
New Semiconductor Laboratory of the Max-Planck-Society at Garching | Germany

MAX PLANCK
SEMICONDUCTOR
LABORATORY

# Super-$g_q$ DePFET

# Put to the Test

*Speaker: Sebastian Stadler*

*Semiconductor laboratory of the Max Planck Society*

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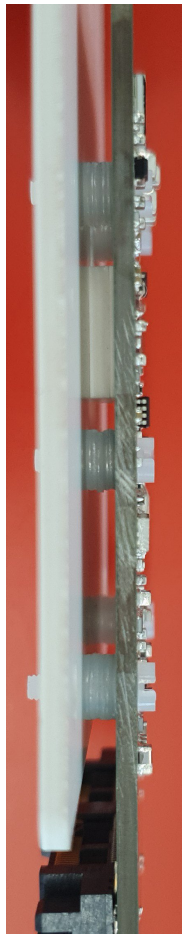
# EXPERIMENTAL SETUP

## Device under test


Top view of Hybrid-PCB



Left view

### Device Layout:

- 64x64 matrix
- 130 µm pixel size
- 3.5 µm gate length
- 20 µm gate width
- 450 µm thickness

### Device Operation:

- Rolling shutter mode
- Integration time 1 µs
- Shaping time 6.3 µs
- Frame rate 13 ms
- Exposure time 12.5 ms

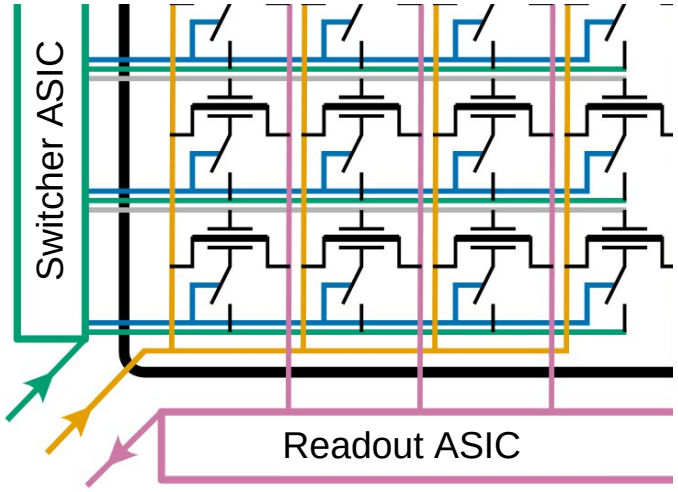
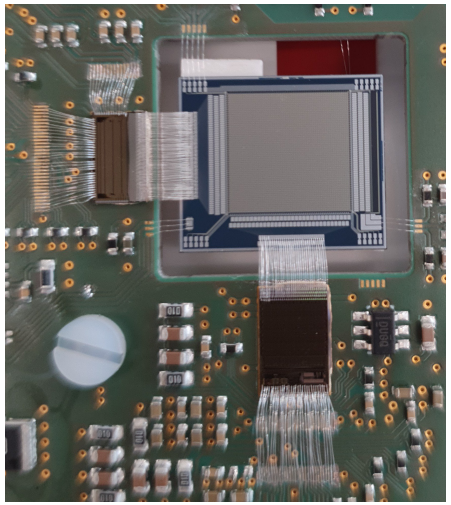
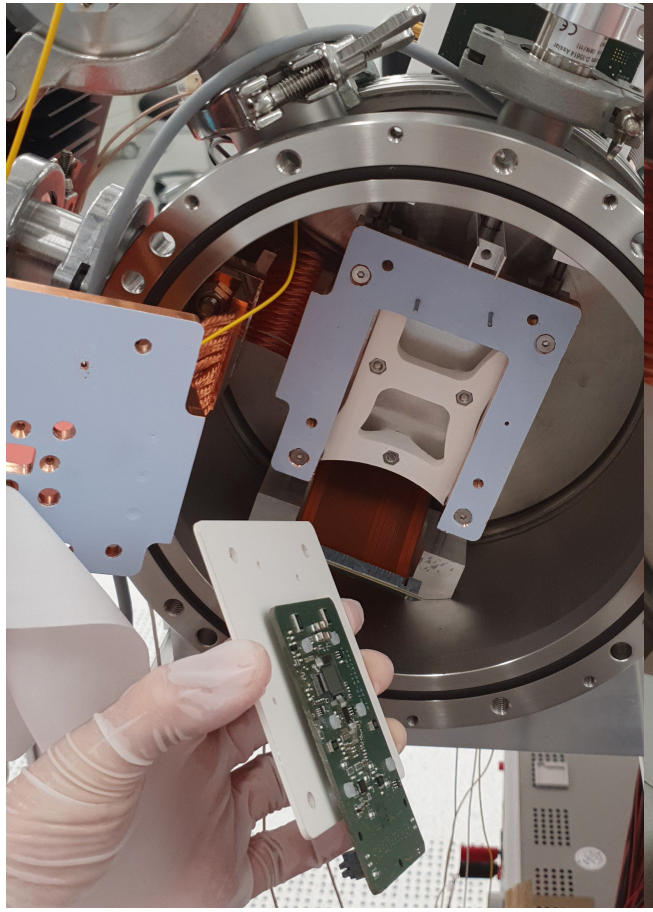



Figure from [1]

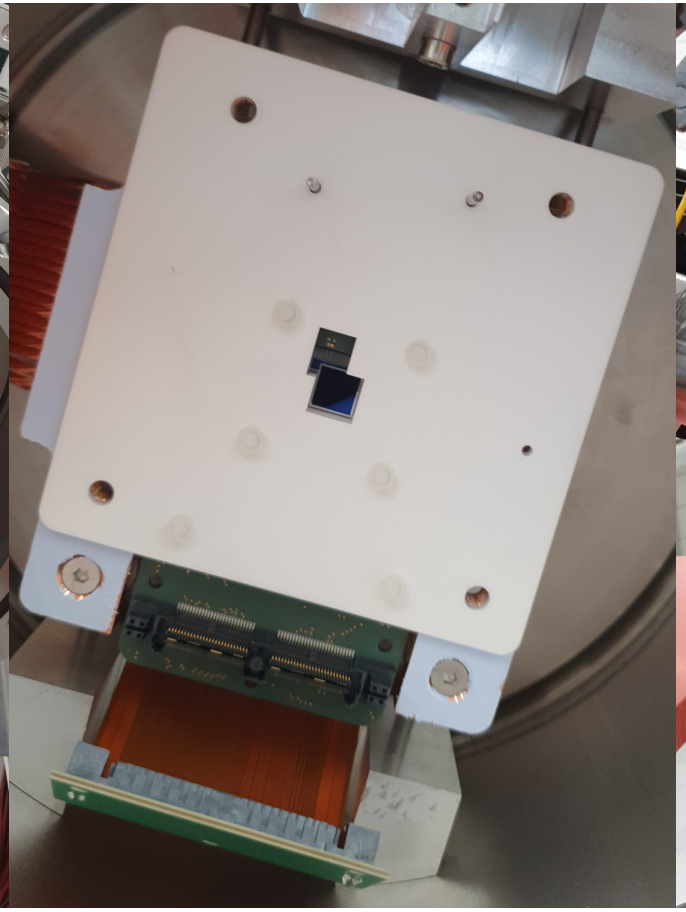


Zoom on DePFET Matrix

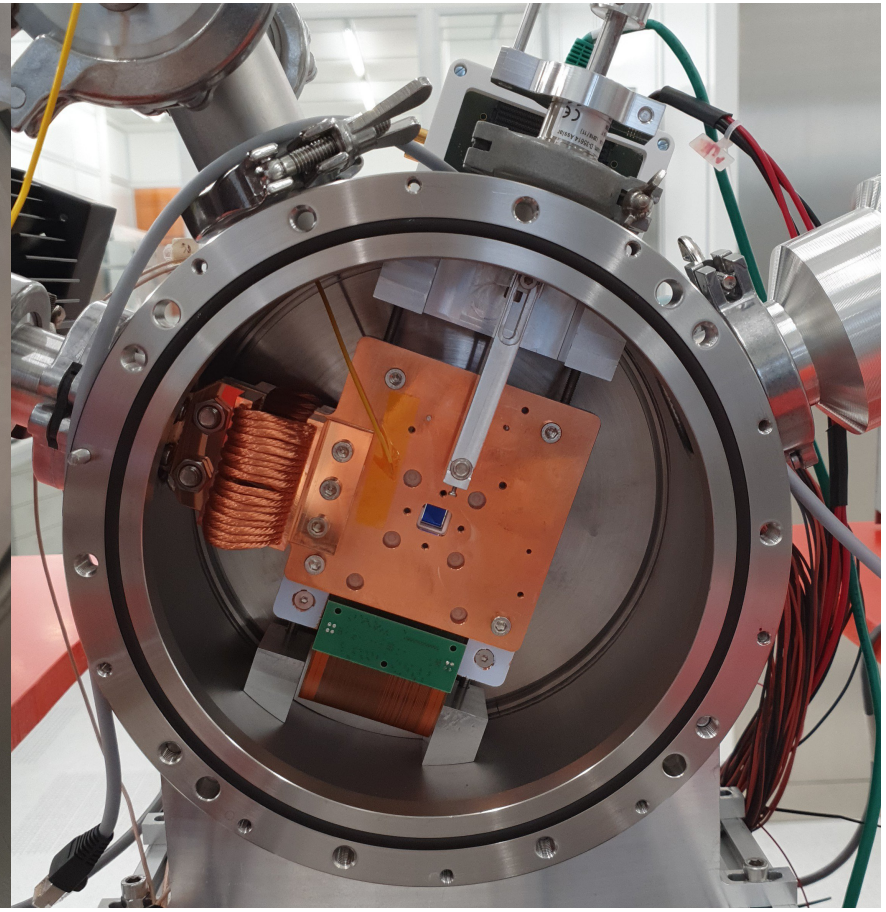
# EXPERIMENTAL SETUP
## Instrumentation



Opened cooling plates and detached Hybrid-PCB

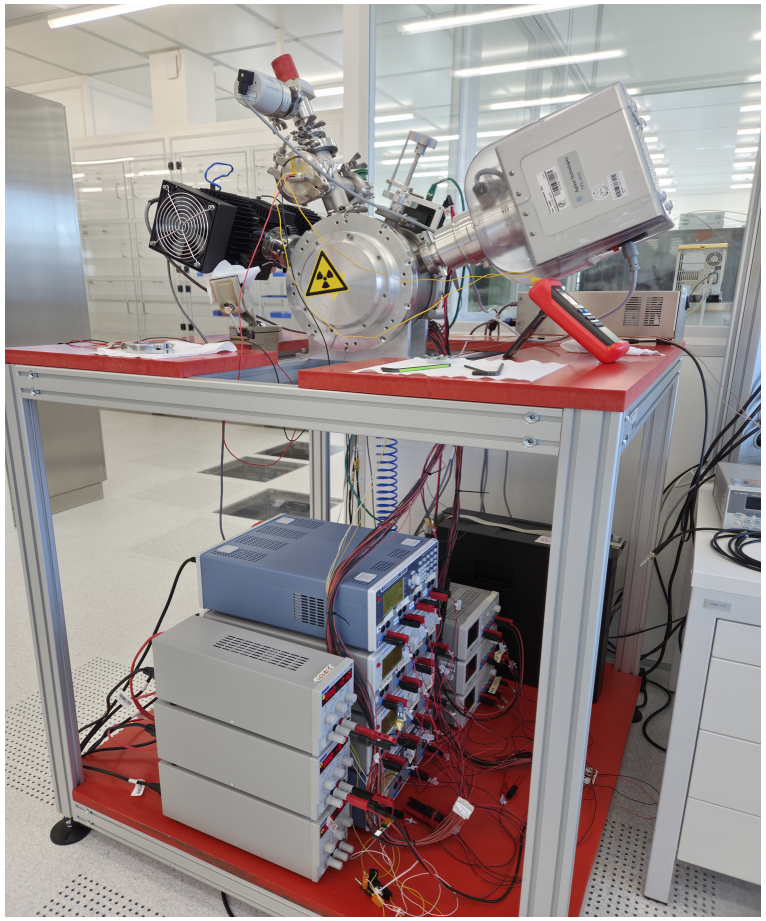


Zoom on entrance window (center) of the installed Hybrid-PCB

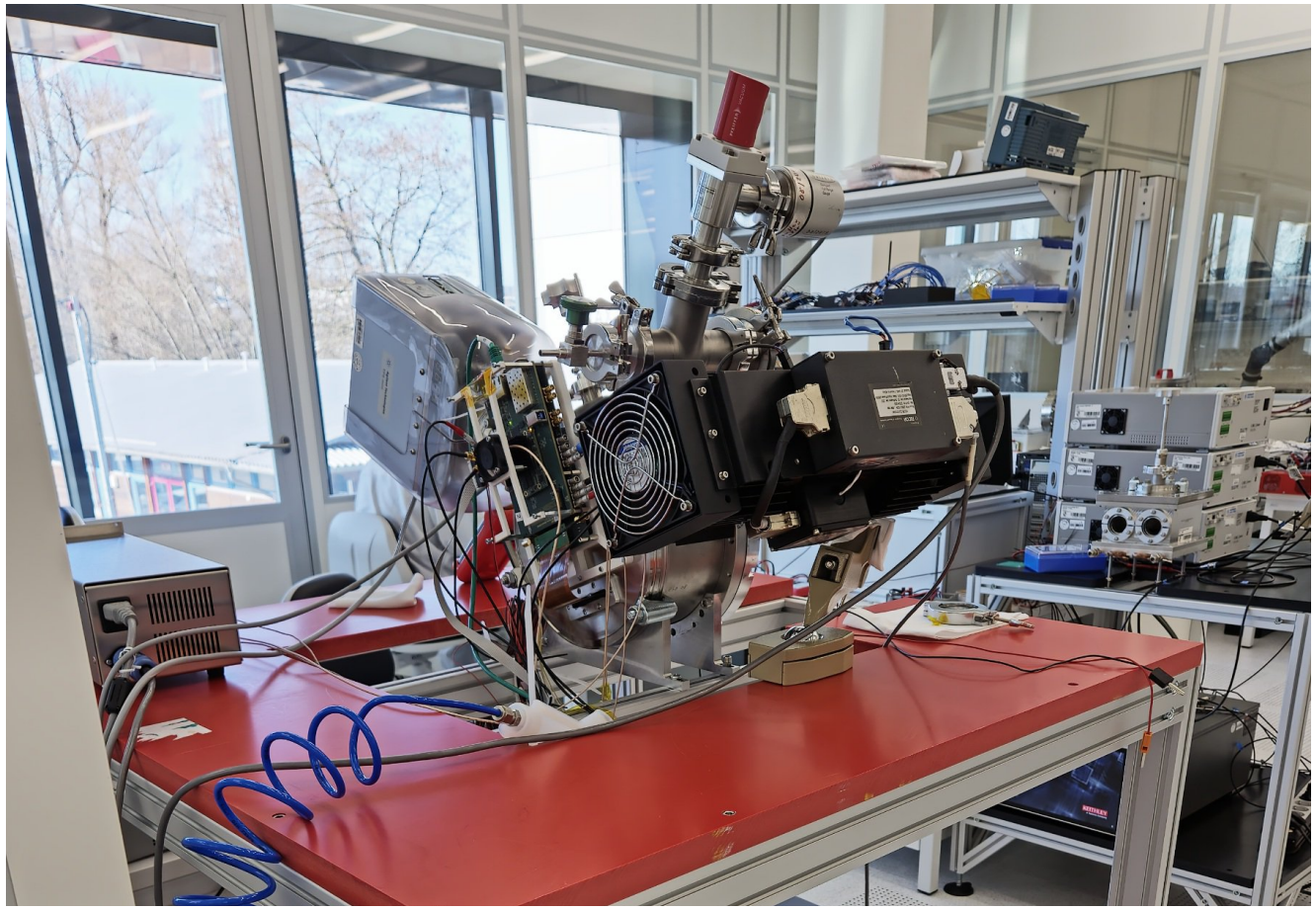


Open vacuum chamber with installed DUT ready for Fe55 energy resolution measurement

# EXPERIMENTAL SETUP
## Instrumentation

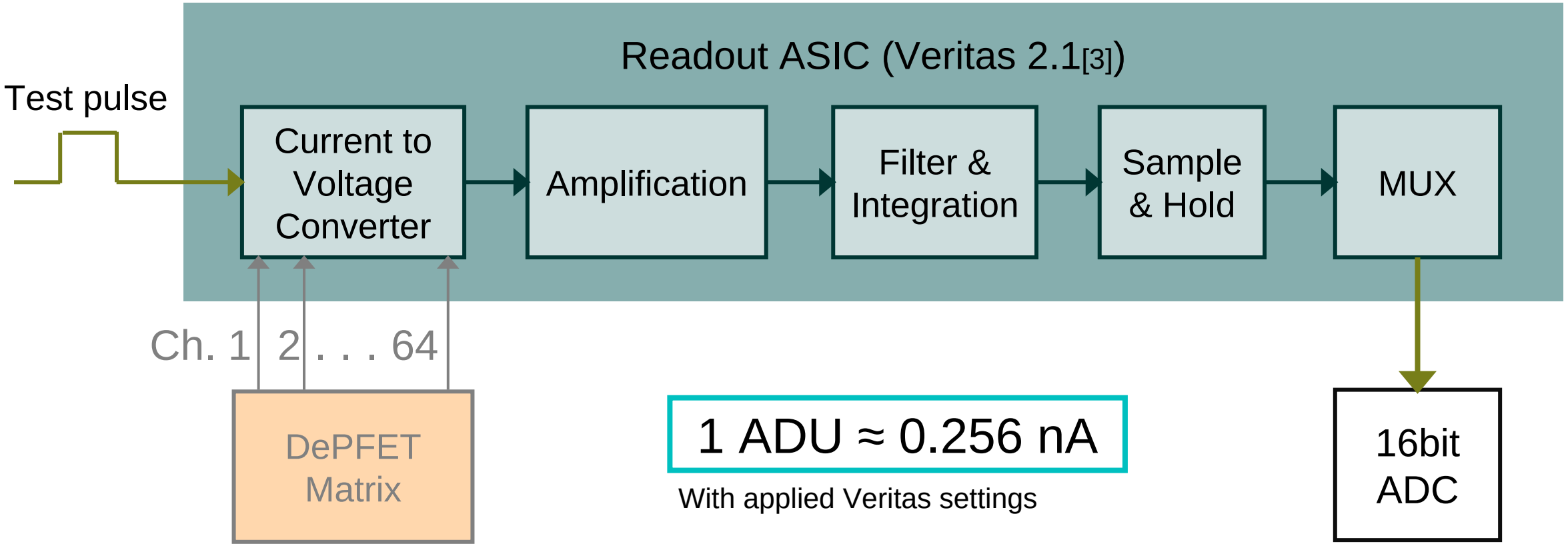


Power supplies beneath the table, Vacuum pump top right, Cryo-Cooler top left.



