HALBLEITERLABOR DER MAX-PLANCK-GESELLSCHAFT

EDET DH80k – Characterization of the sensors with low noise setup

23rd International Workshop on DePFET Detectors and Applications

12/03/2019

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- Motivation and Introduction
- DePFET Structure and Measurement Setup
- Optimization of Operation Parameters and Response Function
- Summary and Outlook

Motivation

for the project

Stroboscopic imaging provides insights to the dynamics of processes:

- short, discrete illumination periods with high intensity
- decouples exposure time, image contrast and motion blur
- pulse intensity defines the image contrast
- frequency of illumination defines time resolution
- pulse duration defines impact of motion blur

Challenges of stroboscopic imaging in TEM world:

- real space imaging → high granularity
- high intensity → high dynamic range
- direct electron detection → thin substrate
- high pulse frequency → high framerate
- “grey scale” image → no data reduction possible

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Introduction

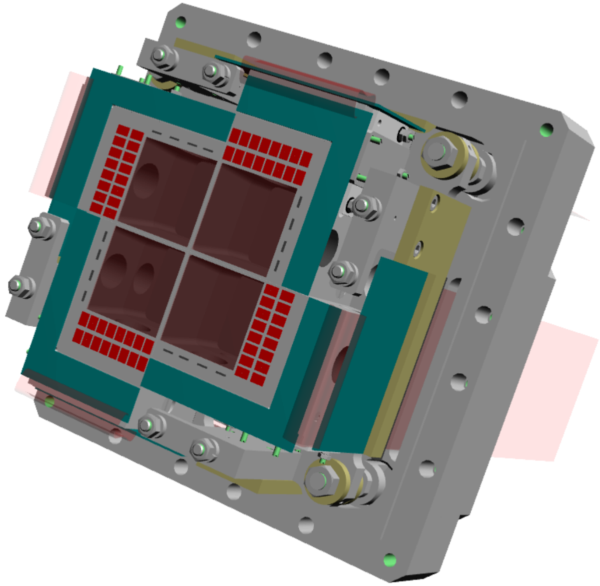
to the camera system and its challenges

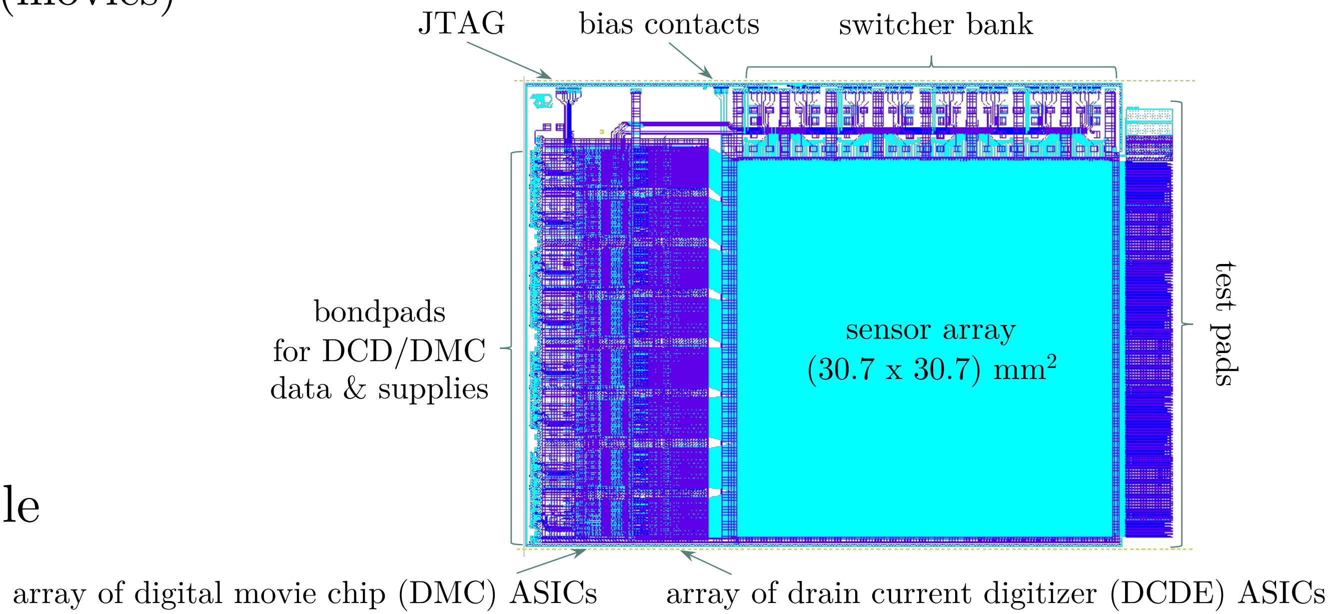
Camera system:

- focal plane area (FPA) consists of 4 individual and independent modules (“tiles”), each capable of stand-alone operation
- small sensitivity gap between tiles (1.2 mm)
- All Silicon Module (ASM)
- readout in rolling shutter mode, 100 ns/row, 4 rows in parallel
- maximum framerate of 80 kHz or 12.8 µs/frame
- front end electronics (FEE) buffers bursts (movies) with 100 frames
- maximum burst rate 100 Hz

Data rate:

- 8 bit digitization resolution:
  - tile module data rate of ~3 GB/s
  - total data rate of ~12 GB/s
- data reduction difficult if not impossible





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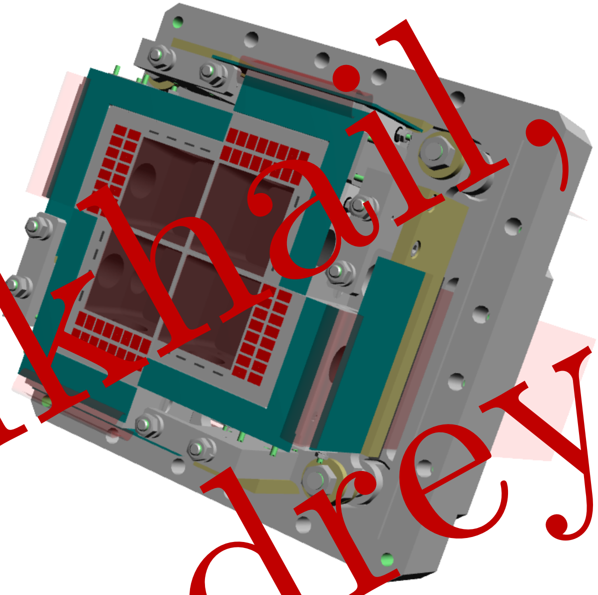

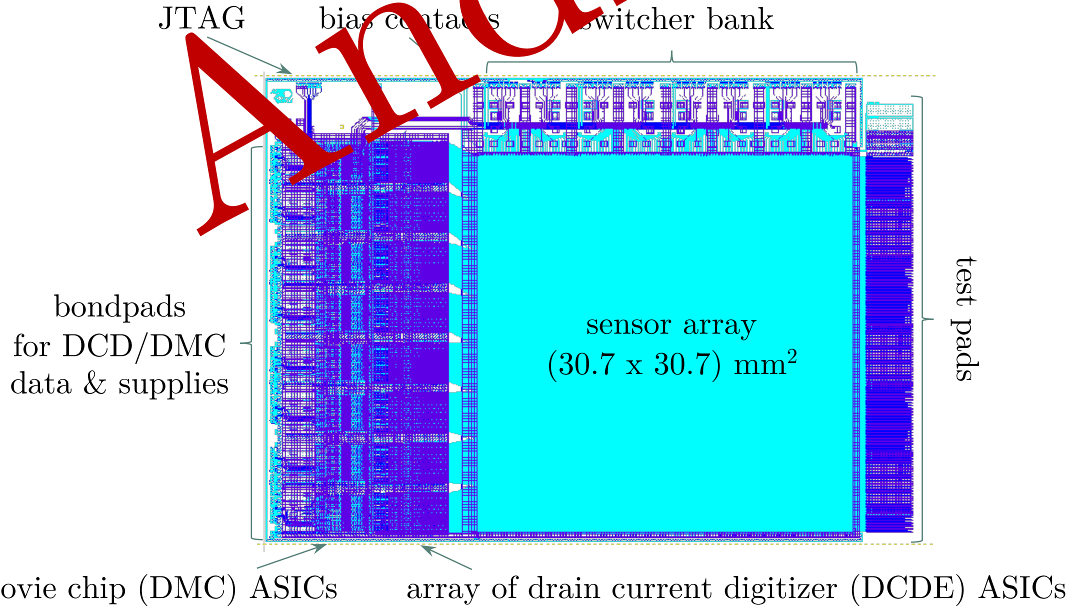

Introduction

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Sensor array

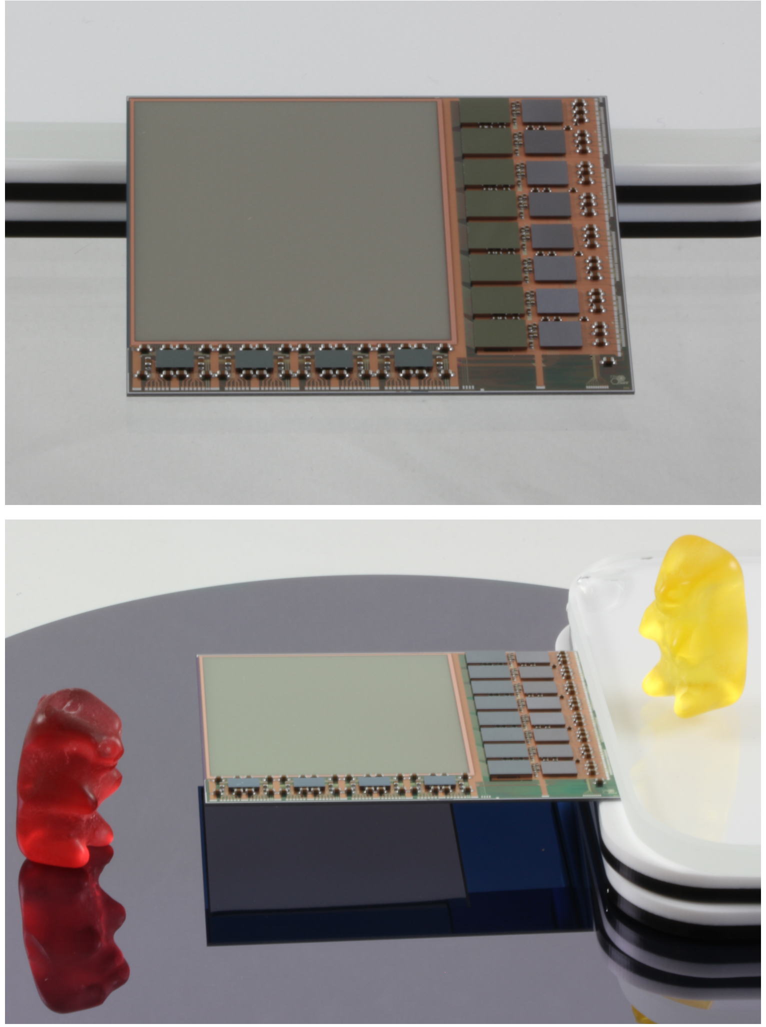
- 1 MPixel for the complete FPA
- 512 x 512 pixels per tile
- (60 x 60) µm² pixel size

Dynamic range of pixels:

- single primary e⁻ sensitivity
- capable of storing the signal from 100 primary e⁻ at 300 keV (~800k signal e⁻)

Spatial resolution improvements:

- reduce e⁻ multiple scattering
  - thin sensitive detector substrate (50 µm and 30 µm)
- reduce e⁻ back scattering
  - no support layer
  - highly effective beam dump



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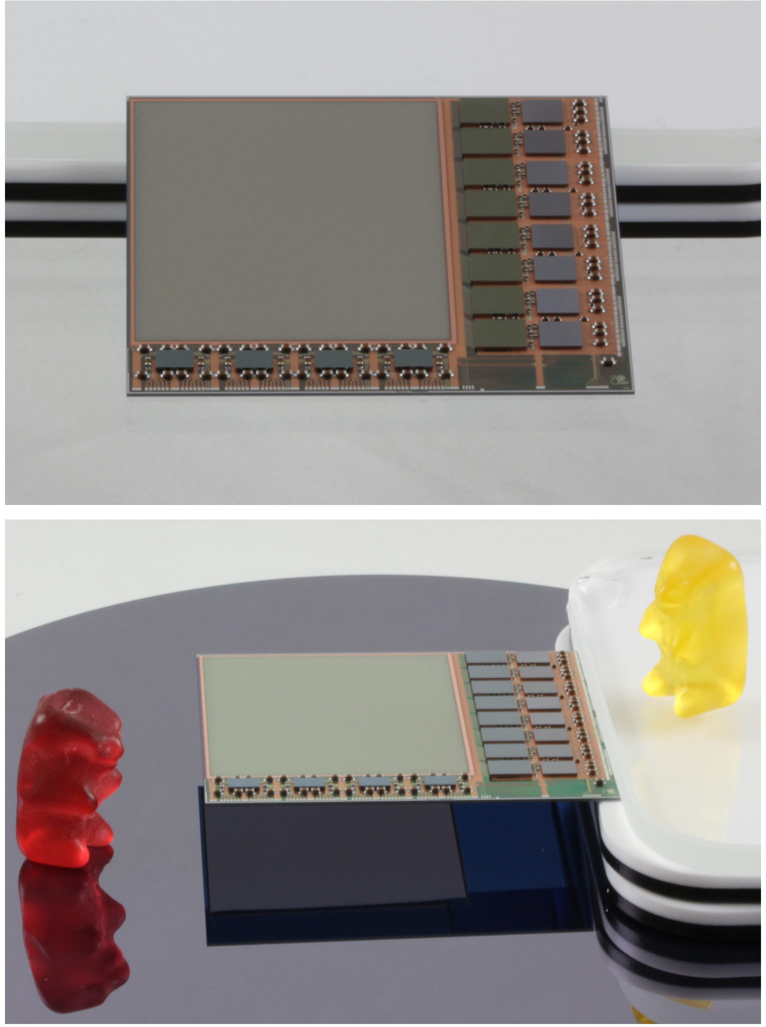


Motivation and Introduction

DePFET Structure and Measurement Setup

Optimization of Operation Parameters and Response Function

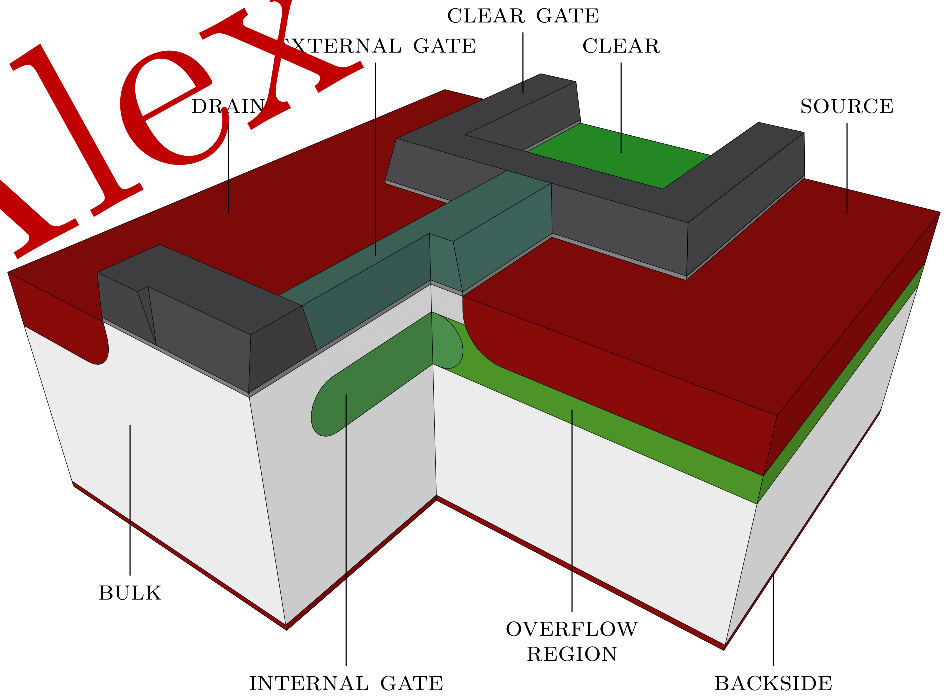
Summary and Outlook

The DePFET structure

and its positive sides

Depleted p-channel Field Efect Transistor on high resistive n-doped bulk

- integrated 1st stage amplification (g_q)
- charge storage capability
  - readout on demand
  - rolling shutter mode
- small capacitance and low noise
- high quantum efficiency and fill factor
- fully depleted bulk
  - optionally thinned
- front- or back-side illumination possible
- easily scalable
- adjustable dynamic range
- signal compression
  - achieved by overflow charge storage regions with different g_q

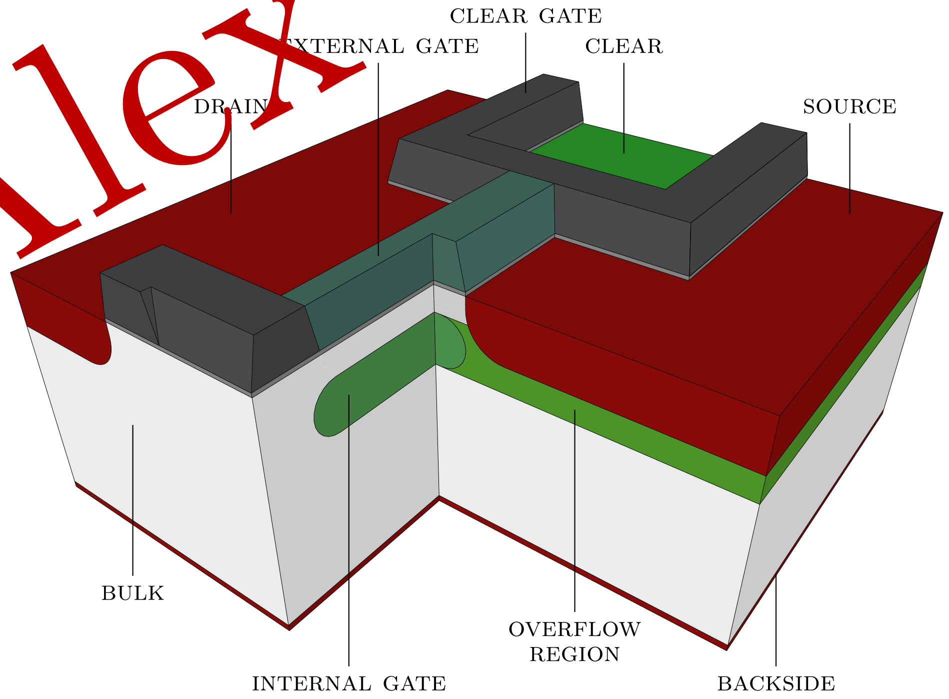


The DePFET structure

and its operation principle

Two states of operation:

- OFF state:
  - idle state, no power dissipation, but collecting signal charge
- ON state:
  - transistor current depending on signal charge in internal gate



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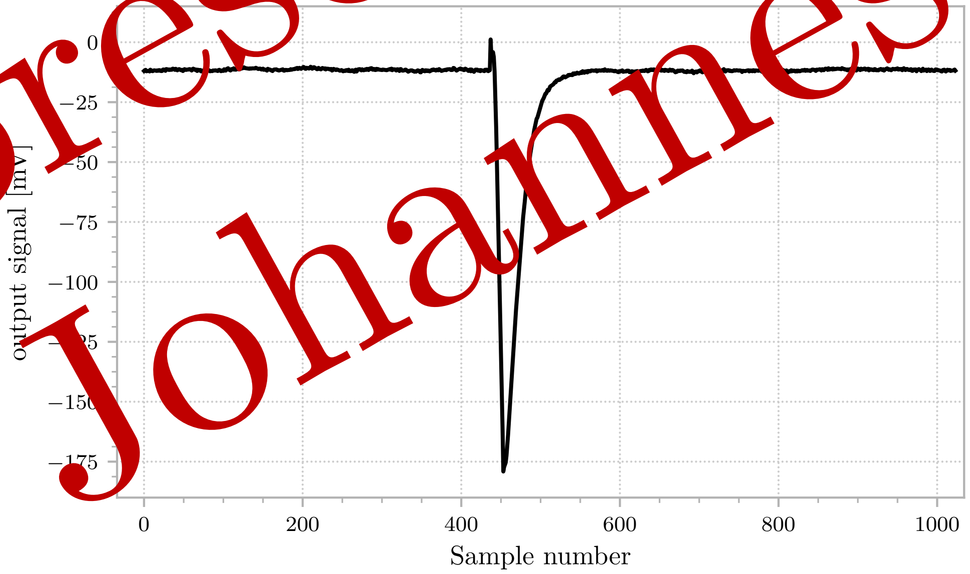

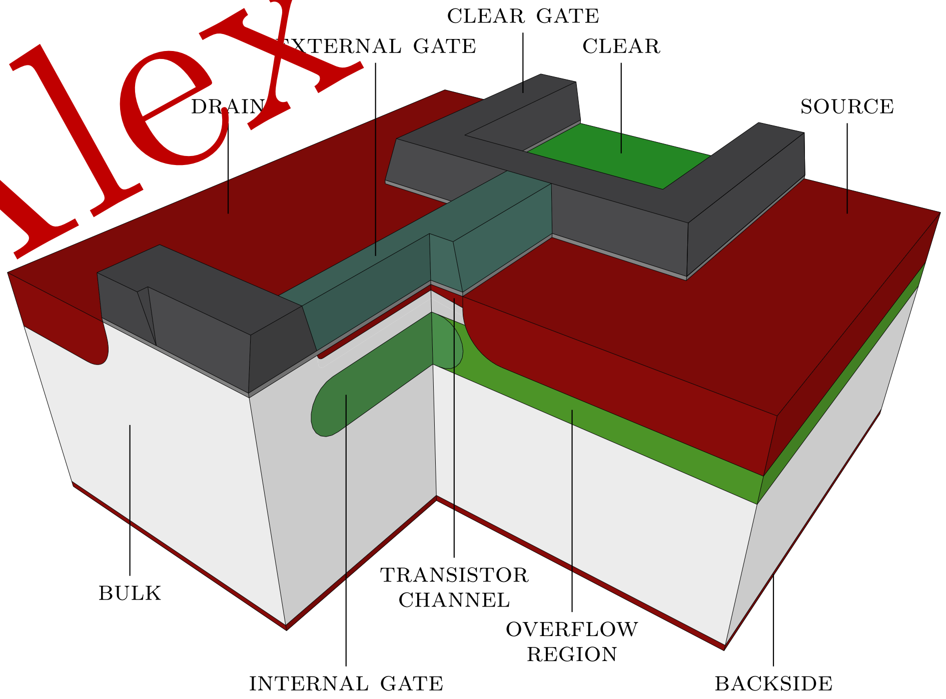

EMPTY ON STATE

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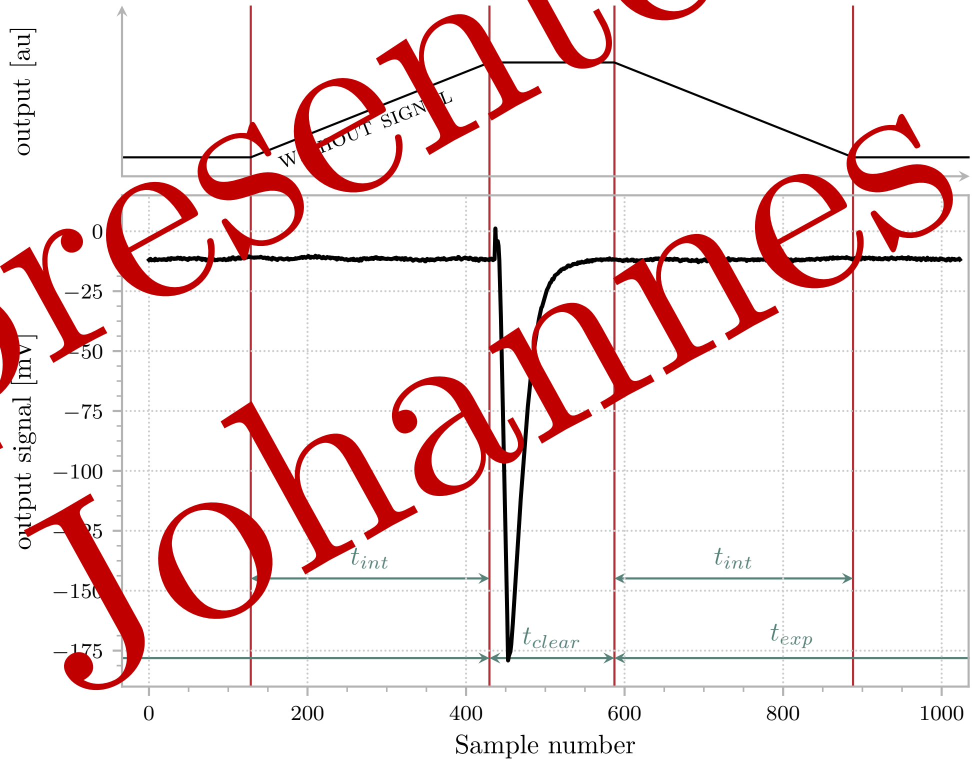

