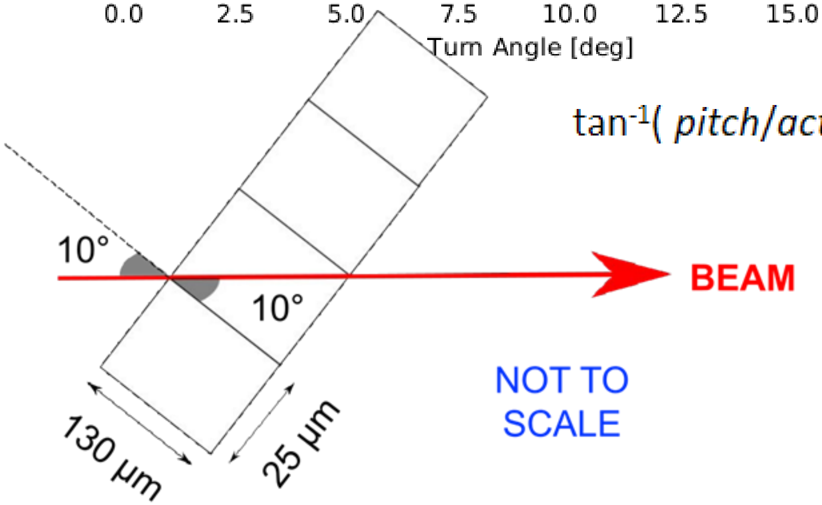
V_{bias} = 30 V



Resolution vs Turning angle: 25×100 µm²



- Module rotated around short 25 µm pitch coordinate
- Best σ_{DUT}~3 µm @ ~10°
- In most of the angular range σ_{DUT} is 4.5 µm or better
- First measurement for a 3D 25×100 µm² along 25 µm direction

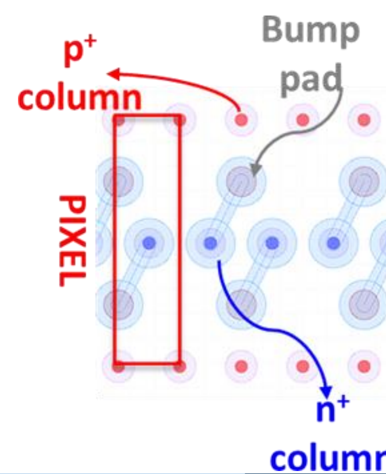


$\tan^{-1}(\,\textit{pitch/active\_thickness}\,) = \tan^{-1}(\,25/130\,) \simeq 11°$

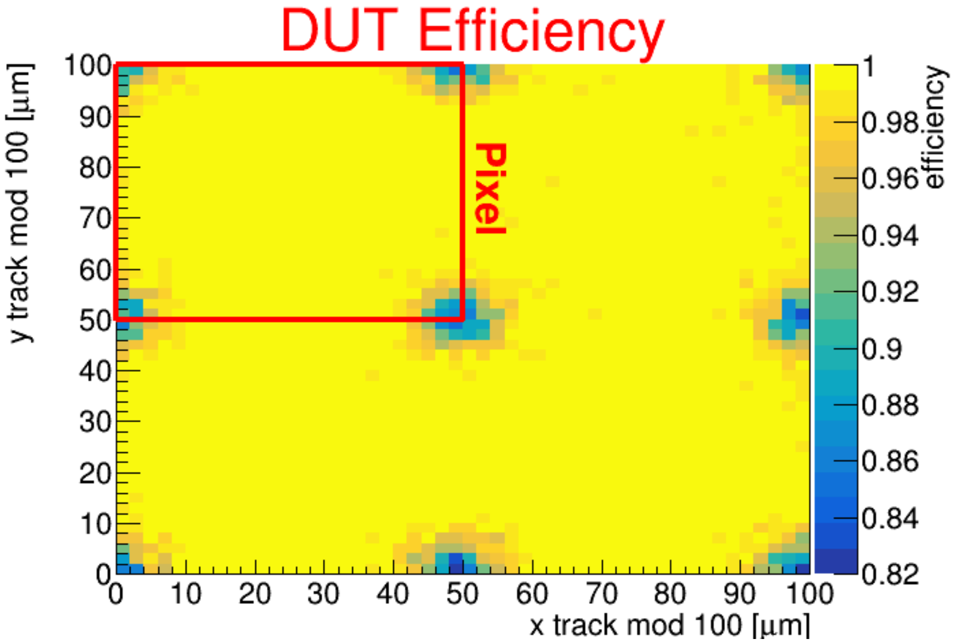
Cluster size = 2

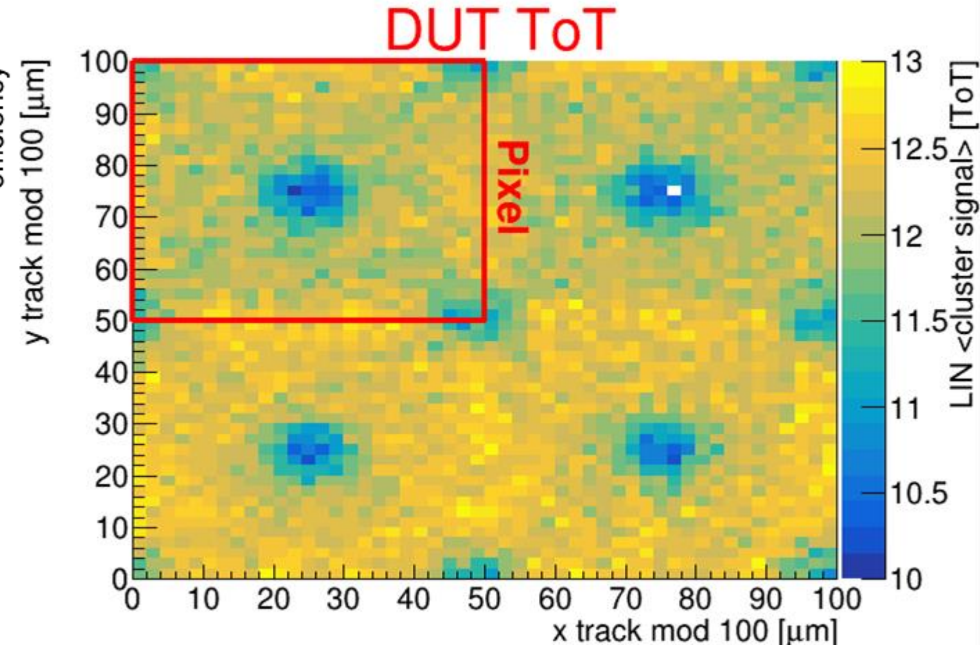
NOT TO SCALE

V_{bias} = 30 V



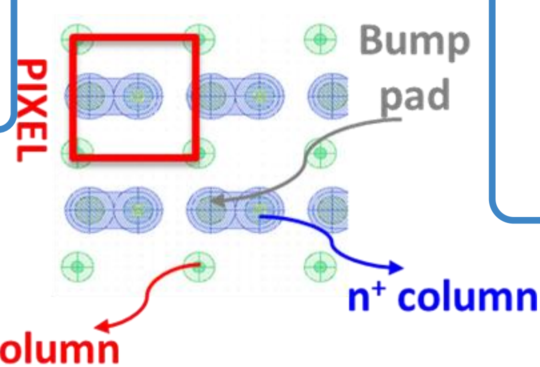
Hit efficiency and ToT: 50×50 μm² (MA)





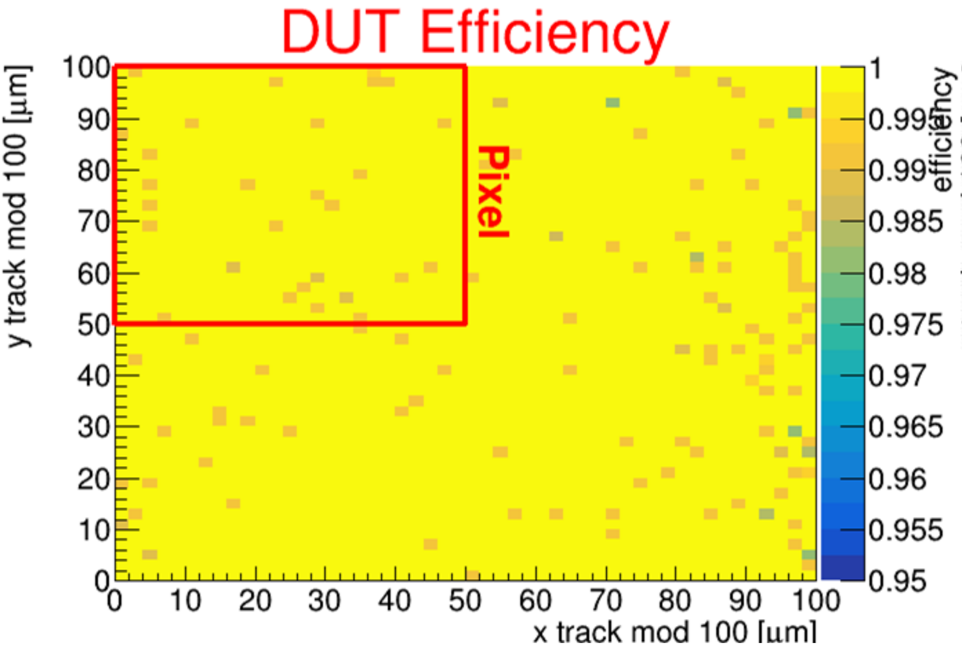
- Efficiency map for 2×2 pixel grid
- Efficiency drop near p^+ columns
- High efficiency near n^+ columns
- Global efficiency > 99%

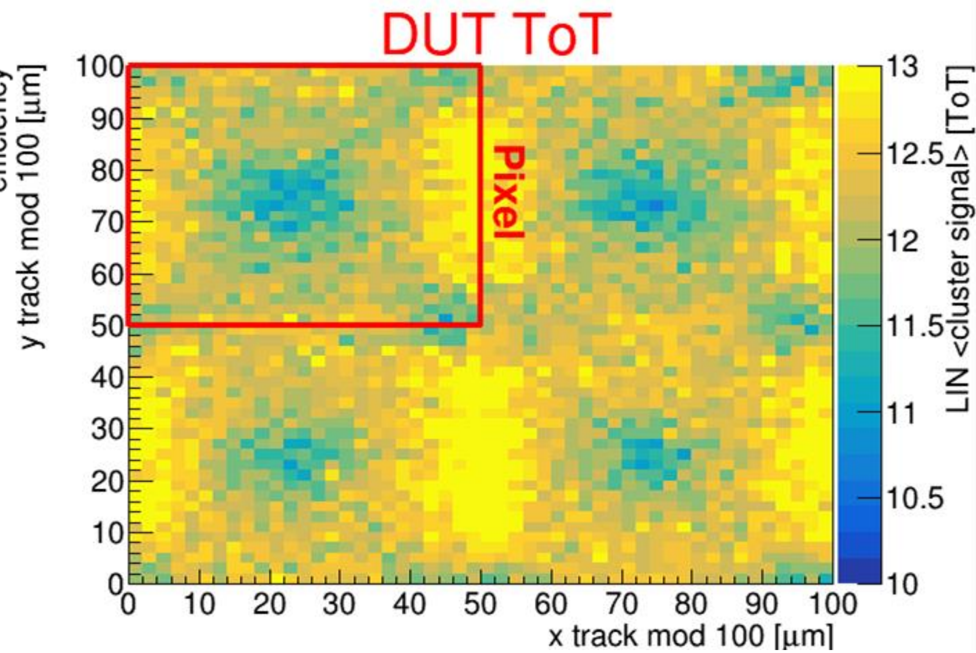
V_{bias} = 30 V
Orthogonal beam incidence



- Tot map for 2×2 pixel grid
- Low average Tot near n^+ columns
  - Low collected charge (due to passive column), but high efficiency

Cluster size, ToT, Efficiency: 50×50 μm² (MA) @6°

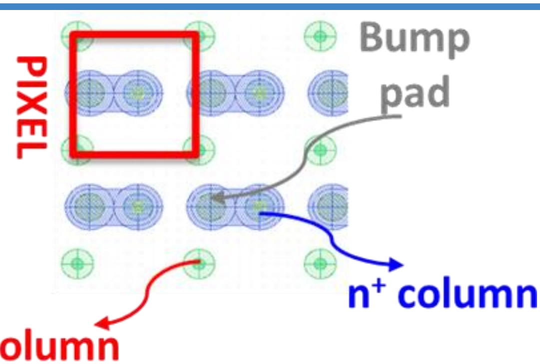




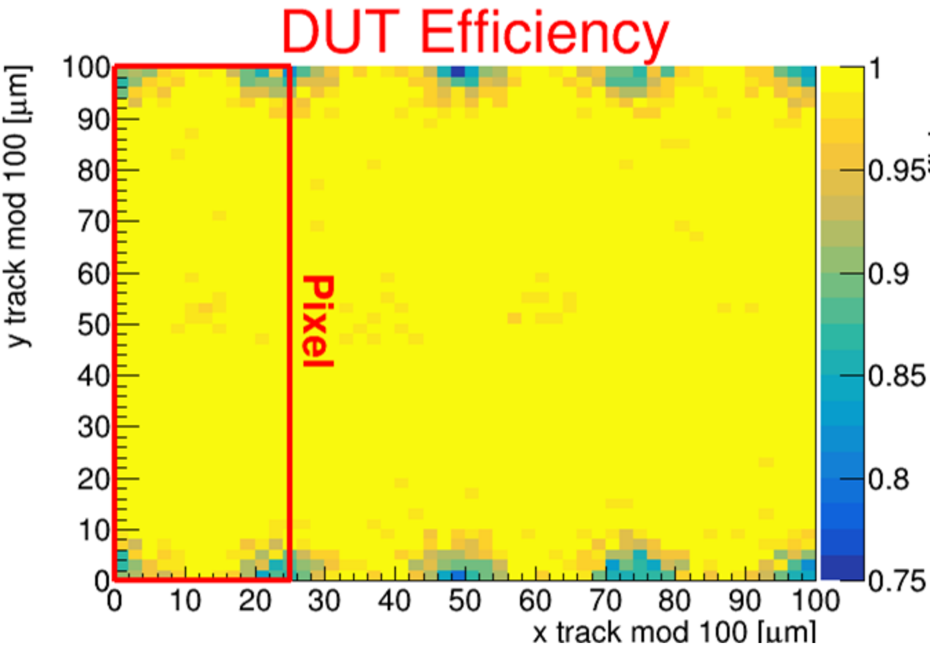
- Column inefficiencies are no longer there @6°
- Charge sharing due to rotation visible from ToT maps for 2×2 pixel grid

