Characterisation of Neutron-Irradiated Deep Diffused APDs

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31st RD50 Workshop, CERN

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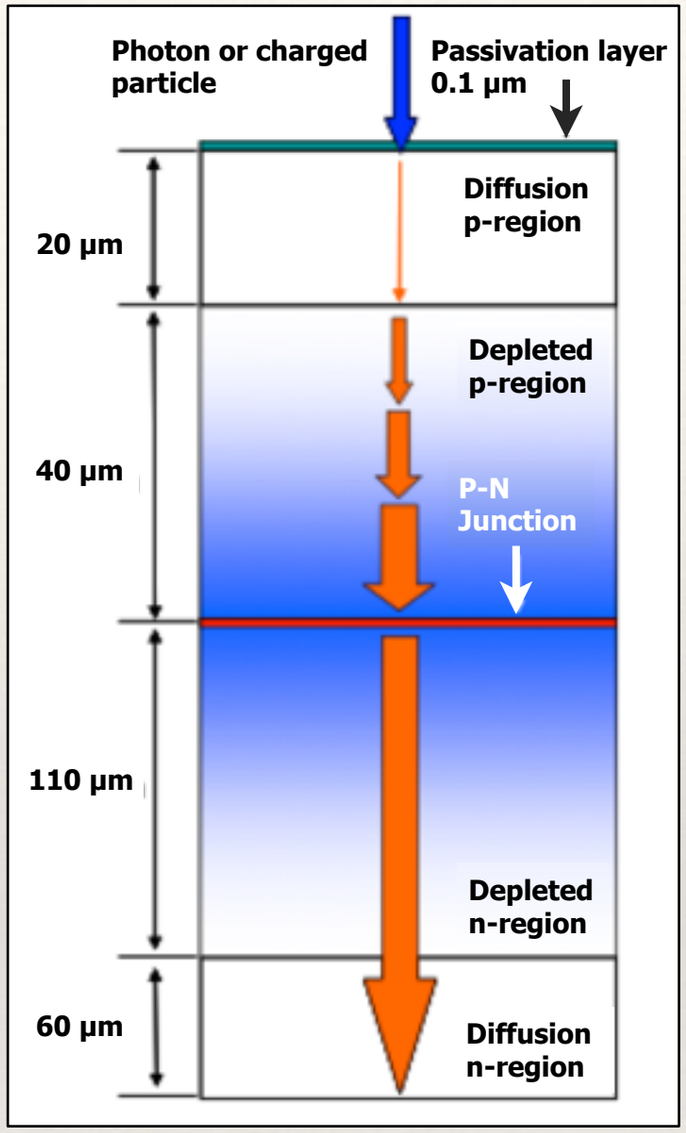
Samples and Irradiation Campaign

Deep Diffused APDs (DD-APDs).

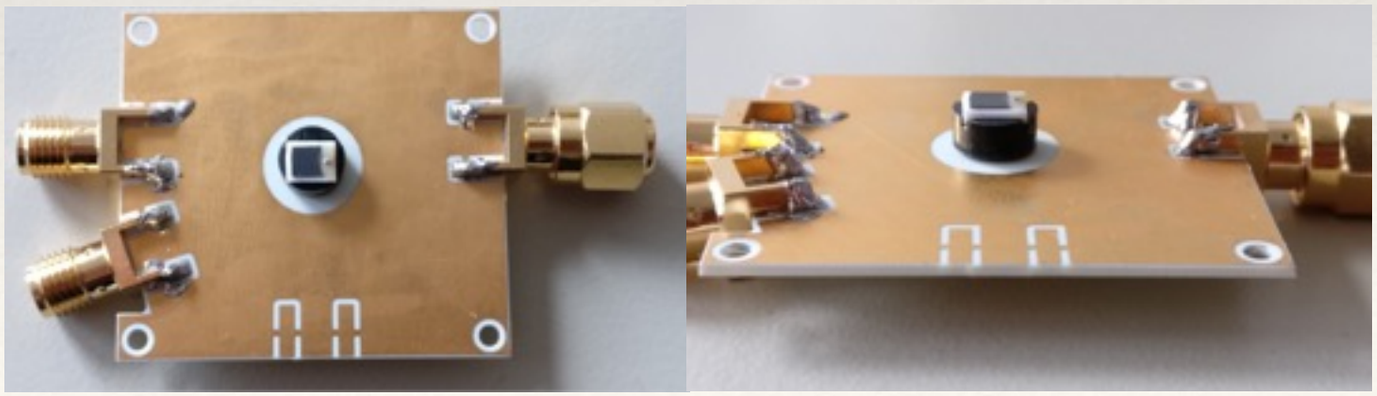
- Manufactured by RMD.
- Amplification deep inside the bulk of the sensor.
- Requires high voltage (1700 V - 1800 V).
- Delivers high gain and fast response time

See M. Centis Vignali, 31st RD50 Workshop.



8 devices.

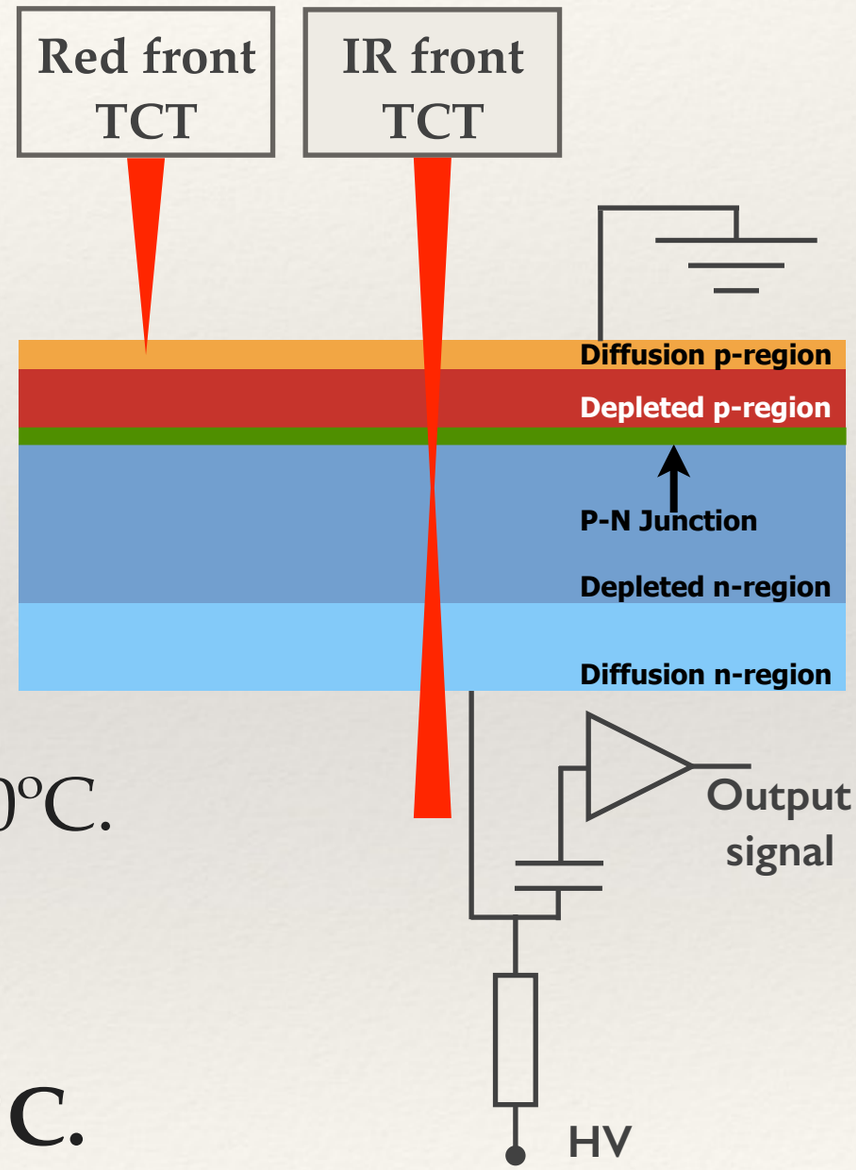
- Sent to Ljubljana for neutron irradiation.
- 2 samples per fluence.
  - $3x10^{13}$ n/cm^2.
  - $6x10^{13}$ n/cm^2.
  - $3x10^{14}$ n/cm^2.
  - $1x10^{15}$ n/cm^2.



Measurements

Before and after irradiation for all samples.

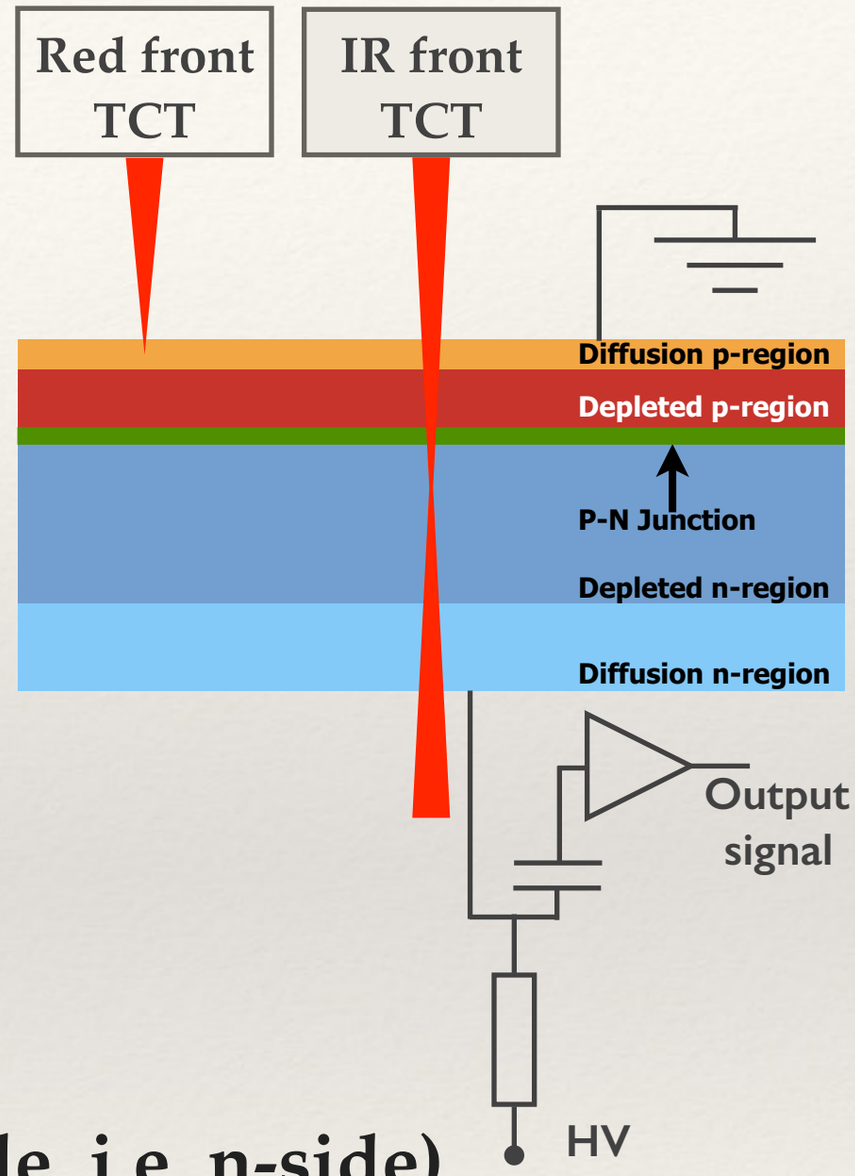
- **Transient Current Technique (TCT).**
  - **XY scans.**
    - Red and IR front illumination.
  - **Voltage scans.**
    - Red and IR front illumination.
  - All TCT measurements were done at -20ºC.
- **CV at -20°C.**
- **IV at 20°C, 10°C, 0°C, -10°C, and -20°C.**



TCT Measurements

Transient Current Technique (TCT)

- **Temperature -20°C.**
- **10 dB effective amplification.**
  - 40 dB CIVIDEC amplifier.
    - Linearity range: ± 1 V output.
  - 30 dB attenuator (before amplifier).
- **Laser intensities (peak power):**
  - Red ≈ 87 μW.
  - IR ≈ 129 μW.
- **Read-out and biasing from the back (cathode, i.e. n-side).**
  - Customised bias T (C = 4.4 nF; R = 1 MΩ).
- **Compliance set to 10 μA.**



