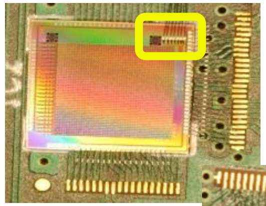
PSI Center for Photon Science

Optimising hybrid pixel detector sensor layout with 25 µm pitch for the radiation levels of 4th generation synchrotron light sources

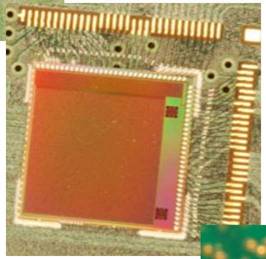
J. Heymes, R. Barten, F. Baruffaldi, A. Bergamaschi,
B. Braham, M. Brückner, M. Carulla Areste, R. Dinapoli,
S. Ebner, K. Ferjaoui, E. Fröjdh, D. Greiffenberg, S. Hasanaj,
V. Hinger, T. King, P. Kozłowski, C. Lopez-Cuenca, D. Mezza,
K. Moustakas, A. Mozzanica, K. A. Paton, C. Ruder, B. Schmitt,
P. Sieberer, D. Thattil, X. Xie, J. Zhang

25th iWoRiD, Lisbon (Portugal), 03 July 2024

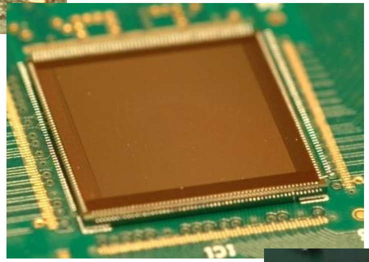
MÖNCH: Micropixel with enhanced pOsition rEsolution usiNg CHarge integration



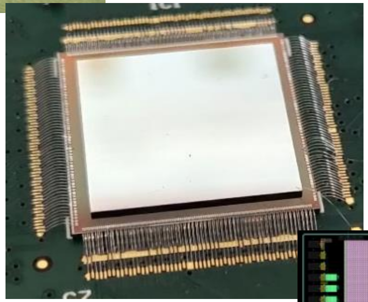
MÖNCH0.1
2012



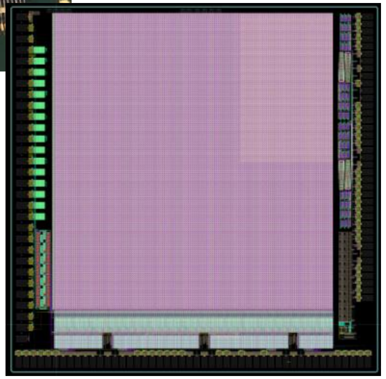
MÖNCH0.2
2012



MÖNCH0.3
2014



MÖNCH0.4
2018



MÖNCH0.5
2024

Charge integrating with analogue readout

Small pixel (25 µm pitch) → low noise, reduced dark current, high spatial resolution (with charge sharing), limited area

Designed in UMC 110 nm

Sensors: 300-320 µm thick n-type Si, LGADs, high-Z

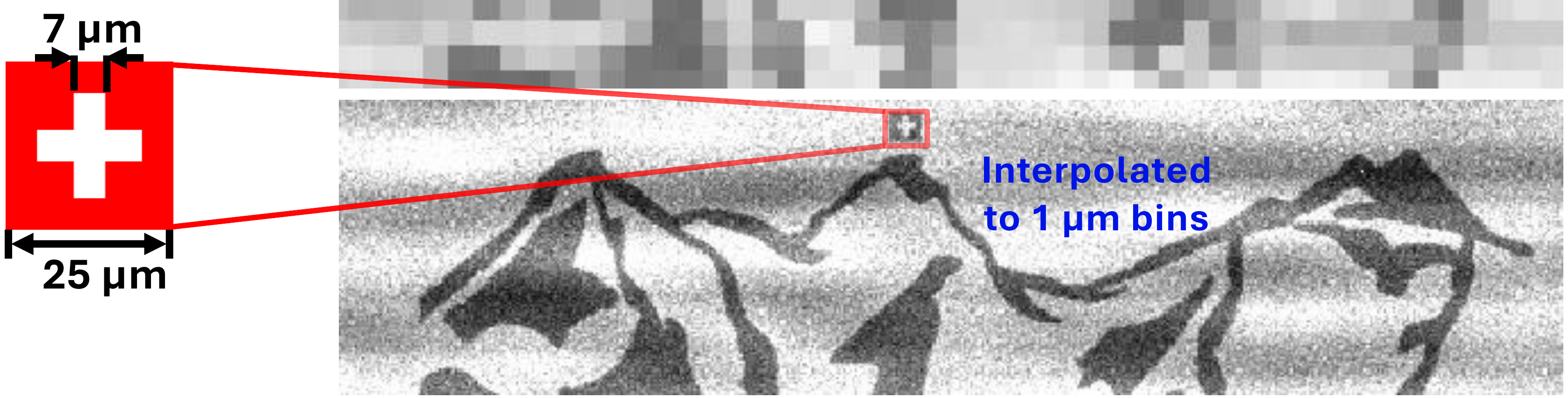
<u>Applications for MÖNCH</u>:

(In-vivo) tomography, Resonant Inelastic X-ray Scattering (RIXS), Fourier ptychography, High-resolution imaging, colour imaging, electron microscopy, (Laue diffraction), ...

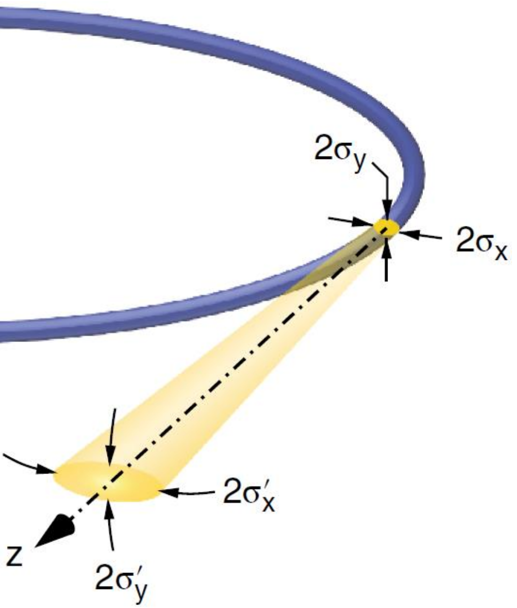
Interpolation with MÖNCH0.3

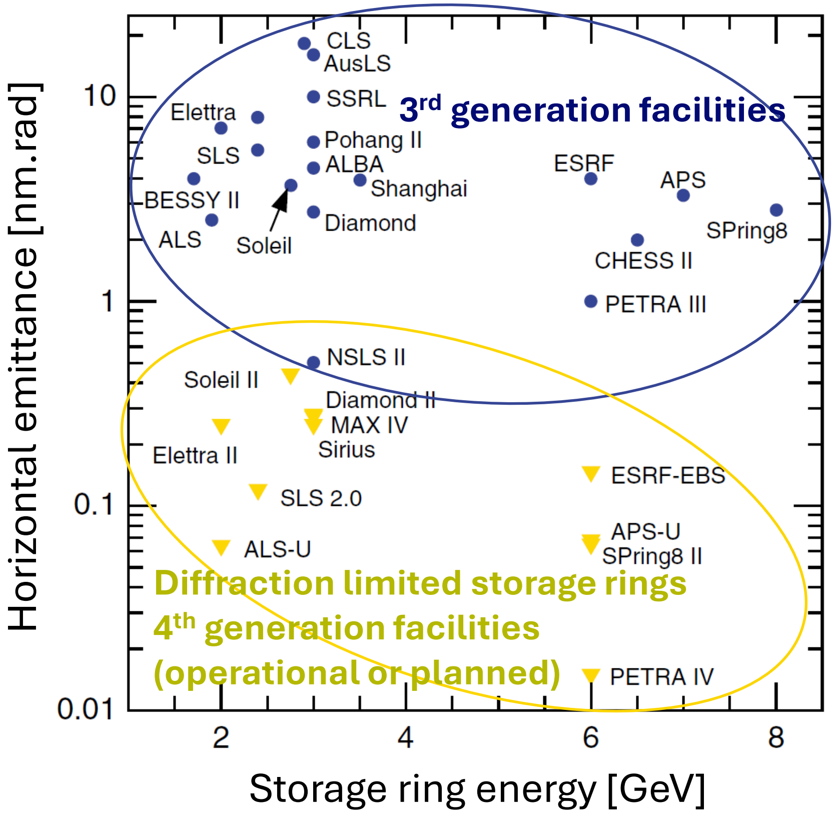
2 µm gold on 200 µm silicon sample fabricated at LXN, PSI

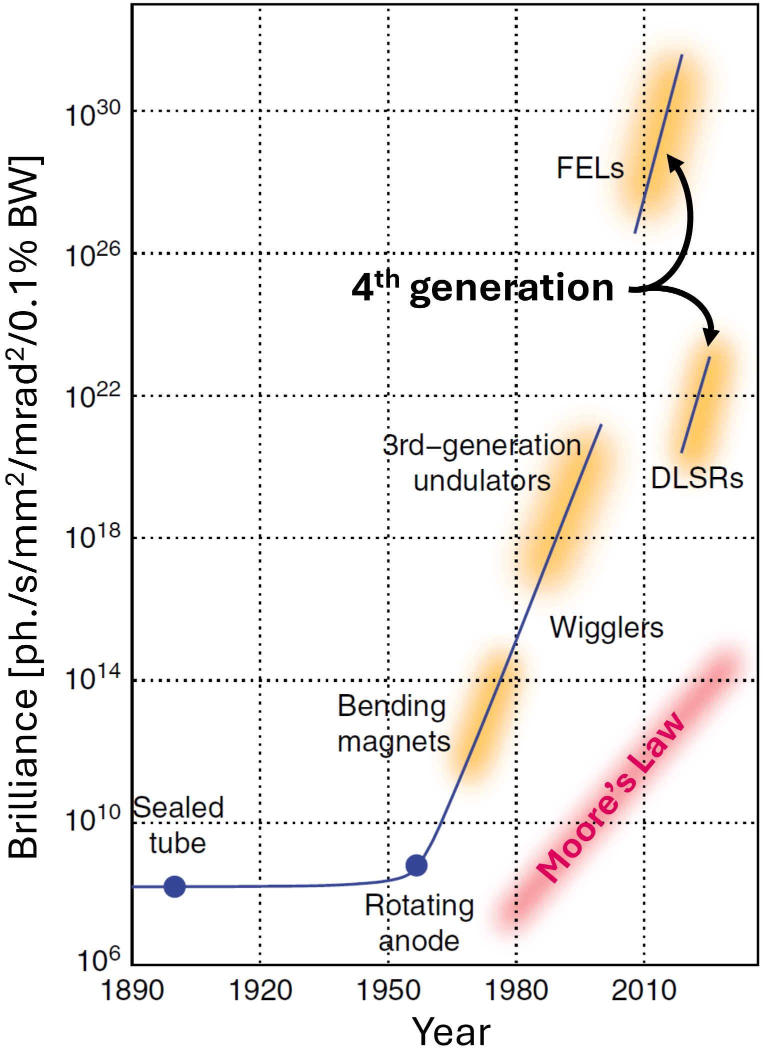
Measurement with 10 keV photons at TOMCAT
Low flux for single photon detection



Diffraction Limited Storage Rings
(4^{th} generation synchrotron light sources)