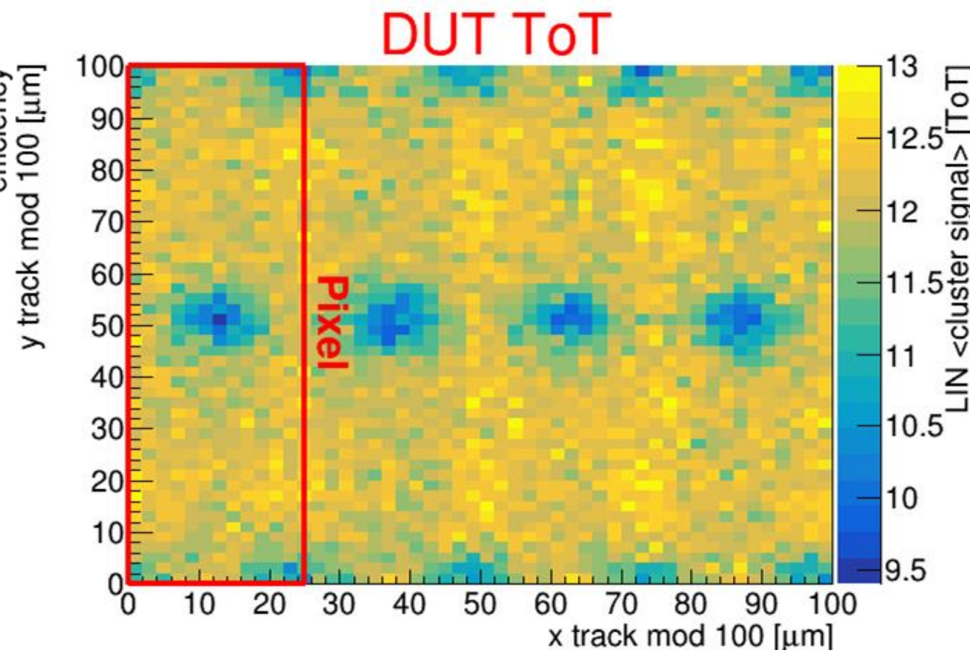
V_{bias} = 30 V

Rotation of 6°



Hit efficiency and signal charge: 25×100 μm²

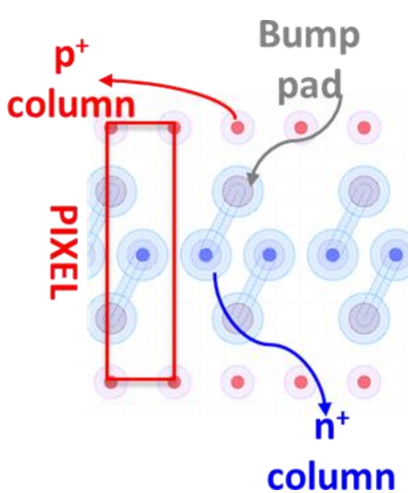




- Efficiency map for 4×1 pixel grid
- Efficiency drop near p^+ columns
- High efficiency near n^+ columns
- Global efficiency > 99%

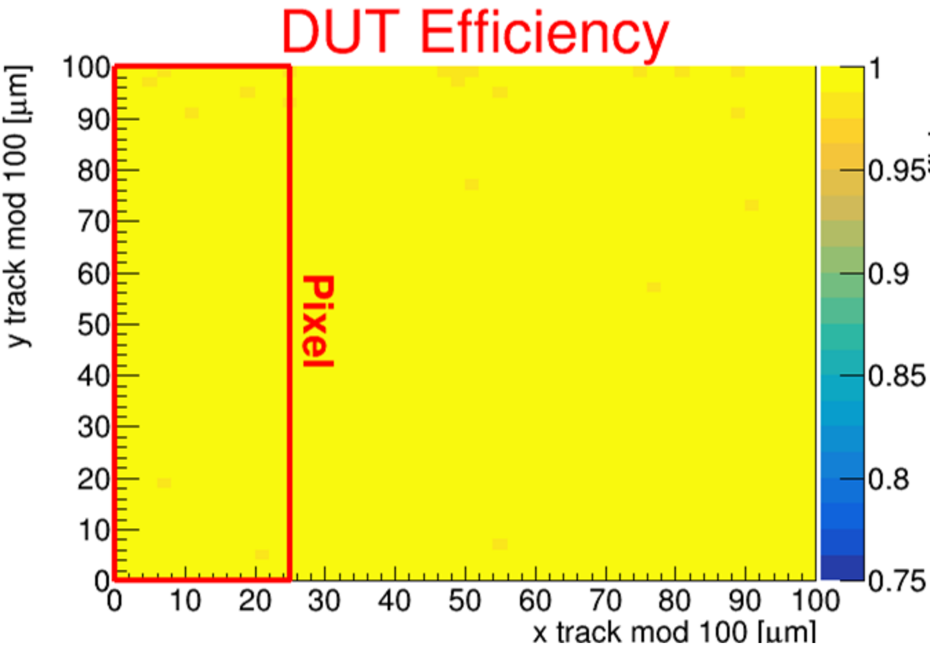
V_{bias} = 30 V

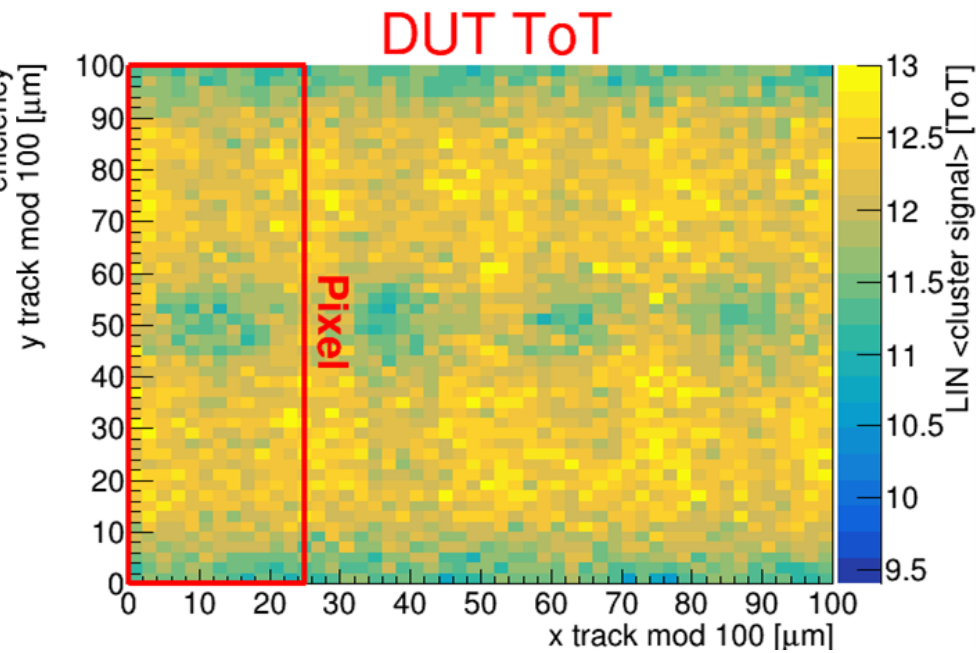
Orthogonal beam incidence



- Tot map for 4×1 pixel grid
- Low average Tot near n^+ columns
  - Low collected charge (due to passive column), but high efficiency

Cluster size, ToT, Efficiency: 25×100 μm² @5°





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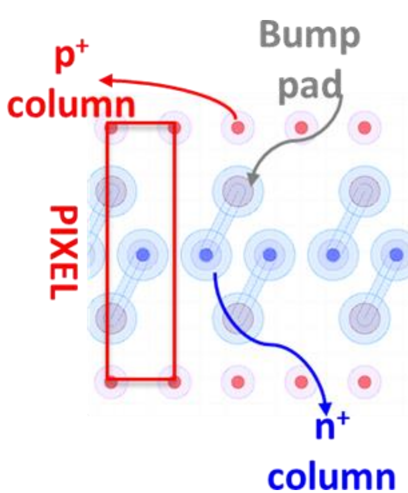
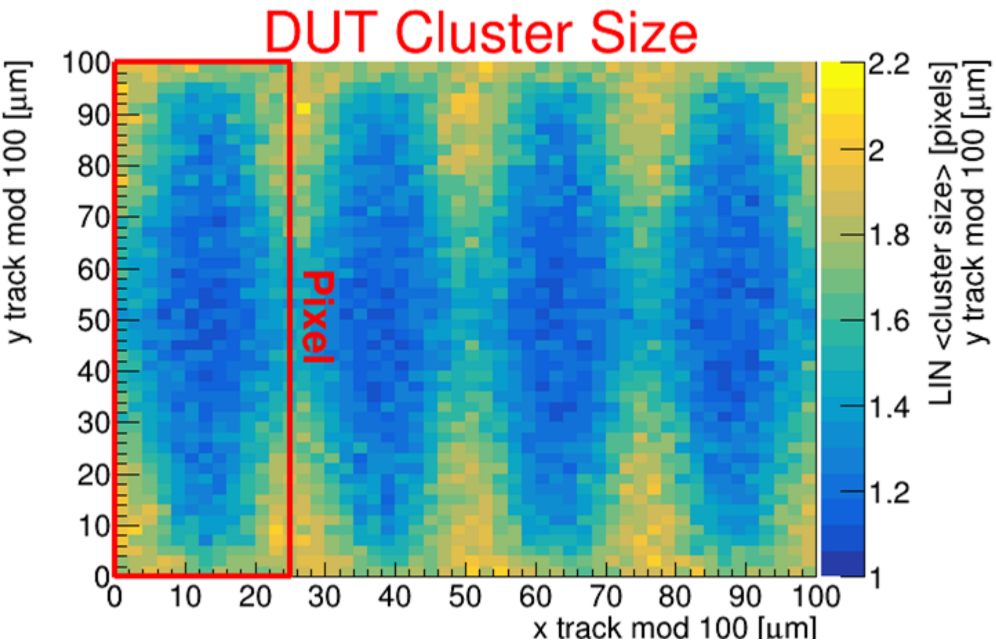


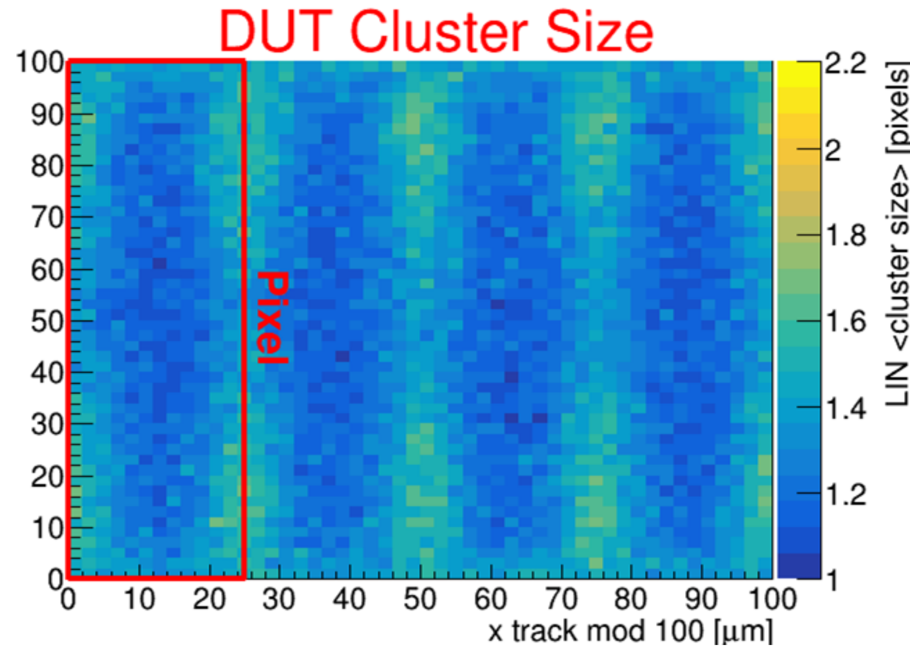
- Charge sharing due to rotation visible from ToT maps for 4×1 pixel grid

