Simulation and testbeam analysis of passive CMOS strip sensors

Summary of results

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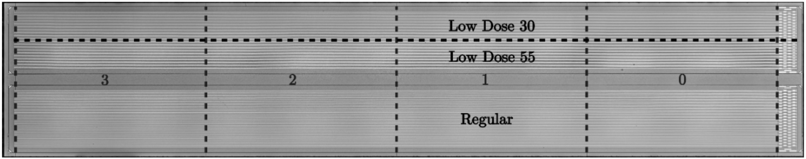
27.02.23

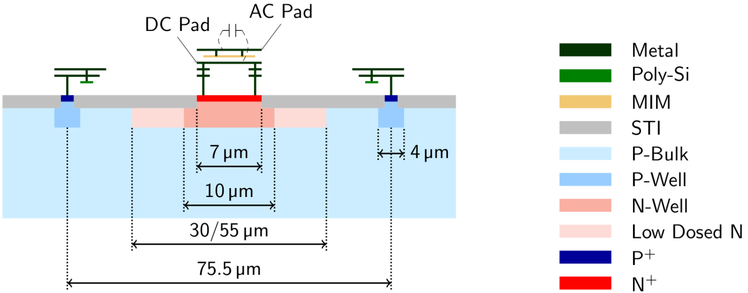
Investigated sensors

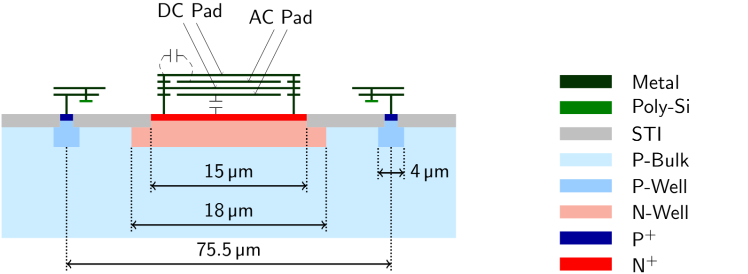
General information



- Passive sensors produced by LFoundry in 150 nm process with additional backside processing from IZM Berlin
- $(150 \pm 10)\,\mu m$ thickness, 3-5 kΩ resistivity, 75.5 µm strip pitch, 40 strips per sensor, up to 5 stitch lines
- Two different lengths: 4.1 cm & 2.1 cm
- Three different designs: Regular, Low Dose 30 and 55, developed by University of Bonn
- Irradiation of sensors to different fluences with: 23 MeV protons (KIT), reactor neutrons (Ljubljana), 24 GeV protons (IRRAD@CERN)

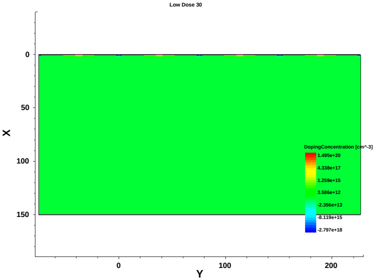
Investigated Sensors
Regular and Low Dose Design

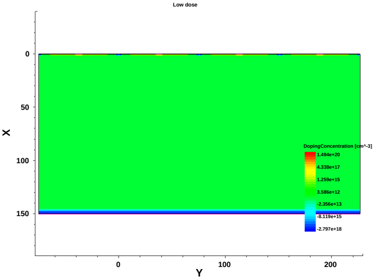


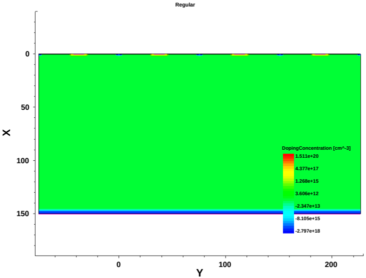


Simulations
Overview

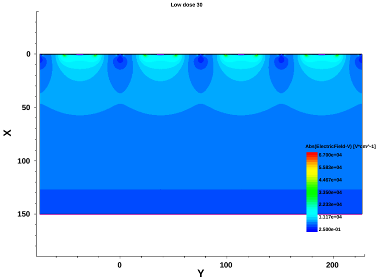
- Simulations of all three design in Sentaurus TCAD by Iveta Zatocilova, doping profiles by Marta Baselga
- Sensors simulated as 4 strip structure with vacuum boundary conditions
- Macroscopic electrical characteristics, electric fields and transient currents successfully simulated

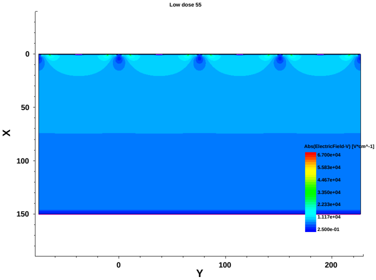


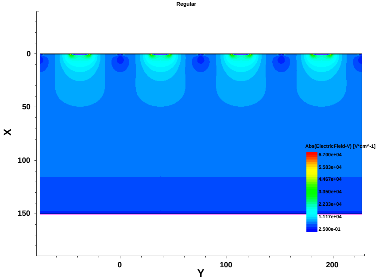




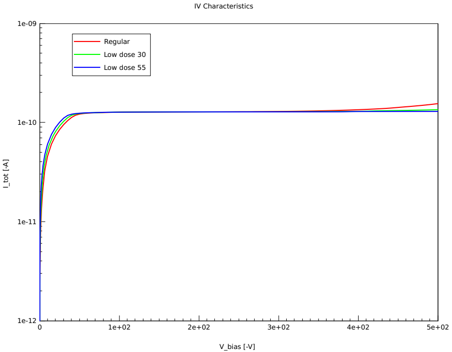
Simulations
Electric Field Configuration