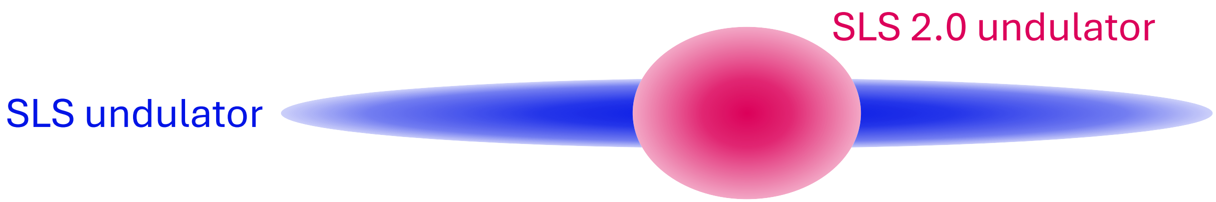






P. Willmott, An introduction to synchrotron radiation: techniques and applications, 2nd ed. Wiley, 2019, 540 p. https://doi.org/10.1002/9781119280453

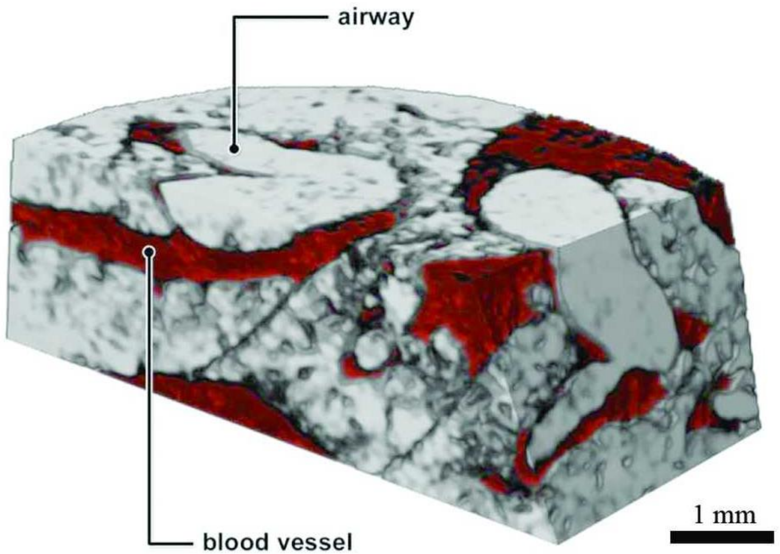
The upgraded Swiss Light Source: SLS 2.0



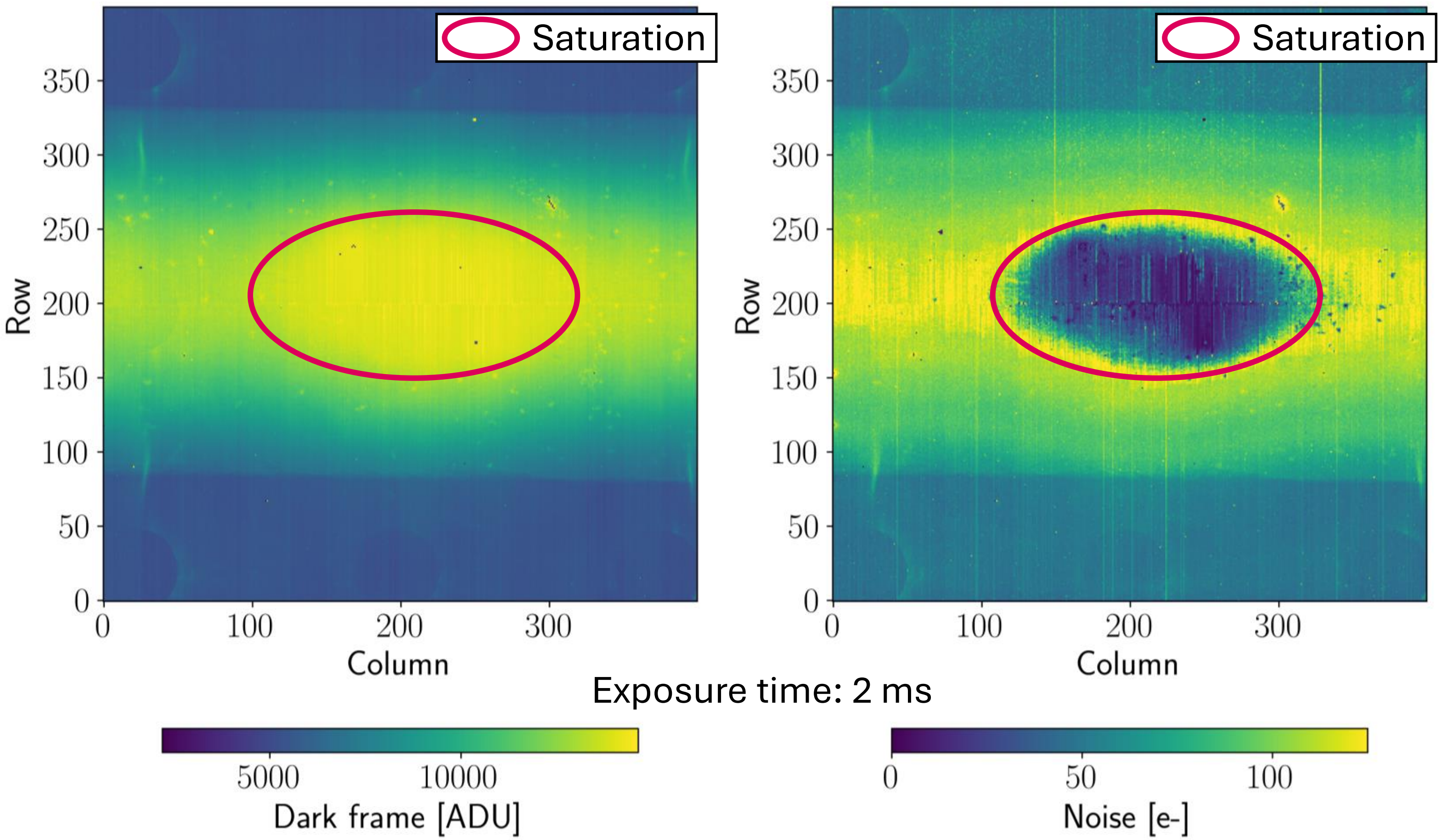
Brilliance up to x1000 at certain beamlines

Radiation damage of a MÖNCH0.3

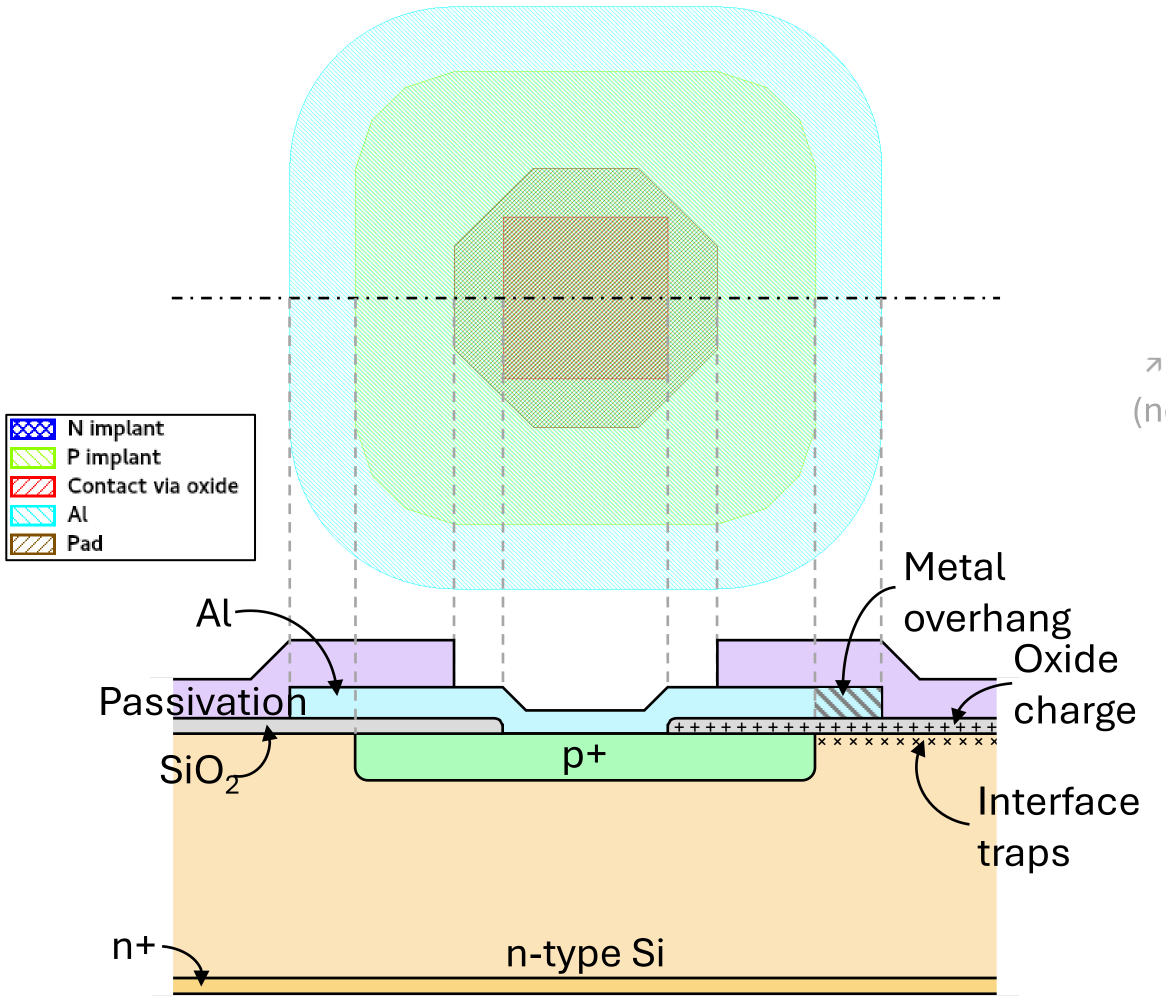
Dark frames at different exposure times showing radiation damage after two days of beam time for *in-situ* mouse lungs tomography. Conducted at the SYRMEP beamline of the Italian synchrotron light source, Elettra at 22 keV



Dullin C., *et al.*, MÖNCH detector enables fast and low-dose free-propagation phase-contrast computed tomography of in situ mouse lungs. J. Synchrotron Rad. 25, 565-569. 2018



The effects of irradiation on hybrid pixel sensors



Irradiation

Microscopic level

↗ Border traps (not discussed)

