16th (Virtual) "Trento" Workshop
Tuesday, 16th February 2021

E-TCT characterisation of neutron irradiated 180 nm HV-CMOS pixel test structures

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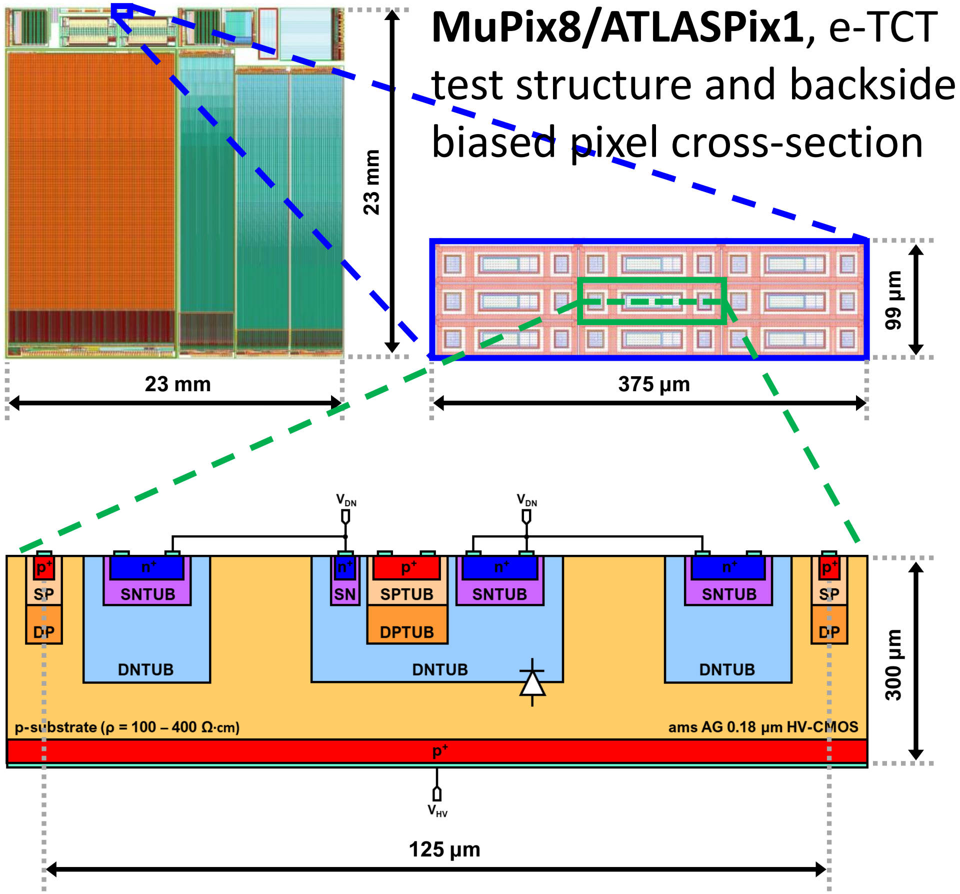
Outline

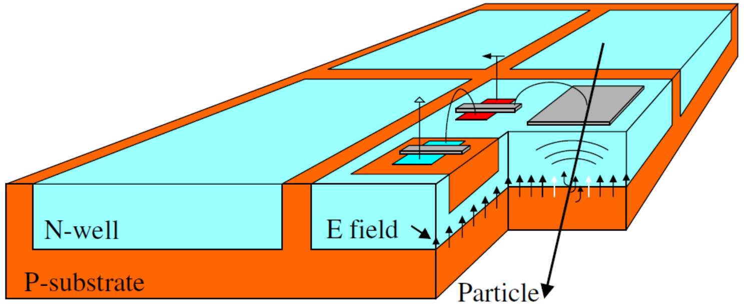
- Introduction
    - MuPix8/ATLASPix1 chip
    - Two sample types
    - I-V measurements
    - E-TCT setup and technique
- Wafer 1 (topside biased)
    - E-TCT measurements
- Wafer 2 (backside biased)
    - E-TCT measurements
- Comparison of effective doping conc. with fluence
- Summary

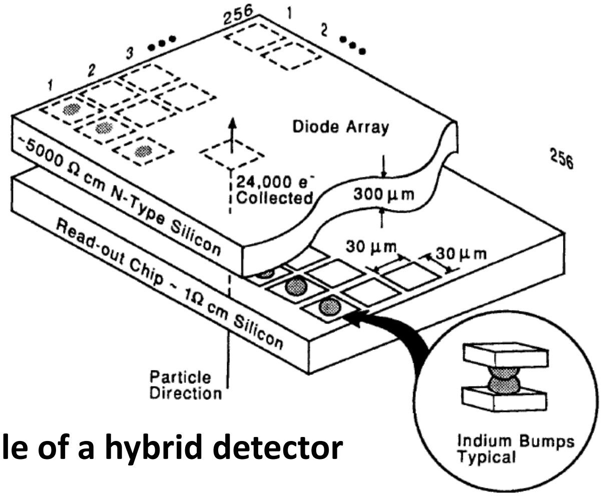


MuPix8/ATLASPix1, e-TCT test structure and backside biased pixel cross-section

Introduction

Four HV-CMOS pixels - I. Peric



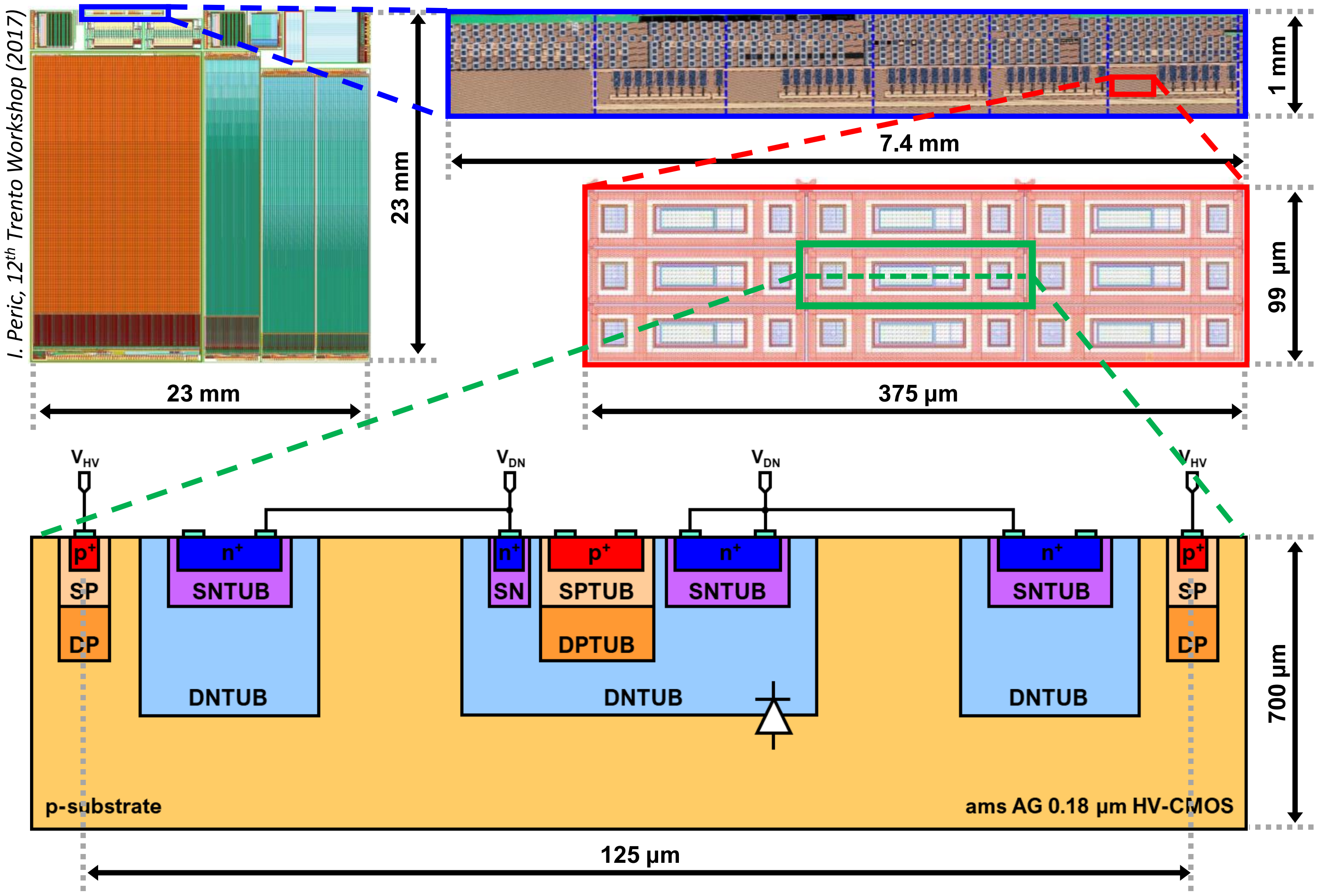


Example of a hybrid detector

Why use HV-CMOS in particle physics experiments?