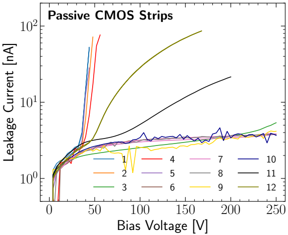


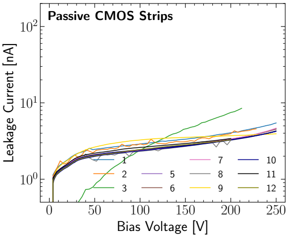




- Electric field simulated @100 V
- Stronger electric field gradient for regular design
- Regions of higher electric field shared between strips for lowdose design

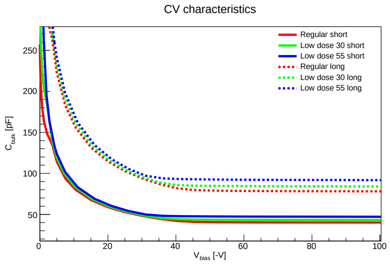


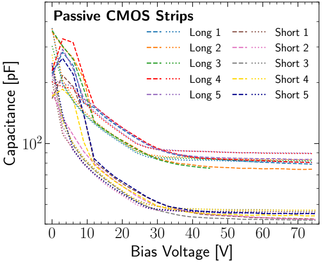




- Simulated current: $\sim 0.1\,\mathrm{nA}$
- Measured current: $\sim 3\,\mathrm{nA}$
- Difference due to only strip being simulated compared to 40 strips in real detector

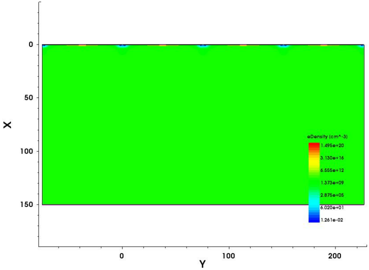
Simulations
Macroscopic Characteristics 2

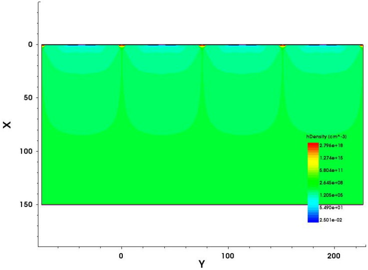




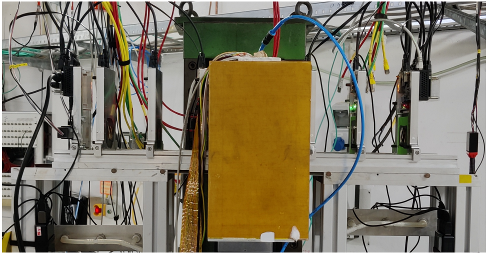
- Bulk capacitance simulated for one strip multiplied number of strips
- Artifact in capacitance not reproduced by simulations

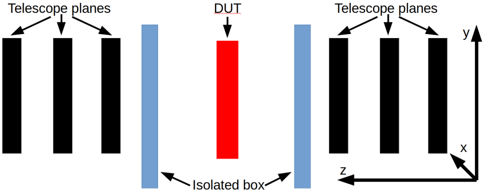
⇒ Overall very good agreement between simulated and measured IV/CV characteristics





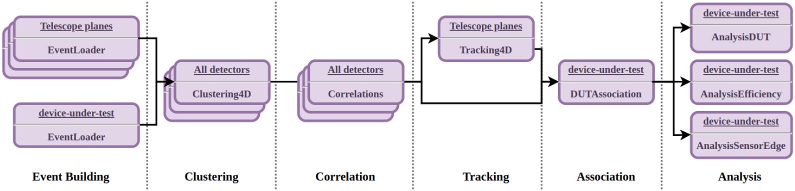
- Simulation electron/hole density of heavy ion penetrating sensor at 45° angle off-center
- Nicely visible how electron cloud moves faster than hole cloud
- Moving electron cloud also visible in hole density
- Hole cloud pushed away from strip implant due to electric field
- Enables calculation of charge collected by strips

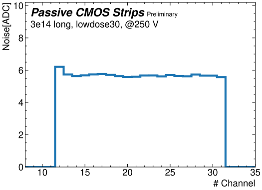


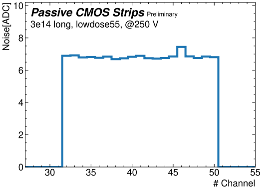


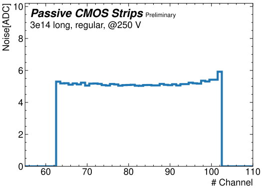
- Two testbeam campaigns conducted at the DESY-II testbeam (November 21 and May 22)
- Beam energy of 3 GeV and 3.4 GeV
- EUDET telescope with 6 ALPIDE planes
- ALPIDE sensors: 1024 x 512 pixels, 29.24 μm x 26.88 μm, total area of 30 mm x 15 mm
- DUT monitored by ALiBaVa system, cooled with dry ice in styrofoam box

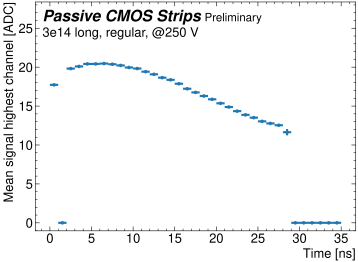
- Created in December 2019 for the reconstruction and analysis of testbeam data
- Modular architecture: Core handling central functionality, (user created) modules for specific reconstruction tasks (ALiBaVaEventLoader module created for this analysis)
- Events processed sequentially, with each module being executed in linear order inside event loop
- Analysis of data a multi-step process:
  - Prealignment of telescope
  - (Iterative) exact alignment of telescope
  - Prealignment of DUT
  - (Iterative) exact alignment of DUT
  - Full analysis







