Testing HPK Planar Pixel Sensors for the CMS Phase 2 Upgrade

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Finn Feindt
On behalf of the CMS Tracker Group

University of Hamburg

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Introduction – CMS Phase-2 Upgrade

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High-Luminosity LHC

- Lumi. $= 7.5 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$; Pileup $= 200$

To avoid cluster merging and improve spatial resolution
$\Rightarrow$ reduce pixel size by factor 6

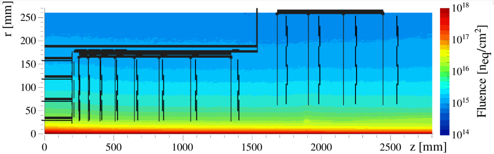
- 25x100 μm^2 or 50x50 μm^2

To deal with trapping due to radiation damage
$\Rightarrow$ reduce drift distance and enlarge electric fields

- Thickness of 150 μm for planar sensors
- Or 3D sensors (layer 1)

Key criterion

- Efficiency $> 99\,\%$ for bias voltages $< 800\,\text{V}$



1 MeV neutron equivalent in silicon, 3000 fb^{-1}

Layer	Φ_{eq} [$10^{16}\,\text{cm}^{-2}$]	Dose [MGy]
1	2.3	12
2	0.5	3
3	0.2	1
4	0.15	1

Expected radiation damage in barrel (TDR numbers)

Sensor Design – Cross Section for ROC4SENS

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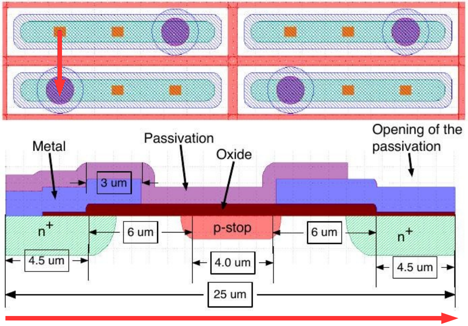
CMS Phase-2 Prototype Design Variants

- Manufactured by Hamamatsu
- n^+p-pixel sensors ($n^+ \Rightarrow$ collecting electrons)
- Geometry: 100x25 μm^2 and 50x50 μm^2
- Pixel isolation schemes, p-stop and p-spray
- With and without biasing scheme
- **Goal: Find best design for CMS Phase-2**

Two Readout Chips

- PSI ROC4SENS readout chip
  No zero suppression, 12 bit digitization
- RD53A 65 nm, prototype
  Threshold $< 1000\,e^-$, 4 bit digitization

Top view 100x25 μm^2, ROC4SENS



Cut image along red arrow

Sensor Design – Variants for ROC4SENS

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CMS Phase-2 Prototype Design Variants

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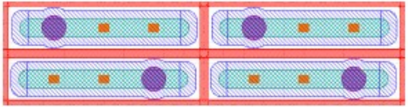
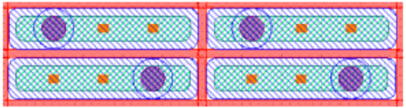
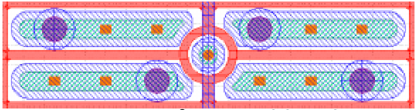


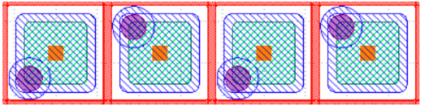
100x25 µm² p-stop



100x25 µm² p-stop enlarged implant



100x25 µm² p-stop bias dot



50x50 µm² p-stop

Sensor Design – Two Submissions

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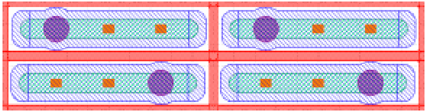
2017 HPK for ROC4SENS and RD53A

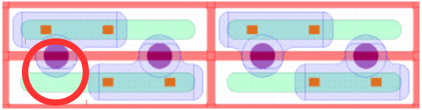
- Test large variety of design variants
- Study sensor physics
- Work with new RD53A

2019 HPK for RD53A and CROC

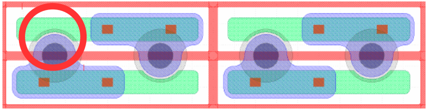
- Several enhancements implemented:
  - Bitten implants to reduce crosstalk
  - Implant size increased
- Limited to most promising design choices:
  - 100x25 μm^2 and 50x50 μm^2
  - With and <u>without</u> punch through
  - Bricked 100x25 μm^2