- Need for low-cost, large area detectors
  - Produced in commercially available CMOS technologies
- Need for lower material budget
  - Read-out electronics embedded in sensing chip
  - No bump-bonding required (hybrids)
- Need for high radiation tolerance
  - HV-CMOS can be biased to high voltage for fast charge collection via drift

MuPix8/ATLASPix1

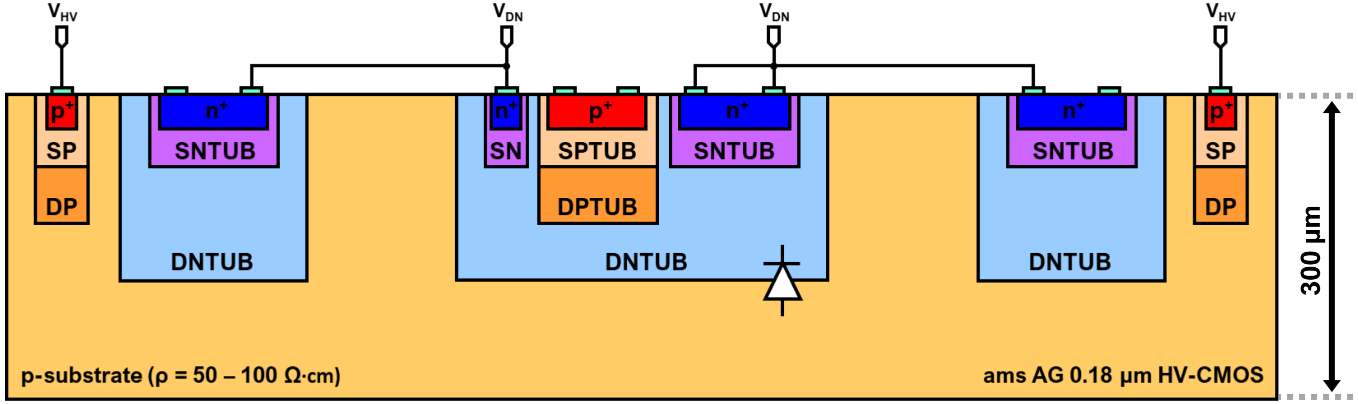


(top-left) MuPix8/ATLASPix1 shared submission ***(top-right)*** Liverpool contribution ***(middle-right)*** 3×3 test structure ***(bottom)*** Cross-section diagram of central pixel (not to scale)

- General design features
  - ❑ Engineering run in ams AG 180 nm HV-CMOS technology
  - ❑ Fabricated in multiple substrate resistivities 20 Ω·cm, 50–100 Ω·cm, 100–400 Ω·cm
  - ❑ Shared submission between Mu3e and ATLAS experiments
- E-TCT test structure
  - ❑ 3 × 3 matrix
  - ❑ Passive pixels
  - ❑ Pixels are 125 µm × 33 µm

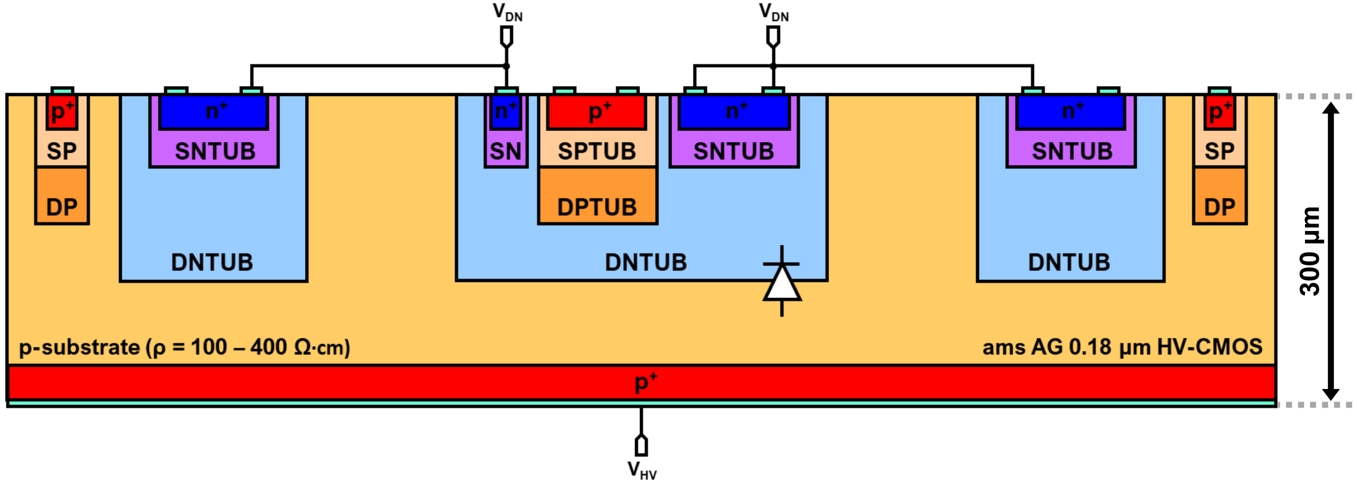
MuPix8/ATLASPix1 two sample types

Wafer 1 (W1) pixel cross-section:



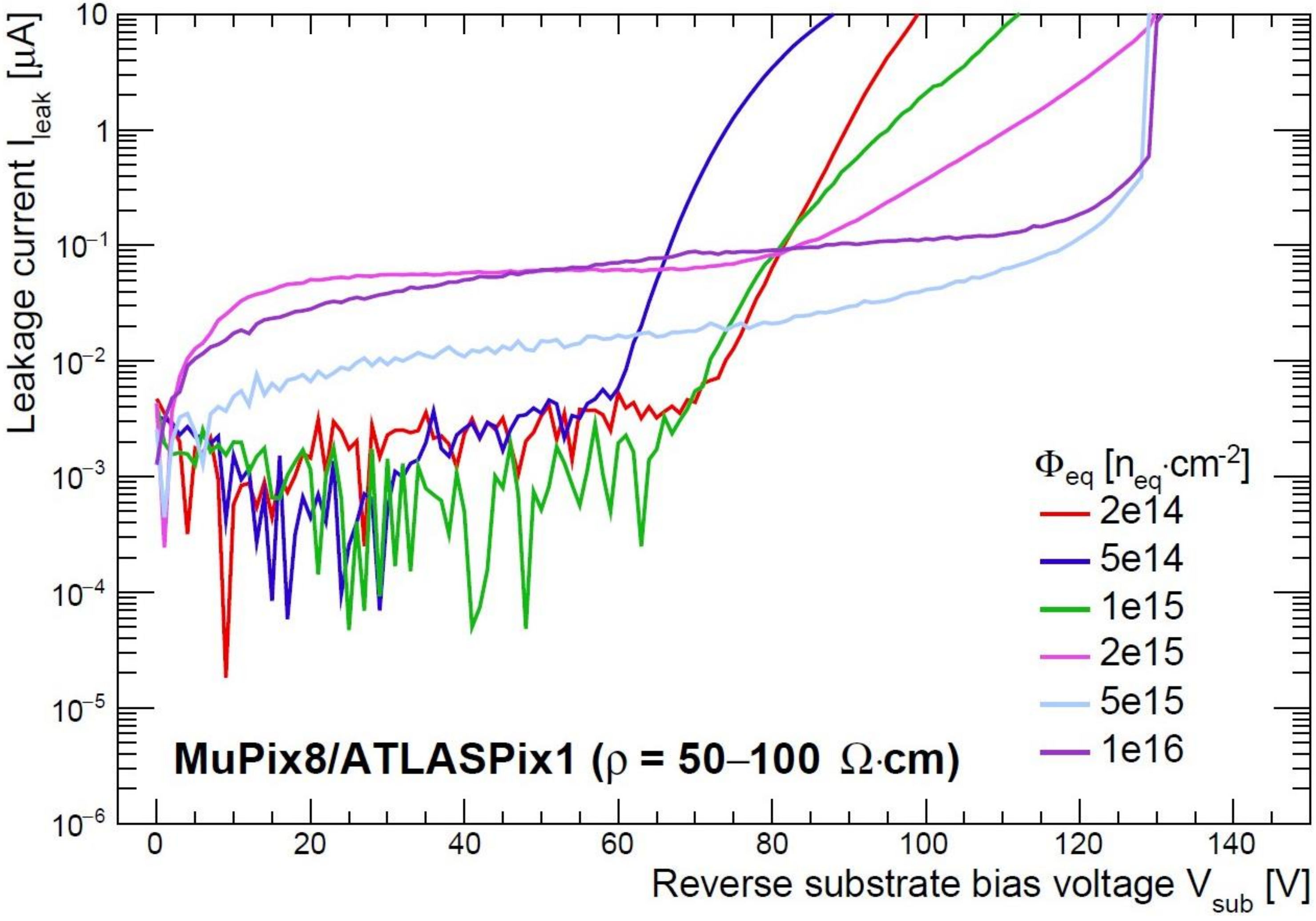
- 50–100 Ω·cm substrate resistivity
- Topside biased
- Thinned to 300 µm
- Measured fluences 1e14 < Φ_{eq} < 1e16 $n_{eq}\cdot cm^{-2}$