Homogeneity Analysis

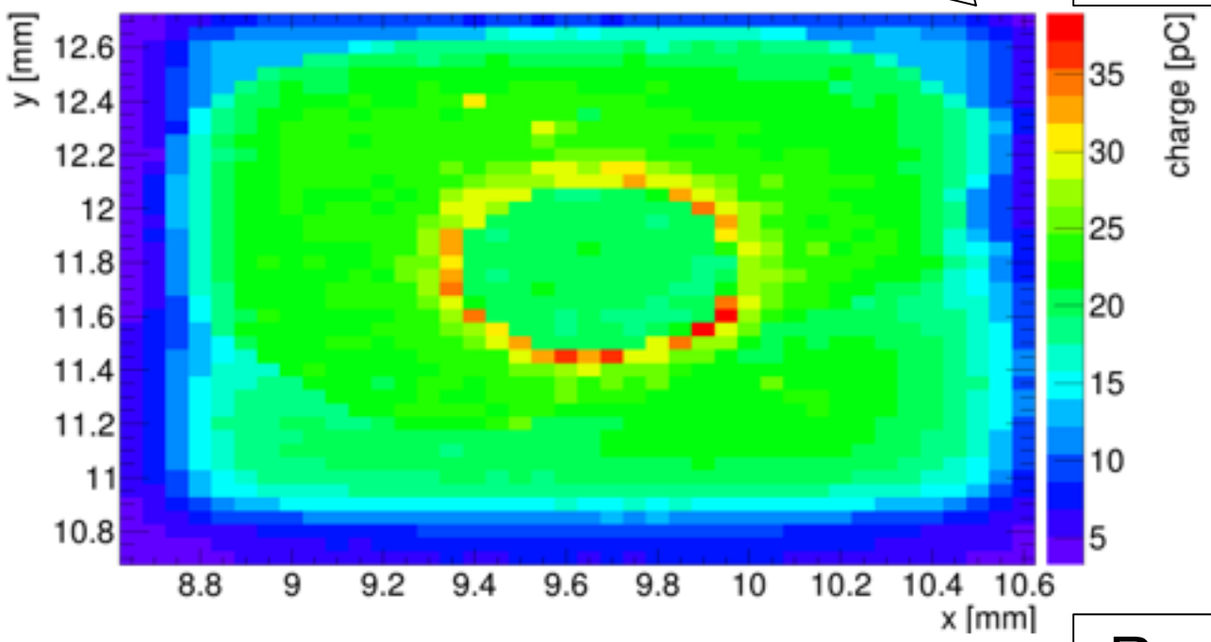
Charge collection XY scans

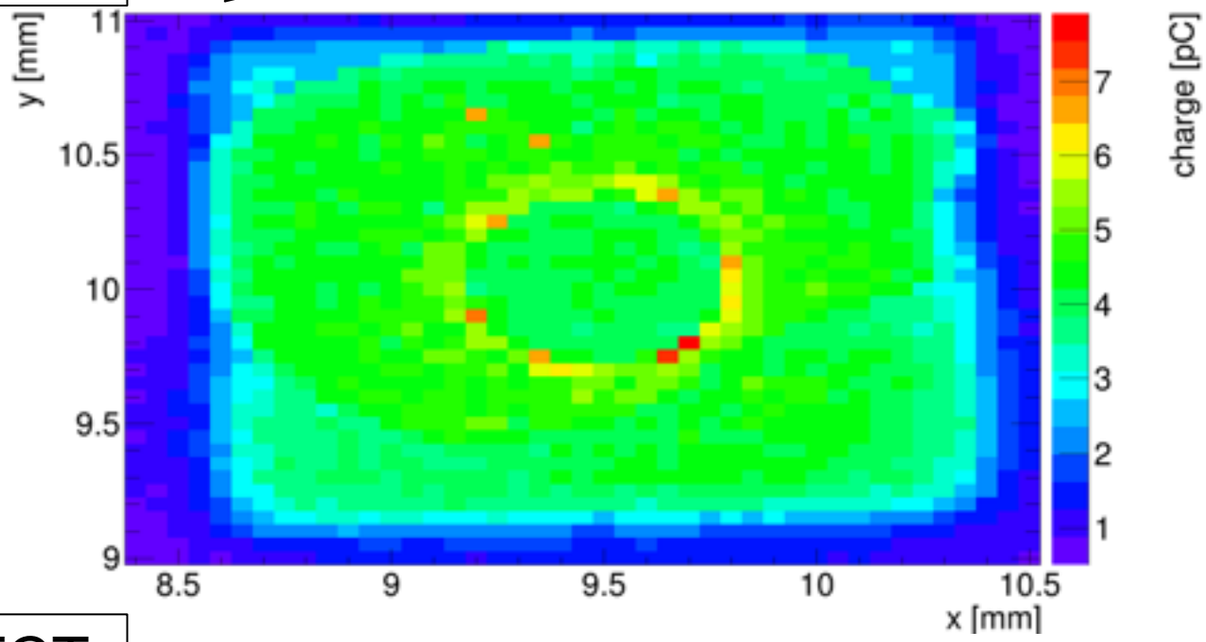
XY scans at 1700 V, -20°C

Before irradiation

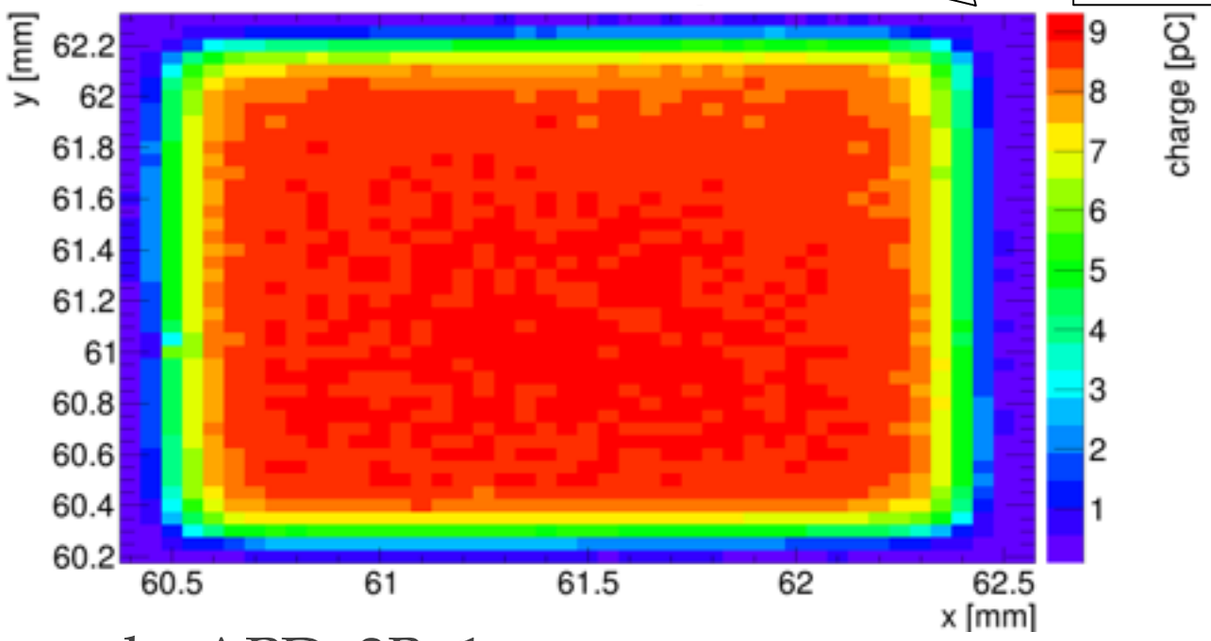
After irradiation 3×10^{13} n/cm^2

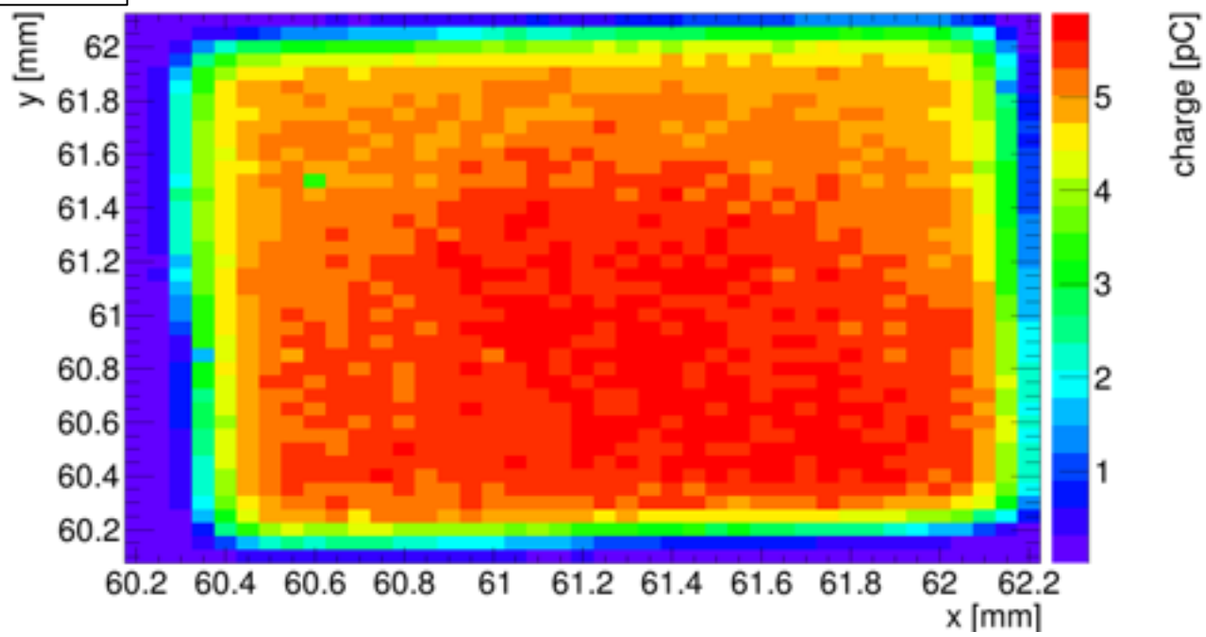
IR TCT





Red TCT





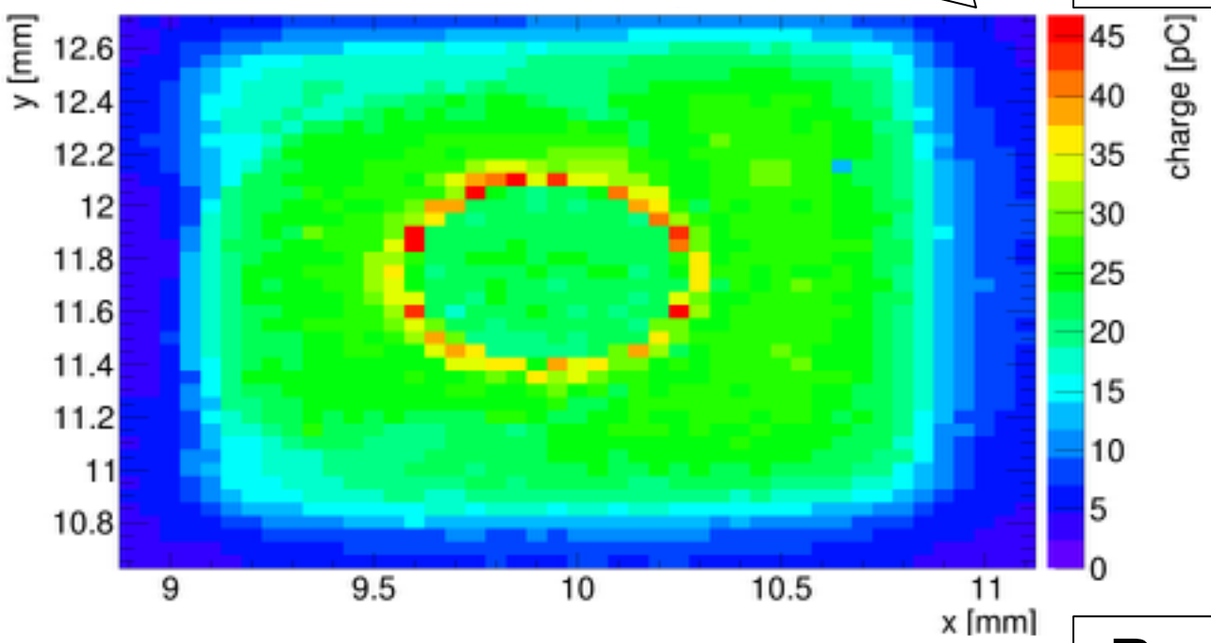
Sample: APD_2B_1

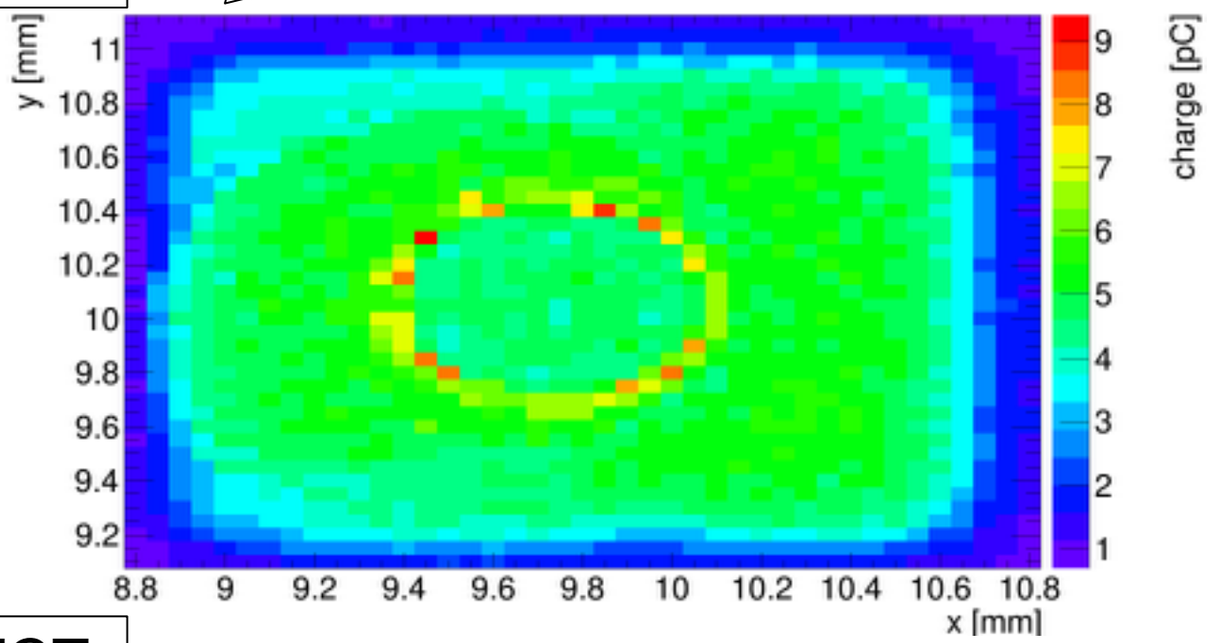
XY scans at 1700 V, -20°C

Before irradiation

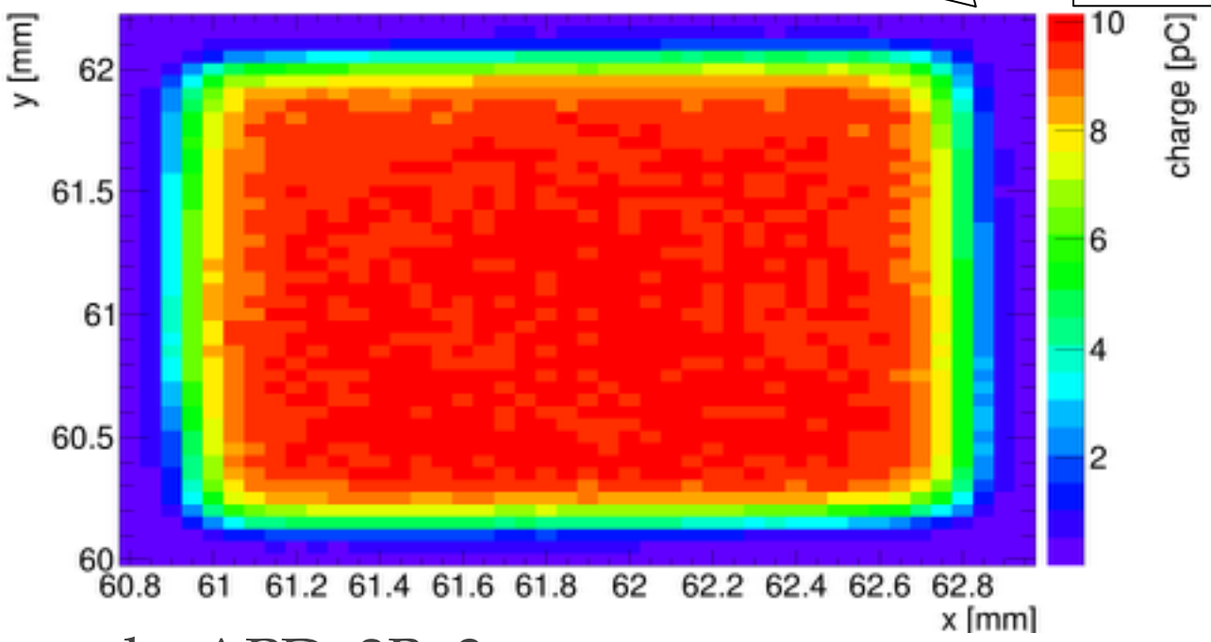
After irradiation 3×10^{13} n/cm^2

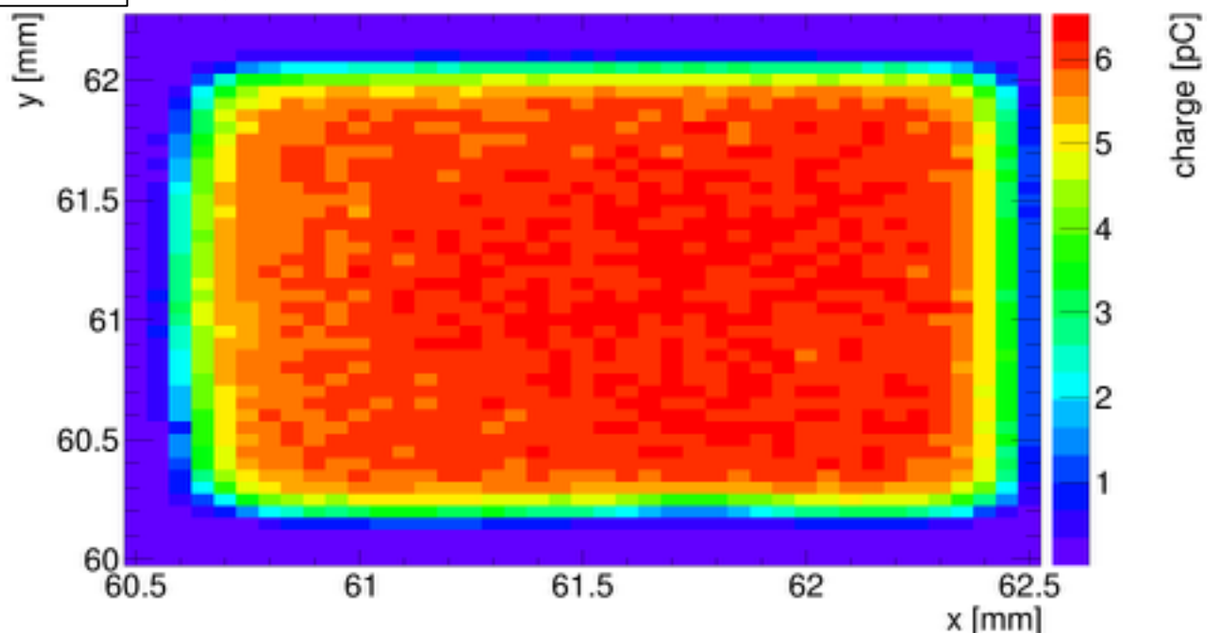
IR TCT





Red TCT





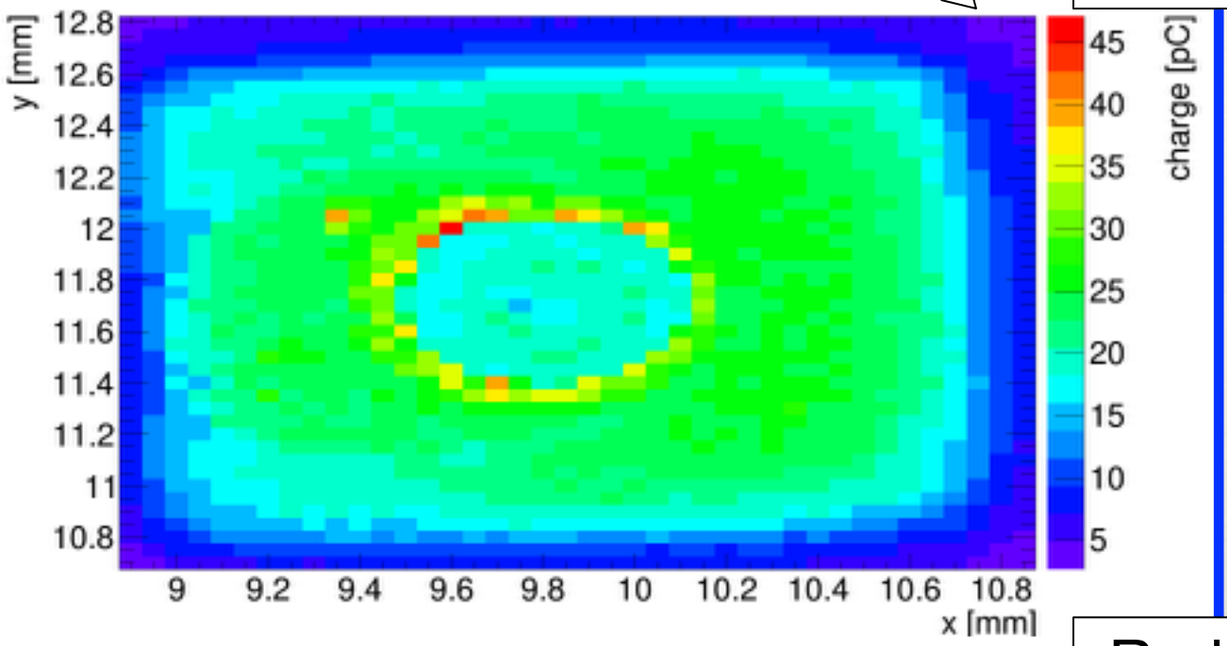
Sample: APD_2B_3

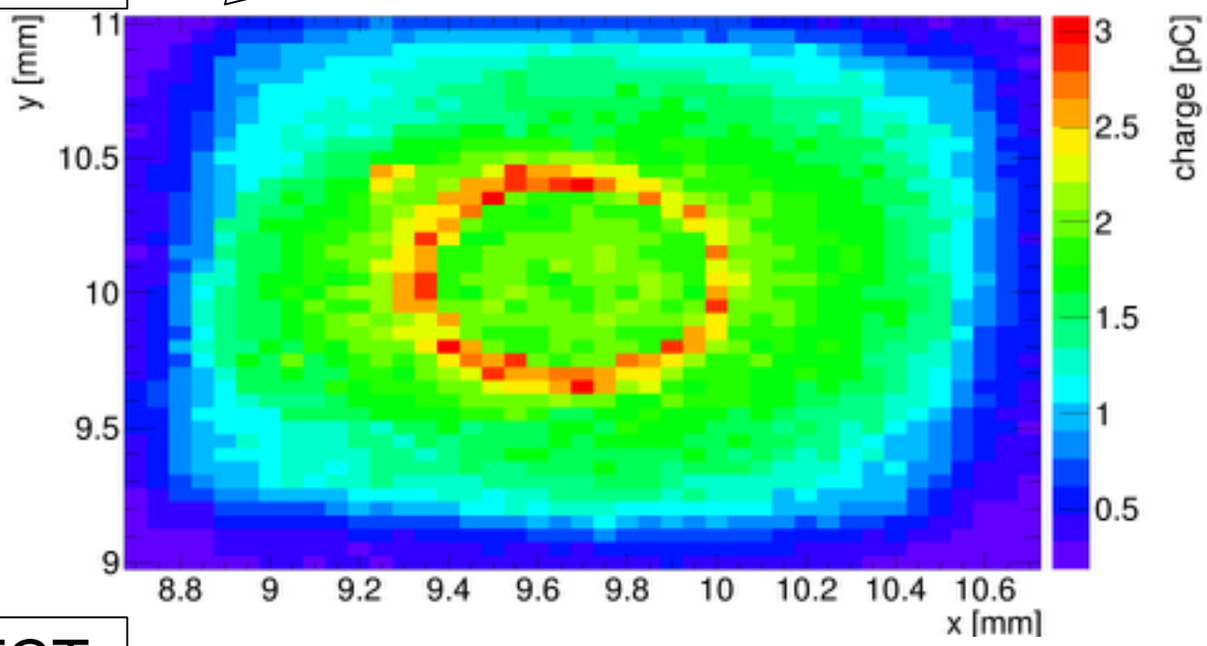
XY scans at 1700 V, -20°C

Before irradiation