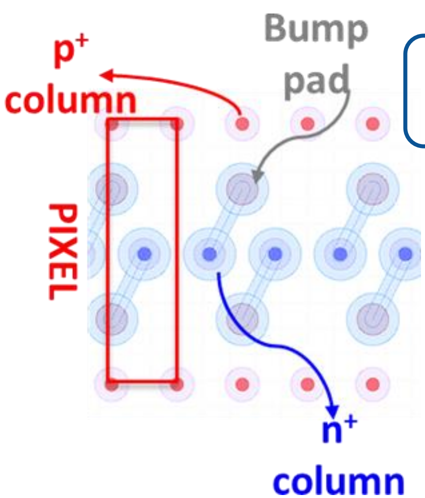
V_{bias} = 30 V

Rotation of 5°

Cluster size: 25×100 μm²







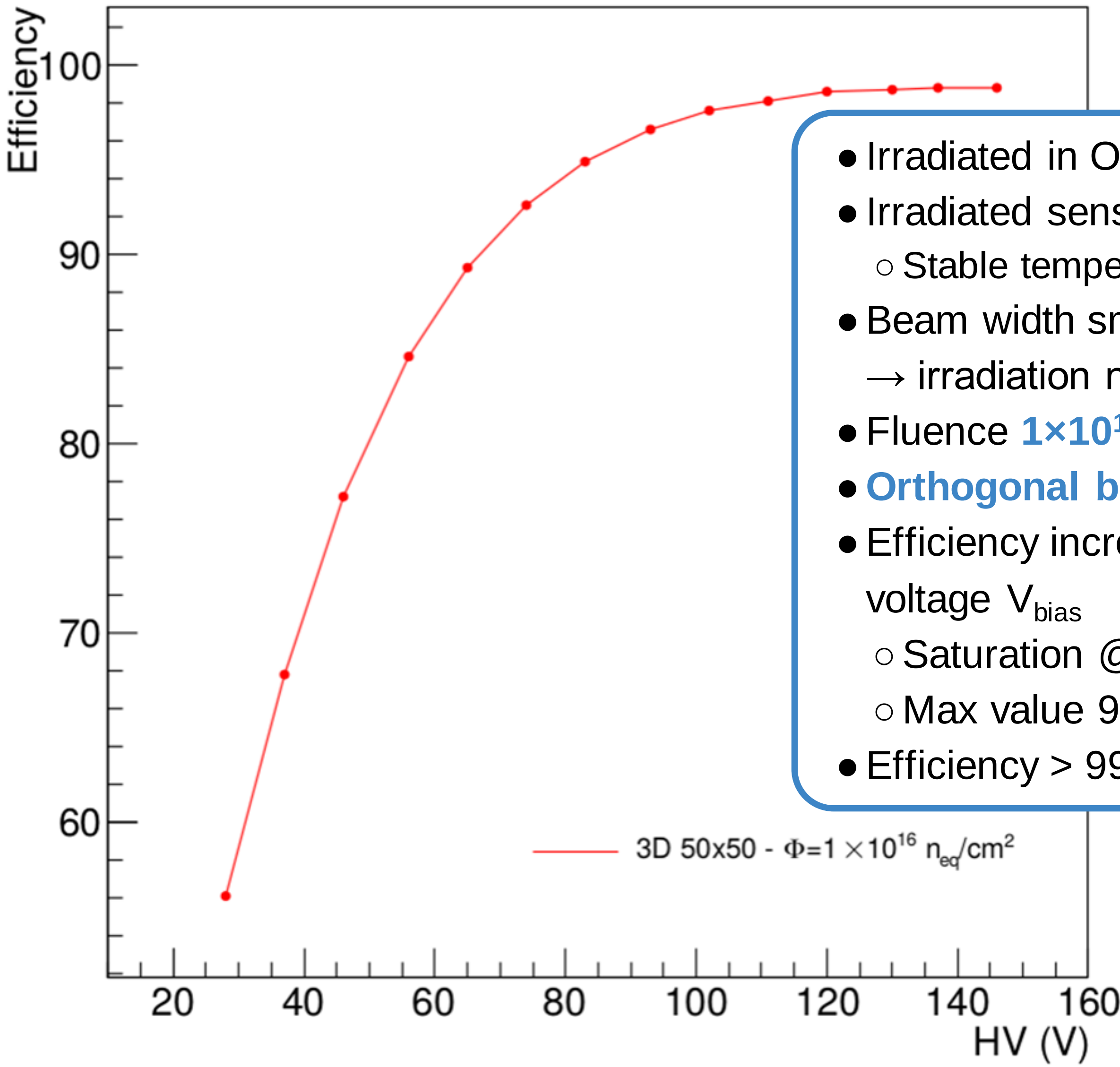
V_{bias} = 6 V

Orthogonal beam incidence

V_{bias} = 30 V

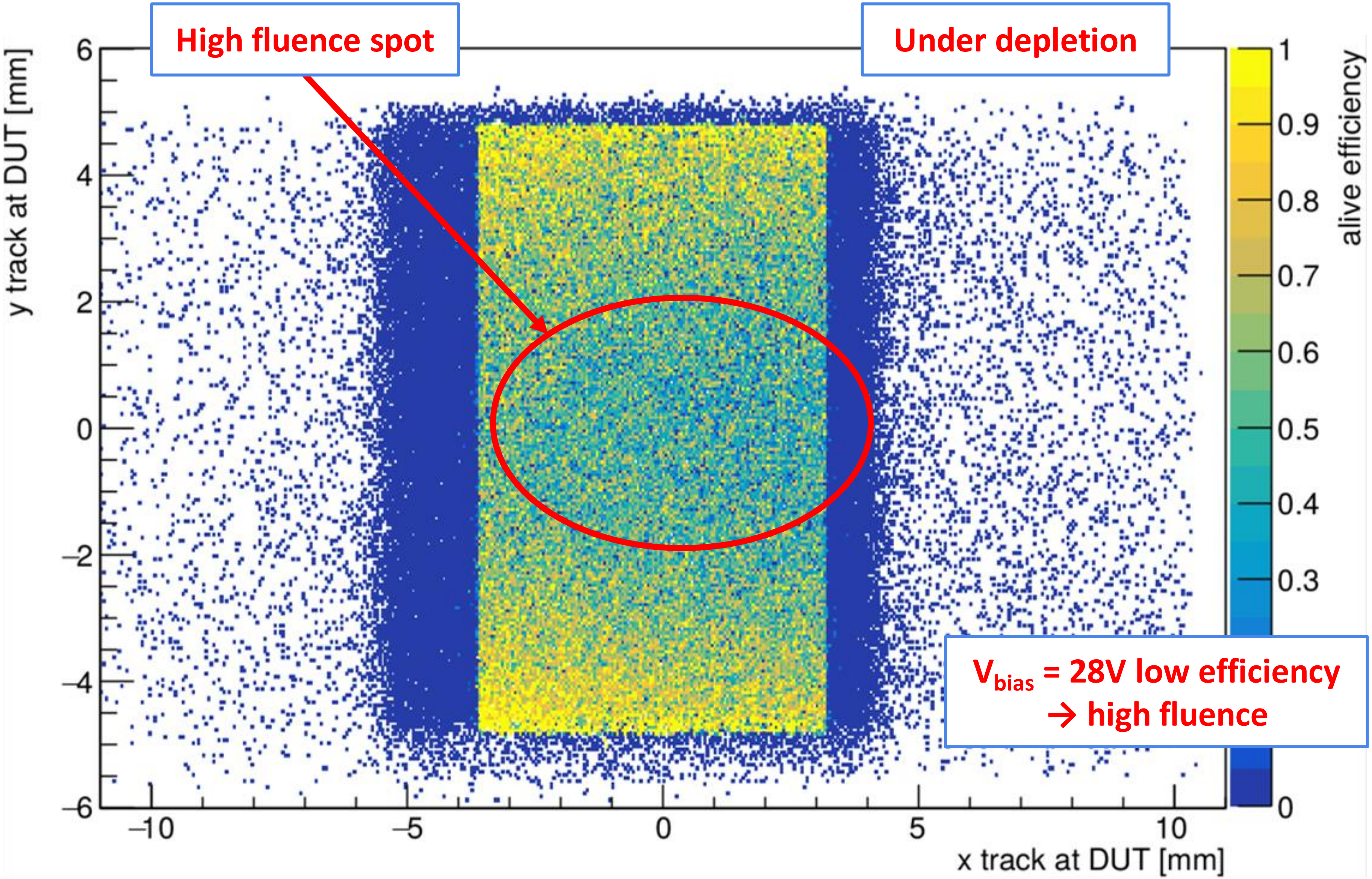
- Cluster size maps for 4×1 pixel grid
- Higher cluster size at lower bias voltage
  - More diffusion → more charge sharing between pixels

Irradiated 50×50 μm²: bias scan



- Irradiated in Oct 2018 @ CERN
- Irradiated sensor kept inside a cooling box:
  - Stable temperature of -27°C
- Beam width smaller than chip → irradiation not uniform
- Fluence **$1\times10^{16} n_{eq} cm^{-2}$, 6 MGy**
- **Orthogonal beam incidence**
- Efficiency increases with effective bias voltage V_{bias}
  - Saturation @ V_{bias} = 110V
  - Max value 98.8% @V_{bias} = 146V
- Efficiency > 99% with rotations > 6°

Irradiated 50×50 μm^2: hit efficiency studies



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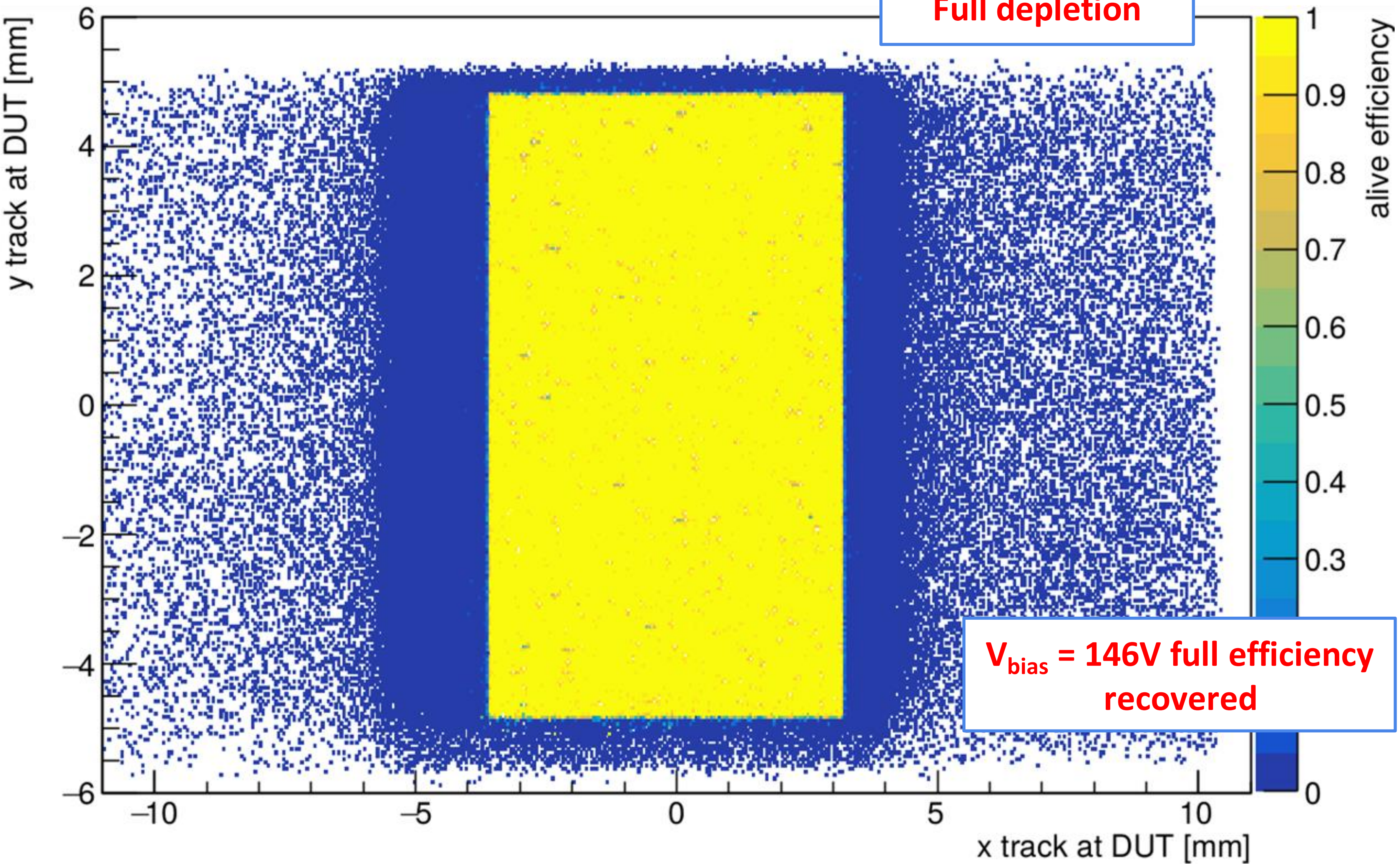
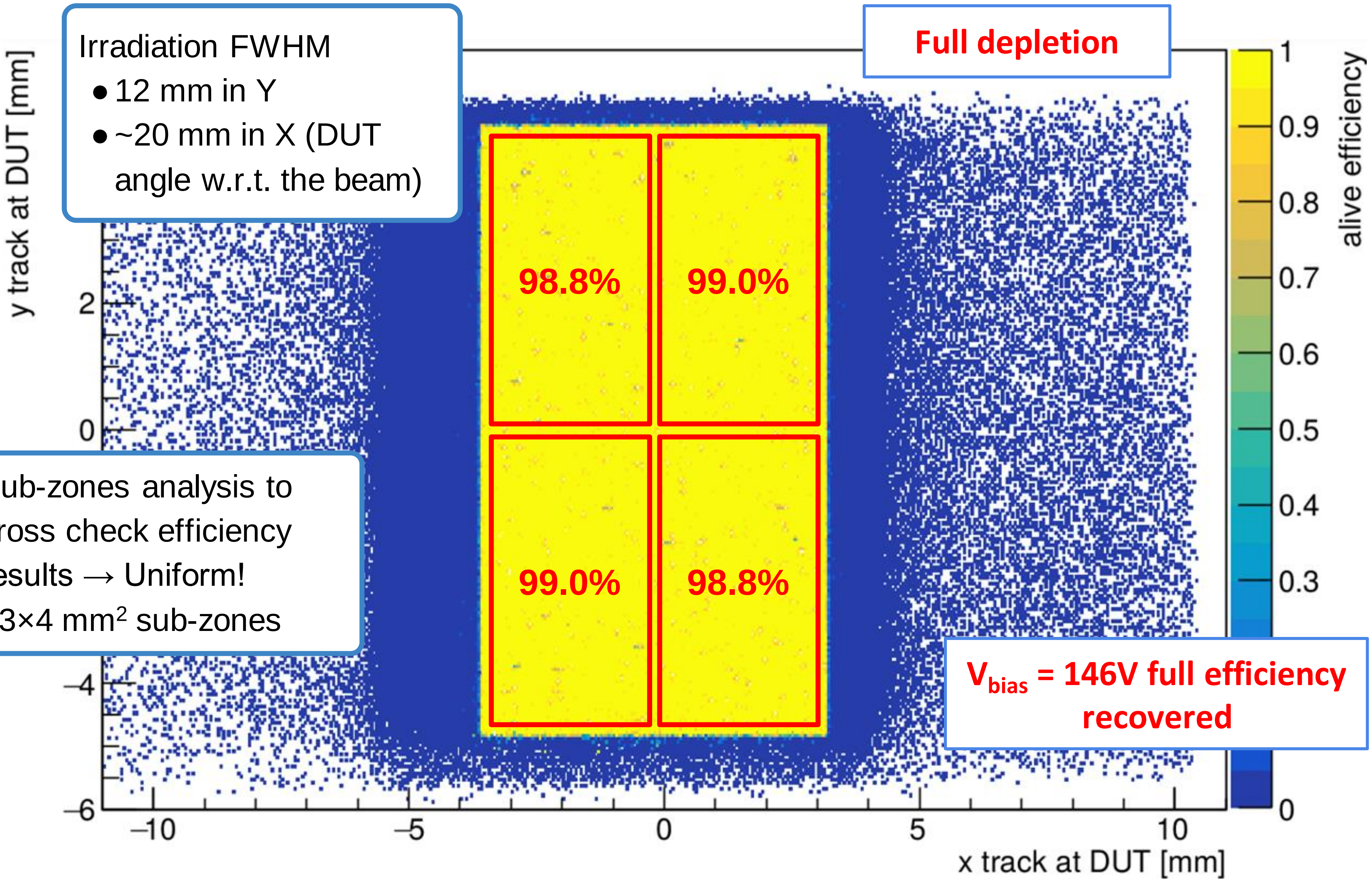


Full depletion

V_{bias} = 146V full efficiency recovered

Irradiated 50×50 μm^2: hit efficiency studies

Irradiation FWHM
- 12 mm in Y
- ~20 mm in X (DUT angle w.r.t. the beam)



Sub-zones analysis to cross check efficiency results → Uniform!
~3×4 mm^2 sub-zones

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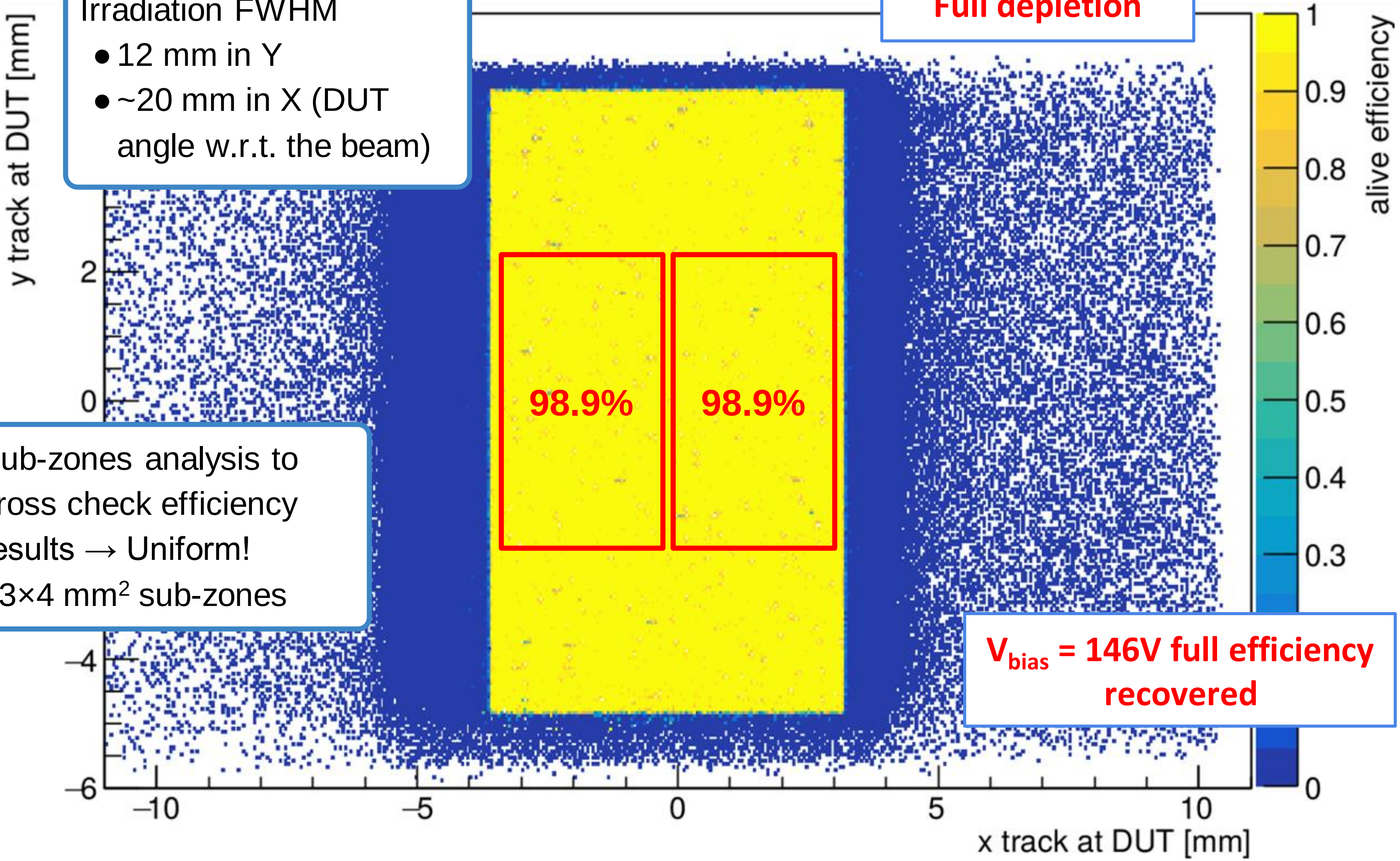