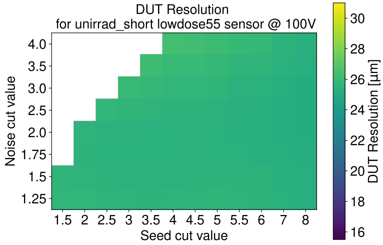


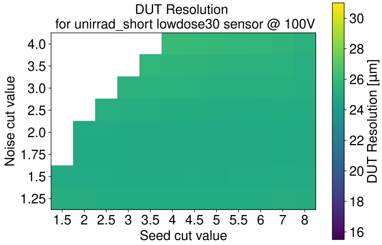


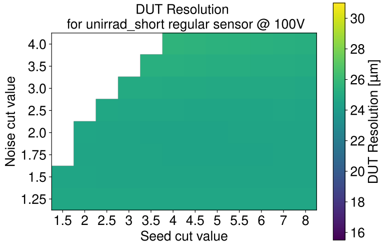
- Noise distributed evenly in ROI
- Noise for regular and ld30 similar, higher for ld55
- Noise level differs, depending on Beetle Chip
- Shape of pulse nicely reconstructed in time profile
- Timecut of 10 ns around peak of pulse chosen for further analysis

Testbeam Analysis

Comparison of Detector Resolution - Unirradiated



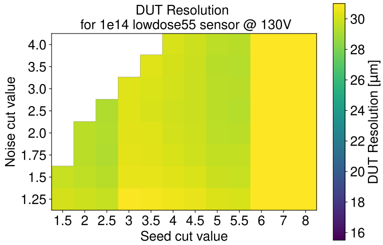


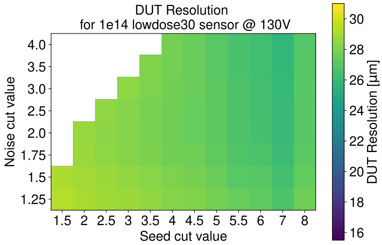


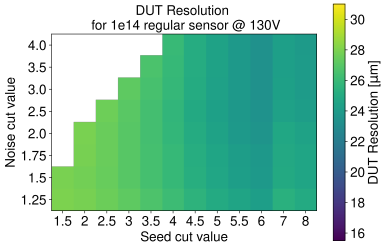
- $\sigma_{DUT} = \sqrt{\sigma_{meas}^2 - \sigma_{telescope}^2}$, with $\sigma_{telescope} = 8.9\,\mu m$
- Expected binary resolution: 21.8 µm; measured resolution: ∼23.5 µm
- No difference between designs
- No influence of seed cut on resolution, slight increase of resolution with noise cut

Testbeam Analysis

Comparison of Detector Resolution - 1e14



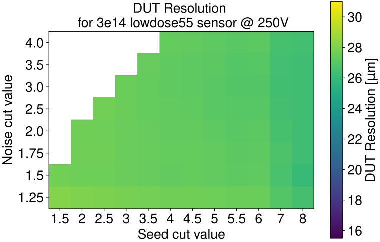


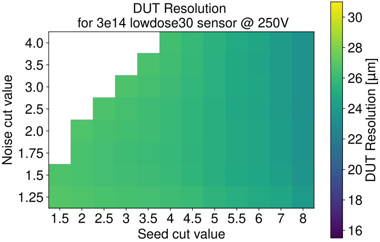


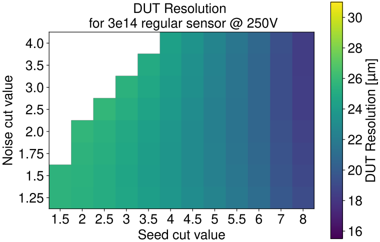
- Resolution worse than for unirradiated sensor
- $\sigma_{lowdose55} > \sigma_{lowdose30} > \sigma_{regular}$
- Strong dependence of resolution on seed cut
- Inconsistencies most probably due to limited statistics for alignment
- Resolution increases slightly for decreased voltage

Testbeam Analysis

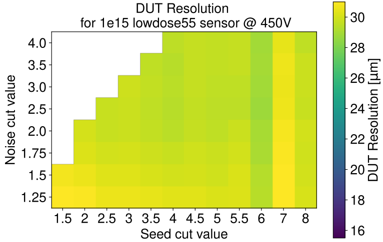
Comparison of Detector Resolution - 3e14

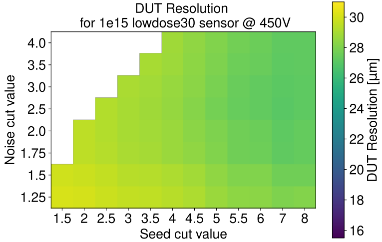


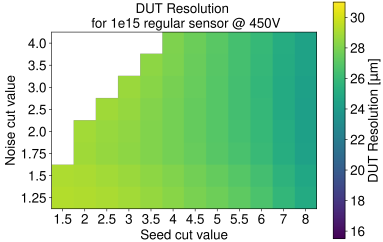




- Same general trends as for 1e14 sensor
- Resolution better than for unirradiated sensor
- Reason not yet understood - complicated due do limited amount of sensors measured in testbeam