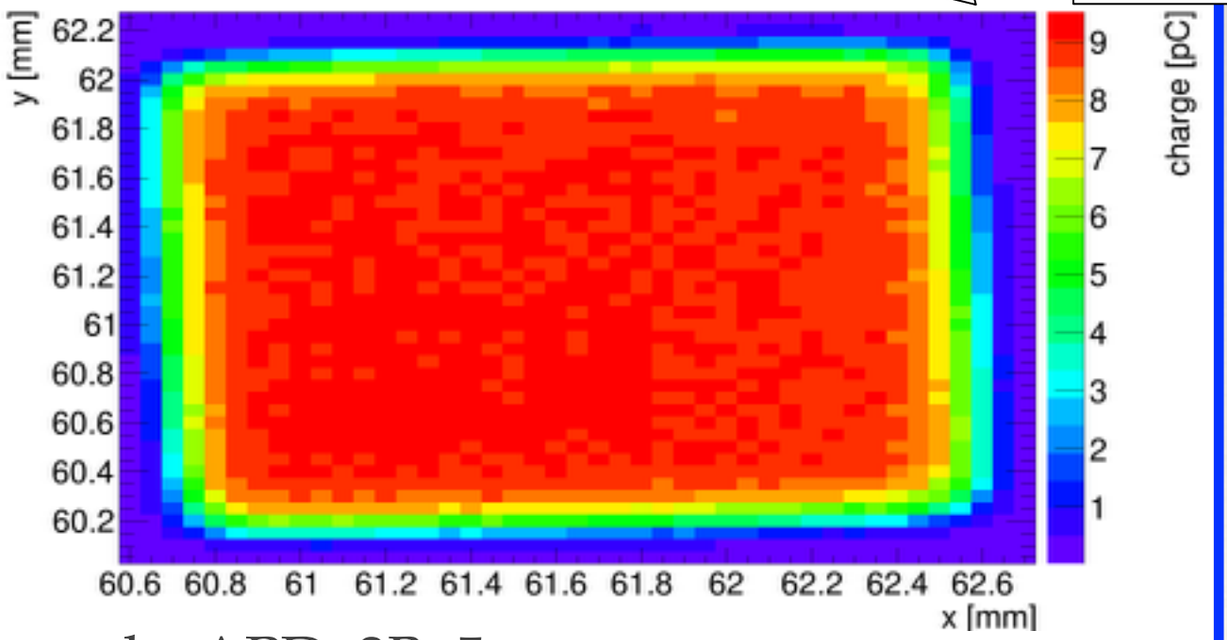
After irradiation 6×10^{13} n/cm^2

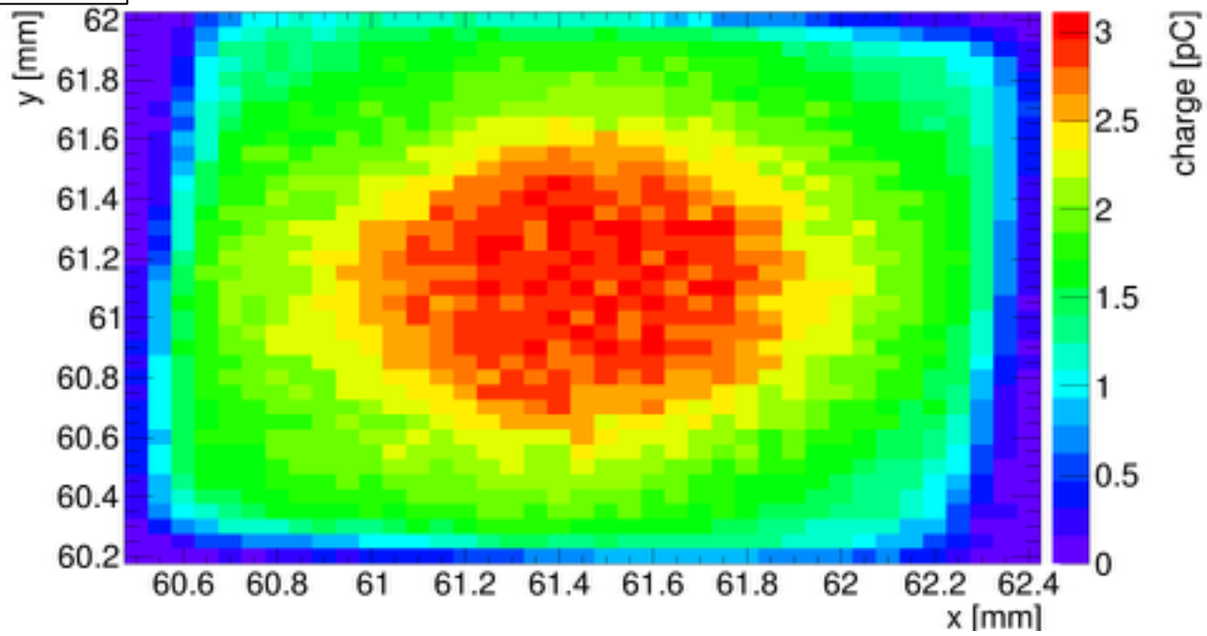
IR TCT





Red TCT





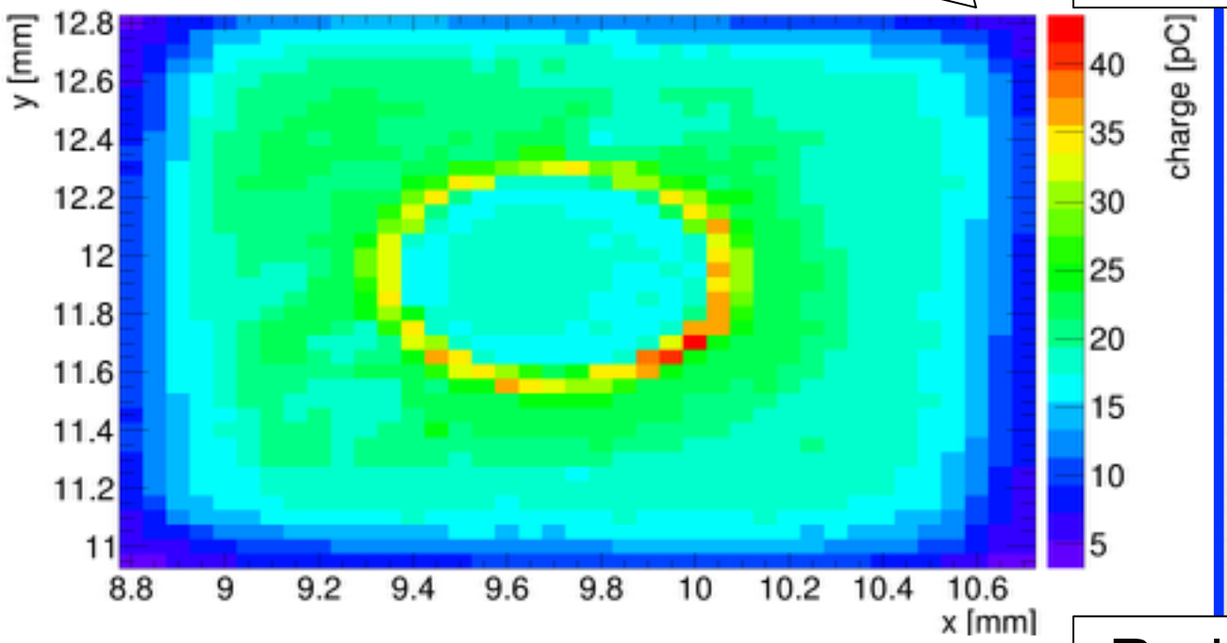
Sample: APD_2B_5

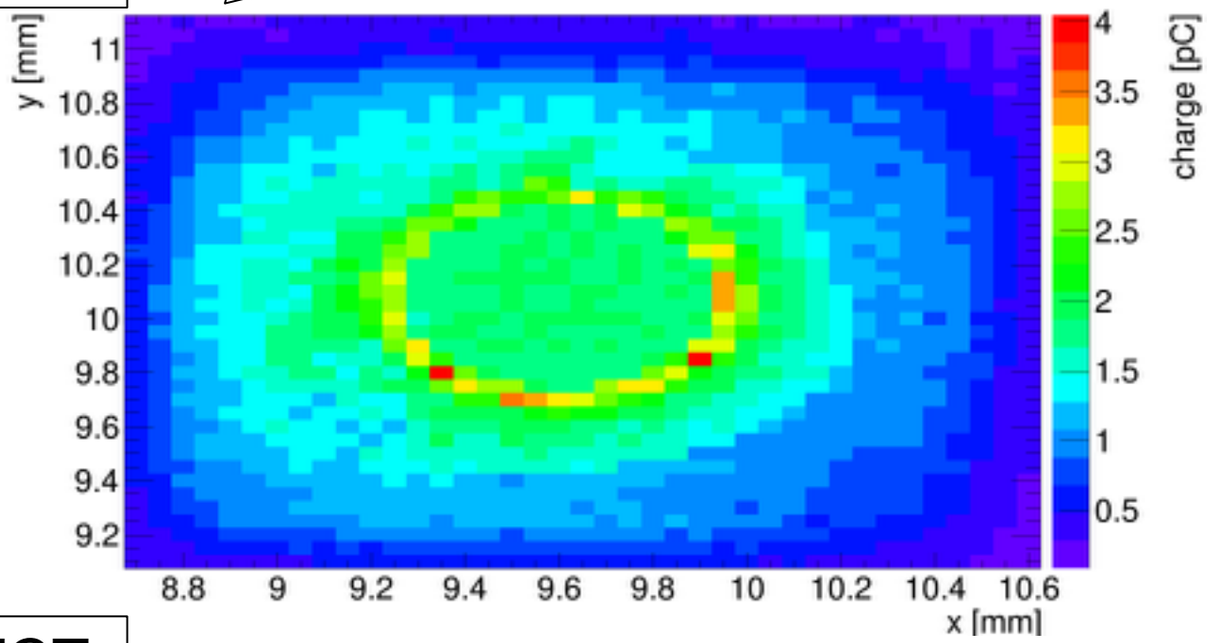
XY scans at 1700 V, -20°C

Before irradiation

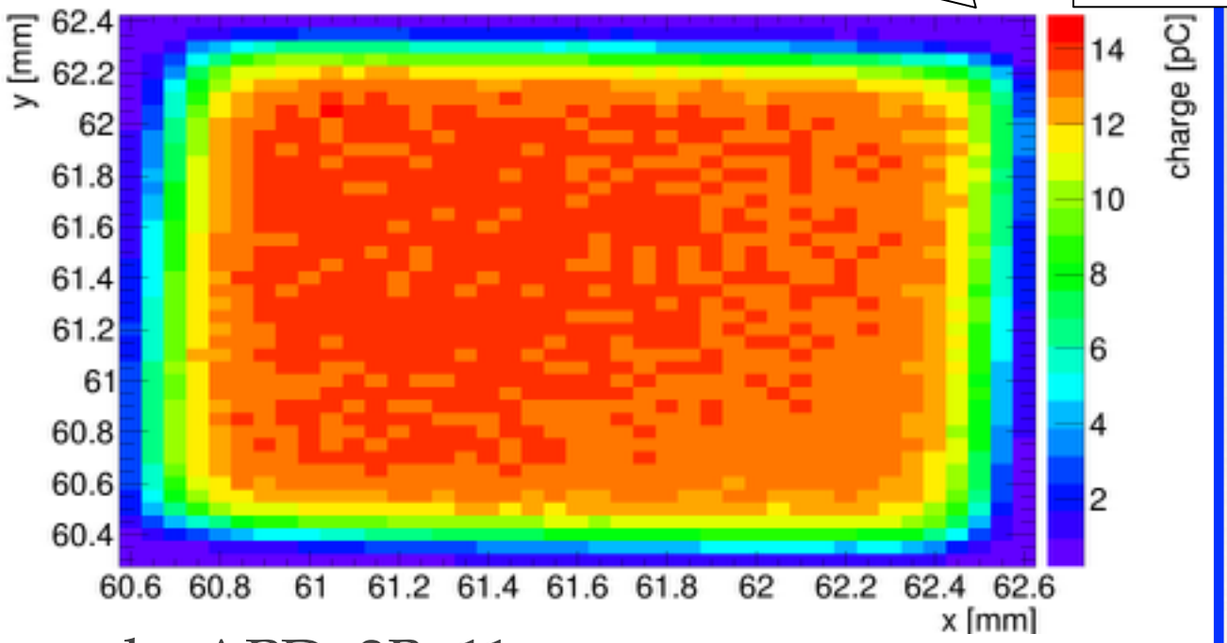
After irradiation 6×10^{13} n/cm^2

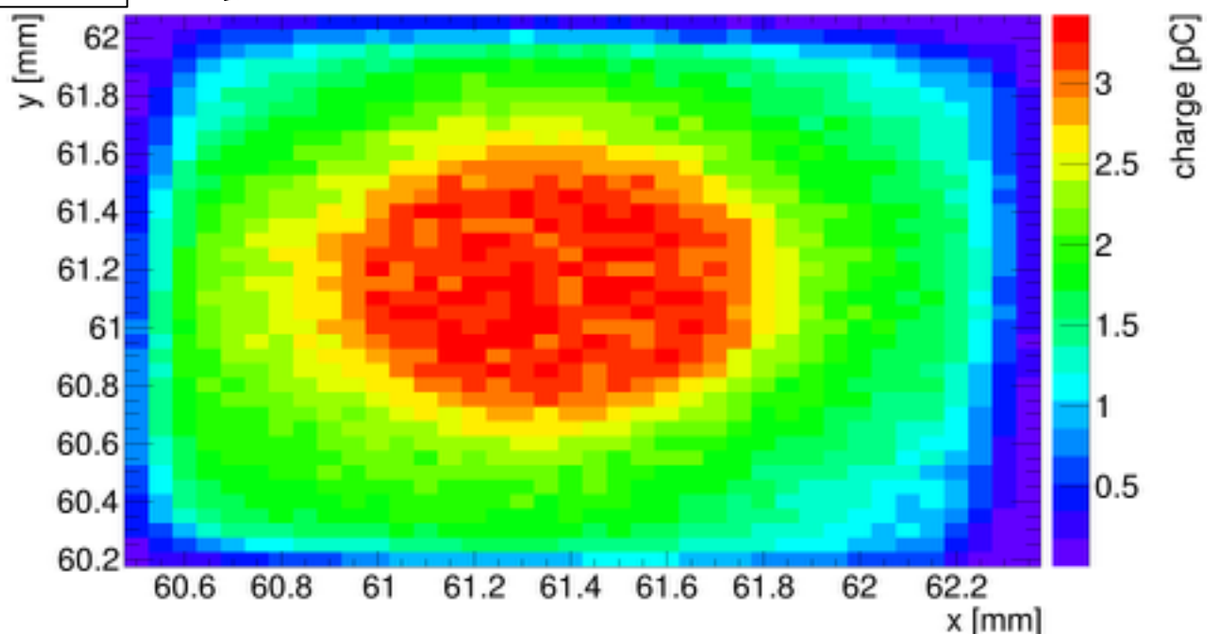
IR TCT





Red TCT



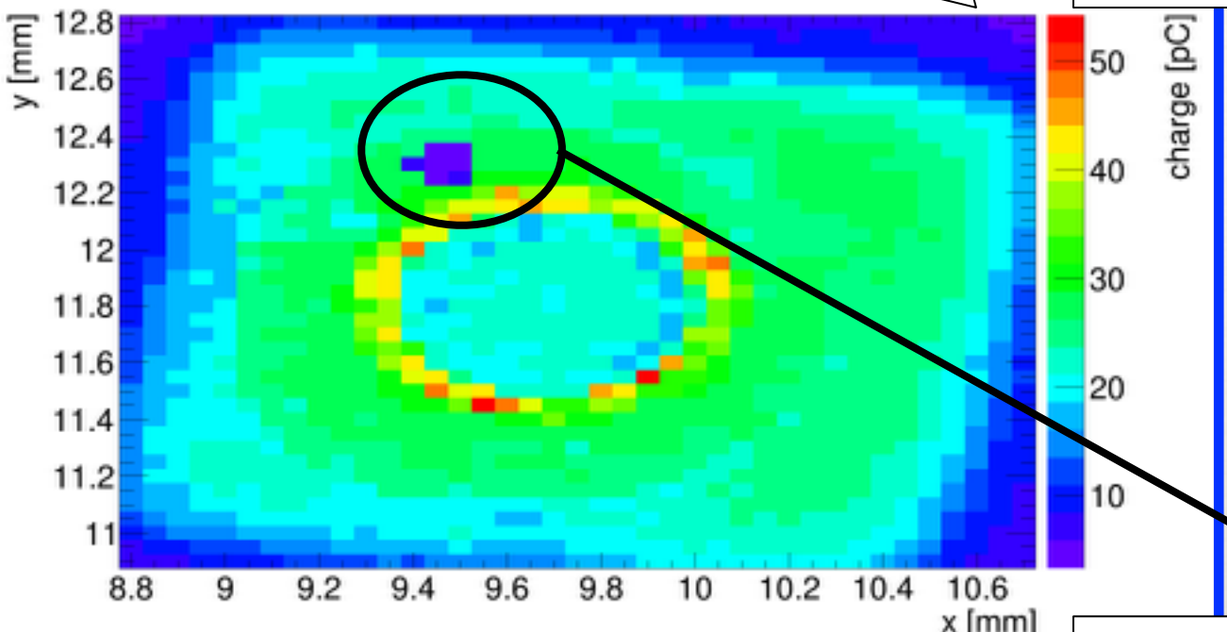


Sample: APD_2B_11

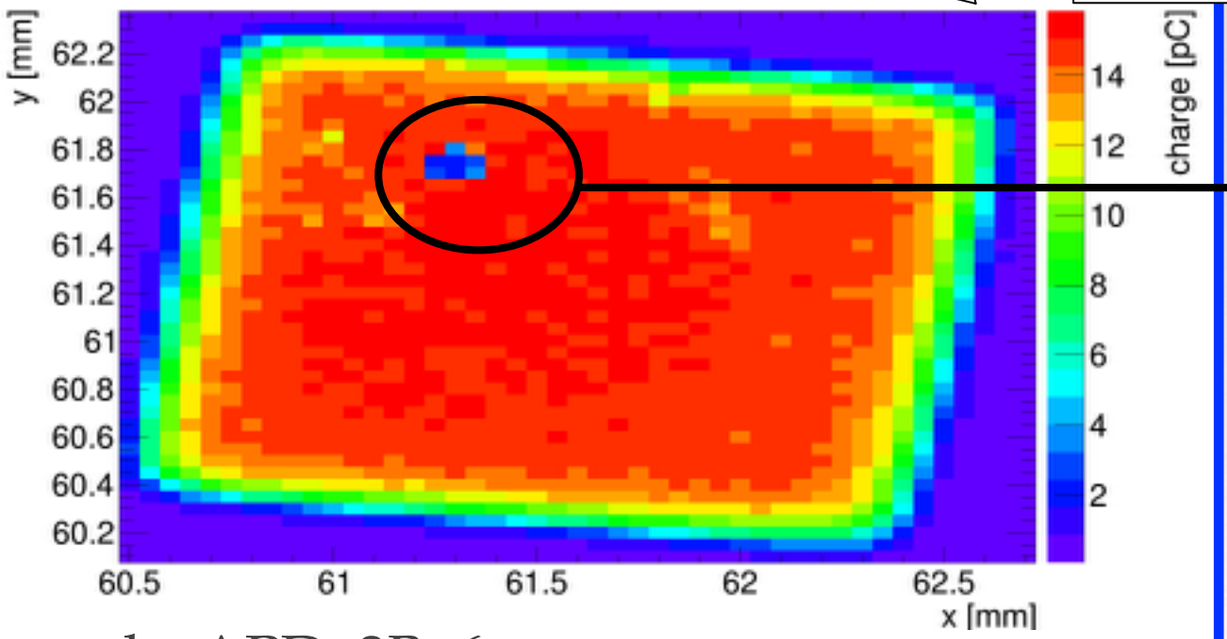
XY scans at 1700 V, -20°C

Before irradiation

IR TCT



Red TCT

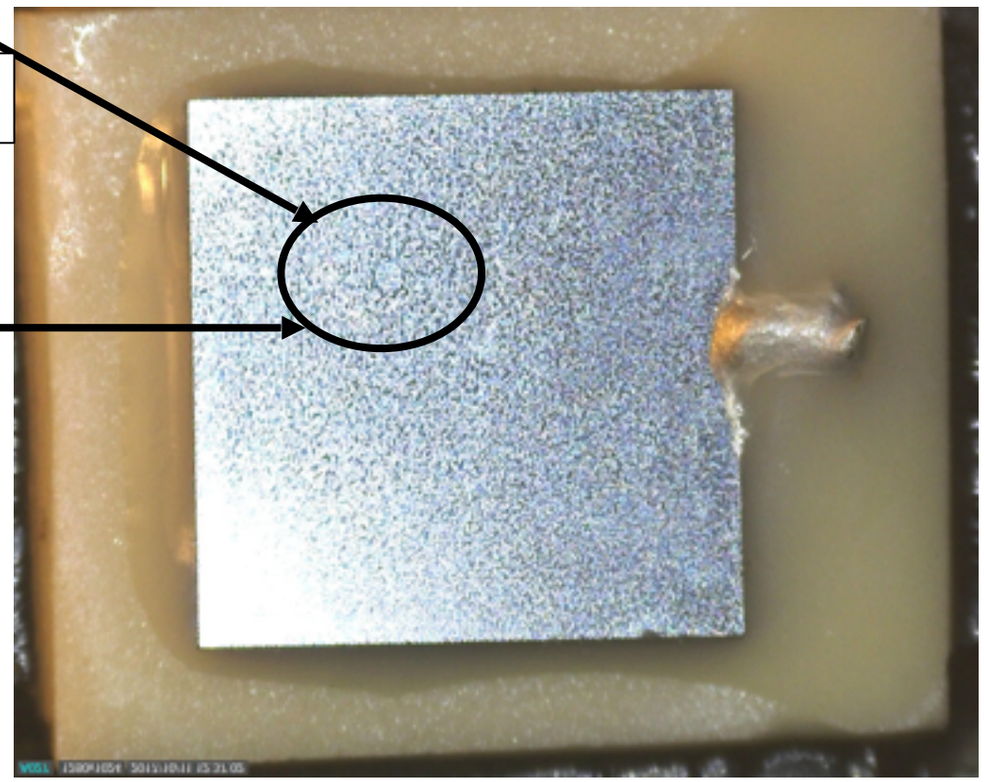


Sample: APD_2B_6

After irradiation 3×10^{14} n/cm^2

Impossible to perform the measurements.

- Leakage current > 1.5 mA at 7 V.