Center: PCB-Stack of XU1, MSM, MSMA and flex cable.

# EXPERIMENTAL SETUP
## Calibration

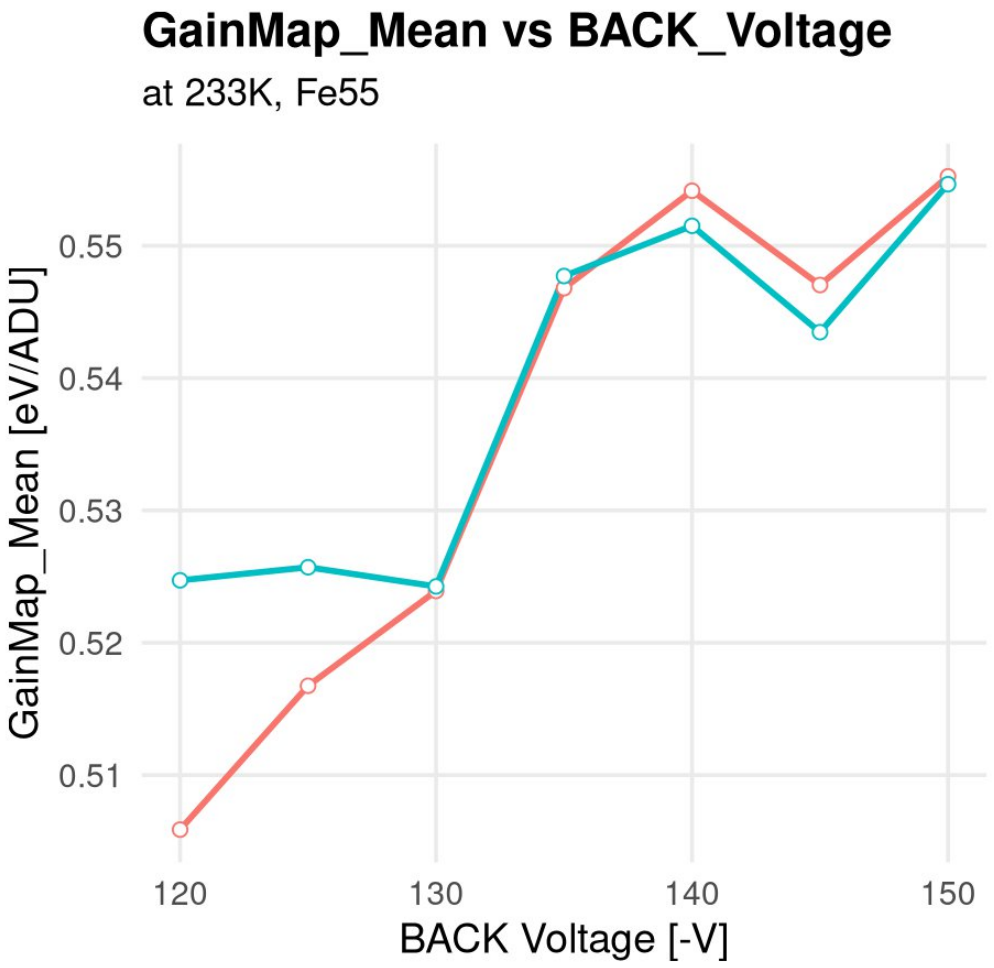


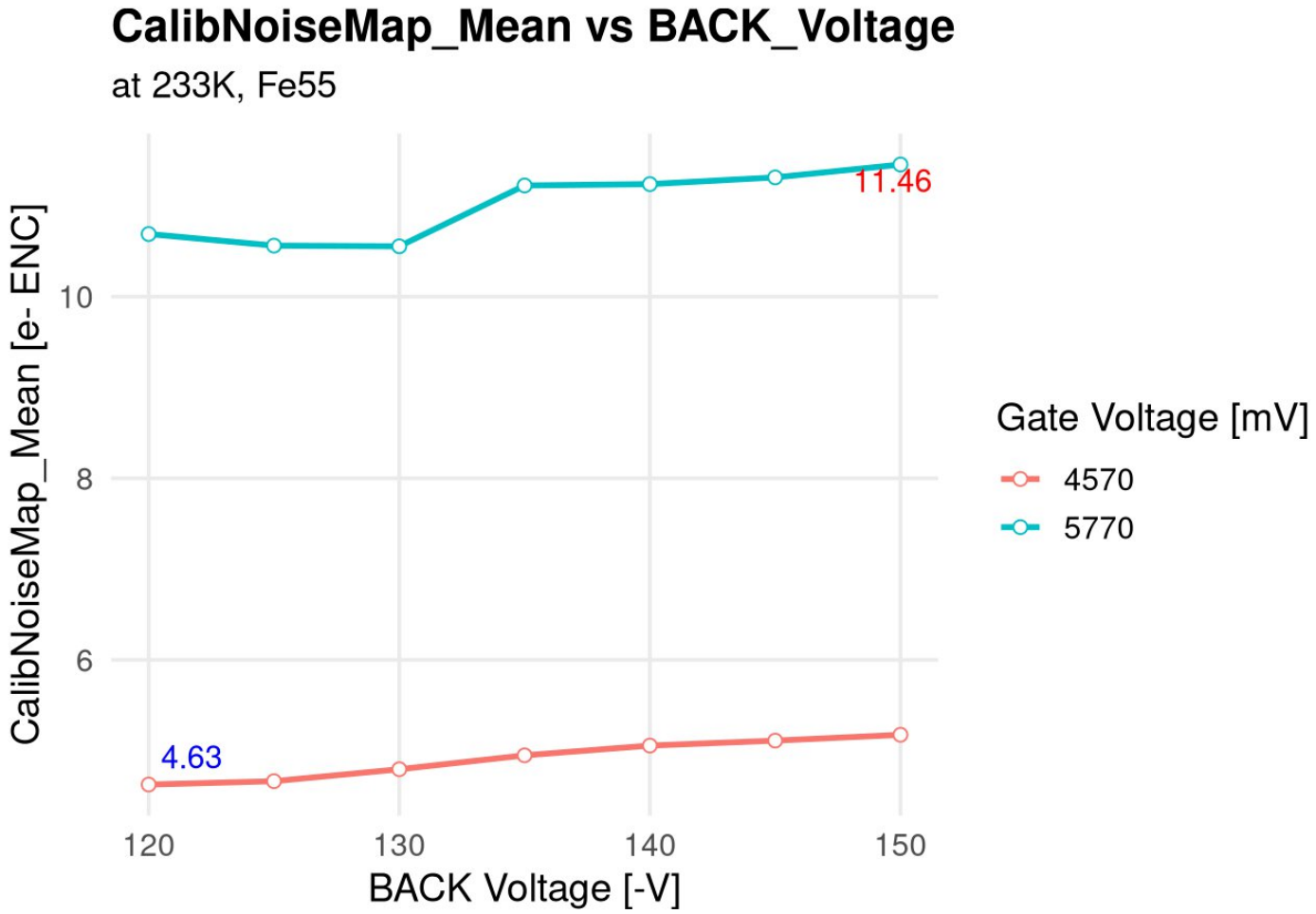

1 ADU ≈ 0.256 nA

With applied Veritas settings

# CHARACTERIZATION

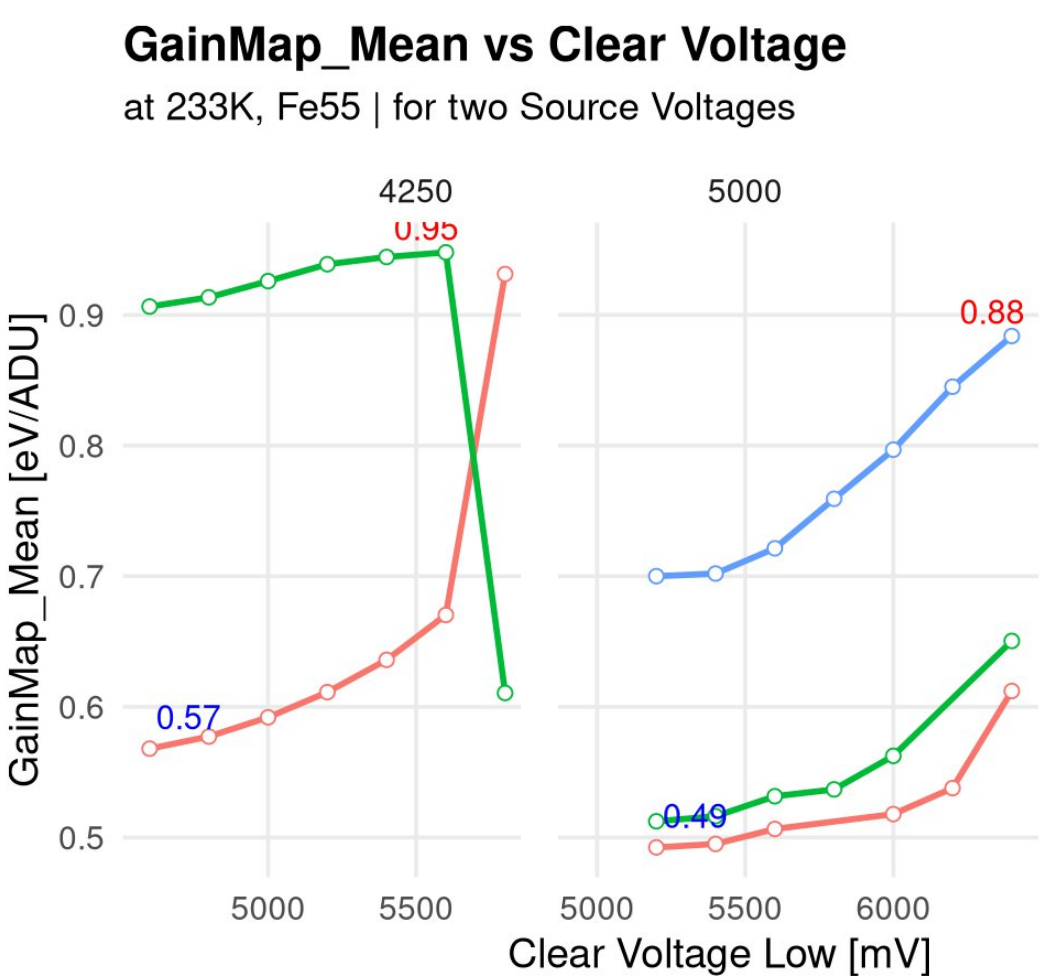
## Super-$g_q$ technology (Backside sweep)

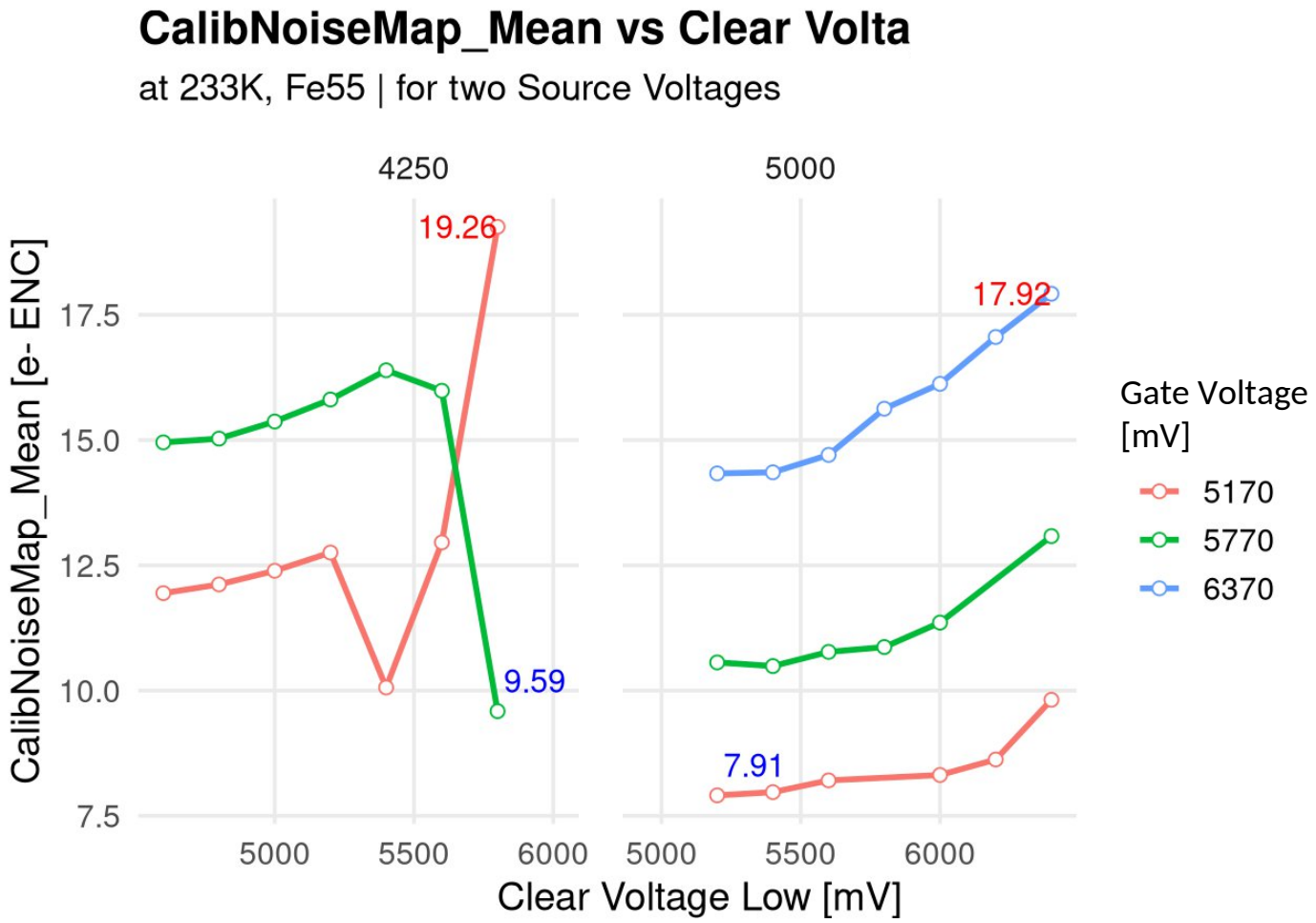


# CHARACTERIZATION

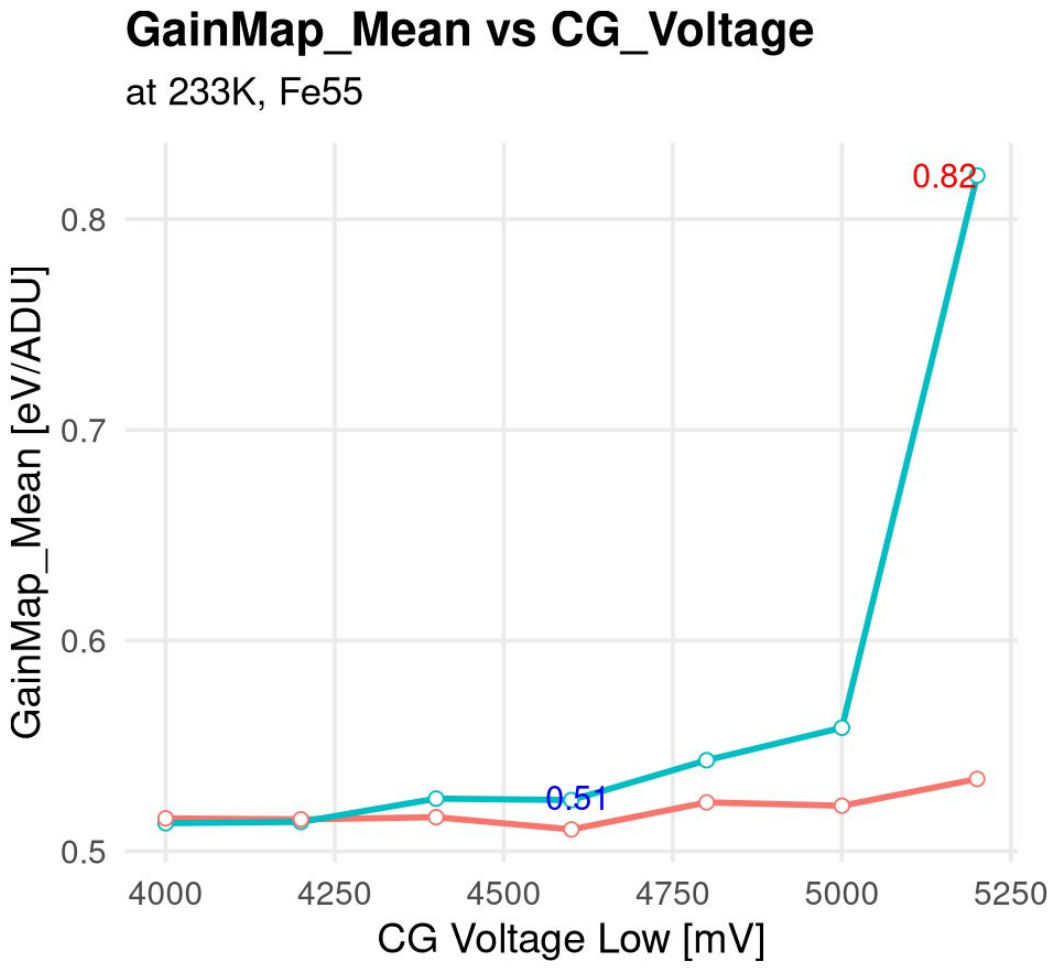
## Super-$g_q$ technology (Clear sweep)