↗ Oxide charge

↗ Interface traps

Expected changes

Electron accumulation layer below the interface ➔ ↗ interpixel capacitance

Surface leakage current at the depleted interface

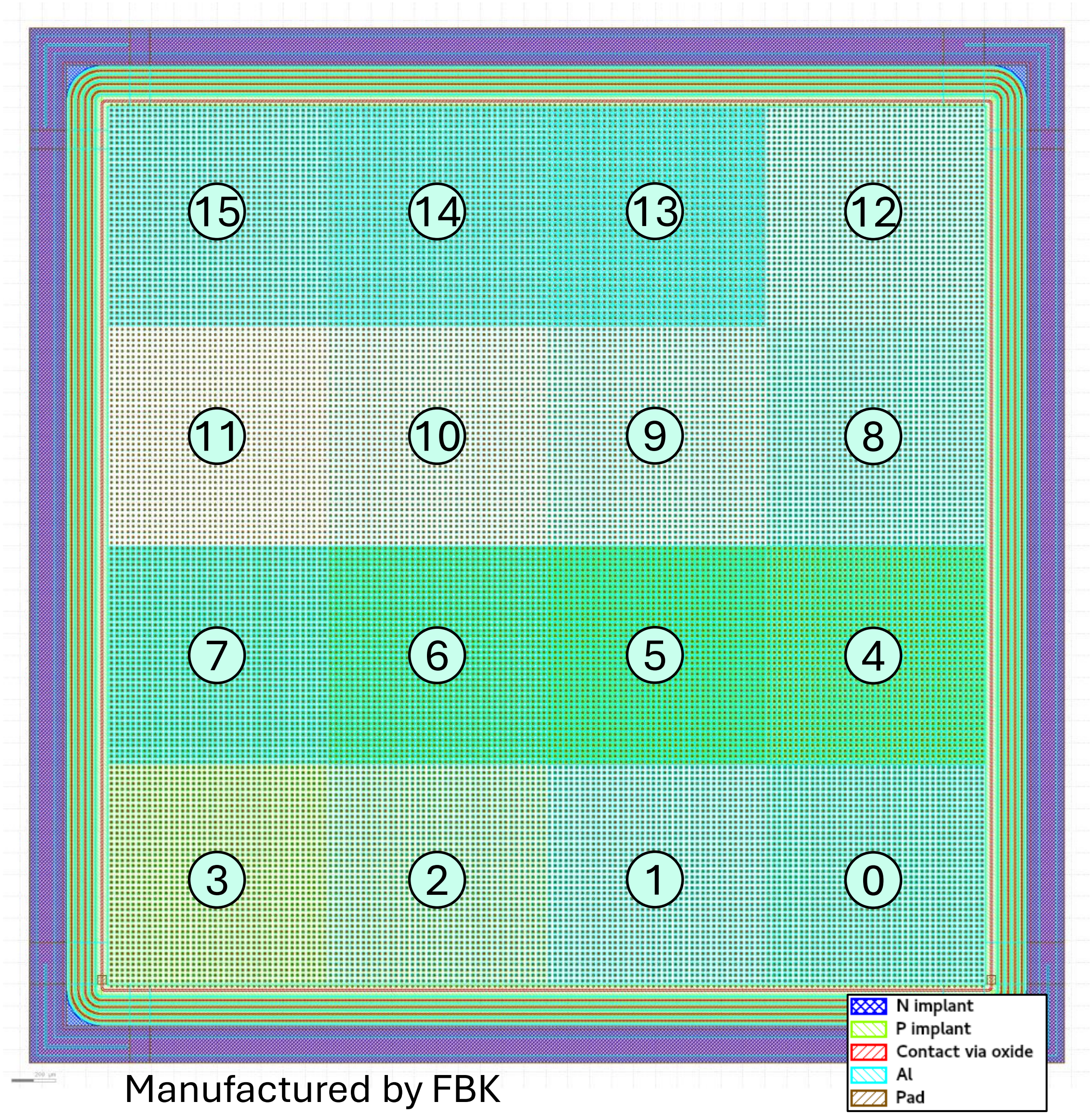
Layout strategies

Inter implant gap optimisation

Metal overhang sizing

Sensor designs for increased radiation hardness

PSI

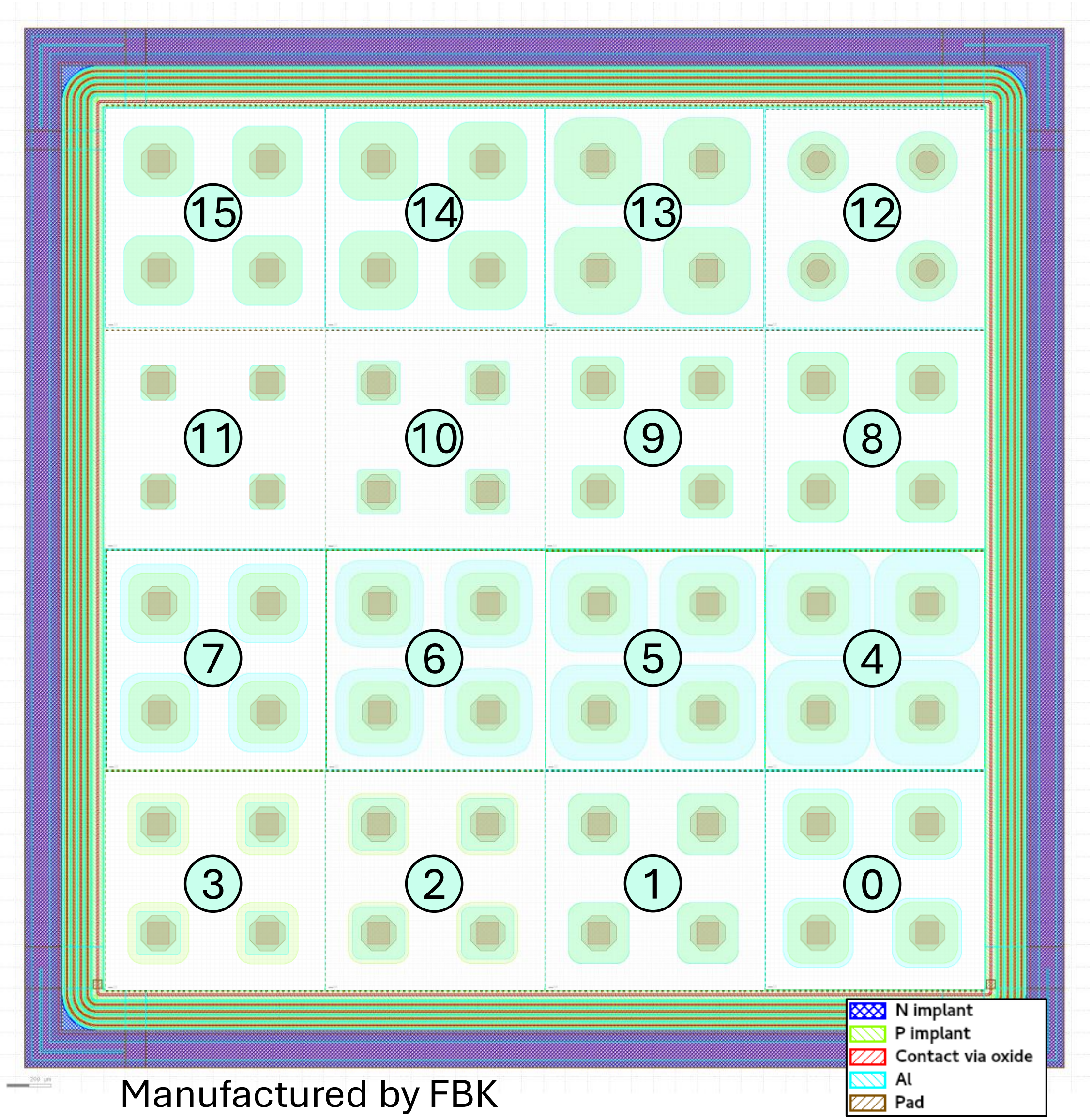


Manufactured by FBK

Variant	P+ Implant	Al	Contact	
0	M	L	M	
1	M	M	M	← Default size
2	M	S	M	← Metal < Implant
3	M	XS	M	
4	M	XXXXL	M	
5	M	XXXL	M	
6	M	XXL	M	← Metal > Implant
7	M	XL	M	
8	M	M	M	
9	S	S	M	
10	XS	XS	M	
11	XXS	XXS	M	} ← Metal = Implant Small capacitance
12	ROUND	ROUND	ROUND	
13	XXL	XXL	M	← Metal = Implant Largest implant
14	XL	XL	M	
15	L	L	M	

Implant > Metal, Metal = Implant, Metal > Implant

Sensor designs for increased radiation hardness



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0	M	L	M
1	M	M	M
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4	M	XXXXL	M
5	M	XXXL	M
6	M	XXL	M
7	M	XL	M
8	M	M	M
9	S	S	M
10	XS	XS	M
11	XXS	XXS	M
12	ROUND	ROUND	ROUND
13	XXL	XXL	M
14	XL	XL	M
15	L	L	M

← Default size (variant 1)

← Metal < Implant (variant 2)

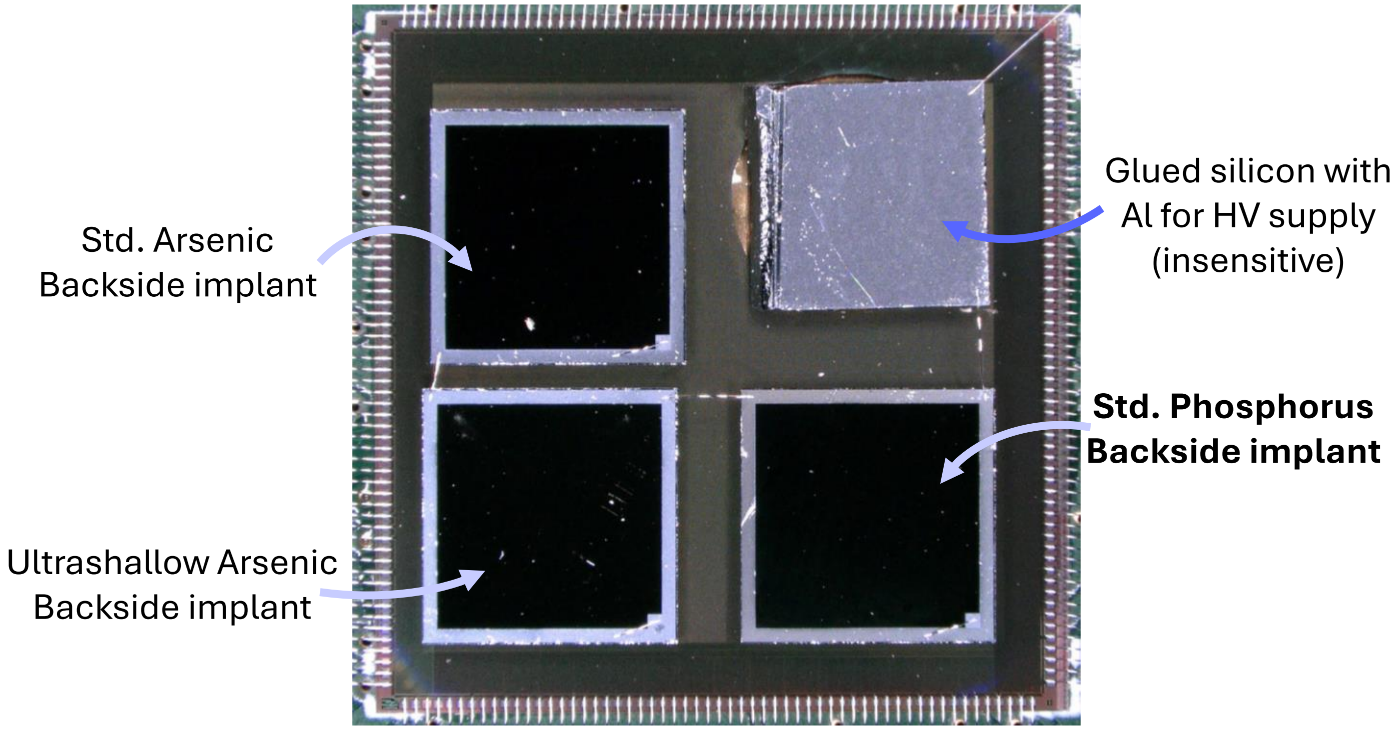
← Metal > Implant (variant 6)

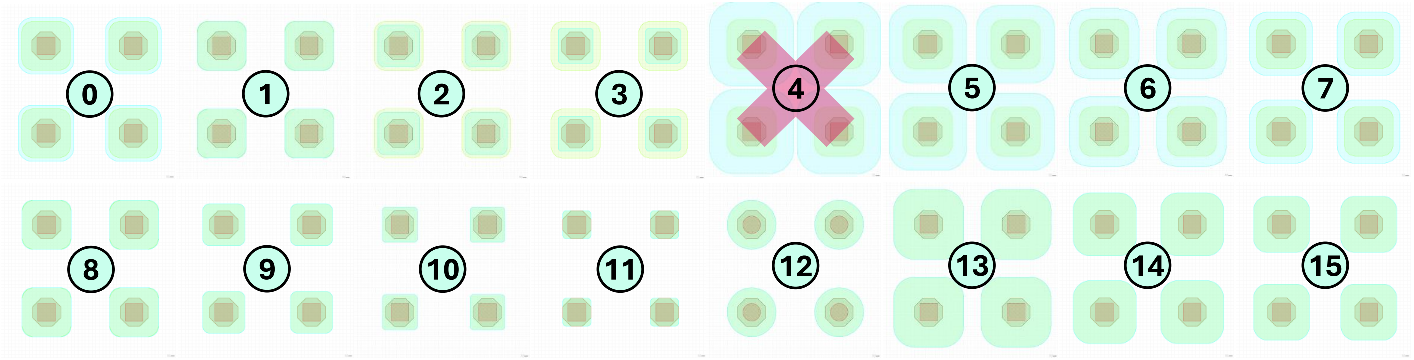
← Metal = Implant, Small capacitance (variants 11–12)