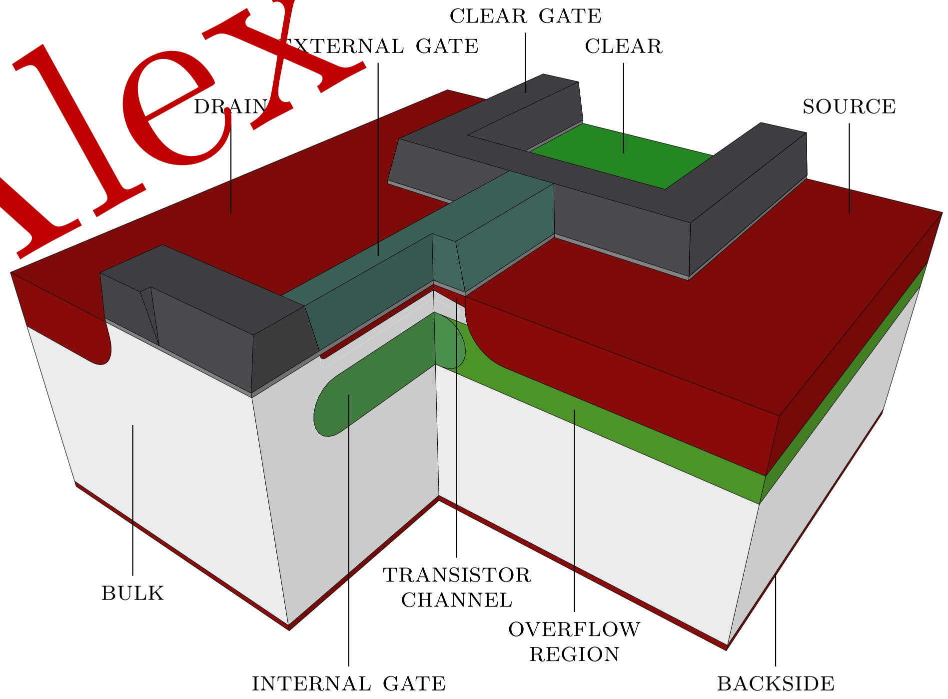

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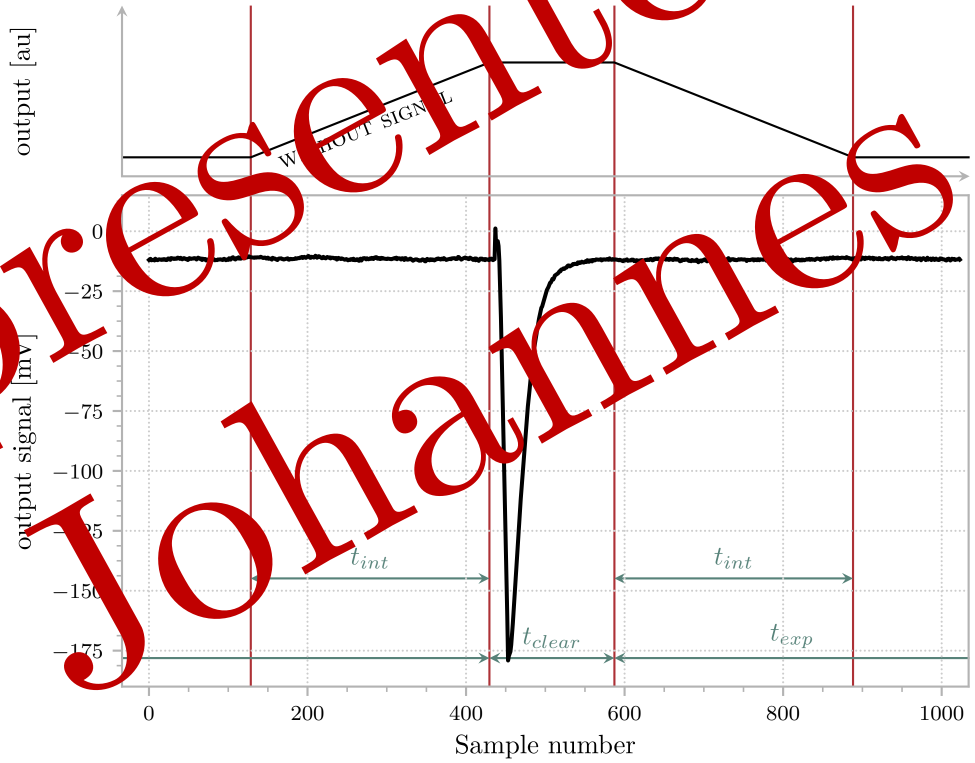

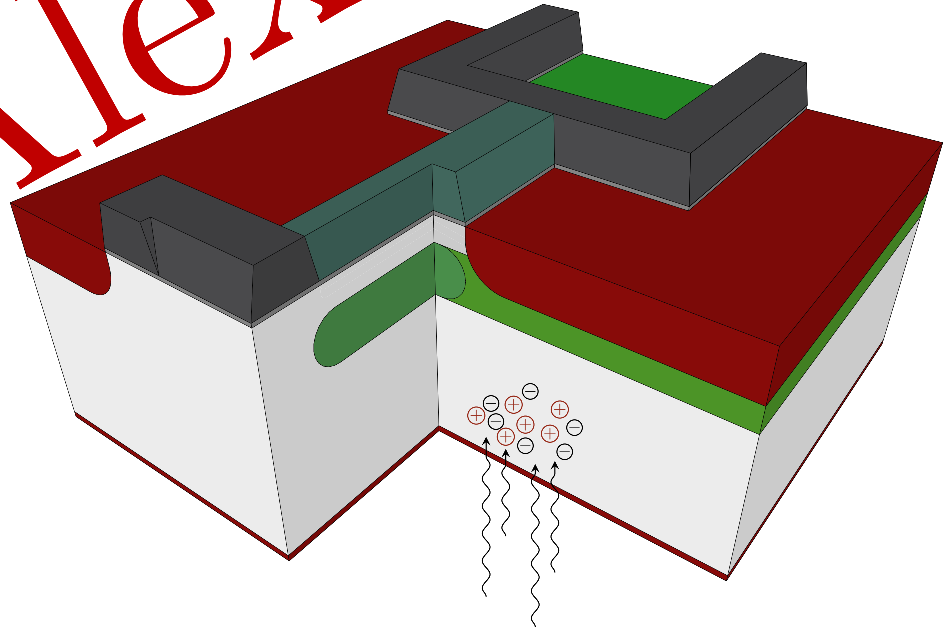

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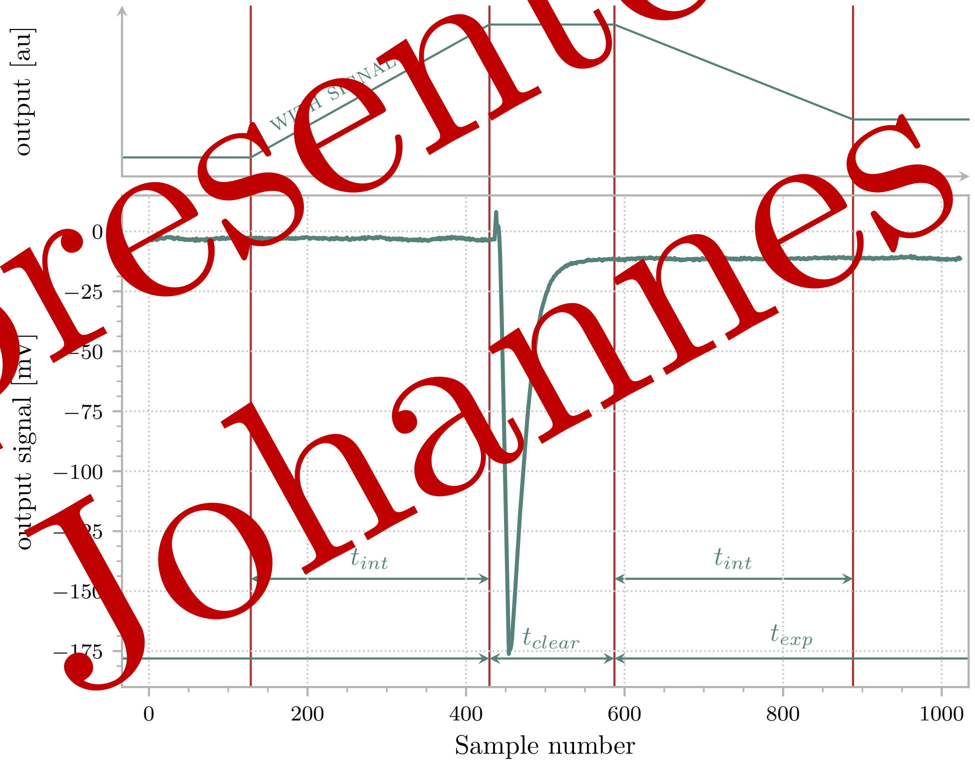

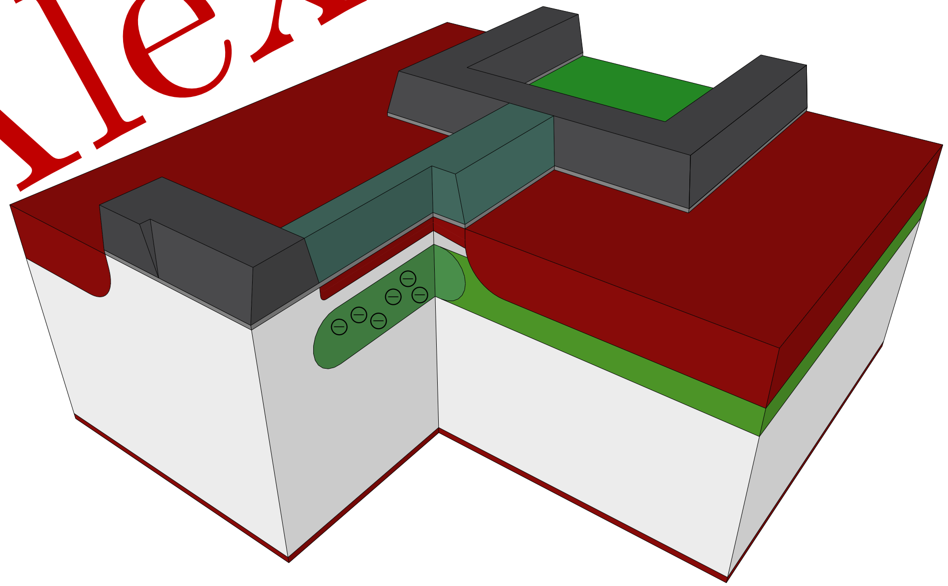

FILLED ON STATE

The DePFET structure

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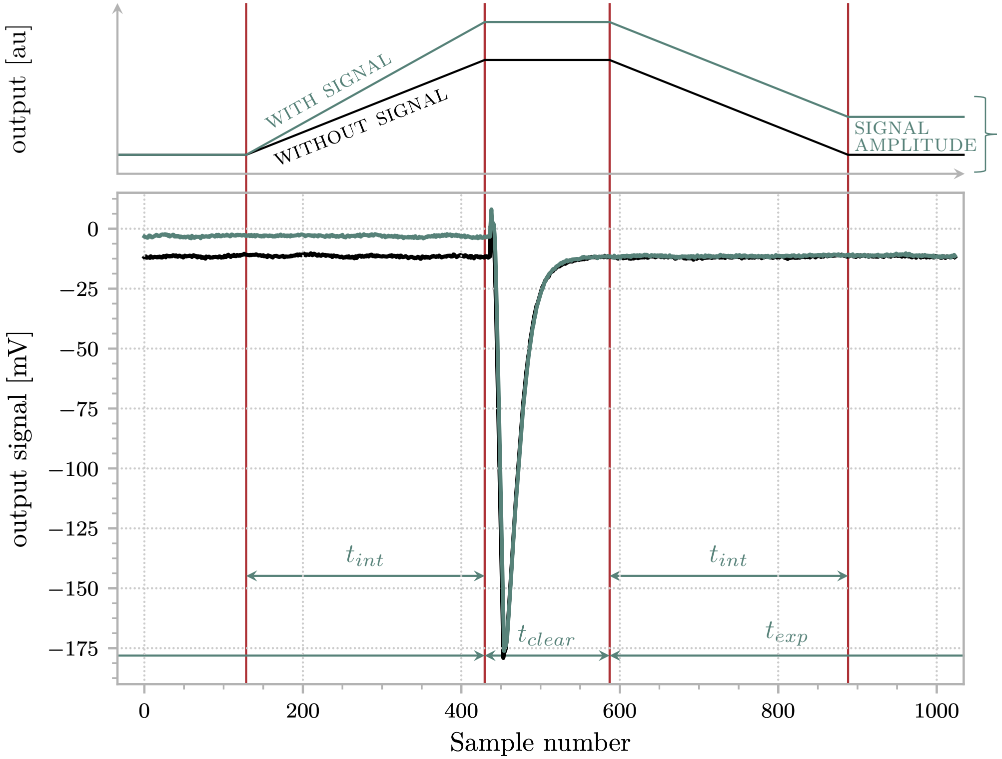
INITIAL STATE VS. FILLED STATE

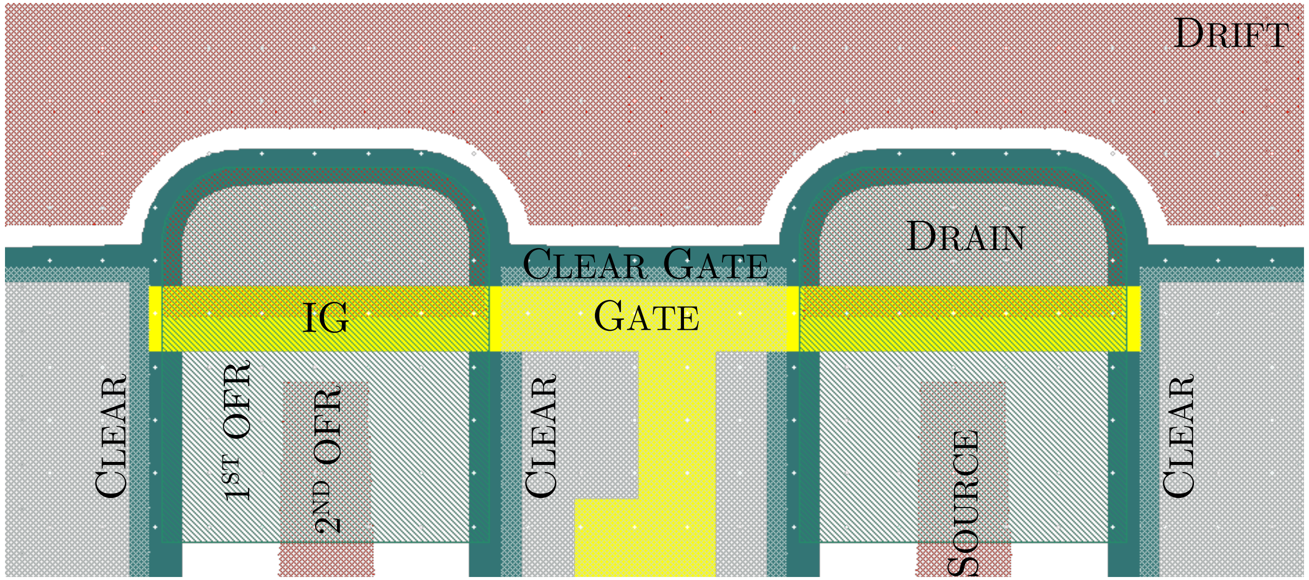


INITIAL DEPFET RESPONSE IS LINEAR

CALIBRATION WITH A KNOWN RADIOACTIVE SOURCE

The EDET DePFET structure

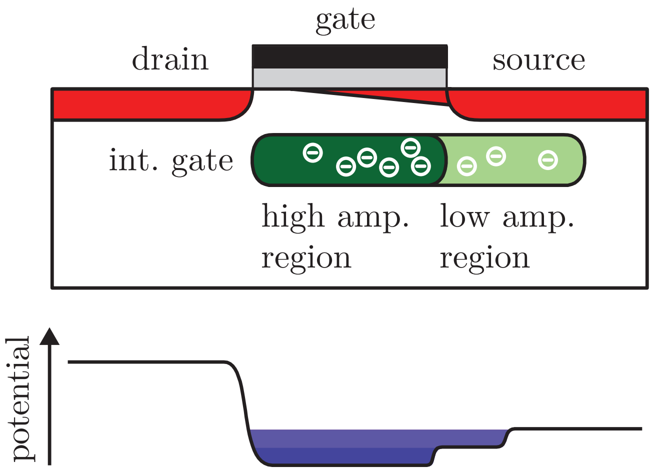
and its operation principle

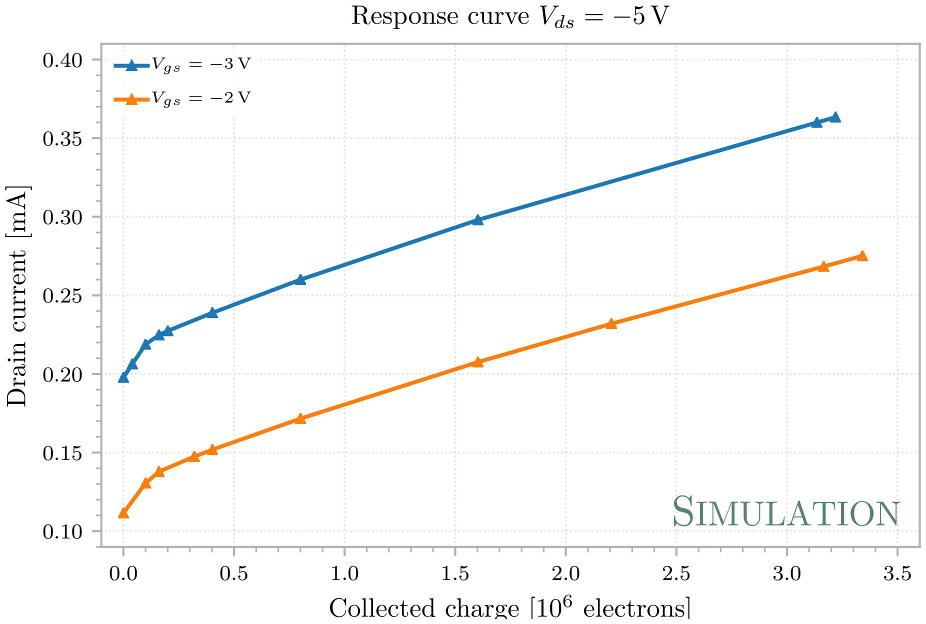


Internal Gate is under the Gate

1$^{\text{st}}$ OverFlow Region is around the Source

2$^{\text{nd}}$ OverFlow Region is under the Source

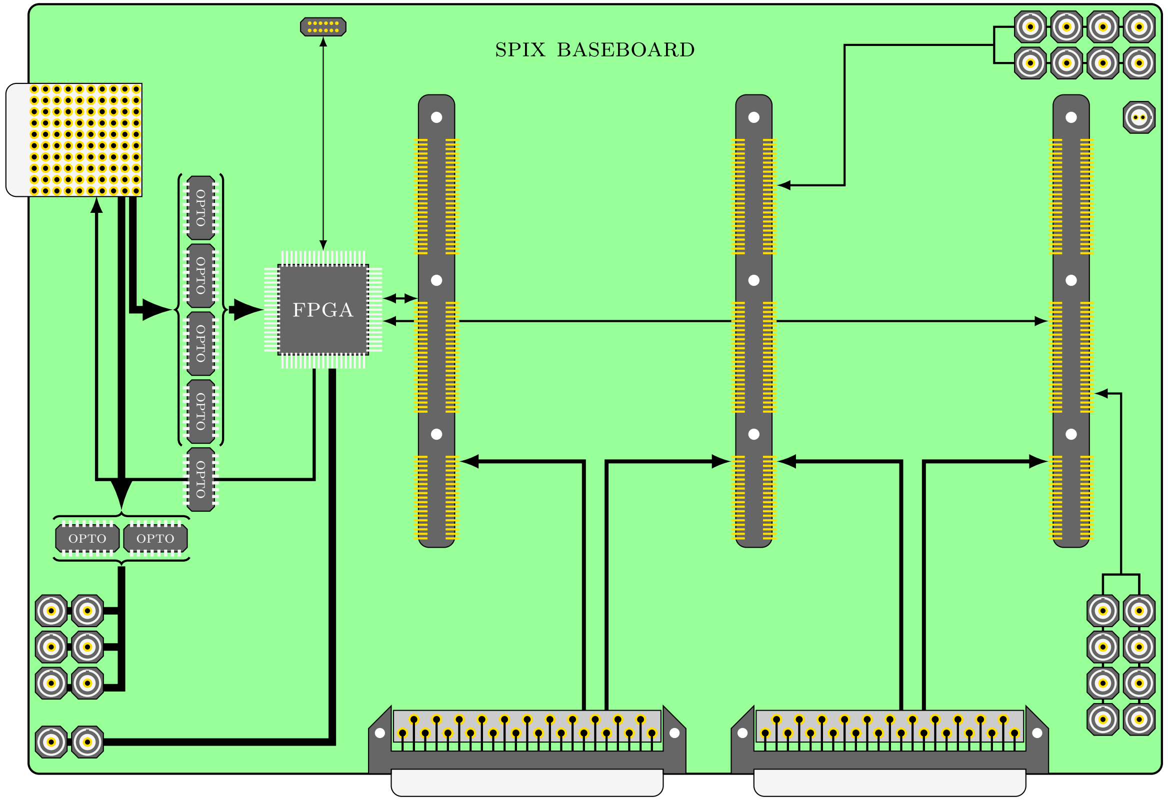




Measurement setup

operating principle

Design concept: MODULARITY



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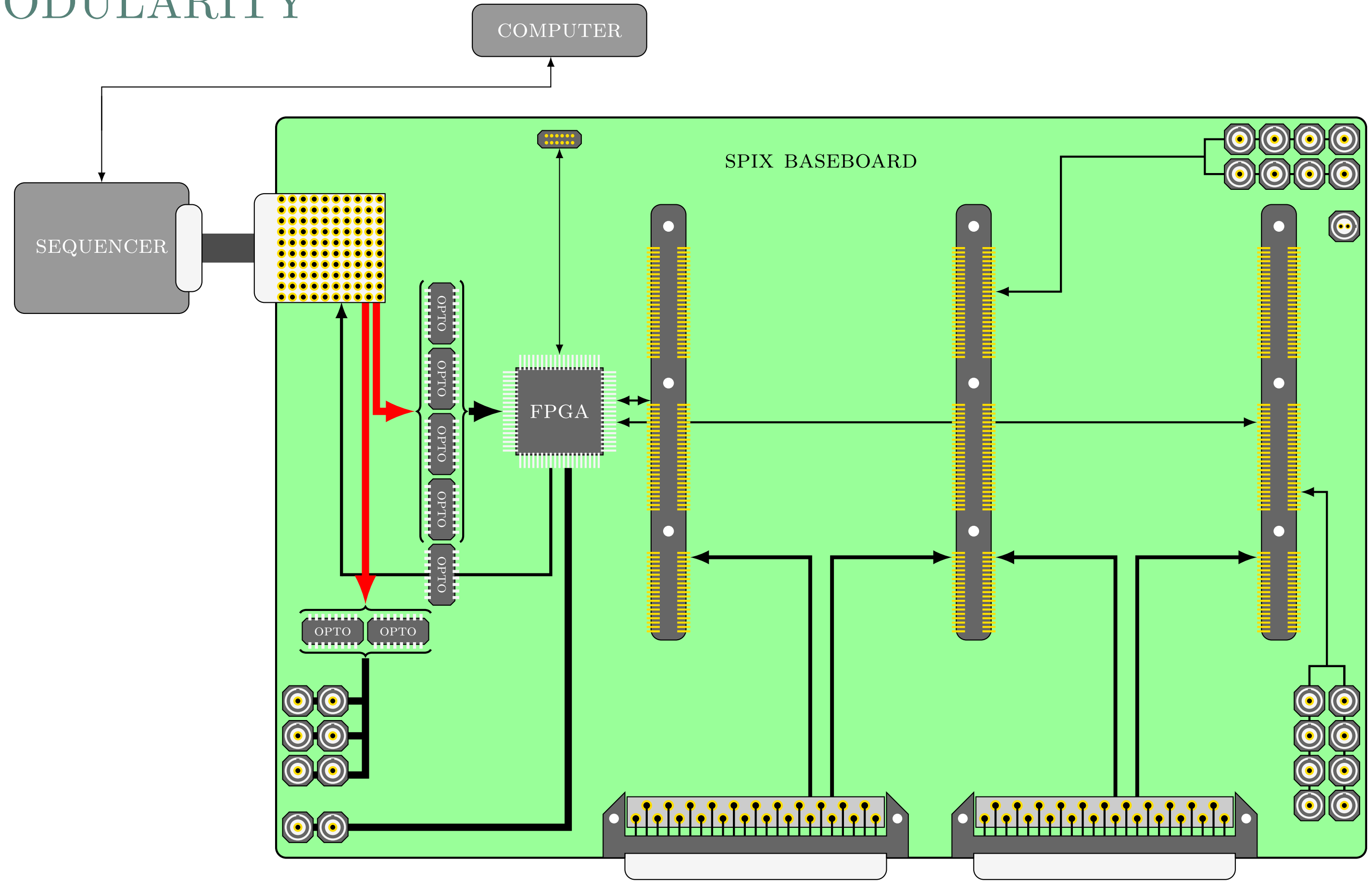