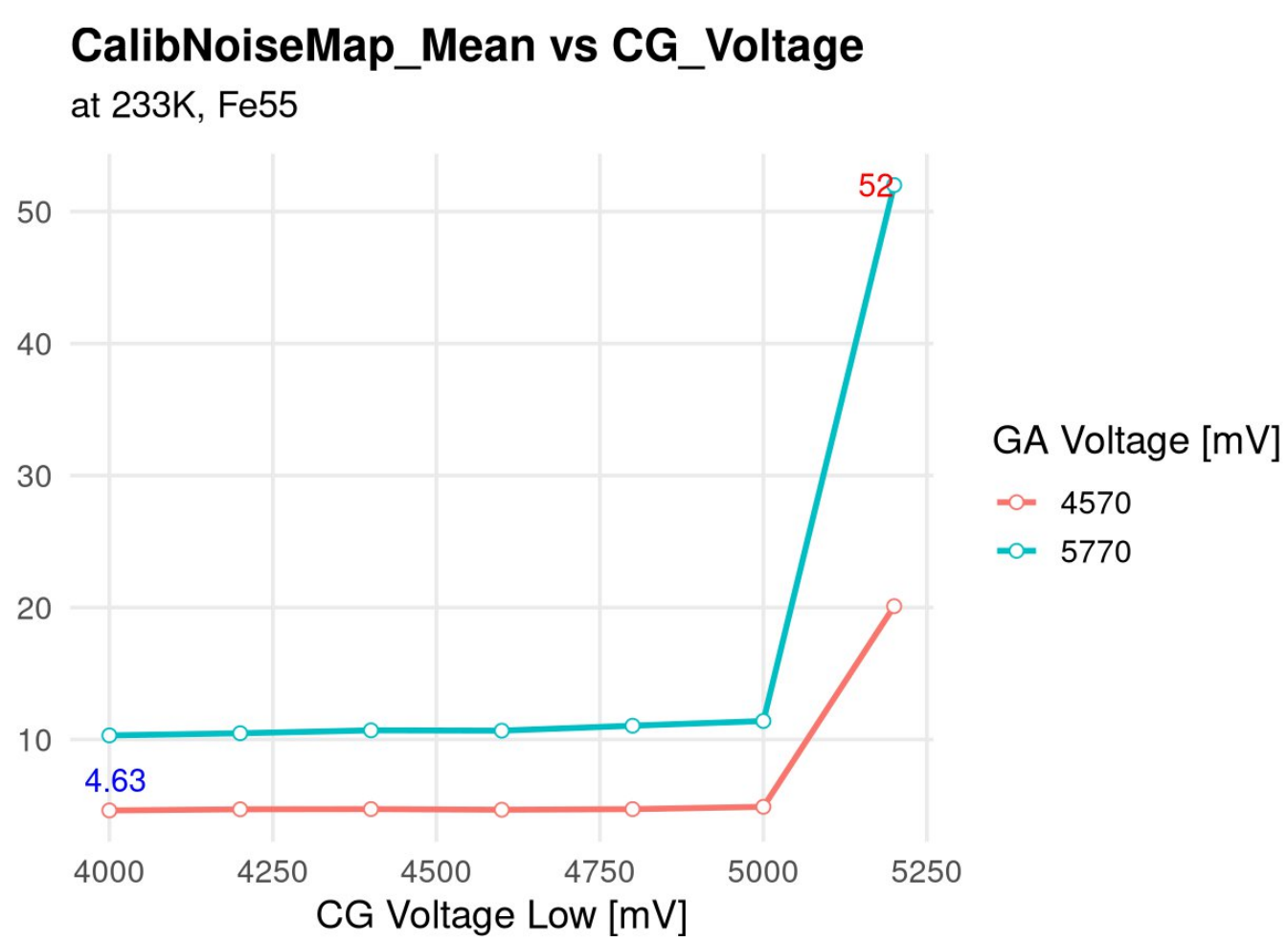


# CHARACTERIZATION

## Super-$g_q$ technology (Clear Gate sweep)



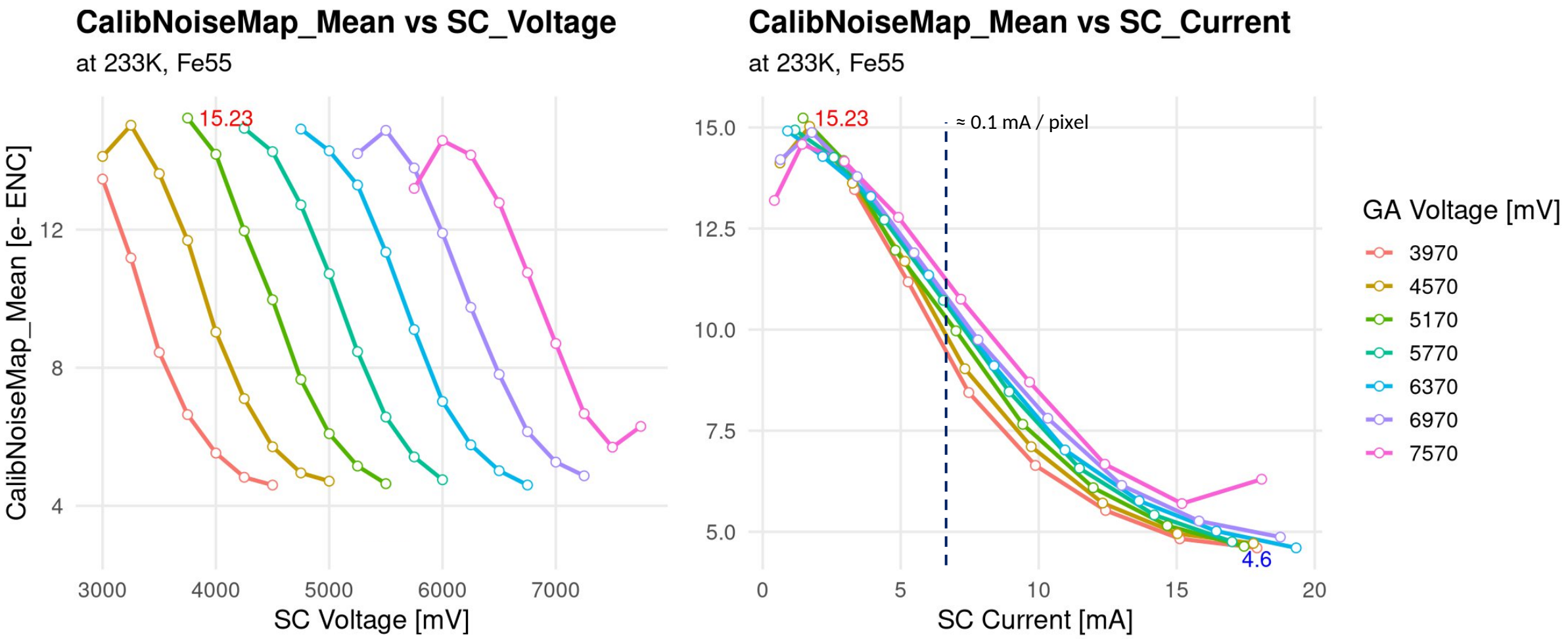
# CHARACTERIZATION

## Super-$g_q$ technology (Interim Summary)

=> Clear = 400 mV greater than Source
=> Clear Gate = 600 mV less than Source
=> Back/BIGR = -120 V

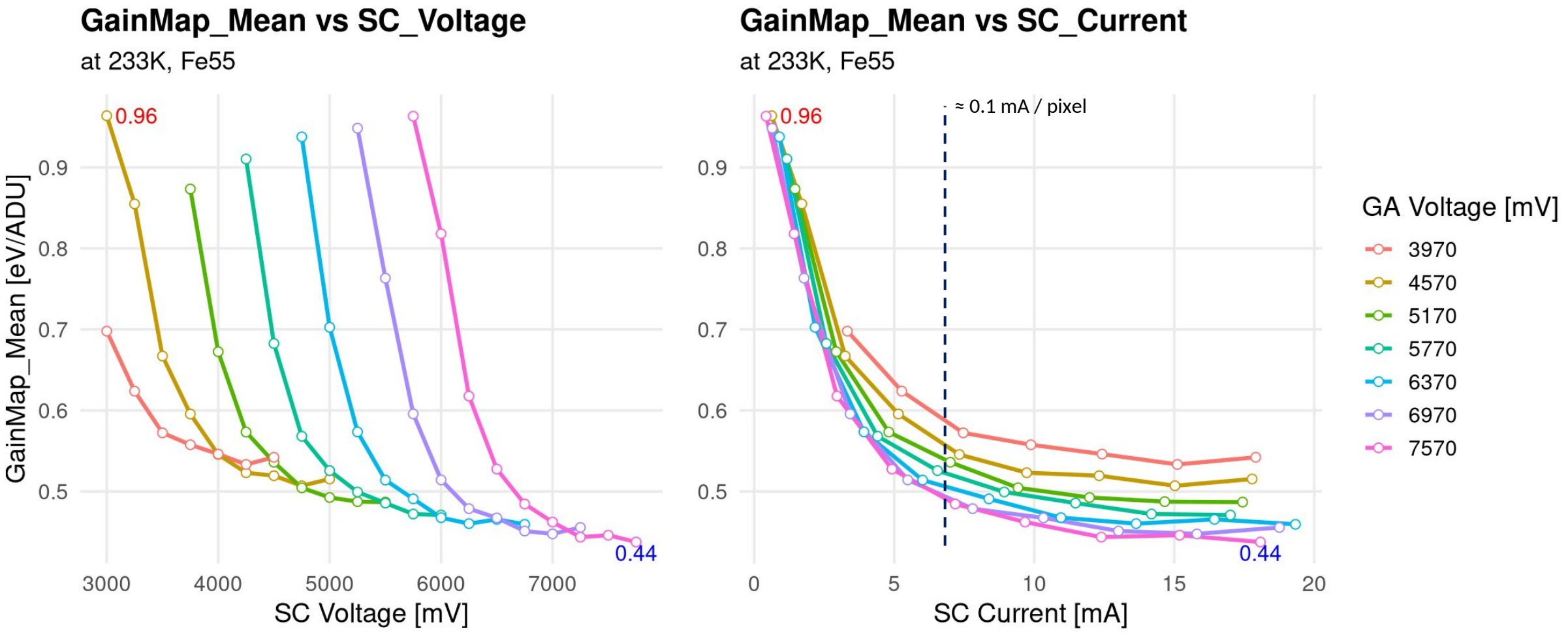
# CHARACTERIZATION

## Super-$g_q$ technology (Gate & Source sweep)



# CHARACTERIZATION

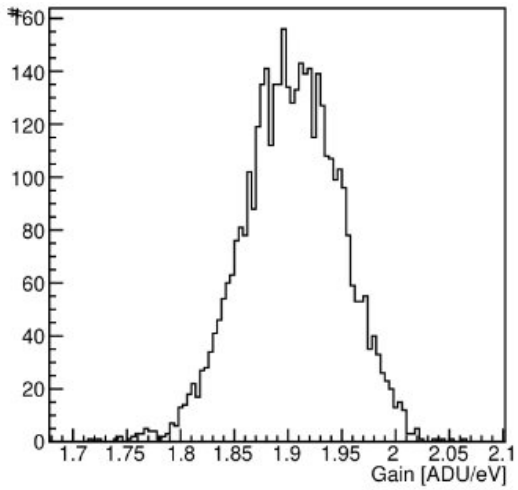
## Super-$g_q$ technology (Gate & Source sweep)

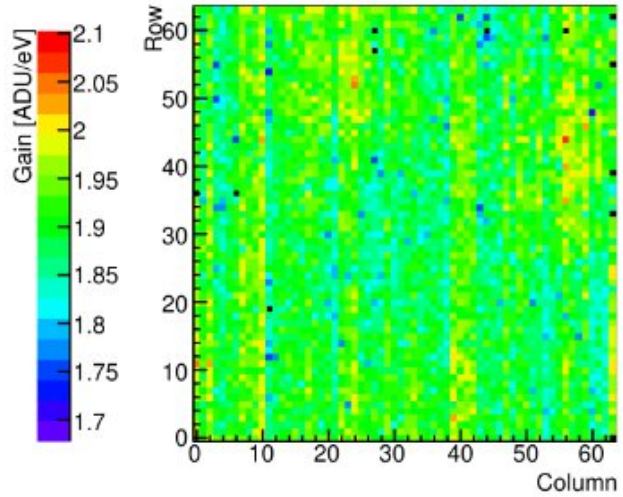


# GAIN AND NOISE PERFORMANCE

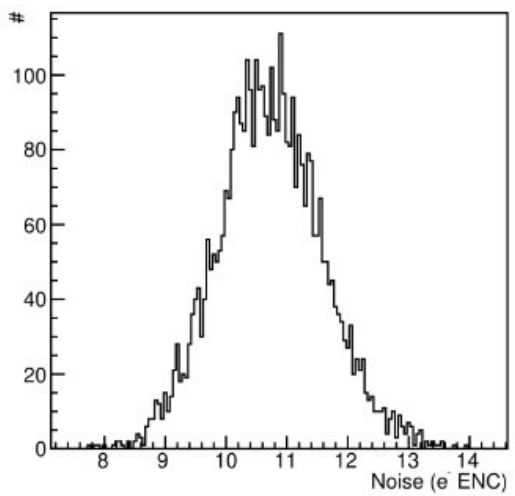
## Super-$g_q$ technology (GA=5.8V, SC=5V => ~100µA/pix)

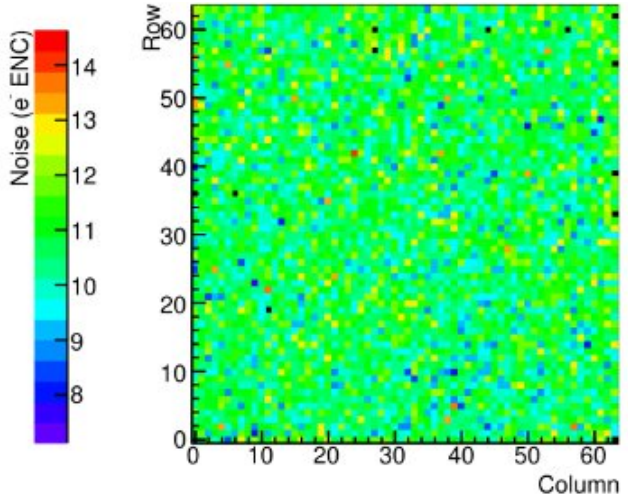
gain




calibrated noise



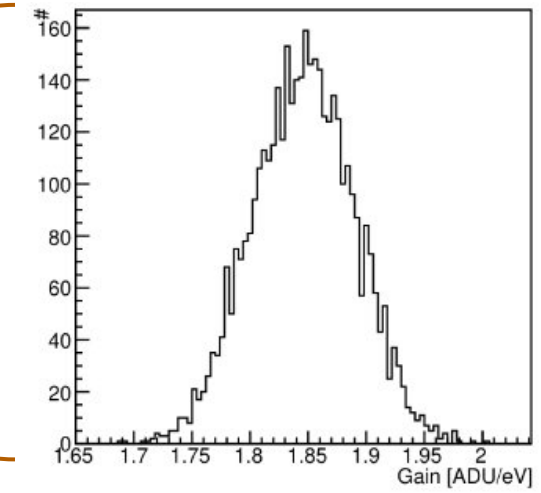



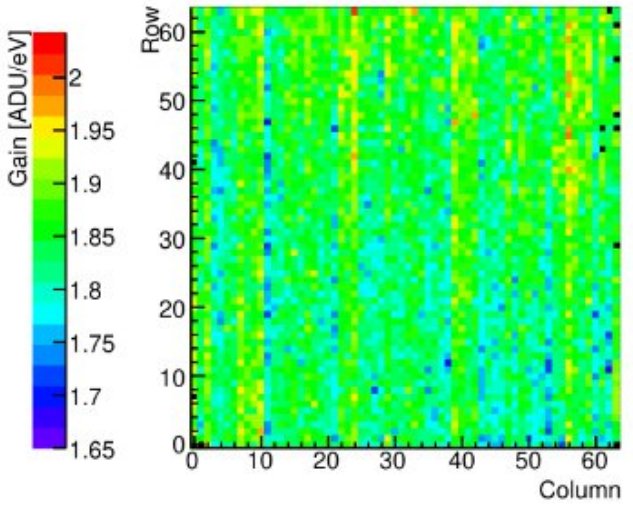

- **Gain**
  - *1.887 [ADU/eV]*
  - 0.483 *[nA/eV]*
  - *1.77 [nA/e⁻] (charge gain $g_q$)*
- **Noise**
  - Mean: 10.72 (1σ: 0.86) [e⁻ ENC]
  - Mean: 75.71 (1σ: 6.14) [ADU]