Wafer 2 (W2) pixel cross section:



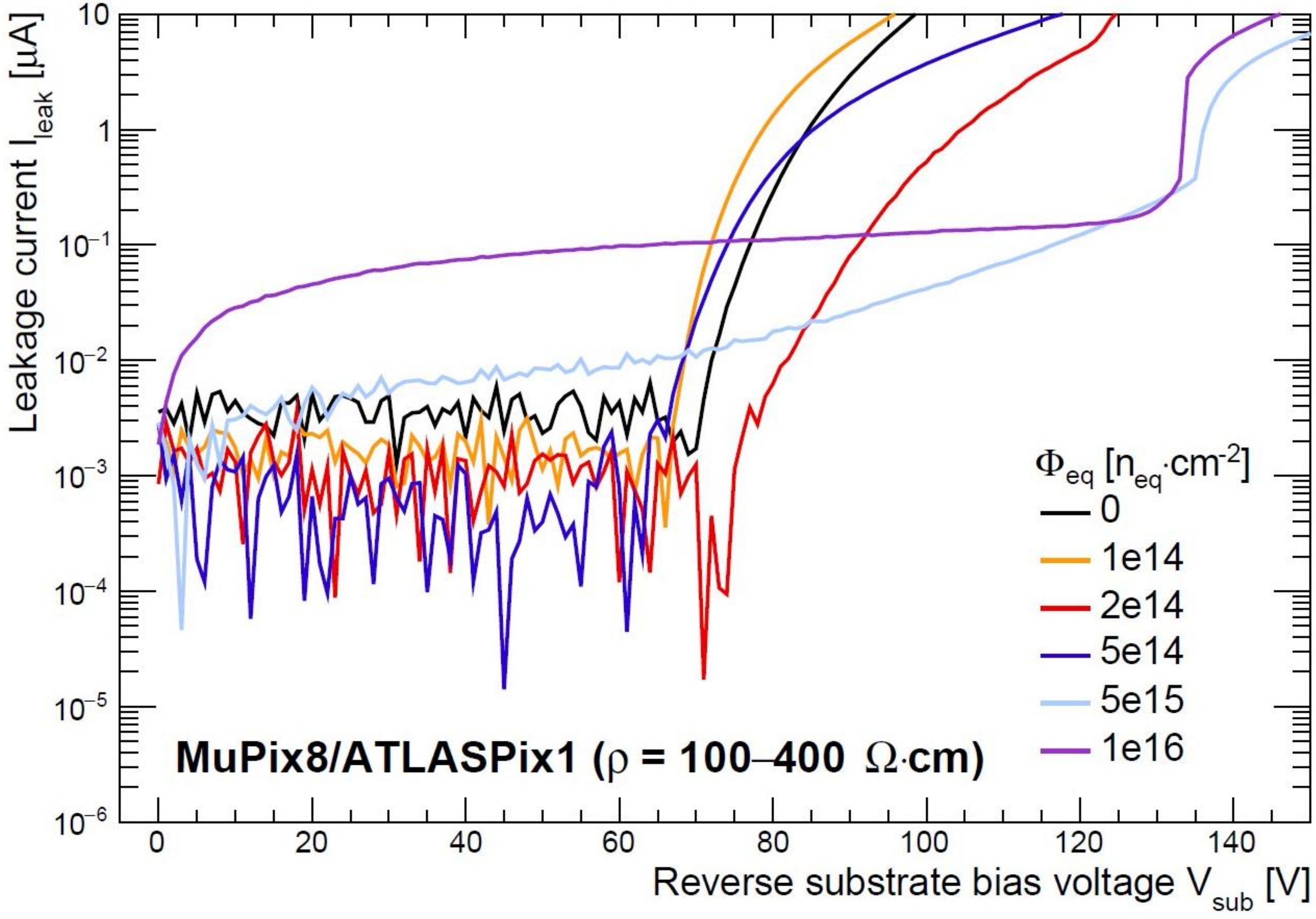
- 100–400 Ω·cm substrate resistivity
- Wafer thinning at OPTIM (300 µm)
- Backside processing at IBS
  - ☐ p+ implantation
  - ☐ backside metalisation
- Measured fluences 0 < Φ_{eq} < 1e16 $n_{eq}\cdot cm^{-2}$

MuPix8/ATLASPix1 W1 I-V measurements



- Samples irradiated with neutrons at TRIGA reactor (Jožef Stefan Institute)
  - ❑ $1 \cdot 10^{14} \rightarrow 1 \cdot 10^{16}$ $n_{eq} \cdot cm^{-2}$
- Leakage current increases with fluence (some variation)
- Breakdown voltage increased for higher fluence samples

MuPix8/ATLASPix1 W2 I-V measurements



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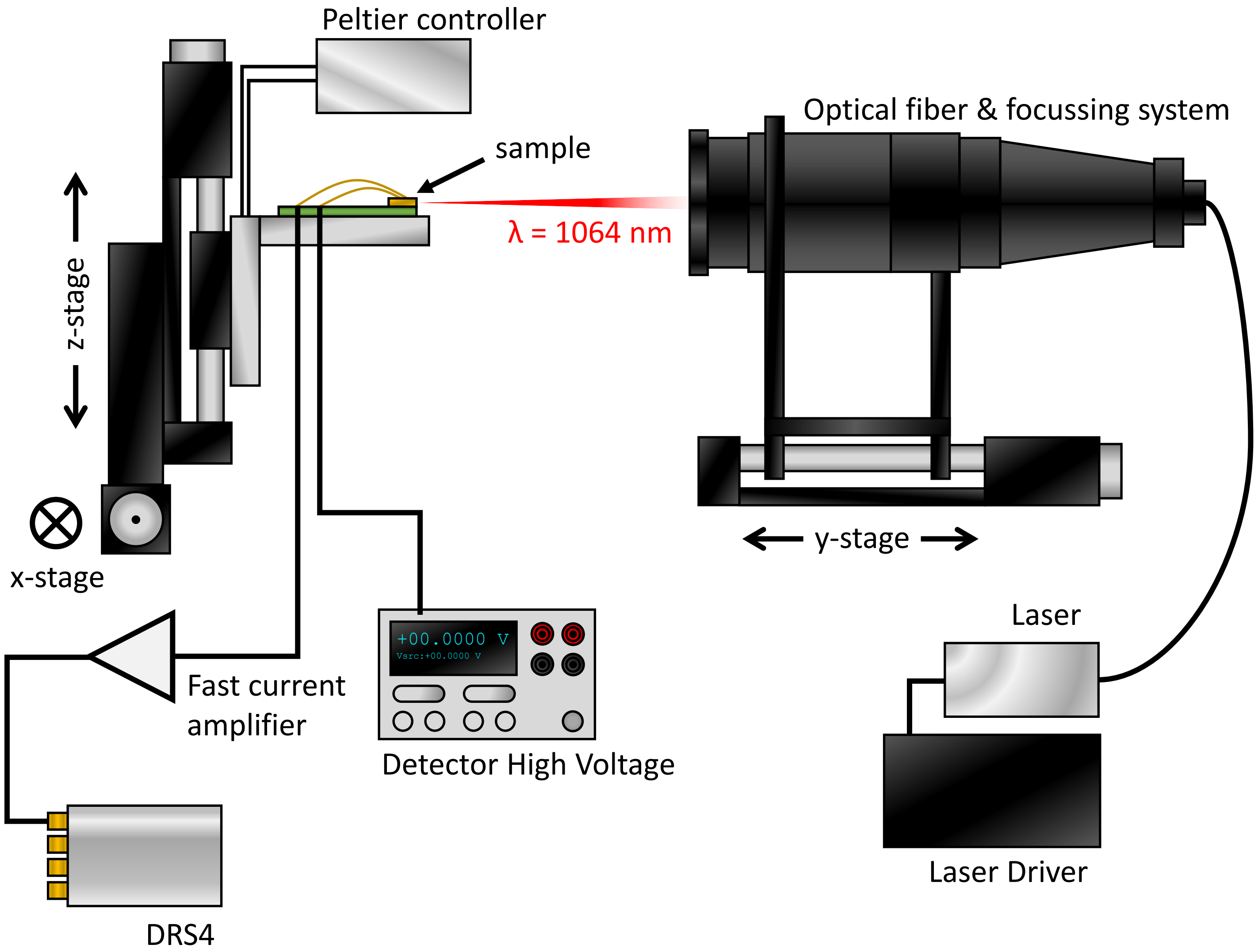
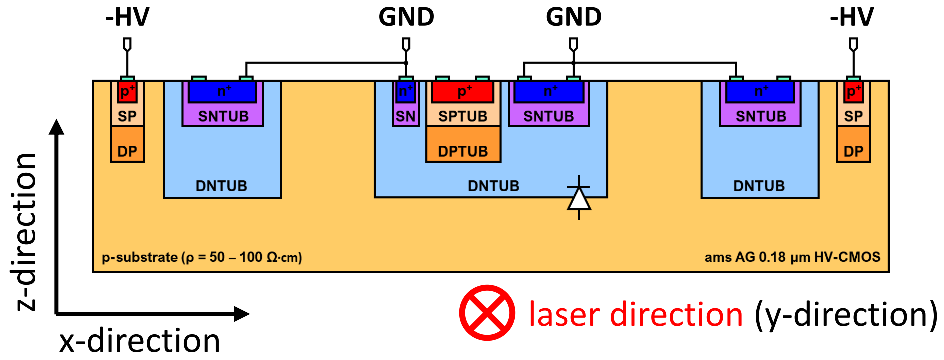
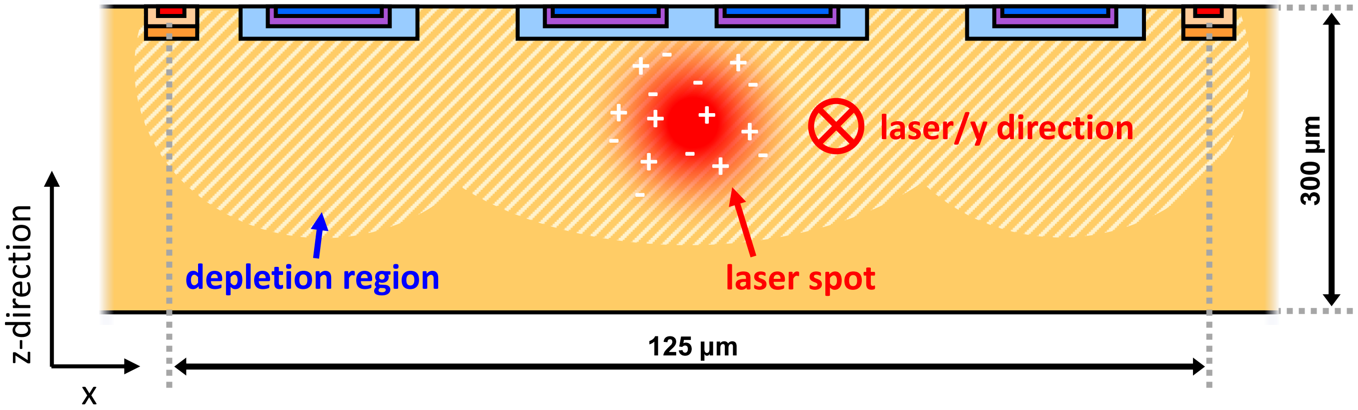
E-TCT experimental setup

