Annealing and Characterization of Low Gain Avalanche Detectors

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33[rd] RD50 workshop, CERN November 2018

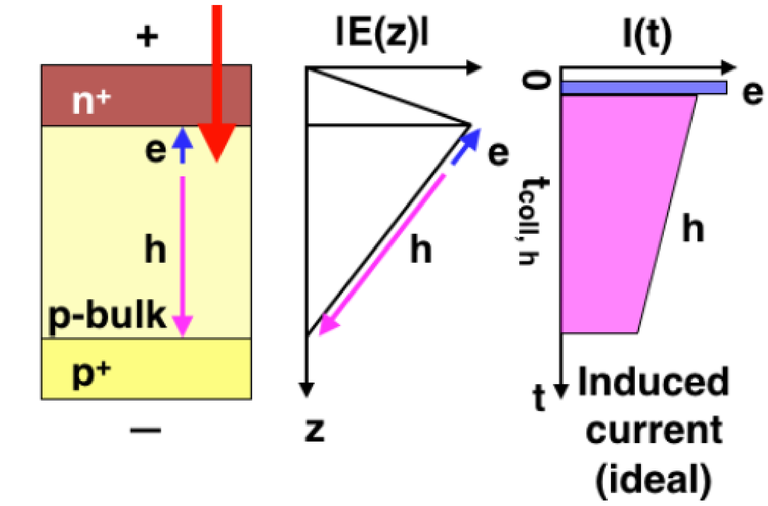
Outline

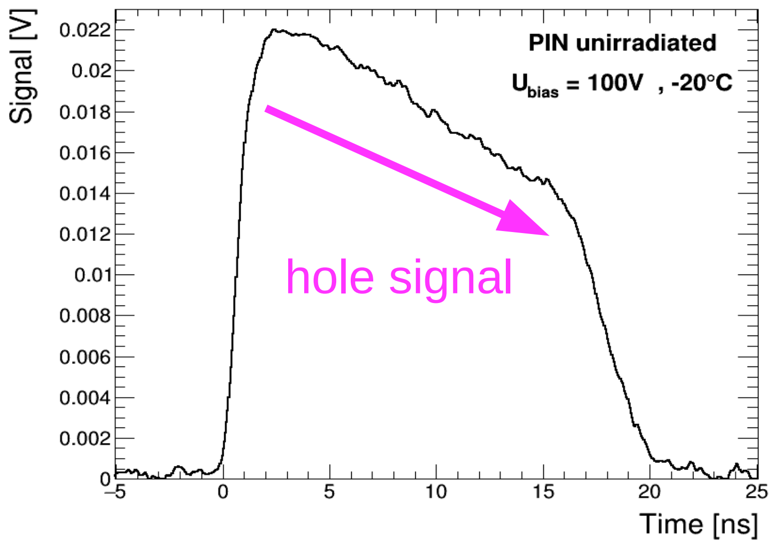
- Introduction:

  Samples, setup and previous studies
- Gain after annealing
- Onset voltage for IV and TCT measurements
- E-Field profile after annealing
- Conclusions

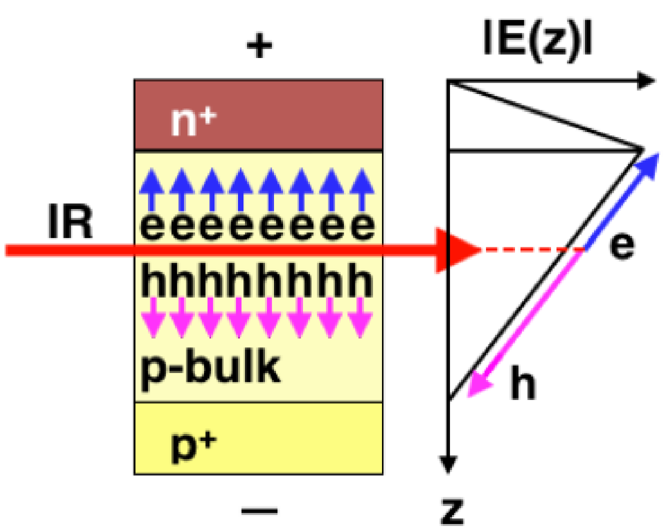
TCT - Transient Current Technique

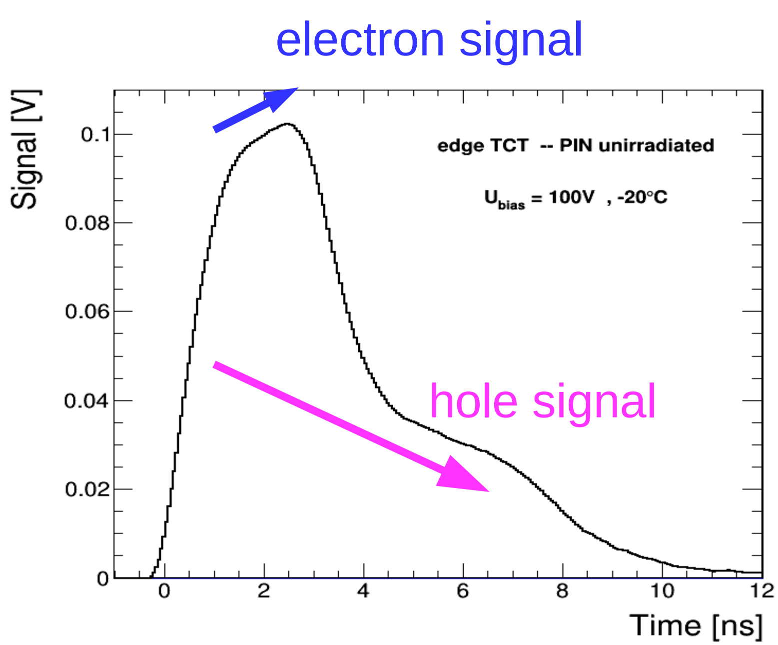
Red Front TCT





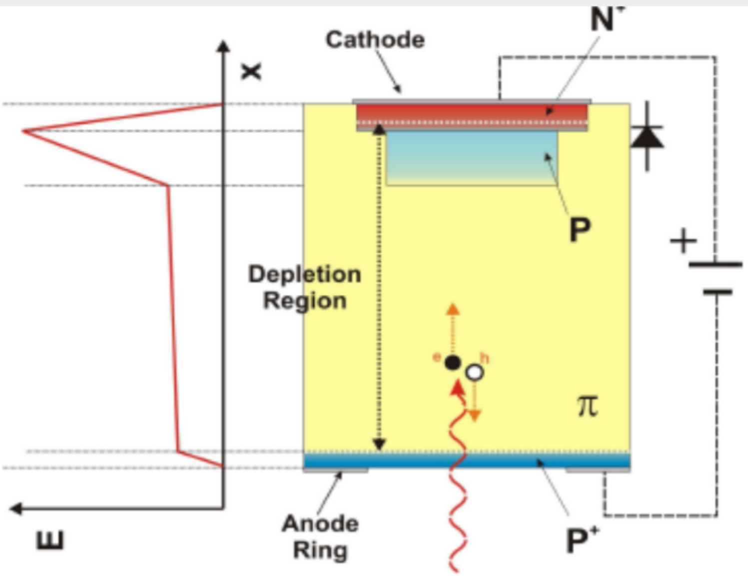
IR edge-TCT



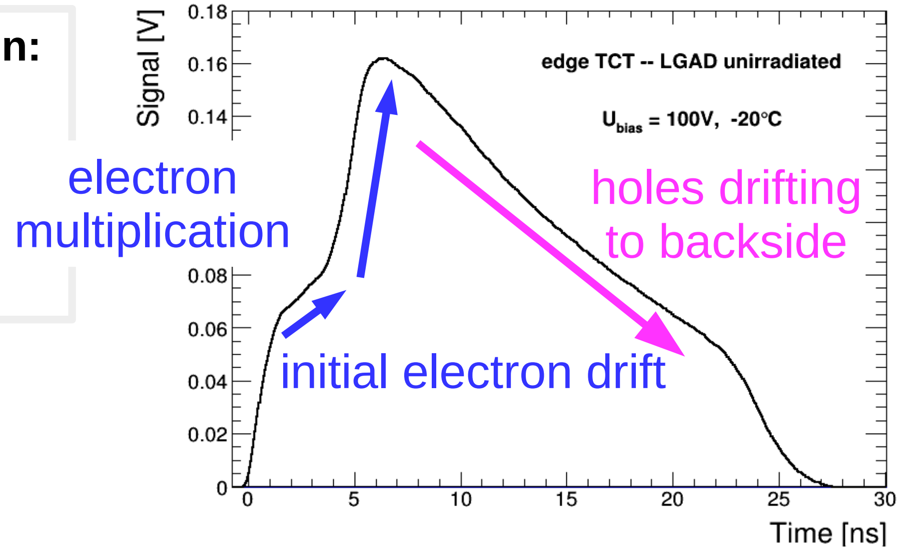


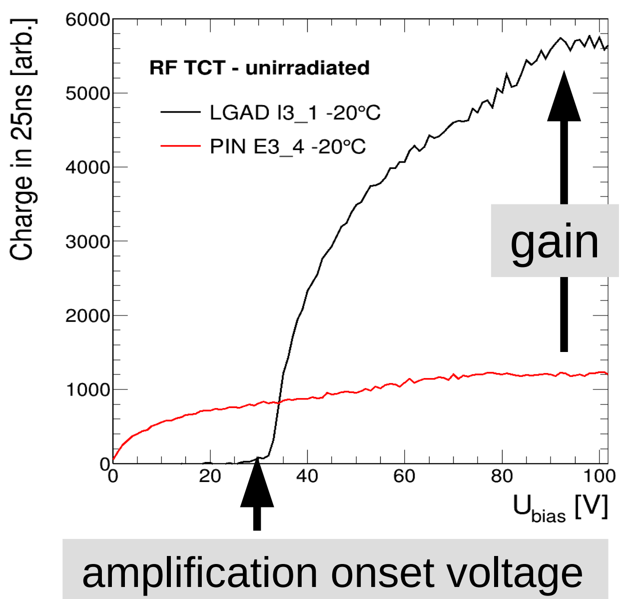
Low Gain Avalanche Detectors

LGADs are based on APDs but have lower gain:
.. optimal S/N ratio
.. reduced cross-talk among neighboring strips/pixel
.. limited collection times



M. Carulla,
Low Gain Avalanche Detectors





Depletion of p^+-multiplication layer at ~ 30V
Full depletion of device at ~ 70V - 100V

Radiation Effects

Acceptor Removal

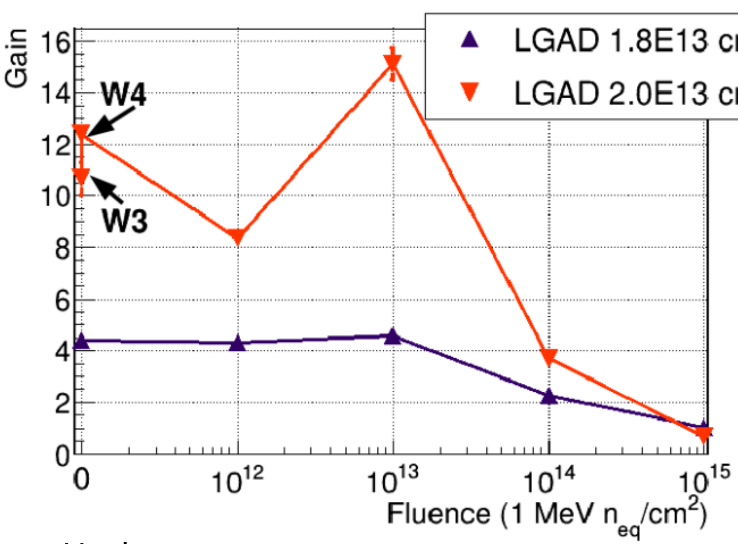
- yet to be fully understood
- believed to be originating from dislocated acceptors (boron) forming complex states with oxygen (B_iO_i)

→ boron electrically deactivated

→ N_{eff} decreases

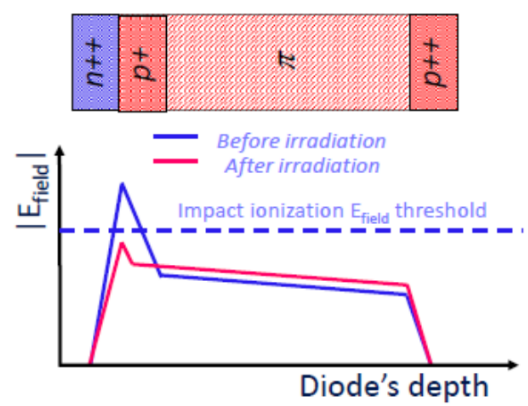
Deterioration of Electric Field

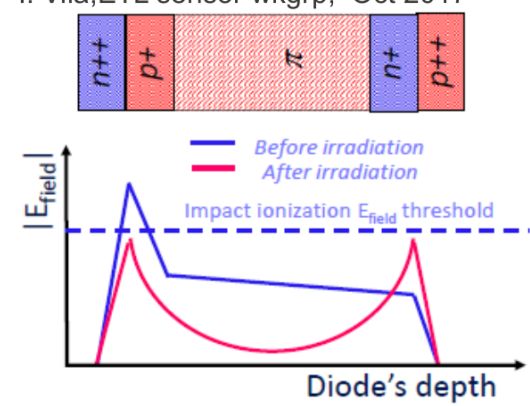
- trapping of charge carriers in bulk material alters electrical properties
- can lead to space charge sign inversion
- creating apparent junction at the back side of the detector

