Multiplication onset and electric field properties of proton irradiated LGADs

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[6]*Universitat de Barcelona*

HL-LHC: Challenging Technology

HL-LHC Upgrade:

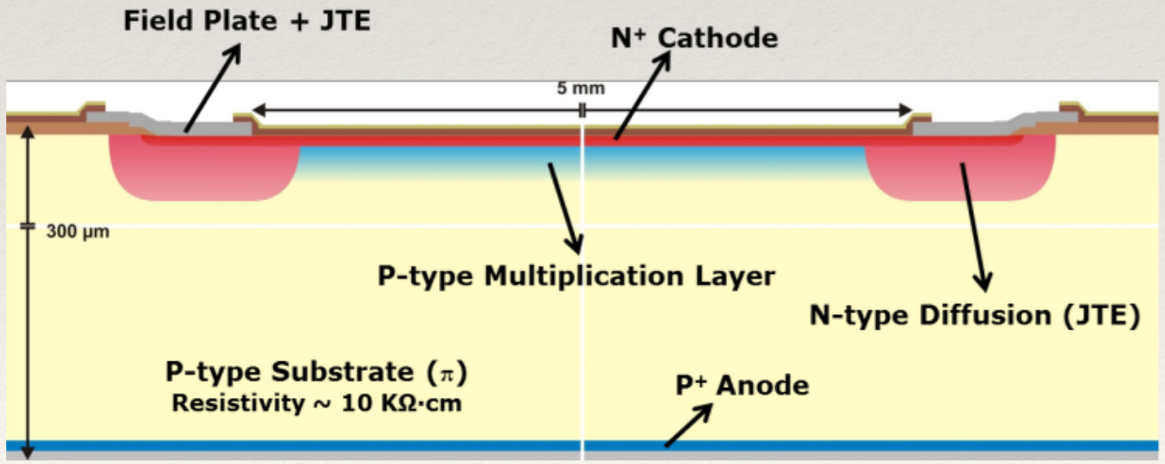
- Increase in luminosity.
- Radiation levels up to 1.6×10^{16} cm^{-2}.
  - 10 times the current fluence.
- Higher event pile-up.
  - Better timing resolution needed (~20 ps).
- Maintain spatial accuracy.

Possible solution:

Detectors with intrinsic gain.

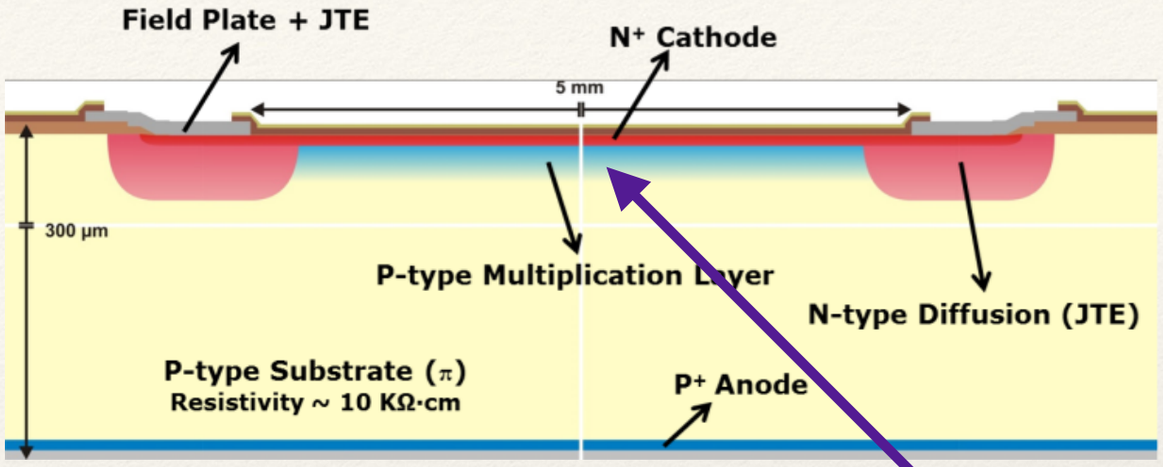
Detectors with Intrinsic Gain

- Internal multiplication of charge: increase in signal.
  - Better signal-to-noise ratio, even after irradiation.
  - Better timing capabilities.
- One possible technology:
  - Low Gain Avalanche Detectors (LGAD).



Low Gain Avalanche Detectors

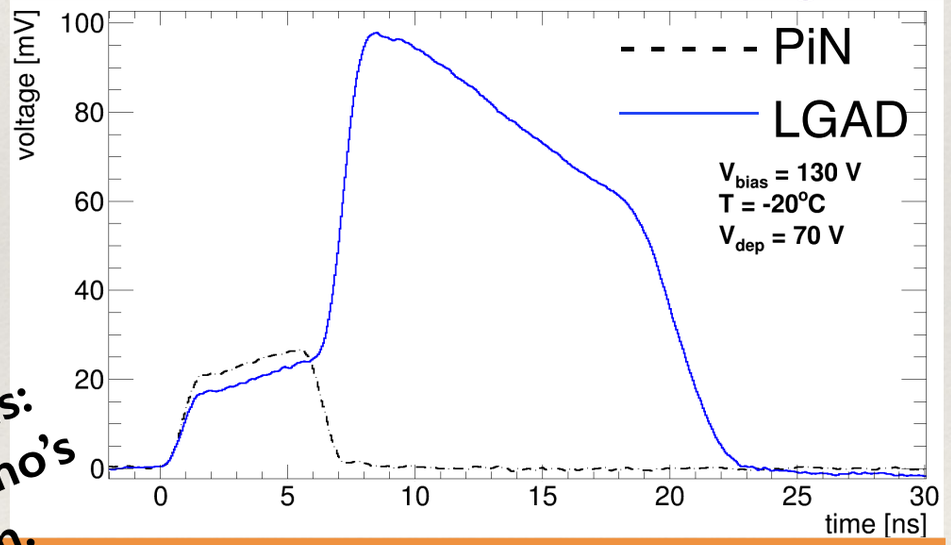
- Planar silicon sensors (**$n^+/p/p^-$**).
  - n^+ implant, π substrate.
  - p-type multiplication layer.



Low Gain Avalanche Detector (LGAD)

High electric field region

- **High electric field region in the multiplication layer.**
  - Charges undergo impact ionisation.
  - Gain depends on:
    - multiplication layer doping,
    - bias voltage,
    - temperature.

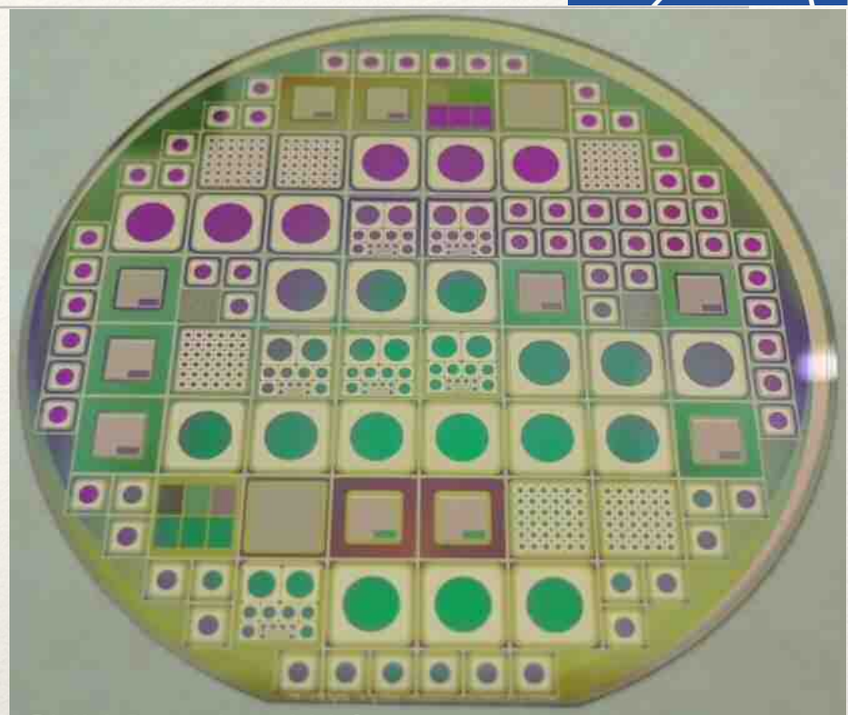


Further details: M.M. Obertino's presentation.

- **Low gain (~10 to 30)**
- Signal increase & low noise.
- Low risk of breakdown.

Irradiation Campaign

- **LGADs from CNM Run 7859.**
  - Wafers 1 and 2.
    - Multiplication layer dose: **1.8×10^{13} cm^{-2}**.
  - Wafers 3 and 4.
    - Multiplication layer dose: **2.0×10^{13} cm^{-2}**.
- **Irradiated at the CERN IRRAD facility with 24-GeV/c protons.**
- Fluences:
  - 10^{12} 1 MeV n_{eq}/cm^2
  - 10^{13} 1 MeV n_{eq}/cm^2
  - 10^{14} 1 MeV n_{eq}/cm^2
  - 10^{15} 1 MeV n_{eq}/cm^2
- Annealing: 80 min at 60ºC.