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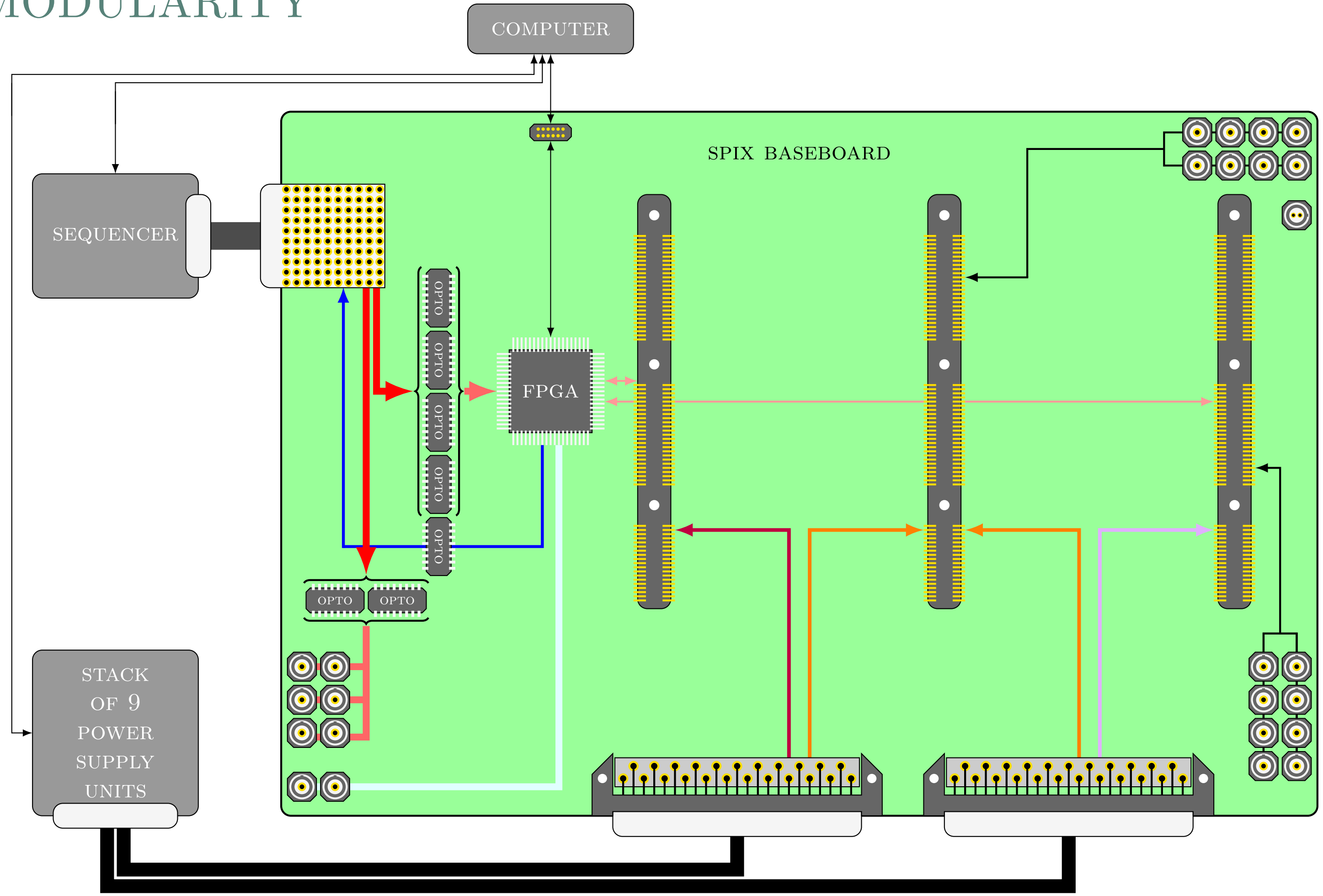

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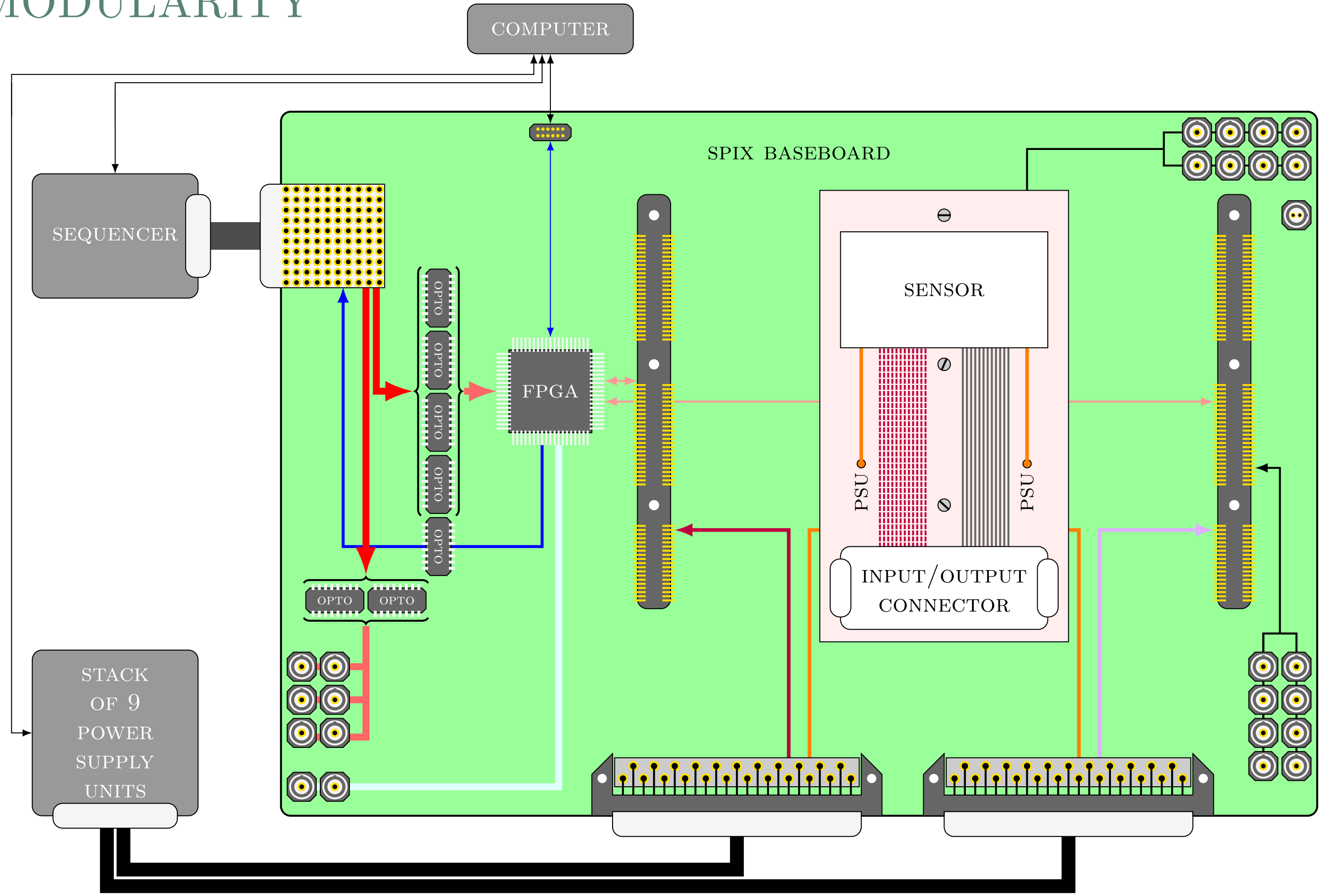

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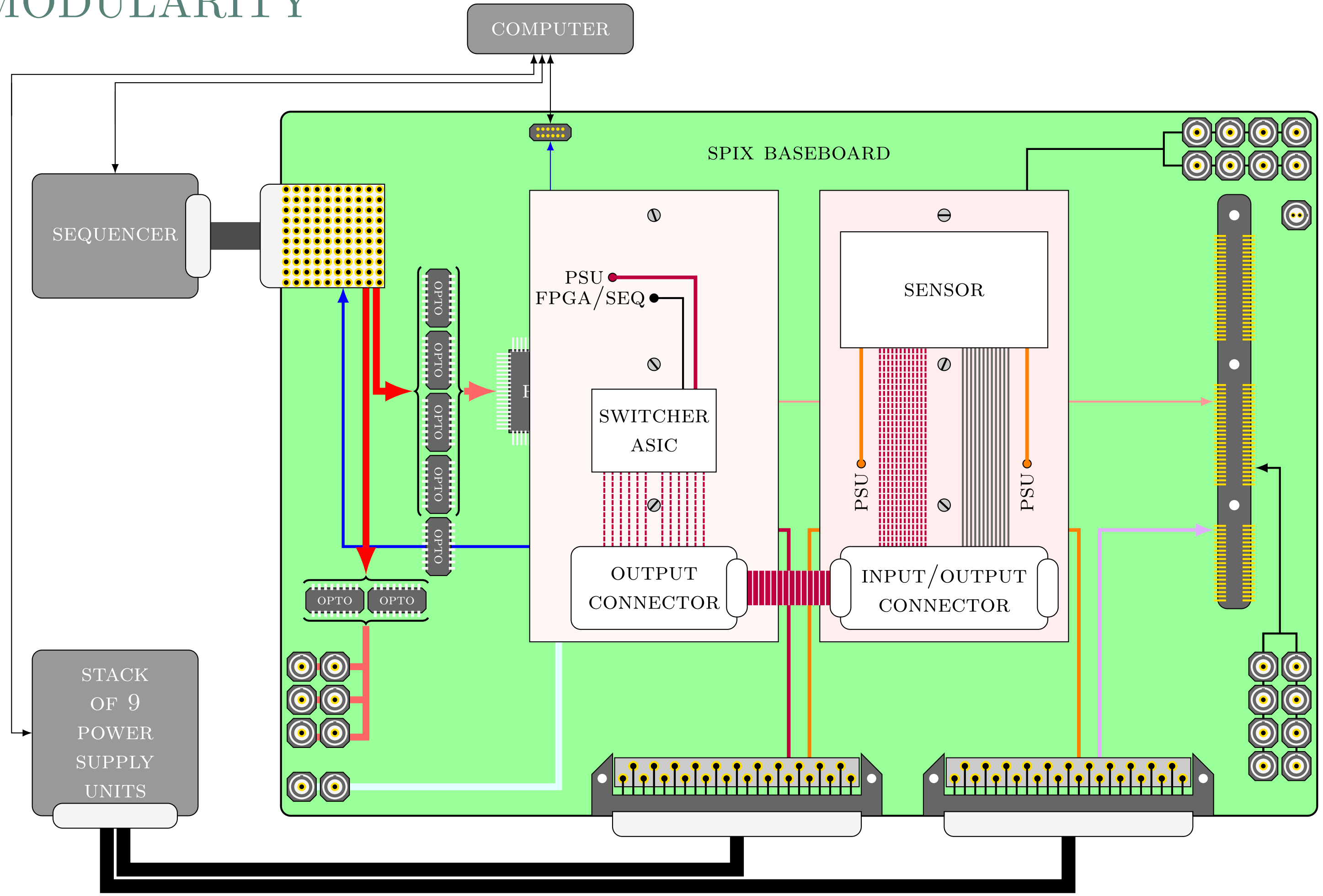

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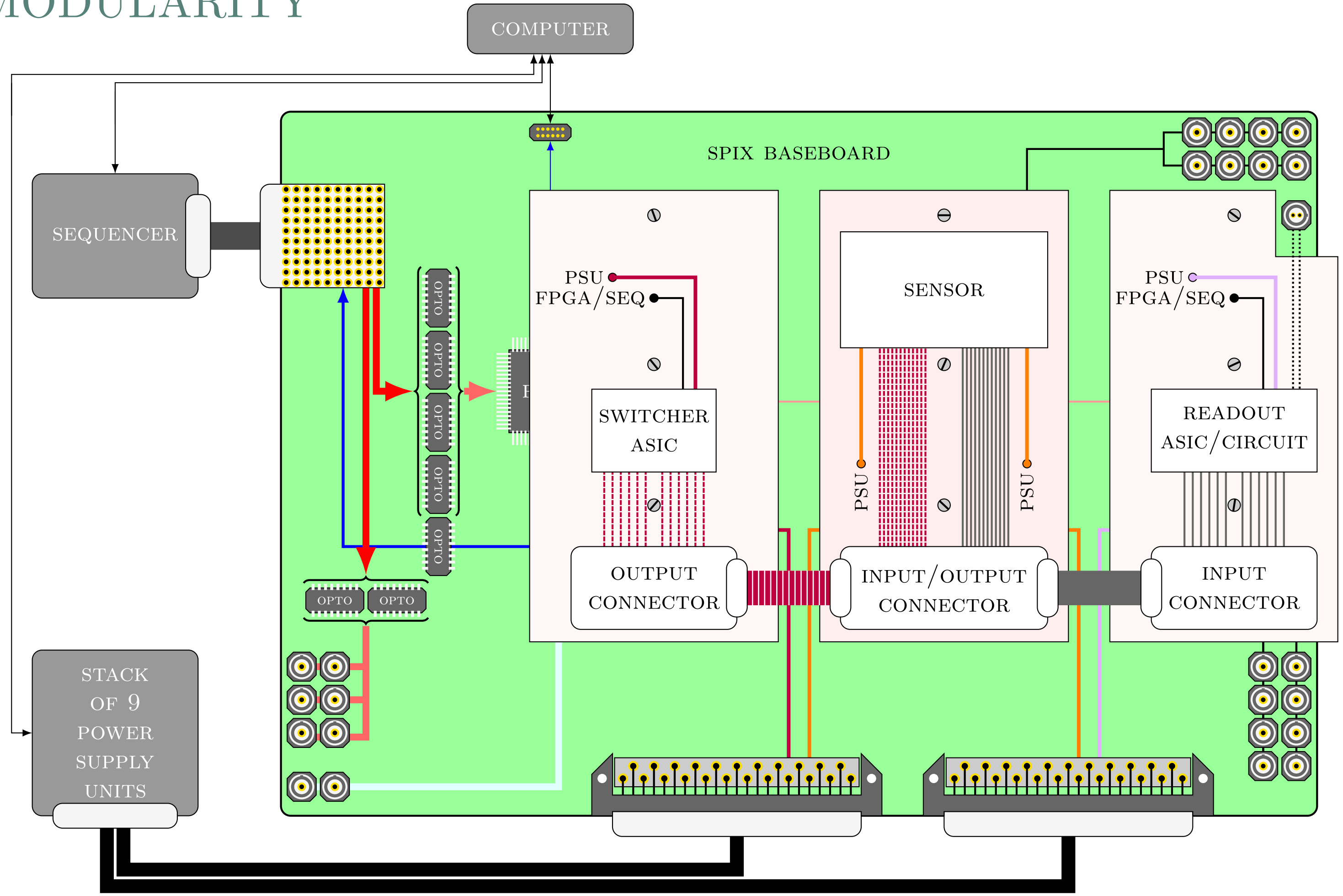

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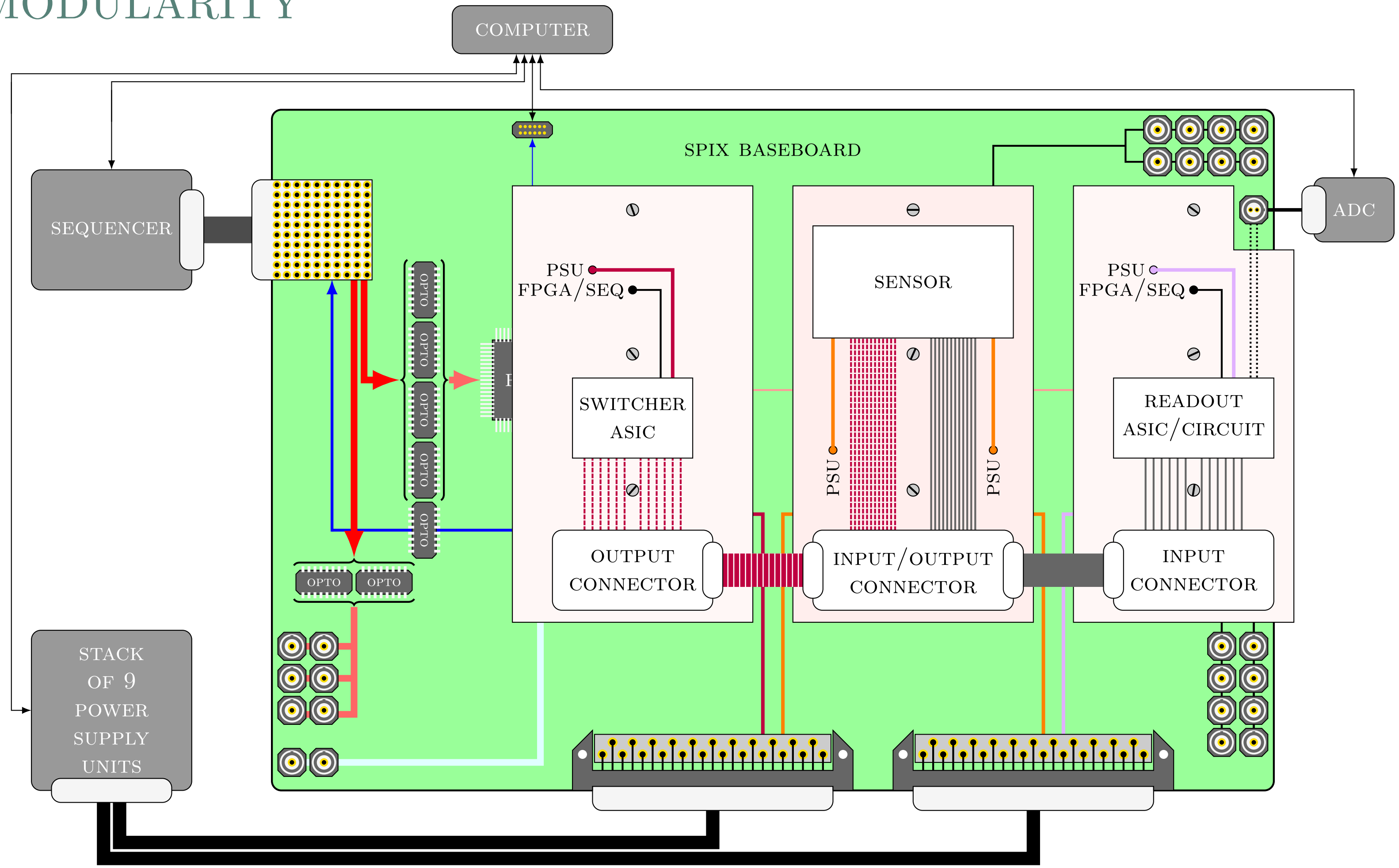
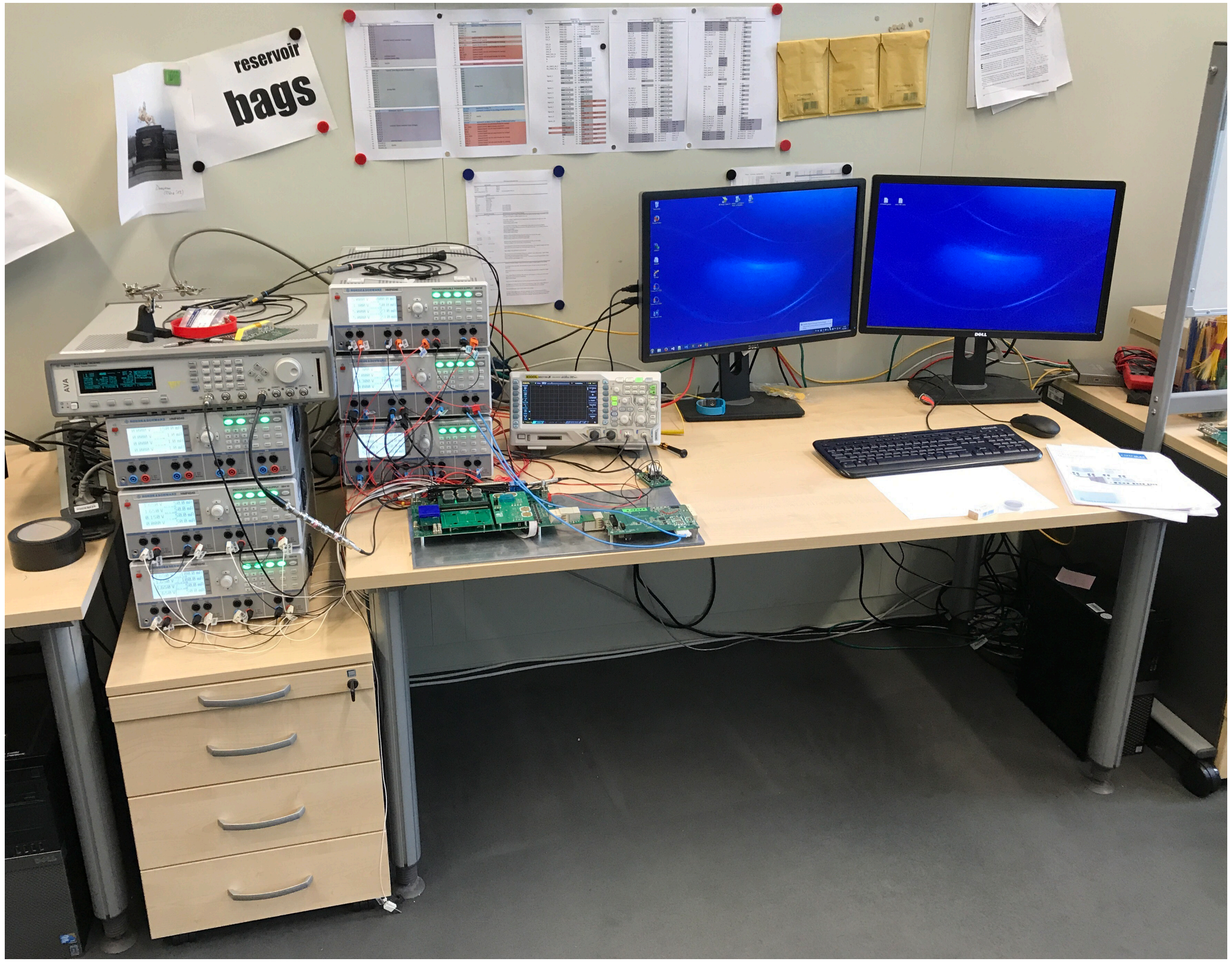


Single PIXle setup

actual setup

Design concept:
MODULARITY



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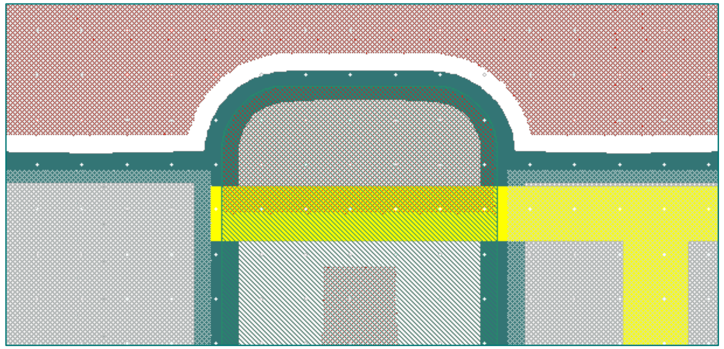
Measurements – operation window

on depleted 50 µm thick EDET structures

Clear Gate and Clear low voltage influence

- back-emission of e⁻ from clear contact,
- inversion (parasitic channel under the Clear Gate), and
- charge loss to clear contact.



