First test beam results of HPK planar pixel sensors with the CROC readout chip for the CMS Phase 2 Upgrade

CMS

Massimiliano Antonello

On behalf of the
CMS Tracker Group

SPONSORED BY THE

UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Federal Ministry of Education and Research

18th "Trento" Workshop on Advanced Silicon Radiation Detectors

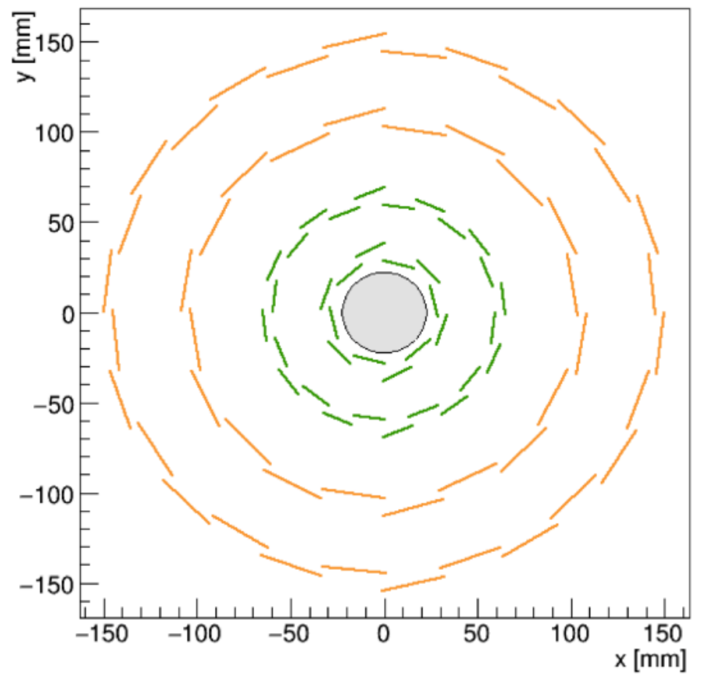
FBK, Trento 28-02-2023

The CMS Inner Tracker for the Phase 2 Upgrade

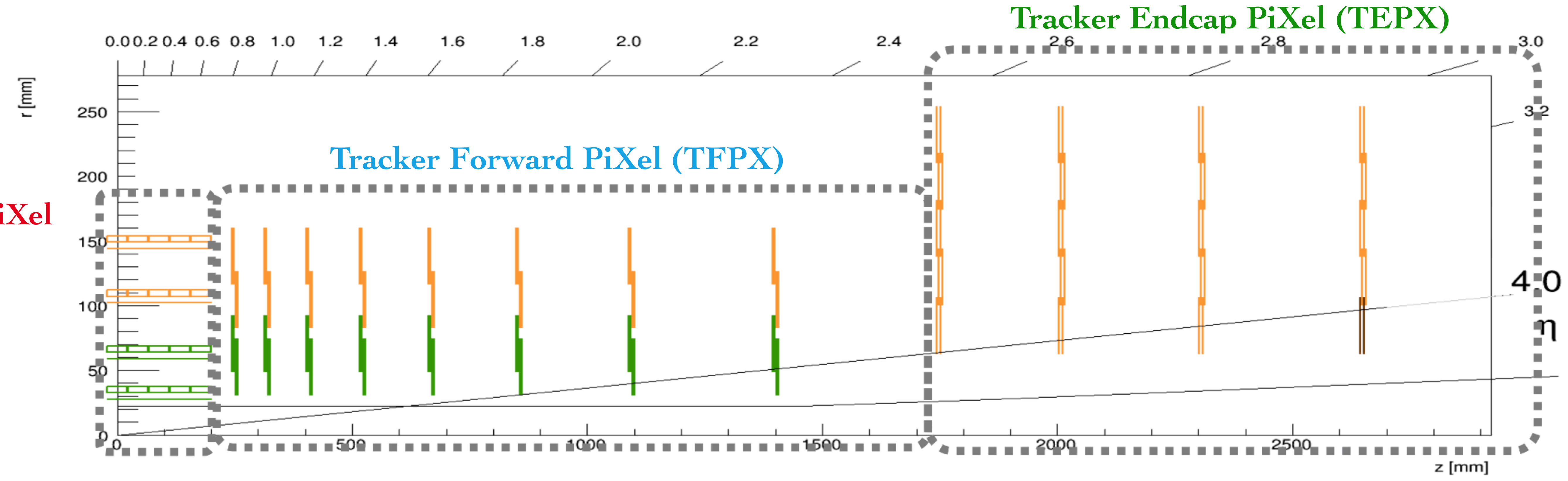
For the **HL-LHC** phase, the CMS **Inner Tracker (IT)** system will be entirely upgraded[1]

Detector layout:

- Coverage extended up to $|\eta| = 4$ = improved sensitivity in corners of the phase space important for the HL-LHC precision & discovery physics program
- Innermost layer @ **3 cm** from the beamline = max dose of **19.1 MGy** but same occupancy as in current Phase 1 detector (**10^{-4}**)



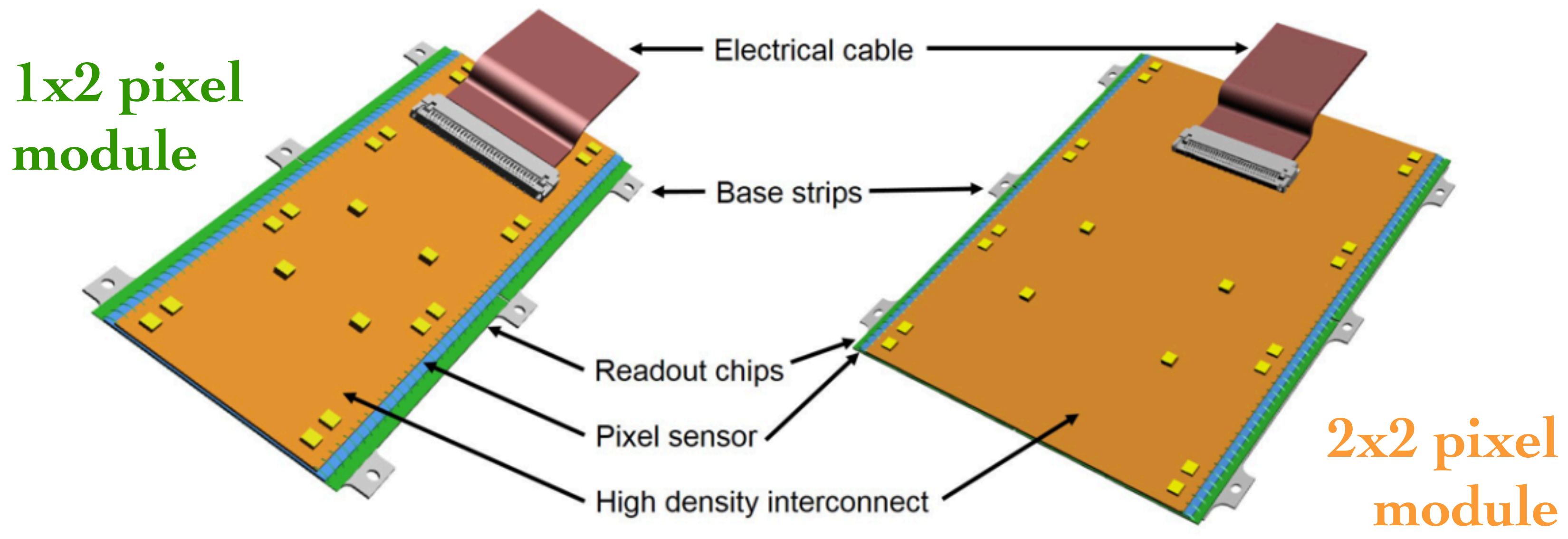
Tracker Barrel PiXel (TBPX)



- Only two types of **hybrid pixel modules** = complexity reduced & flexible management of spares

1156 1x2 pixel modules:
  - 2 readout chips (ROCs) per module
  - dimension: roughly **1.8 x 4.4** cm^2

2736 2x2 pixel modules:
  - 4 ROCs per module
  - dimension: roughly **3.7 x 4.4** cm^2

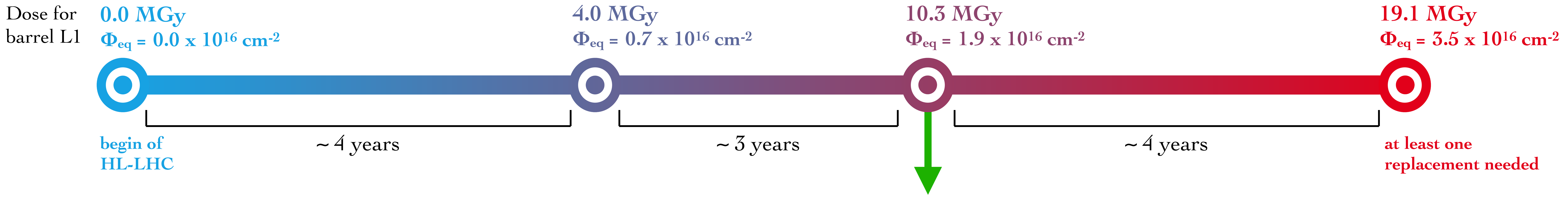


[1] The Phase 2 Upgrade of the CMS Tracker (TDR)

Fluence scenario and sensor requirements

The new **HL-LHC** upgrade environment:
- Luminosity @ **7.5×10^{34} cm^{-2}s^{-1}**, with an integrated luminosity of **4000 fb^{-1}** (10x times more than Phase 1)
- Pile-up to $<\mu>$ = **200** (5x times more than Phase 1)

Based on the integrated luminosity scenario of **4000 fb^{-1}** and the latest FLUKA simulation:



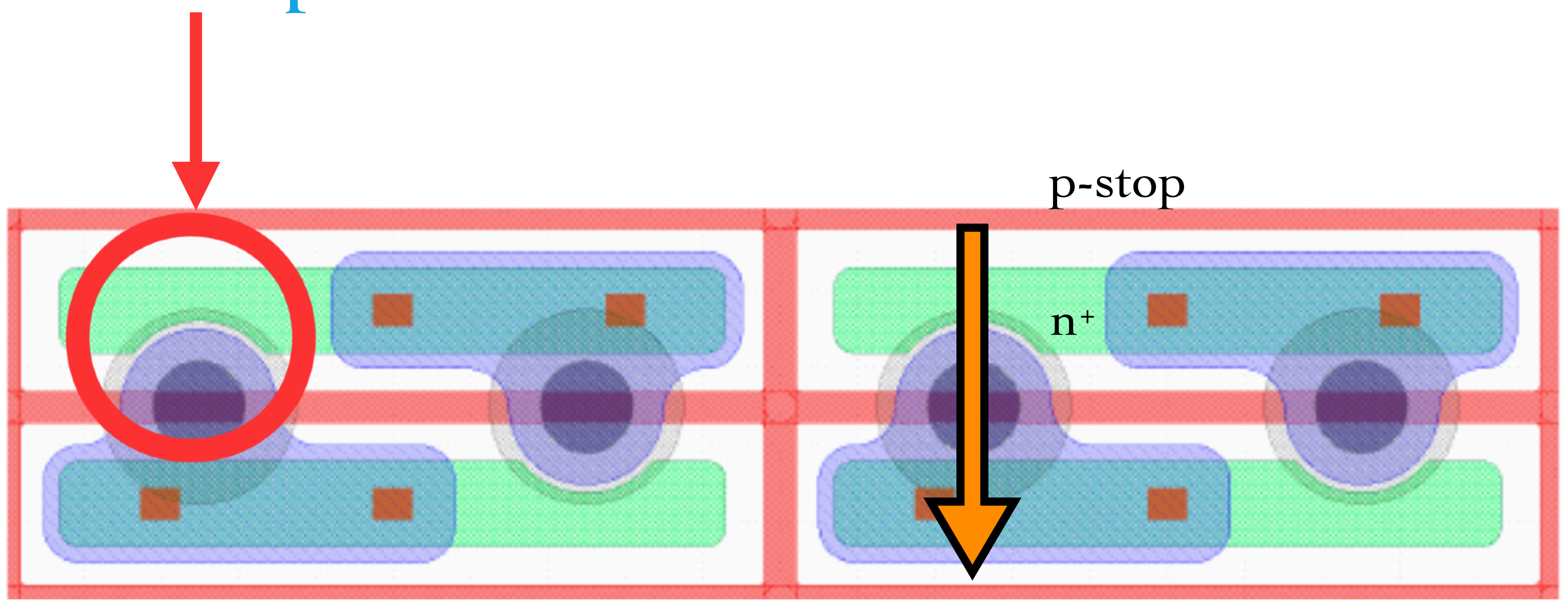
Final chip (**CROC**) validated up to **Φ_{eq} = 2.0×10^{16} cm^{-2}** : **replacement of layer 1 of the barrel** required

Some **planar sensor design** constraints:
- High radiation tolerance: largest average fluence for TFPX ring 1 is Φ_{eq} = 1.3×10^{16} cm^{-2} (dose of 8.1 MGy)
- Avoid cluster merging & keep the occupancy below **10^{-4}**: from **100 x 150 μm²** to 25 x 100 μm²
- High single hit reconstruction efficiency: ε_{hit} > 98% for L1 and ε_{hit} > 99% for L2-L4 (end of lifetime)
- High spatial resolution: $\sigma_{hit} < pitch/\sqrt{12}$
- No **thermal runaway**

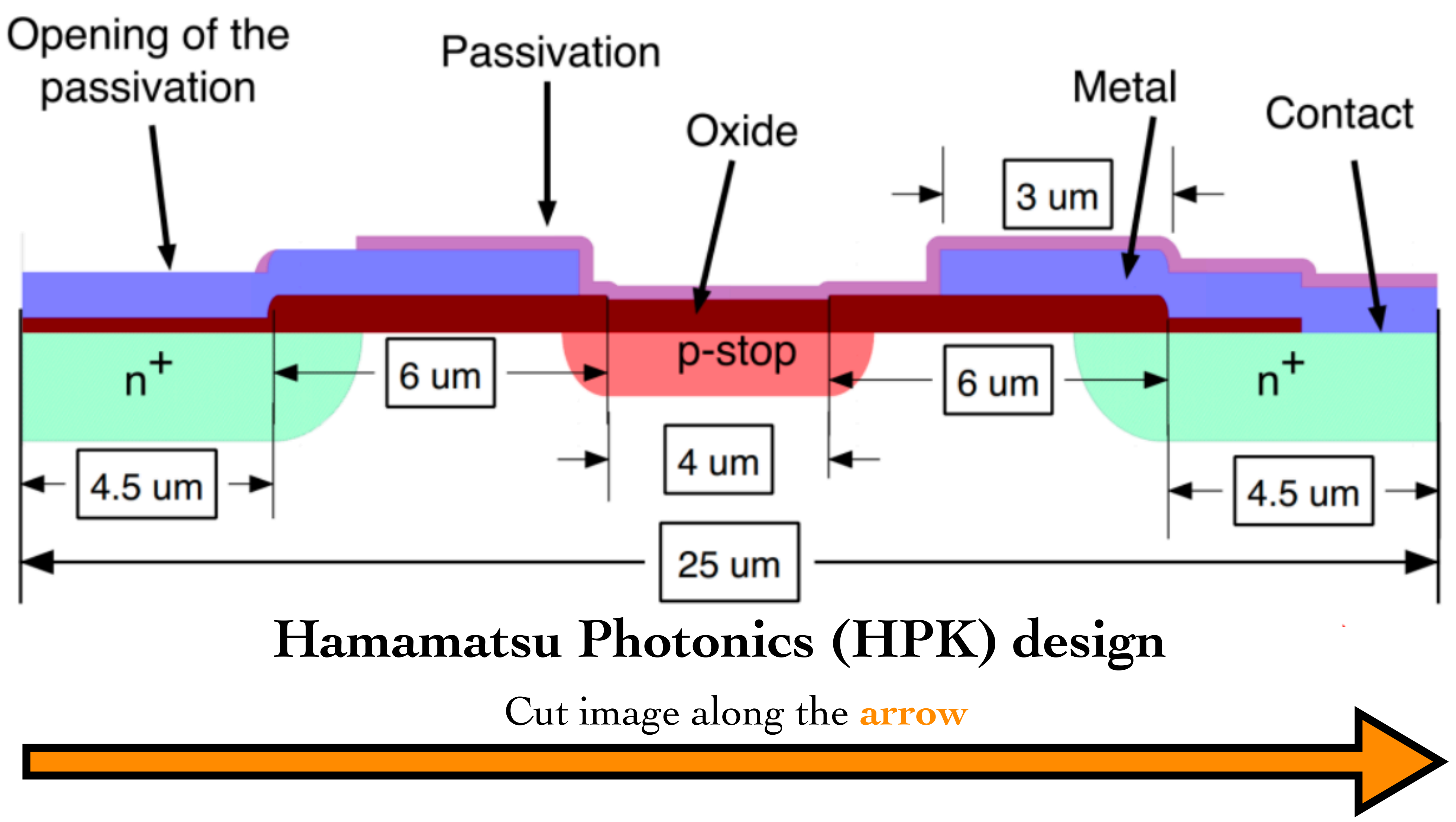
The planar sensor baseline design

Baseline design chosen:

- ✓ Hybrid pixel detectors = powerful solution in terms of readout speed & radiation tolerance
- ✓ n-in-p planar sensors for all but first barrel layer:
  - Single sided processing (front-side only) = less prod. steps & lower cost
  - Active thickness: 150 μm (from 285 μm) = higher rad. hardness & lower V_{bias} for high ε (lower power dissipation)
  - 25 x 100 μm² cell size
  - Inter-chip regions with **long** pixels (for both 1x2 and 2x2 modules)
  - **Parylene coating** of the module = spark protection
  - No punch through bias (higher ε)[1]
- ✓ No n⁺ implant under metal to reduce crosstalk



✓ Bitten implant design



Hamamatsu Photonics (HPK) design

Cut image along the arrow

[1] F.Feindt - 16th Trento Workshop (Link)

Readout chips

All sensors bonded to RD53 chips[1]:

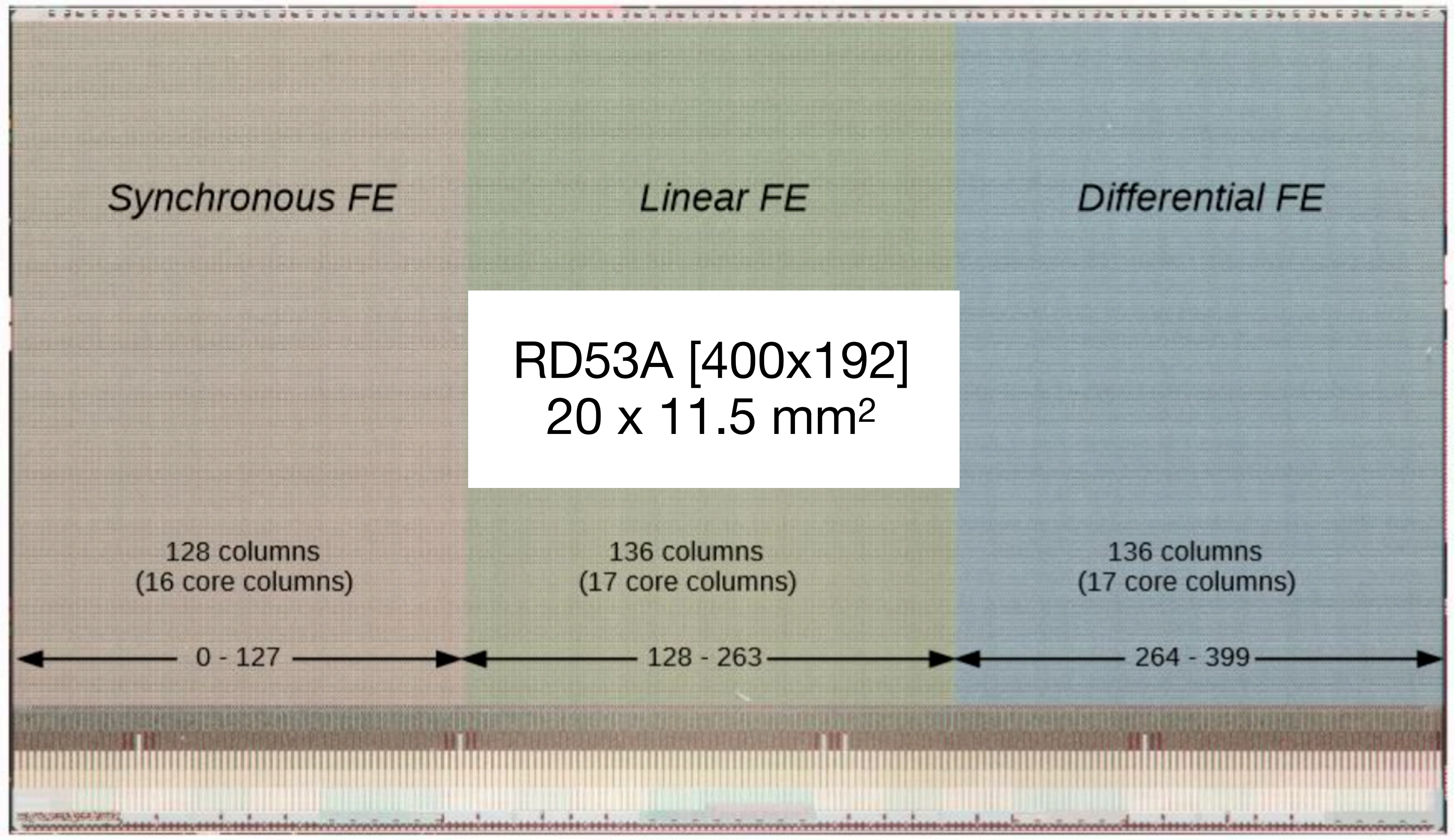
- **65 nm CMOS technology** (TSMC), radiation hard design
- 50 x 50 μm² pixel pitch
- Adjustable online threshold: below **1000 e⁻**
- Charge digitization via 4-bit Time-over-Threshold (ToT unit)

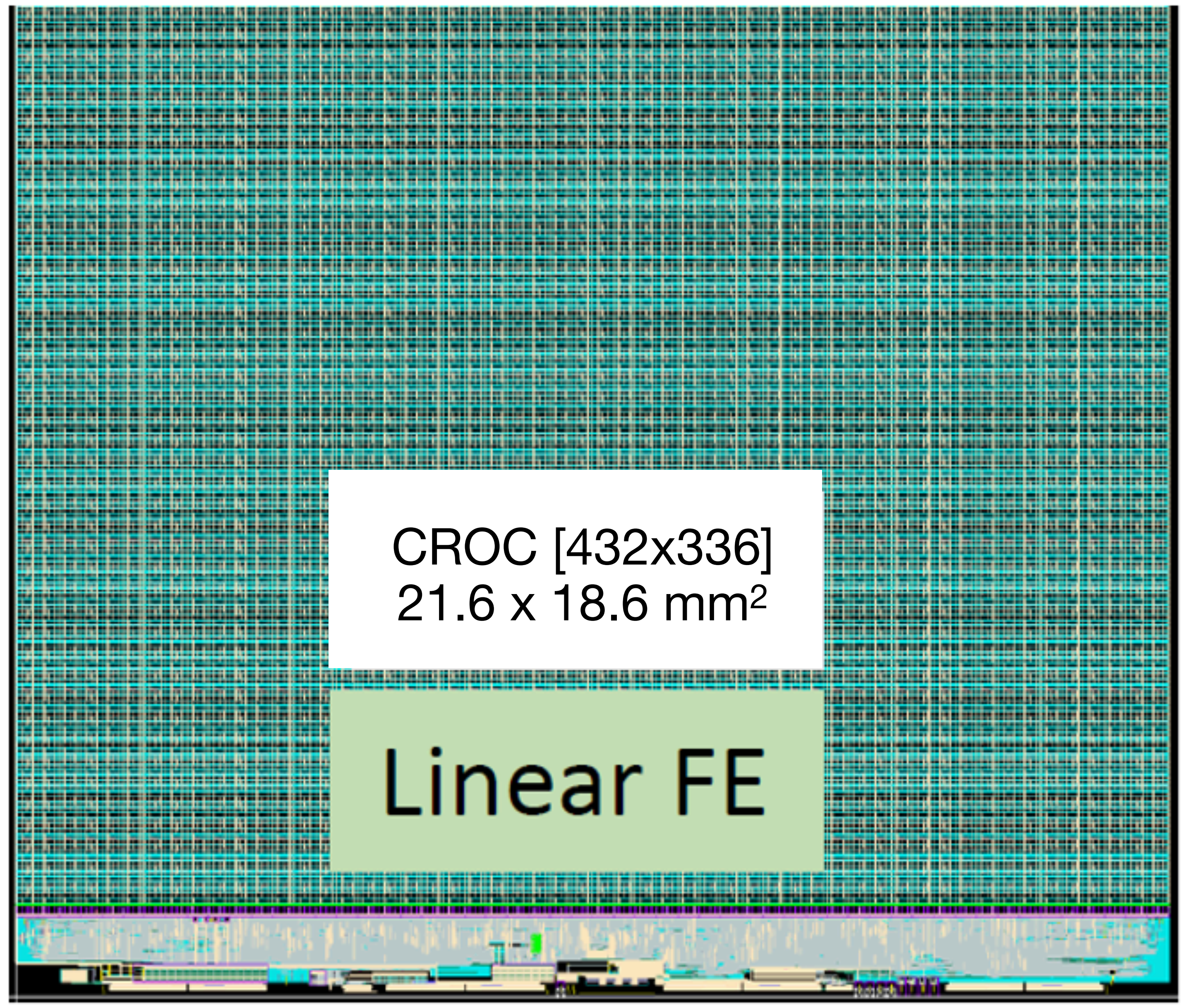
All the RD53 chips for CMS:

- RD53A: half-size module demonstrator with 3 FE designs
- RD53B_CMS/CROC: full-size pre-production chip (only LIN FE)
- **RD53C**: full-size production final chip

Main improvements from RD53A (Linear FE) to CROC (CMS Read-Out Chip):

- Increased TDAC circuit **dynamic range** (with an extra 5th bit) —> to compensate for saturation at low temperatures
- Improved **cluster charge** estimation —> with dual slope ToT (under test)





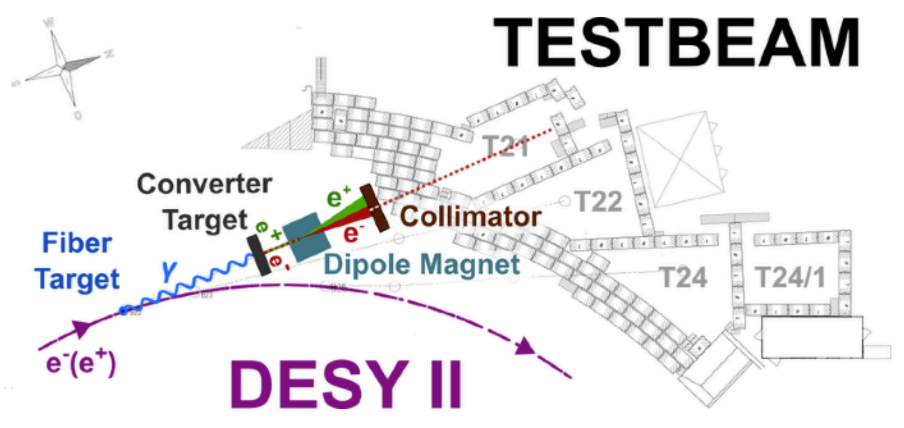
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

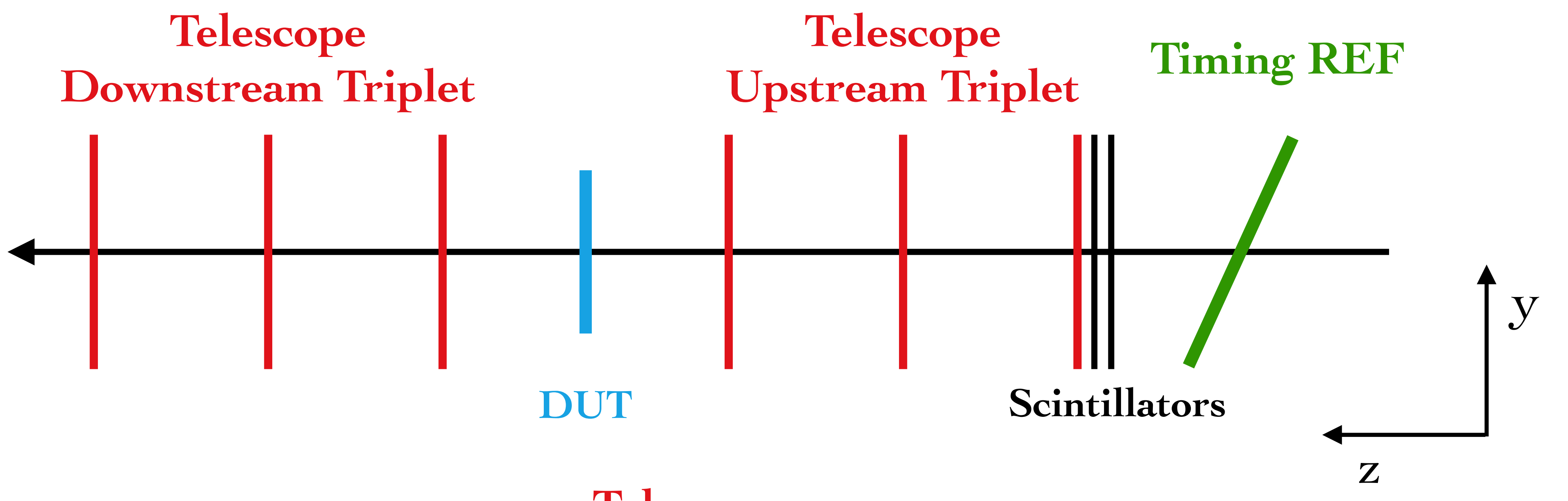
[1] RD53 Collaboration (Link)

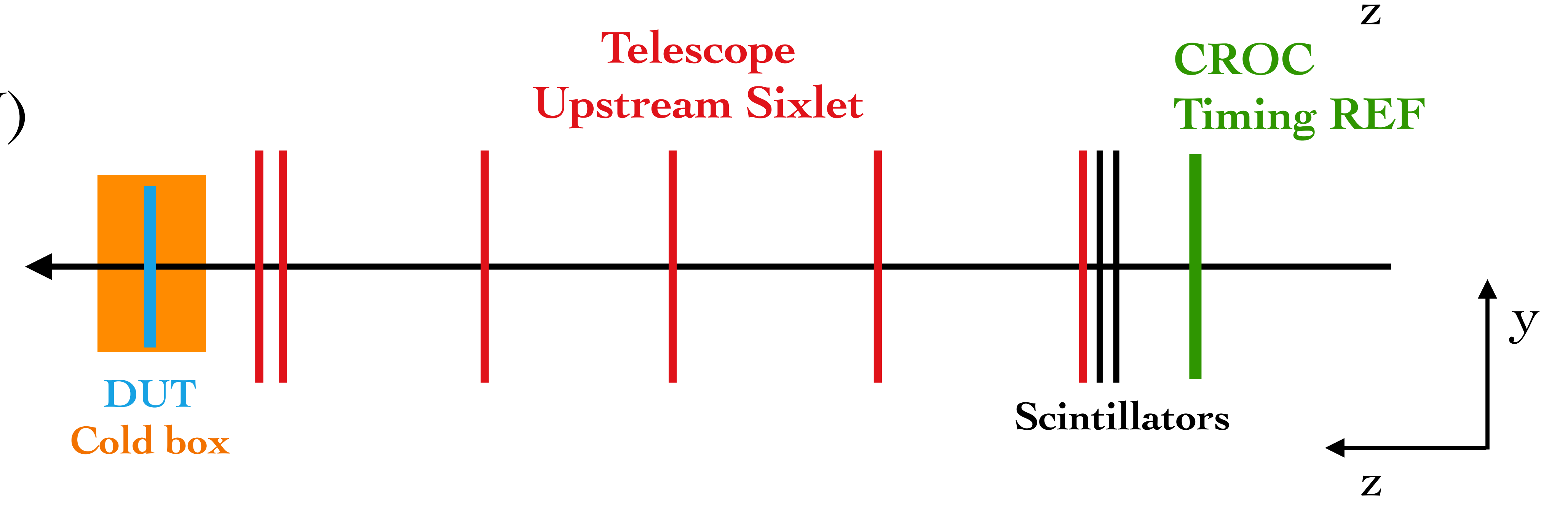
DESY II test beam setup

All data taken at TB21/22 areas:
- Electron/positron beam
- Energies: from 1 to 6 GeV (data @ 5.2 or 5.6 GeV)

- **Trigger:** two upstream scintillators (2x1 cm^2 overlap)
- **Tracking:** EUDET DATURA/DURANTA Telescope[1]
  6 MIMOSA-26 planes* (t_{int} = 115 μs)
- **Timing layer:** CMS Phase 1 or CROC 50x50 μm^2
- Device Under Test (DUT): cold box (T ~ -20/-10°C)







Irradiation:

RD53A: 23 MeV protons at ZAG Zyklotron AG Karlsruhe (KIT)

CROC: 24 GeV protons at Proton Irradiation Facility (PS_IRRAD CERN)

Characterization procedure:

- Lab measurements: I-V
- **Test beam measurements:**
  - Hit efficiency for various bias voltages, angles, temperatures and fluences
  - Single hit resolution for various angles, bias voltages, thresholds, temperatures and fluences
  - Chip ToT operation mode studies