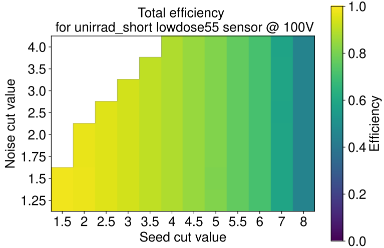


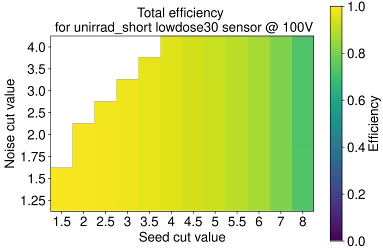


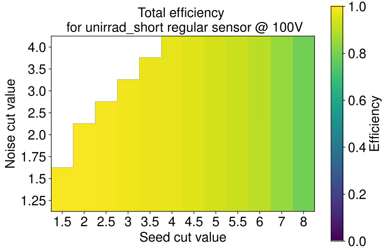


- Same trends as for other irradiated senors
- Resolution worse than for 1e14 sensor

Testbeam Analysis
Comparison of Detector Efficiency - Unirradiated



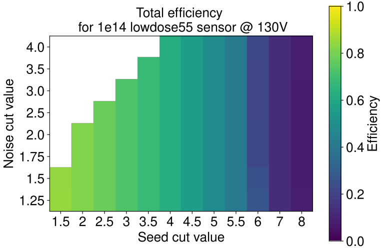


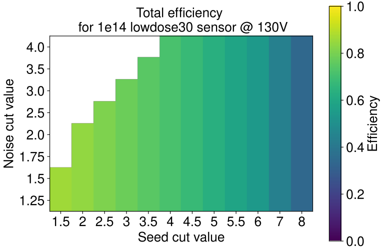


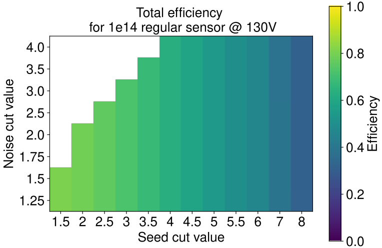
- Strong dependence of efficiency on seed cut, no dependence on noise cut
- $\epsilon_{regular} > \epsilon_{lowdose30} > \epsilon_{lowdose55}$
- Efficiency of $> 97\%$ for seed cut of: 1.5 (lowdose55), 3 (lowdose30), 3.5 (regular)
- Efficiency decreased for lower voltages

Testbeam Analysis

Comparison of Detector Efficiency - 1e14





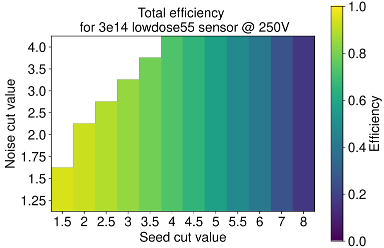


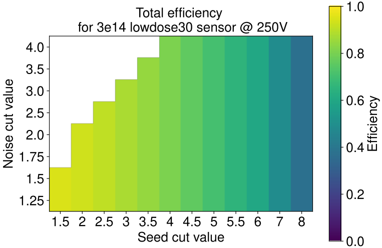
- Efficiency worse than for unirradiated sensor (max. 85%)
- For small seed cuts:

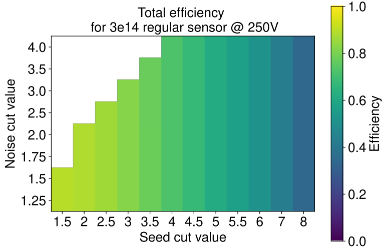
  $\epsilon_{lowdose30} > \epsilon_{lowdose55} > \epsilon_{regular}$
- Lowdose55 shows stronger dependence on seed cut than other designs
- Maybe possible to recover some efficiency with stricter time cuts

Testbeam Analysis

Comparison of Detector Efficiency - 3e14



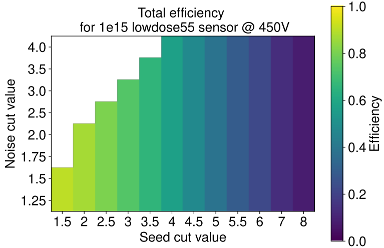


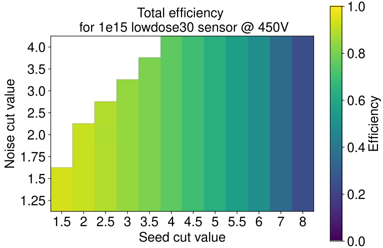


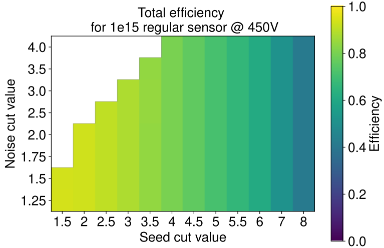
- Same general trends as for 1e14 sensor
- Efficiency increased compared to 1e14 sensor (max 94%)