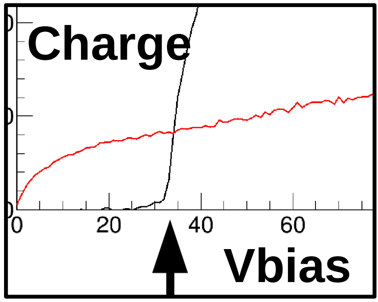


S. Otero Ugobono

I. Vila,ETL sensor wkgrp, Oct 2017



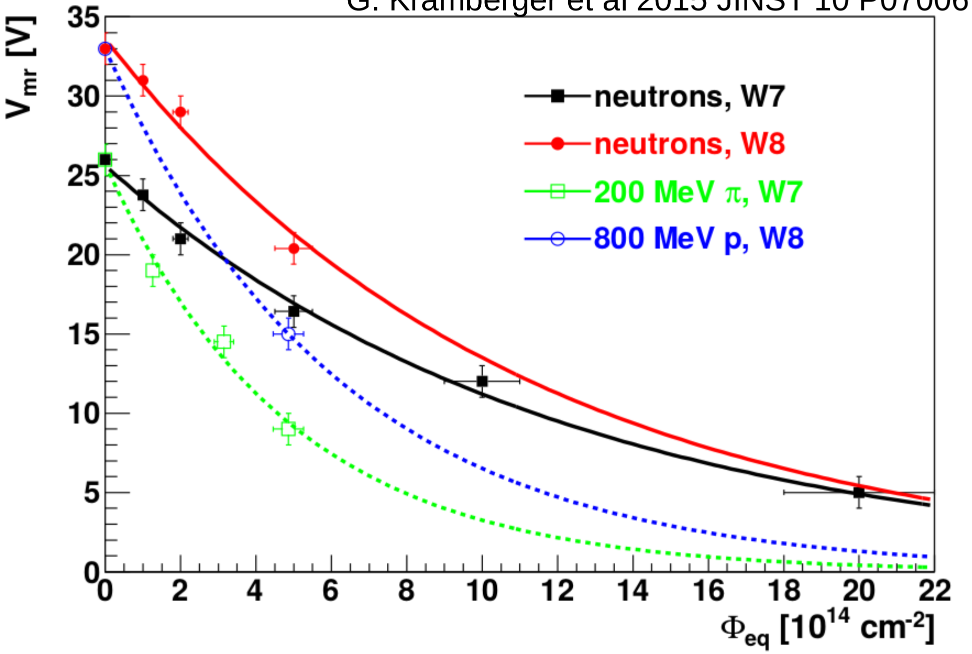




Previous Studies

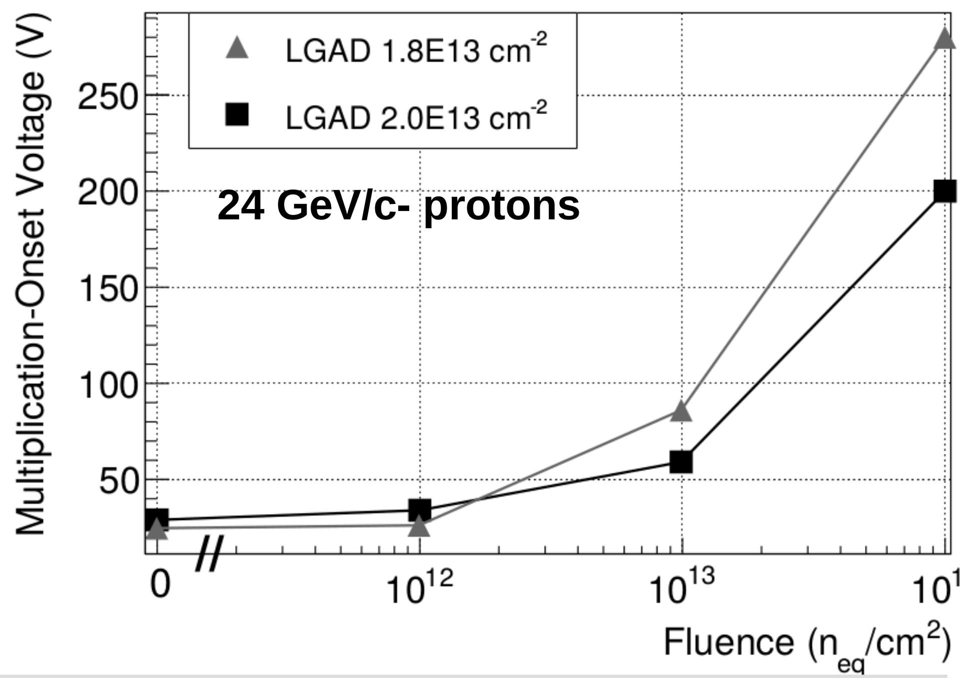
Gregor Kramberger, 2015:
Radiation effects in Low Gain Avalanche Detectors after hadron irradiations

G. Kramberger et al 2015 JINST 10 P07006



Acceptor removal in p+ layer
- decreasing onset voltage (V_{mr})
- no temperature dependence

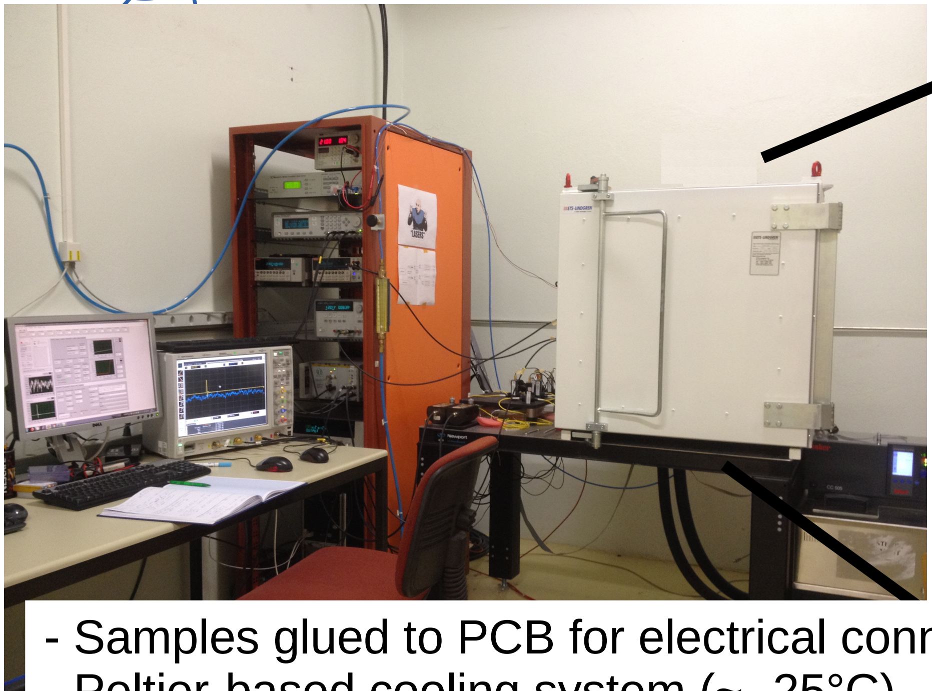
Sofía Otero Ugobono, 2018:
Characterisation and Optimisation of Radiation-Tolerant Silicon Sensors with Intrinsic Gain

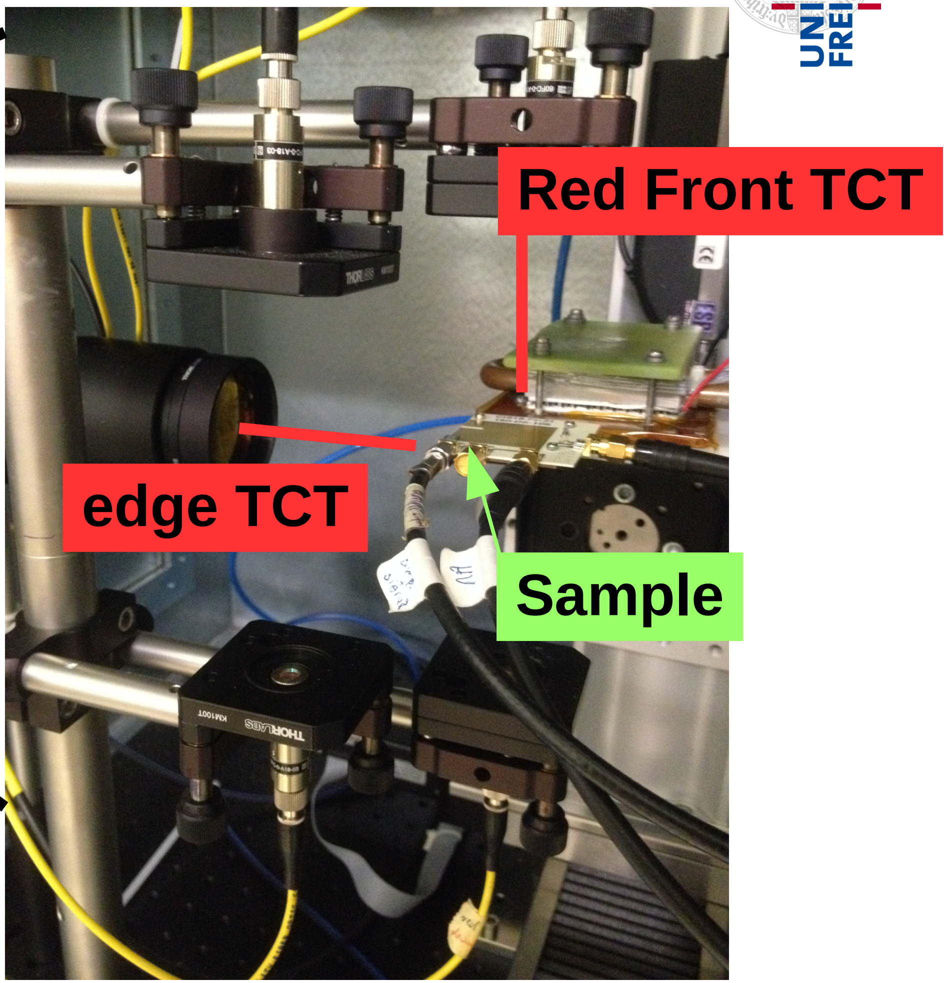


Double junction effect
- increasing onset voltage
- strong temperature dependence

samples annealed at 60°C for 80min before characterization

TCT+ setup at CERN





- Samples glued to PCB for electrical connection
- Peltier-based cooling system (~ -25°C)
- Temperature sensor attached to PCB
- 3D stage system to align laser and sample

Two laser heads:
- Red (top and bottom measurements)
  λ=660nm
- Infrared (edge + top/bottom)
  λ=1064nm

LabView based DAQ and control

CERN – SSD TCT+ (B186)

Christian Gallrapp, "The TCT+ setup - a system for TCT, eTCT and timing measurements", 1st TCT Workshop DESY

LGAD Annealing Study - Samples

- Two **LGADs** from **CNM** Run 8622, Wafer 5

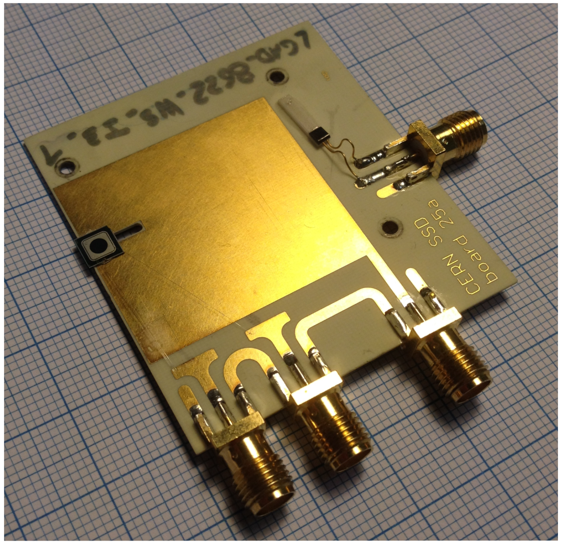
  ‘E3_1’, ‘I3_1’

  Amplification layer: ‘medium dose’

- **PIN** diode, Run 8622, Wafer 5

  ‘E3_4’

  no amplification layer, otherwise identical



- all samples:

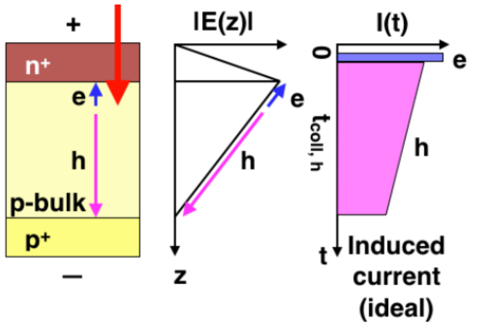
  Thickness: **285µm**, active area **3x3mm^2**