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Gate L	5.0 µm
Gate W	27.2 µm
Drain	-5.0 V
Source	0.0 V
Gate Off	5.0 V
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Clear low	sweep
Clear high	17.0 V
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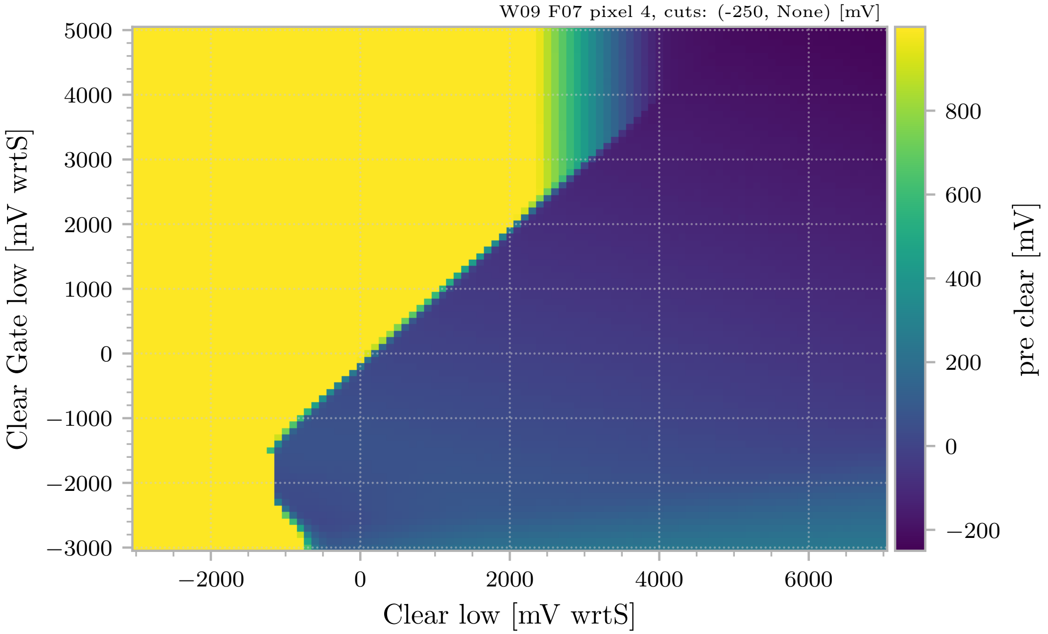
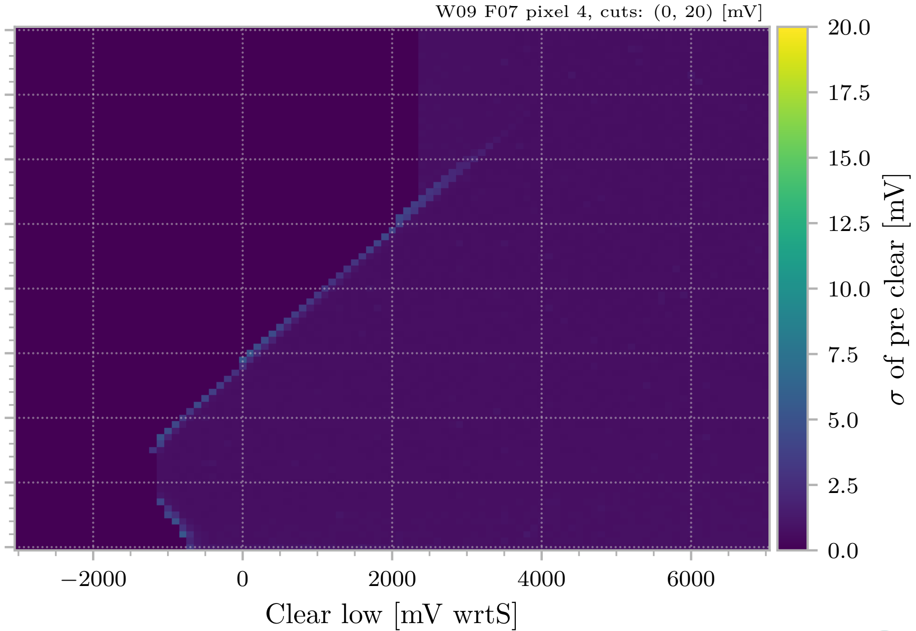
Drift	-5.0 V
Guard	-5.0 V

No external illumination; Observing only the initial state





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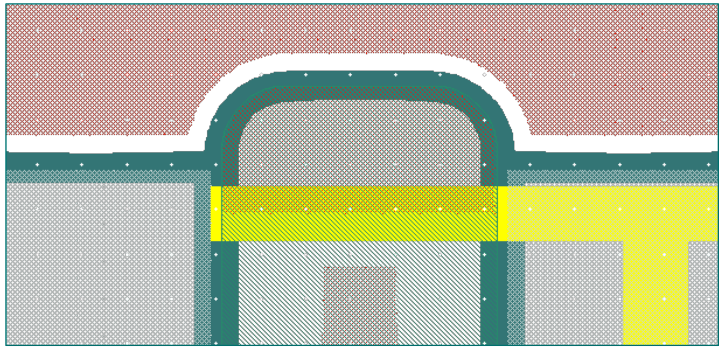

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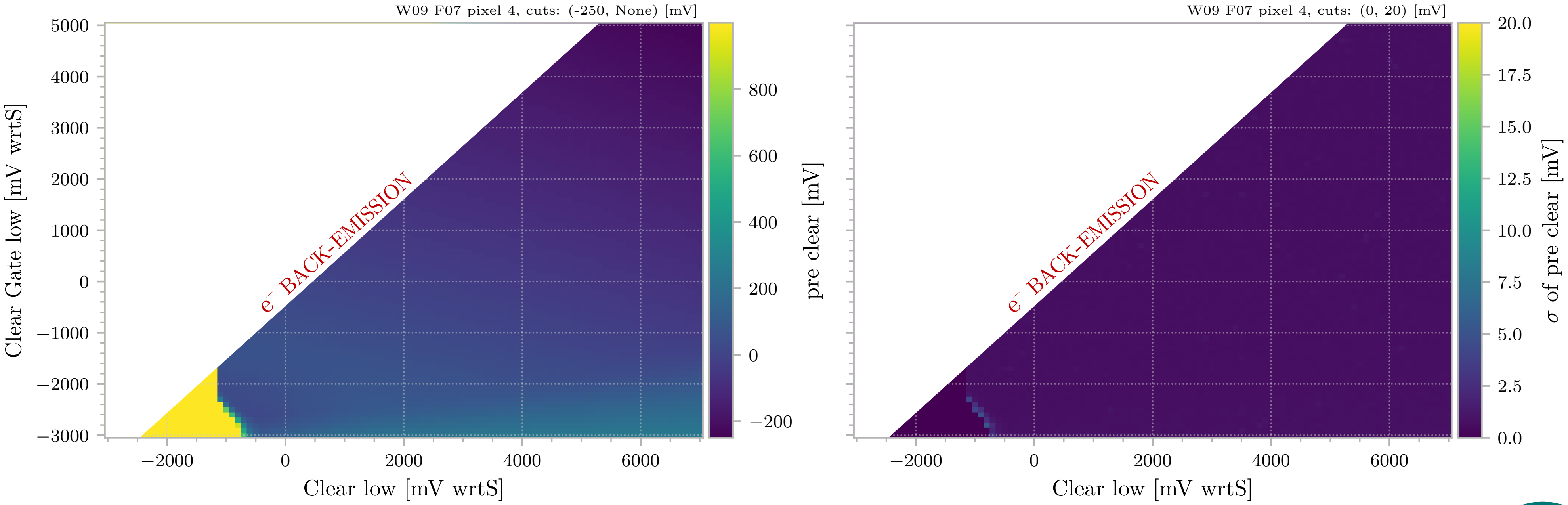

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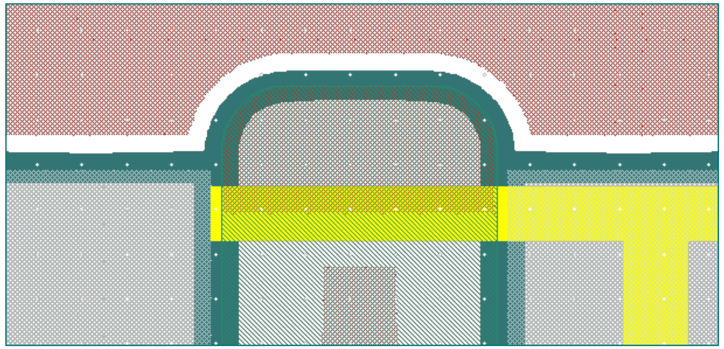

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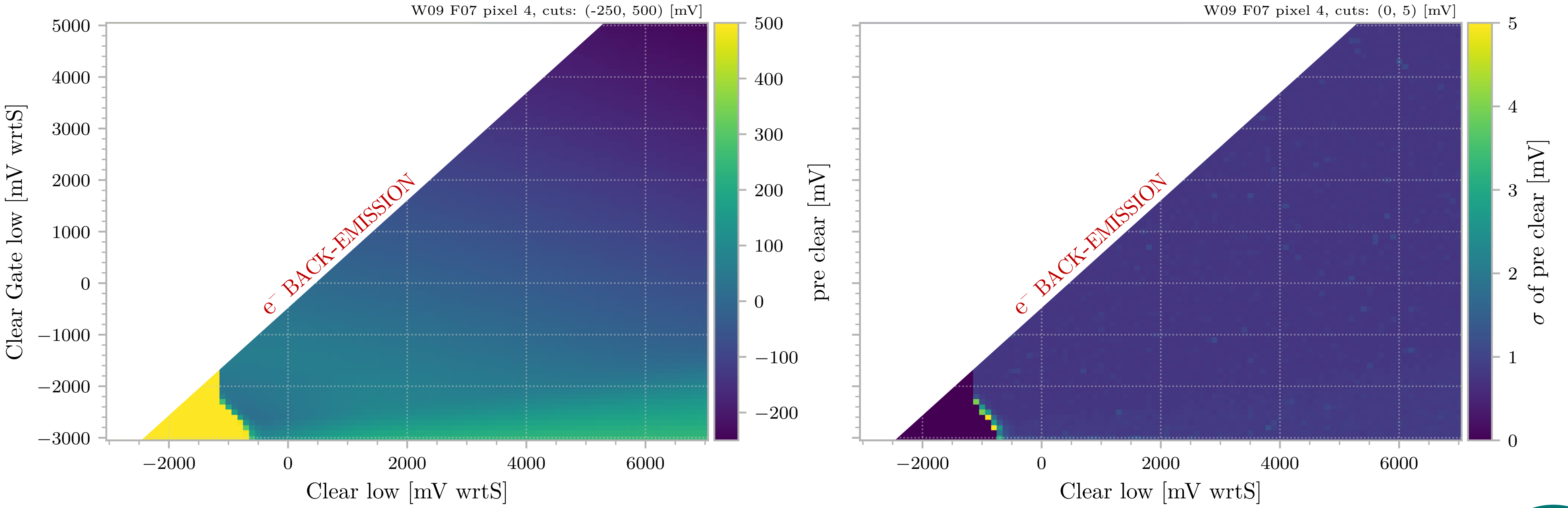

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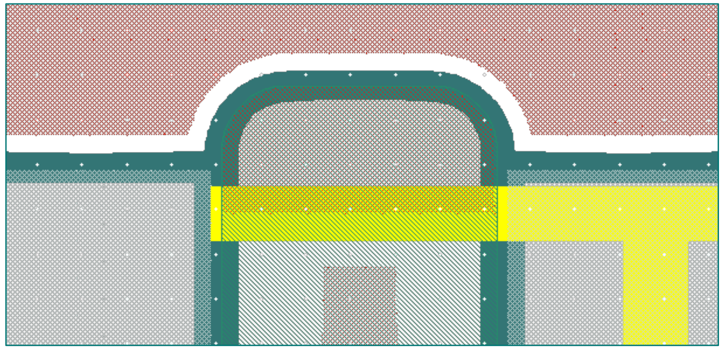

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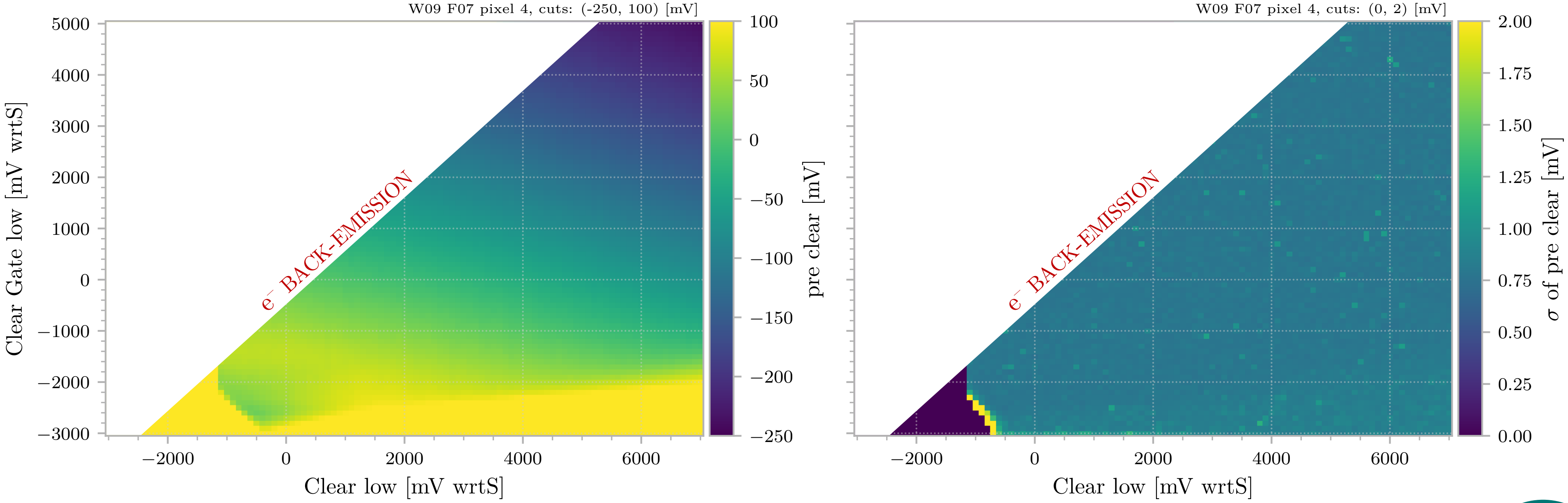

W09 F07 pixel 4, cuts: (-250, 100) [mV]

W09 F07 pixel 4, cuts: (0, 2) [mV]

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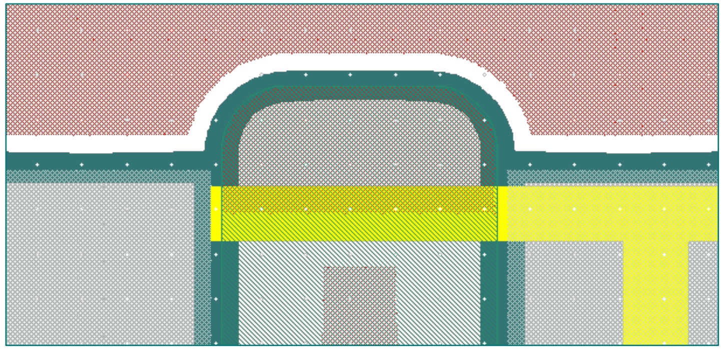

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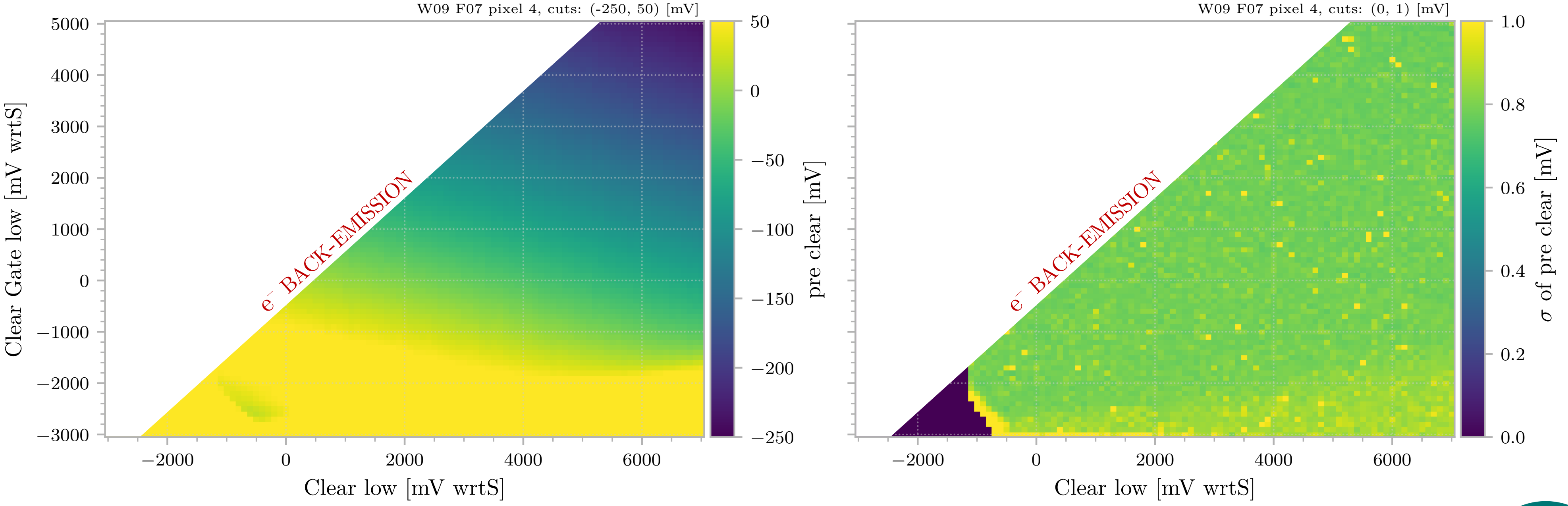

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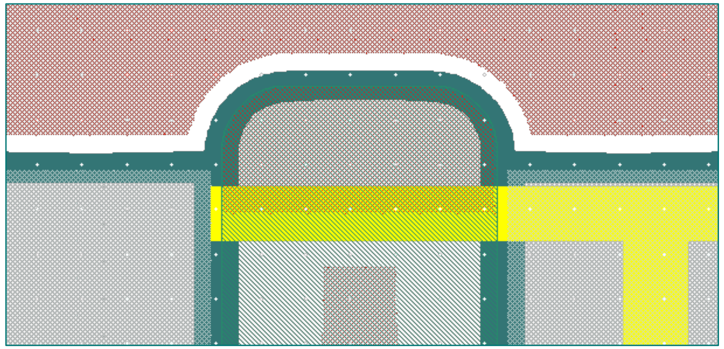

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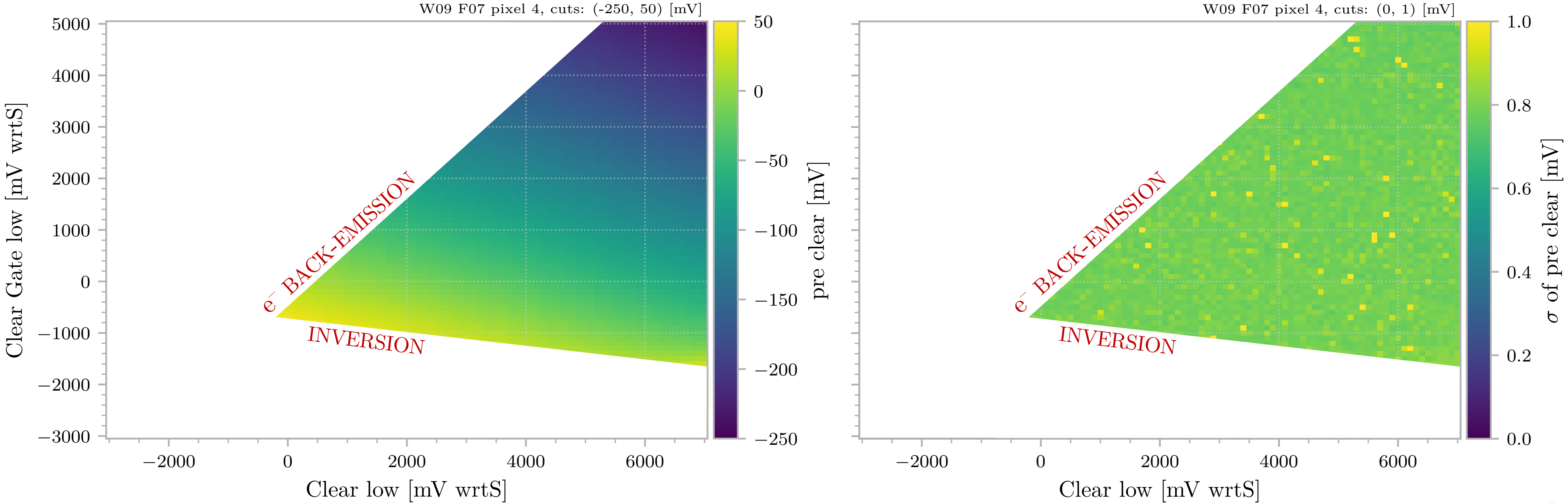

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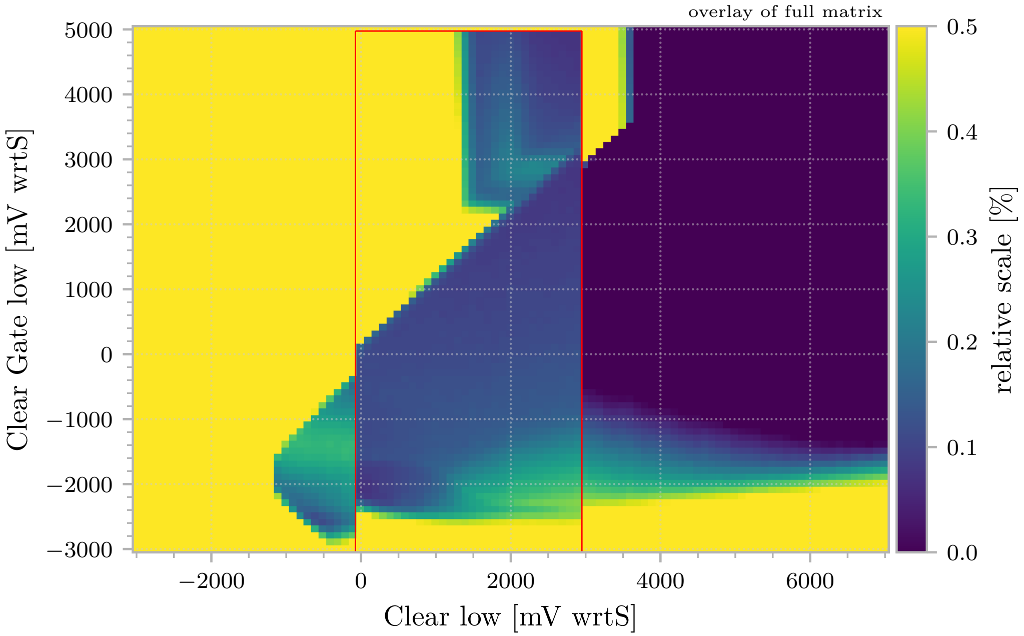

OVERLAY (RED BOX) OF AN IDENTICAL MEASUREMENT DONE WITH THE SMALLER VERSION OF THE FINAL CAMERA SETUP.