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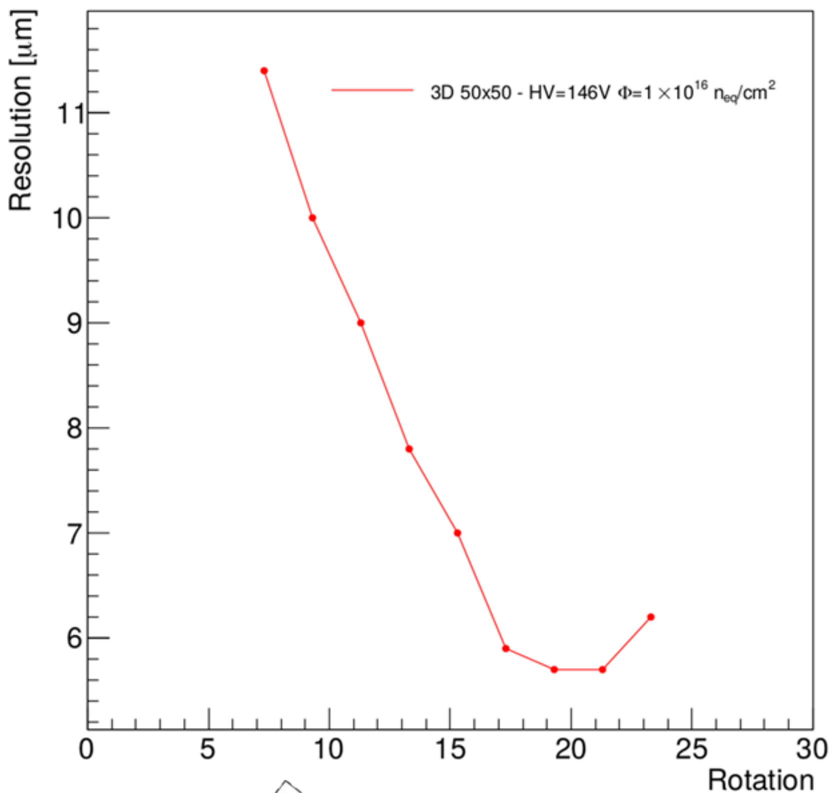
Irradiated 50×50 μm²: Resolution vs Turning angle



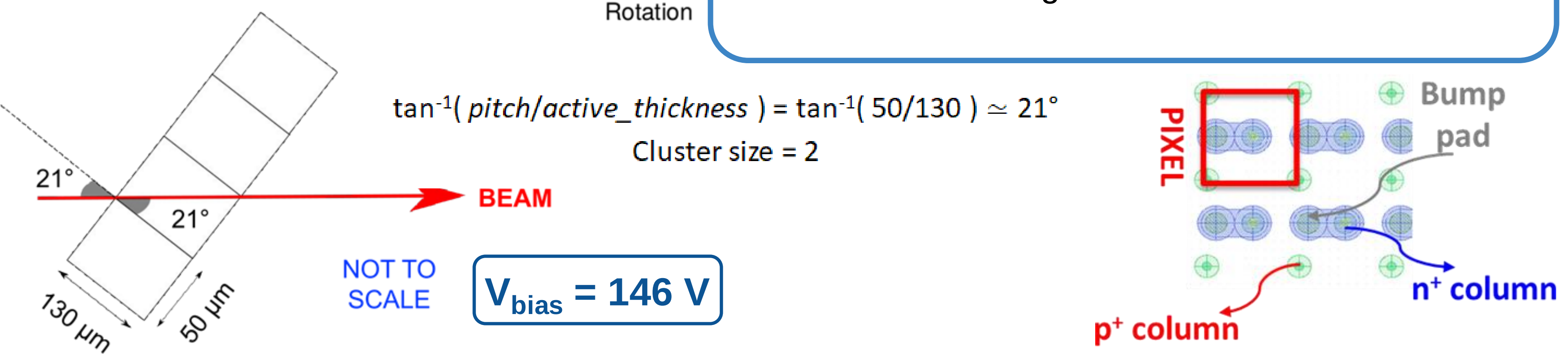
- Residuals fit (Student's t-distribution) on rotated (rot) and unrotated (no-rot) coordinates
- Using σ from fit, telescope resolution (res_{tele}) estimated with

$res^2_{tele} = \sigma^2_{no\text{-}rot} - res^2_{trivial}$, with $res_{trivial} = (50/\sqrt{12})$ μm

- The resolution of the rotated coordinate (res_{rot}) has been estimated with (conservative):

$res^2_{rot} = \sigma^2_{rot} - res^2_{tele}$

- Irradiated 3D sensor resolution is 5.7 μm at about 20° turn angle



$\tan^{-1}(\textit{pitch/active\_thickness}) = \tan^{-1}(50/130) \simeq 21°$

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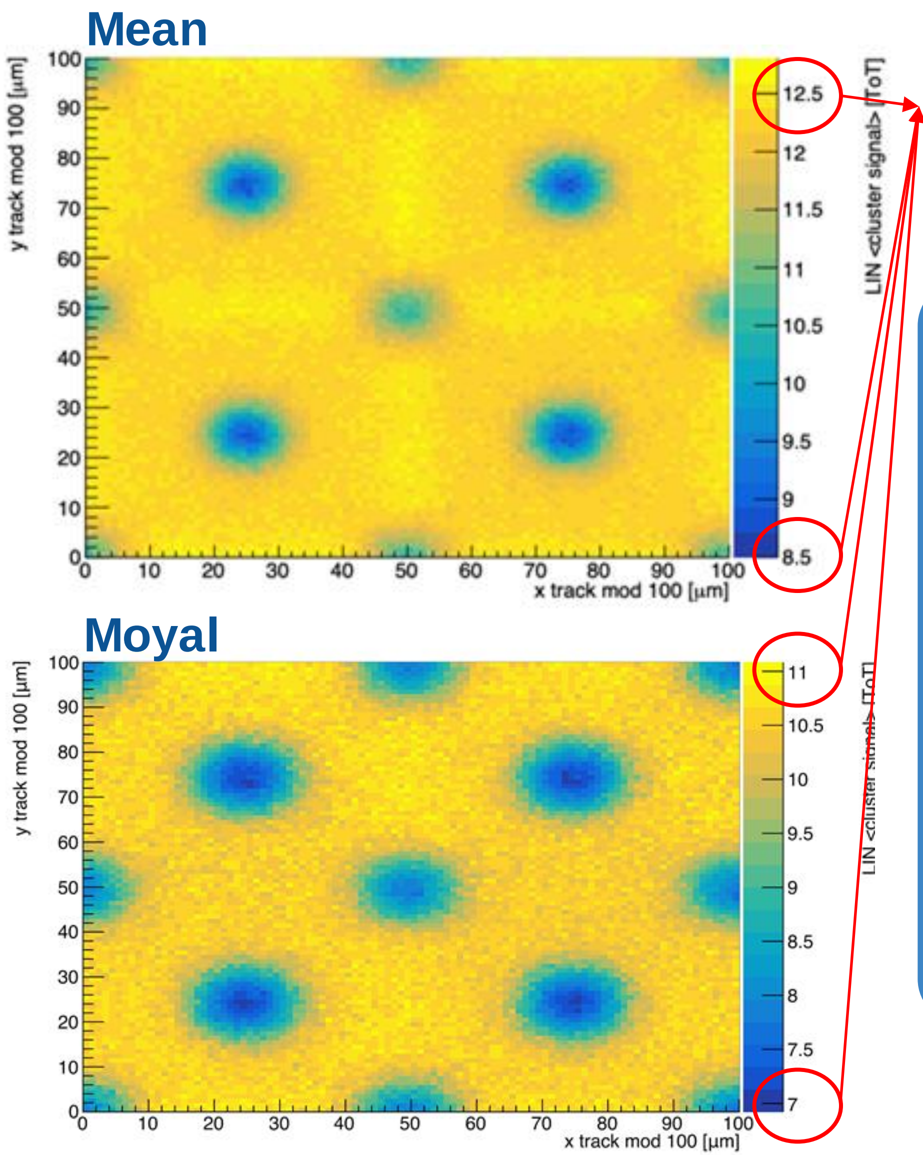
V_{bias} = 146 V

Fresh 50×50 μm²: recent studies on ToT estimation

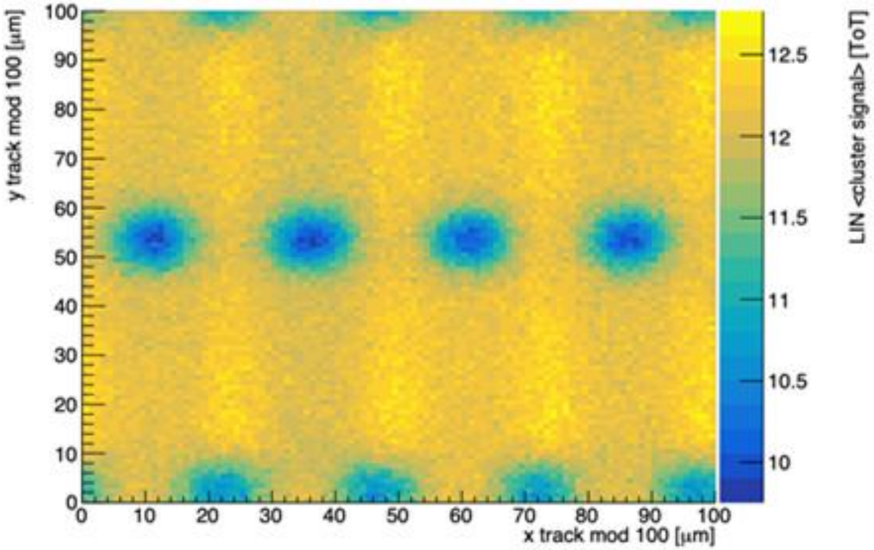


Different scales, but same range "shifted". Takes into account the different "mean value" of the plot

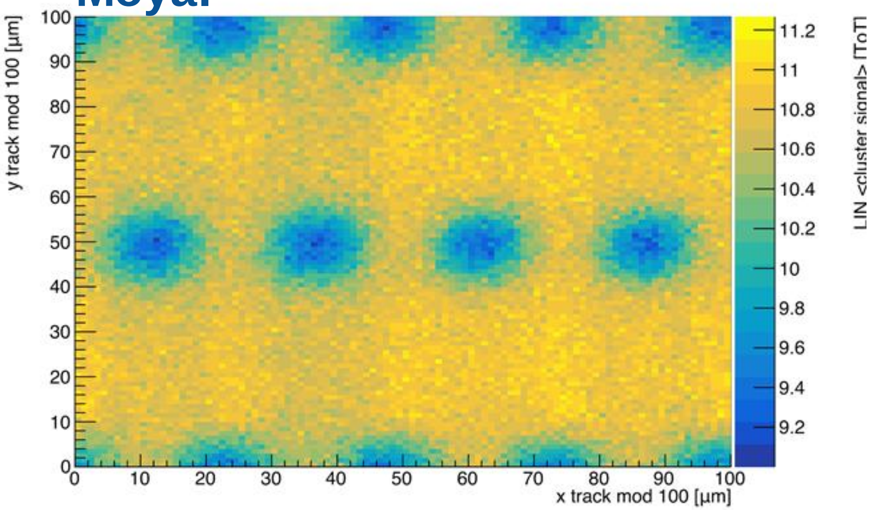
- High statistics plot with 100×100 bins, low statistics with 50×50 bins, contributions from the whole sensor moduled 100 μm (2×2 pixels for 50×50 μm² pitch)
- Mean value of ToT inside the bins tend to over-estimate the MPV and is sensible to cut_off
- Moyal distribution, on the other hand, needs post processing → different possible approaches studied
- All the methods give very similar and reliable results

Fresh 25×100 μm²: recent studies on ToT estimation

Mean



Moyal



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Conclusions

- CMS Inner Tracker Upgrade is extremely challenging
- Good results with fresh FBK 3D modules, both 50×50 μm^2 and 25×100 μm^2:
  - ✓ Fully efficient (>99%) at 6 V of bias voltage for perpendicular tracks
  - ✓ Resolution up to ~5(3) µm for 50×50 (25×100) μm^2
- Irradiated ($1\times10^{16} n_{eq} cm^{-2}$) FBK 3D module is also very good in performances:
  - ✓ Fully efficient at ~100 V
  - ✓ Resolution up to ~5.7 µm for 50×50 μm^2
  - ✓ 98.8% hit efficiency
- 3D pixels are confirmed to be strong candidates for the inner layers of the silicon trackers to be built for the HL-LHC

Thank you for your attention

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Many thanks to:

M. Meschini, R. Ceccarelli, S. Gennai, A. Cassese, M. Boscardin, E. Curras, L. Demaria, M. Dinardo, J. Duarte, A. Ebrahimi, G. F. Dalla Betta, M. Fernandez, F. Ficorella, L. Gaioni, A. Garcia, C. Gemme, S. Gennai, G. Gomez, J. Gonzalez, R. Mendicino, A. Messineo, E. Monteil, L. Moroni, S. Parolia, D. Pitzl, S. Ronchin, G. Sguazzoni, E. Silva, J.Sonneveld, G. Steinbrück, I. Vila, L. Viliani, D. Zuolo

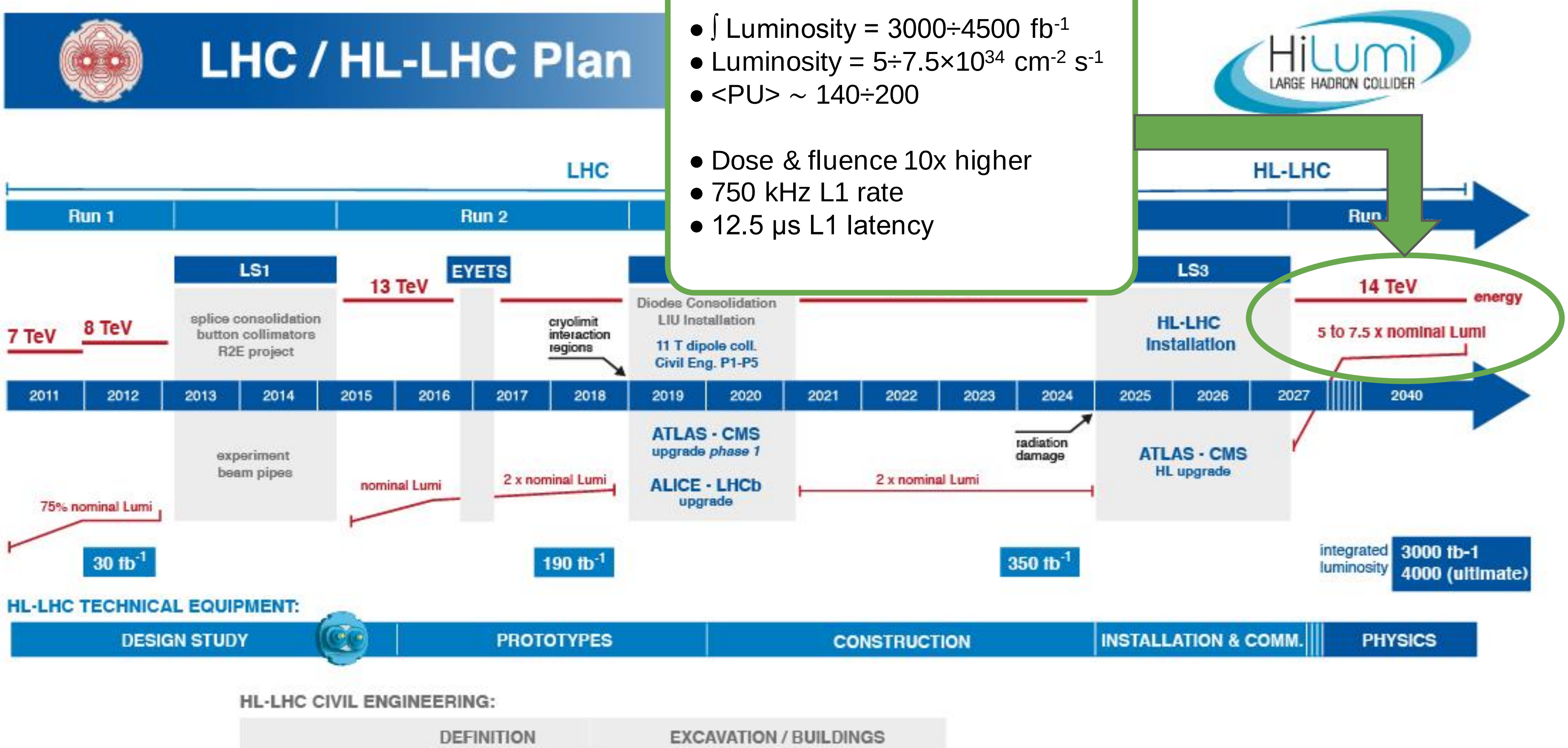
Backup

CMS Phase-2 tracker @ HL-LHC

CMS Phase-2 tracker @ HL-LHC

- $\int$ Luminosity = 3000÷4500 fb^{-1}
- Luminosity = 5÷7.5×10^{34} cm^{-2} s^{-1}
- <PU> ~ 140÷200