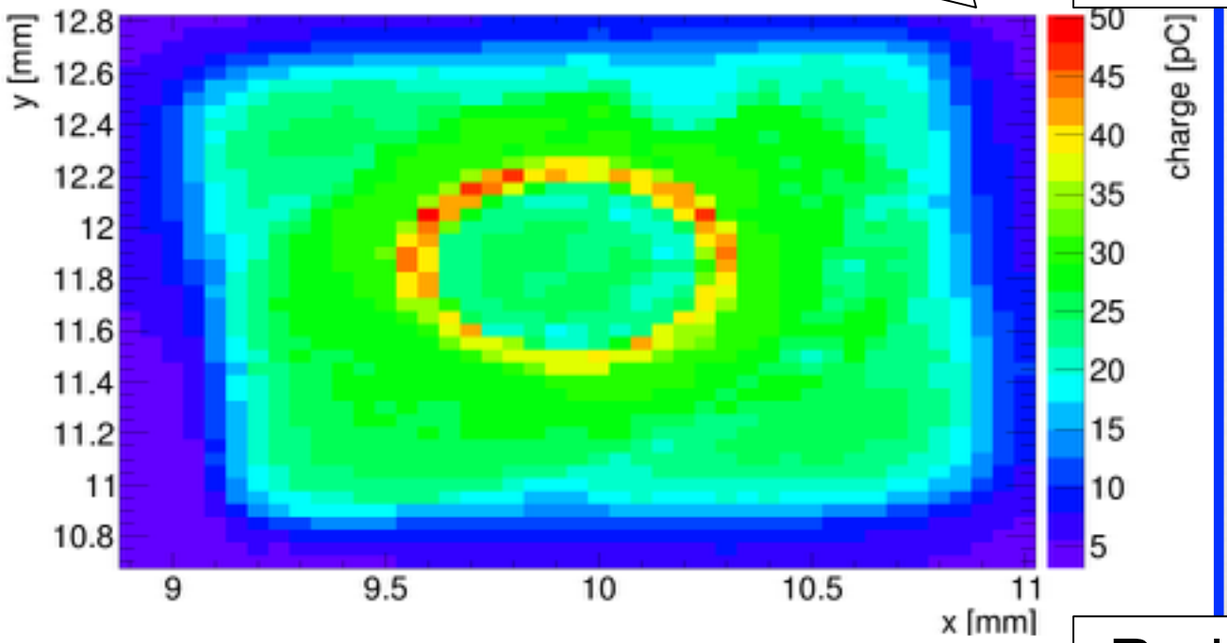


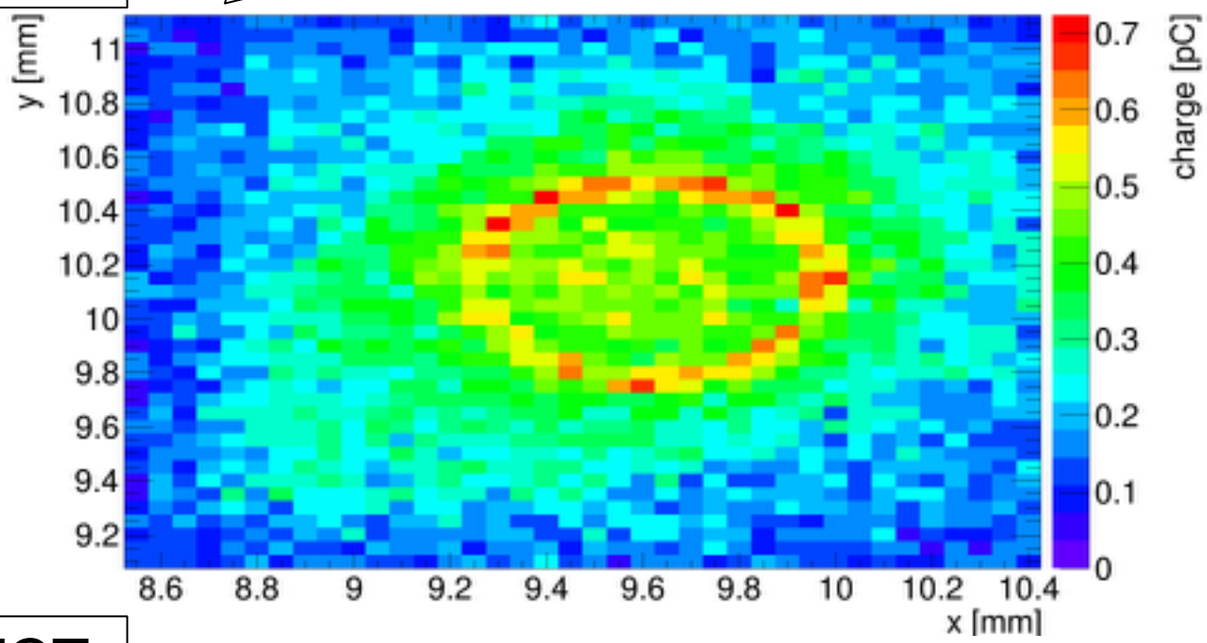
XY scans at 1700 V, -20°C

Before irradiation

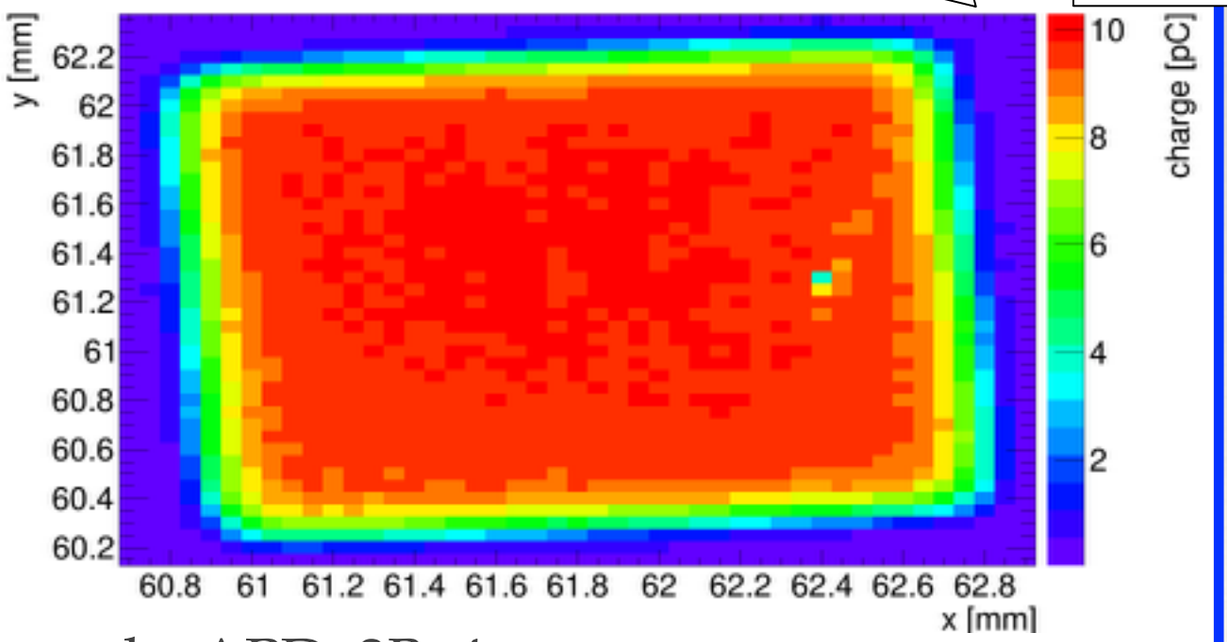
After irradiation 3×10^{14} n/cm^2

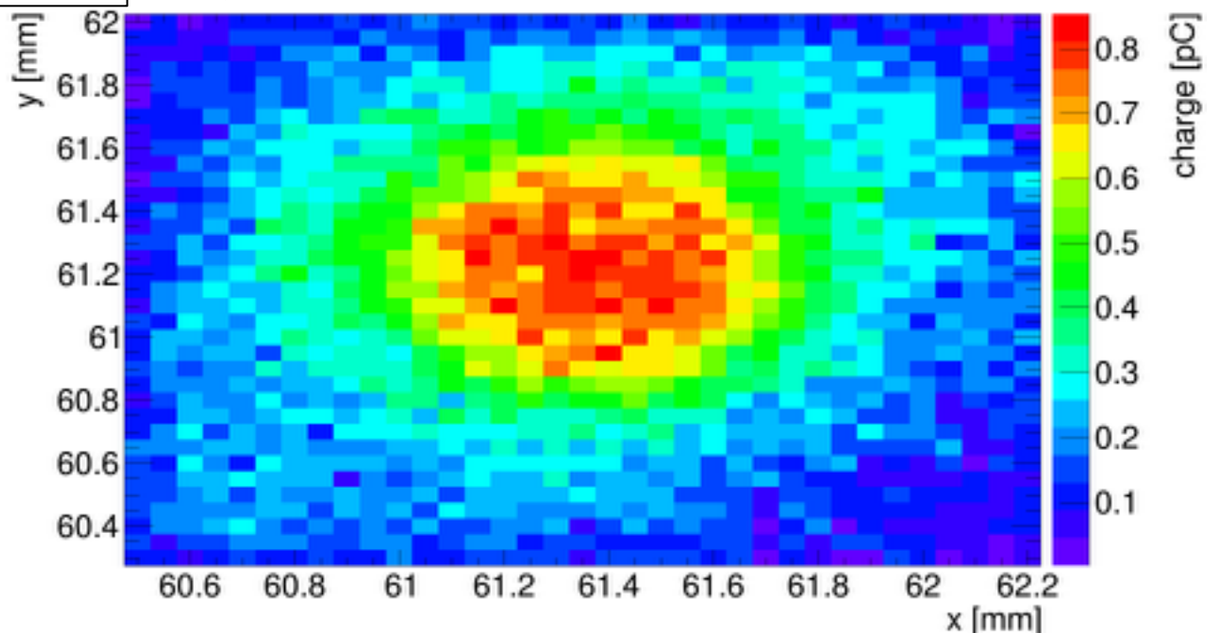
IR TCT





Red TCT





Sample: APD_2B_4

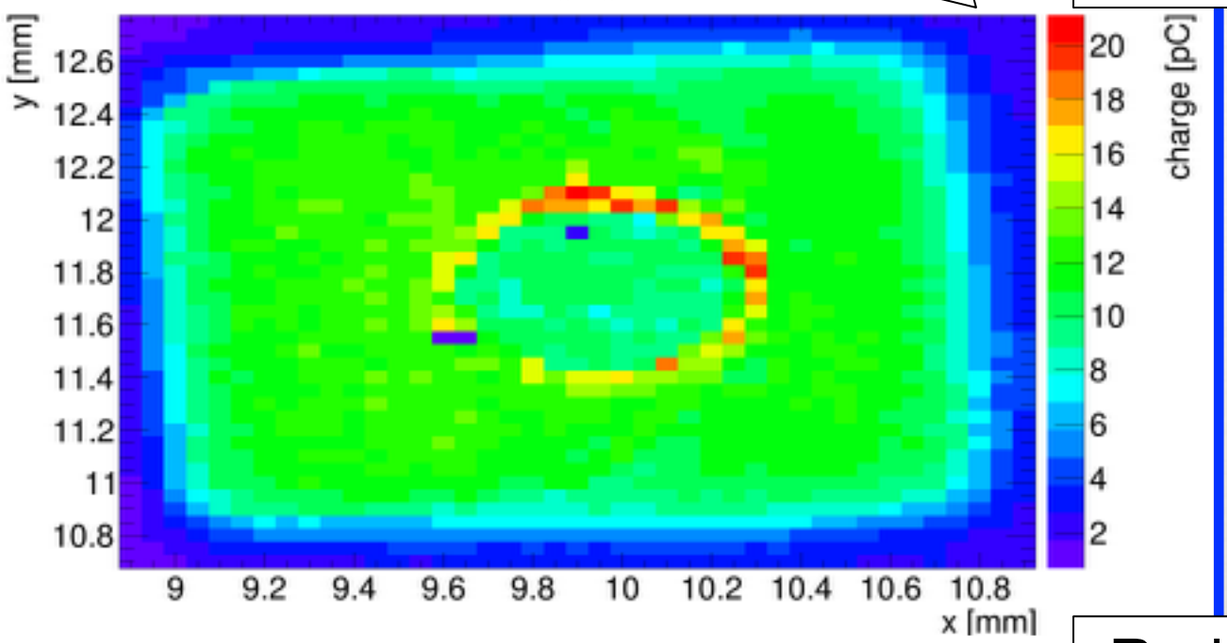
XY scans at -20°C

Before irradiation

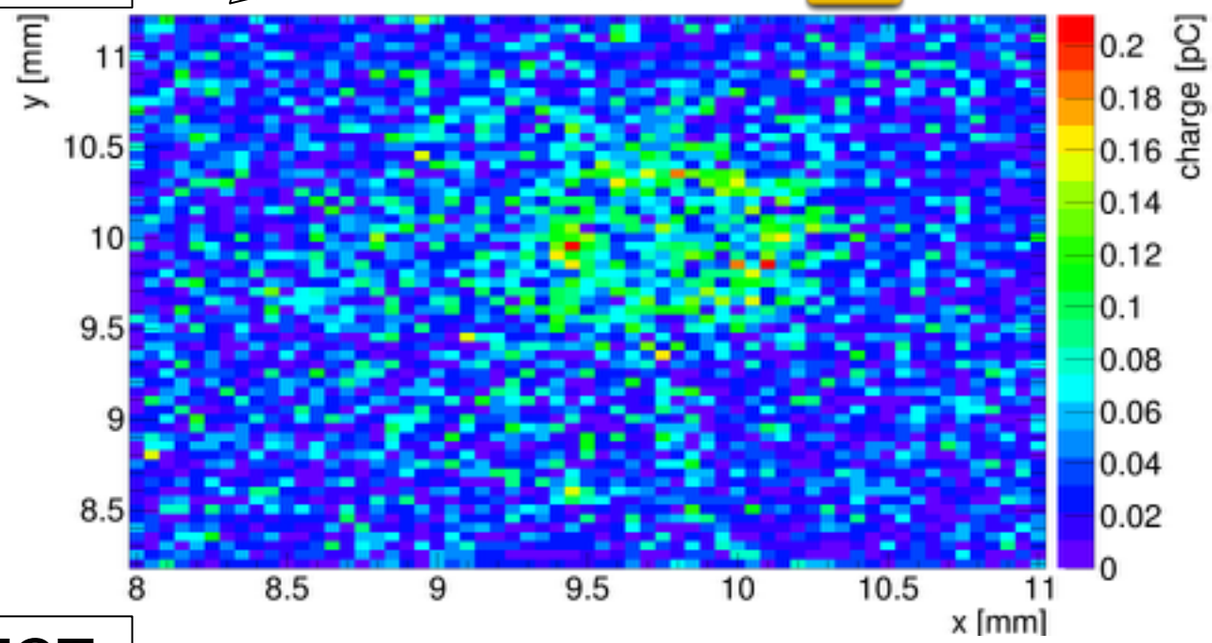
After irradiation $1x10^{15}$ n/cm^2

IR TCT

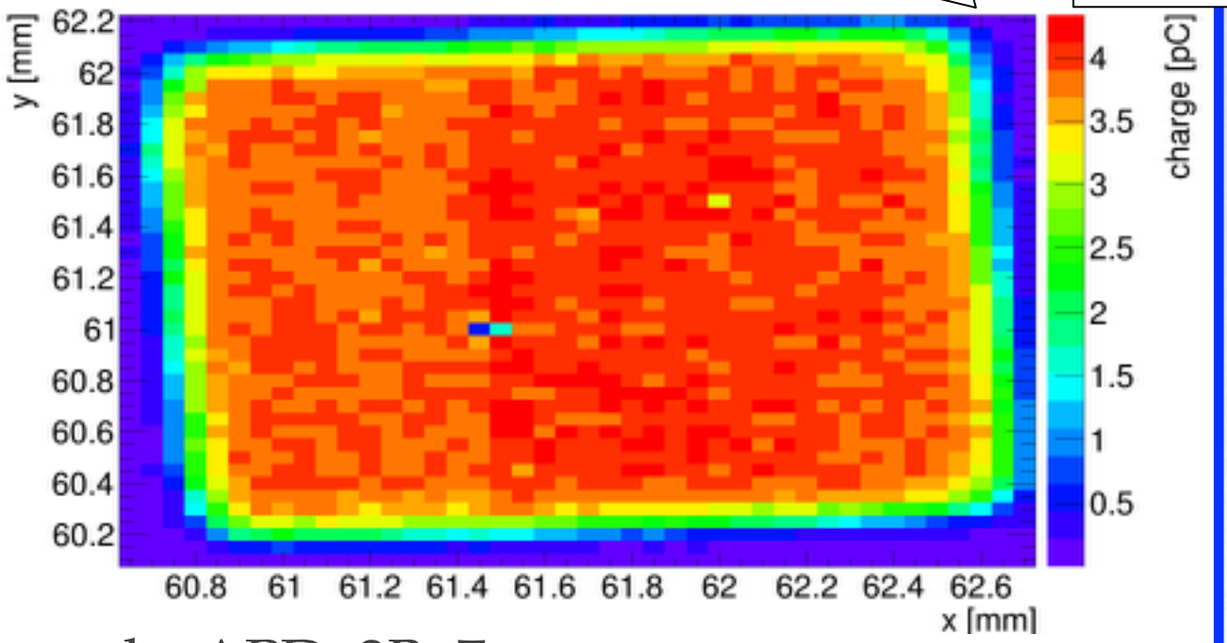
1700 V

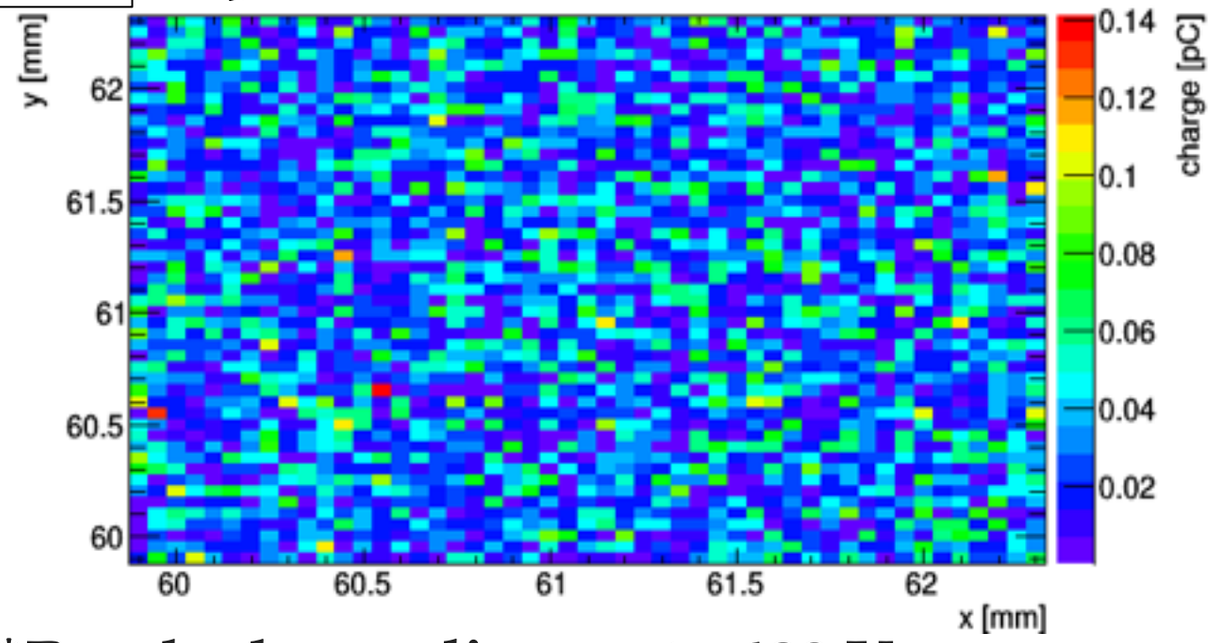


450 V*



Red TCT





Sample: APD_2B_7

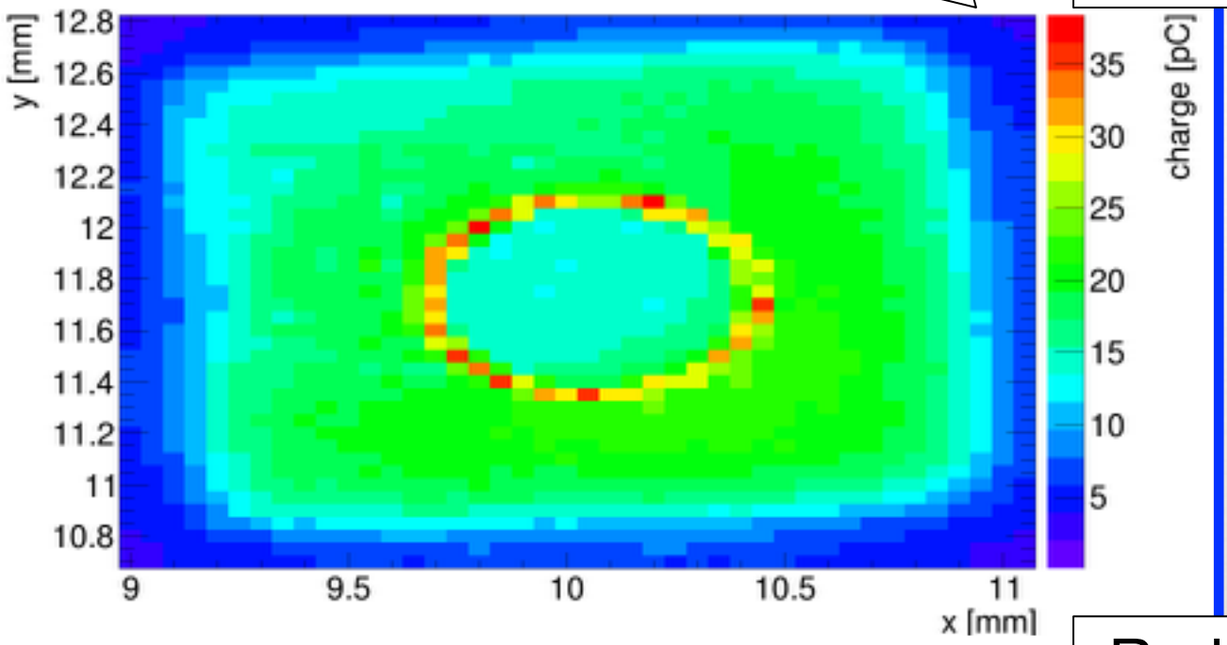
*Reached compliance at ~480 V.