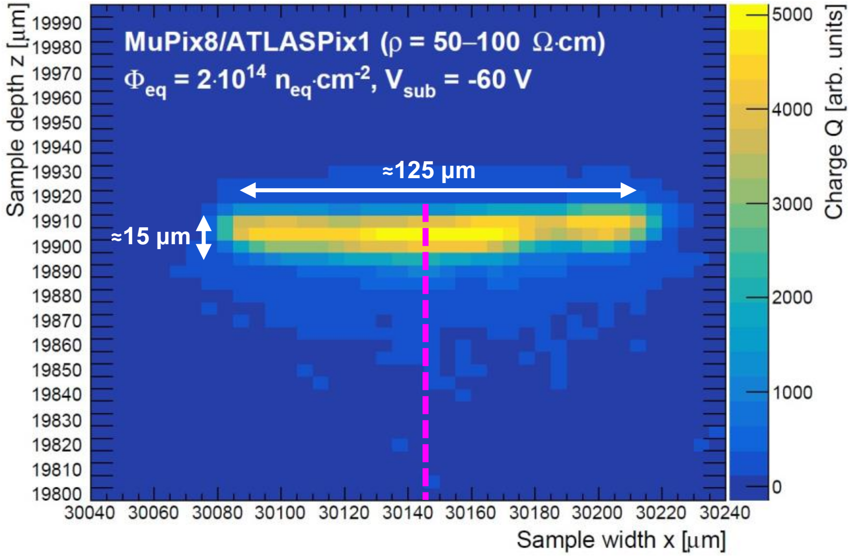


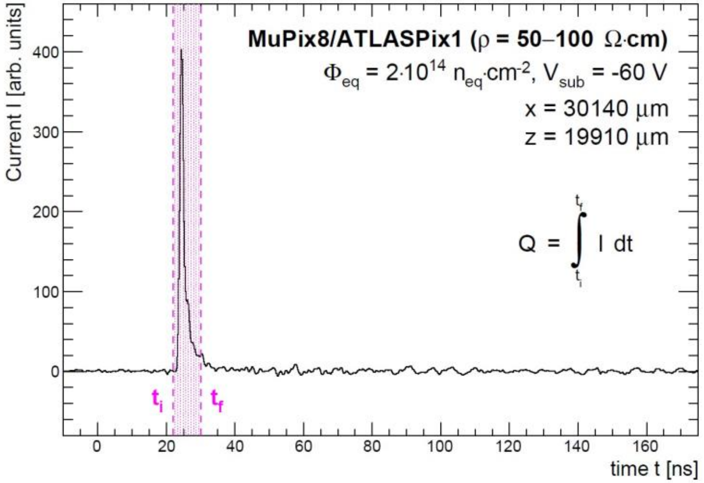
- Particulars Scanning TCT system
- Measurement parameters
    - Collimated, pulsed, infrared laser
    - Beam diameter ≈ 10 µm
- Sample connection scheme
    - Sensing DNTUB = GND
    - P-type substrate = -HV



Edge-TCT measurements x focus finding

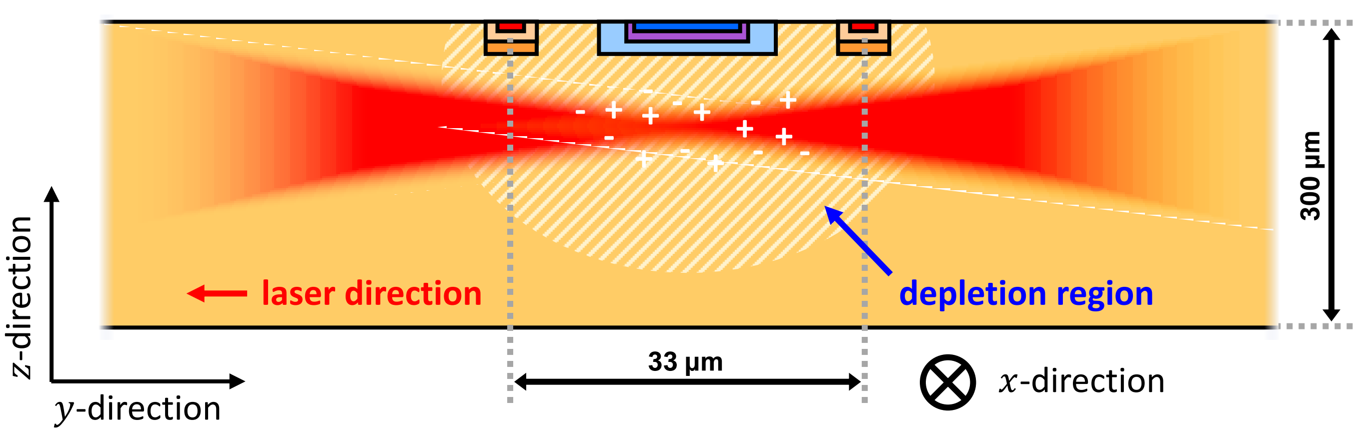


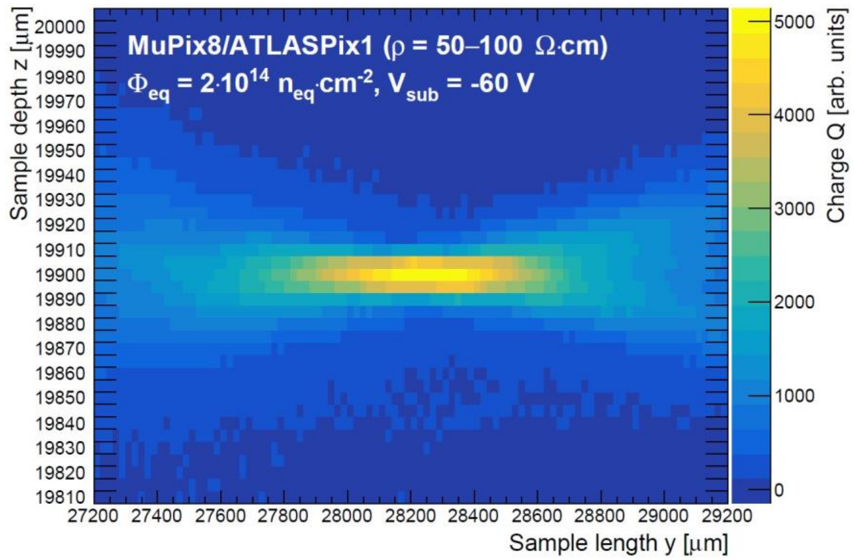


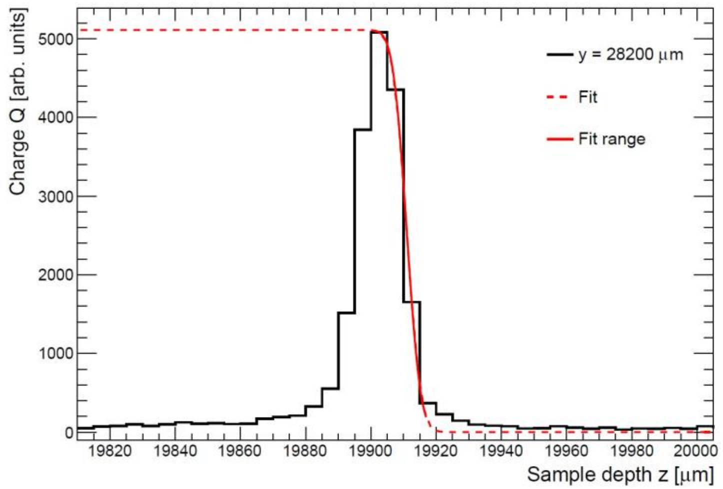


- Fixed parameters
  - Substrate bias voltage V_{sub}
  - Optics to sample distance y
- Step size 5 µm in x and z
- Waveform recorded and integrated at each position
- Centre of the pixel $x_0 \approx 30145$ µm