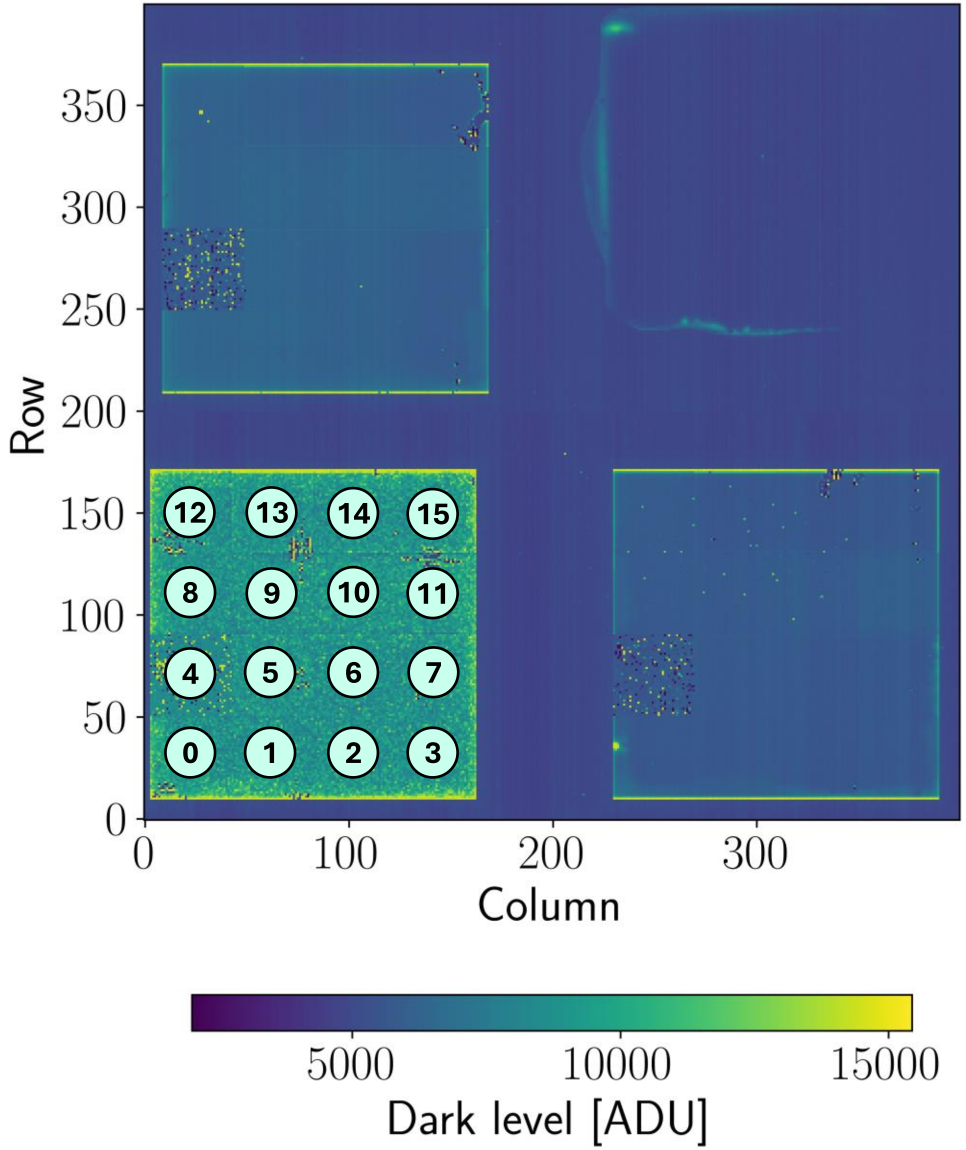
← Metal = Implant, Largest implant (variant 13)

Implant > Metal, Metal = Implant, Metal > Implant

Sensors bump bonded to MÖNCH0.3







Test and irradiation setup

X-ray tube with W anode, 40 kV, 40 mA
Distance to sensor: 12 cm

100 kGy/h
Mean energy @ sensor: 13.3 keV

Fluorescence

Direct beam

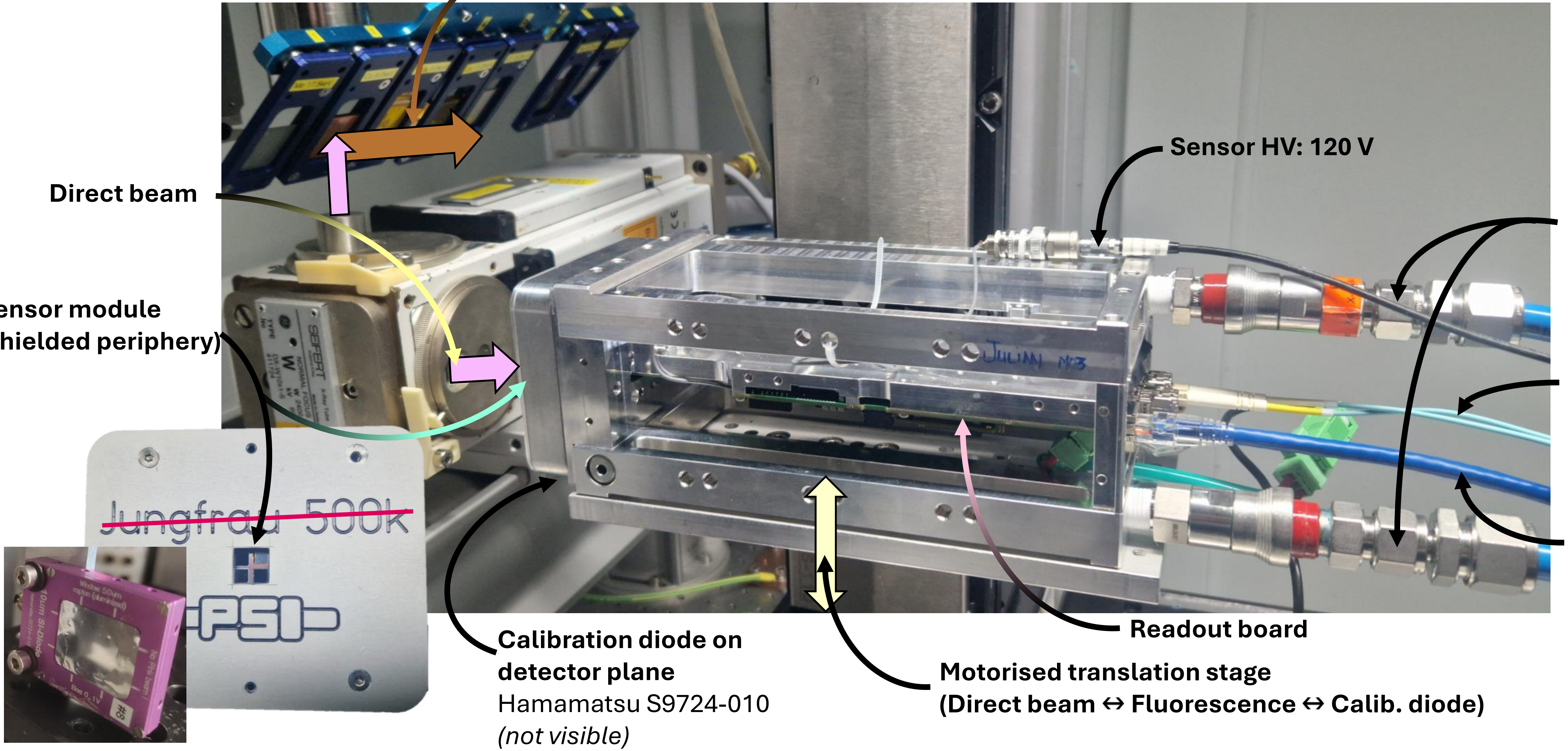
Sensor module (shielded periphery)

Sensor HV: 120 V

Cooling loop
$T_{coolant}$=18 °C
T_{sensor}≈27 °C

10G data transfer

1G control

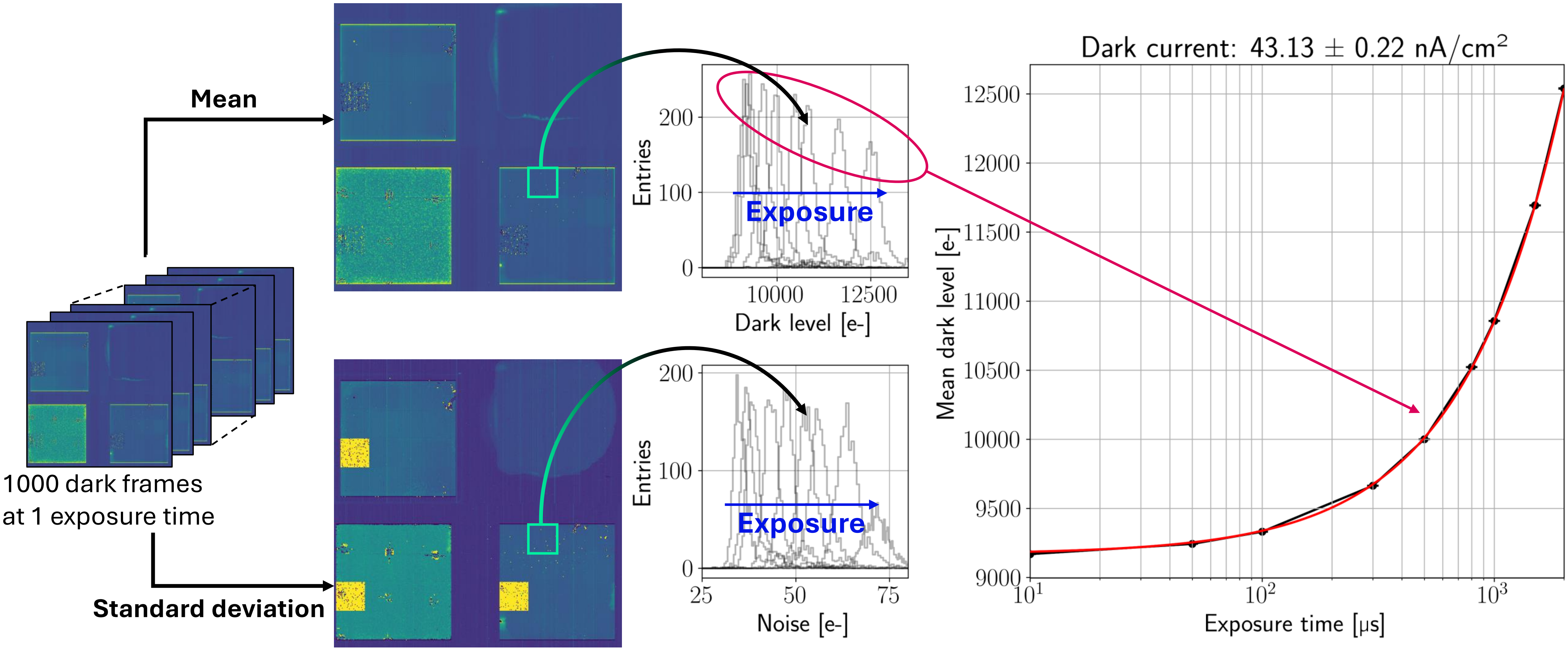


Calibration diode on detector plane
Hamamatsu S9724-010
(not visible)