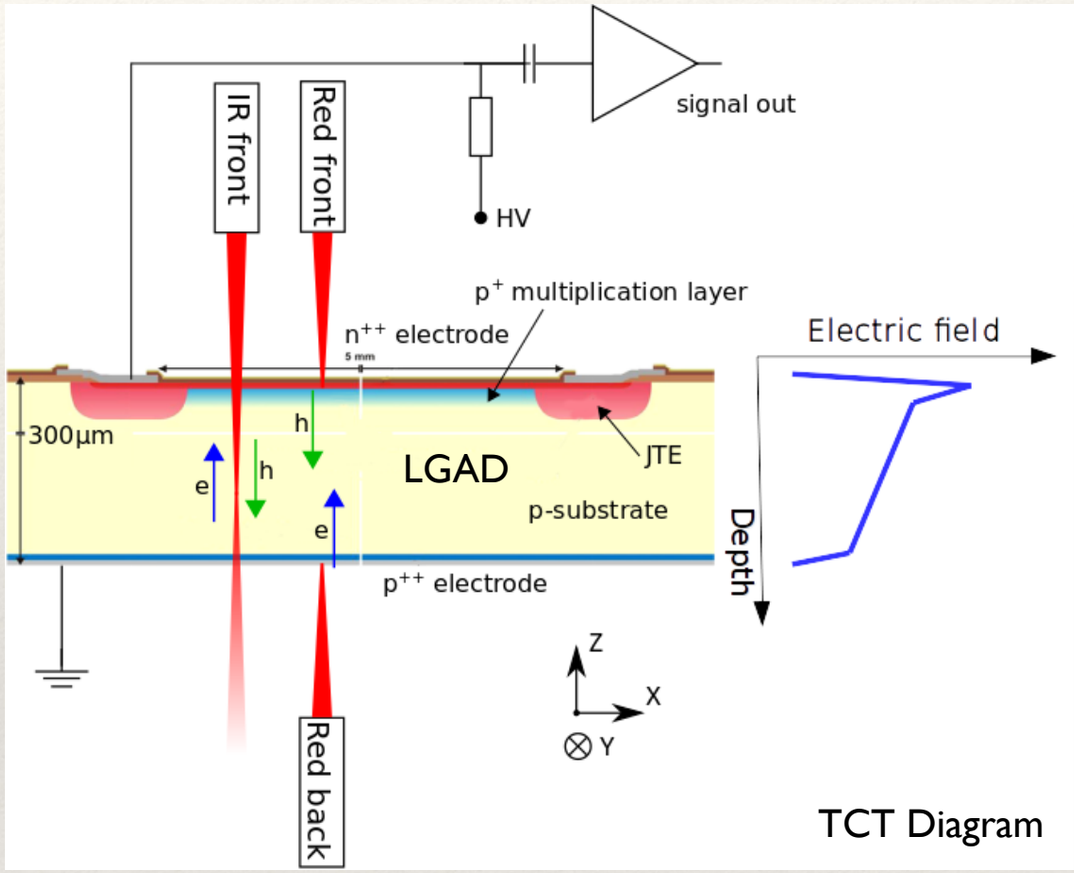


CNM-Barcelona Wafer

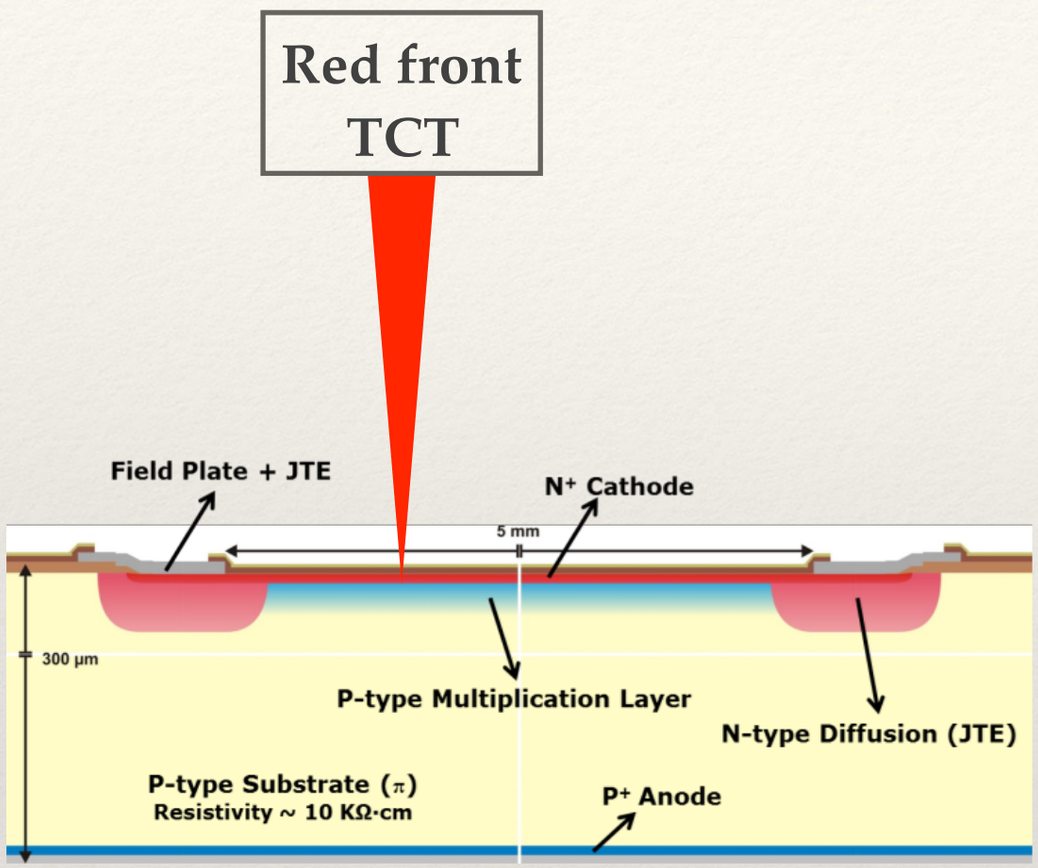
Measurements Performed

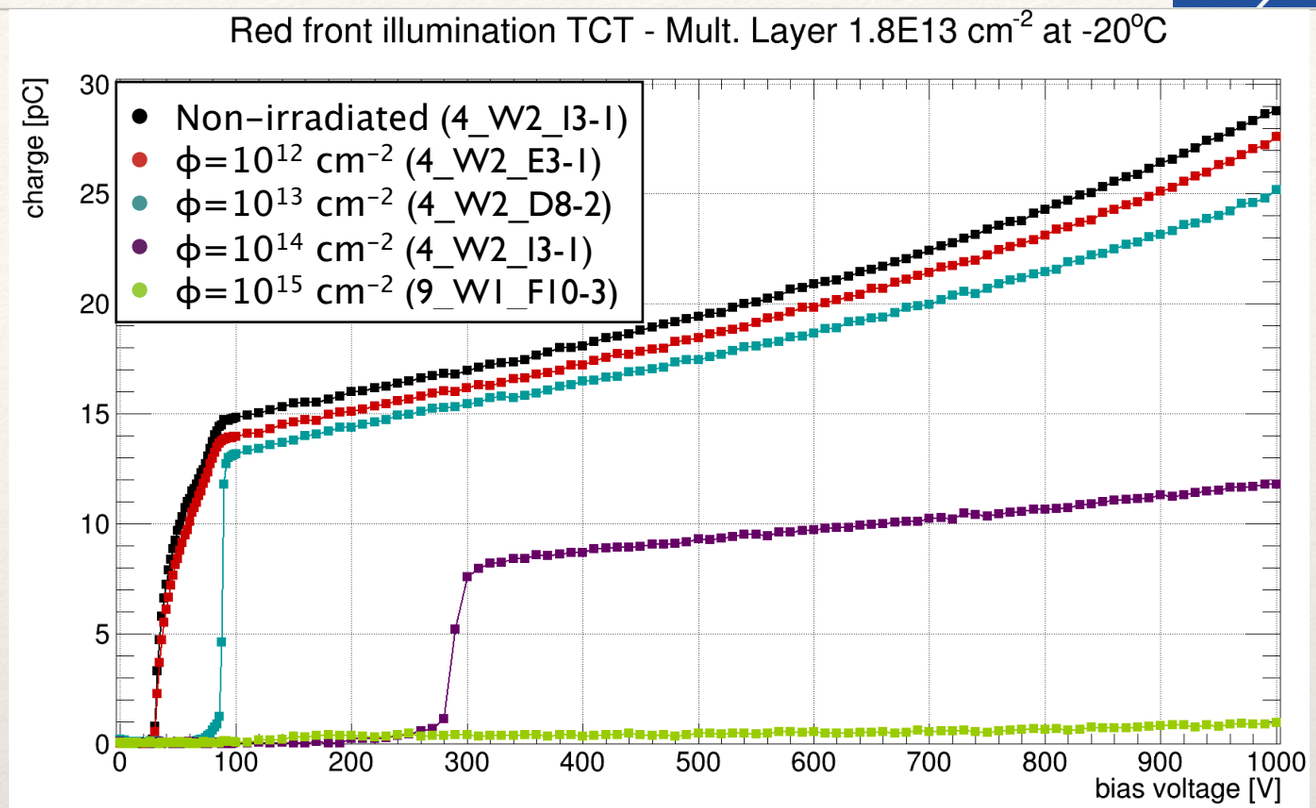
Transient Current Technique (TCT)