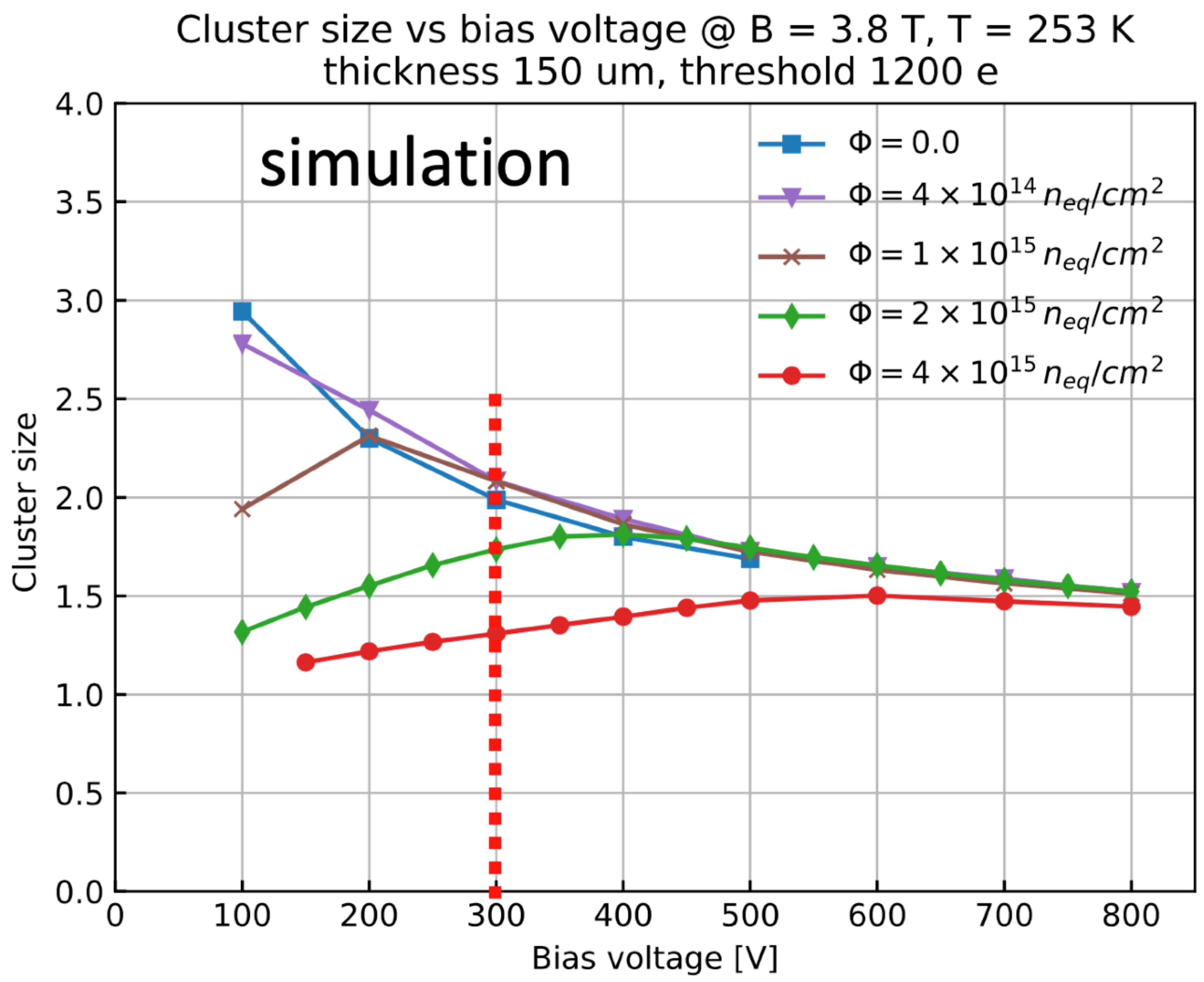
[1] EUDET Telescope (Link) *MAPS with a pixel size of 18.4x18.4 μm^2

Data analysis performed with Corryvreckan

Results: breakdown

Requirements:

- **Breakdown:** > 300 V before irradiation (for optimal resolution)
  > 800 V **after** irradiation to $\mathbf{\Phi_{eq} = 0.5 \times 10^{16}\ cm^{-2}}$ & beyond



Results: breakdown

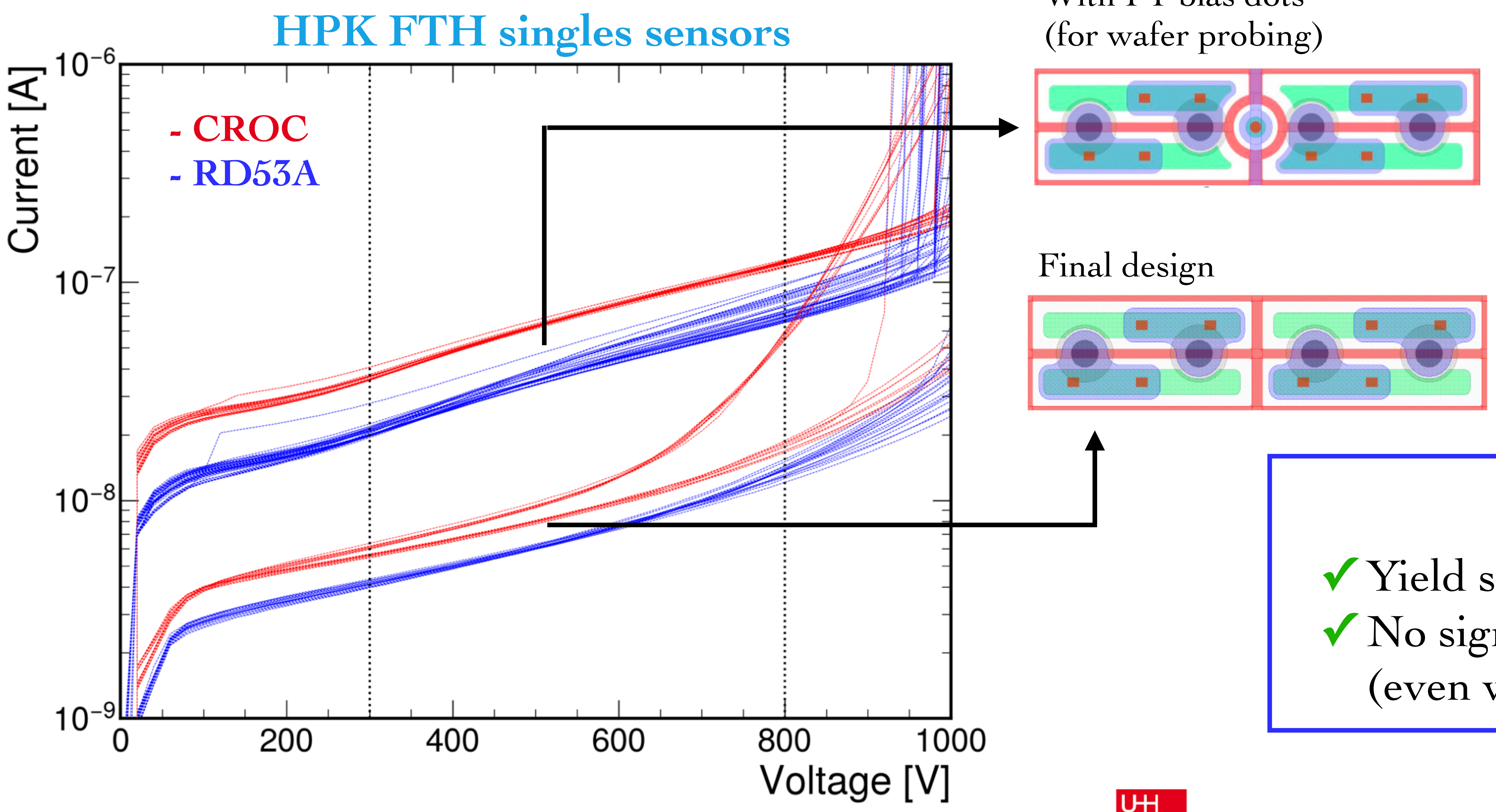
Requirements:

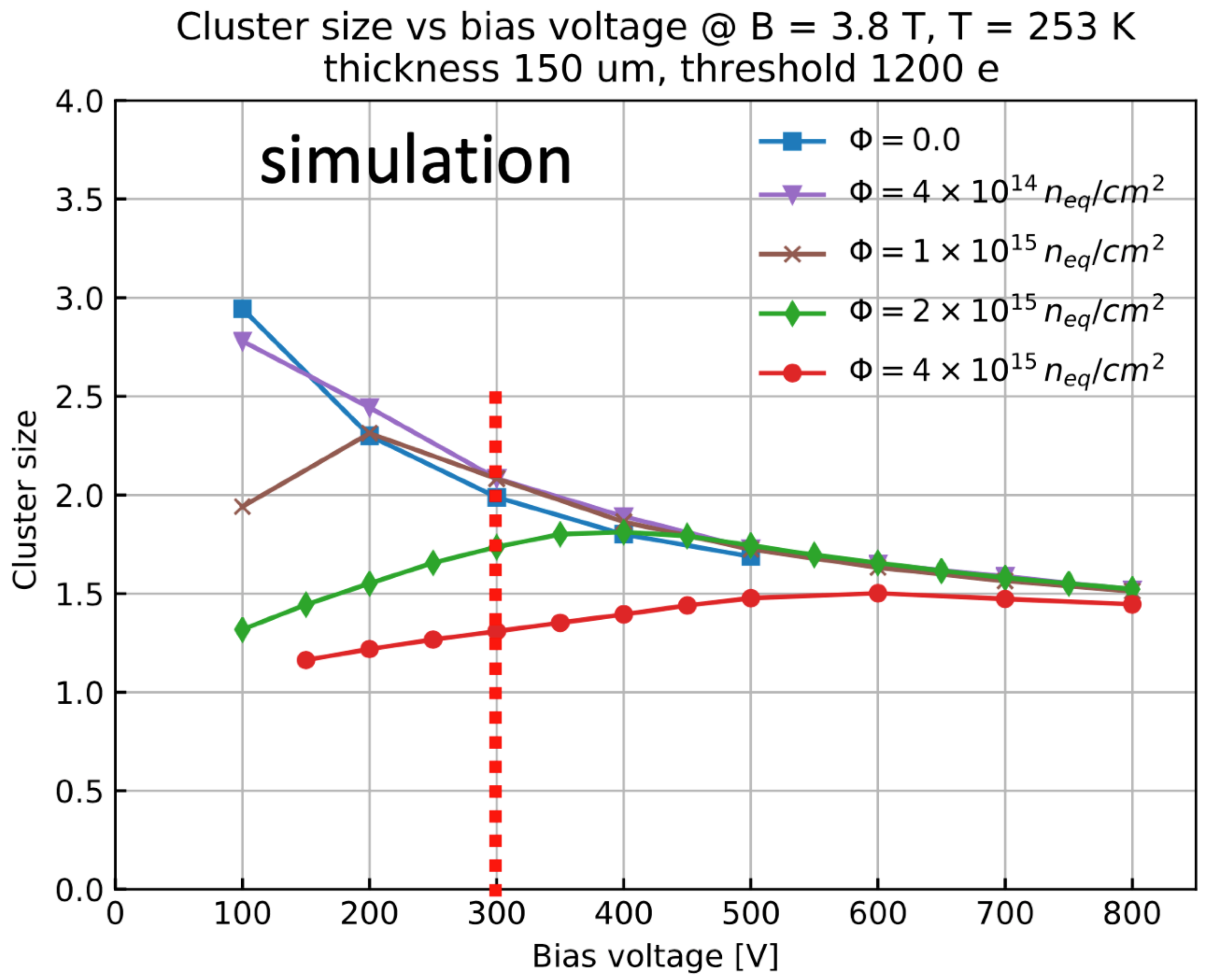
- **Breakdown:** > 300 V before irradiation (for optimal resolution)
  > 800 V **after** irradiation to Φ_{eq} = **0.5 x 10^{16} cm^{-2}** & beyond

Results:

✓ Yield for CROC singles (50x50 μm^2 and 25x100 μm^2): 97% (29/30)

✓ No sign of breakdown up to **800 V** during the beam tests (even with fluences up to Φ_{eq} = **1 x 10^{16} cm^{-2}**)





RD53A results

✓ Yield singles (50x50 μm^2 and 25x100 μm^2): 100% (75/75)

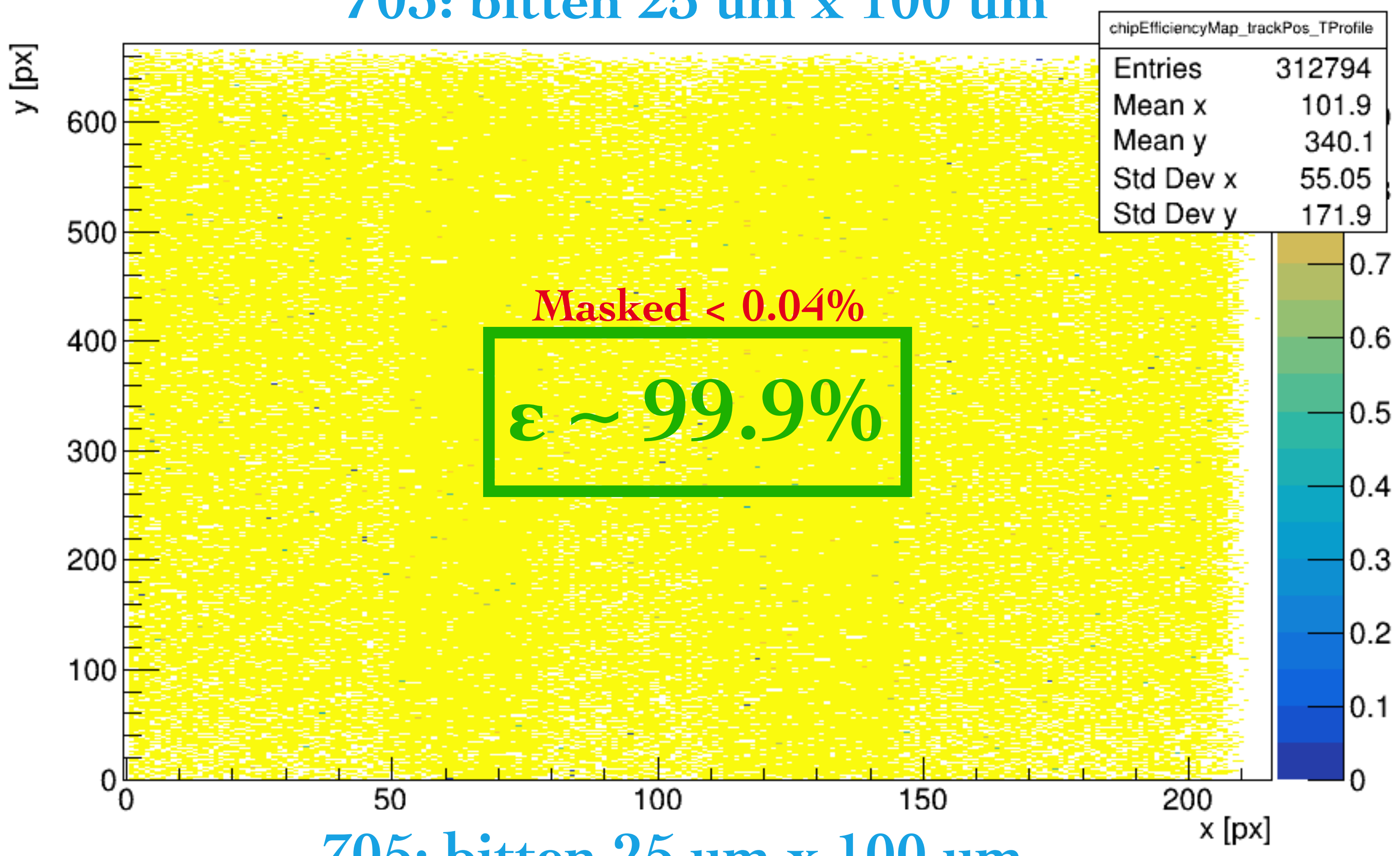
✓ No sign of breakdown up to **800 V** (even with fluences up to Φ_{eq} = **2 x 10^{16} cm^{-2}**)

Results: hit efficiency

PRELIMINARY RESULTS

$\epsilon_{hit} = \frac{N^{DUT}_{tracks}}{N^{total}_{tracks}}$ at V_{bias} = **120 V** and normal incidence — **Patch scan** = 3 merged runs*

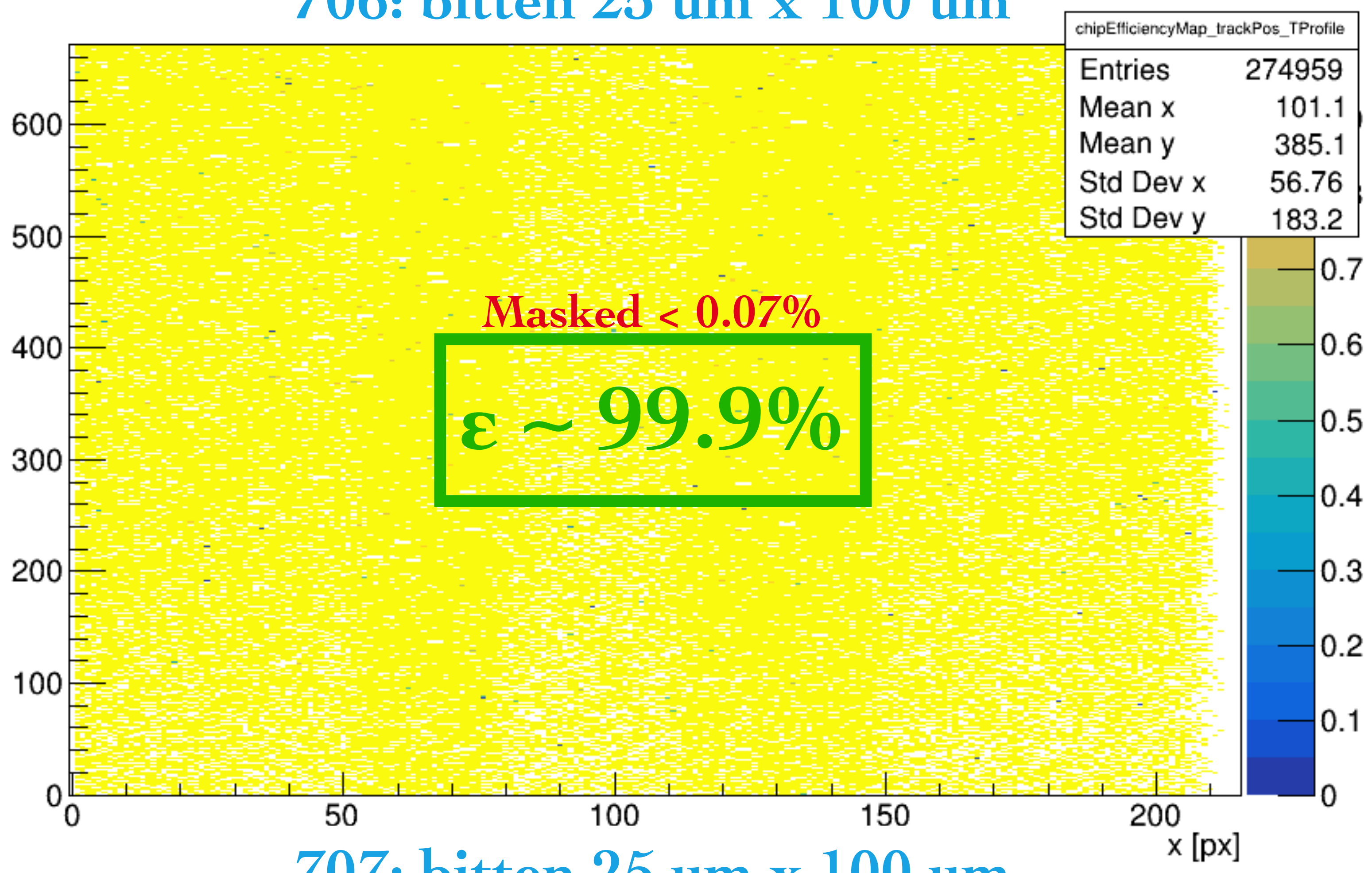
703: bitten 25 um x 100 um



Masked < 0.04%

ε ~ 99.9%

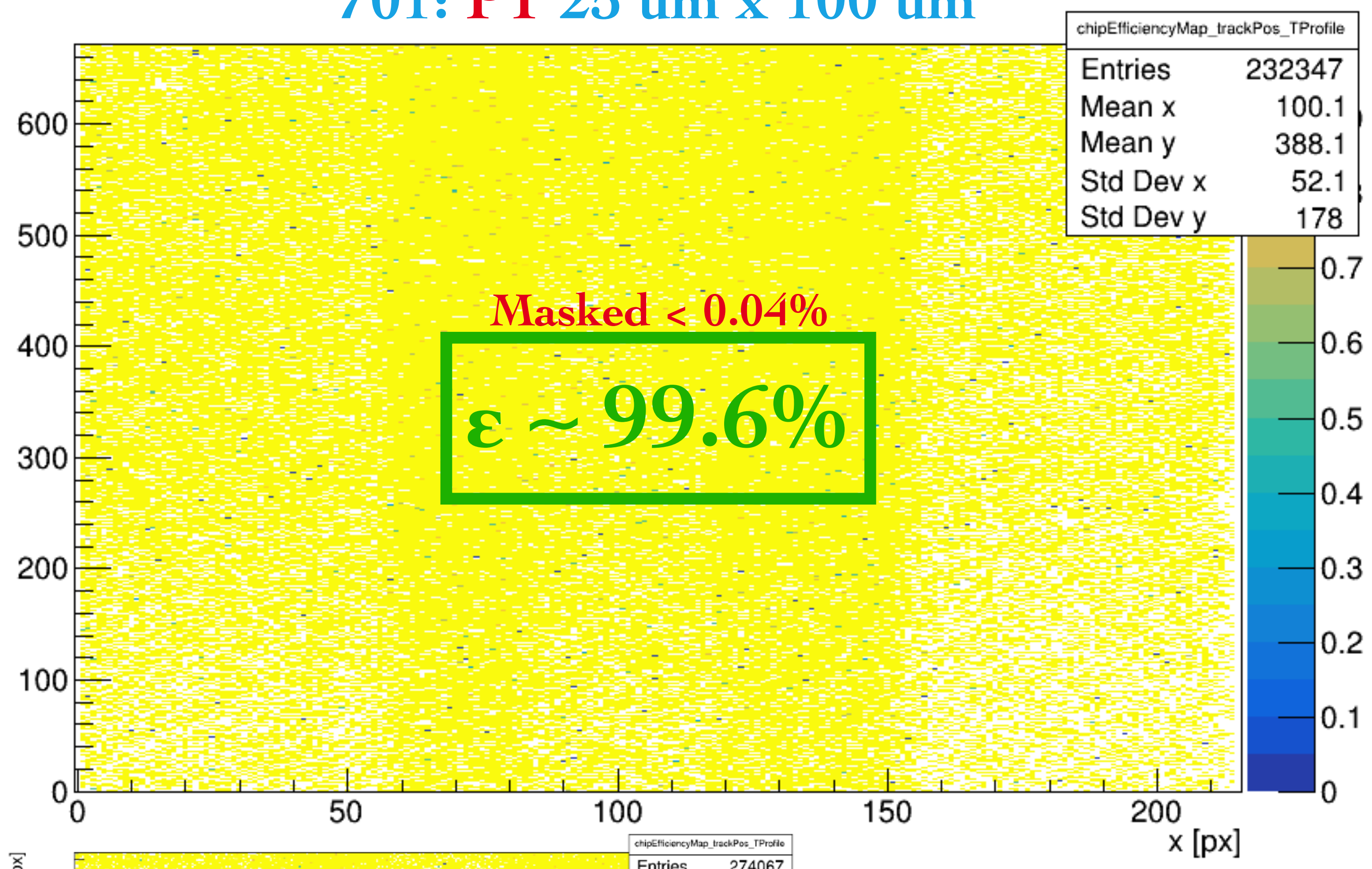
706: bitten 25 um x 100 um



Masked < 0.07%

ε ~ 99.9%

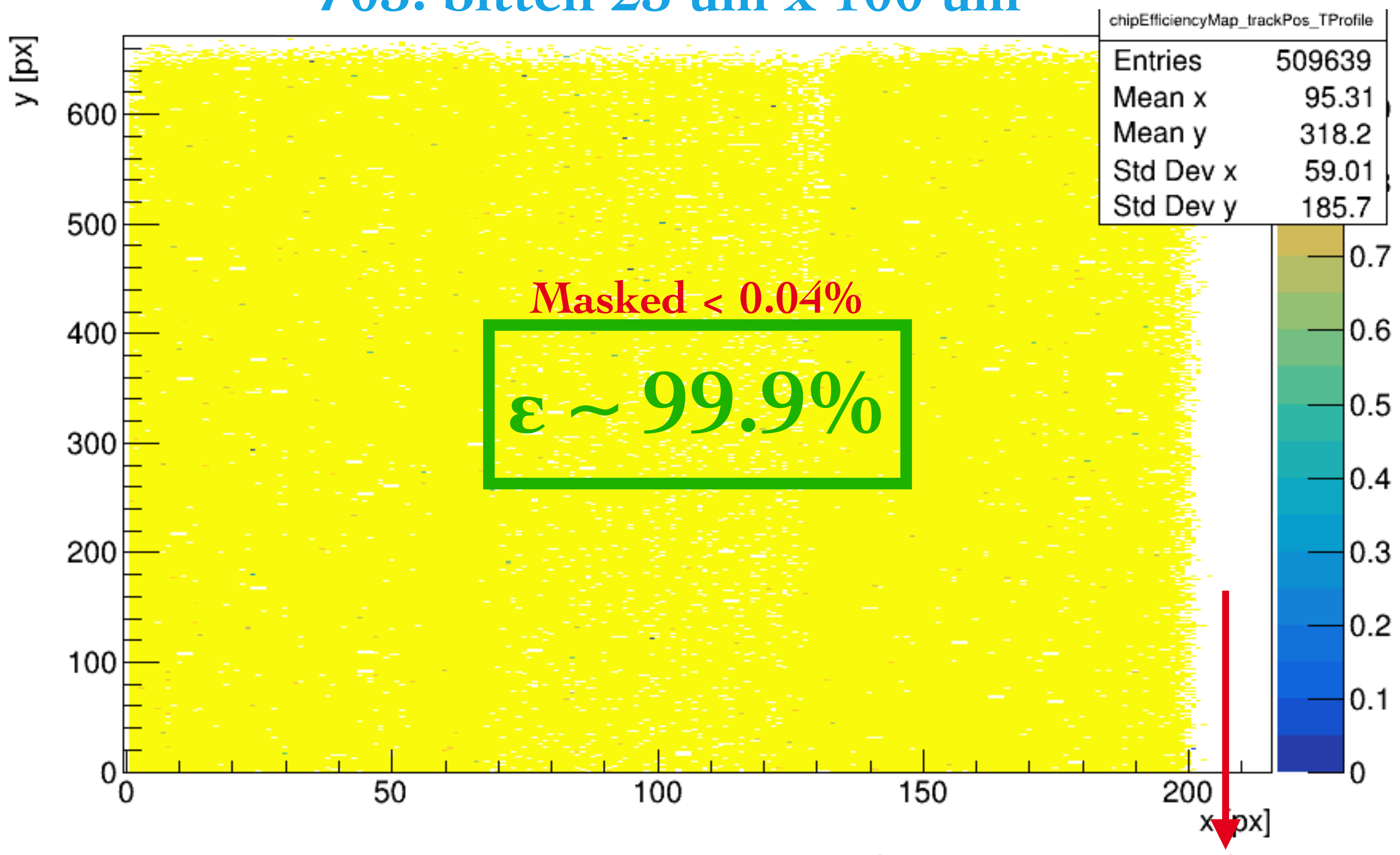
701: PT 25 um x 100 um



Masked < 0.04%

ε ~ 99.6%

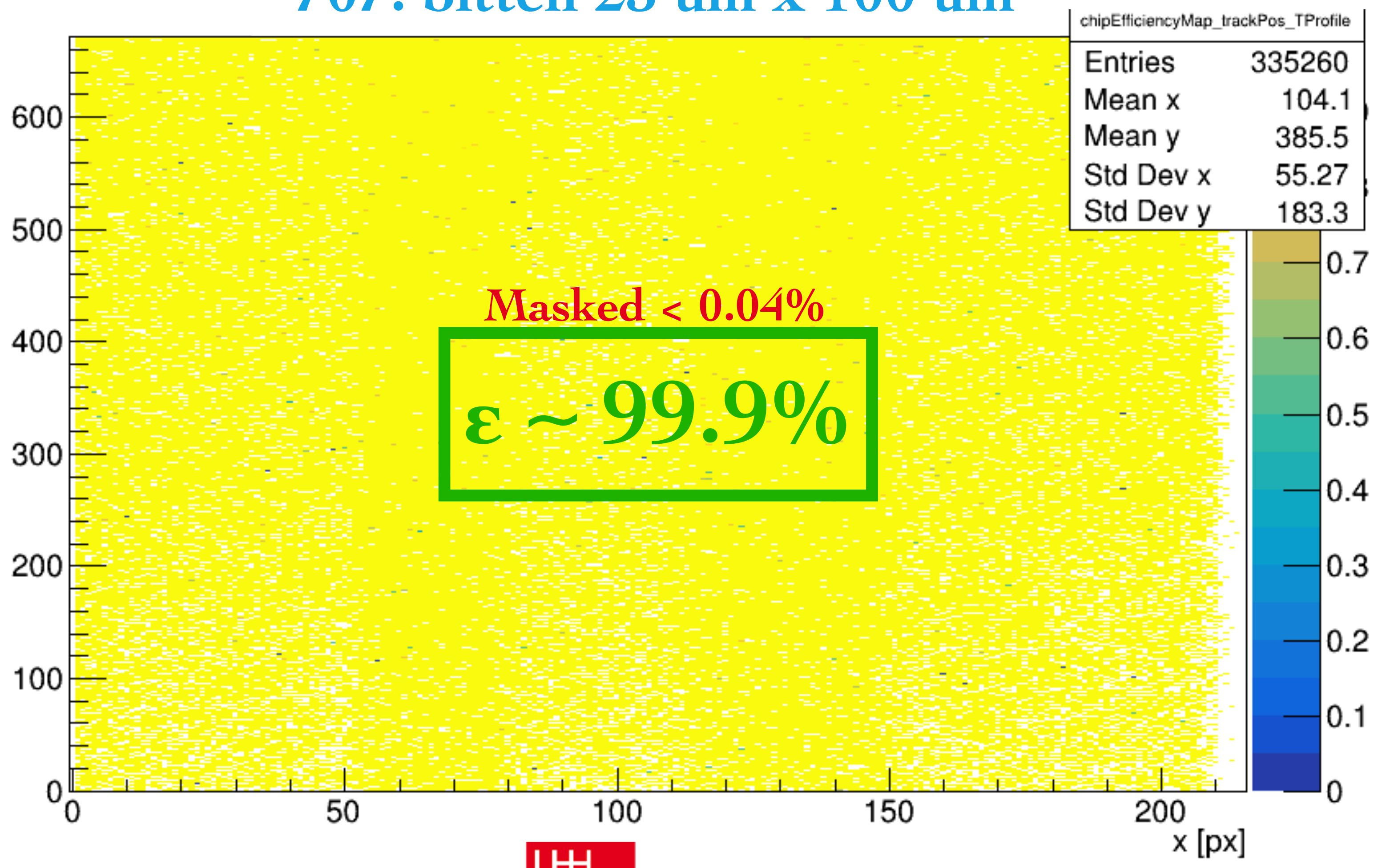
705: bitten 25 um x 100 um



Masked < 0.04%

ε ~ 99.9%

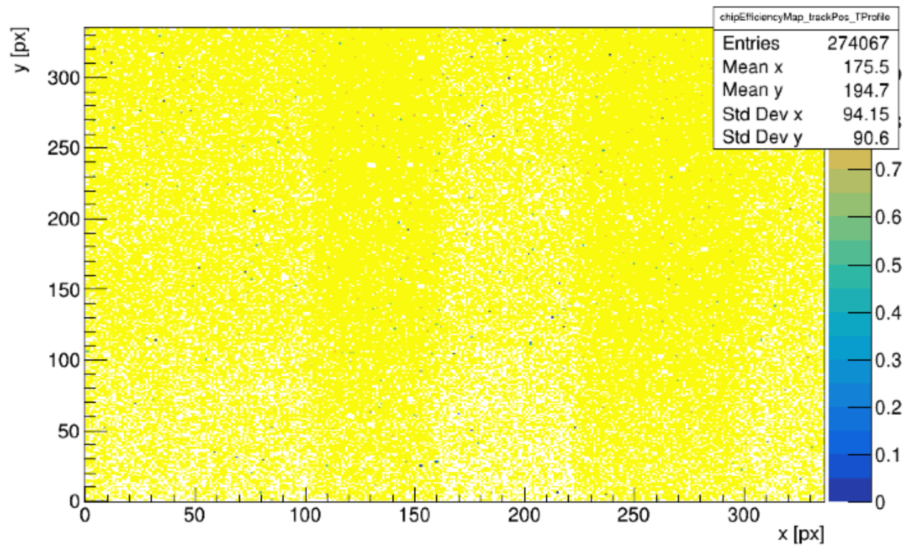
707: bitten 25 um x 100 um



Masked < 0.04%

ε ~ 99.9%

702: 50 um x 50 um



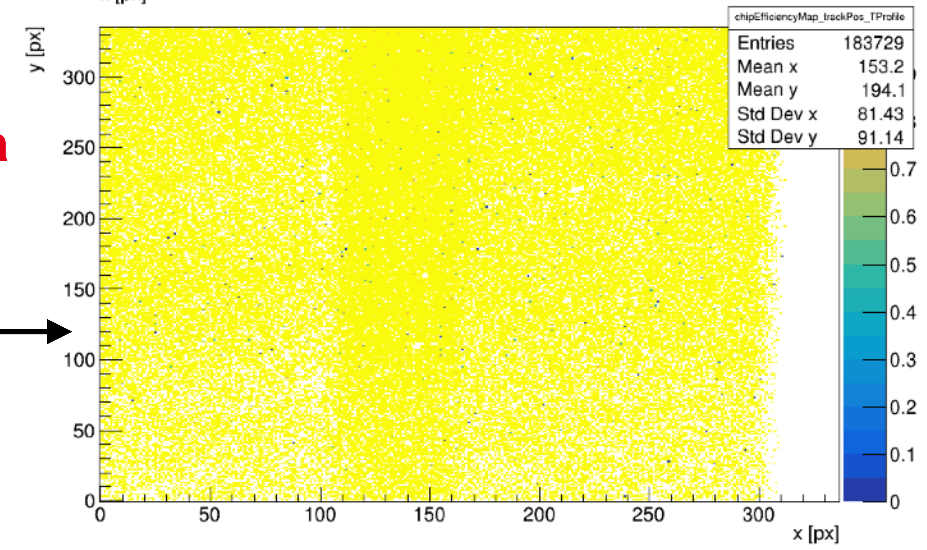
Masked < 0.06%

ε ~ 99.8%

704: 50 um x 50 um

Masked < 0.03%

ε ~ 99.8%



Manual alignment: not always full coverage of the beam at the edges

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

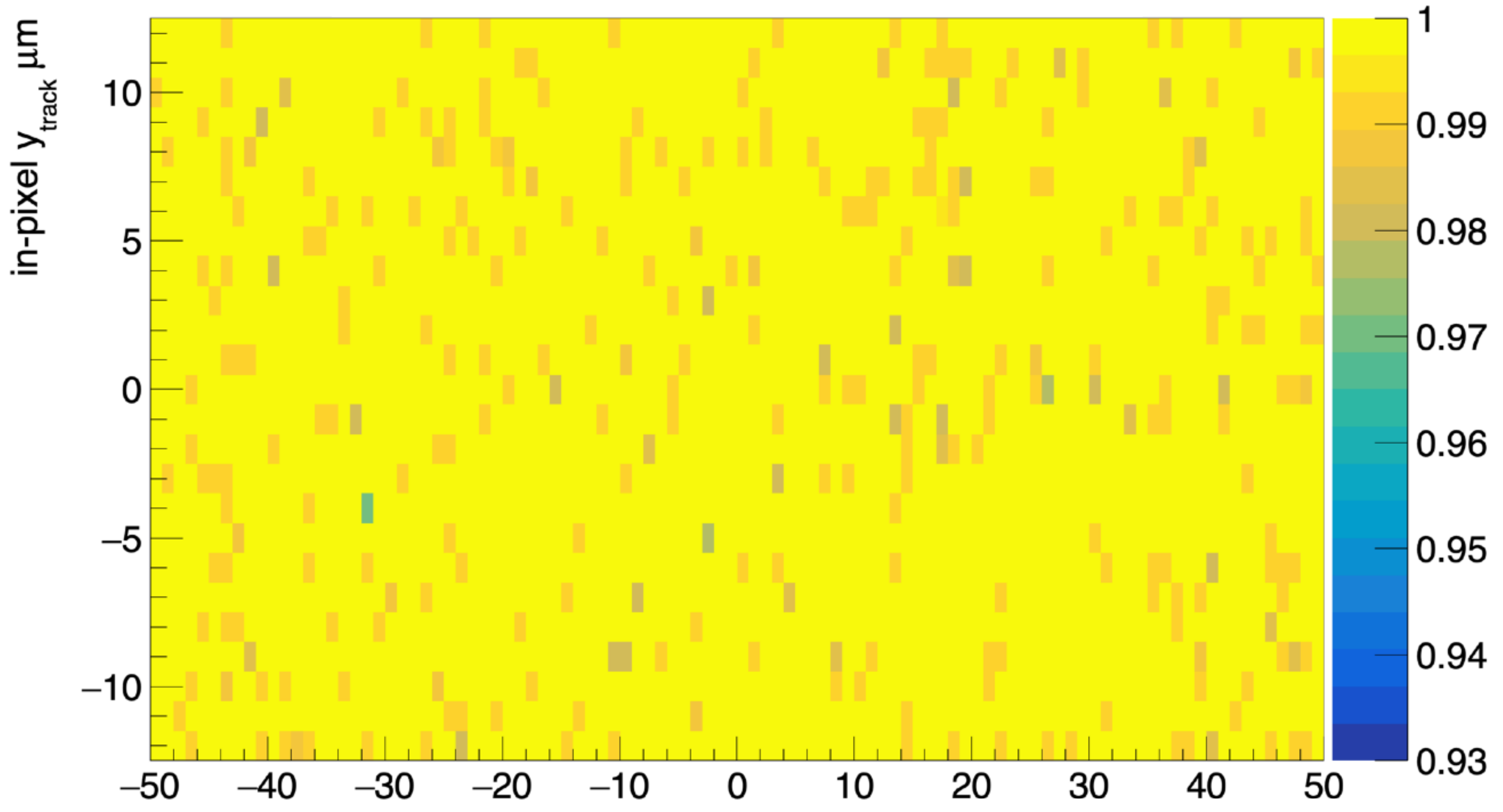
*Low statistic for these tests: mean pixel occupancy ~ 5 hits