Knife-edge measurement - y focus finding

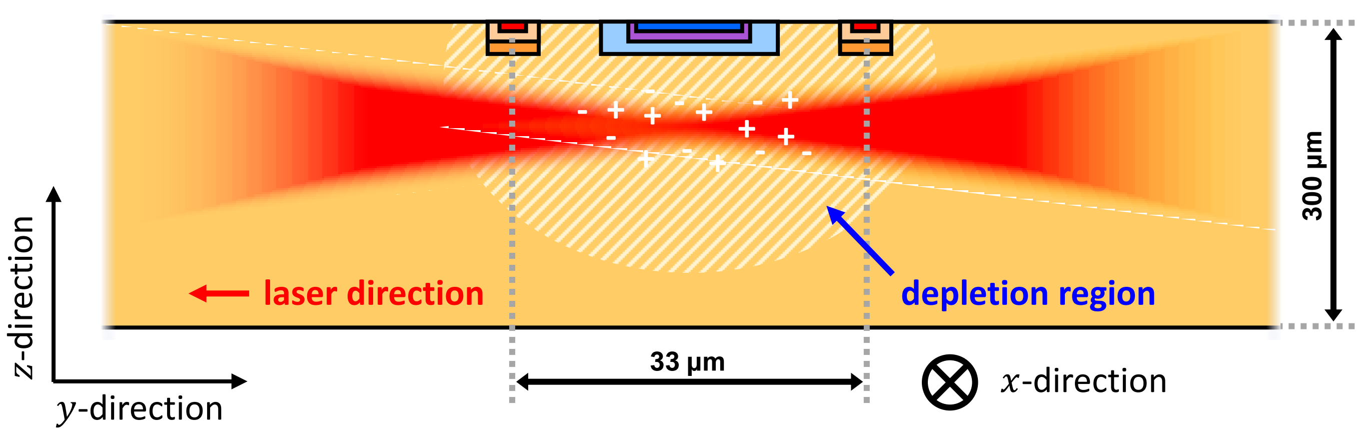


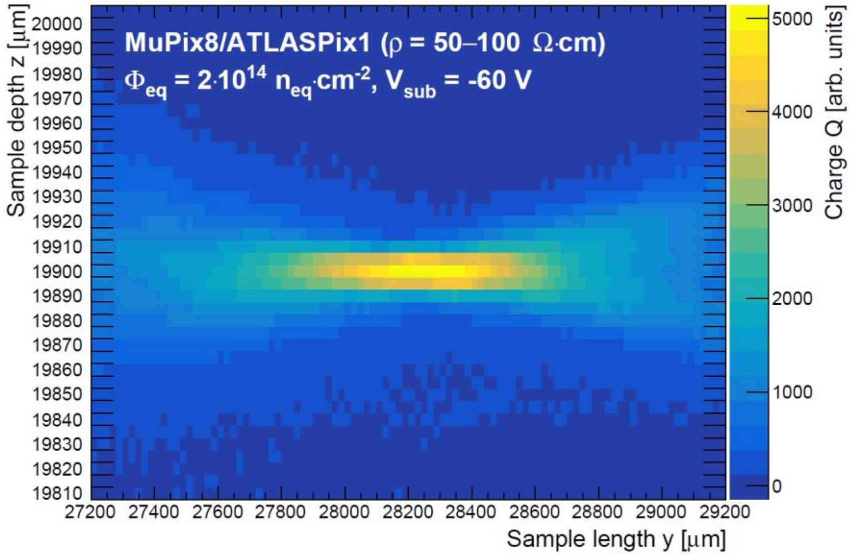




- Fixed parameters
    - Substrate bias voltage V_{sub}
    - Sample width x
- Step size 5 µm in z, 20 µm in y
- Waveform recorded and integrated at each position
- Error function fit to each y

Knife-edge measurement - y focus finding

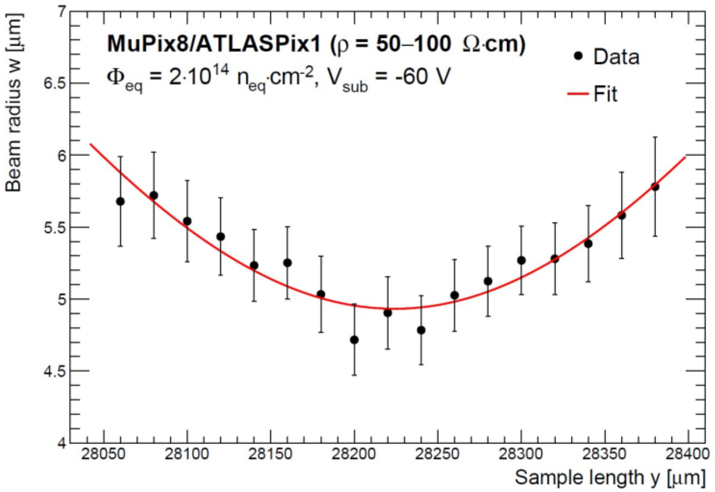


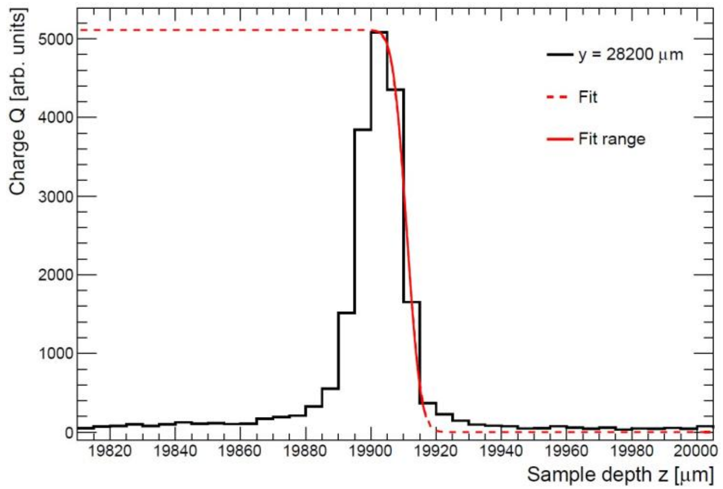


- Assuming gaussian beam:

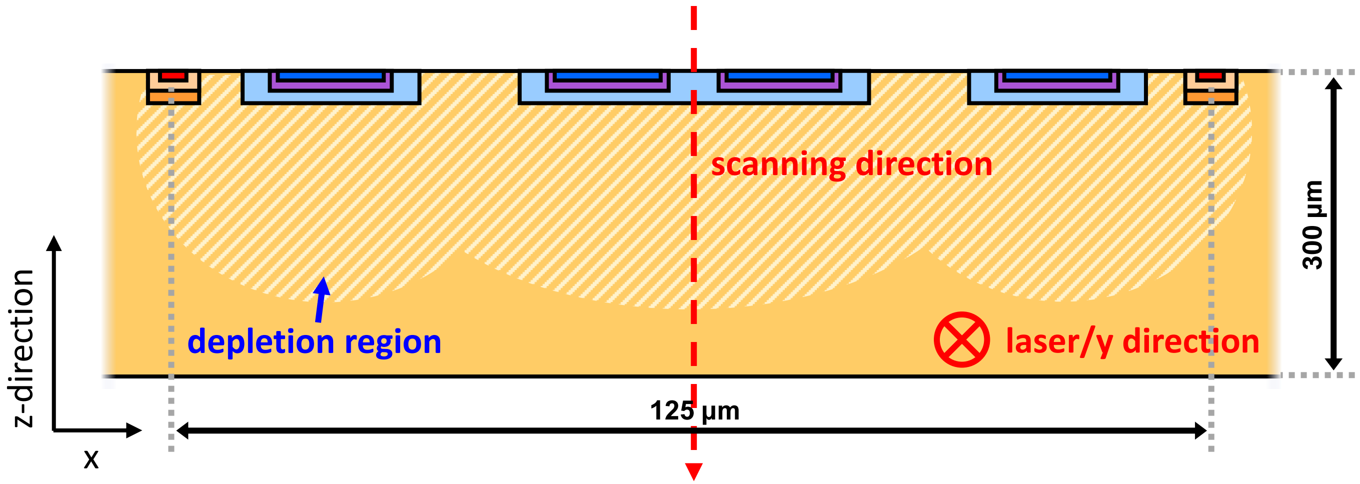
$$w(y) = w_0\sqrt{1+\left(\frac{y-y_0}{y_R}\right)^2}$$

