Measurements with Si detectors irradiated to extreme fluences

V. Cindro, A. Gorišek, B. Hiti, G. Kramberger, I. Mandić, M. Mikuž, P. Skomina, M. Zavrtanik et al.

Jožef Stefan Institute, Ljubljana, Slovenia
University of Ljubljana, Slovenia

Introduction

- continuation of work presented at 34th RD50 Workshop in Lancaster, June 2019:
  https://indico.cern.ch/event/719814/contributions/3022499

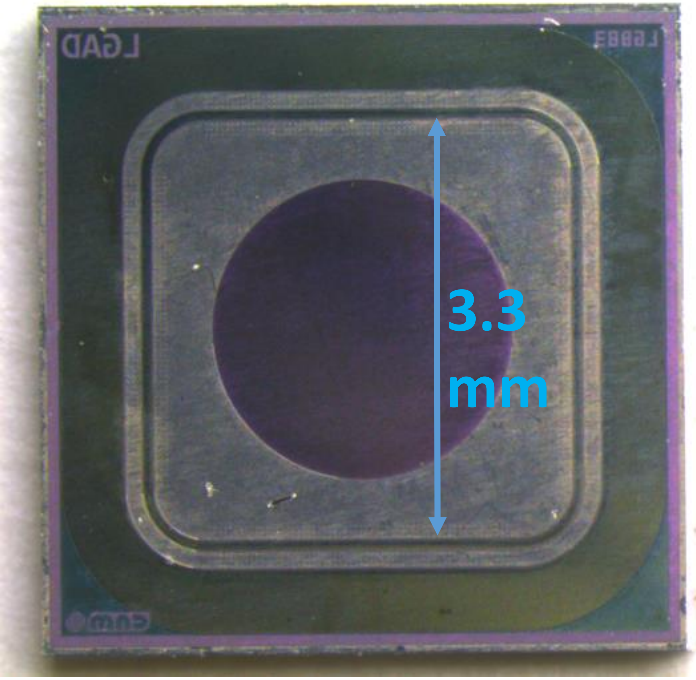
  - measurements with 50 µm epitaxial LGADs irradiated up to 3e17 n/cm^2
    → unusual behavior of the device irradiated to 1e17 n/cm^2 :
      → transition from "normal" to "LGAD" kind of behavior (charge multiplication at low bias voltage) after few weeks at room temperature

- this contribution: more systematic measurements with 75 µm (epitaxial) LGADs irradiated up to 1e17 n/cm^2

Samples

- CNM LGAD run 9256
- 75 µm epitaxial on low resistivity Cz substrate
- chip thickness ~ 600 µm

- irradiated with reactor neutrons to **2.5e16**, **5.7e16** and **1e17 n/cm^2**
- two devices per fluence



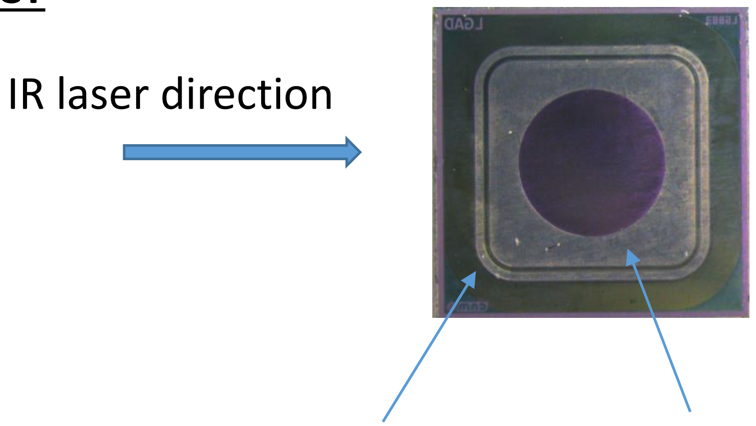
Measurements

- Edge-TCT: depletion depth, active thickness
- Sr-90 (Q-TCT) setup: charge collection, I-V

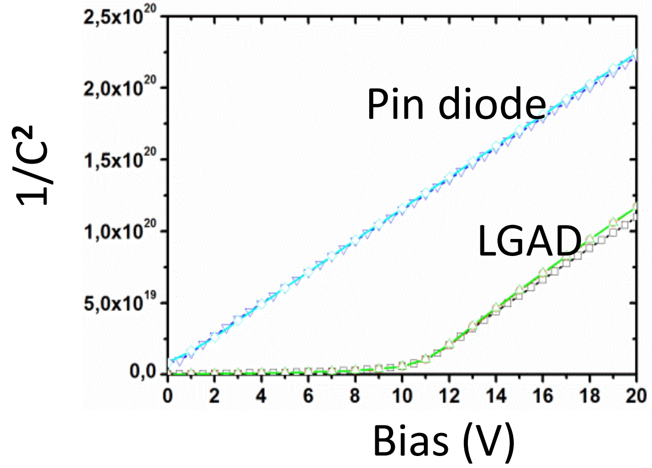
Plan

- systematically measure the effect of annealing at 60°C
- annealing times: 0, 80, 240, 560 and 1200 minutes
- measure in reverse and forward bias

Edge - TCT

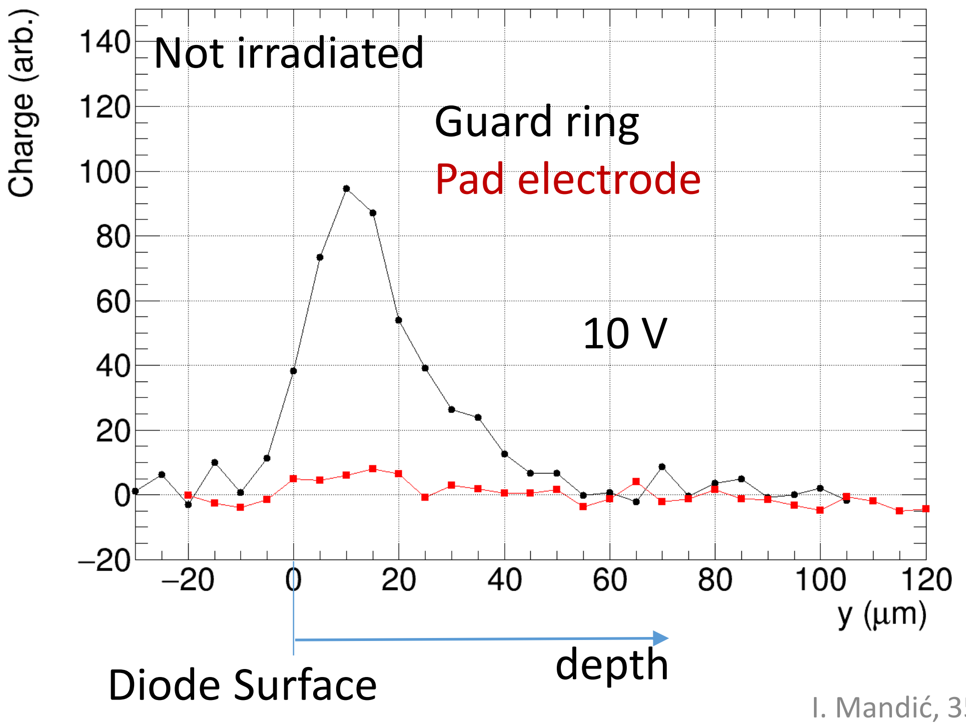


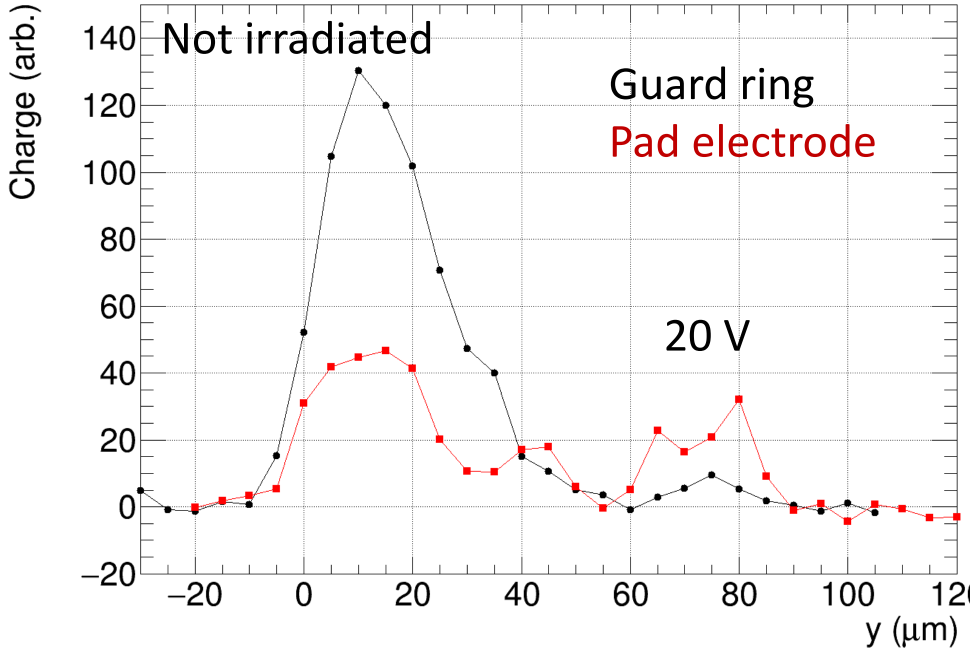
Signal from **guard ring** or **pad electrode**
➔ pad electrode large, affects E-TCT response



