RESULTS BASED ON 1D AND 2D ARRAYS AT IPHC STRASBOURG

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19.11.2024

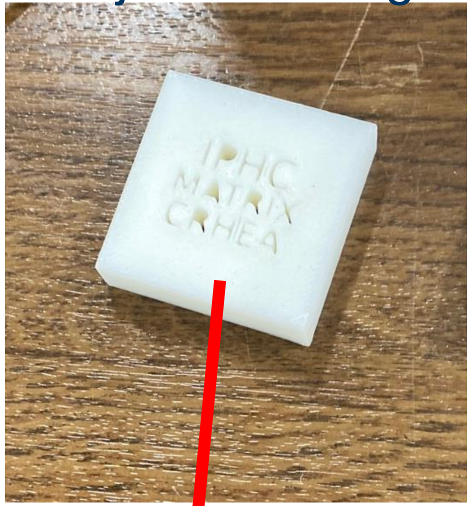
Schedule (I‘ll leave room for discussion after each block)

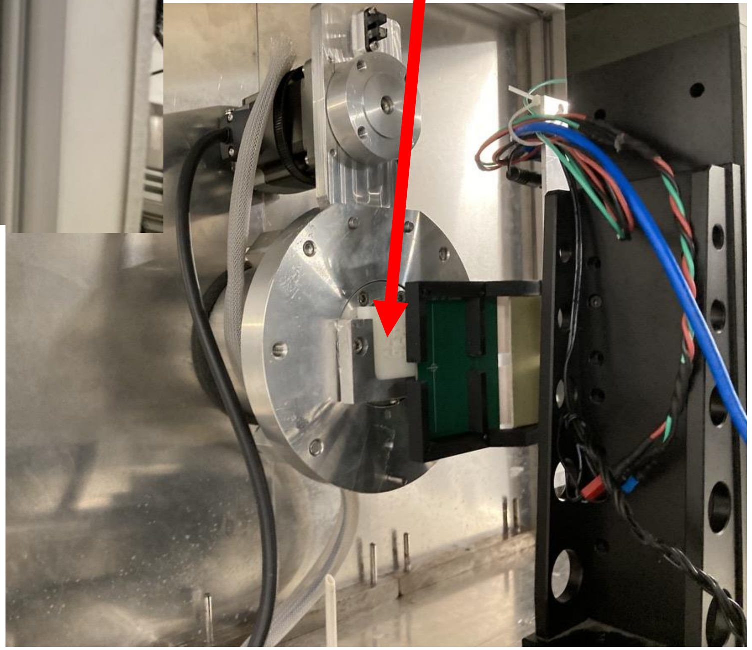
- **Short Reminder: How we measure at Cyrcé**
- **Reminder: First arrays measured at Cyrcé (partially shown at Lacassagne meeting)**
- **Comparison: Difference between bonding fanout on GaN and direct bonding**
- **Results: Voltage of AMS readout circuit + Linearity checks**
- **Results: Homogeneity of array response**
- **Some details of the image generation**
- **Results: Imaging with different arrays**
- **Results: Imaging in time dependence (creating movies of the beam)**
- **Results: Signal in dependence of the proton energy**
- **Results: Comparison with Gafchromic scans**
- **Outlook: What results I haven‘t shown / What‘s to come**

Reminder Setup at Cyrcé

- Protons with ≈ 24 MeV
- Usual current ≈ 2 nA
- GaN arrays on XY-translation stage
- Optional: Diffuser in proton beam line (homogenize beam)
- Diodes read out by AMS Test Kit
- We do not vary the beam any longer (as done at the first measurements with 1 s pulses)
- We usually integrate for 3 s

Objects to image

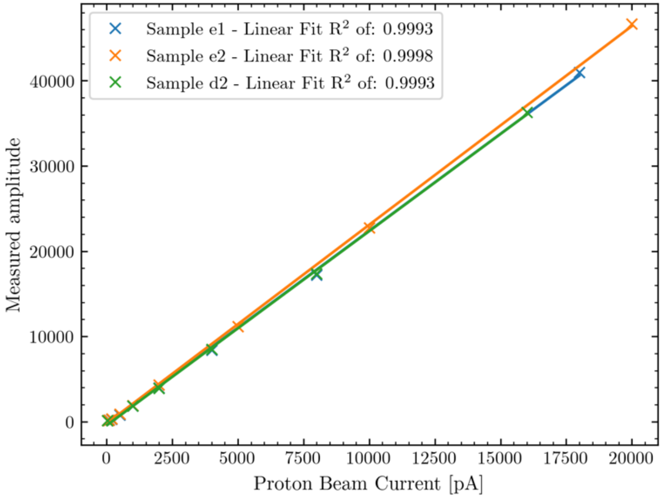




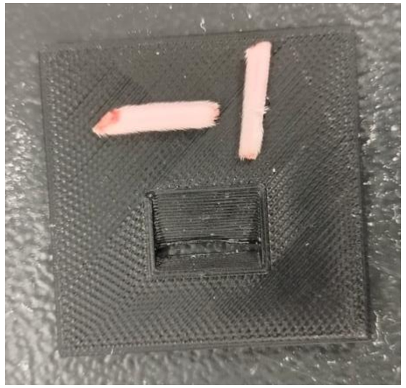
Aftwerwards: Data processing and image generation (code written by me)

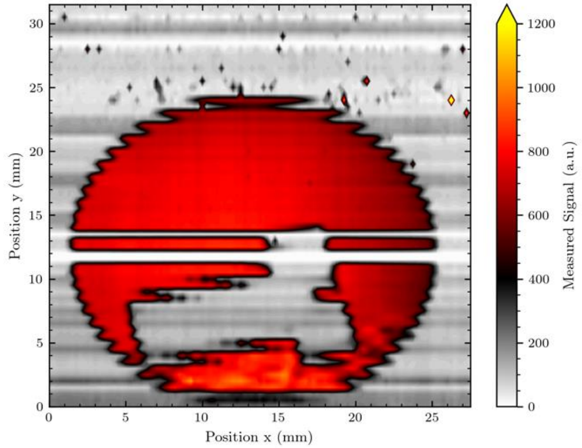
Results until June this year

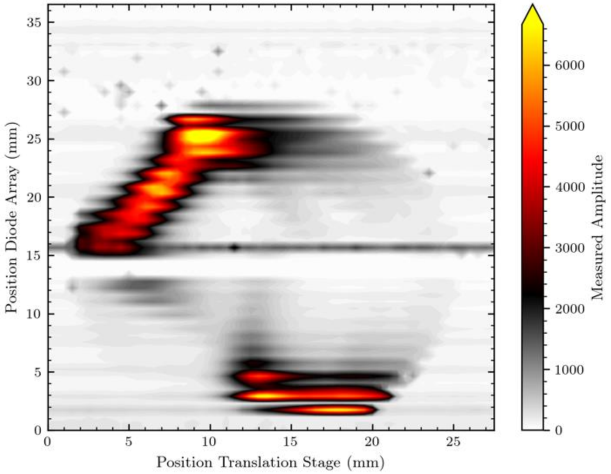
Excellent Linearity

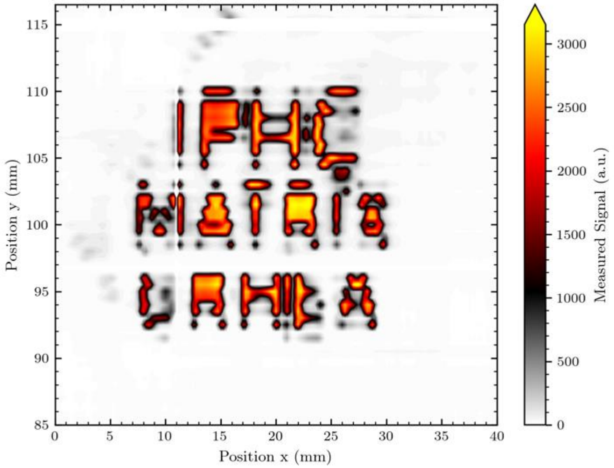


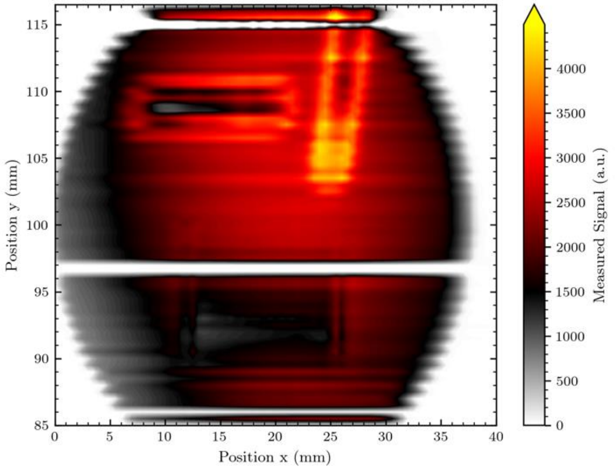
We can resolve the energy of protons (and thus biological objects)







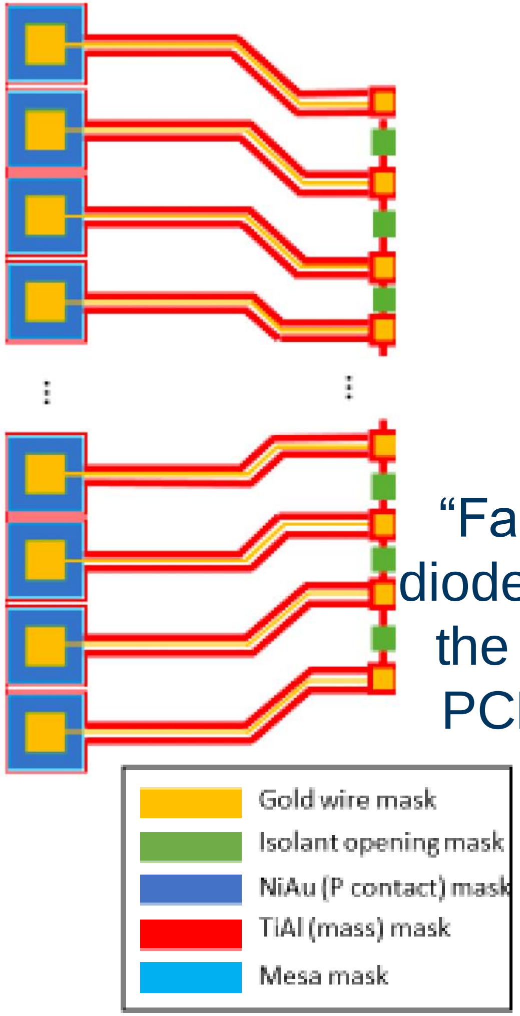




Ability to image objects (or the undiffused beam)

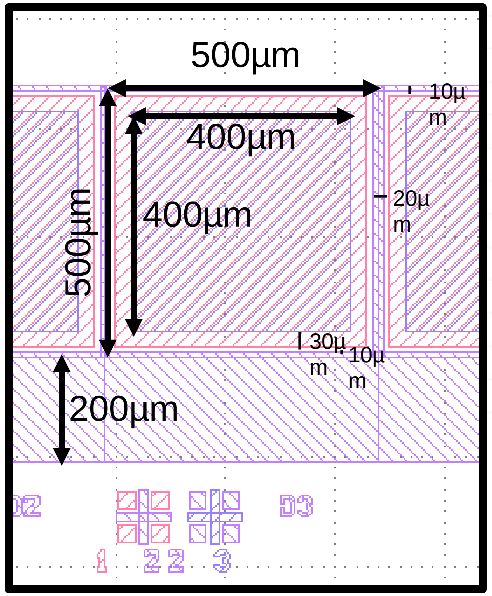
Difference in array design afterwards

Previous 64 diode arrays

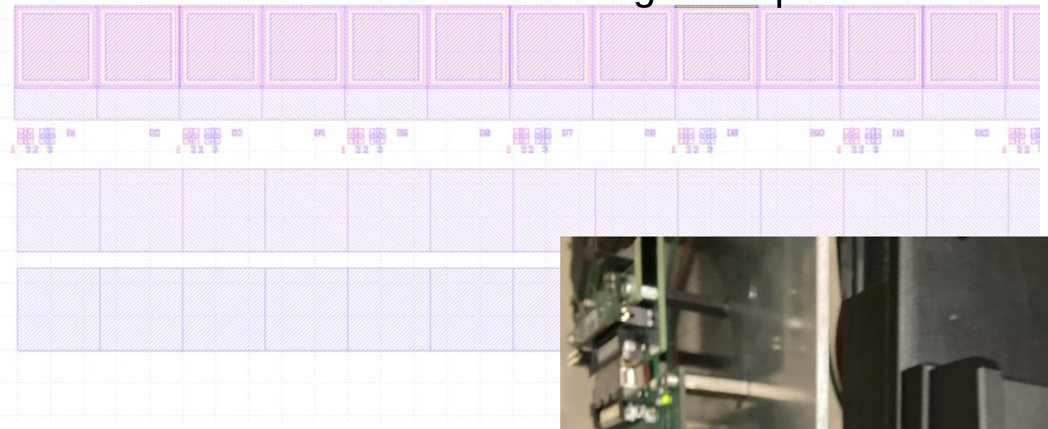


“Fan out” from diode contacts on the GaN wafer PCB card and diode

SINGLE DIODE



Maximum total length 500µmx140=7cm

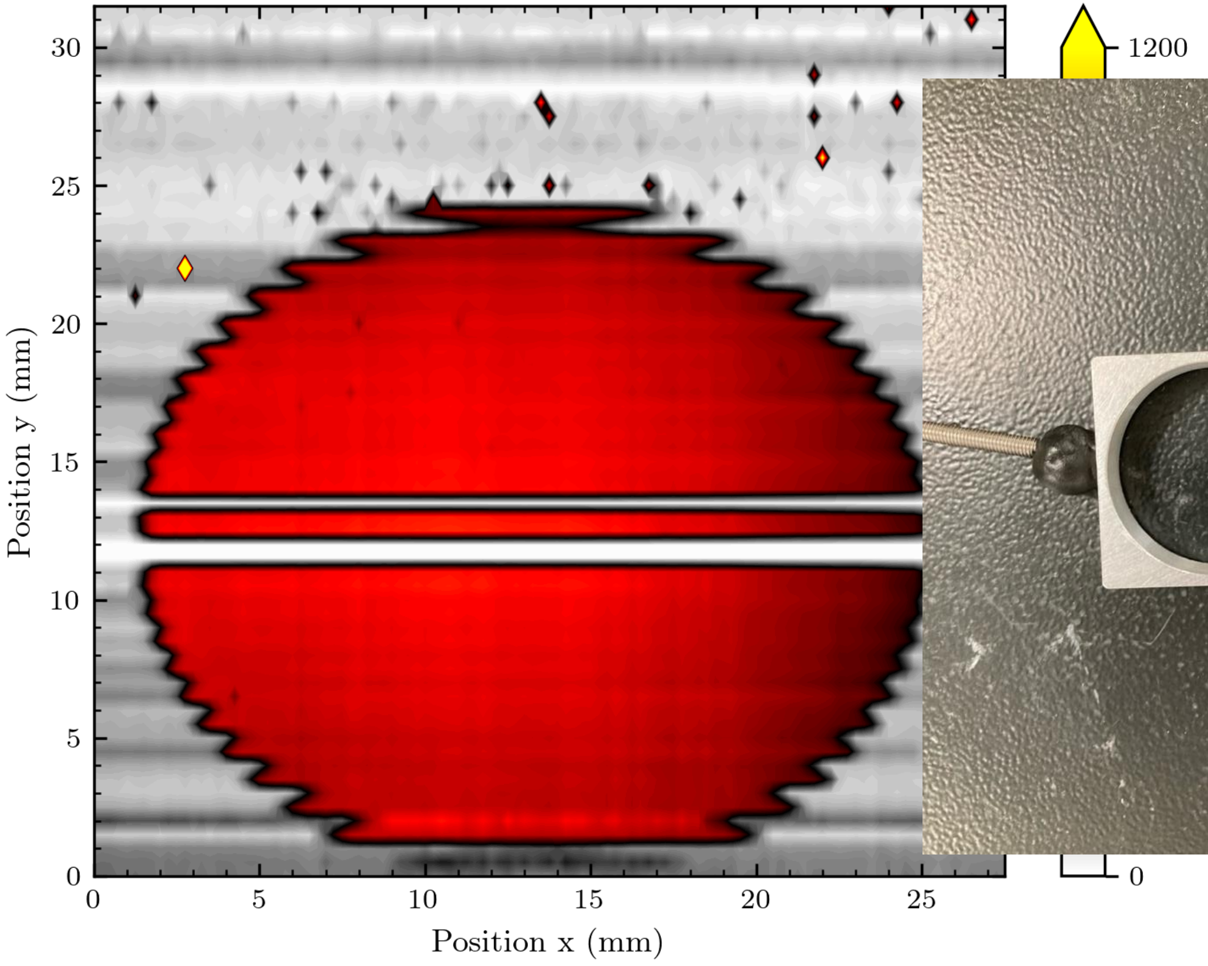


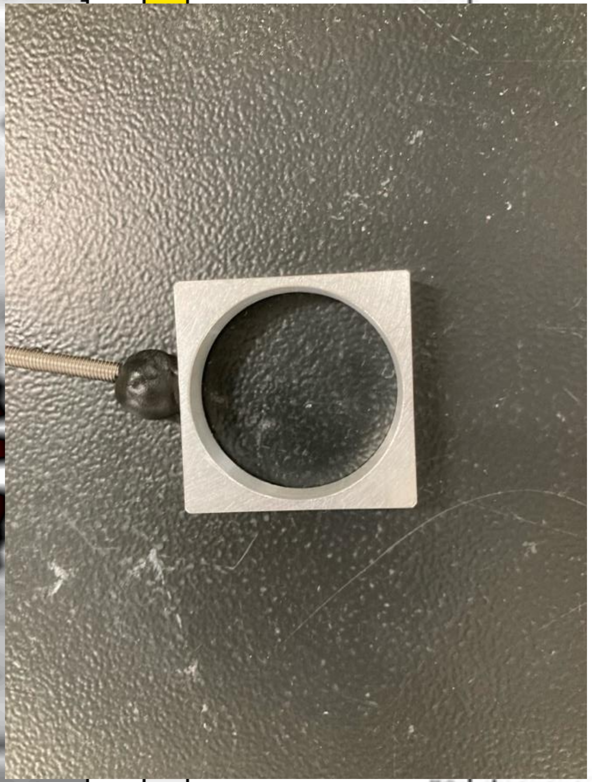
Direct bonding between PCB card and diode

All measurements following are done with arrays without the ”fan out” = fewer fabrication steps + direct bonding!

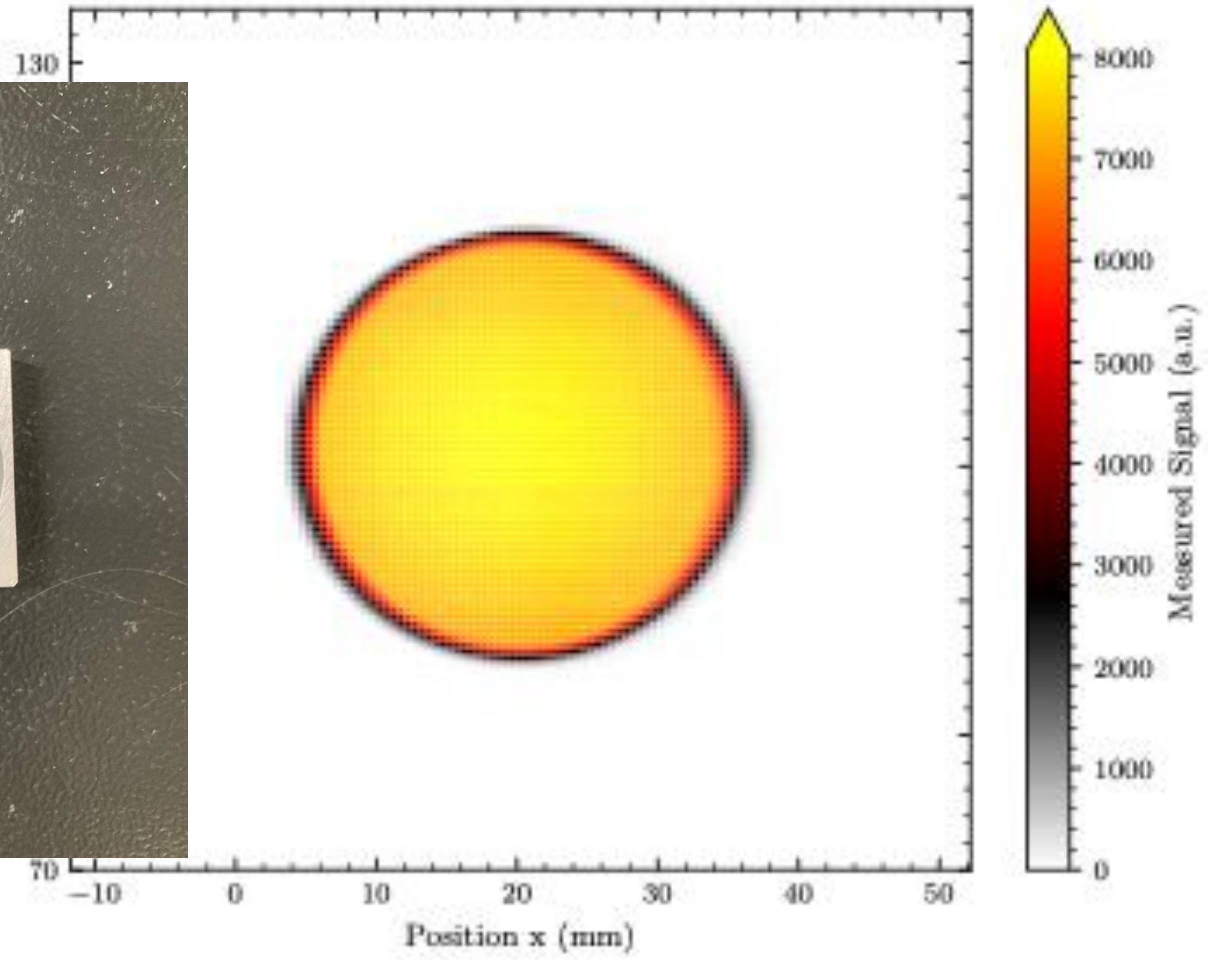
Comparison between array designs

“Old” 1x64 0.5x0.5 mm^2 array:



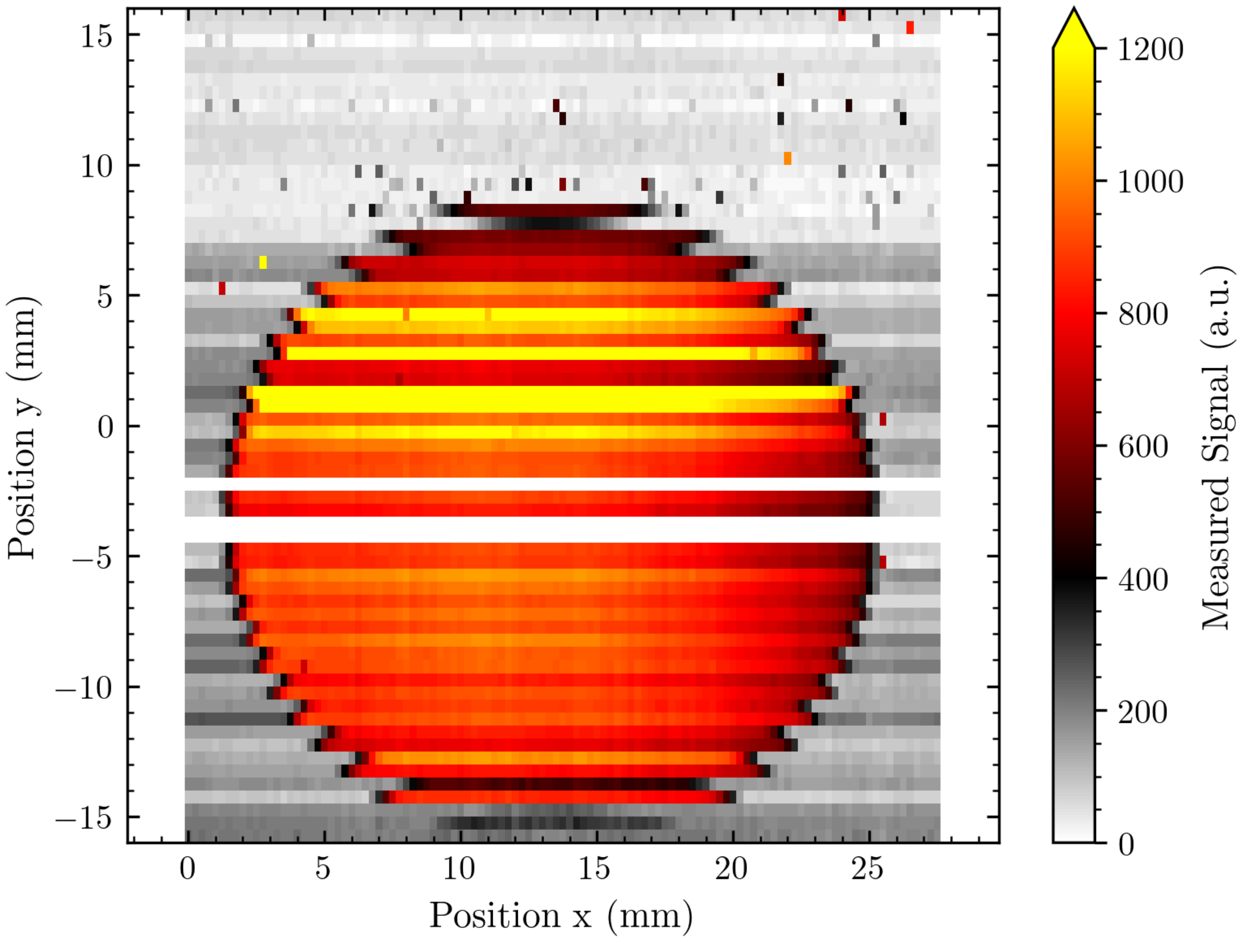


“New” 1x128 0.5x0.5 mm^2 diodes:

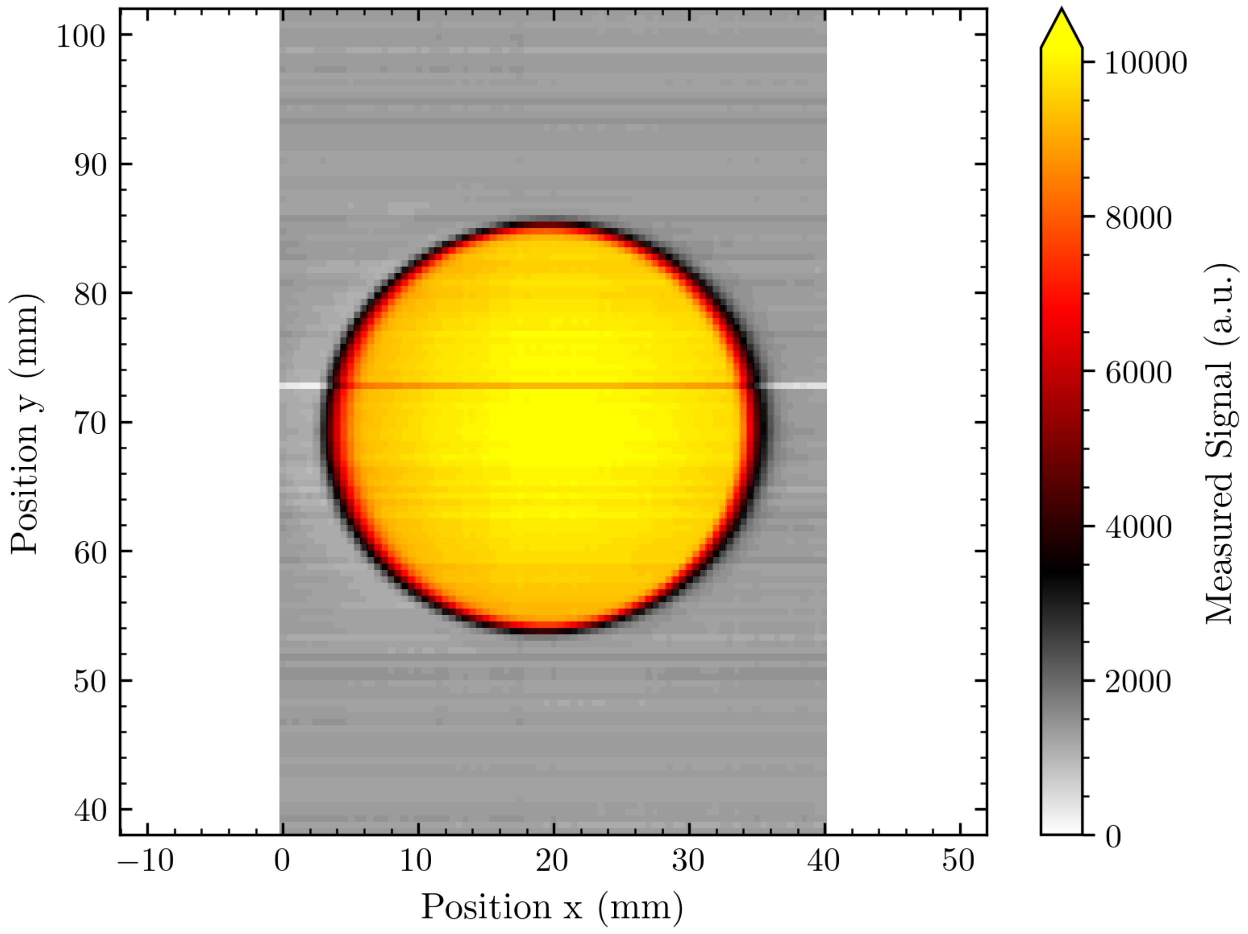


Let’s just compare the raw data

“Old” 1x64 0.5x0.5 mm^2 array:



“New” 1x128 0.5x0.5 mm^2 diodes:

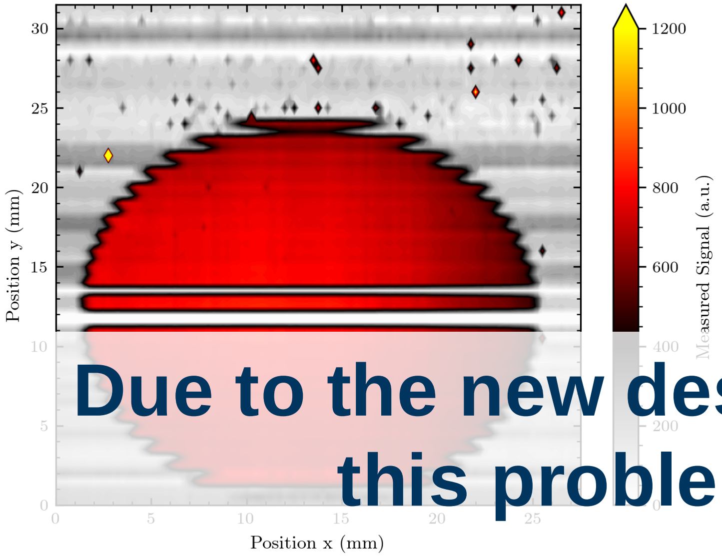


Why the difference?

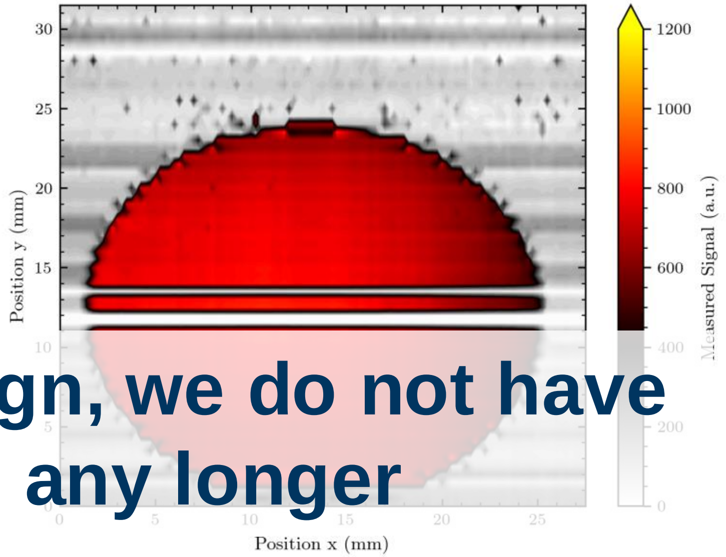
- **Better quality (fewer fabrication steps)**
- **Impact of metal ”fan out” on GaN wafer**
- **We observe a transfer of irradiation-induced electrons between lines of “fan out”!**

(We also modelled and partially corrected for this)

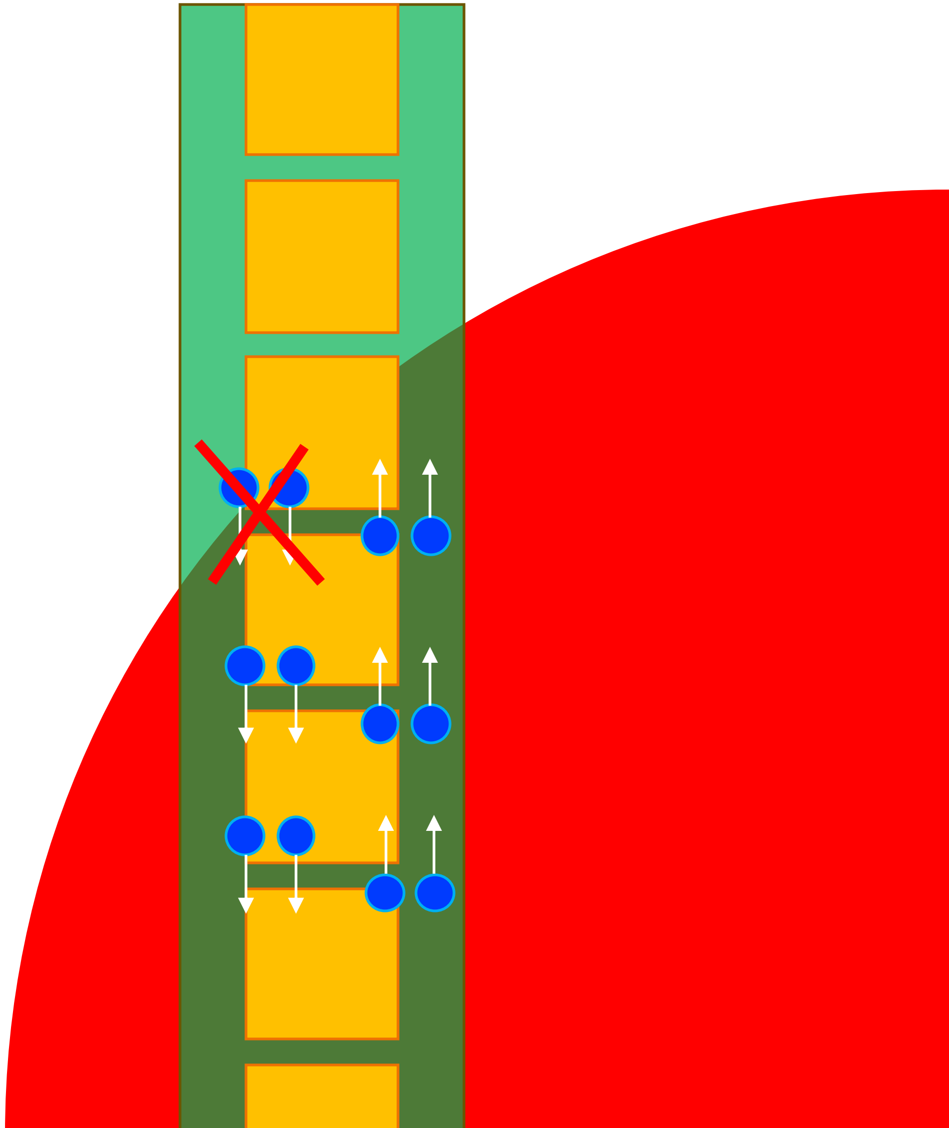
Before



After correction



Due to the new design, we do not have this problem any longer



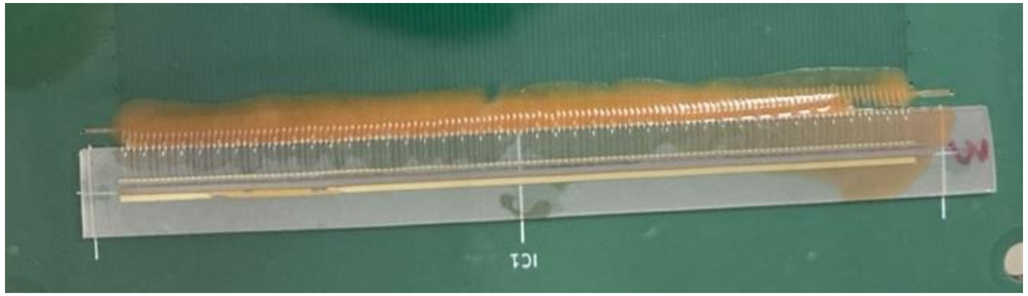
Overview of arrays measured so far

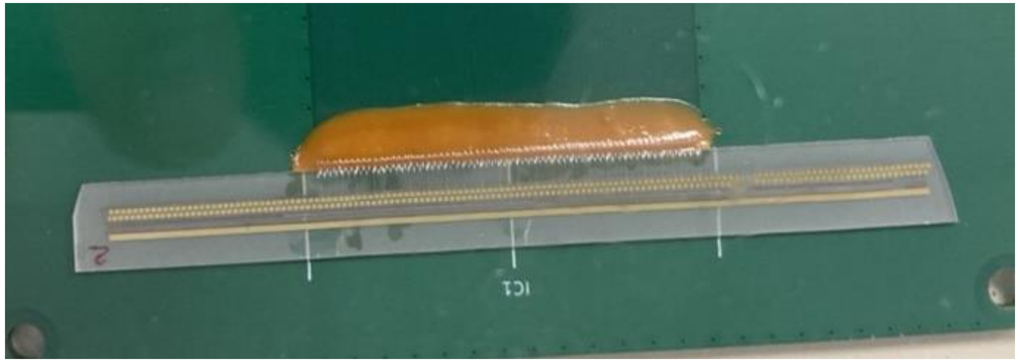
With “fan out”:

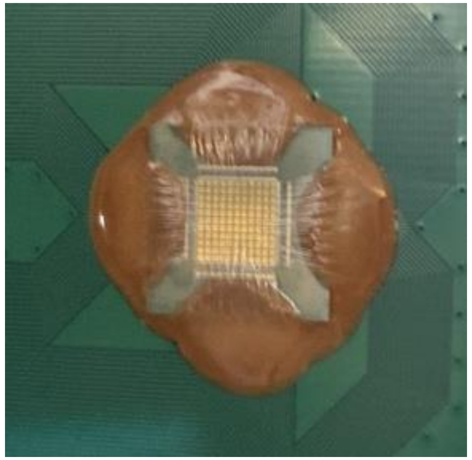
- **3 different 1x64 0.5x0.5 mm^2 line arrays**