# GAIN AND NOISE PERFORMANCE

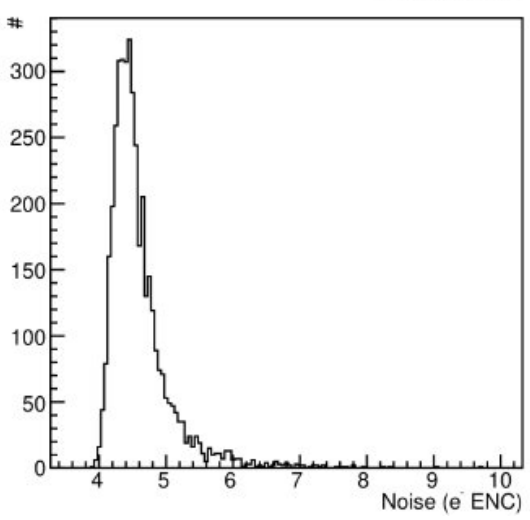
## Super-$g_q$ technology ((GA=4V, SC=4.5V => ~ 281µA/pix || good Noise)

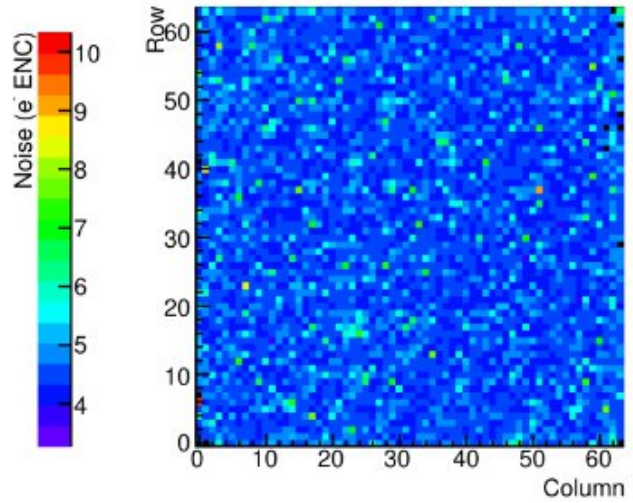
gain




calibrated noise



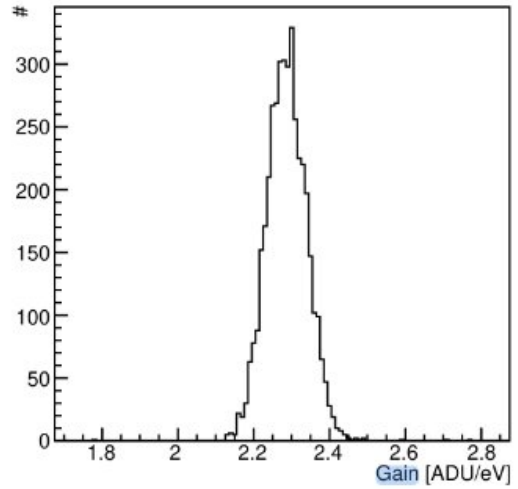

- **Gain**
  - *1.851 [ADU/eV]*
  - 0.474 *[nA/eV]*
  - *1.74 [nA/e⁻] (charge gain $g_q$)*

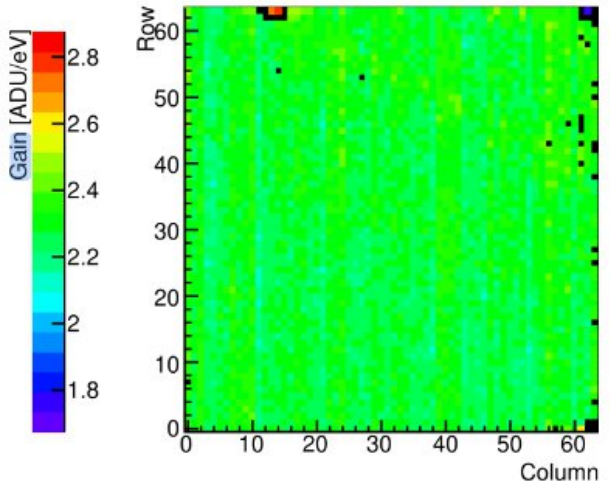
- **Noise**
  - Mean: 4.60 (1σ: 0.48) [e⁻ ENC]
  - Mean: 31.51 (1σ: 3.33) [ADU]

# GAIN AND NOISE PERFORMANCE

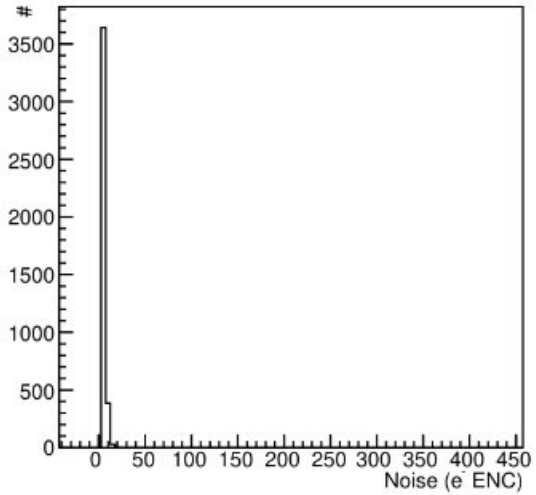
## Super-$g_q$ technology ((GA=7.6V, SC=7.8V => ~ 281µA/pix || good Gain)

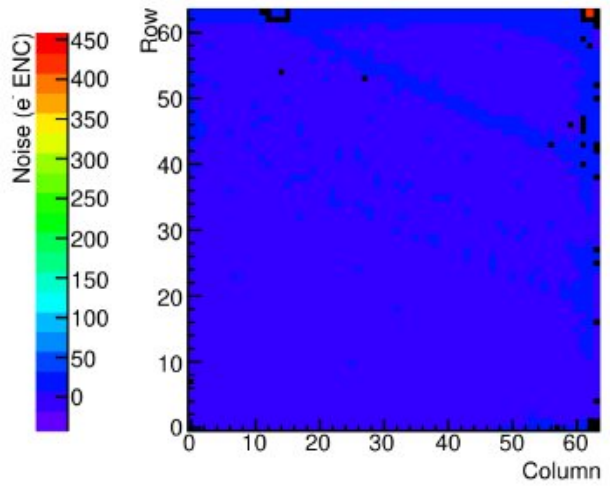
gain




calibrated noise



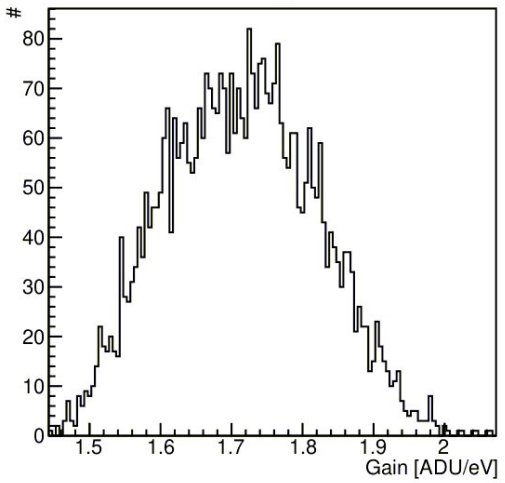

- **Gain**
  - ❖ *2.273 [ADU/eV]*
  - ❖ 0.*581 [nA/eV]*
  - ❖ *2.129 [nA/e⁻] (charge gain $g_q$)*

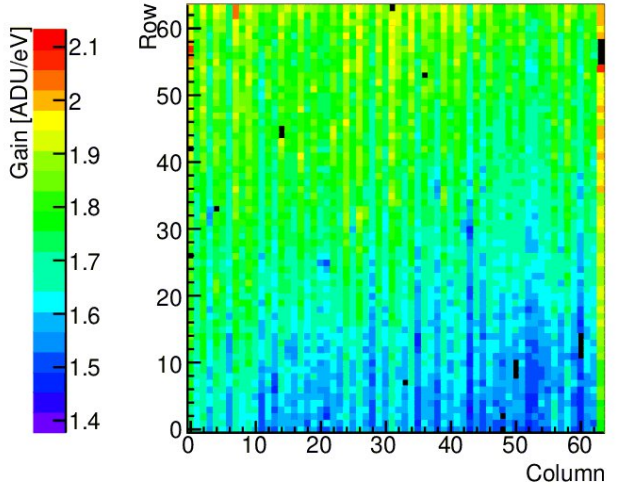
- **Noise**
  - ❖ Mean: 6.30 (1σ: 6.54) [e⁻ ENC]
  - ❖ Mean: 53.77 (1σ: 44.08) [ADU]

# GAIN AND NOISE PERFORMANCE

## Standard technology (GA=5.8V, SC=5V => ~100µA/pix)

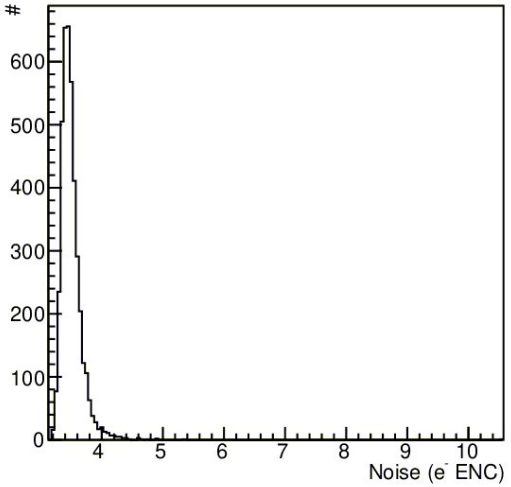
Full range gain

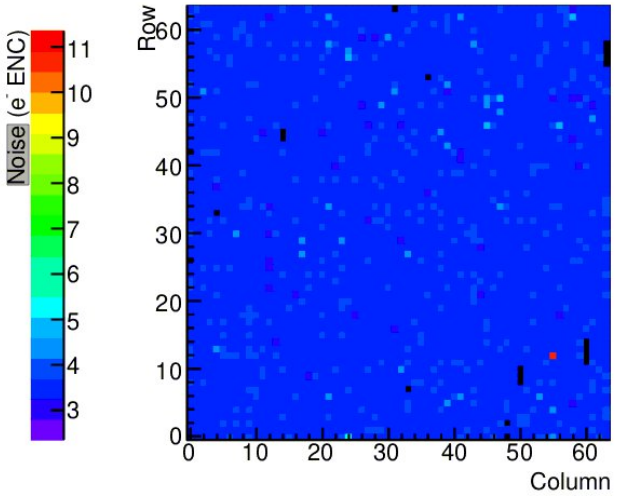



- **Gain**
  - ❖ 0.857 *[ADU/eV]*
  - ❖ 0.210 *[nA/eV]*
  - ❖ 0.769 *[nA/e⁻] charge gain ($g_q$)*

Full range calibrated noise




- **Noise**
  - ❖ Mean: 3.50 [e⁻ ENC]
  - ❖ Mean: 22.40 [ADU]

# COMPARISON TO STANDARD TECHNOLOGY

| | **Standard @ 100µA/pix** | **Super-$g_q$ @ 100µA/pix** | ***Super-$g_q$ good Noise*** | ***Super-$g_q$ good Gain*** |
|---|---|---|---|---|
| Charge Gain [nA/$e^-$] | 0.769 | 1.77 (x 2.3) | *1.74 (x 2.26)* | ***2.13** (x 2.77)* |
| Noise Mean [$e^-$ ENC] | **3.5** | 10.72 | *4.6* | *6.3* |
| Energy Res. (all events) [eV] | 134.36 | 188.53 | *139.53* | *166.31* |

## SUMMARY

- ✓ **Overall successful super-$g_q$ production**
- ✓ **Principal functionality could be confirmed**
- ✓ **Charge gain increase by a factor of 2.77**
  - ✓ In good agreement with simulation

## NEXT STEPS

- ➢ **Thorough investigation of noise performance**
  - ➢ Thermal, shot and 1/f noise
- ➢ **Rectification of simulation deviations**
  - ➢ Higher gain @ 5.9 keV, Noise density

MAX PLANCK SEMICONDUCTOR LABORATORY

# MANY THANKS FOR YOUR INTEREST

Reference:
[1] N. Meidinger and J. Müller-Seidlitz, “DEPFET Active Pixel Sensors,”. doi: 10.48550/arXiv.2204.13099.
[2] A. Bähr *et al.*, “Advanced DePFET concepts: super gq DePFET,”. doi: 10.1117/12.2562484.
[3] M. Porro *et al.*, “VERITAS 2.0 a multi-channel readout ASIC suitable for the DEPFET arrays of the WFI for Athena,”. doi: 10.1117/12.2056097.

Sebastian Stadler
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# BACKUP

# INTRODUCTION

## The DePFET standard technology

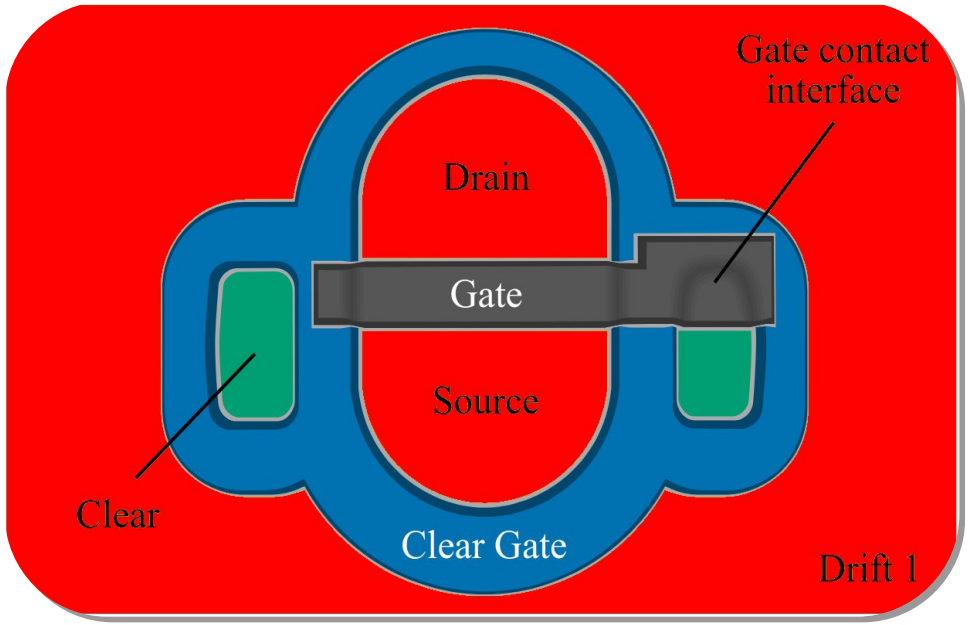
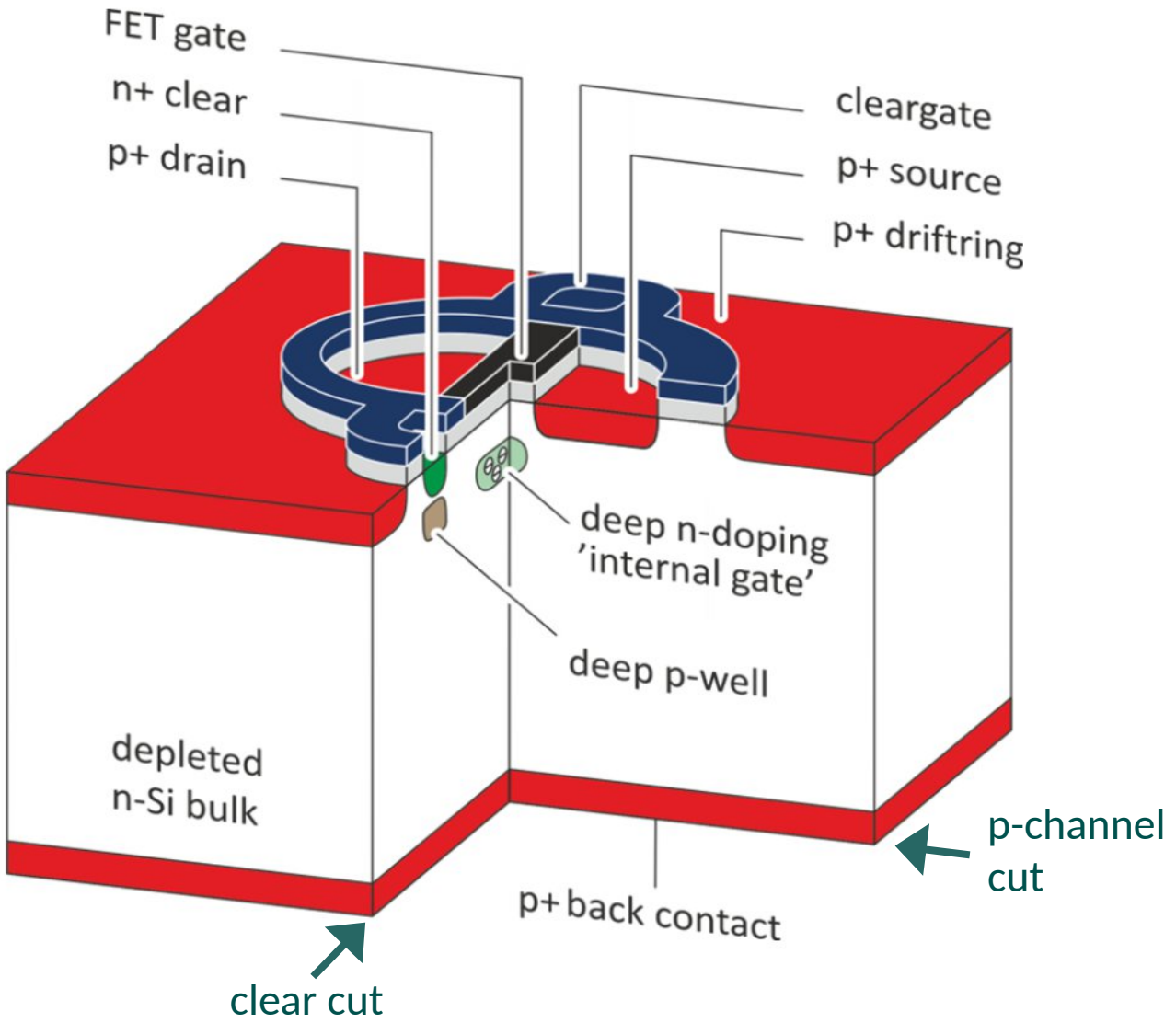
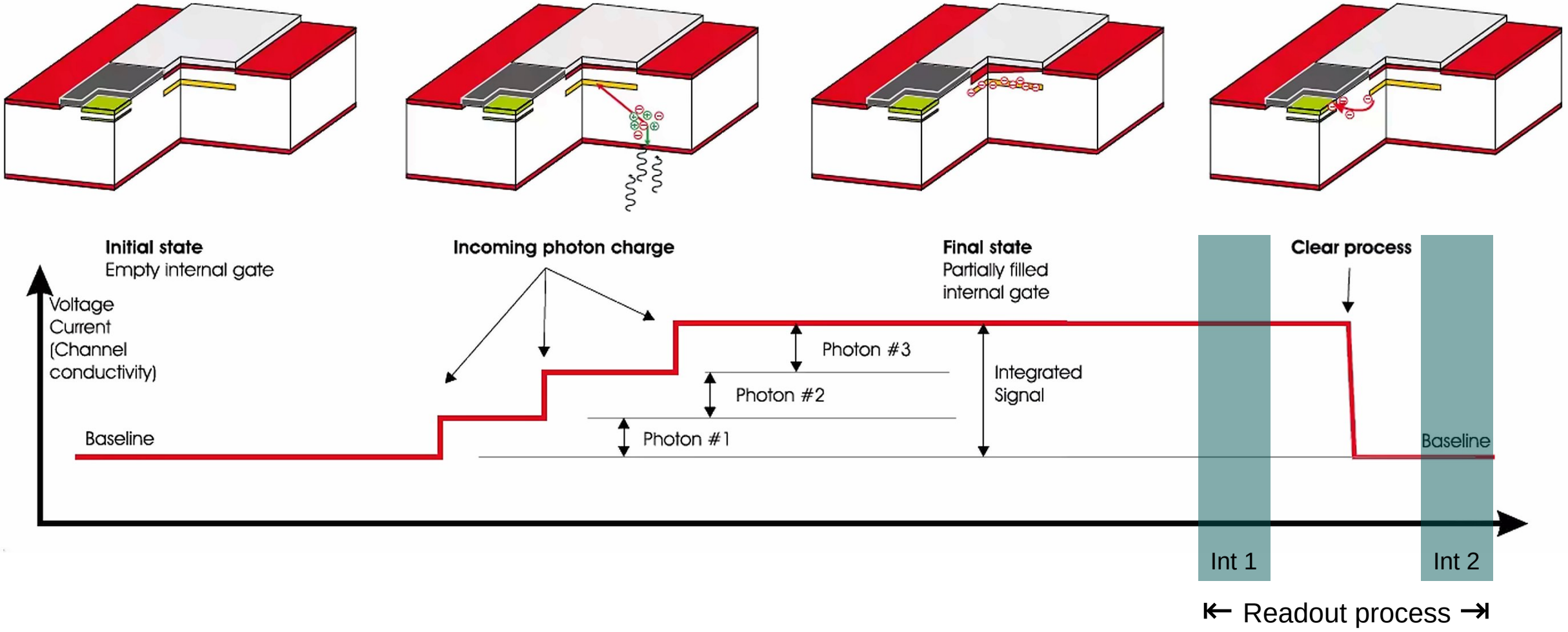



