New test beam results of HPK planar pixel sensors for the CMS Phase 2 upgrade

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On behalf of the CMS Tracker Group

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Federal Ministry of Education and Research

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University of Freiburg (Virtual)

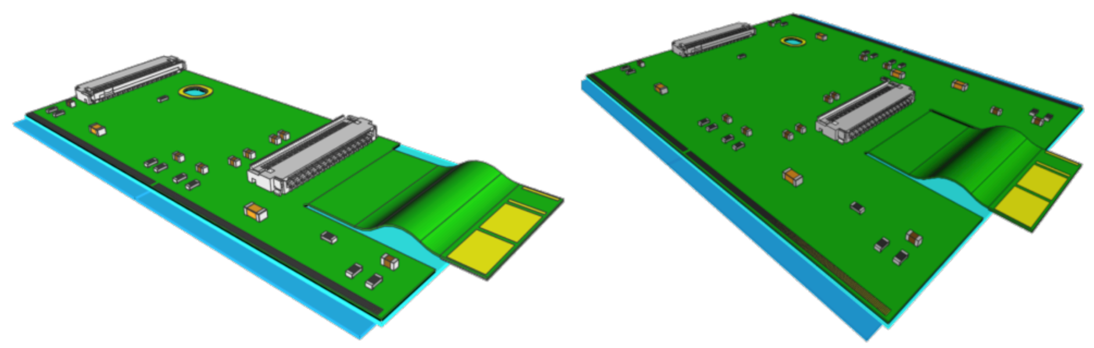
03 - 03 - 2022

The CMS Inner Tracker for Phase 2 upgrade

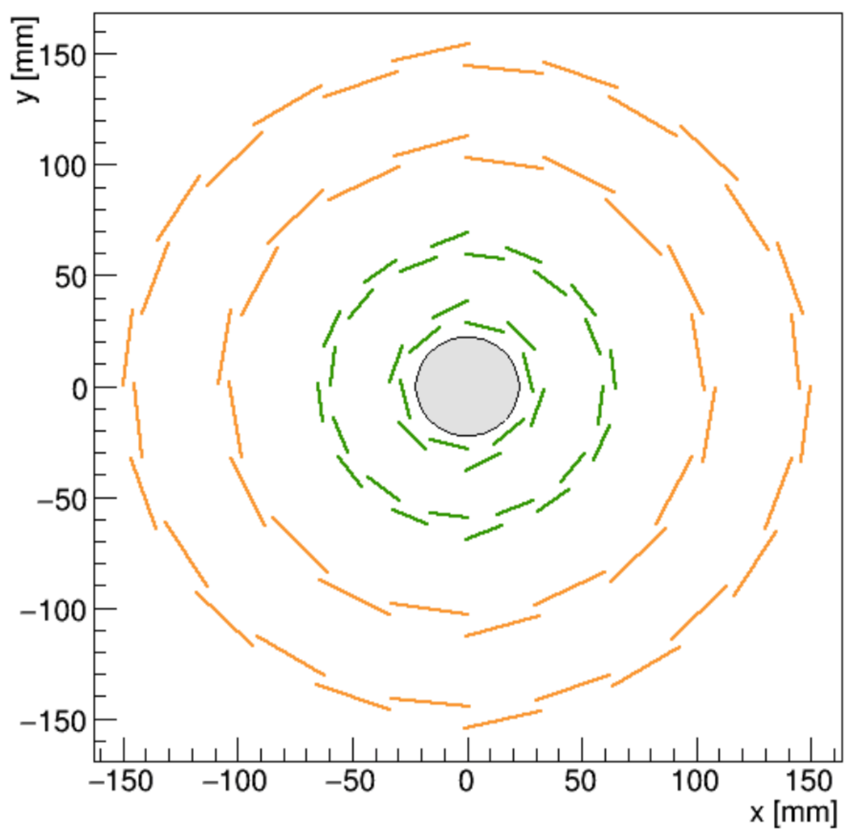
For the HL-LHC phase, the CMS Inner Tracker (IT) system will be entirely upgraded[1]

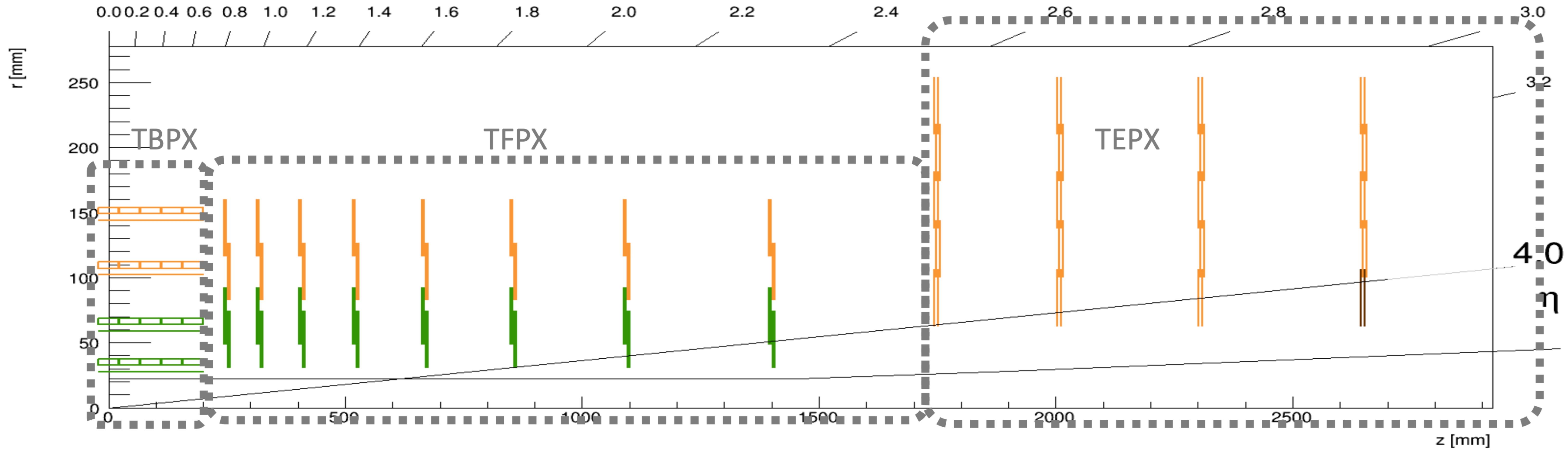
Detector layout:

- Coverage extended up to $|\eta| = 4$
- **Tracker Barrel PiXel** (TBPX): 4 layers (no crack at z=0)
- **Tracker Forward PiXel** (TFPX): 8 small disks for each side
- **Tracker Endcap PiXel** (TEPX): 4 large disks for each side



Two types of **hybrid pixel modules**: 1x2 and 2x2 readout chips (ROCs) per module (1156 and 2736 modules)





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

Fluence scenarios 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 **<μ>** = **200** (10x times more than Phase 1)

Based on the **"ultimate luminosity scenario"** for HL-LHC & the latest FLUKA simulation:

	RUN 4		RUN 4+5		RUN 4+5+6	
	1E16 n_{eq}/cm^2	Grad	1E16 n_{eq}/cm^2	Grad	1E16 n_{eq}/cm^2	Grad
TBPX L1	0.73	0.40	1.88	1.03	3.51	1.91
TFPX R1	0.48	0.31	1.25	0.81	2.34	1.50
TBPX L2	0.20	0.11	0.51	0.29	0.94	0.55

Not feasible regardless of the sensor technology choice

Baseline scenario: replacement in LS5 and define the LS5 fluence and dose as benchmark

Some **sensor design** constraints:

- High radiation tolerance: fluence of **1.88×10^{16} n_{eq}/cm^2** dose of **1.03 Grad**
- Keep the occupancy below **10^{-4}**: from **100 x 150 µm^2** to **25 x 100 µm^2**
- High single hit reconstruction efficiency: ε_{hit} > **98%** for L1 and ε_{hit} > **99%** for L2-L4 (end of lifetime)
- High spatial resolution: $\sigma_{hit} \ll pitch/\sqrt{12}$
- No **thermal runaway**

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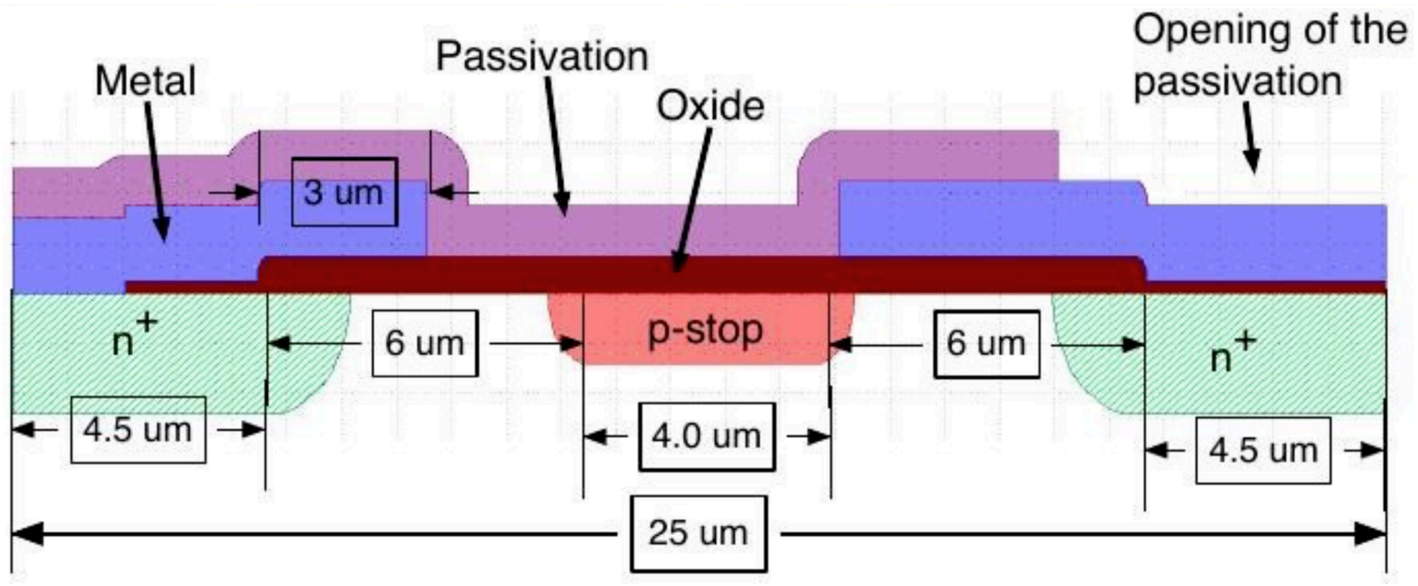
The baseline design

Baseline design proposed:

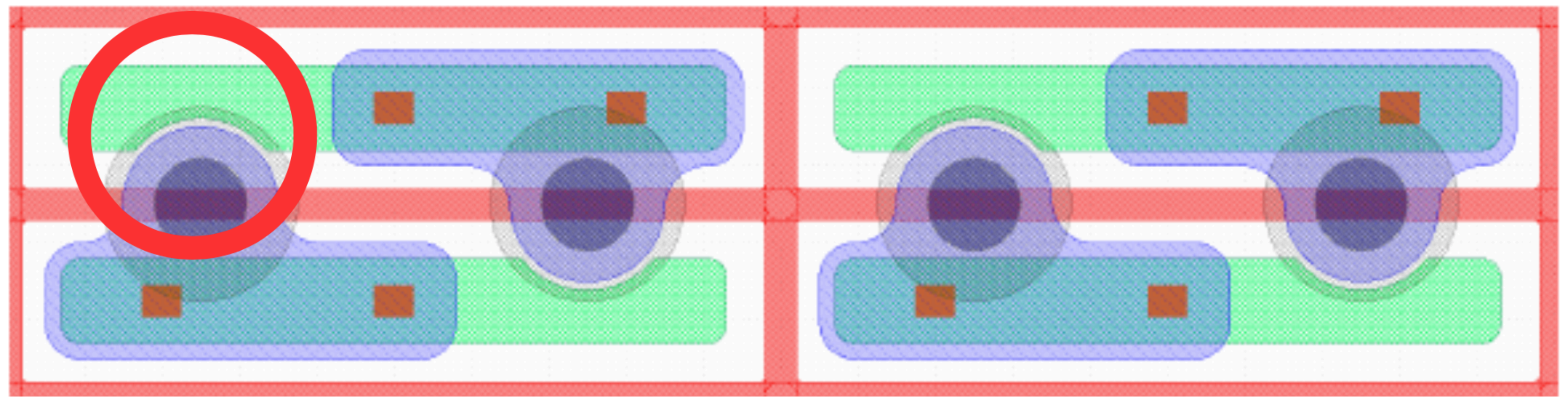
✓ Hybrid pixel detectors

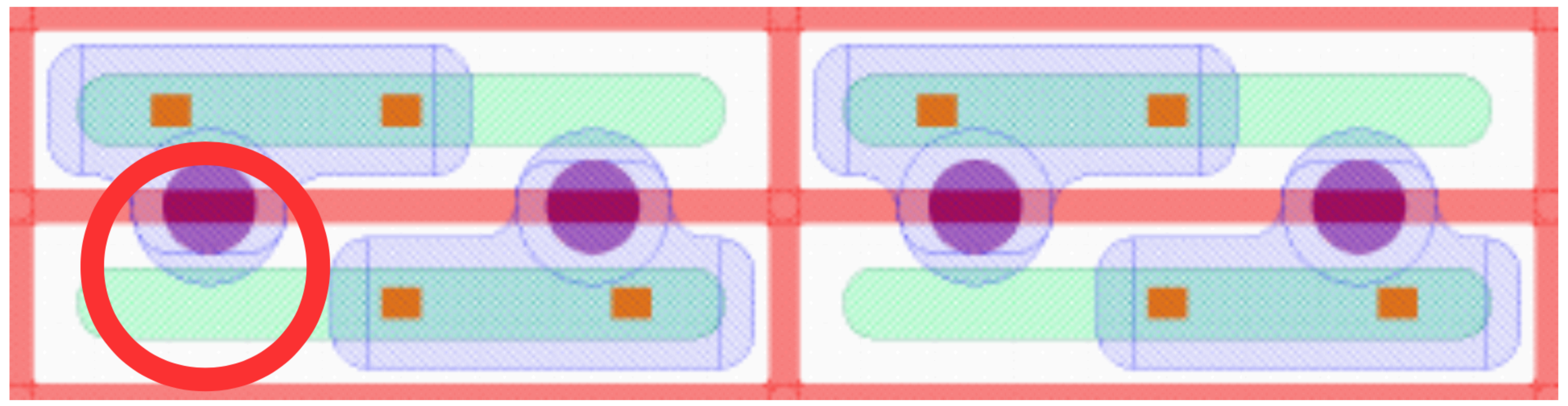
✓ n-in-p planar sensors for **TBPX (L2-L4)**, **TFPX** and **TEPX** (all disks):
- Single side processing (front-side only)
- Active thickness: 150 μm (from 285 μm)
- 25 x 100 μm² cell size (50 x 50 μm² option discarded)
- Inter-chip regions with **long** pixels
- No punch through bias (higher ε)[1]



Hamamatsu Photonics (HPK) design

✓ Bitten implant to reduce cross talk[1]