- Dose & fluence 10x higher
- 750 kHz L1 rate
- 12.5 μs L1 latency



CMS Phase-2 tracker @ HL-LHC

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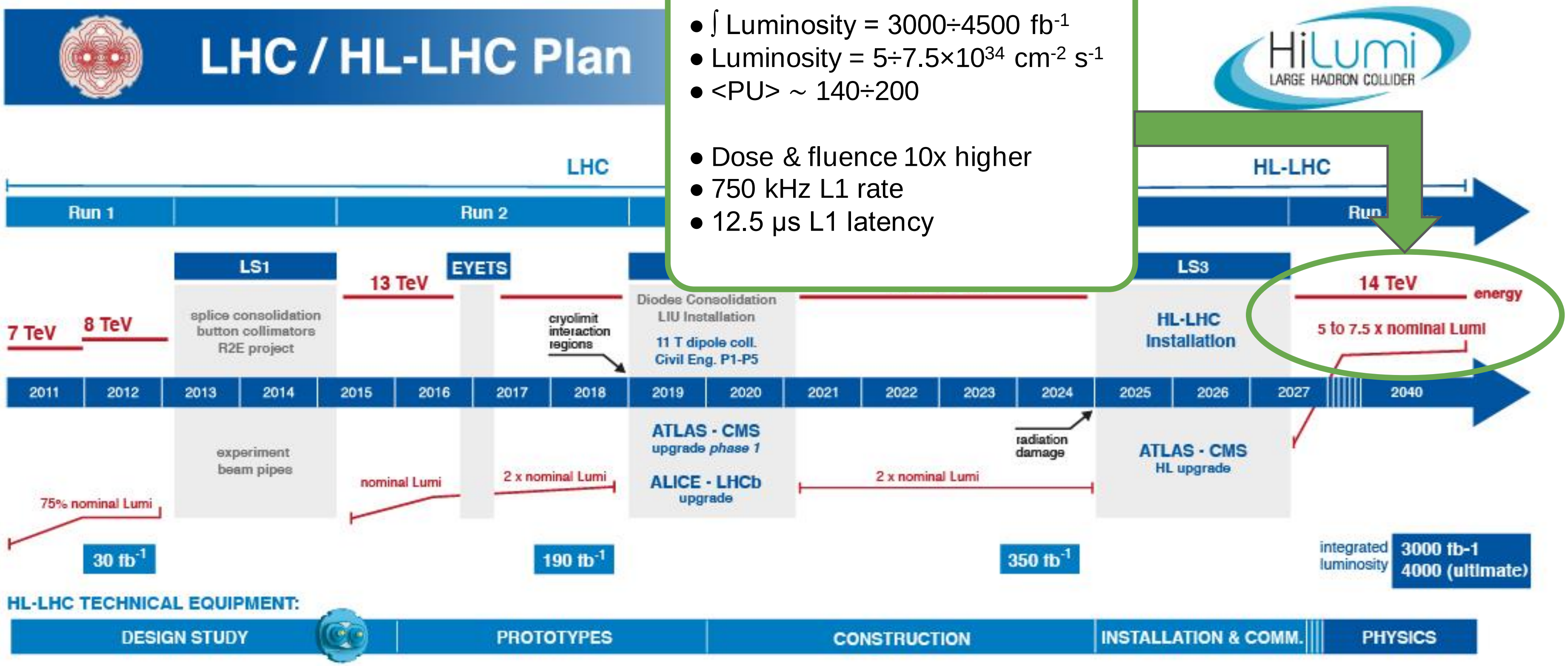
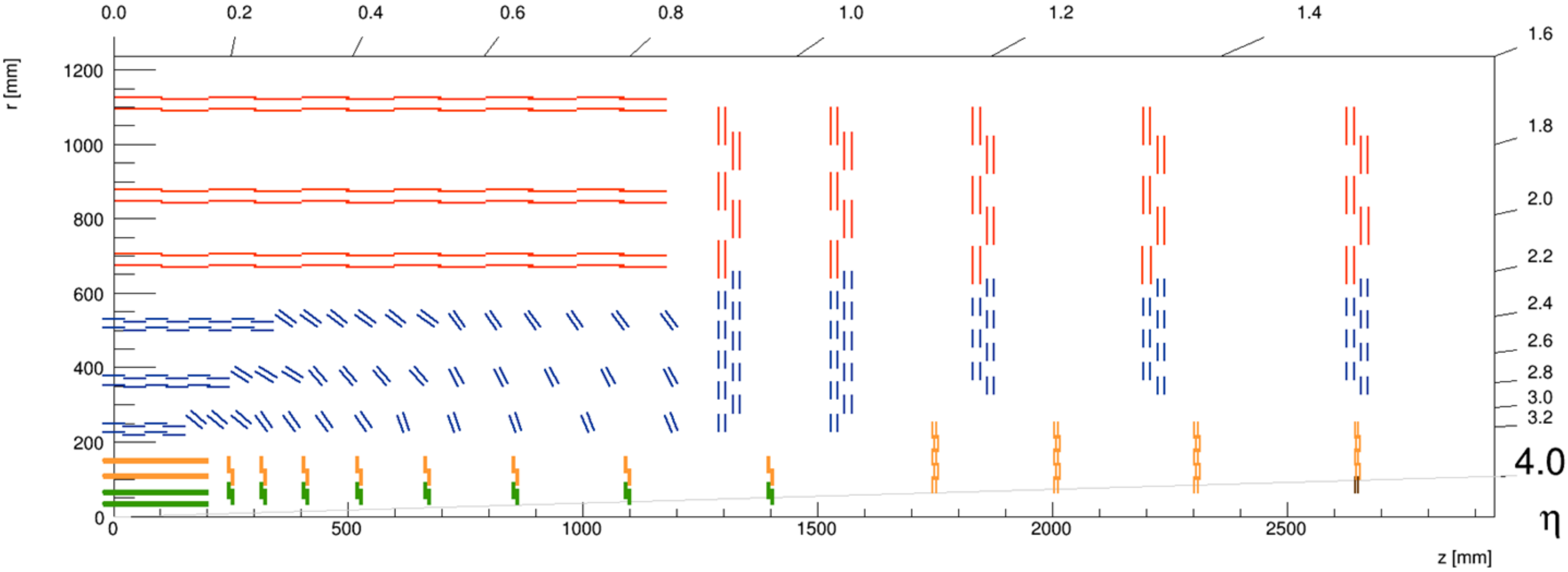
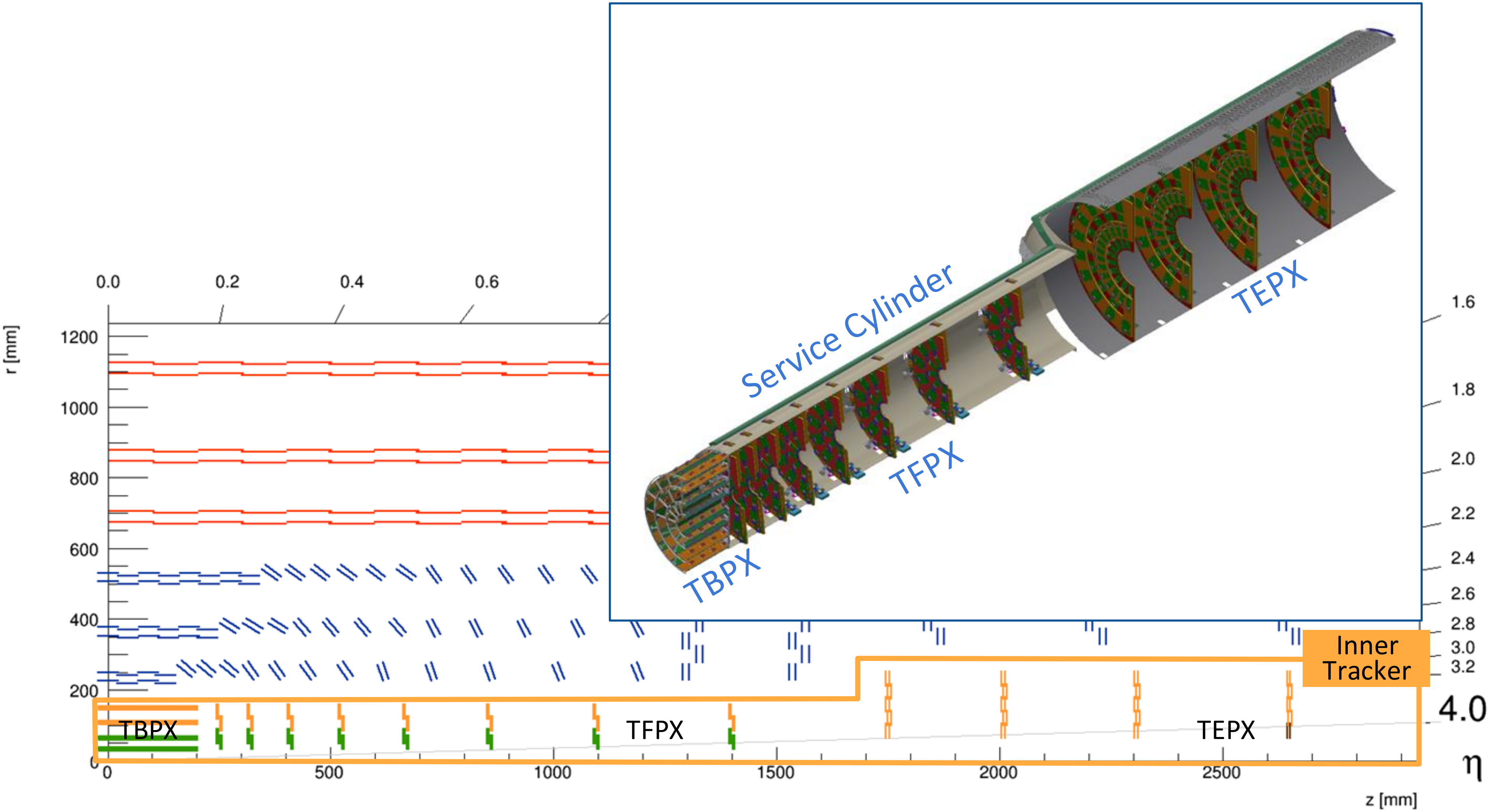


The present CMS tracker cannot sustain the foreseen radiation levels and data rates and has to be completely replaced

Inner Tracker upgrade for High Luminosity



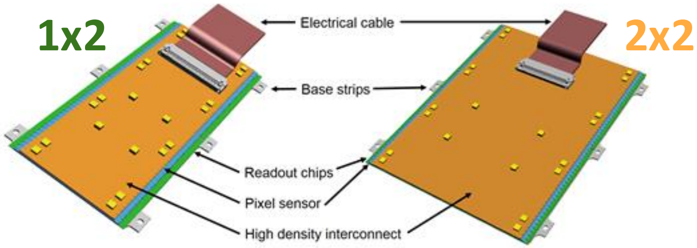
Inner Tracker upgrade for High Luminosity



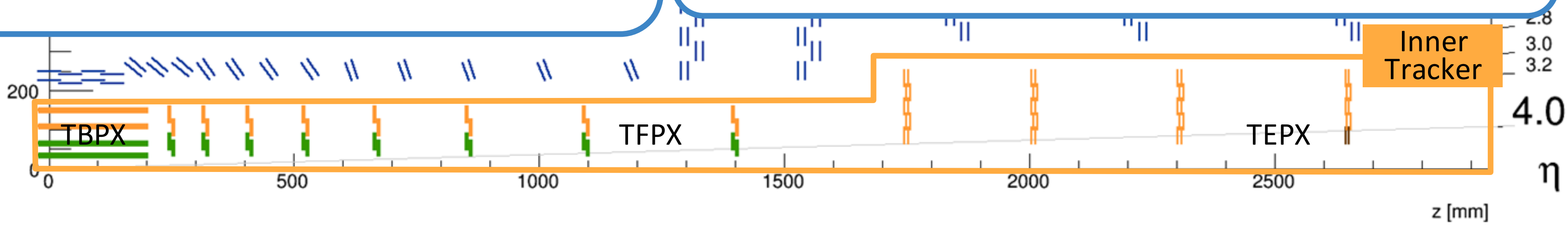
Inner Tracker upgrade for High Luminosity

Main requests and innovations

- **High radiation tolerance:**
  - 2.3×10^{16} n_{eq}/cm^2, fluence
  - 1.2 Grad, TID
- **Improve tracks separation:**
  - High granularity
  - High bandwidth (up to 3.5 GHz/cm^2 occupancy)
  - Low material budget
- **Extend tracking coverage:**
  - $|\eta| \leq 4$
- **Stringent space constraints**



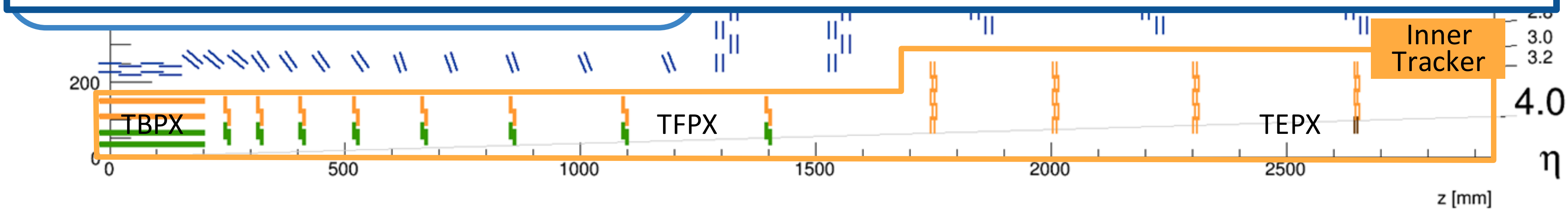
- TBPX 4 layers, TFPX 2x8 disks, TEPX 2x4 disks
- **3900 modules**
- **2×10^9 pixels** (124×10^6 in Phase-1)
- 4.9 m^2
- Hybrid modules with **2 (1×2)** or **4 (2×2)** readout chips
- **1156 modules, 2736 modules**
- Simple mechanics:
  - Can be removed for maintenance
  - Barrel splits in half at z ~ 0
  - Disks with planar geometry