Results: hit efficiency

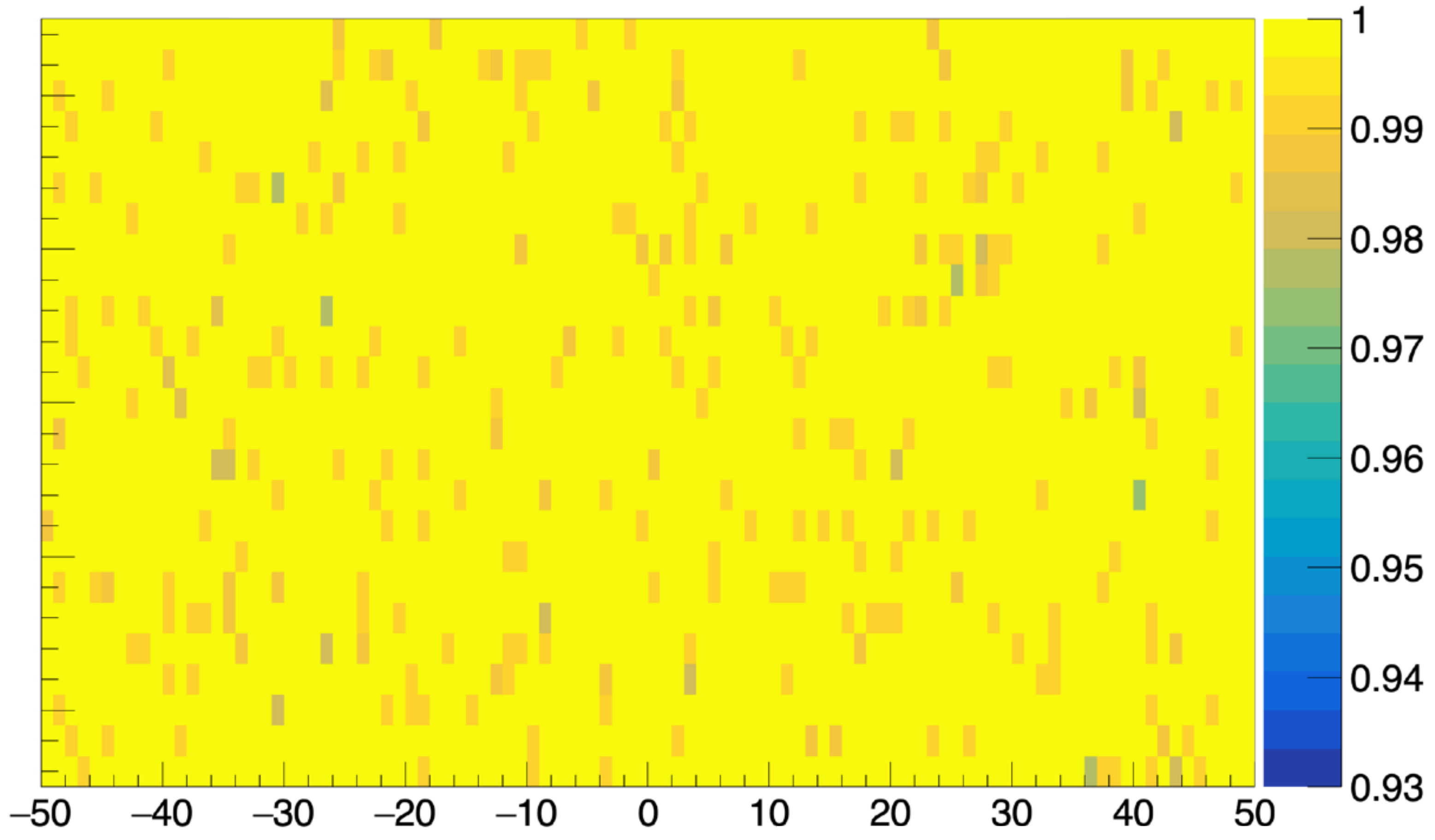
PRELIMINARY RESULTS

$\epsilon_{hit} = \frac{N^{DUT}_{tracks}}{N^{total}_{tracks}}$ at V_{bias} = 120 V and normal incidence — In pixel efficiency

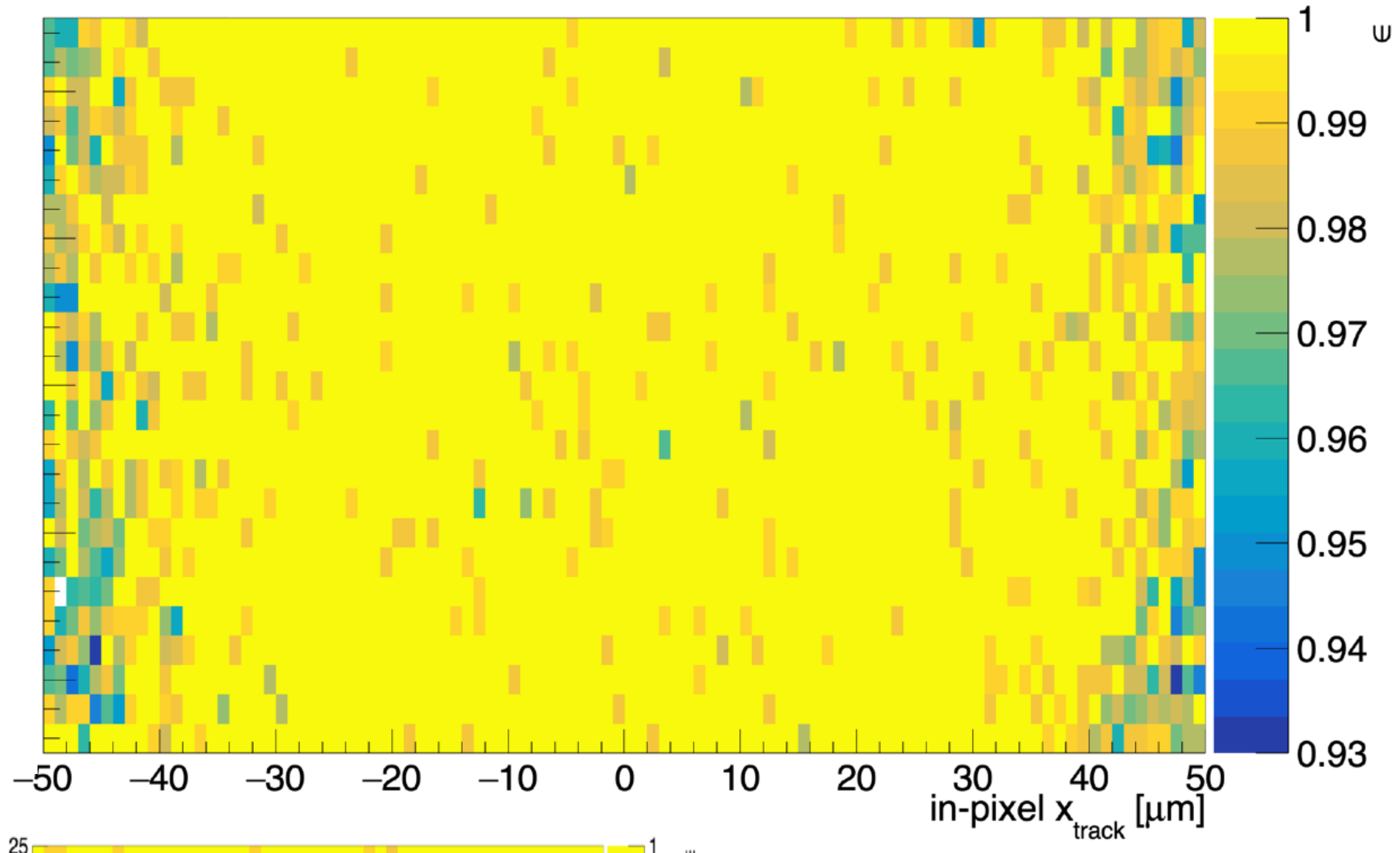
703: bitten 25 um x 100 um



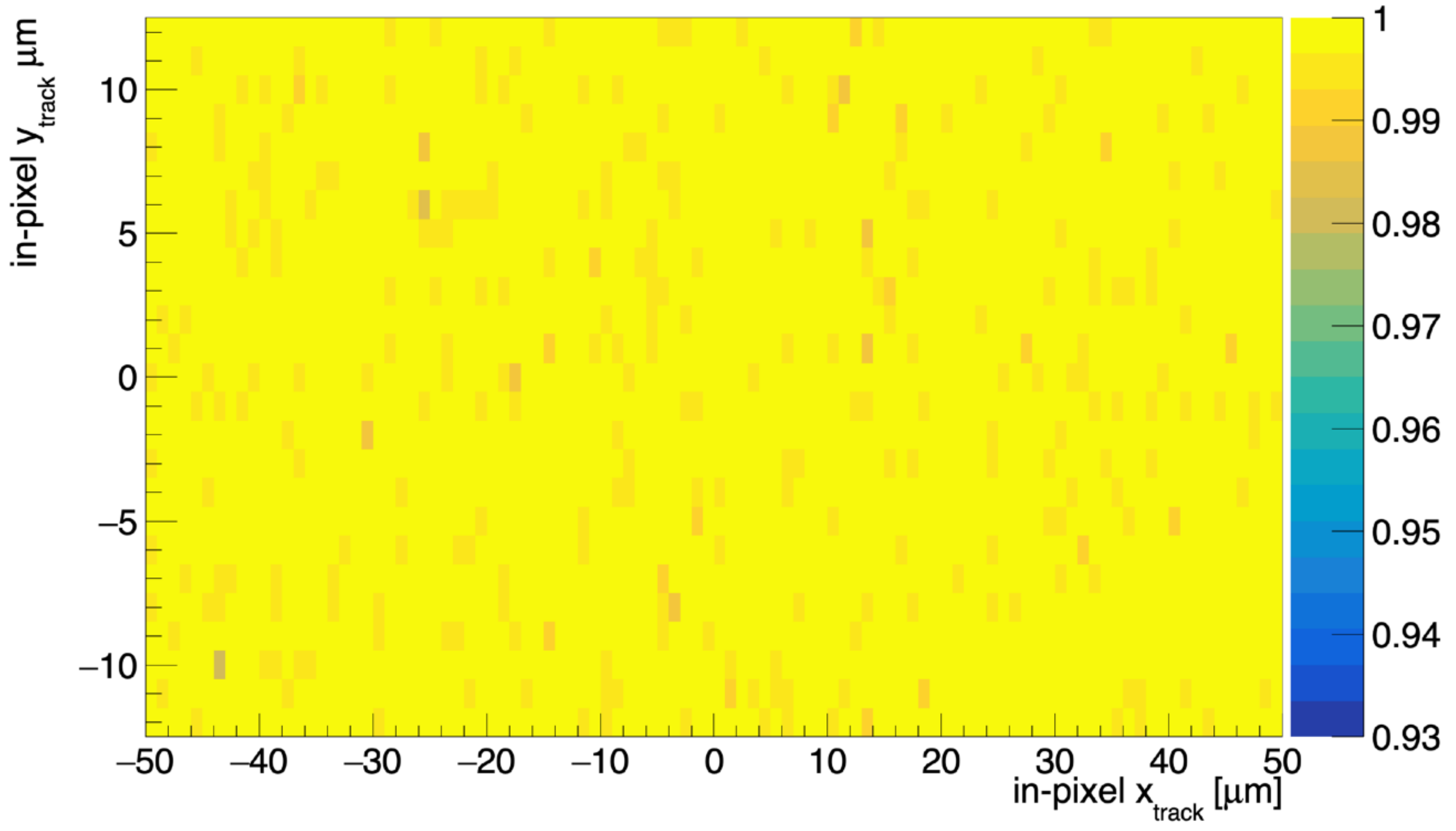
706: bitten 25 um x 100 um



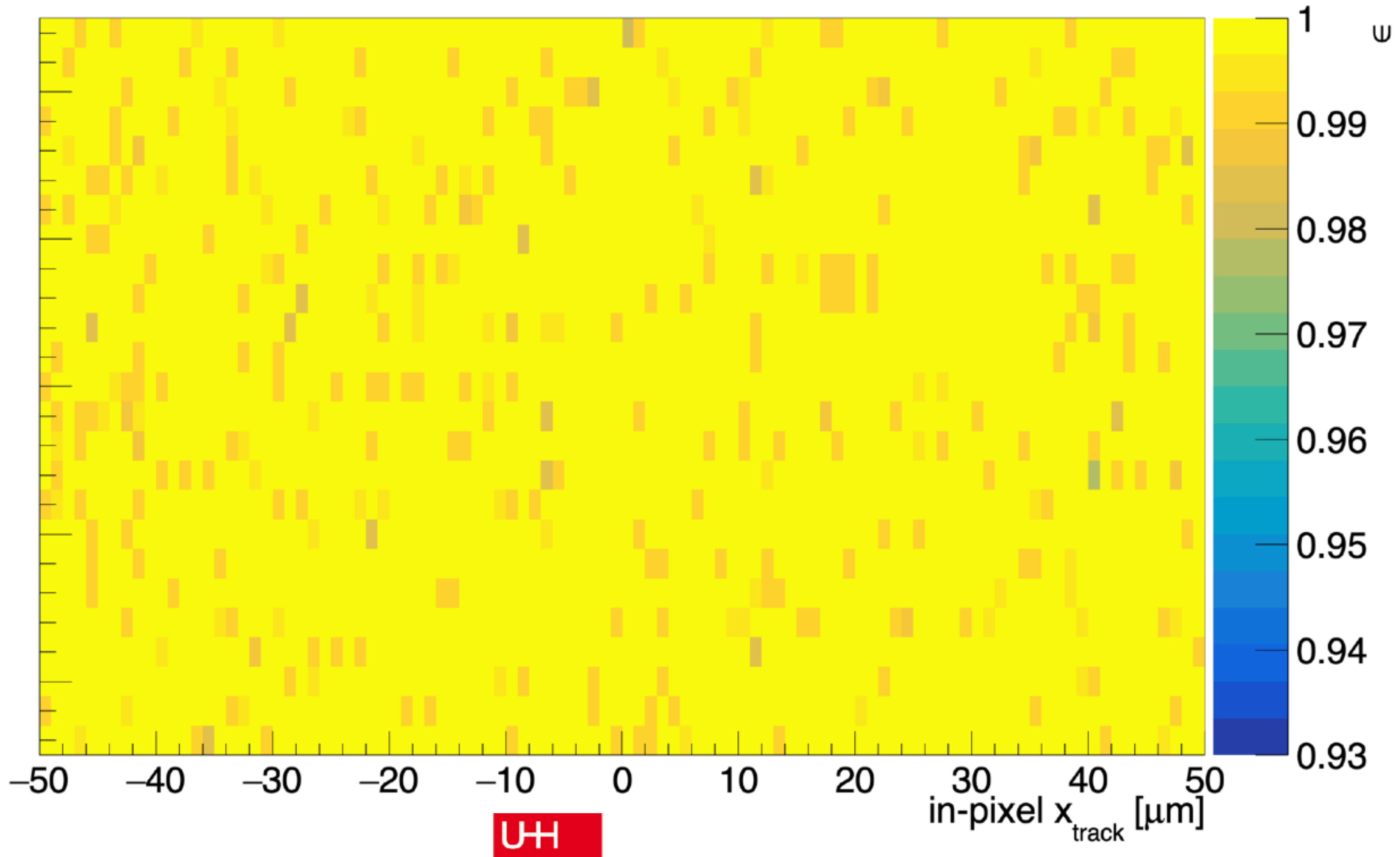
701: PT 25 um x 100 um

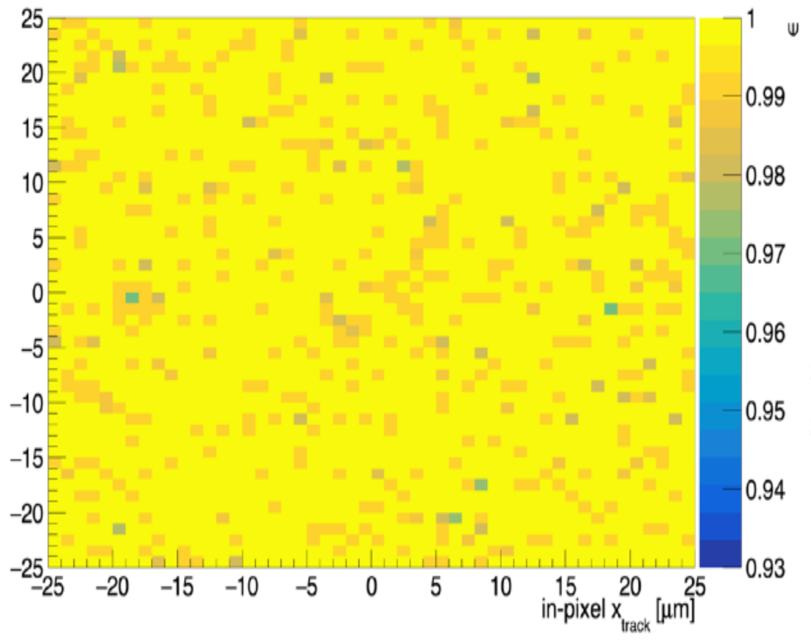


705: bitten 25 um x 100 um



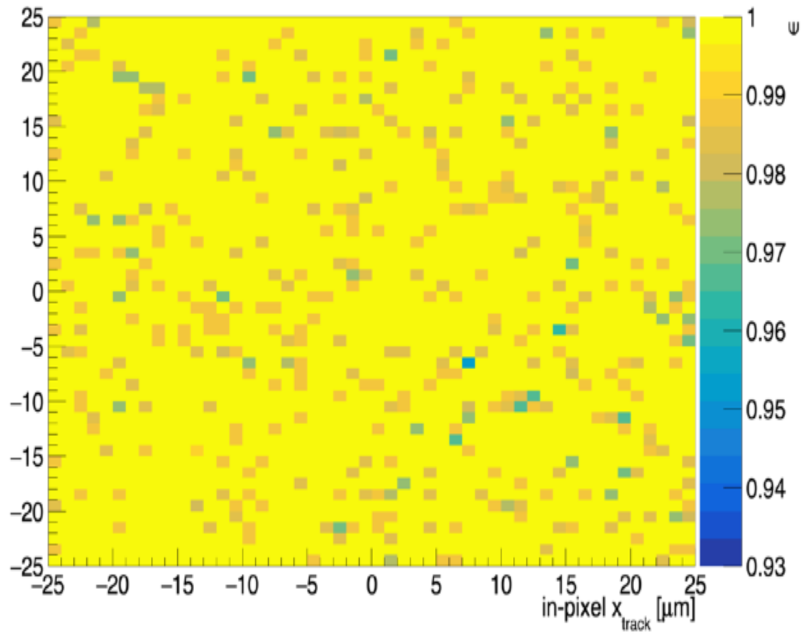
707: bitten 25 um x 100 um





← 702: 50 um x 50 um

704: 50 um x 50 um →



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Results: hit efficiency

PRELIMINARY RESULTS

Requirements:

- **Hit efficiency:** ε_{hit} > 99% **before** irradiation (vertical incidence @ V_{bias} = V_{dep} + 50 V and 20°C)

ε_{hit} > 99% **after** irradiation to Φ_{eq} = **0.5 x 10^16 cm^-2** (vertical incidence @ V_{bias} ≤ **600 V** and -20°C)

ε_{hit} > 98% **after** irradiation to Φ_{eq} = **1.0 x 10^16 cm^-2** (vertical incidence @ V_{bias} ≤ **800 V** and -20°C)

$$\epsilon_{hit} = \frac{N^{DUT}_{tracks}}{N^{total}_{tracks}}$$

Before irradiation*

CROC results

Non-irradiated:

Online threshold** ~ 1200 e^- - T ~ +25°C

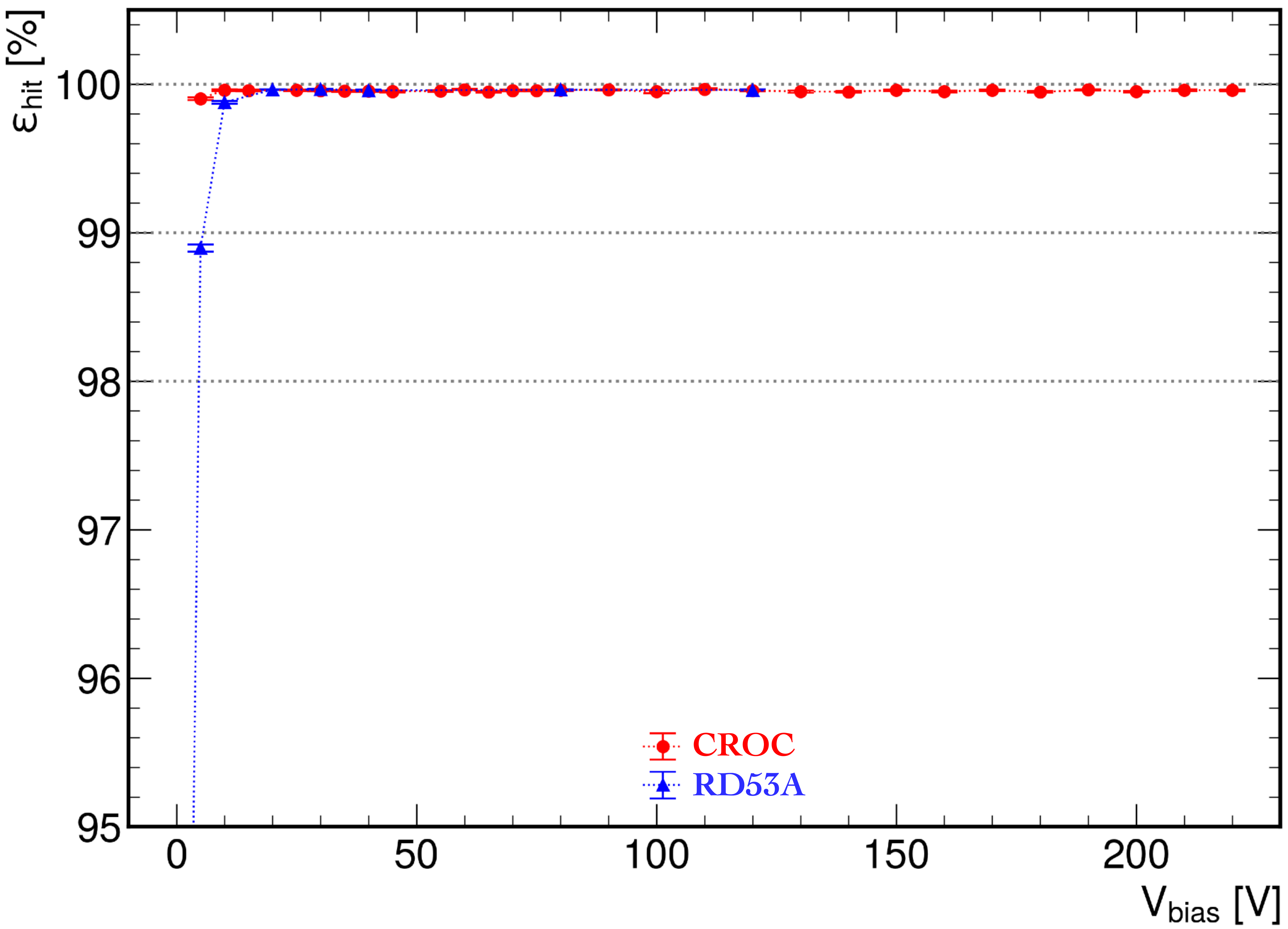
✓ ε_{hit} > 99% for V_{bias} > 5 V

RD53A results

Non-irradiated:

Online threshold** ~ 1400 e^- - T ~ +25°C

✓ ε_{hit} > 99% for V_{bias} > 5 V



* Excluding effects coming from readout chain

** Exp. deposited charge for a MIP in 150 μm Si before irr. ~ 11000 e^-

Results: hit efficiency

PRELIMINARY RESULTS

Requirements:

- **Hit efficiency:** ε_{hit} > 99% **before** irradiation (vertical incidence @ V_{bias} = V_{dep} + **50 V** and **20°C**)
  ε_{hit} > 99% **after** irradiation to Φ_{eq} = **0.5 x 10^16 cm^-2** (vertical incidence @ V_{bias} ≤ **600 V** and **-20°C**)
  ε_{hit} > 98% **after** irradiation to Φ_{eq} = **1.0 x 10^16 cm^-2** (vertical incidence @ V_{bias} ≤ **800 V** and **-20°C**)

$$\epsilon_{hit} = \frac{N^{DUT}_{tracks}}{N^{total}_{tracks}}$$

After irradiation*

CROC results

Φ_{eq} = 1.0 x 10^{16} cm^{-2}

Online threshold** ~ 1200 e^- - T ~ -20°C

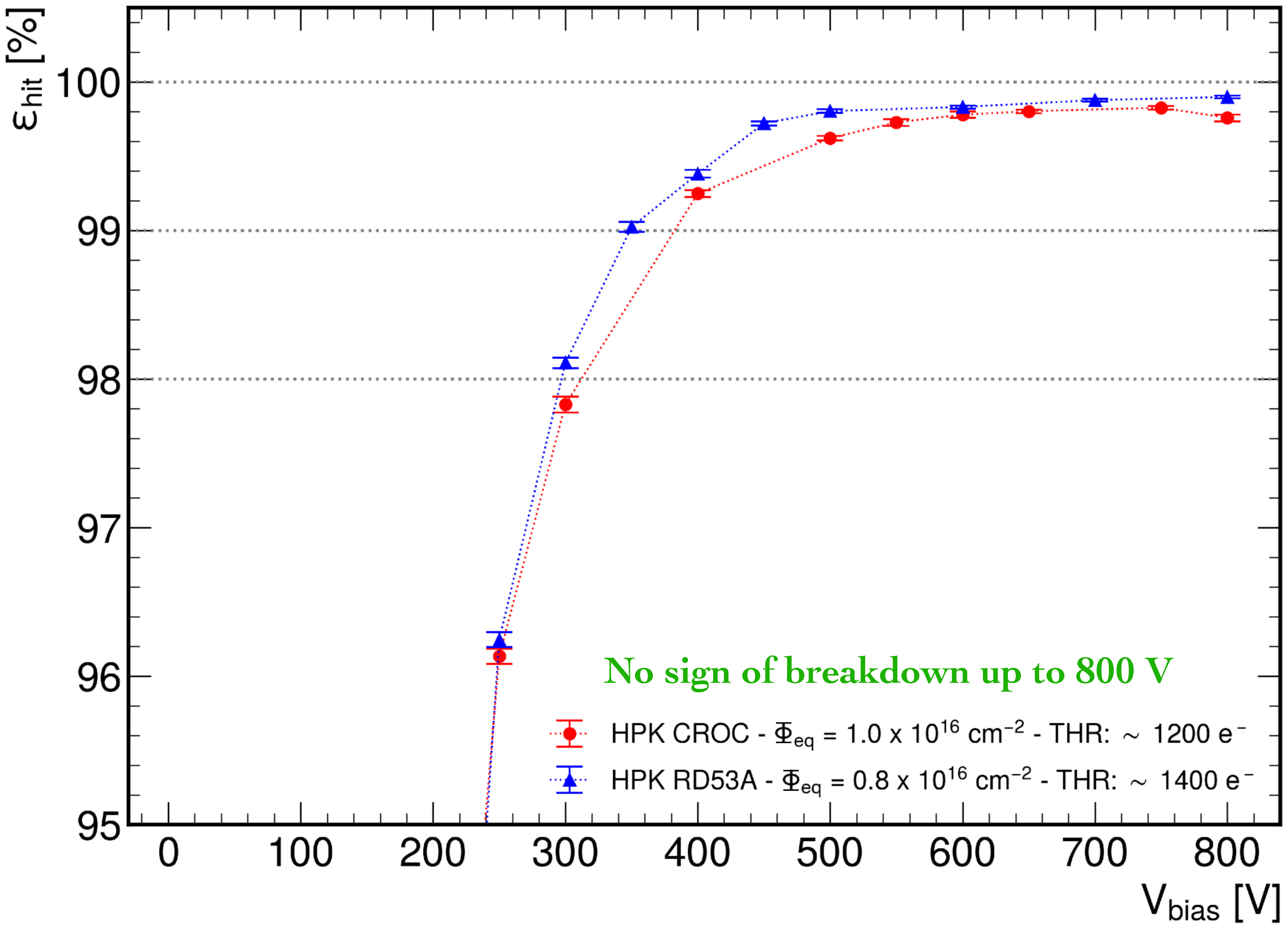
✓ ε_{hit} > 99% for V_{bias} > 400 V

RD53A results

Φ_{eq} = 0.8 x 10^{16} cm^{-2}

Online threshold** ~ 1400 e^- - T ~ -25°C

✓ ε_{hit} > 99% for V_{bias} > 350 V



* Excluding effects coming from readout chain

** Exp. deposited charge for a MIP in 150 μm Si before irr. ~ 11000 e^-

Results: efficiency*acceptance

PRELIMINARY RESULTS

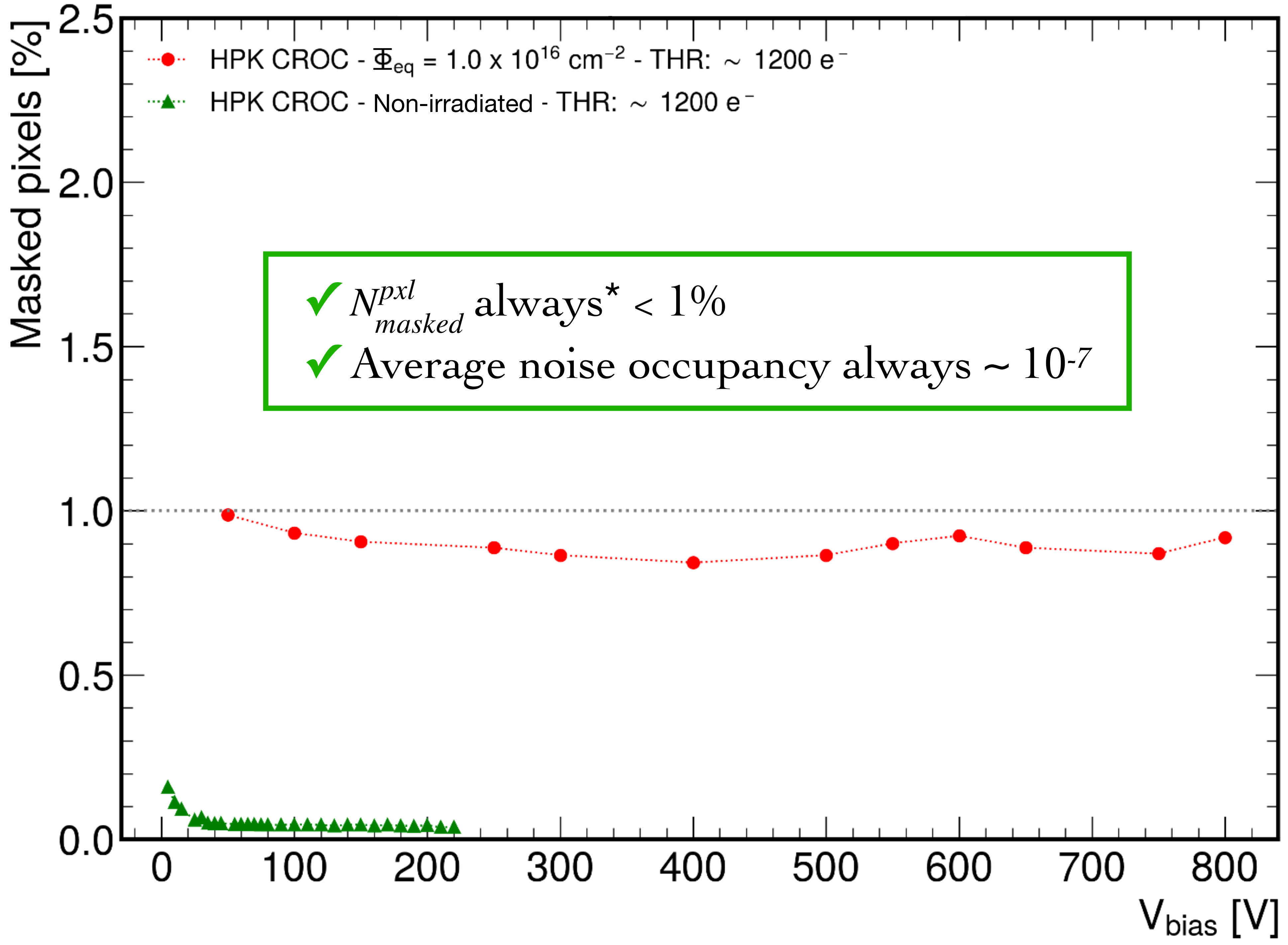
Requirements for the entire module:

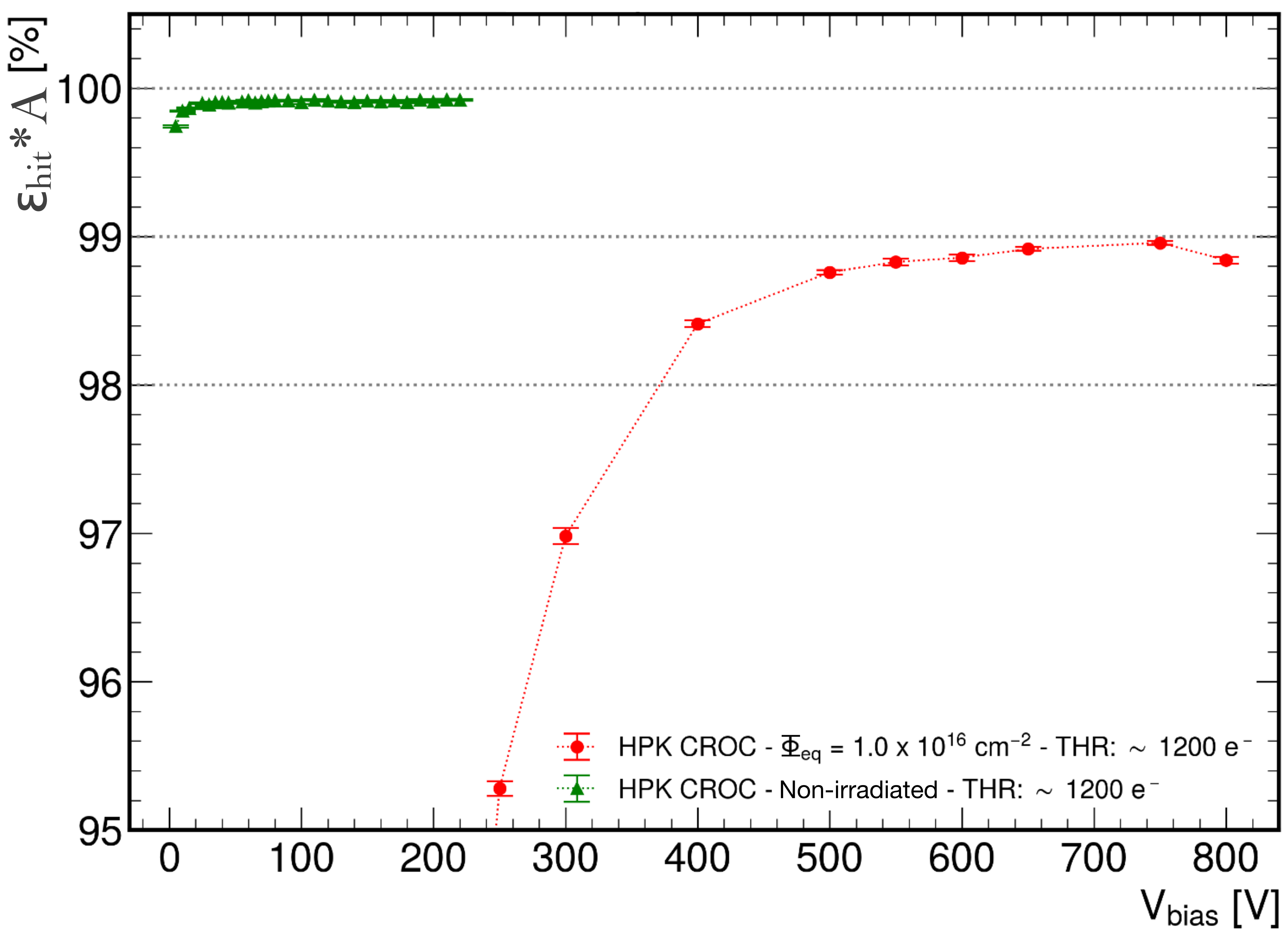
- **Acceptance** ε_{hit}*A > 99% **before** irradiation (vertical incidence @ V_{bias} = V_{dep} + 50 V and 20°C)
  ε_{hit}*A > 99% **after** irradiation to Φ_{eq} = 0.5 x 10^{16} cm^{-2} (vertical incidence @ V_{bias} ≤ 600 V and -20°C)
  ε_{hit}*A > 98% **after** irradiation to Φ_{eq} = 1.0 x 10^{16} cm^{-2} (vertical incidence @ V_{bias} ≤ 800 V and -20°C)

$$A = 1 - \frac{N^{pxl}_{masked}}{N^{pxl}_{total}}$$

- **Noise:** Total # of masked pixels = N^{pxl}_{masked} < 1%
  Average noise occupancy of un-masked pixels < 10^{-6}

Non-irradiated: ✓ ε_{hit}*A > 99% for V_{bias} > 5 V
Φ_{eq} = 1.0 x 10^{16} cm^{-2}: ✓ ε_{hit}*A > 98% for V_{bias} > 400 V





Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

* For a single pixel noise occupancy threshold of 2 x 10^{-5}

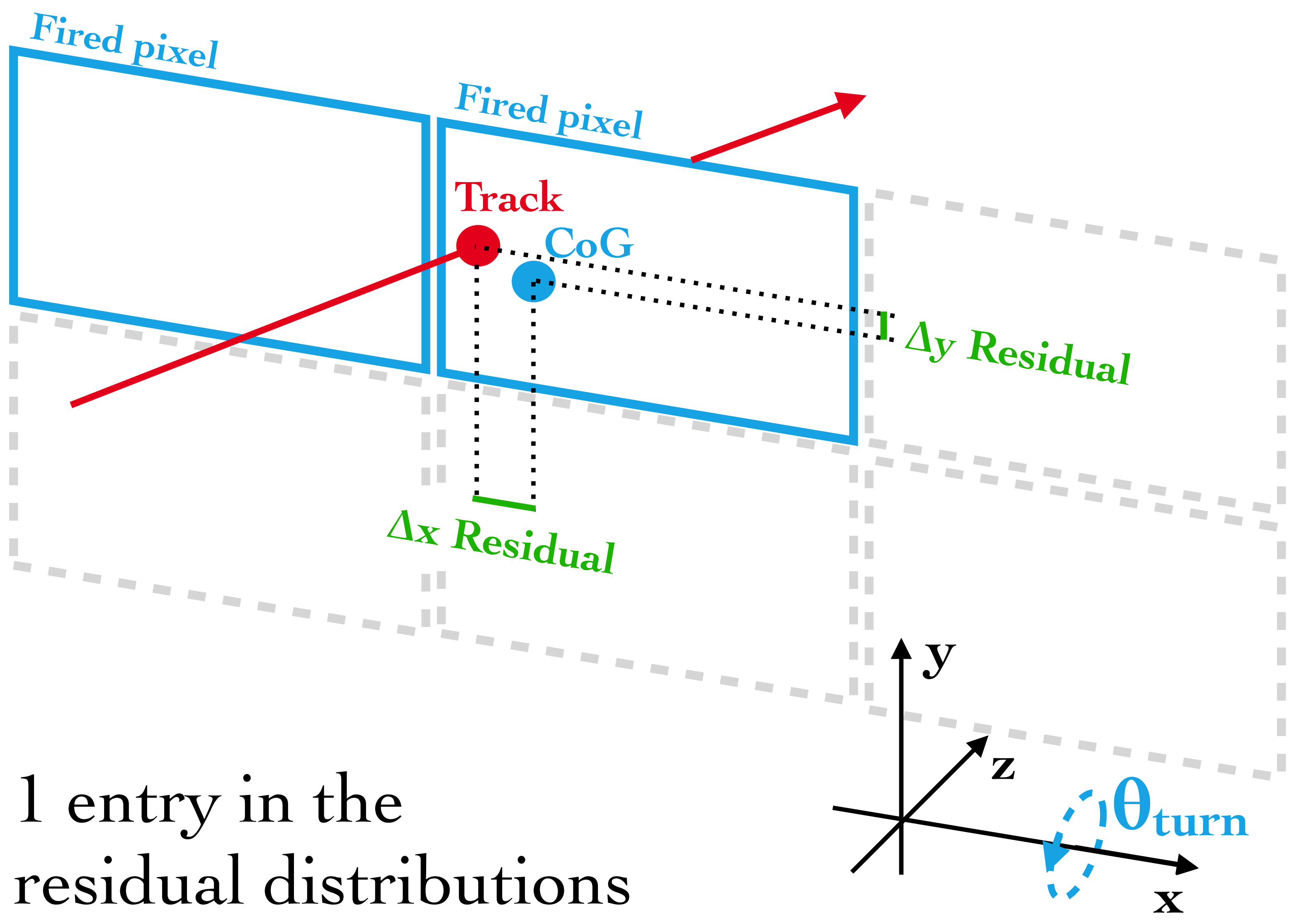
Results: spatial resolution

PRELIMINARY RESULTS

Hit spatial resolution: $\sigma_{hit} = \sqrt{RMS_{trc}^2 - \sigma_{TEL}^2}$

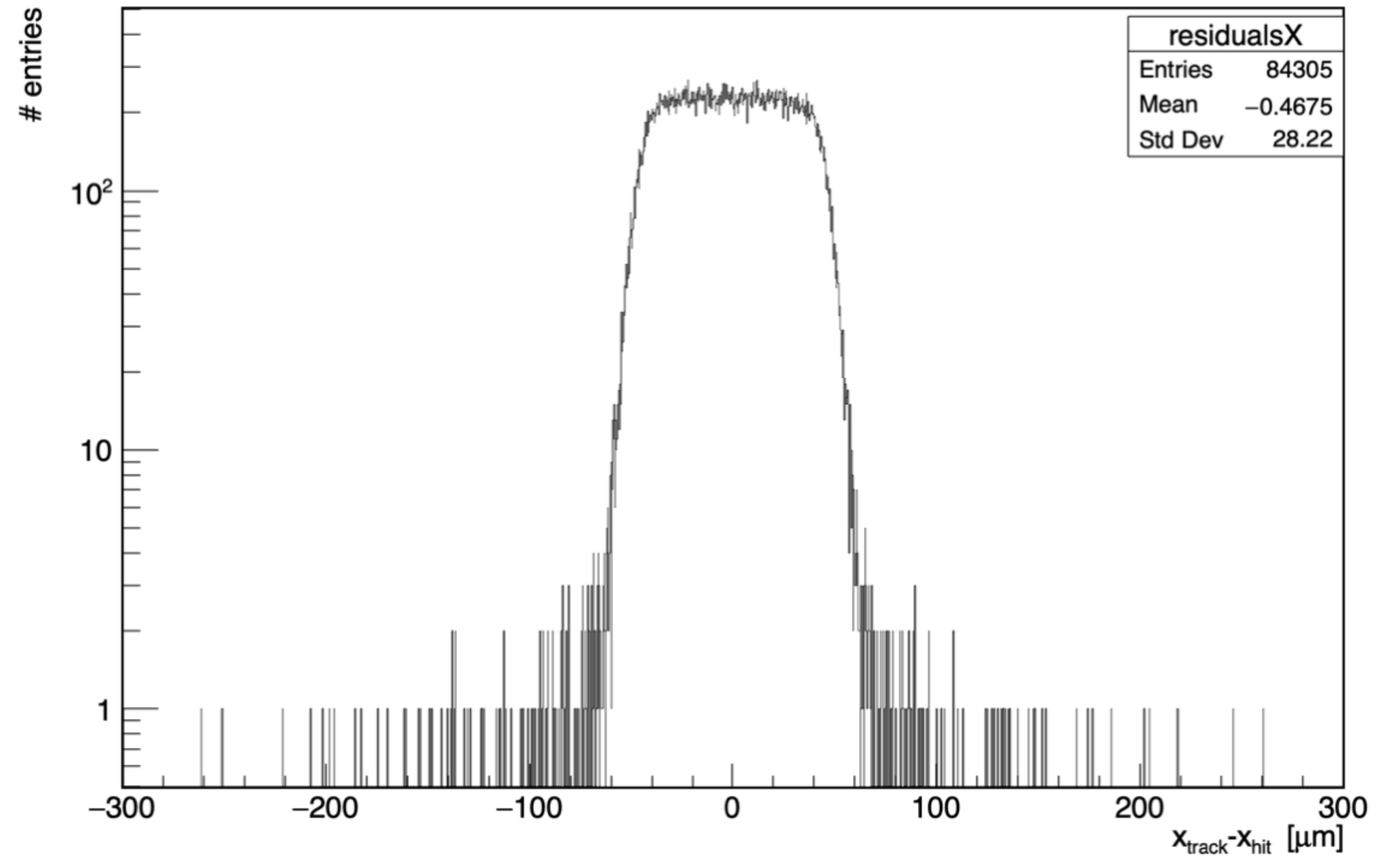
- **RMS_{trc} = truncated RMS from DUT residual distribution*:** outliers effect on RMS suppressed calculating it with iterative** method, discarding values outside of **± 3 RMS_{trc}**
- **σ_{TEL} = telescope resolution**

For each **reconstructed telescope track** with a **DUT cluster** match:

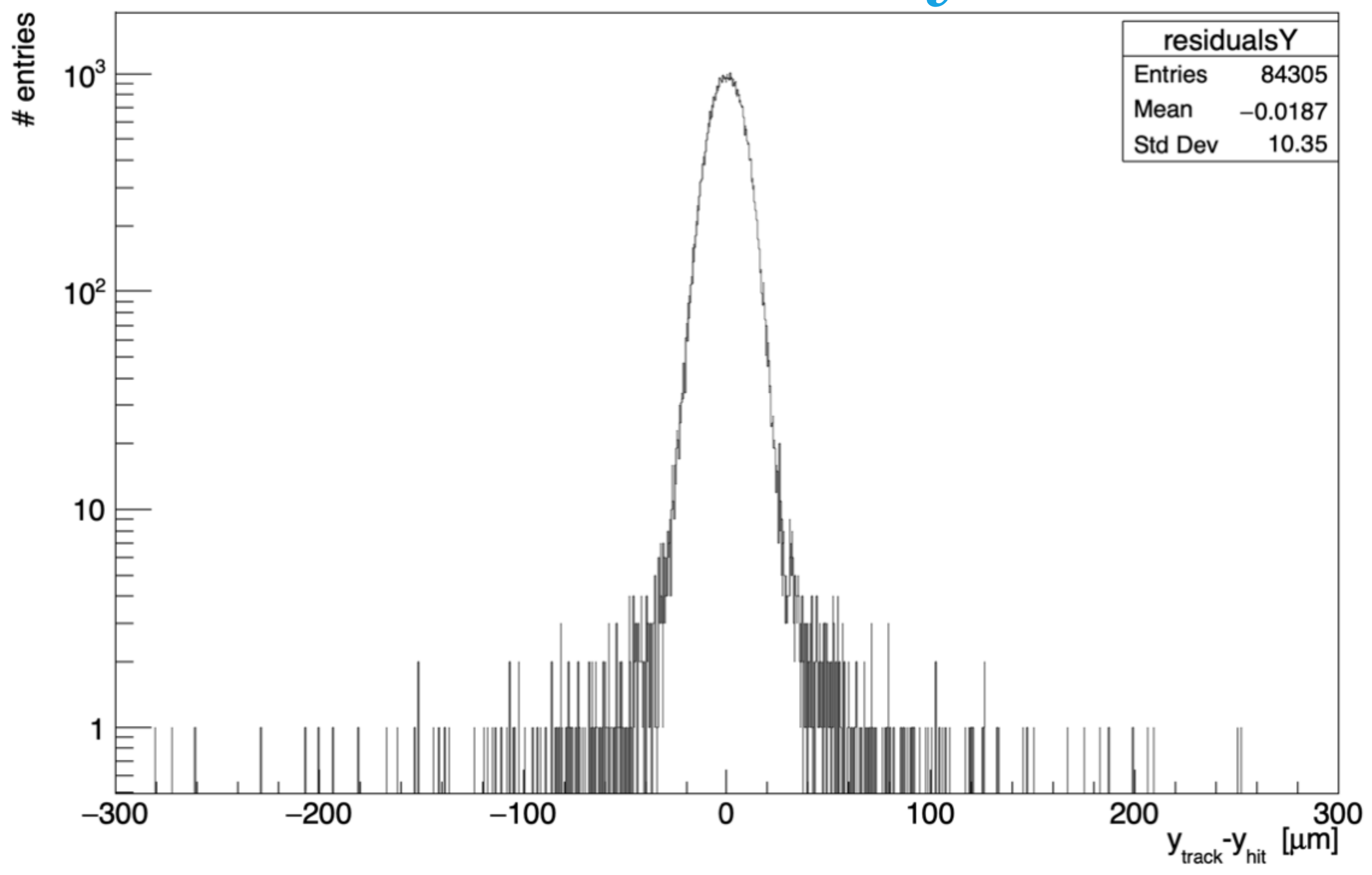


1 entry in the residual distributions

DUT residual Δx



DUT residual Δy



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

* After event selection cuts

** Considered range converges with few iterations & contains > 98% of residual distribution entries

Results: spatial resolution

PRELIMINARY RESULTS

Requirements:

- Best single point **resolution**:
  $\sigma_{hit} < 25/\sqrt{12} \sim 7.2\ \mu m$

r-ϕ (25 μm direction)

After irradiation*

CROC results

Φ_{eq} = 1.0 x 10^{16} cm^{-2}

Online threshold** ~ 1200 e- - T ~ -20°C

✓ σ_{hit} better than: σ_{binary} = 7.2 μm

✓ Cluster size above 1

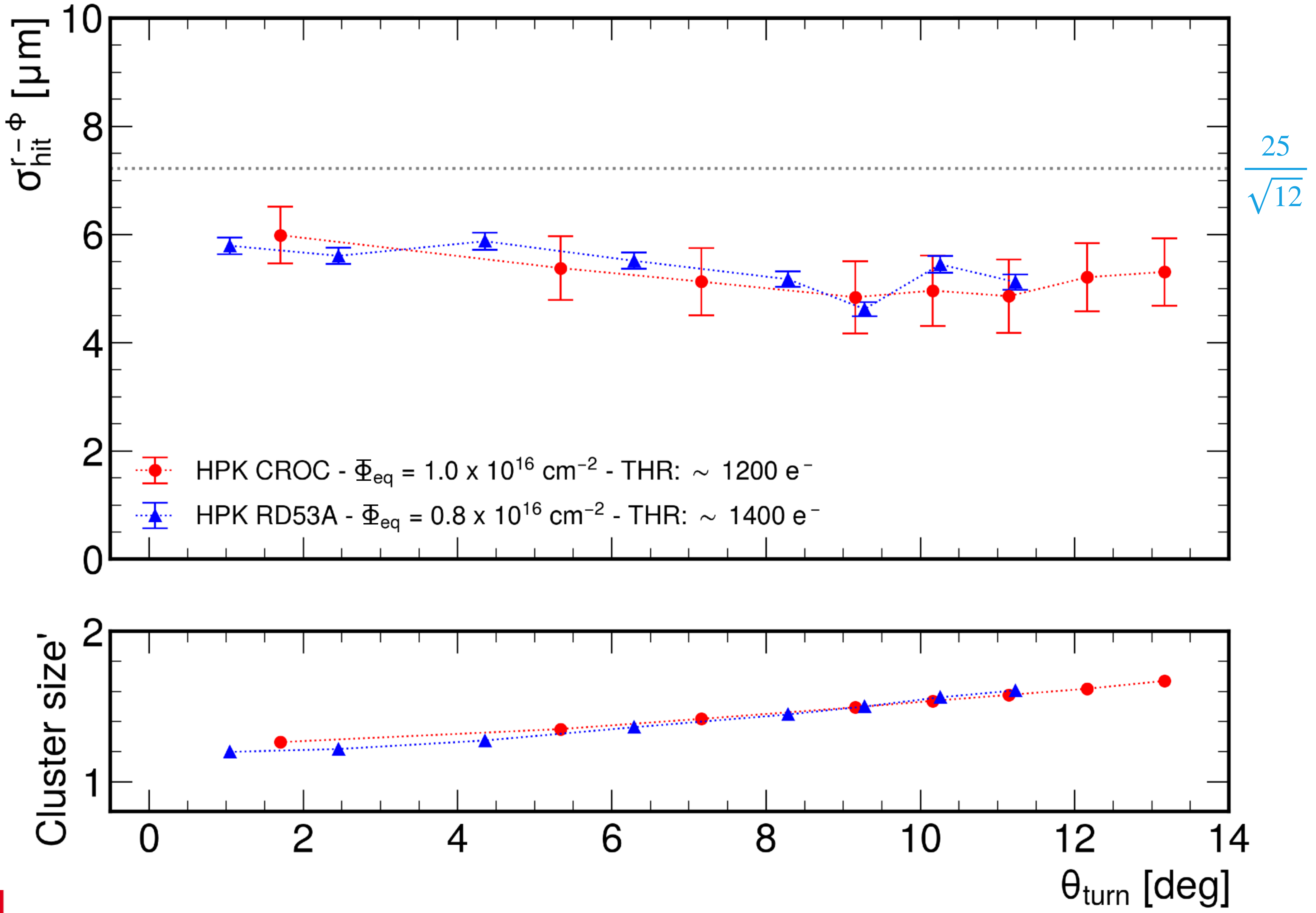
RD53A results

Φ_{eq} = 0.8 x 10^{16} cm^{-2}

Online threshold** ~ 1400 e- - T ~ -25°C

✓ σ_{hit} better than: σ_{binary} = 7.2 μm

✓ Cluster size above 1



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

* V_{bias} = 600 V

** Exp. deposited charge for a MIP in 150 μm Si before irr. ~ 11000 e-

Results: spatial resolution

PRELIMINARY RESULTS

Requirements:

- Best single point **resolution**:
  $\sigma_{hit} < 100/\sqrt{12} \sim 28.9\ \mu m$
  θ_{turn} independent

z (100 µm direction)

After irradiation*

CROC results

Φ_{eq} = 1.0 x 10^{16} cm^{-2}

Online threshold** ~ 1200 e^- - T ~ -20°C

✓ σ_{hit} better than: σ_{binary} = 28.9 µm

✓ Cluster size still above 1

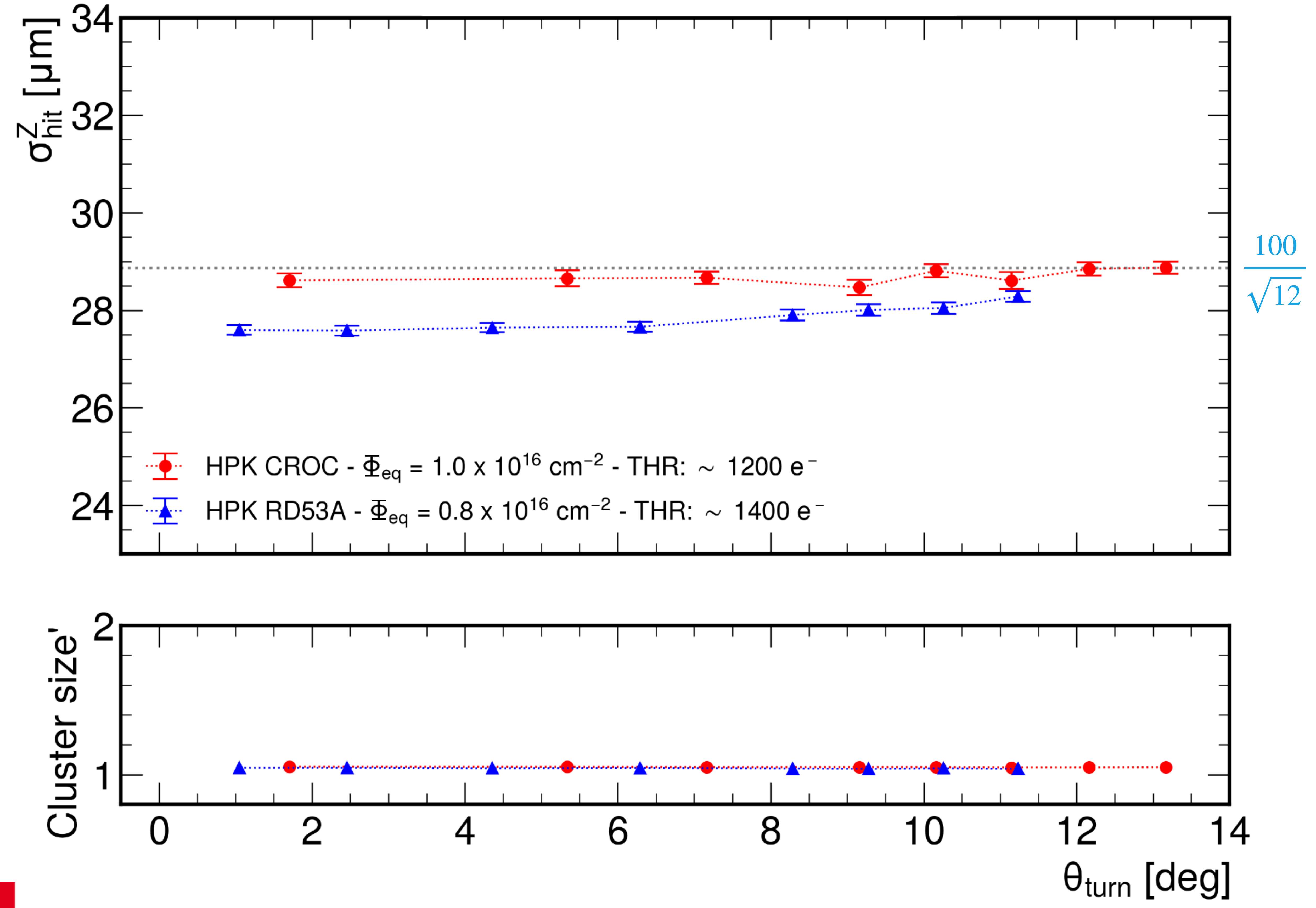
RD53A results

Φ_{eq} = 0.8 x 10^{16} cm^{-2}

Online threshold** ~ 1400 e^- - T ~ -25°C

✓ σ_{hit} better than: σ_{binary} = 28.9 µm

✓ Cluster size still above 1



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

* V_{bias} = 600 V

** Exp. deposited charge for a MIP in 150 µm Si before irr. ~ 11000 e^-

Summary

The preliminary analysis of the **characterization campaign** for the planar HPK sensors with the RD53B_CMS/CROC chip results in:

- Excellent **production yield**
- Very good electrical behavior before and after irradiation (**breakdown always > 800 V**)
- Hit efficiency and acceptance ~ 99% also for modules with **Φ_{eq} up to 1.0 x 10^{16} cm^{-2}**
- Resolution along the **r-ϕ (25 μm) direction always < $25/\sqrt{12}$ ~ 7.2 μm**
- Resolution along the **z (100 μm) direction always < $100/\sqrt{12}$ ~ 28.9 μm**

Good agreement with RD53A results

Analysis is still ongoing, more results will be available in the next months: spatial resolution for non-irradiated modules, dual slope ToT test, chip performance in cold, …

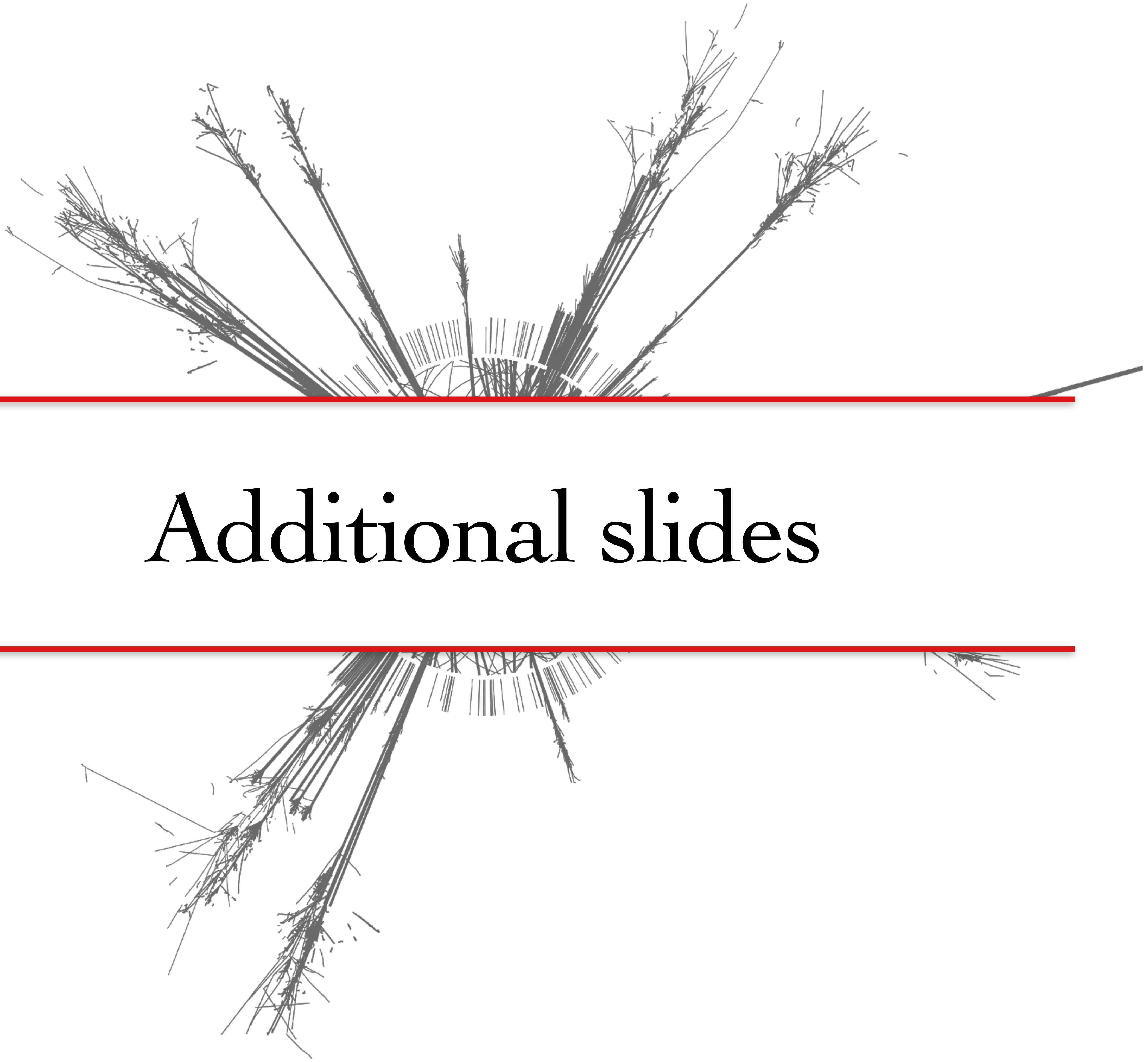
Outlooks

- Transition to sensor production phase —> wafer design for kickoff batch submitted to HPK
- First irradiated quad module to be tested on beam later this year

Other CMS Inner Tracker talks

Martina Manoni: "Test beam results of planar pixel quad modules and spatial resolution of 3D pixels for the Phase 2 CMS Tracker"
Clara Lasaosa Garcia: "Test Beam Results of 3D pixel sensors for the Phase 2 CMS Tracker with the RD53A and CROC readout chips"
Antonio Cassese: "Serial powering for the CMS Inner Tracker detector at High Luminosity LHC"