  24 GeV/c - proton irradiated with 10^{14} n$_{eq}$/cm^2 at CERN IRRAD facility

  high resistivity p-FZ wafers

- **annealing steps at 60°C: 80, 240, 560, 1200, 2480, 5040 … minutes**

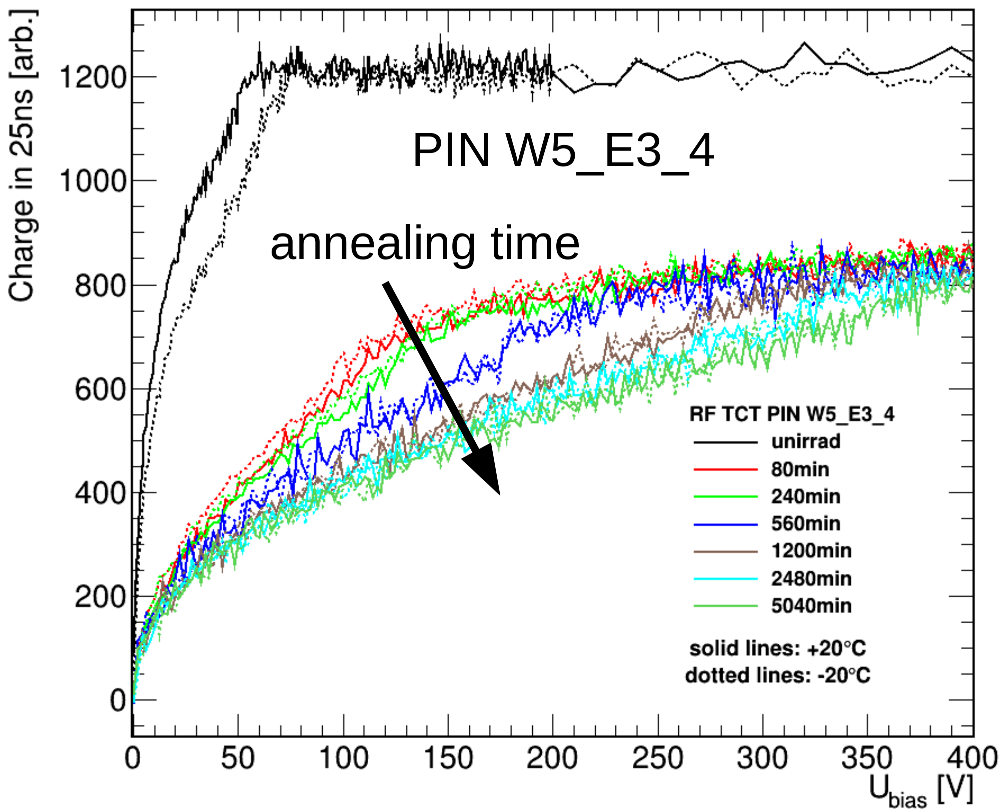
Red Front TCT

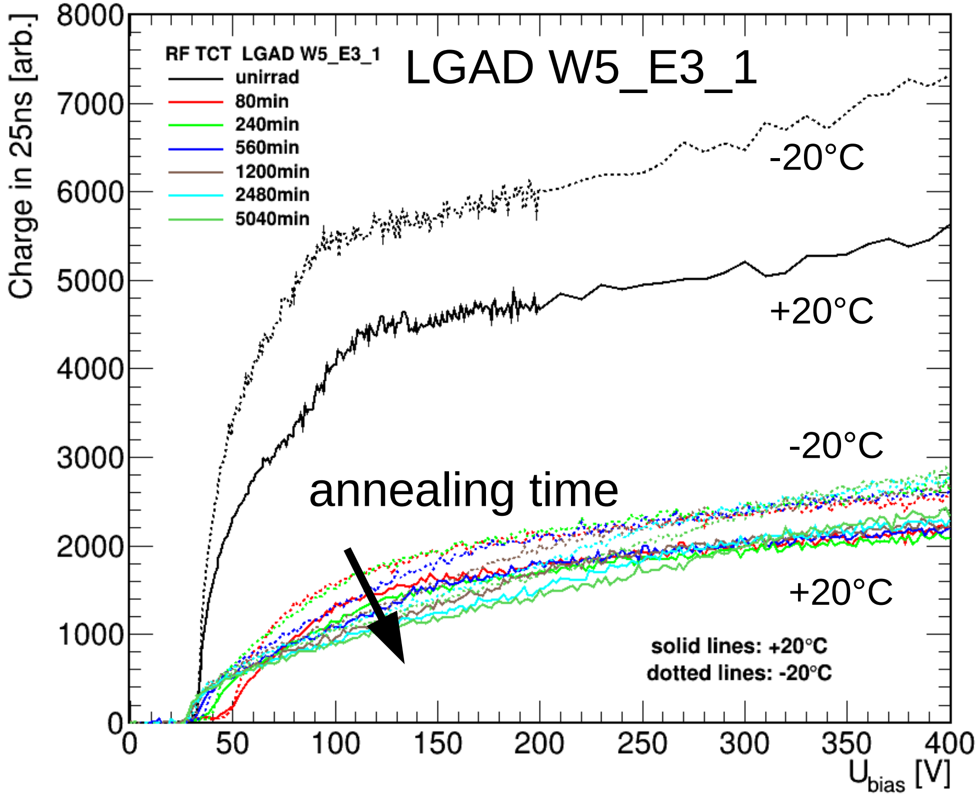


- **Red Front TCT measurements at -20°C and +20°C**
- all measurements normalized by the laser power

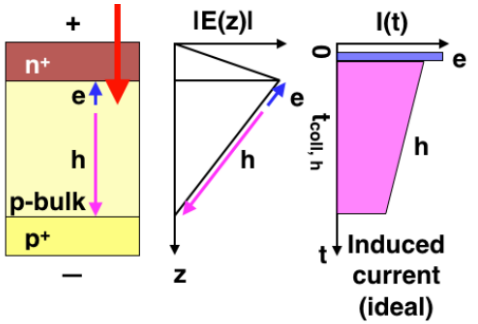
devices are biased from the backside
signal read-out at the top
guard ring grounded

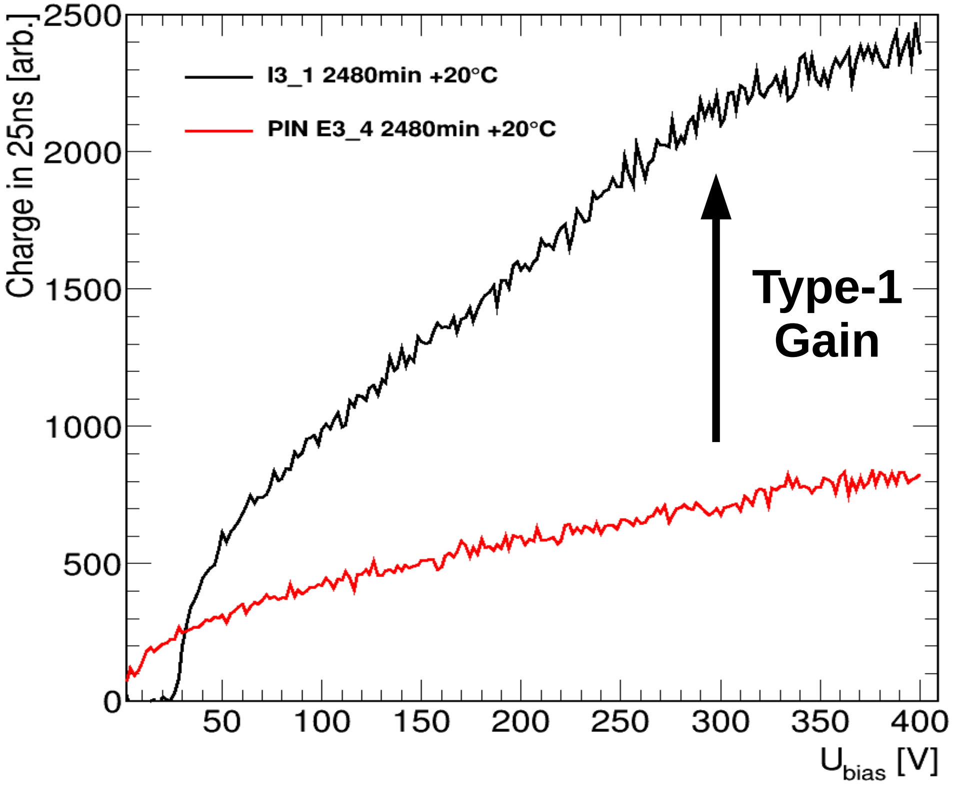
all samples:
10^{14} n_{eq} / cm^2

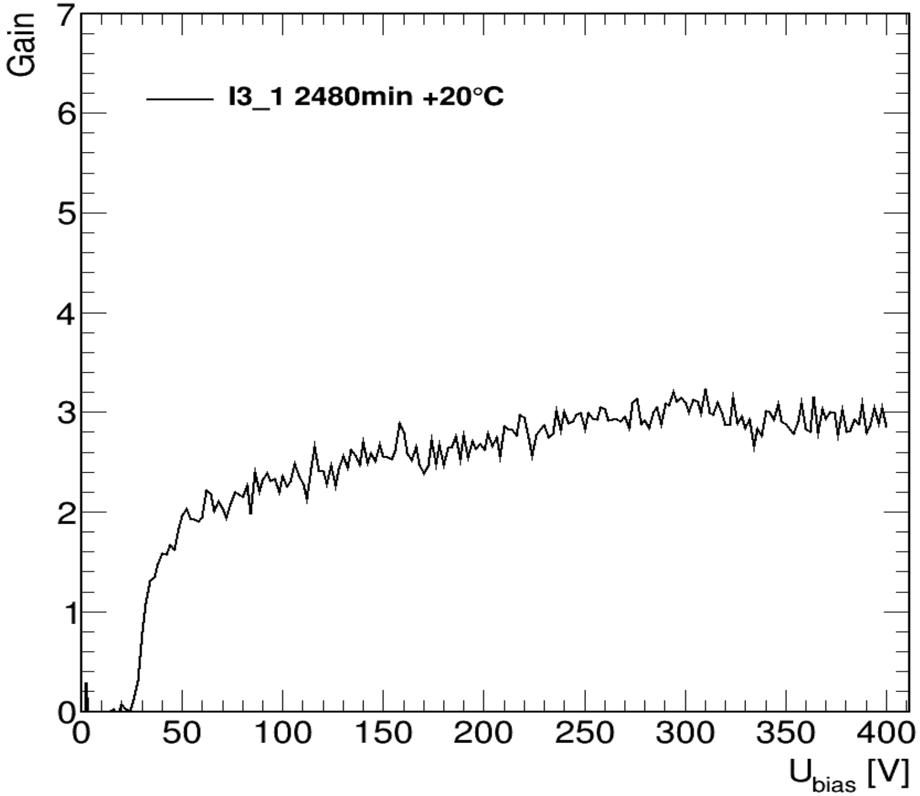




Gain after Annealing





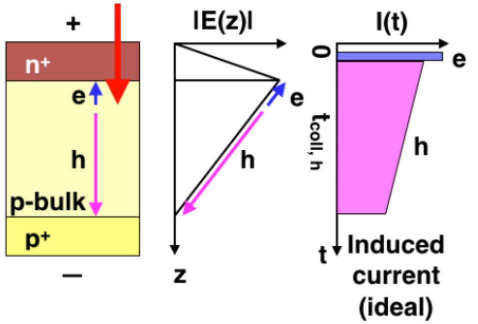


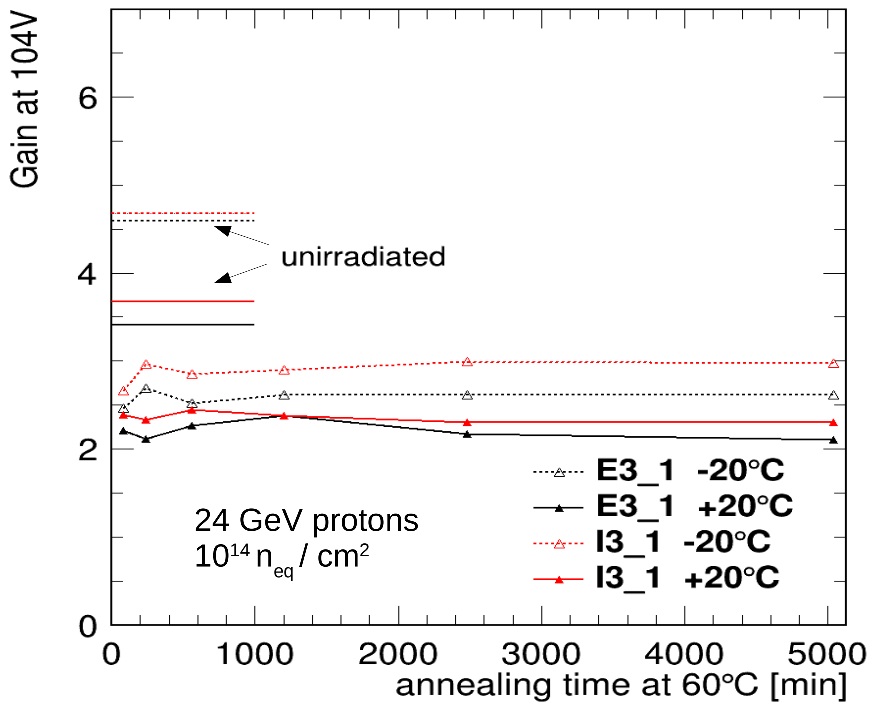
Gain/U_{bias} calculated for each annealing step
PIN diode (at same annealing state) used as reference (type-1 gain):