M. Carulla, TREDI 2017, Trento

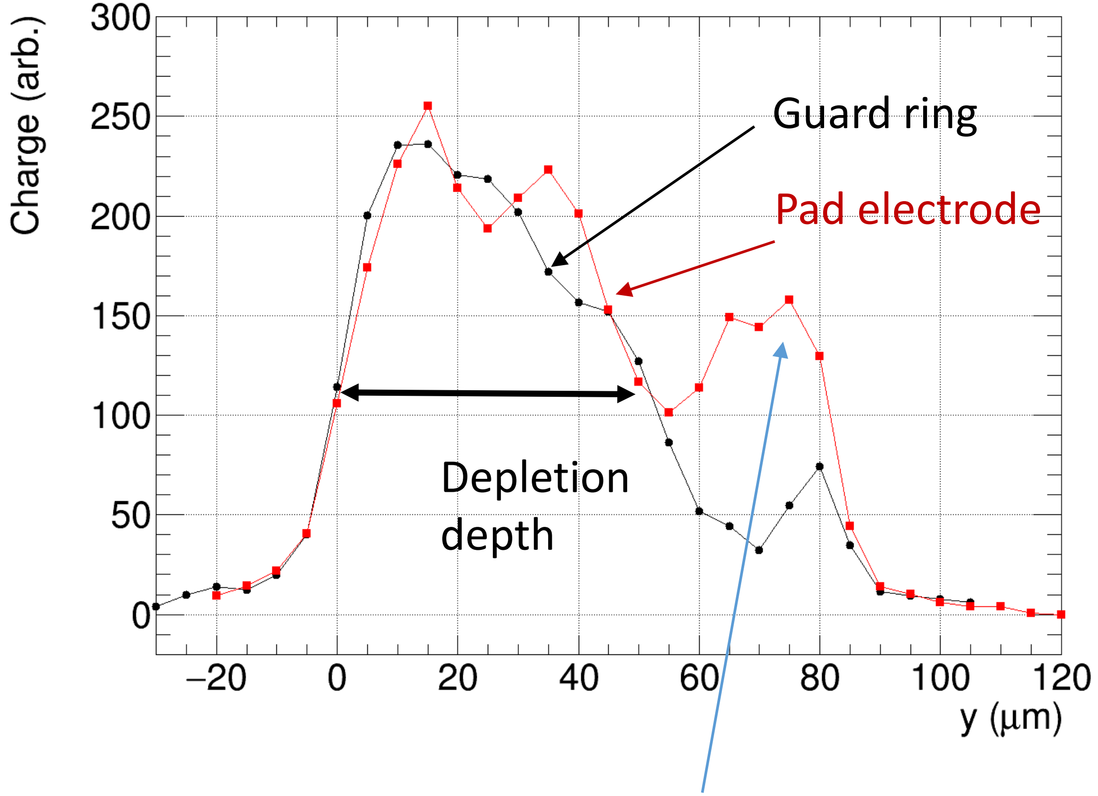
→ No signal on pad electrode before depletion of multiplication layer





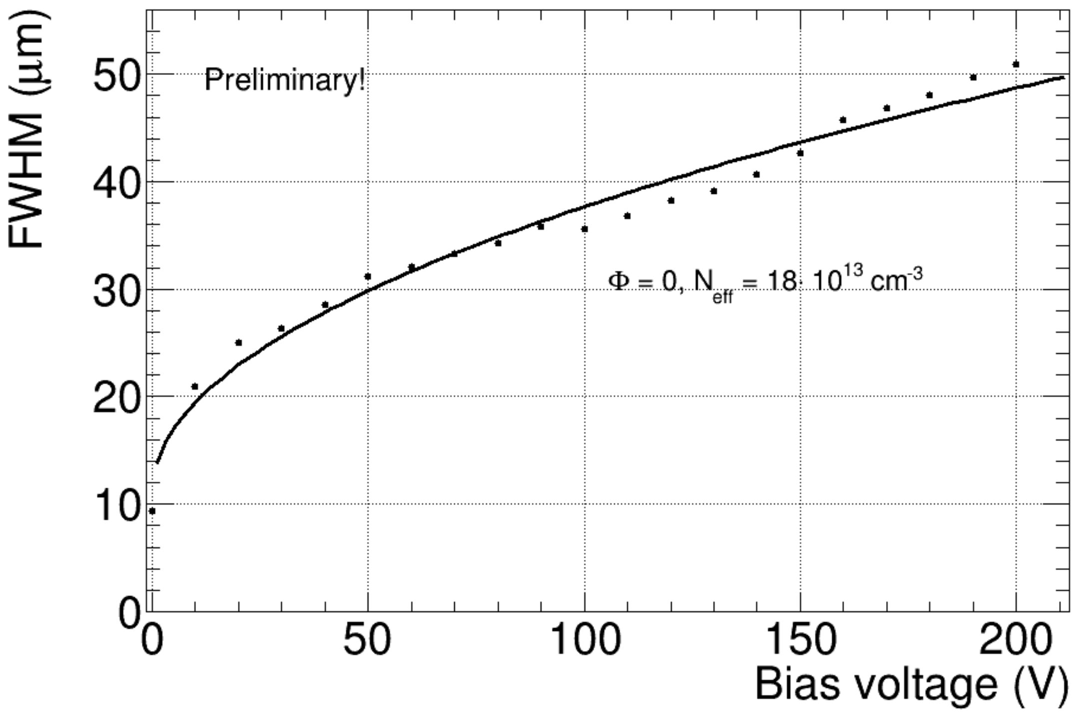
Edge- TCT

Not irradiated
Bias = 200 V



Field at the back, effect enhanced in E-TCT because of large pad electrode

➔ Measure depletion depth on guard ring



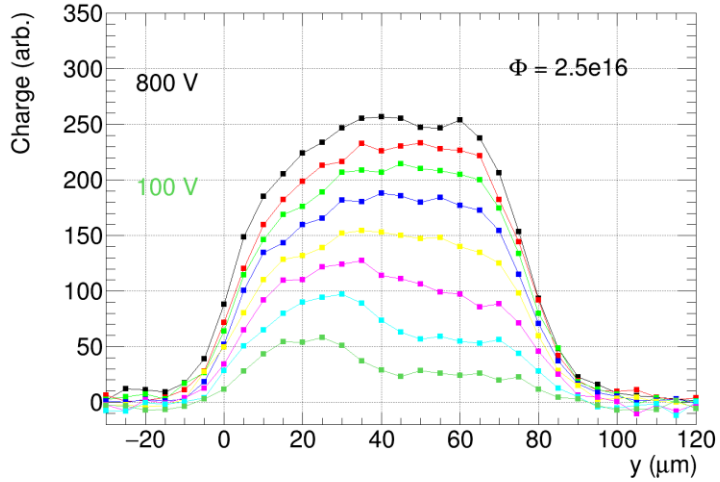
N_{eff} = 1.8e14 cm^{-3} → Resistivity ~ 70 Ωcm

Nominal: resistivity 100 Ωcm → N_{eff} = 1.3e14 cm^{-3}

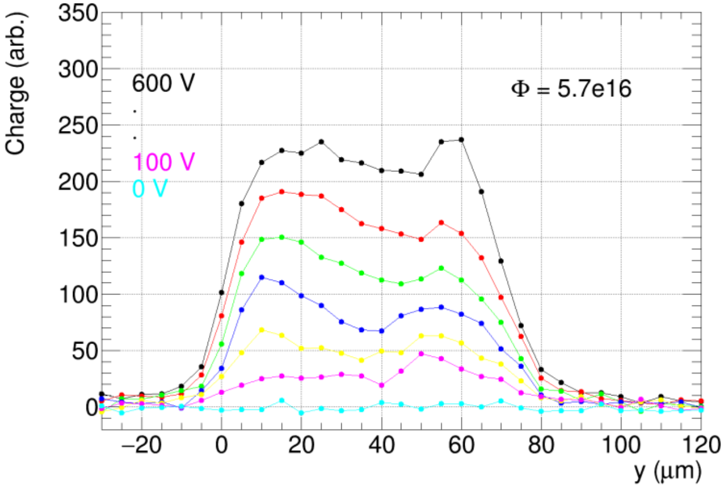
E-TCT, irradiated detectors

- electric field across epitaxial layer already at 100 V in reverse or forward bias
- no charge from low resistivity substrate