Figure from [1]



# INTRODUCTION

## The DePFET working principle

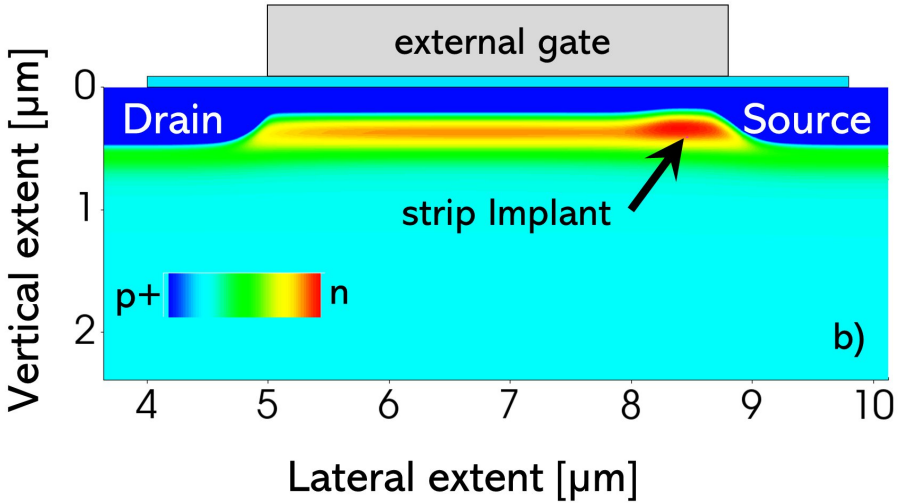


# THE SUPER-$G_Q$ TECHNOLOGY[2]

## Doping concentration p-channel cut

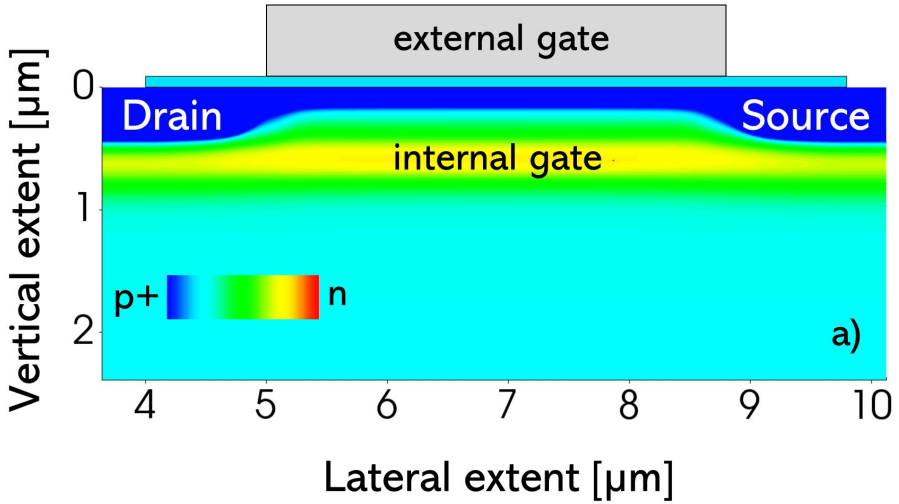
**Super-$g_q$ DePFET:**

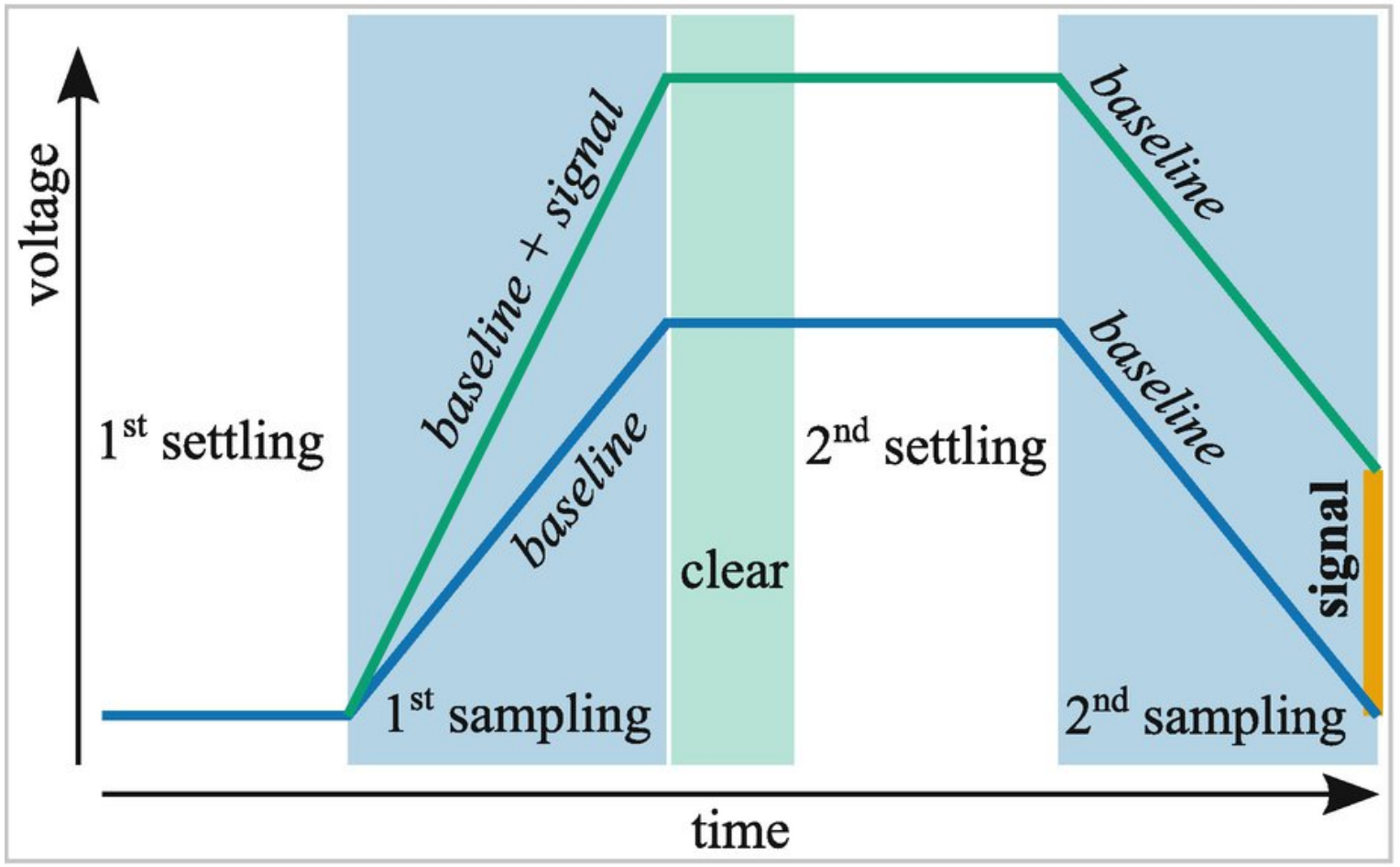
- Deep n-implant + strip implant
  - ➢ *Greater design freedom*
  - ➢ *Localized steering effect*
  - ➢ *Mitigating impact ionization noise*




**Standard-DePFET:**

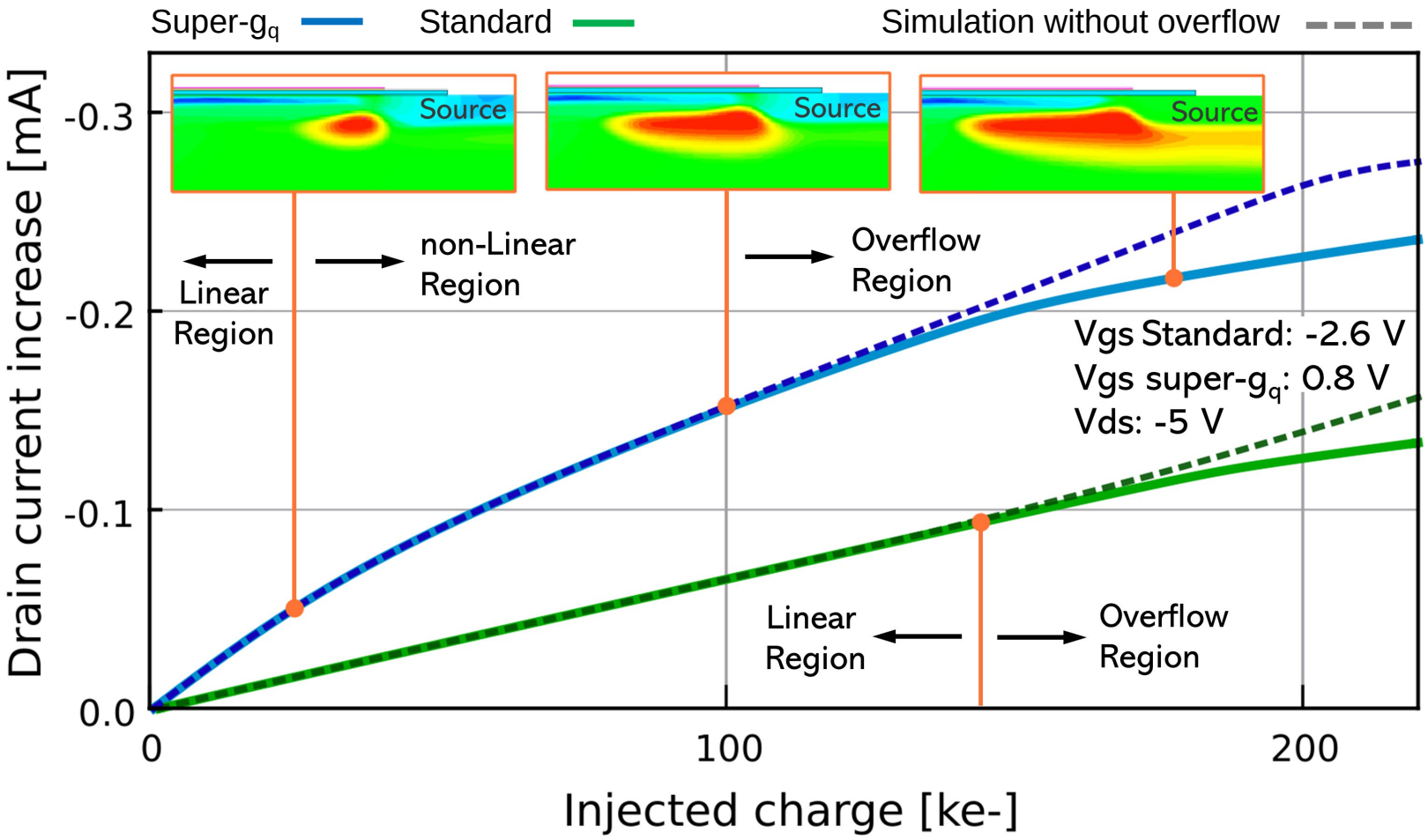
- Deep n-implant
  - ➢ *Internal gate defined by gate oxide size*
  - ➢ *Steering effect over hole p-channel*




voltage
1st settling
baseline + signal
baseline
1st sampling
clear
2nd settling
baseline
baseline
signal
2nd sampling
time

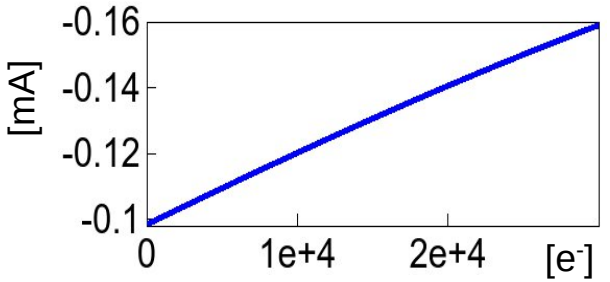
# TCAD SIMULATIONS

## Device simulation results




In linear region below 25 ke⁻:

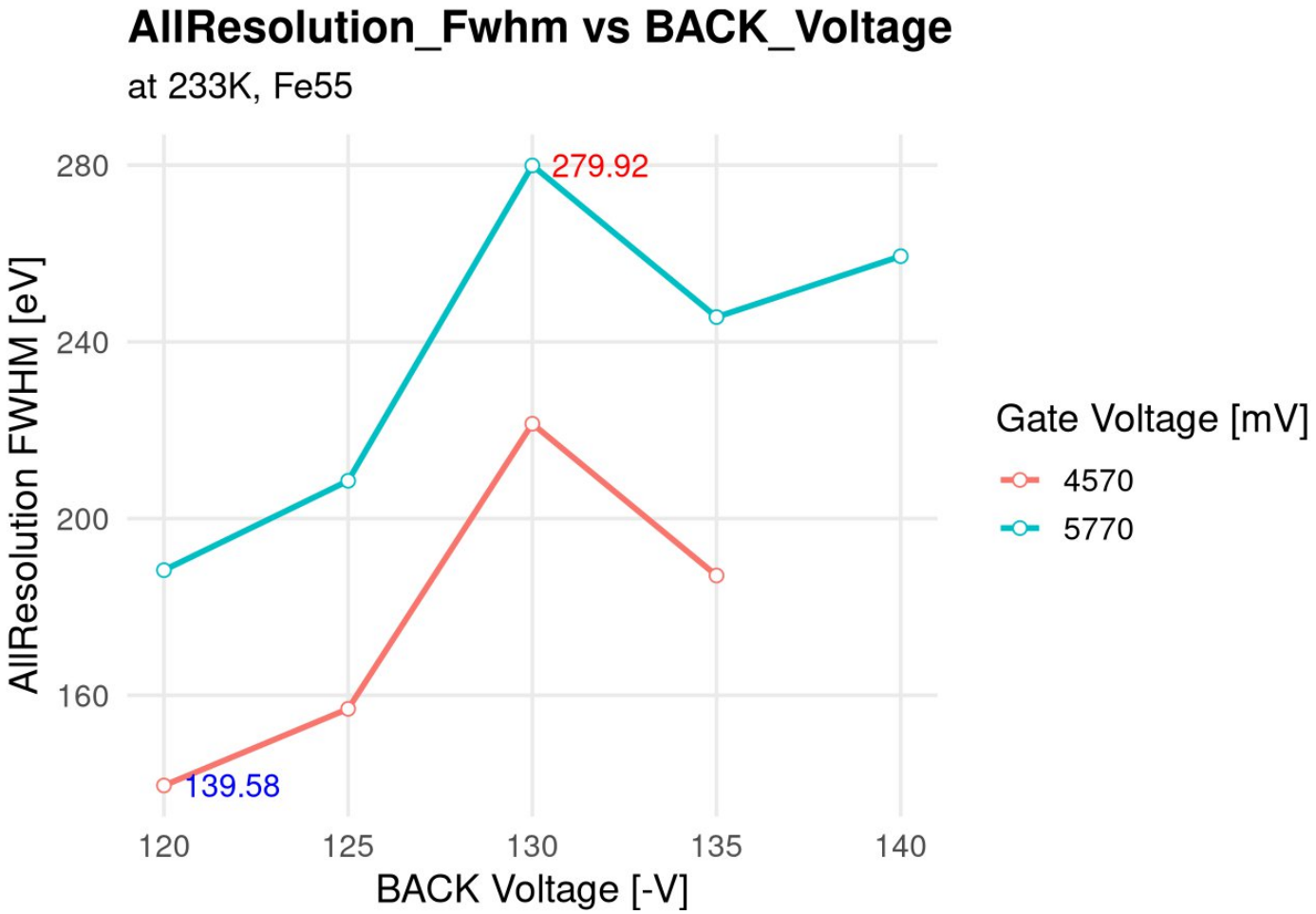
- Zoom on linear region




- Charge gain ≈ 1.7nA/e⁻
  - increase by a factor of ~3
- white noise of ≤ 1 e⁻ ENC
  - ½ compared to standard