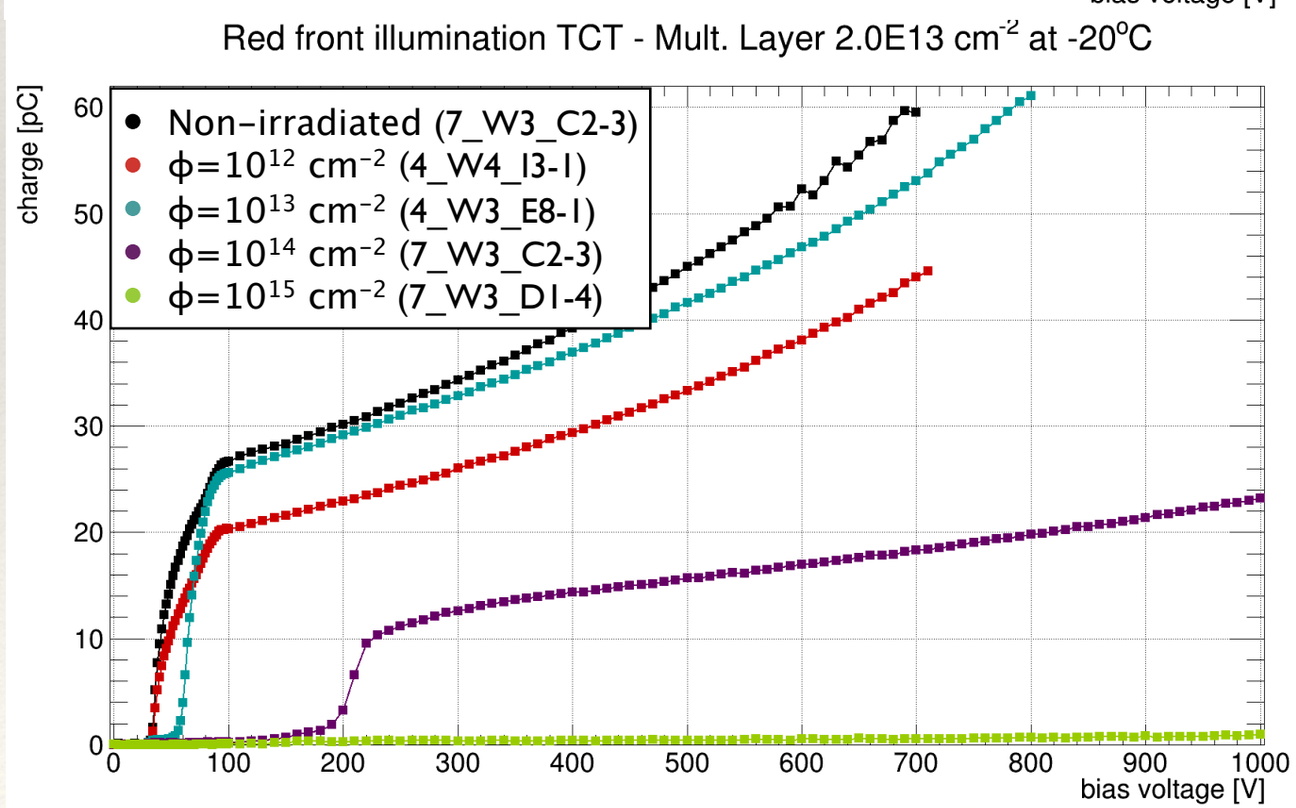
- **Picosecond-pulsed LASER (200 ps).**
- **Laser-induced charge injection.**
  - **Red front and back illumination.**
    - ~3 μm absorption length in Si.
    - Charge injection close to the surface.