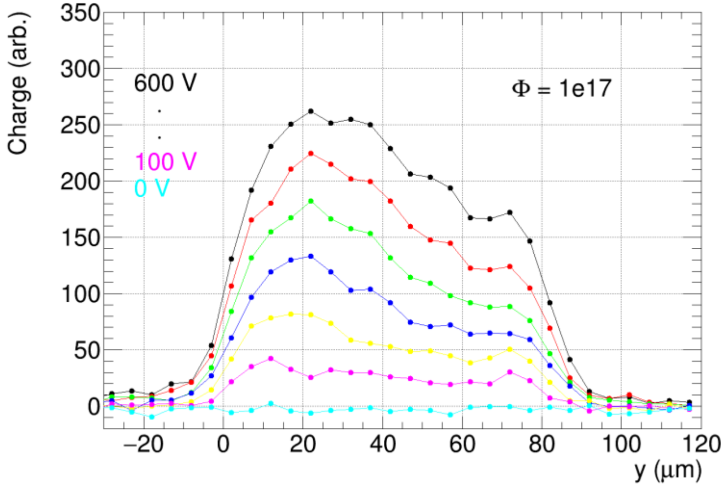
2.5e16

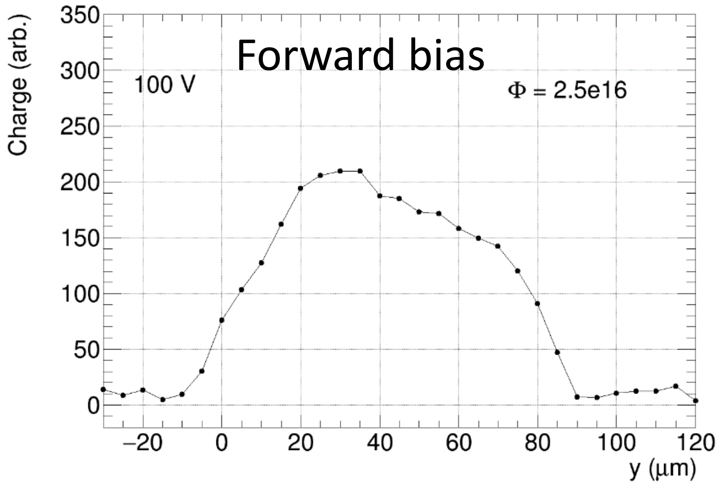


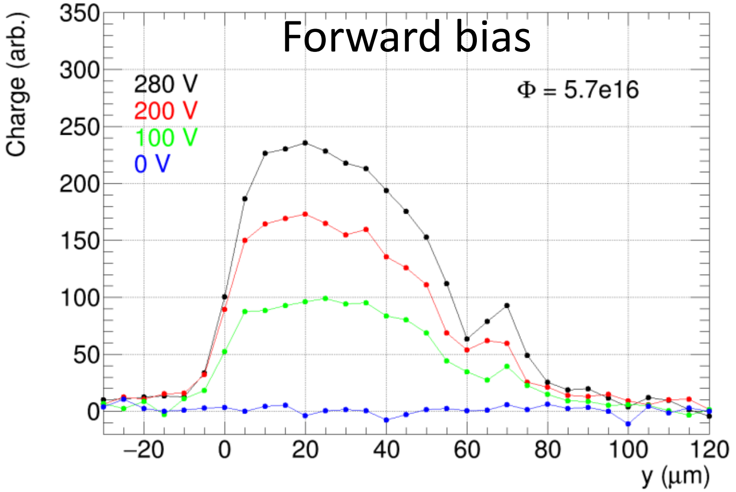
5.7e16

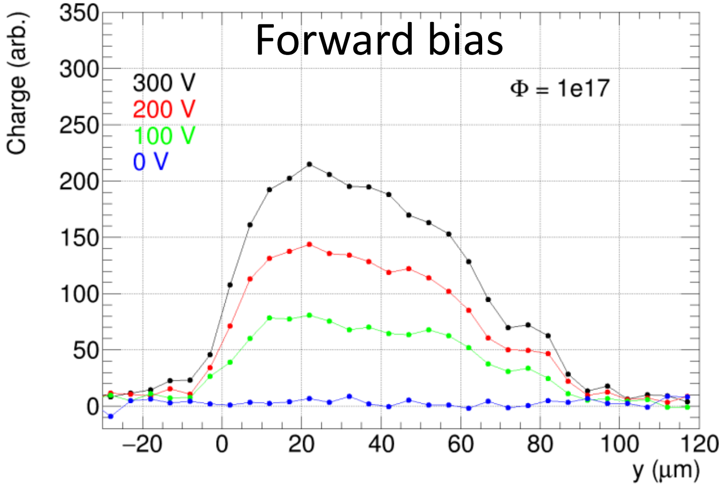


1e17



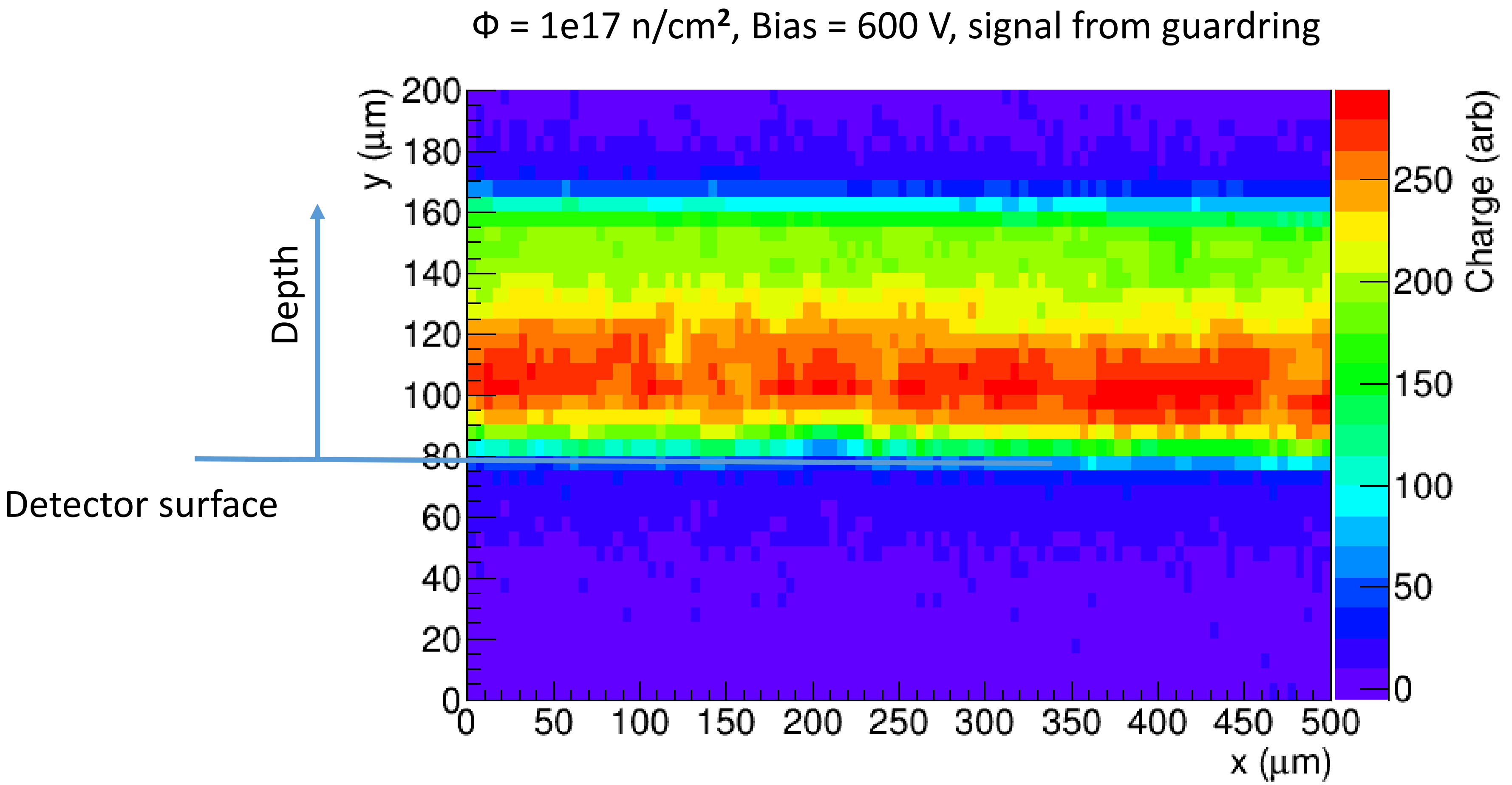


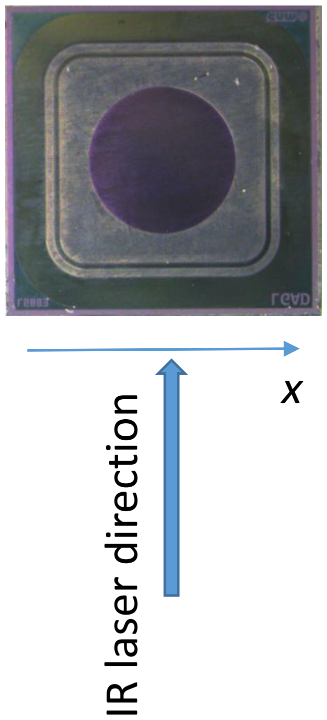




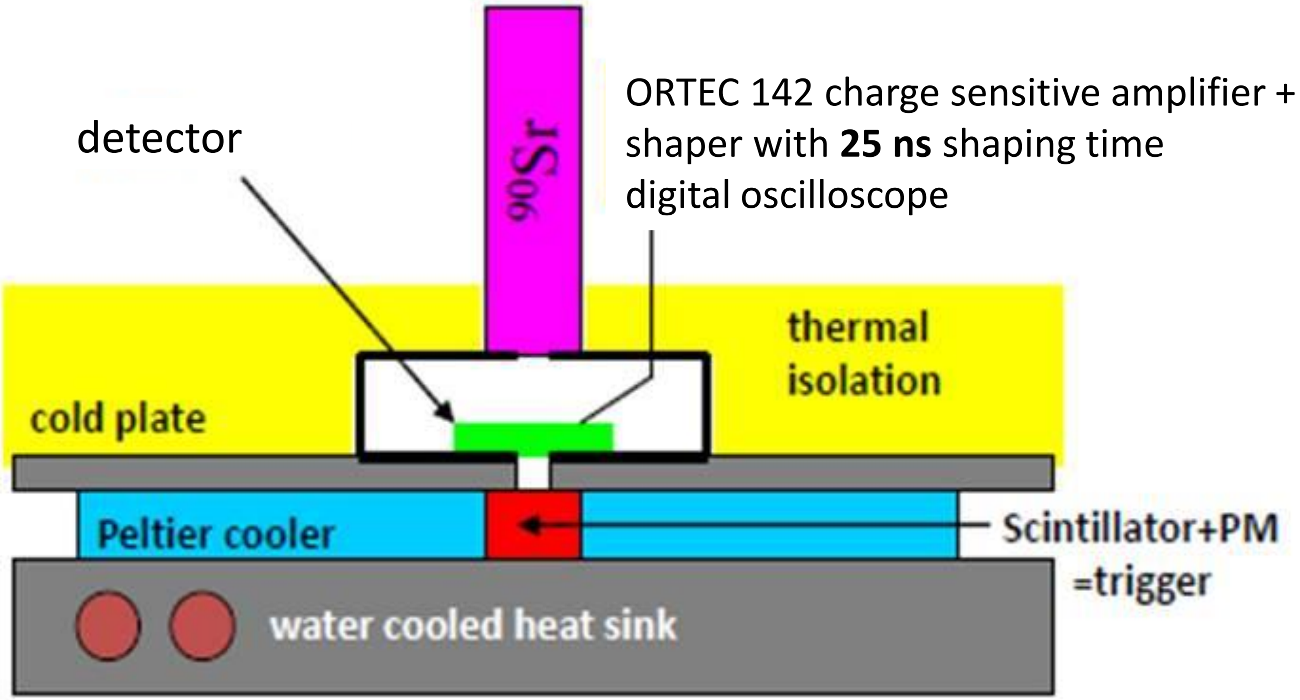
E-TCT

- uniform response across x direction





Charge Collection measurements with Sr-90



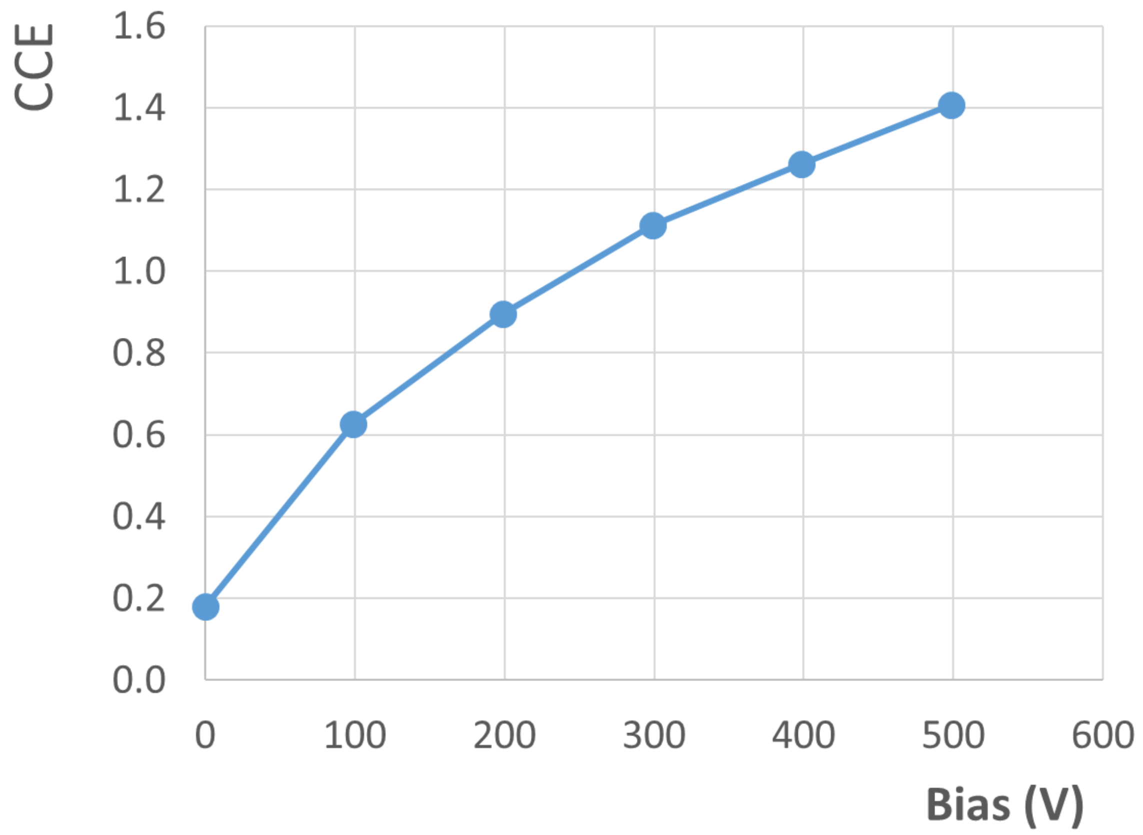
- large (3x3 mm) pad detector and small collimator holes enable recording of a clean sample of waveforms ➔ no "empty triggers" → can measure average charge after passage of Sr90 electron also at small signal/noise