Additional slides

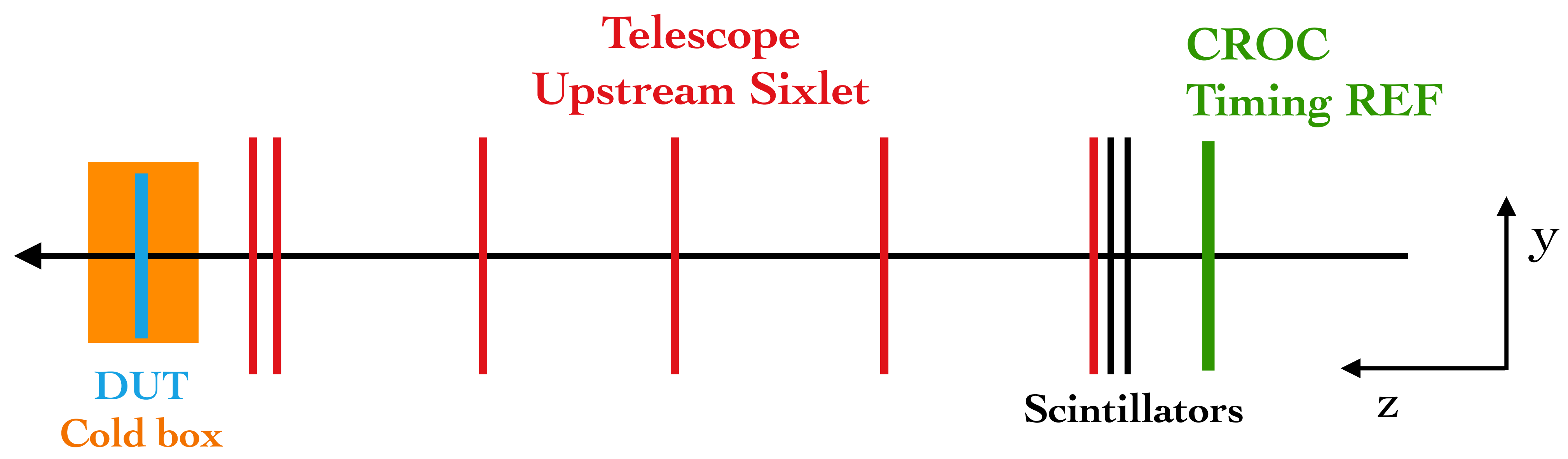


Telescope resolution

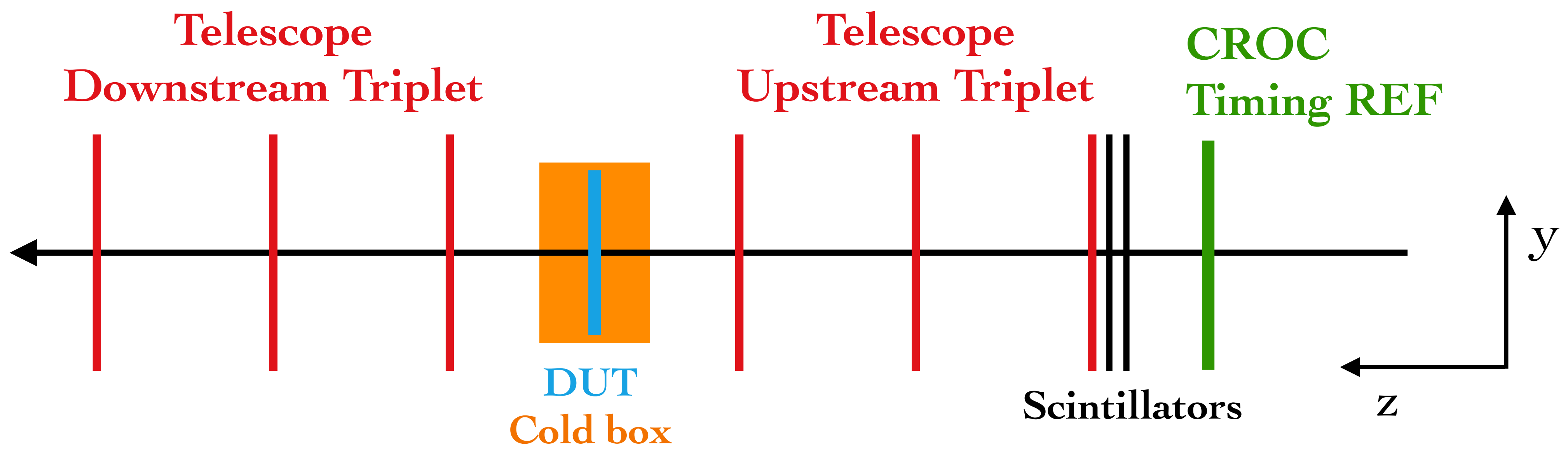
For the preliminary analysis of CROC modules resolution, the telescope resolution was calculated using a dedicated tool:

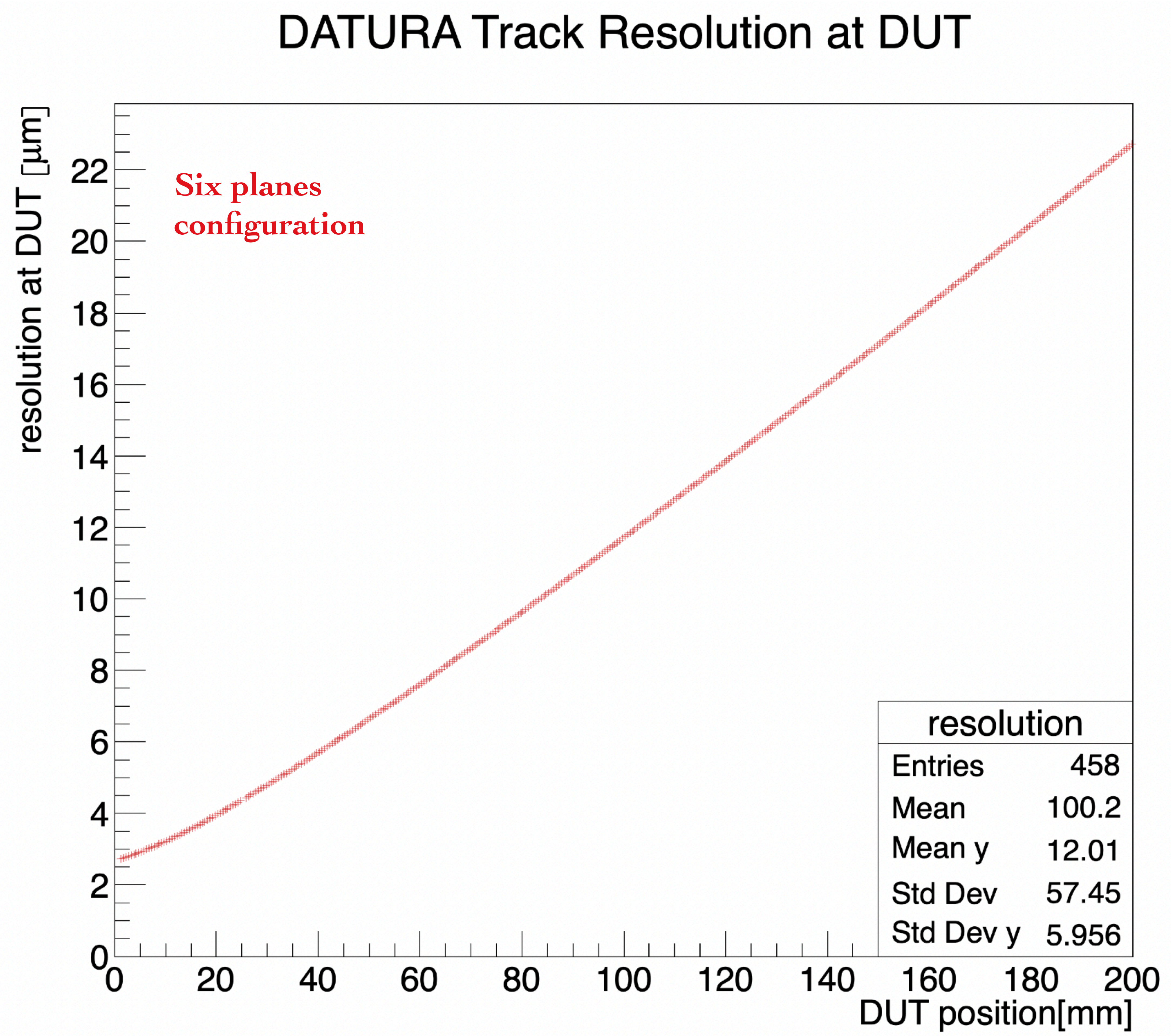
GBL Track Resolution Calculator 2.0[1]
- developed for EUDET-type beam telescopes performances studies[2]
- use the **General Broken Lines** formalism
- scattering in materials estimated via the PDG Highland formula

All the planes and the material budget considered:



Results for the "not irradiated" setup agree with the telescope resolution measured for the RD53A campaign **within 0.4 μm**





[1] GBL Track Resolution Calculator v2.0 (Link)

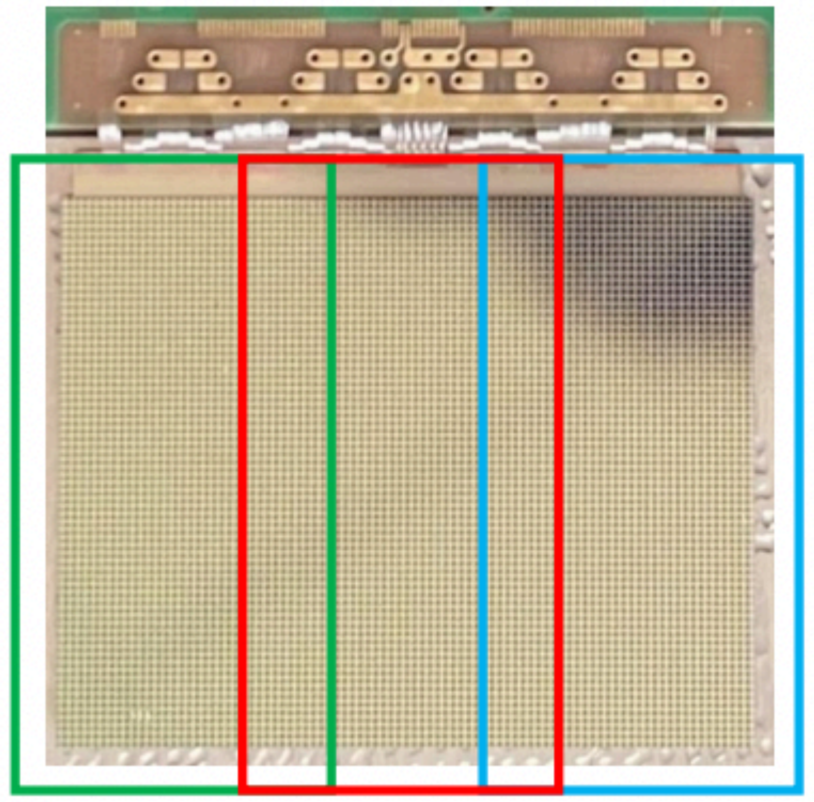
[2] H. Jansen, S. Spannagel et al. "Performance of the EUDET-type beam telescopes" (Link)

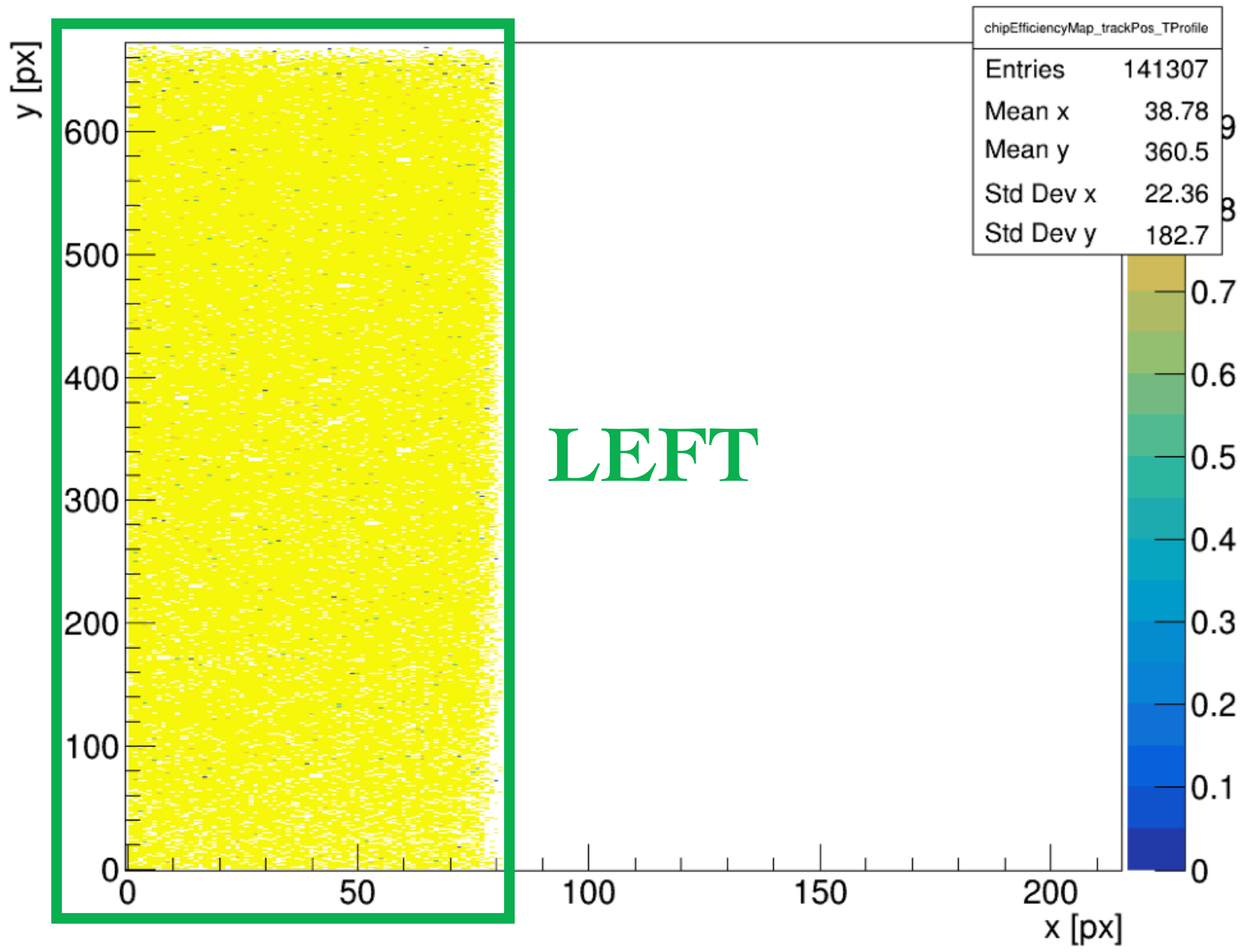
The patch scan

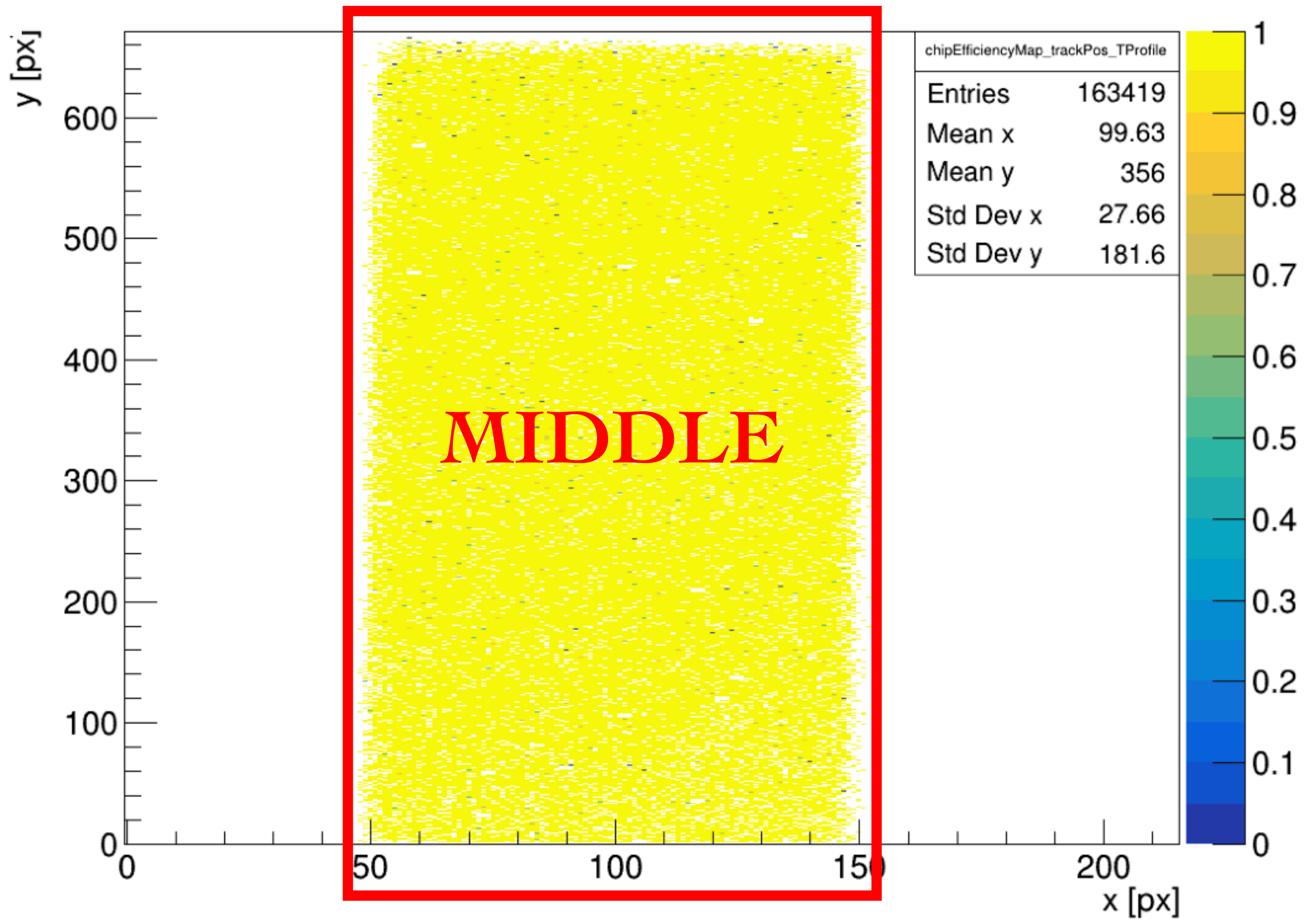
PRELIMINARY RESULTS

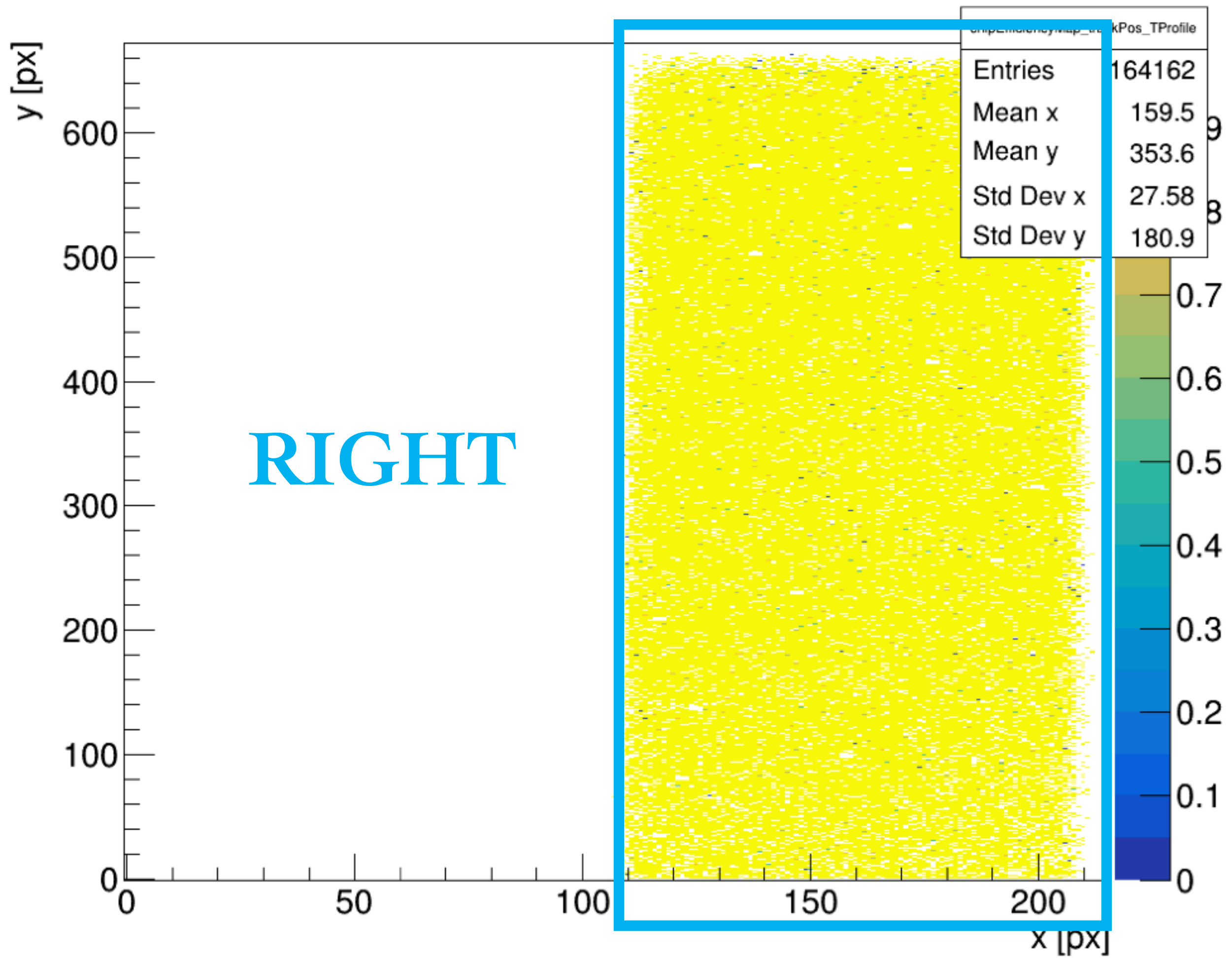
$\epsilon_{hit} = \frac{N^{DUT}_{tracks}}{N^{total}_{tracks}}$ at V_{bias} = 120 V and normal incidence — Patch scan

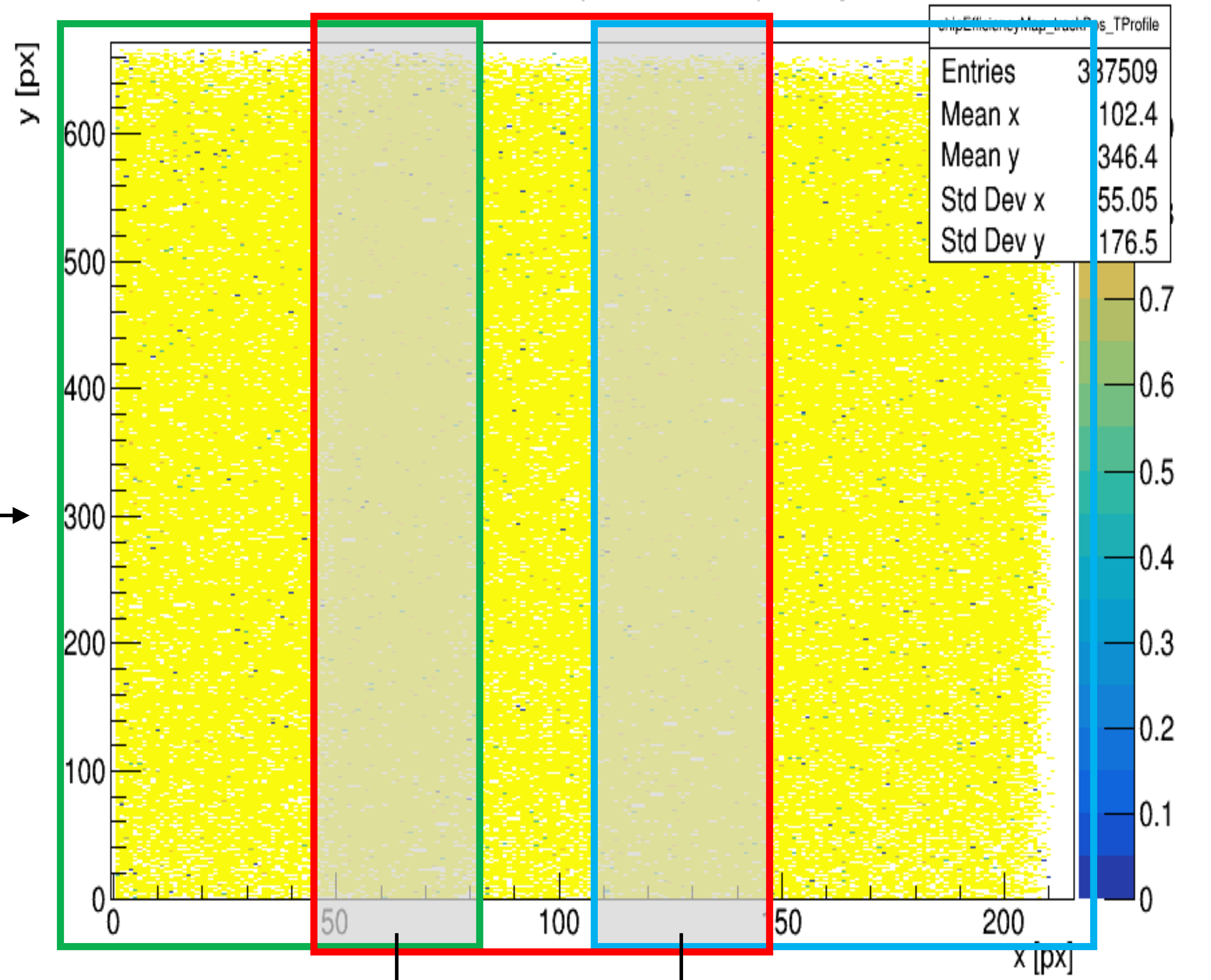
LEFT MIDDLE RIGHT











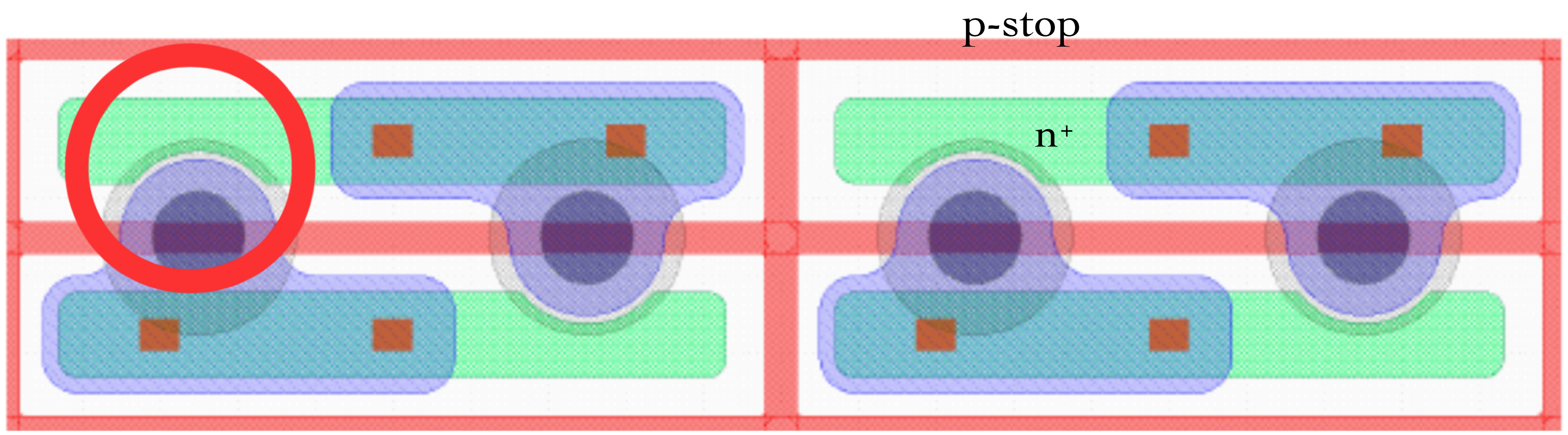
Overlap of two runs = 2x entries

Low statistic for these tests: mean pixel occupancy ~ 5 hits

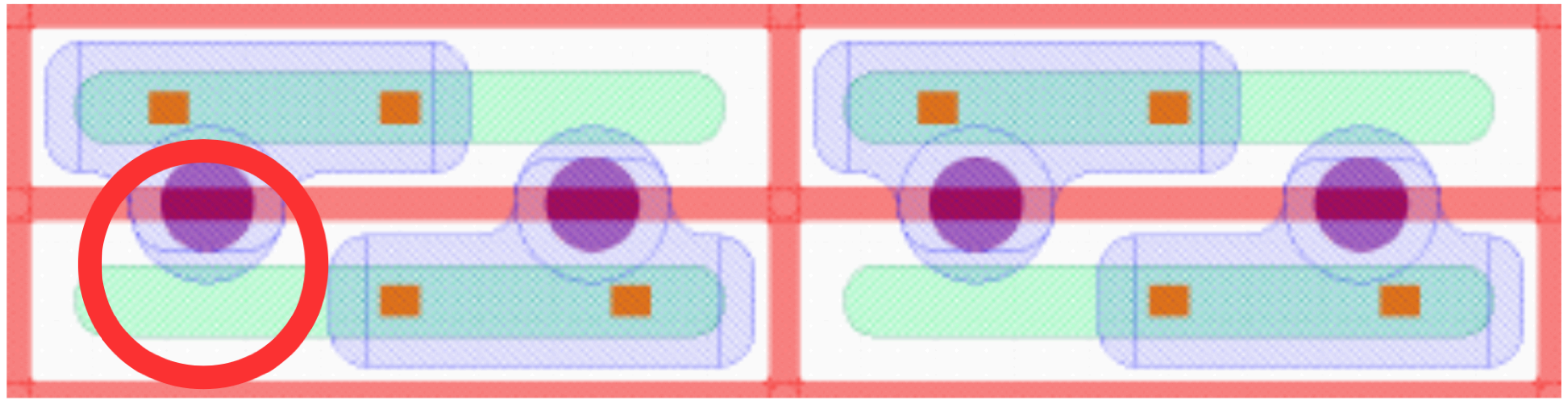
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

The planar sensor designs

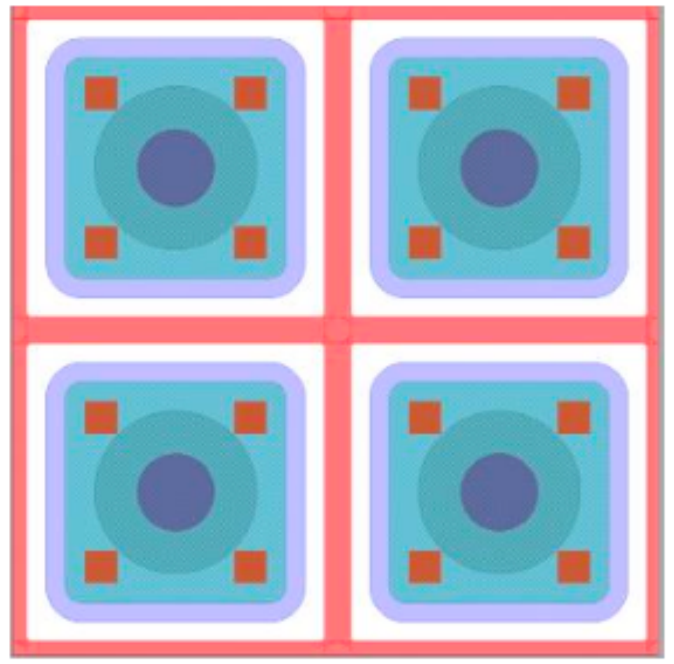
All the different planar sensor design tested:



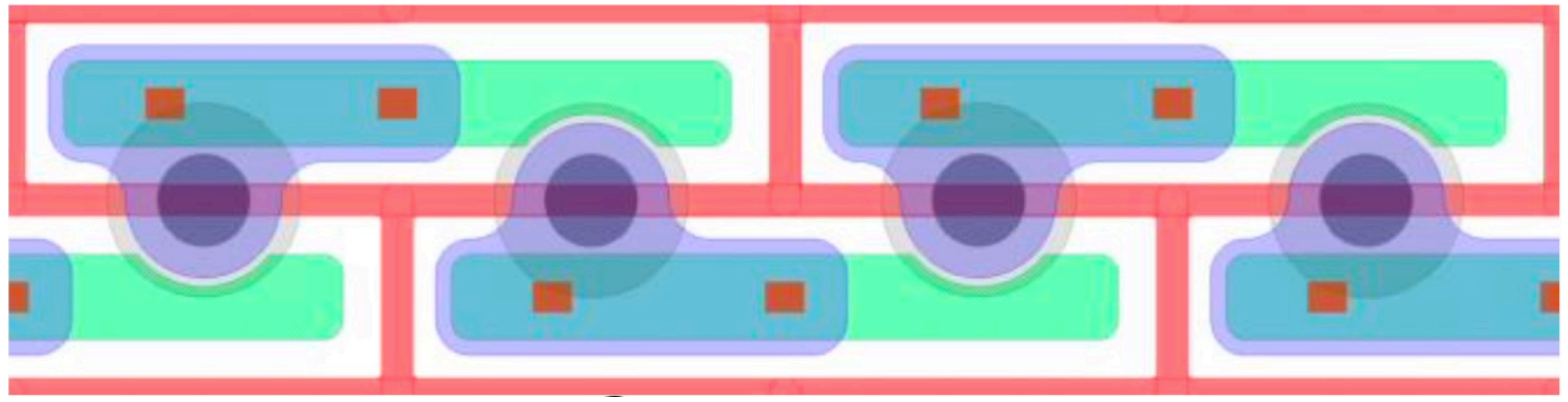
✓ Bitten implant design —> Final design



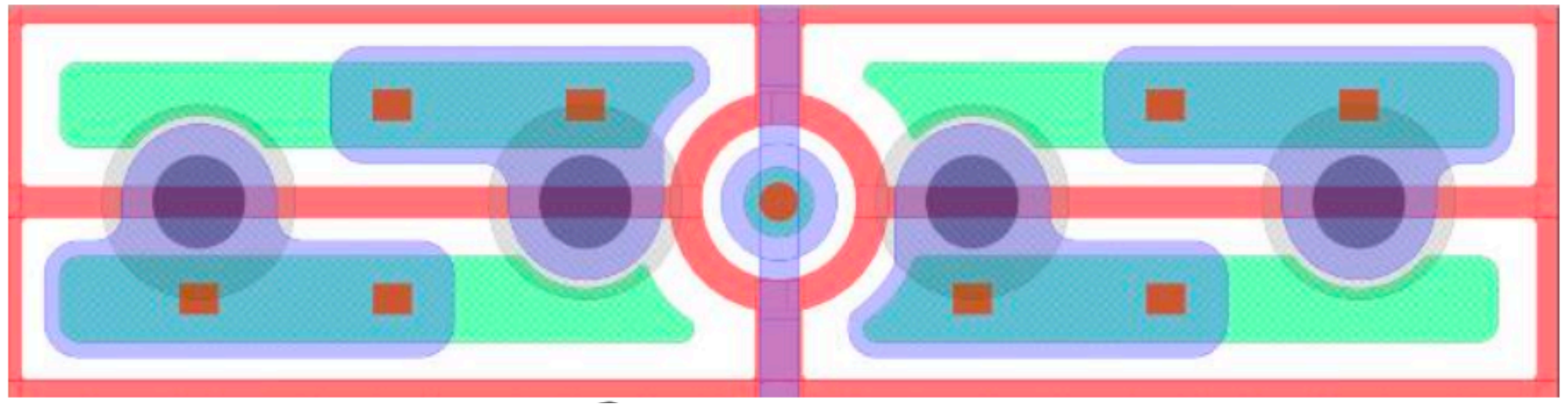
✗ "Standard" design



✗ "Standard" design
50x50 µm²



✗ "Bricked" design



✗ "Standard" design with bias dot

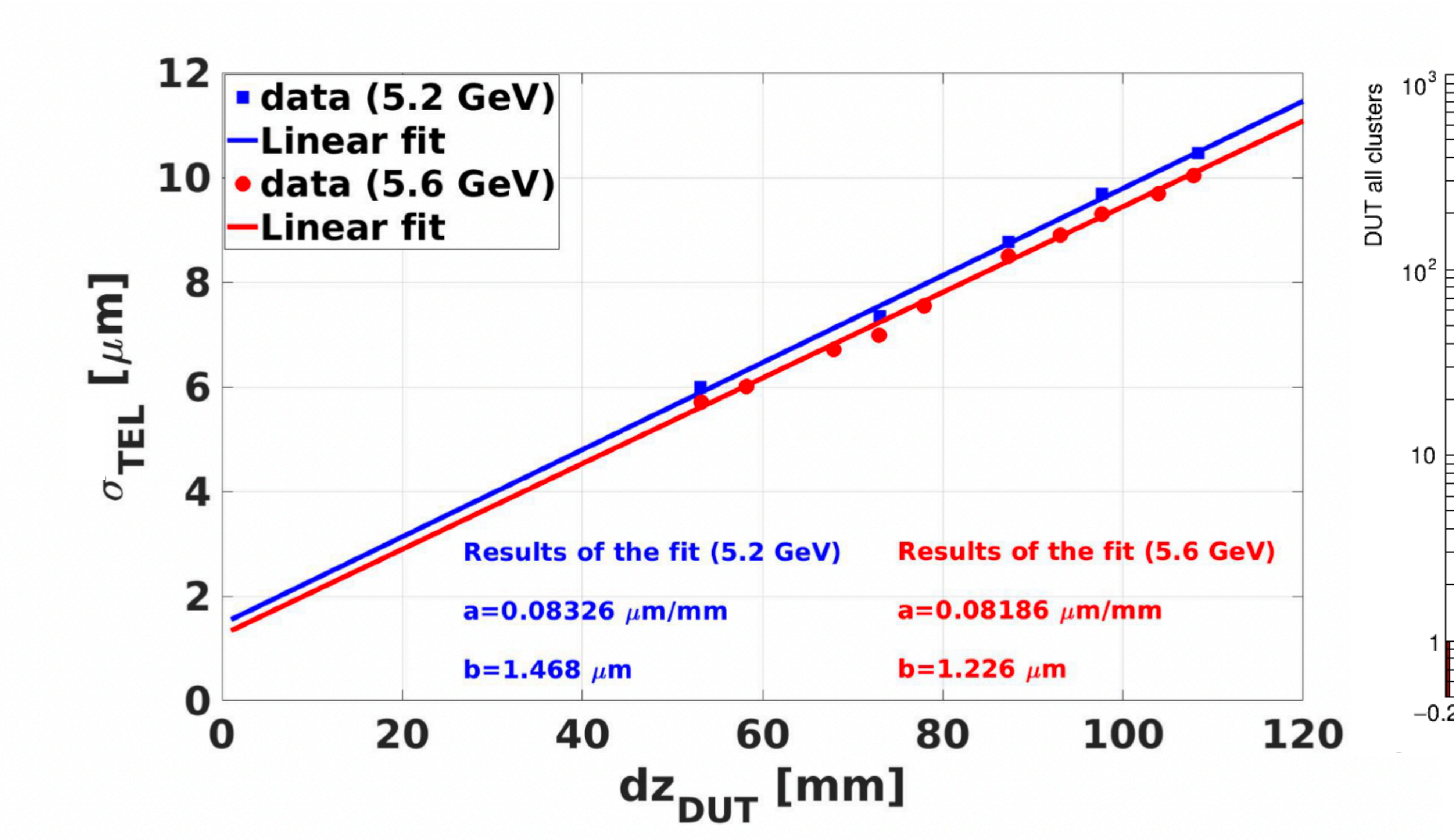
[1] GBL Track Resolution Calculator v2.0 (Link)

[2] H. Jansen, S. Spannagel et al.
" Performance of the EUDET-type beam telescopes"(Link)

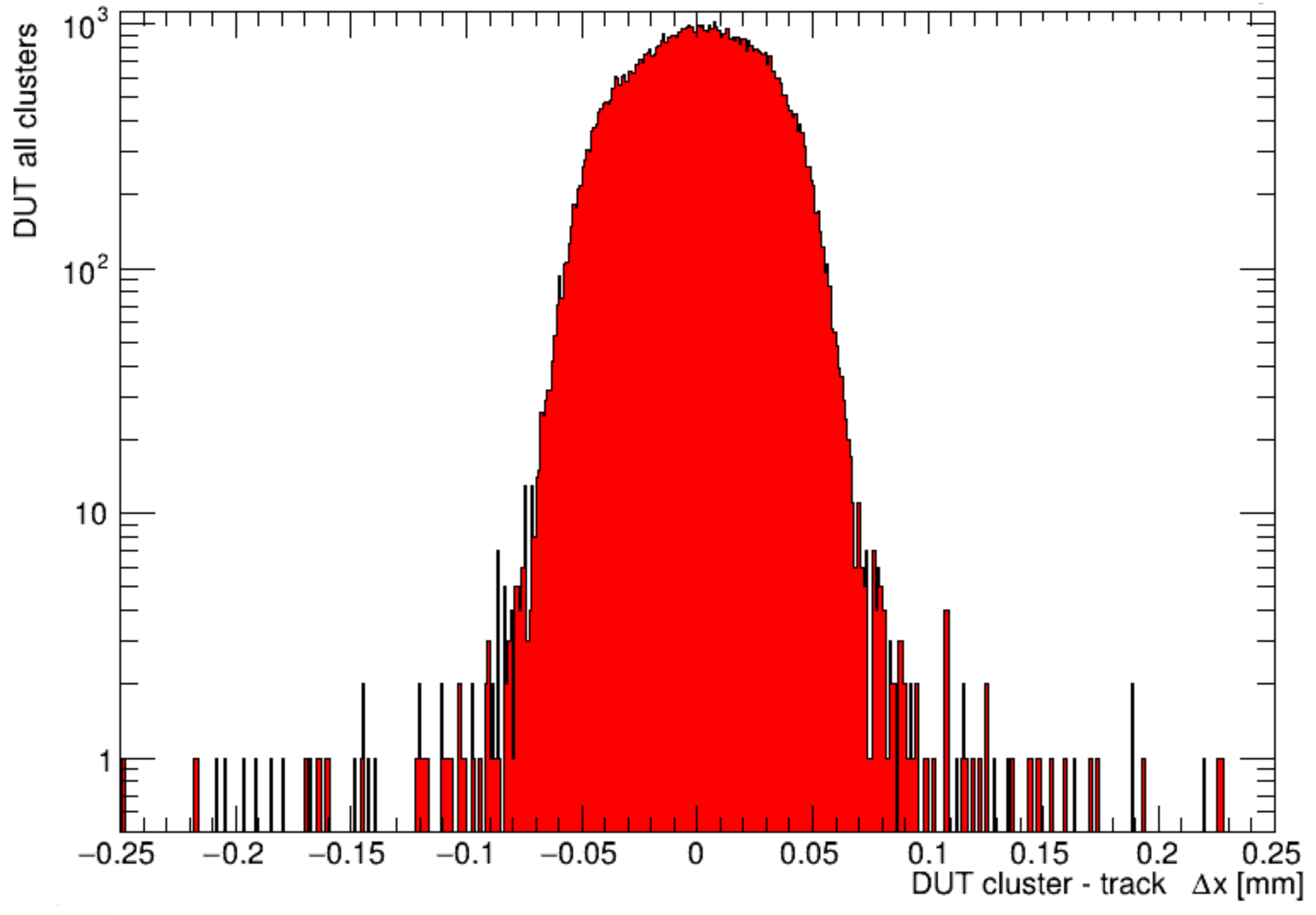
Single hit spatial resolution

Hit spatial resolution: $\sigma_{hit} = \sqrt{RMS_{trc}^2 - \sigma_{TEL}^2}$

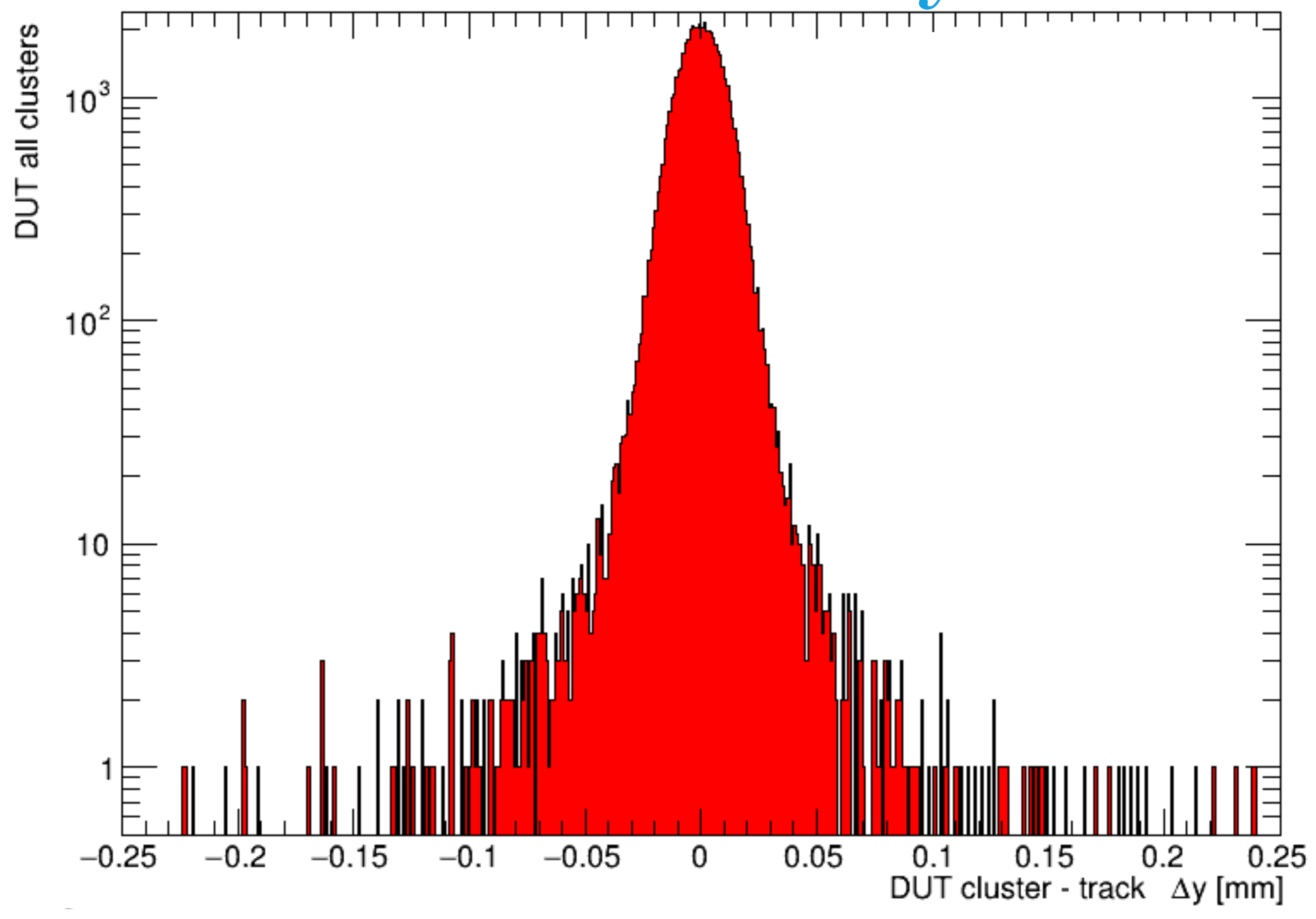
- **RMS_{trc} = truncated RMS from DUT residual distribution*:** outliers effect on RMS suppressed calculating it with iterative** method, discarding values outside of ± 3 RMS_{trc}
- **σ_{TEL} = telescope resolution:**
  no cold box: extracted as residual distribution of triplets & driplets extrapolation @ DUT with iterative method within ± 3 RMS_{trc}: $\sigma^x_{TEL} = RMS_{trc}/2cos(\theta_{Turn})$, $\sigma^y_{TEL} = RMS_{trc}/2cos(\theta_{Tilt})$
  cold box: extrapolated from linear fit of dedicated measurements with fresh 612 (σ_{DUT} = 5.32 ± 0.04 µm)
  $\sigma_{TEL} = m_{E_{beam}}(dz_{DUT}) + q_{E_{beam}}$ (fits available for E_{beam} = 5.2 & 5.6 GeV)



DUT residual Δx



DUT residual Δy



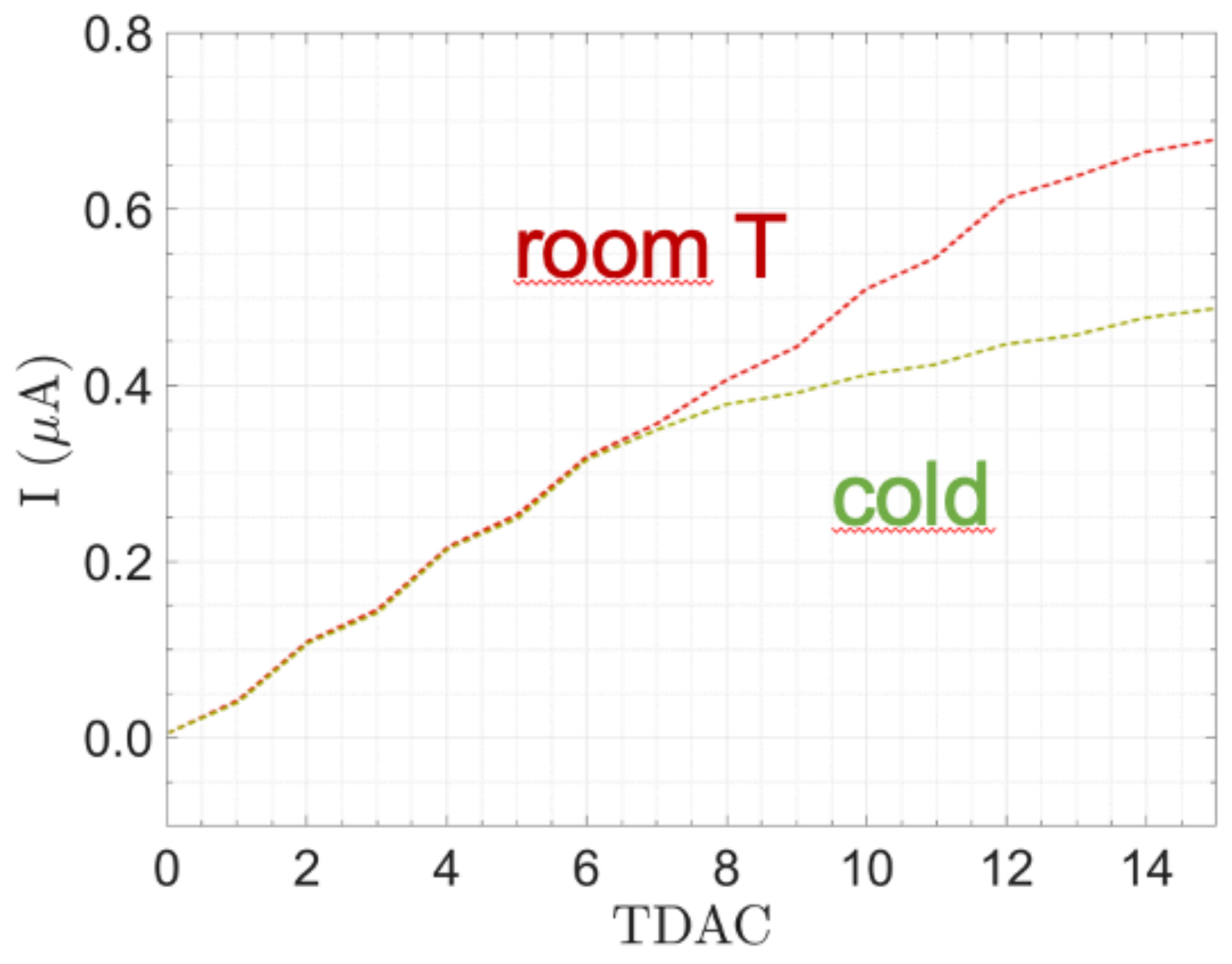
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

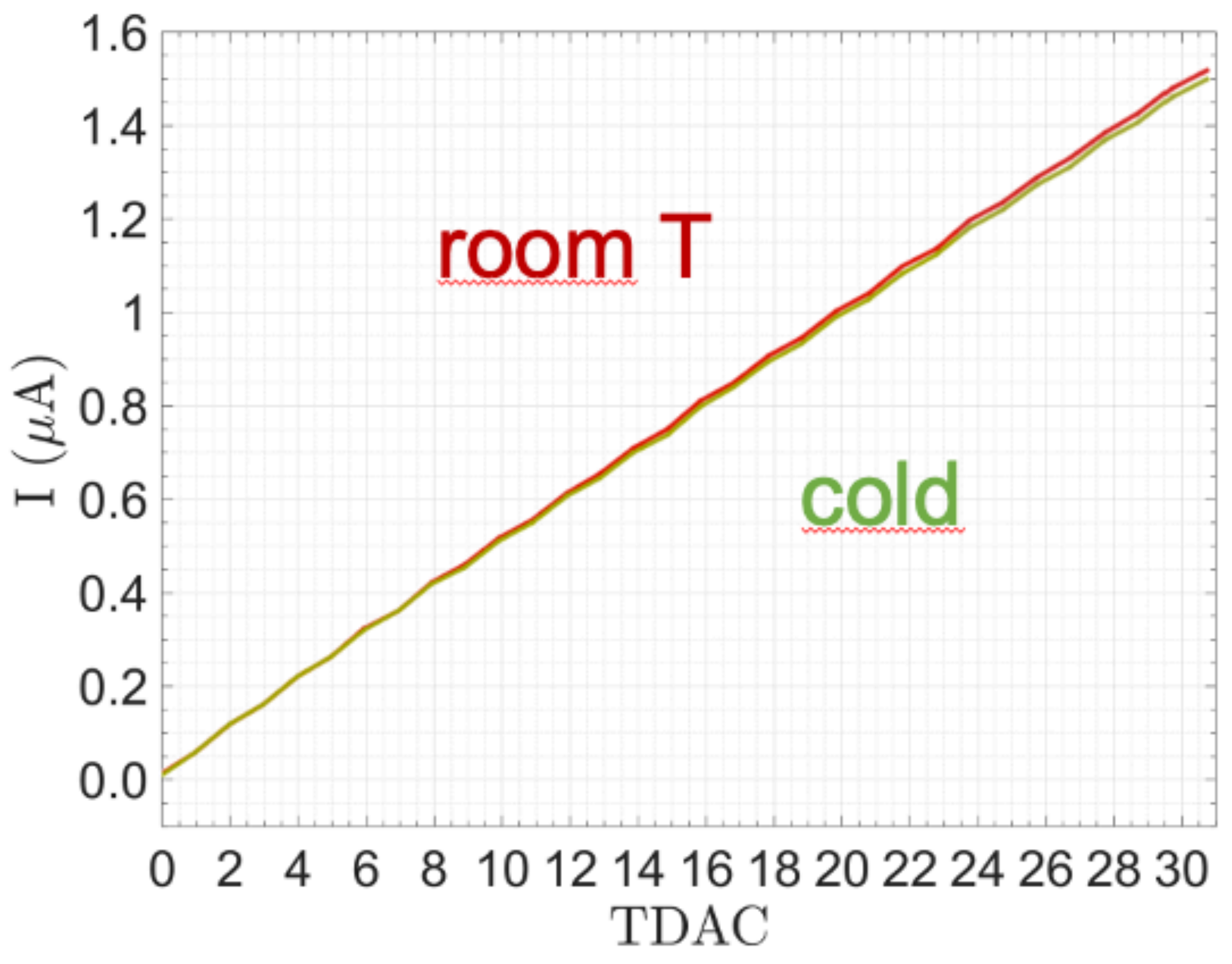
* After event selection cuts

** Considered range converges with few iterations & contains > 98% of residual distribution entries

CROC main improvements

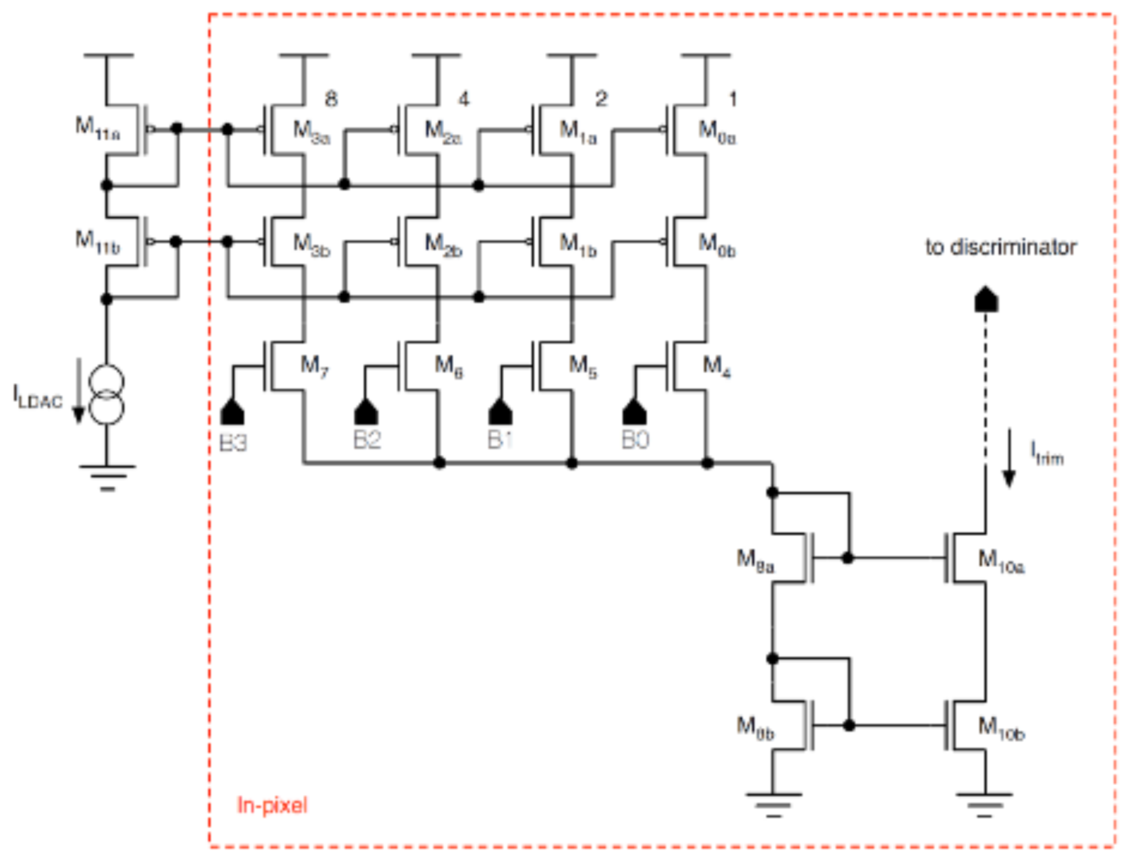
Increased TDAC circuit **dynamic range** (with an extra 5th bit) to compensate for saturation at low temperatures