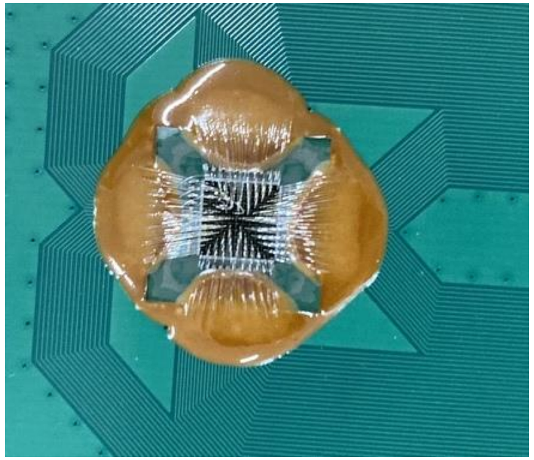
Without ”fan out”:

- **1x128 0.5x0.5 mm^2 line array**
- **1x128 0.5x0.25 mm^2 line array**
- **2x64 0.5x0.5 mm^2 line array (0.25 mm shifted)**
- **2 different 11x11 1x1 mm^2 matrix arrays**
- **11x11 0.5x0.5 mm^2 matrix arrays**





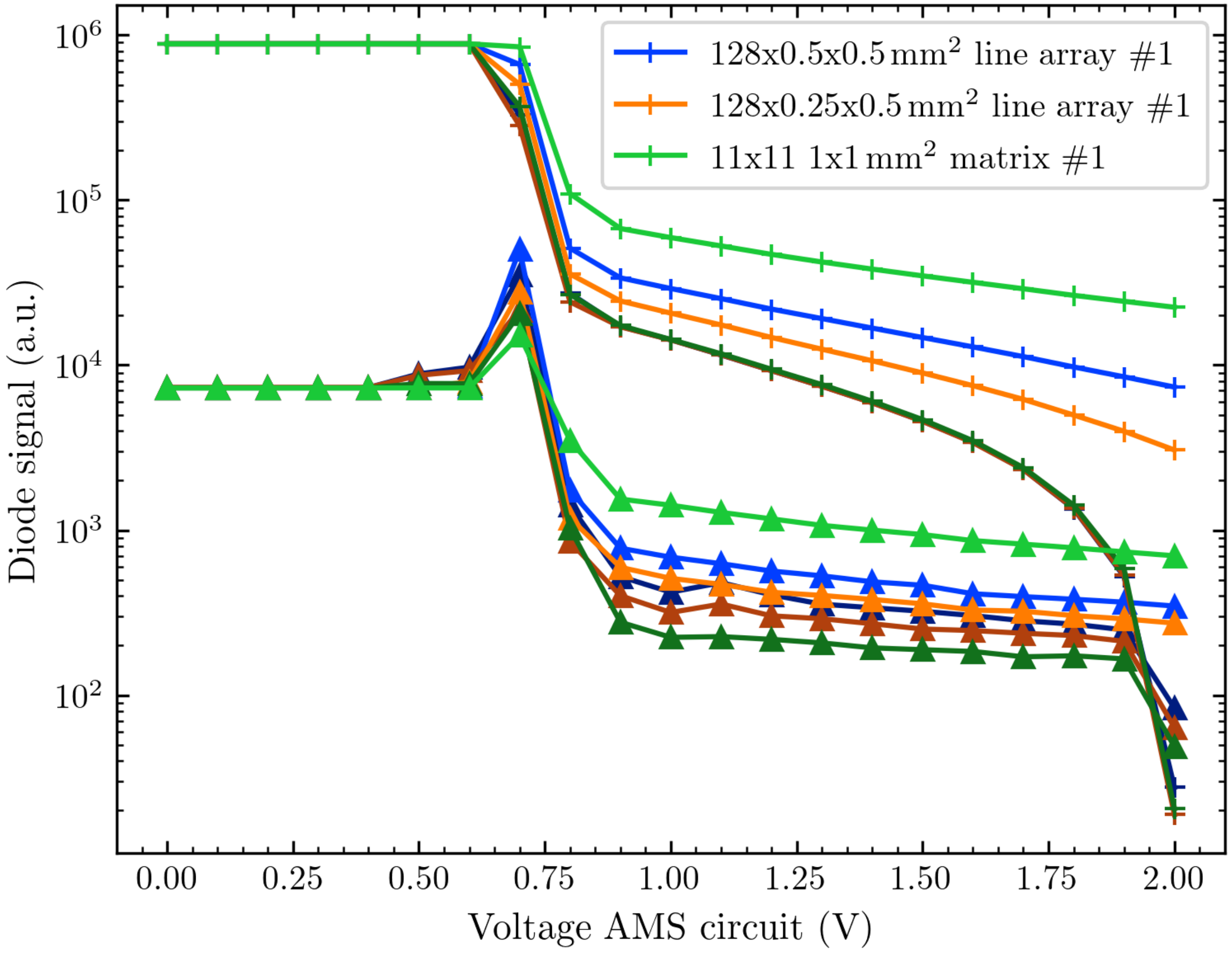


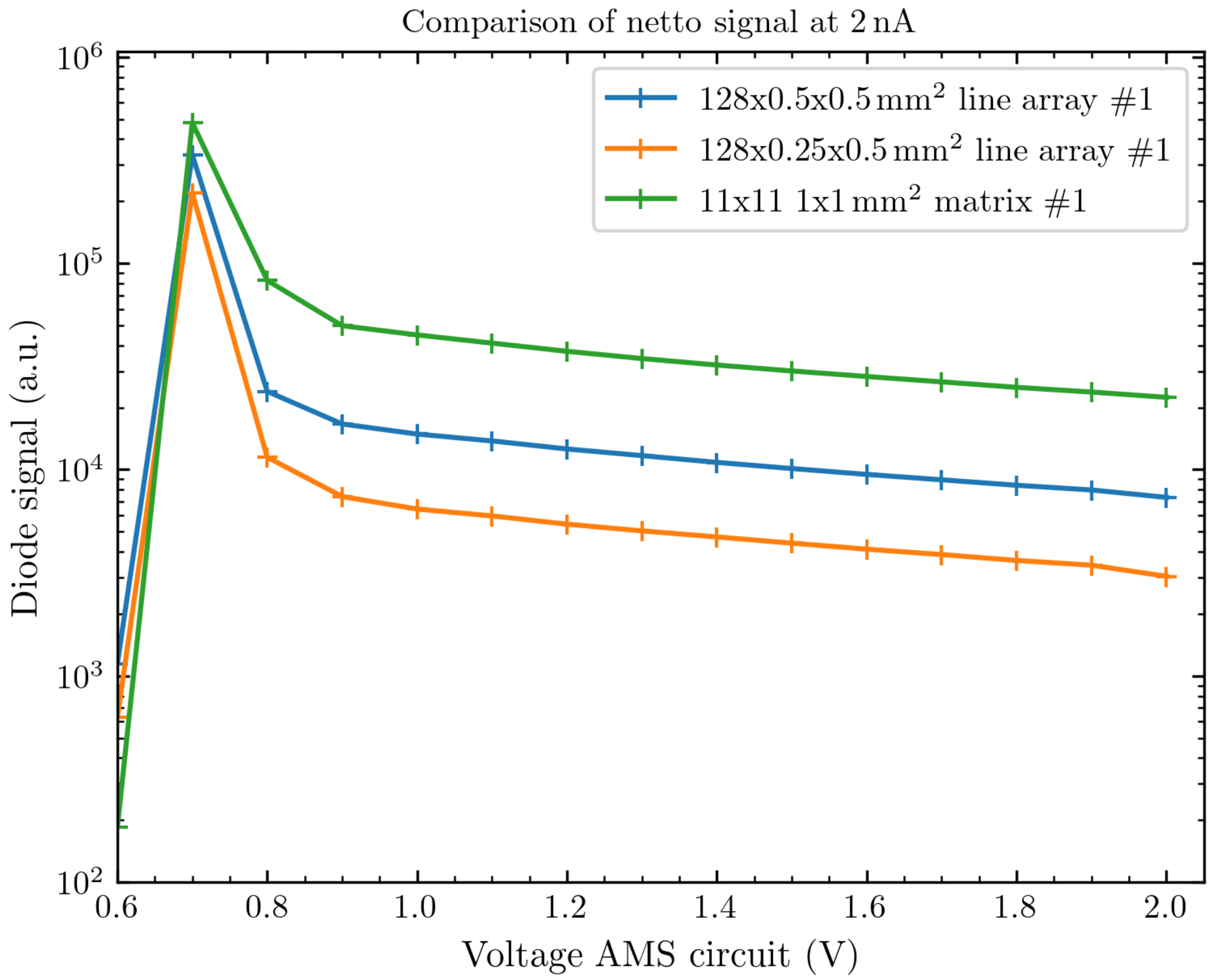


Part II

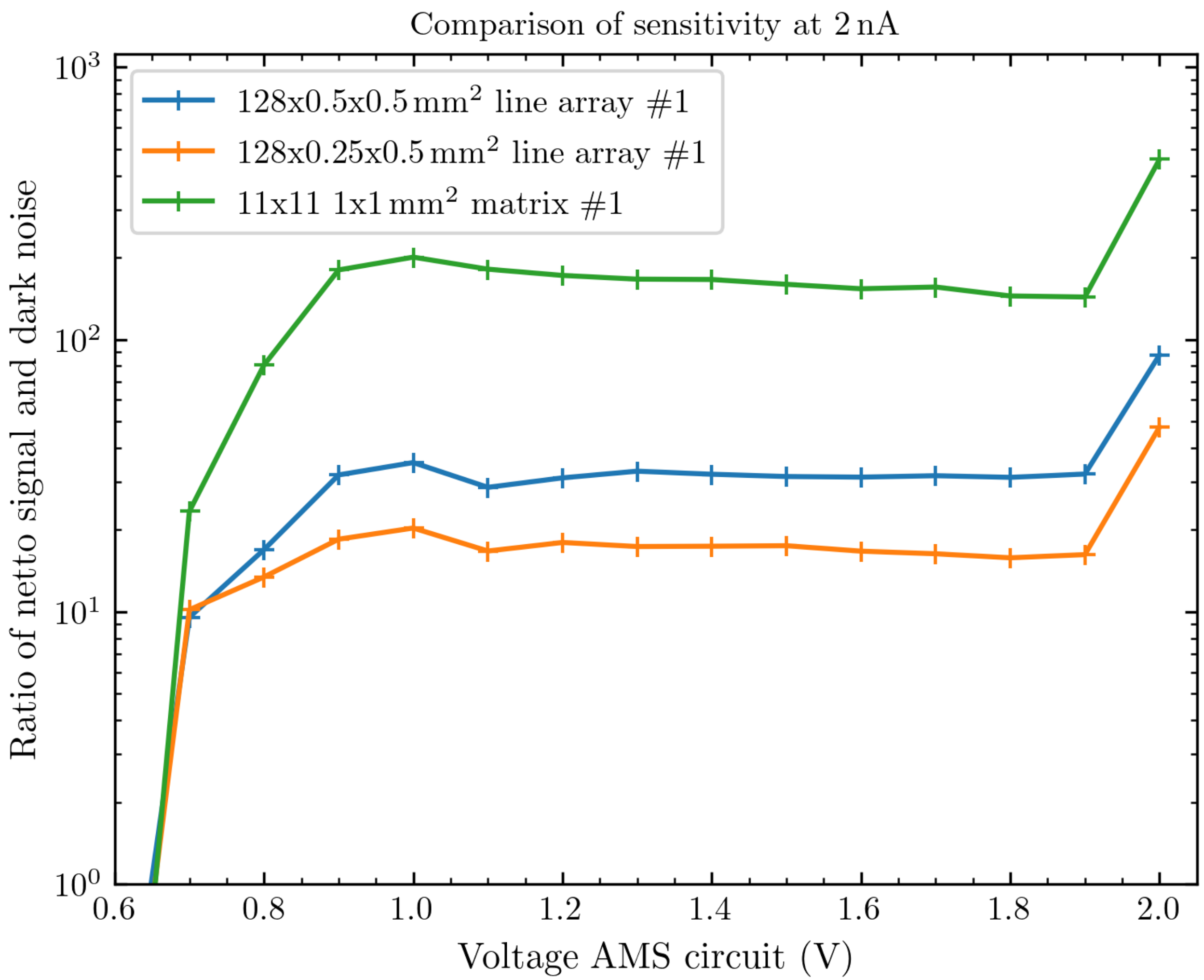
- **Voltage tests**
- **Linearity checks**
- **Homogeneity of array response**

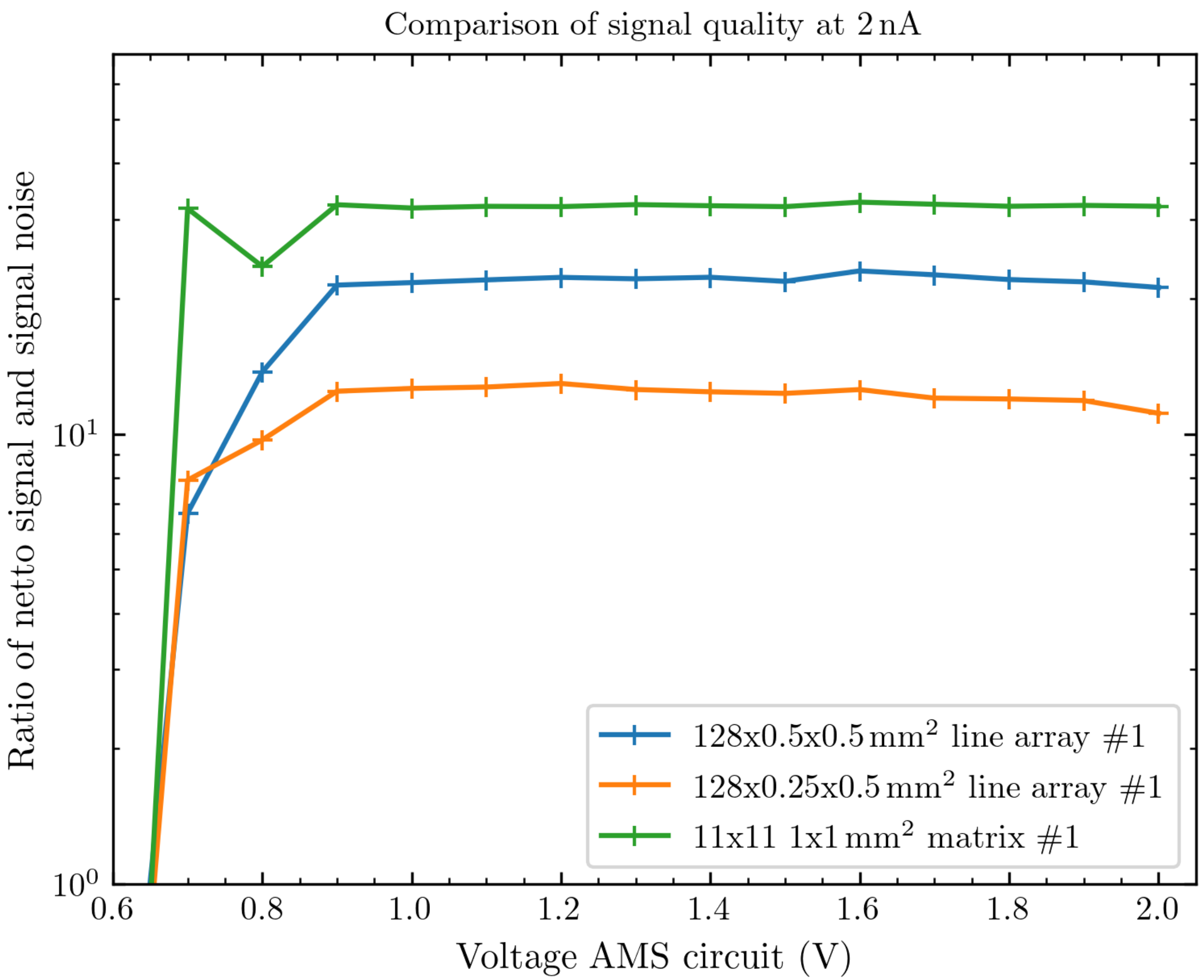
Voltage tests



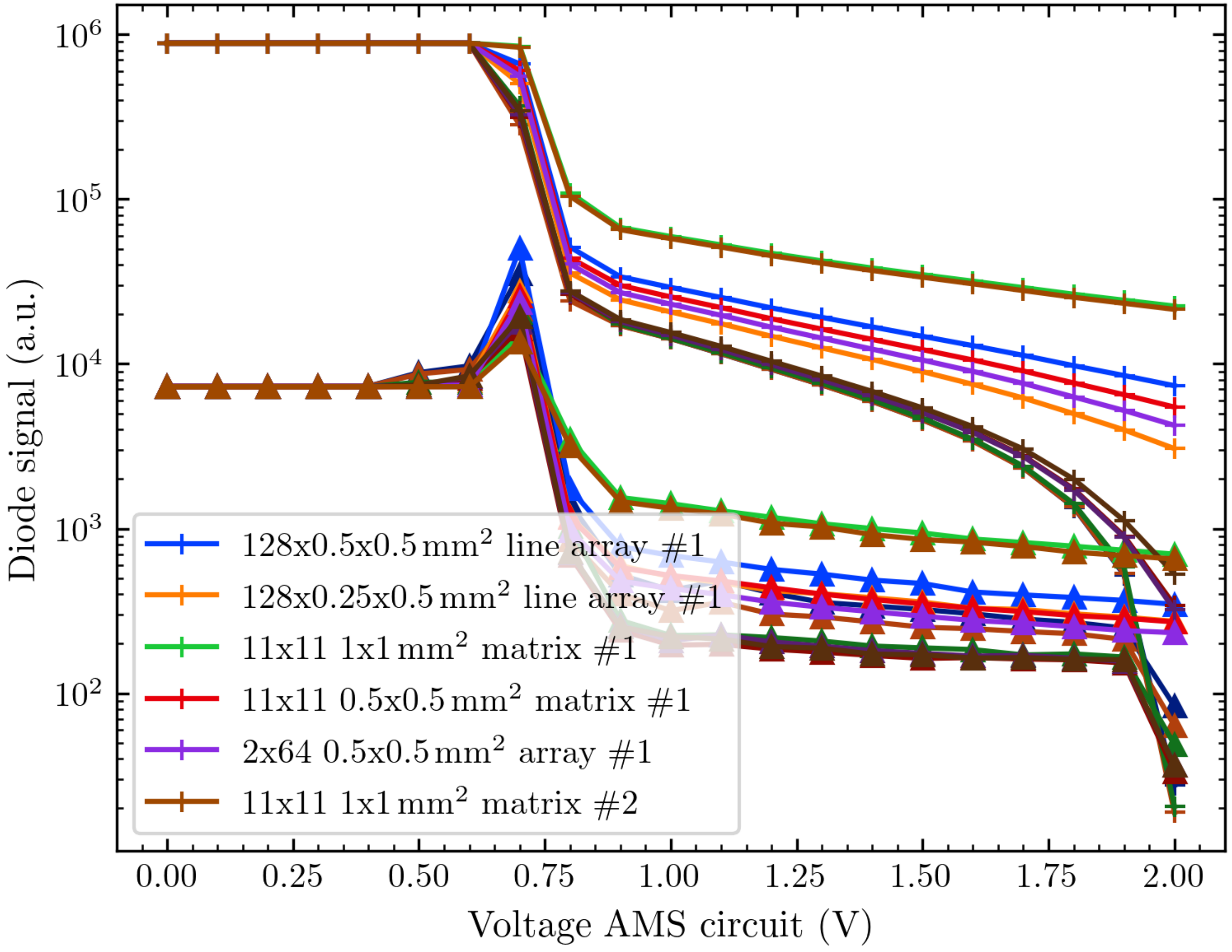


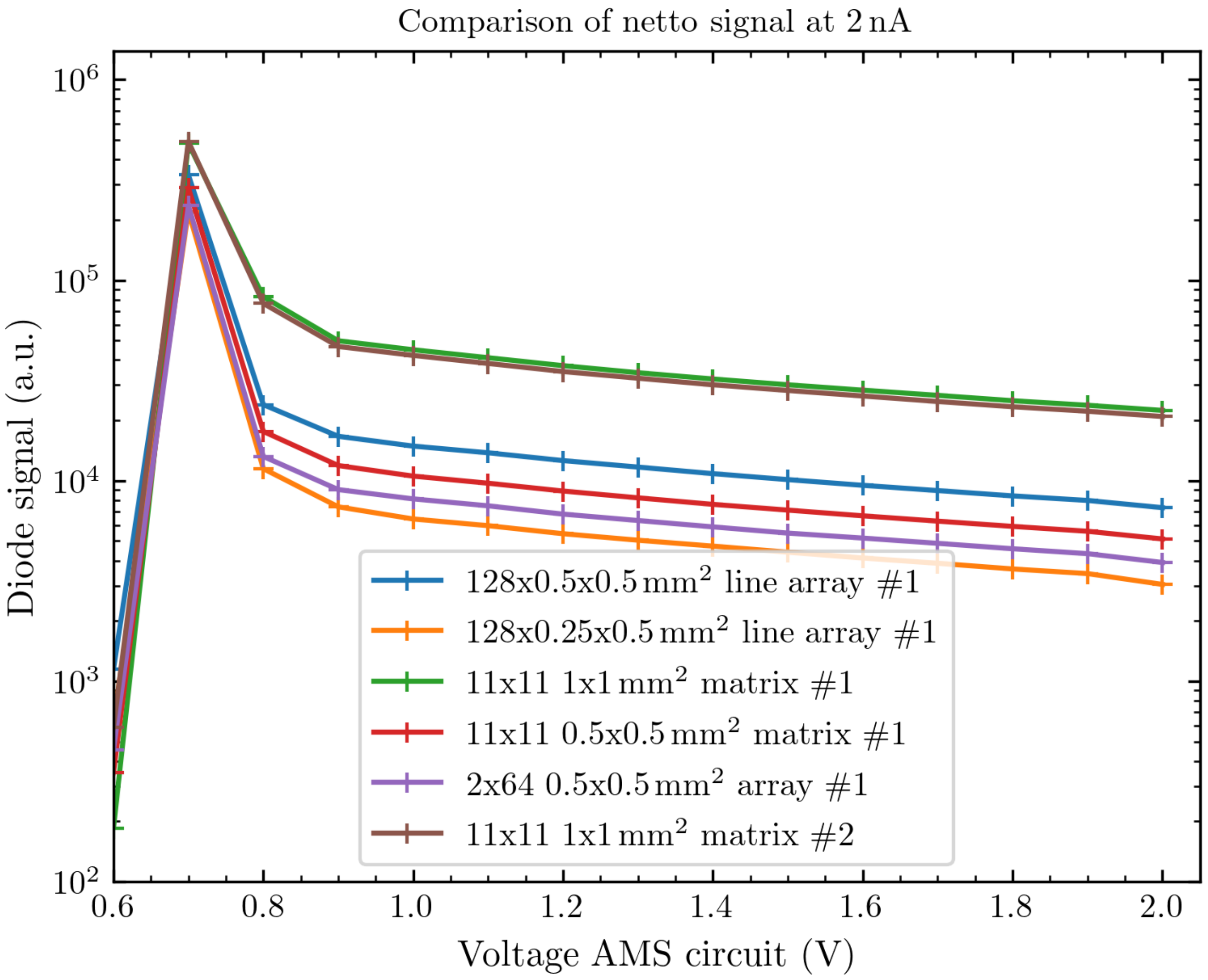
Sensitivity and signal quality



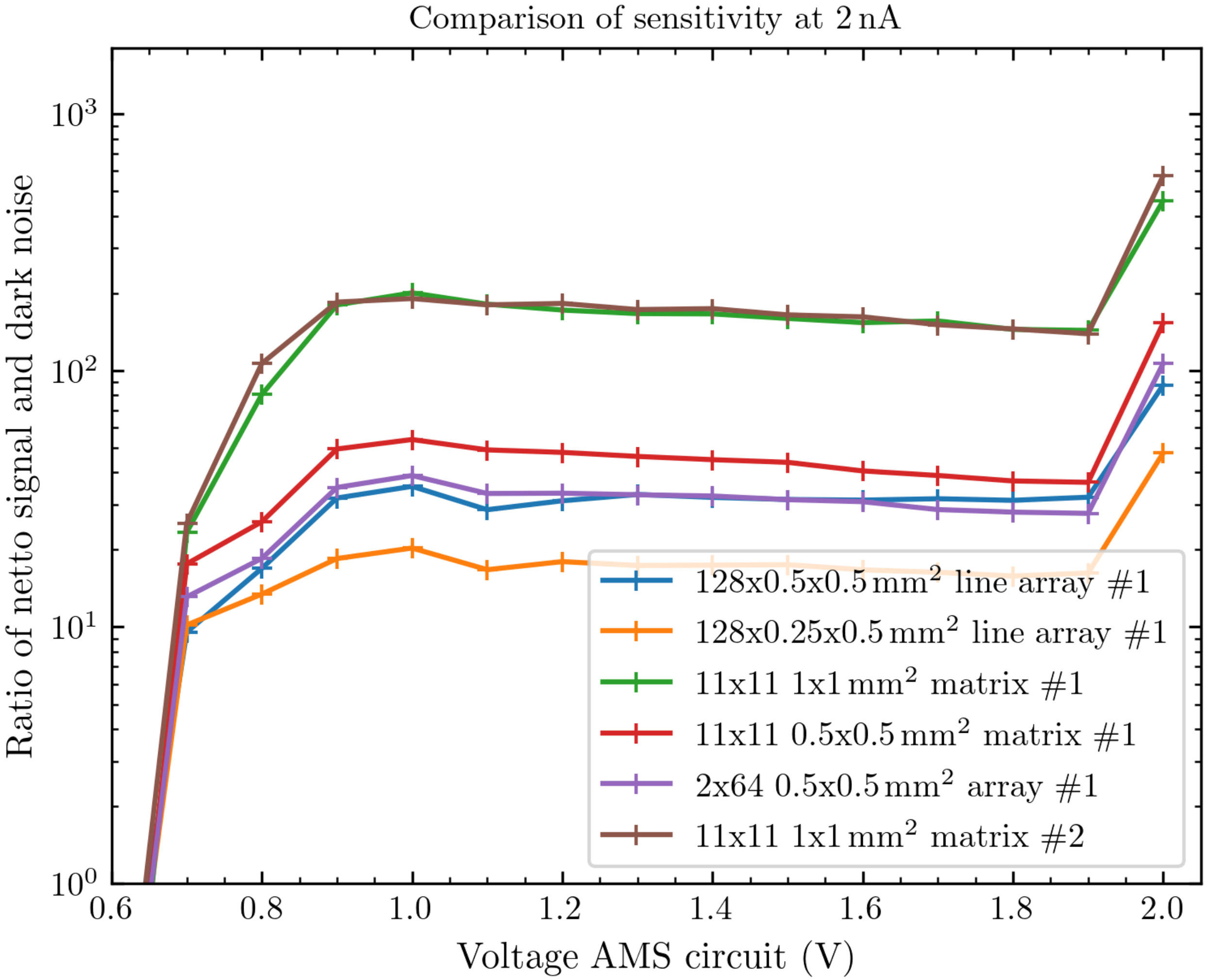


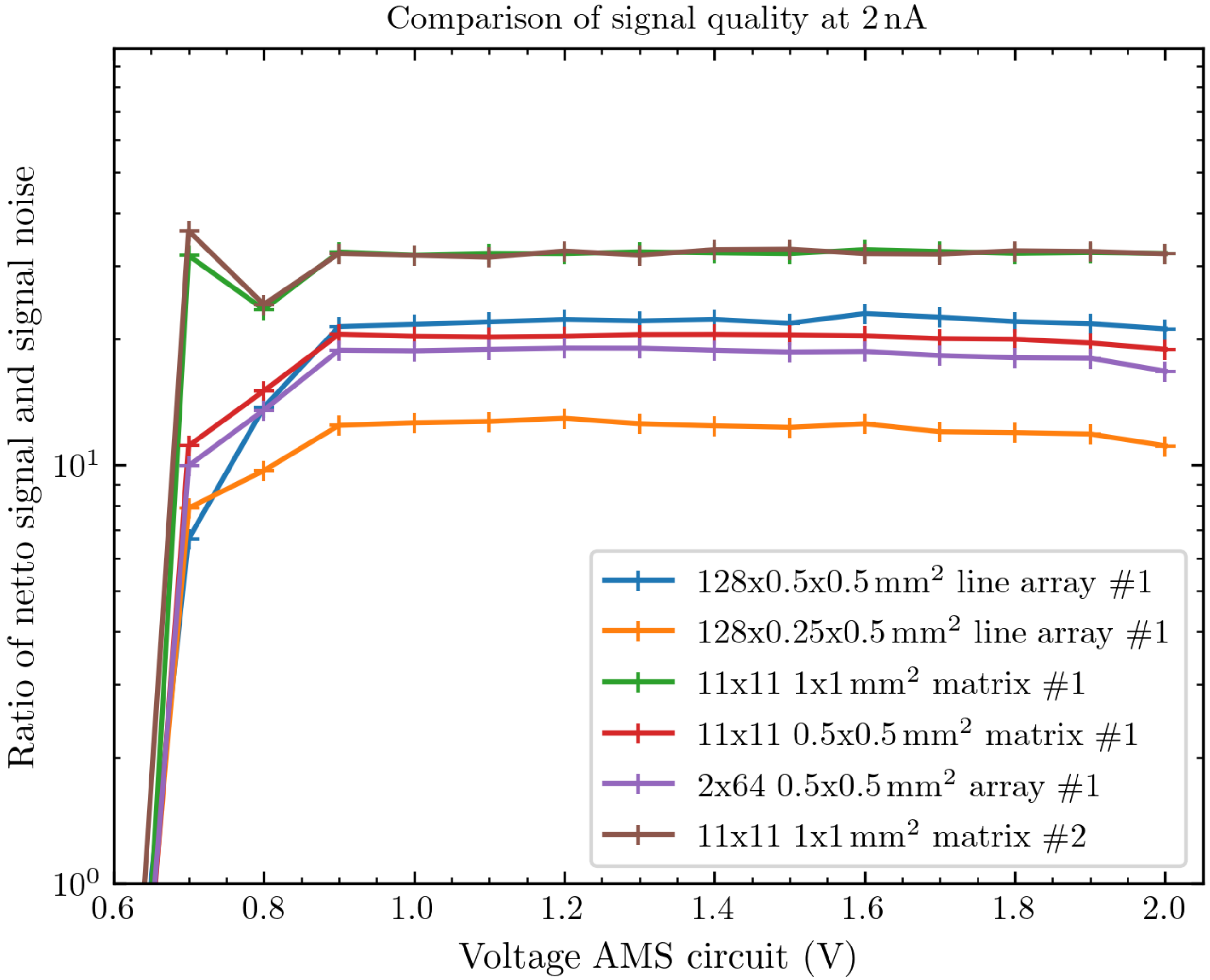
All voltage scans up to the 22nd of October





Sensitivity and signal quality

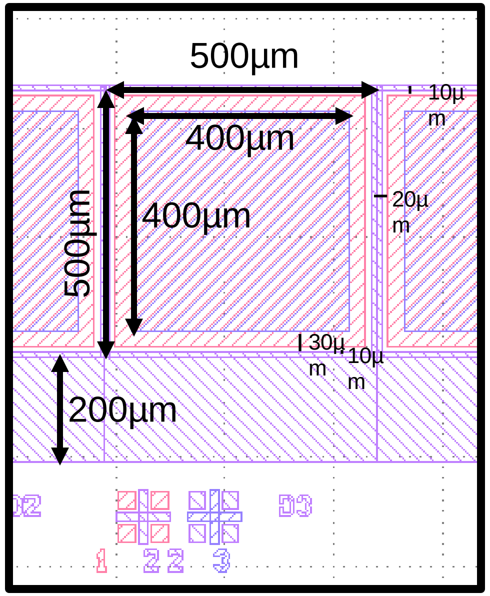




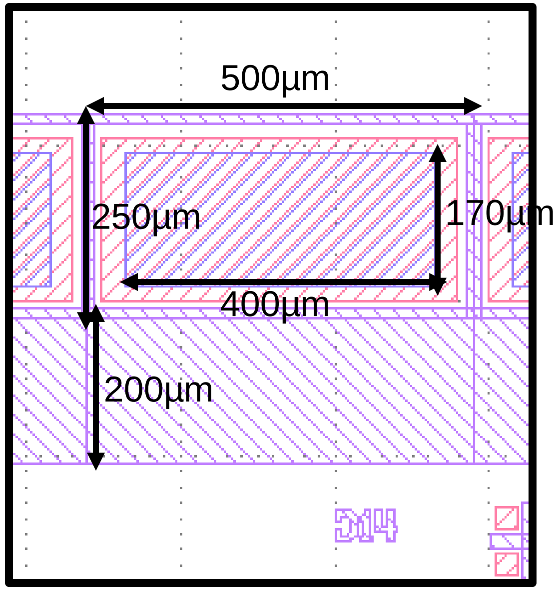
Note that the sensitivity implies that we could e.g. detect a current ~ 200 lower than we had for the big matrix arrays)
Meaning: 2 nA at Faraday cup / 200 = 10 pA at Faraday cup under these conditions for the large diodes.