Standard design ROC4SENS

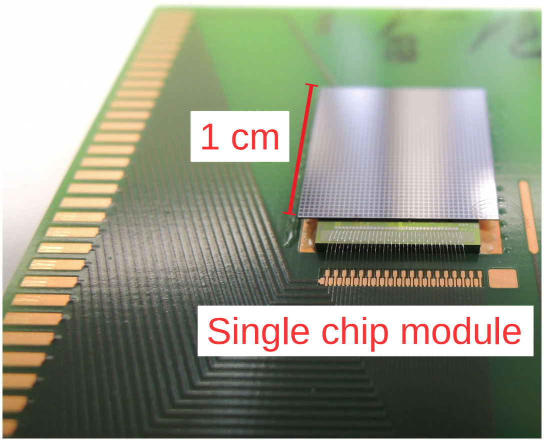


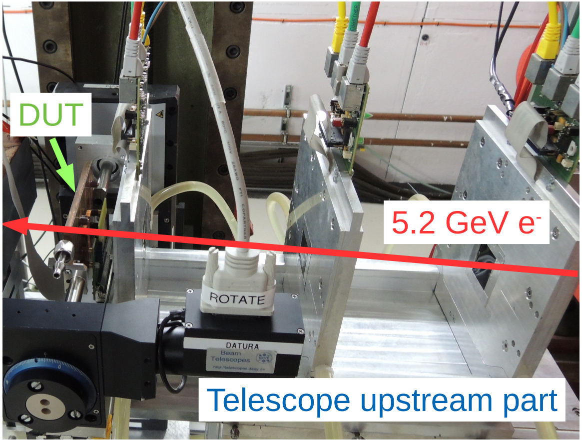
Standard design RD53A 2017



Standard design RD53A 2019

Beam Test Setup – In Pictures





Most studies: Beam incidence 0° to sensor normal, temperature T ≈ −24 °C, no annealing

Efficiency Measurements – Summary

Learnings from Previous Results*

- Larger n^+ implants reduce efficiency losses at the pixel boundaries
- Efficiency losses at the bias dot, especially for small track angles

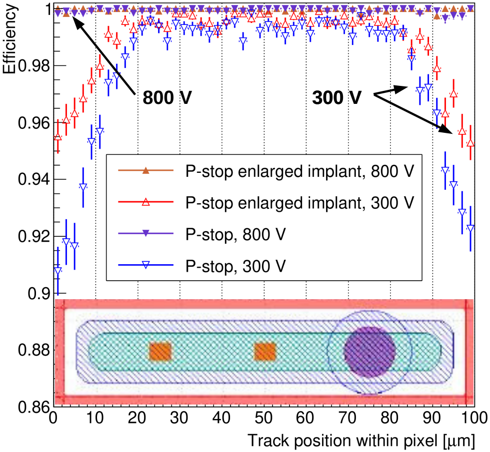
Measurements with ROC4SENS

- $100\text{x}25\,\mu\text{m}^2$, $\phi_{eq} = 5.4 \times 10^{15}\,\text{cm}^{-2}$
- Results in a difference of 100 V to reach efficiency $= 99\,\%$

Measurements with RD53A (lin FE)

- $100\text{x}25\,\mu\text{m}^2$, $\phi_{eq} = 5.6 \times 10^{15}\,\text{cm}^{-2}$
- Losses up to $\approx 30\,\%$ at bias dot

Implant sizes: 9 x 84.5 μm² VS 12.5 x 87.5 μm²



*See TREDI15 or IEEE2019

Efficiency Measurements – Exploring the Final Fluence

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Conditions

- RD53A readout chip (lin FE)
- Various designs, irradiation facilities and fluences
- Vertical incidence, $T \approx -26\,^{\circ}C$
- At best achievable threshold (varies $\approx 900 - 1300\,e$)
- Different numbers of masked pixels

- Requirements are fulfilled even at $\phi_{eq} = 2 \times 10^{16}\,cm^{-2}$
- Track angles above 30° need to be studied

Table 1: Selected requirements for planar pixel sensors. The full depletion voltage and the hit efficiency are denoted by V_{depl} and hit ϵ, respectively.