Inner Tracker upgrade for High Luminosity

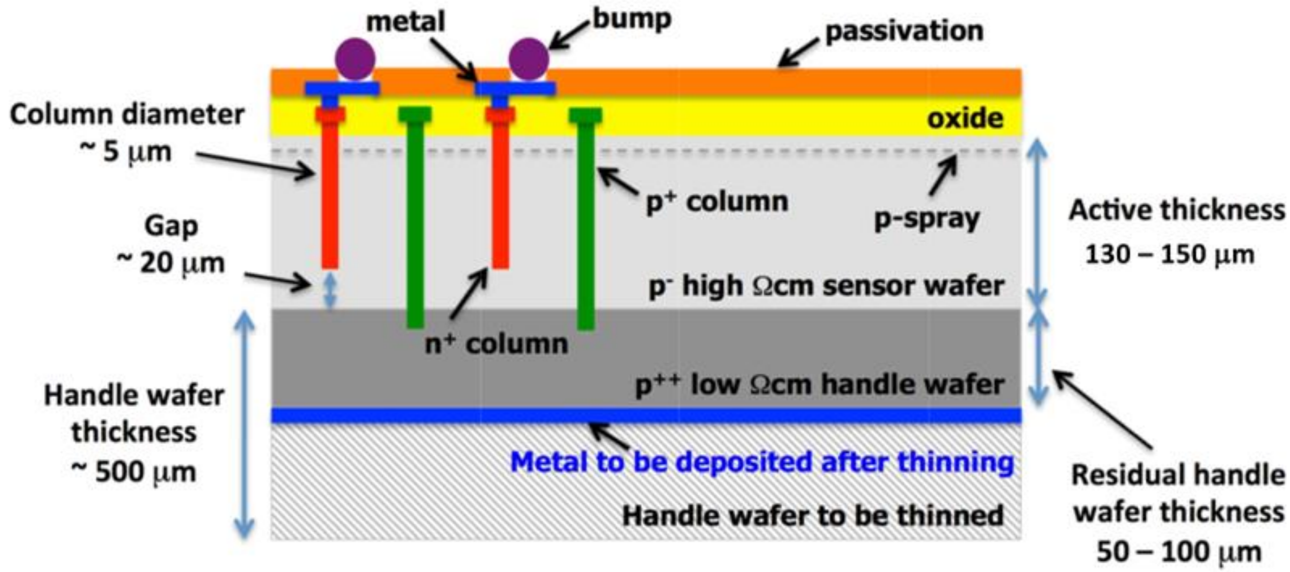
A lot of talks on HL-LHC CMS Inner Tracker (and not only):

- Jory Sonneveld talk (17th Feb 2020, 12:55): “The CMS Pixel Detector for the High Luminosity LHC” https://indico.cern.ch/event/813597/contributions/3727821/
- Corrinne Mills talk (17th Feb 2020, 15:15): “Performance of highly irradiated pixel sensors for the CMS HL-LHC upgrade” https://indico.cern.ch/event/813597/contributions/3727828/
- Finn Feindt talk (17th Feb 2020, 15:55): “Test Beam Characterization of Planar Pixel Sensors for the CMS Phase 2 Upgrade” https://indico.cern.ch/event/813597/contributions/3727834/
- Jordi Duarte Campderros talk (19th Feb 2020, 10:00): “Study of 3D pixel sensors after non-uniform proton irradiation” https://indico.cern.ch/event/813597/contributions/3727824/
- Roberto Seidita talk (19th Feb 2020, 16:00): “Serial powering at CMS silicon tracker detector for High Luminosity Upgrade” https://indico.cern.ch/event/813597/contributions/3727820/



3D Pixel Sensors R&D

- 3D sensors at FBK Foundry (Trento, Italy): a common R&D program with FBK shared between Italian researchers of CMS and ATLAS and funded by INFN (Italy)
- 6" Si-Si DWB (Direct Wafer Bonding). Active Device Float Zone, P type, resistivity>3kOhm cm, 130μm (or 150μm) thick. CZ Handle wafer, 0.1-1 Ohm cm resistivity, 500μm thick.
- FBK Fully Top-side process: DRIE (Deep Reactive Ion Etching) technique
- Most of the sensors shown in this talk have been thinned down to a total thickness of 200μm; the thickness foreseen for HL-LHC CMS Inner Tracker is 250-275μm



HSTD12 Hiroshima M.Meschini, INFN Firenze 3

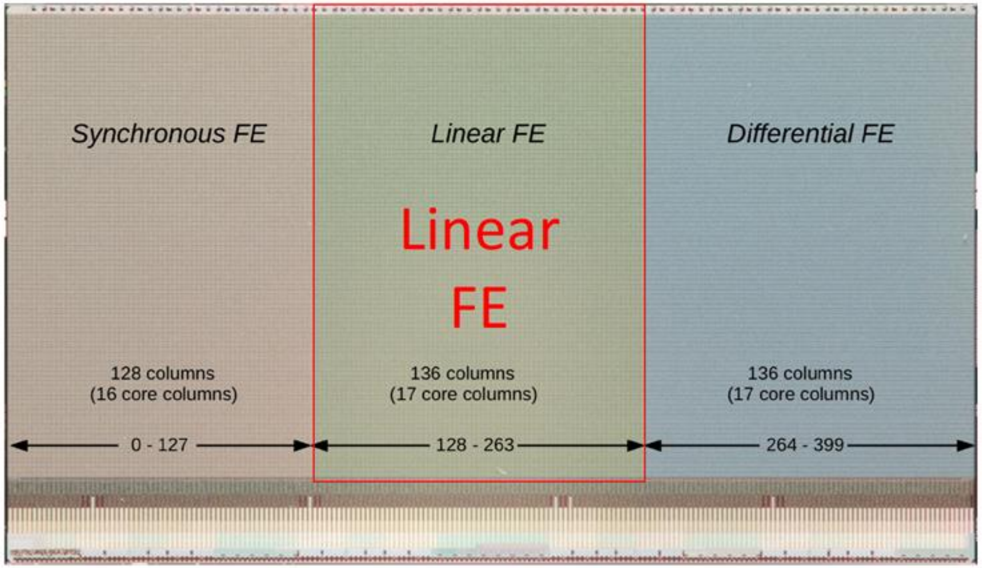
RD53: the inner tracker readout chip

RD53 ROC

RD53 collaboration is developing an ROC with:

- Dead time ≤1% @3.2 GHz/cm^2
- 0.5 (possibly 1) Grad TID resistant
- 65 nm technology
- 50×50 μm^2 cell
- low threshold (≤ 1000 e$^-$)
- High hit and trigger rate (up to 4×1.28 Gb/s output links)
- Serial powering capabilities
- CMS chip size (16.8×21.6 mm^2, 336×432 cells)

RD53: the inner tracker readout chip



RD53A first prototype

- ½ total size (**50×50 μm² cell**, 65 nm technology)
- Used for R&D
- Radiation hard up to 0.5 Grad
- Low threshold and high hit and rate capabilities (160 Mbps input and 1.28 Gbps output links)
- 3 analog Front-Ends (Synchronous, Linear, Differential)
- Time over Threshold counter to measure charge (4 bits); caveat ToT as charge unit
- CMS choice: Linear F.E.
- **All results presented here obtained using Linear F.E. (central section)**

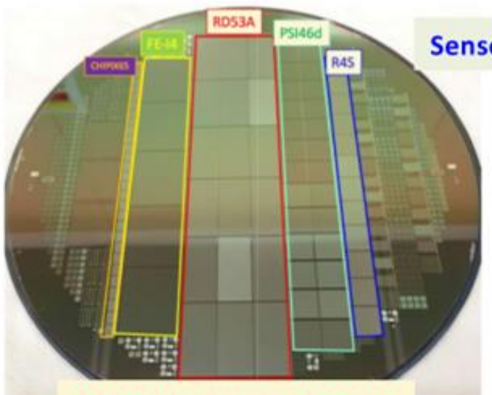
RD53 ROC

RD53 collaboration is developing an ROC with:

- Dead time ≤1% @3.2 GHz/cm²
- 0.5 (possibly 1) Grad TID resistant
- 65 nm technology
- 50×50 μm² cell
- low threshold (≤ 1000 e⁻)
- High hit and trigger rate (up to 4×1.28 Gb/s output links)
- Serial powering capabilities
- CMS chip size (16.8×21.6 mm², 336×432 cells)

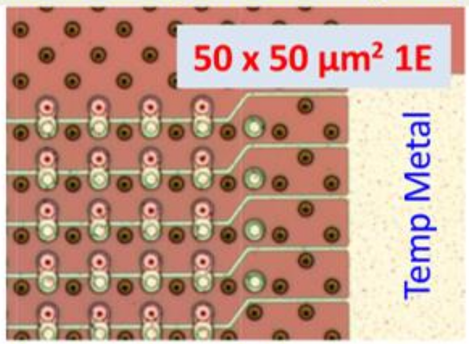
FBK 3D Pixel Batches: Mask Aligner and Stepper processes

"RD53A type" Sensors have **50 x 50 µm²** or **25 x 100 µm² unit pixel cell size**



3D Mask Aligner Oct 2017
18x RD53A sensors

Sensor corner with guard columns (photo)

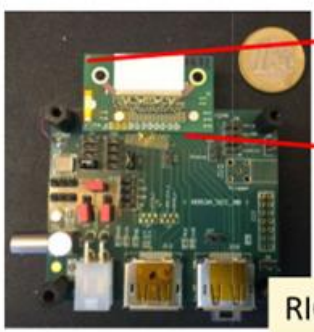


I-V curves done with Temporary Metal at FBK on all sensors

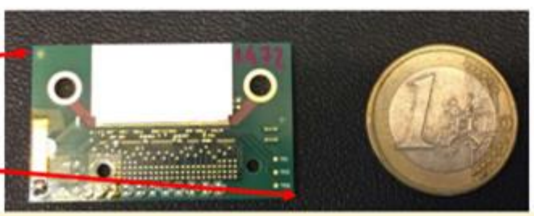
47x RD53A sensors

3D Stepper_1 July 2019

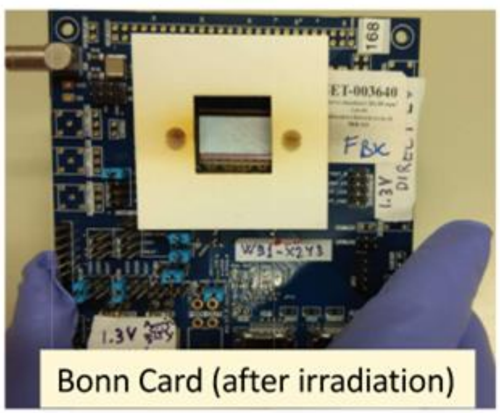
Readout Cards



RICE adapter card



RICE irradiation card (before irradiation)



Bonn Card (after irradiation)

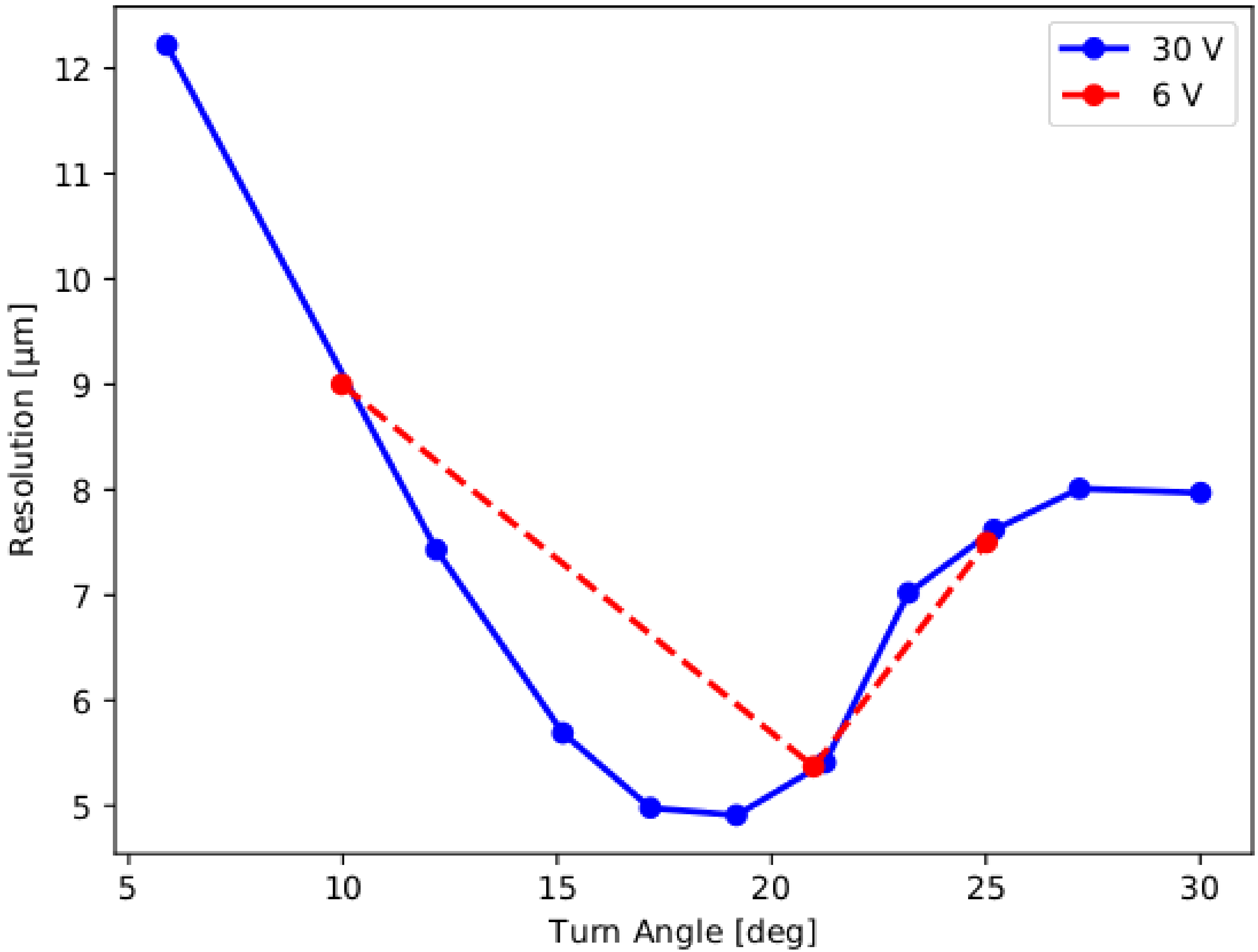
25×100 μm² setup

Telescope 4th plane

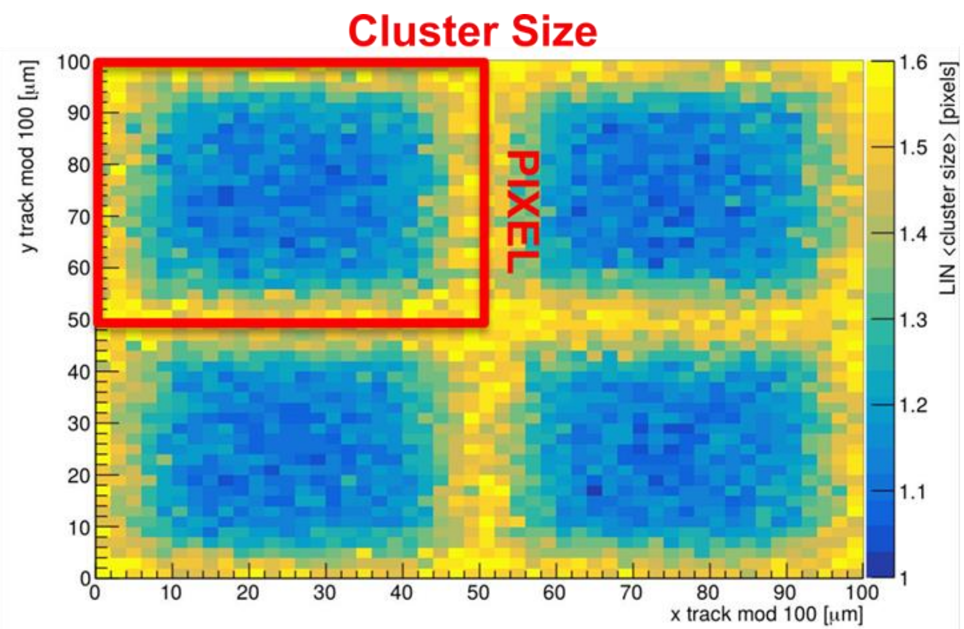
DUT
(on beam, turned)