Modified for very high fluences: a) replaced bias resistor in ORTEC 142 ➔ 1 MΩ instead of 10 MΩ
b) improved cooling (measure at -30°C)

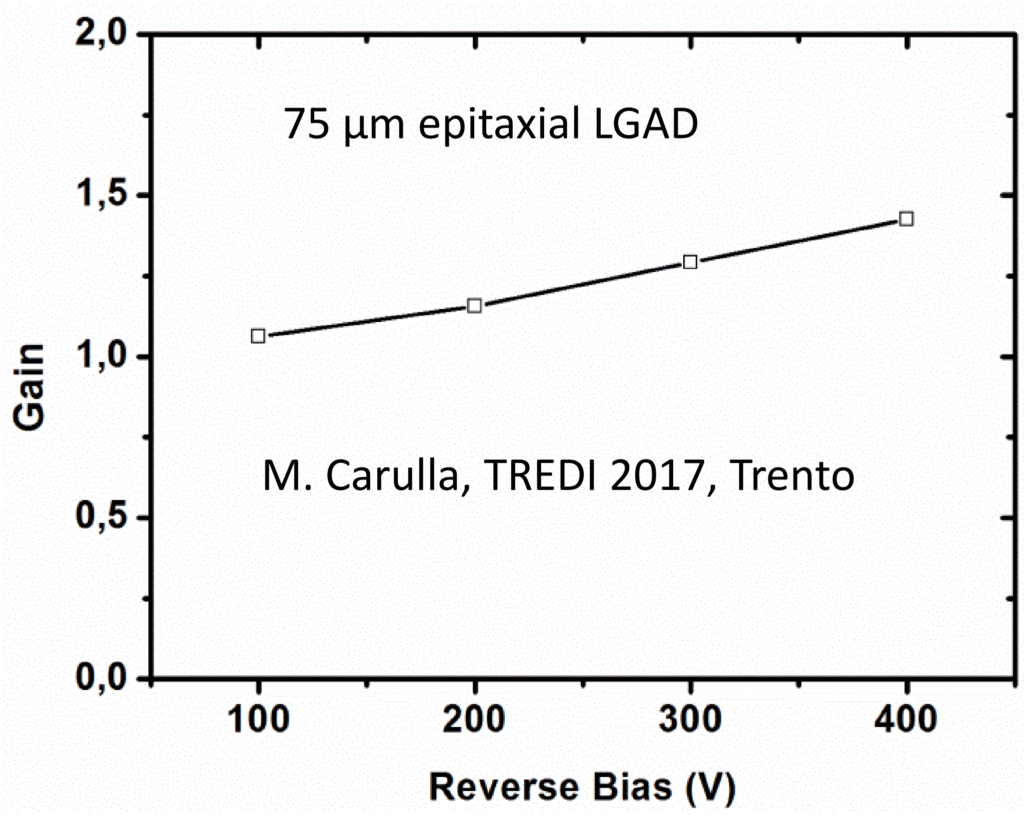
Charge Collection measurement with Sr-90

- LGAD, 75 µm, relatively low gain
- setup not optimized for low noise, low charge after irradiation → mean charge instead of MPV

➔ CCE = measured_mean/7500 el



Measured with alpha source:



Charge collection

- G. Kramberger *et al,* 2013 *JINST* **8** P08004
  300 µm spaghetti, Φ > 1e15, up to 1.6e17:

$$Q_{MPV} = k \cdot \Phi^{b} \cdot V,$$

k = 26.4 el/V, b = -0.683
(Φ in 1e15 n/cm^2, V in volts)

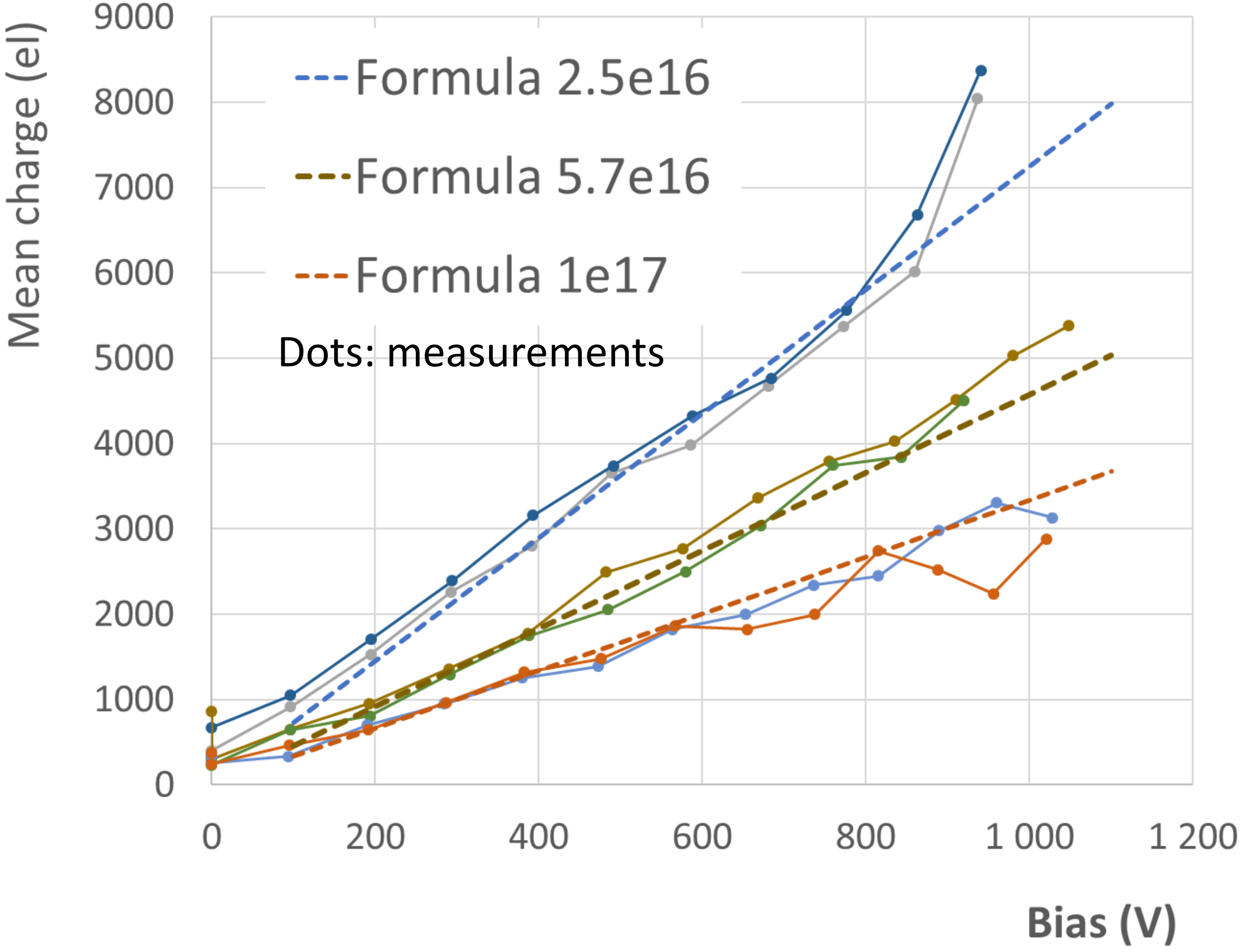
- more charge at same bias voltage with thinner detectors