Charge Collection vs. Bias

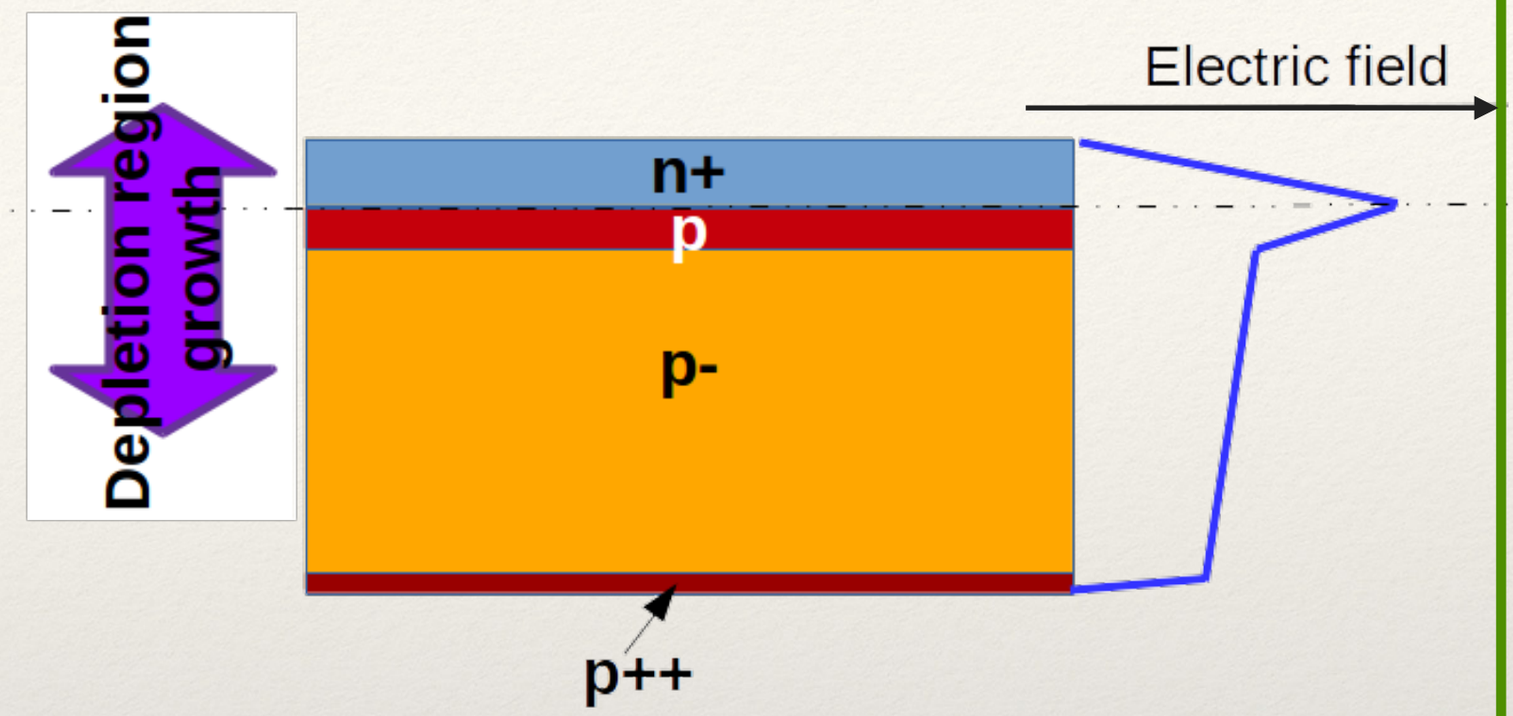






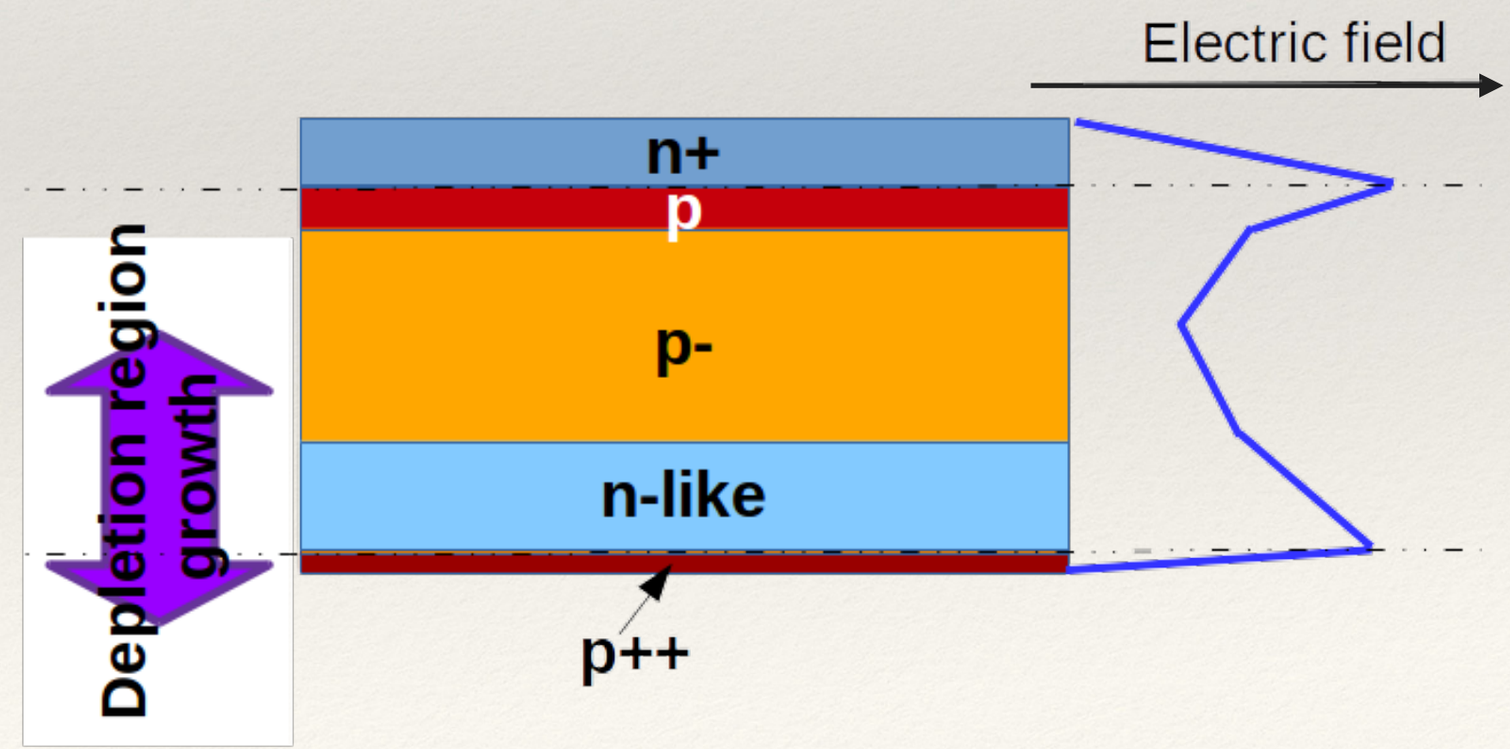
Depletion Region

Before Irradiation

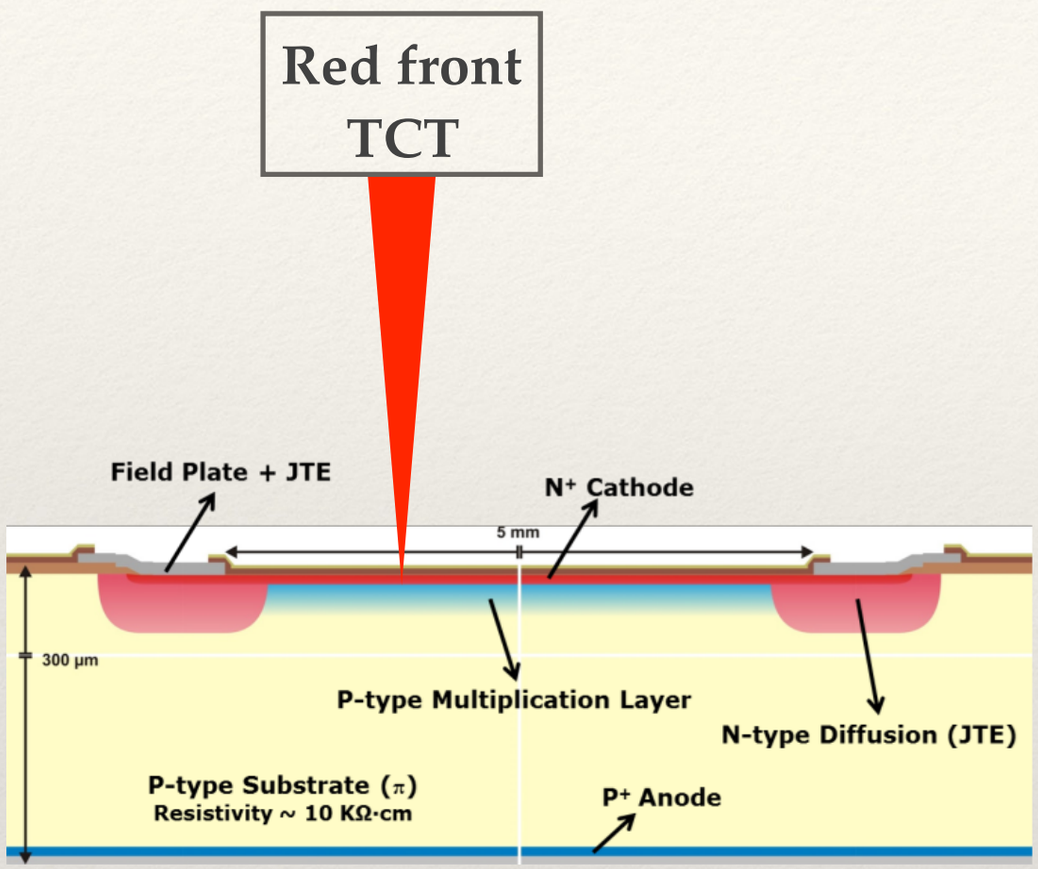