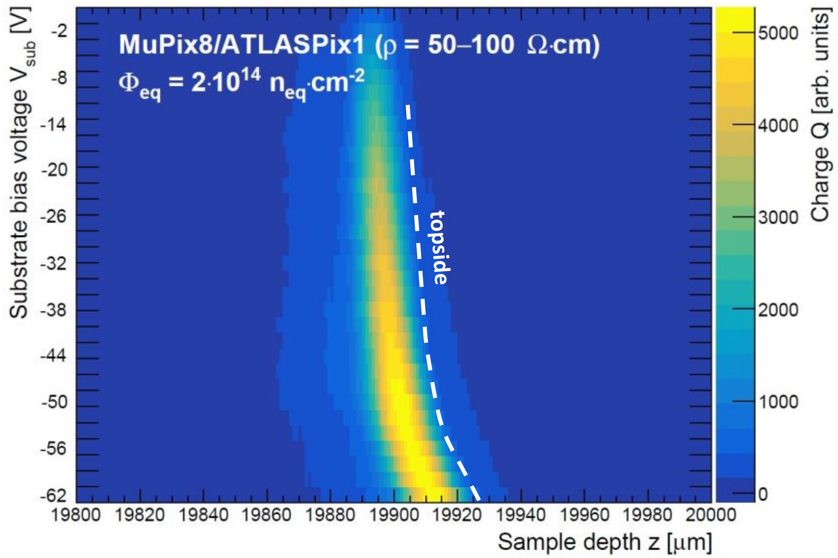
- $y_0 \approx 28220$ µm extracted from fit

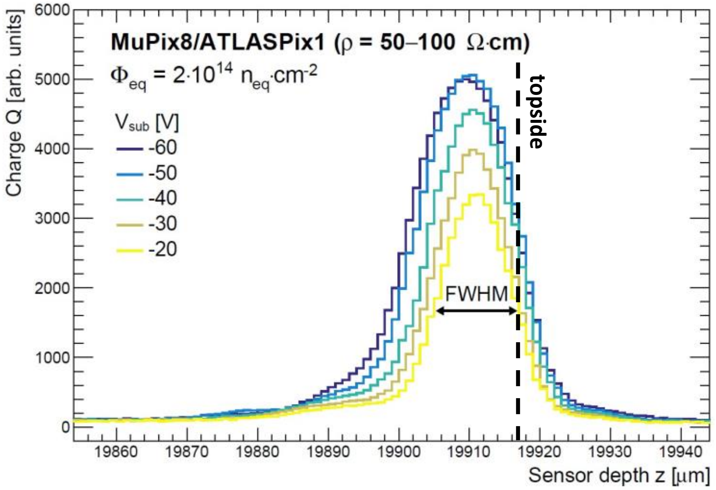




Edge-TCT measurements

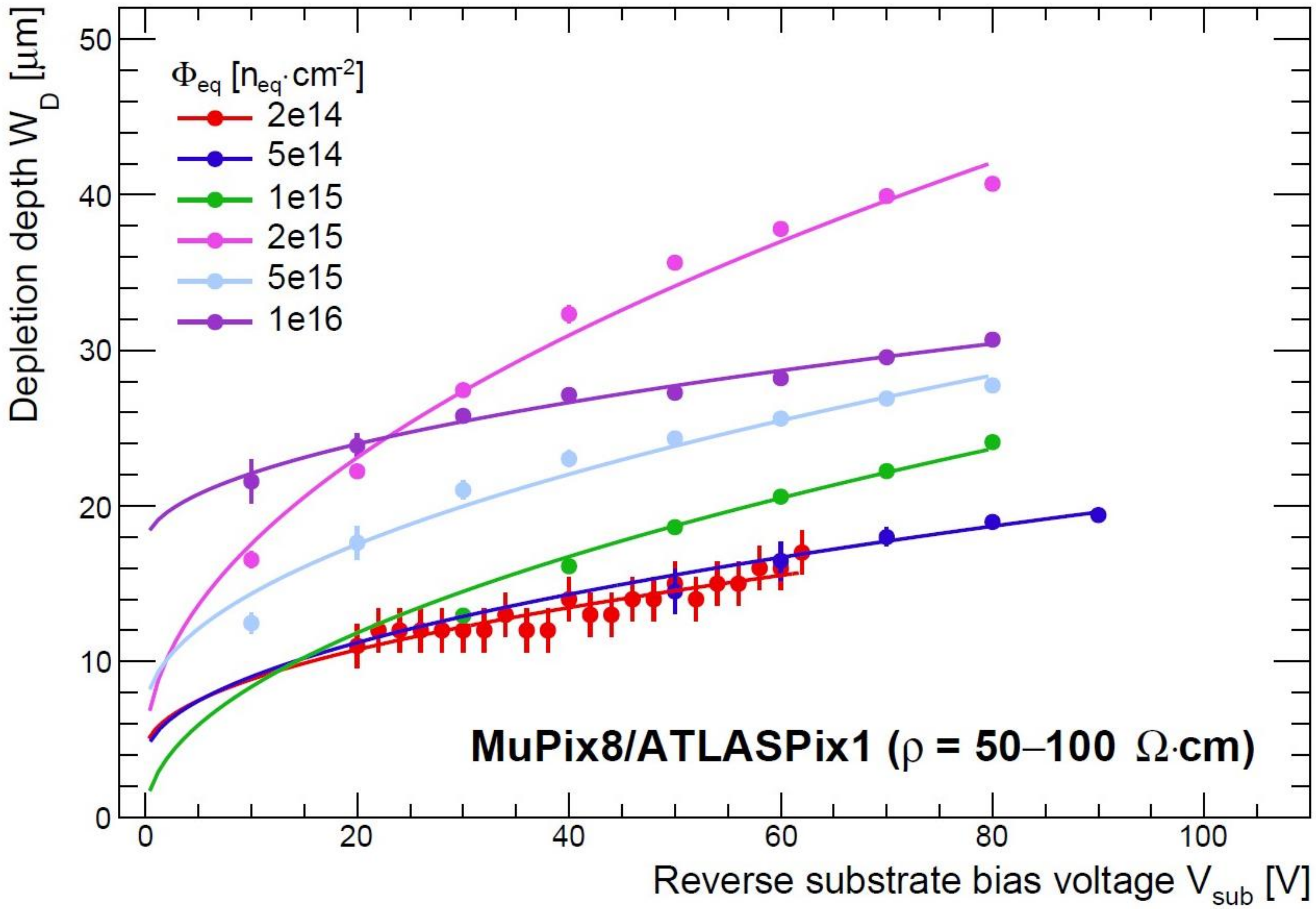






- Fixed parameters
  - Sample width x
  - Optics to sample distance y
- Step size 1 µm in z, 2 V in V_{sub}
- Waveform recorded and integrated at each position
- Depletion depth W_D estimated from FWHM of charge collection profiles

MuPix8/ATLASPix1 W1 $W_D(V_{sub})$ measurements



Fits:

$$W_D = W_{D_0} + \sqrt{\frac{2\varepsilon_{Si}\varepsilon_0}{qN_{eff}}\cdot V_{sub}}$$