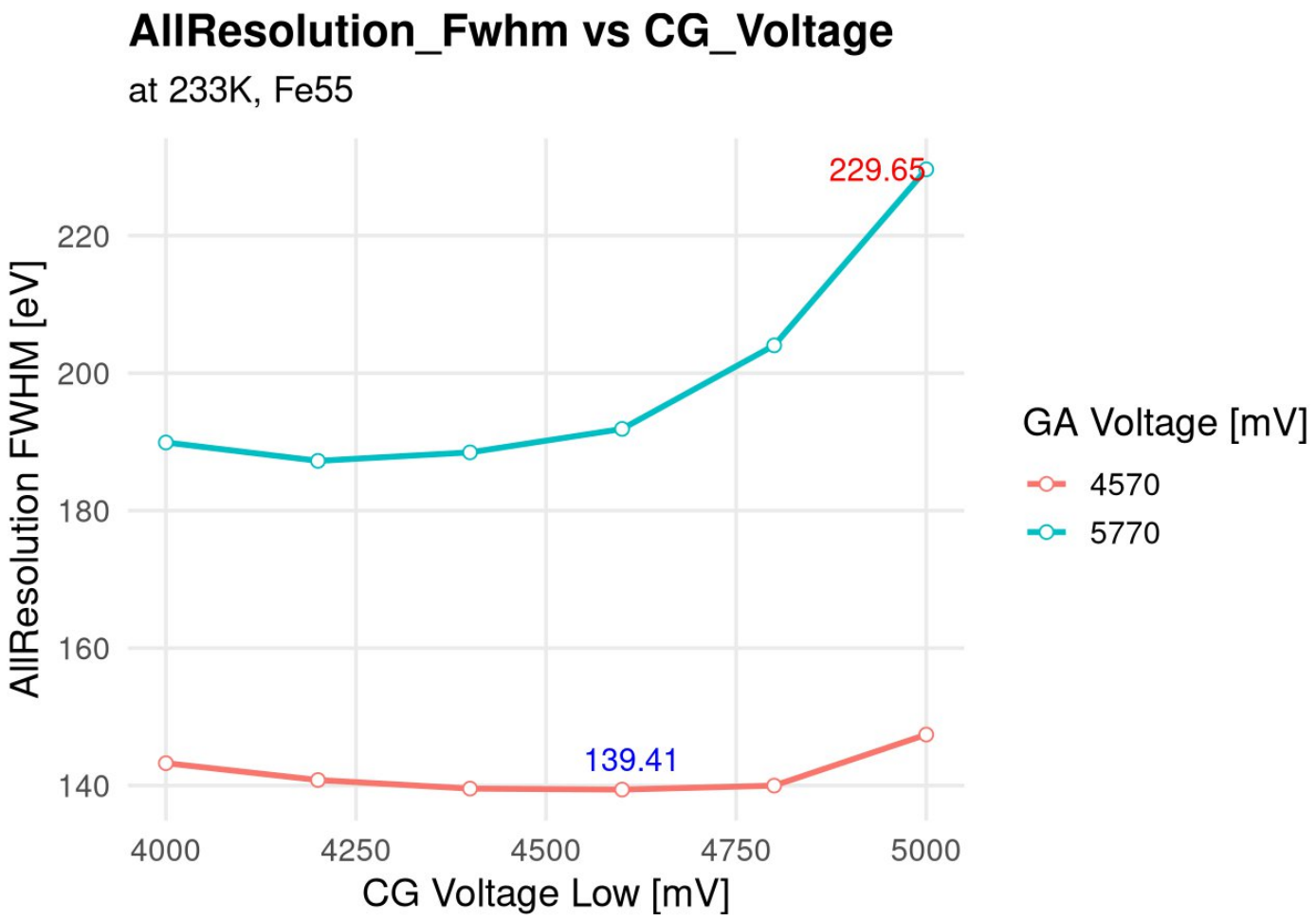
# CHARACTERIZATION

## Super-$g_q$ technology (Backside sweep)



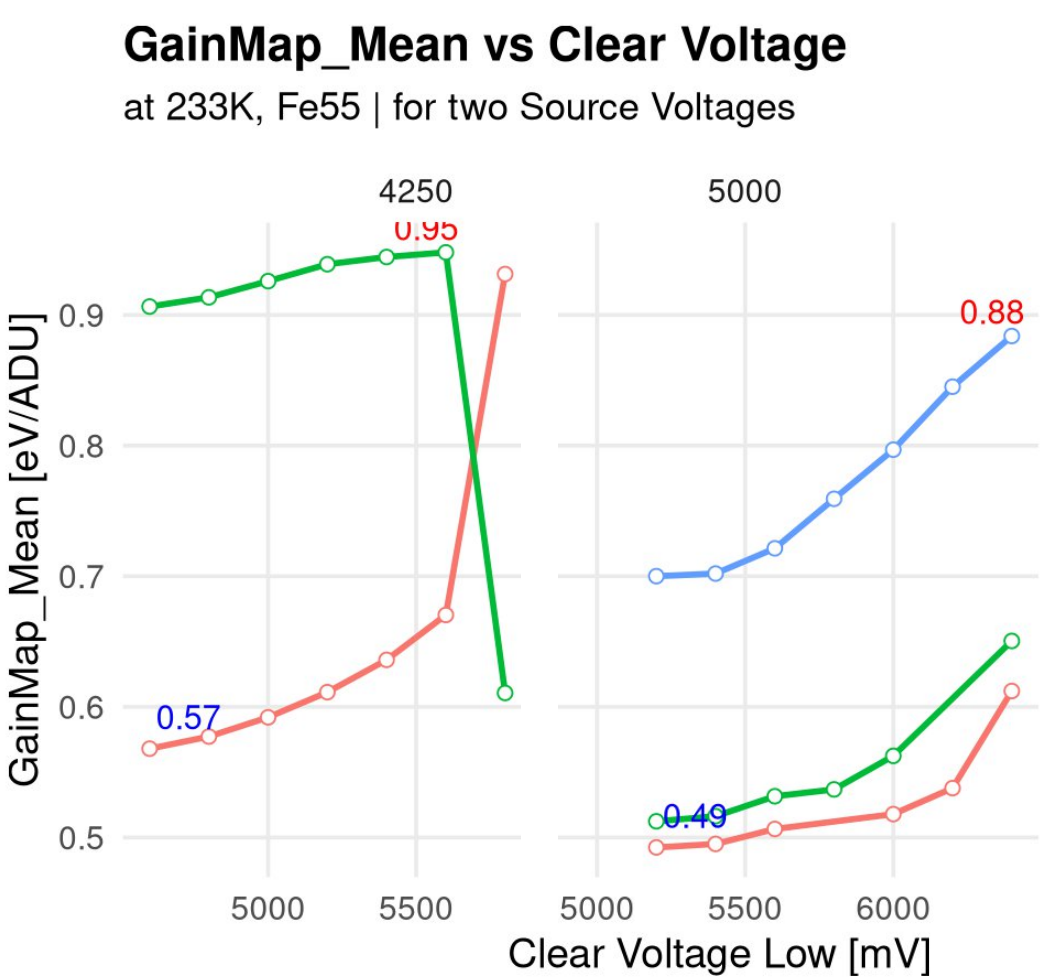
# CHARACTERIZATION

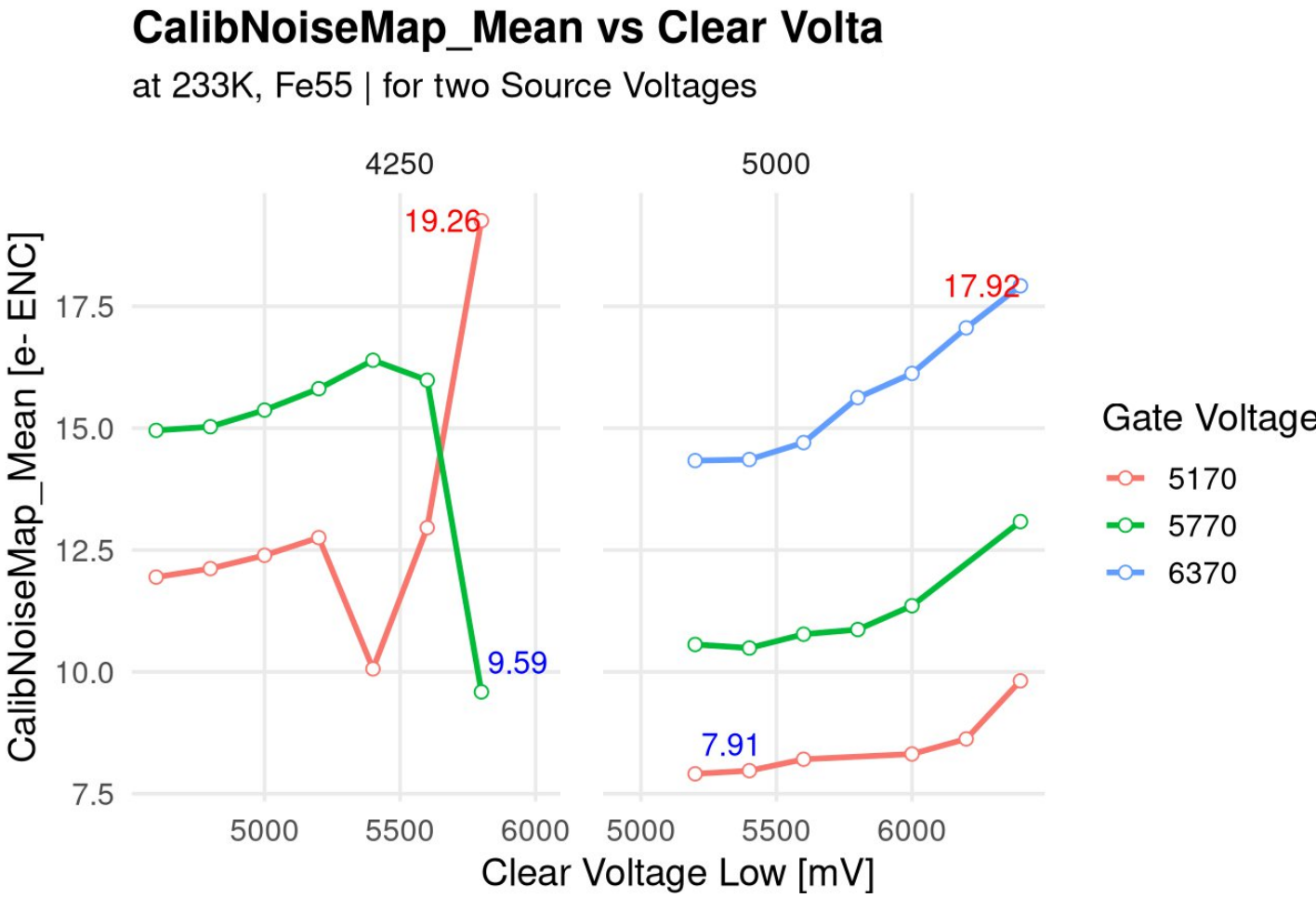
## Super-$g_q$ technology (Clear Gate sweep)



# CHARACTERIZATION

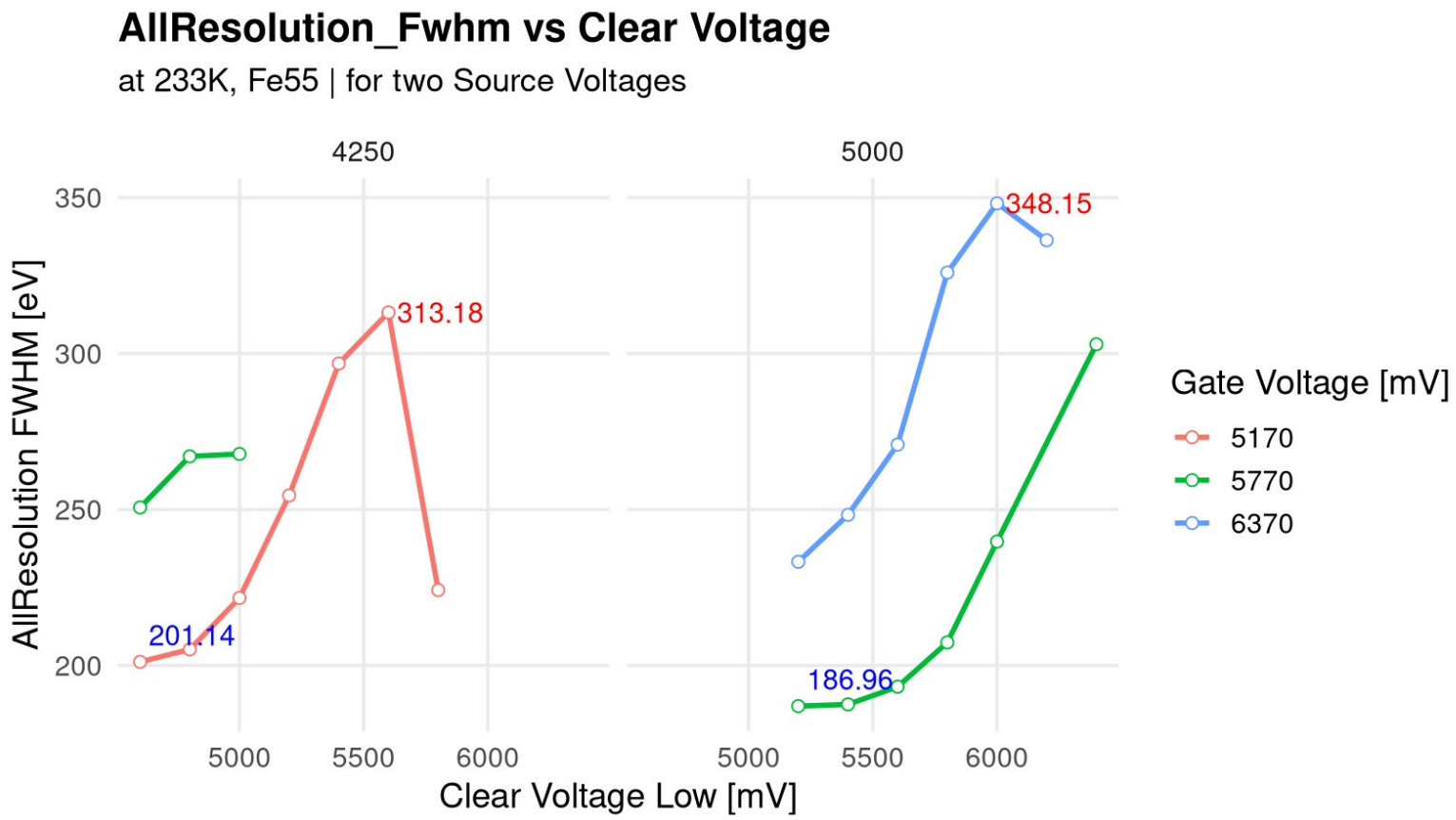
## Super-$g_q$ technology (Clear Gate sweep)