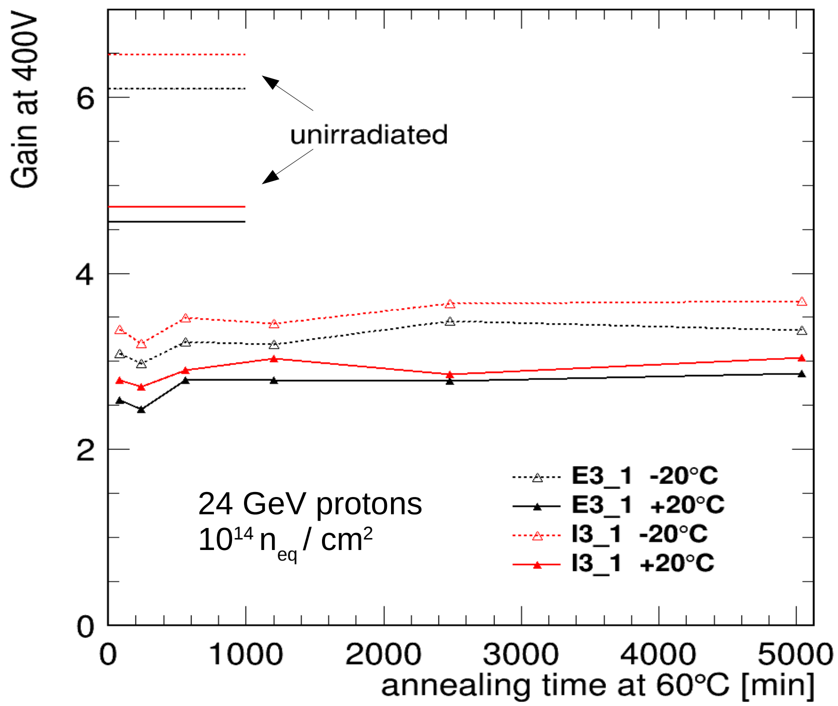
all samples:
$10^{14}\, n_{eq} / cm^2$

$$Gain = Q_{25ns}^{LGAD} / Q_{25ns}^{PIN}$$

Gain after Annealing



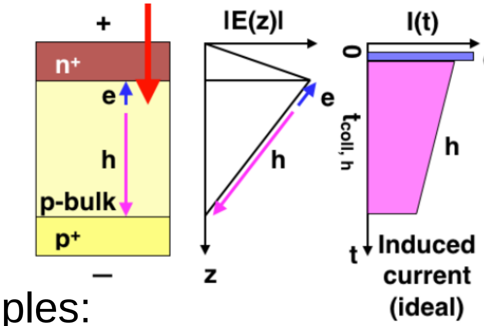




Stable gain after irradiation
→ Annealing does not affect the gain layer

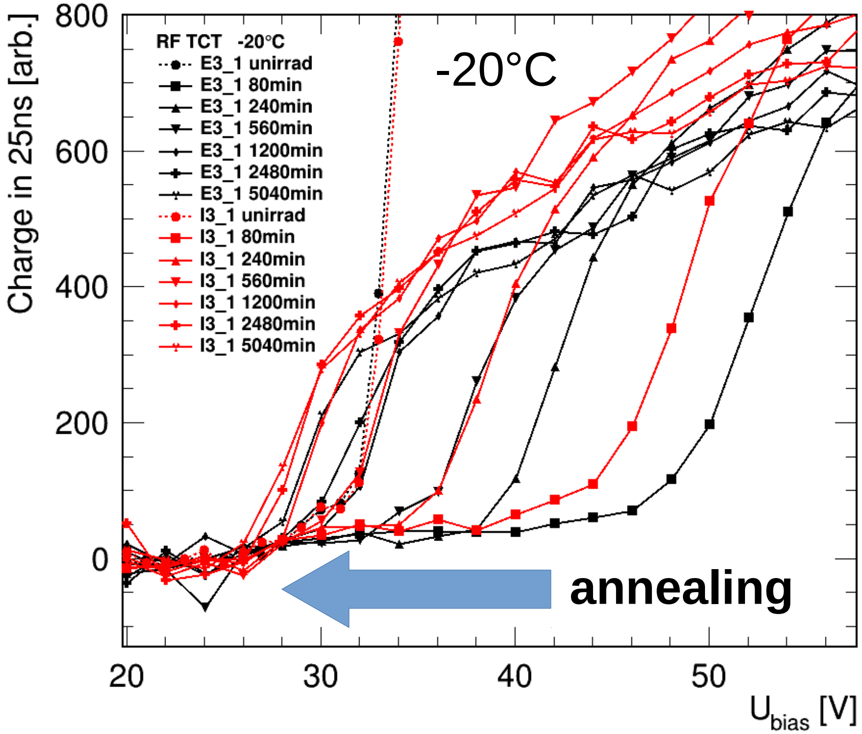
Note: Impact ionization coefficient is temperature dependent
→ higher gain for -20°C before and after irradiation

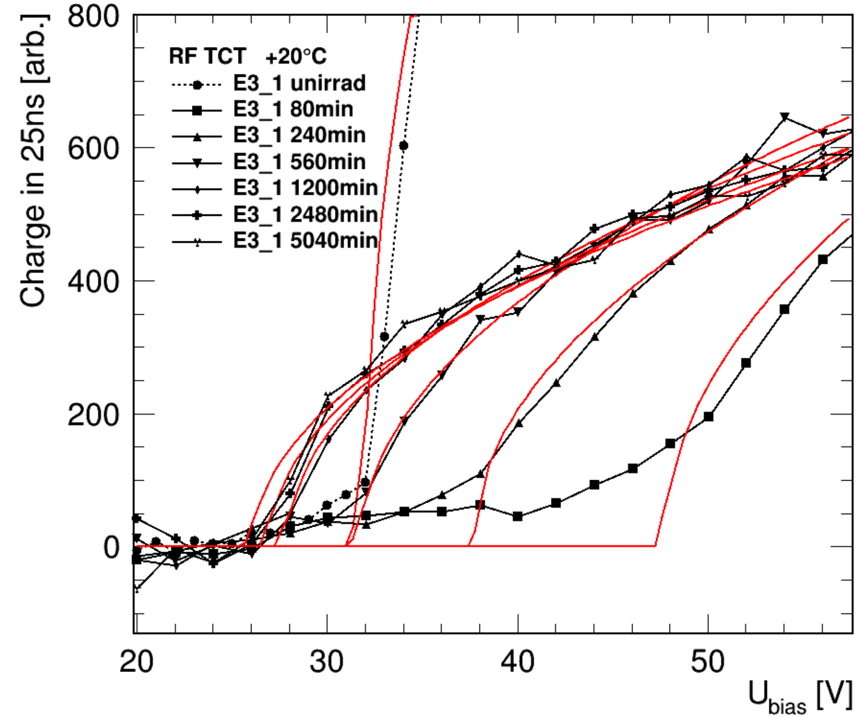
Charge Collection – Onset Voltage



Red Front TCT measurements at -20°C and +20°C

all samples:
$10^{14}\ n_{eq}/cm^2$





- all measurements normalized by the laser power
- devices are biased from the backside
- signal read-out at the top
- guard ring grounded

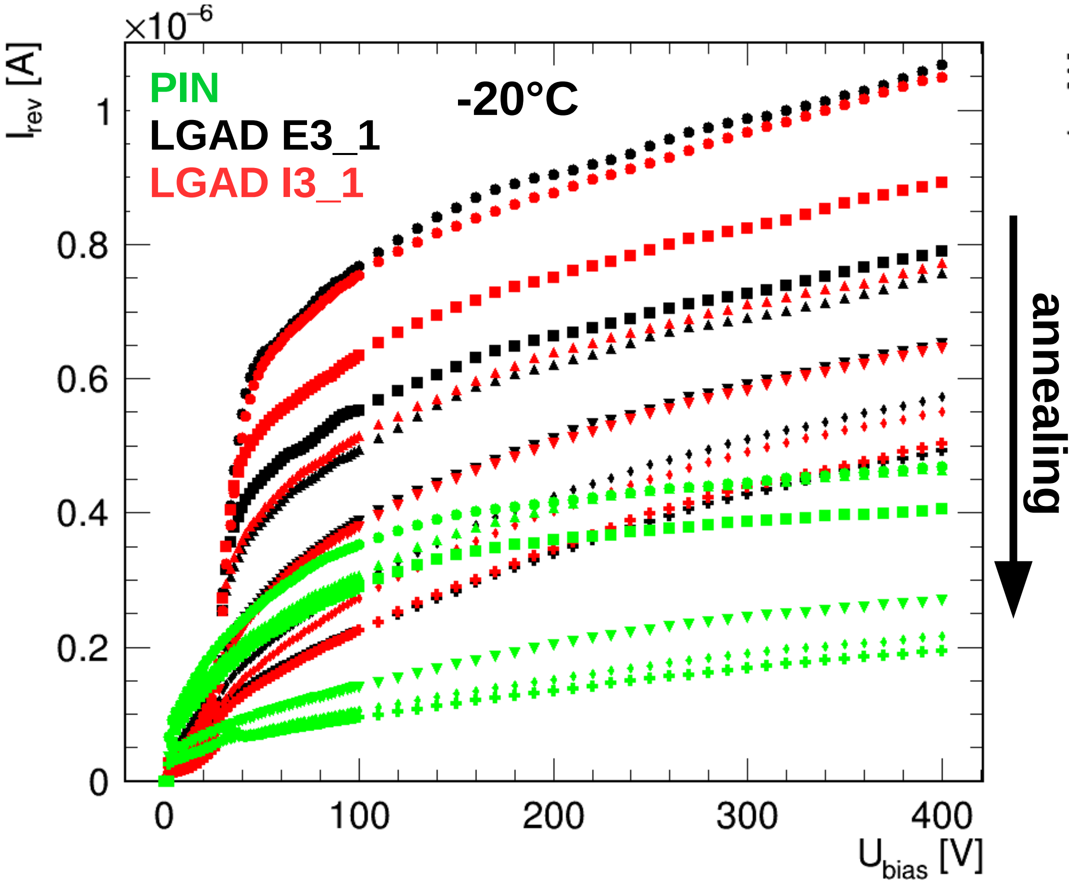
Determination of onset voltage by fit:

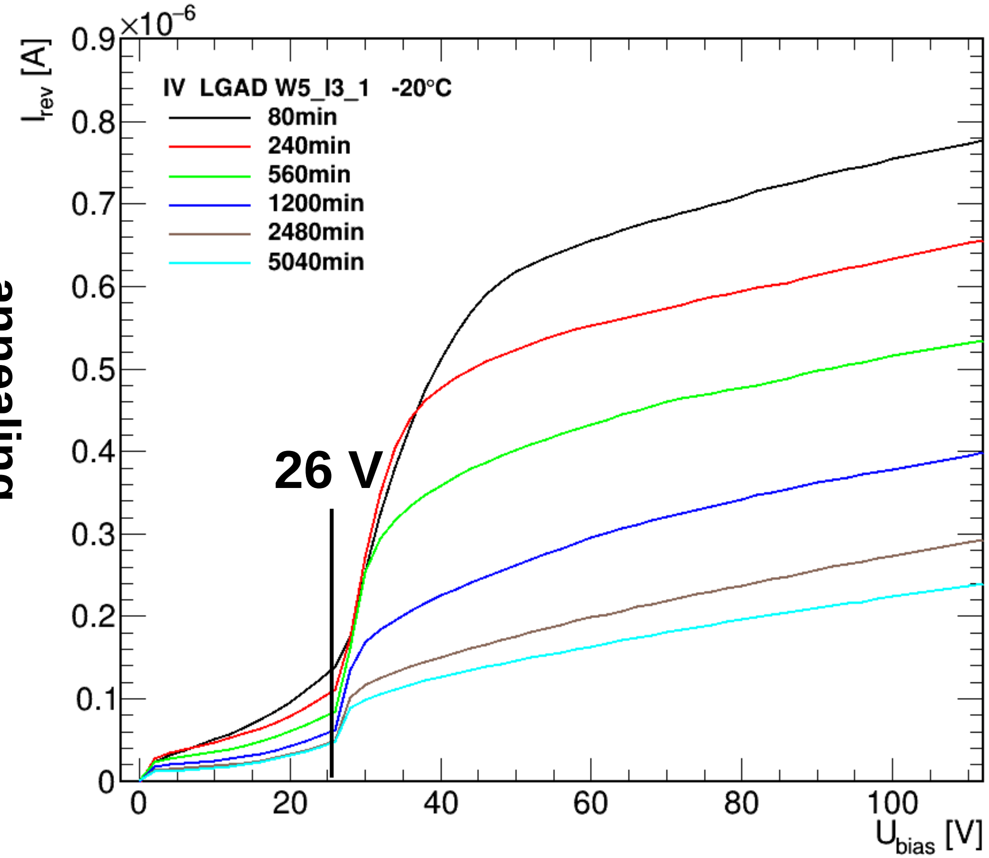
$$Q_{25ns}(U_{bias}) = \sqrt{U_{bias} - U_{onset}}$$