Parameter	Value	Measured at
polarity	n^+p	
active thickness	150 µm	
pixel size	50×50 µm^2 100×25 µm^2	
breakdown voltage	300 V	before irradiation
breakdown voltage	800 V	after $5x10^{15}$ n_{eq}/cm^2
leakage current at V_{depl}+50 V	0.75 µA/cm^2	before irradiation
leakage current at 600 V	45 µA/cm^2	after $5x10^{15}$ n_{eq}/cm^2
hit ϵ before irradiation	99%	V_{depl}+50 V
hit ϵ > $5x10^{15}$ n_{eq}/cm^2	99%	800V, -20°C
hit ϵ > $1x10^{16}$ n_{eq}/cm^2	98%	800V, -20°C

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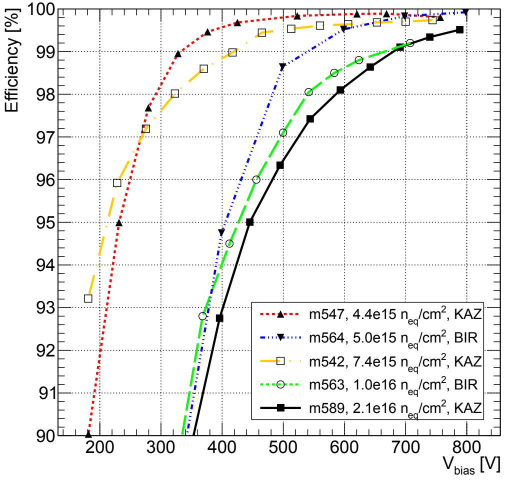
Conditions

- RD53A readout chip (lin FE)
- Various designs, irradiation facilities and fluences
- Vertical incidence, T $\approx -2\,^\circ$C
- Threshold range 1200 – 1320 e)
- Different numbers of masked pixels



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Spatial Resolution – Non-Irradiated Samples

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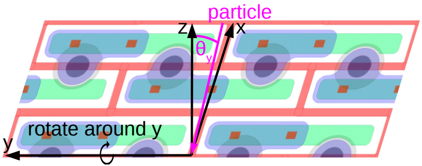
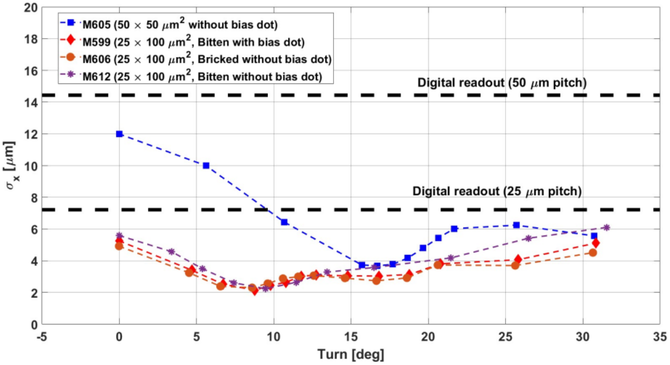
Conditions

- RD53A readout chip (lin FE)
- Room temperature, 120 V
- Thresholds 750 e – 1250 e

Observations

- For 25 × 100 μm^2
  Minimum at ≈ 9°
  Resolution σ_x ≈ 2 μm
- For 50 × 50 μm^2
  Minimum at ≈ 17°
  Resolution σ_x ≈ 4 μm





Spatial Resolution – Non-Irradiated Samples

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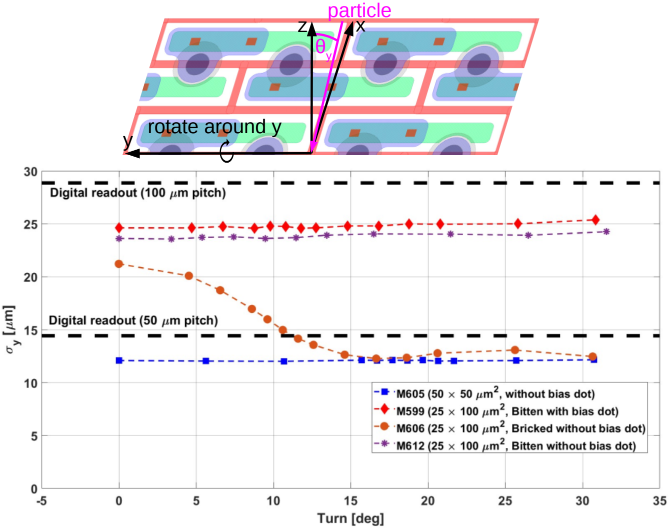
Conditions