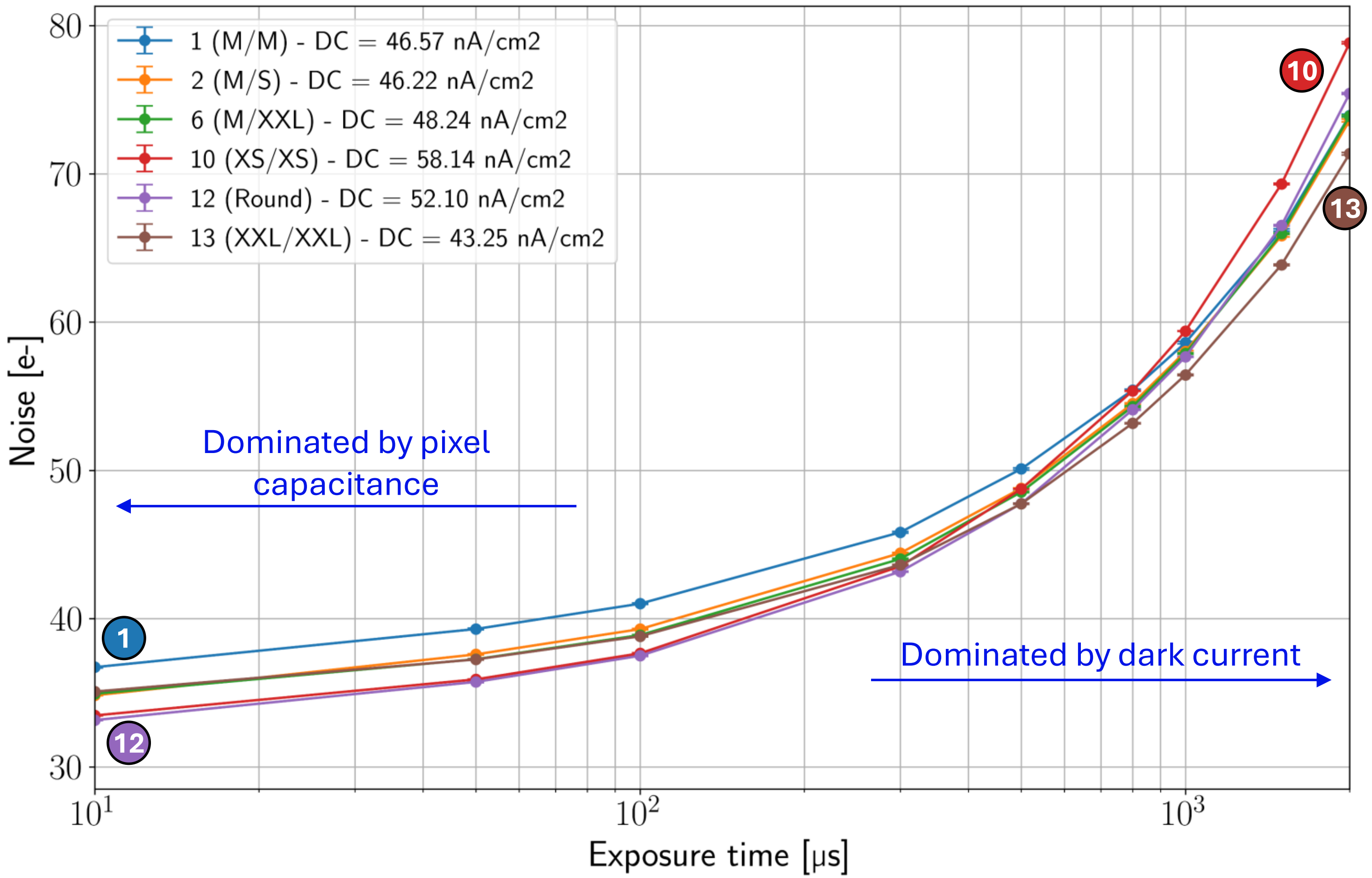
Readout board

Motorised translation stage
(Direct beam ↔ Fluorescence ↔ Calib. diode)

Noise and dark current extraction

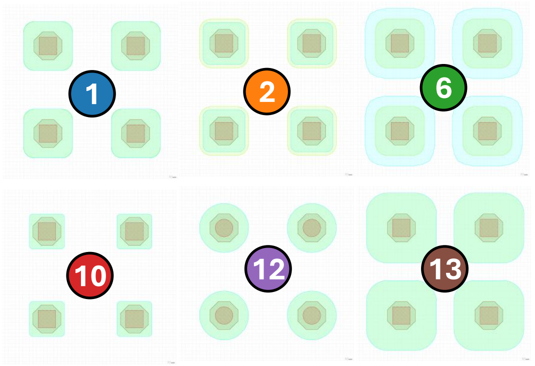


Pre-irradiation behaviour

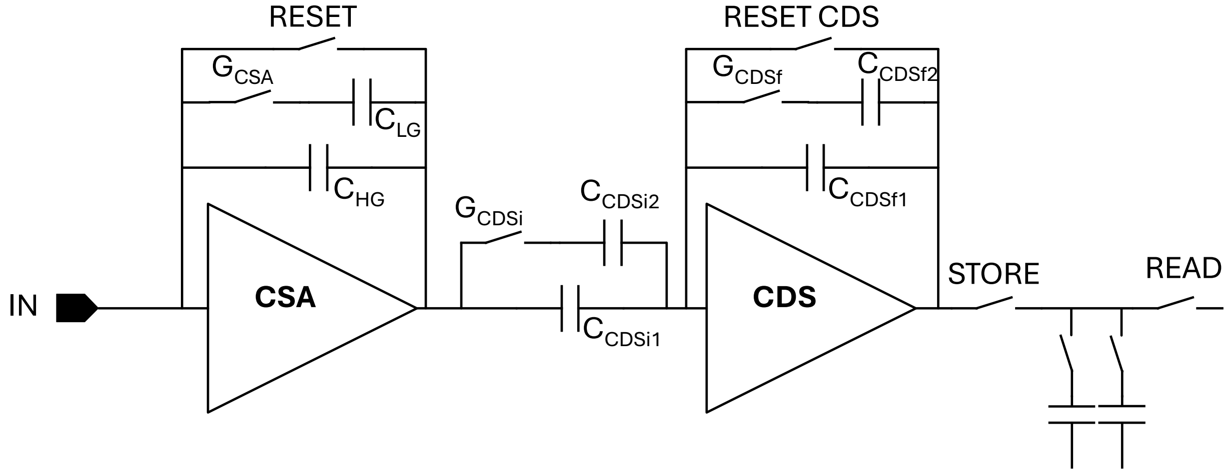


Std. Phosphorus backside implant

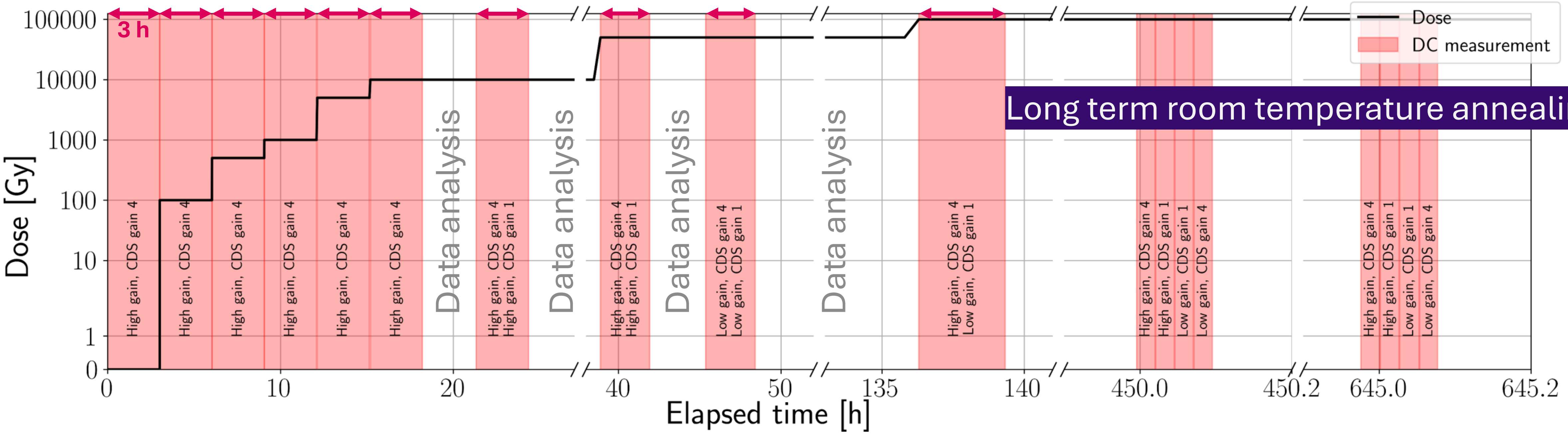
Variant	P+ Implant	Al
1	M	M
2	M	S
6	M	XXL
10	XS	XS
12	ROUND	ROUND
13	XXL	XXL



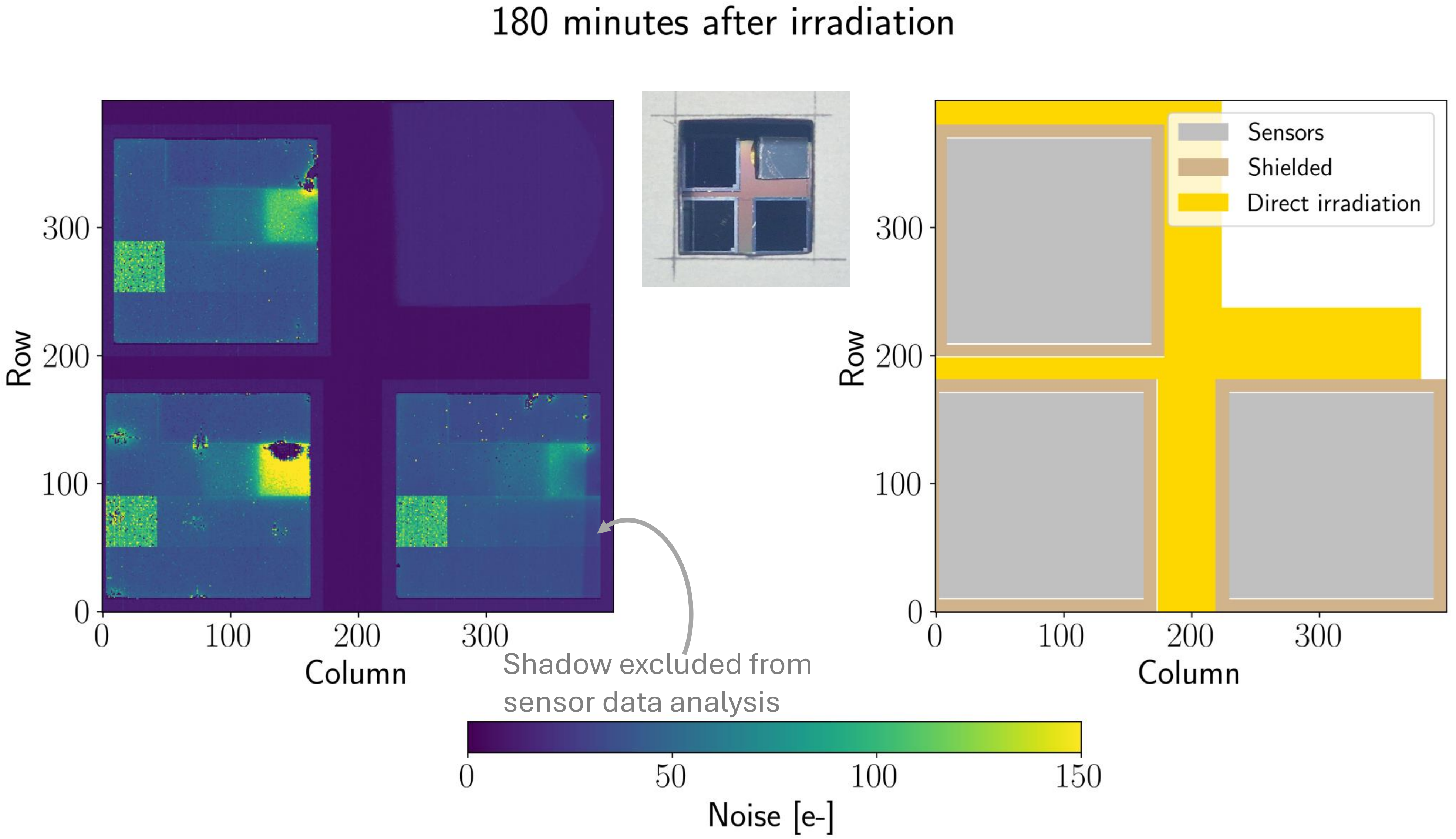
Irradiation plan and gain configurations