✓ **Bitten implant design RD53A 2019**


✗ **"Standard" design RD53A 2017**

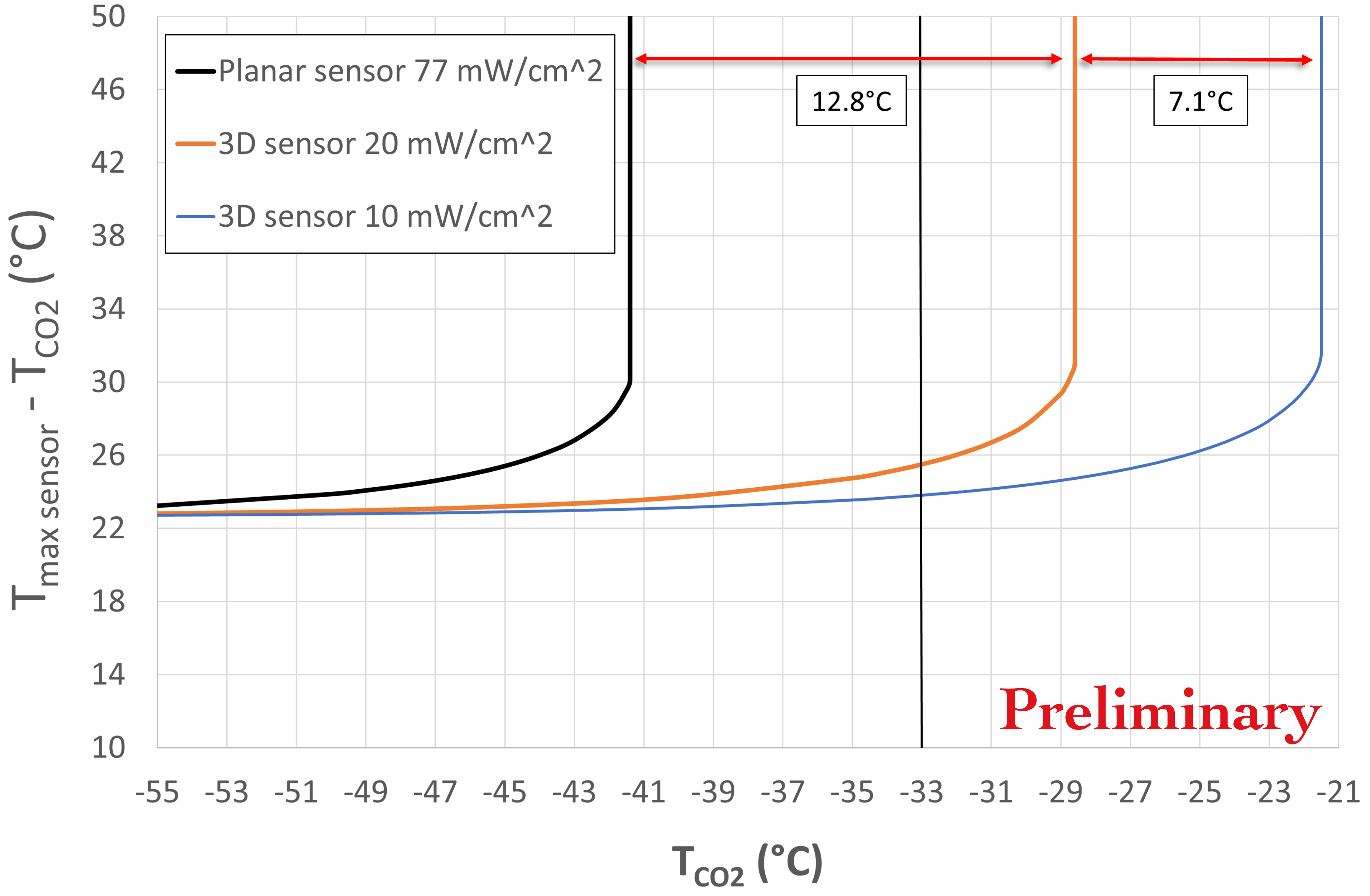
[1] F.Feindt - 16th Trento Workshop (Link)

Open points: 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**:

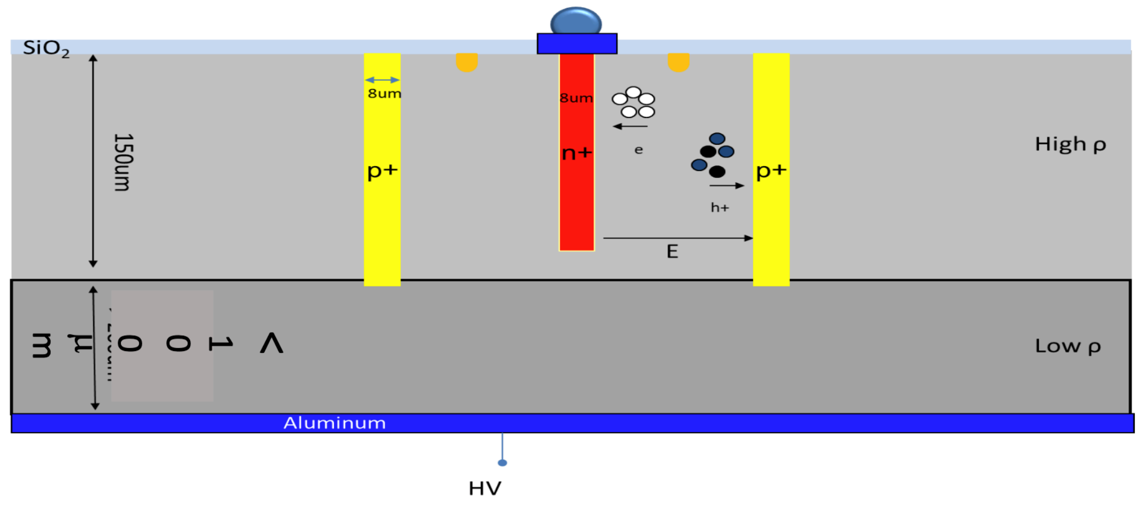
- **Planar sensors:** the required **T_{CO2} is much lower than -33°C**
- **3D sensors:** more than 4°C margin (confirmed power dissipation **below 20 mW/cm²** also after 2E16 n_{eq}/cm^2)



Two contributions for the 3D option:

- **G. Bardelli talk**: **today @ 17:05**
  "Test Beam results of FBK 3D pixel sensors interconnected to RD53A readout chip after high irradiation"

- **S. J. Dittmer talk**: **today @ 17:45**
  "Study of irradiated CNM 3D sensors"



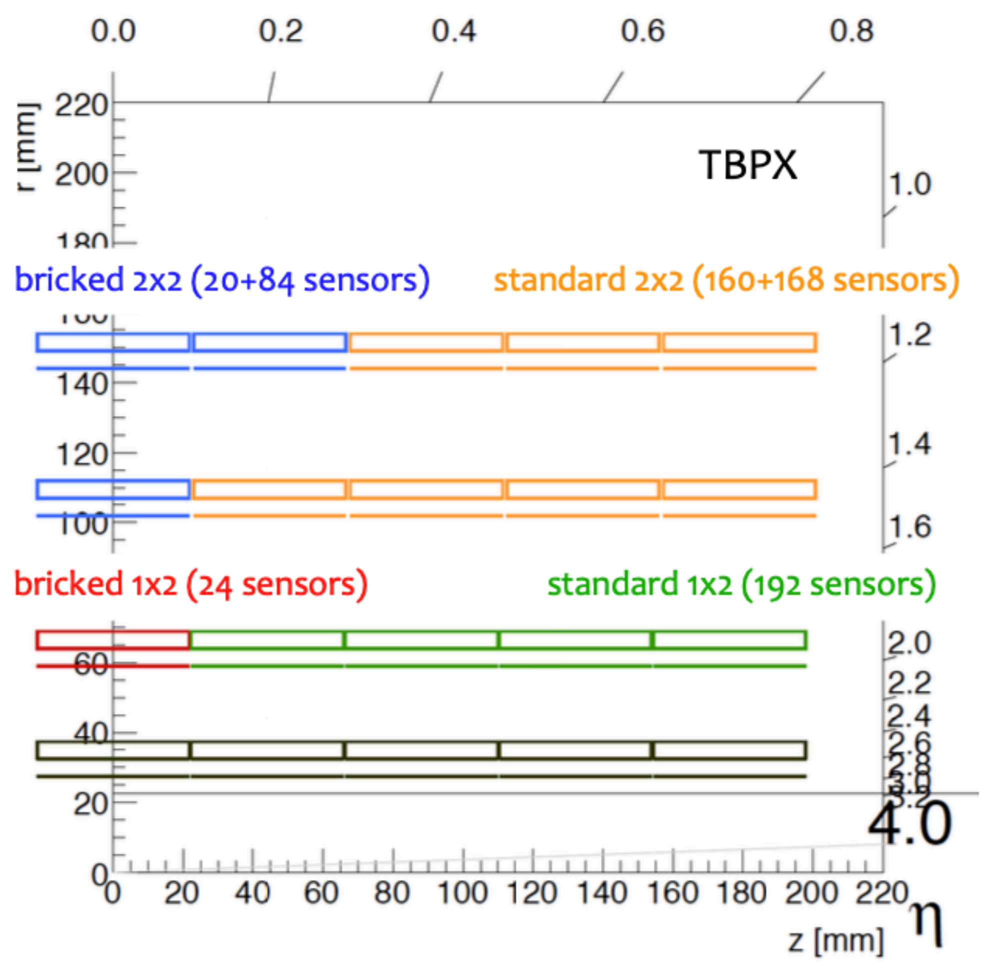
Open points: bricked geometry

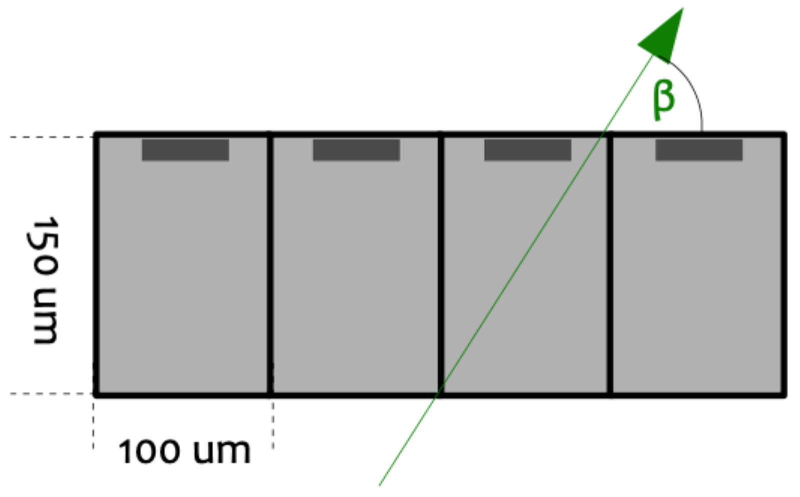
Bricked geometry option:

- **Aim**: improve the resolution along the 100 μm direction (without affecting the 25 μm resolution)

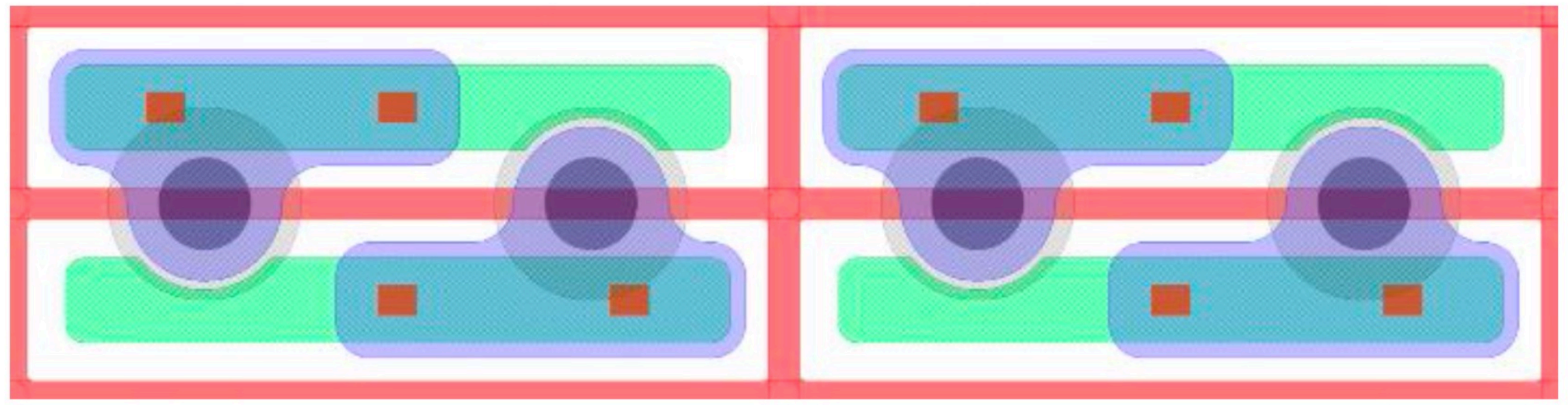
- Design effective only if **charge is shared** on more than one pixel (in 25 μm direction)

- Option for central η region of TBPX L2-L3-L4
  - Barrel: no advantage for **η ≥ 0.62** (cotg(β) = 100 μm/150 μm)
  - Endcaps: little charge sharing, no advantage for **η ≤ 1.8**