- RD53A readout chip (lin FE)
- Room temperature, 120 V
- Thresholds 750 e – 1250 e

Observations

- Standard design: Resolutio σ_y independent of turn angle
- Bricked design: Resolution σ_y improves with increasing angle 30 % – 40 % around 9°



Spatial Resolution – 50x50 µm² Proton Irradiated

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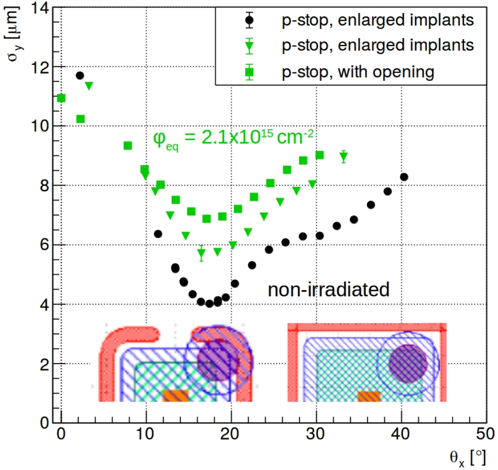
Is the resolution after irradiation better than for 'digital readout' (14.4 µm)?

Conditions

- ROC4SENS readout chip
- Non-irradiated at 120 V, T ≈ 20 °C
- Irradiated at 800 V, T ≈ −24 °C
- Thresholds at ≈ (5), 10 % of the Landau MPV for the (non-)irradiated samples
- Implant sizes 26 × 26 µm² and 36 × 36 µm²

Observations

- Larger implant ⇒ better at minimum
- Smaller implant ⇒ smaller variations



$50x50\,\mu m^2$ Proton Irradiated – Charge Sharing

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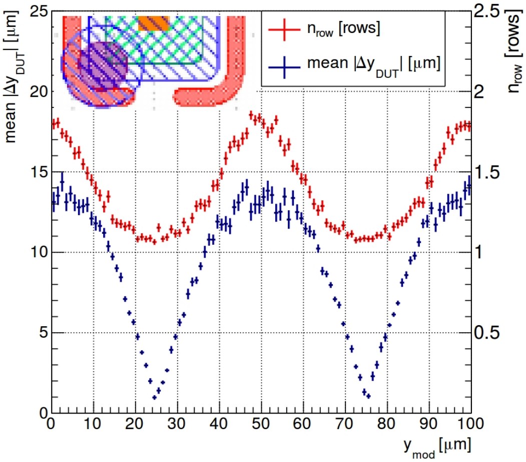
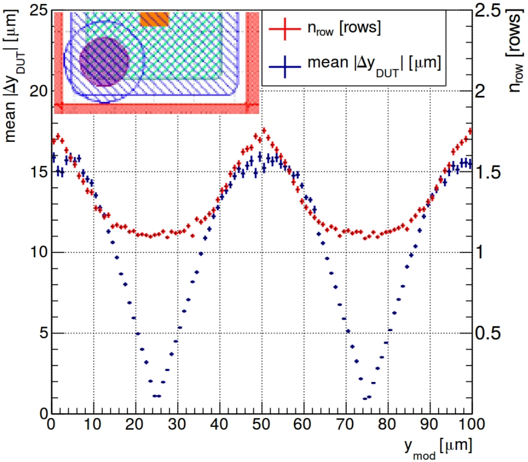


P-stop, with opening, at $\theta_x = 0°$



P-stop, enlarged implants, at $\theta_x = 0°$

Spatial Resolution – 25x100 µm^2 Proton Irradiated

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Is the resolution after irradiation better than for 'digital readout' (7.2 µm)?