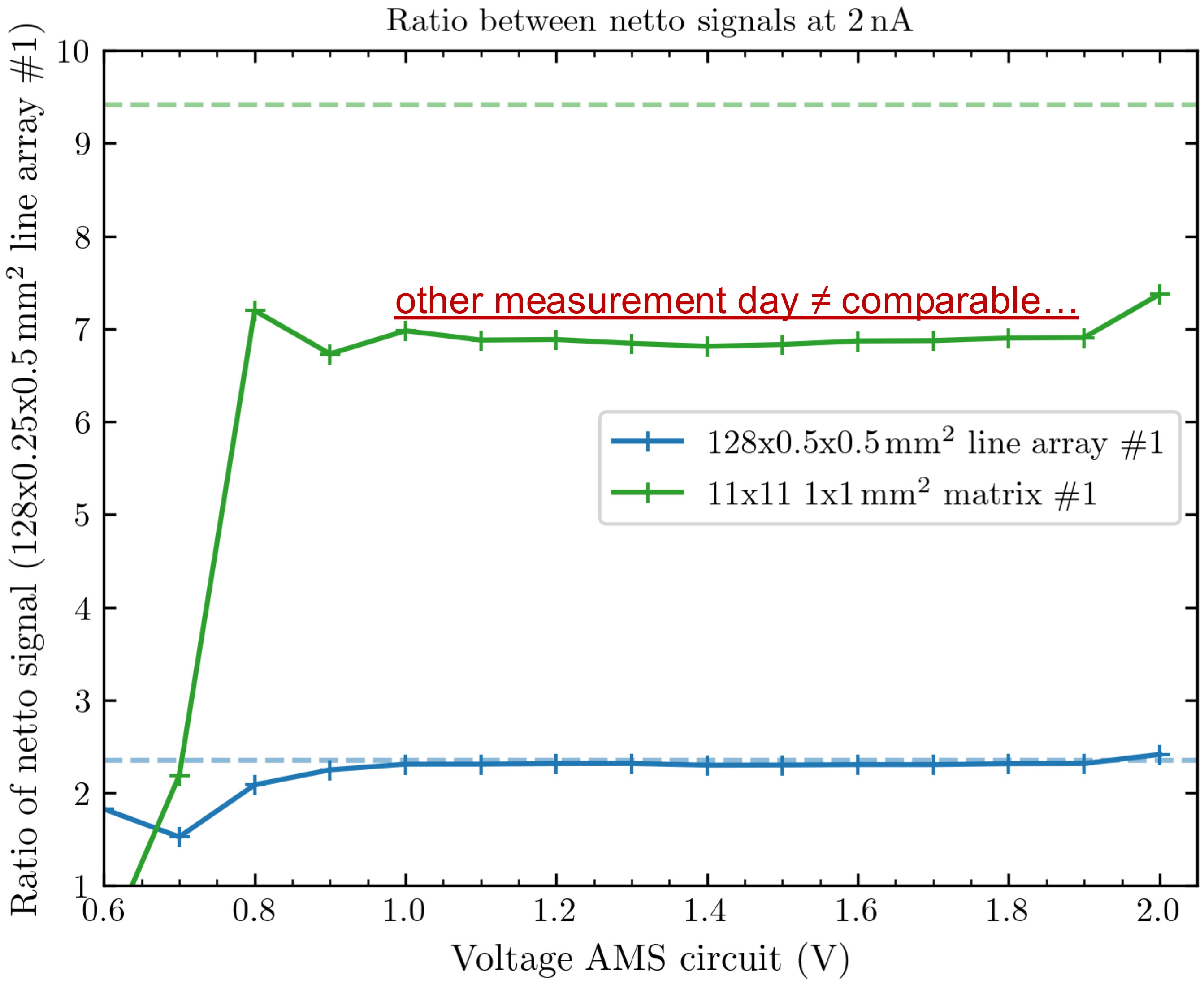
Ratio between the signals

SINGLE DIODE



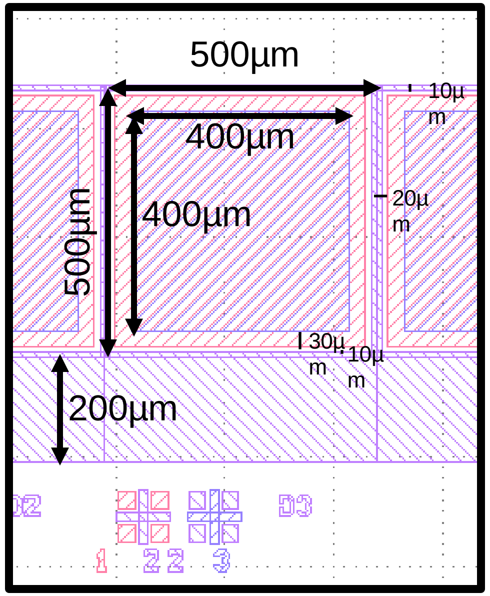
SINGLE DIODE

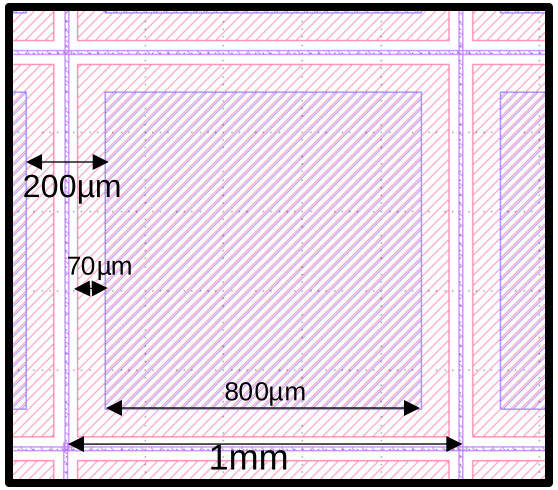


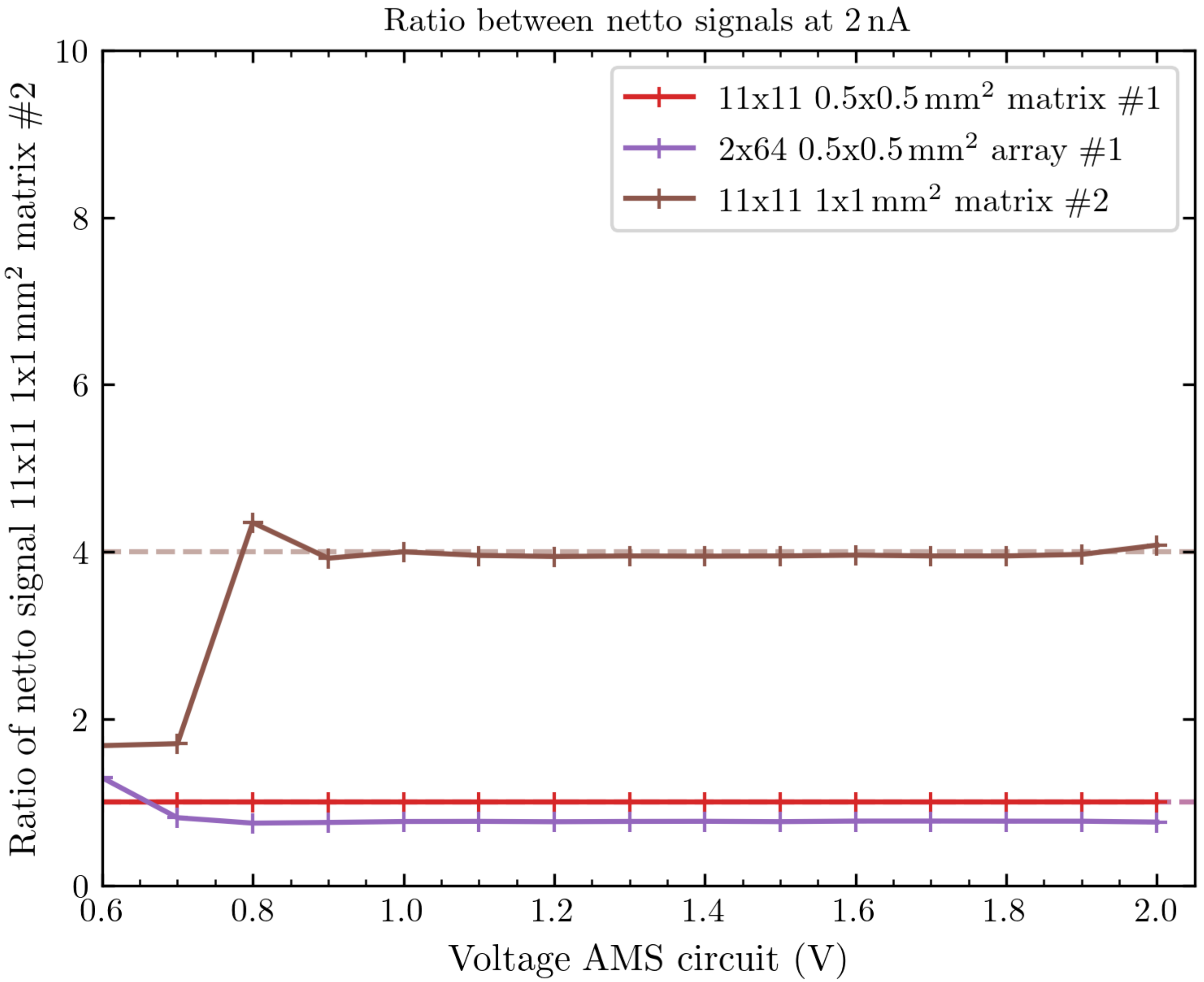


Ratio between the signals

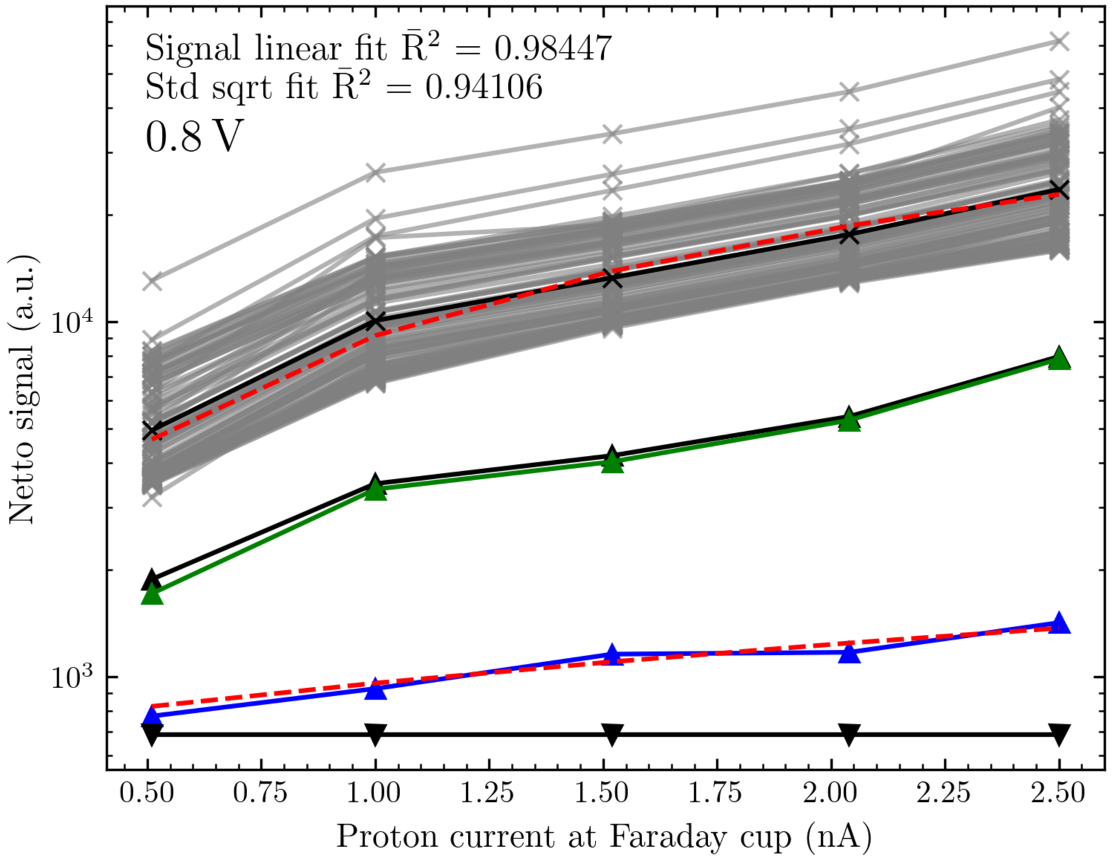
SINGLE DIODE

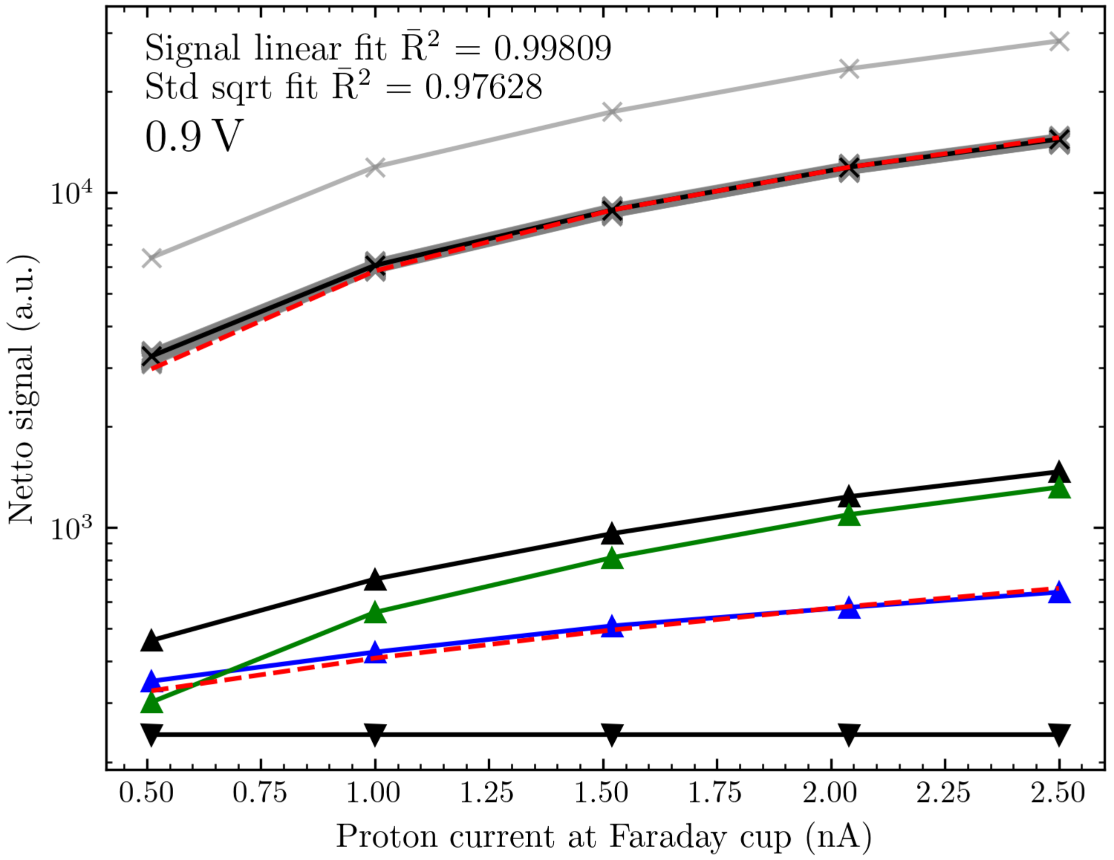




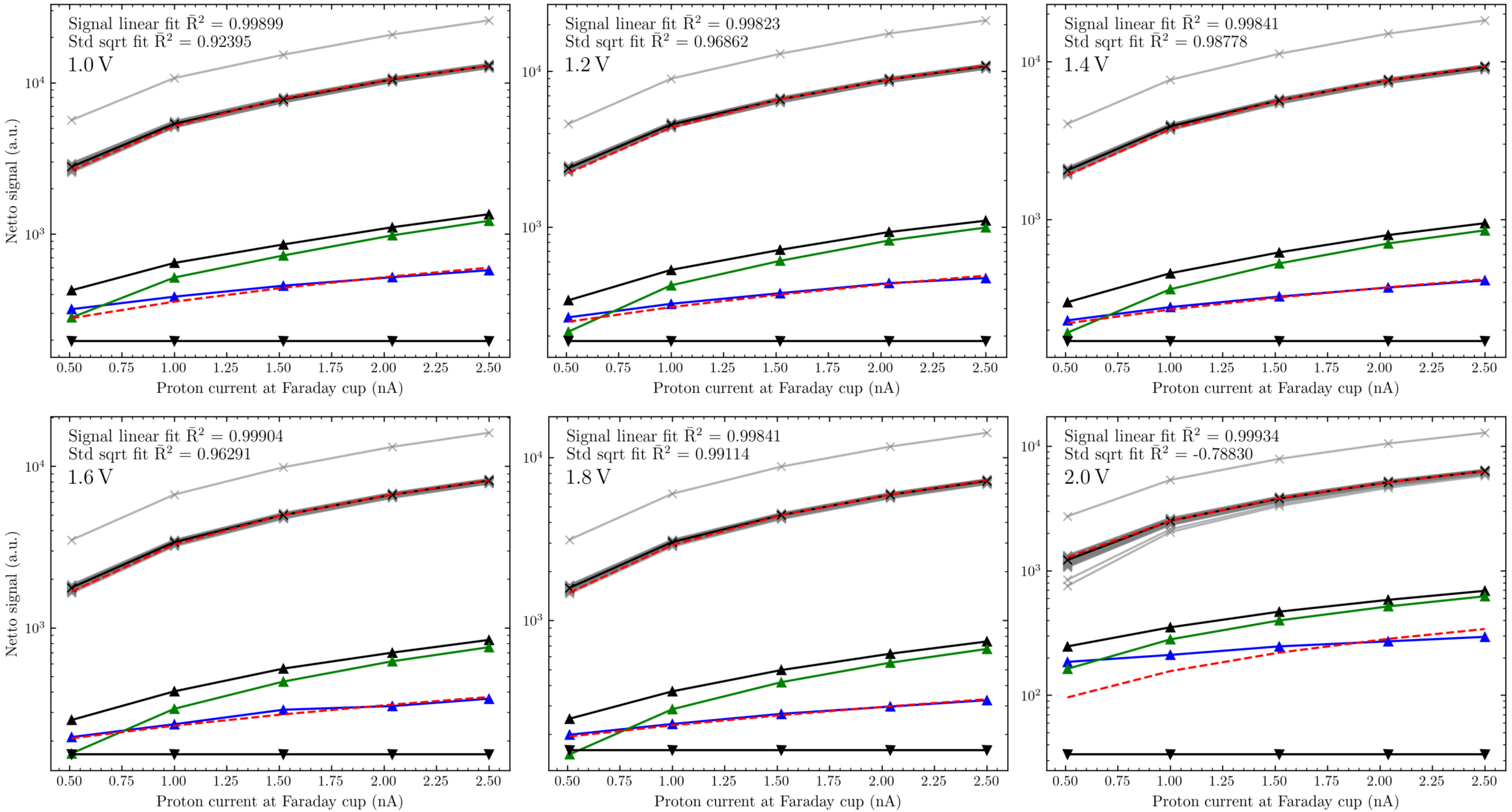


Linearity in dependence of voltage





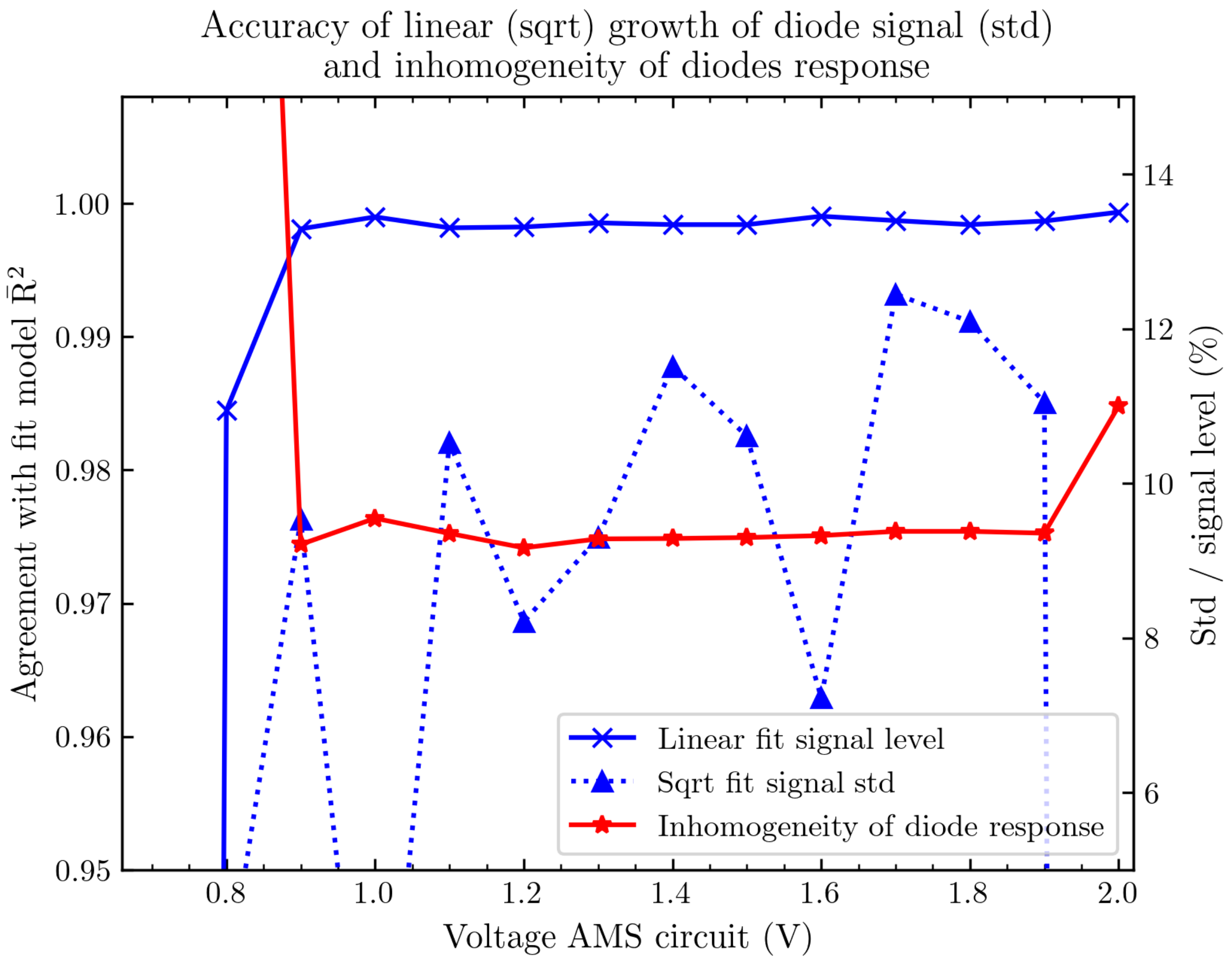
Small matrix array



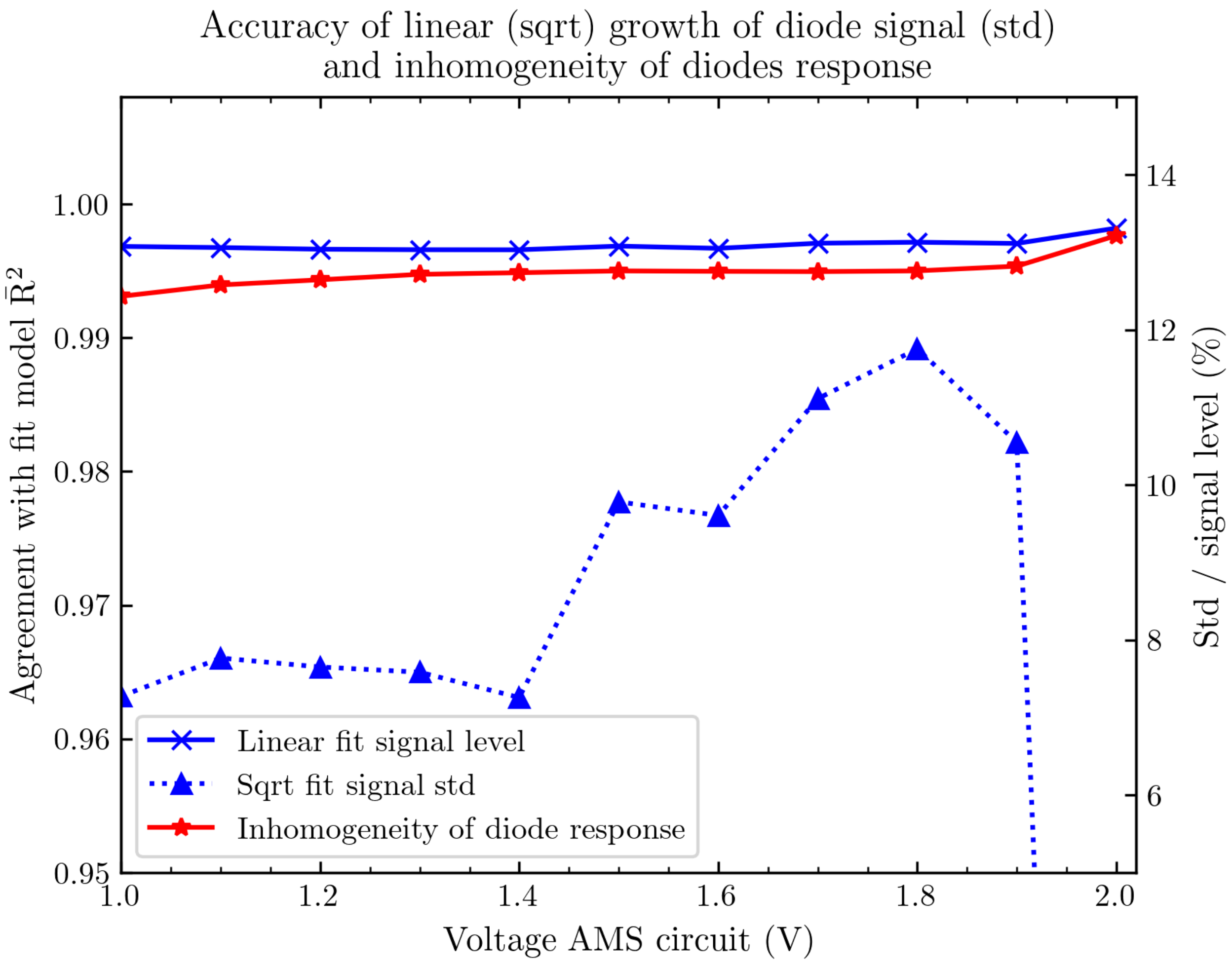
Small matrix array

Comparison with voltage

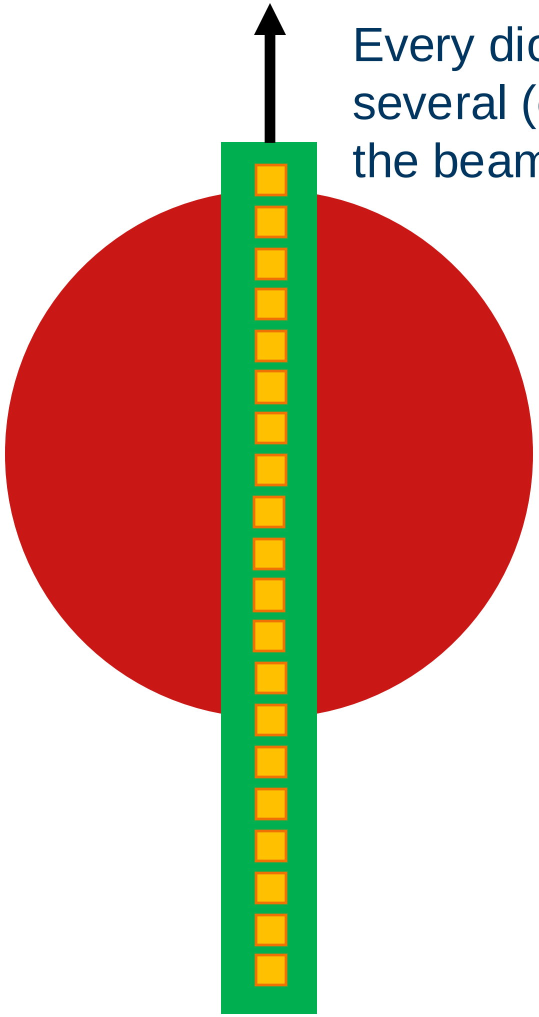
Small matrix array



Big matrix array #1

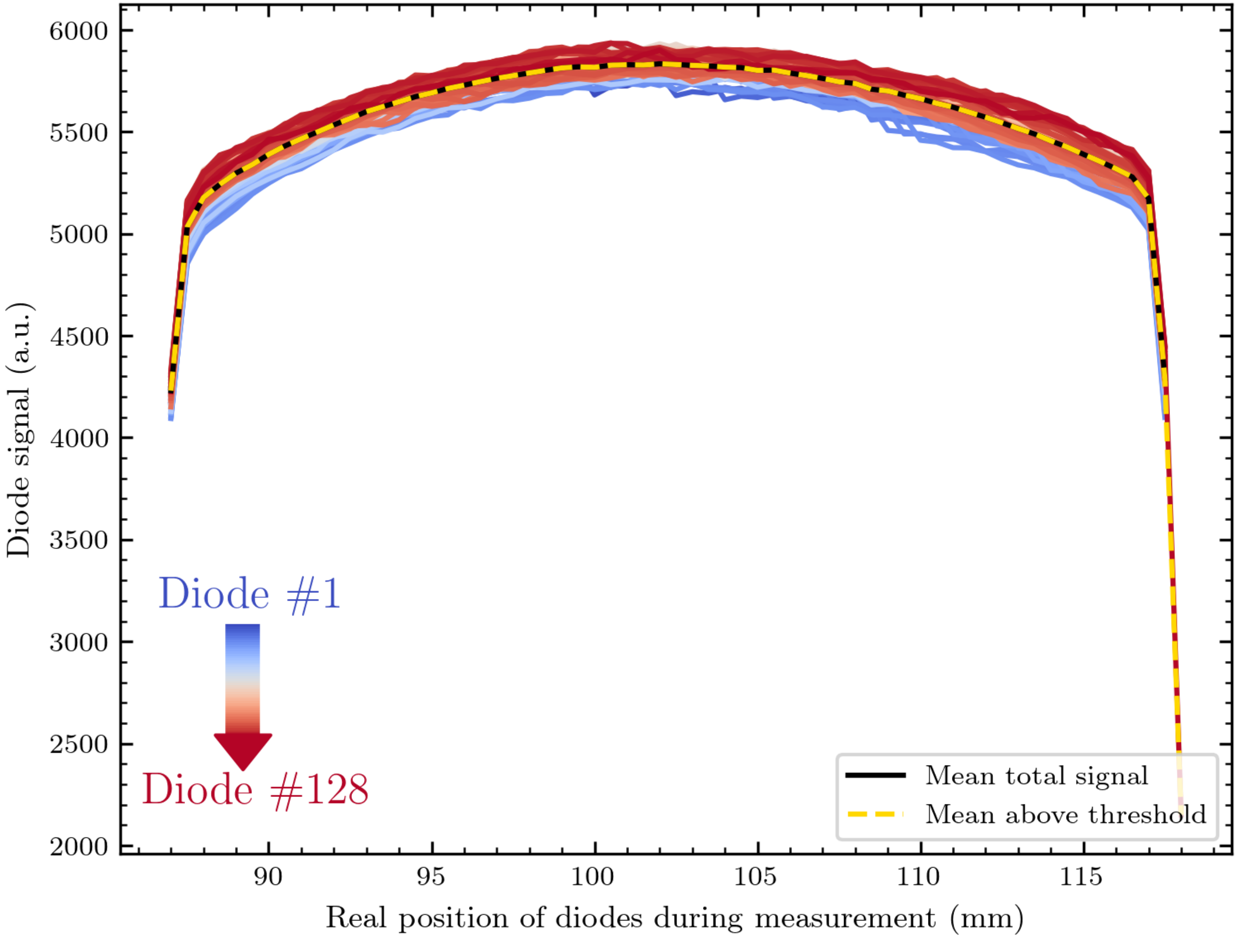


Homogeneity in diode response

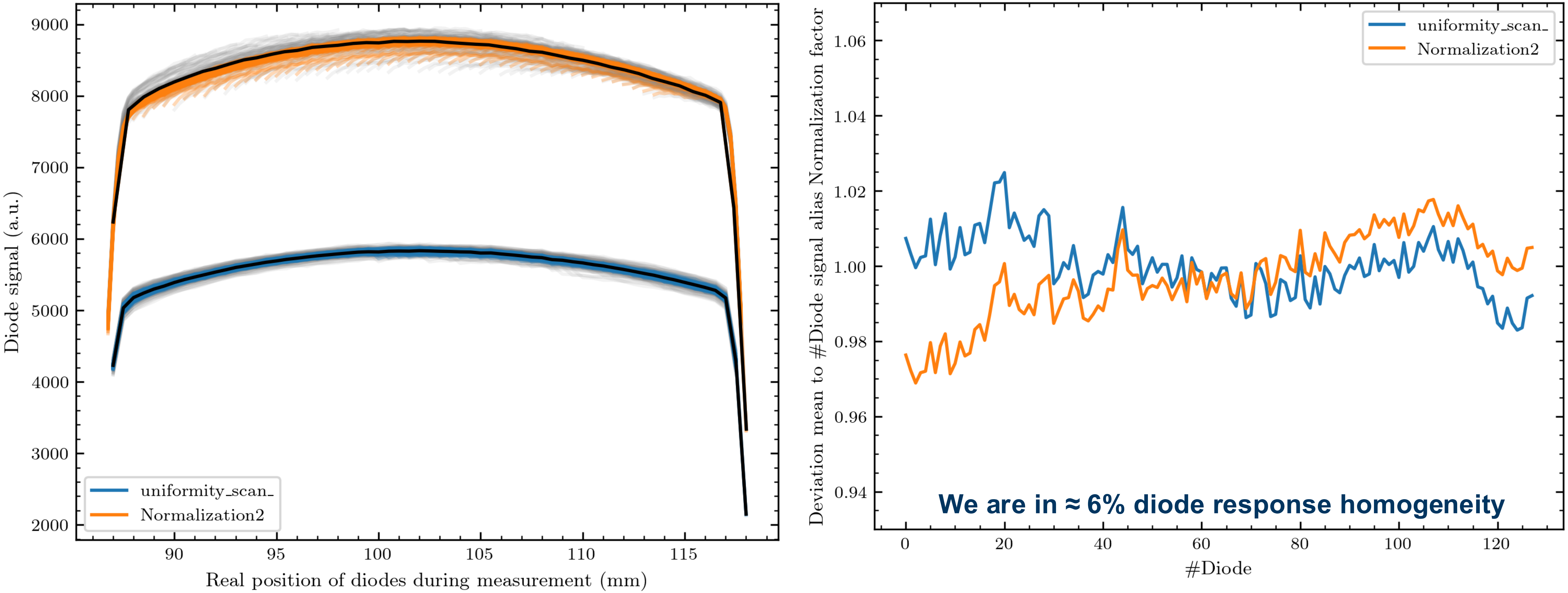


Every diode is measured at several (overlapping) positions in the beam

1x128 0.5x0.5 mm^2 array

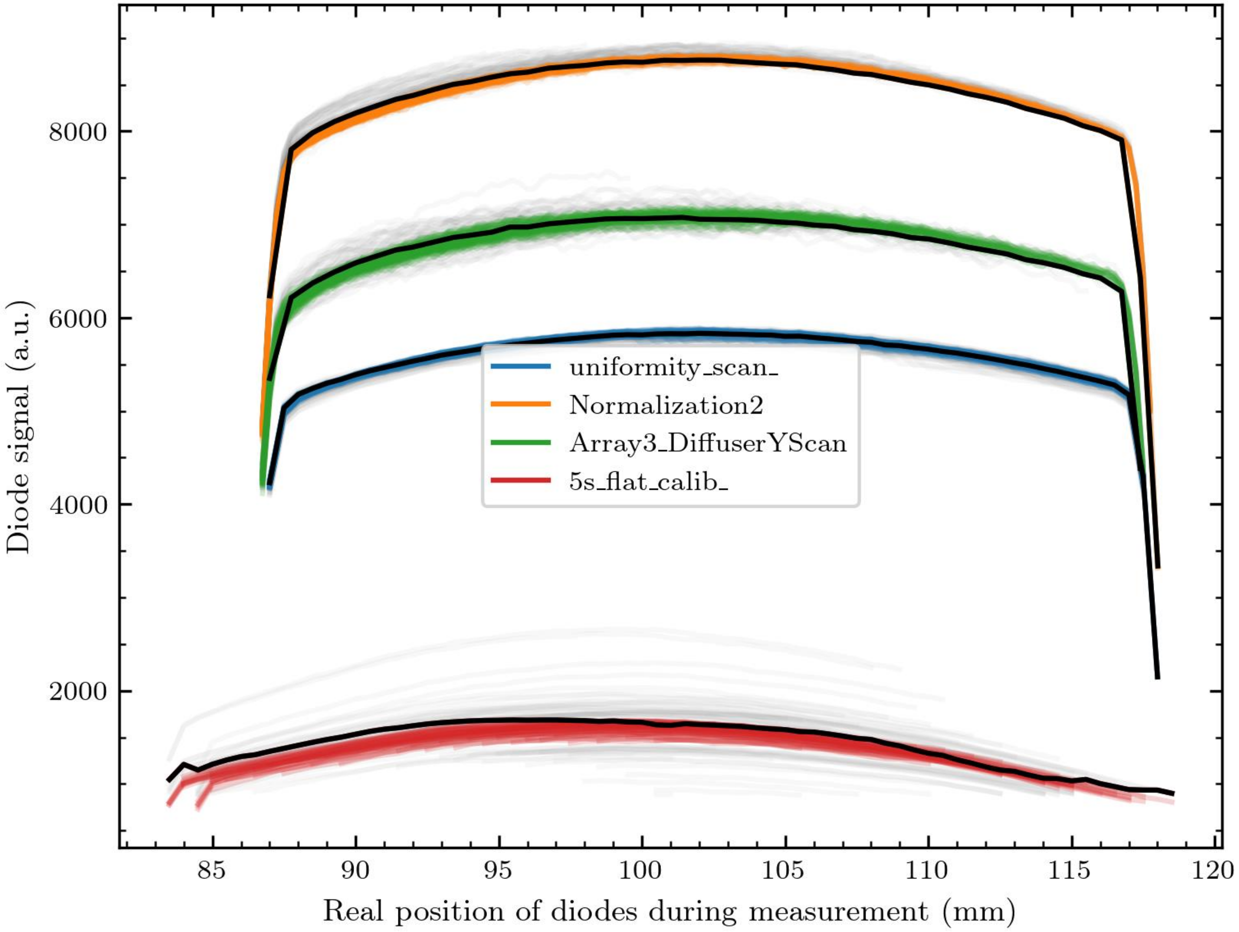


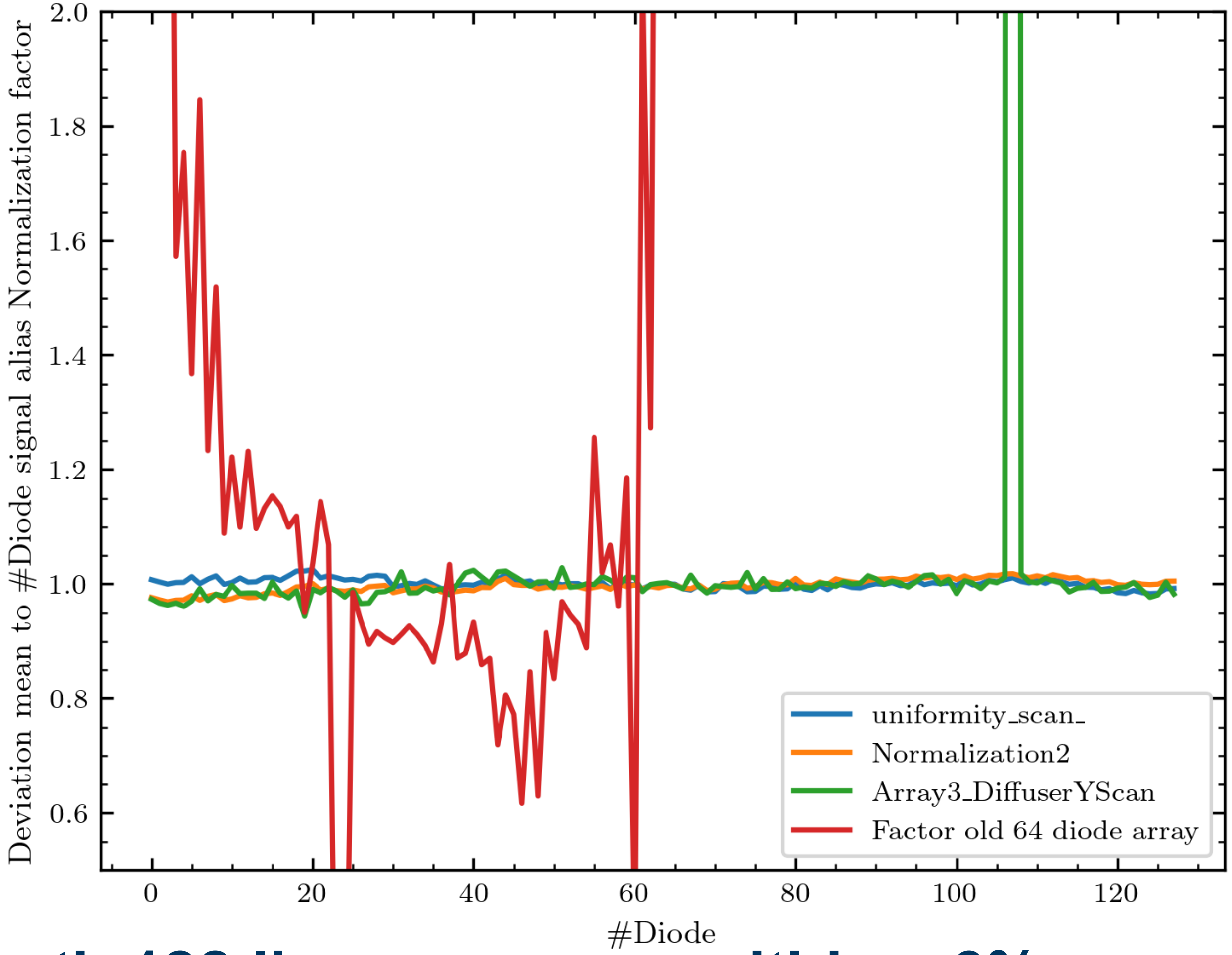
Factor for normalizaton



1x128 0.5x0.5 mm^2 array – 2 measurements at different times

Comparison with old array design

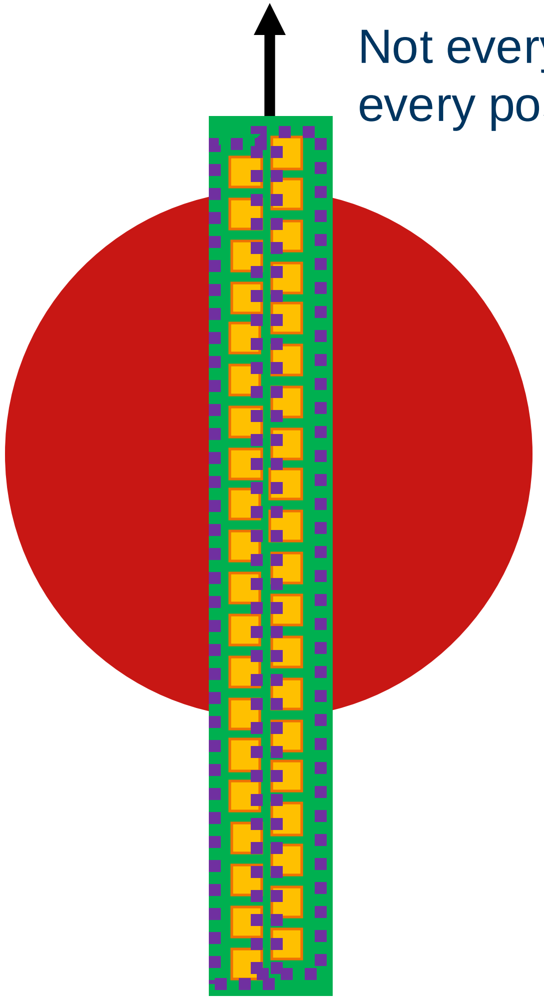




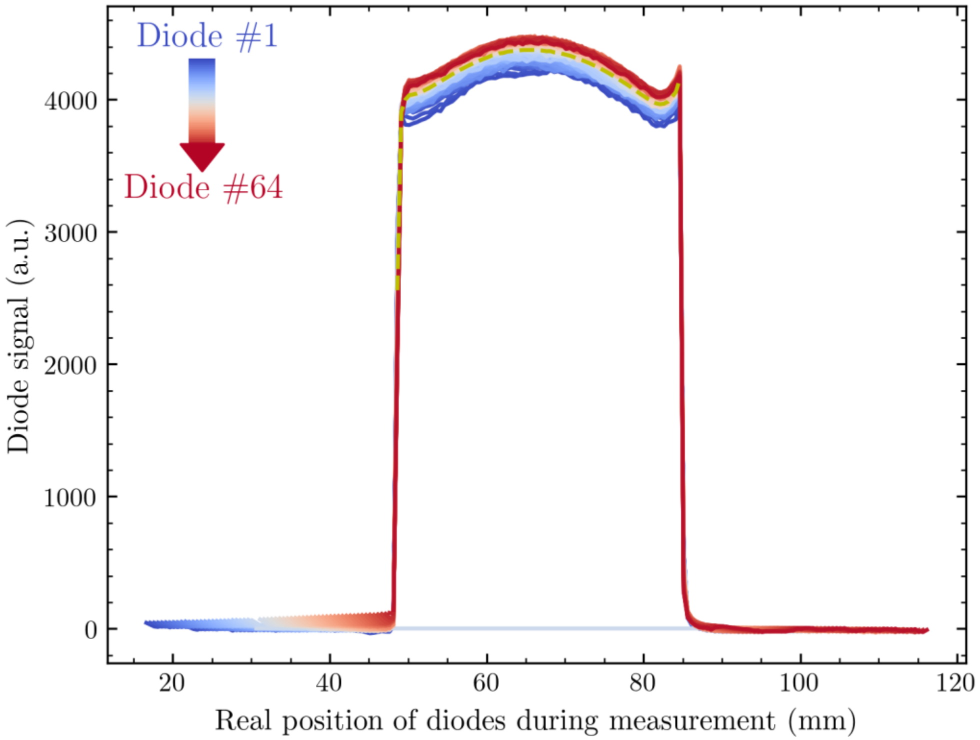
Old design had ≈ 120 % deviation, both 128 line arrays are within ≈ 6%

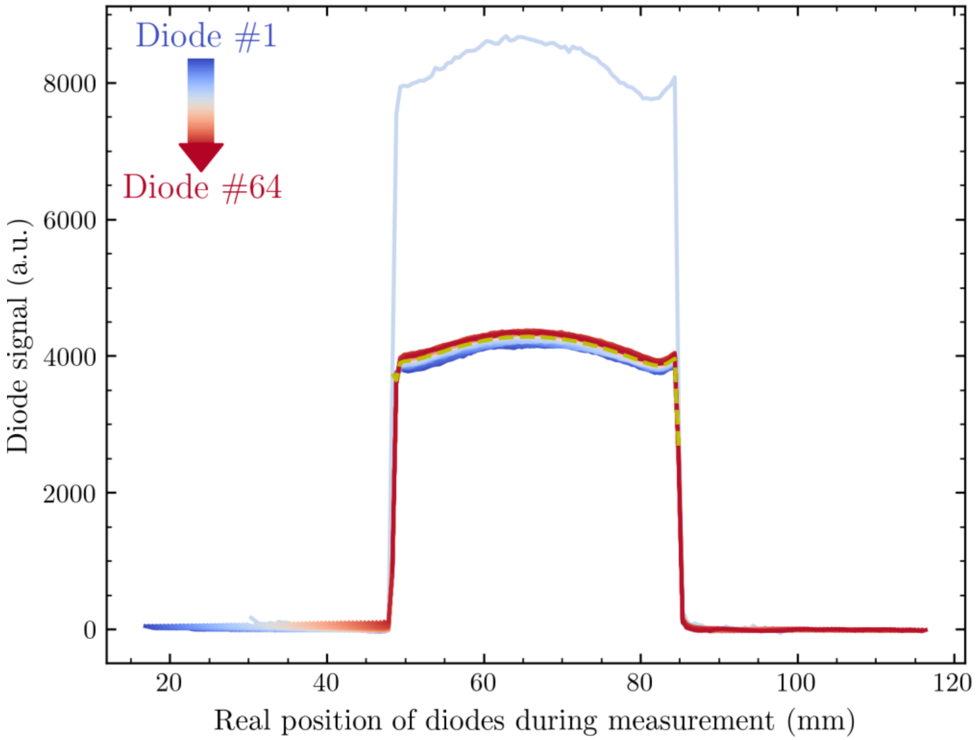
Only one not working diode out of 2 times 128 diodes ≈ efficiency of 99,6 %

Same for 2x64 array / matrix arrays



Not every diode is overlapping at every position!