➔empirical formula adapted for 75 µm detectors:

$$Q_{mean\_75um} = k \cdot \Phi^{b} \cdot V$$

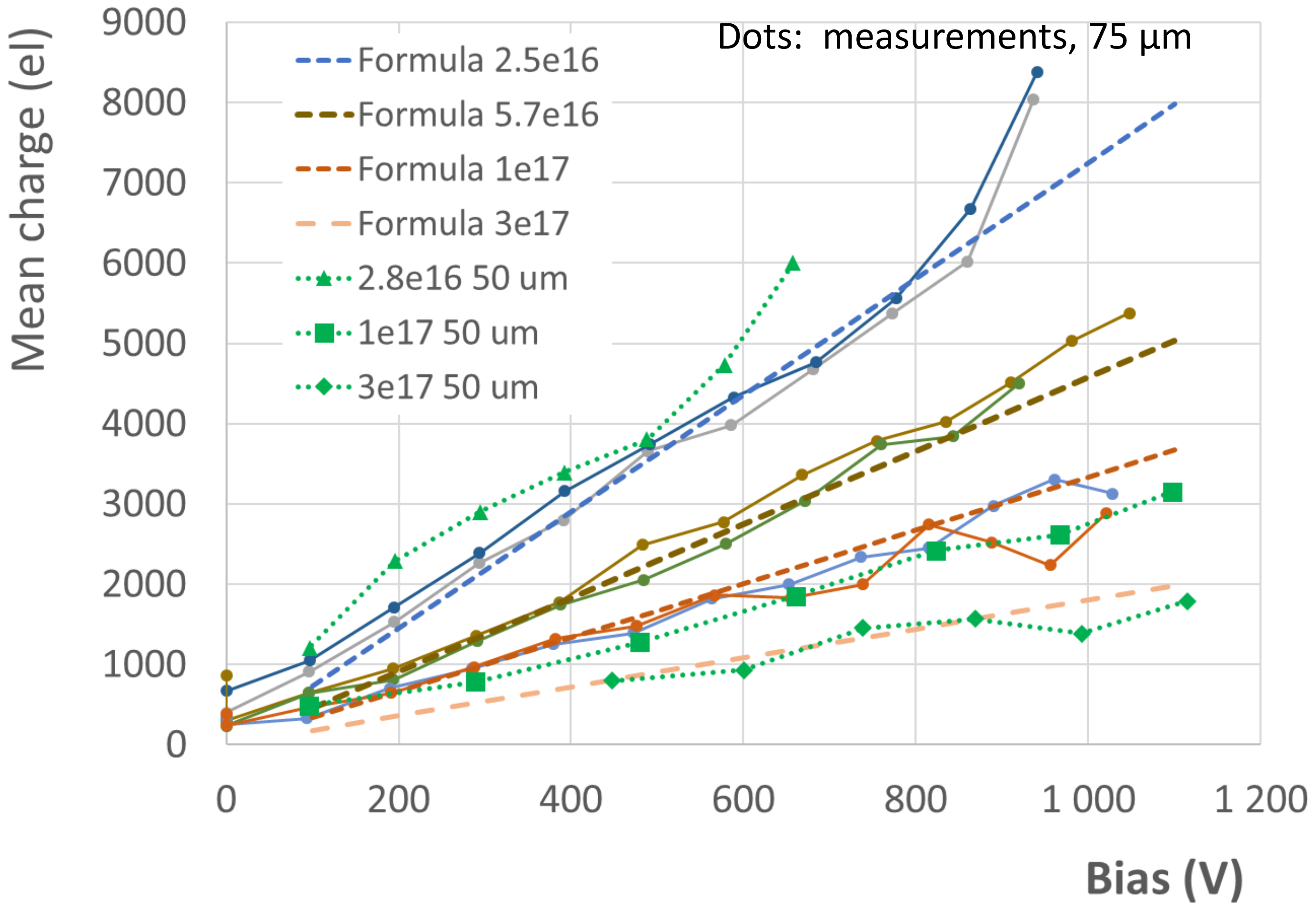
k = 44 el/V, b = -0.56
(Φ in 1e15 n/cm^2, V in volts)

Annealed 80 minutes

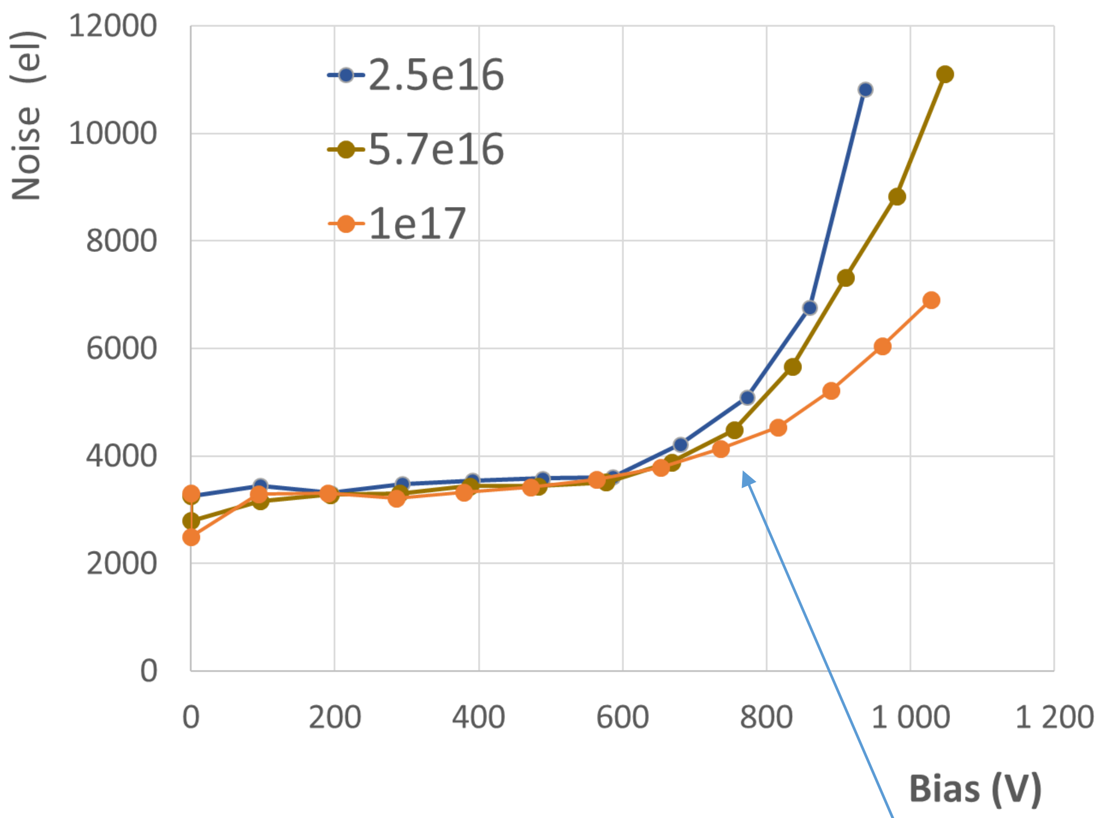


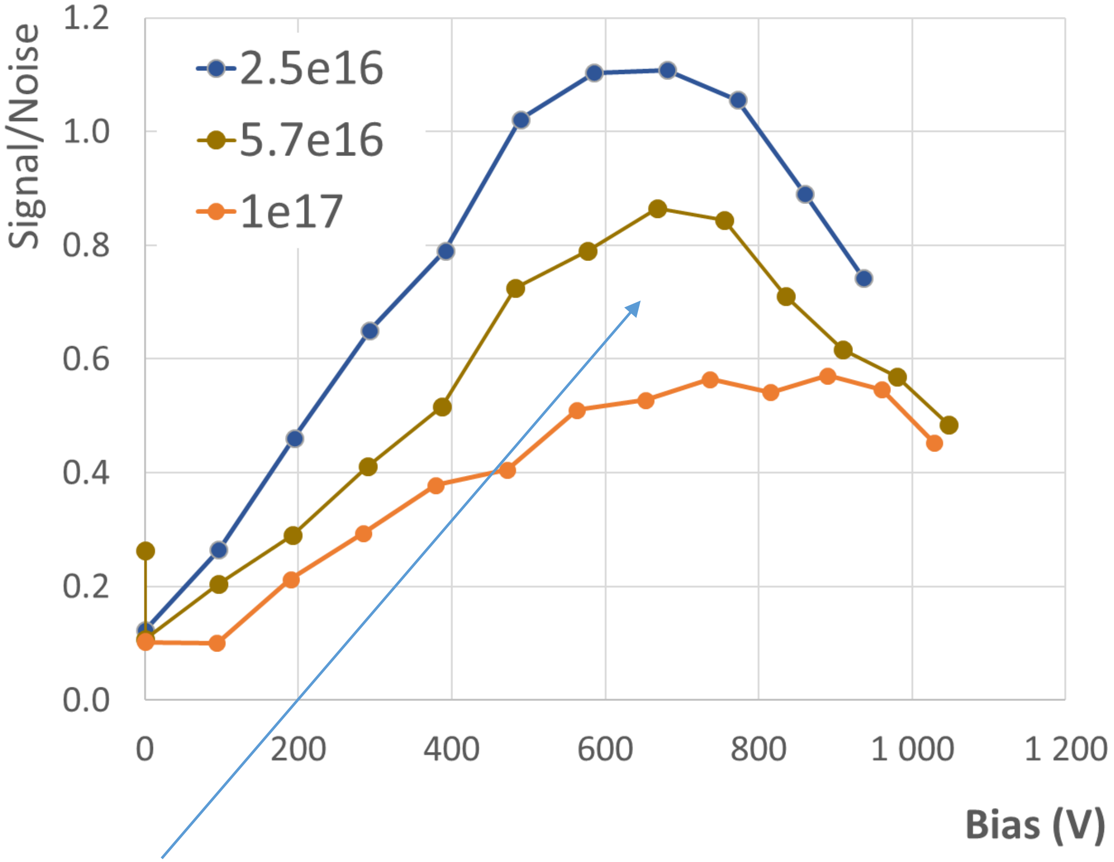
Compare with 50 µm LGAD

- 50 µm epitaxial LGAD (see https://indico.cern.ch/event/719814/contributions/3022499)
  - ➔ not very different than 75 um
  - ➔ can be approximated with the same empirical formula, up to 3e17