Onset voltage **~ 33V before irradiation**
~ 50V after irradiation (80min annealing)

reduces with increasing annealing time
no obvious dependence on temperature

Leakage Current – Onset Voltage

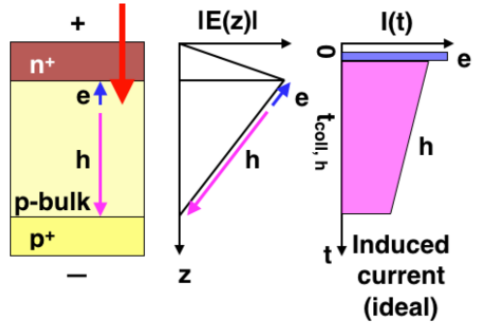


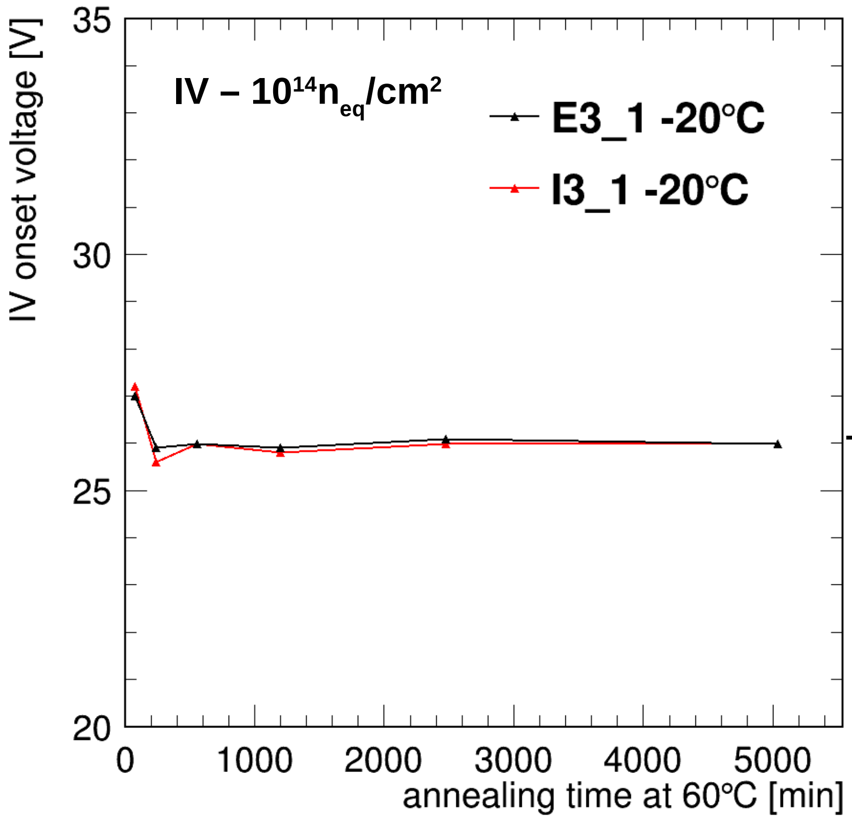


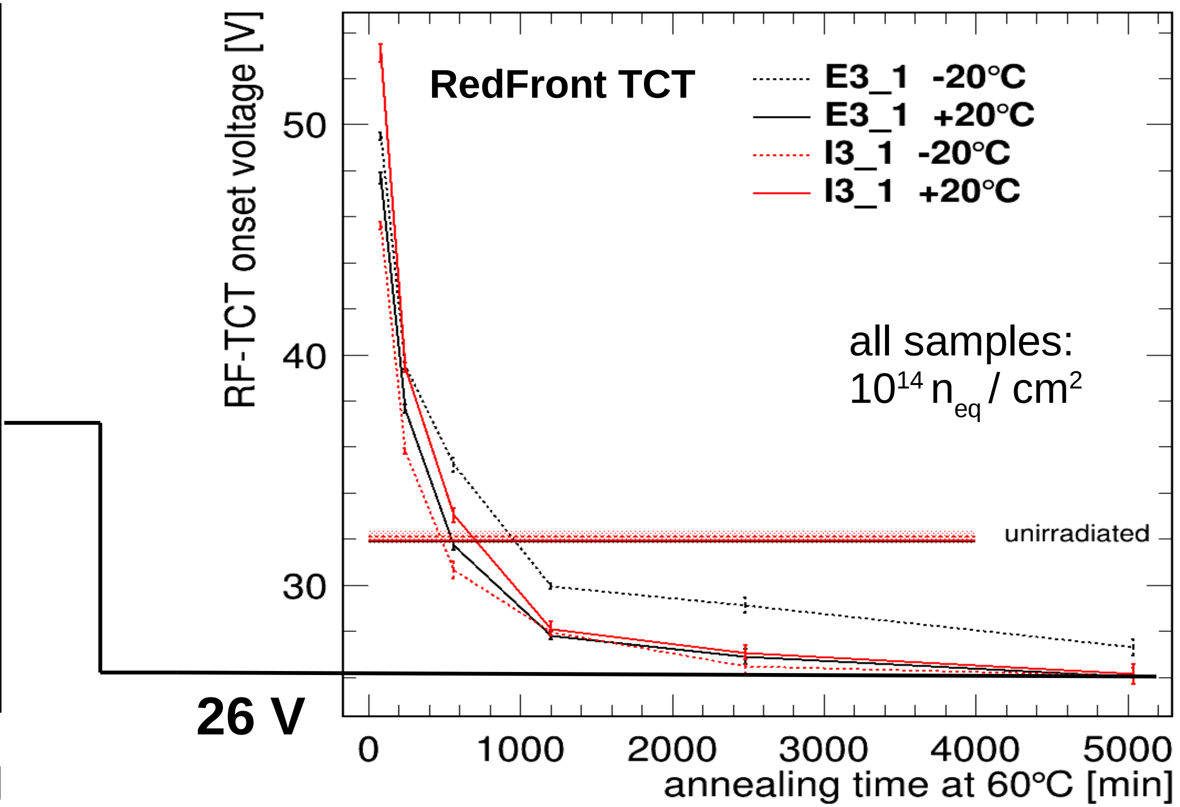
- Decrease of leakage current with annealing as expected
- 'Kink' visible for LGADs at ~ 26V, **independent of annealing time!**

all samples:
$10^{14}\ n_{eq} / cm^2$

IV vs. TCT Onset Voltage





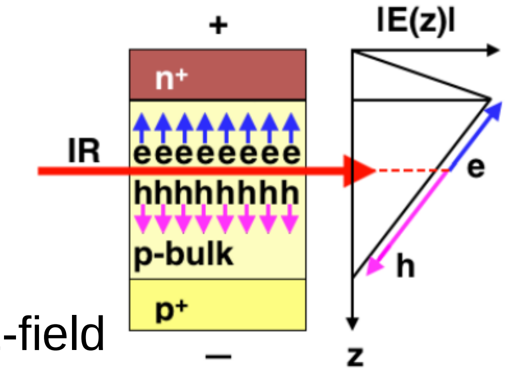


Kink position in **IV measurements**

80min annealing: 27V
>80min: **stable at 26V**

TCT - Onset voltage decreases from 50V to ~ 26V with annealing.

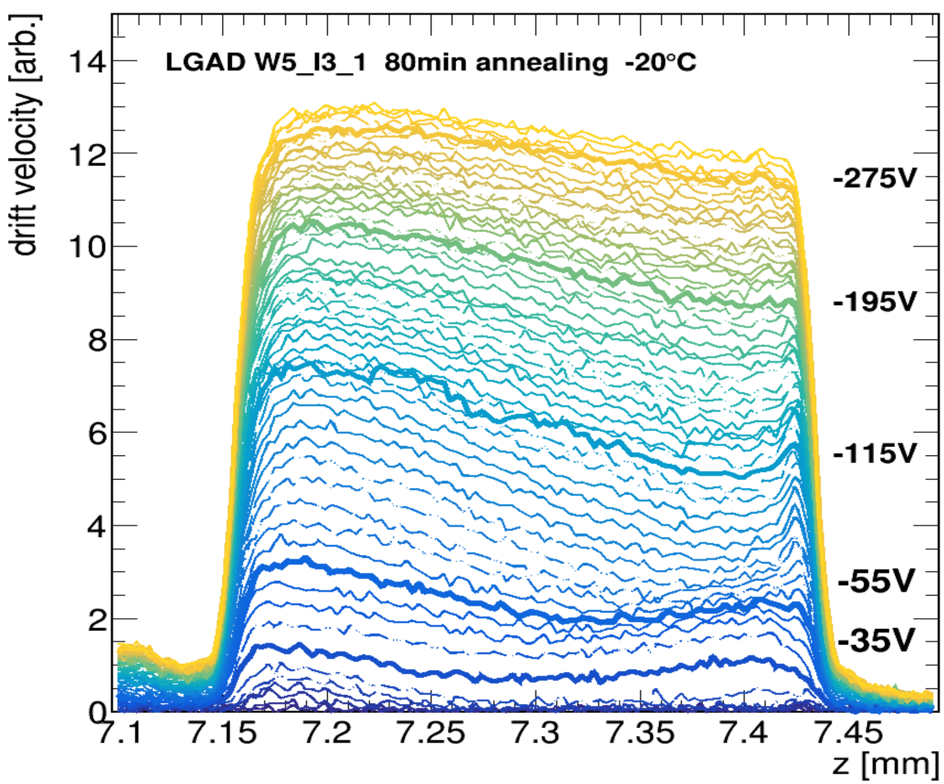
Edge-TCT

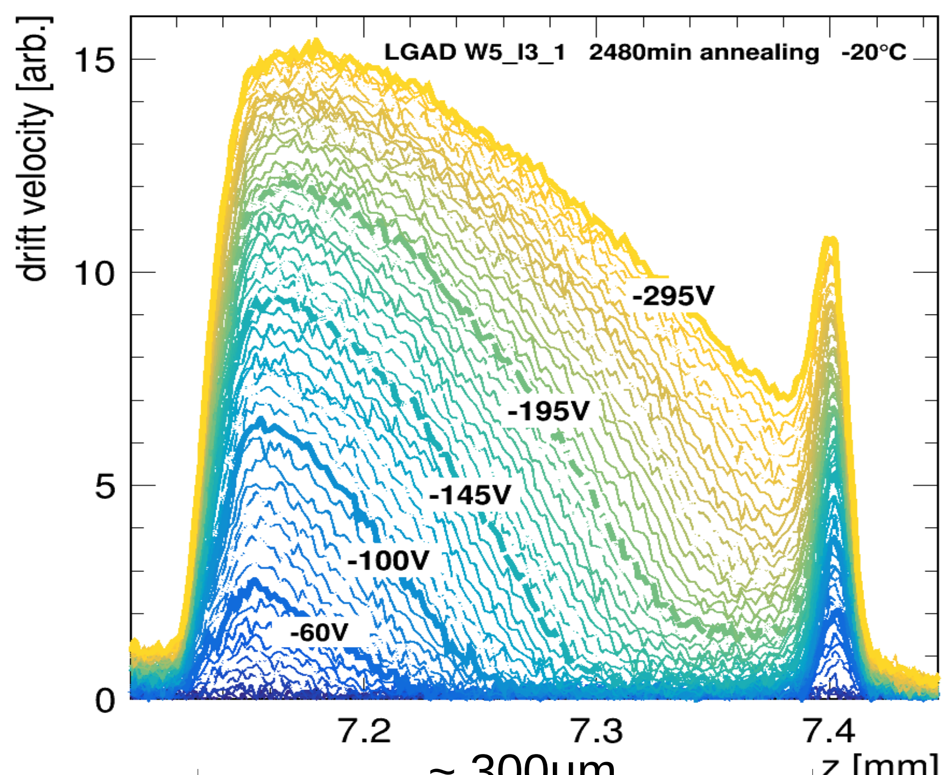


Drift velocity vs. z-position for 80 and 2480min annealing

Signal after ~500ps used to estimate E-field (simplified!):

$$I(t \approx 0) \propto v_{drift} \propto \mu(E)E(z)$$





frontside amplification layer

backside

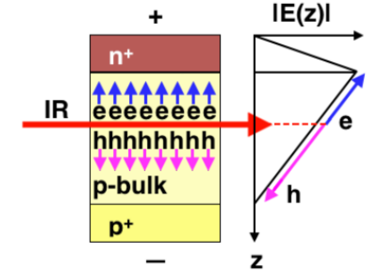
Indication of **double junction at ~ 50V** after 80min annealing (60°C)