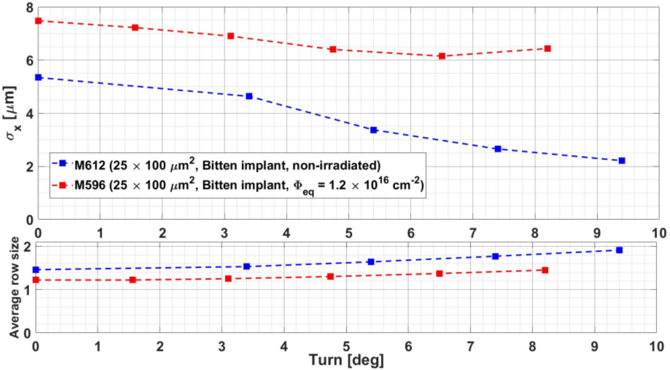
Conditions

- RD53A readout chip (lin FE)
- $\phi_{eq} = 1.2 \times 10^{16}\,\text{cm}^{-2}$ (KIT)
- At 800 V, $T \approx -27\,°\text{C}$
- Threshold 1250 e

Observations

- Resolution degraded, but still better than 'digital readout'
- Cluster still well above 1

Constrains on setup permit larger angles



- Subtracted $\sigma_{TEL} = 8.9\,\mu\text{m}$ (calculated)
- Find resolution $\sigma_x = 6.3\,\mu\text{m}$ at $8°$

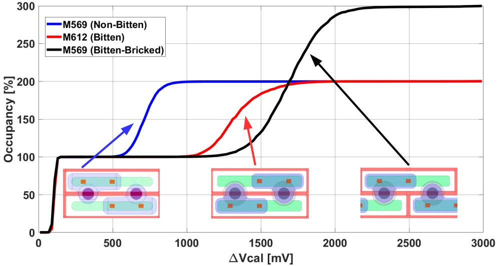
Cross Talk – In 25x100 μm^2 Sensors

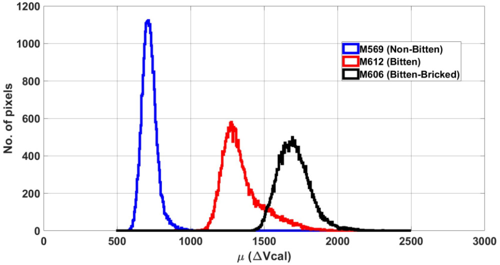
Test Pulse Measurements on RD53A Modules

- Send test pulse to all pixels (consecutively)
- Count number of pixels above threshold
- Find amplitude μ_{50} required for occupancy of 50 % (correspondingly for 150 %, 250 %)
- Cross talk $x = \frac{r}{r+1}$, $r = \frac{\mu_{50}}{\mu_{150}}$ for standard
  Cross talk $x = \frac{r}{2r+1}$, $r = \frac{\mu_{50}}{\mu_{250}}$ for bricked

Results (similar chip settings, thresholds)

- Non-bitten $x = 13\,\%$
- Bitten, bricked (each pixel) $x = 6\,\%$
- Bitten $x = 8\,\%$



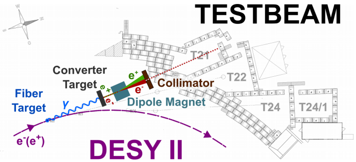


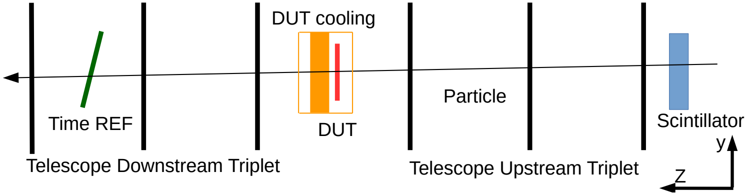
Conclusion

- Testing planar pixel prototype sensors for the CMS Inner Tracker Phase 2 Upgrade
  - Pixel size $25 \times 100\,\mu m^2$ and $50 \times 50\,\mu m^2$
  - Radiation hardness qualification up to $\phi_{eq} = 2 \times 10^{16}\,cm^{-2}$
- Concluded on intense sensor studies $\Rightarrow$ New submission to Hamamatsu in 2019
  - Bitten implants for reduced crosstalk
  - Increase implant size for better efficiency and resolution
  - Decided for design without punch through bias dot for better efficiency
  - Bricked design is a promising, non-baseline option
    $\Rightarrow$ better resolution demonstrated for small track angles (central barrel) and reduced crosstalk
- Many efficiency studies with RD53A on sensors from the 2017 Submission
  - Irradiated up to $\phi_{eq} = 2 \times 10^{16}\,cm^{-2}$ (KIT) $\Rightarrow$ Reach 99 % at $\approx 620\,V$
- First sensors from 2019 submission tested
  - Spatial resolution $\sigma_x = 6.3\,\mu m$ at 8° after proton irradiation to $\phi_{eq} = 1.2 \times 10^{16}\,cm^{-2}$ (KIT)