Charge collection – noise

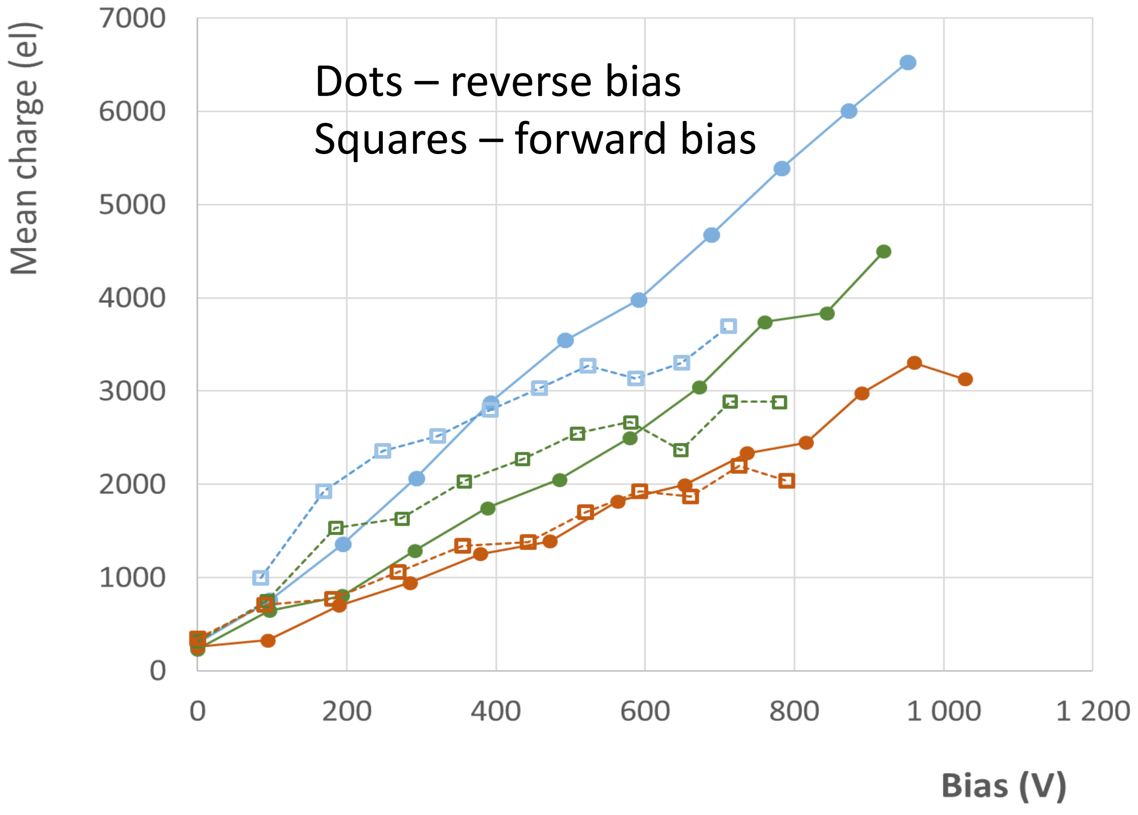


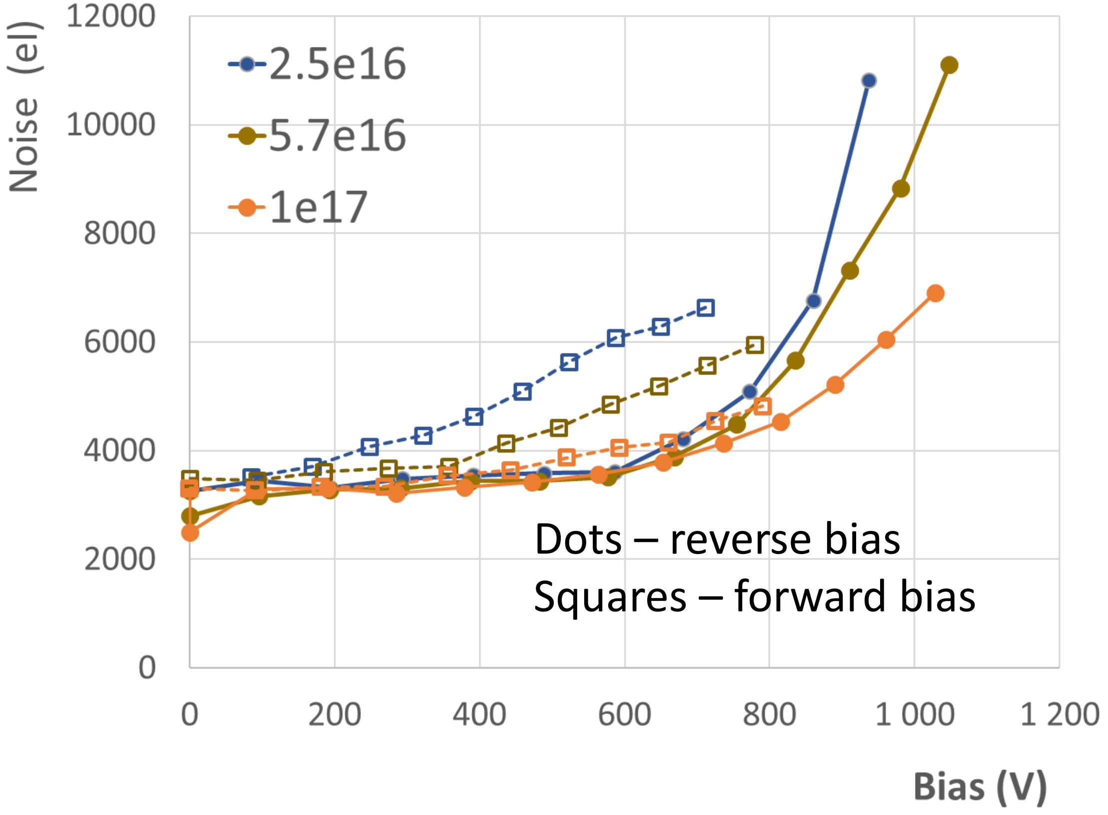


➔ not useful to bias far above ~ 700 V because of noise increase

- current increases, multiplication
- noise increase larger at lower fluence → higher multiplication factor

Forward bias

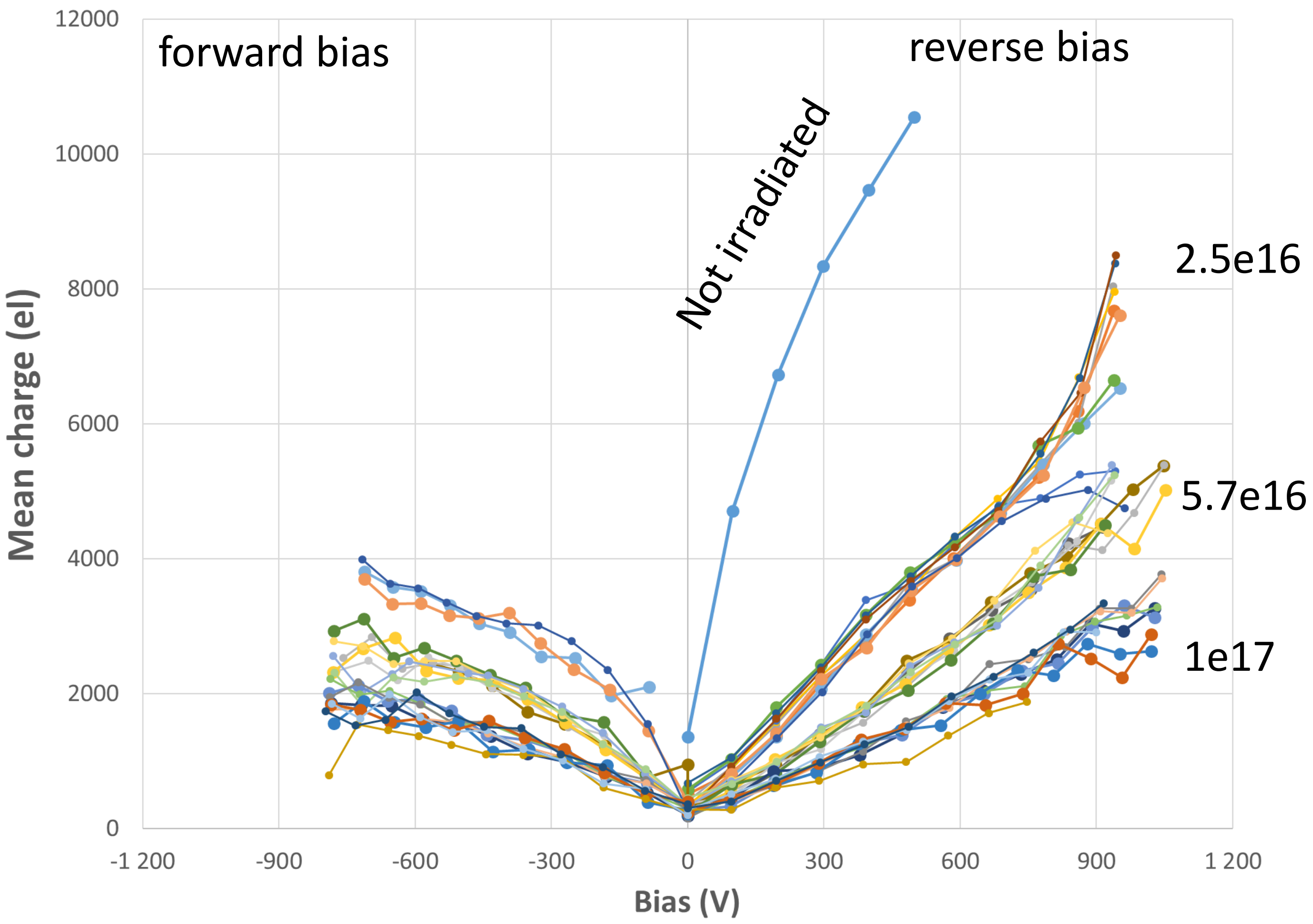




- For lower fluence at lower forward bias voltages somewhat more charge than in reverse bias
- at 1e17 not much difference
- lower current in reverse bias → can go to higher bias voltages
  - ➔ better performance under reverse bias
  - ➔ difference smaller at higher fluence