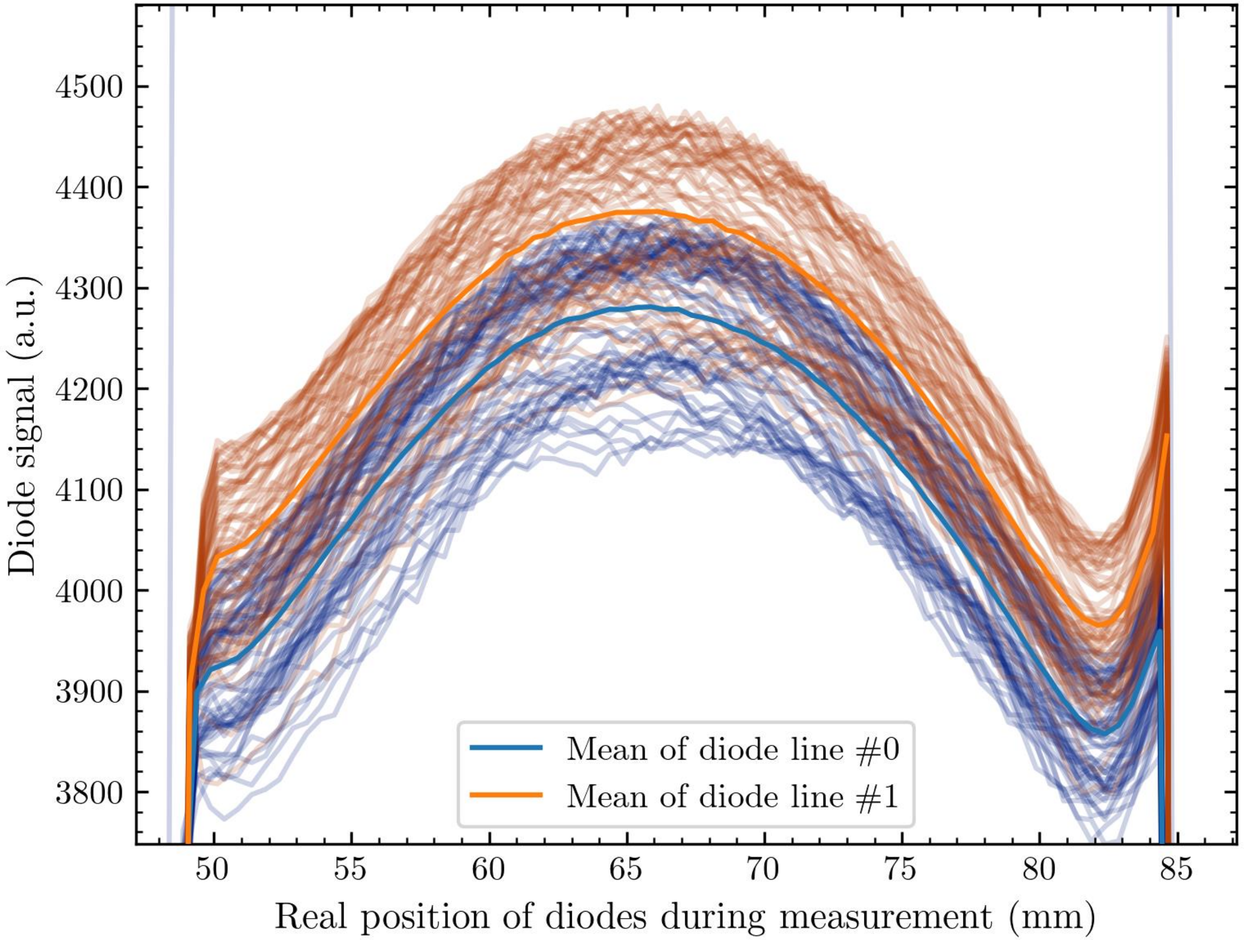


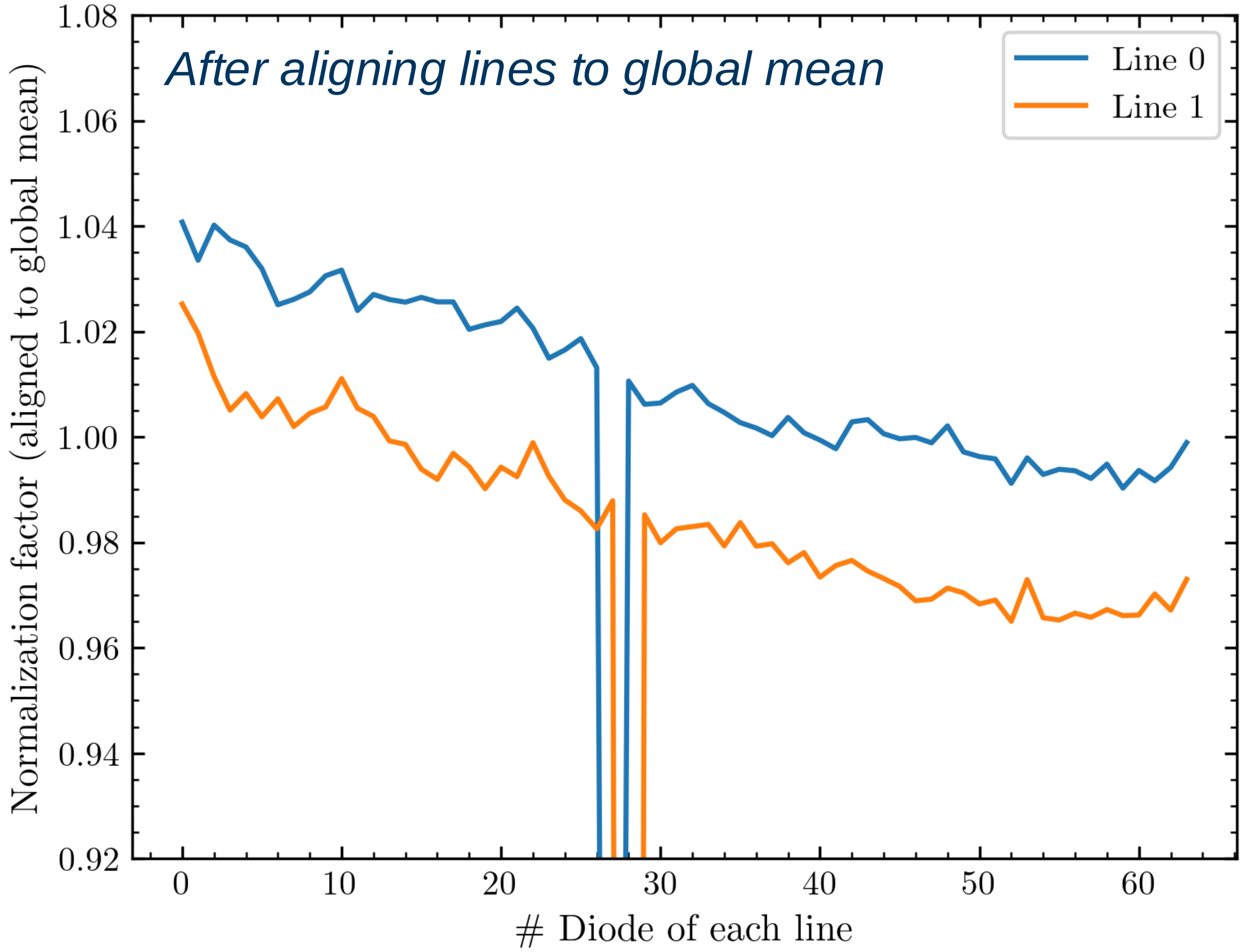


2x64 0.5x0.5 mm^2 array

Factor for each line

There seems to be a difference between the two lines?!

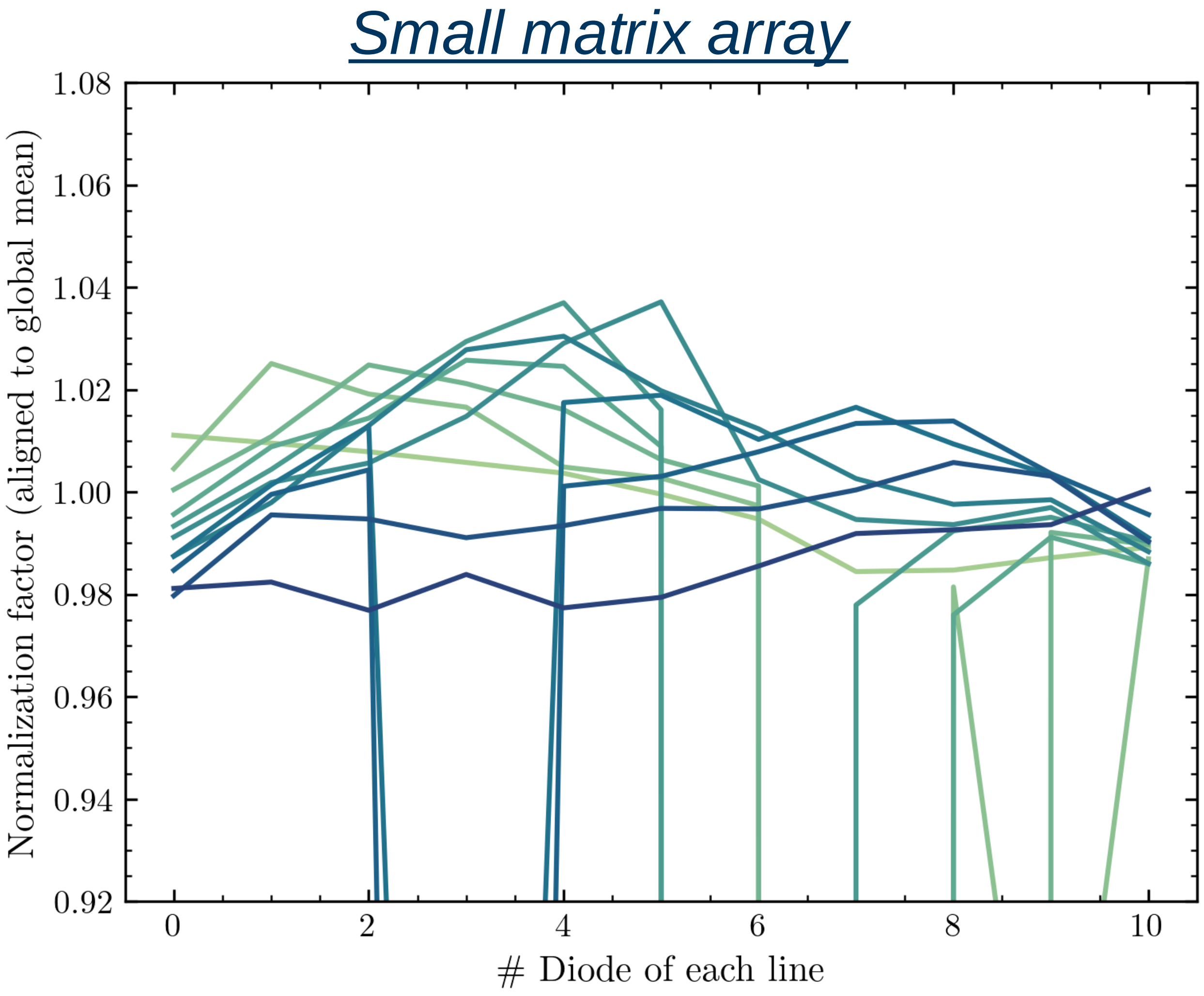


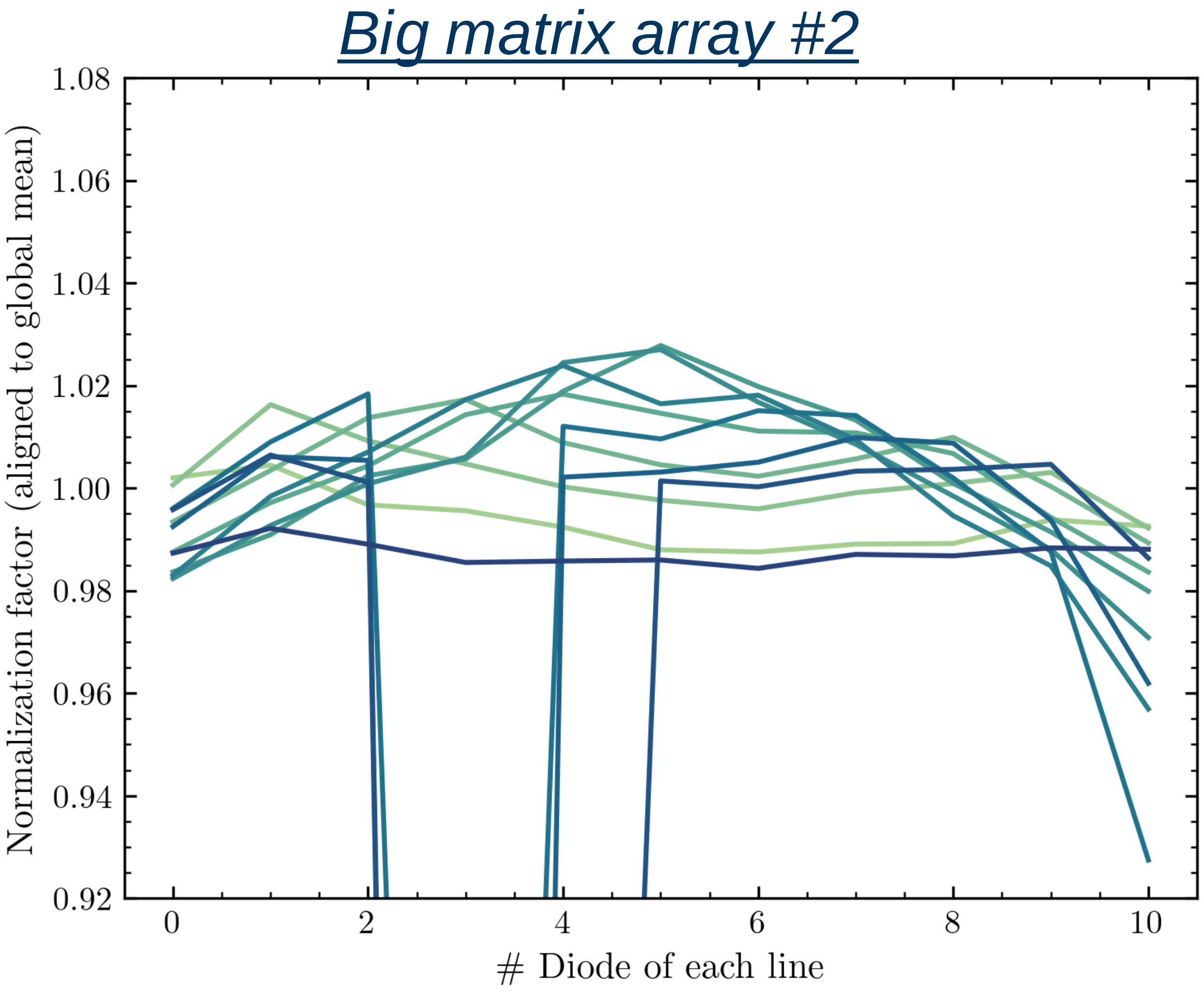


- Note that there is a pattern underneath both curves
- The proton current decreased during the measurement
- This low-frequency pattern will be filtered in the future!

2x64 0.5x0.5 mm^2 array

Homogeneity for matrix arrays





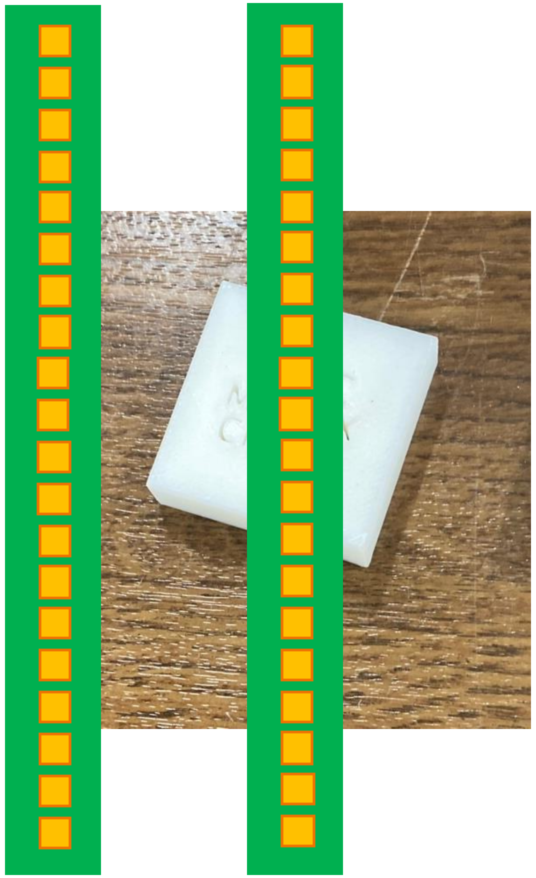
Part III

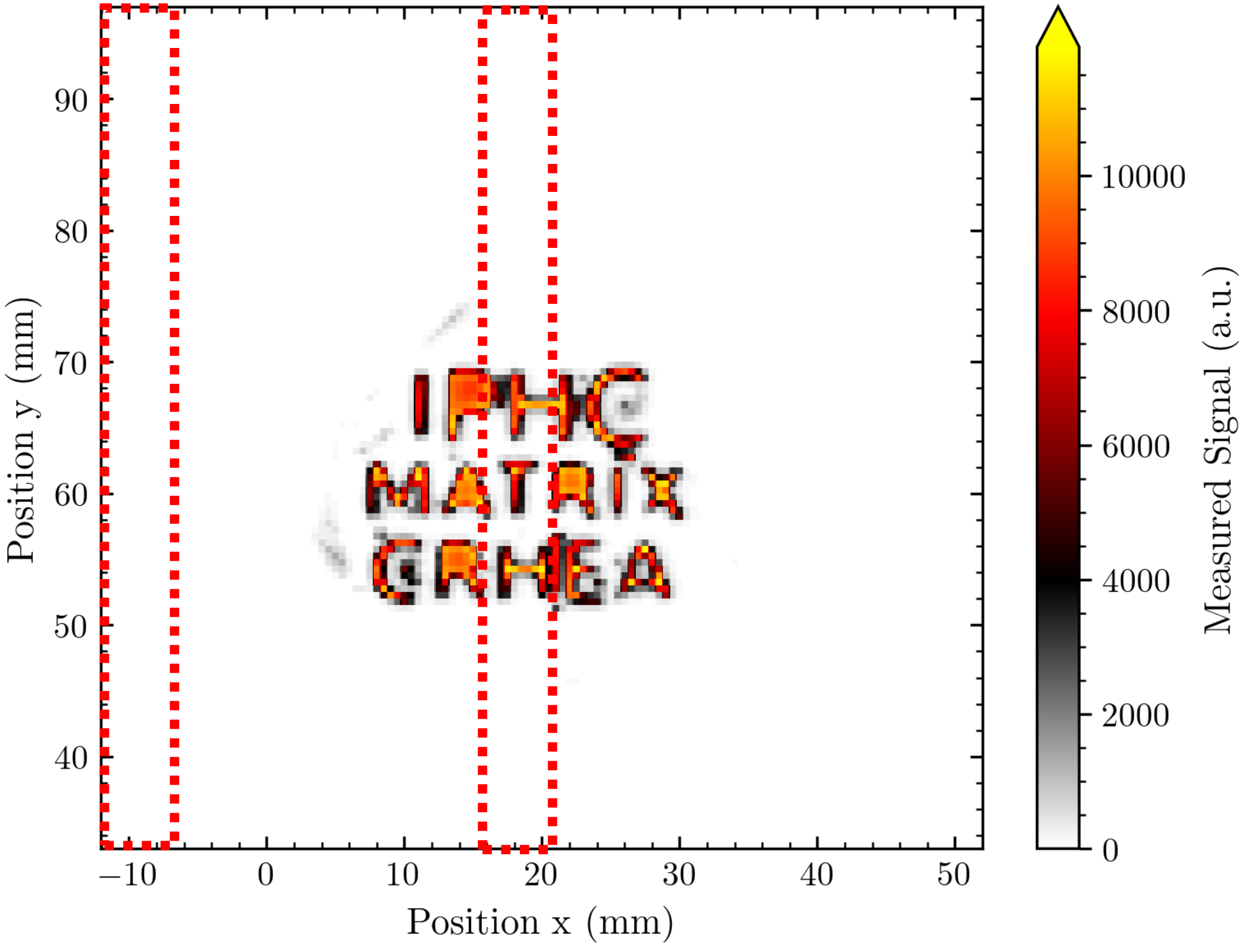
Details on image generation

Imaging

How I create the images

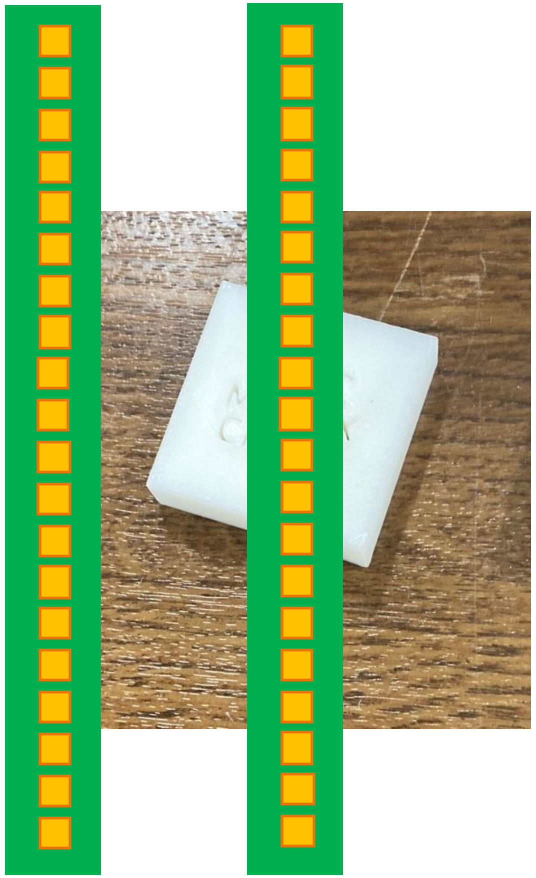
Out of translation

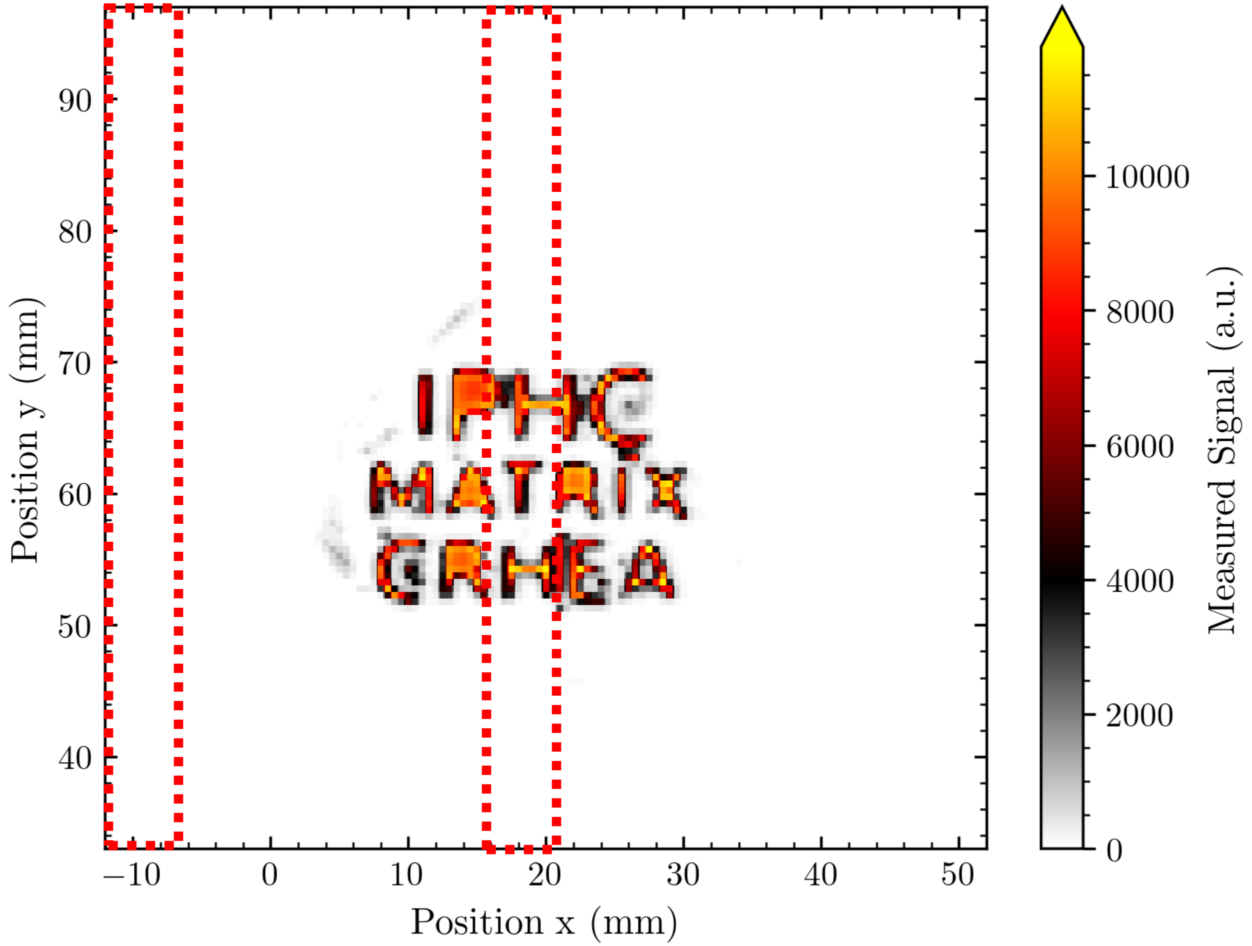




How I create the images

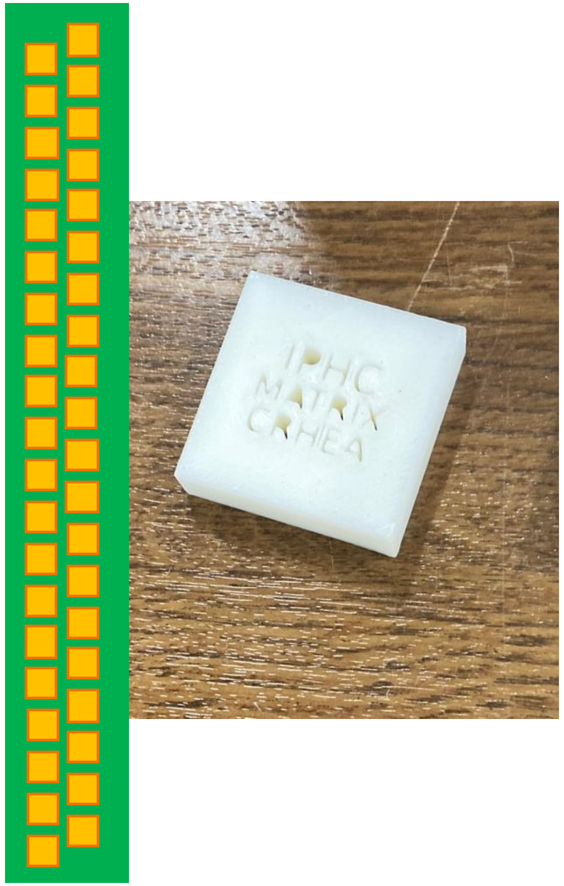
Out of translation

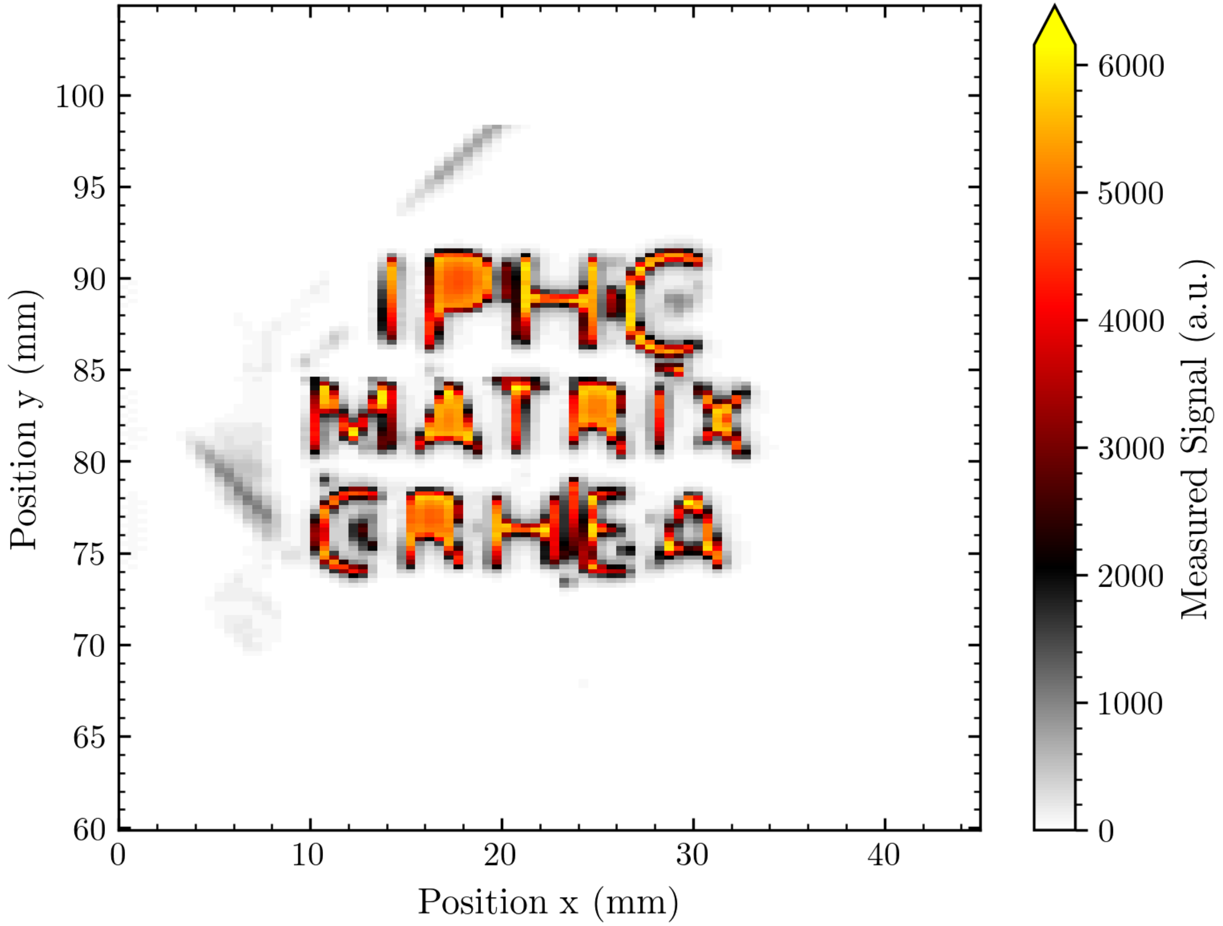




How I create the images

Out of translation + diode geometry

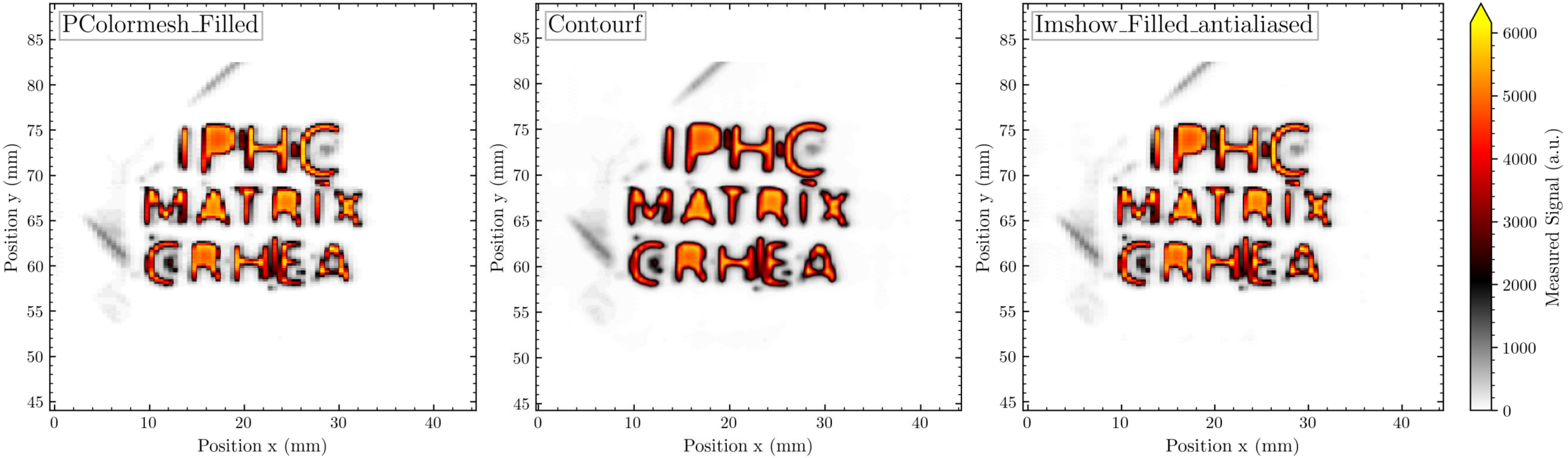




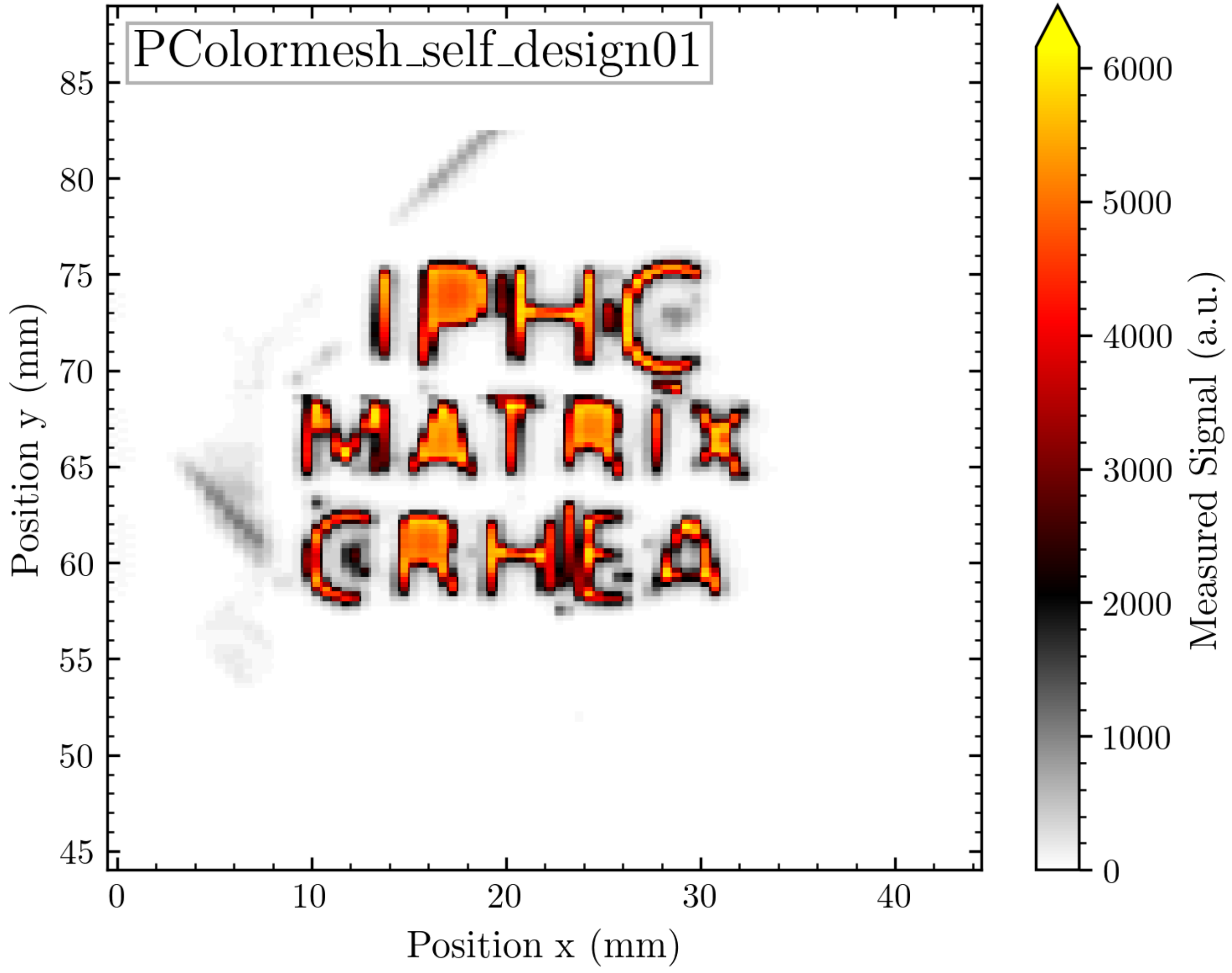
Different techniques

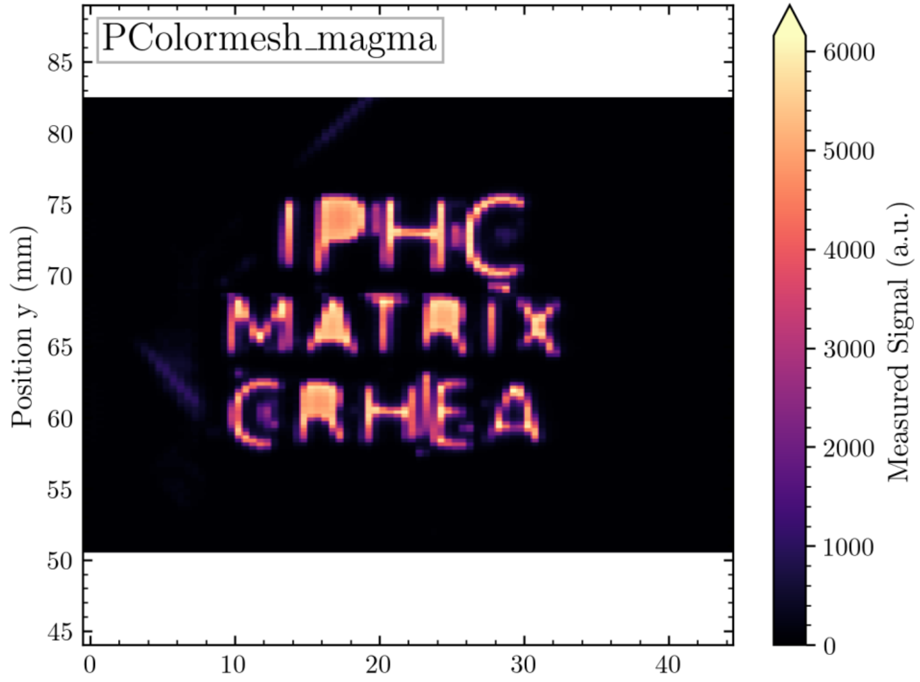
I create our images (and in general all plots) with Python's library Matplotlib:

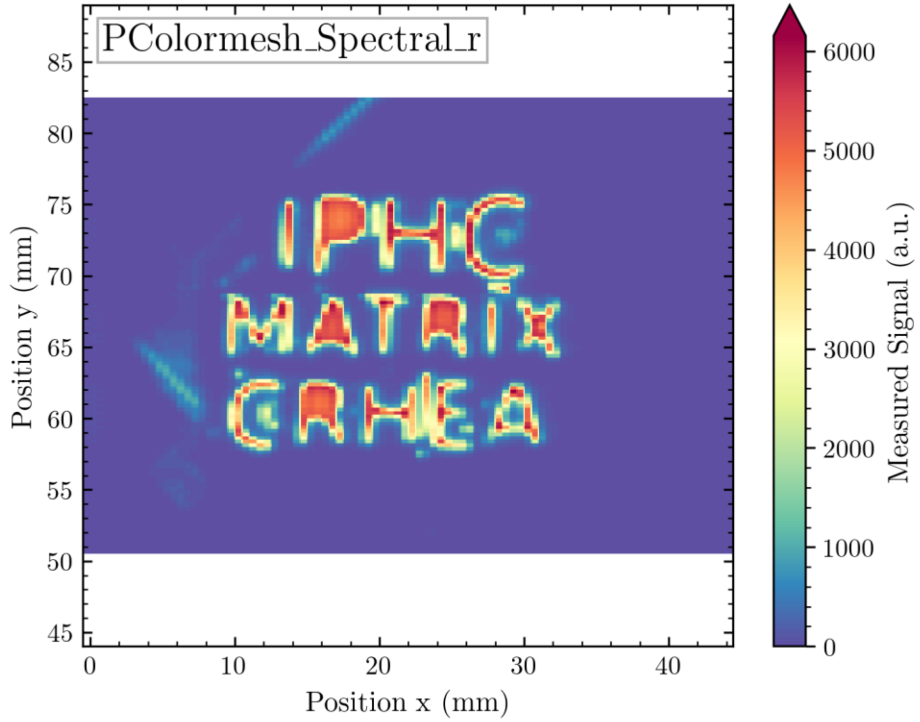
- **Pcolourmesh = Different - sized rectangles with colour**
- Contourf = Values are assigned to coordinate points in between the colour is interpolated
- Also possible (but no real gain in my tests): Imshow (equally sized pixels, standard for images)



All colourmaps possible!

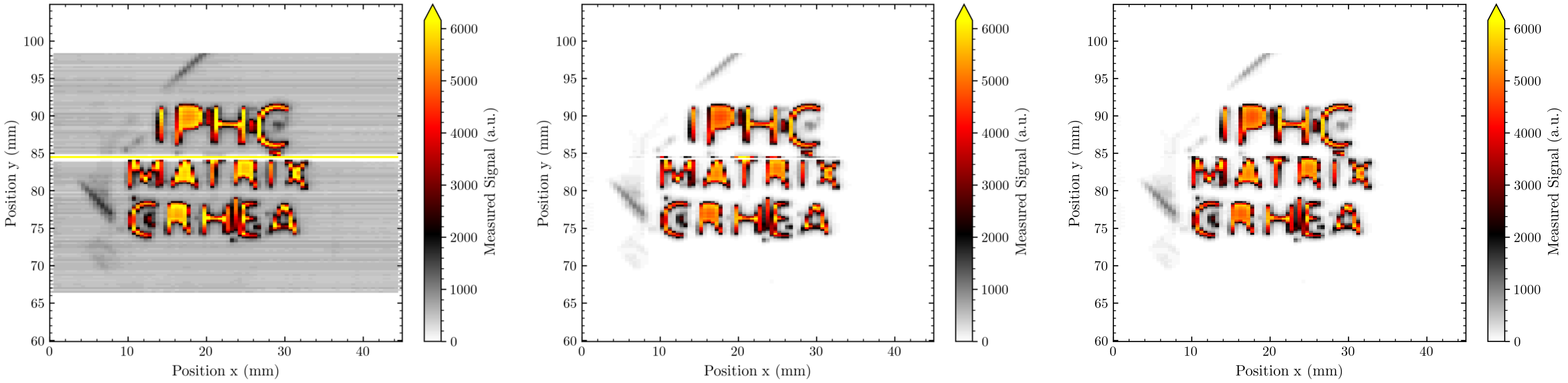




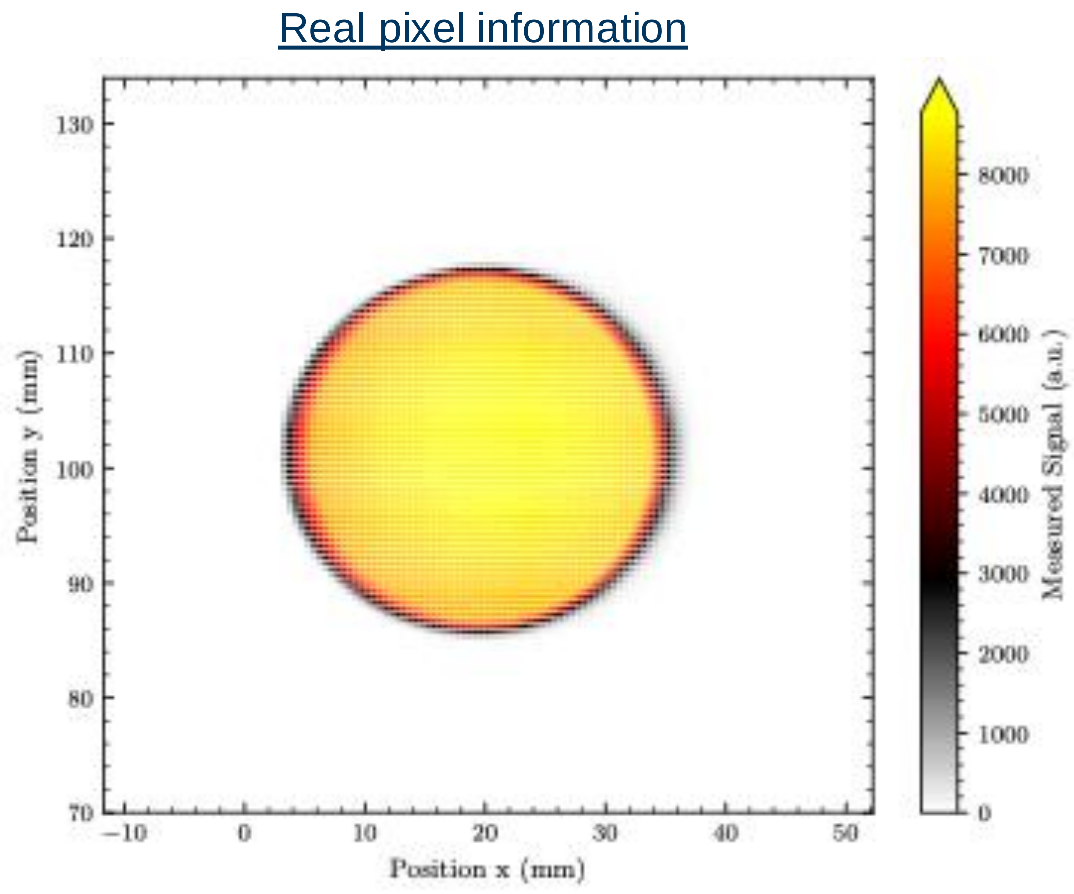


General info about images I'll show

- **Signals are for now shown in units of the AMS circuit output (unclear how to exactly calculate the current out of the AMS output amplitude)**
- **Images are background subtracted and normalized (as shown)**
- **In some cases, I might compensate for single lines not working**
- **I stay with oversampling since I still need to implement a deconvolution into super-resolved pixels**