We are finalizing the design of a planar pixel sensor for the CMS Phase-2 Upgrade

Backup – Beam Test Setup





DESY II Beam Test Facility

- Circumference u = 293 m
- Electron/ positron beam
- Conversion $e^-(e^+) \to \gamma \to e^-(e^+)$
- Energies from 1 to 6 GeV
- Peak rates around 10 kHz

Beam Telescope

- EUDET DATURA Telescope for tracking
- Scintillators for triggering
- 6 MIMOSA-26 planes ($t_{int} = 115\,\mu s$)
- Phase 1 module as time **REF**erence
- **D**evice **U**nder **T**est

Backup – Efficiency Definition

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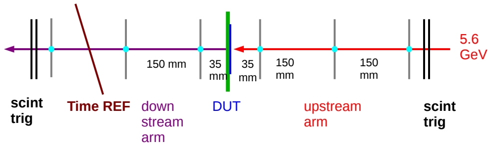
Hit Efficiency

- Eff: $\epsilon = \frac{N_h(hit\ on\ track)}{N(track)}$, $\sigma_\epsilon = \sqrt{\frac{\epsilon(1-\epsilon)}{N}}$
- Track definition:
  - Get upstream and downstream triplets
  - Match triplets using 0.1 mm cut
  - Demand REF-link; 0.15 mm cut
  - Demand 0.6 mm isolation at time REF
- Hit on track definition:
  - Extrapolate upstream-track to DUT
  - Demand DUT-link (pixel); 0.2 mm cut
  - Pixel PH cut
    - Significance cut of 4 (RMS $\approx$ 7 ADC)
- Fiducial region 0.2 mm to sensor edges



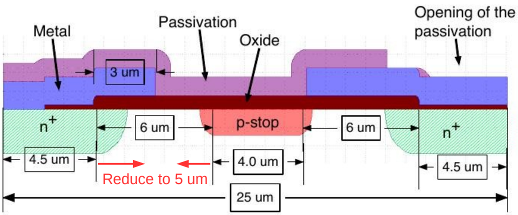
Signal Definition

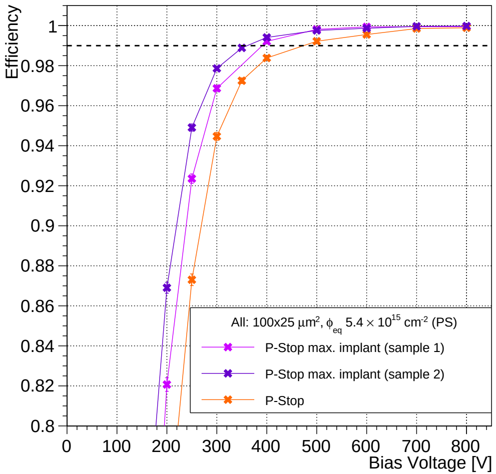
- Same selection as for efficiencies
- If efficient $\Rightarrow$ fill larges cluster charge in 0.2 mm cut (for proton irradiated)
- If inefficient fill 0
- Perform Moyal fit in xy-bins (excl. 0)
- For proton irradiated 2 mm beam-spot radius

Backup – Efficiency Measurements – Implant Size

- Nonuniform irradiation: Efficiency quoted for beam spot region ($r = 2\,\text{mm}$)
- $100\,\text{V}$ difference for efficiency $= 99\,\%$

- Go for p-stop with enlarged implants
- No early breakdown for $\approx$ 70 samples





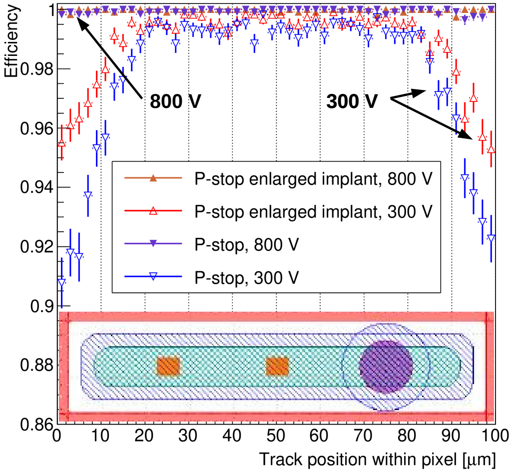
Backup – Efficiency Measurements – In-Pixel Variations

Where do we lose efficiency?