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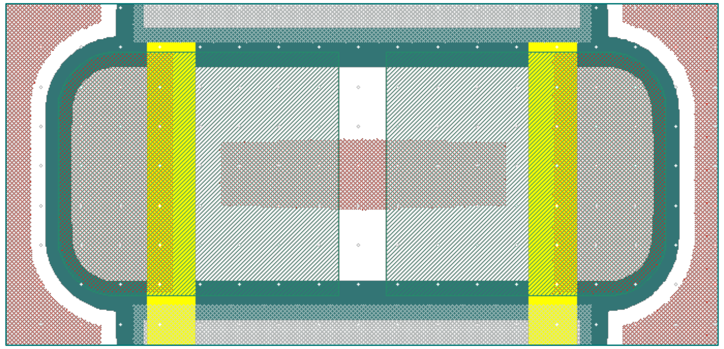

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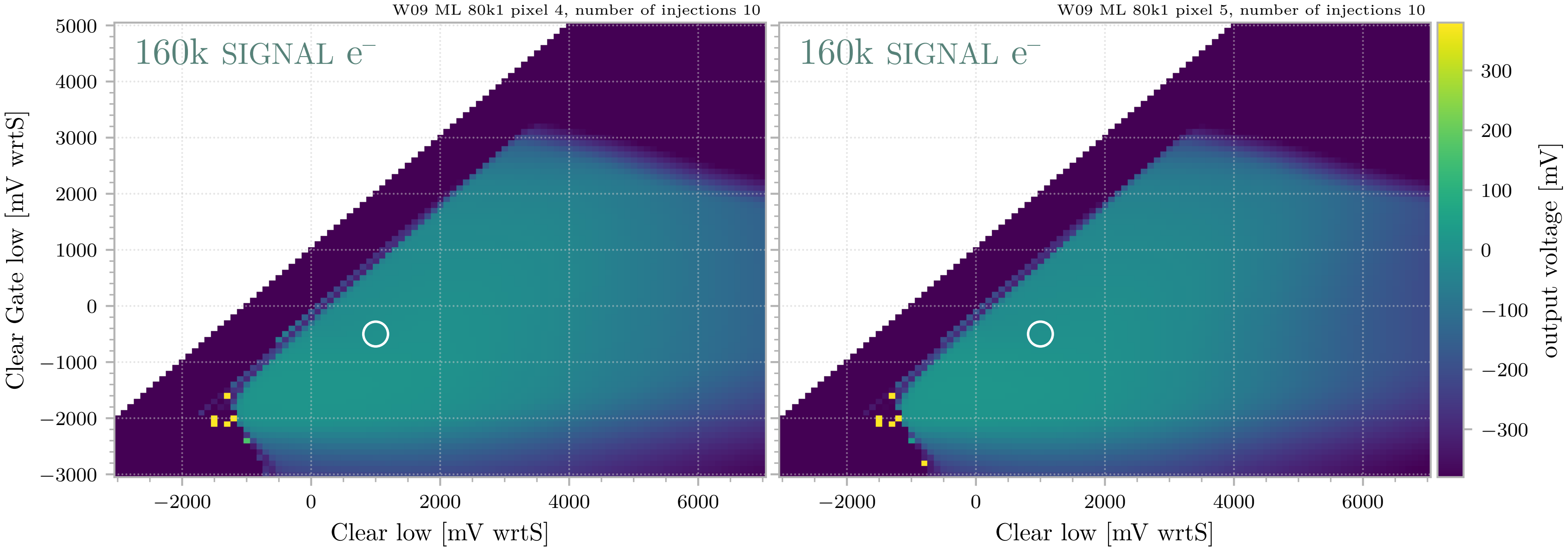
LED FLATFIELD ILLUMINATION (FFIL); 1 INJECTION CORRESPONDS TO ~10X ^{55}Fe K_α

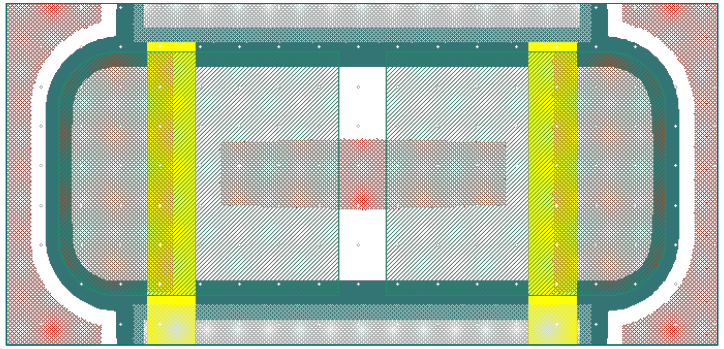


Measurements – operation window

on depleted 50 μm thick EDET structures

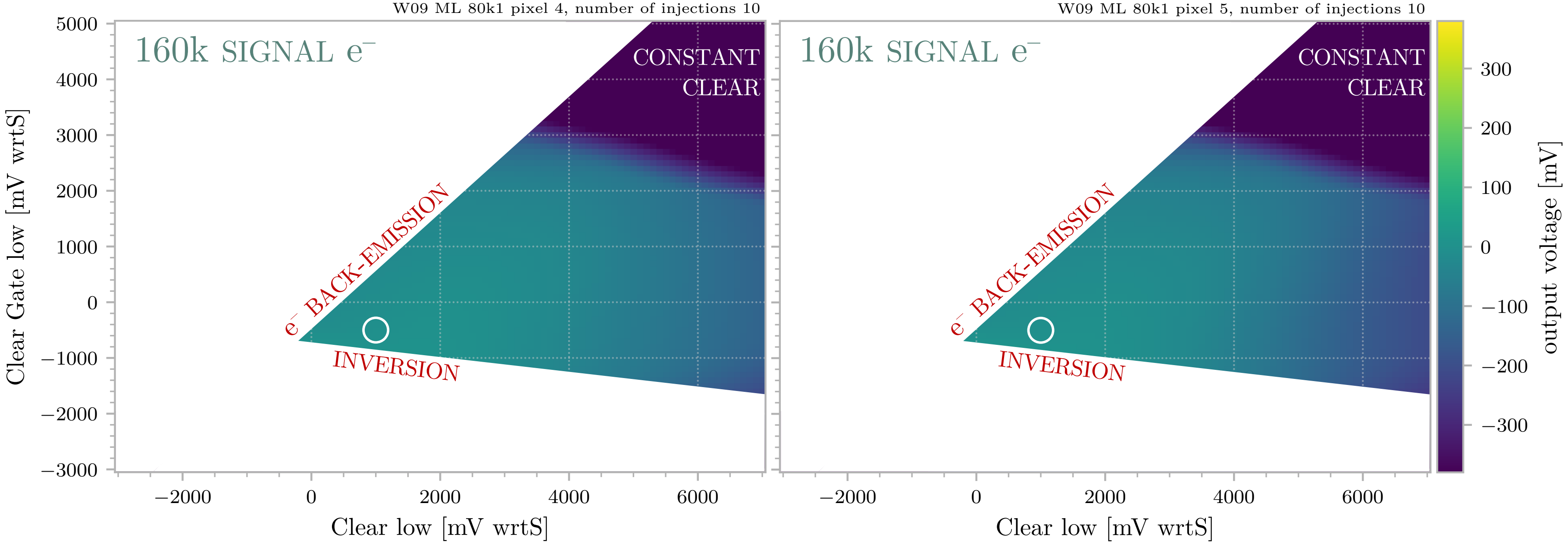
Clear Gate and Clear low voltage influence

- back-emission of e⁻ from clear contact,
- inversion (parasitic channel under the Clear Gate), and
- charge loss to clear contact.



W09 F07	
Thickness	50 μm
Gate L	5.0 μm
Gate W	27.2 μm
Drain	-5.0 V
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	sweep
Clear high	17.0 V
Clear Gate	sweep
Depletion	-35.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

LED FLATFIELD ILLUMINATION (FFIL); 1 INJECTION CORRESPONDS TO ~10X ^{55}Fe K_α



Measurements – operation window

on depleted 50 µm thick EDET structures

Clear Gate and Clear low voltage influence

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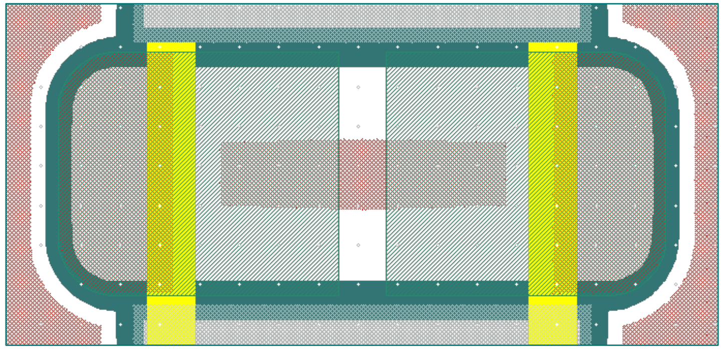

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Gate W	27.2 µm
Drain	-5.0 V
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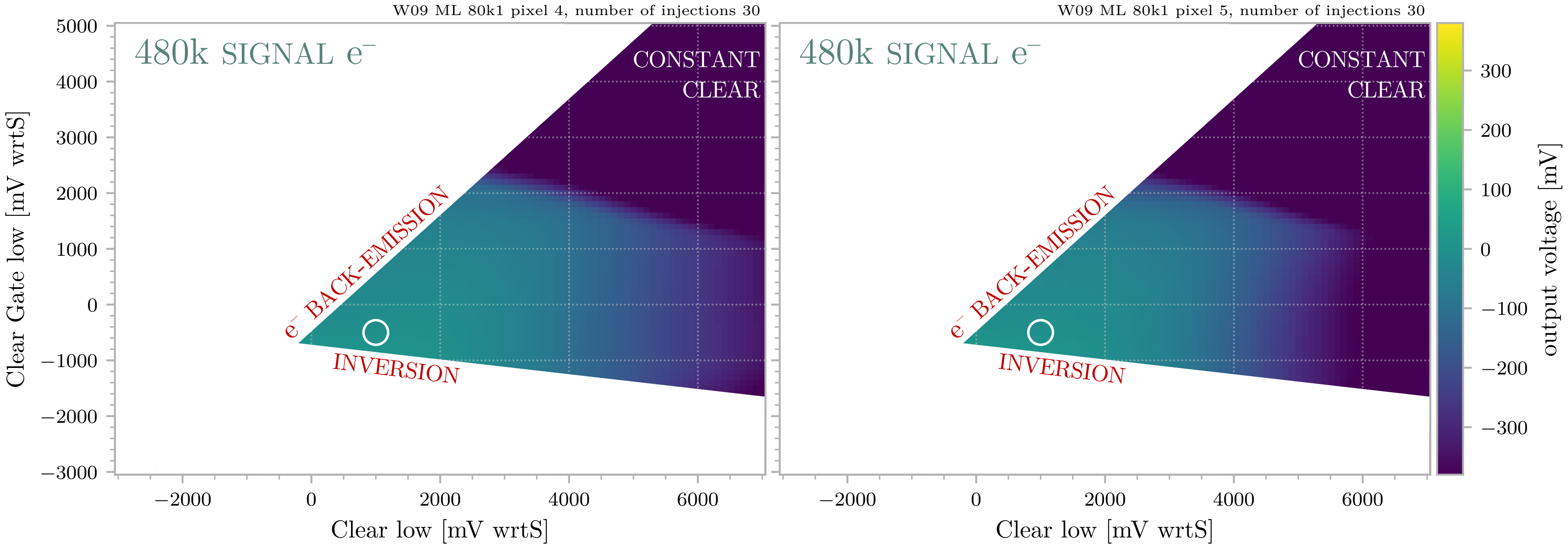

Measurements – operation window

on depleted 50 µm thick EDET structures

Clear Gate and Clear low voltage influence

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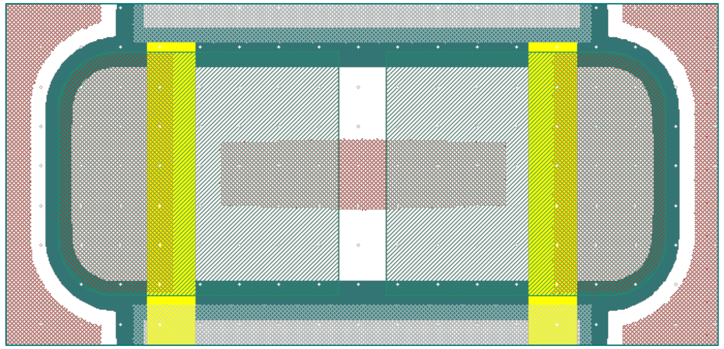

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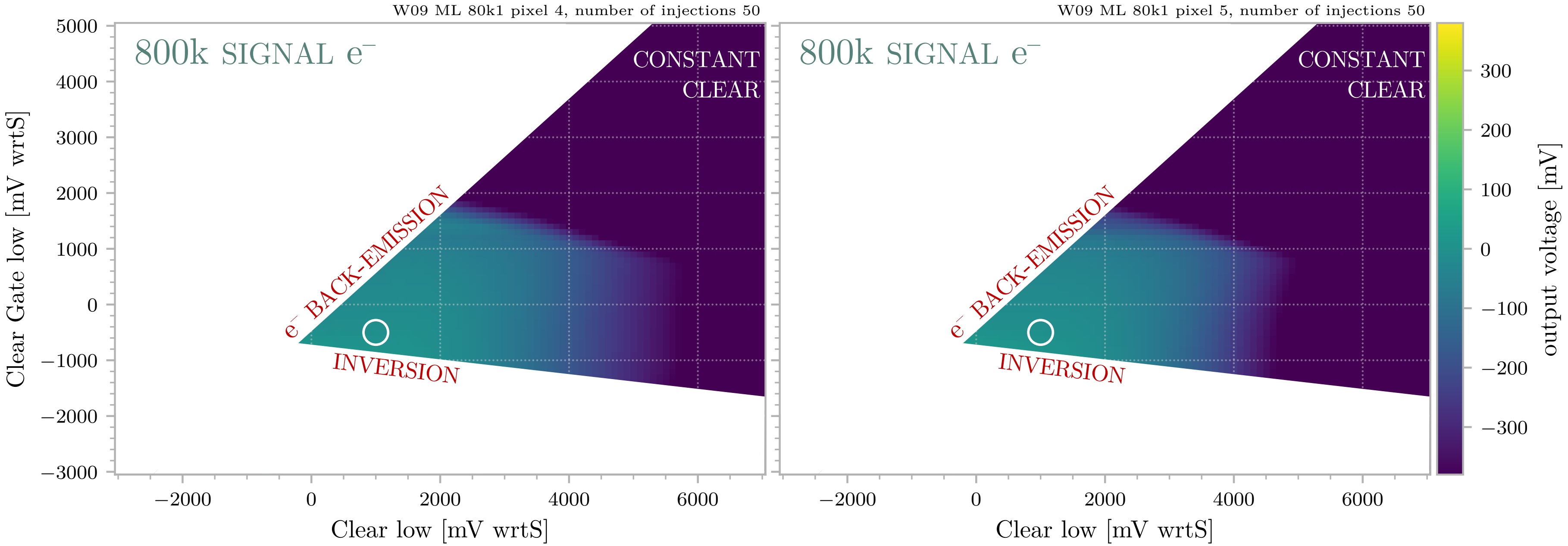
LED FLATFIELD ILLUMINATION (FFIL); 1 INJECTION CORRESPONDS TO ~10X ^{55}Fe K_α



Measurements – operation window

on depleted 50 µm thick EDET structures

Clear Gate and Clear low voltage influence

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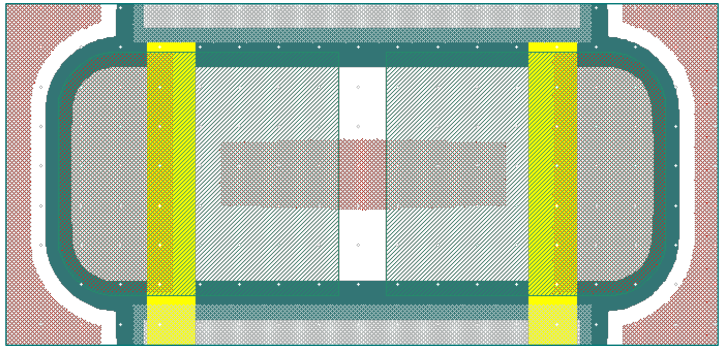
- charge loss to clear contact.



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Drain	-5.0 V
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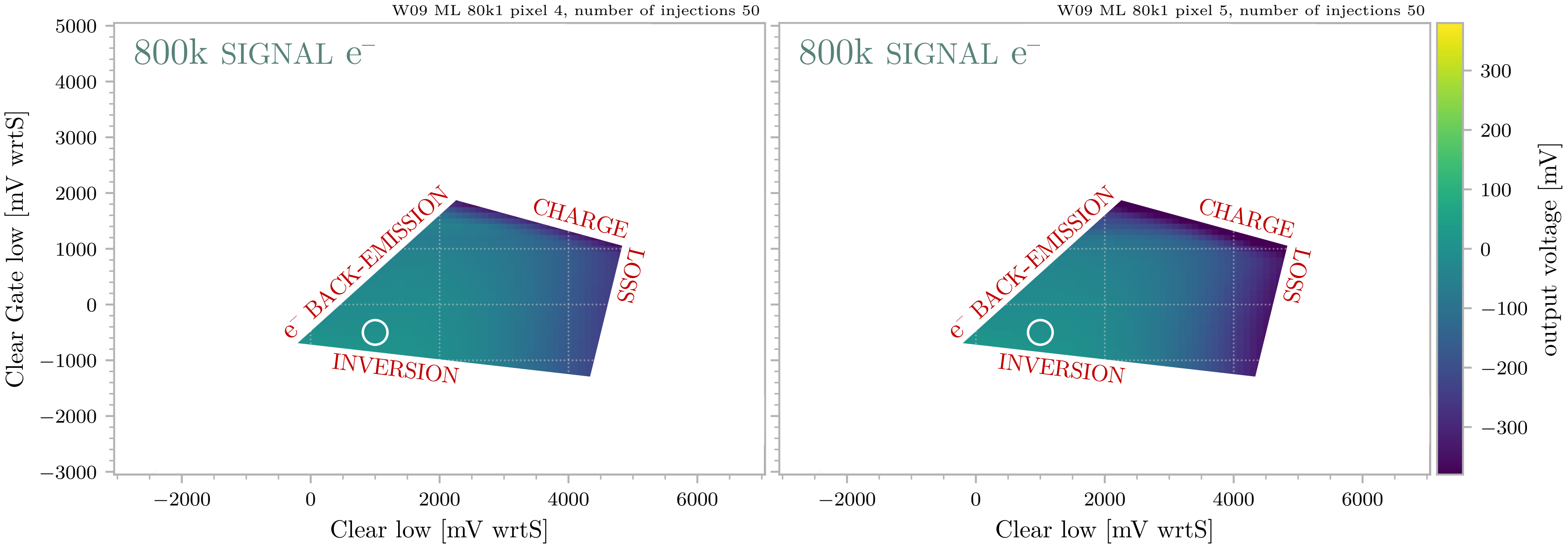

Measurements – operation window

on depleted 50 µm thick EDET structures

Clear Gate and Clear low voltage influence

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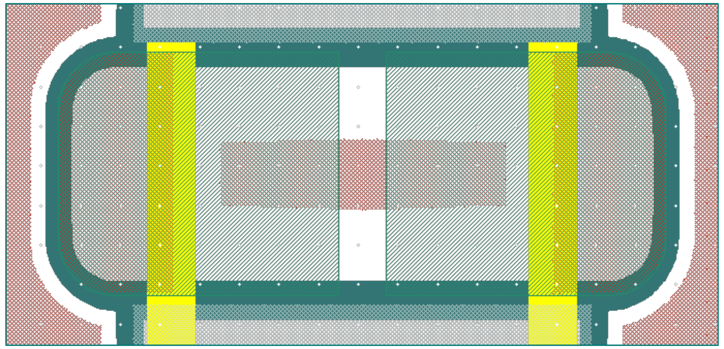

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Drain	-5.0 V
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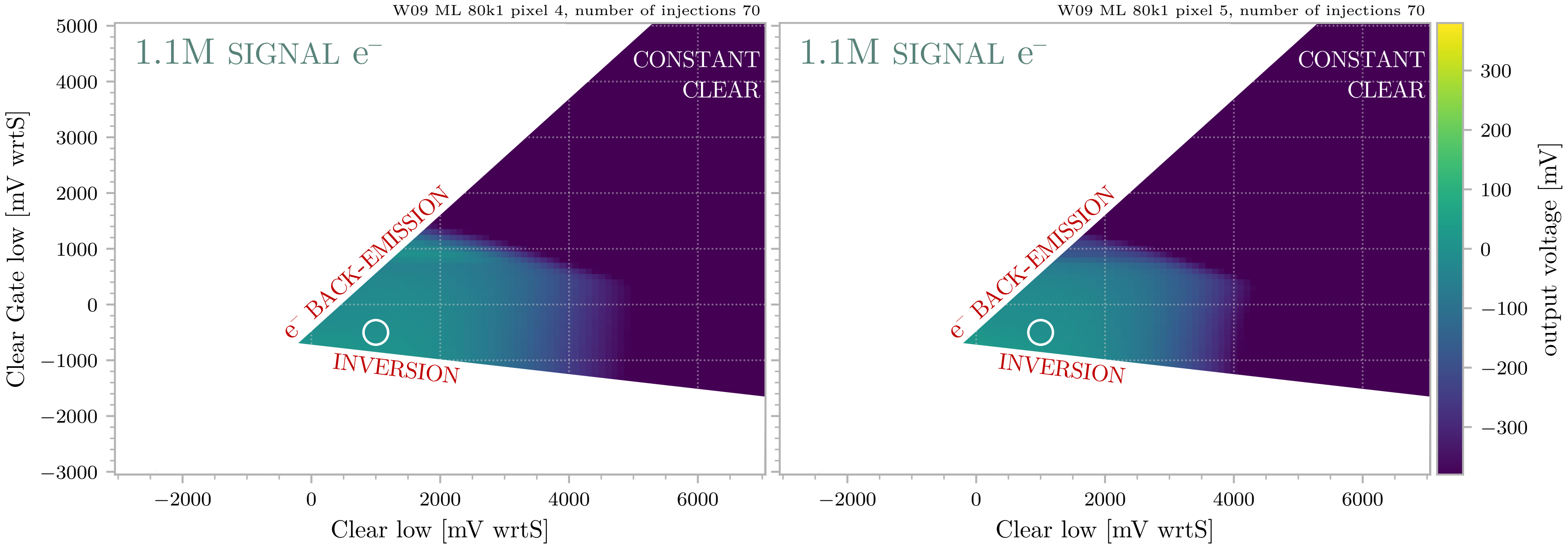
Drift	-5.0 V
Guard	-5.0 V

LED FLATFIELD ILLUMINATION (FFIL); 1 INJECTION CORRESPONDS TO ~10X ^{55}Fe K$_\alpha$

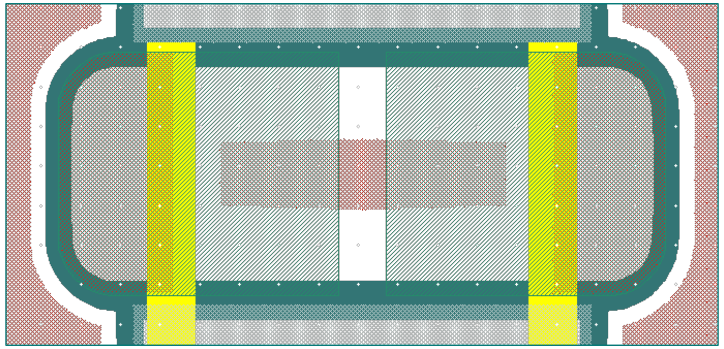


Measurements – operation window

on depleted 50 μm thick EDET structures

Clear Gate and Clear low voltage influence

- back-emission of e^- from clear contact,
- inversion (parasitic channel under the Clear Gate), and
- charge loss to clear contact.