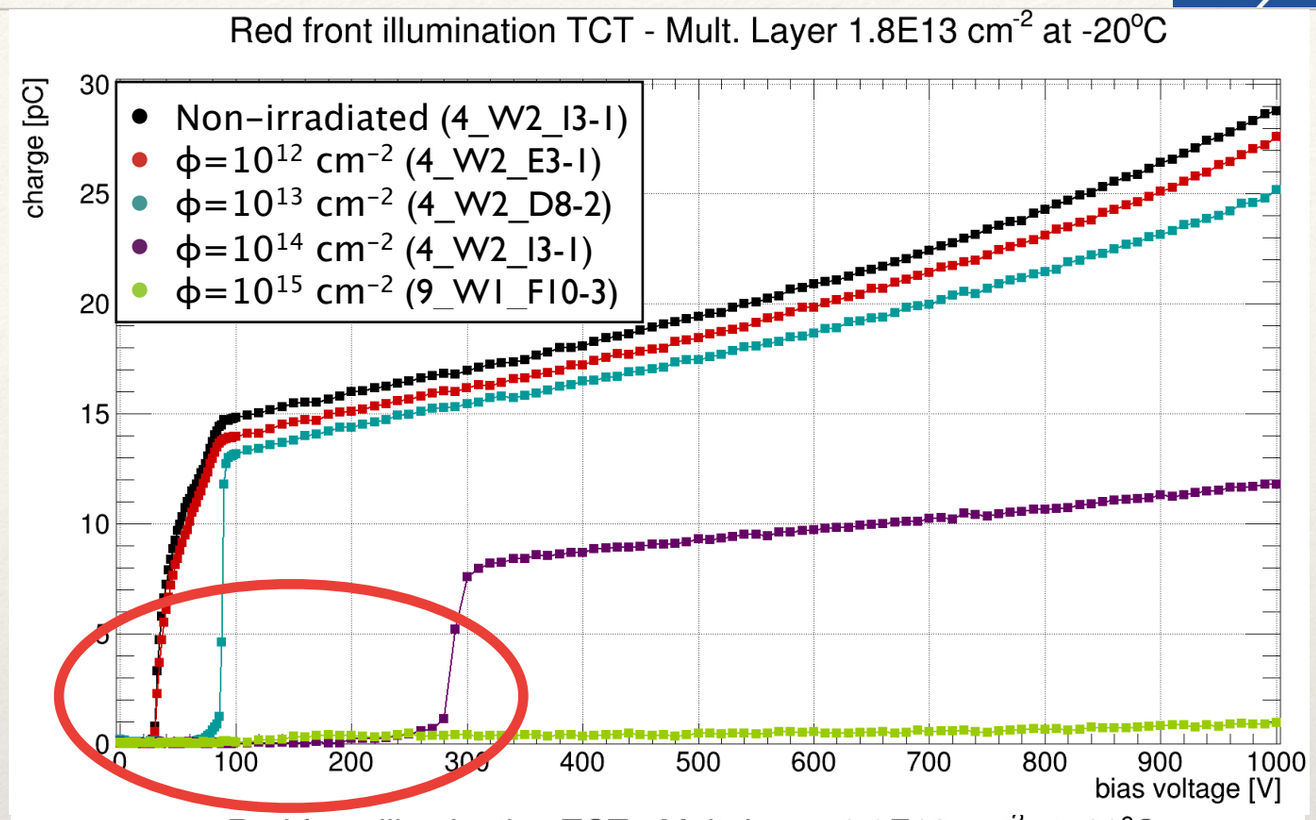
After Irradiation

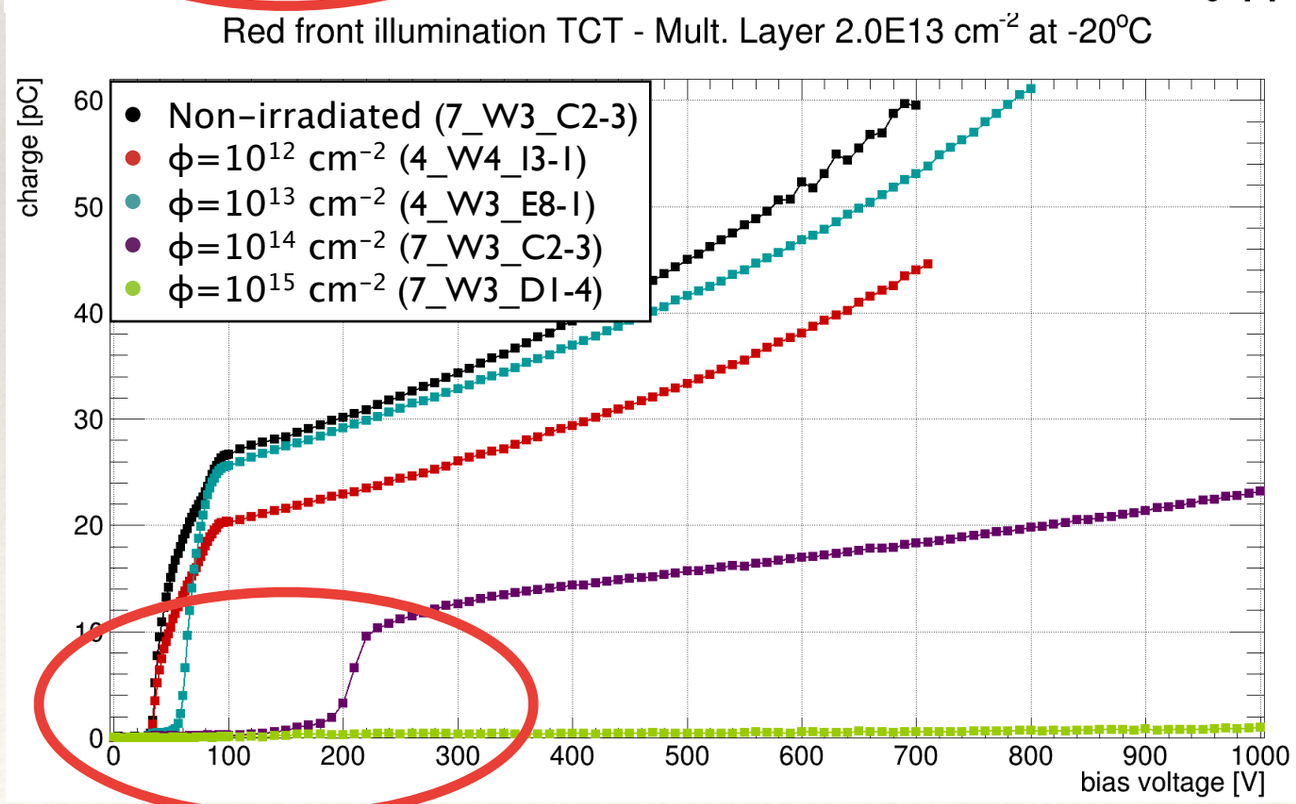
Double junction effect



Charge Collection vs. Bias

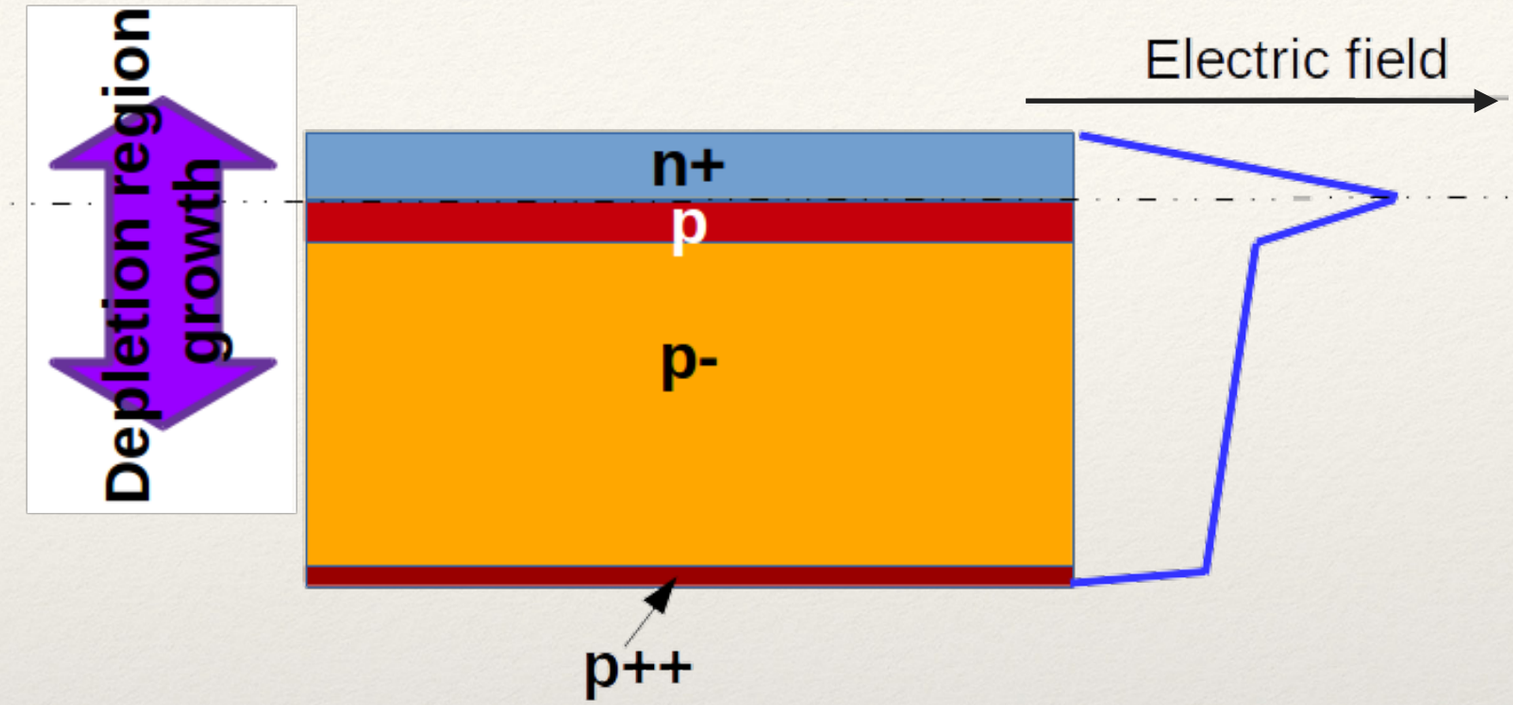






Depletion Region