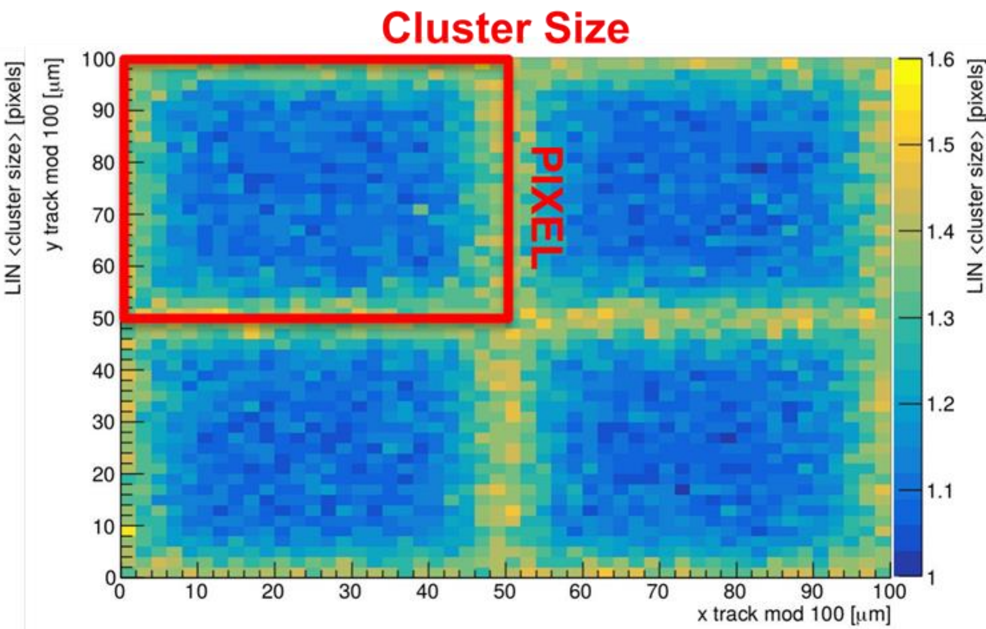
Telescope 3rd plane

Rotation wrt bias voltage



Cluster size: 50×50 μm² (MA)

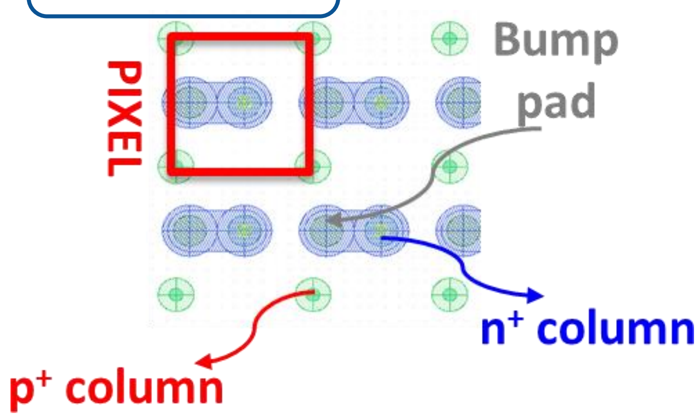




V_{bias} = 6 V

Orthogonal beam incidence

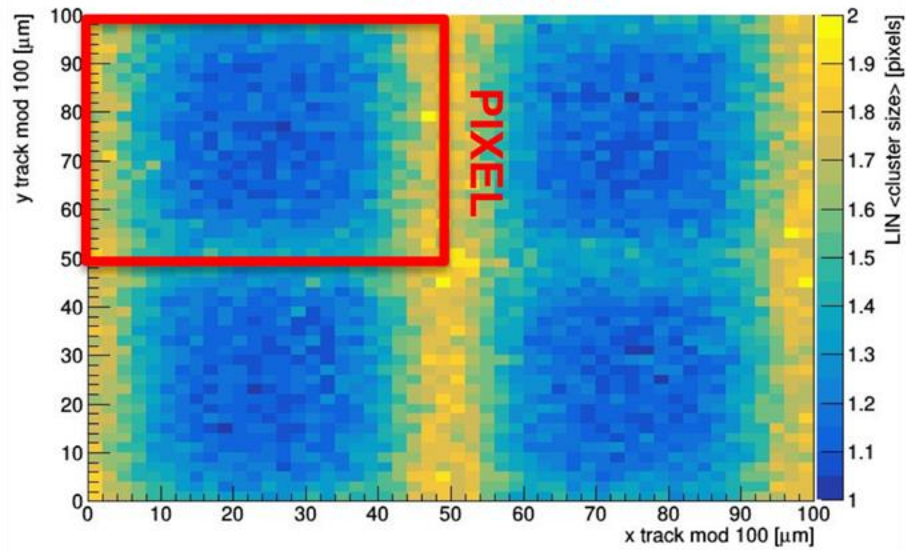
V_{bias} = 30 V



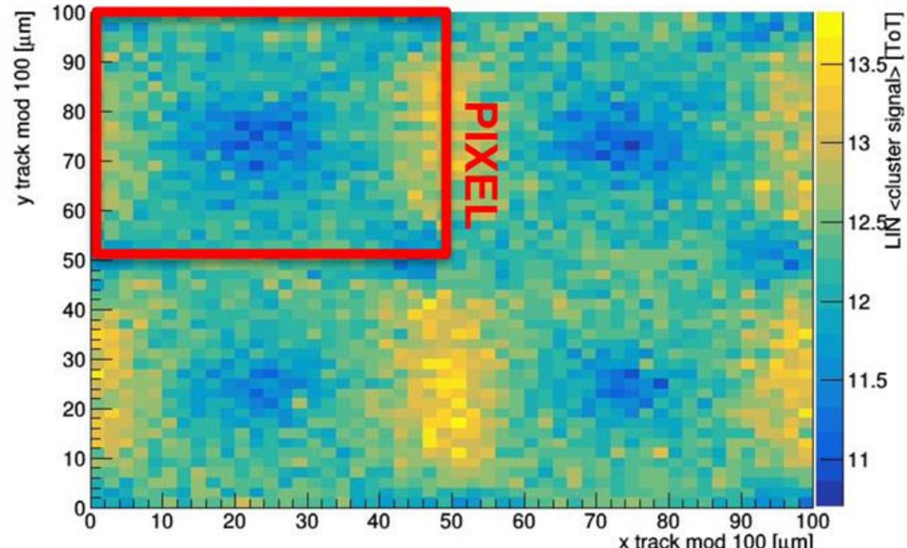
- Cluster size maps for 2×2 pixel grid
- Higher cluster size at lower bias voltage
  - More diffusion → more charge sharing between pixels

Cluster size, ToT, Efficiency: 50×50 μm² (MA) @6°

Cluster Size

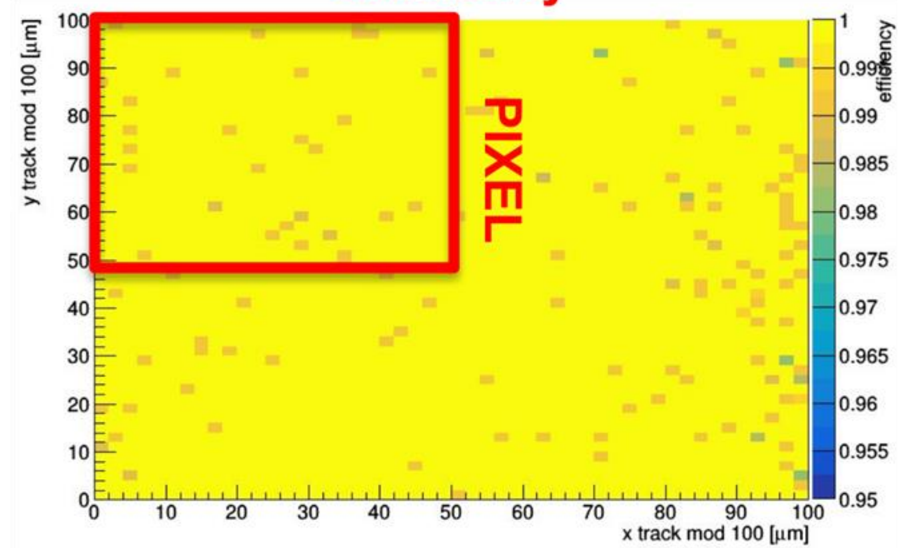


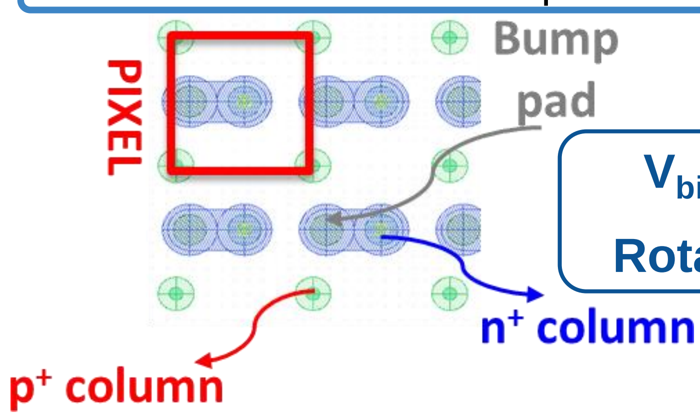
ToT



- Column inefficiencies are no longer there @6°
- Charge sharing due to rotation visible from cluster size and ToT maps for 2×2 pixel grid

Efficiency

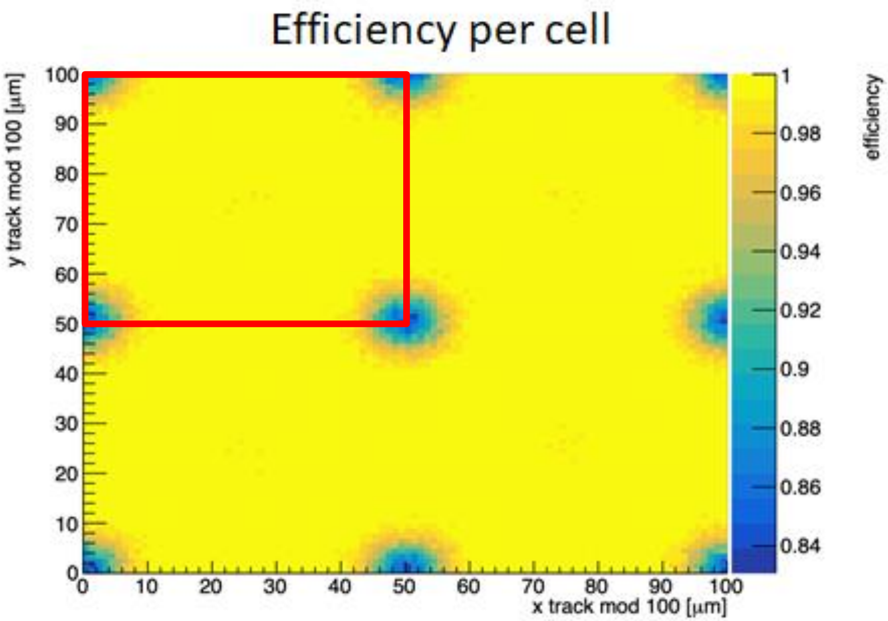


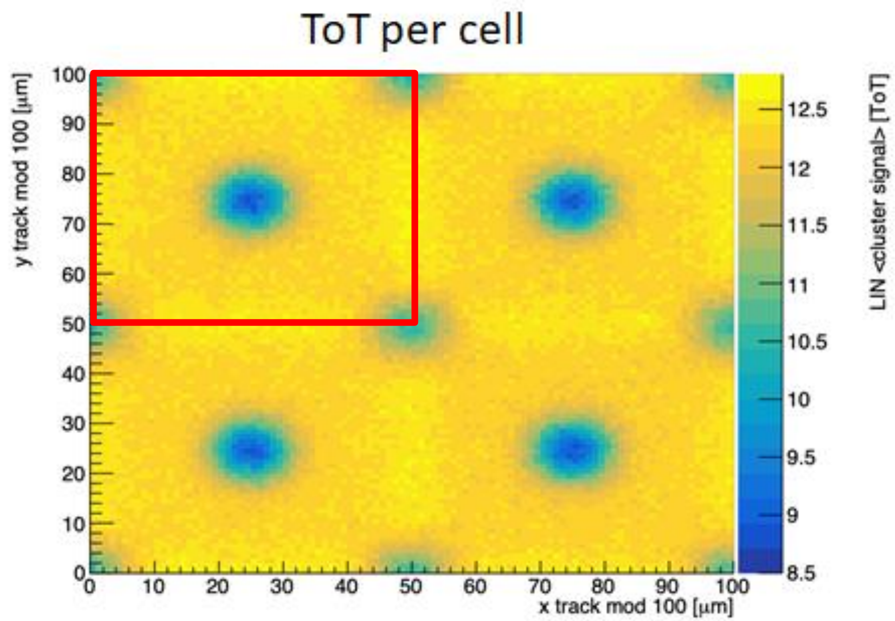


V_{bias} = 30 V

Rotation of 6°

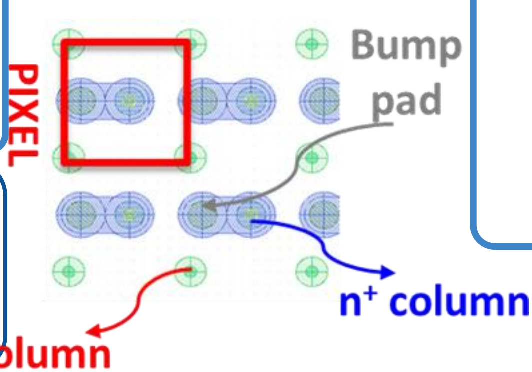
Hit efficiency and ToT: 50×50 μm² (Stepper)





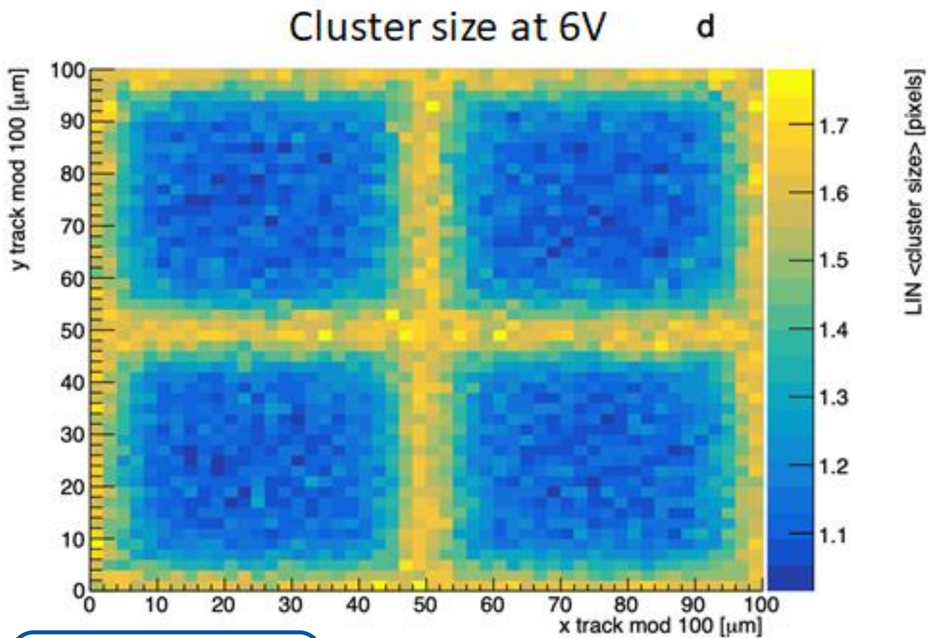
- Efficiency map for 2×2 pixel grid
- Efficiency drop near p^+ columns
- High efficiency near n^+ columns
- Global efficiency > 99%