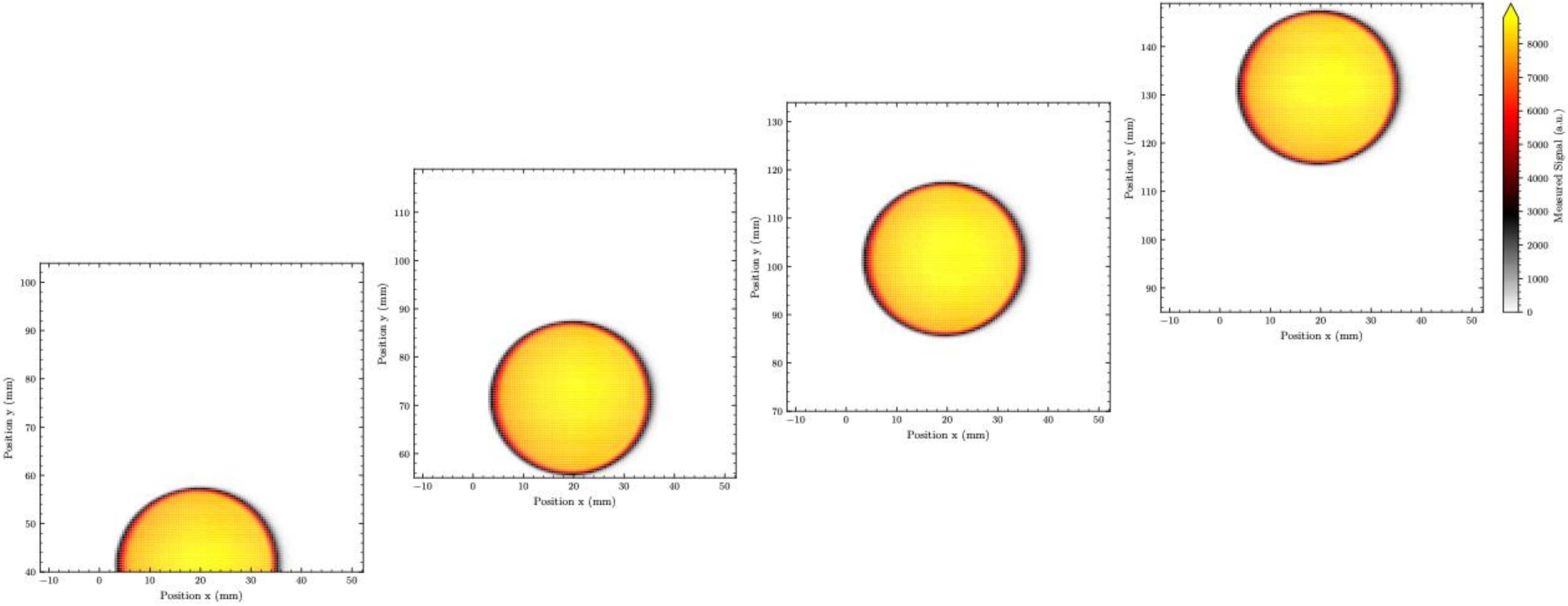


The round aperture / 200 μm diffuser



1x128 0.5x0.5 mm^2 array

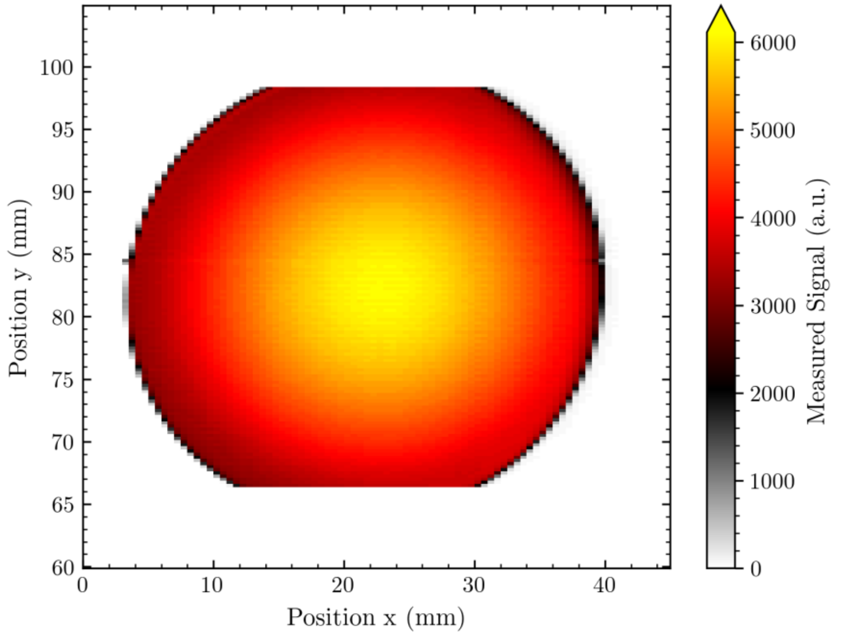
Sunrise of the proton beam ☺



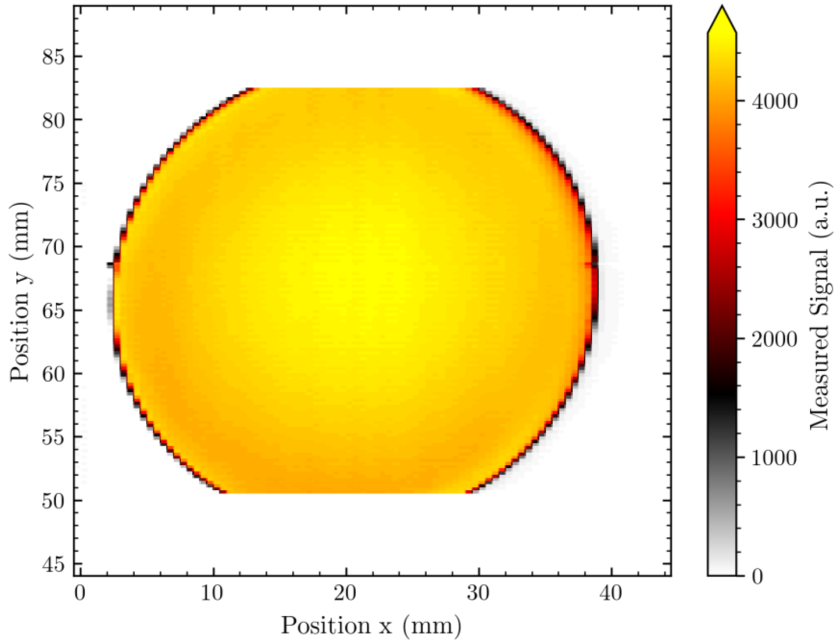
1x128 0.5x0.5 mm^2 array

The three available diffusers

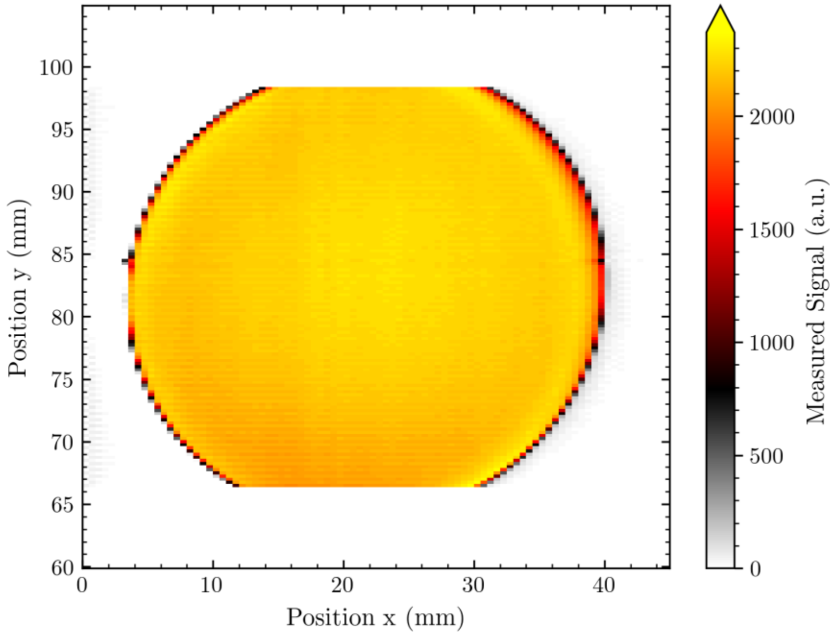
40 µm



200 µm



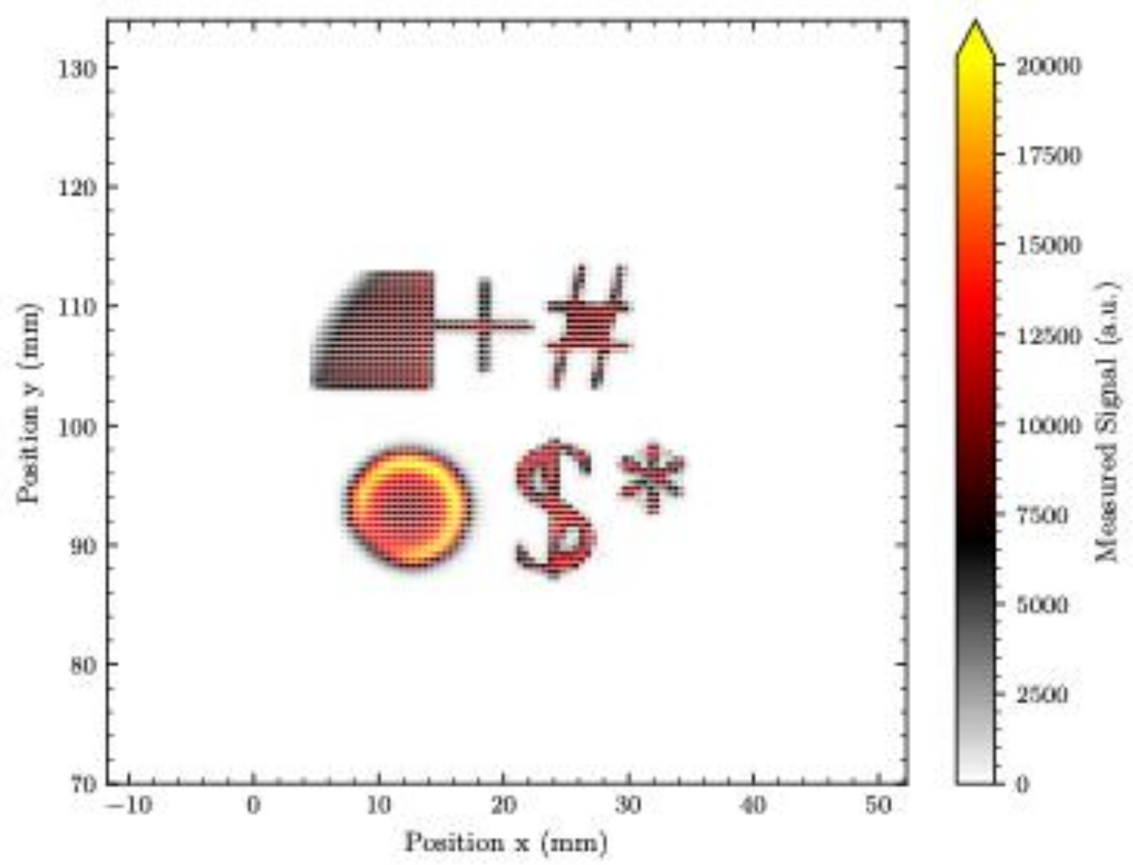
400 µm

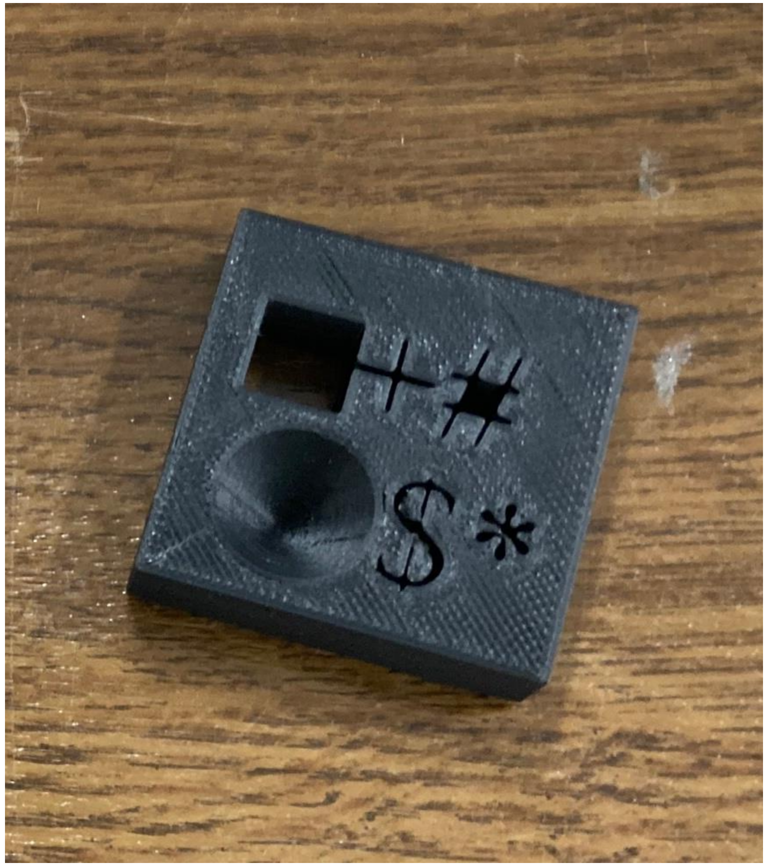


2x64 0.5x0.5 mm^2 array

The misc shape

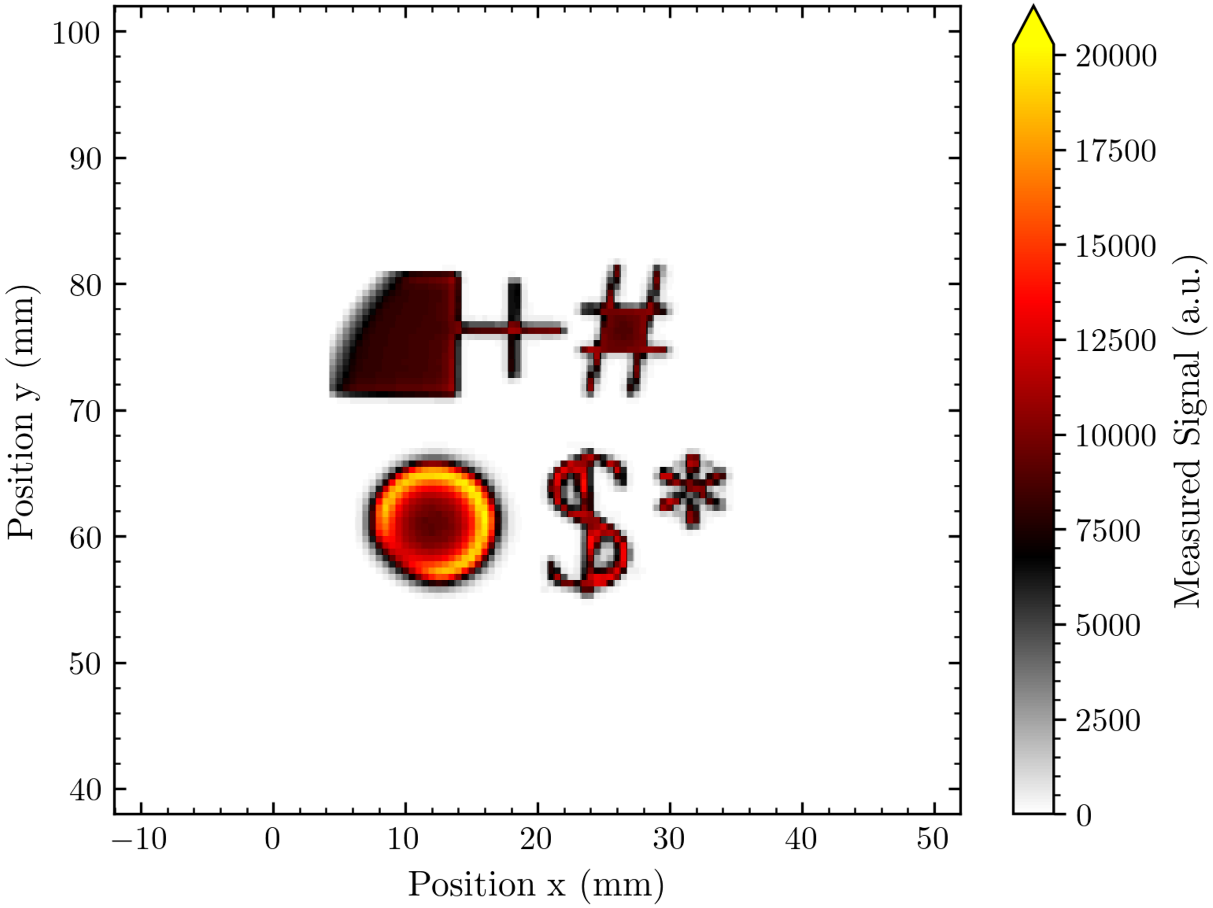
Real pixel information



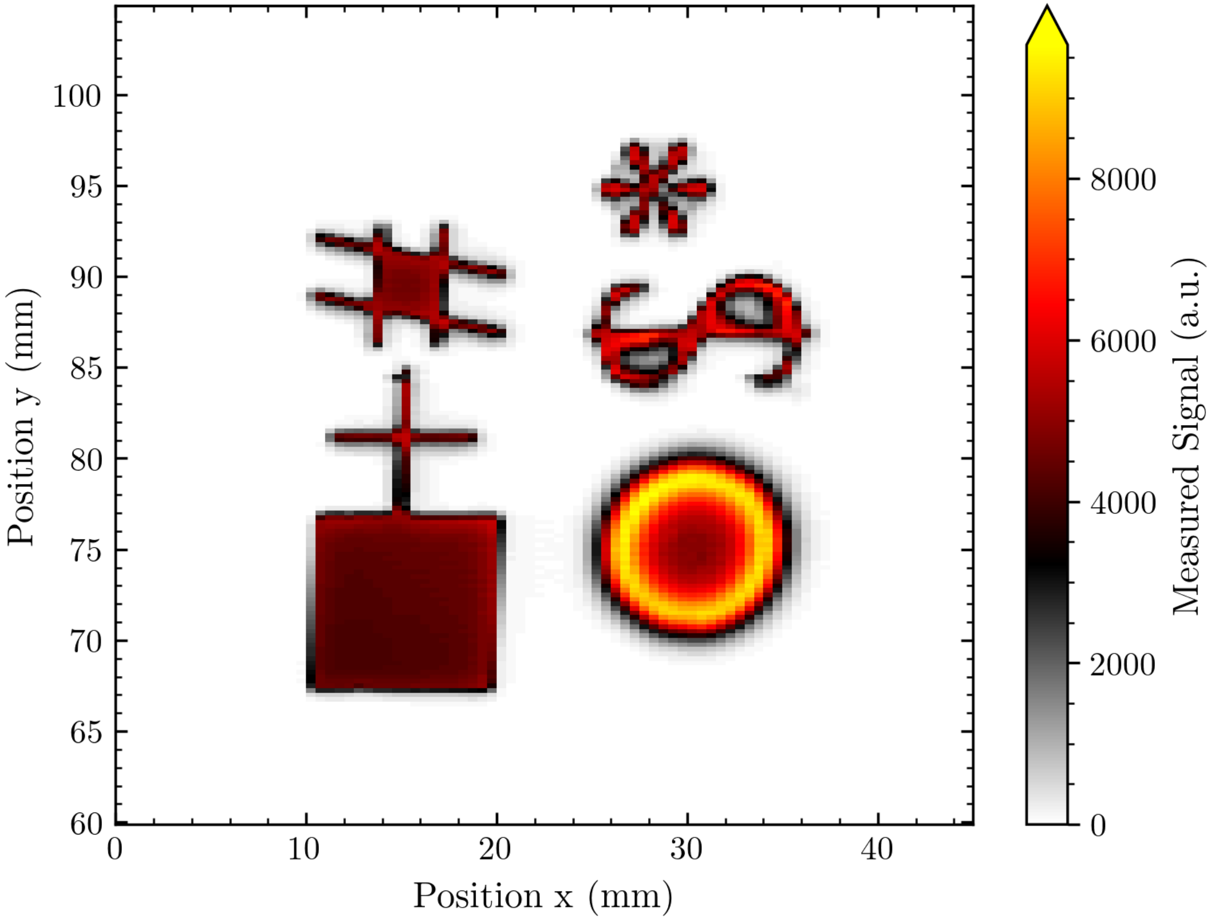


1x128 0.5x0.5 mm^2 array

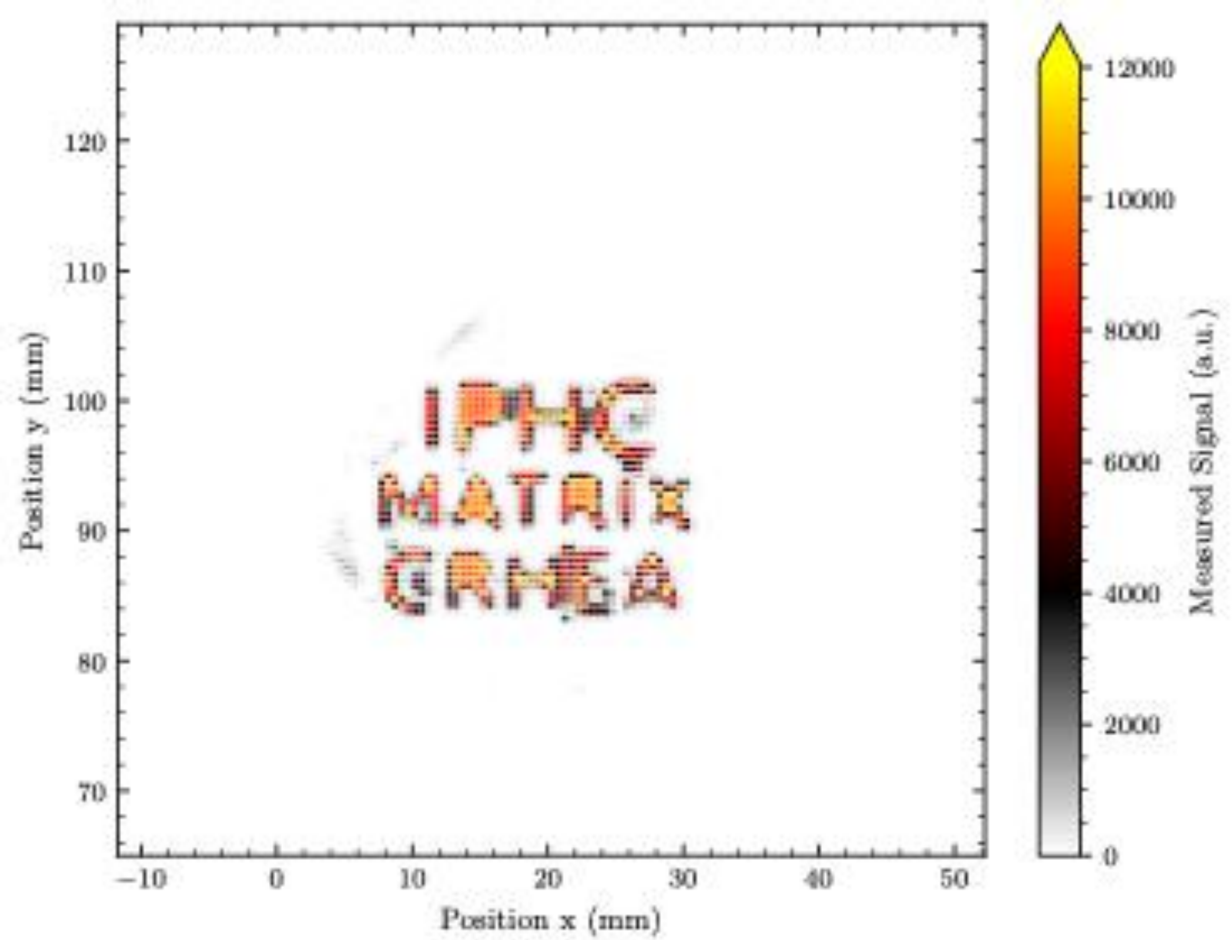
1x128 0.5x0.5 mm^2 array



2x64 0.5x0.5 mm^2 array

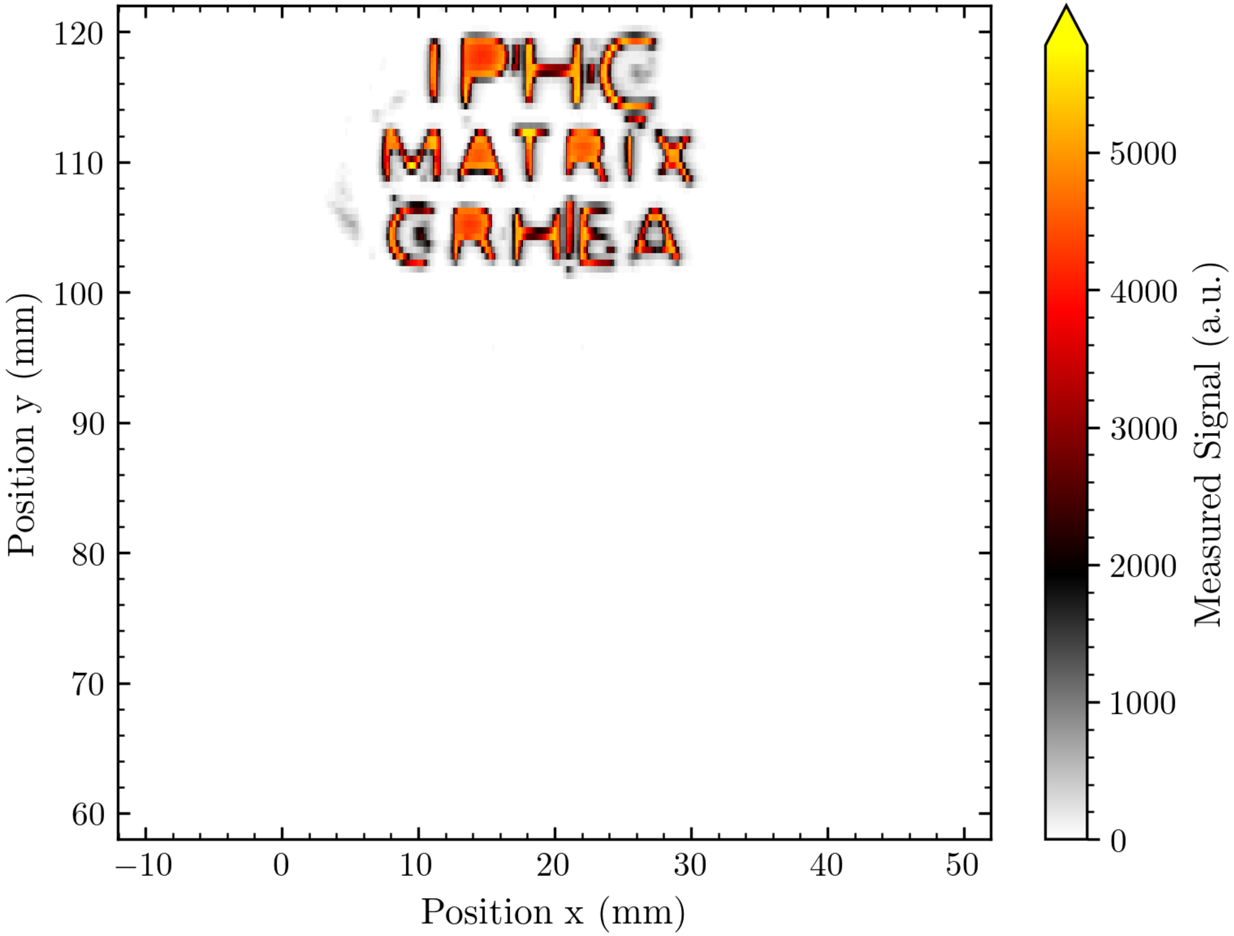


The logo



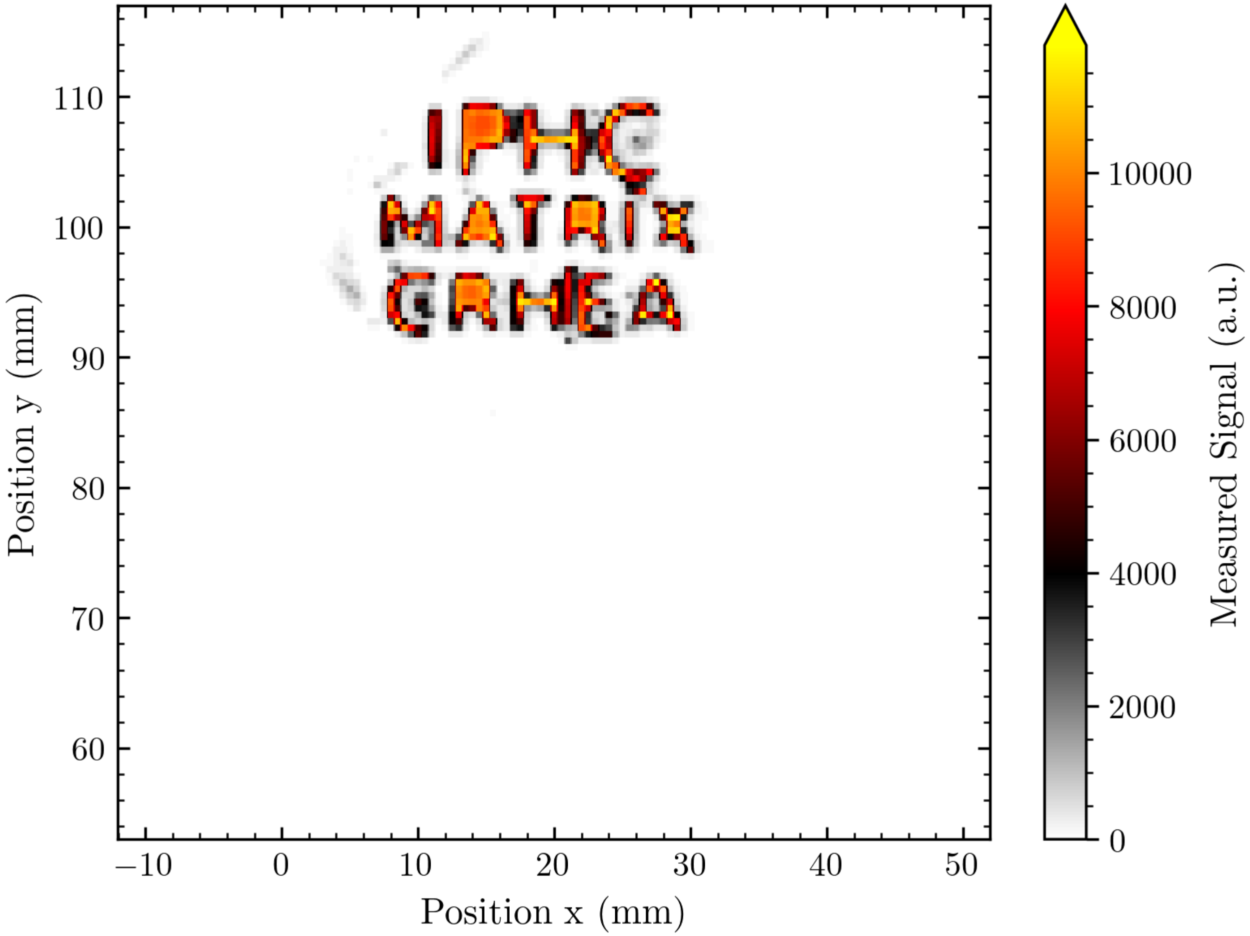
1x128 0.5x0.5 mm^2 array

Smaller diodes 0.25 mm in scan direction + 0.25 mm steps



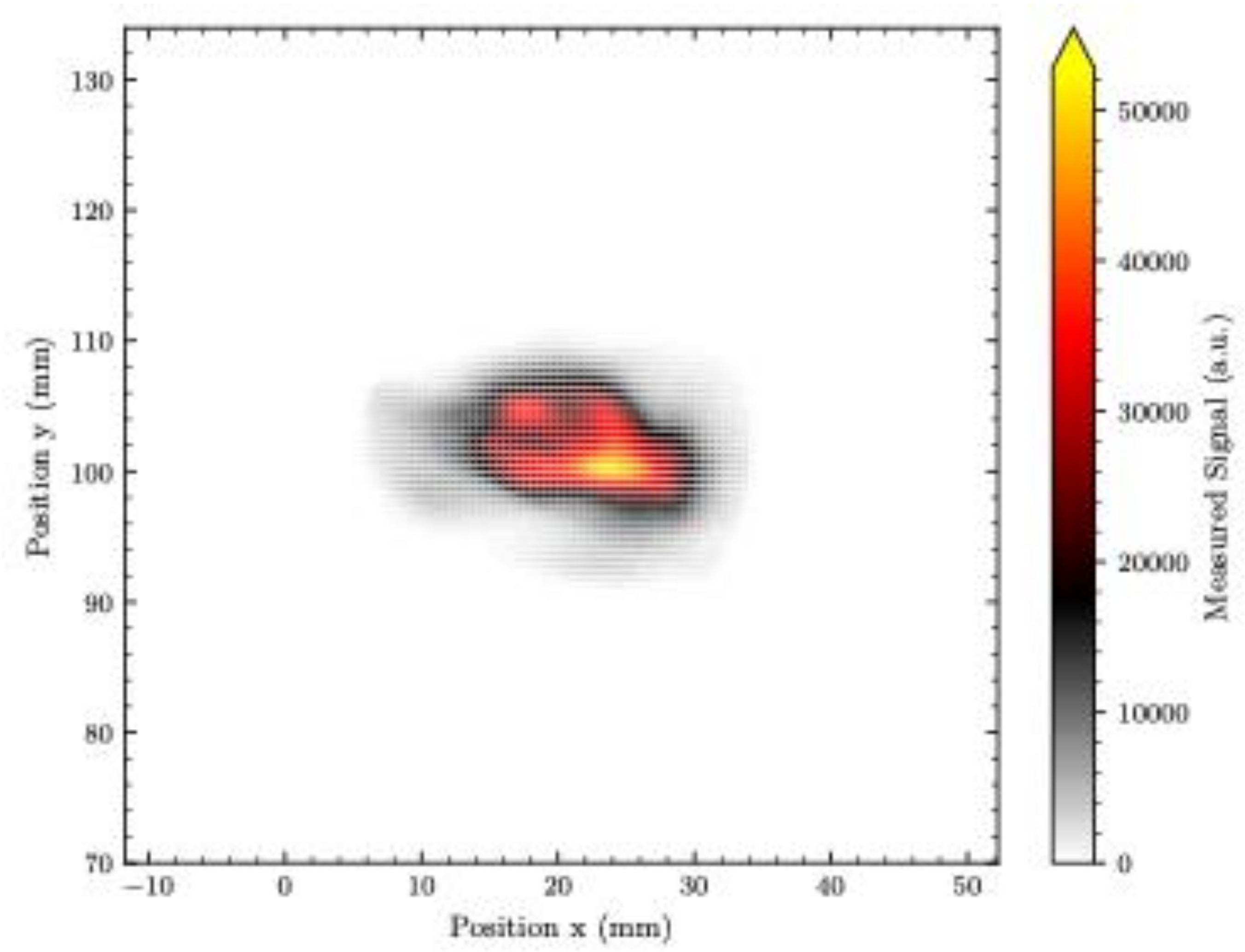
1x128 0.5x0.25 mm^2 array

0.5 mm diodes + 0.5 mm steps



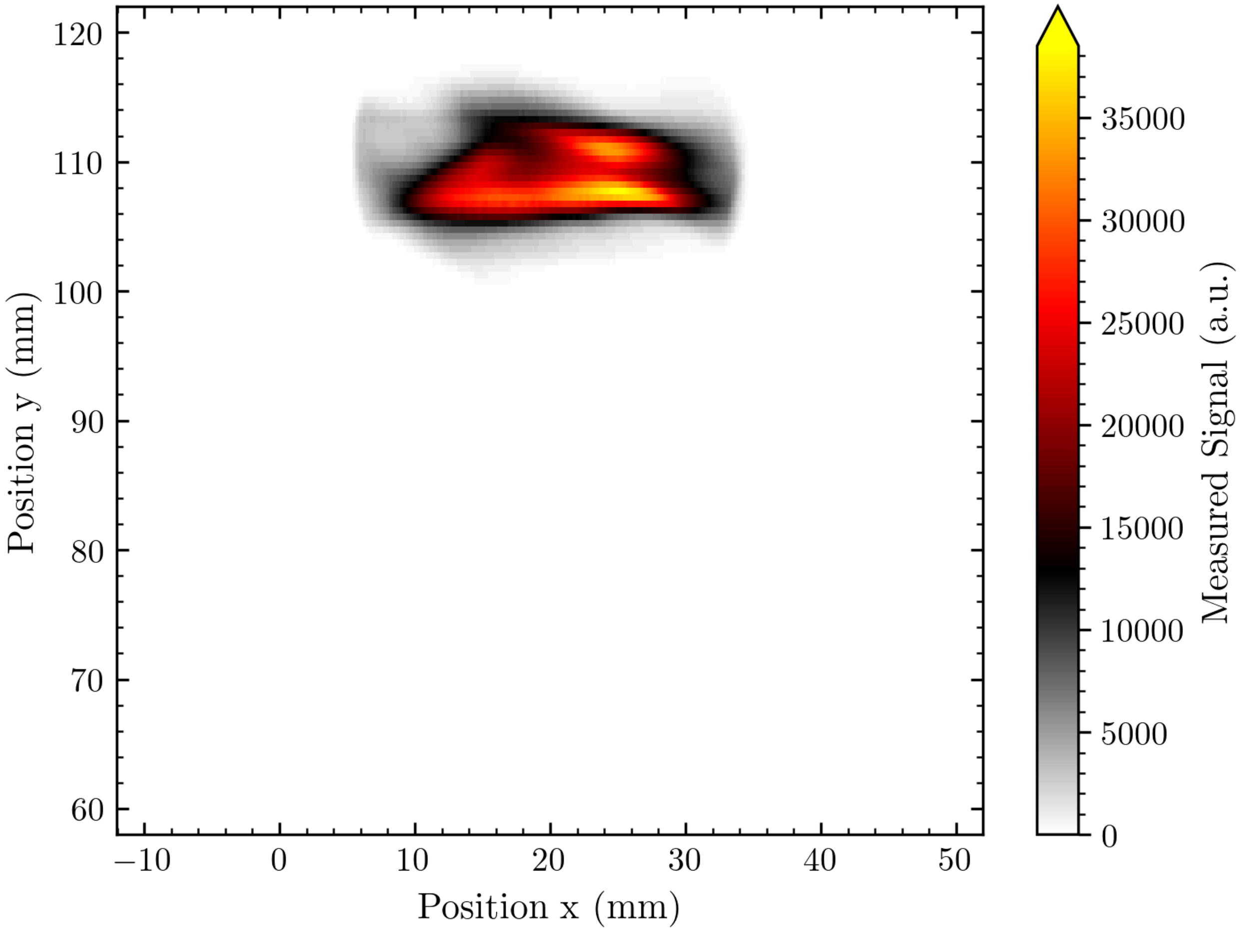
1x128 0.5x0.5 mm^2 array

Beam imaging without diffuser

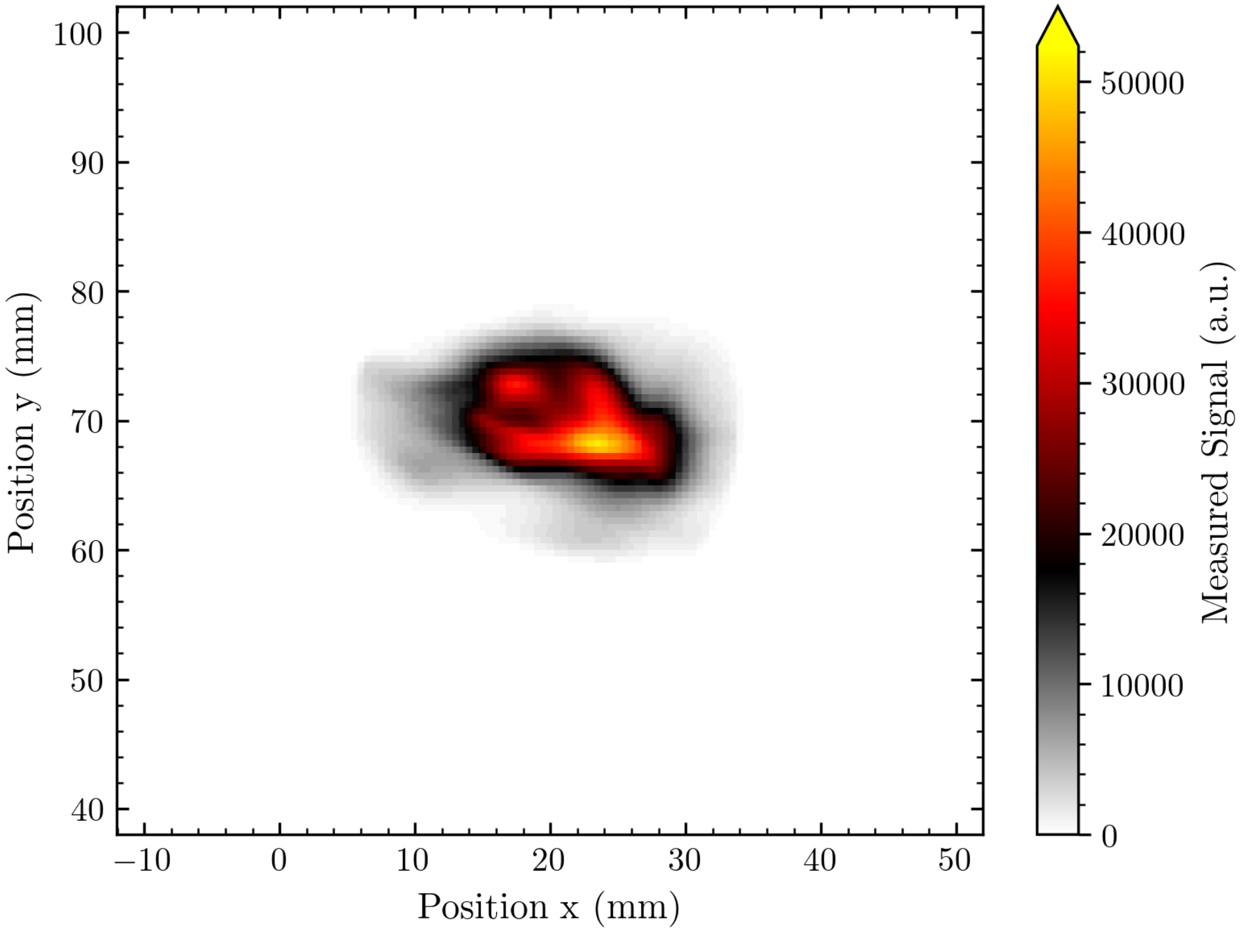


1x128 0.5x0.5 mm^2 array

Smaller diodes 0.25 mm in scan direction + 0.25 mm steps



0.5 mm diodes + 0.5 mm steps



Quite some change of the beam within our measurement day!

Can we get a better time resolution? Live imaging?

Note that we cannot compare the signal here due to the different set voltages!

Part IV

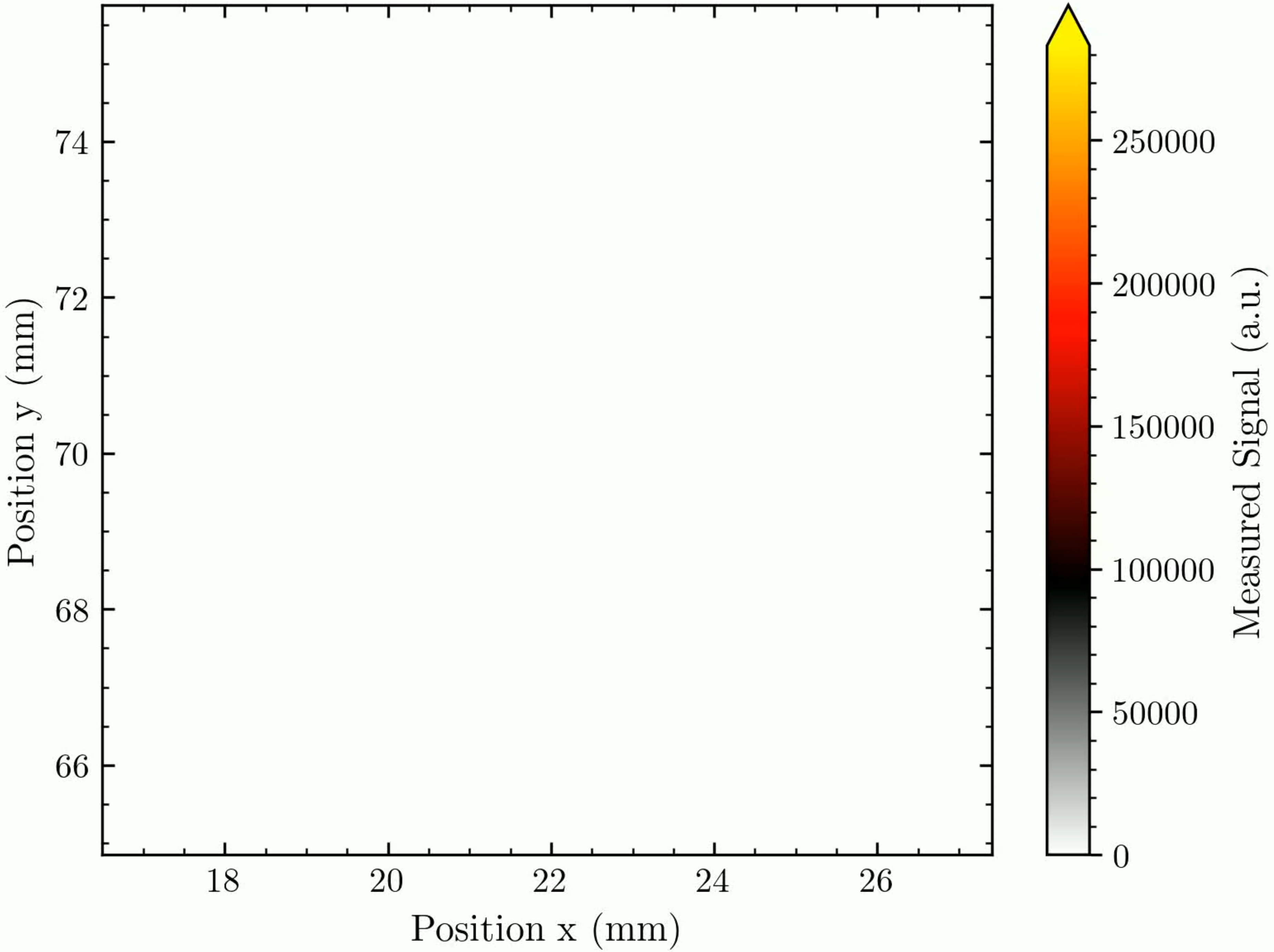
Imaging in time dependence = movies

What was measured?

- **11x11 1x1 mm^2 matrix #1 with higher time resolution (≈ 0.7 fps in this case; 1540 images over 36 minutes!)**
- **Video will be x50 increased in speed**
- **The array was fixed during the measurement.**
- **Three phases:**

1. Beam stability (no changes)
2. Changes with collimation magnets
3. Wire moving through the beam

(To get a beam profile Cyrcé facility moves wires through the beam line and measures a current. For us this means something shadows the array.)



Three phases:

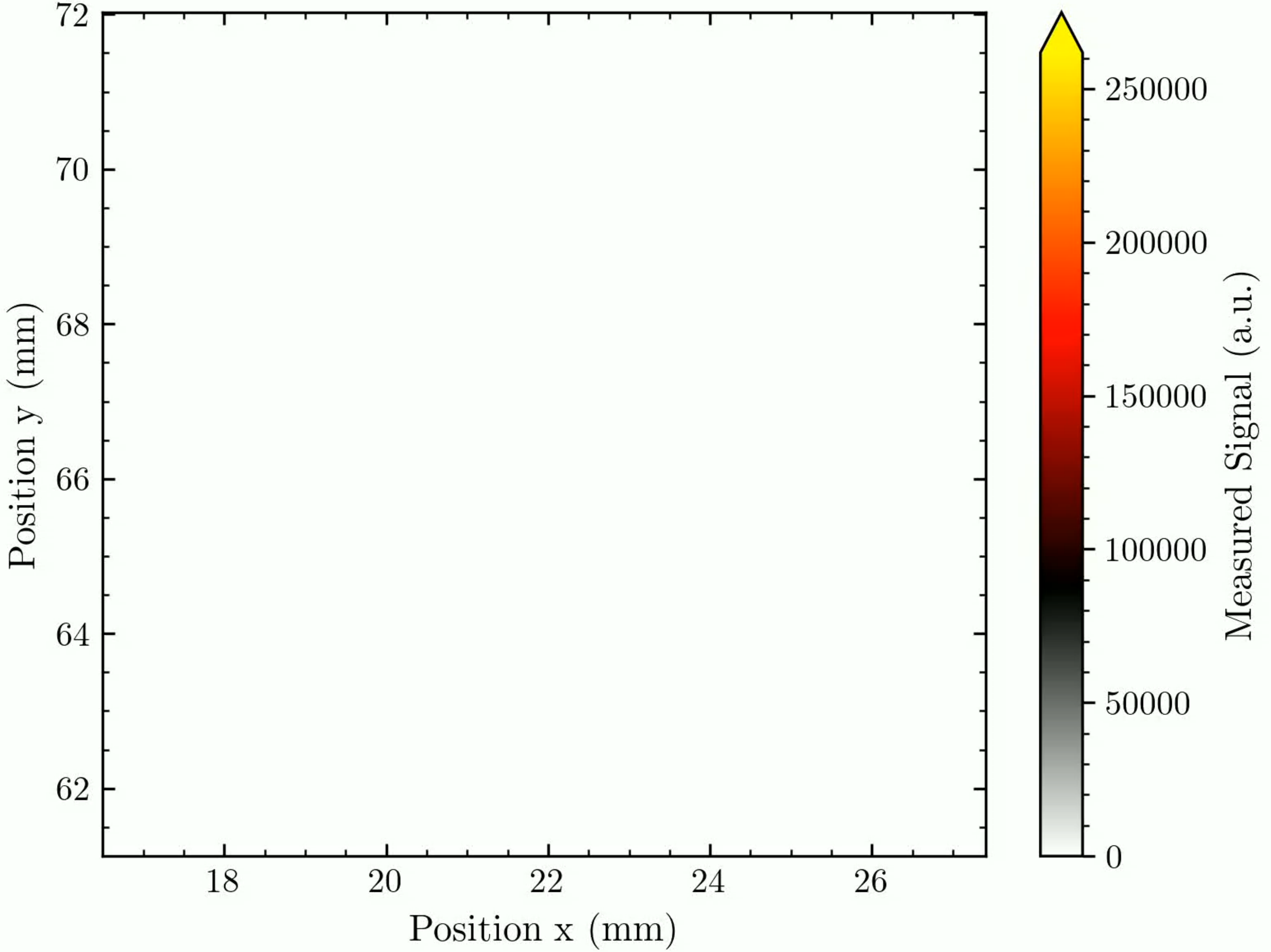
1. Beam stability (no changes)
2. Changes with collimation magnets
3. Wire moving through the beam

11x11 1x1 mm^2 matrix array #1

What was measured?

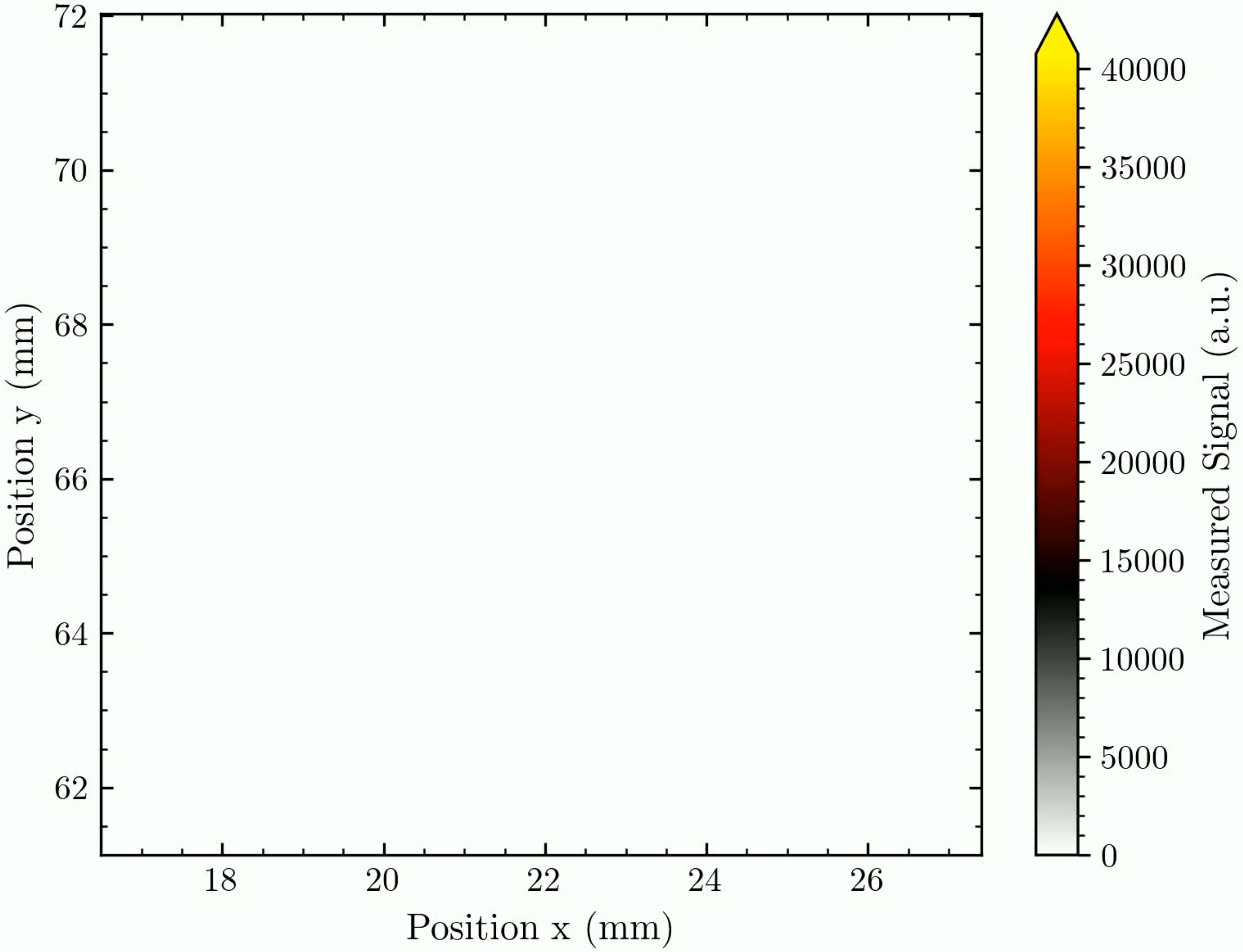
- **11x11 1x1 mm^2 matrix #2 with 1 fps**
- **Video will be x30 increased in speed**
- **The array was fixed during the measurement.**

What limits faster measurements so far: The readout circuit, or more precisely the software we have to use in the test kit…



1. Live diffuser in and out
2. Slit closing
3. Wire moving
4. Magnet shift

11x11 1x1 mm^2 matrix array #2



Square aperture

200 µm diffuser

Current increase from 100 pA to 3.6 nA

(Array is tilted a bit)

11x11 1x1 mm^2 matrix array #2

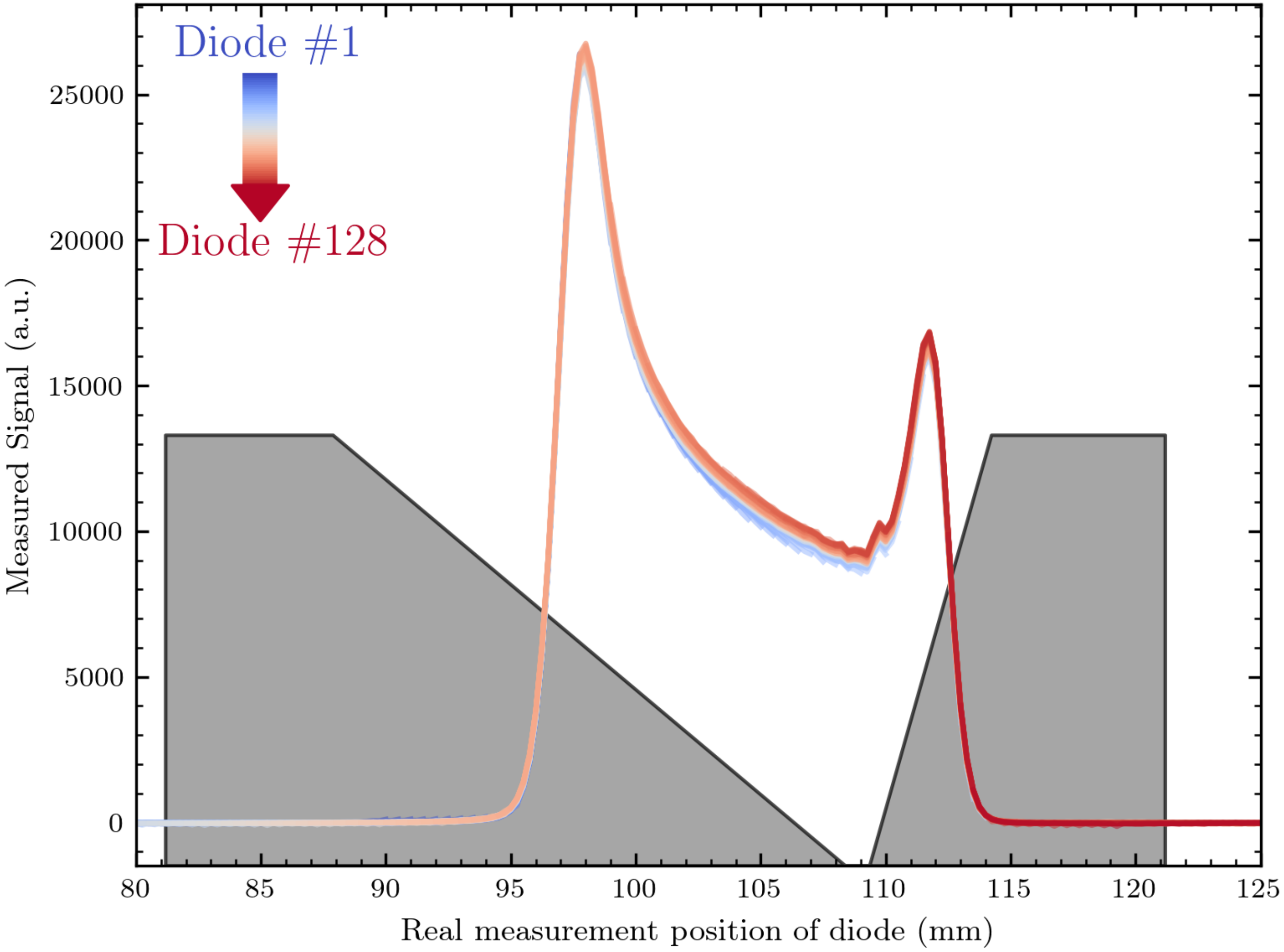
Part V

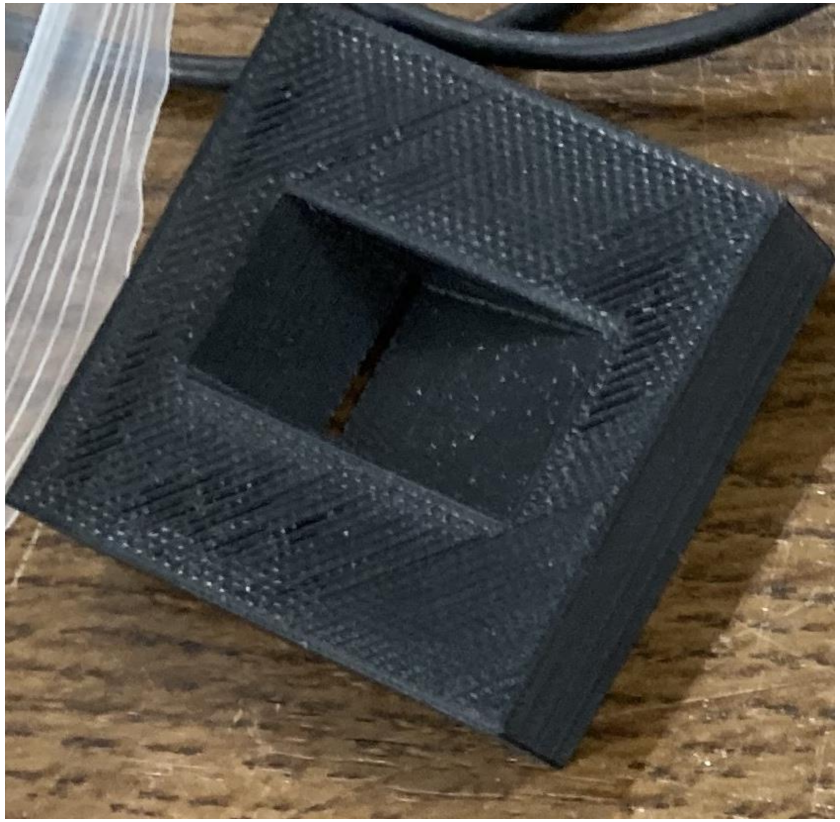
Resolving proton energy

PEEK wedge

Imaging of biological tissue

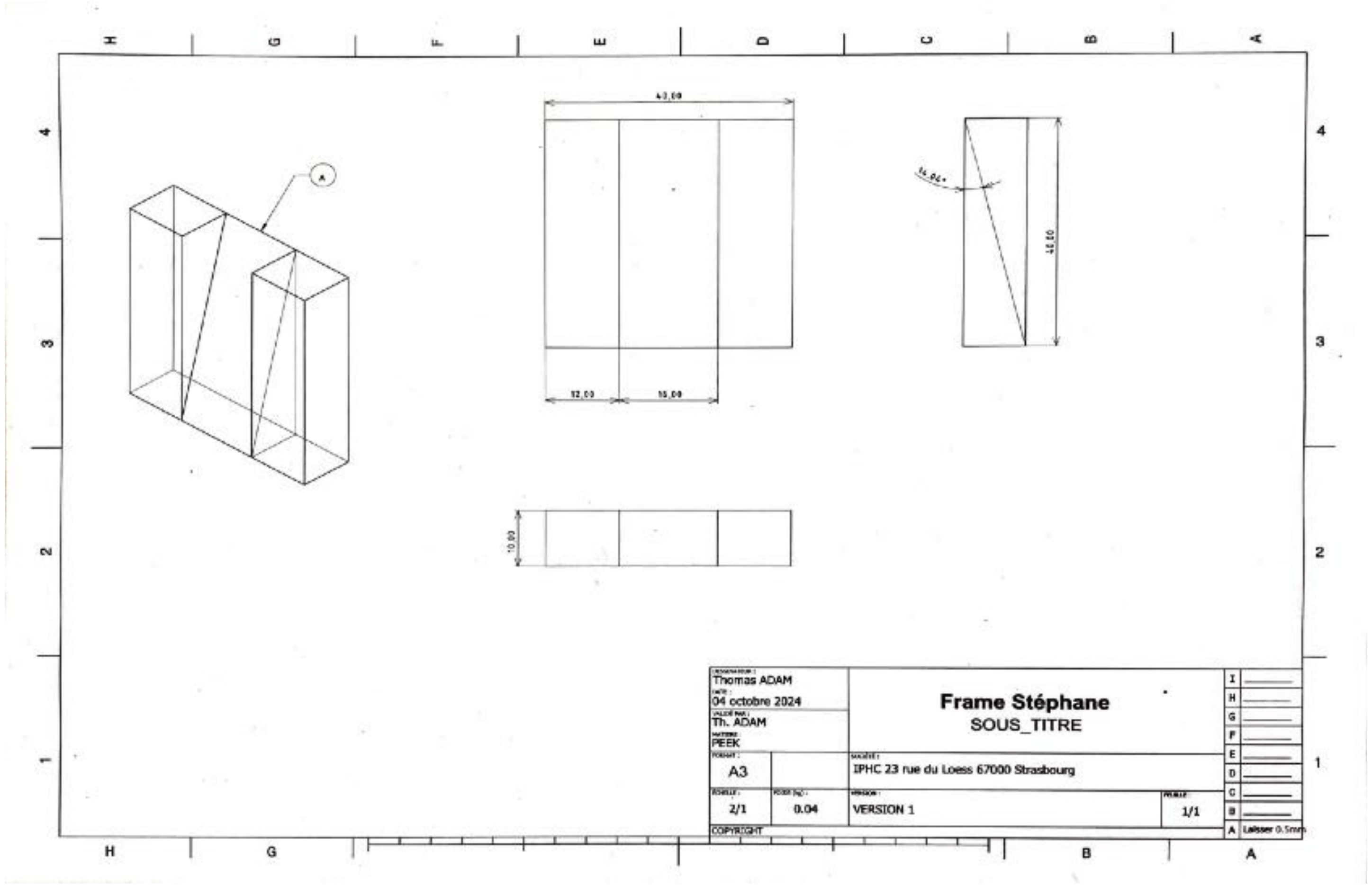
The Bragg peak (1 map and y translated data)