Testbeam Analysis

Comparison of Detector Efficiency - 1e15

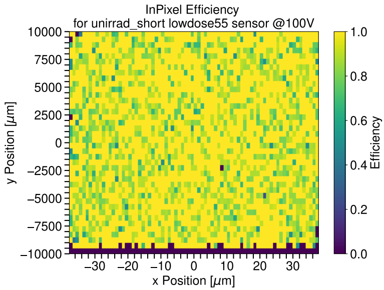


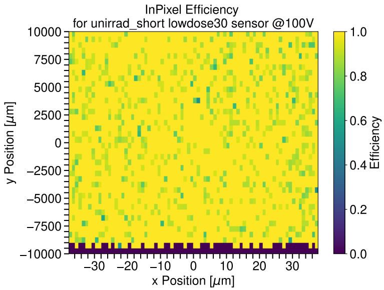


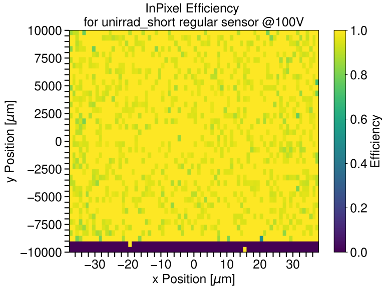


- Small decrease in efficiency (max 93%)
- For small seed cuts:
  $\epsilon_{lowdose30} > \epsilon_{regular} > \epsilon_{lowdose55}$

Testbeam Analysis
Comparison of In-Pixel Efficiency - Unirradiated



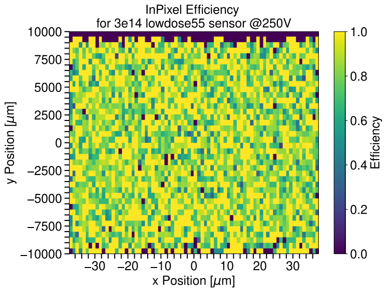


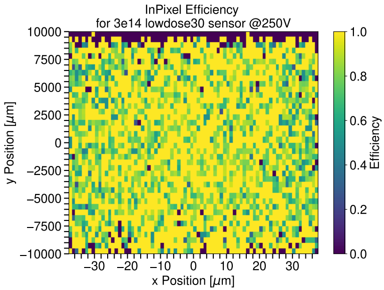


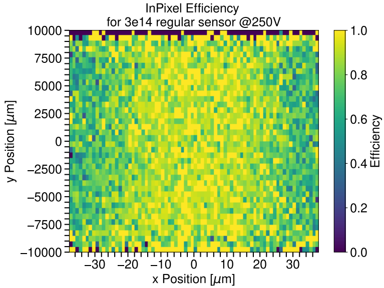
- Seed cut of 3; Noise cut of 2
- No decrease in efficiency over the entire area of the strip $\Rightarrow$ Stitch has no effect on efficiency!
- Low efficiency edge is artifact of ROI on telescope planes

Testbeam Analysis

Comparison of In-Pixel Efficiency - 3e14







- Seed cut of 3; Noise cut of 2
- Regular design shows efficiency decrease in inter-strip region
- Still no effect of stitches visible
- Similar for all fluences

Summary and outlook

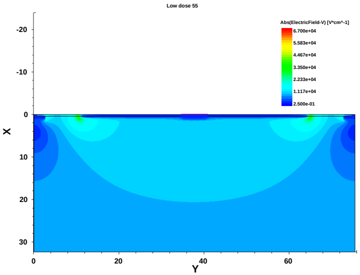
Summary:

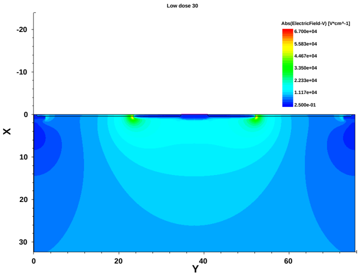
- Simulation of all three designs in TCAD have been conducted
- Results of simulation and measurements agree very well so far
- Unirradiated as well as irradiated sensor have been measured in two testbeam campaigns
- Sensor generally work well, but still a few phenomenons left to explain
- So far no signs of stitches impacting sensor performance!

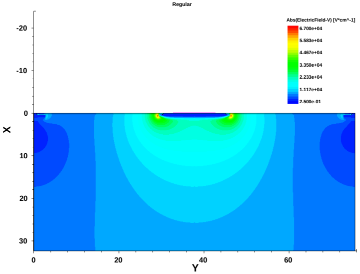
Outlook:

- Testbeam campaign next week with additional timing plane
- Increased focus on bondpad and egde regions
- Plans to irradiate sensors to higher fluences to test their radiation tolerance

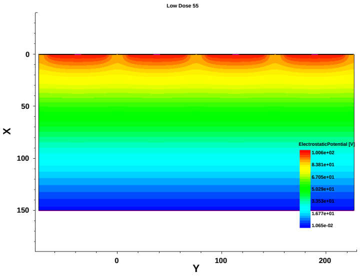
Backup

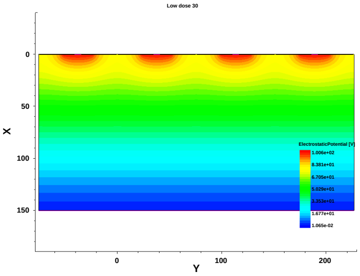

Low dose 55
Abs(ElectricField-V) [V*cm^-1]
6.700e+04
5.583e+04
4.467e+04
3.350e+04
2.233e+04
1.117e+04
2.500e-01
X
Y

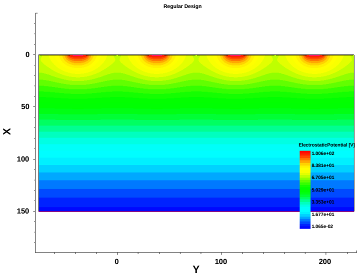

Low dose 30
Abs(ElectricField-V) [V*cm^-1]
6.700e+04
5.583e+04
4.467e+04
3.350e+04
2.233e+04
1.117e+04
2.500e-01
X
Y