W09 F07	
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Gate Off	5.0 V
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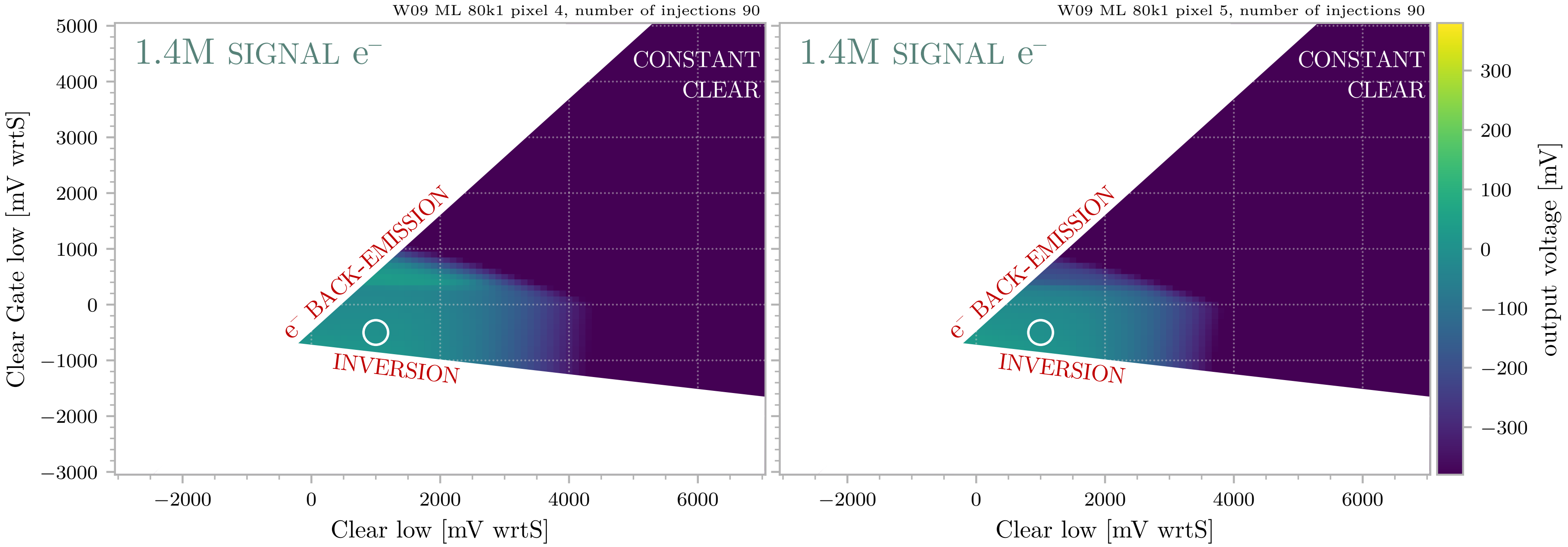
Clear Gate	sweep
Depletion	-35.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

LED FLATFIELD ILLUMINATION (FFIL); 1 INJECTION CORRESPONDS TO ~10X ^{55}Fe K$_\alpha$



Measurements – operation window

on depleted 50 µm thick EDET structures

Clear Gate and Clear low voltage influence

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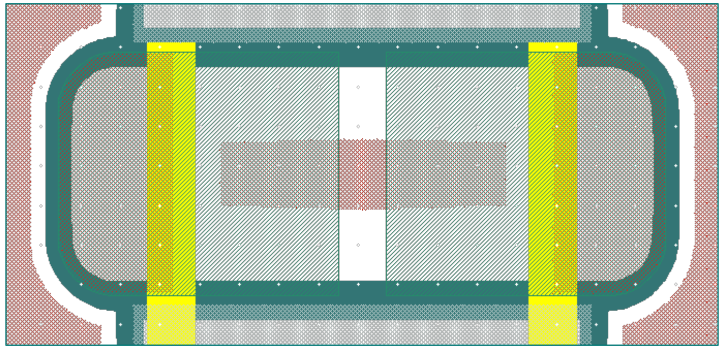

W09 F07	
Thickness	50 µm
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Drain	-5.0 V
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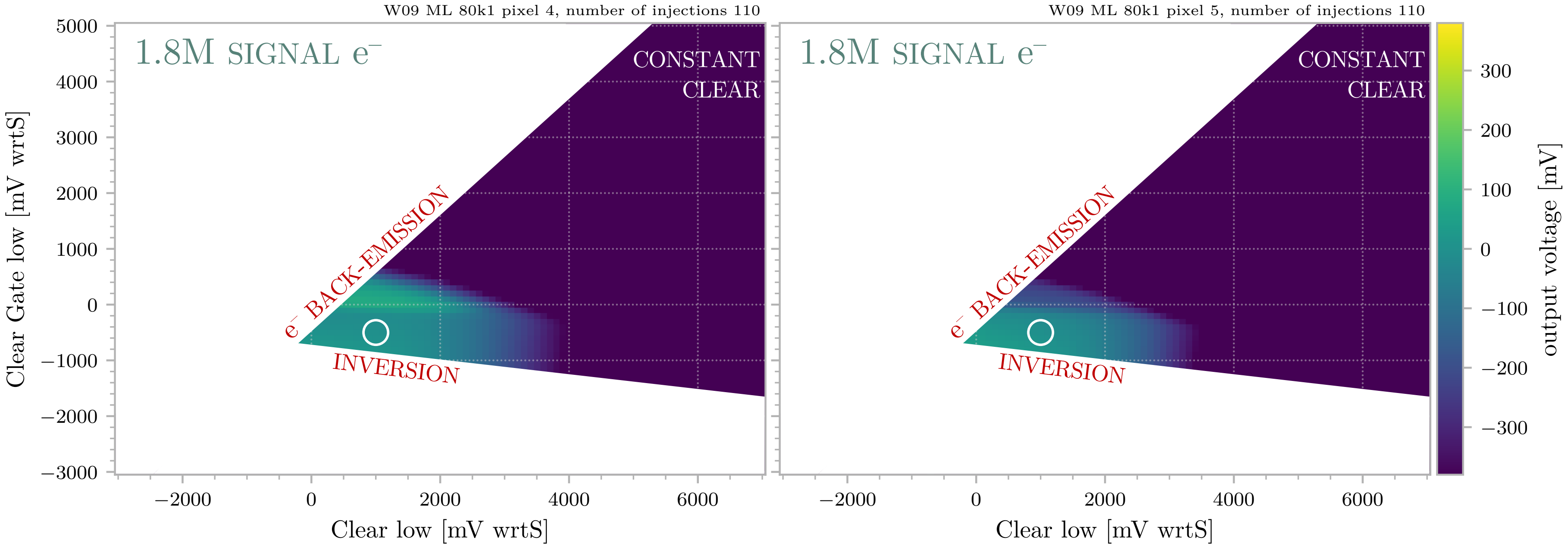
Clear low	sweep
Clear high	17.0 V
Clear Gate	sweep
Depletion	-35.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

LED flatfield illumination (FFIL); 1 injection corresponds to ~10x ^{55}Fe K_α



Measurements – incomplete clear

on depleted 50 µm thick EDET structures

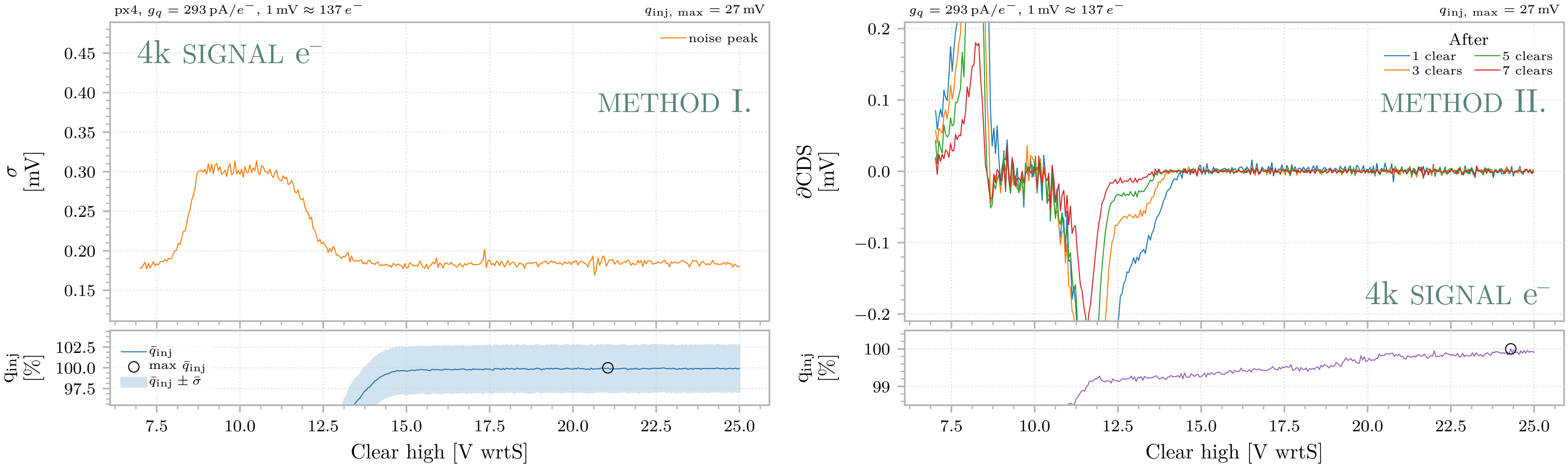
Clear high voltage and clear pulse length (t_c) influence

- efficiency of complete charge removal from internal gate and overflow regions.

Slow switching stage of SwitcherS ASIC limits $t_c > 70$ ns. Final camera setup $t_c \sim 20$ ns achieved with SwitcherB ASIC.

W09 F07	
Thickness	50 µm
Gate L	5.0 µm
Gate W	27.2 µm
Drain	-5.0 V
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
Clear high	sweep
Clear Gate	-0.5 V
Depletion	-35.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

FFIL; SMALL SIGNAL CHARGE ~2.5X ^{55}Fe K_α; HARDEST TO REMOVE



Measurements – incomplete clear

on depleted 50 µm thick EDET structures

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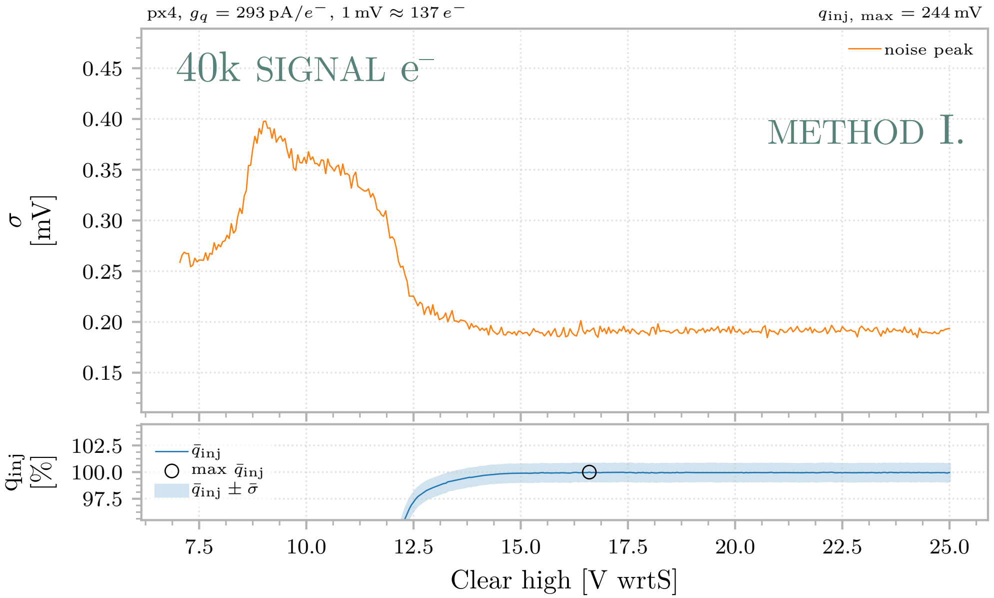
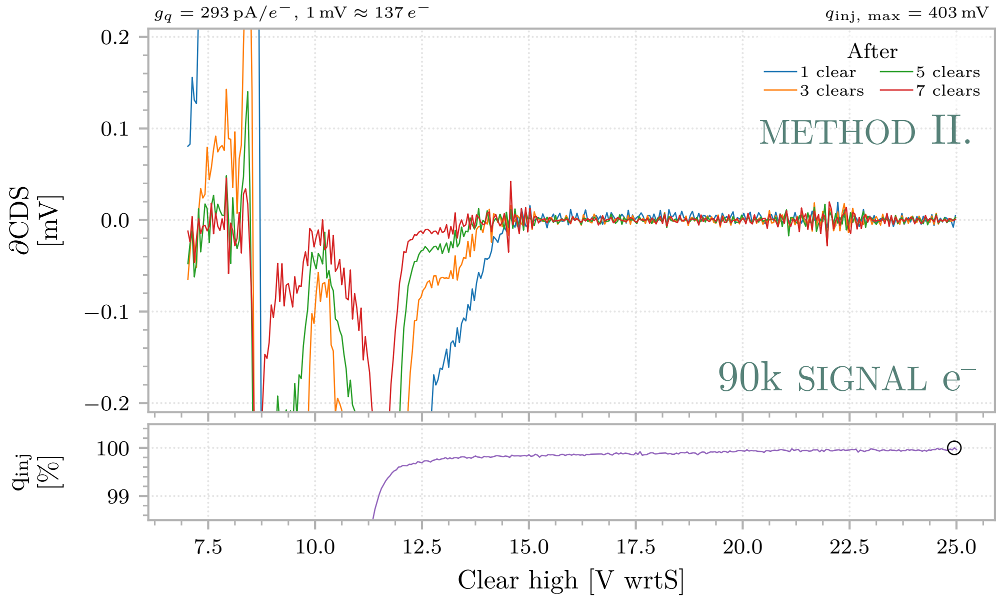
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
Clear high	sweep
Clear Gate	-0.5 V
Depletion	-35.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

FFIL; ALMOST FULL INTERNAL GATE



FFIL; FILLING THE OVERFLOW REGIONS



Measurements – incomplete clear

on depleted 50 µm thick EDET structures

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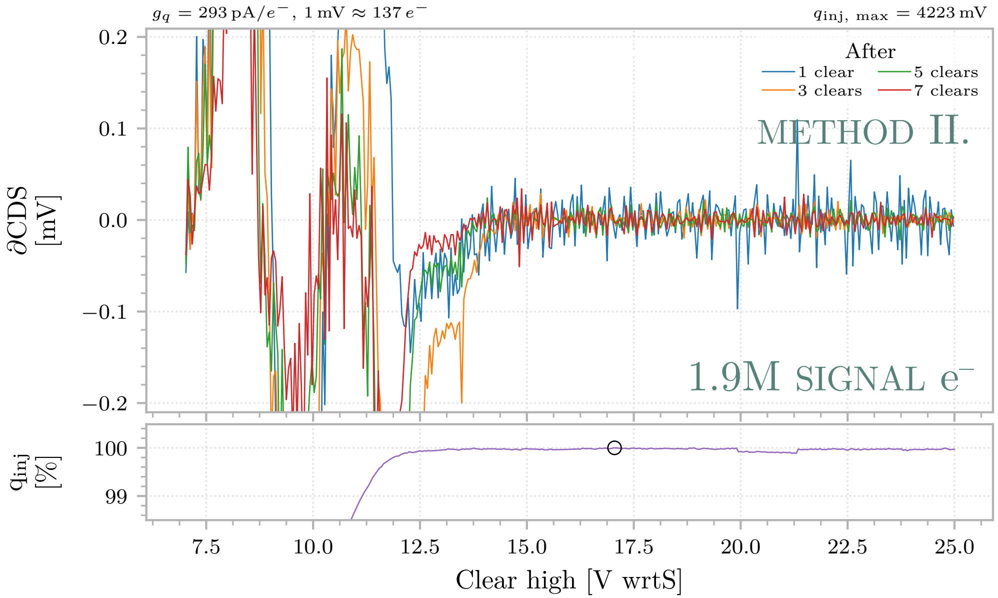
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
Clear high	sweep
Clear Gate	-0.5 V
Depletion	-35.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

FFIL; COMPLETELY FILLED STATE

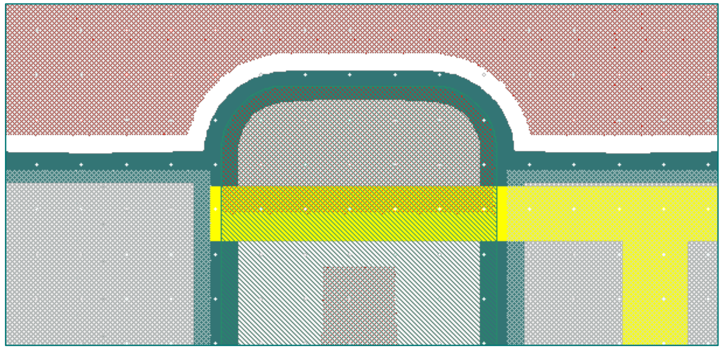


Measurements – charge collection

on depleted 50 µm thick EDET structures

Depletion and Drift voltage influence

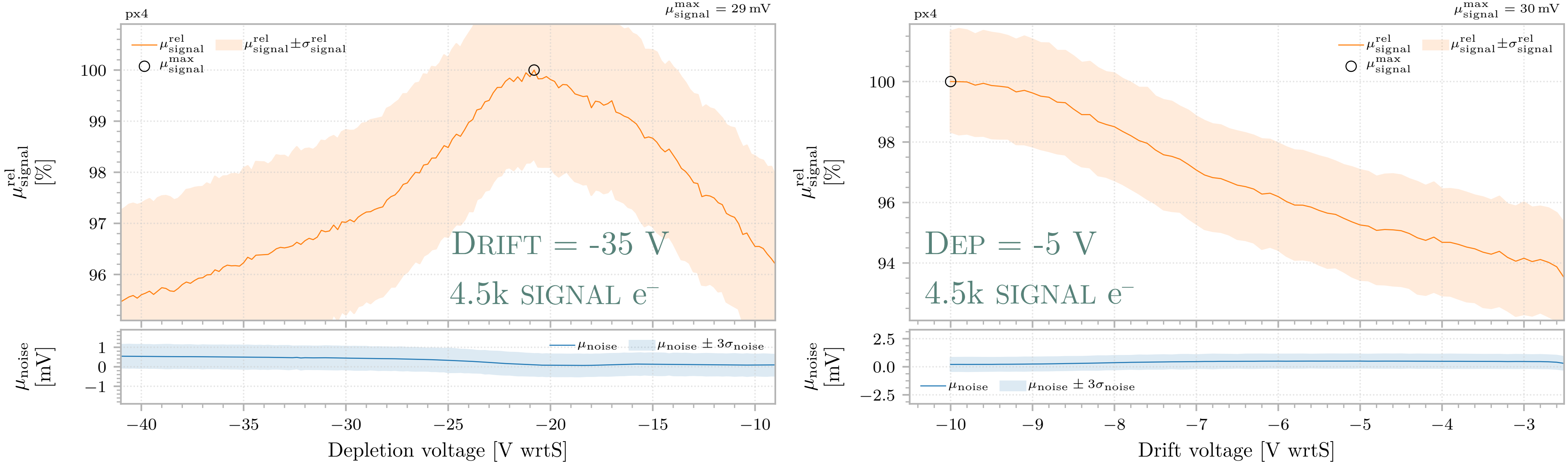
- integrated 1st stage amplification (g_q),
- charge loss to Clear, and
- charge loss to Drift region.