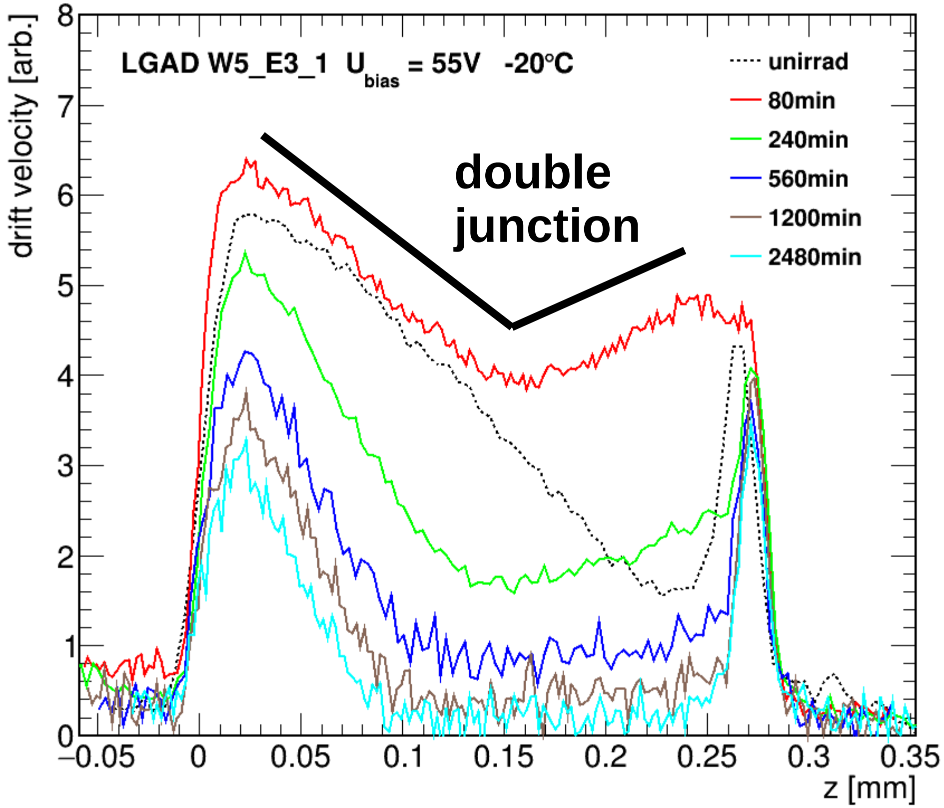
all samples: $10^{14}\ n_{eq} / cm^2$

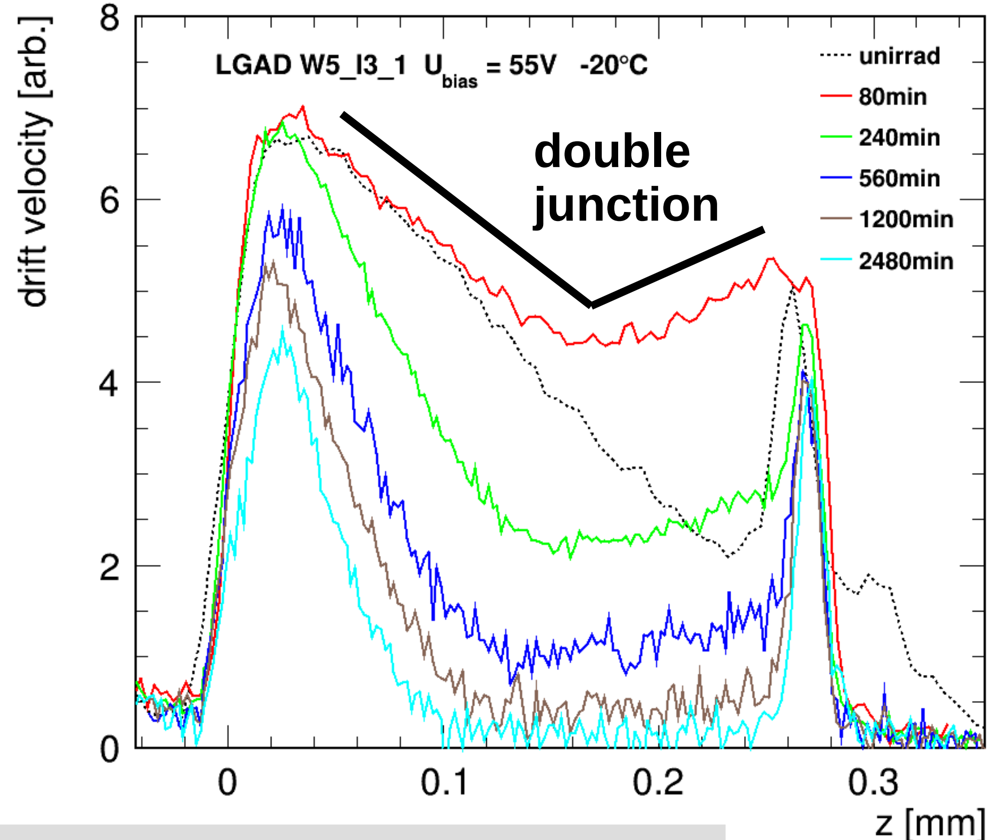
Edge-TCT

Annealing behavior at 55 V

all samples:
$10^{14}\, n_{eq} / cm^2$







<u>Double junction after 80 minutes of annealing visible at low voltages</u>

→ affects Charge Collection for TCT measurements

→ **increased TCT- onset voltage**

<u>Double junction disappears with longer annealing times</u>

→ acceptor removal dominant

→ **reduced onset voltage wrt. before irradiation**

Annealing of LGADs - Conclusion

Sensors functional after irradiation with 10^{14} n_{eq}/cm^2 (24 GeV/c protons)
No recovery of (type-1) gain after annealing

Complex annealing behavior observed

Double junction at short annealing times
→ Charge collection - onset voltage increased to ~ 50V due to change in E-Field

IV – onset voltage stable at ~26V independent of annealing time

Deterioration of gain layer with irradiation

→ Reduced gain
→ Depletion of gain layer already at 26V (~33V before irradiation)

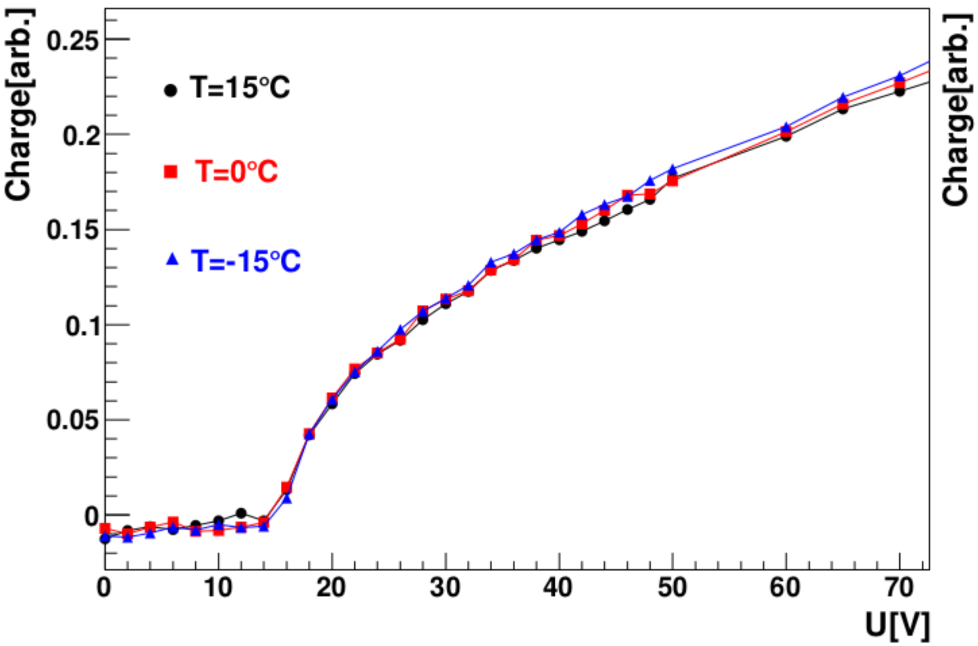
→ Gain layer is not affected by annealing (see IV + gain)

Onset voltage measured by TCT is not directly related to the depletion of the amplification layer

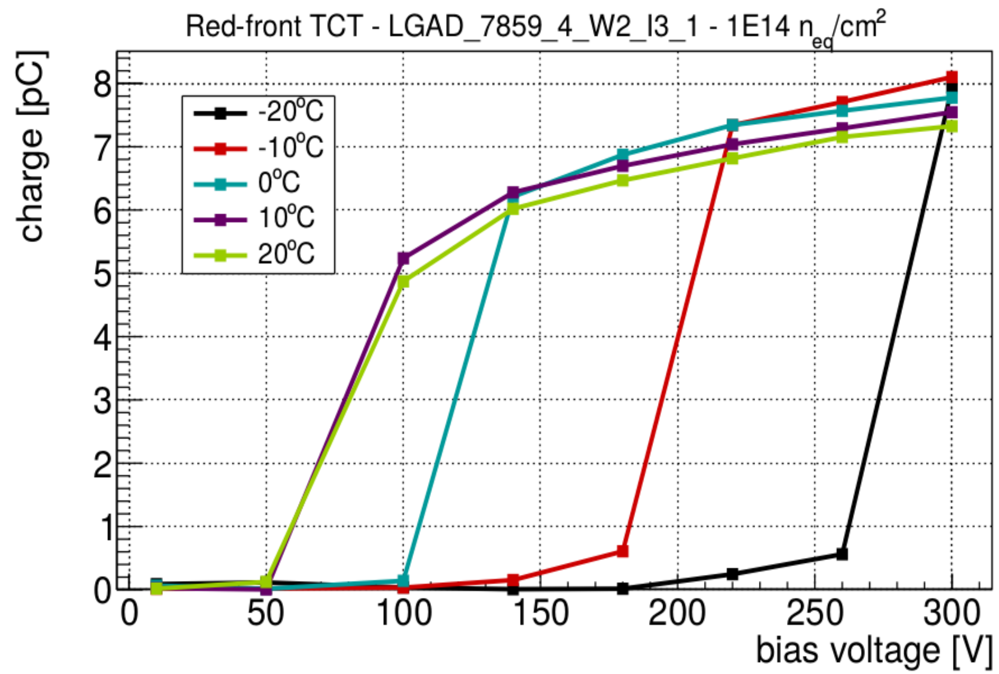
Backup

Previous Studies

G. Kramberger



S. Otero Ugobono



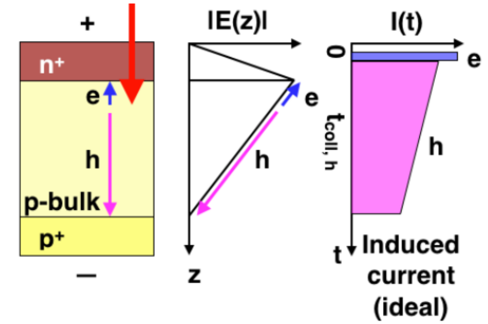
Decreasing onset voltage (V_{mr})
- explained by acceptor removal in p+ layer

No temperature dependence of V_{mr} rules out possible explanation of compensation of effective acceptors by trapped holes

Increasing onset voltage
- explained by double junction effect

Strong temperature dependence of V_{mr} supports explanation by trapped holes, creating double junction

Recap: Gain



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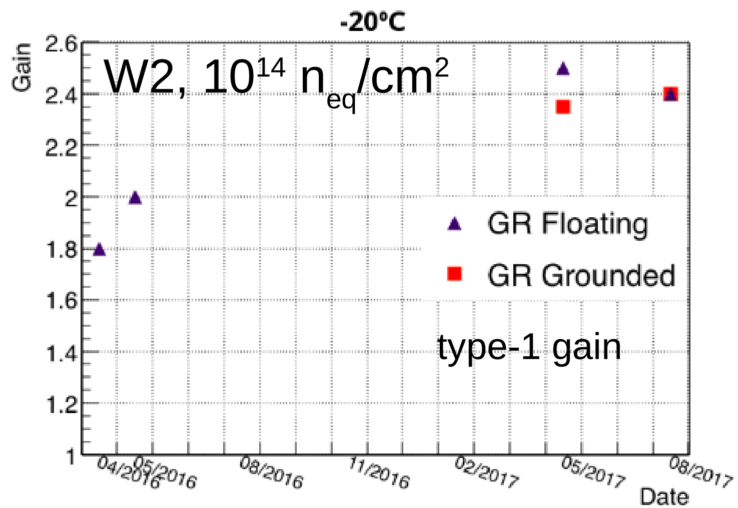
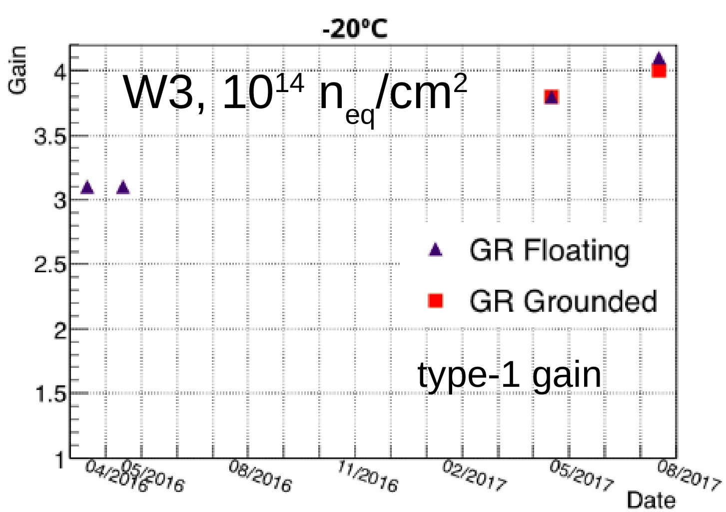