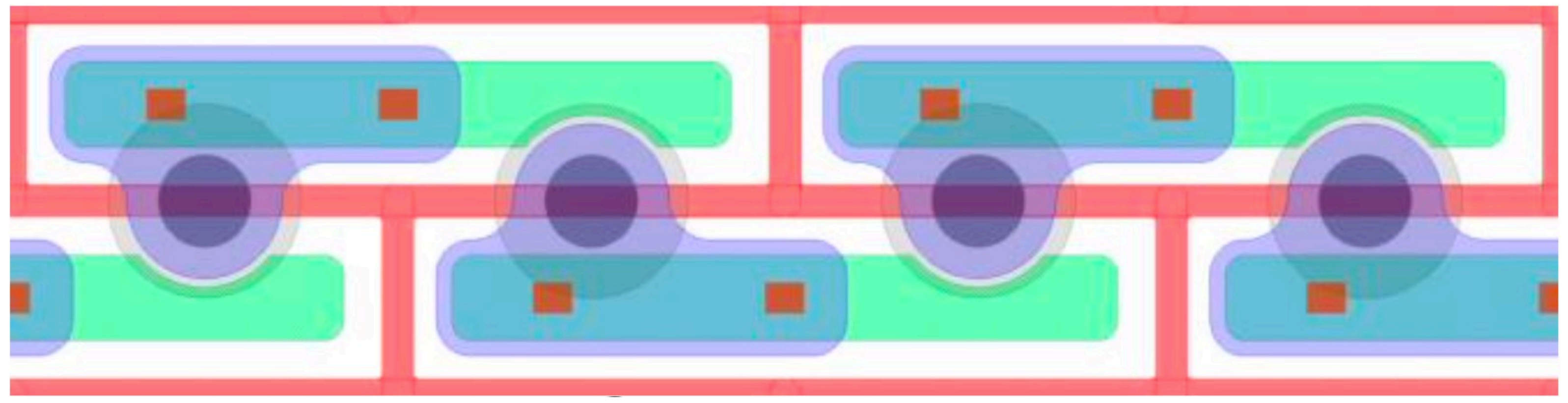




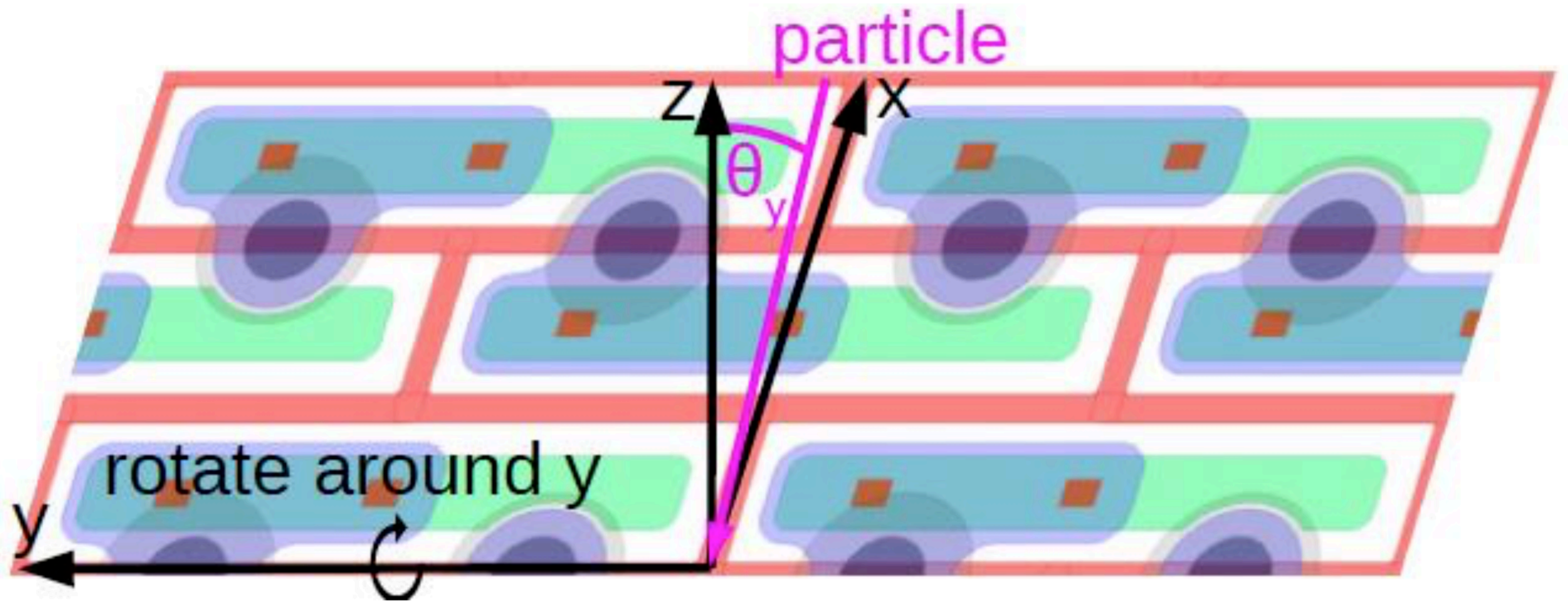
Simulations in progress



Bitten implant design RD53A



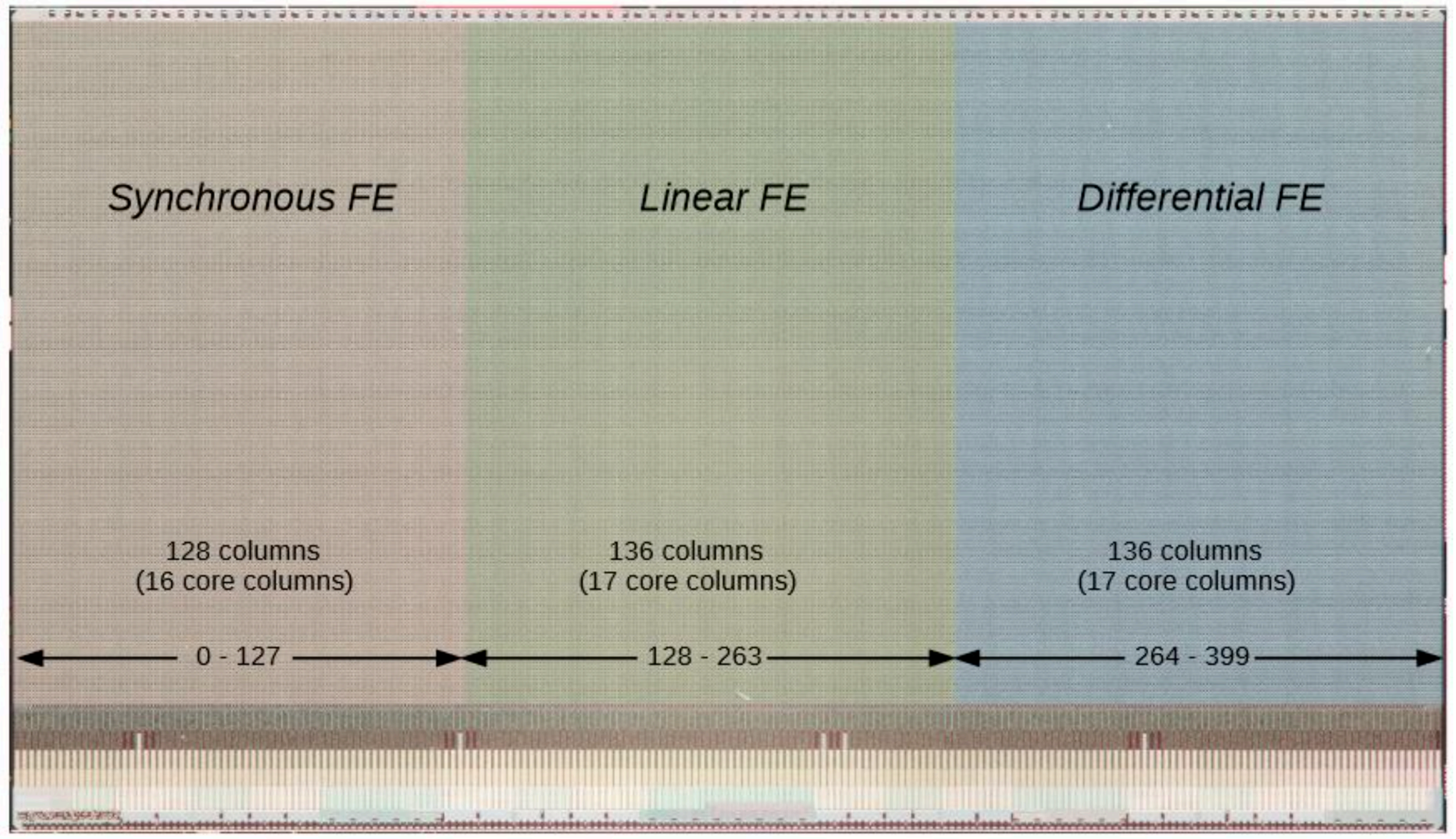
Bricked design RD53A

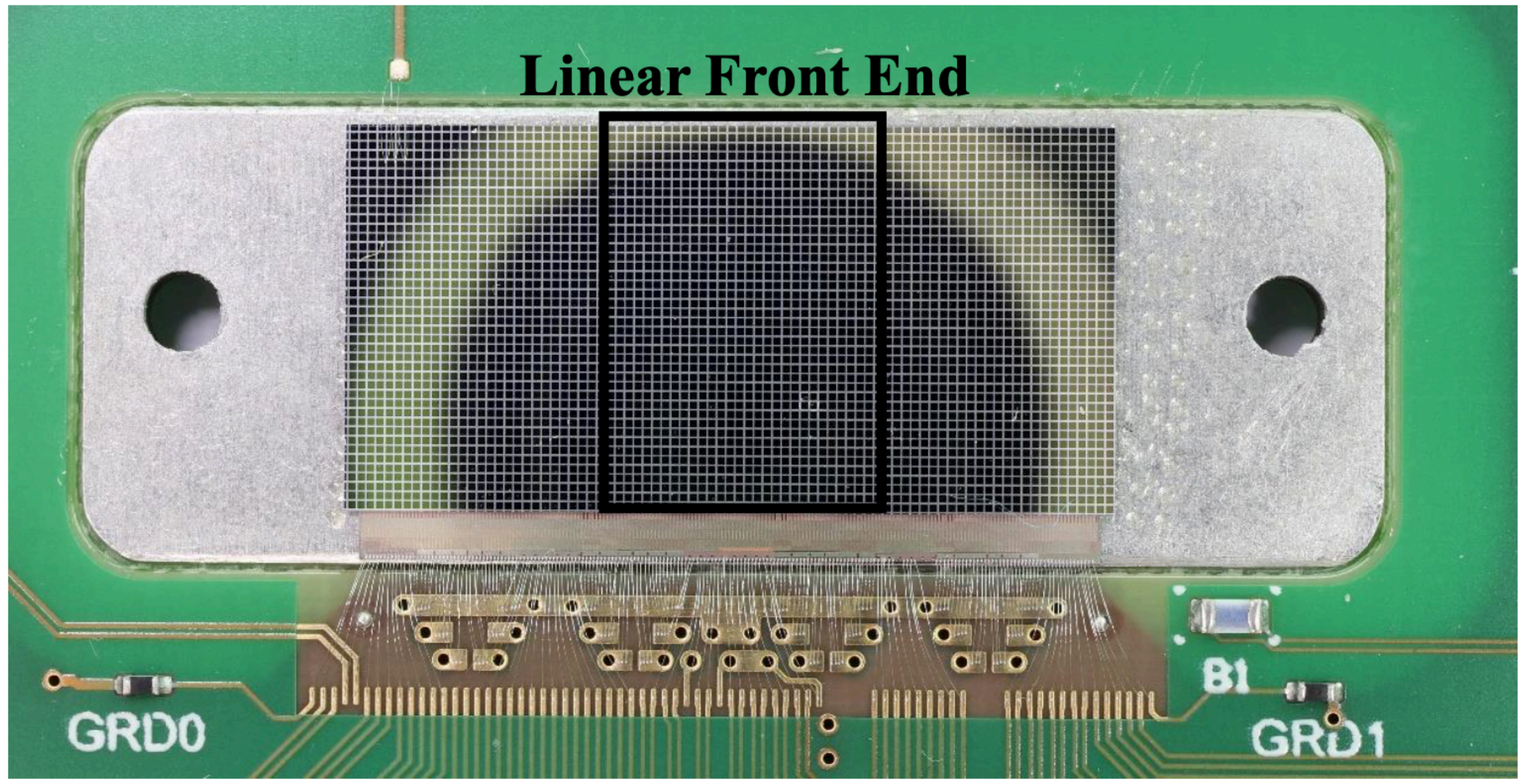


RD53A chips

All sensors bonded to RD53A Chips[1]:

- **76 800** pixels (26 112 pixels for the LIN section)
- **50 x 50 μm² pixel pitch**
- **65 nm CMOS technology** (TSMC), radiation hard design
- **Serial powering** via on-chip shunt-LDO regulators
- Three different FE available: Synchronous, **Linear** and Differential
- Adjustable **online threshold:** below **1000 e⁻** (LIN FE)
- Charge digitization via **4-bit Time-over-Threshold** (ToT unit)

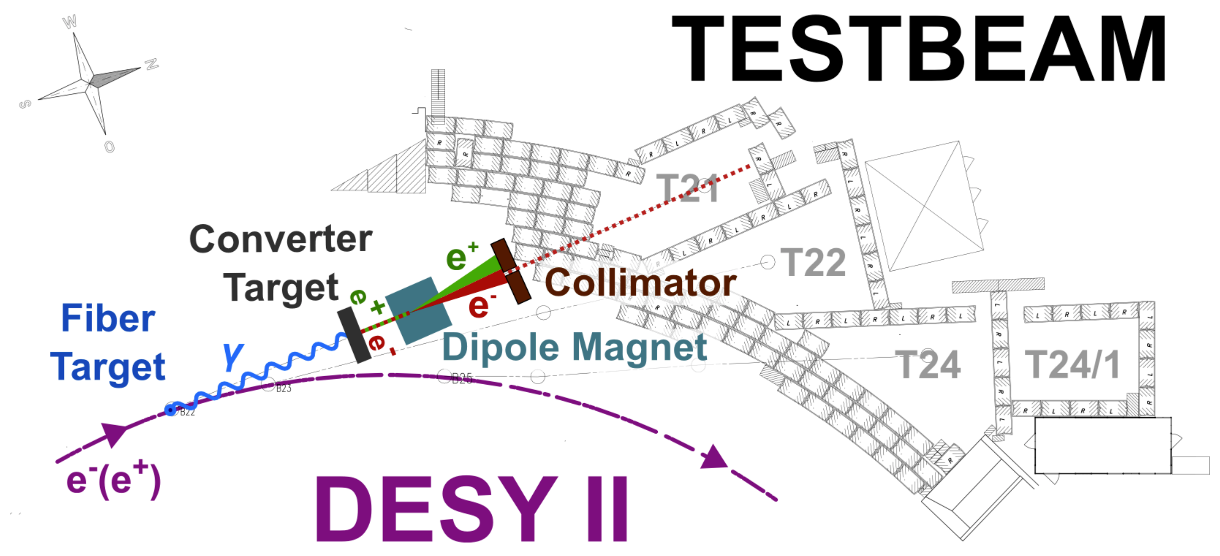




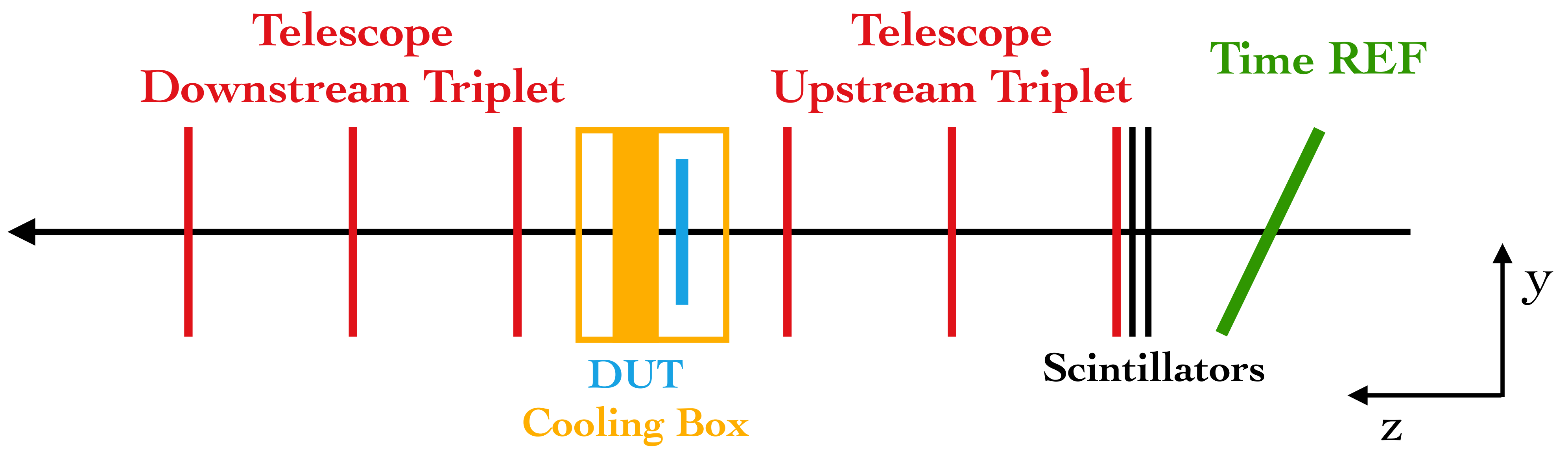
[1] RD53 Collaboration (Link)