W09 F07

Thickness	50 µm
Gate L	5.0 µm
Gate W	27.2 µm
Drain	-5.0 V
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
Clear high	18.0 V
Clear Gate	-0.5 V
Depletion	sweep
Bulk	10.0 V
Drift	sweep
Guard	-5.0 V

FFIL; SMALL SIGNAL CHARGE ~2.8x ^{55}Fe K_α



12/03/2019

Measurements – charge collection

on depleted 50 µm thick EDET structures

Depletion and Drift voltage influence

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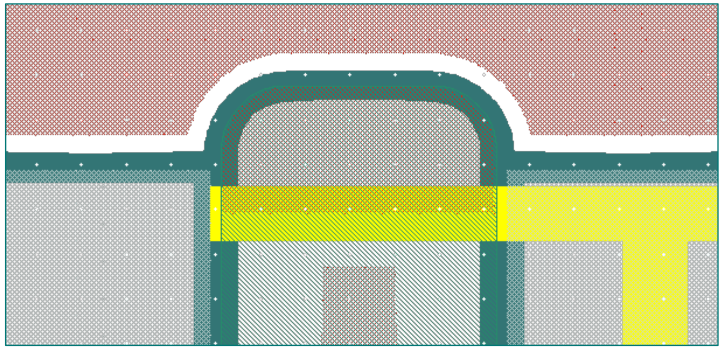

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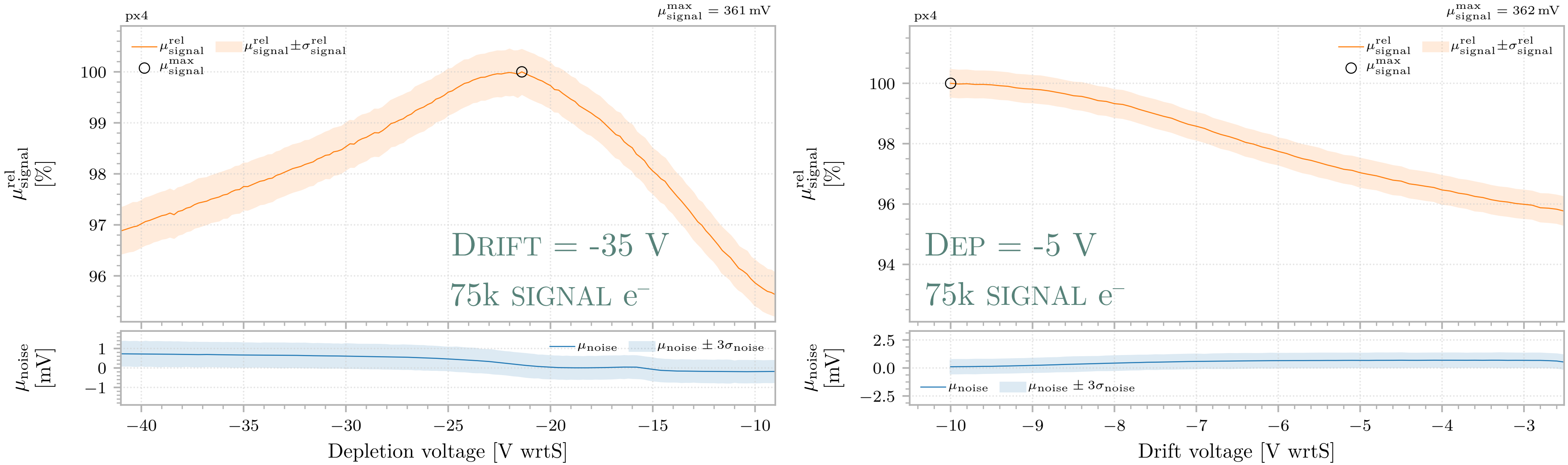
Drain	-5.0 V
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
Clear high	18.0 V
Clear Gate	-0.5 V
Depletion	sweep
Bulk	10.0 V
Drift	sweep
Guard	-5.0 V

FFIL; FILLING THE OVERFLOW REGIONS; LESS LOSSES – FILLED POTENTIAL POCKET UNDER DRIFT



Measurements – charge collection

on depleted 50 µm thick EDET structures

Depletion and Drift voltage influence

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Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
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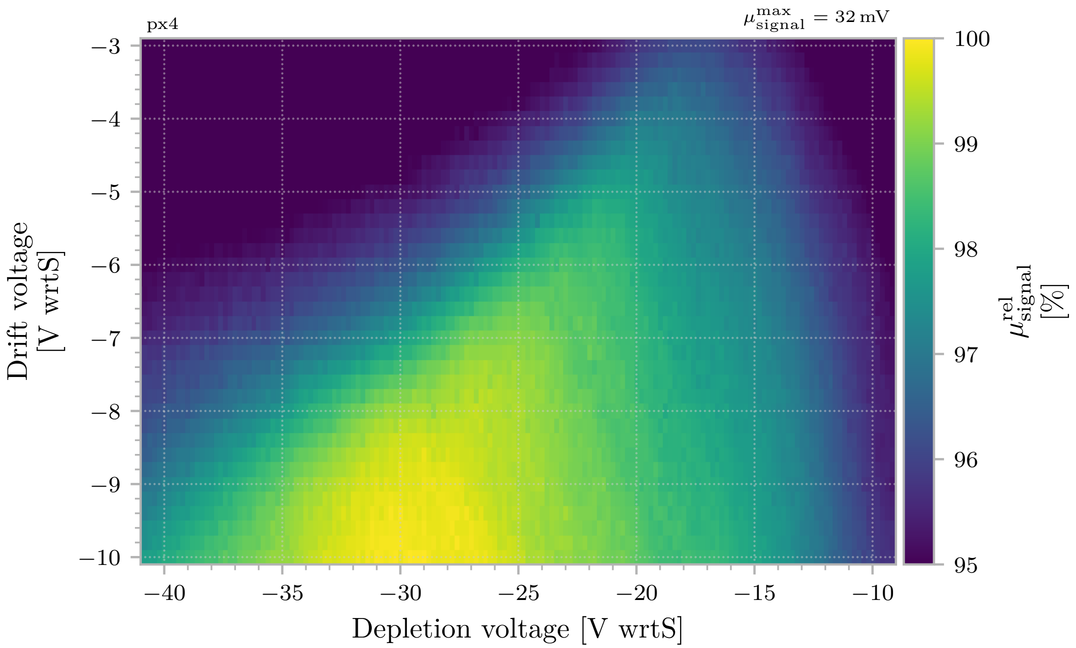
Clear Gate	-0.5 V
Depletion	sweep
Bulk	10.0 V
Drift	sweep
Guard	-5.0 V

FFIL; SMALL SIGNAL CHARGE ~2.8X ^{55}Fe K_α



OPERATIONAL POINT ALSO DEPENDS ON THE DRIFT AND THE DEPLETION CURRENT DUE TO PROBLEMATIC HEAT DISSIPATION IN THIN DEVICES.

Measurements – charge collection

on depleted 50 µm thick EDET structures

Depletion and Drift voltage influence

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Source	0.0 V
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Clear low	1.0 V
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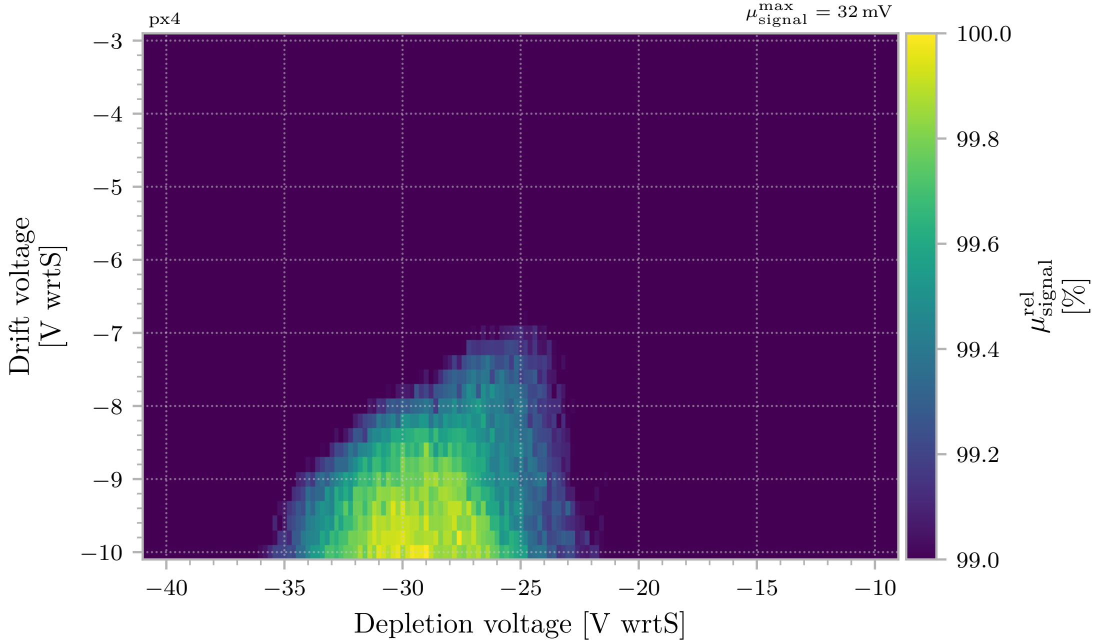
Clear Gate	-0.5 V
Depletion	sweep
Bulk	10.0 V
Drift	sweep
Guard	-5.0 V

FFIL; SMALL SIGNAL CHARGE ~2.8X ^{55}Fe K_α



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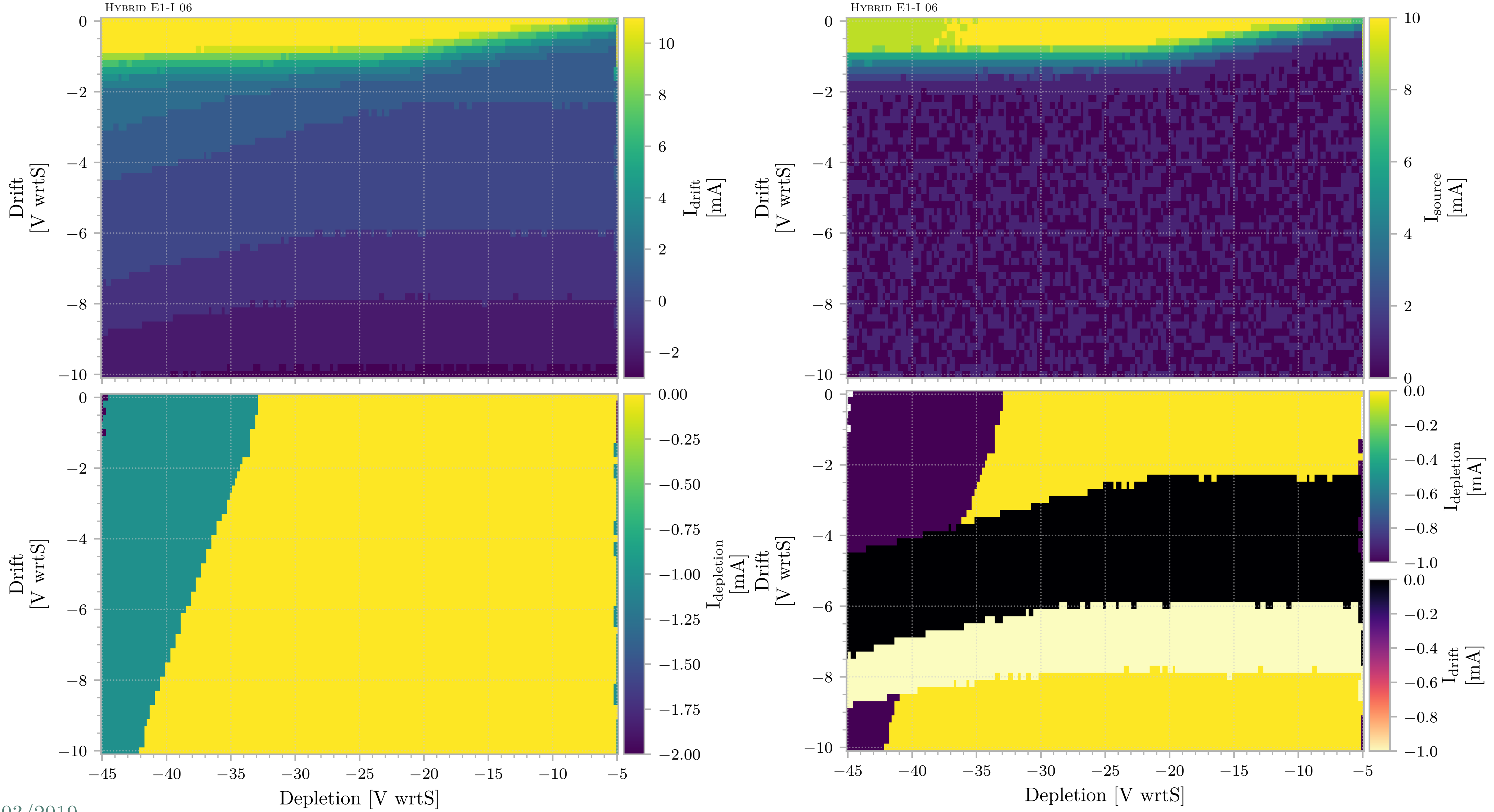
Measurements – charge collection

on depleted 50 µm thick EDET structures



Measurements – charge collection

on depleted 50 µm thick EDET structures

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W09 F07

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Gate Off	5.0 V
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Clear low	1.0 V
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Clear Gate	-0.5 V
Depletion	sweep
Bulk	10.0 V
Drift	sweep
Guard	-5.0 V

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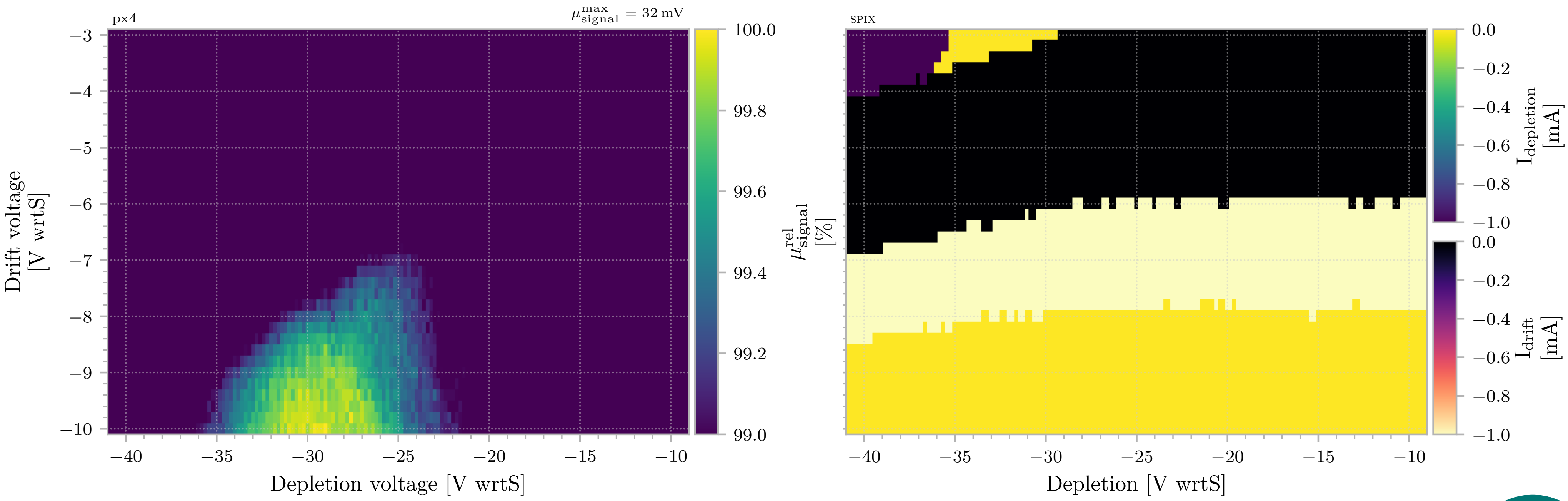
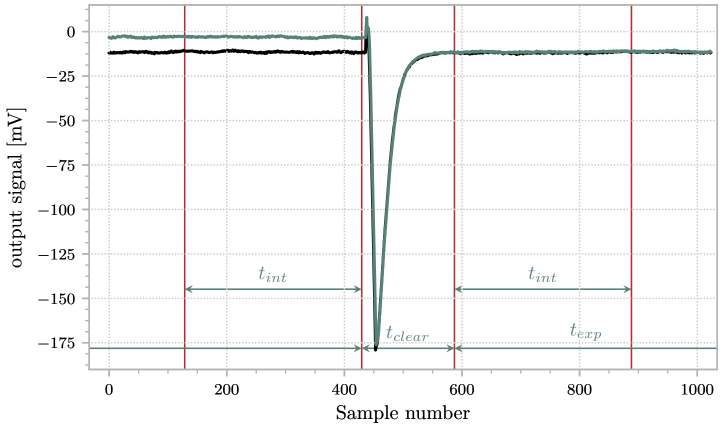


Measurements – noise v integration time

on depleted 50 µm thick EDET structures

Integration time (t_{int}) influences

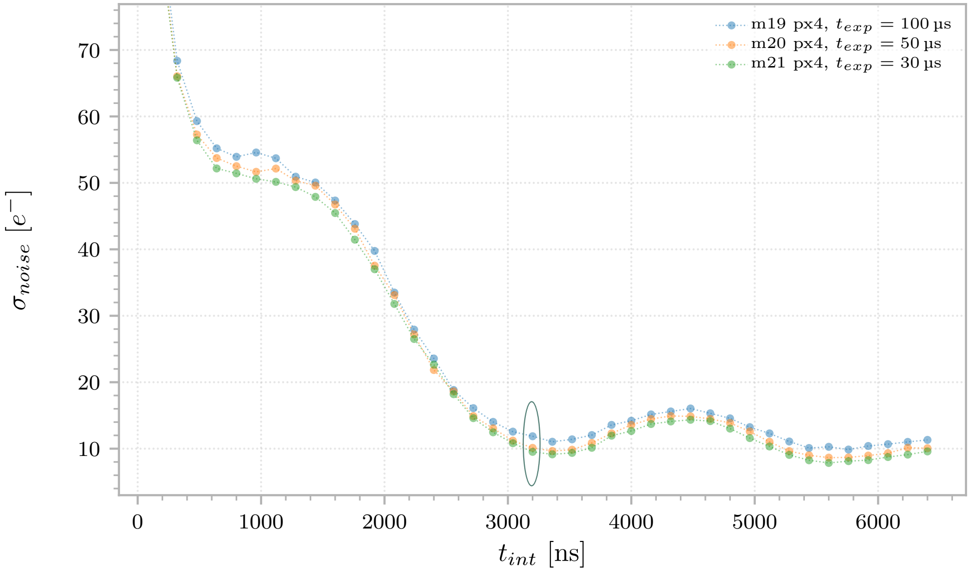
- the overall noise performance of the system.

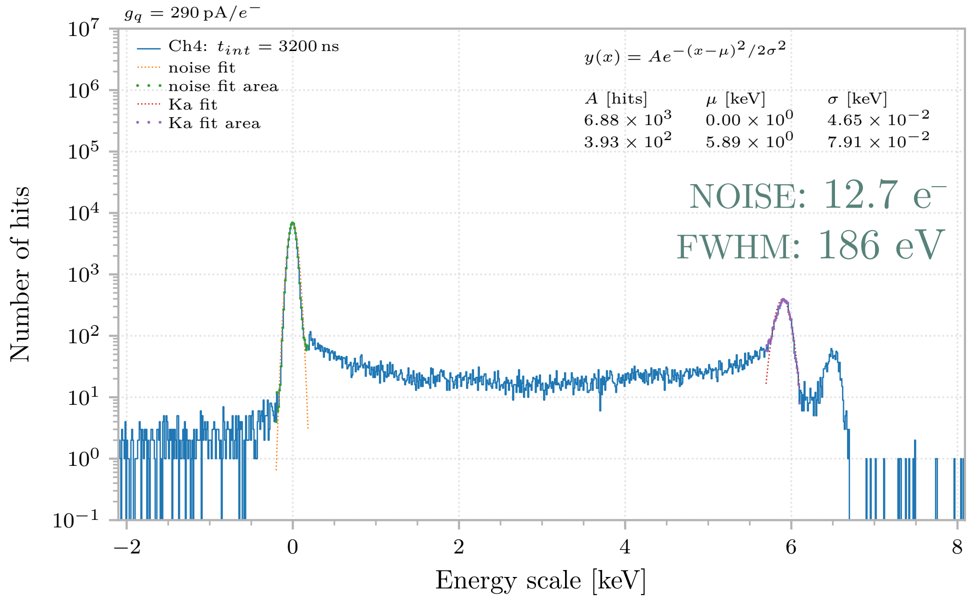


Noise dominated by Leakage Current and Common Mode Noise.

W09 F07	
Thickness	50 µm
Gate L	5.0 µm
Gate W	27.2 µm
Drain	-5.0 V
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
Clear high	18.0 V
Clear Gate	-0.5 V
Depletion	-21.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

^{55}Fe RADIOACTIVE SOURCE ILLUMINATION





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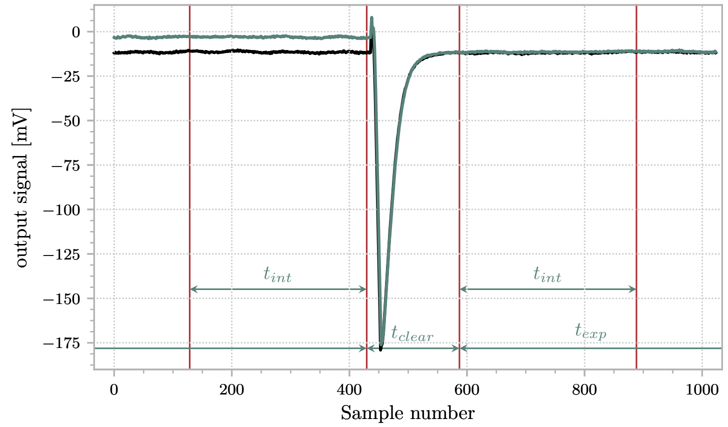

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W09 F07	
Thickness	50 µm
Gate L	5.0 µm
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Drain	-5.0 V
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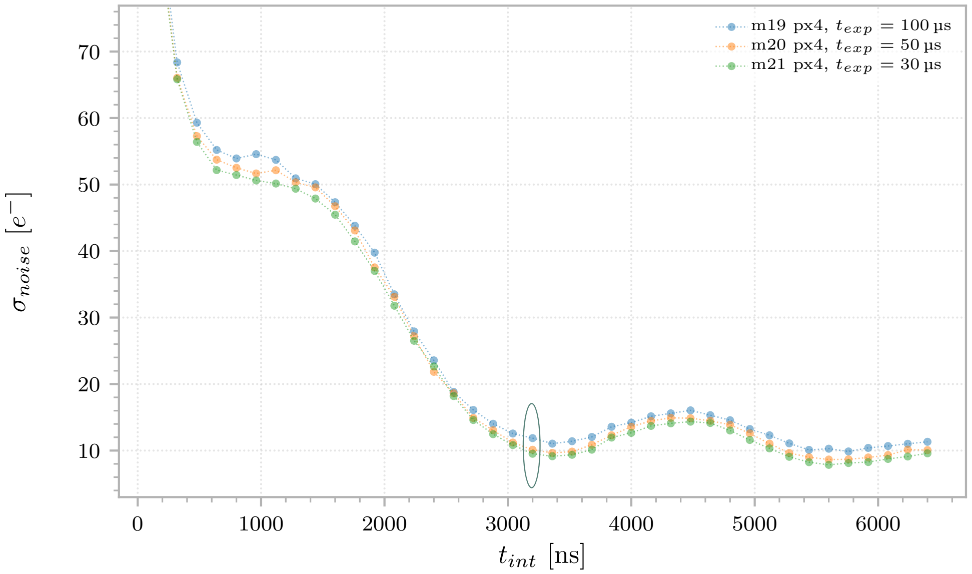
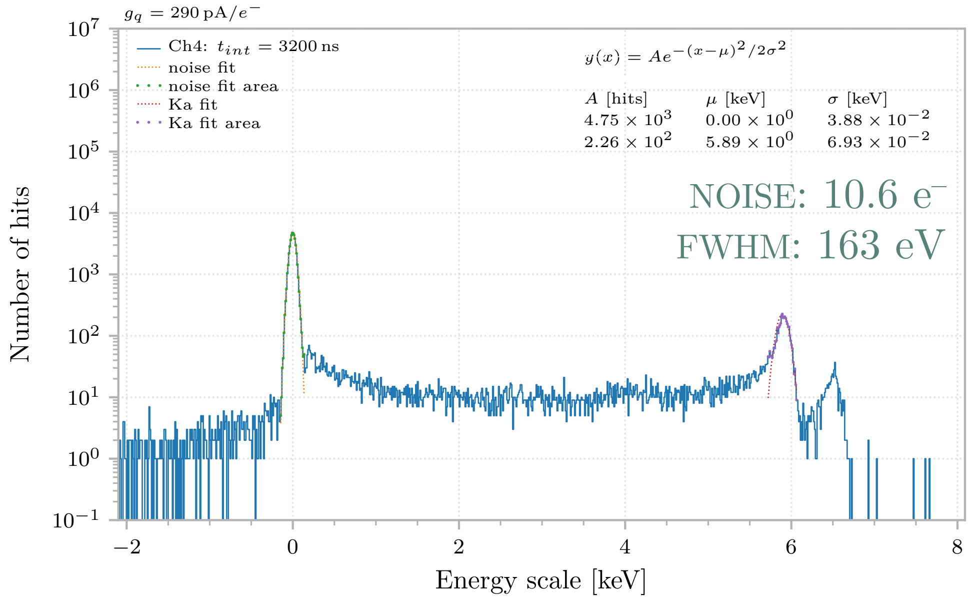
Depletion	-21.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

^{55}Fe RADIOACTIVE SOURCE ILLUMINATION





NOISE: 10.6 e$^-$

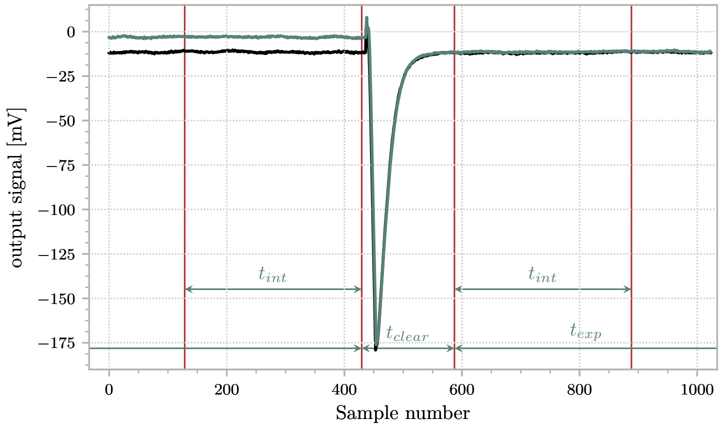
FWHM: 163 eV

Measurements – noise v integration time

on depleted 50 µm thick EDET structures

Integration time (t_{int}) influences

- the overall noise performance of the system.