Before Irradiation



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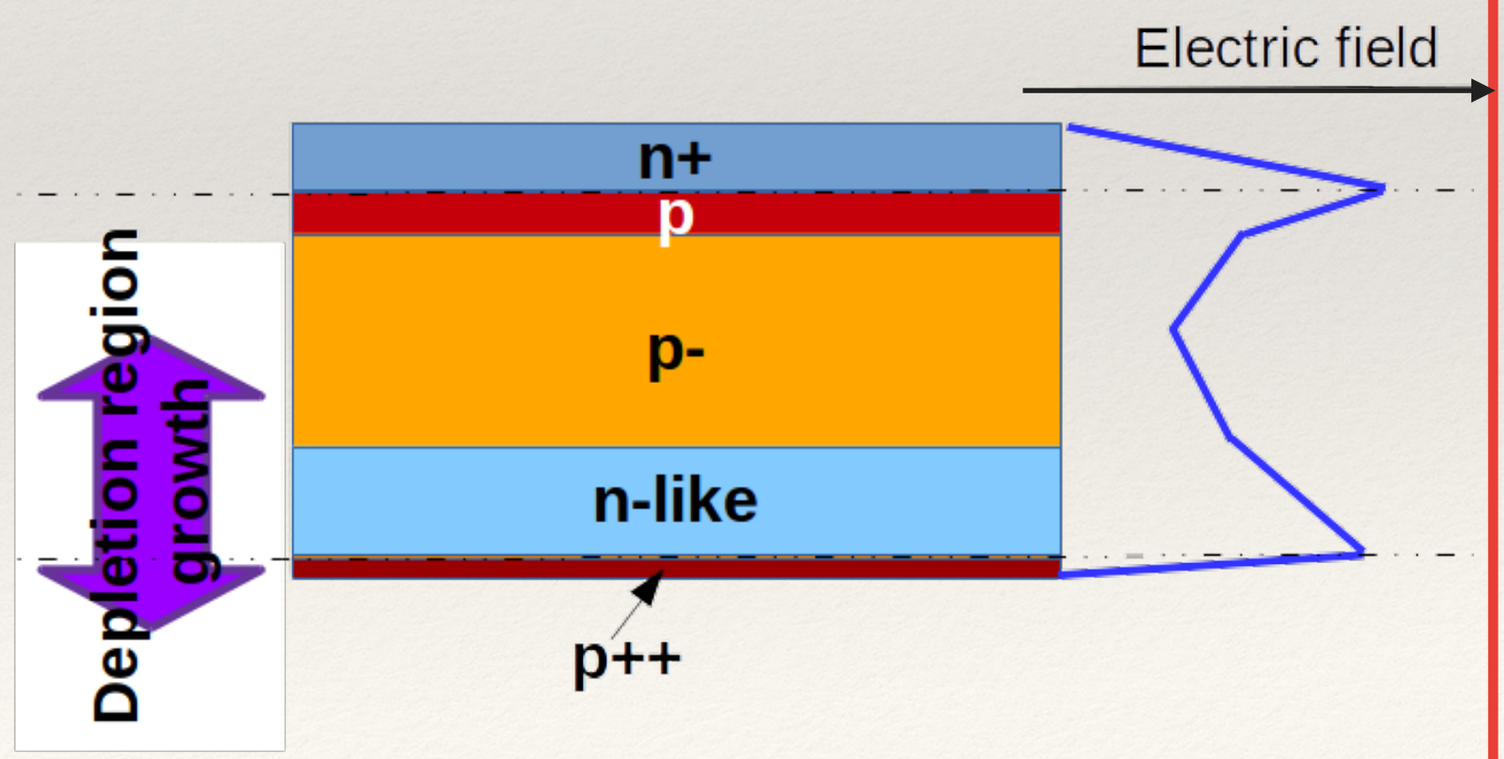
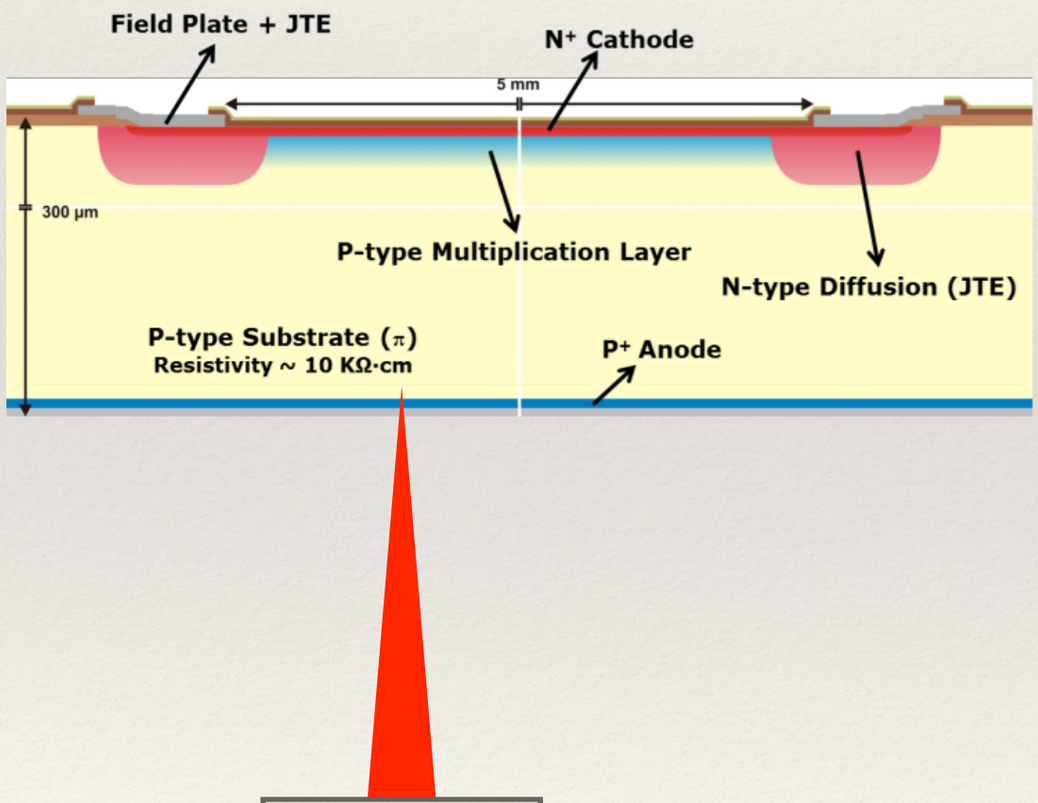
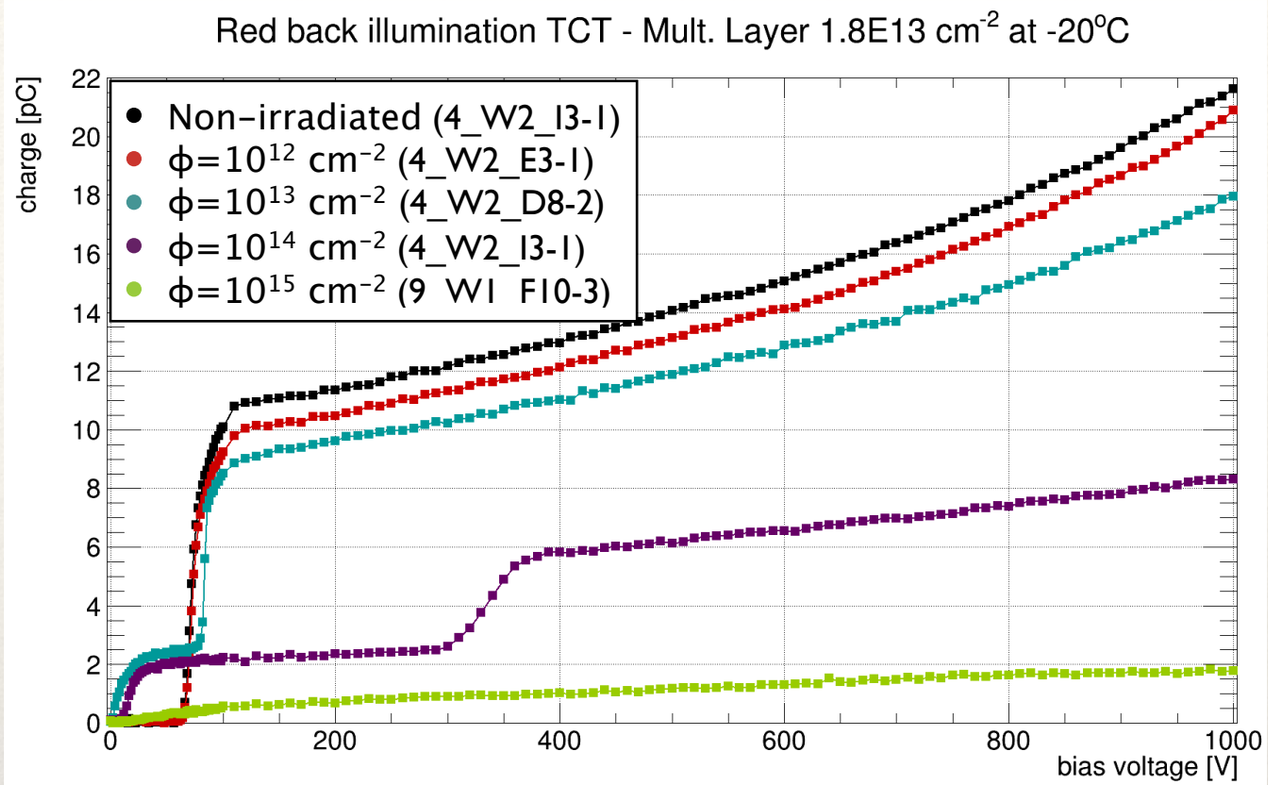
Double junction effect