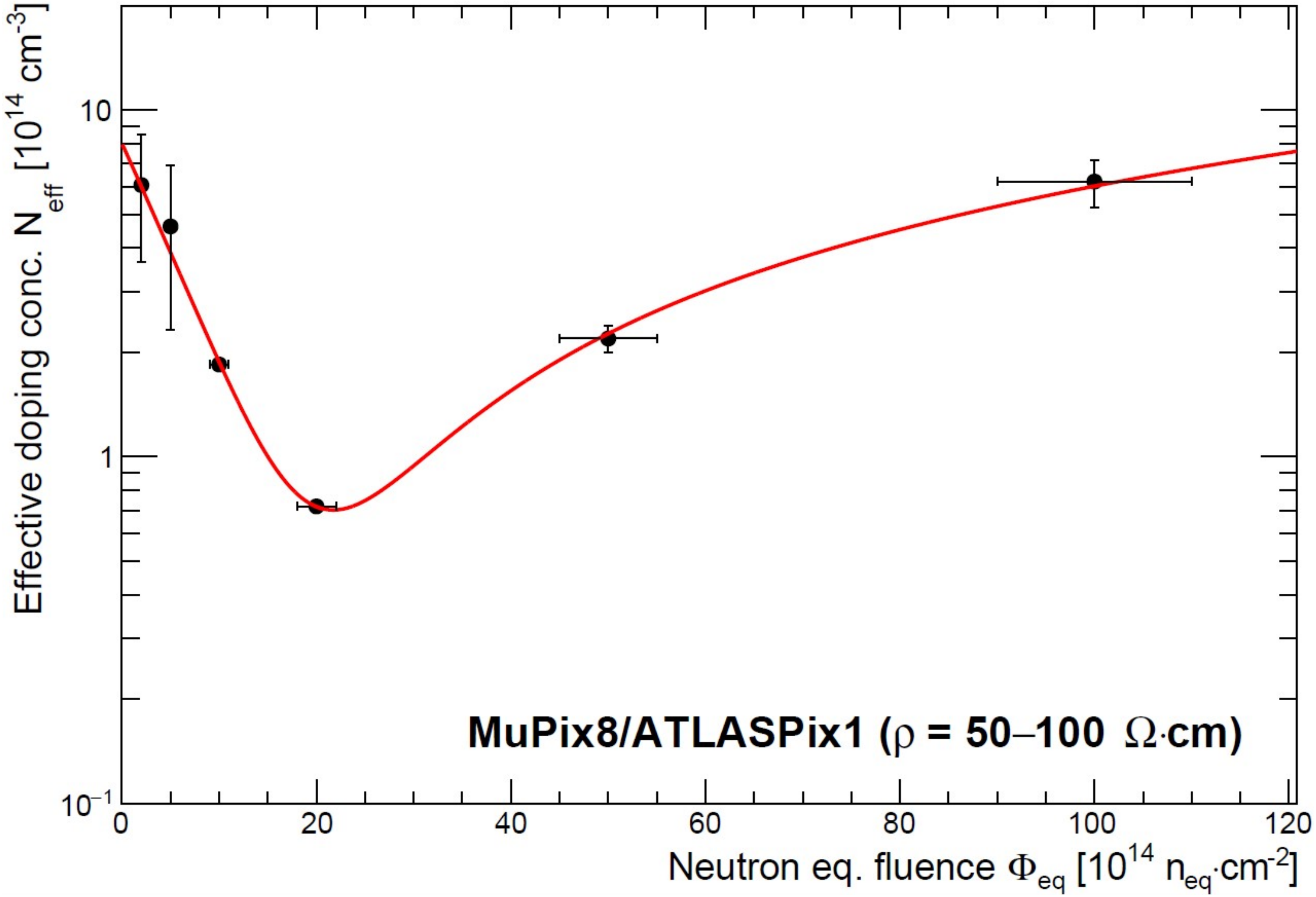
Free parameters:

W_{D_0} =	Parameter to describe collected charge measured at V_{sub} = 0V
N_{eff} =	Effective doping concentration

Constants:

ε_0 =	Permittivity of free space
ε_{Si} =	Relative permittivity of silicon
e_0 =	Elementary charge

MuPix8/ATLASPix1 W1 $N_{\mathrm{eff}}(\Phi_{\mathrm{eq}})$



$$N_{\mathrm{eff}}(\Phi_{\mathrm{eq}}) = N_{\mathrm{eff}_0} - N_c\left(1 - \mathrm{e}^{-c\Phi_{\mathrm{eq}}}\right) + g_c\Phi_{\mathrm{eq}}$$

Free parameters:

N_{eff_0} =	Effective doping concentration at $\Phi_{\mathrm{eq}} = 0$
N_c =	Concentration of acceptors that have been removed
c =	Acceptor removal constant
g_c=	Stable damage introduction rate

	W1
N_{eff_0} $[10^{14}\ \mathrm{cm}^{-3}]$	8.02 ± 3.15
N_c $[10^{14}\ \mathrm{cm}^{-3}]$	9.55 ± 2.45
c $[10^{-14}\ \mathrm{cm}^{2}]$	0.13 ± 0.05
g_c $[\mathrm{cm}^{-1}]$	0.08 ± 0.02

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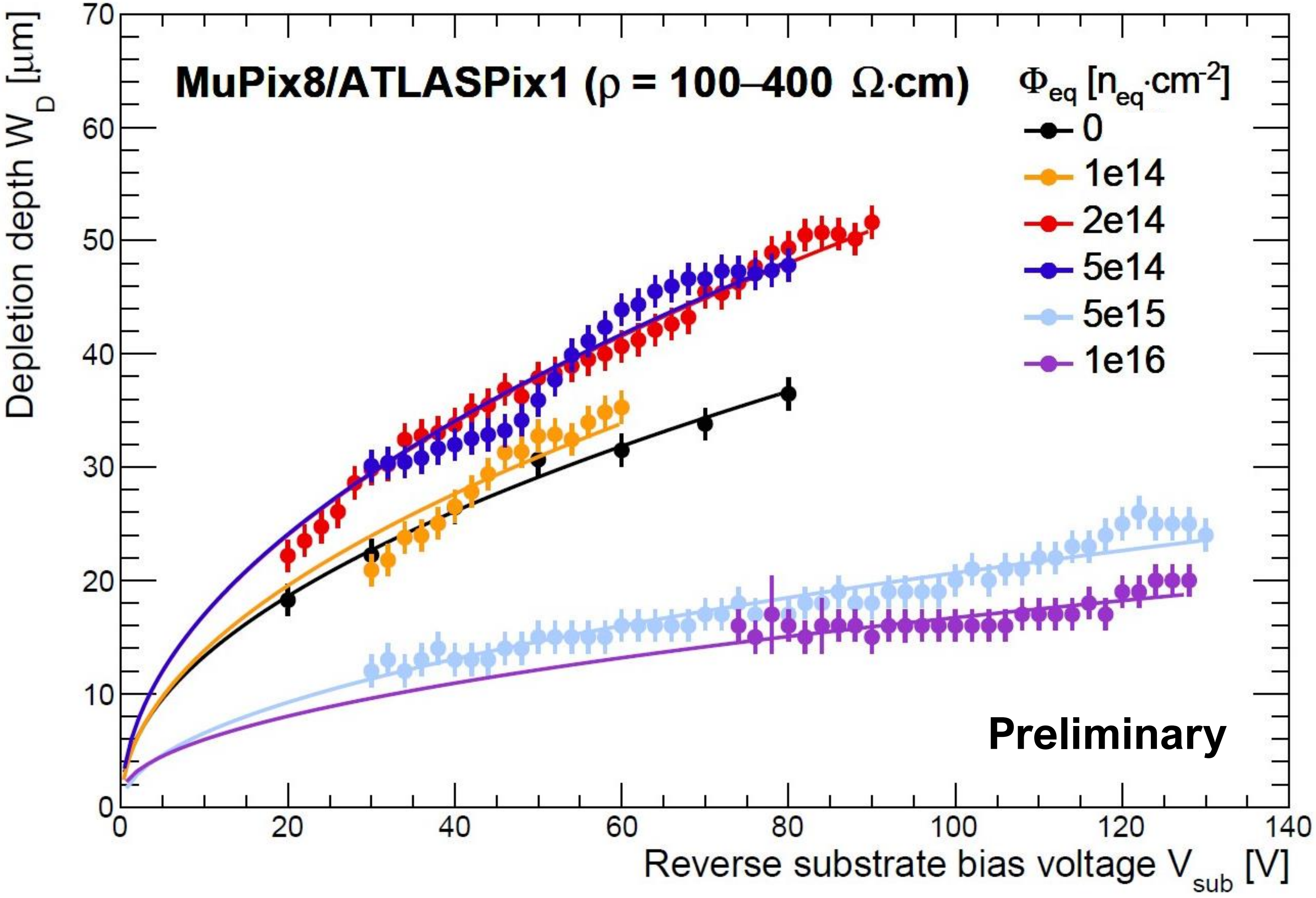
MuPix8/ATLASPix1 W2 $W_D(V_{sub})$



Fits:

$$W_D = W_{D_0} + \sqrt{\frac{2\varepsilon_{Si}\varepsilon_0}{qN_{eff}} \cdot V_{sub}}$$