- 300 and 800 V runs from previous slide
- Efficiency projected into 1 pixel cell in the 100 μm direction
- Comparing at 300 V
  - Default design has 3 % more loss than max implant design at pixel edges
  - **Larger pixel implant increases efficiency in pixel edge regions**

- P-Spray would allow even larger implants
- Chose p-stop (HPK Recommendation)

Implant sizes: 9 x 84.5 μm² VS 12.5 x 87.5 μm²



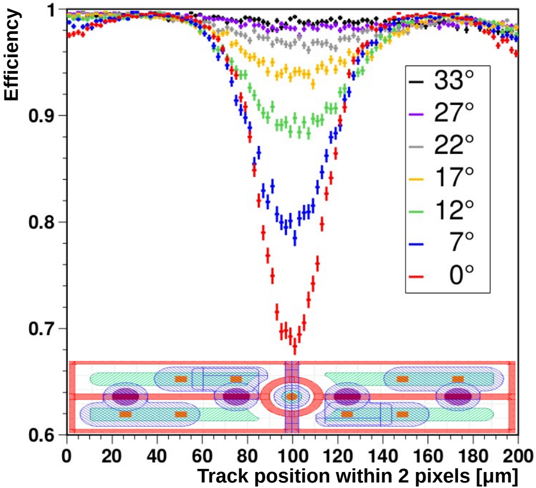
Backup – Efficiency Loss at Bias Dot

- **Using RD53A readout chip (lin FE)**
- $\phi_{eq} = 5.6 \times 10^{15}\,\text{cm}^{-2}$ (PS), T $\approx -26\,°\text{C}$
- Inclined in the 100 µm direction
- Up to 30 % efficiency drop at bias dot

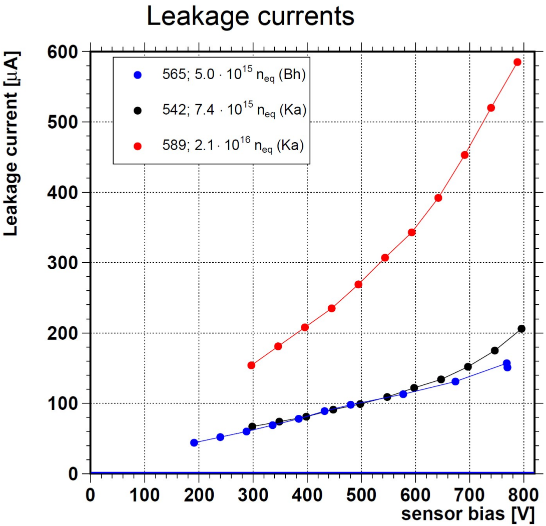
Decision taken

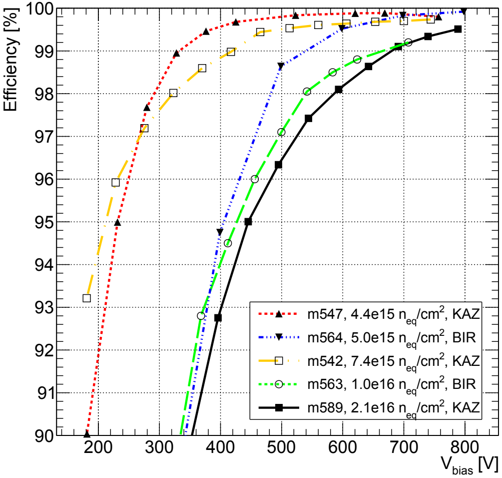
- Favor design without bias dot
- But bias dot design can be tested

⇒ include some in the 2019 submission (as backup)



Backup – Final Fluence Leakage Current





Backup – Cross Talk from Test beam

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