# CHARACTERIZATION

## Super-$g_q$ technology (Clear Gate sweep)

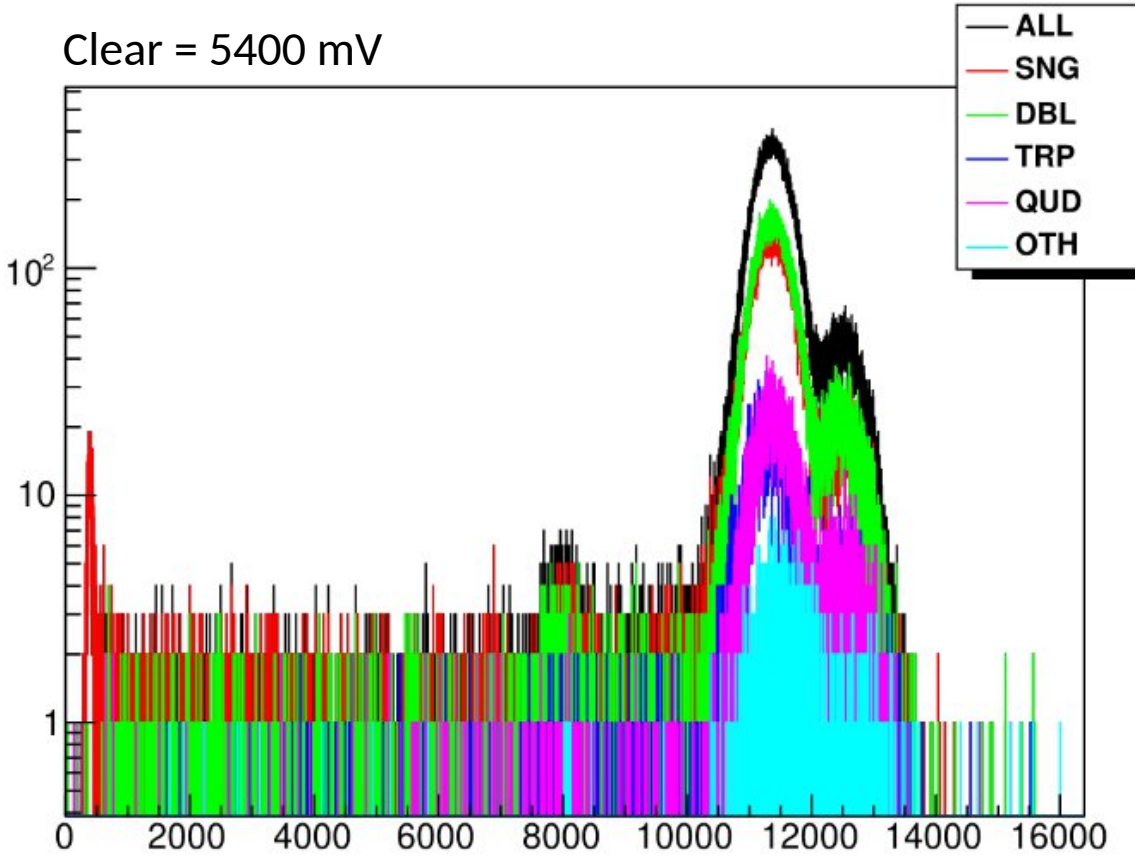


# CHARACTERIZATION

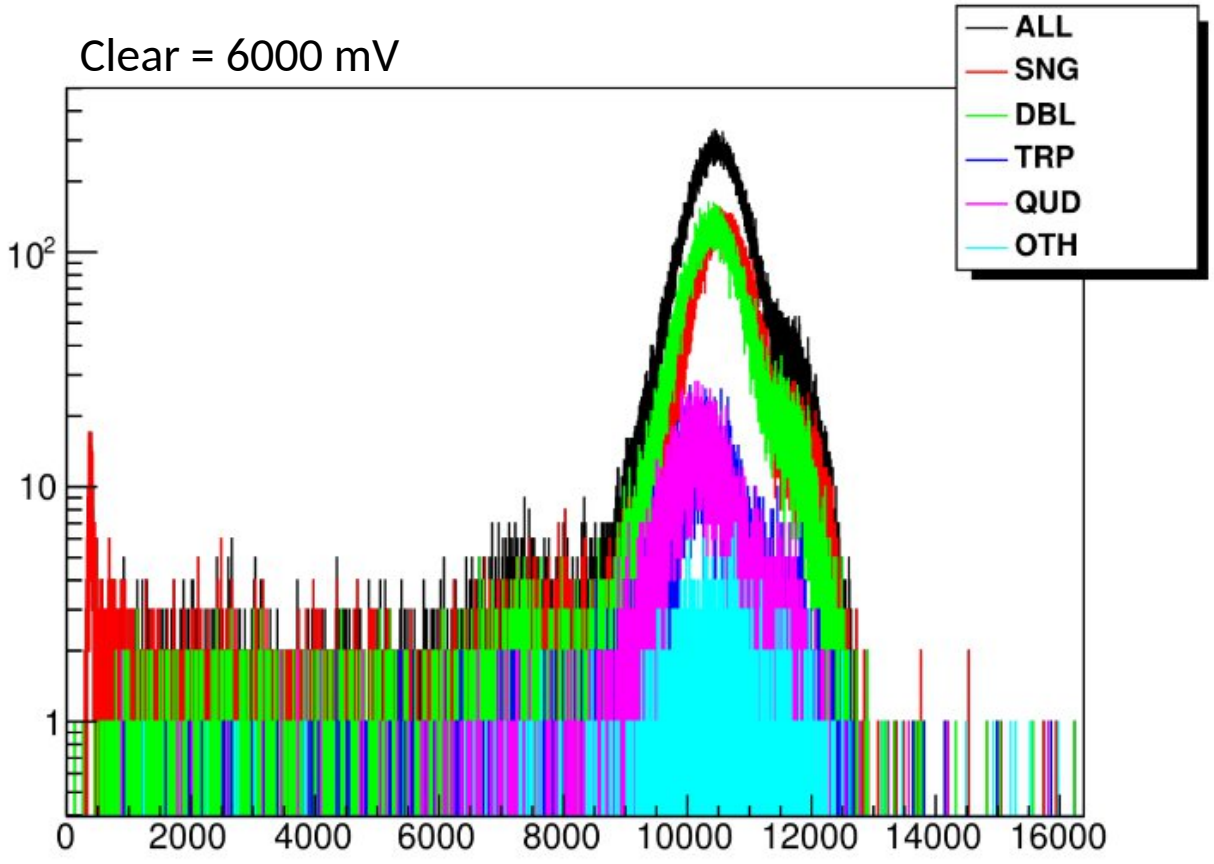
## Super-$g_q$ technology (Clear Gate sweep)

Gate Bias = 5770 mV, Source Bias = 5V

Clear = 5400 mV

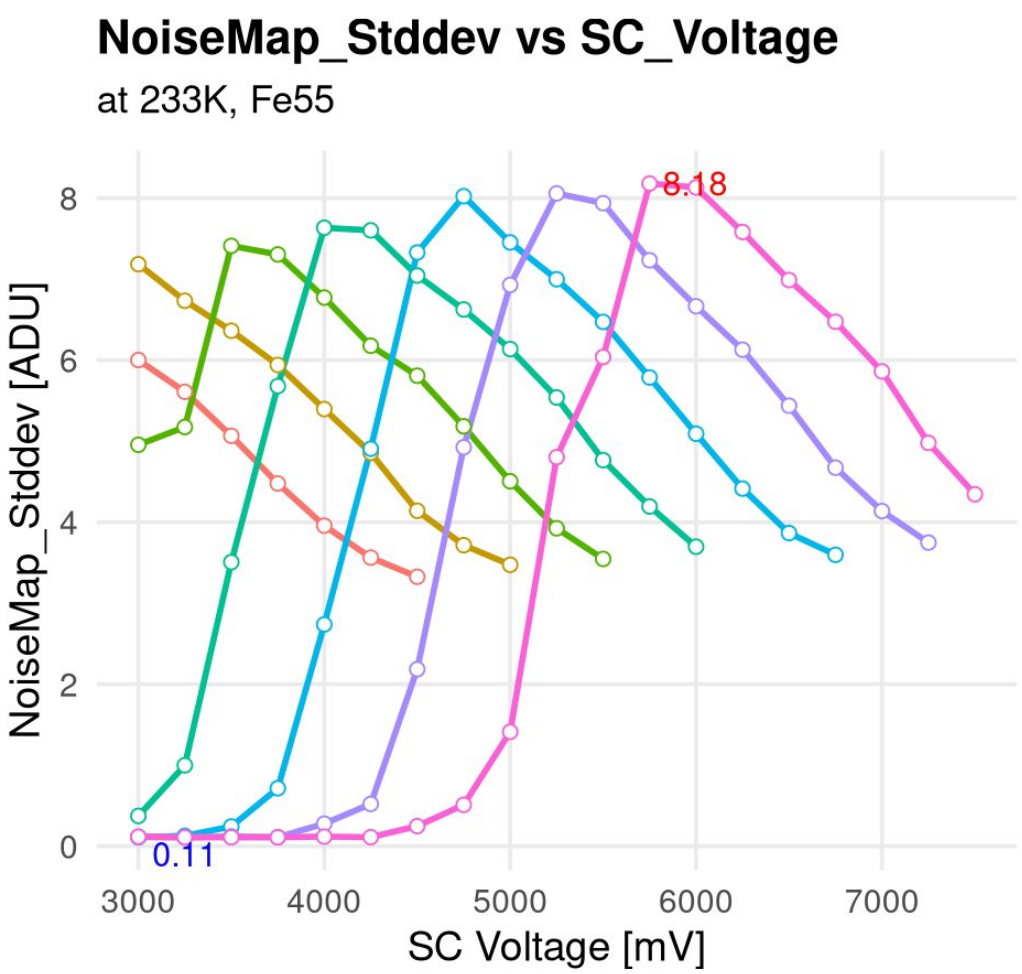


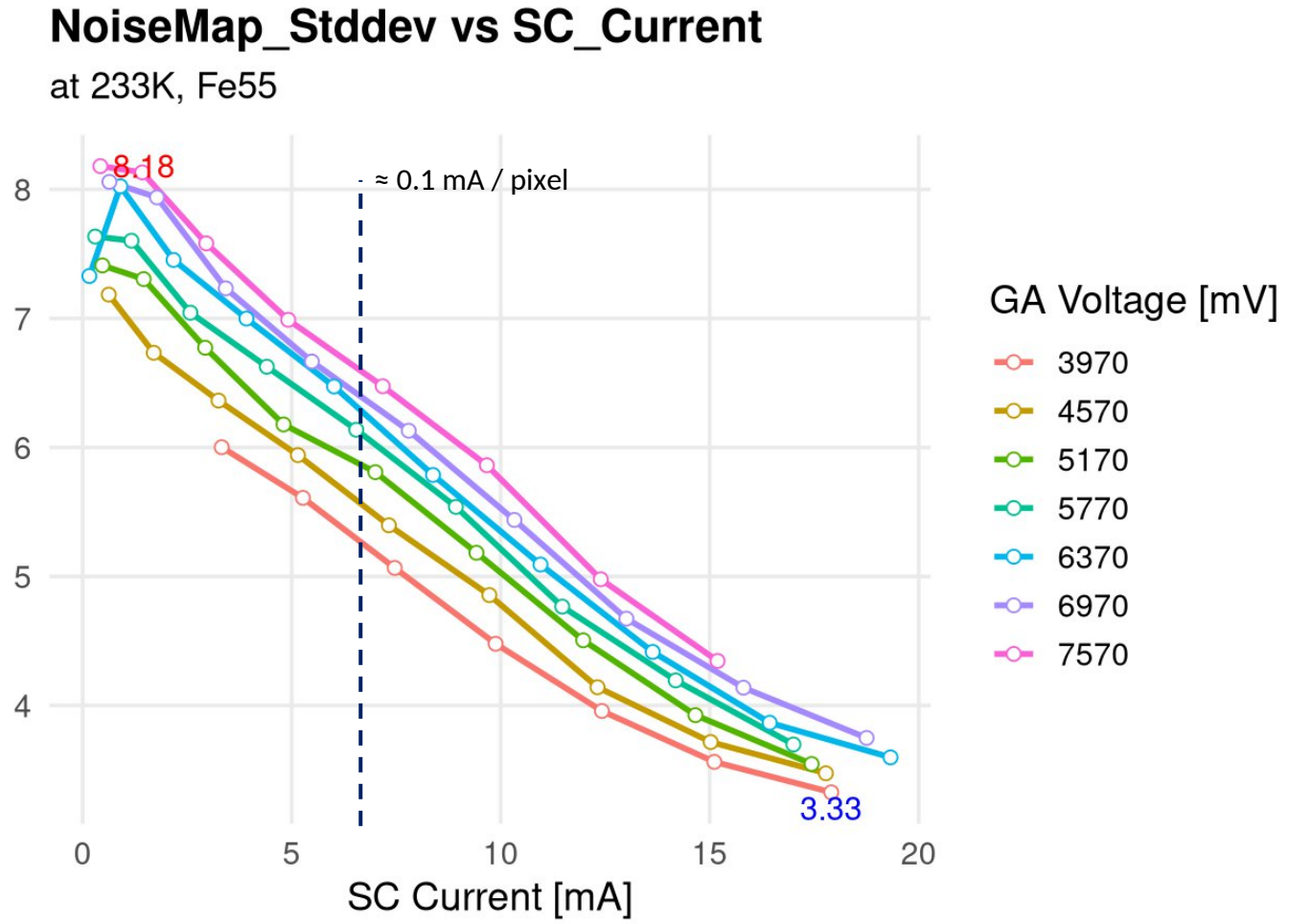

Clear = 6000 mV



# CHARACTERIZATION

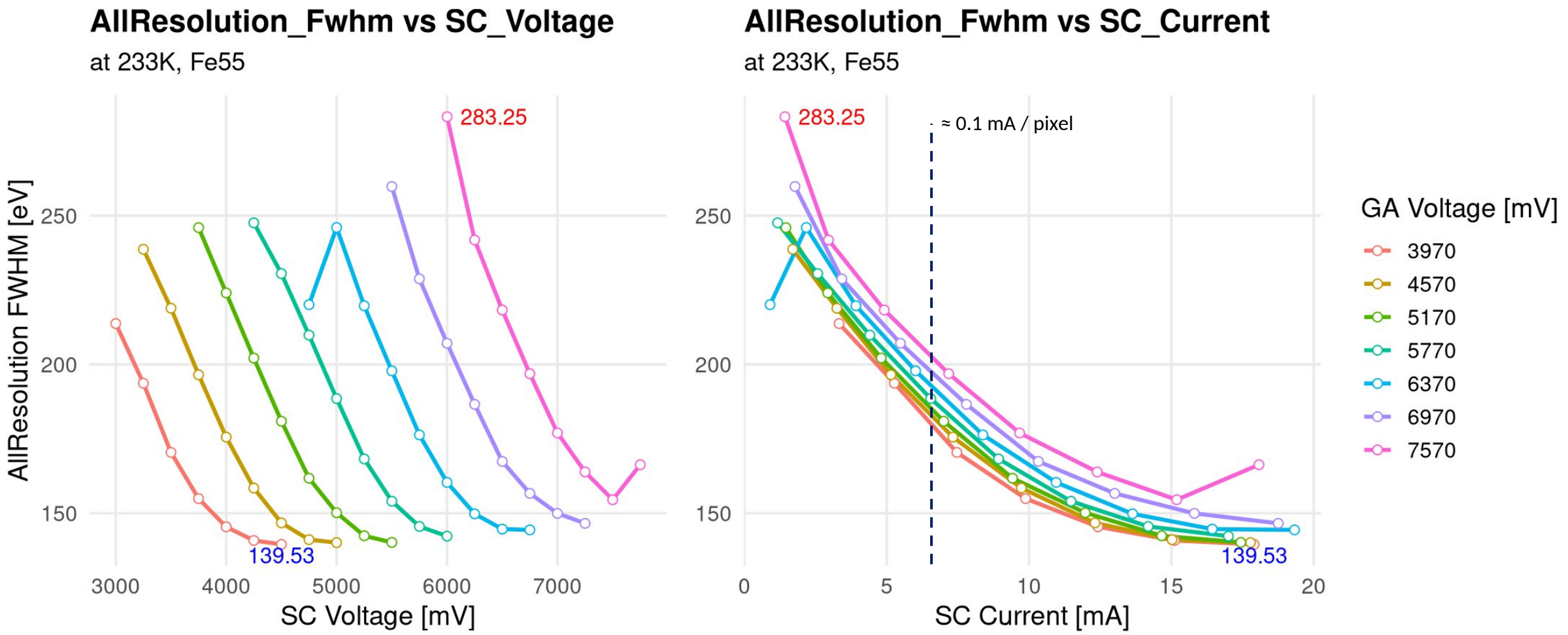
## Super-$g_q$ technology (Gate & Source sweep)