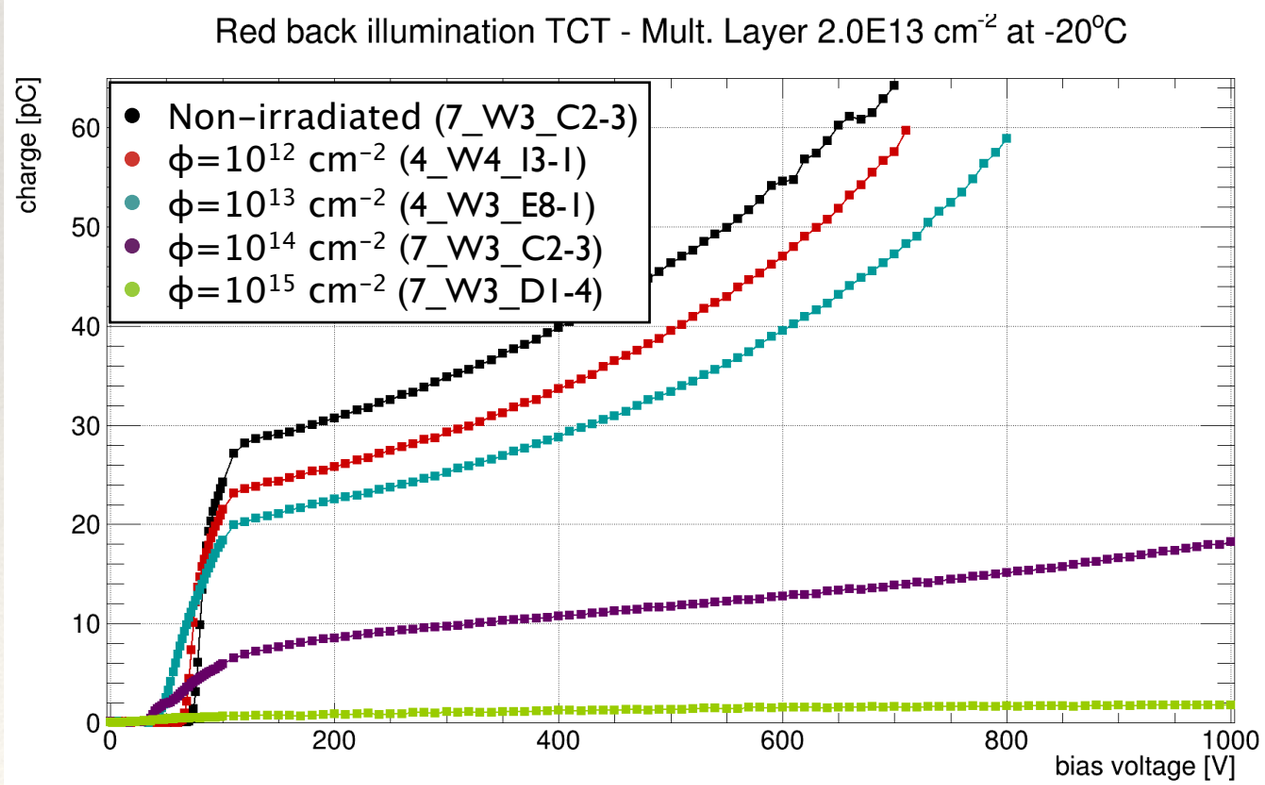


Charge Collection vs. Bias

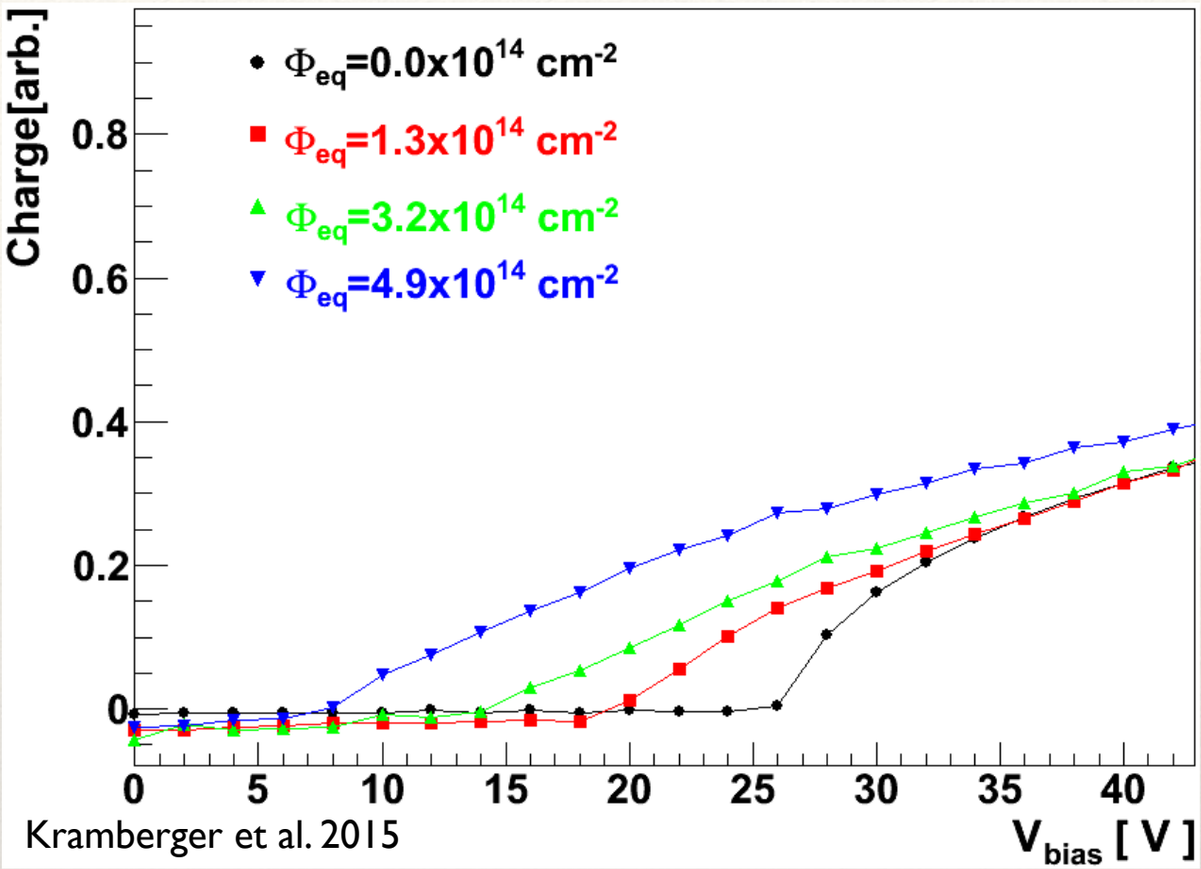


Red back TCT

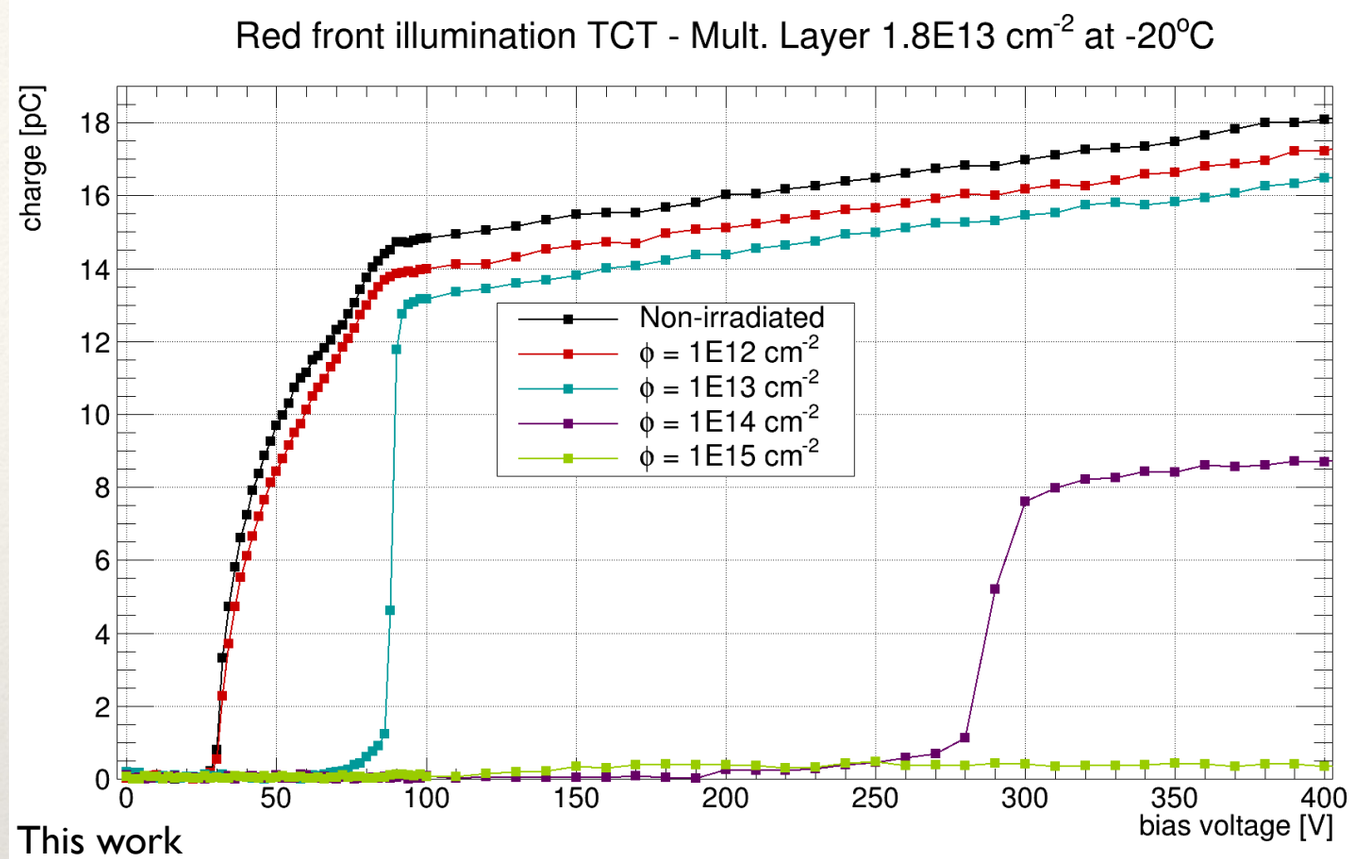




Onset Voltage and Fluence



Kramberger et al. 2015

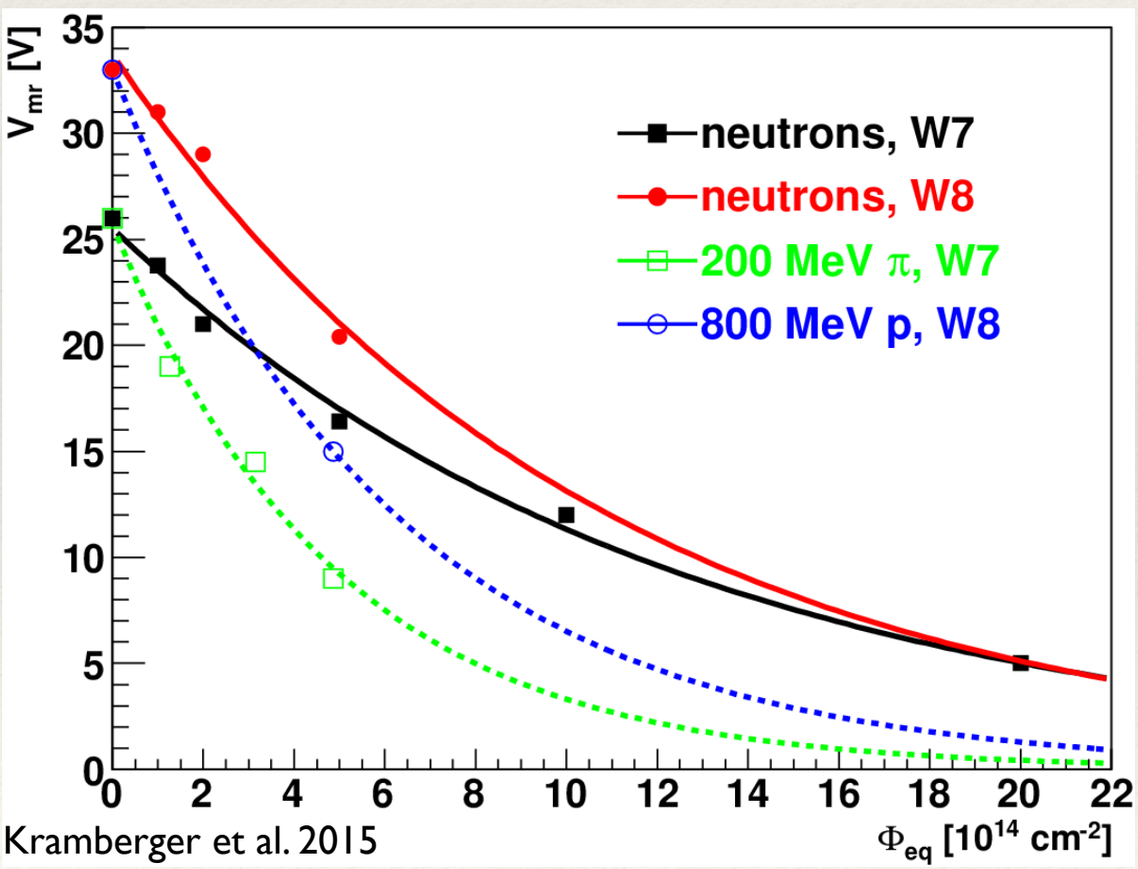


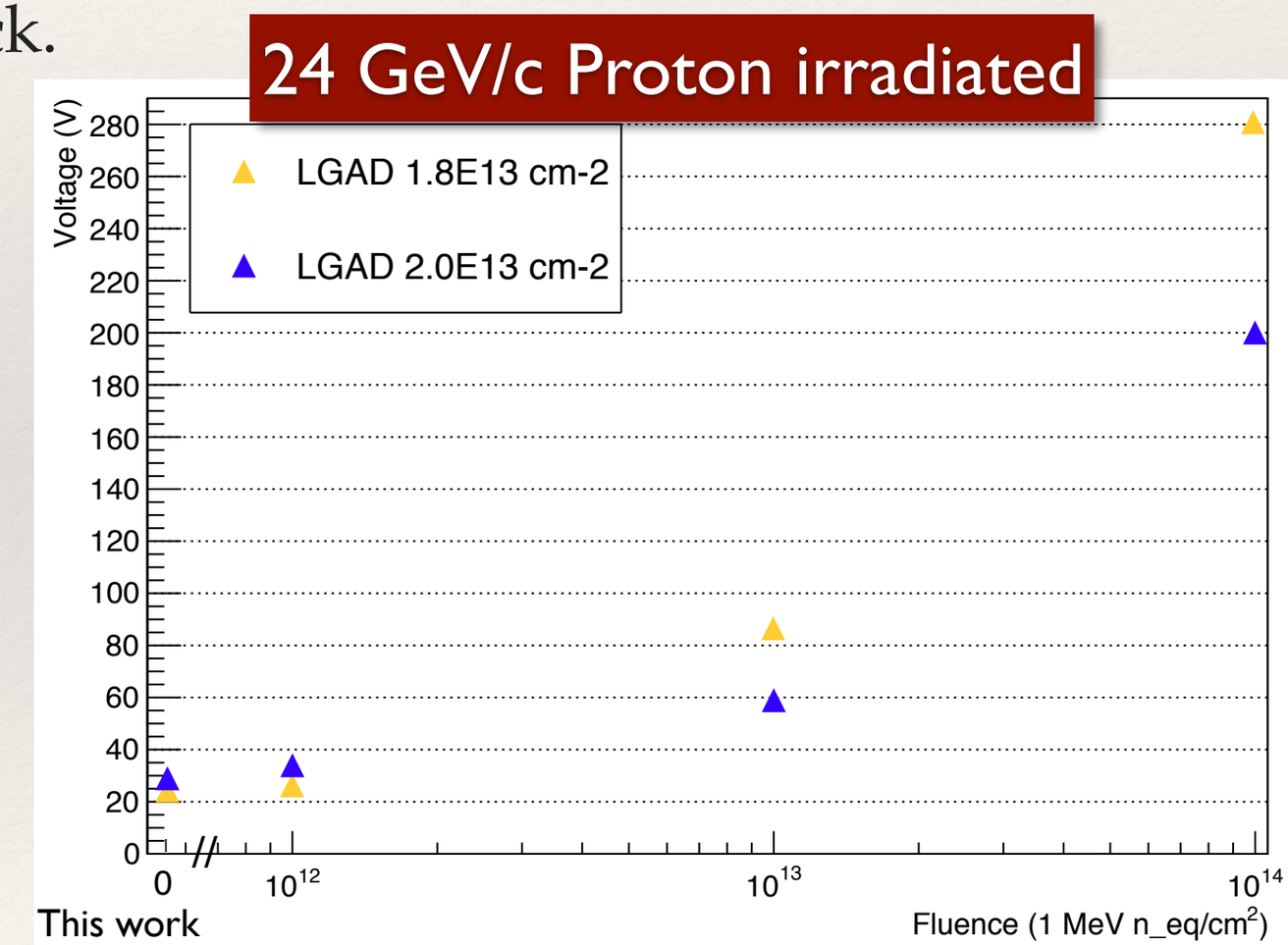
This work

- To actually have gain the multiplication layer must be depleted.
- The *multiplication onset voltage* indicates as from which voltage the multiplication layer is depleted.
- The multiplication onset voltage can be determined by red front TCT.
  - Observed as a *foot* in the charge collection vs. bias voltage curves.

Onset Voltage and Fluence

- According to G. Kramberger's results* (CNM run 6474), the mult. onset voltage decreases with fluence in LGADs with low leakage current (≤ 1 μA at V_{fd}, 20ºC).