DESY test beam setup

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

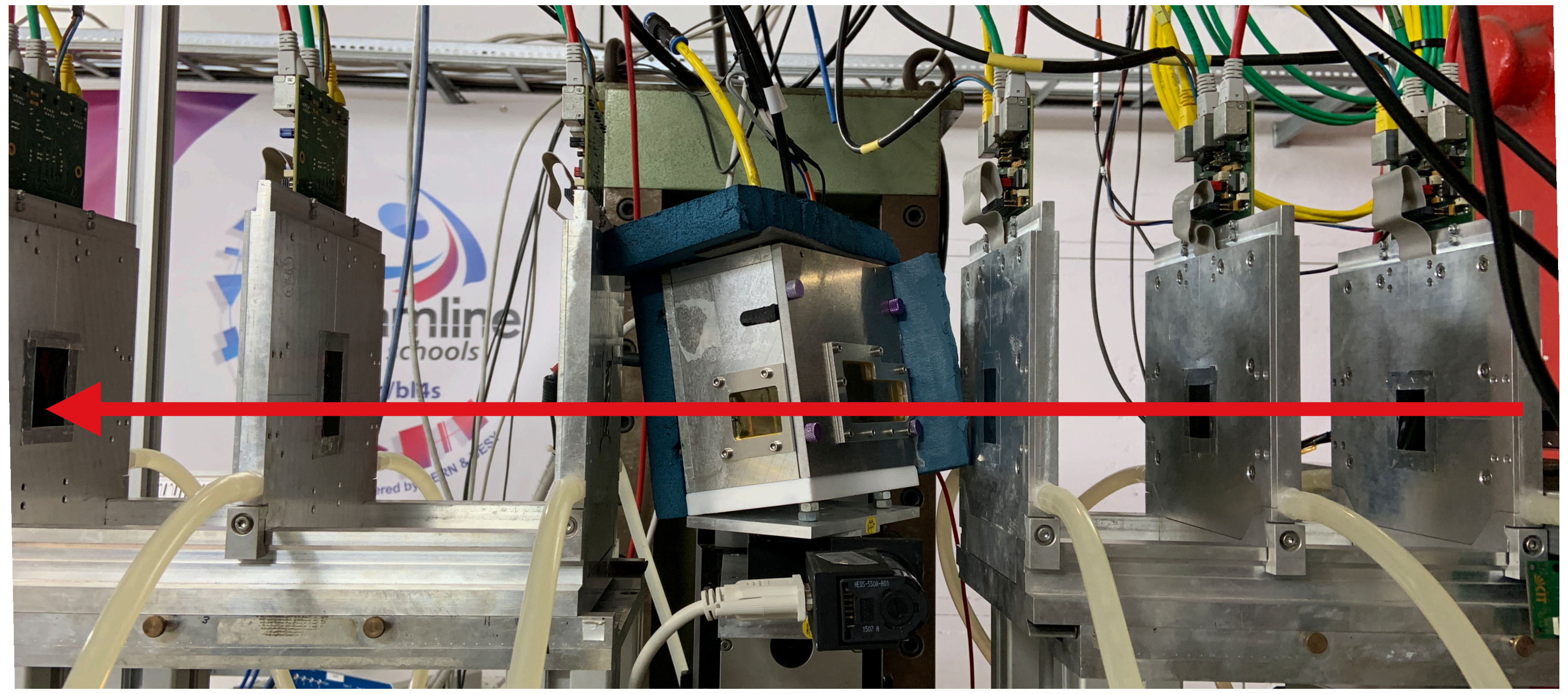


- **Trigger:** two upstream scintillators (2x1 cm² overlap)
- **Tracking:** EUDET DATURA Telescope
  6 MIMOSA-26 planes (t_{int} = 115 μs)
- **Timing layer:** CMS Phase 1 module
- Device Under Test (DUT): cooling box ($T_{chiller}$ ~ -35°C)



Characterization procedure:

- Lab measurements: I-V
- Test beam measurements:
  - Hit efficiency wrt telescope tracks
  - Single hit resolution @ various angles



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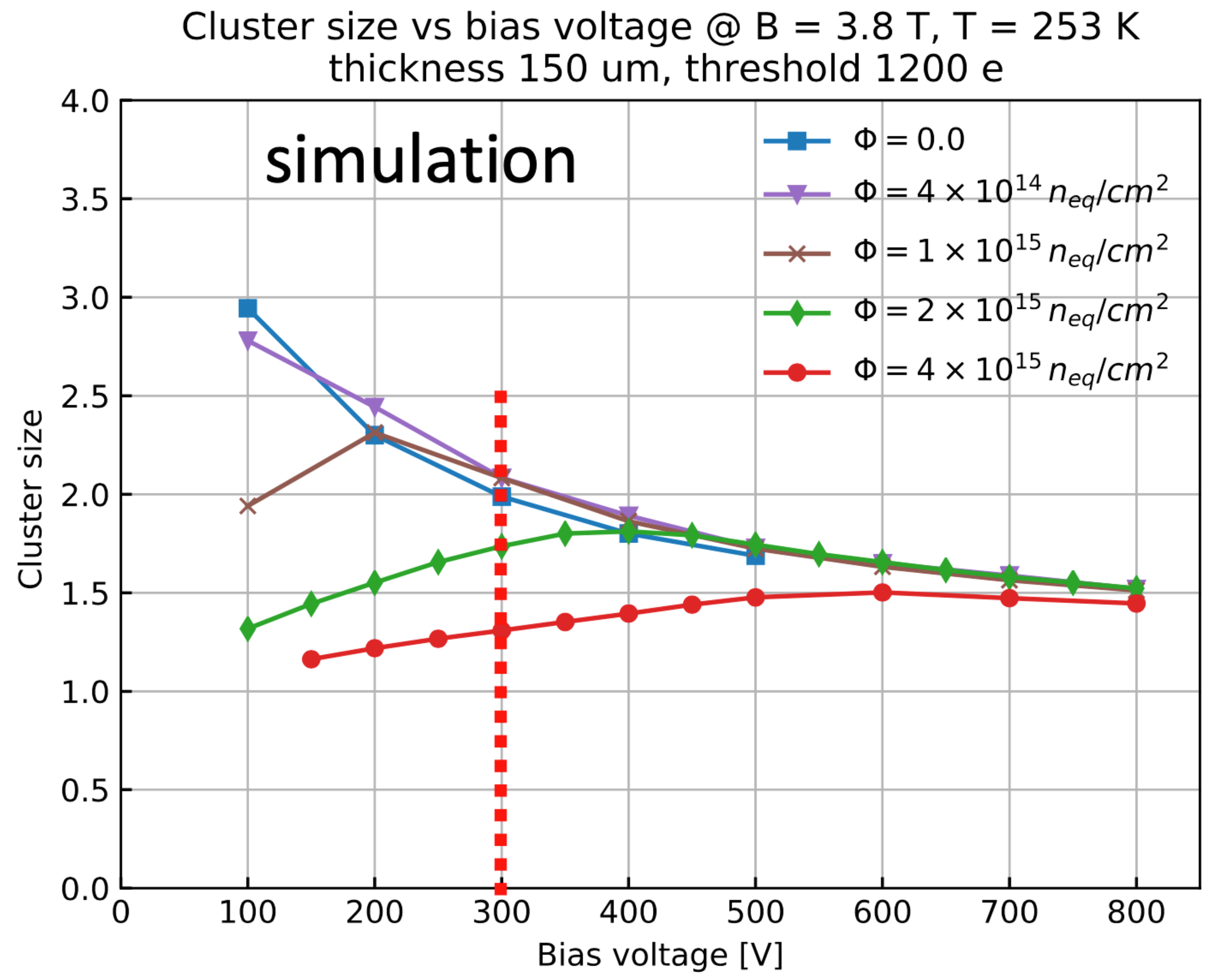
Results: I-V

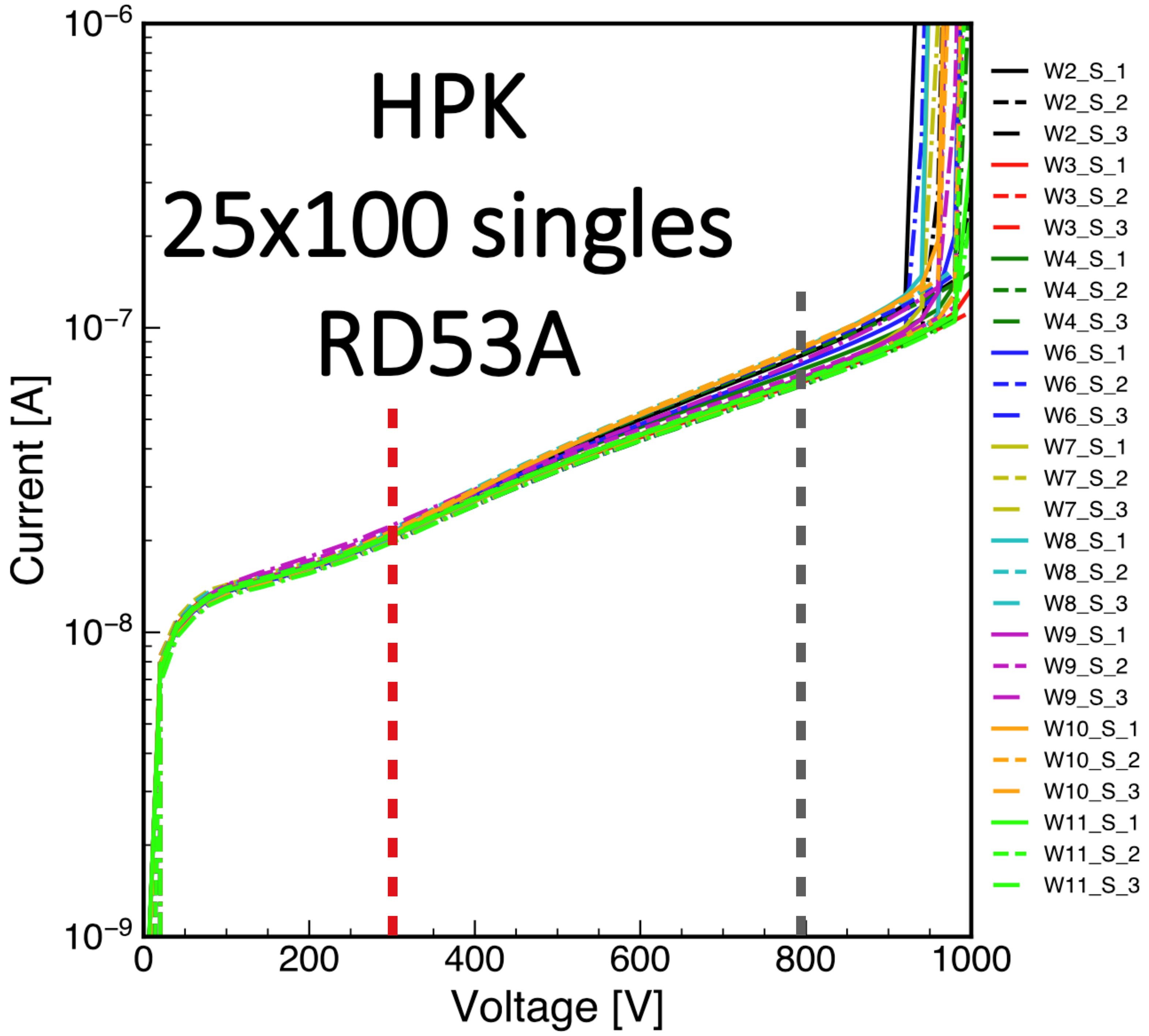
Requirements:

- **Breakdown:** > 300 V before irradiation
  > 800 V **after** irradiation to **0.5 x 10^{16} n_{eq}/cm^2**

From simulation: at least 300 V required for optimal resolution

- High voltage stability for **Φ_{eq} = 0-1 x 10^{15} n_{eq}/cm^2**





✓ Yield for RD53A singles (50x50 μm and 25x100 μm): 100% (75/75)

✓ No sign of breakdown up to **800 V** during the test beams (even with fluences up to **2 x 10^{16} n_{eq}/cm^2**)