Regular
Abs(ElectricField-V) [V*cm^-1]
6.700e+04
5.583e+04
4.467e+04
3.350e+04
2.233e+04
1.117e+04
2.500e-01
X
Y

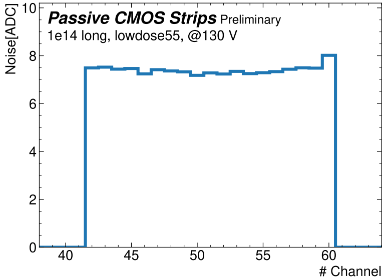
Backup

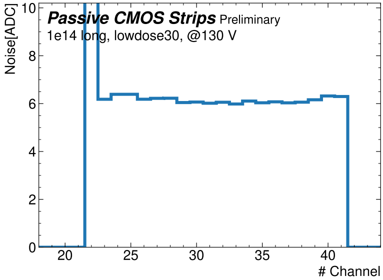

Low Dose 55
ElectrostaticPotential [V]
1.006e+02
8.381e+01
6.705e+01
5.029e+01
3.353e+01
1.677e+01
1.065e-02
X
Y
0
50
100
150
0
100
200

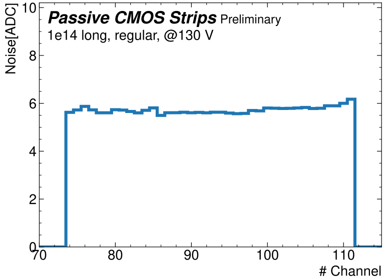

Low dose 30
ElectrostaticPotential [V]
1.006e+02
8.381e+01
6.705e+01
5.029e+01
3.353e+01
1.677e+01
1.065e-02
X
Y
0
50
100
150
0
100
200


Regular Design
ElectrostaticPotential [V]
1.006e+02
8.381e+01
6.705e+01
5.029e+01
3.353e+01
1.677e+01
1.065e-02
X
Y
0
50
100
150
0
100
200

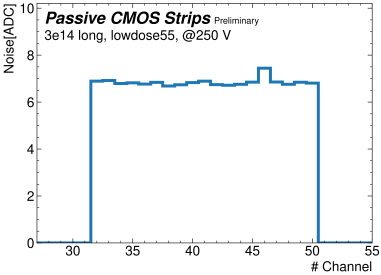
Backup

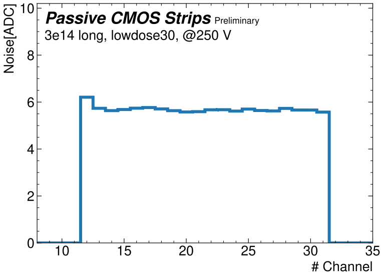

Passive CMOS Strips Preliminary
1e14 long, lowdose55, @130 V
Noise[ADC]
Channel

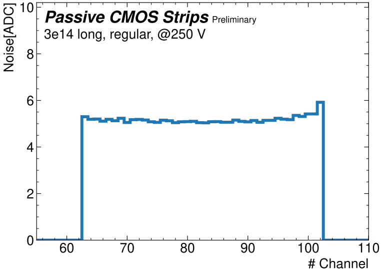

Passive CMOS Strips Preliminary
1e14 long, lowdose30, @130 V
Noise[ADC]
Channel


Passive CMOS Strips Preliminary
1e14 long, regular, @130 V
Noise[ADC]
Channel

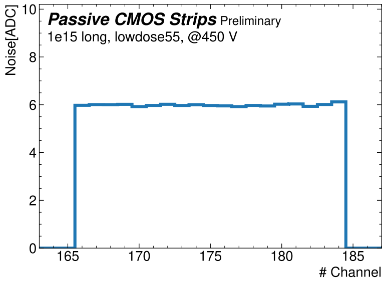
Backup

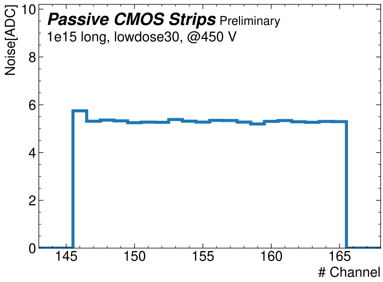

Passive CMOS Strips Preliminary
3e14 long, lowdose55, @250 V
Noise[ADC]
Channel
0
2
4
6
8
10
30
35
40
45
50
55

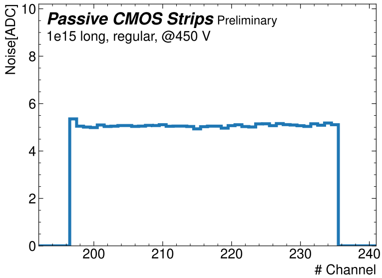

Passive CMOS Strips Preliminary
3e14 long, lowdose30, @250 V
Noise[ADC]
Channel
0
2
4
6
8
10
10
15
20
25
30
35


Passive CMOS Strips Preliminary
3e14 long, regular, @250 V
Noise[ADC]
Channel
0
2
4
6
8
10
60
70
80
90
100
110

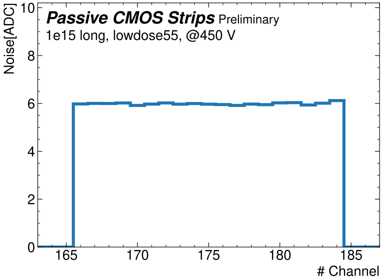
Backup

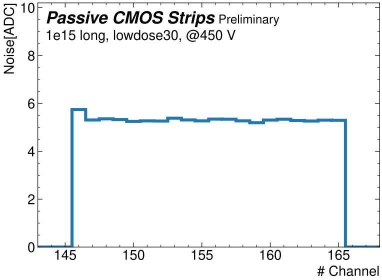

Passive CMOS Strips Preliminary
1e15 long, lowdose55, @450 V
Noise[ADC]
Channel
0
2
4
6
8
10
165
170
175
180
185