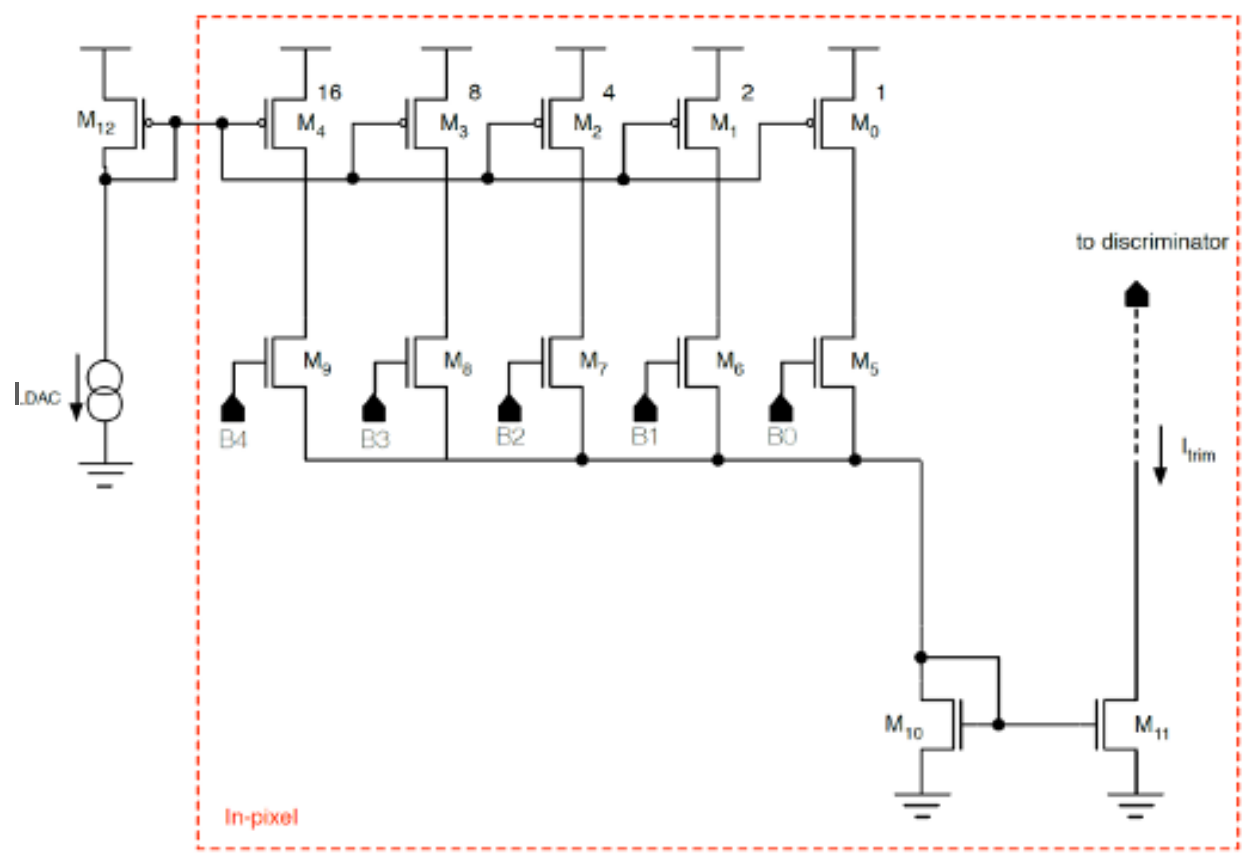




RD53A

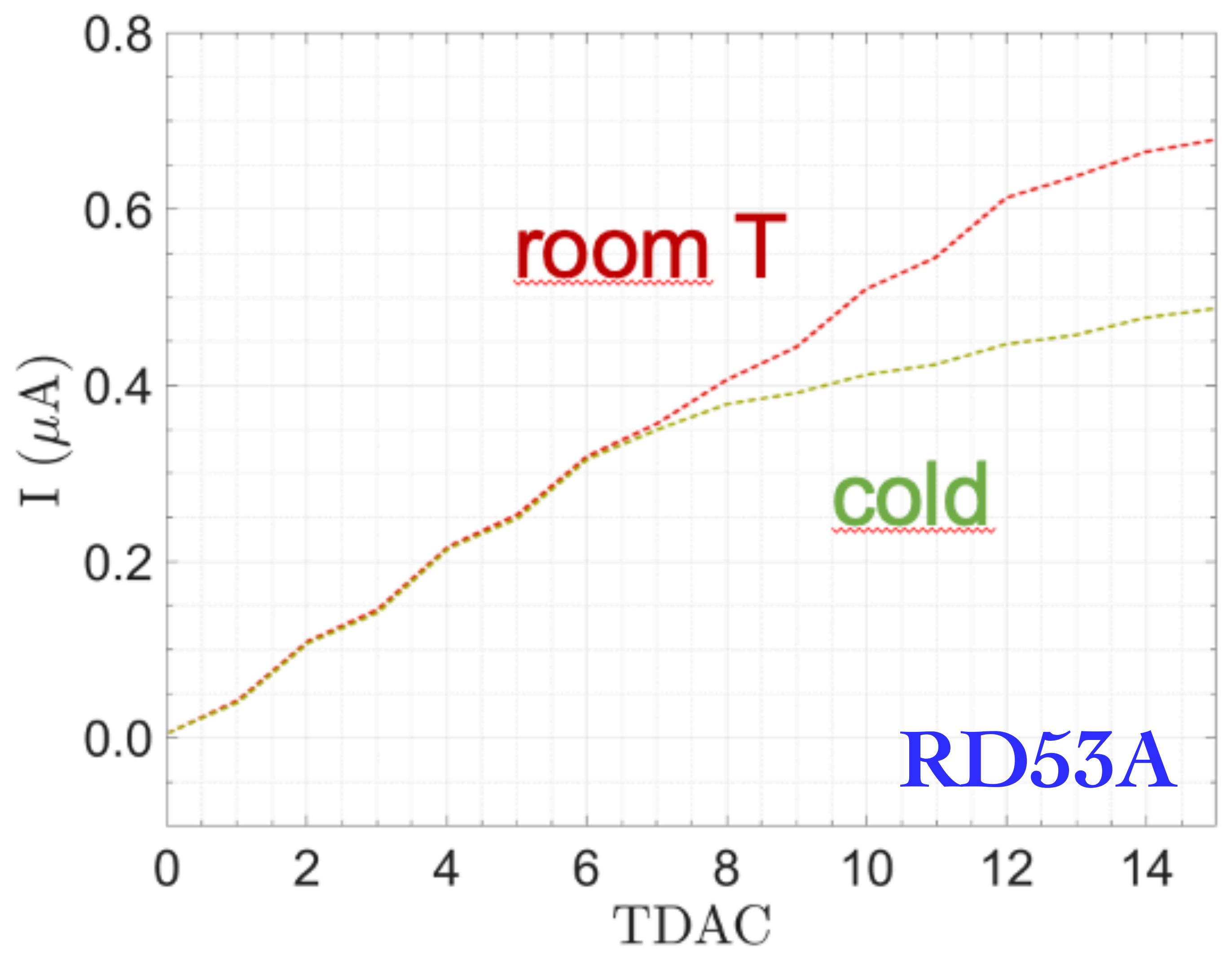
CROC

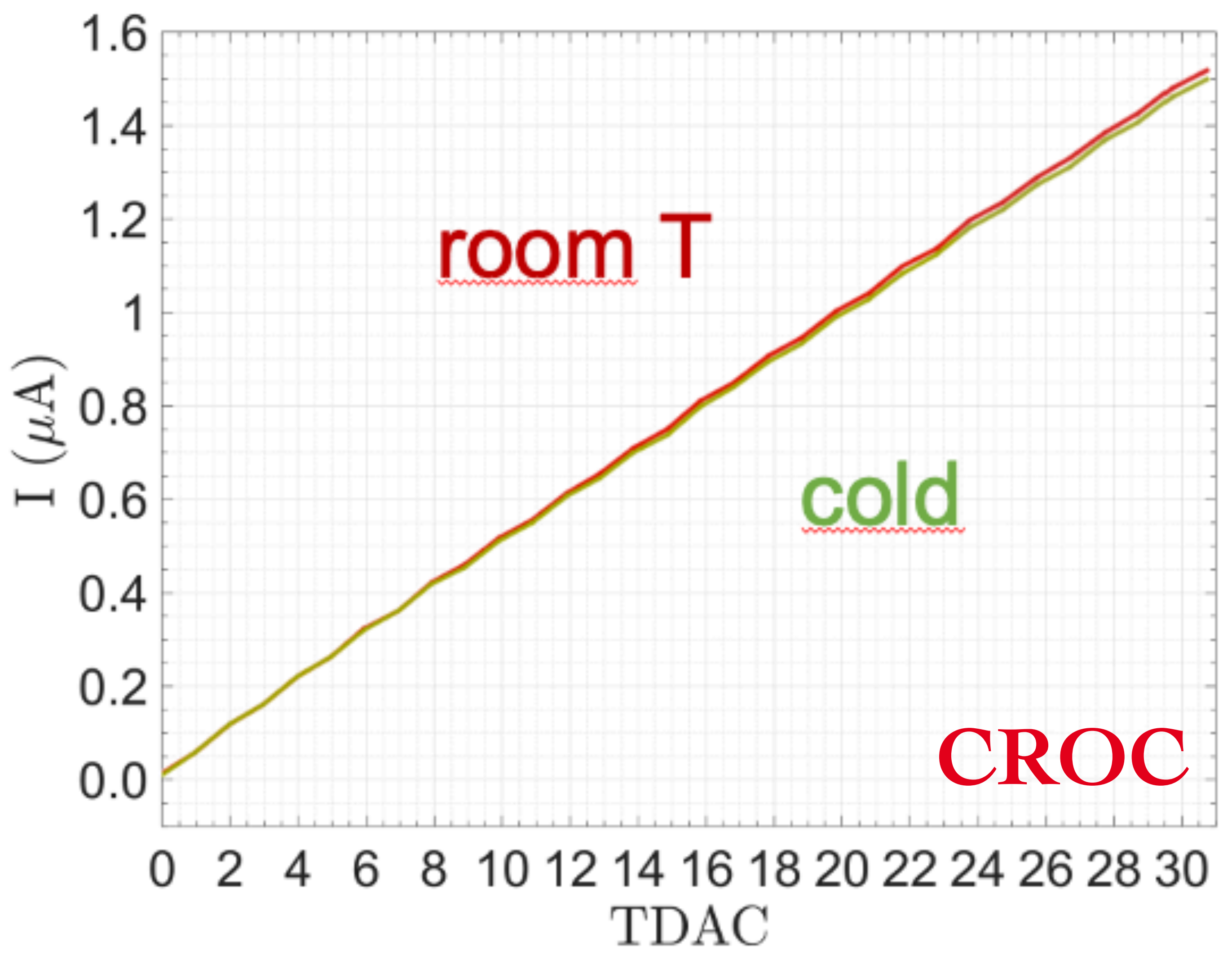




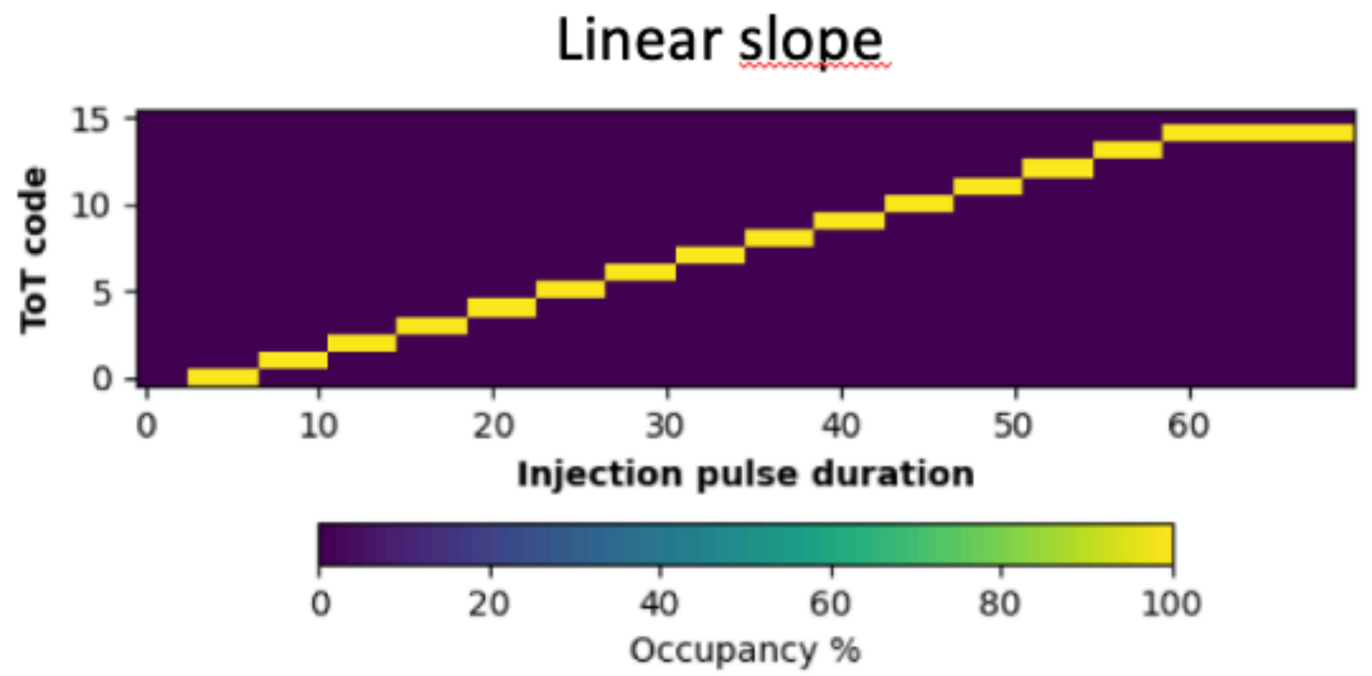
CROC main improvements

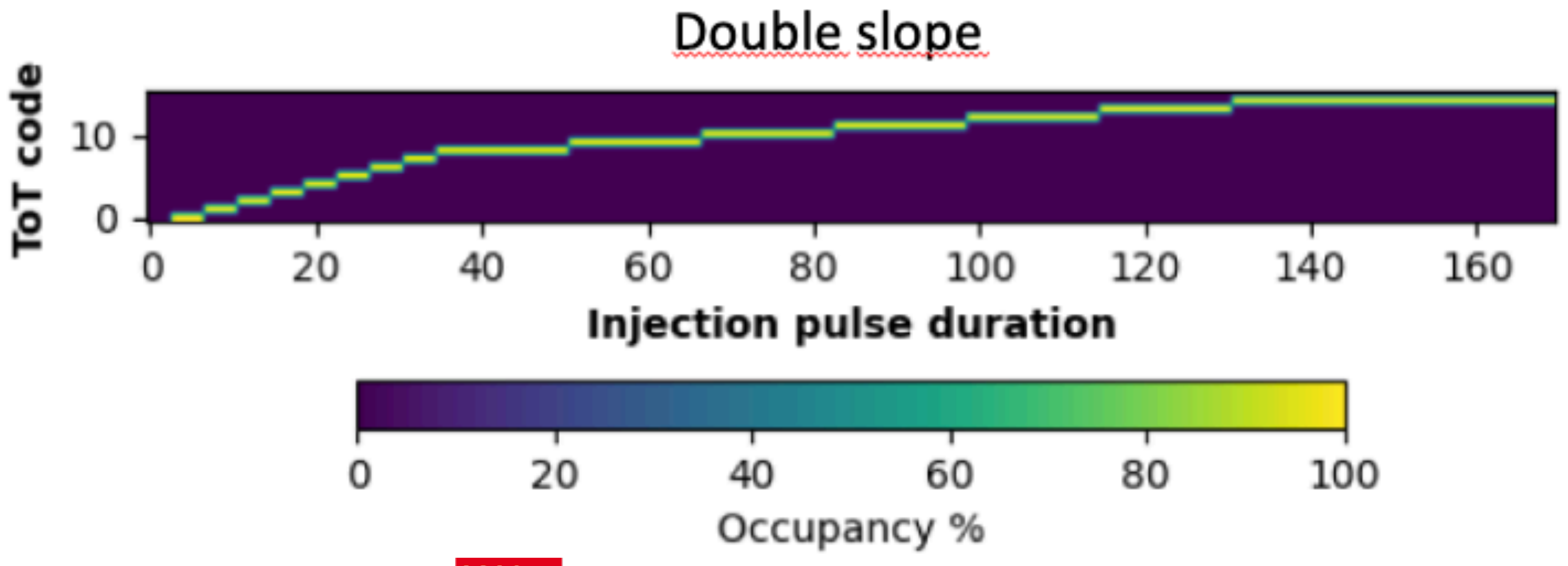
Increased TDAC circuit **dynamic range** (with an extra 5th bit) to compensate for saturation at low temperatures

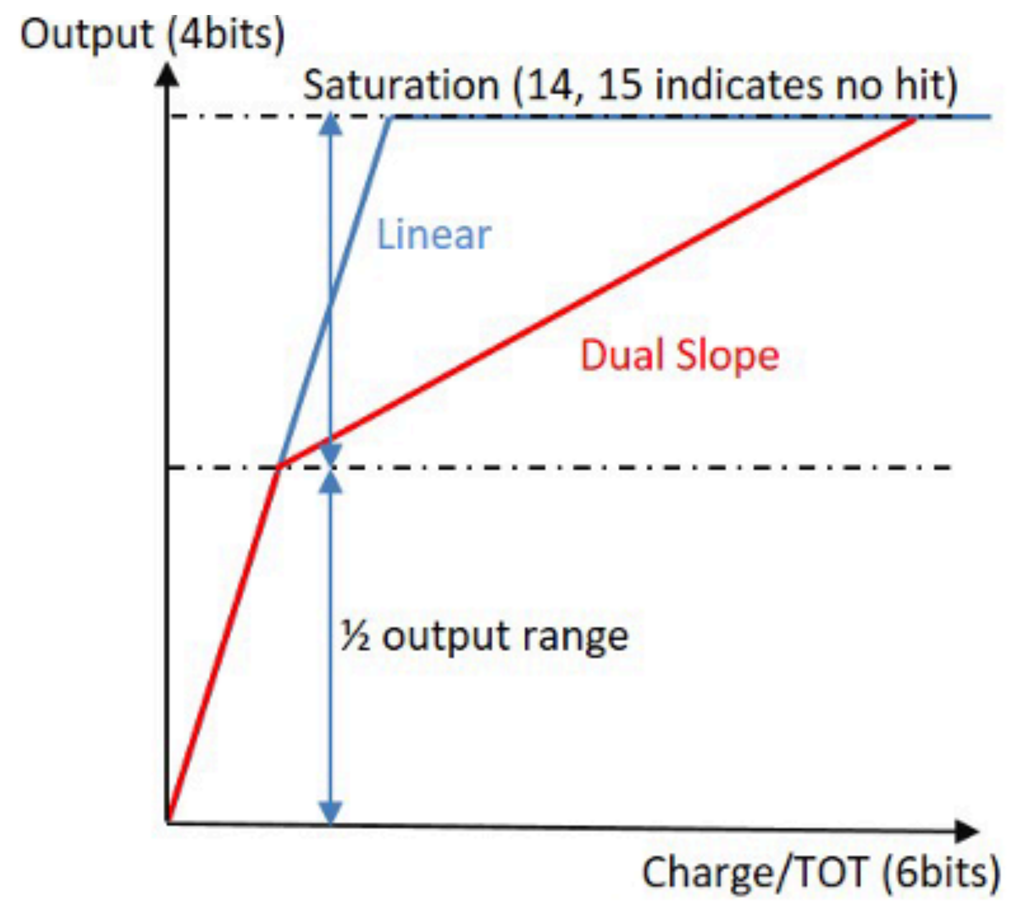




Improved **cluster charge** estimation —> with dual slope ToT (under test)

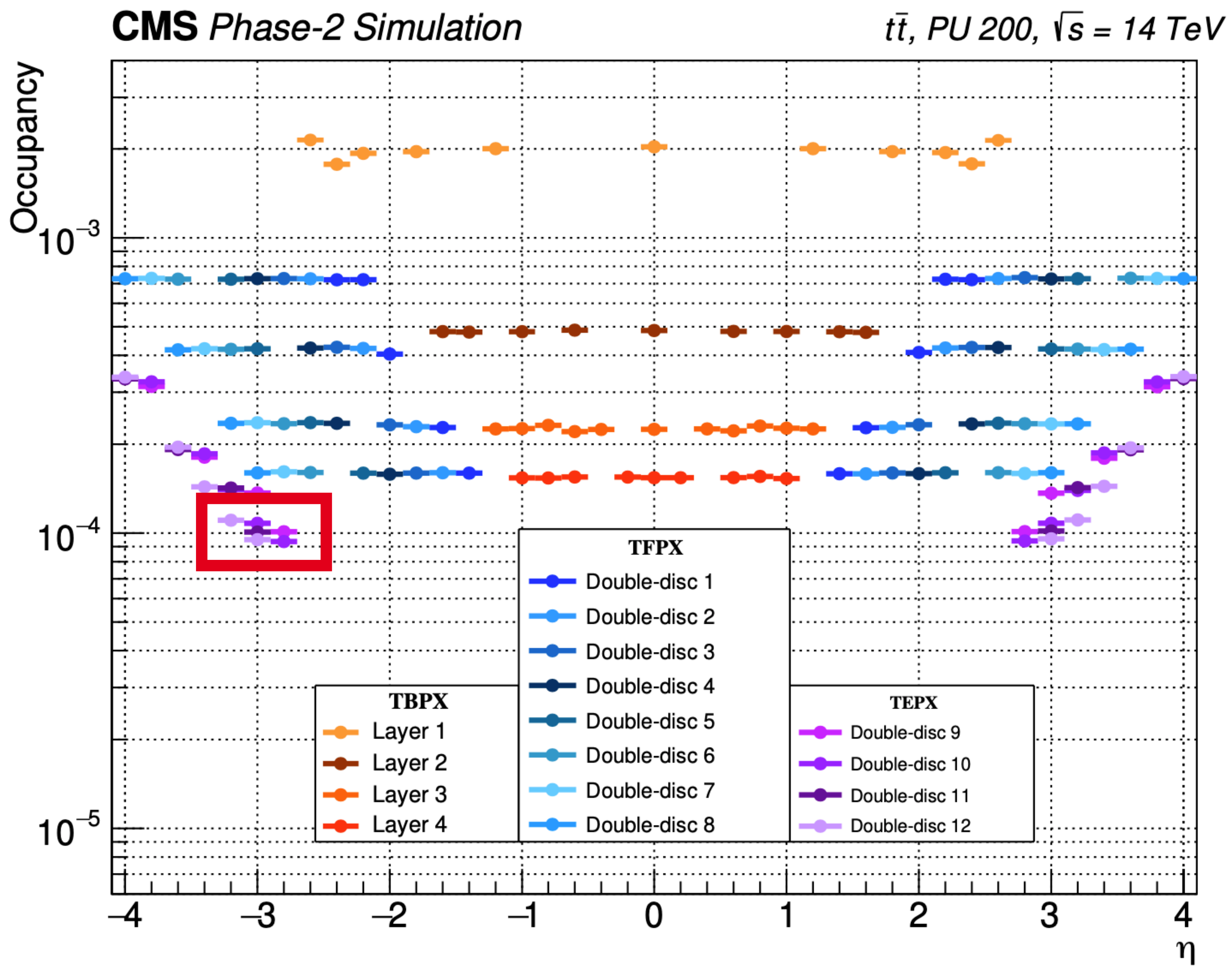






Noise impact on hit efficiency

- A sizable increase of the occupancy would affect the system negatively:
  - **Saturating the available bandwidth**
  - **Increasing the tracking complexity** (fake tracks)



Simulation of the hit occupancy as a function of pseudorapidity for all IT layers and double disks for top quark pair production events with 200 events pileup [1]

Noise requirements for Phase 2 IT modules:

- Reference single pixel noise occupancy threshold sets as the most stringent one: TEPX layers (10^{-4} hit occupancy)
  - Pixels masked if they had > 1000 hits in 10^{7} triggers
    ✓ good if: # of masked pixel <1% of the total # of pixels
- **Average** noise occupancy of **un-masked** pixels measured
  ✓ good if: mean noise occupancy < 10^{-6}

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

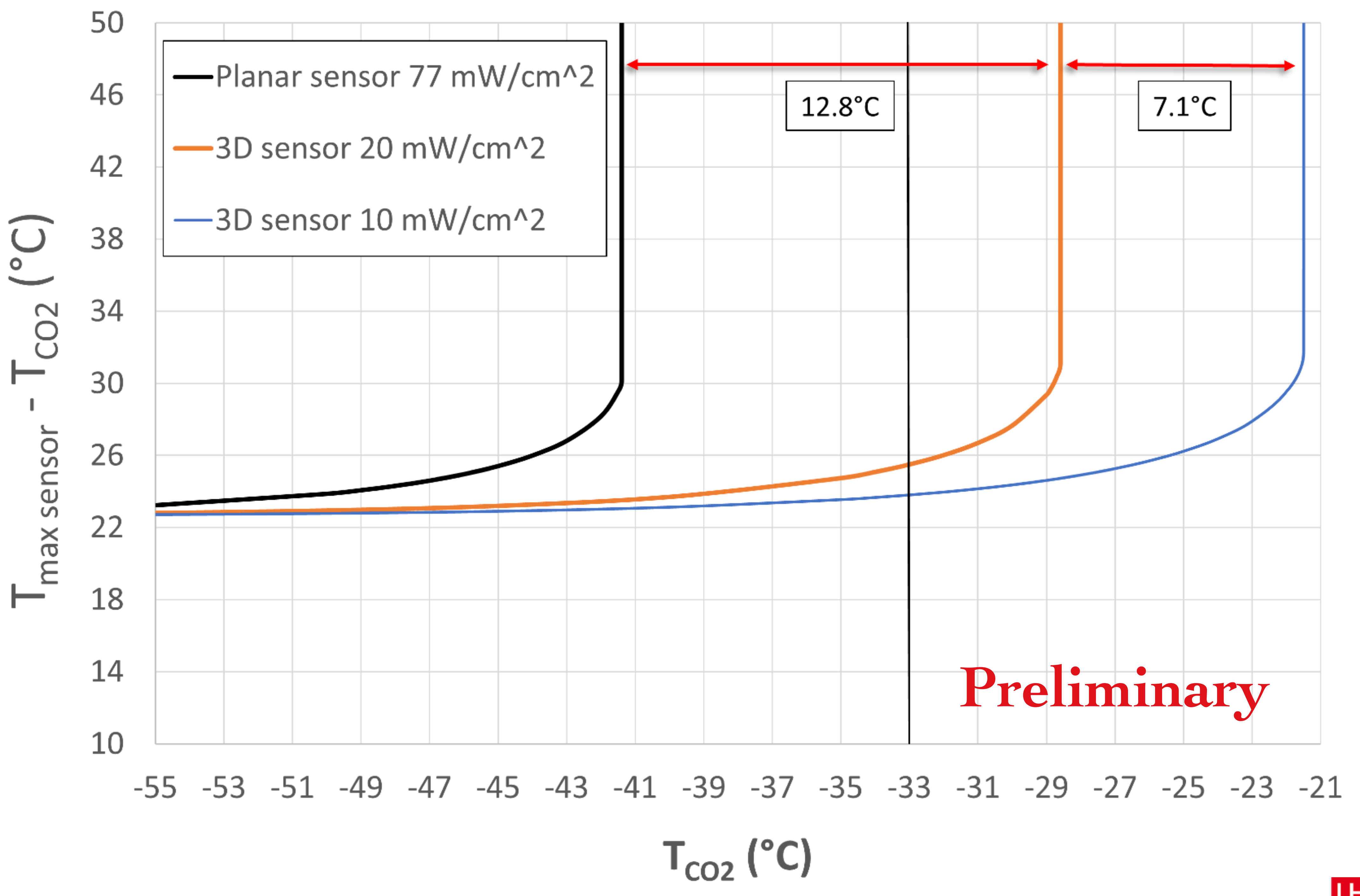
[1] JINST 16 P12014 (Link)

3D sensors for TBPX L1

For the **“ultimate luminosity scenario”**: min. T_{CO2} reachable underneath the module: **-33°C**

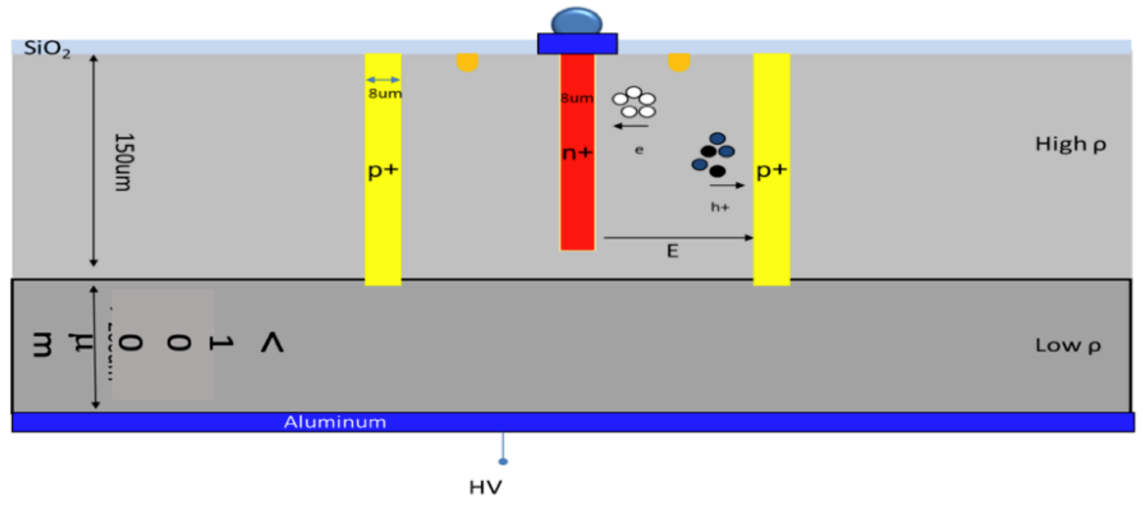
From power dissipation simulations for **L1**, to **avoid sensors thermal runaway**:

- **Planar sensors:** the required **T_{CO2} is much lower than -33°C**
- **3D sensors:** more than 4°C margin (confirmed power dissipation **below 20 mW/cm²** also after Φ_{eq} = 2.0 x 10^{16} cm^{-2})

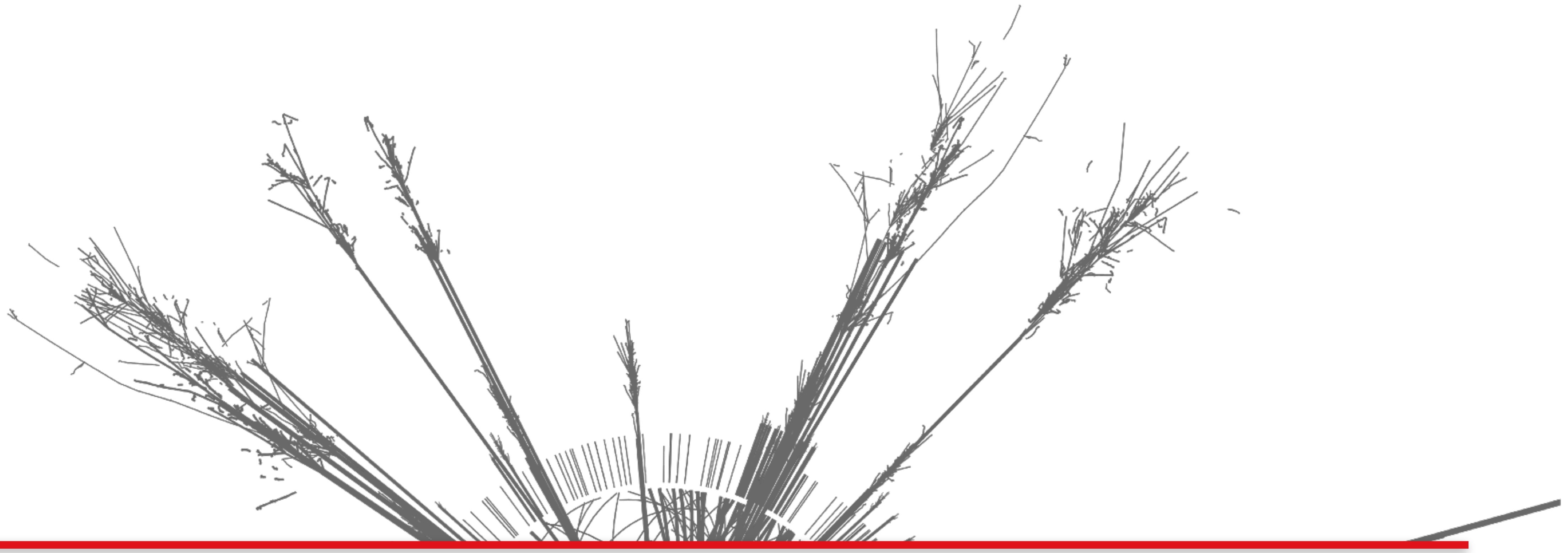


Two contributions from 17th “Trento” Workshop on Advanced Silicon Radiation: (link)

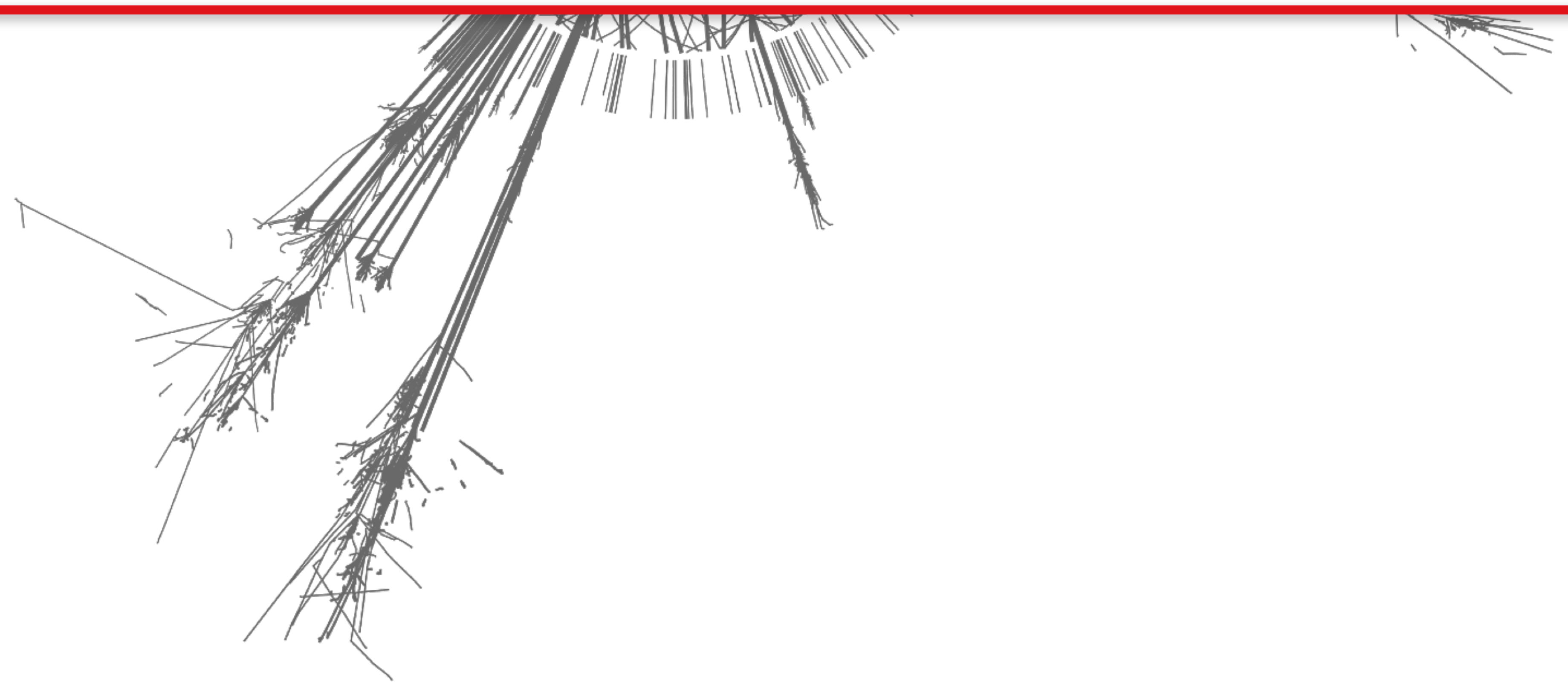
- **G. Bardelli**:
  “Test Beam results of FBK 3D pixel sensors interconnected to RD53A readout chip after high irradiation”
- **S. J. Dittmer**:
  “Study of irradiated CNM 3D sensors”



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



RD53A



Results: crosstalk

Test Pulse Measurements on RD53A modules:

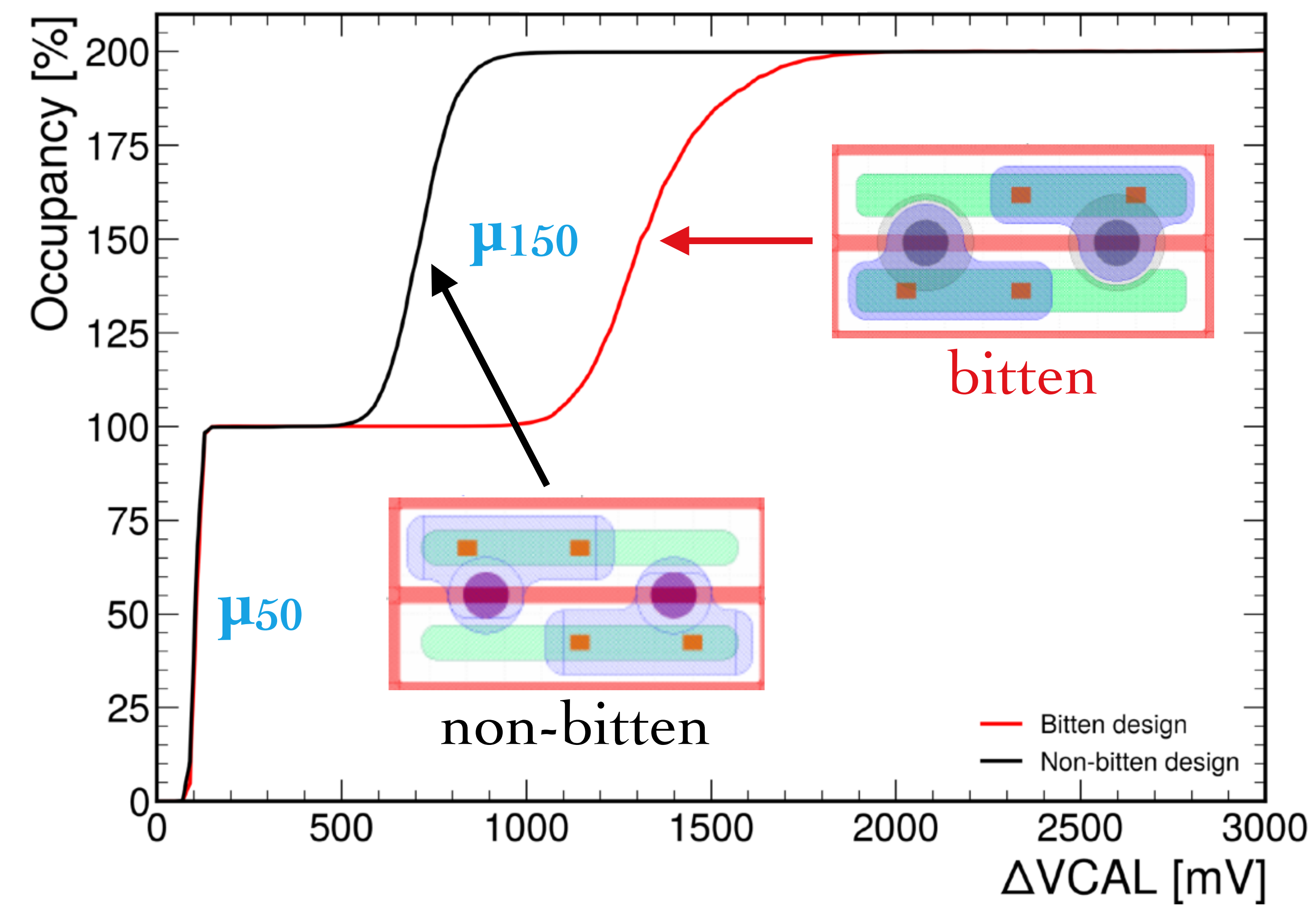
- Send test pulse to all pixels (consecutively)
- Count the number of pixels above threshold
- Find the amplitude μ_{50} required for 50% occupancy
- Calculate the crosstalk x:

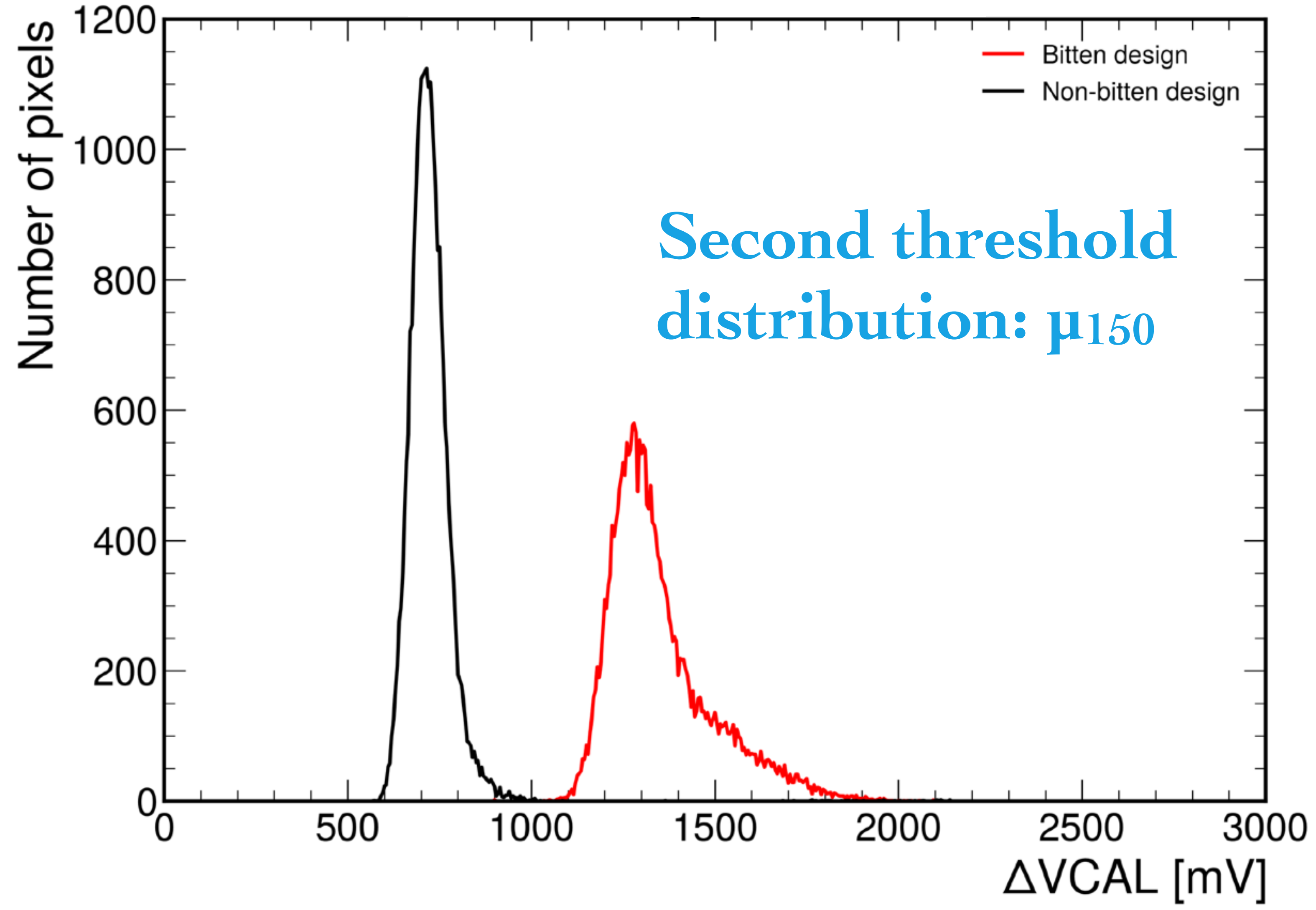
$$x = \frac{r}{r+1} \quad \text{with:} \quad r = \frac{\mu_{50}}{\mu_{150}}$$