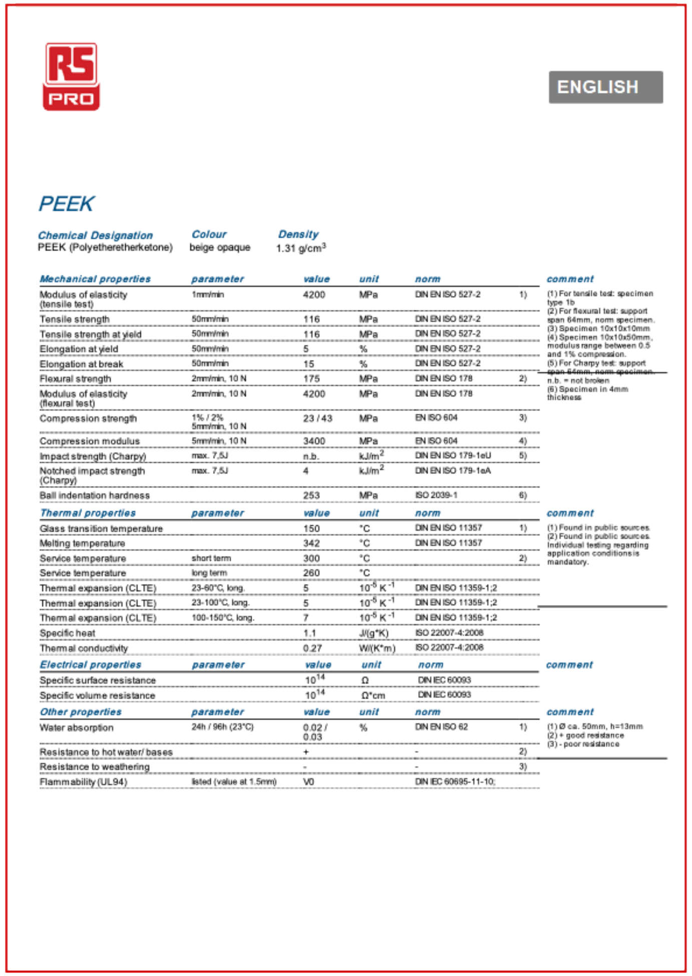




1x128 0.5x0.5 mm^2 array

Wedge out of PEEK material





ENGLISH

PEEK

Chemical Designation	Colour	Density
PEEK (Polyetheretherketone)	beige opaque	1.31 g/cm³

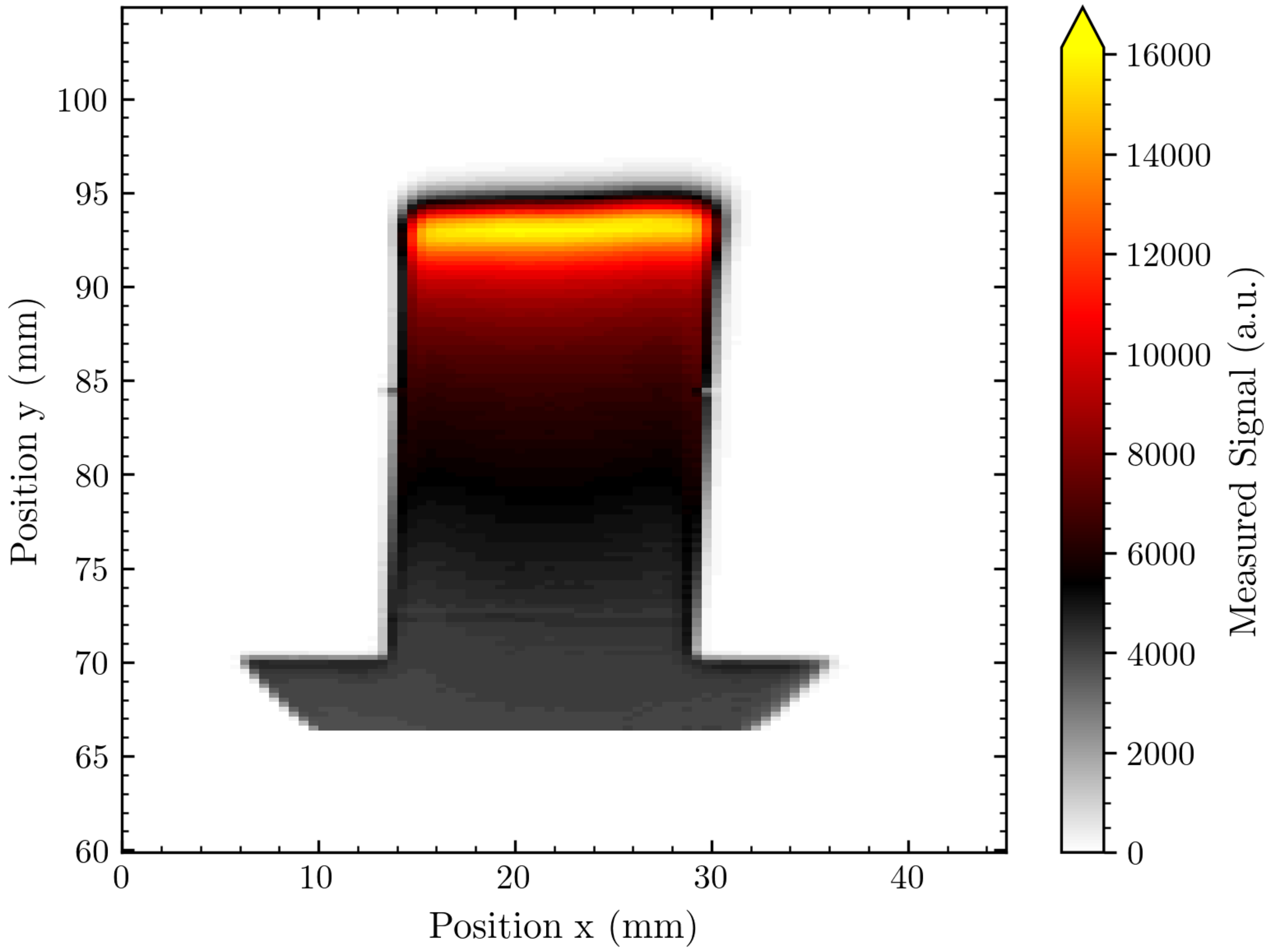
Mechanical properties	parameter	value	unit	norm		comment
Modulus of elasticity (tensile test)	1mm/min	4200	MPa	DIN EN ISO 527-2	1)	(1) For tensile test: specimen type 1b (2) For flexural test: support span 64mm, norm specimen. (3) Specimen 10x10x10mm (4) Specimen 10x10x50mm, modulus range between 0.5 and 1% compression. (5) For Charpy test: support span 64mm, norm specimen. n.b. = not broken (6) Specimen in 4mm thickness
Tensile strength	50mm/min	116	MPa	DIN EN ISO 527-2		
Tensile strength at yield	50mm/min	116	MPa	DIN EN ISO 527-2		
Elongation at yield	50mm/min	5	%	DIN EN ISO 527-2		
Elongation at break	50mm/min	15	%	DIN EN ISO 527-2		
Flexural strength	2mm/min, 10 N	175	MPa	DIN EN ISO 178	2)	
Modulus of elasticity (flexural test)	2mm/min, 10 N	4200	MPa	DIN EN ISO 178		
Compression strength	1% / 2% 5mm/min, 10 N	23 / 43	MPa	EN ISO 604	3)	
Compression modulus	5mm/min, 10 N	3400	MPa	EN ISO 604	4)	
Impact strength (Charpy)	max. 7,5J	n.b.	kJ/m²	DIN EN ISO 179-1eU	5)	
Notched impact strength (Charpy)	max. 7,5J	4	kJ/m²	DIN EN ISO 179-1eA		
Ball indentation hardness		253	MPa	ISO 2039-1	6)	

Thermal properties	parameter	value	unit	norm		comment
Glass transition temperature		150	°C	DIN EN ISO 11357	1)	(1) Found in public sources. (2) Found in public sources. Individual testing regarding application conditions is mandatory.
Melting temperature		342	°C	DIN EN ISO 11357		
Service temperature	short term	300	°C		2)	
Service temperature	long term	260	°C			
Thermal expansion (CLTE)	23-60°C, long.	5	10^{-5} K^{-1}	DIN EN ISO 11359-1;2		
Thermal expansion (CLTE)	23-100°C, long.	5	10^{-5} K^{-1}	DIN EN ISO 11359-1;2		
Thermal expansion (CLTE)	100-150°C, long.	7	10^{-5} K^{-1}	DIN EN ISO 11359-1;2		
Specific heat		1.1	J/(g*K)	ISO 22007-4:2008		
Thermal conductivity		0.27	W/(K*m)	ISO 22007-4:2008		

Electrical properties	parameter	value	unit	norm		comment
Specific surface resistance		10^{14}	Ω	DIN IEC 60093		
Specific volume resistance		10^{14}	Ω*cm	DIN IEC 60093		

Other properties	parameter	value	unit	norm		comment
Water absorption	24h / 96h (23°C)	0.02 / 0.03	%	DIN EN ISO 62	1)	(1) Ø ca. 50mm, h=13mm (2) + good resistance (3) - poor resistance
Resistance to hot water/ bases		+		-	2)	
Resistance to weathering		-		-	3)	
Flammability (UL94)	listed (value at 1.5mm)	V0		DIN IEC 60695-11-10;		

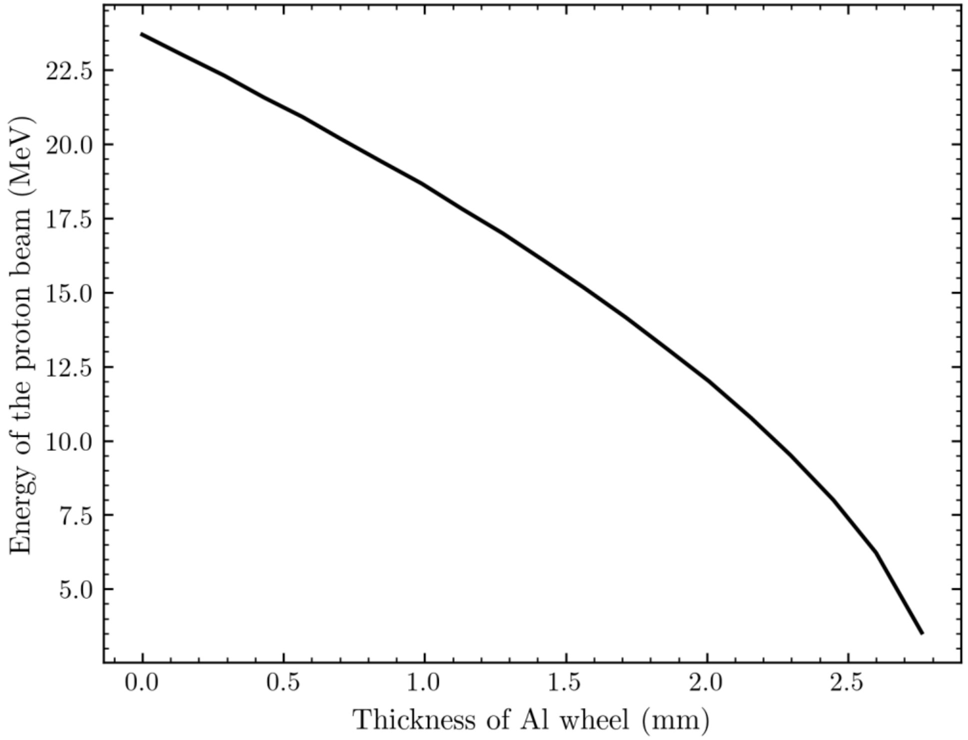
Map of PEEK wedge



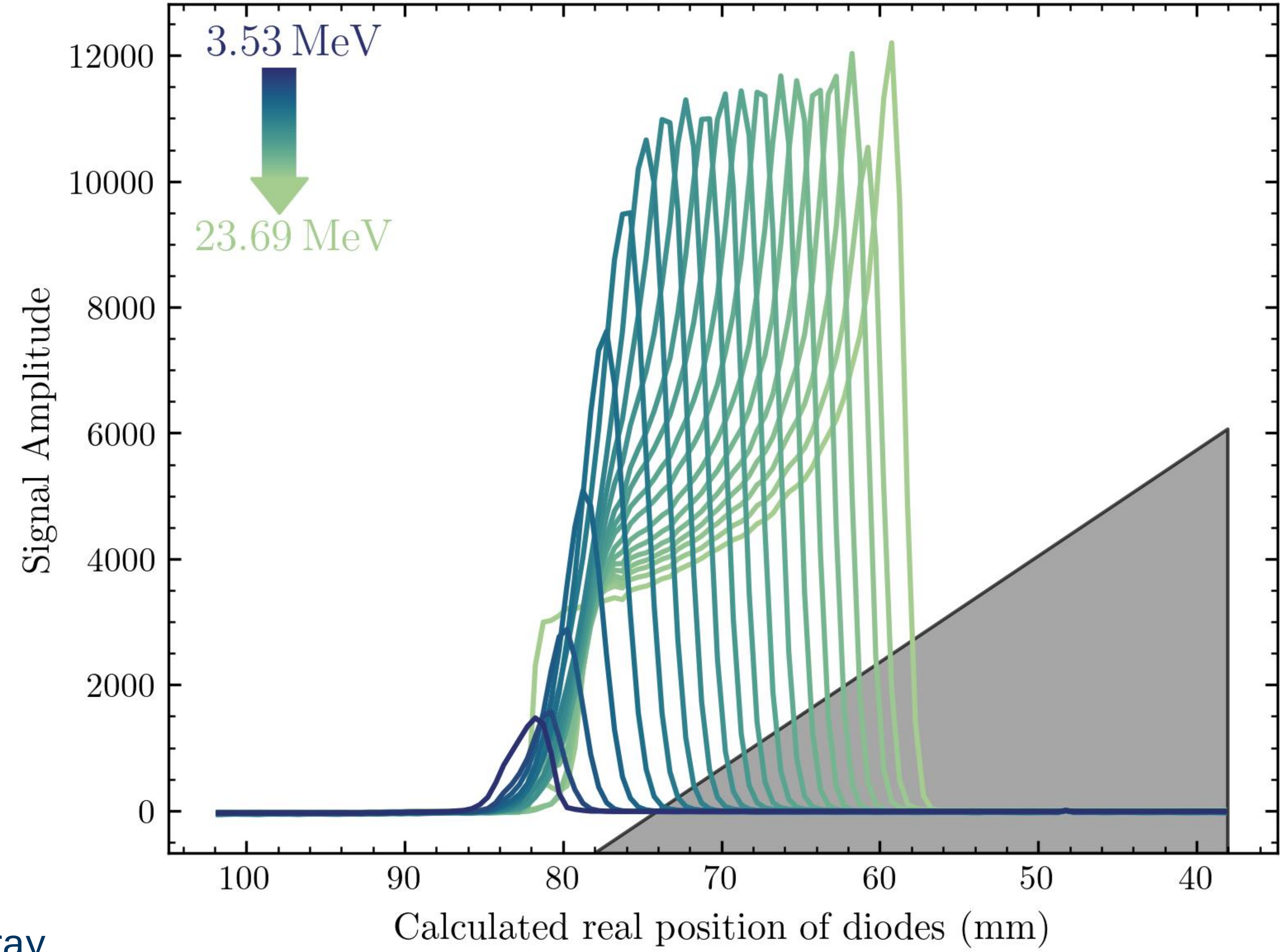
2x64 0.5x0.5 mm^2 array

What if we change the energy of the protons?

We have 20 wheel positions = 20 proton energies!



Energy-dependent wedge measurement



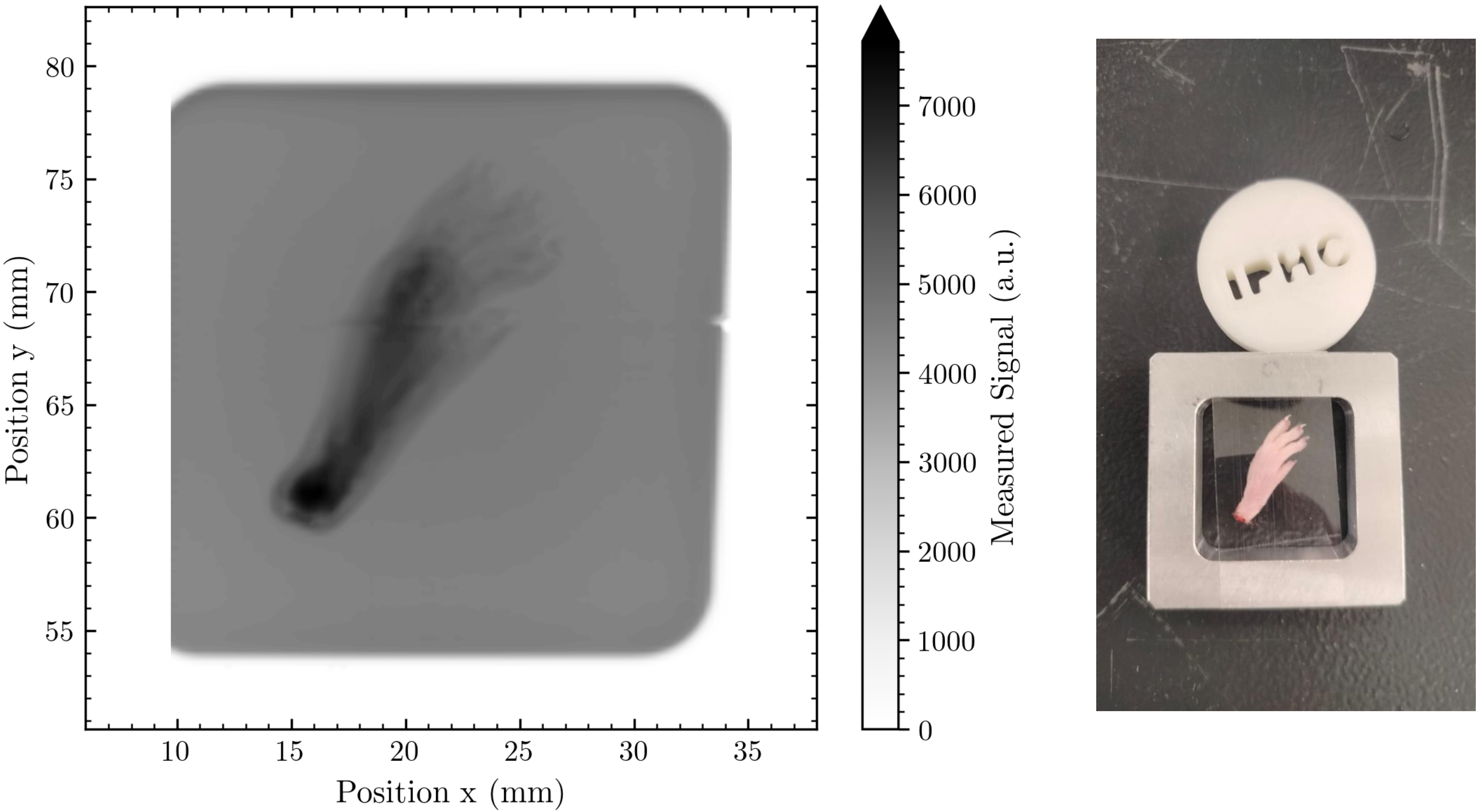
1x128 0.5x0.5 mm^2 array

Biological tissue

I put this into this category because the mechanism to image tissue is based on our diodes' energy resolution.

Disclaimer: No animals were harmed exclusively for our measurements!

Measurement with 2x64 array (1 no signal diode replaced, oversampling)

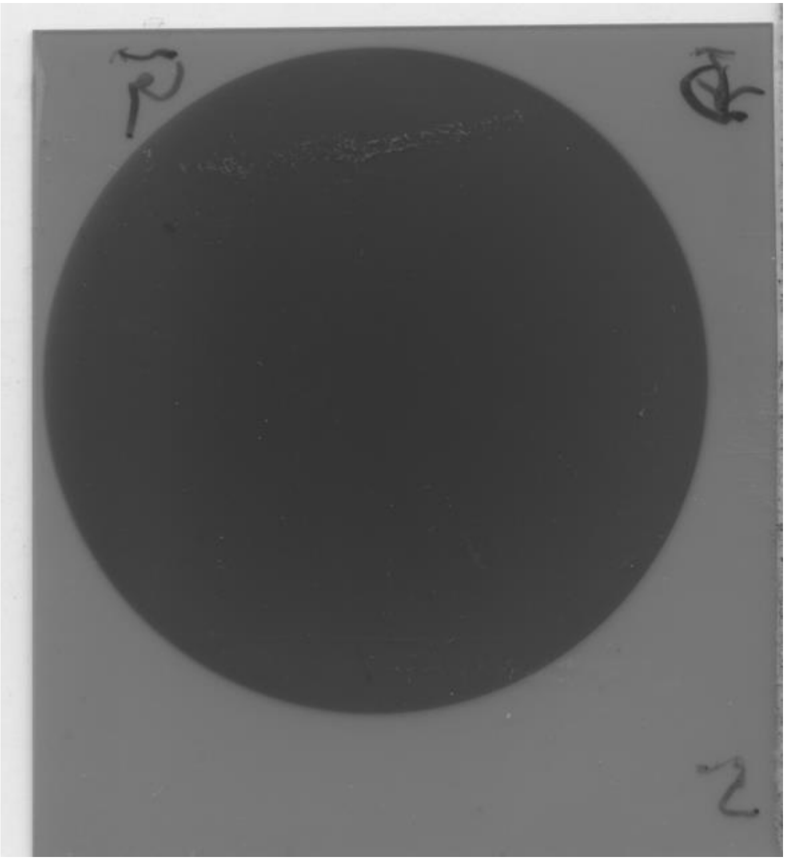


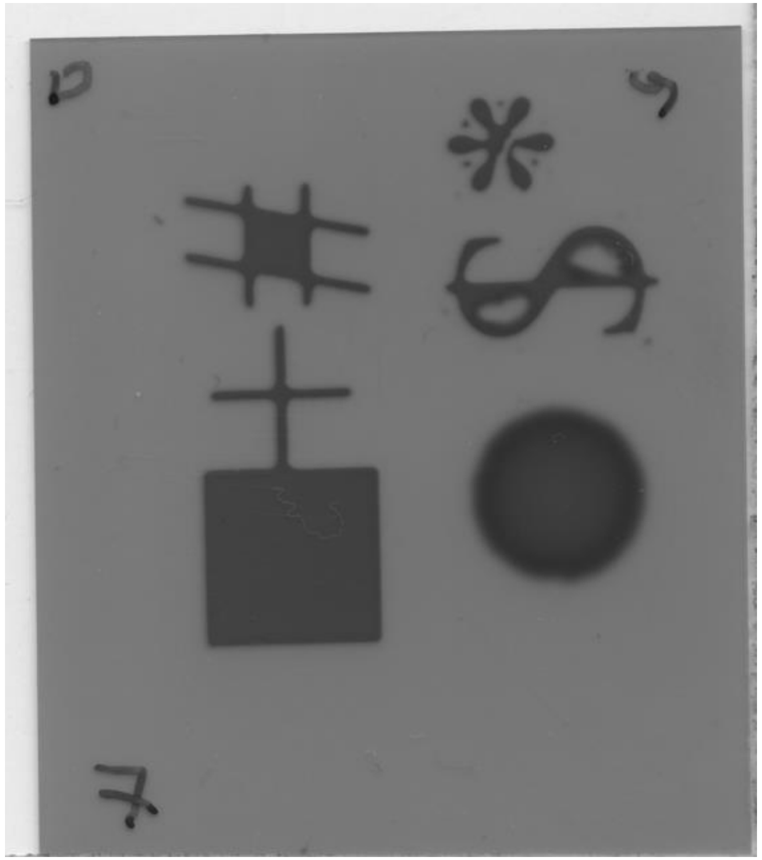
Position y (mm)
80
75
70
65
60
55
10
15
20
25
30
35
Position x (mm)
Measured Signal (a.u.)
7000
6000
5000
4000
3000
2000
1000
0
IPHC