Gain	G_{CSA}	G_{CDSi}	G_{CDSf}
High gain, CDS gain 1	0	0	1
High gain, CDS gain 4	0	1	0
Low gain, CDS gain 1	1	0	1
Low gain, CDS gain 4	1	1	0



Noise map after 50 kGy with 5 µs exposure time



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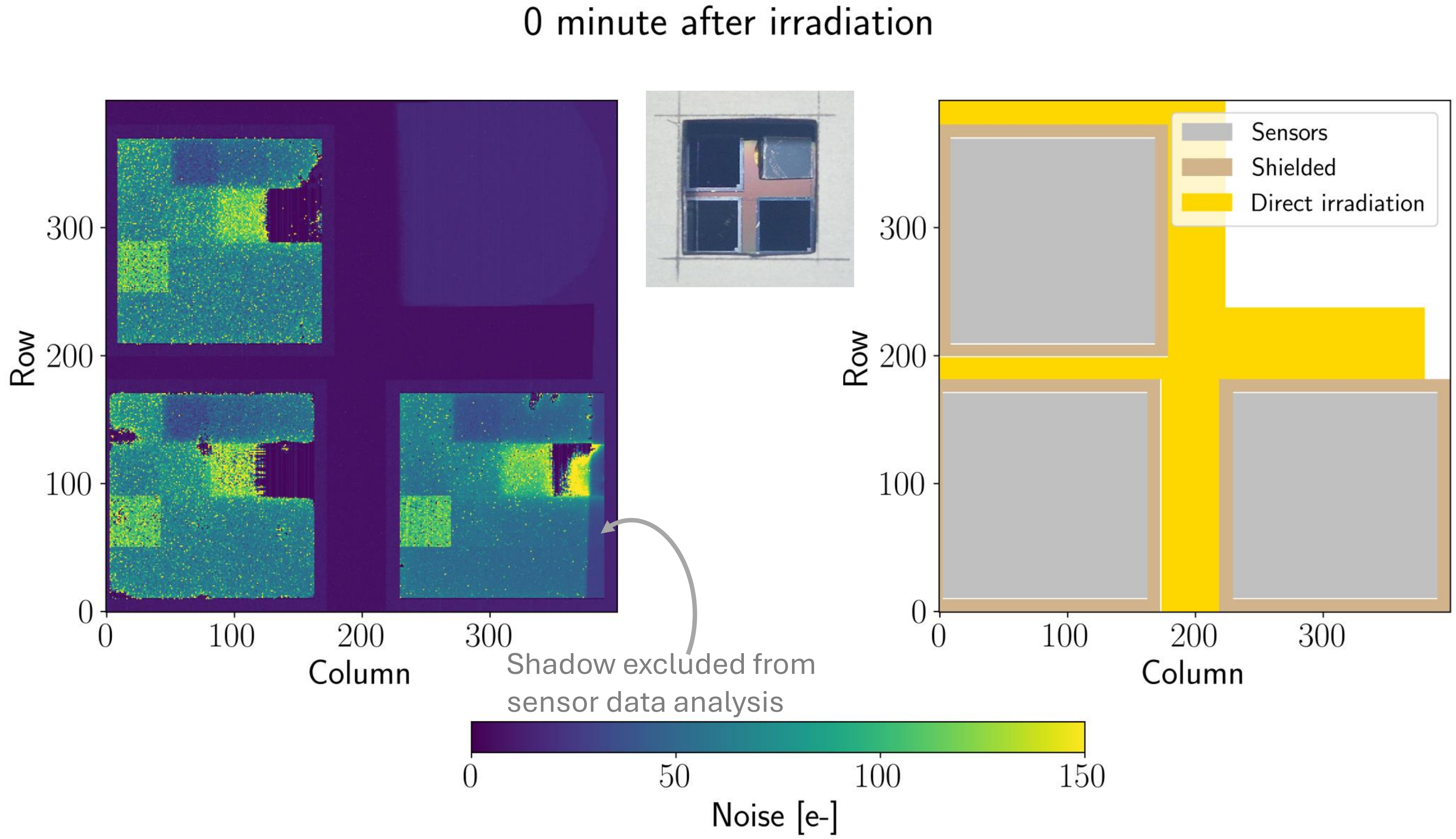
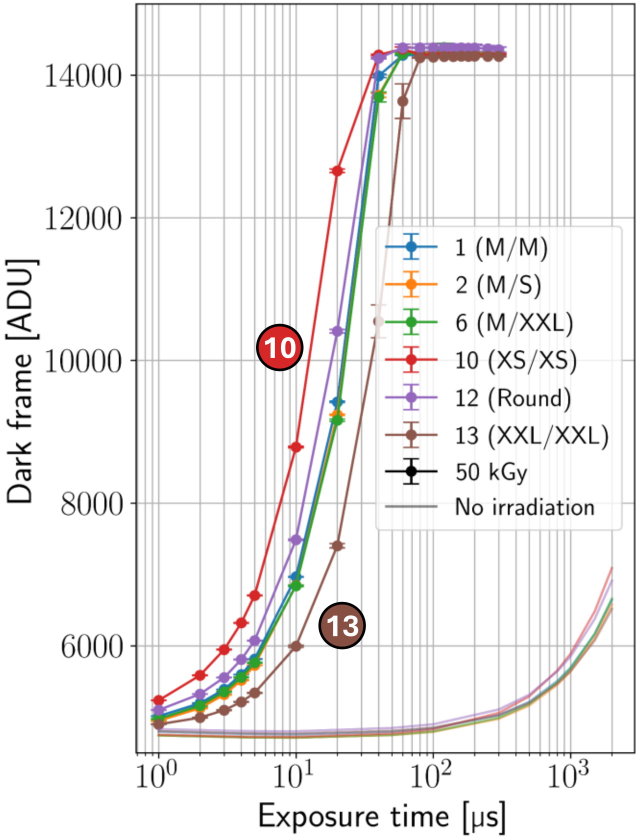
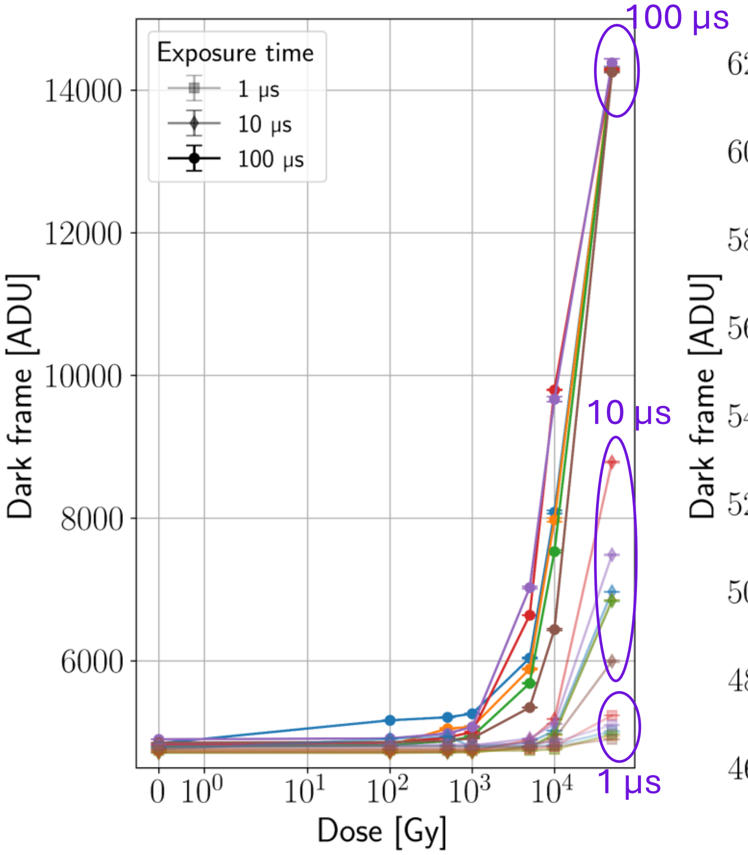
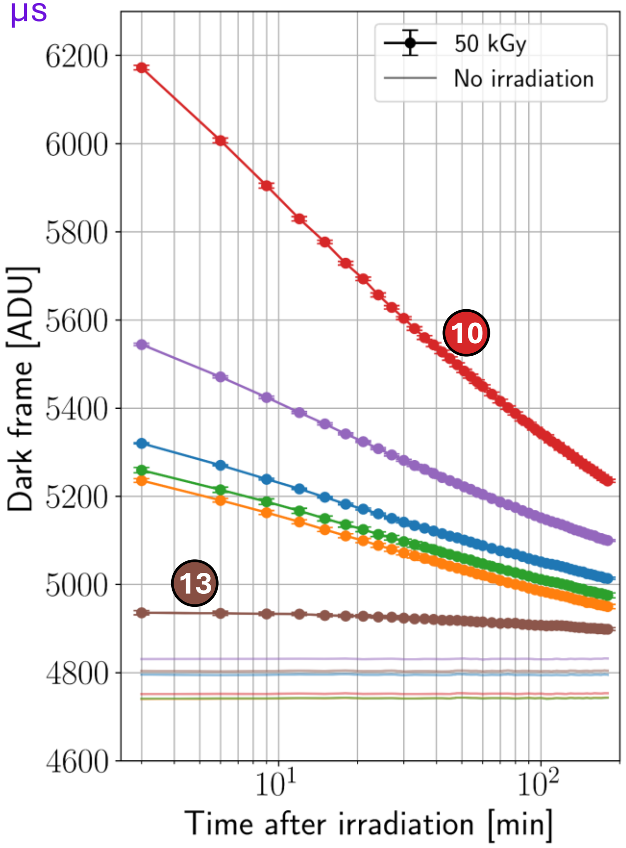