Results (similar chip settings, thresholds):

- **non-bitten**: x = 14%
- **bitten**: x = 8%

✓ **Crosstalk considerably reduced**
(residual effects can be corrected in offline reconstruction)





Results: spatial resolution

Requirements:

- Best single point **resolution**:
  $\sigma_{hit} < 25/\sqrt{12} \sim 7.2\ \mu m$

Results* before irradiation:

Online threshold** ~ 1250 e$^-$ - T ~ +25°C

Φ_{eq} = 0.0 x 10^{16} cm^{-2}: V_{bias} = 120 V

Optimal angle: **$\tan^{-1}(25/150) \sim 9.5°$**

✓ **σ_{hit} ~ 2 μm** @ cluster size = 2

Results* after irradiation:

Online threshold ~ 1250 e$^-$ - T ~ -25°C

Φ_{eq} = 0.8 x 10^{16} cm^{-2}: V_{bias} = 600 V

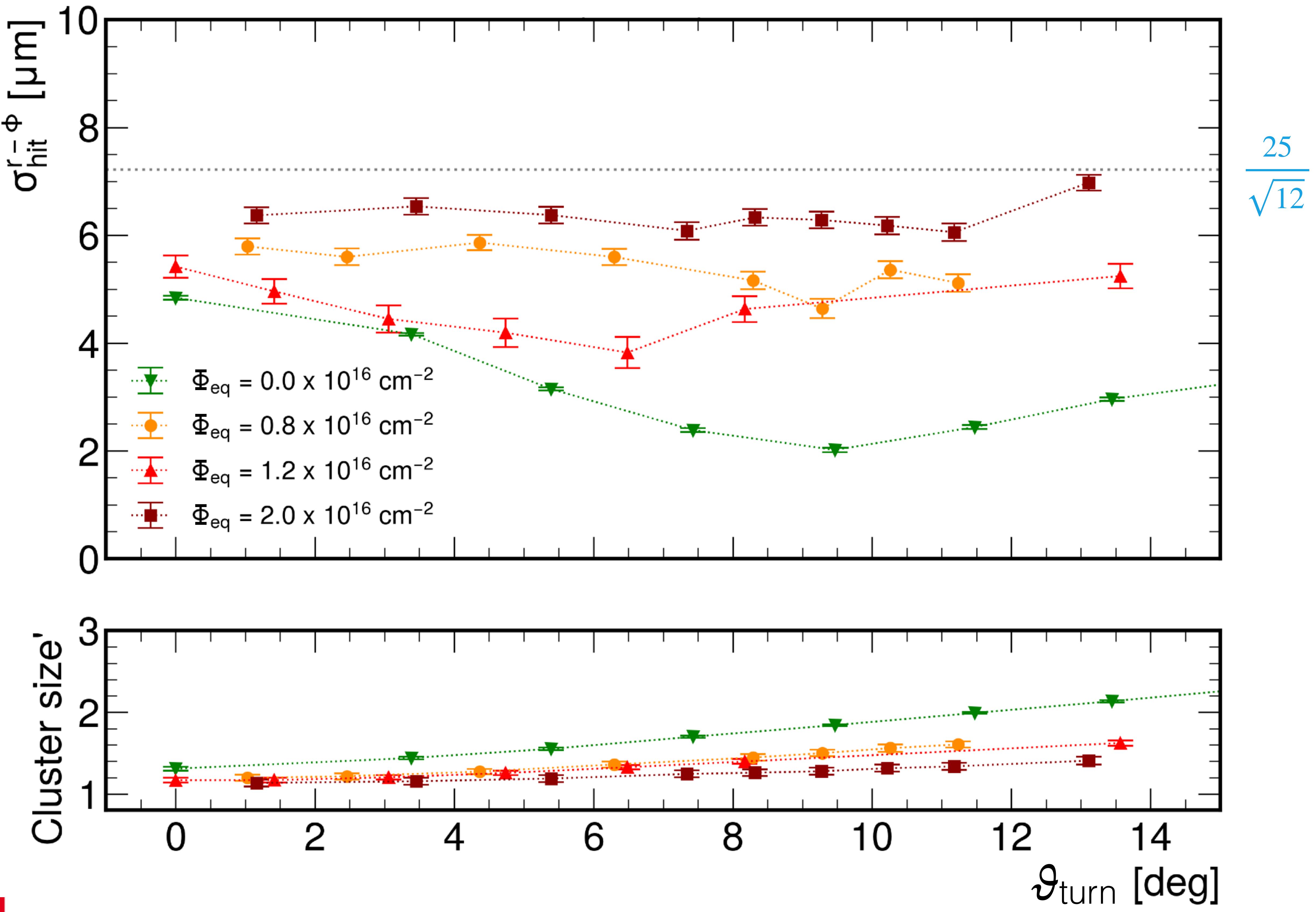
Φ_{eq} = 1.2 x 10^{16} cm^{-2}: V_{bias} = 800 V

Φ_{eq} = 2.0 x 10^{16} cm^{-2}: V_{bias} = 800 V

✓ **σ_{hit}** better than: σ_{binary} = 7.2 μm

✓ Cluster size still above 1

r-ϕ (25 μm direction)



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

* Excluding effects coming from readout chain

** Exp. deposited charge for a MIP in 150 μm Si before irr. ~ 11000 e$^-$

Results: spatial resolution

Requirements:
- Best single point **resolution**:
  $\sigma_{hit} < 100/\sqrt{12} \sim 28.9\ \mu m$

Results* before irradiation:

Online threshold** ~ 1250 e⁻ - T ~ +25°C

Φ_{eq} = 0.0 x 10^{16} cm^{-2}: V_{bias} = 120 V

✓ σ_{hit} independent of the turn angle

✓ σ_{hit} better than: σ_{binary} = 28.9 μm

Results* after irradiation:

Online threshold ~ 1250 e⁻ - T ~ -25°C

Φ_{eq} = 0.8 x 10^{16} cm^{-2}: V_{bias} = 600 V

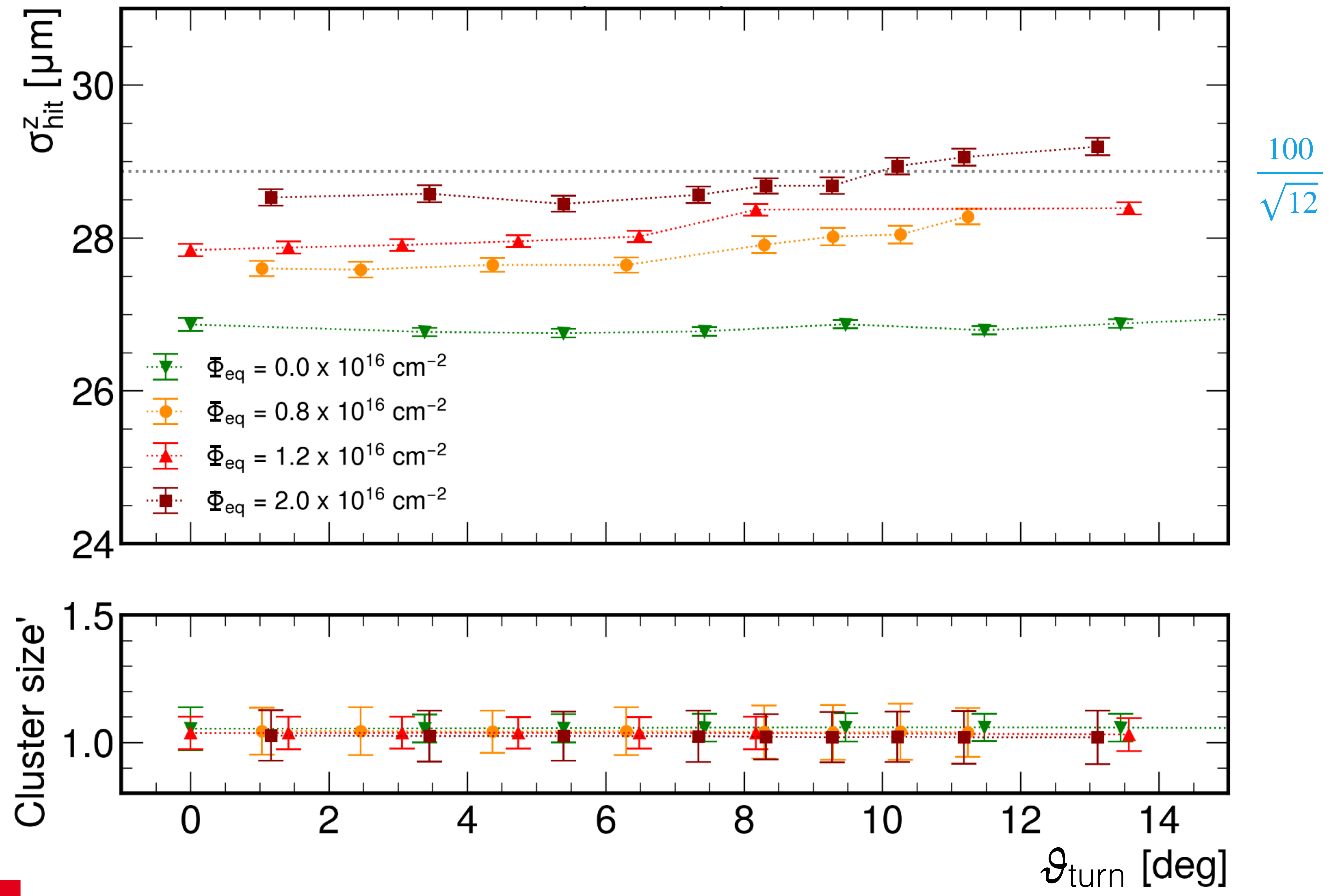
Φ_{eq} = 1.2 x 10^{16} cm^{-2}: V_{bias} = 800 V

Φ_{eq} = 2.0 x 10^{16} cm^{-2}: V_{bias} = 800 V

✓ σ_{hit} better than: σ_{binary} = 28.9 μm

✓ Cluster size still above 1

z (100 μm direction)

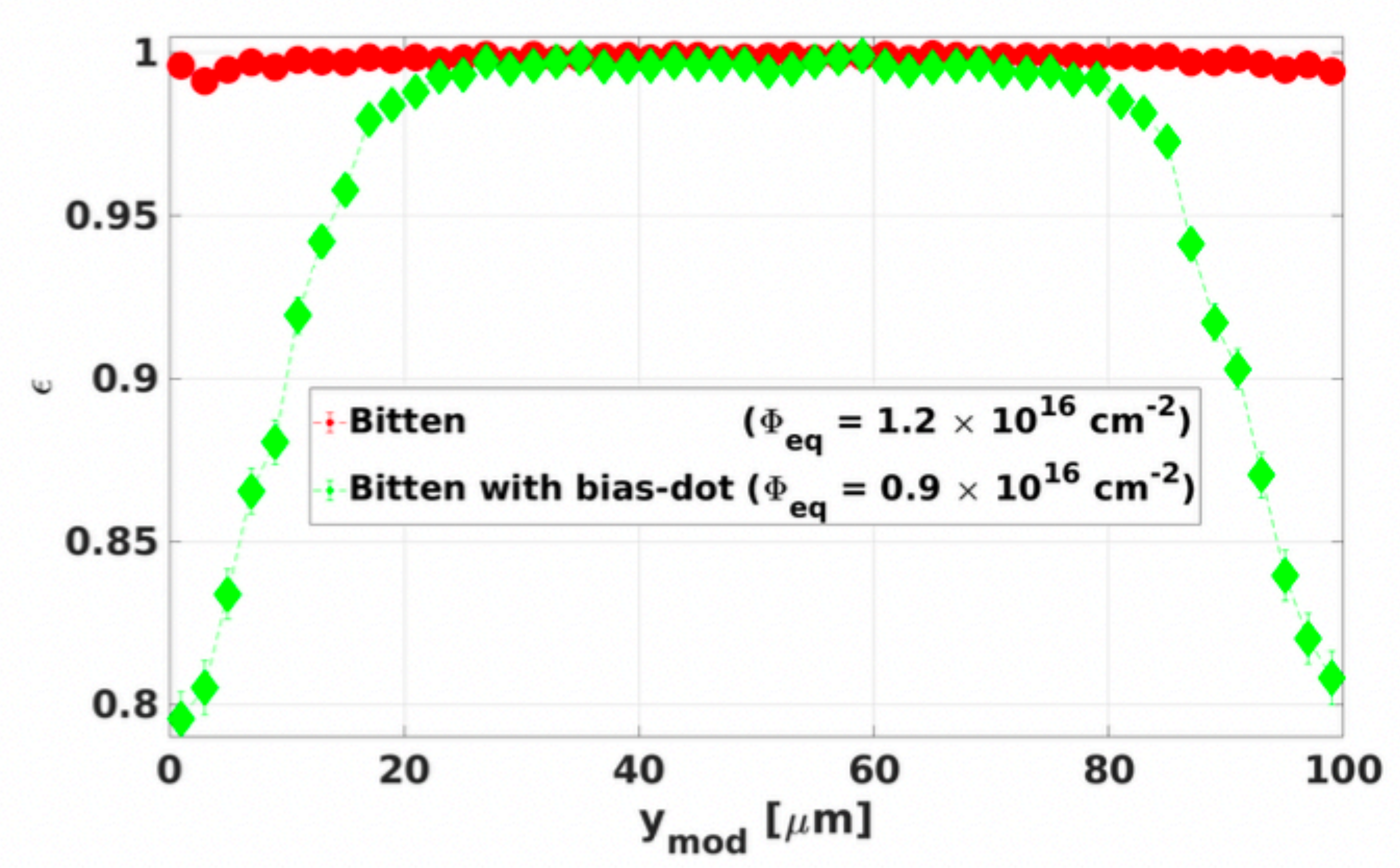


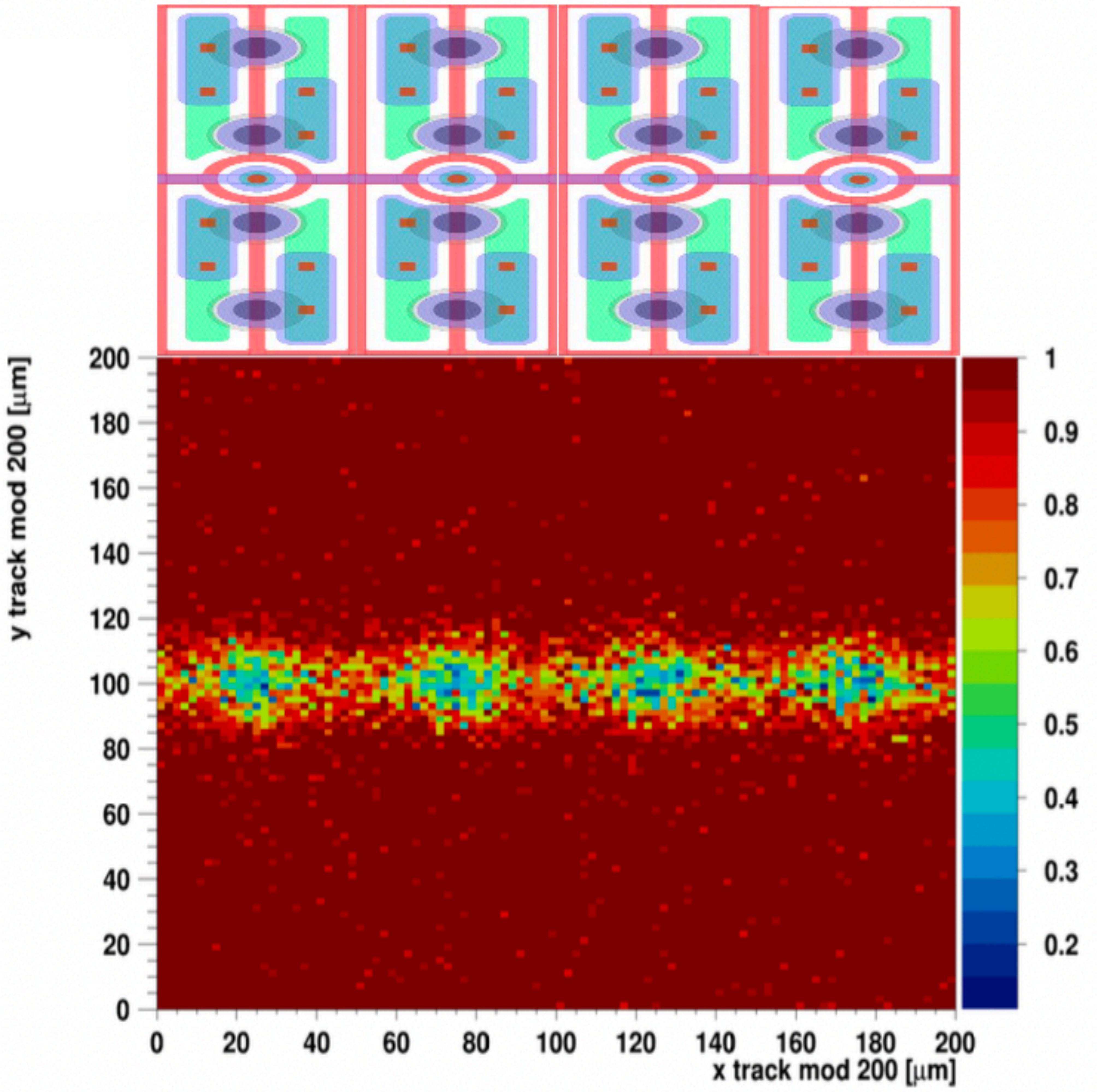
* Excluding effects coming from readout chain

** Exp. deposited charge for a MIP in 150 μm Si before irr. ~ 11000 e⁻

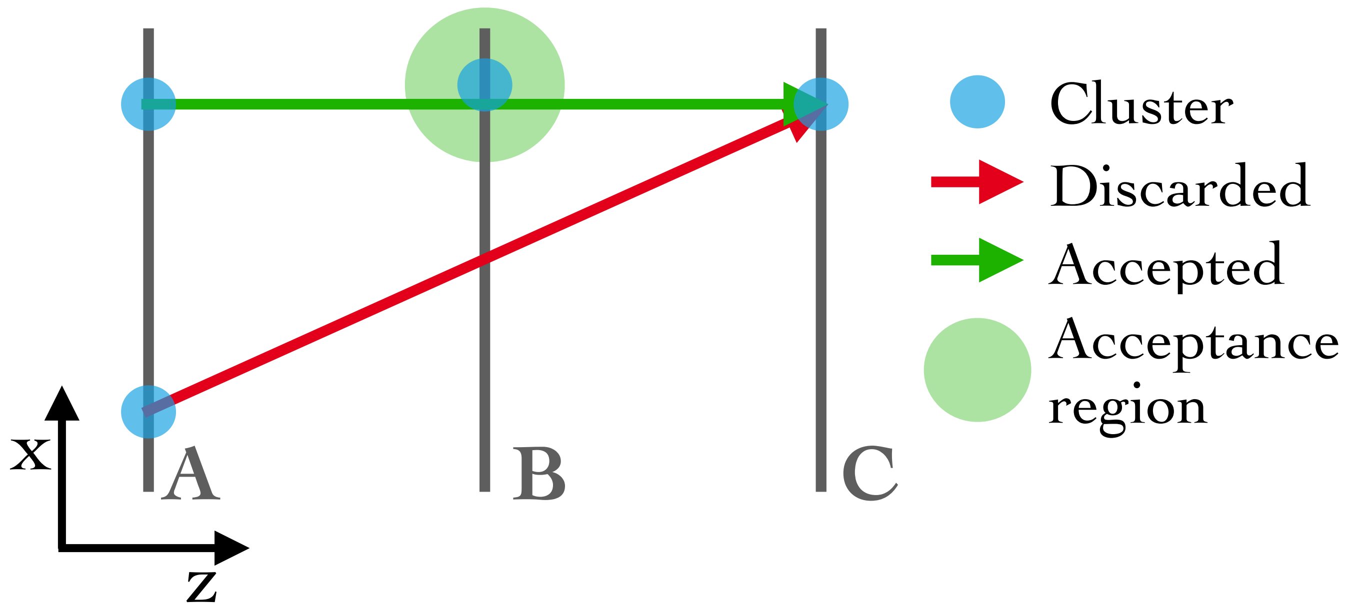
Hit efficiency of bias dot design

- Sensors with PT bias dots do not reach ε_{hit} > **98%** and do not meet the requirement of 99% @ perpendicular incidence
- Similar hit efficiencies in the **central region** of the pixel
- Efficiency loss @ the bias dot position to **80%**





Event selection cuts

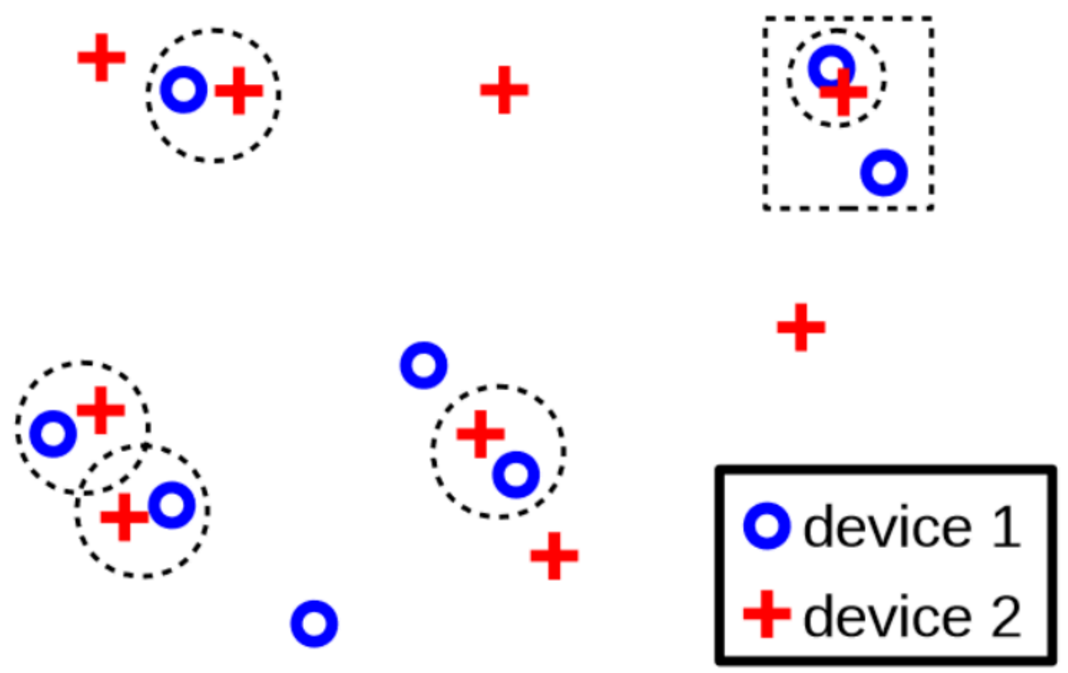


Telescope:

- **Triplets absolute slope > 5 mrad**
- **Residual @ triplet middle plane:** $|x_{extr} - x_B| \geq 50$ µm
- **Residual for sixlets @ DUT plane:** $|x_{tri} - x_{dri}| \geq 30$ µm (if no box)

DUT Residuals: (+ masked tracks*)

- **C1 fake tracks:** for 25 µm: $|\Delta^{100}_{DUT}| \geq 2\mathrm{x}100/\sqrt{12}$ µm, for 100 µm: $|\Delta^{25}_{DUT}| \geq 2\mathrm{x}25/\sqrt{12}$ µm
- **C2 timing link:** $|\Delta^{x}_{MOD}| \geq 150$ µm or $|\Delta^{y}_{MOD}| \geq 150$ µm
- **C3 isolation @ MOD:** $r^{@MOD_{1-2}}_{tele} = \sqrt{(x^{@MOD_1}_{tele} - x^{@MOD_2}_{tele})^2 + (y^{@MOD_1}_{tele} - y^{@MOD_1}_{tele})^2} \leq 600$ µm
- **C4 residual pairing:** finding the correct pair of events in DUT & telescope →
- **C5 (requires C2) fiducial region:** rot 0: $|y^{@DUT}_{tele}| > 4.7$ mm & $x^{@DUT}_{tele} > 3.1$ mm & $x^{@DUT}_{tele} < -3.5$ mm
  rot 90: $|x^{@DUT}_{tele}| > 4.7$ mm & $y^{@DUT}_{tele} > 3.5$ mm & $y^{@DUT}_{tele} < -3.1$ mm
- **C6 isolation @ DUT:** $r^{clust_{1-2}}_{DUT} = \sqrt{(x^{clust_1}_{DUT} - x^{clust_2}_{DUT})^2 + (y^{clust_1}_{DUT} - y^{clust_1}_{DUT})^2} \leq 600$ µm
- **C7 BC:** minbc < 8 & maxbc > 12
- **C8 (requires all the other cuts) cluster charge:** $Q > Q_{H10\%}$



Efficiency:

- **Cuts:** C2 (timing link) + C3 (isolation @ MOD) + C5 (fiducial region) + masked tracks*
- **Hit matching:** $r_{min} = \sqrt{(x_{TEL} - x^{min}_{DUT})^2 + (y_{TEL} - y^{min}_{DUT})^2}$ > **200 µm**

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

All cuts are independent but:
C4 requires C2 & C8 requires all the others

* Events with reconstructed track firing a masked pixel are removed

Off-line noise extrapolation

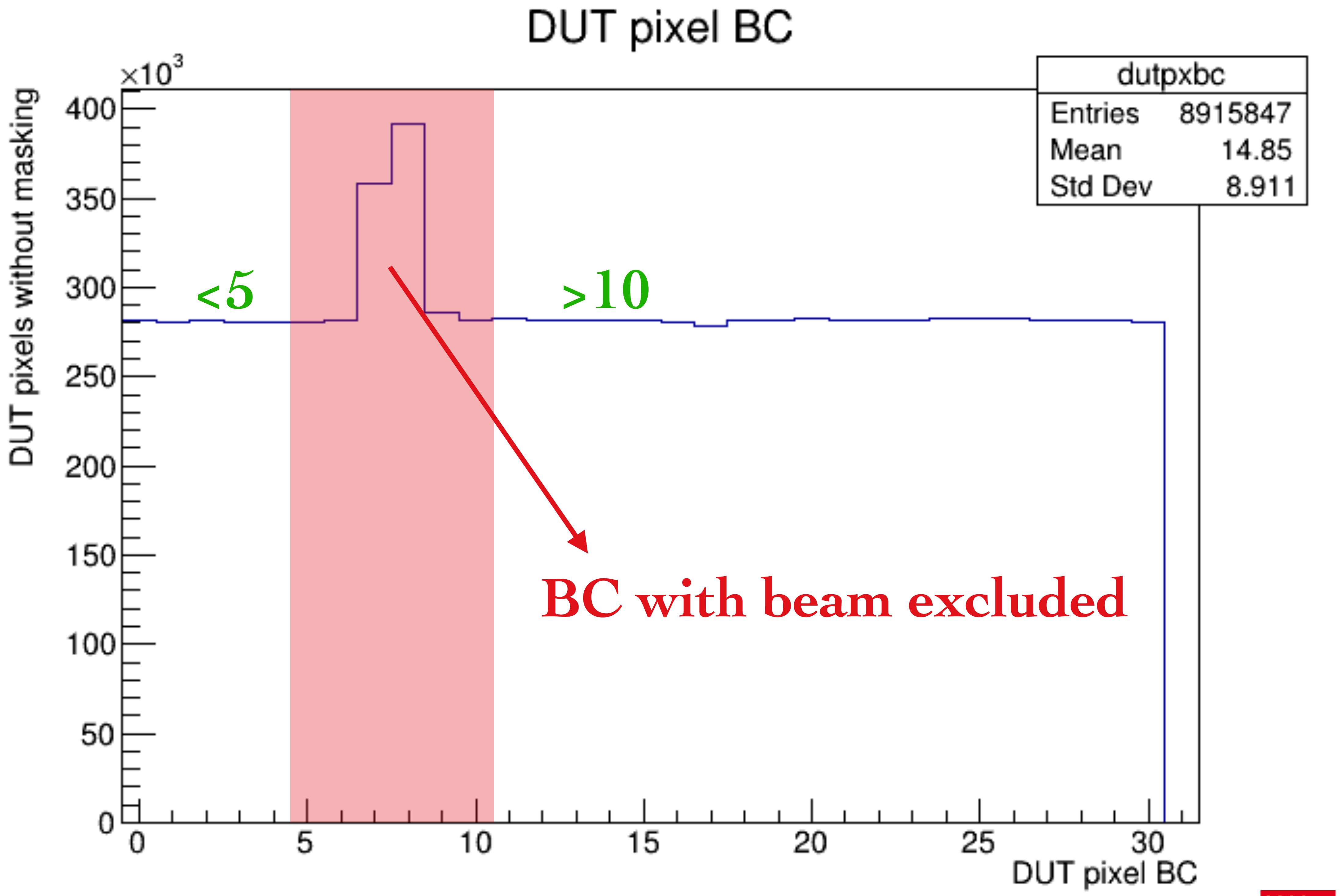
An example: real run with beam with **5 x 10^5 events**, 32 BC recorded for each event (**25 BC** without the beam),
single pixel noise occupancy of **1 x 10^{-4}** (L4 occ. thr)

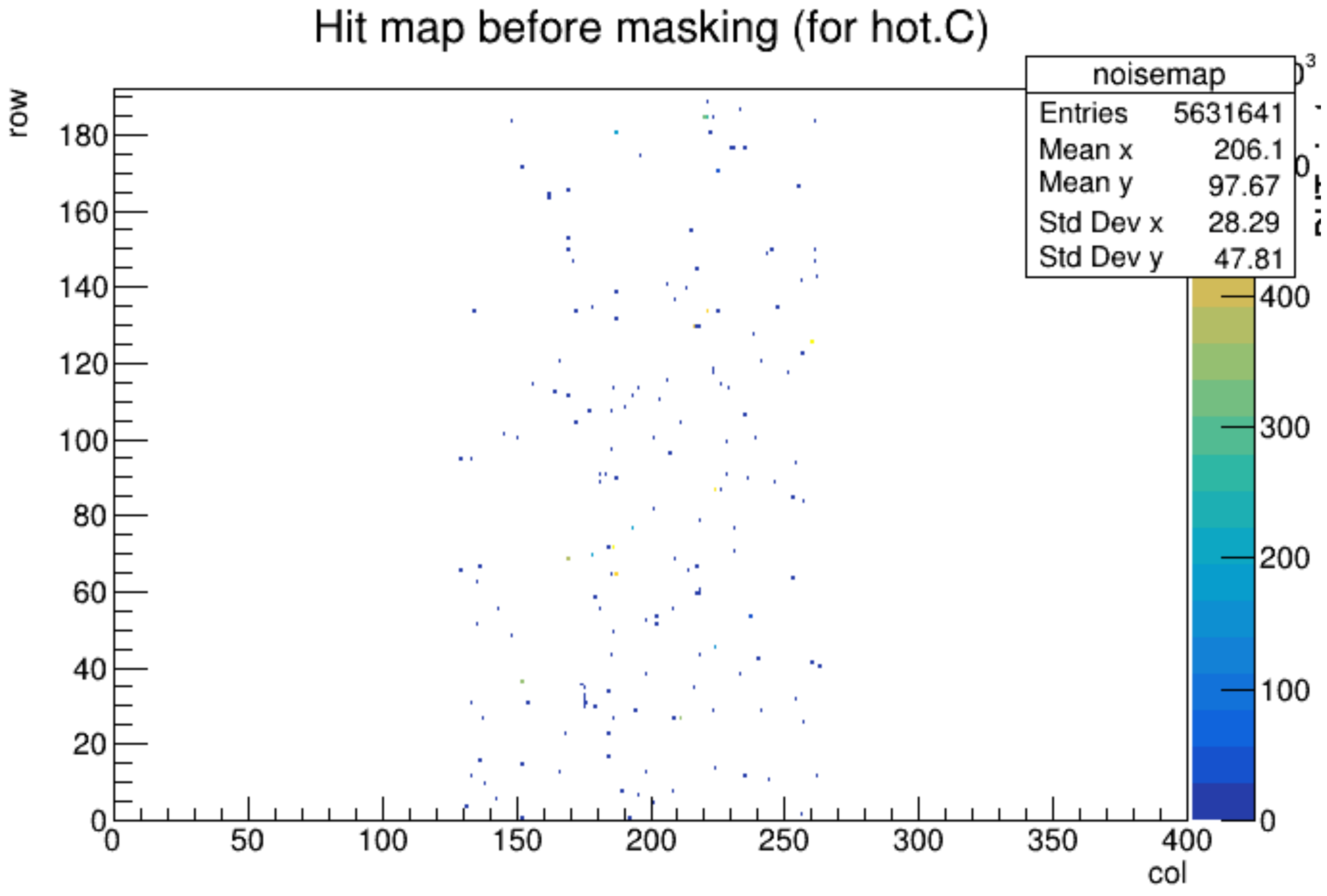
—> A "noisy" pixel is masked if counts more than: (5 x 10^5) x (25) x (1 x 10^{-4}) = **1250 hits**

—> Average noise occupancy : $N^{hits}_{unmasked}$ / [(5 x 10^5) x (25) x $N_{unmasked}$]

Noisy: 48 pixels above 1250 hits (0.01%)

noisemap: Occupancy map from raw data (25 BC)





Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Off-line noise extrapolation

An example: real run with beam with **5×10^5 events**, 32 BC recorded for each event (**25 BC** without the beam),
single pixel noise occupancy of **1×10^{-4}** (L4 occ. thr)

—> A "noisy" pixel is masked if counts more than: $(5 \times 10^5) \times (25) \times (1 \times 10^{-4})$ = **1250 hits**

—> Average noise occupancy : $N^{hits}_{unmasked}$ / $[(5 \times 10^5) \times (25) \times N_{unmasked}]$

Noisy: **48** pixels above **1250** hits (0.01%)

noisemap: Occupancy map from raw data (25 BC)