Results: hit efficiency

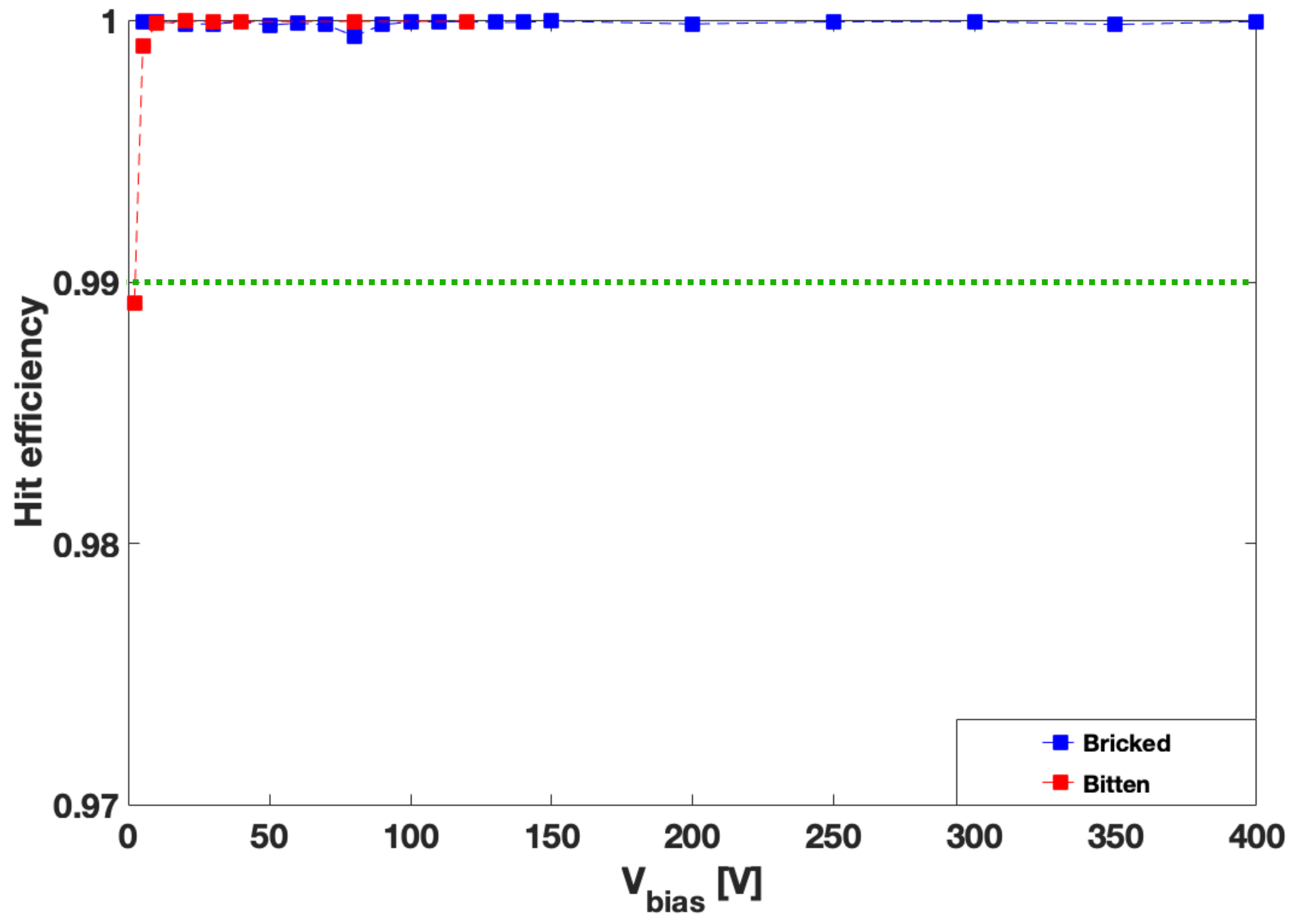
Before irradiation

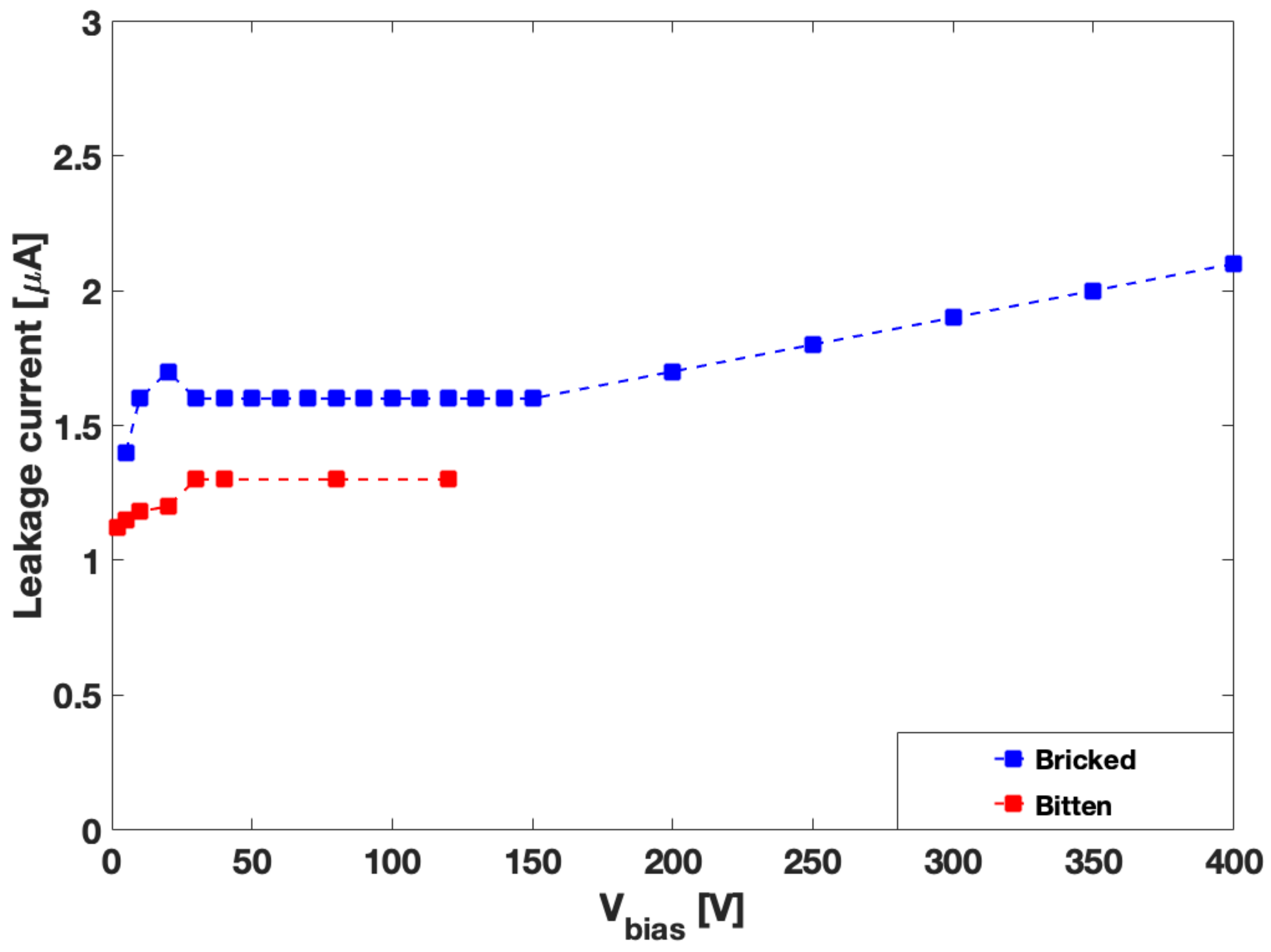
Requirements:

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

✓ ε_{hit} > 99% already for V_{bias} > 5 V
✓ No sign of breakdown up to 400 V during the test beams

Online thresholds° ~ 990 e$^-$ - 1250 e$^-$
T ~ 20°C





* Excluding effects coming from readout chain

° Exp. deposited charge for a MIP in LIN FE before irr. ~ 10 500 e$^-$

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Results: hit efficiency

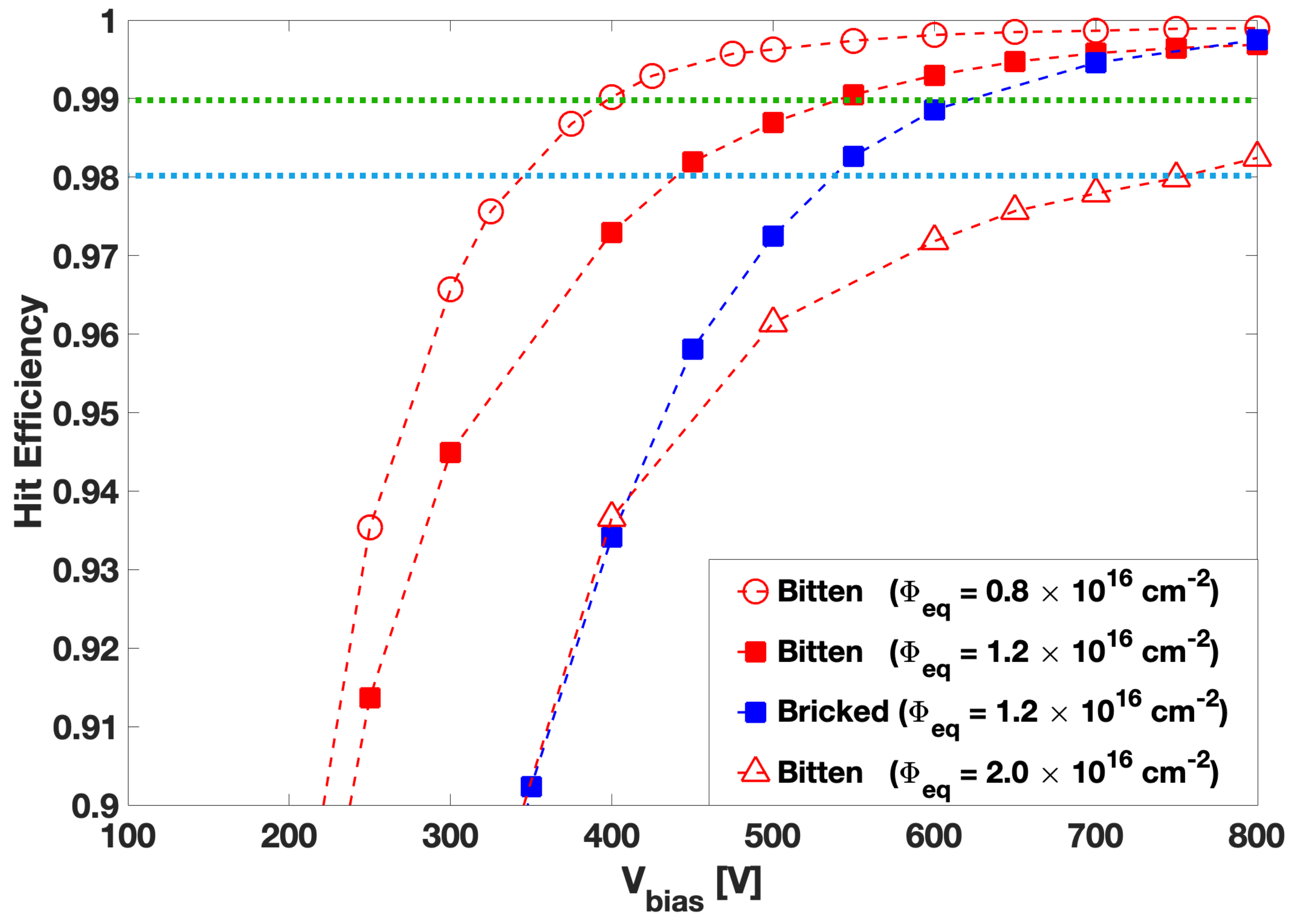
After irradiation

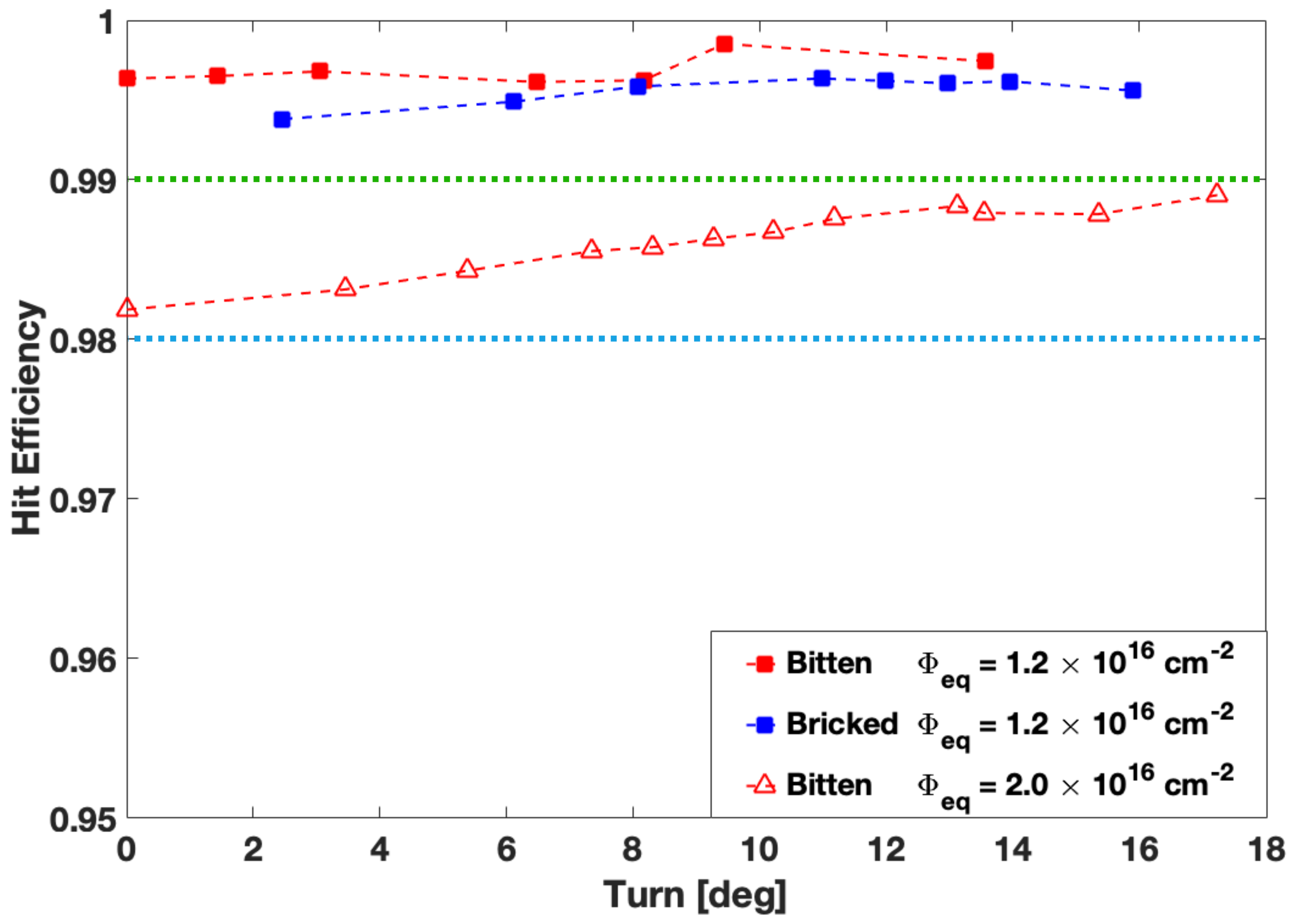
Requirements:

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

✓ ε_{hit} > 99% already for V_{bias} ≤ 600 V (for Φ_{eq} up to 1.2 x 10^{16} n_{eq}/cm^2)
✓ No sign of breakdown up to **800 V** during the test beams
✓ Sensor with Φ_{eq} = 2.0 x 10^{16} n_{eq}/cm^2 reaches 98% @ 650 V

Online thresholds ~ 1200-1400 e-
$T_{Chiller}$ ~ -27°C/-35°C
V_{bias} = 800 V





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* Excluding effects coming from readout chain

Results: spatial resolution

Before irradiation

Requirements:

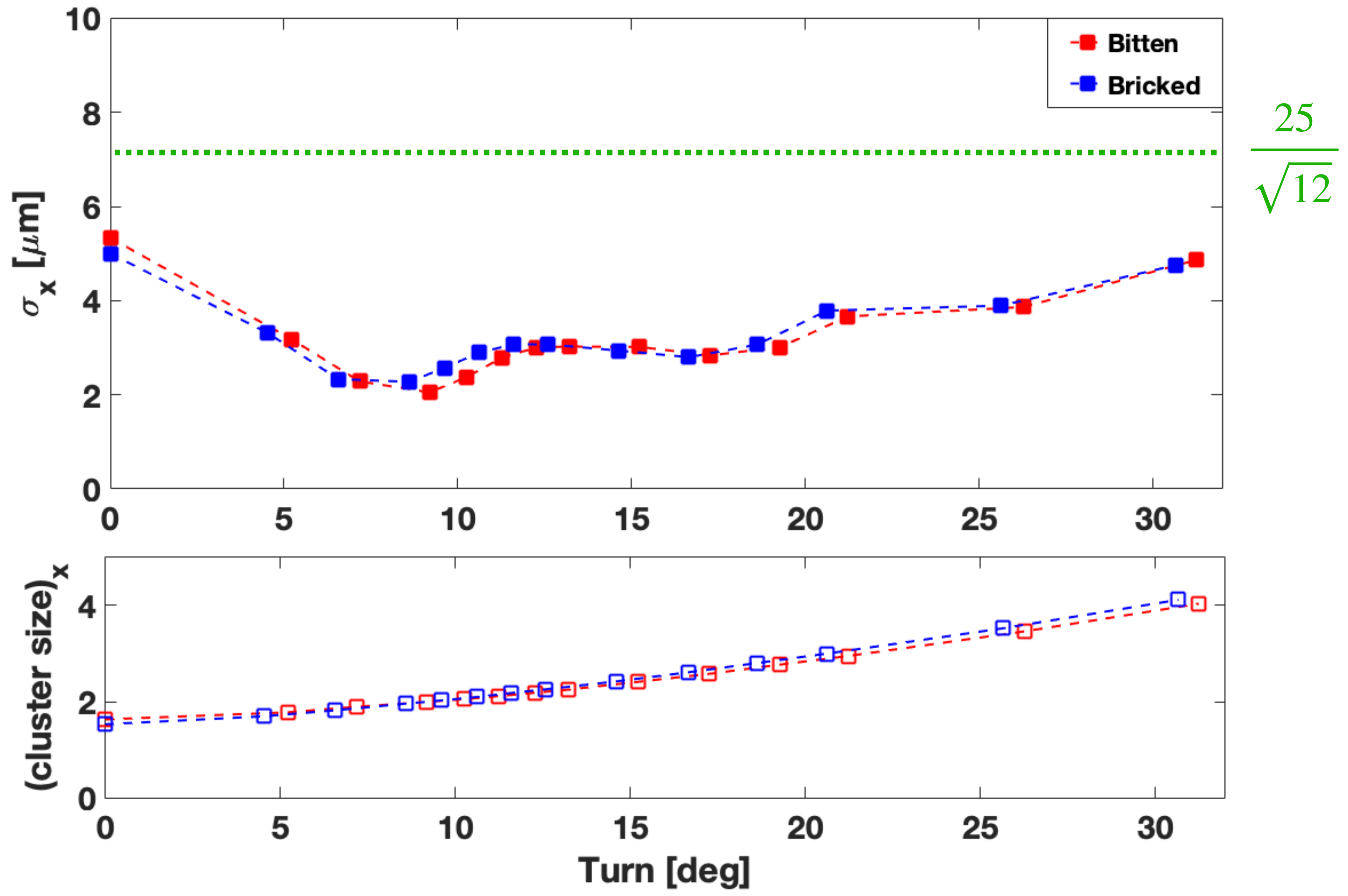
- Best single point **resolution**: $\sigma_{hit} << pitch/\sqrt{12}$

V_{bias} = **120 V**; T ~ **20°C**; online threshold* ~ **980 e⁻**

r-ϕ (25 µm direction)

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

✓ Both designs reach $\sigma_{hit} \sim 2$ µm @ cluster size = 2

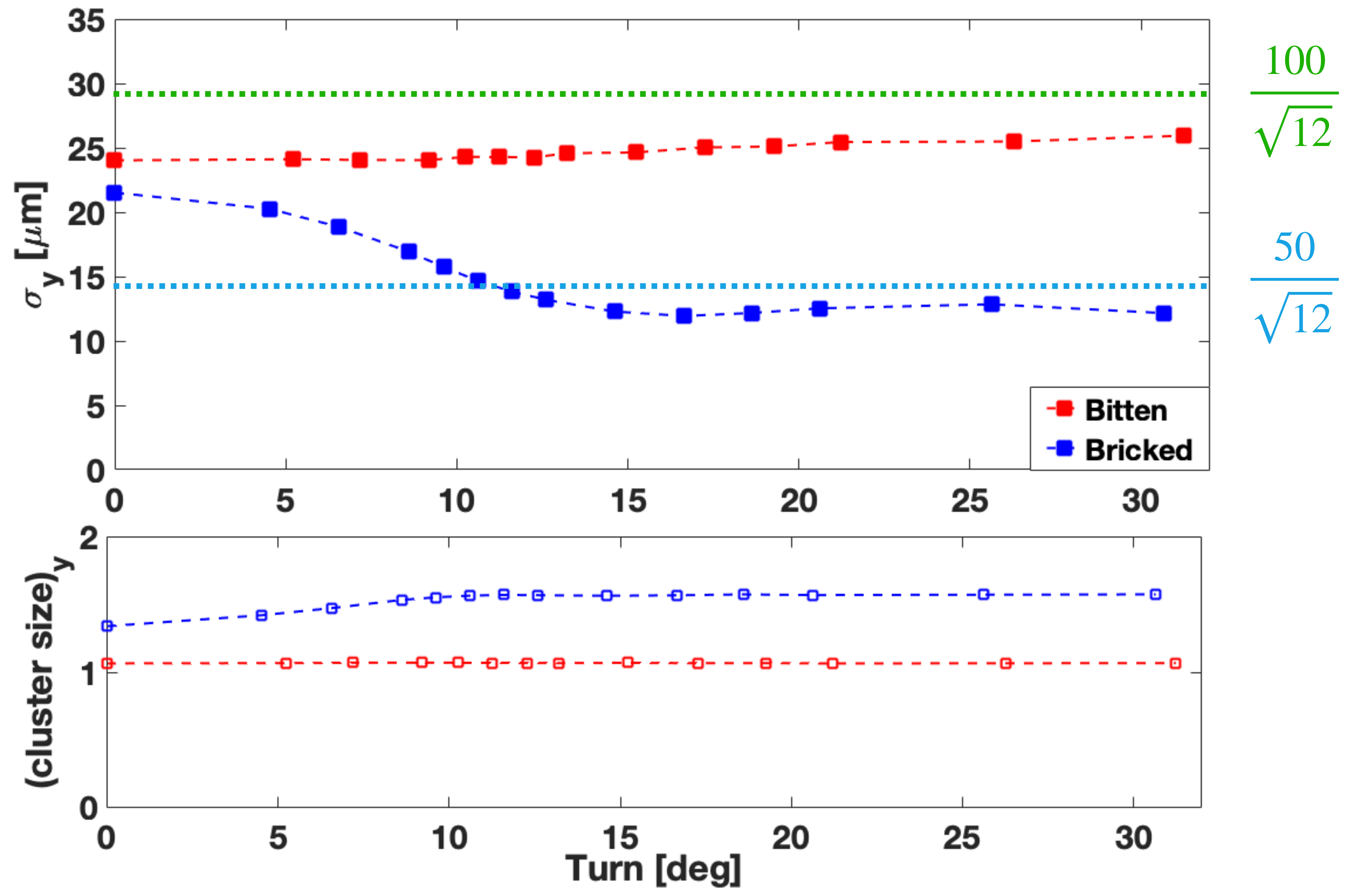


z (100 µm direction)

Resolution independent of turn angle

✓ **Bricked** design resolution improves with turn angle

✓ Bricked design effective pitch is **50 µm**



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* Exp. deposited charge for a MIP in LIN FE before irr. ~ 10 500 e⁻

Results: spatial resolution

After irradiation

Requirements:

- Best single point **resolution**: $\sigma_{hit} << pitch/\sqrt{12}$

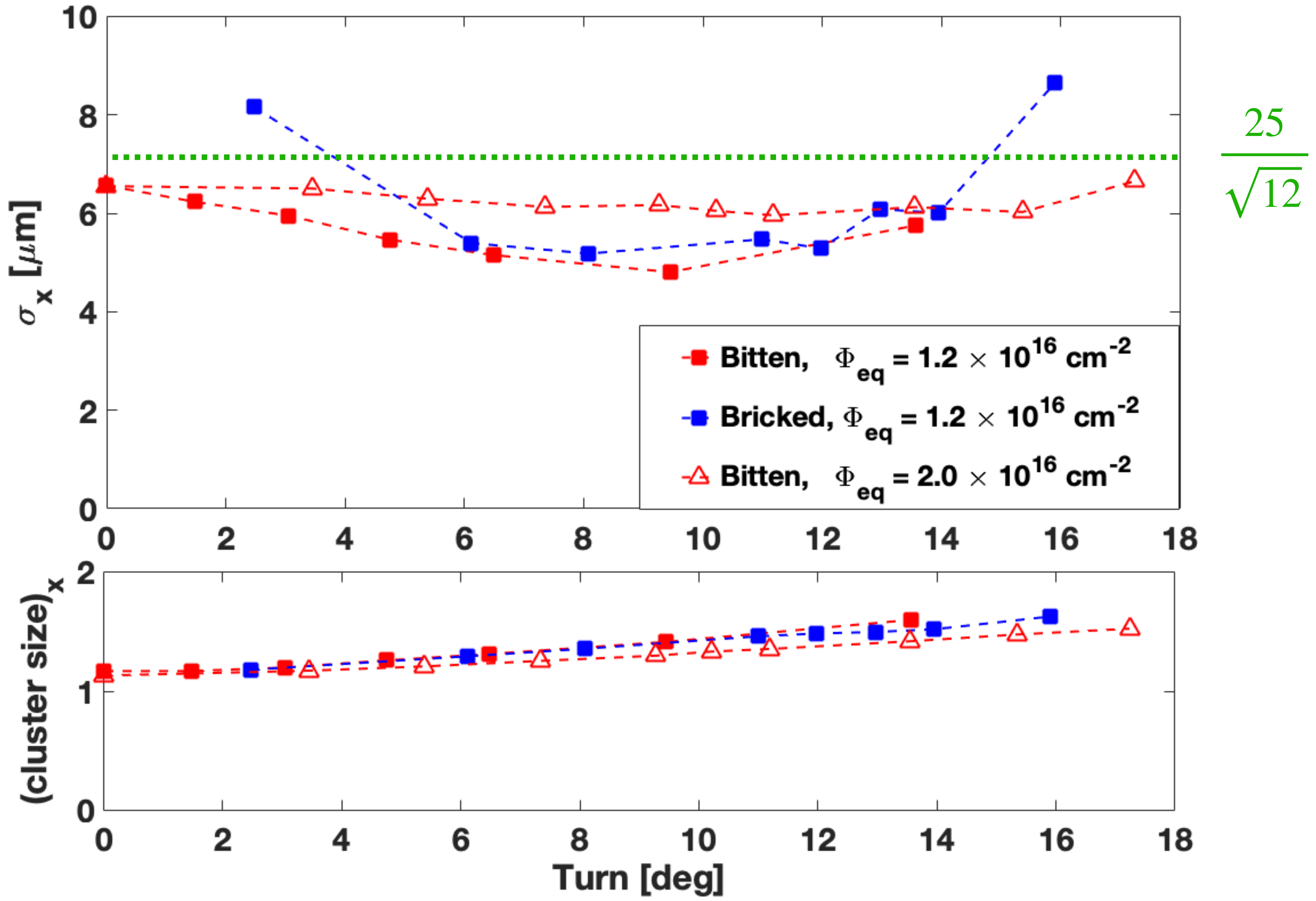
V_{bias} = **800 V**; $T_{chiller}$ ~ **-35°C**; online threshold **~ 1400 e⁻**

r-ϕ (25 µm direction)

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

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

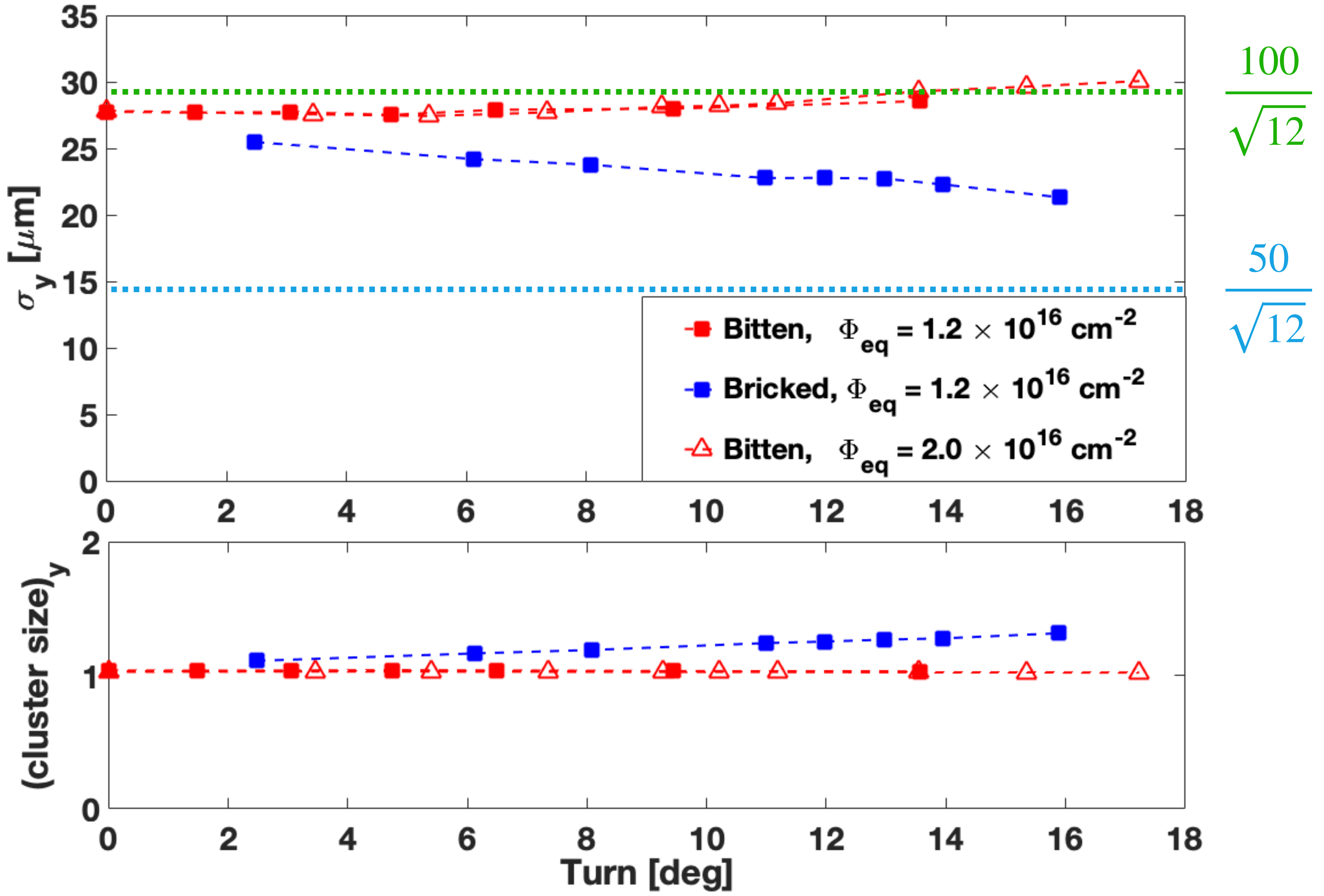
Cluster size still above 1



z (100 µm direction)

Resolution independent of turn angle (but **degraded**)

✓ **Bricked** design resolution improves with turn angle (but effect **much smaller** than before)



Results: cross talk

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 cross talk x:

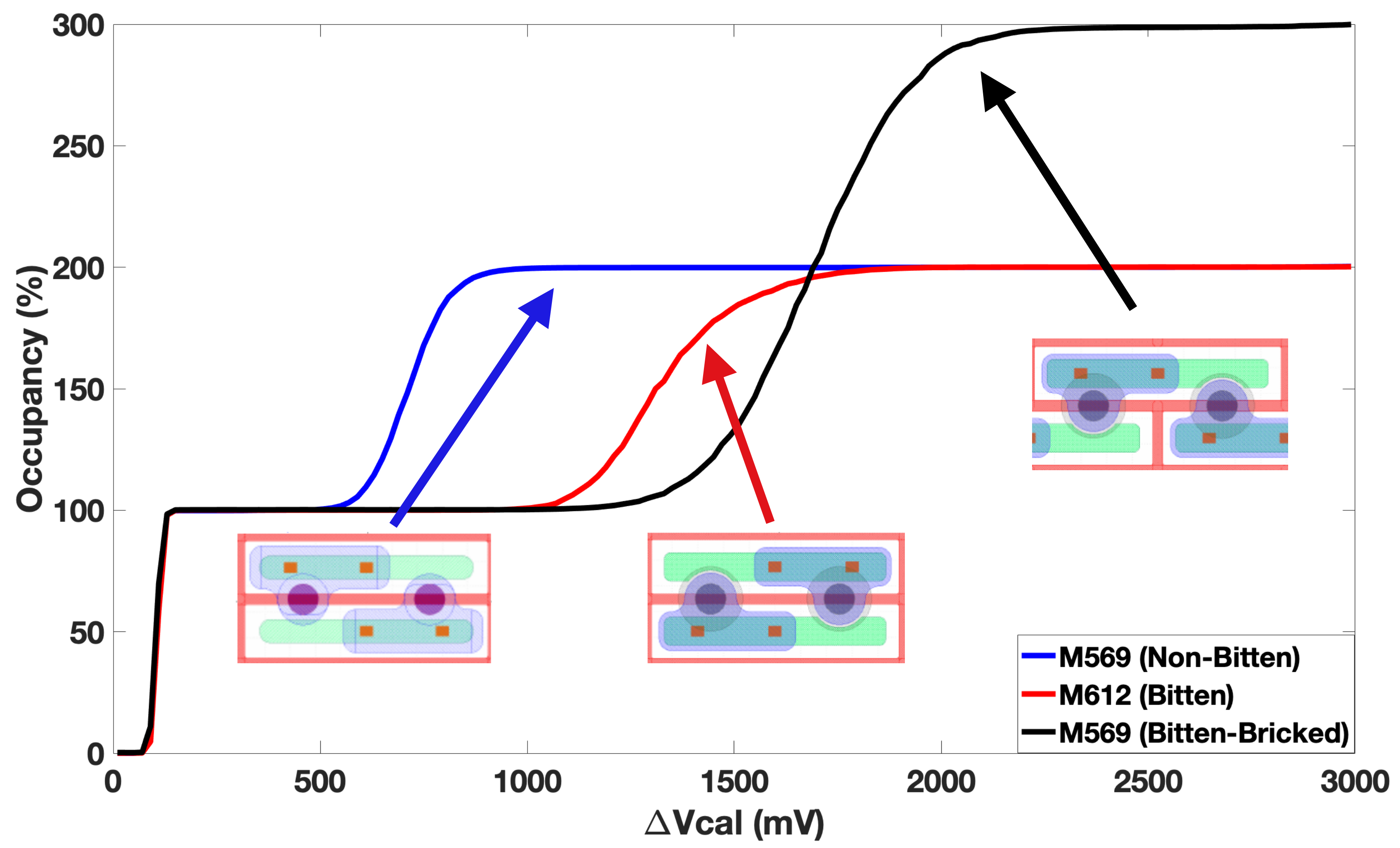
$x = \frac{r}{r+1}$ with: $r = \frac{\mu_{50}}{\mu_{150}}$ for **non-bitten** and **bitten** designs

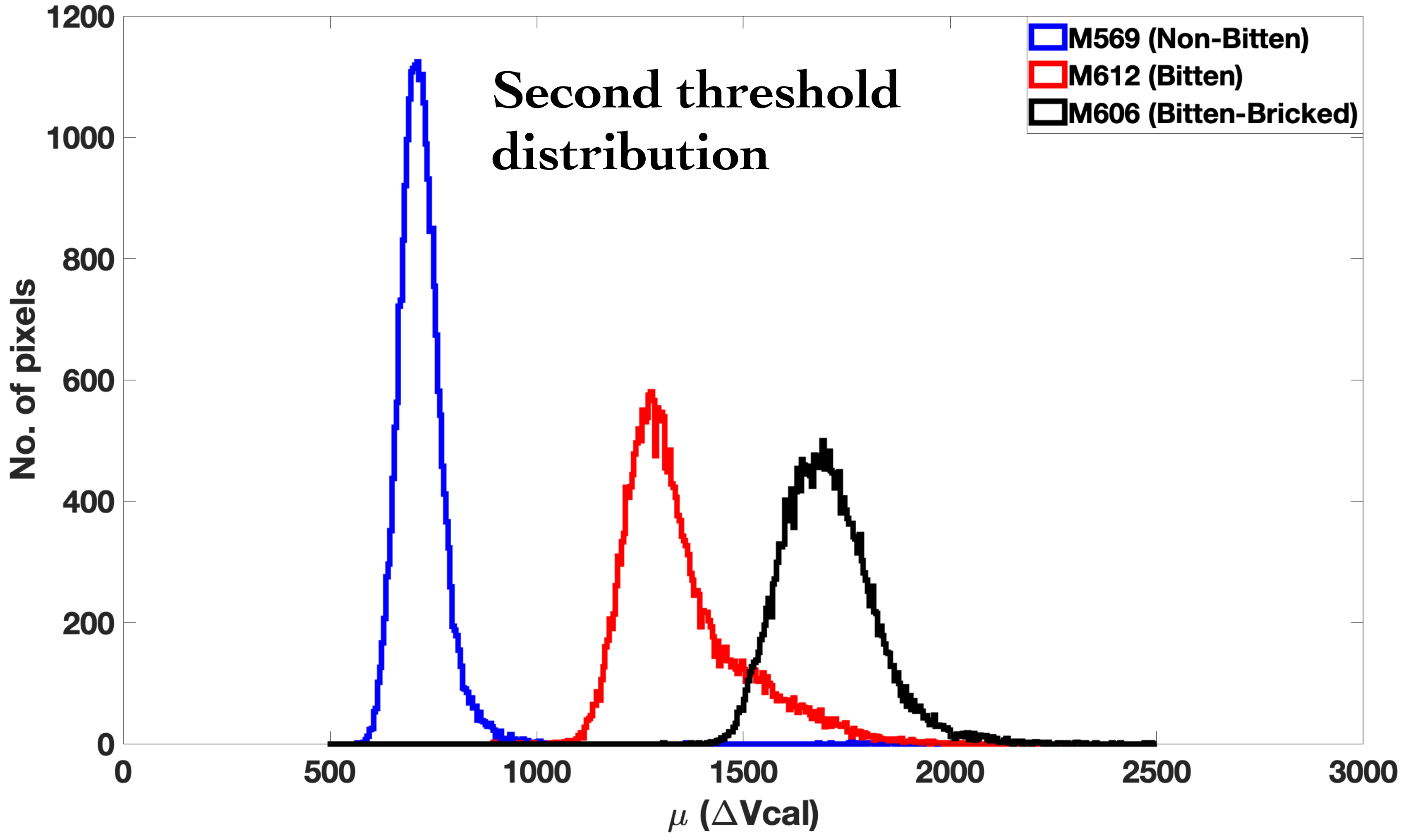
$x = \frac{r}{2r+1}$ with: $r = \frac{\mu_{50}}{\mu_{200}}$ for **bricked** design

Results (similar chip settings, thresholds):

- **non-bitten**: x = 14%
- **bitten**: x = 8%
- **bricked**: x = 6% (cross talk to two neighboring pixels)

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





Results: noise

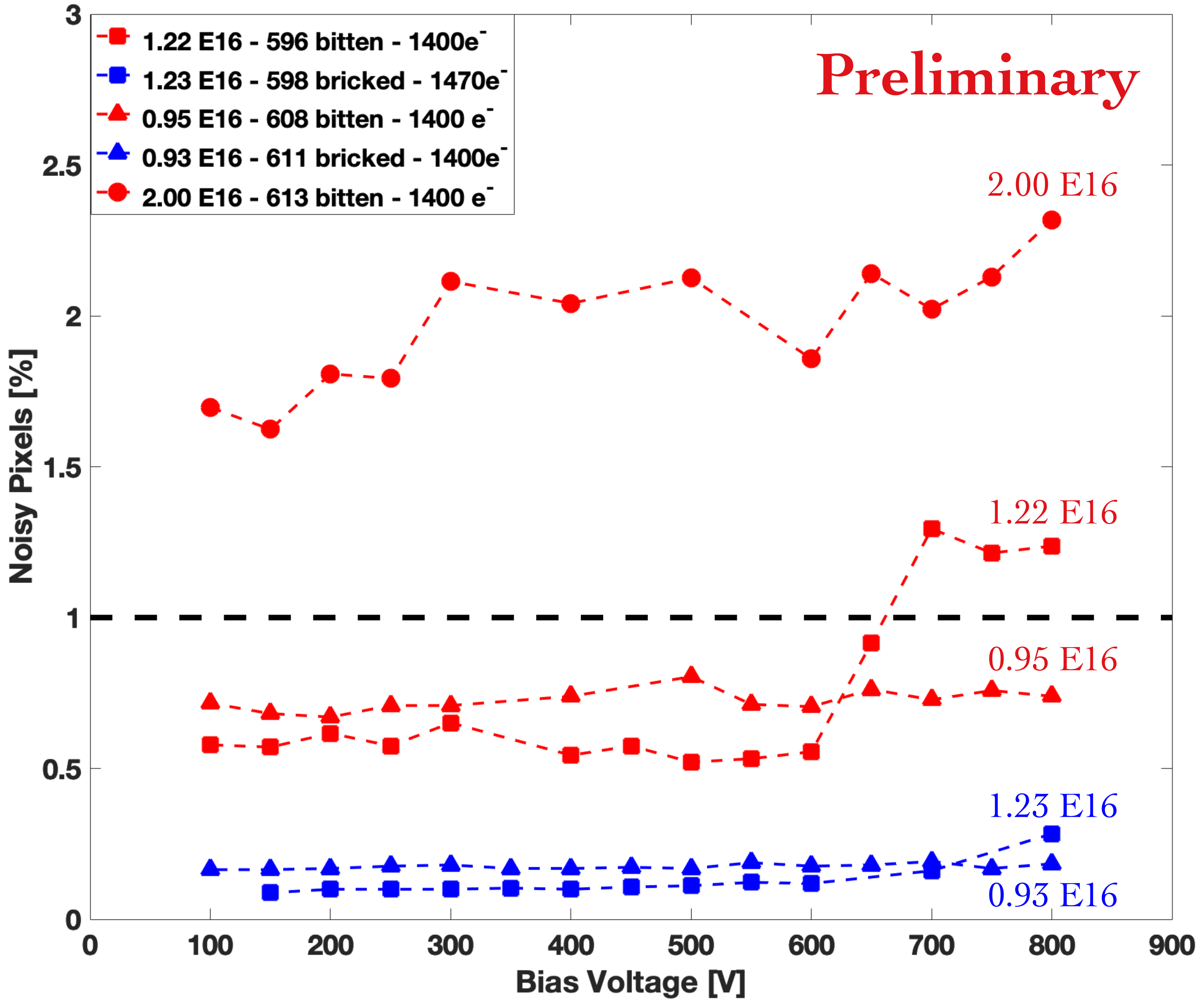
Currently under study: different requirements for each layer (different expected occupancies and fluences)

TBPX L1 example:

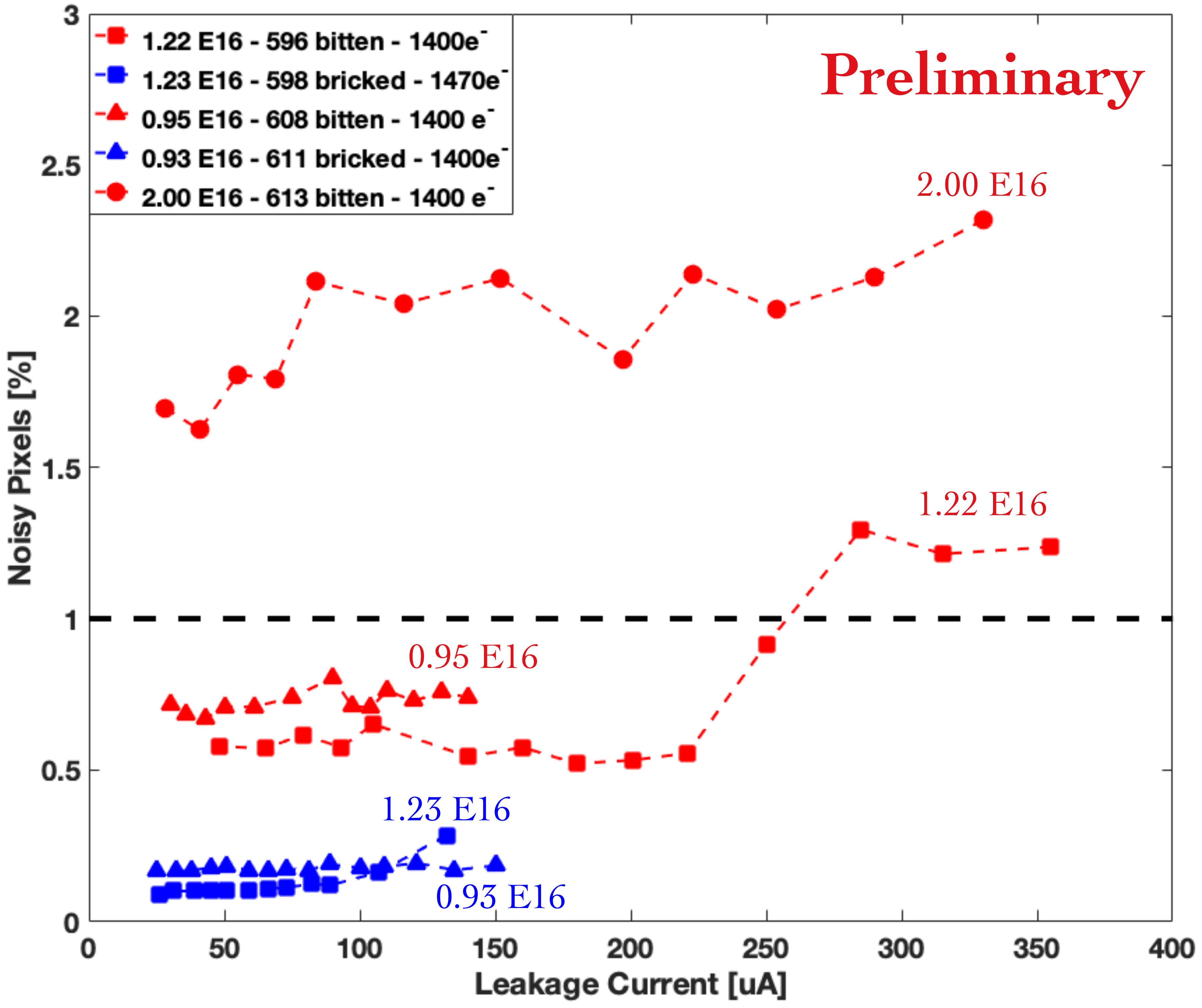
- Noise occupancy: 2×10^{-5} (~ 1% of expected occupancy for one BC)
- Total number of masked pixels < 1%
- Number of noisy pixels stable for leakage currents up to 350 μA