Effects of irradiation on the dark level







Std. Phosphorus backside implant

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6	M	XXL
10	XS	XS
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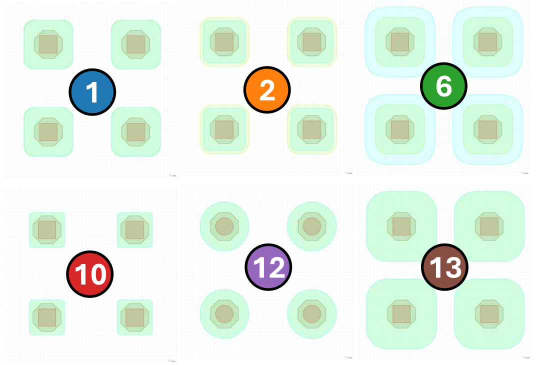
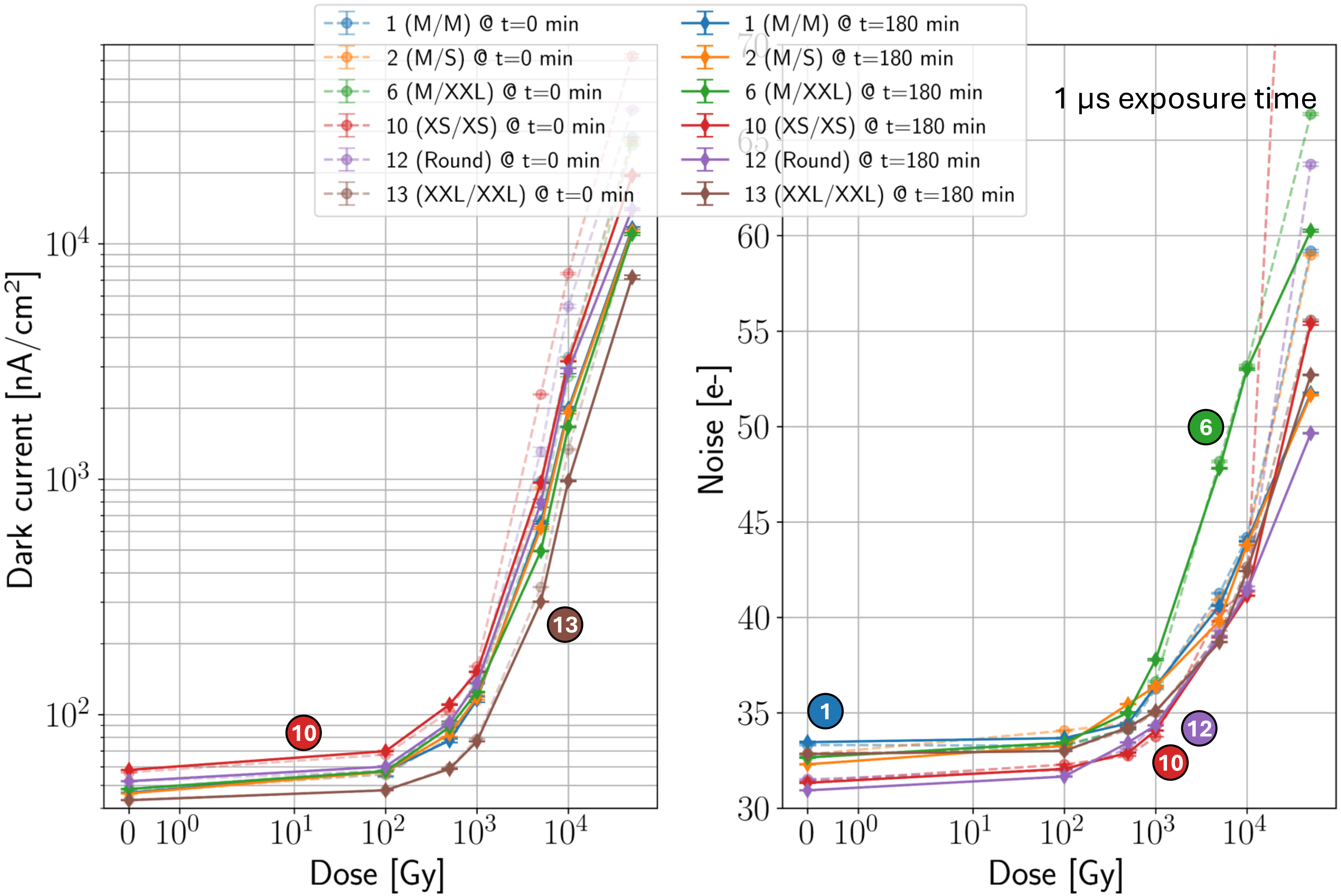
13	XXL	XXL



Dark current and noise vs. dose



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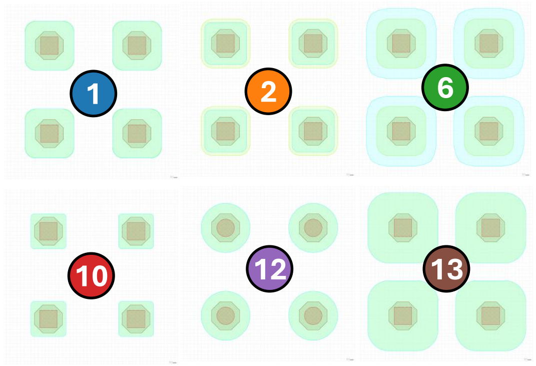
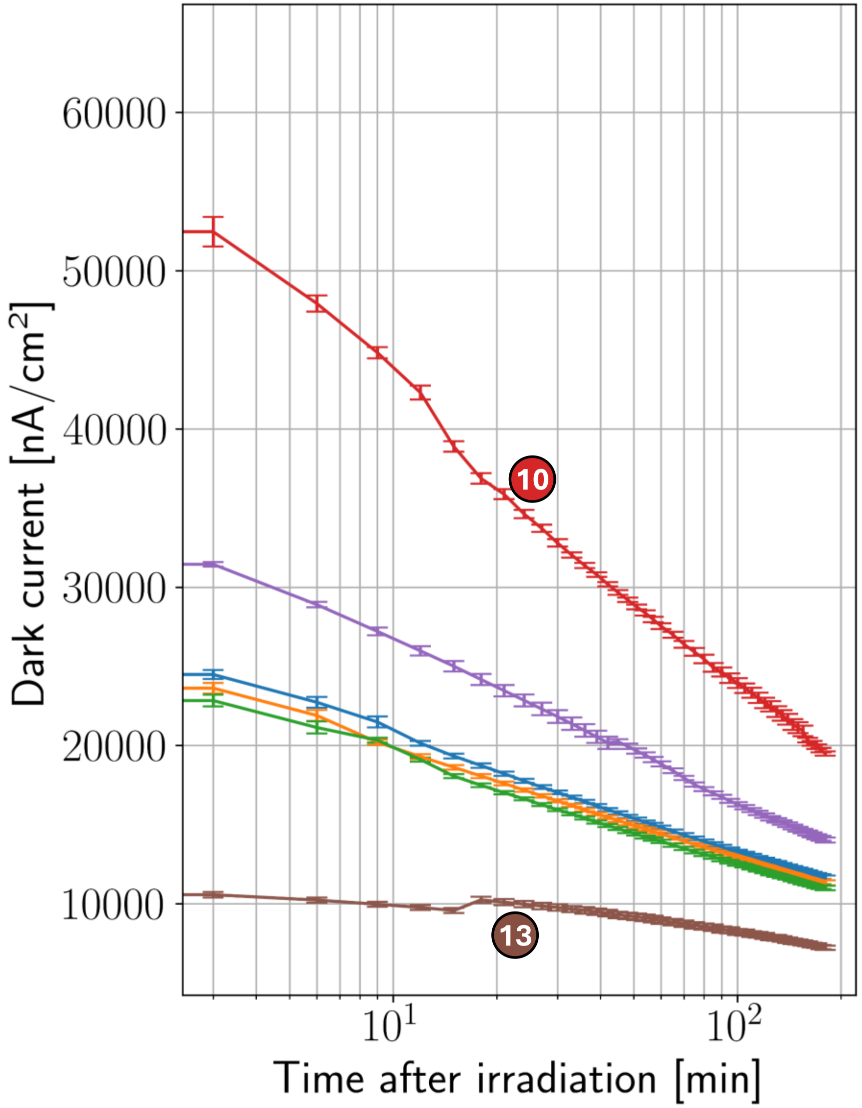
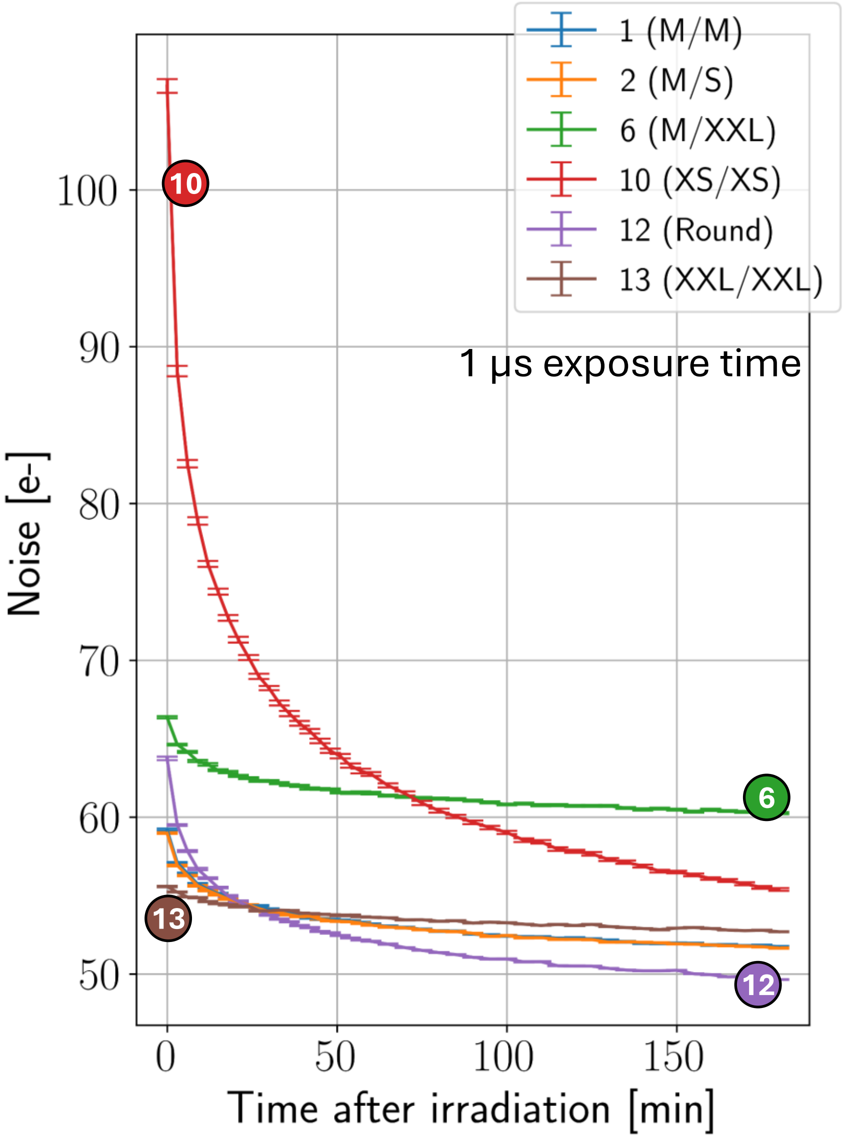


Short term annealing (180 min after 50 kGy)