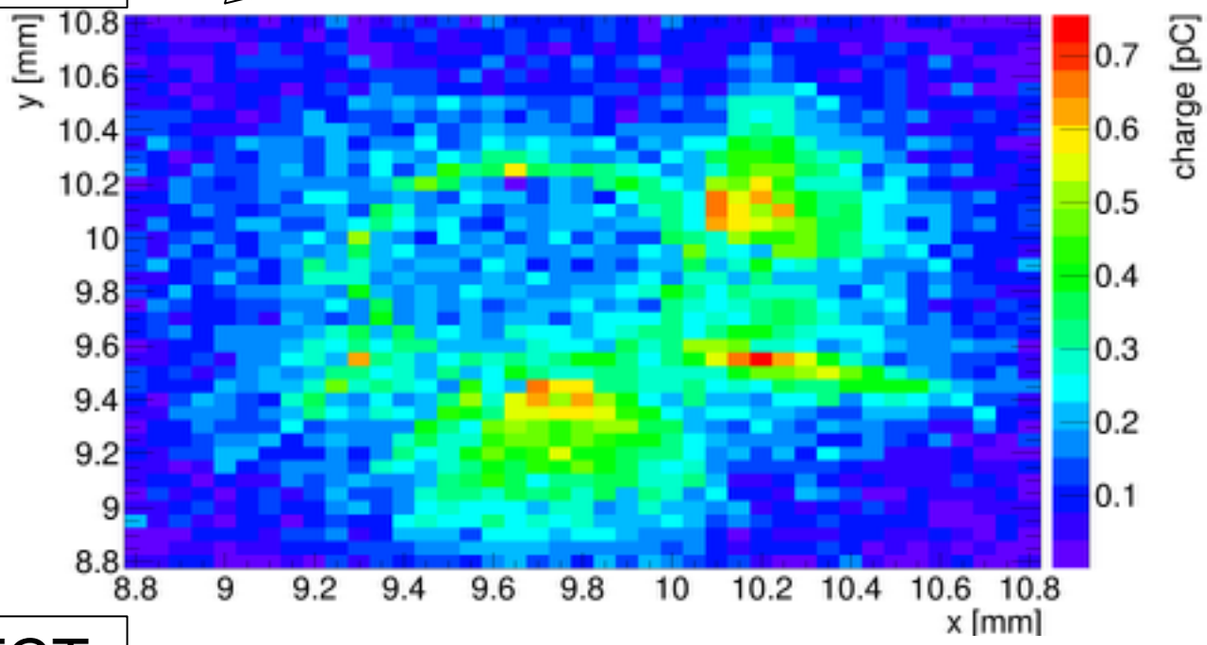
XY scans 1700 V at -20°C

Before irradiation

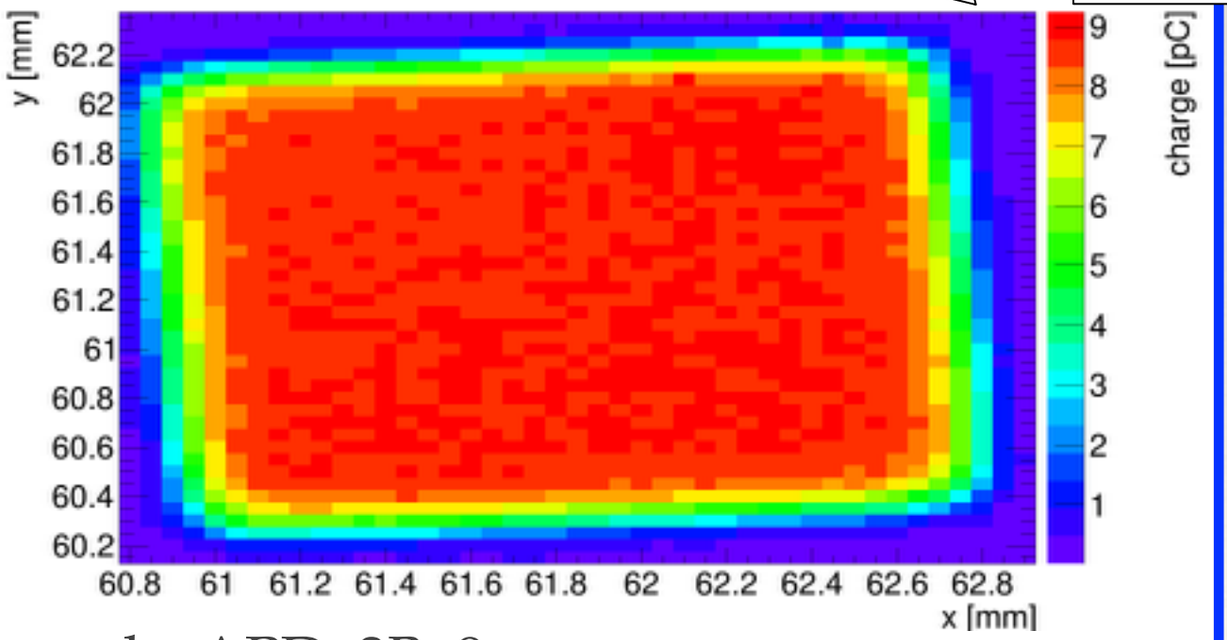
After irradiation $1x10^{15}$ n/cm^2

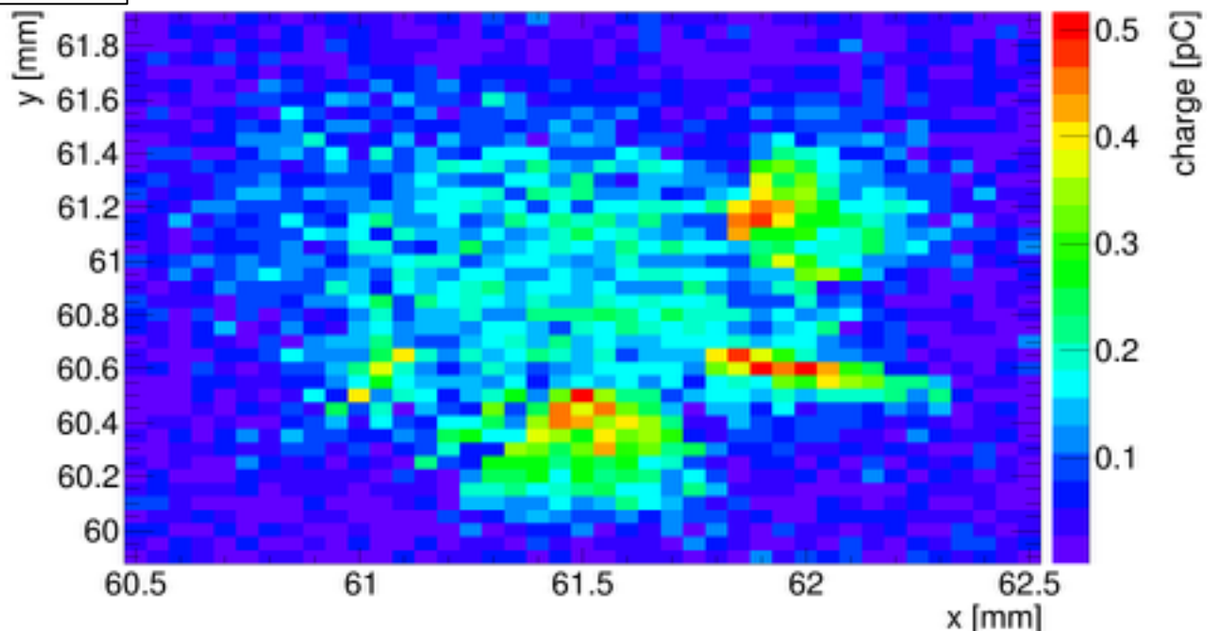
IR TCT





Red TCT





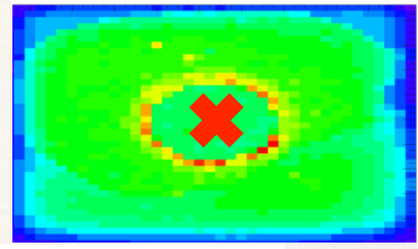
Sample: APD_2B_9

TCT Voltage Scans

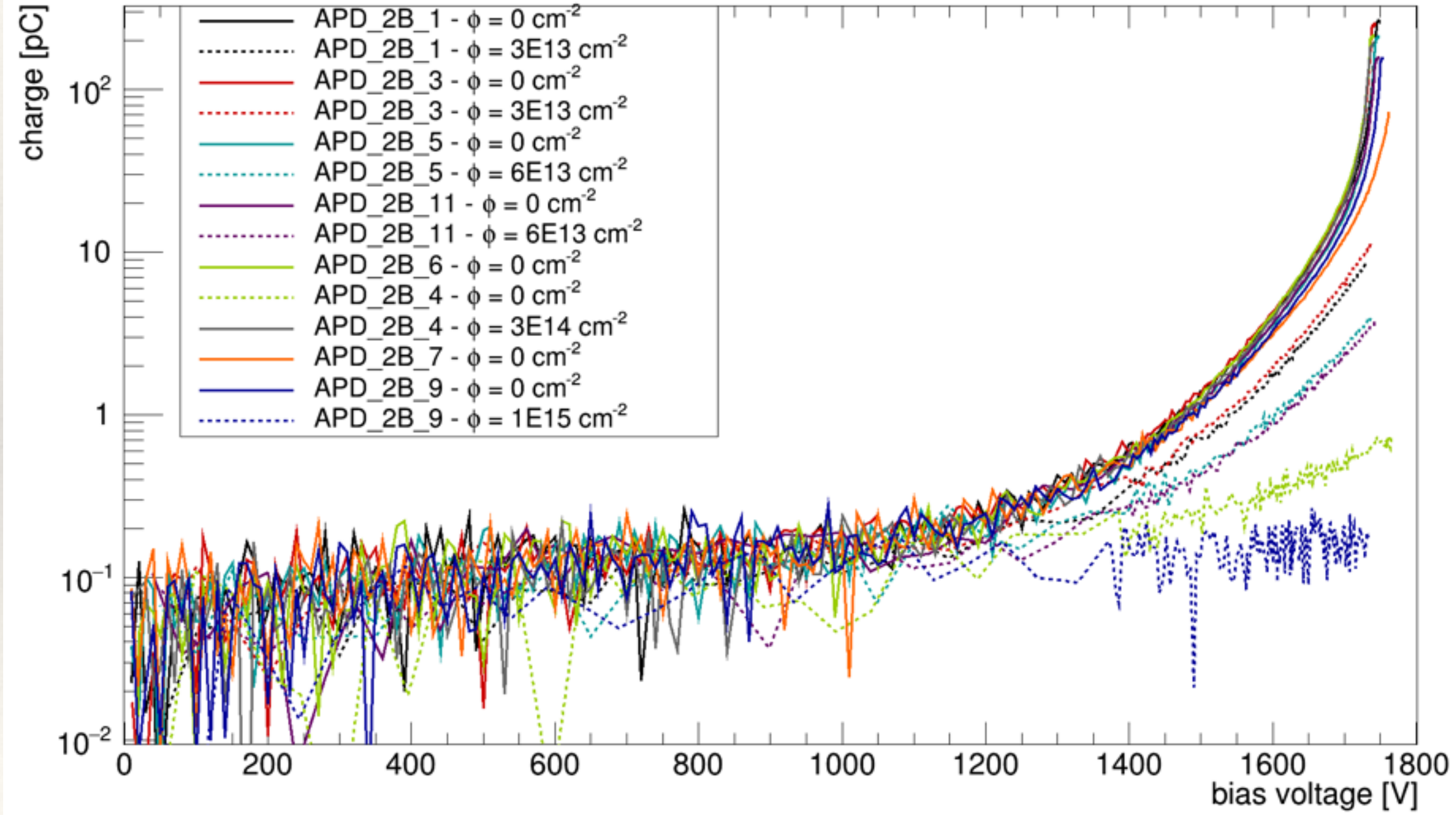
Charge collection vs. bias voltage

Only voltage scans with IR illumination will be shown.
Red illumination voltage scans can be found in the backup slides.

IR-TCT Voltage Scans at -20°C

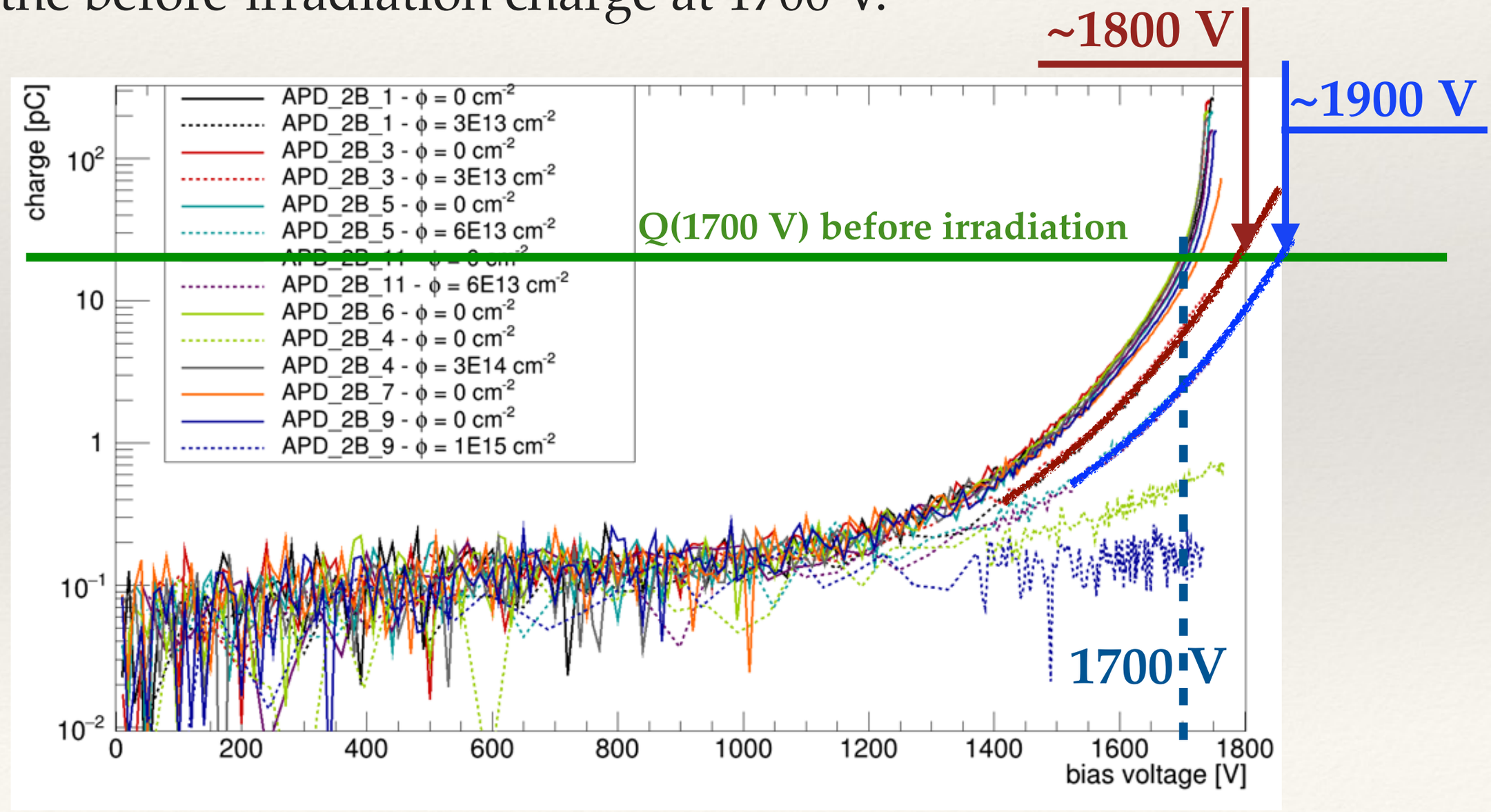


- Measurements before and after irradiation.
- Fixed illumination position.



IR-TCT Voltage Scans at -20°C

- Up to $\phi = 6x10^{13}$ n/cm^2 charge collection can be recovered by increasing the voltage.
- For $\phi = 1x10^{15}$ n/cm^2 a V_{bias} of ~8000 V would be needed to recover the before-irradiation charge at 1700 V.

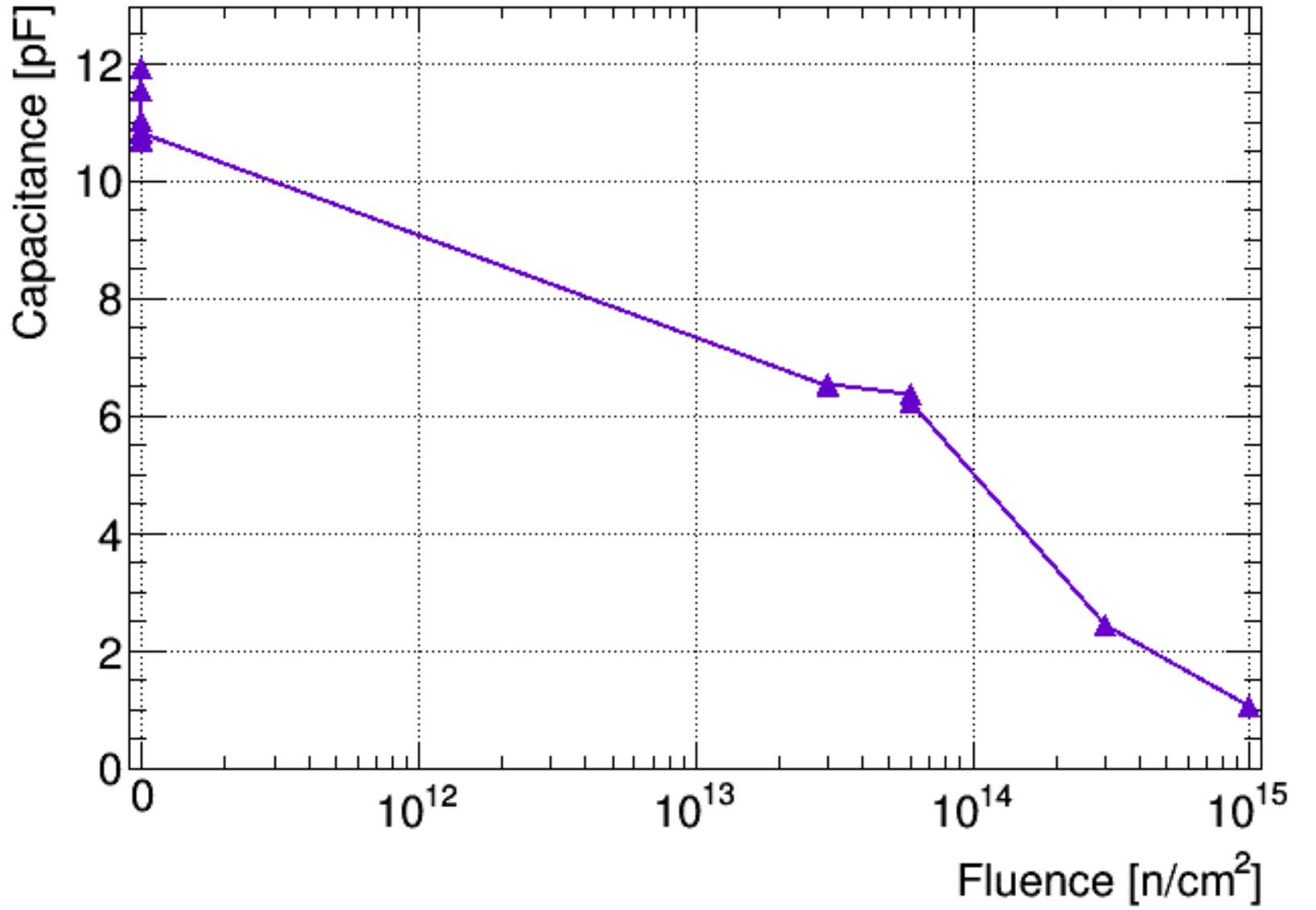


Capacitance vs. Fluence

Capacitance at 500 V, -20°C

- **Measurements before and after irradiation for all samples.**
- **Capacitance decreases with fluence.**
  - Indicative of an increase in thickness of the depletion region.