(b)



(d)

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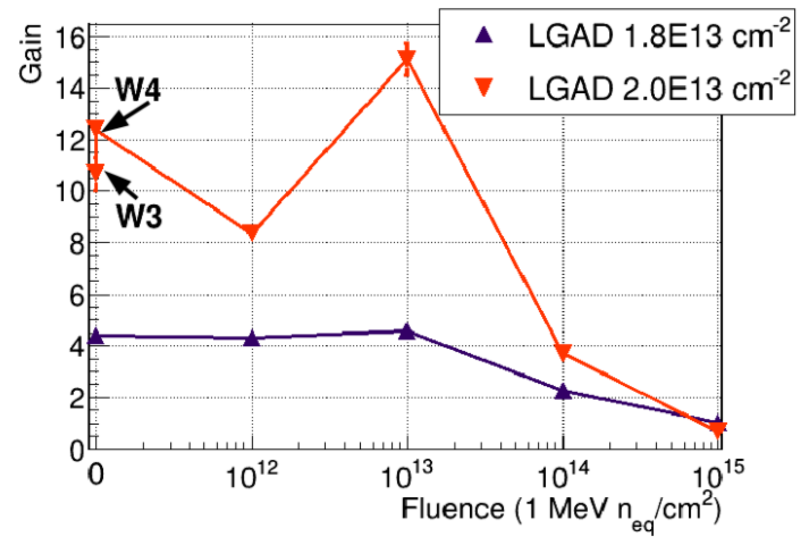
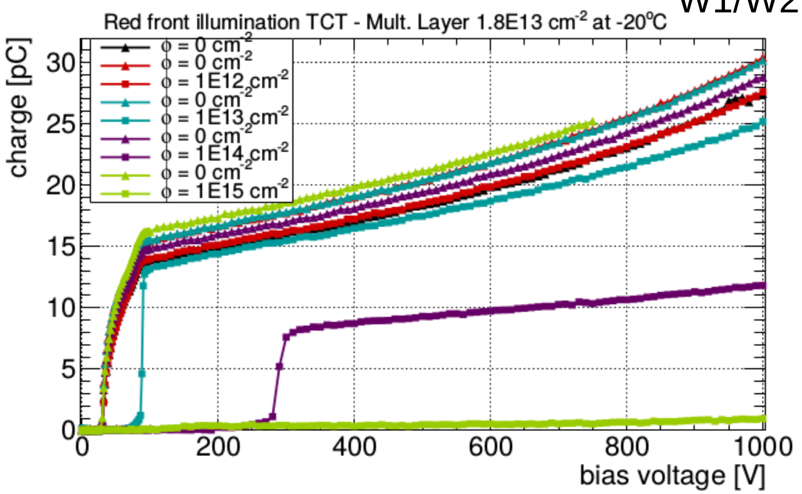


Gain reduced after irradiation

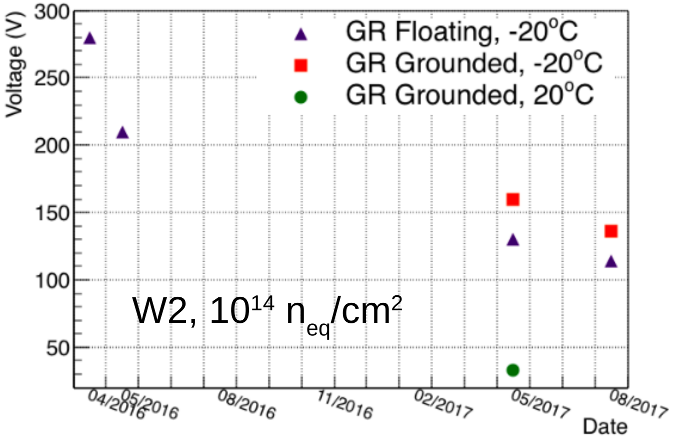
From these previous measurements, some recovery after annealing is expected

Context

W1/W2

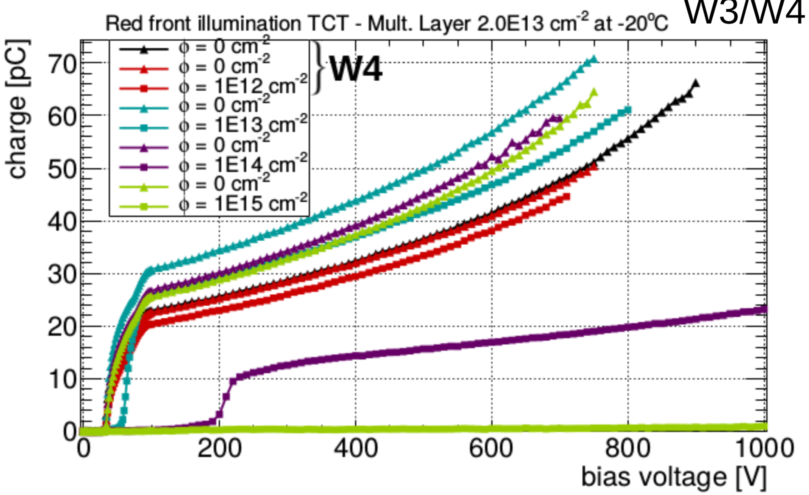


(a)

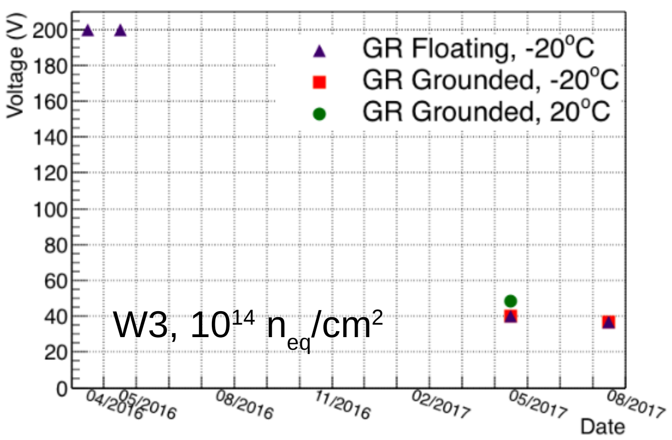


(a)

W3/W4



(b)



(c)

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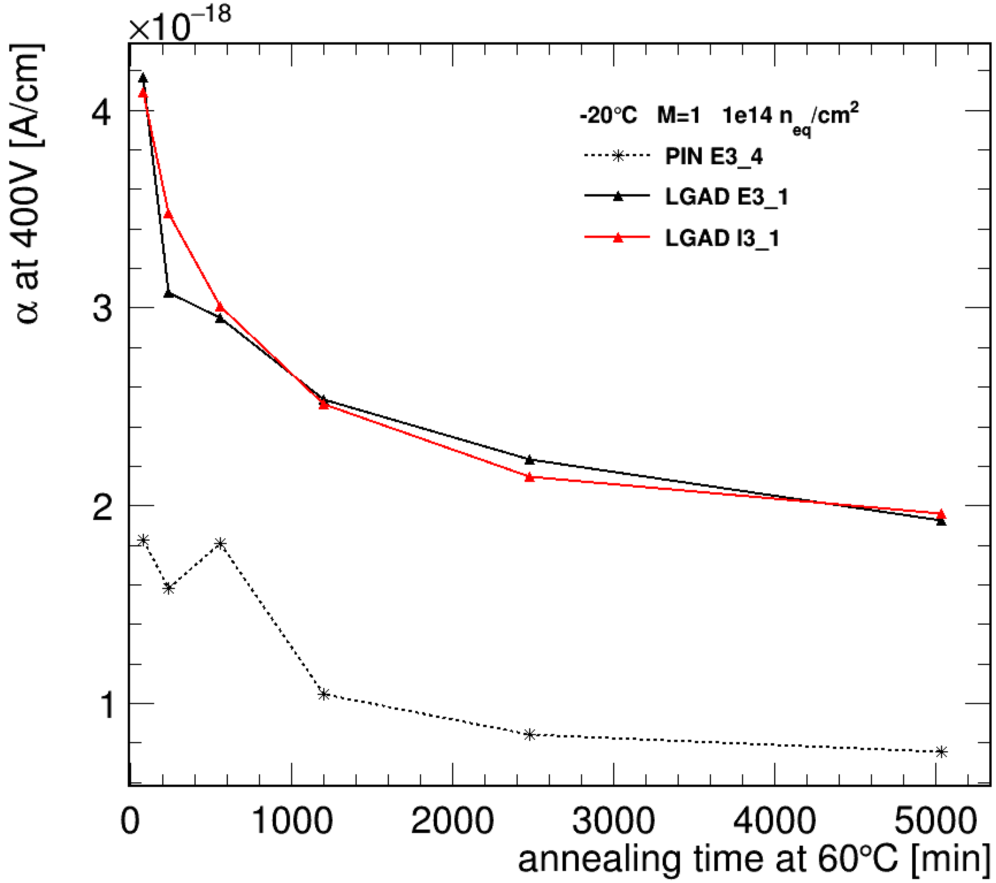
Onset voltage measured at 200-300V for $10^{14} n_{eq}/cm^2$

Current Related Damage Rate



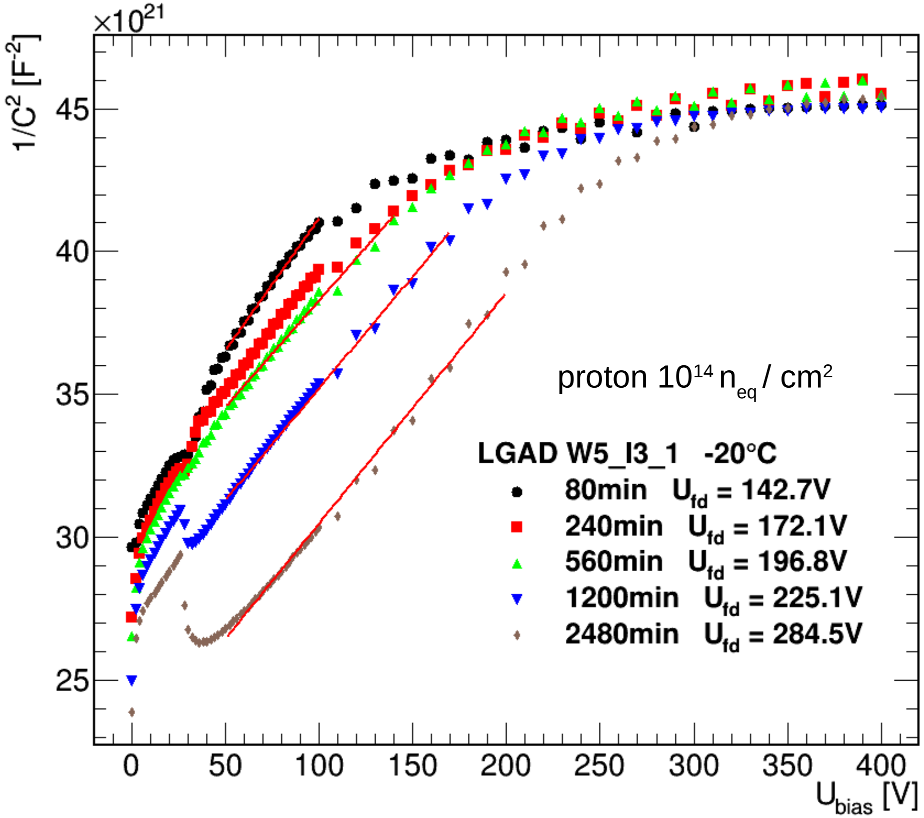
calculated using physical sensor volume: 285µm x 3x3mm^2