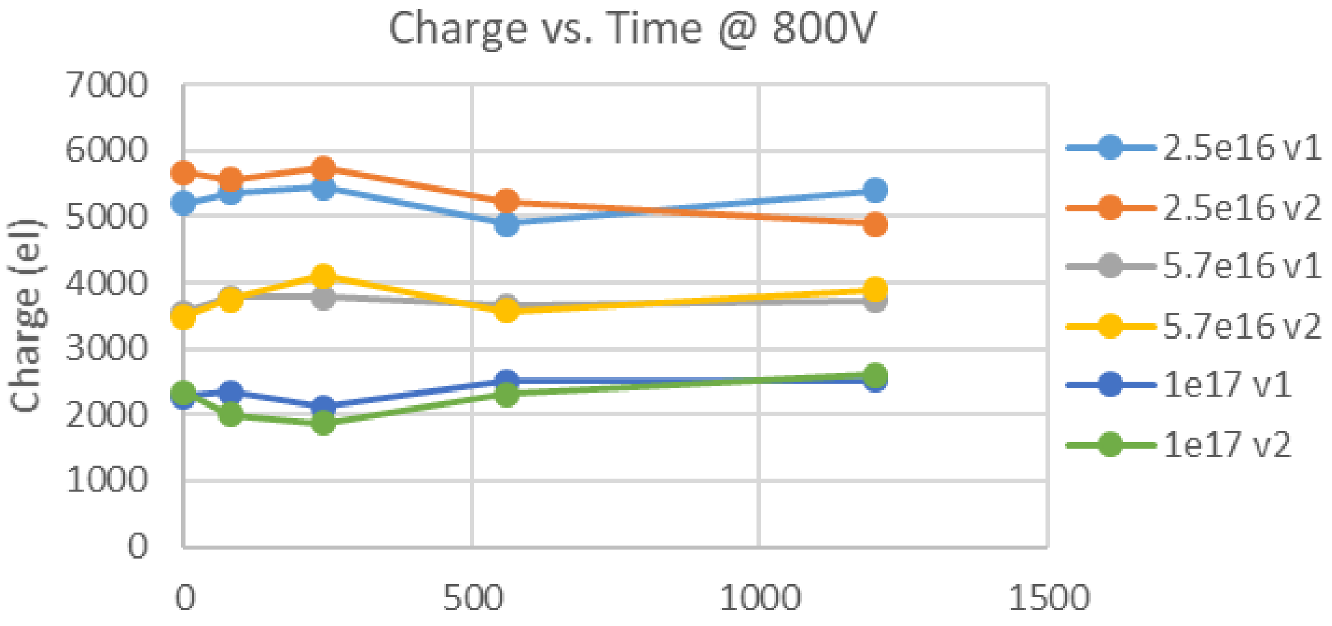
Charge collection - annealing

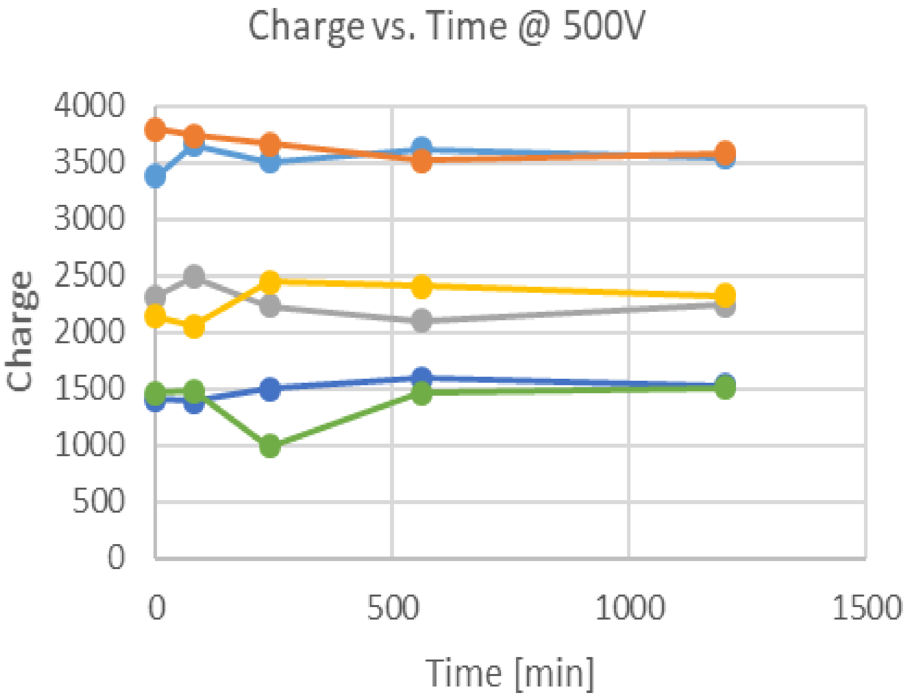
All measurements, different annealing times