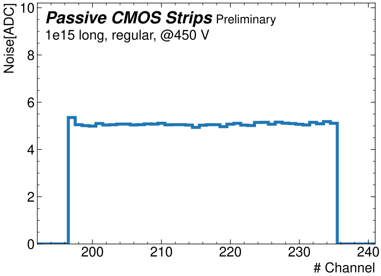

Passive CMOS Strips Preliminary
1e15 long, lowdose30, @450 V
Noise[ADC]
Channel
0
2
4
6
8
10
145
150
155
160
165


Passive CMOS Strips Preliminary
1e15 long, regular, @450 V
Noise[ADC]
Channel
0
2
4
6
8
10
200
210
220
230
240

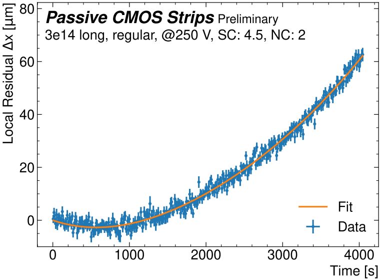
Backup

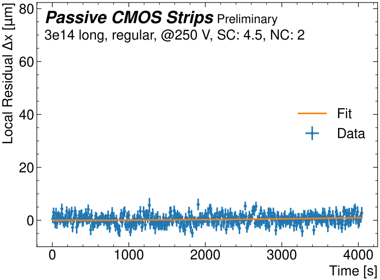

Passive CMOS Strips Preliminary
1e15 long, lowdose55, @450 V
Noise[ADC]
0
2
4
6
8
10
165
170
175
180
185
Channel

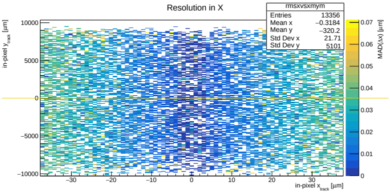

Passive CMOS Strips Preliminary
1e15 long, lowdose30, @450 V
Noise[ADC]
0
2
4
6
8
10
145
150
155
160
165
Channel

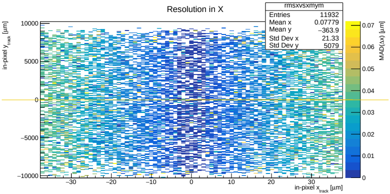

Passive CMOS Strips Preliminary
1e15 long, regular, @450 V
Noise[ADC]
0
2
4
6
8
10
200
210
220
230
240
Channel

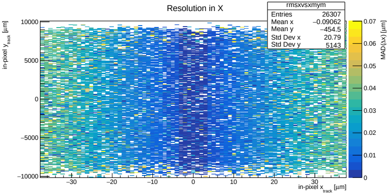
Backup


Passive CMOS Strips Preliminary
3e14 long, regular, @250 V, SC: 4.5, NC: 2
Local Residual Δx [µm]
Time [s]
Fit
Data
0
20
40
60
80
0
1000
2000
3000
4000

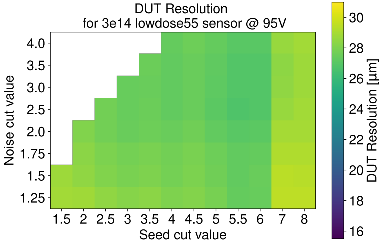

Passive CMOS Strips Preliminary
3e14 long, regular, @250 V, SC: 4.5, NC: 2
Local Residual Δx [µm]
Time [s]
Fit
Data
0
20
40
60
80
0
1000
2000
3000
4000

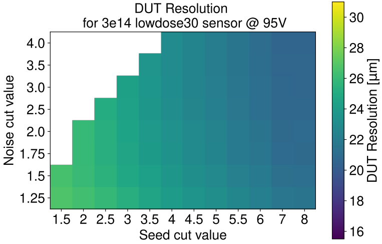

Resolution in X
rmsxvsxmym
Entries 13356
Mean x −0.3184
Mean y −320.2
Std Dev x 21.71
Std Dev y 5101
in-pixel y_track [µm]
in-pixel x_track [µm]
MAD(Δx) [µm]

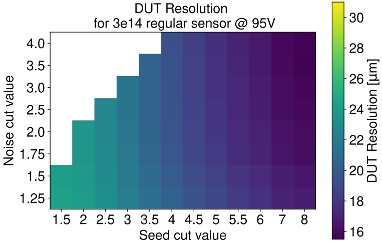

Resolution in X
rmsxvsxmym
Entries 11932
Mean x 0.07779
Mean y −363.9
Std Dev x 21.33
Std Dev y 5079
in-pixel y_track [µm]
in-pixel x_track [µm]
MAD(Δx) [µm]


Resolution in X
rmsxvsxmym
Entries 26307
Mean x −0.09062
Mean y −454.5
Std Dev x 20.79
Std Dev y 5143
in-pixel y_track [µm]
in-pixel x_track [µm]
MAD(Δx) [µm]