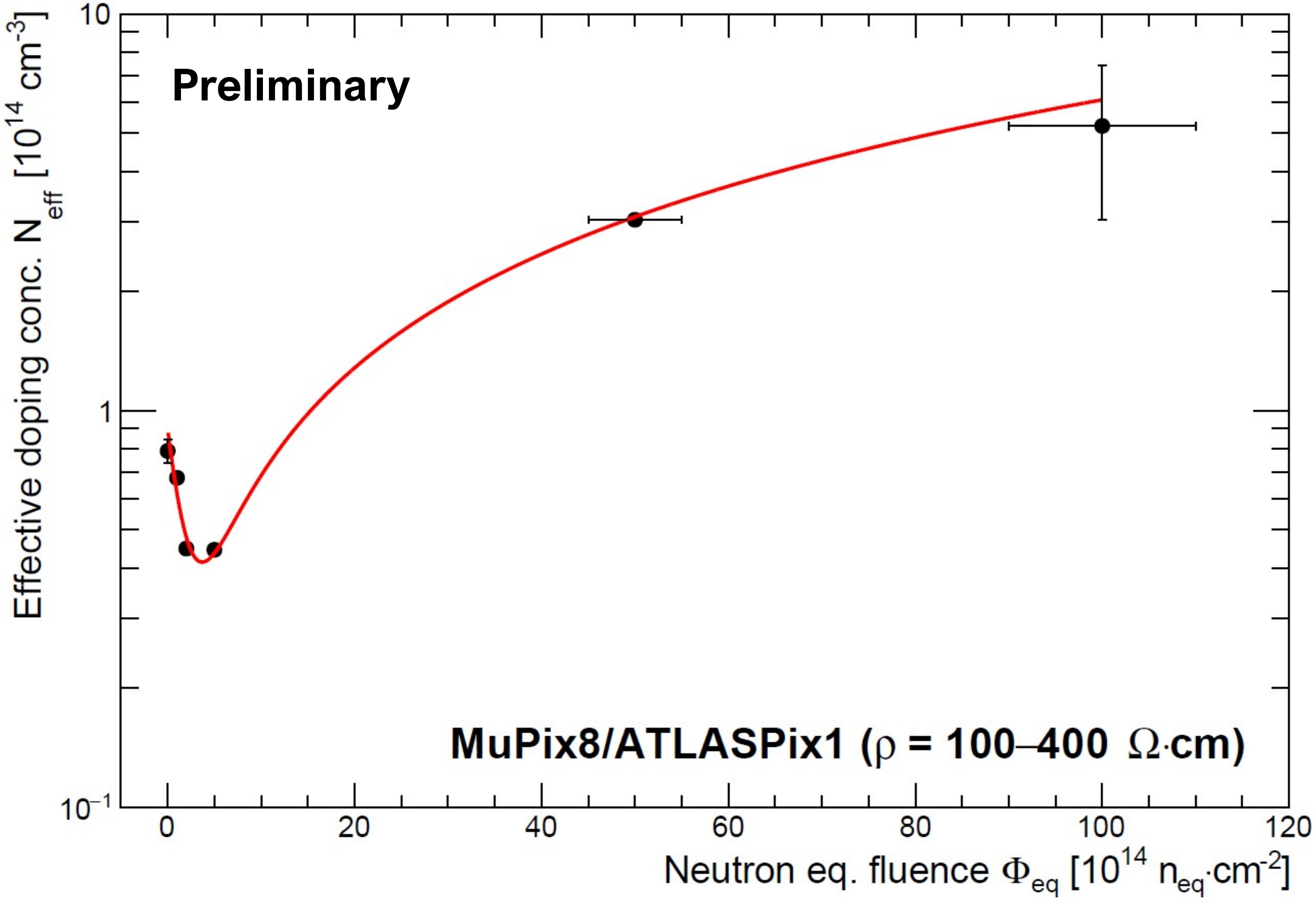
Free parameters:

W_{D_0} = Parameter to describe collected charge measured at V_{sub} = 0V

N_{eff} = Effective doping concentration

Wafer	N_{eff_0} [10^{14} cm^{-3}]	ρ [Ω·cm]	Nominal ρ [Ω·cm]
W1	8.02 ± 3.15	16.8 ± 6.6	50–100
W2	0.79 ± 0.05	168.3 ± 11.7	100–400

MuPix8/ATLASPix1 W2 $N_{\text{eff}}(\Phi_{\text{eq}})$



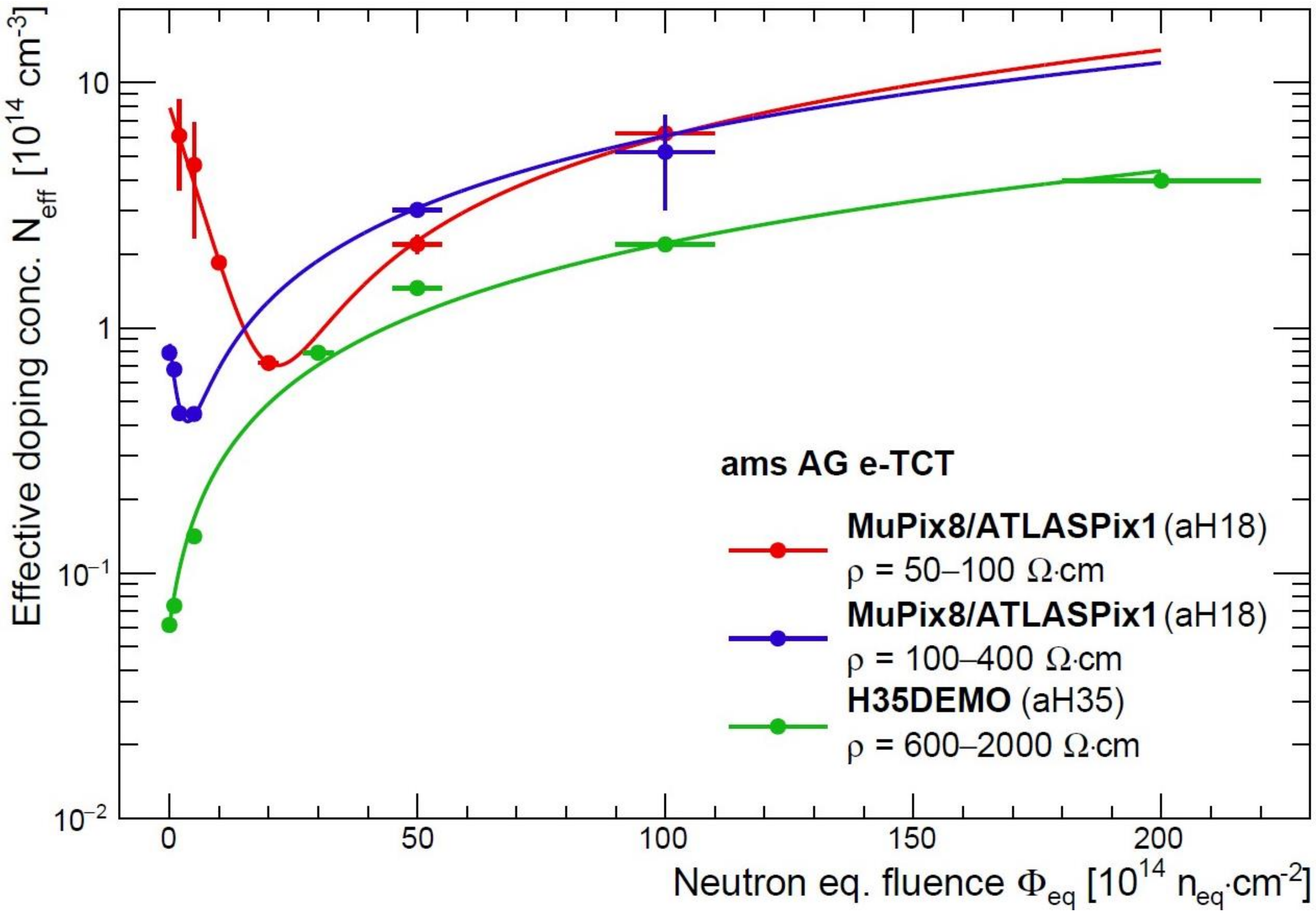
$$N_{\text{eff}}(\Phi_{\text{eq}}) = N_{\text{eff}_0} - N_c\left(1 - e^{-c\Phi_{\text{eq}}}\right) + g_c\Phi_{\text{eq}}$$

Free parameters:

N_{eff_0} =	Effective doping concentration at $\Phi_{\text{eq}} = 0$
N_c =	Concentration of acceptors that have been removed
c =	Acceptor removal constant
g_c=	Stable damage introduction rate

	W2
N_{eff_0} [10^{14} cm^{-3}]	0.90 ± 0.04
N_c [10^{14} cm^{-3}]	0.82 ± 0.06
c [10^{-14} cm^{2}]	0.54 ± 0.07
g_c [cm^{-1}]	0.06 ± 0.01

MuPix8/ATLASPix1 e-TCT measurements



	W1	W2	H35DEMO
Nominal ρ [Ω·cm]	50—100	100—400	600—2000
ρ [Ω·cm]	16.8 ± 6.6	168.3 ± 11.7	2212 ± 35
N_{eff_0} [10^{14} cm^{-3}]	8.02 ± 3.15	0.90 ± 0.04	0.060 ± 0.001
N_c [10^{14} cm^{-3}]	9.55 ± 2.45	0.82 ± 0.06	-
c [10^{-14} cm^2]	0.13 ± 0.05	0.54 ± 0.07	-
g_c [cm^{-1}]	0.08 ± 0.02	0.06 ± 0.01	0.022 ± 0.001

Summary

Aim: Study the radiation tolerance of ams AG aH18 technology

- **MuPix8/ATLASPix1 W1** (**50–100 Ω·cm**), topside biased
  - Irradiated with neutrons at TRIGA (1e14 < Φeq < 1e16 $n_{eq}\cdot cm^{-2}$)
  - I-V & E-TCT measurements
  - Calculated resistivity was lower than the nominal values
- **MuPix8/ATLASPix1 W2** (**100–400 Ω·cm**), backside biased
  - Backside processed wafer
  - Irradiated with neutrons at TRIGA (0 < Φeq < 1e16 $n_{eq}\cdot cm^{-2}$)
  - I-V & E-TCT measurements
  - Calculated resistivity was within tolerances