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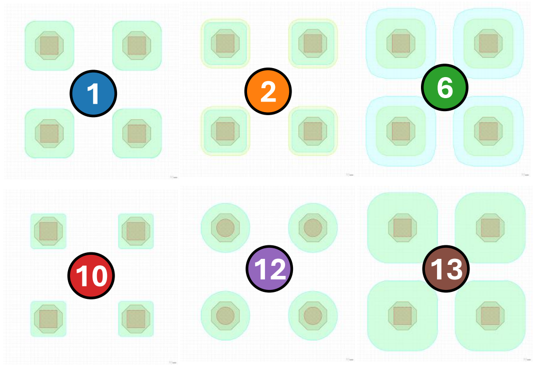
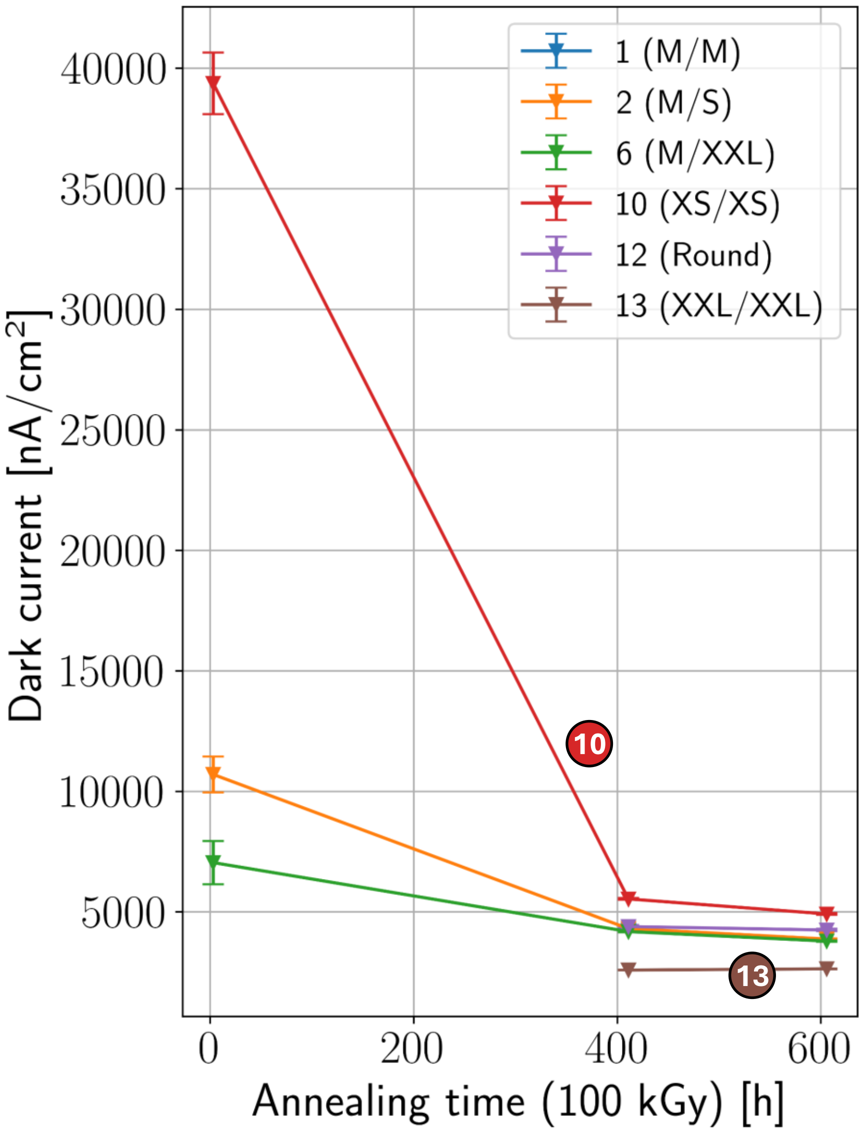
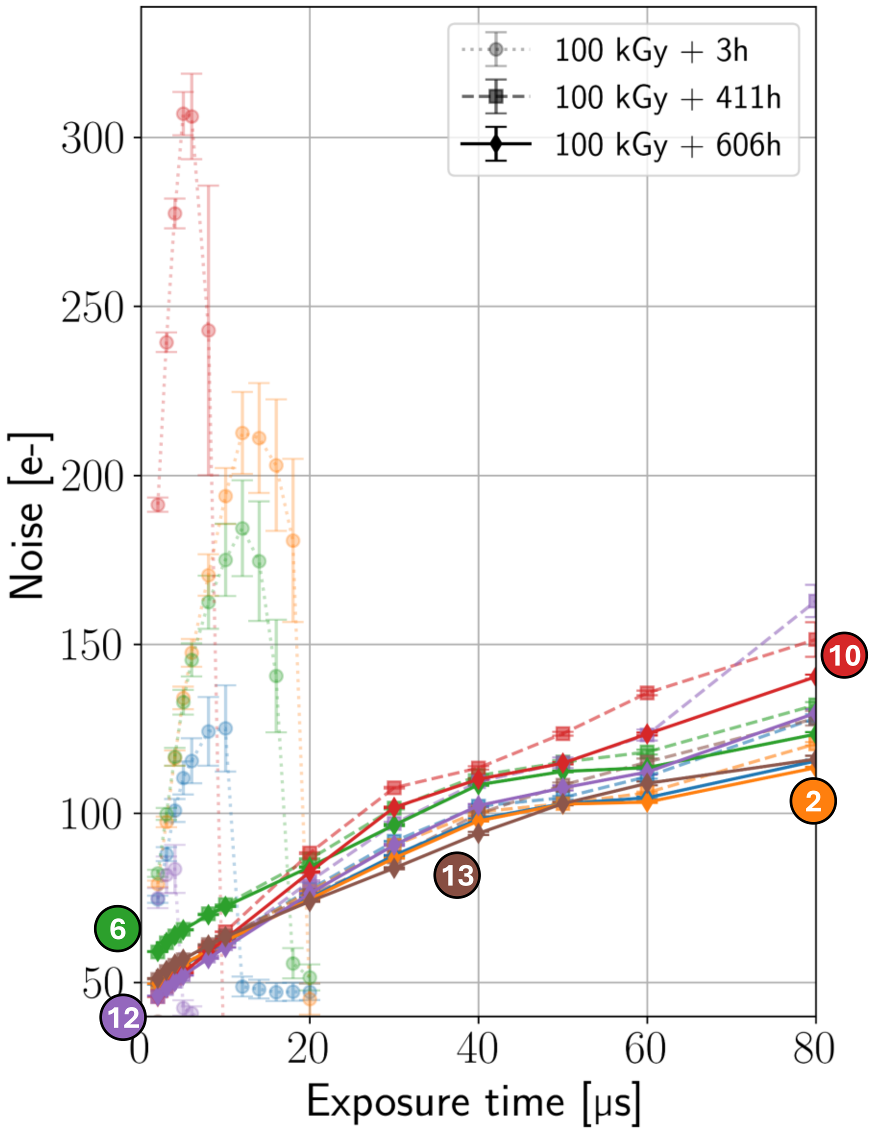


Long term room temperature annealing (100 kGy)





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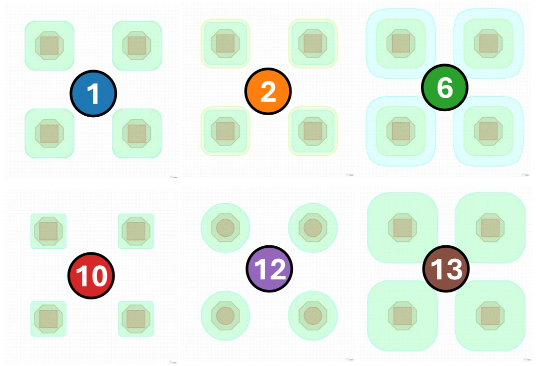
13	XXL	XXL



Conclusions and future work

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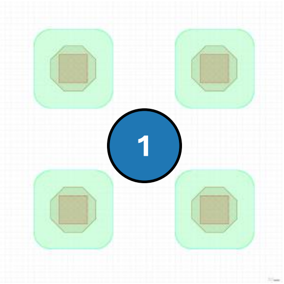
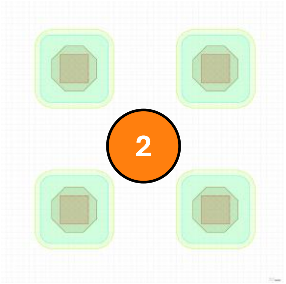


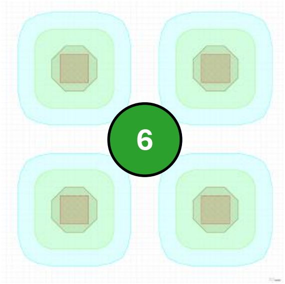
M/M
Default design



M/S
Low noise at high dose

Best after some annealing (interface traps) at longer exposures

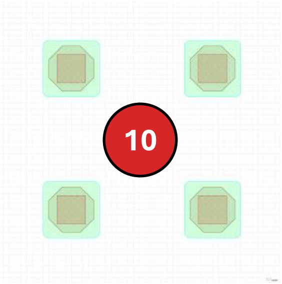
Could show the best noise at higher doses

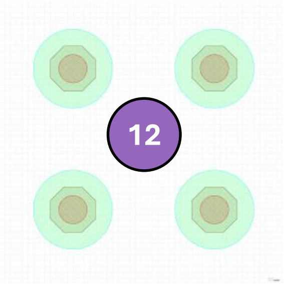


M/XXL
Average DC

Worst noise after irradiation due to interface traps

No significant improvement after annealing



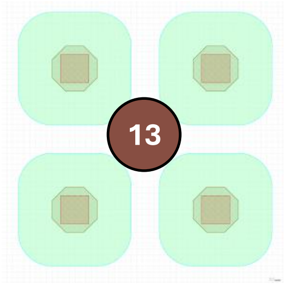


XS/XS **Round/Round**

Best noise at short exposures and before irradiation (low capacitance)

Highest DC at long exposures and after irradiation (large surface leakage current)

Signs of large noise increase at high doses with fast recovery after annealing



XXL/XXL
Significantly best DC after irradiation (oxide charge)

Good noise after irradiation at longer exposure times

Stable operation with time after irradiation

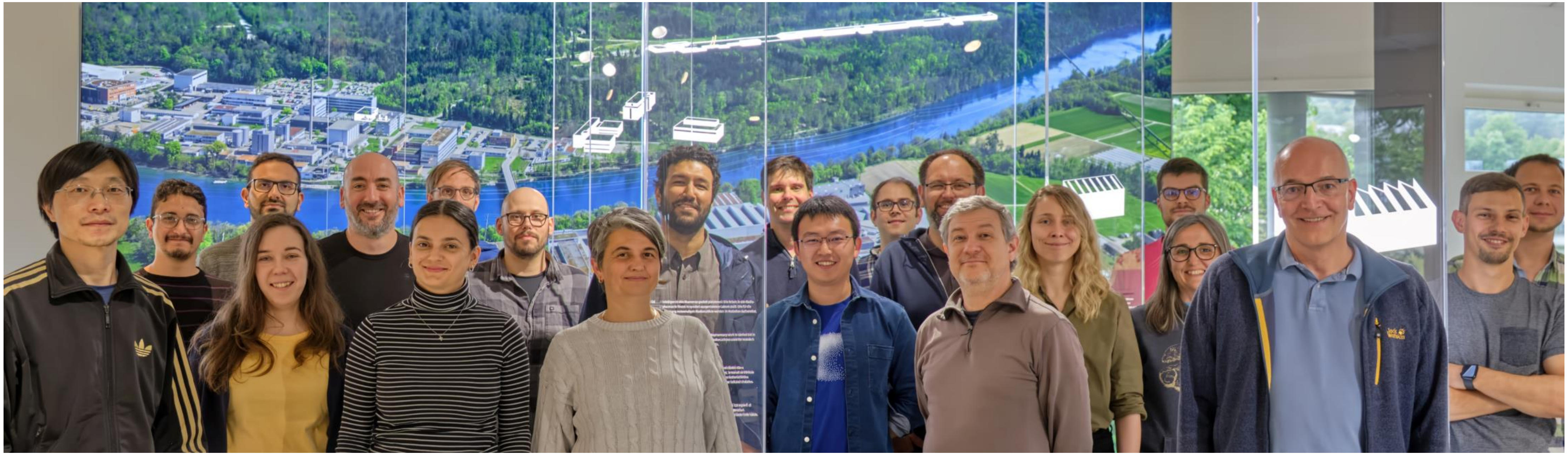
- Irradiation at a lower and more realistic dose rate could be performed (would require new assembly)
- Measurements of the annealing dynamics at higher temperatures (e.g. 60-80 °C)

- How would a large diode with smaller metal design perform?
- Further improvements with X-ray tailored process modifications

PSI Center for Photon Science

Postdoctoral Fellow
Sensor development for soft X-rays

Postdoctoral Fellow
Chip Design



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Missing: E. Fröjdh, A. Mozzanica, R. Barten, S. Ebner, D. Mezza, D. Thattil

Dose rate evaluation of the direct beam (spekpy)