- **V_{bias} = 500 V.**
- **f = 10 kHz.**
- **°T = -20°C.**
- **Back biasing (n-side).**



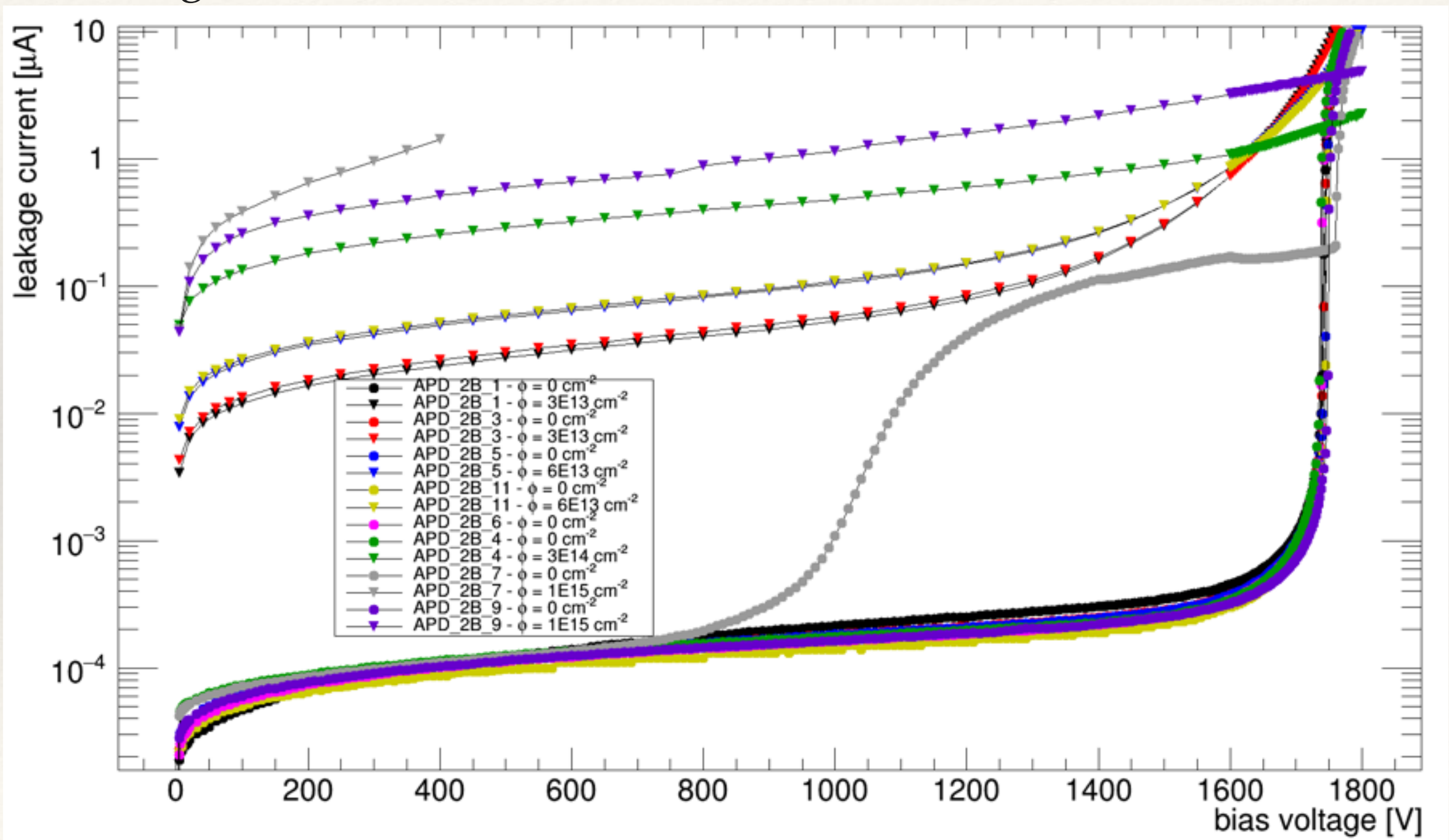
Leakage Current Measurements

Measurement Conditions

- **Measurements before and after irradiation for all samples.**
- **Temperatures:**
  - **20°C, 10°C, 0°C, -10°C, and -20°C.**
- Back biasing (cathode, i.e. n-side).
- **Compliance 10 μA.**

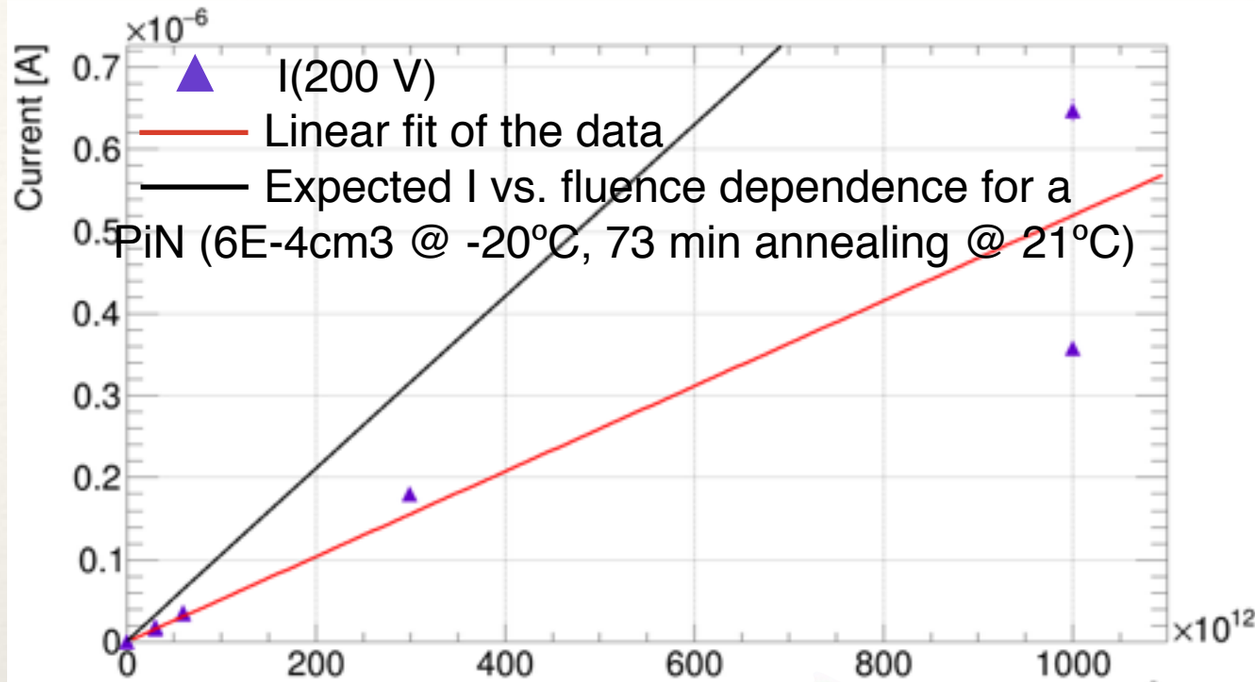
IV curves at -20°C

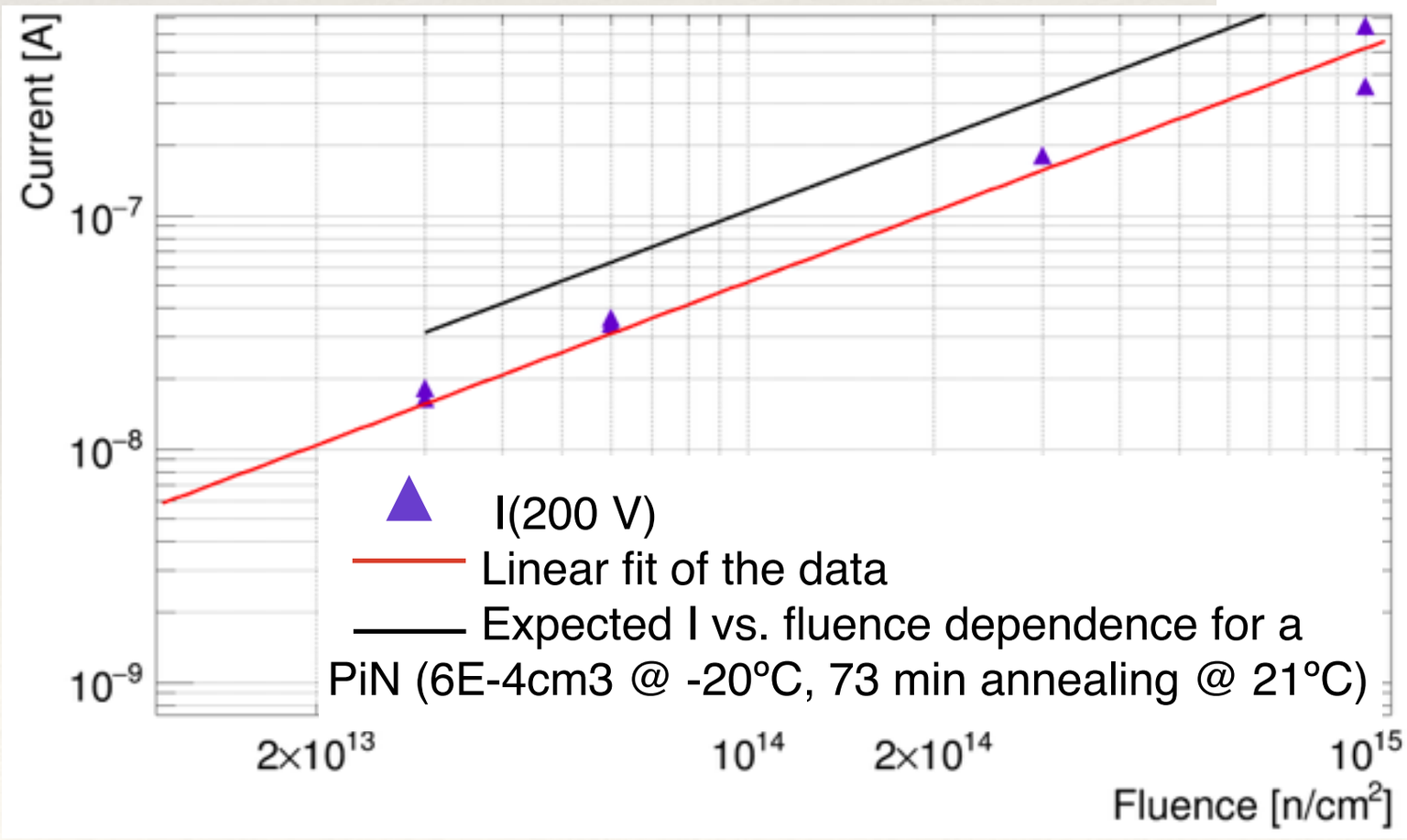
- Before irradiation all samples, but one, behave similarly.
- Leakage current increases with fluence.



Current vs. Fluence at -20°C

- **Leakage current at 200 V (no gain).**
- Estimated average annealing time:
  - **73 min at 21°C.**
- **Dimensions assumed: 6×10^{-4} cm³.**
  - A = 2x2 mm², d = 150 μm.





Fluence [n/cm²]

ESTIMATION

Active volume changes are not being considered.

Damage coefficient:

- From fitting DD-APD data:

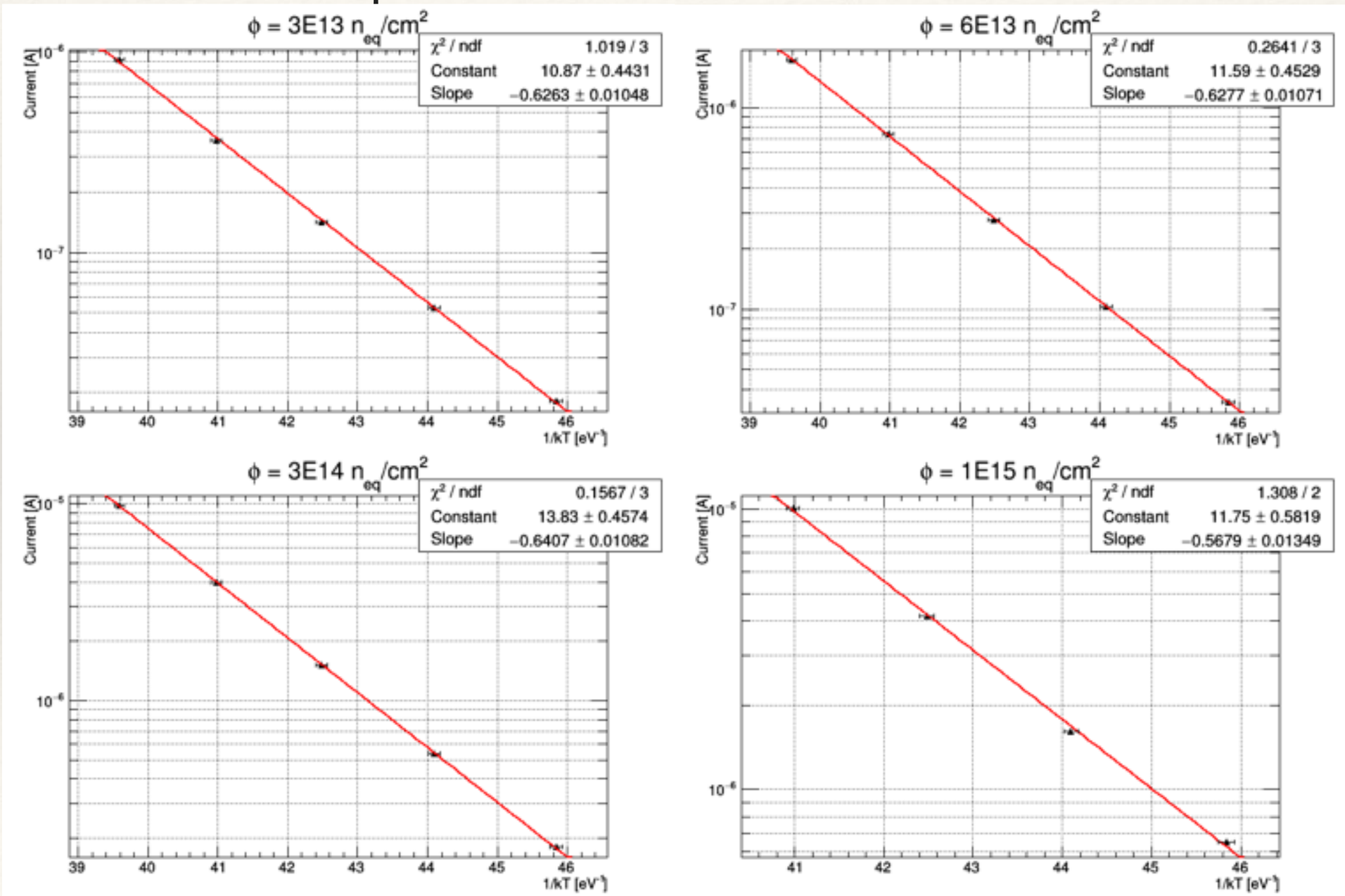
  $\alpha_{fit} \approx 8.66\times10^{-19}$ A/cm

- For a PiN of equal volume and annealing:

  $\alpha_{PiN} \approx 17.5\times10^{-19}$ A/cm

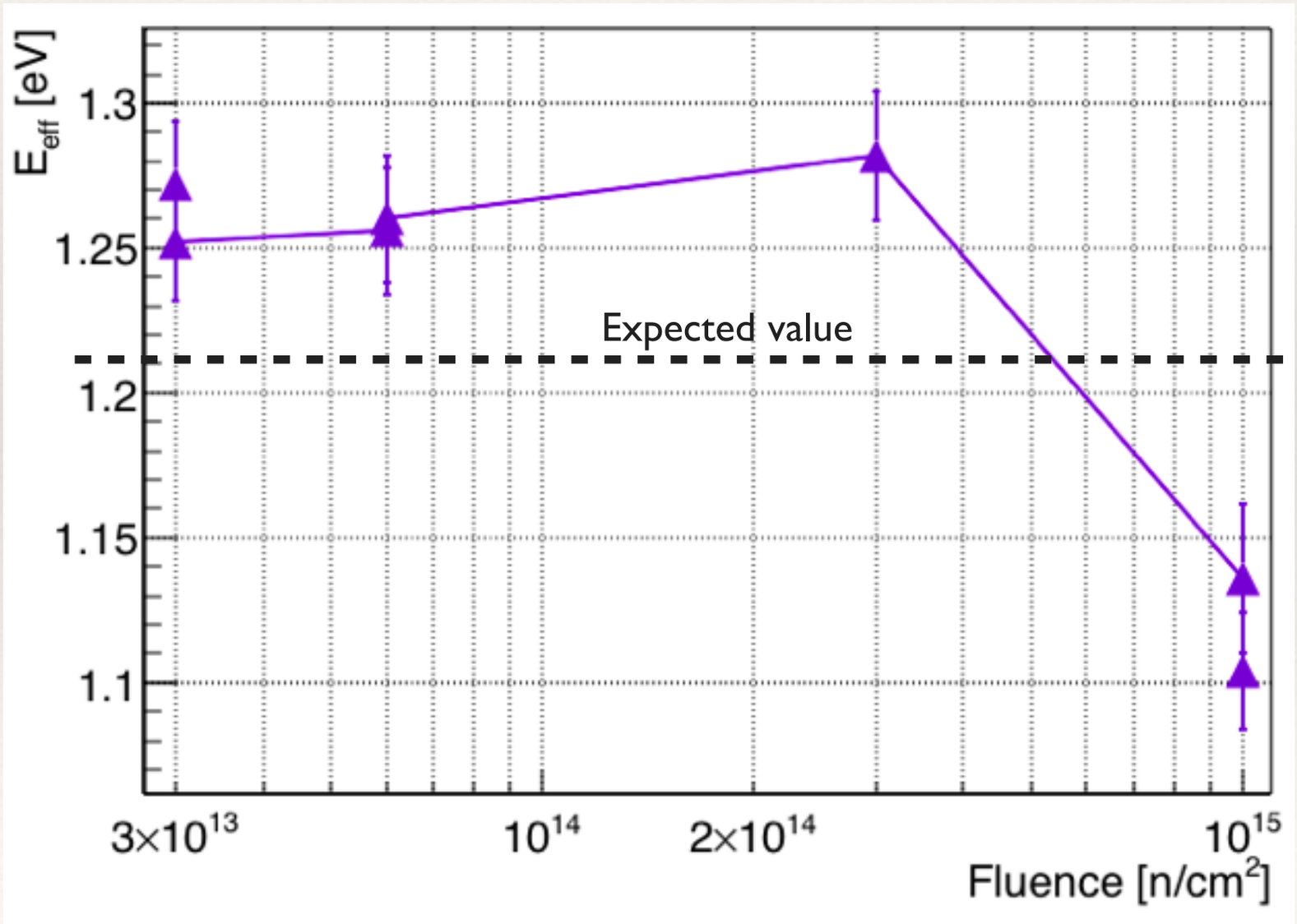
Leakage Current vs. Temperature

- IV curves were measured at 5 different temperatures.
- Objective: produce an Arrhenius plot, calculate the effective energy and compare it with the expected value.



Effective energy

- **Fit to:** $I(T) \propto T^2 \exp\left(-\frac{E_{eff}}{2kT}\right)$ with $E_{eff} = E_g + 2\Delta$
  - Expected value: $E_{eff} = 1.21$ eV. [2013, A. Chilingarov, JINST 8 P10003]
- Average and SD over fit results: $E_{eff}^{fit} = (1.22 \pm 0.07)$ eV.



Conclusions

- XY scans seemingly show a reduction of the active area with fluence.
- Red-TCT XY scans: central inhomogeneity appears for $\phi \geq 6x10^{13}$ n/cm^2.
  - This has yet to be understood.
- **TCT voltage scans show a decrease in charge collection with fluence.**
  - For $\phi \leq 6x10^{13}$ n/cm^2 charge collection can be recovered by increasing V_{bias}.
  - For $\phi \geq 3x10^{14}$ n/cm^2 the bias voltage required to recover before-irradiation charge collection levels is beyond reasonable values.
- From I(200 V) vs. ϕ, α was estimated**: 8.66x10^{-19}A/cm** (expected order of magnitude).
- Effective energy calculation: $E_{eff}^{fit} = (1.22 \pm 0.07)$ eV.
- C vs. ϕ data show an increase in the depletion region thickness with fluence.
- Further studies must be performed for $6x10^{13} \leq \phi \leq 7x10^{14}$ n/cm^2.