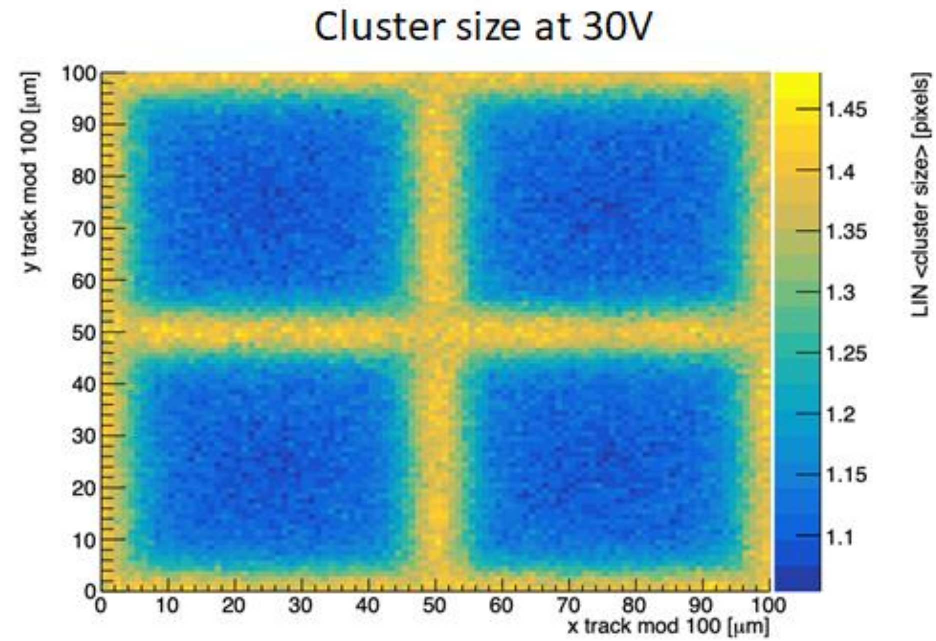
V_{bias} = 30 V
Orthogonal beam incidence
25M events



- Tot map for 2×2 pixel grid
- Low average Tot near n^+ columns
  - Low collected charge (due to passive column), but high efficiency

Cluster size: 50×50 µm² (Stepper)

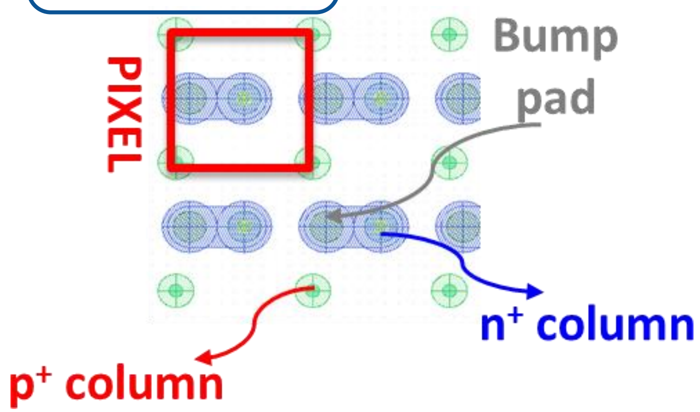




V_{bias} = 6 V
1M events

Orthogonal beam incidence

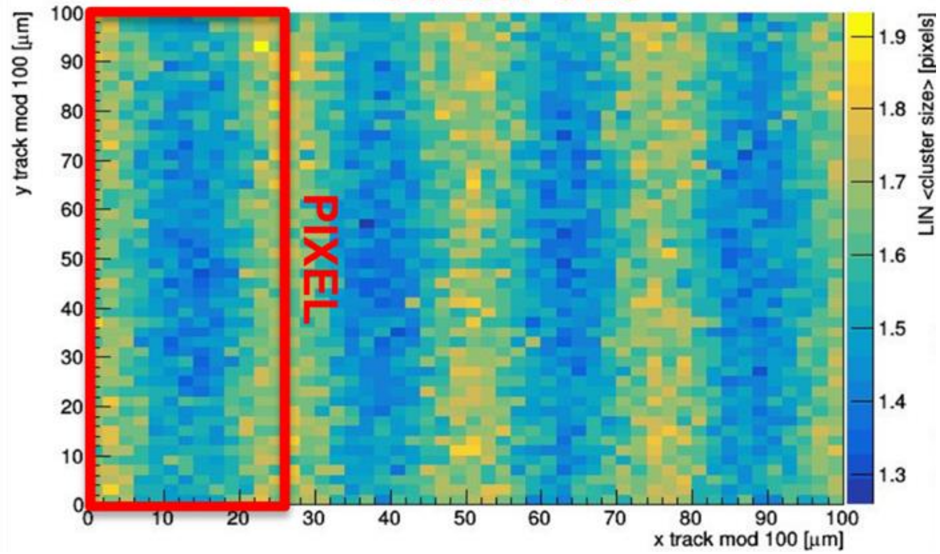
V_{bias} = 30 V
25M events



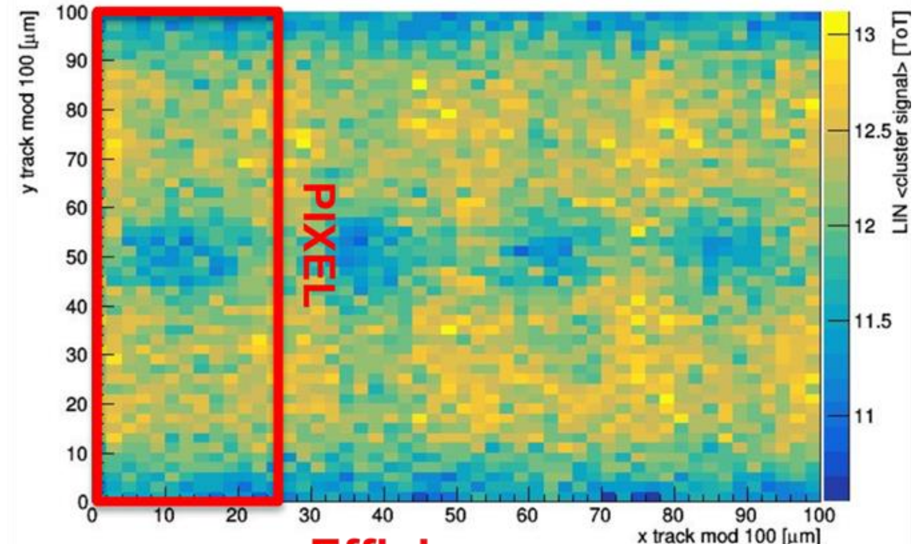
- Cluster size maps for 2×2 pixel grid
- Higher cluster size at lower bias voltage
  - More diffusion → more charge sharing between pixels

Cluster size, ToT, Efficiency: 25×100 μm²

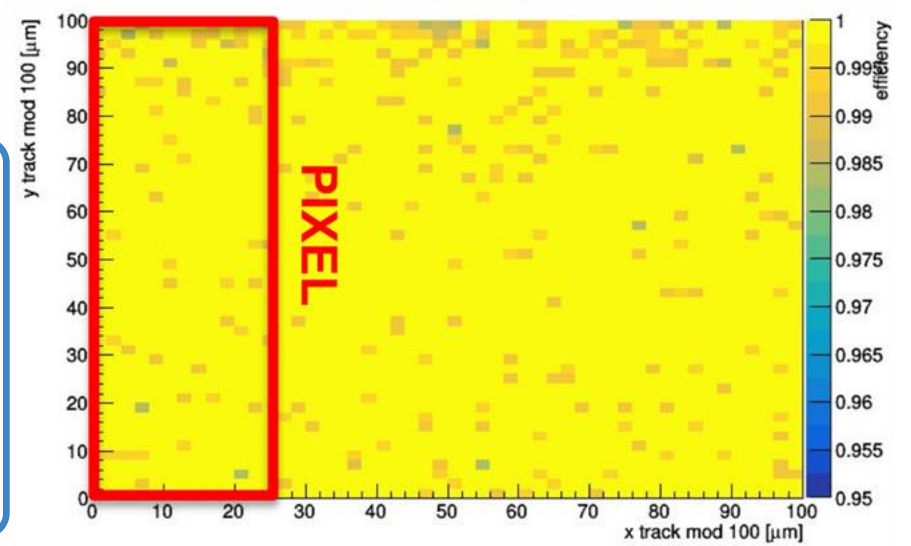
Cluster Size



ToT

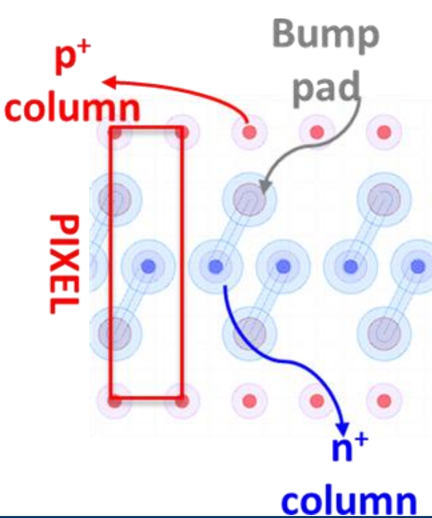


Efficiency



V_{bias} = 30 V

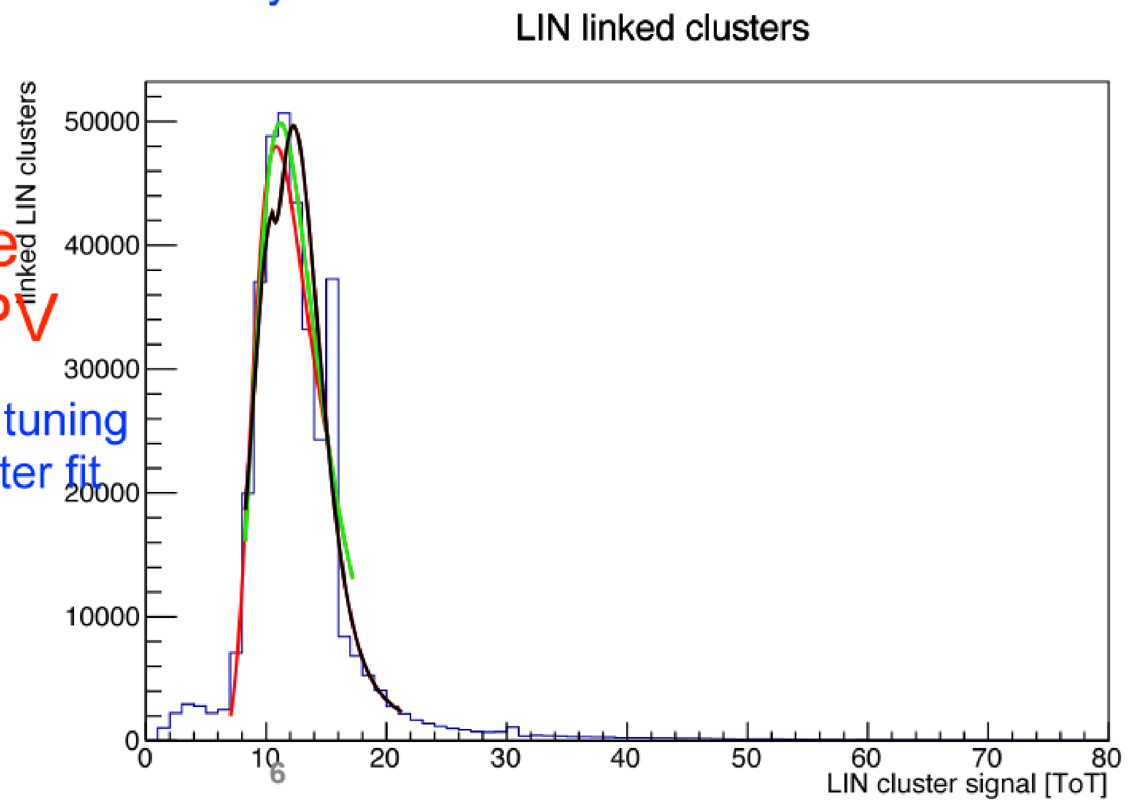
Rotation of 5°



- Column inefficiencies are no longer there @5°
- Charge sharing due to rotation visible from cluster size and ToT maps for 4×1 pixel grid

Estimation methods

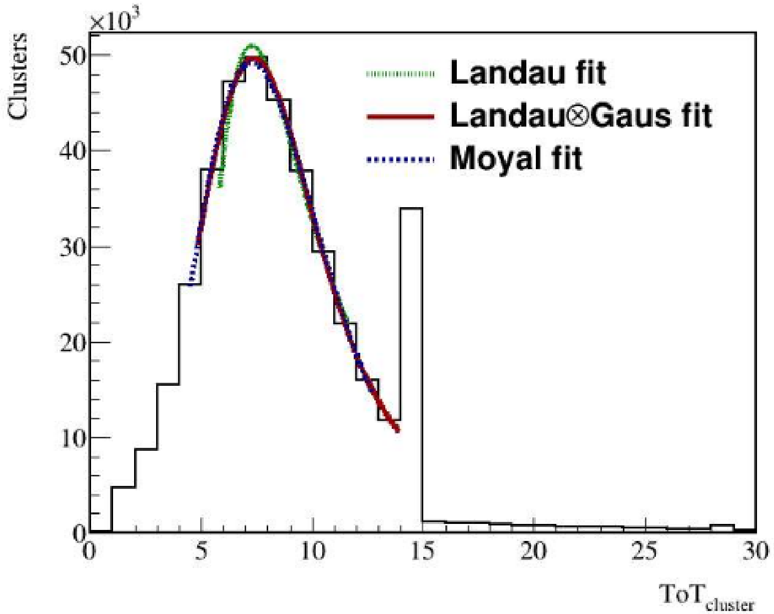
- We use the full sensor ToT distributions
  - Using clusters associated to a reconstructed track
  - We fit the distribution in several ways and we use the width to feed into the Moyal approx
- We then compare the estimated MPV
  - In some cases, some tuning is needed to get a better fit



What should we be using?

- But, an analytical distribution could approximate the Landau-Vavilov distribution → **Moyal** distribution

$$f(x) = \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{x-\mu}{\sigma} + e^{-\frac{x-\mu}{\sigma}}\right)\right\}$$



- Assuming N-measurements, following the Moyal distribution, the maximization of the Likelihood function gives the MPV (mode) estimator as,

$$\mu = -\sigma \ln\left(\frac{1}{N}\sum_{i=1}^{N} e^{-\frac{x_i}{\sigma}}\right) = -\sigma \ln\left\langle e^{-\frac{x_i}{\sigma}}\right\rangle$$

→ This is what it's used in Daniel Pitzl's code

5

Moyal, J.E, "Theory of ionization fluctuations", Lond.Edinb.Dubl.Phil.Mag.(1955) 46:374, 263-280

Rotondi, A.; Montagna, P, "Fast Calculation of Vavilov distirbution", NIM B47 (1990) 215-22