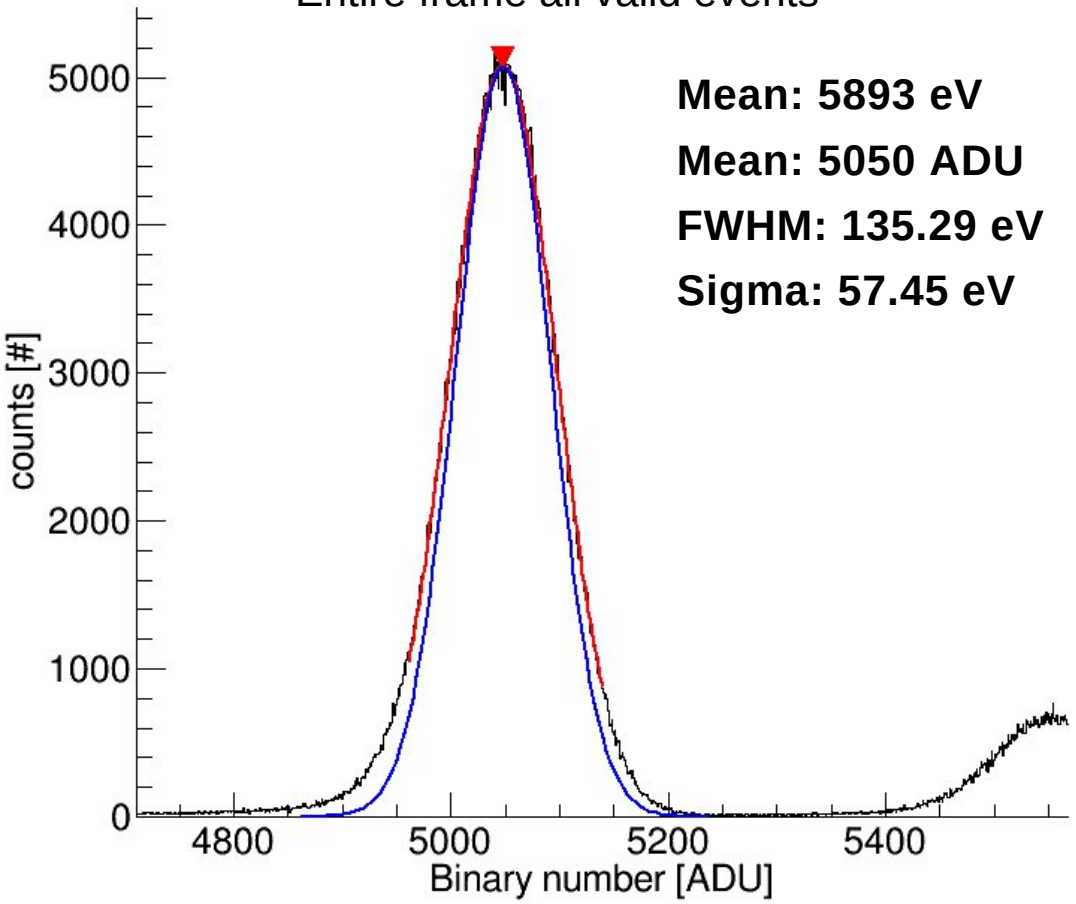
# CHARACTERIZATION

## Super-$g_q$ technology (Gate & Source sweep)



# ENERGY RESOLUTION FINDINGS
## Standard technology

Entire frame all valid events



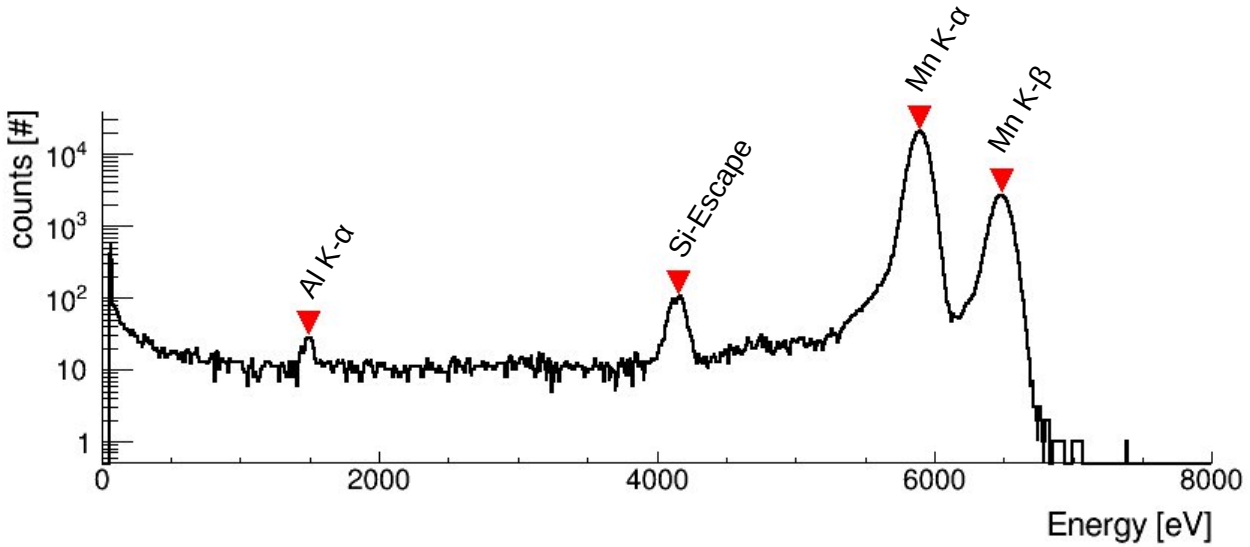

**Mean: 5893 eV**

**Mean: 5050 ADU**

**FWHM: 135.29 eV**

**Sigma: 57.45 eV**

Full range spectrum calibrated




Gaussian fit

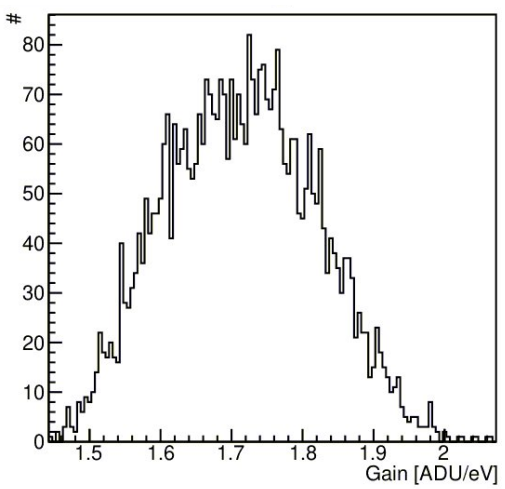
Theoretical Fano noise

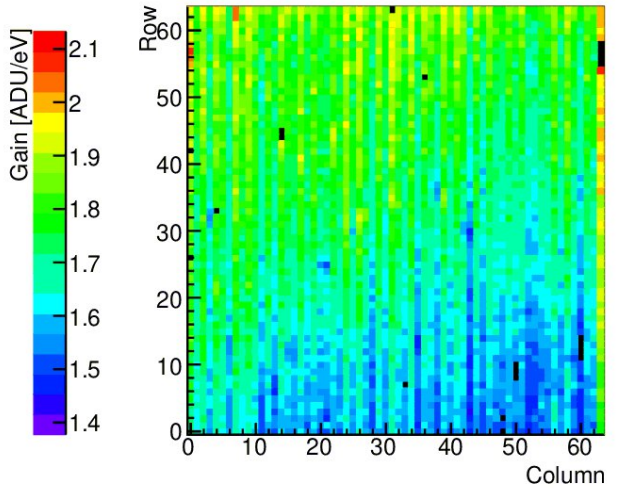
@ -30°C

*preliminary*

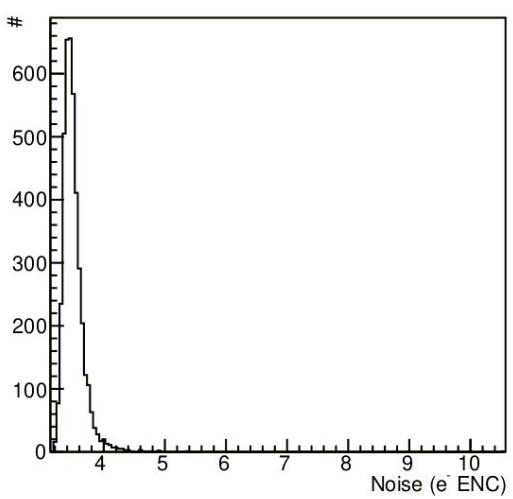
# NOISE, GAIN AND SPECTRUM
## Standard technology

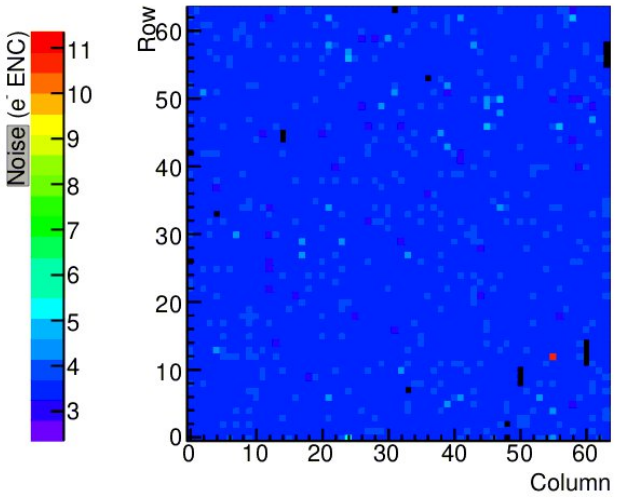
Full range gain




Full range calibrated noise




- **Gain**
  - ❖ 0.857 *in [ADU/eV]*
  - ❖ 0.210 *in [nA/eV]*
  - ❖ 0.769 *in [nA/e⁻] charge gain ($g_q$)*
- **Noise**
  - ❖ Mean: 3.50 [e⁻ ENC]
  - ❖ Mean: 22.40 [ADU]

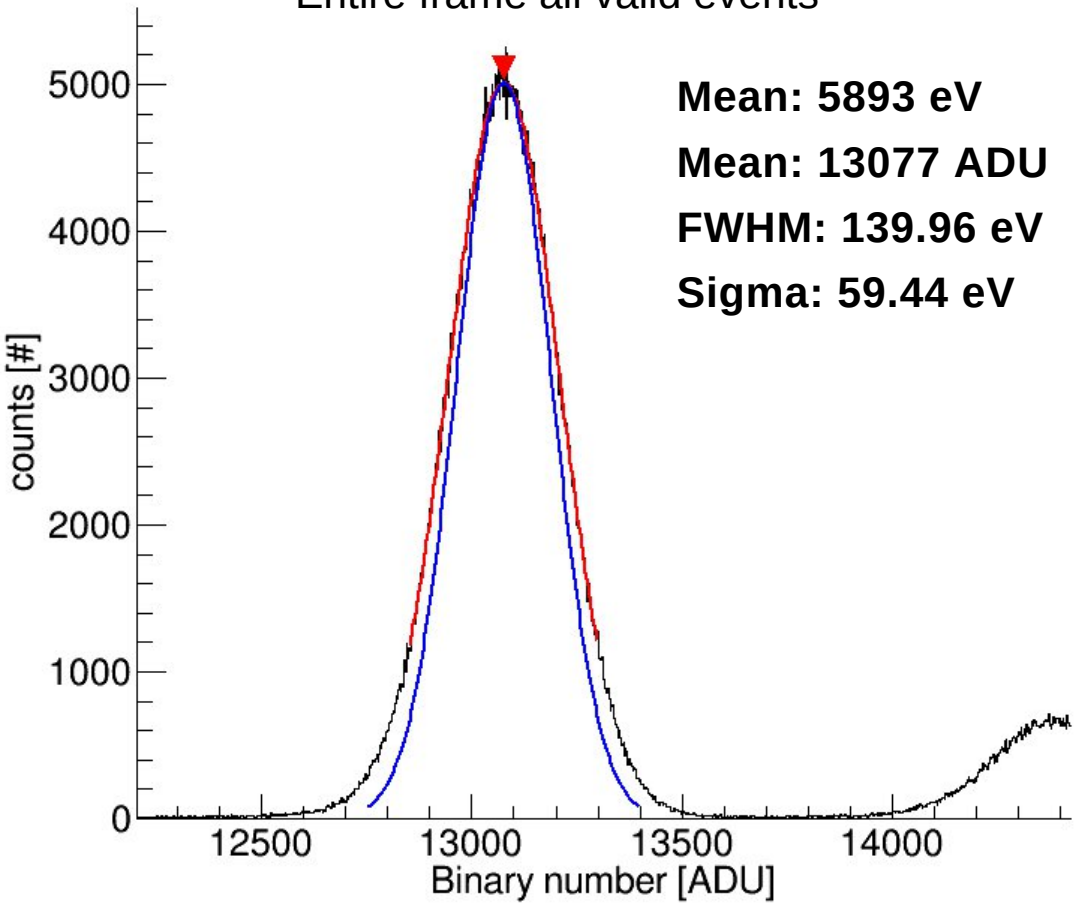
@ -30°C

*preliminary*

# ENERGY RESOLUTION FINDINGS

## Super-$g_q$ technology

Entire frame all valid events



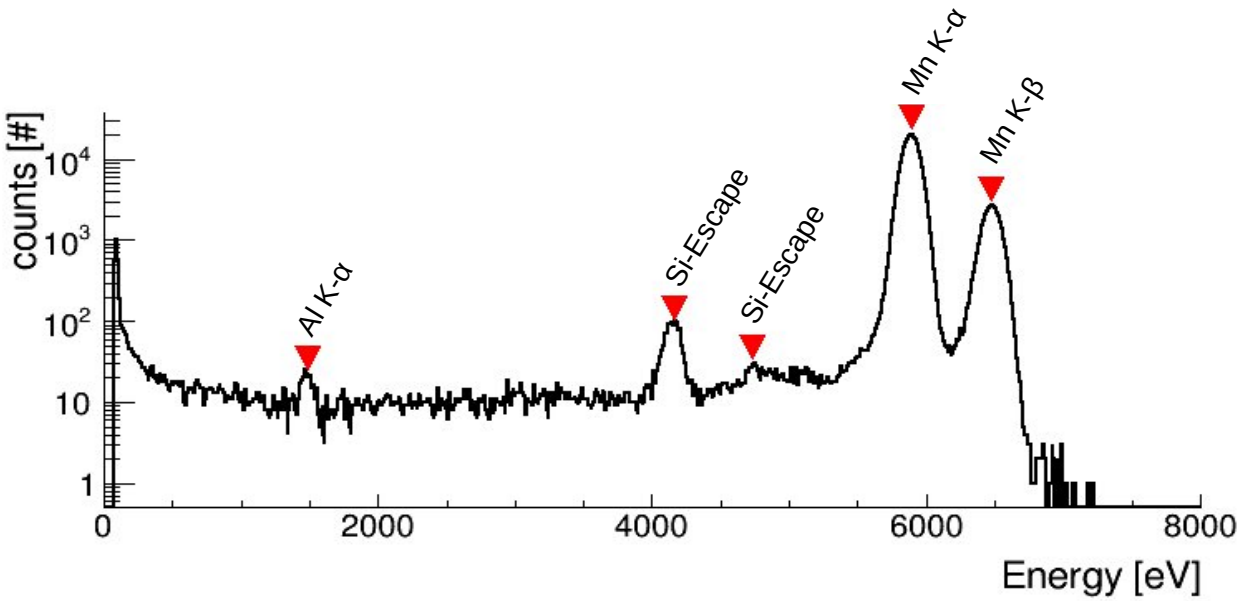

**Mean: 5893 eV**

**Mean: 13077 ADU**

**FWHM: 139.96 eV**

**Sigma: 59.44 eV**

Full range spectrum calibrated




Gaussian fit

Theoretical Fano noise

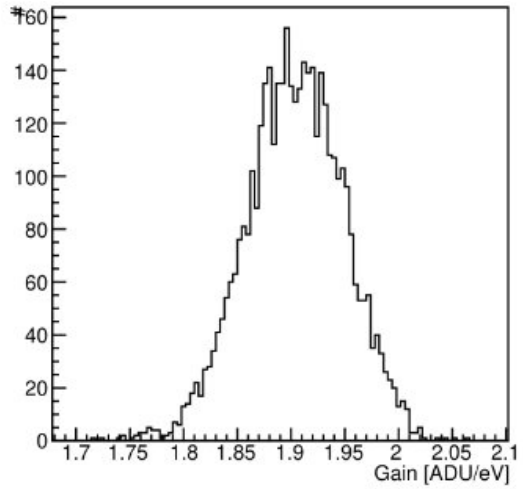
@ -30°C

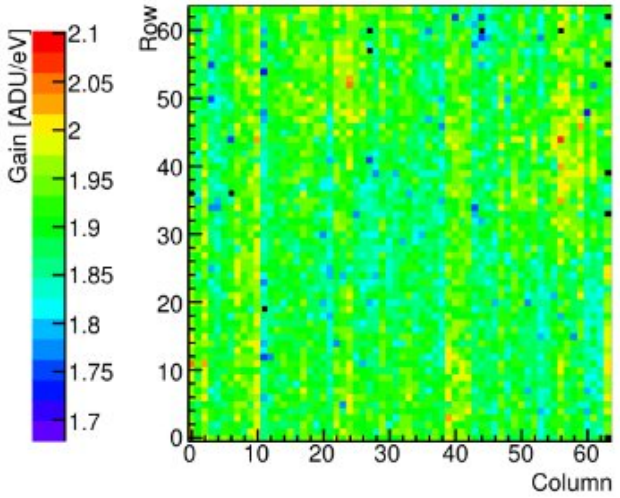
*preliminary*

# NOISE, GAIN AND SPECTRUM

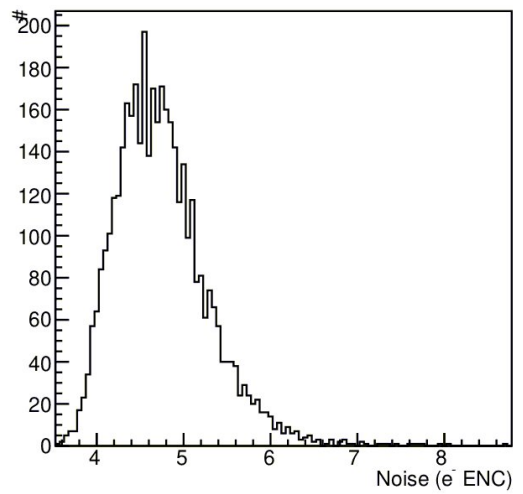
## Super-$g_q$ technology

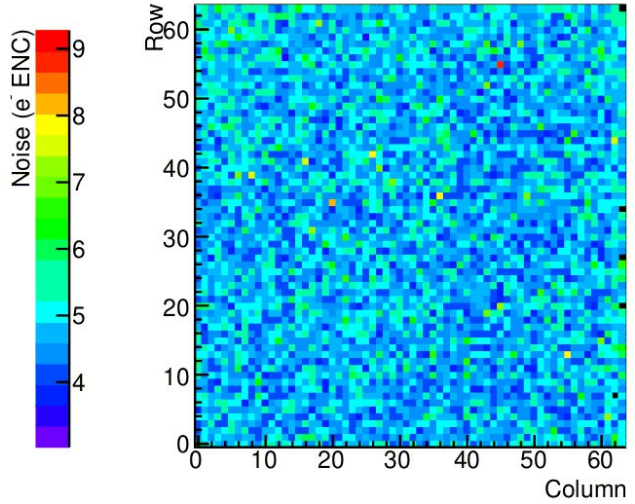
gain




Full range calibrated noise




- **Gain**
  - ❖ *2.219 in [ADU/eV]*
  - ❖ 0.567 *in [nA/eV]*
  - ❖ 2.075 *in [nA/e⁻] charge gain ($g_q$)*
  - ➢ ***2.7** times more than standard*
- **Noise**
  - ❖ Mean: 4.75 [e⁻ ENC]
  - ❖ Mean: 39.10 [ADU]
  - ➢ ***2** times more than standard*

@ -30°C

*preliminary*