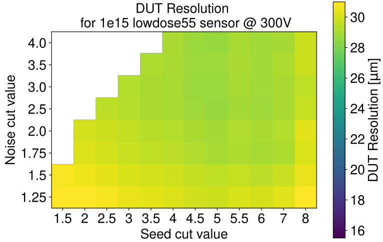
Backup


DUT Resolution
for 3e14 lowdose55 sensor @ 95V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
30
28
26
24
22
20
18
16
DUT Resolution [μm]

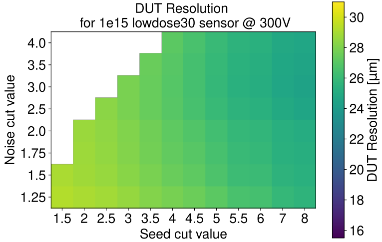

DUT Resolution
for 3e14 lowdose30 sensor @ 95V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
30
28
26
24
22
20
18
16
DUT Resolution [μm]


DUT Resolution
for 3e14 regular sensor @ 95V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
30
28
26
24
22
20
18
16
DUT Resolution [μm]

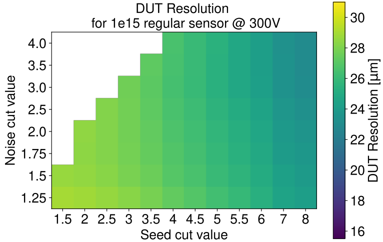
Backup



DUT Resolution
for 1e15 lowdose55 sensor @ 300V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
DUT Resolution [µm]
30 28 26 24 22 20 18 16

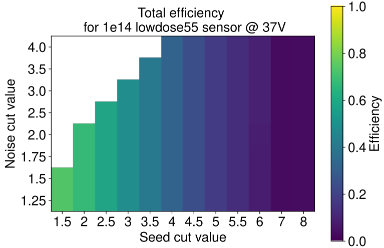


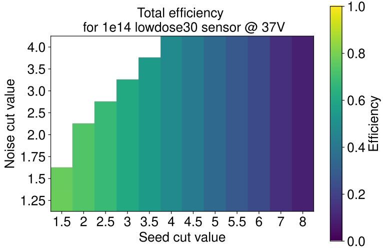
DUT Resolution
for 1e15 lowdose30 sensor @ 300V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
DUT Resolution [µm]
30 28 26 24 22 20 18 16

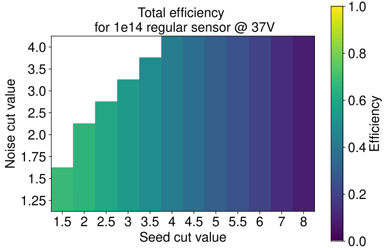


DUT Resolution
for 1e15 regular sensor @ 300V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
DUT Resolution [µm]
30 28 26 24 22 20 18 16

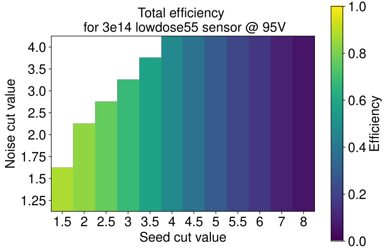
Backup

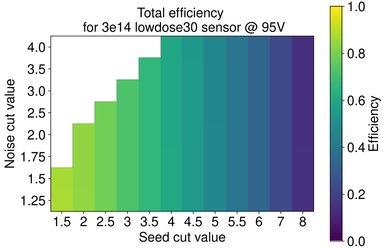

Total efficiency
for 1e14 lowdose55 sensor @ 37V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0

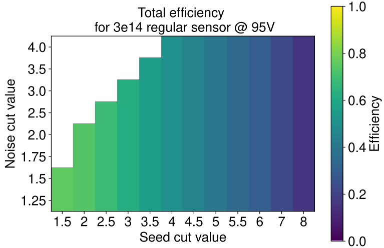

Total efficiency
for 1e14 lowdose30 sensor @ 37V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0


Total efficiency
for 1e14 regular sensor @ 37V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0

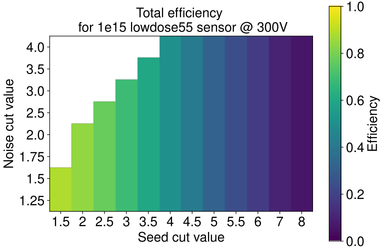
Backup

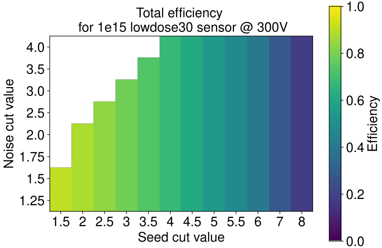

Total efficiency
for 3e14 lowdose55 sensor @ 95V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
Efficiency
0.0 0.2 0.4 0.6 0.8 1.0

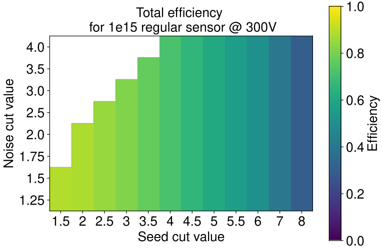

Total efficiency
for 3e14 lowdose30 sensor @ 95V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
Efficiency
0.0 0.2 0.4 0.6 0.8 1.0


Total efficiency
for 3e14 regular sensor @ 95V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
Efficiency
0.0 0.2 0.4 0.6 0.8 1.0

Backup


Total efficiency
for 1e15 lowdose55 sensor @ 300V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0


Total efficiency
for 1e15 lowdose30 sensor @ 300V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0


Total efficiency
for 1e15 regular sensor @ 300V
Noise cut value
4.0
3.5
3.0
2.5
2.0
1.75
1.5
1.25
1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 7 8
Seed cut value
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0