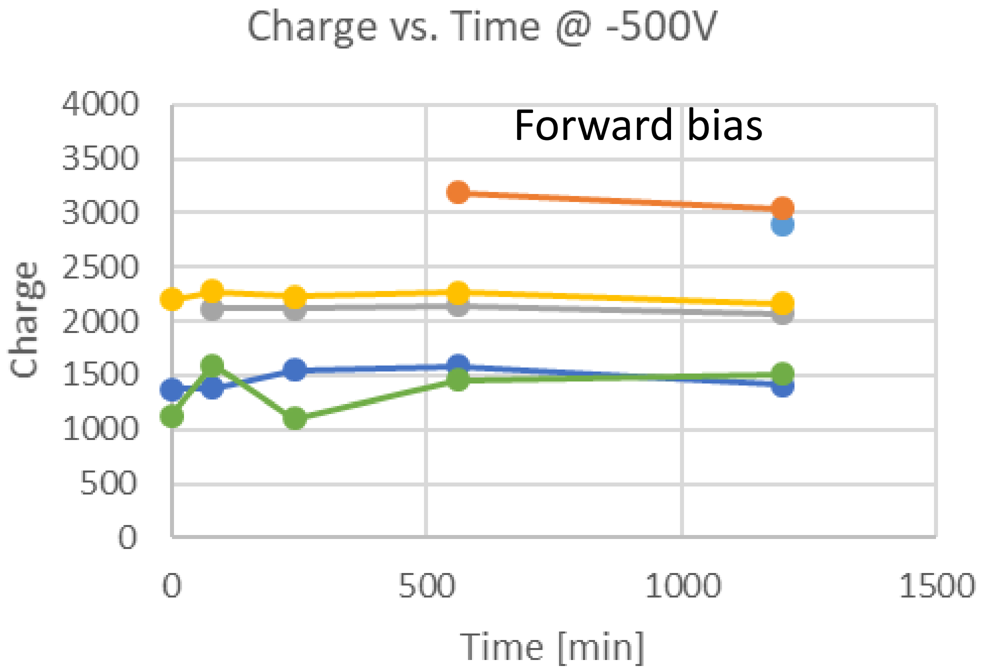


Annealing: collected charge

➔ not much annealing



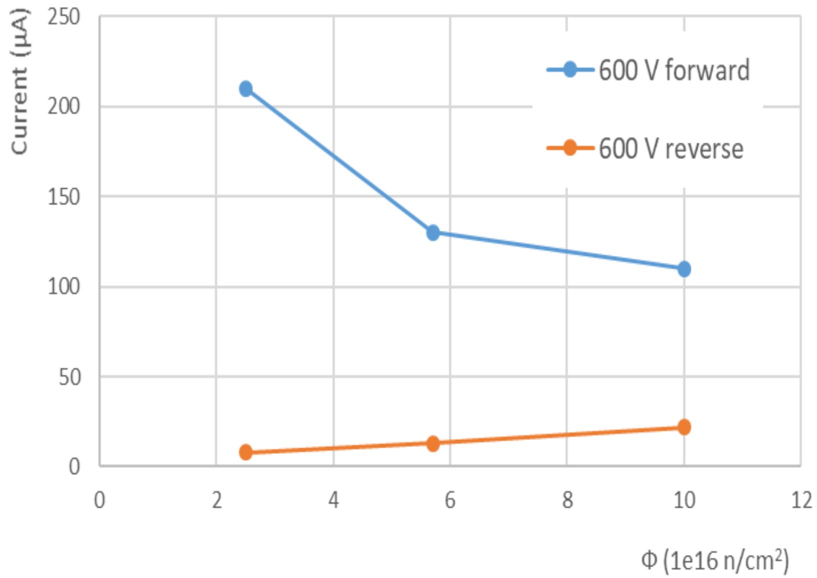


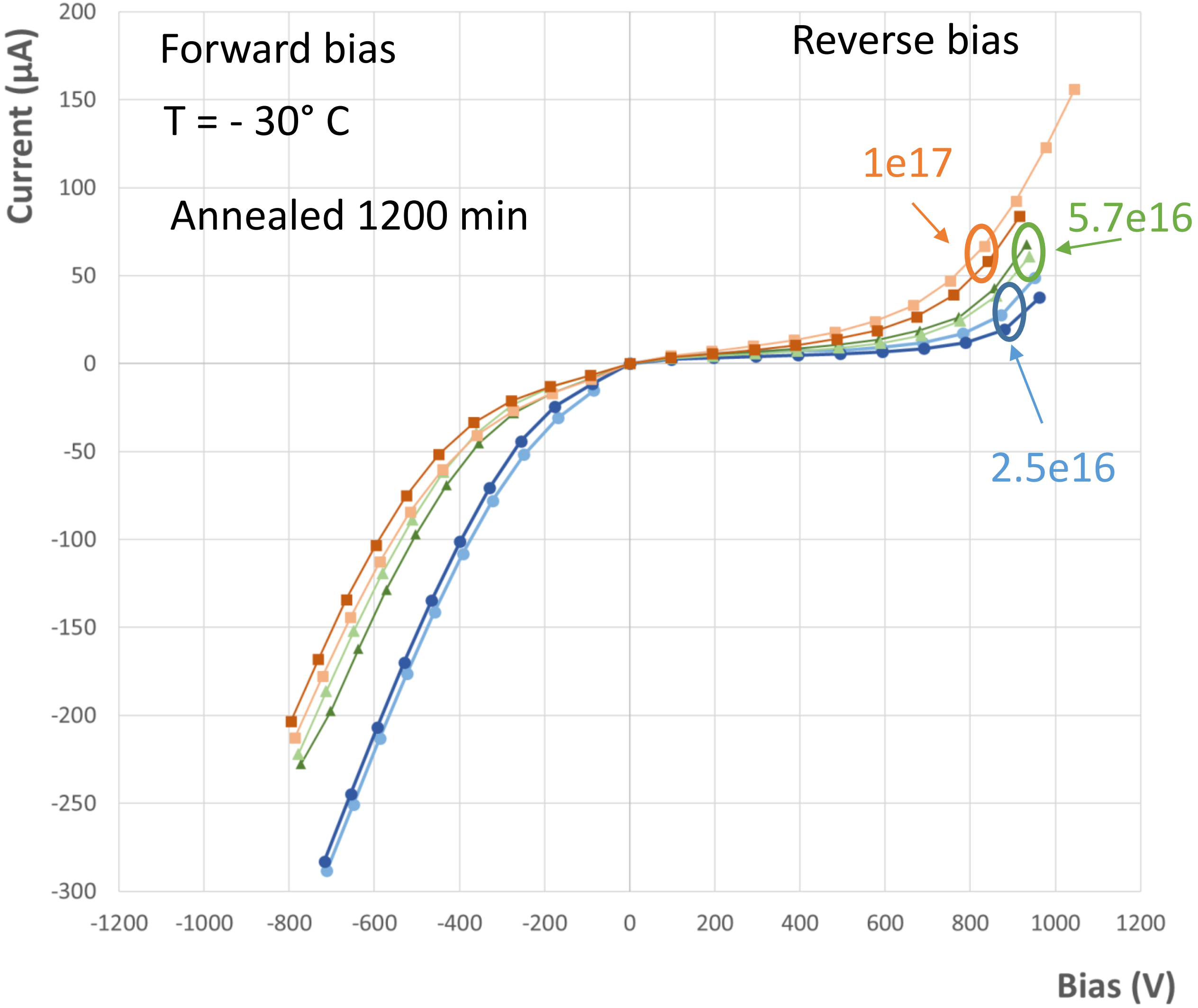


Current

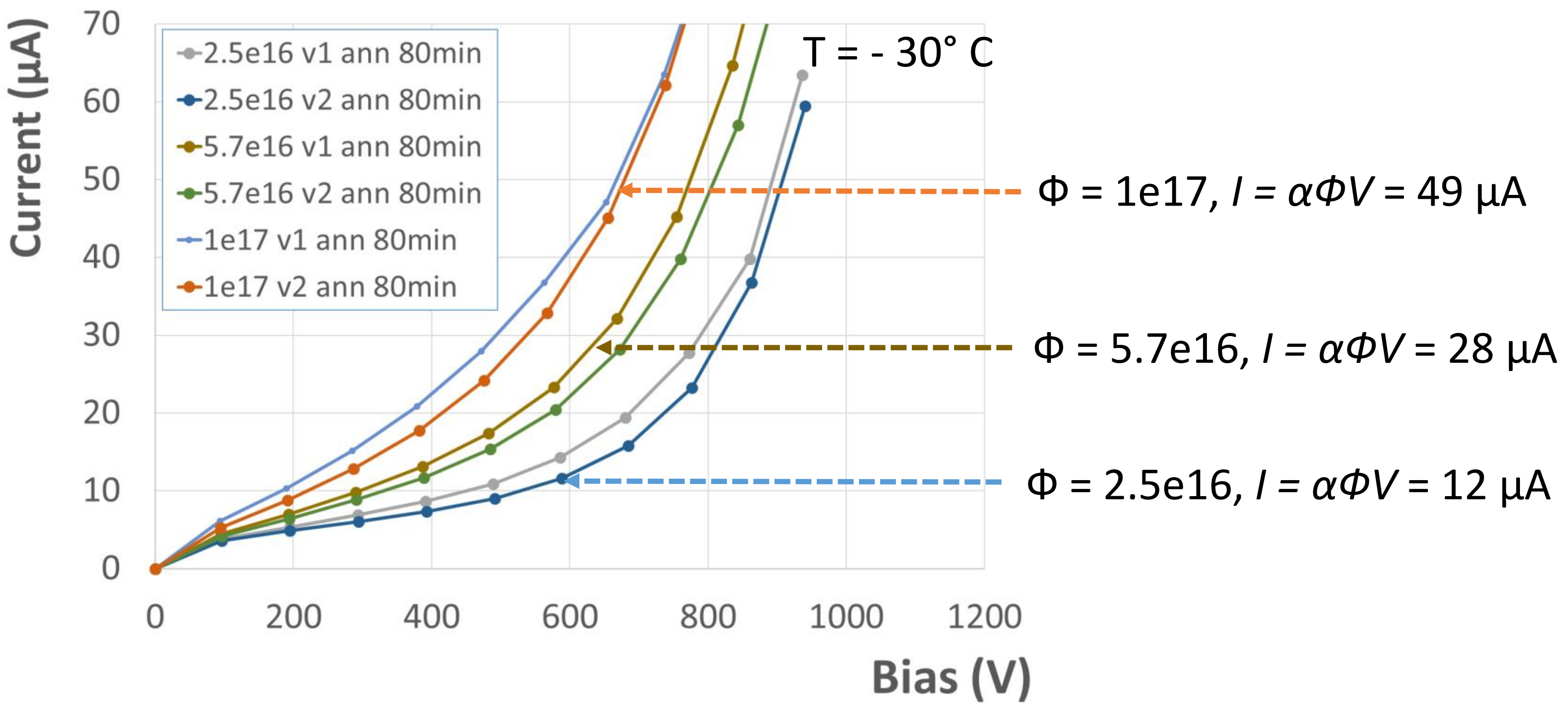
- reverse bias:
  current increases with increasing fluence
  → increase of generation current

- forward bias:
  current decreases with increasing fluence
  → increase of resistance because of
  less free carriers, decrease of mobility





Current



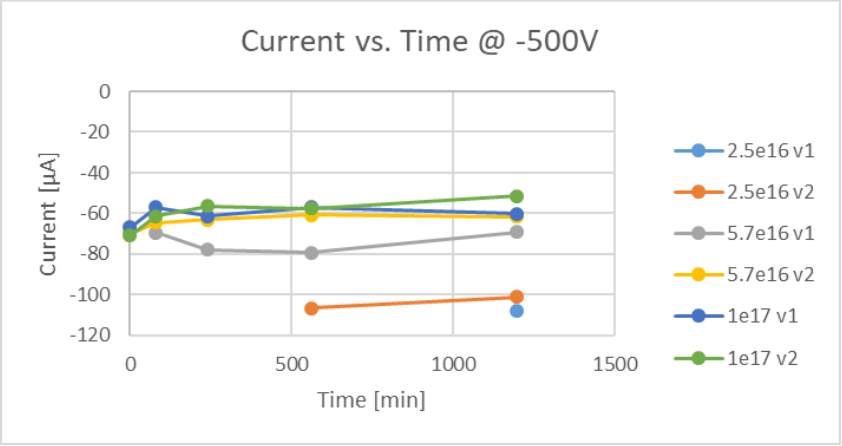
- E-TCT: field in the whole detector volume at low bias but current not generated in the whole detector volume
- current increases with bias
- above ~600 V current higher than calculated from $\alpha = 4e\text{-}17\ \mathrm{Acm^{-1}}$
  → noise in charge measurement starts to increase sharply above ~ 600 V → multiplication, breakdown

Annealing of current (reverse bias)

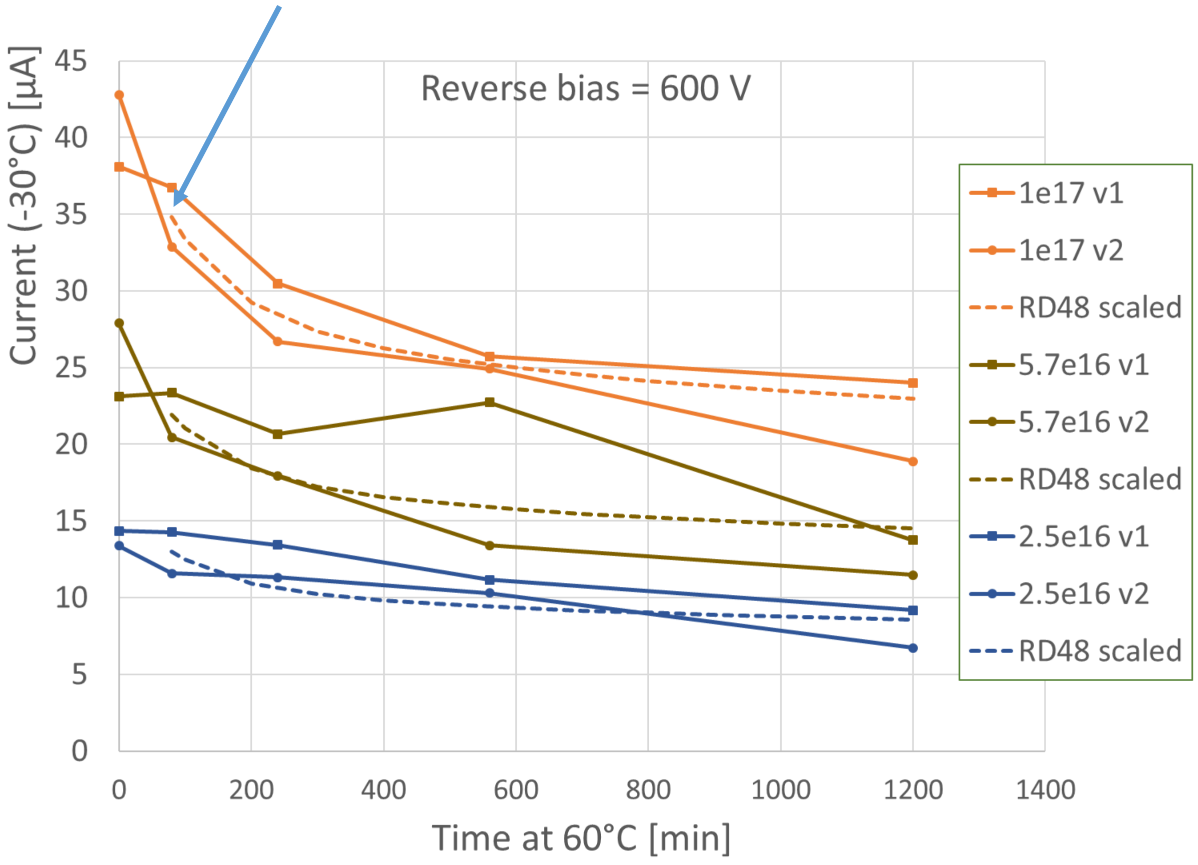
- roughly follows the shape of annealing curve: $\alpha = \alpha_1 e^{-\frac{t}{t1}} + (\alpha_0 - \beta \ln t)$
  RD48 values: α_1 = 1e-17 Acm^{-1}, t_1 = 93 min, α_0 = 5e-17 Acm^{-1}, ß =3.3e-18 Acm^{-1}

→ annealing during irradiation
(irradiation time 4 h, T > 40° C,
temp. probably higher for higher fluences)

Forward bias
→ annealing effects small



Points at t = 80 min set by hand to match data



Summary

- measurements with 75 um thick epitaxial LGAD irradiated 2.5e16, 5.7 e16 and 1e17

- E-TCT:
  - before irradiation: as expected, observed LGAD depletion behavior
  - after irradiation response across whole detector thickness already at 100 V in reverse or forward bias
  - no signal from low resistivity substrate

- Charge collection measurements with Sr-90:
  - charge scales with fluence and voltage as: $\boldsymbol{Q_{mean\_75um} = k \cdot \Phi^{b} \cdot V}$ (k = 44 el/V, b = -0.56, Φ in 1e15 n/cm^2, V in volts)
    → can be used up to 3e17 n/cm^2, approximately OK also for 50 µm LGADs
  - at high bias voltage sharp increase of noise
    → detector can be operated up to ~ 600 V reverse bias, ~ 2000 el (mean) collected at 1e17 n/cm^2
  - better charge collection in reverse bias than in forward bias
    → differences get smaller at higher fluences
  - change of collected charge by annealing at 60°C up to 1200 minutes not very significant in these measurements

- Current
  - reverse current increases with fluence, forward current drops
  - reverse bias: linear increase with bias voltage up to ~ 600 V, sharp increase after that ,
    anneals approximately with RD48 time constants
  - Forward bias: higher current than reverse bias, differences get smaller with increasing fluence, not much annealing seen