Further studies in progress

T_{Bridge} ~ -28°C



- Bricked
- Bitten



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* Stuck pixels not yet considered in these plots

Summary

The characterization campaign for the planar HPK sensors (both bitten and bricked designs) results in:

- Excellent **production yield**
- Very good electrical behavior before and after irradiation (**breakdown always > 800 V**)
- Hit efficiency $\varepsilon_{hit} \sim 99\%$ also for modules with **Φ_{eq} up to 2.0 x 10^{16} n_{eq}/cm^2**
- Resolution along the **r-ϕ (25 µm) direction always below the binary level** ($Pxl_{pitch}/\sqrt{12}$)
- Resolution along the **z (100 µm) direction always below the binary level**, even if degraded at high fluences
- The bricked design exhibits **better resolution** wrt bitten design along the z direction, even if the difference is **smaller after irradiation**
- **Low** levels of **cross talk and noise**

✓ **Both HPK planar sensor designs are qualified for operation in the CMS Pixel Phase 2 upgrade**

The choice about the **bricked design option** for central η region of TBPX L2-L3-L4 will be taken as soon as the final simulation results become available

Single chip sensors bump bonded to the CMS final production prototype chip (**CROC**) are just arrived: test and irradiation campaign in first half of 2022

Additional slides

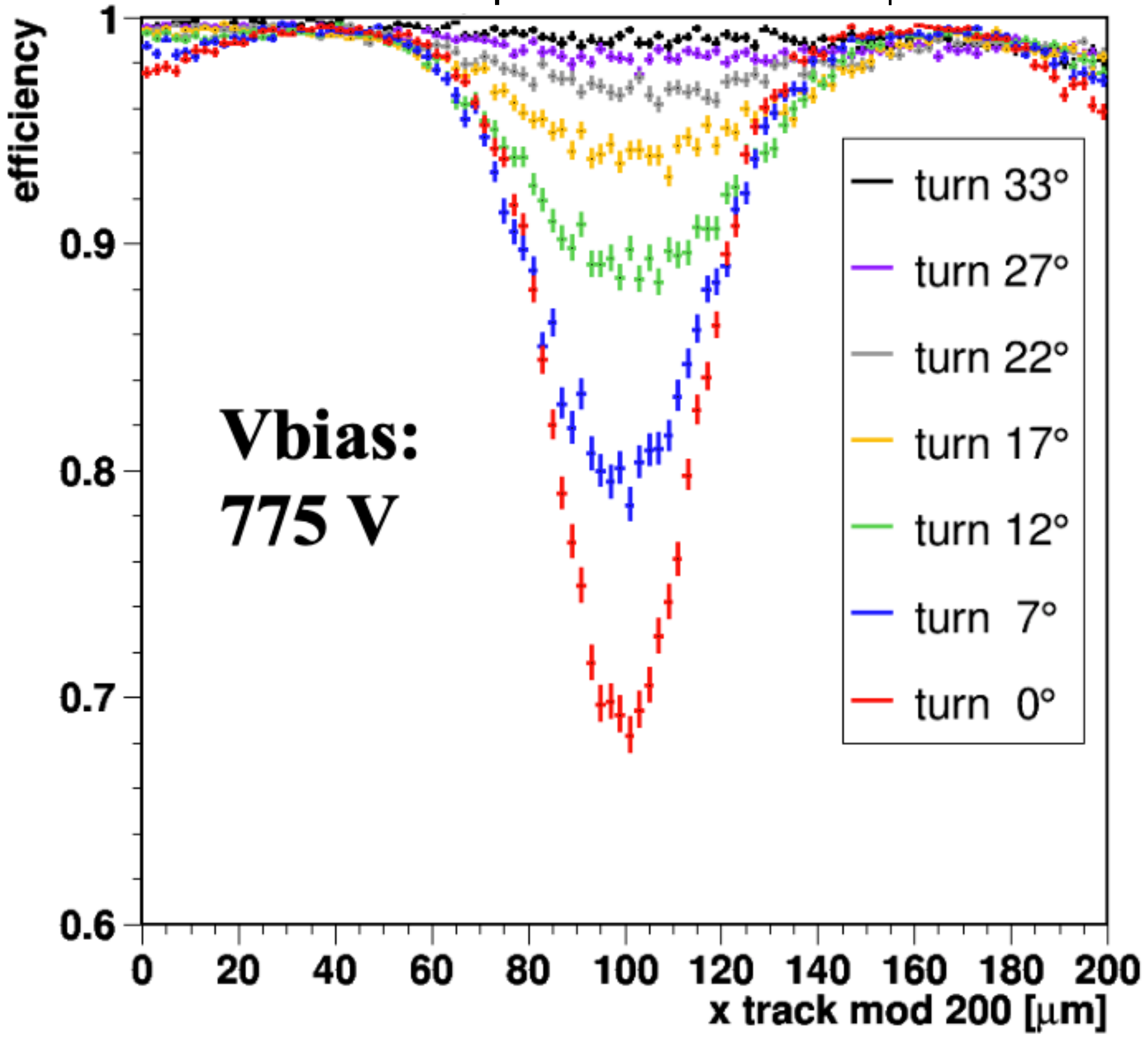
Efficiency loss at bias dot

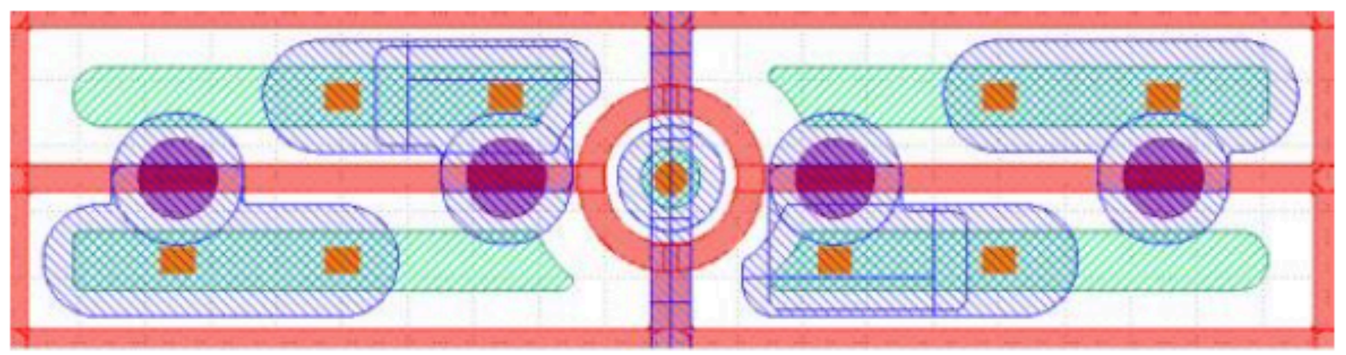
Example with bias dot:

- $5.6 \times 10^{15}\ n_{eq}/cm^2$
- T ~ -26°C
- Inclined in the 100 µm direction
- **Up to 30 % efficiency drop at bias dot**

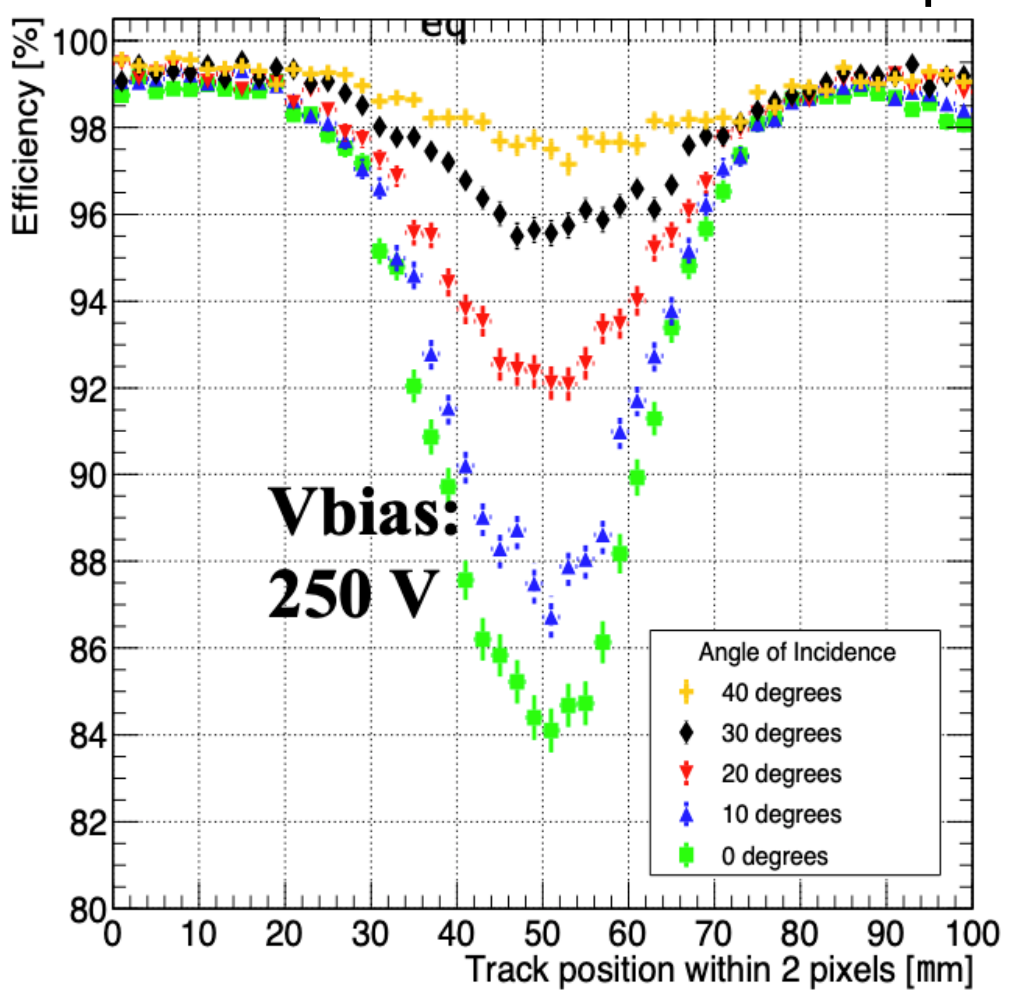
Sensors with PT bias dot do not meet the efficiency requirement of 99% @ perpendicular incidence

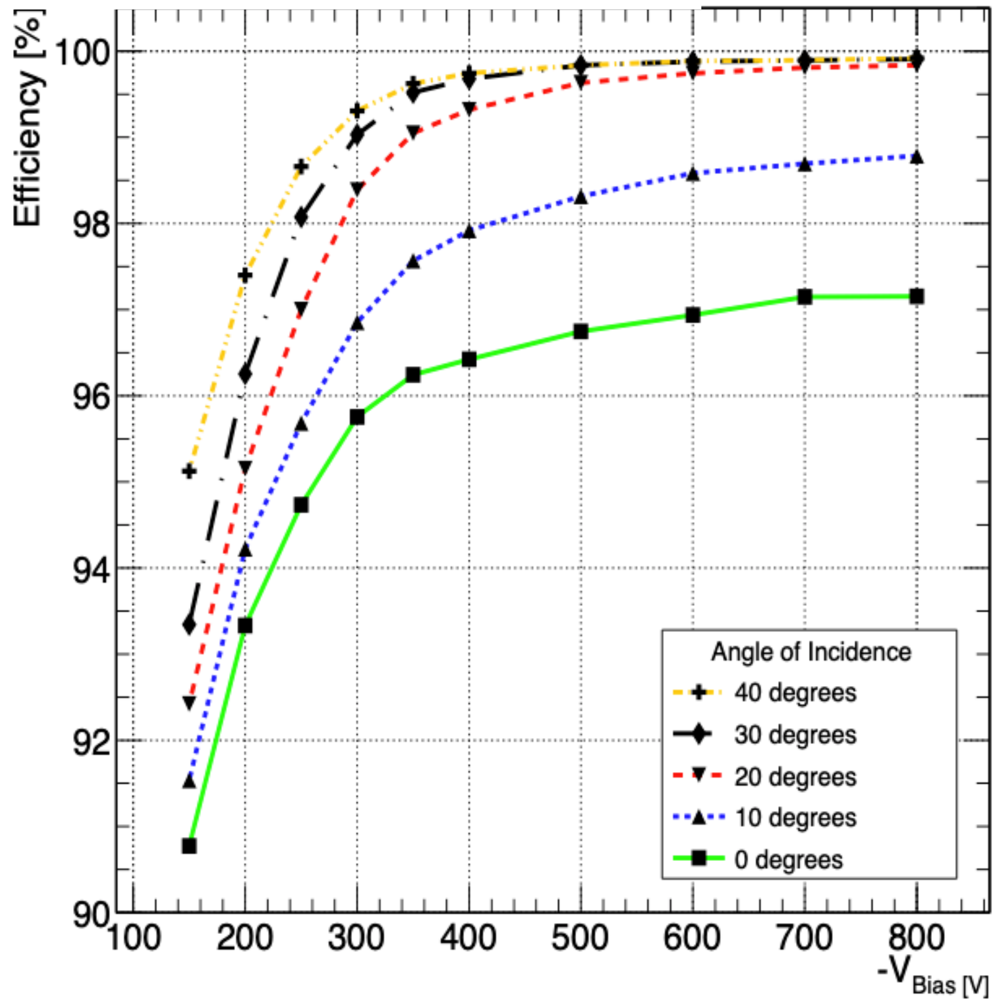
25 x 100 µm - $5.6 \times 10^{15}\ n_{eq}/cm^2$





50 x 50 µm - $5.3 \times 10^{15}\ n_{eq}/cm^2$





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Cuts for resolution

CUTS: for DUT residuals

- C1, for x-axis (short axis): $\Delta y_{dut} < 0.150$ mm, For y-axis (long axis): $\Delta x_{dut} < 0.100$ mm
- C2, timing link: $\Delta x_{mod} < 0.150$ mm and $\Delta y_{mod} < 0.100$ mm
- C3, isolation cut in Reference module plane: $\sqrt{(x_{tele,mod\,1} - x_{tele,mod\,2})^2 + (y_{tele,mod\,1} - y_{tele,mod\,2})^2} > 0.6$ mm
- C4, Fiducial cuts: $(x_{tele,dut}, y_{tele,dut})$ within the fiducial region of DUT
- C5, isolation cut in DUT: $\sqrt{(x_{dut,1} - x_{dut,2})^2 + (y_{dut,1} - y_{dut,2})^2} > 0.6$ mm
- C6, bunch crossing cut: $5 < BCID < 15$
- C7, cluster charge cut: 5 ToT $< Q_{clutser} < Q_{H10\%}$
- C8, Match pairing: finding the correct pair of events in two devices (DUT and telescope):
  - The measurement *j* on device 1 is the closest to measurement *k* on device 2
  - The measurement *k* on device 2 is the closest to measurement *j* on device 1