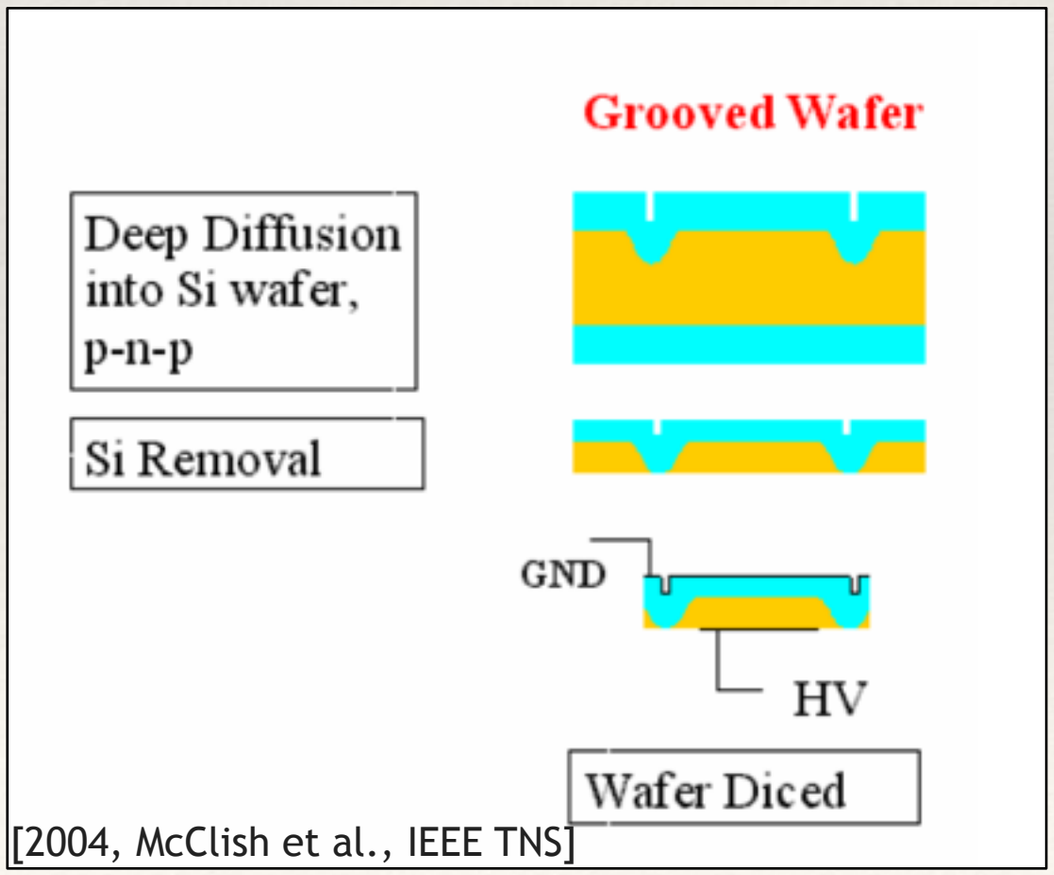
Backup Slides

Deep Diffused APDs

- Manufactured by RMD.
- **Structure:**
  - n-type NTD-doped silicon (Topsil).
  - Grooving wafer.
  - Deep diffusion of p-type dopants.
    - Gallium used as dopant.
  - Etching of surface layer.

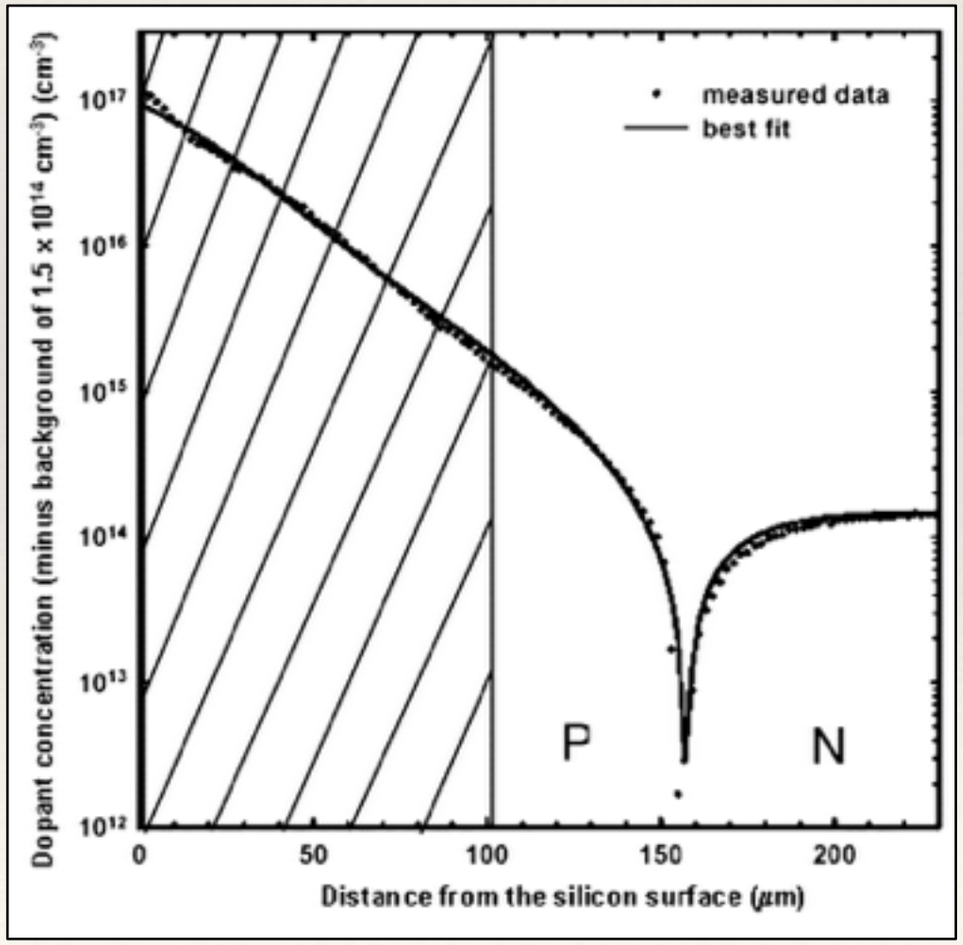
Previous study of neutron-irradiated DD-APDs:

S. Otero Ugobono, Characterisation of HFS Detectors, 29th RD50 Workshop, CERN, November 2016

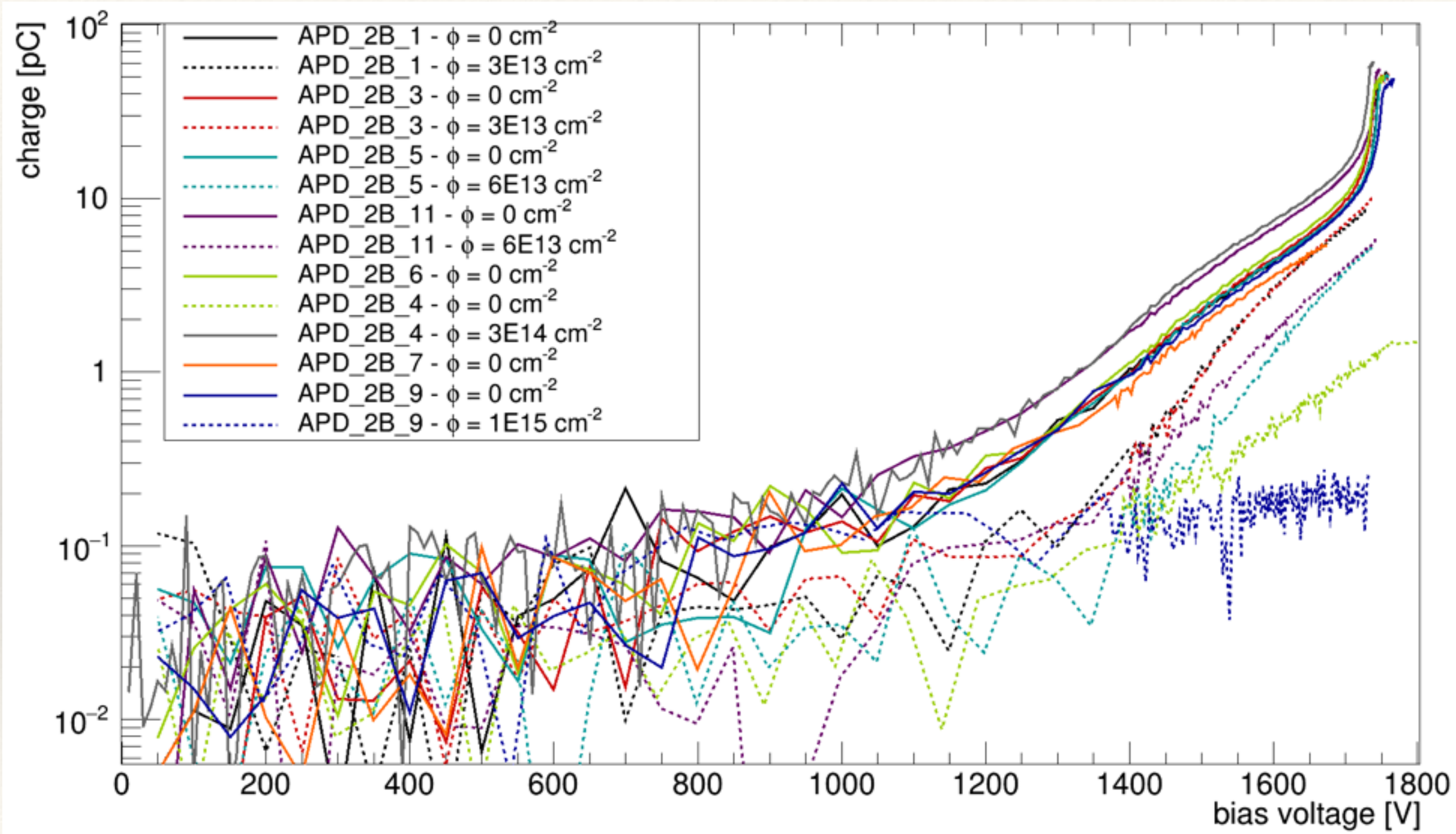


[2004, McClish et al., IEEE TNS]

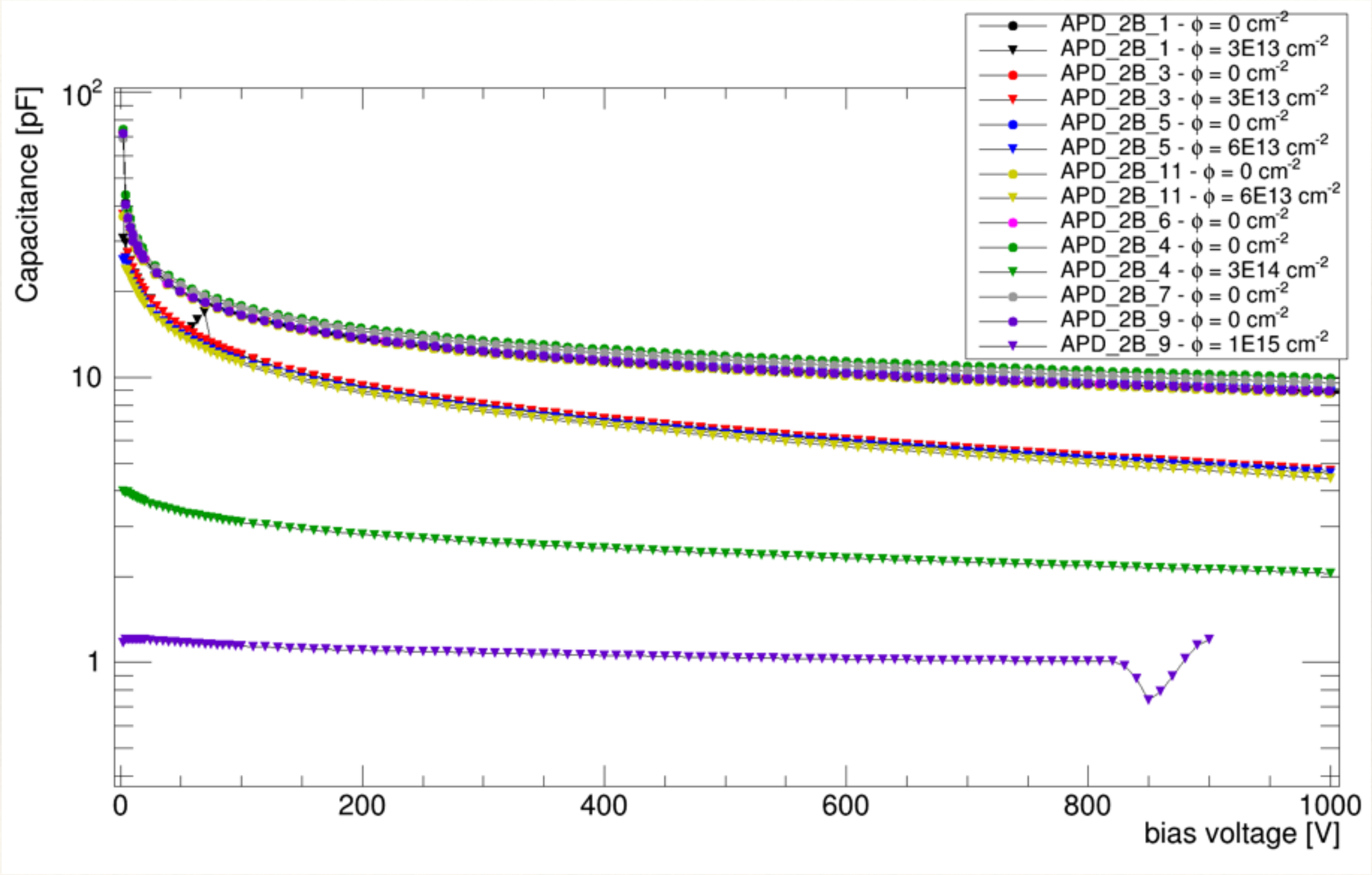
[2006, McClish et al., IEEE TNS, 53, 3049]