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Depletion	-21.0 V
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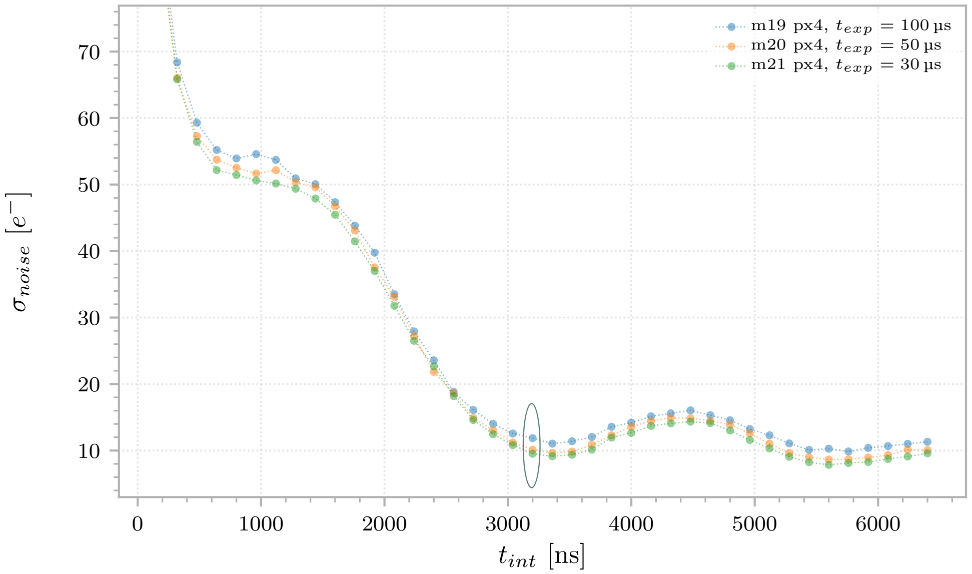
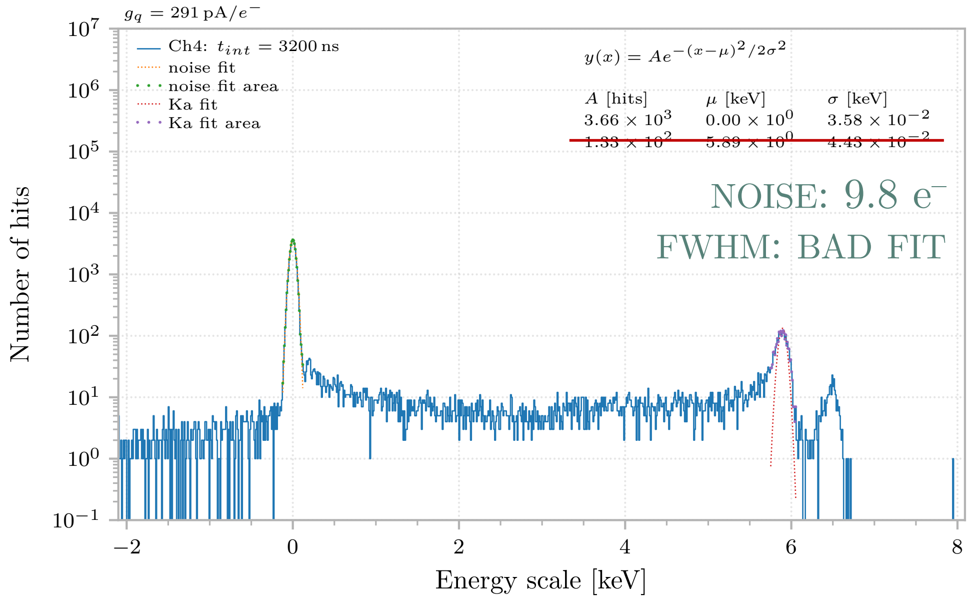
Drift	-5.0 V
Guard	-5.0 V

^{55}Fe RADIOACTIVE SOURCE ILLUMINATION





Response function – Calibration

of depleted 50 µm thick EDET structures

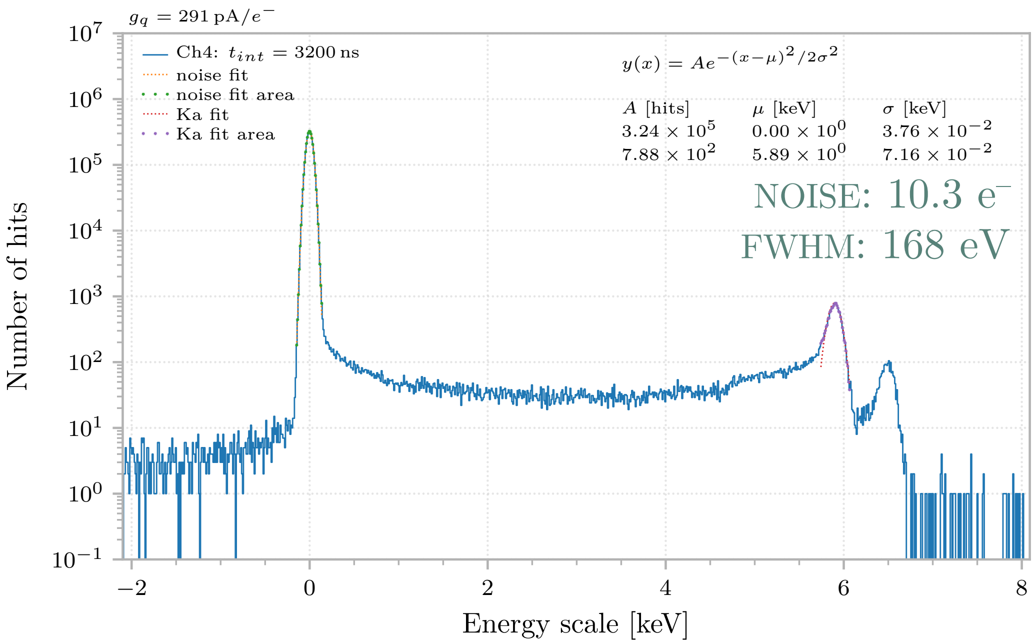
Procedure:

- insertion of fixed amount of charge by ^{55}Fe radioactive source at optimized operation voltages
- extraction of the primary g_q
- explore the full dynamic range with calibrated LED pulses and leakage current

PRIMARY $g_q = 291\ \text{pA/e}^- \ (1 \pm 0.014)$

W09 F07	
Thickness	50 µm
Gate L	5.0 µm
Gate W	27.2 µm
Drain	-5.0 V
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
Clear high	18.0 V
Clear Gate	-0.5 V
Depletion	-21.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

^{55}Fe RADIOACTIVE SOURCE ILLUMINATION



Response function – Dynamic range

of depleted 50 µm thick EDET structures

Procedure:

- insertion of fixed amount of charge by ^{55}Fe radioactive source at optimized operation voltages
- extraction of the primary g_q
- explore the full dynamic range with calibrated LED pulses and leakage current

PRIMARY $g_q = 291\ \mathrm{pA/e^-}\ (1 \pm 0.003)$

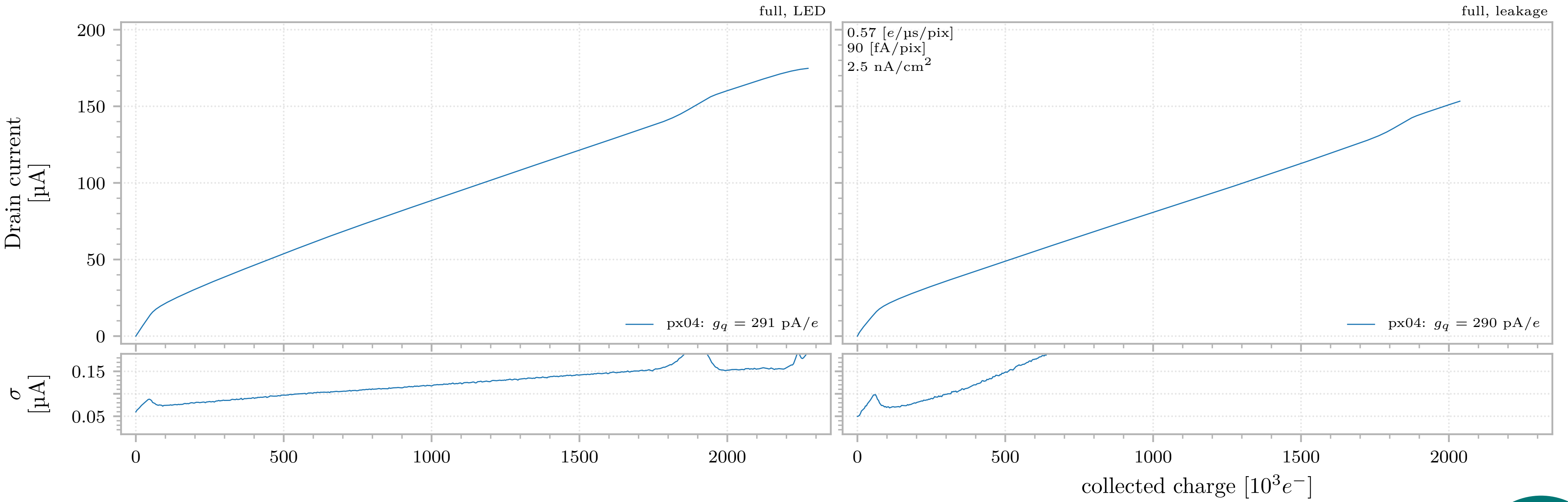
SECONDARY $g_q = 70\ \mathrm{pA/e^-}\ (1 \pm 0.10)$

LEAKAGE $I_L = 0.57\ \mathrm{e^-/\mu s}(1 \pm 0.05)$

W09 F07	
Thickness	50 µm
Gate L	5.0 µm
Gate W	27.2 µm
Drain	-5.0 V
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
Clear high	18.0 V
Clear Gate	-0.5 V
Depletion	-21.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

FFIL; $t_{exp} = 3.1$ ms; 601 PULSES

LEAKAGE CURRENT; $t_{exp} = 3.6$ s;



Motivation and Introduction

DePFET Structure and Measurement Setup

Optimization of Operation Parameters and Response Function

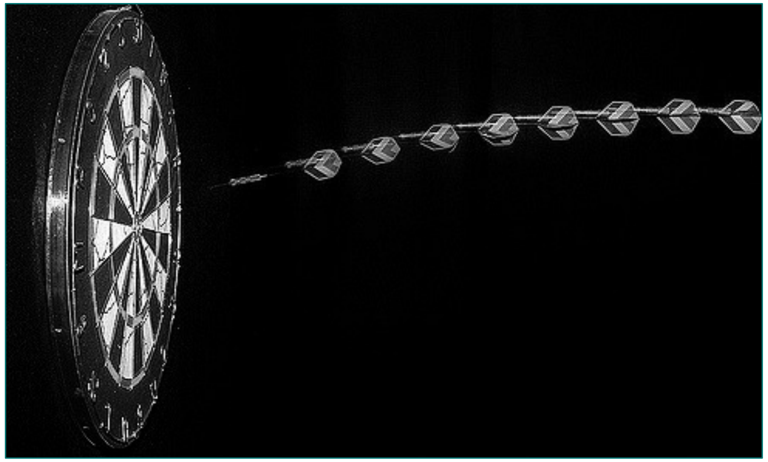
Summary and Outlook

Summary and outlook

for the project

EDET project

- pilot production successfully finished and characterized
- fabrication of the main batch has been resumed
- pilot devices showing expected results
  - signal compression
    - 290 pA/e^- for the first ~50 k signal e^-
    - ~70 pA/e^- for the rest
  - dynamic range of >800k signal e^-
  - operation window big enough to operate the large area devices



FUTURE plans

- characterize 30 µm thin sensor and an additional “wild-card” design
- start the simulations of the design
  - possible optimizations
- radiation hardness studies

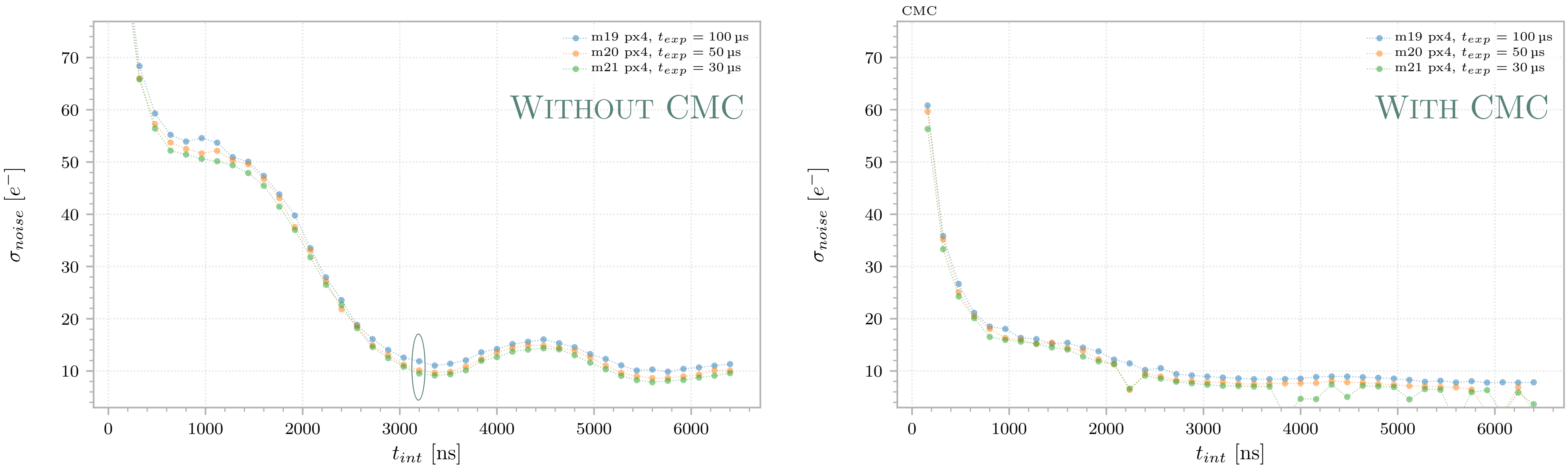
Thank You for Your attention!

Backup slides

Common mode noise

W09 F07	
Thickness	50 µm
Gate L	5.0 µm
Gate W	27.2 µm
Drain	-5.0 V
Source	0.0 V
Gate Off	5.0 V
Gate On	-2.17 V
Clear low	1.0 V
Clear high	18.0 V
Clear Gate	-0.5 V
Depletion	-21.0 V
Bulk	10.0 V
Drift	-5.0 V
Guard	-5.0 V

^{55}Fe RADIOACTIVE SOURCE ILLUMINATION



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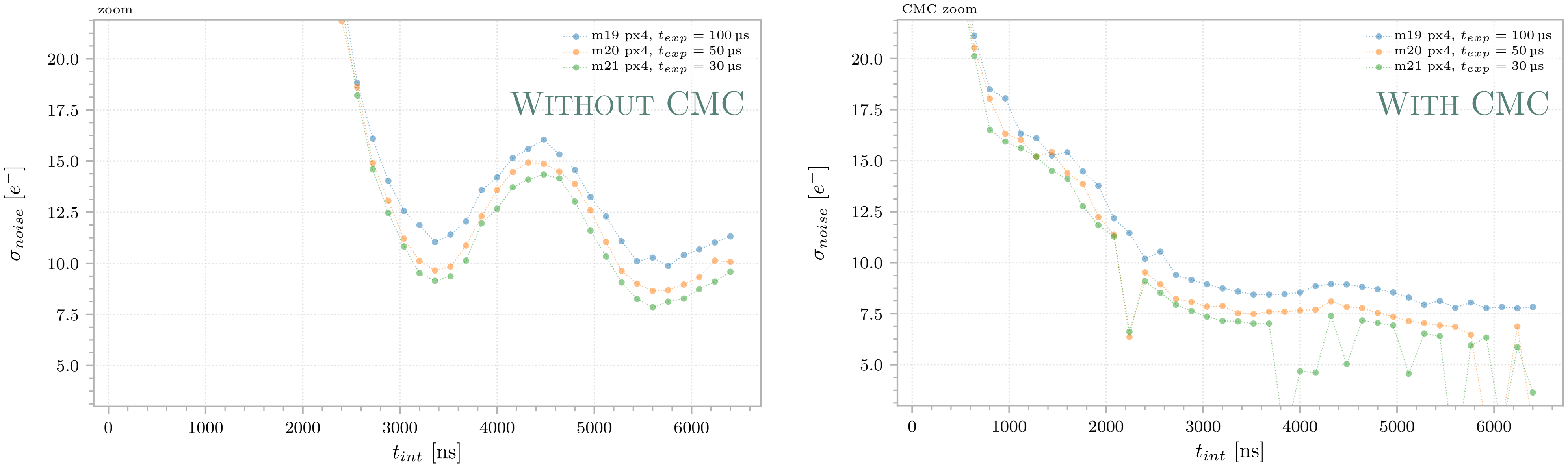
^{55}Fe RADIOACTIVE SOURCE ILLUMINATION

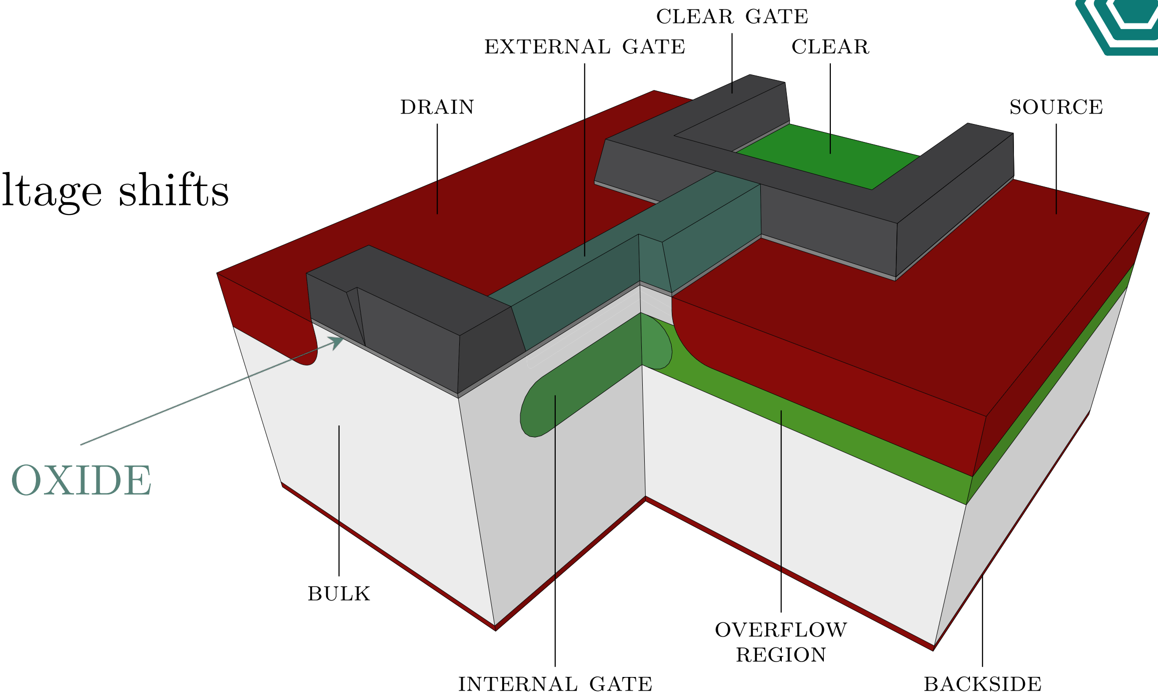


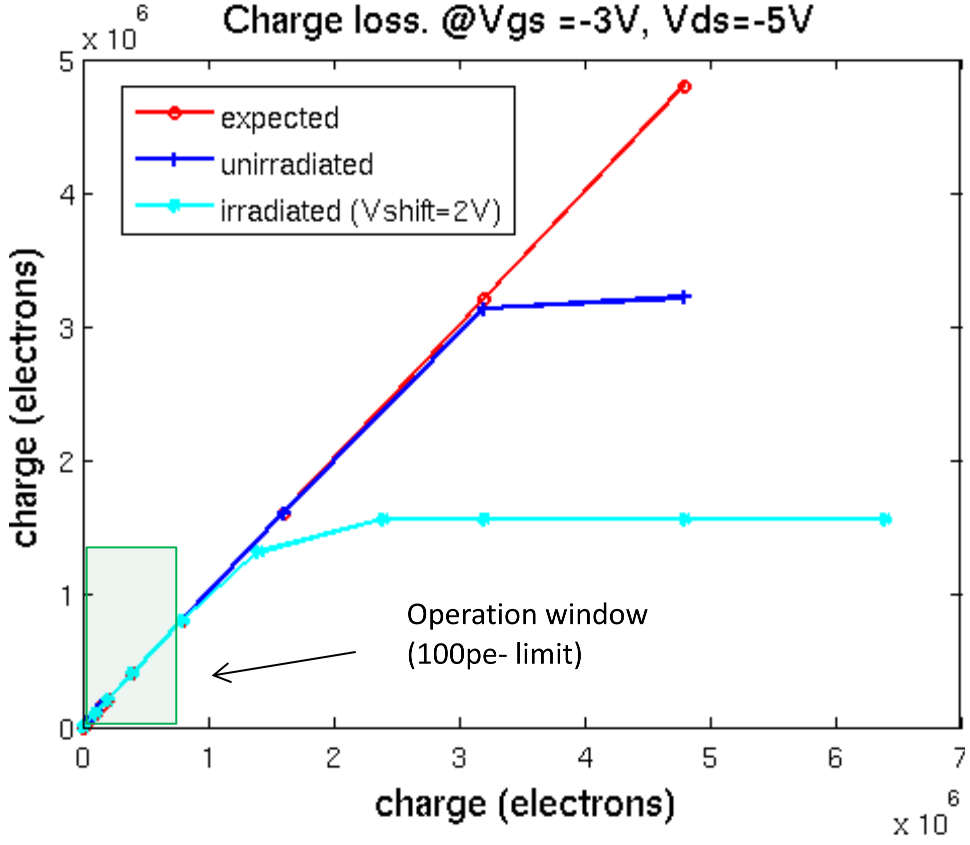
20 % CHANGE IN $\boldsymbol{\sigma}_{\text{noise}}$

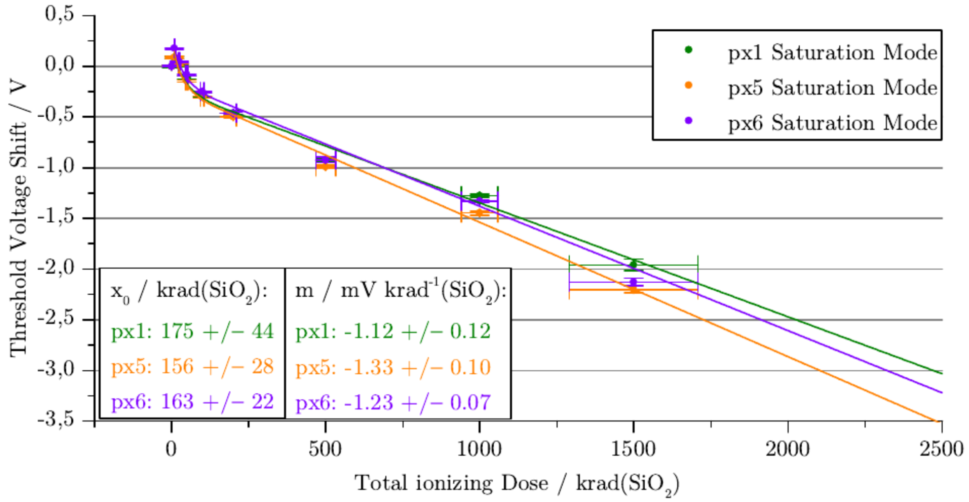
Radiation hardness

Radiation causes positive charge buildup in Oxide:

- homogeneous radiation – compensated by gate voltage shifts
- inhomogeneous radiation – could cause problems







x_0 / krad(SiO$_2$):	m / mV krad^{-1}(SiO$_2$):
px1: 175 +/− 44	px1: -1.12 +/− 0.12
px5: 156 +/− 28	px5: -1.33 +/− 0.10
px6: 163 +/− 22	px6: -1.23 +/− 0.07