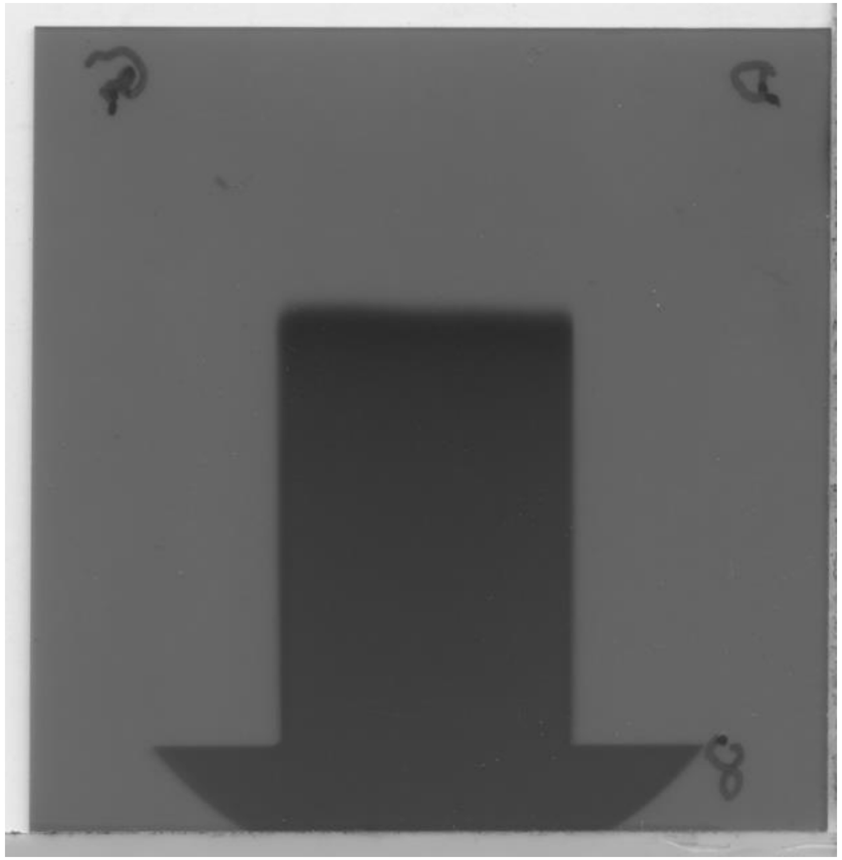
Part VI

Comparison with Gafchromic Images

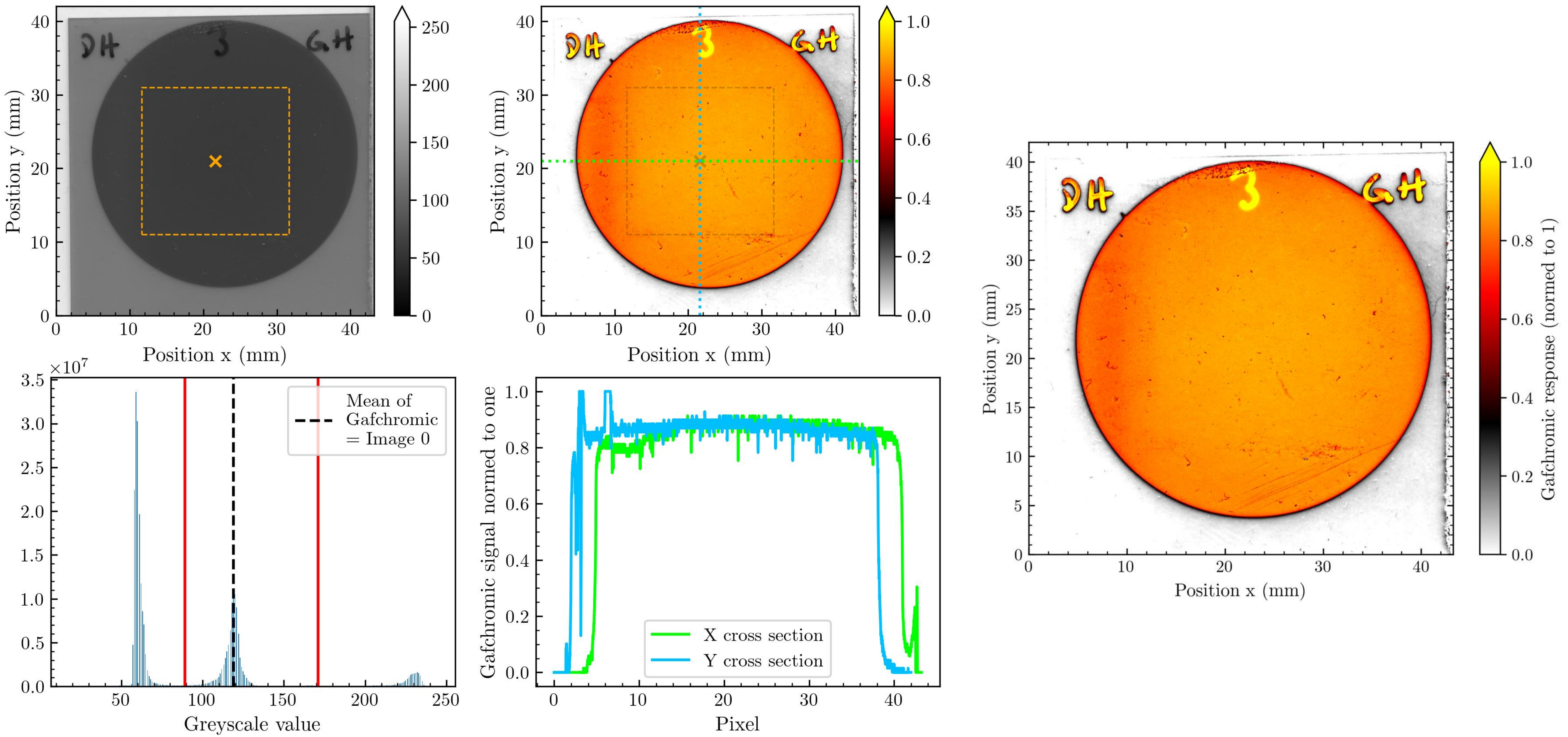
Gafchromic images



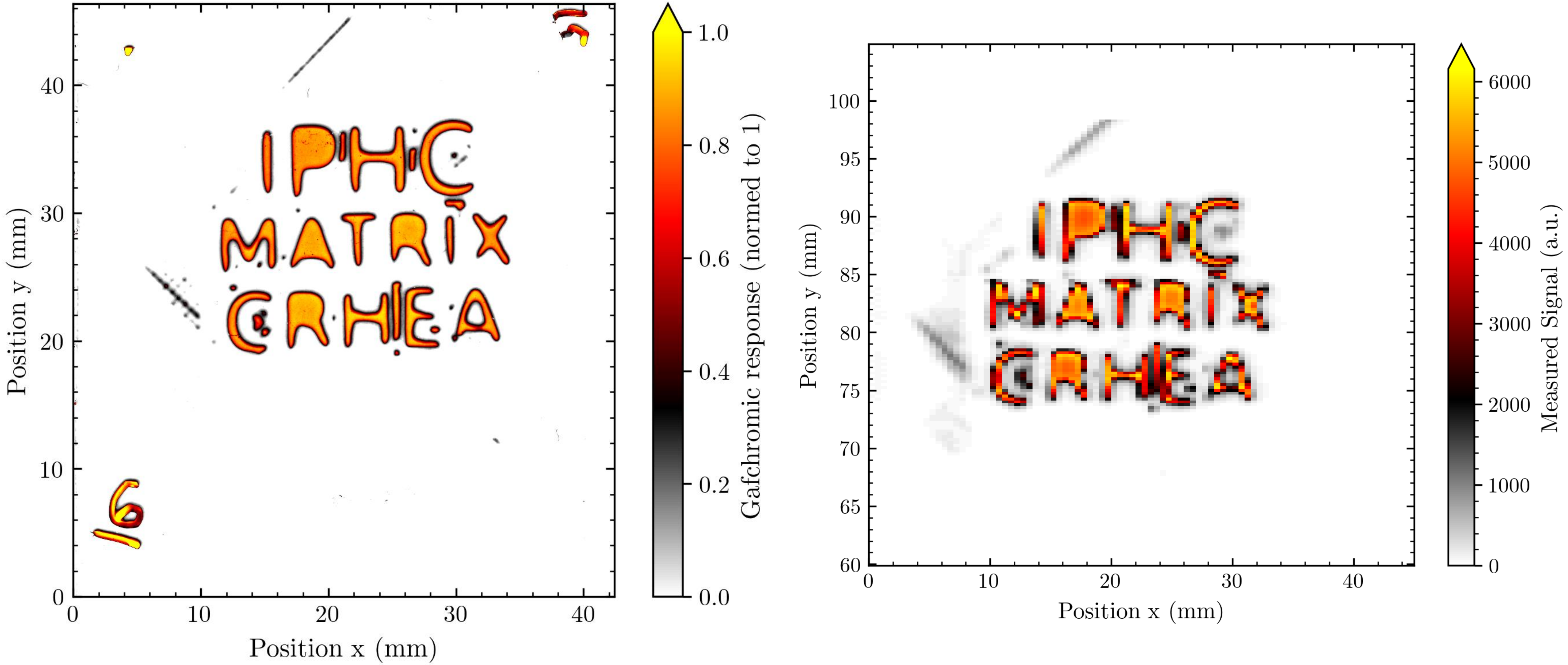




Method to obtain a comparable response

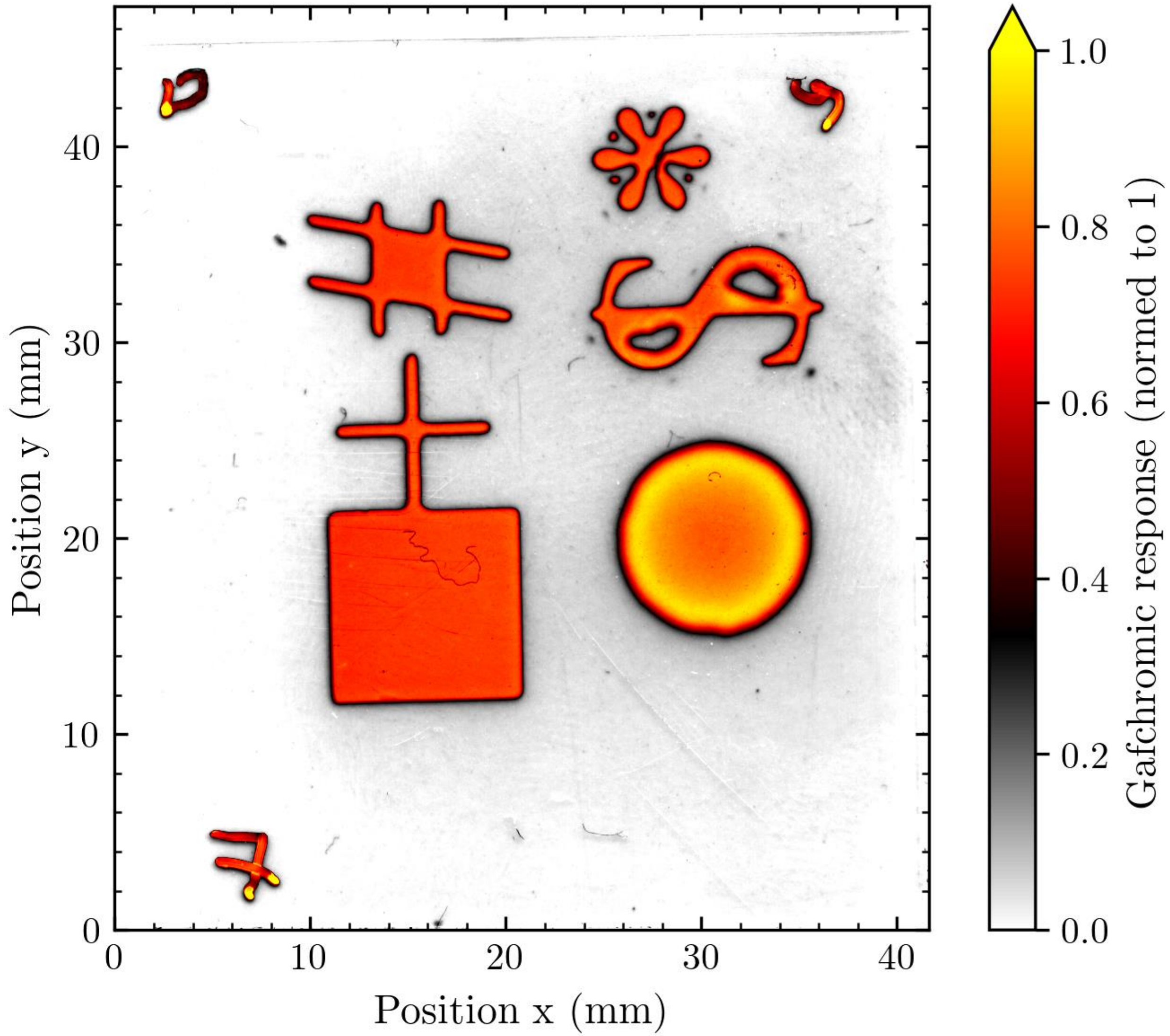


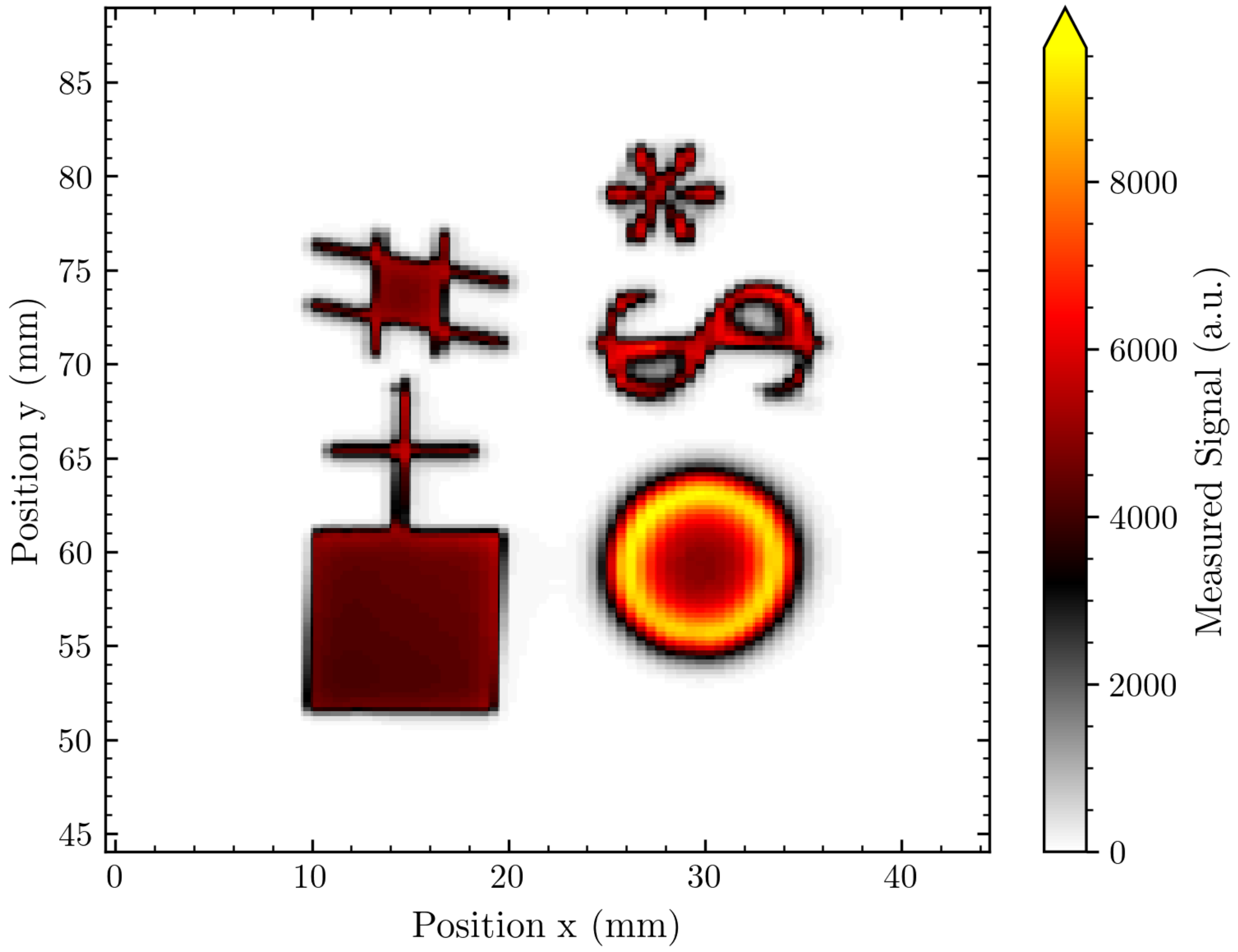
Some qualitative comparisons



2x64 0.5x0.5 mm^2 array

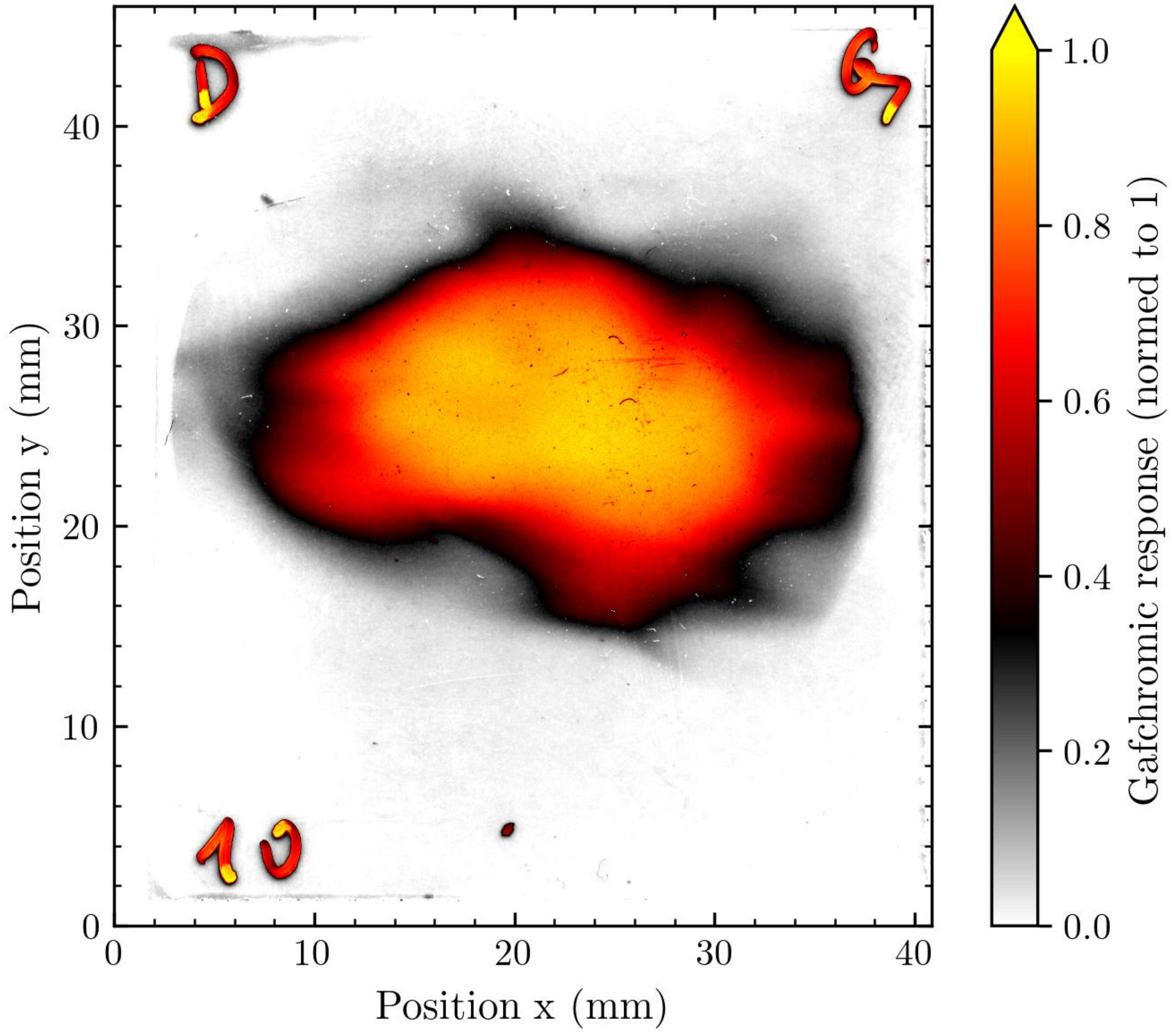
Some qualitative comparisons

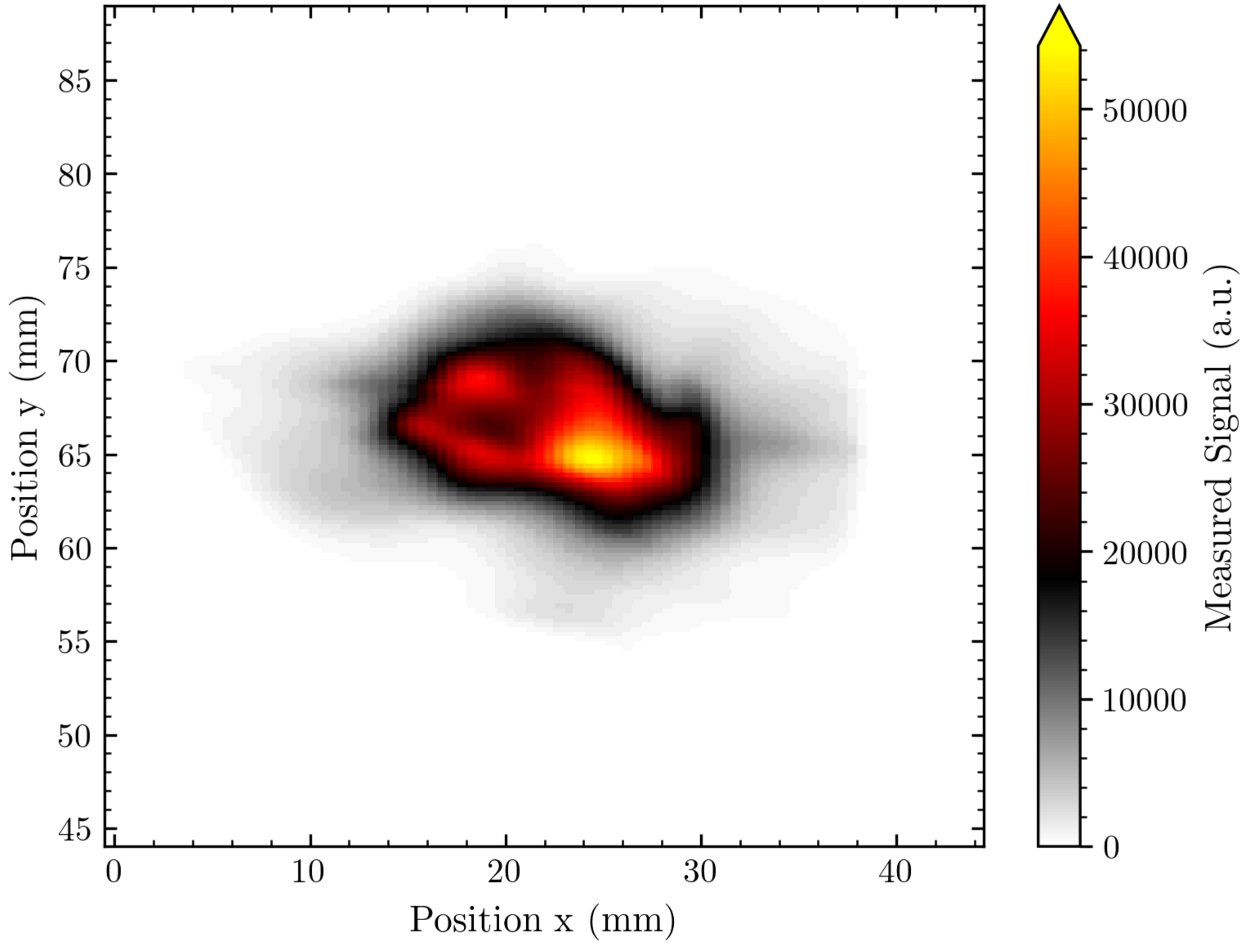




2x64 0.5x0.5 mm^2 array

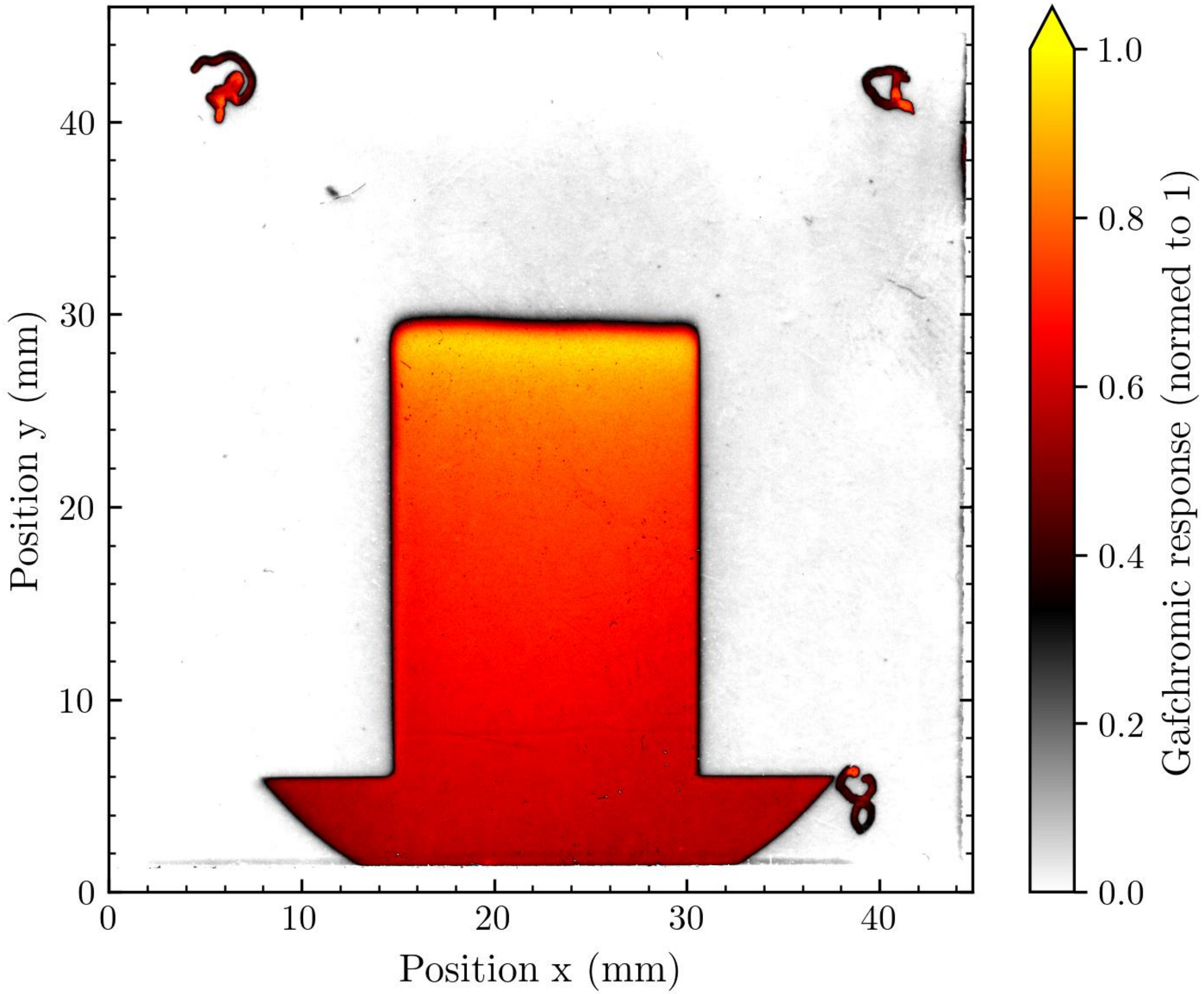
High exposure?

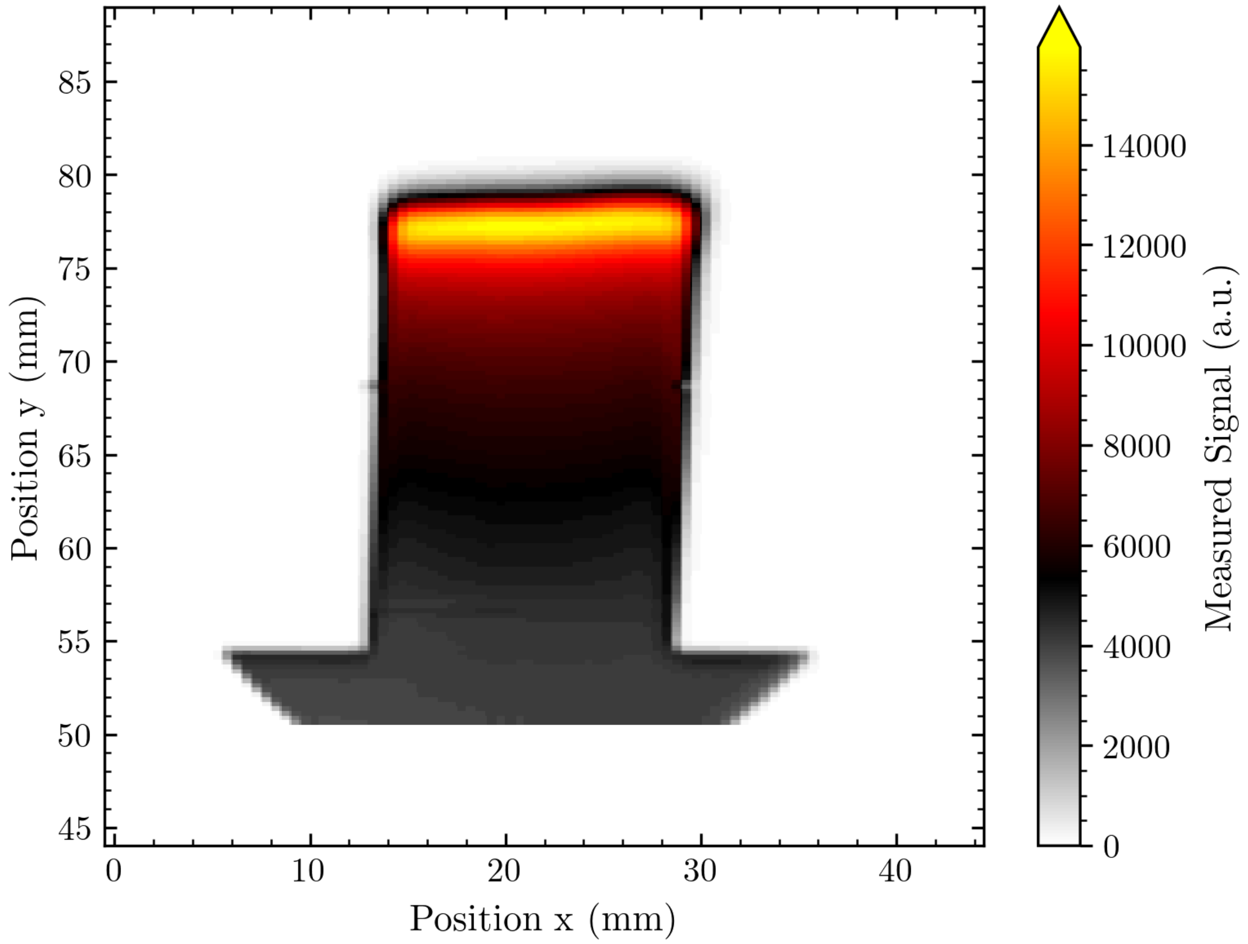




2x64 0.5x0.5 mm^2 array

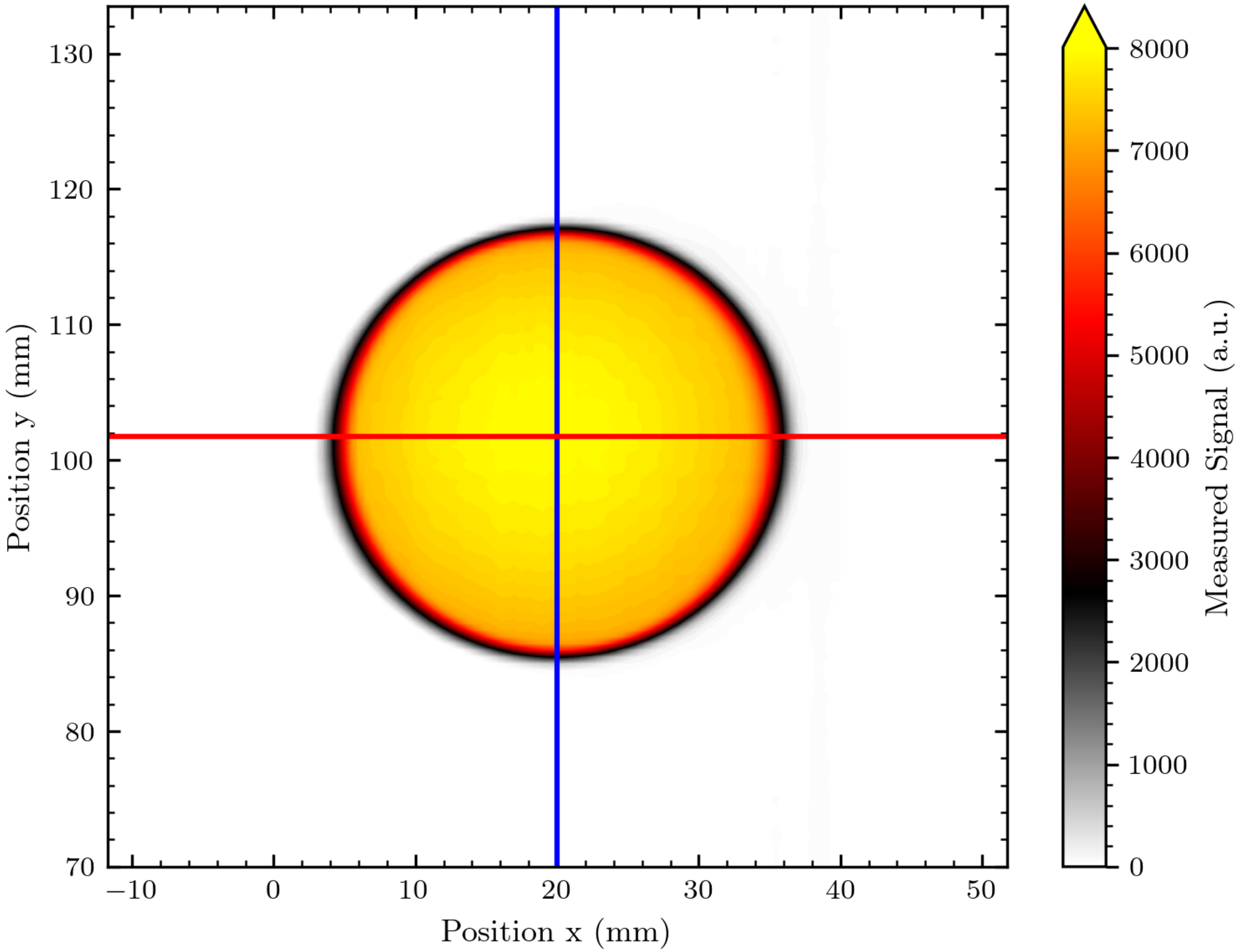
Energy resolution?

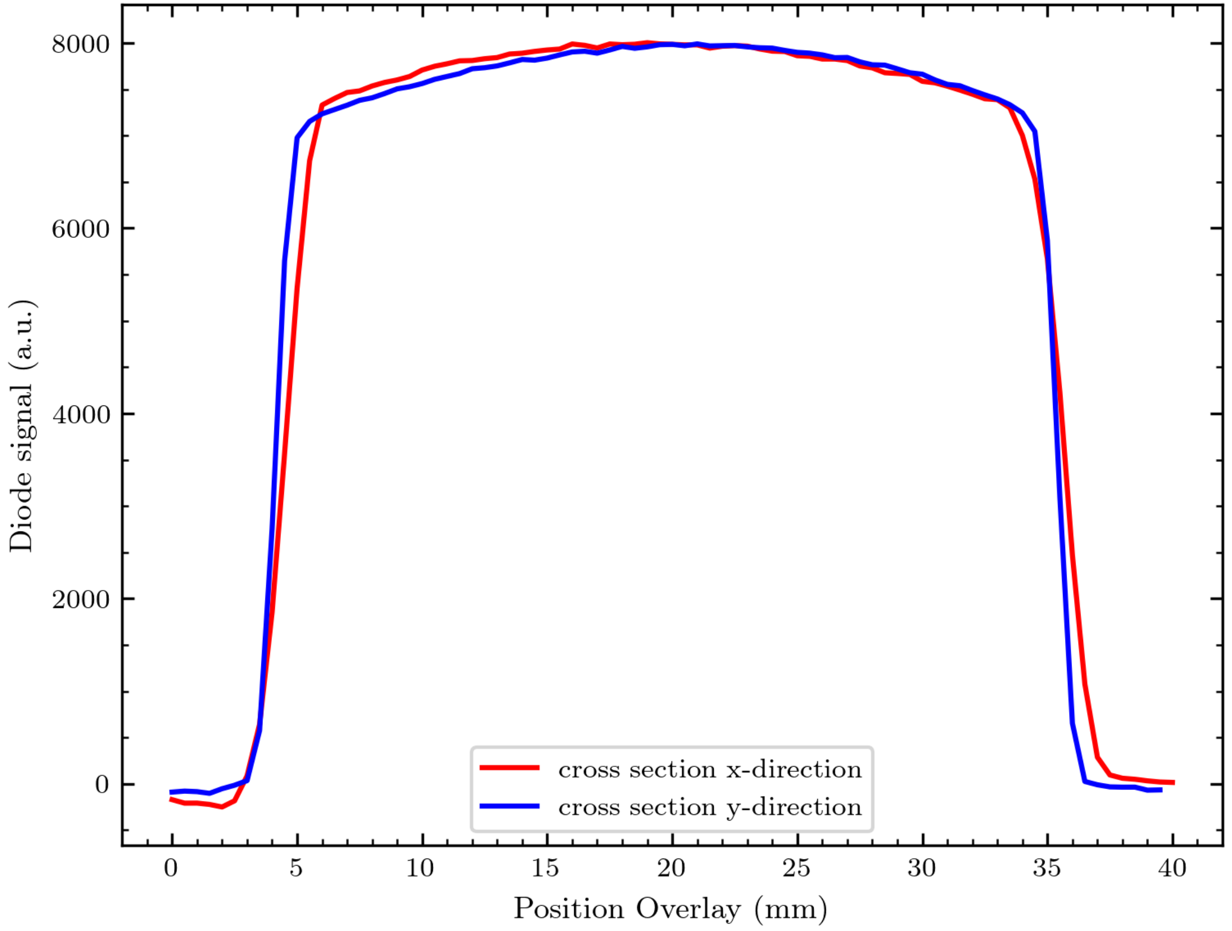




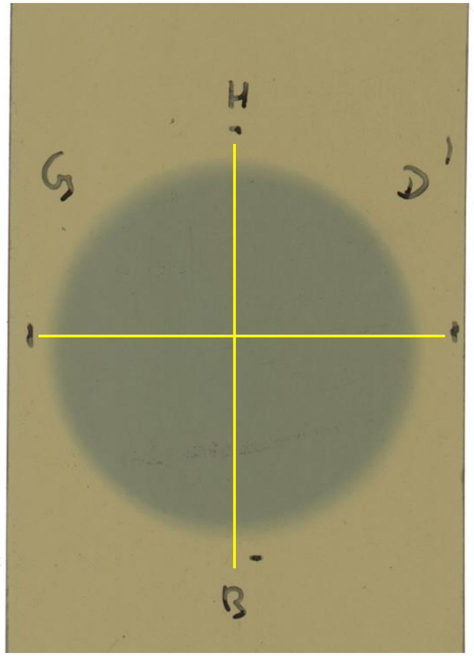
2x64 0.5x0.5 mm^2 array

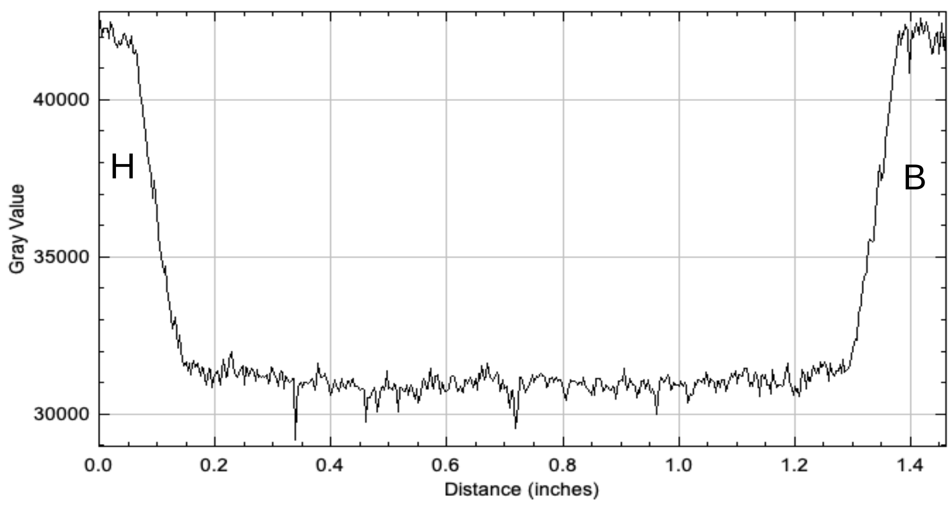
And finally one quantitative comparison

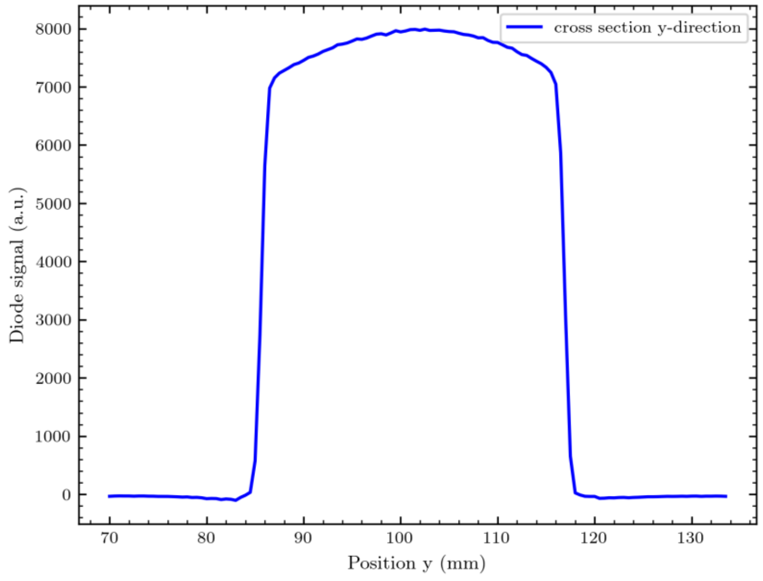


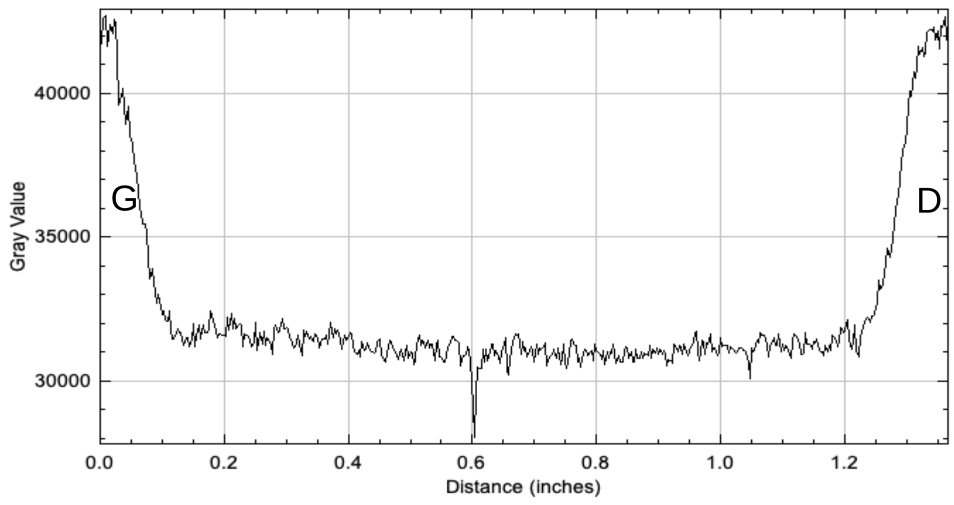


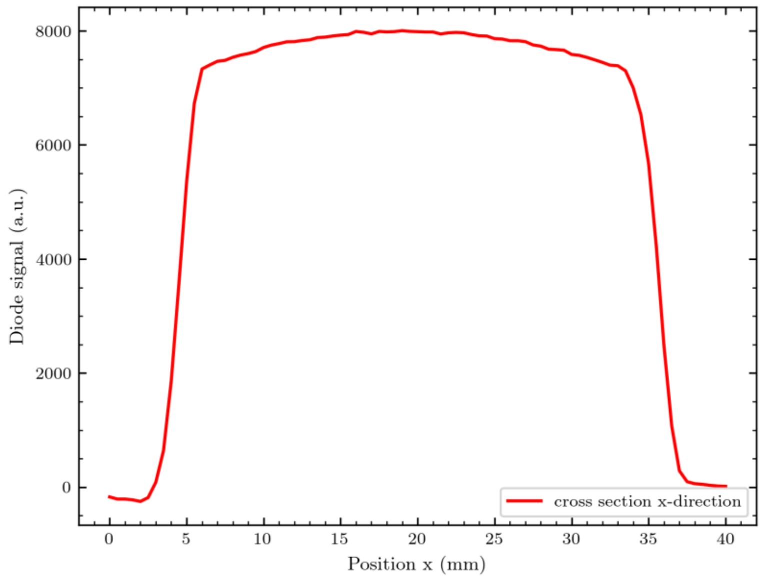
1x128 0.5x0.5 mm^2 array

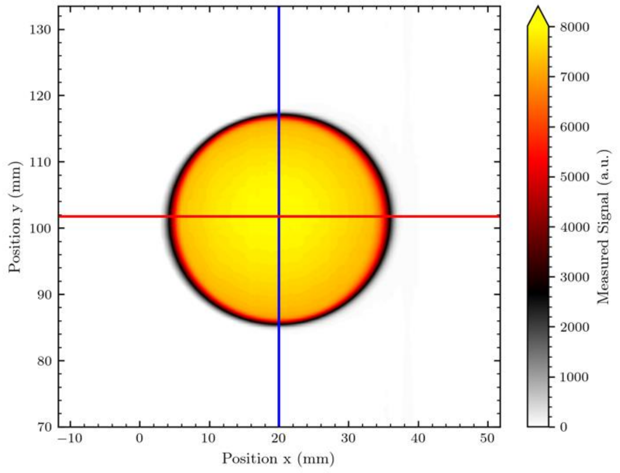




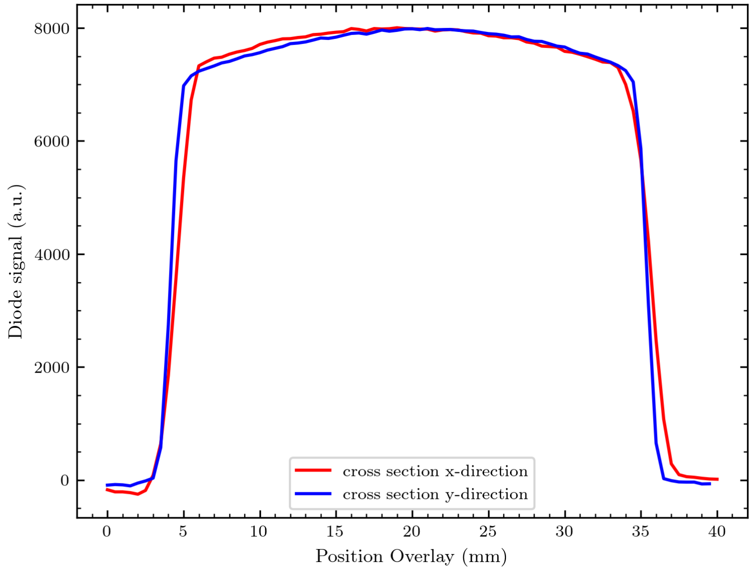


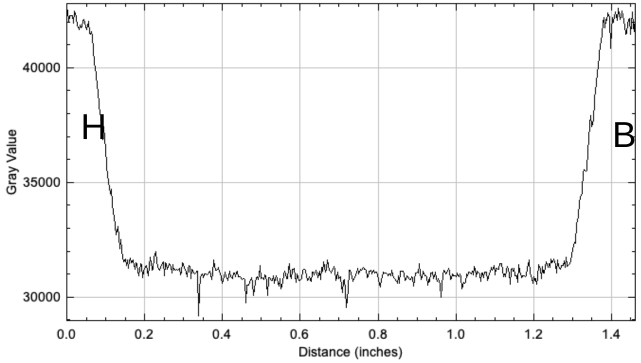


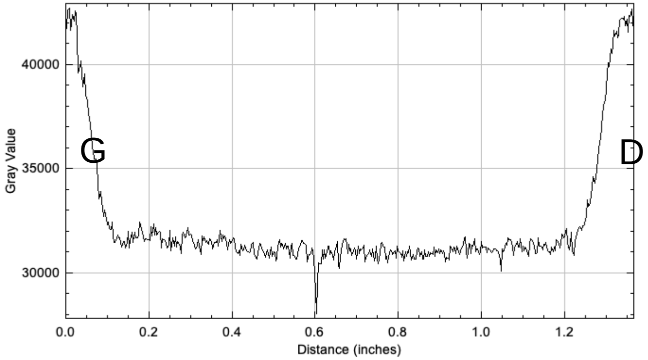




1x128 0.5x0.5 mm^2 array

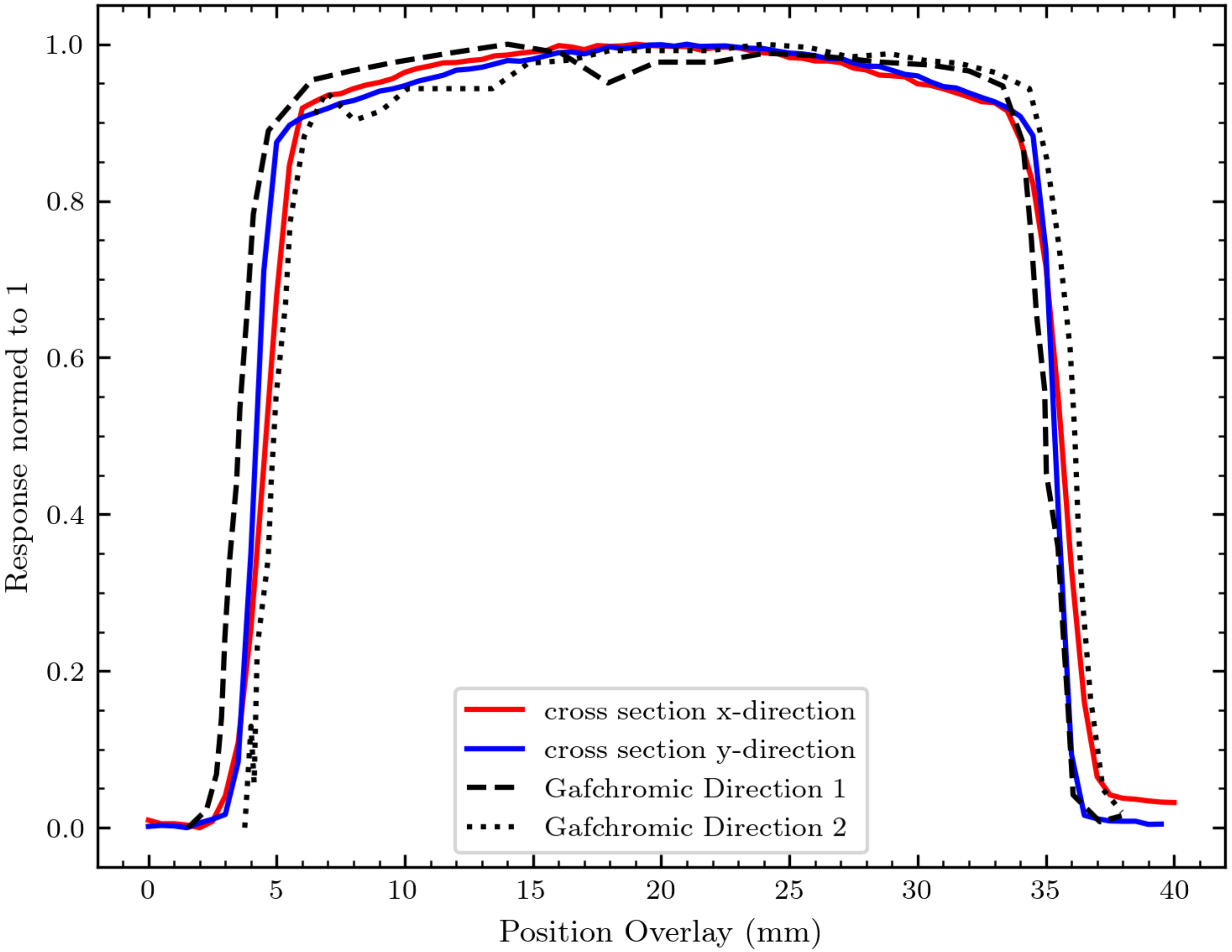






1x128 0.5x0.5 mm^2 array

Norm all to 1 and align x-axes to get a quantitative comparison!
Data from Gafchromic extracted with online tool – points aligned by hand
(without investing several hours this at least gives a nice idea of the data curve)



Looks excellent, and it seems that our normed response can be compared to the response of the gafchromic!

Part VII

Outlook:

Results I haven‘t shown
Future plans

Not shown / results not ready yet

- Energy dependent imaging
- Voltage dependent imaging
- Super-resolution: Can we improve our images by oversampling?
- More movies / images
- Gafchromic difference maps
- How many samples do we need to get good measurements?

And even more different things

Outlook

- Using a simulation software for validation (GEANT4 interfaced by GATE)
    - Deposited energy = signal?
    - Projection on to other facilities (e.g. more energy)
    - Contributions to energy deposition
    - Possible damage channels
- Long-term irradiation damage studies
- Measuring at other facilities
- Detecting carbon ions?
- <u>Important: Getting the new readout circuits!</u>