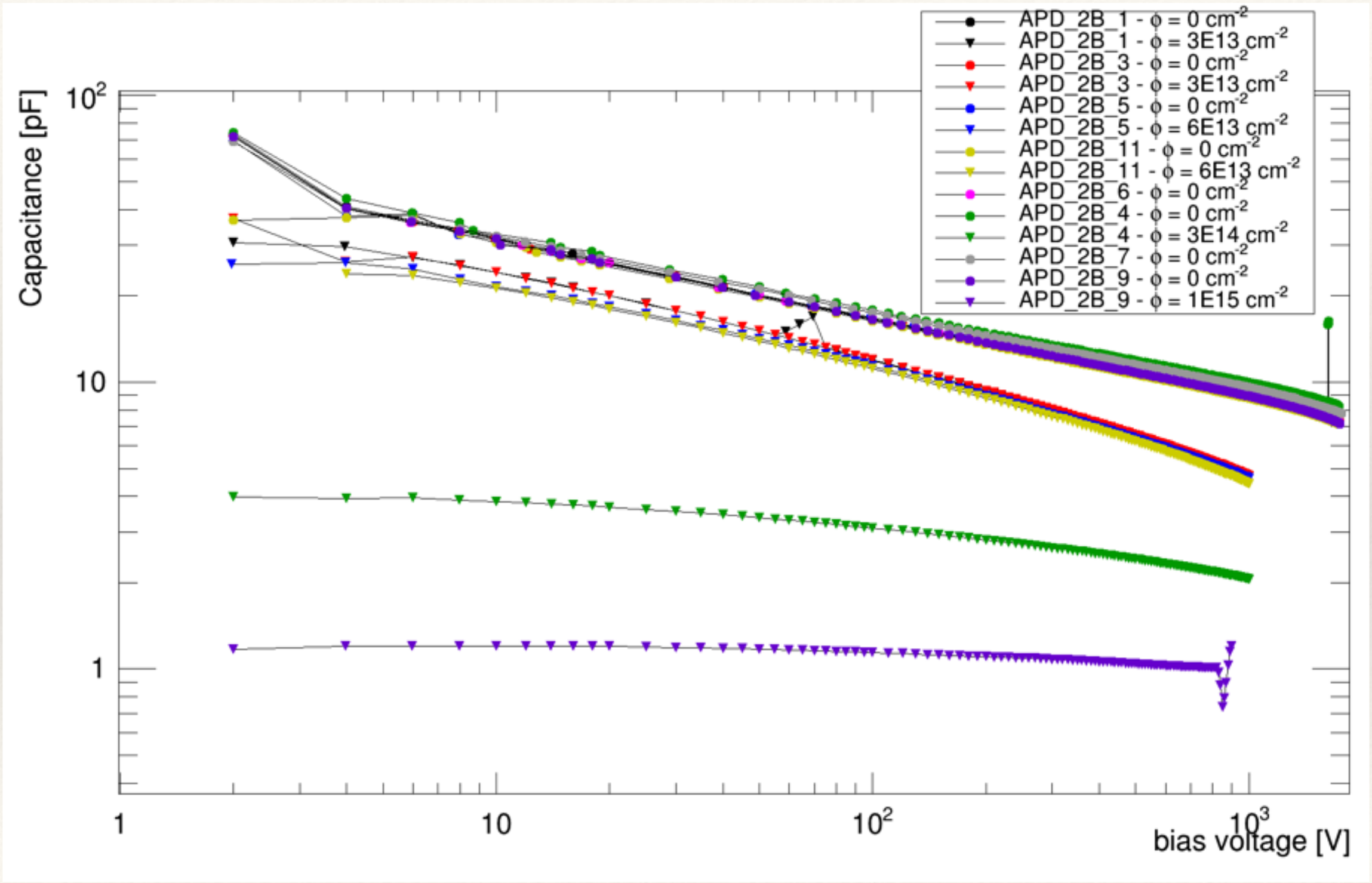
Red-TCT Voltage Scans at -20°C



CV curves at -20°C

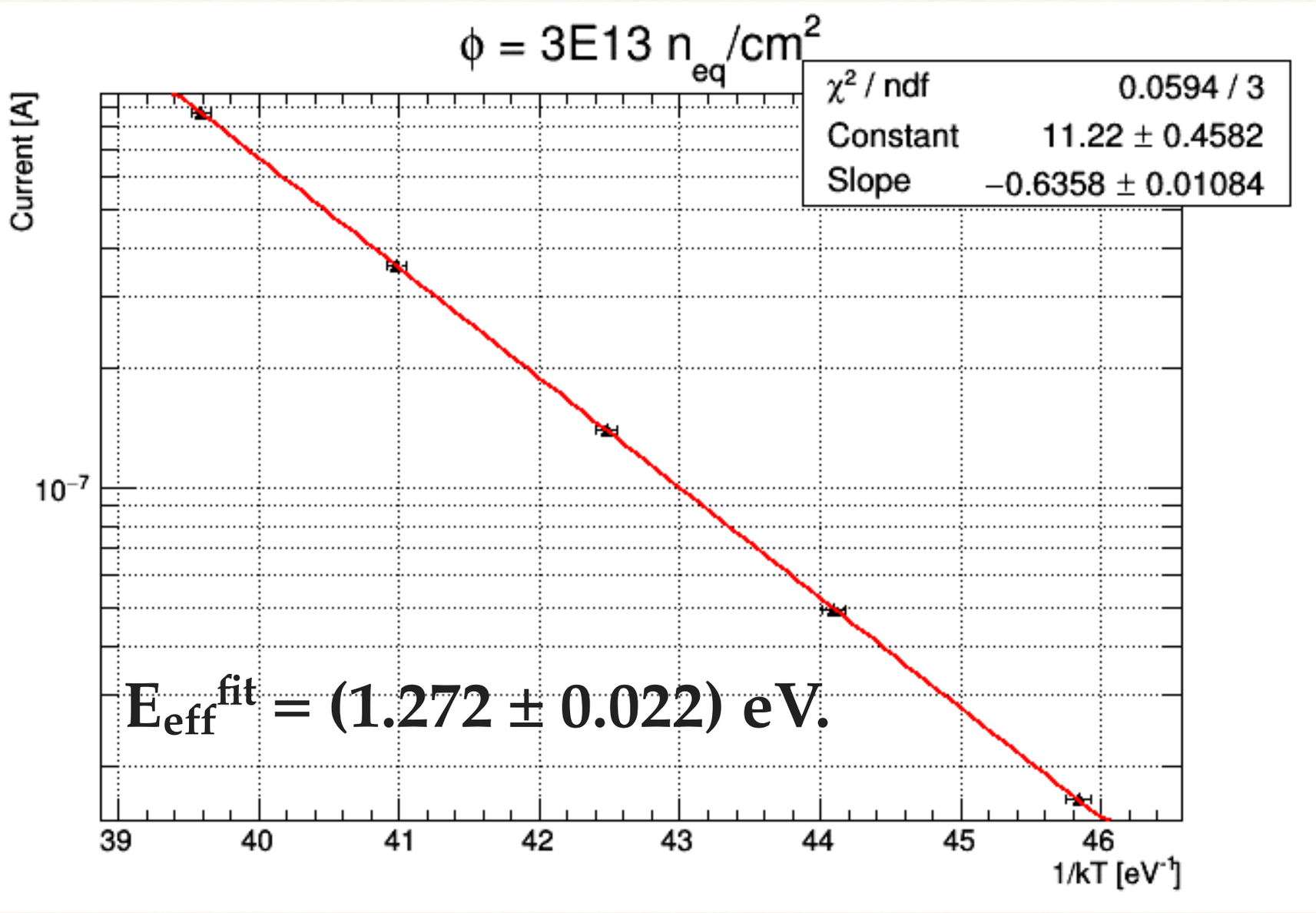


CV curves at -20°C

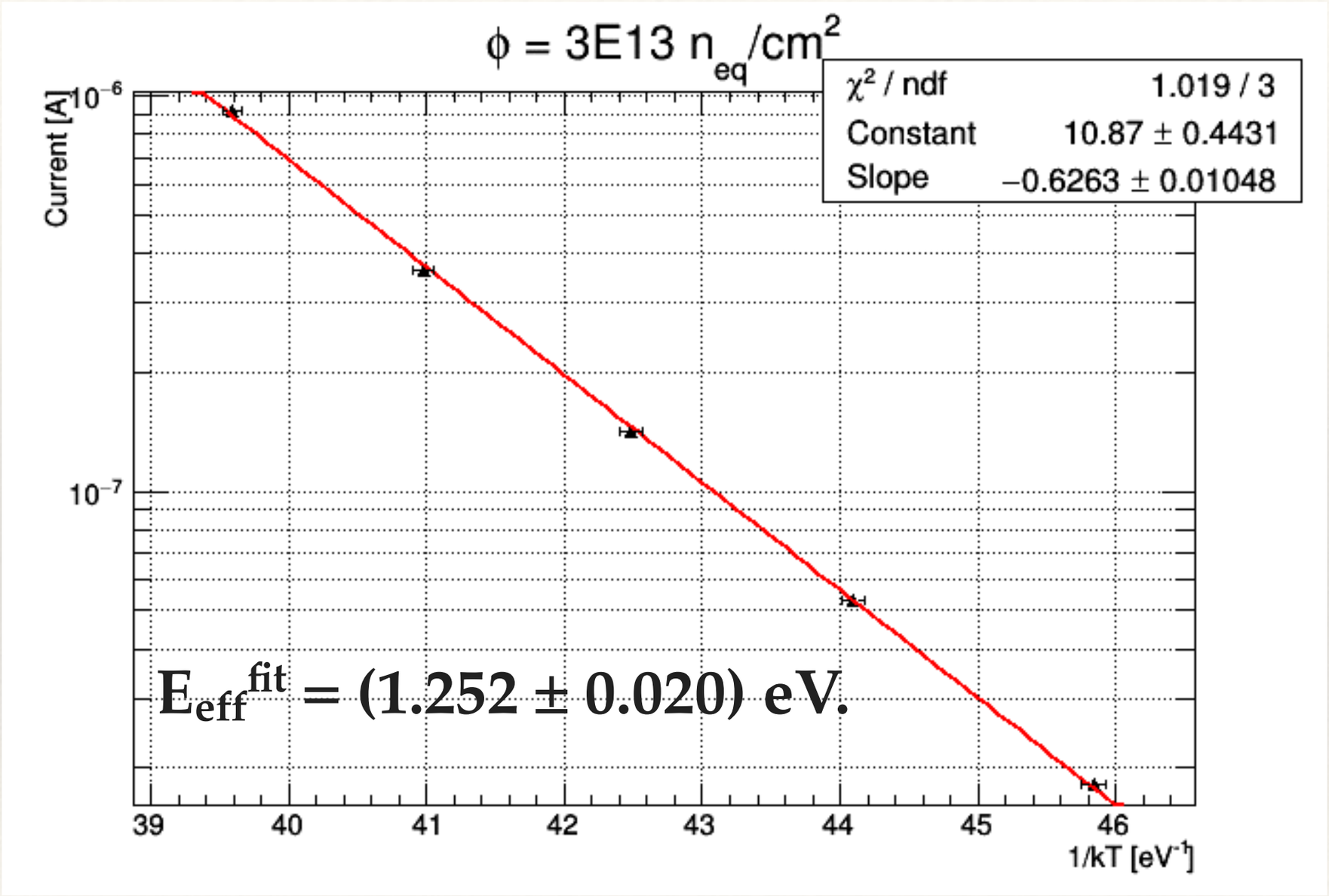


Leakage Current vs. Temperature Plots for all Fluences and Devices

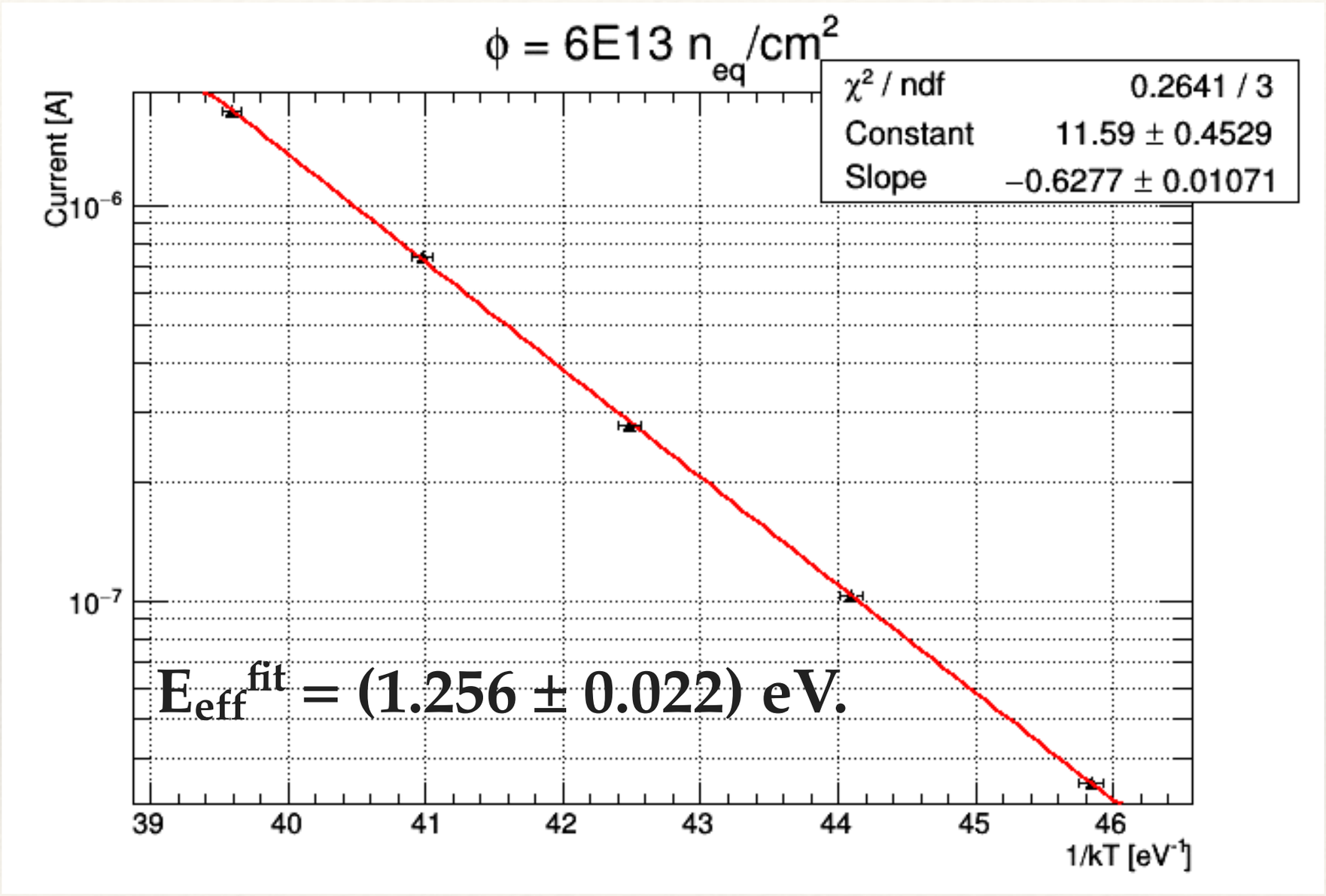
Sample: APD_2B_1



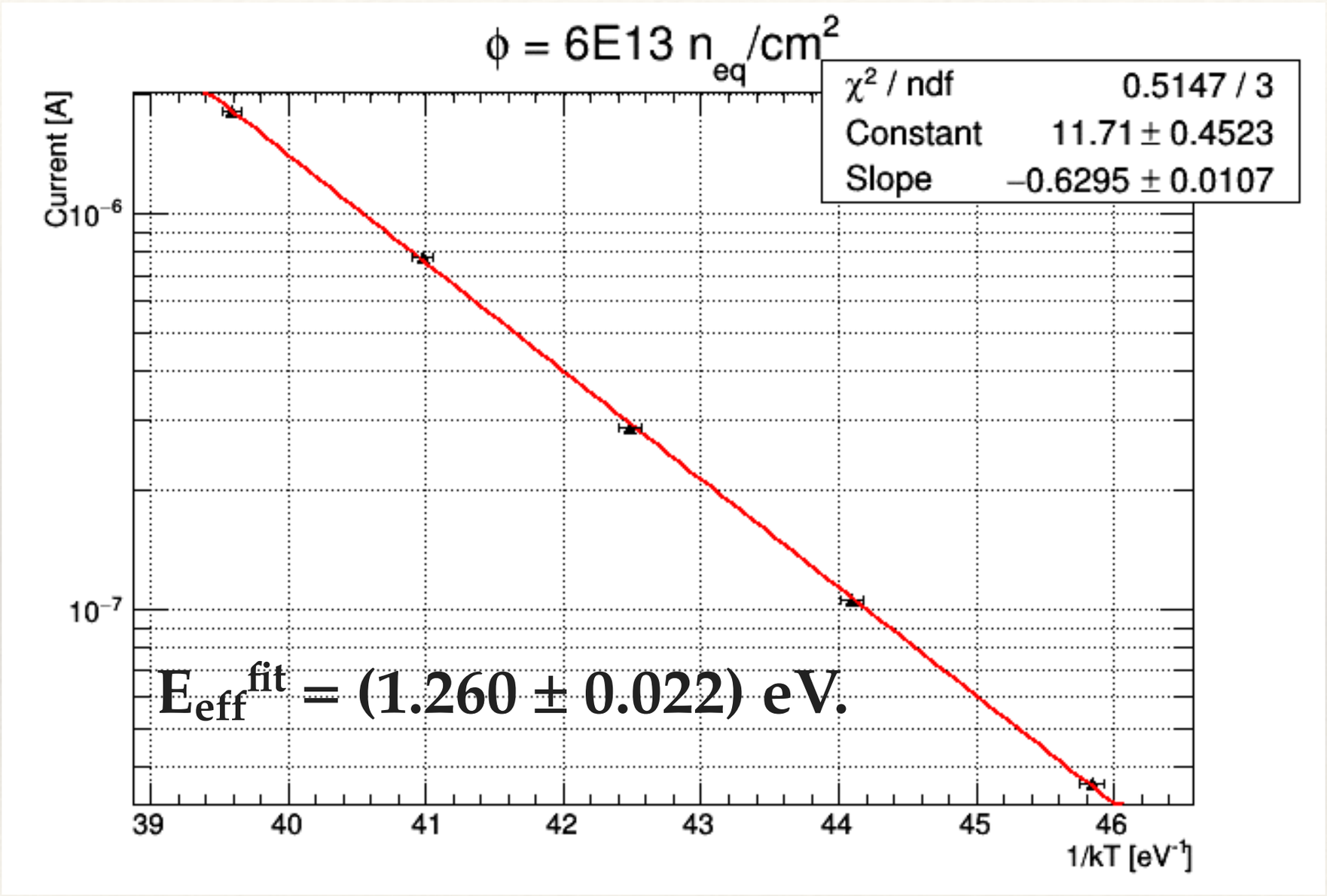
Sample: APD_2B_3



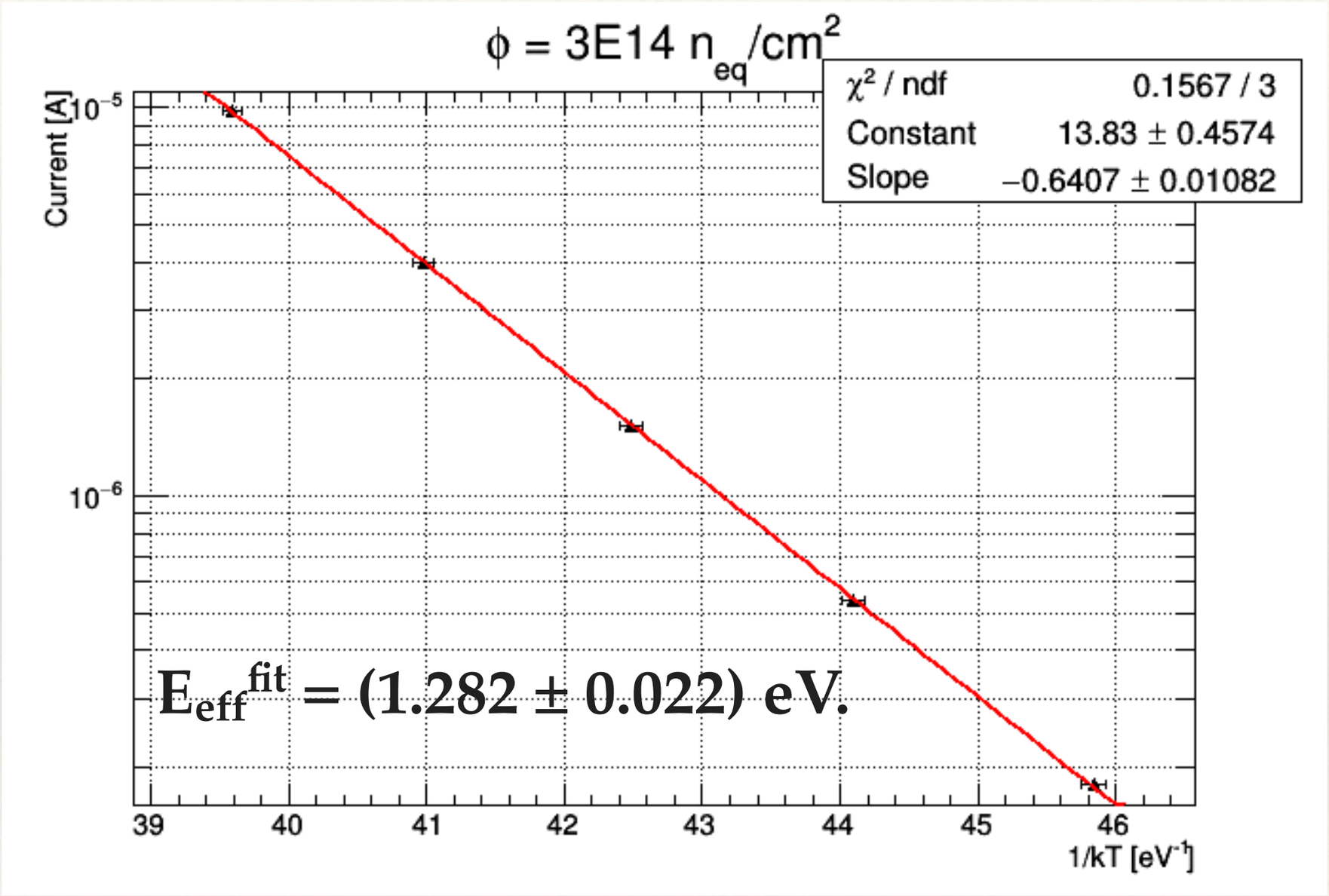
Sample: APD_2B_5



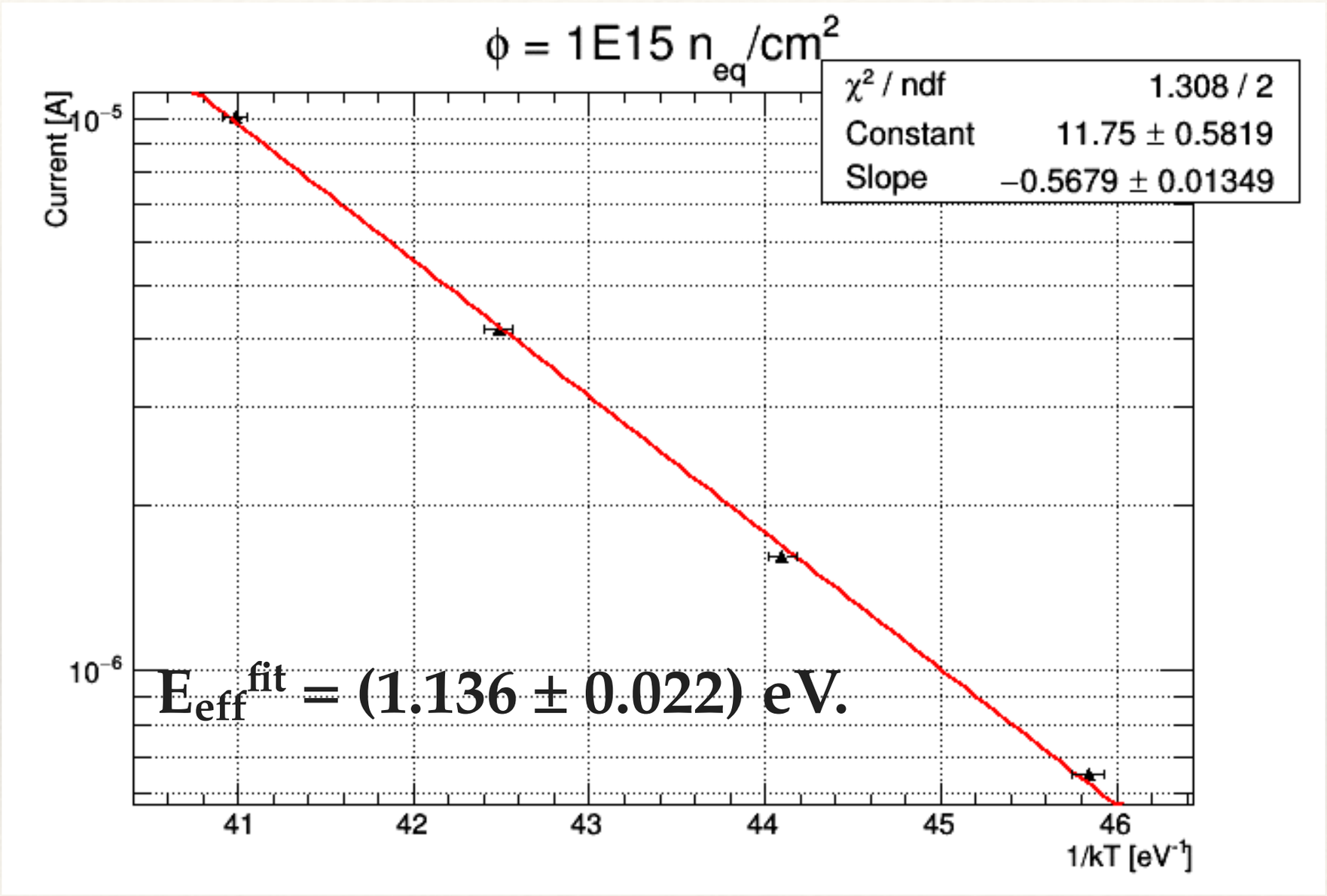
Sample: APD_2B_11



Sample: APD_2B_4



Sample: APD_2B_7



Sample: APD_2B_9