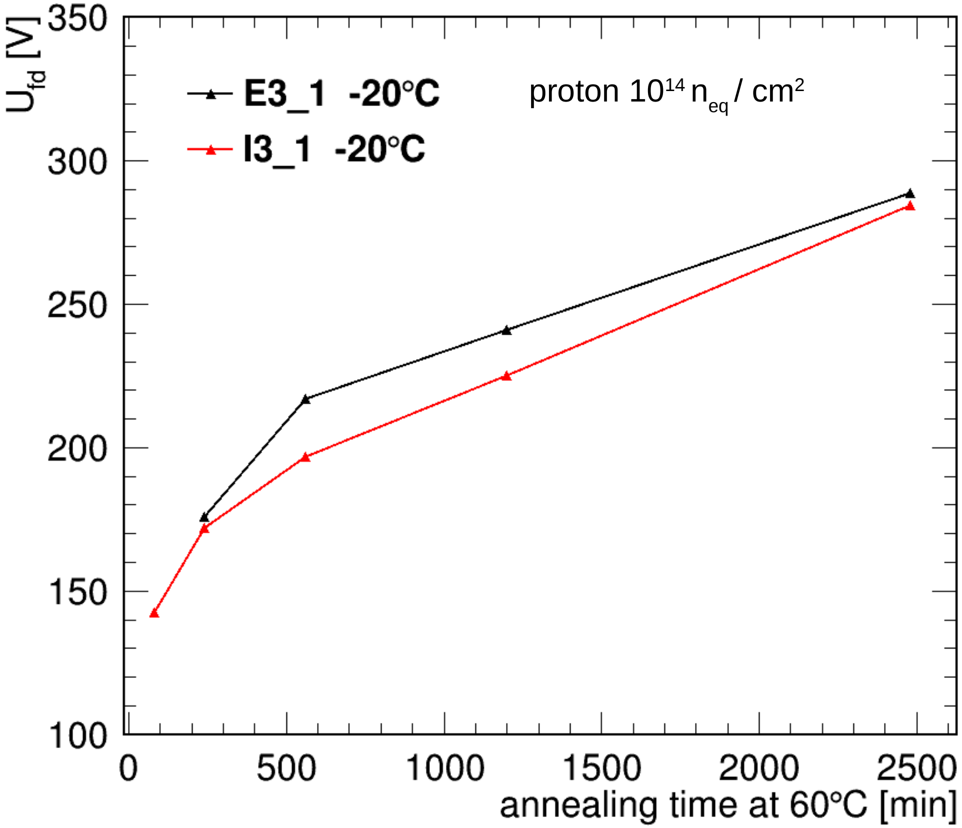
No multiplication factor (M=1)

$$\alpha = \frac{I}{\Phi_{eq} V M}$$

all samples:
10^{14} n_{eq} / cm^2

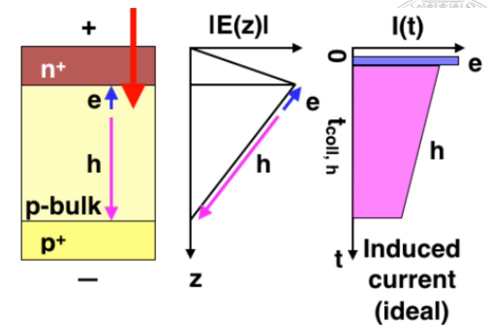
Capacitance - CV



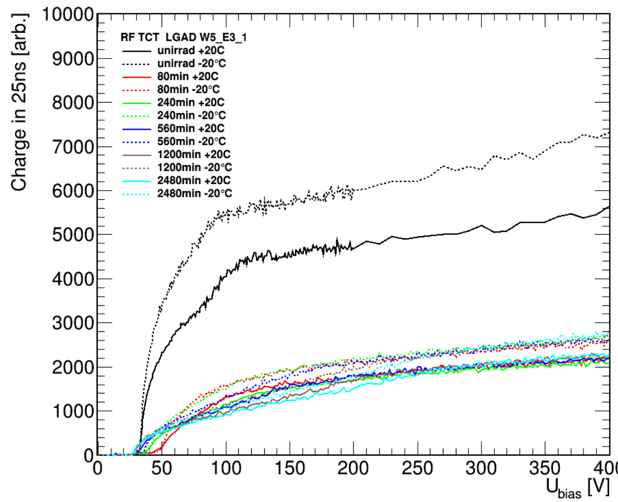


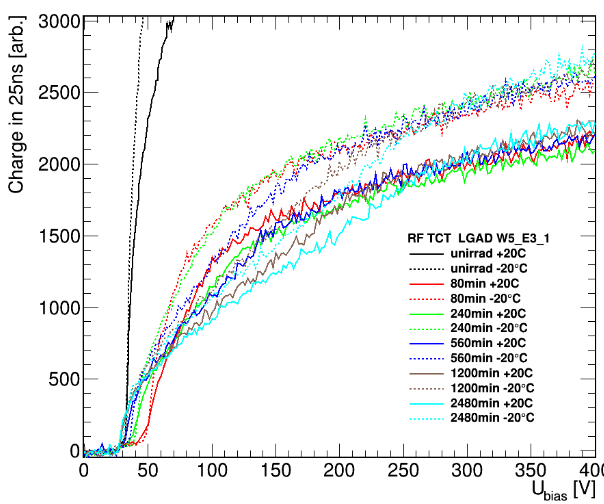
- 'Kink' visible at same voltage as in IV measurement
- depletion voltage increasing with annealing

Red Front TCT

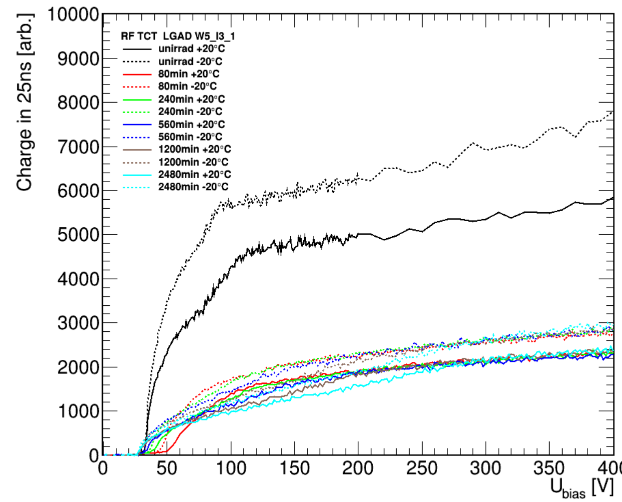


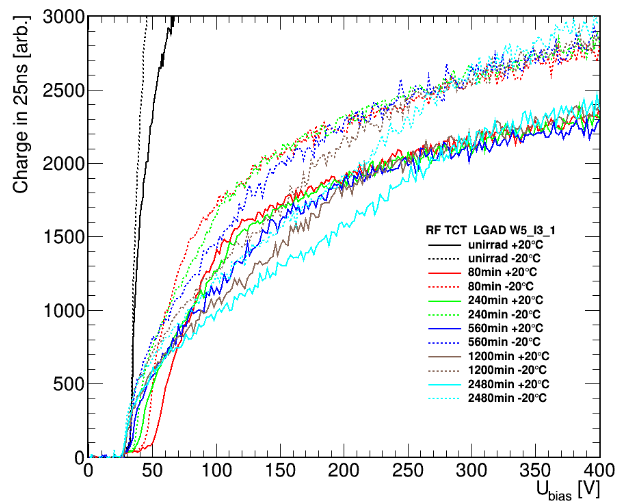
LGAD W5_E3_1



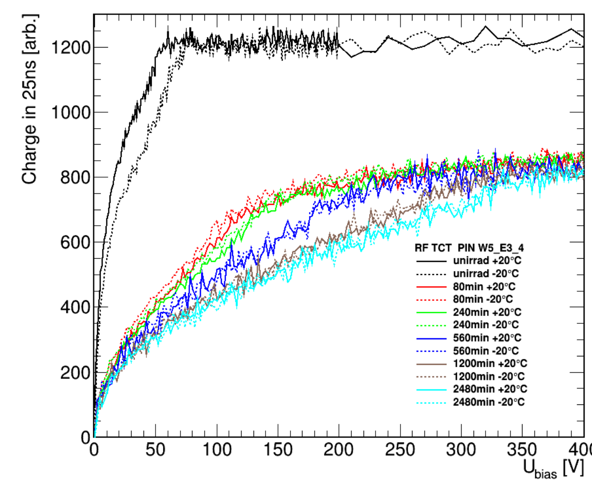


LGAD W5_I3_1





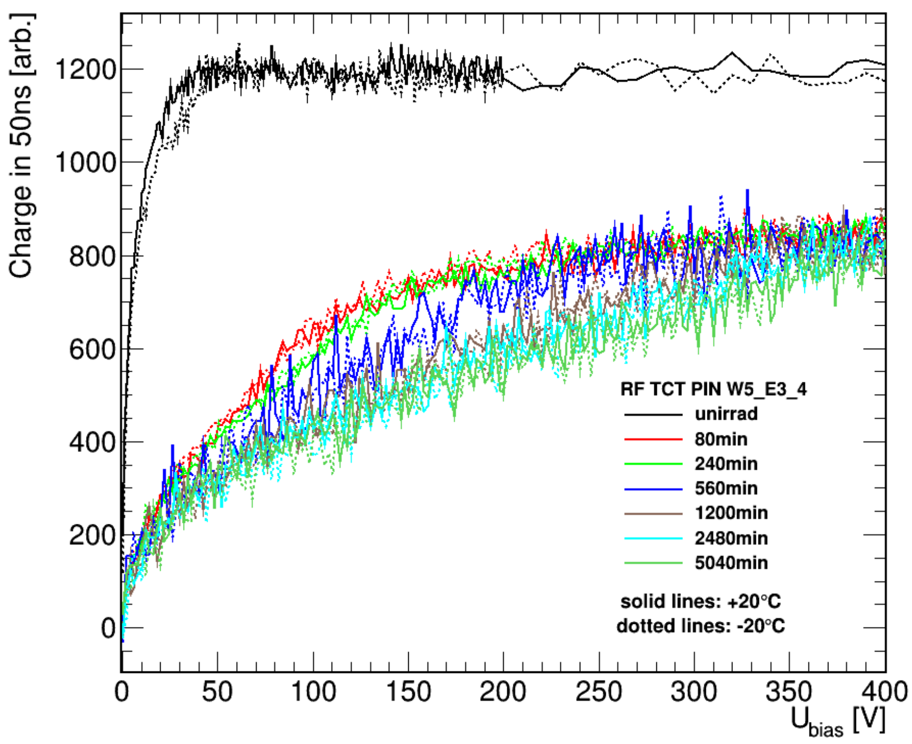
PIN W5_E3_4



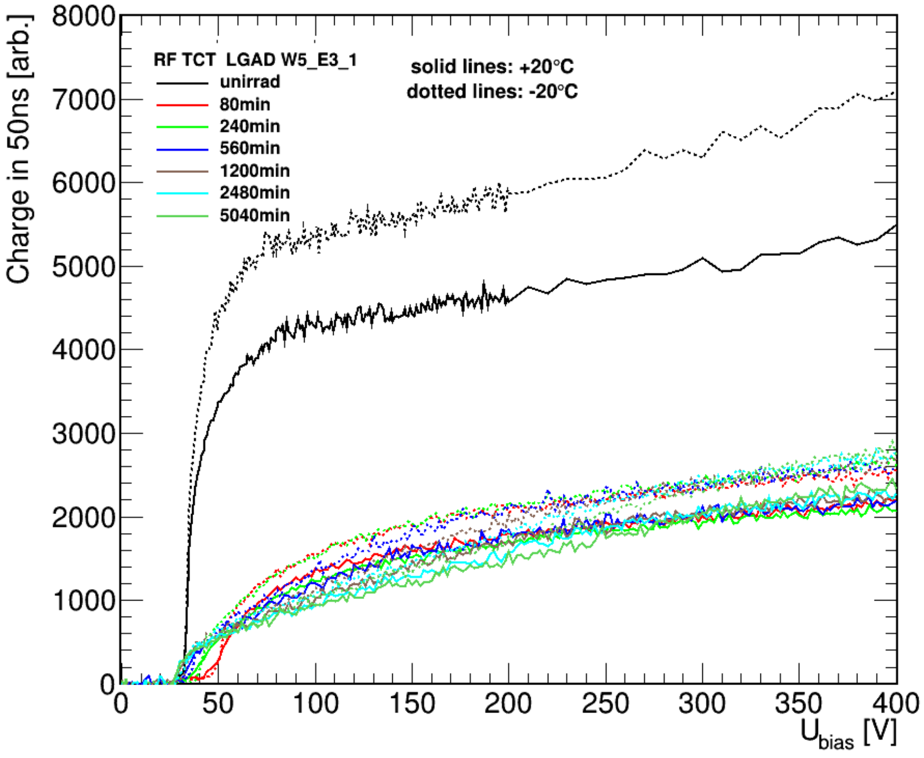
Red Front TCT measurements at -20°C and +20°C
all measurements are normalized by the laser power

devices are biased from the backside
signal read-out at the top
guard ring grounded

RF TCT - 50ns



Charge in 50ns [arb.]
RF TCT PIN W5_E3_4
unirrad
80min
240min
560min
1200min
2480min
5040min
solid lines: +20°C
dotted lines: -20°C
U_bias [V]



Charge in 50ns [arb.]
RF TCT LGAD W5_E3_1
unirrad
80min
240min
560min
1200min
2480min
5040min
solid lines: +20°C
dotted lines: -20°C
U_bias [V]