- The opposite effect was observed in the LGADs from CNM run 7859.
- Most plausible explanation: double junction effect due to hole trapping.
  - The device is depleted from the back.

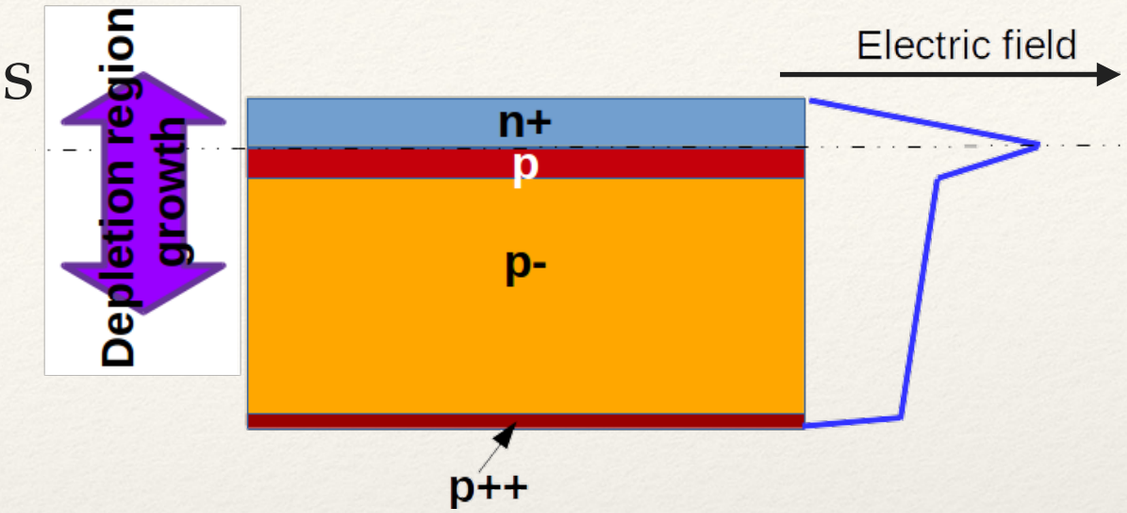




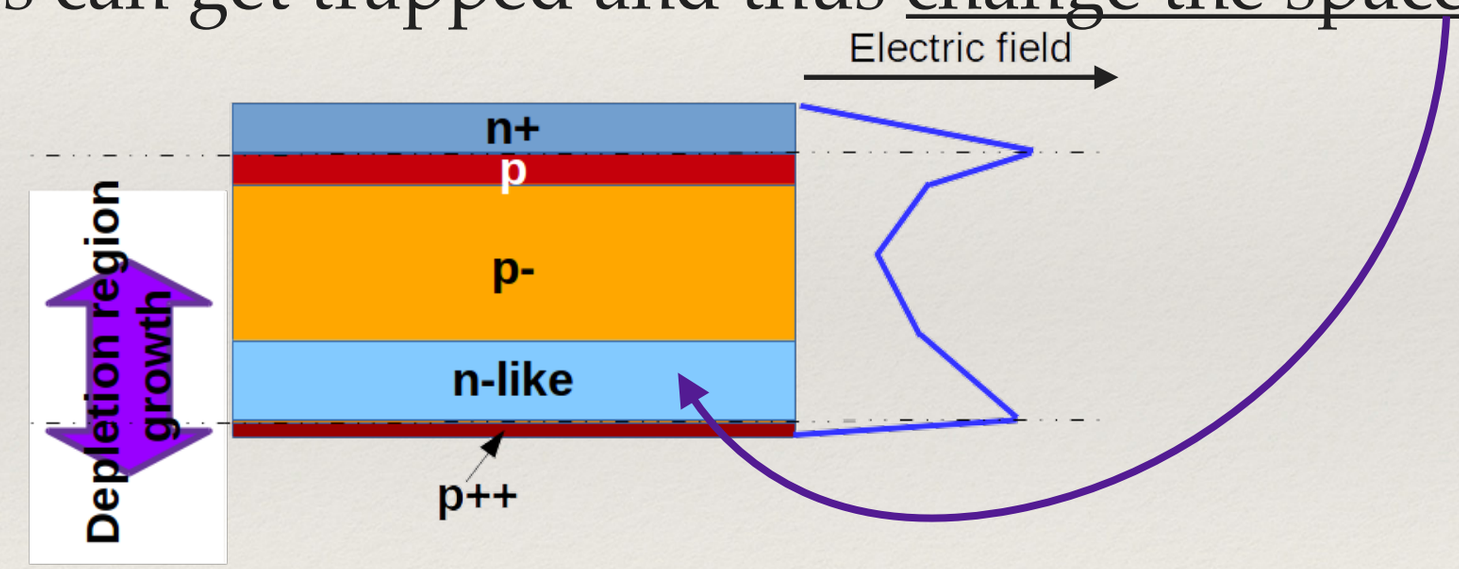
*G. Kramberger et al., Radiation effects in Low Gain Avalanche Detectors after hadron irradiations. J Inst. 2015;10(07):P07006-P07006.

Double Junction Effect

- Before irradiation, there are no deep traps => the depletion region grows from the front (multiplication layer).



- After irradiation, trapping is significant.
- Multiplication holes can get trapped and thus <u>change the space charge</u>.

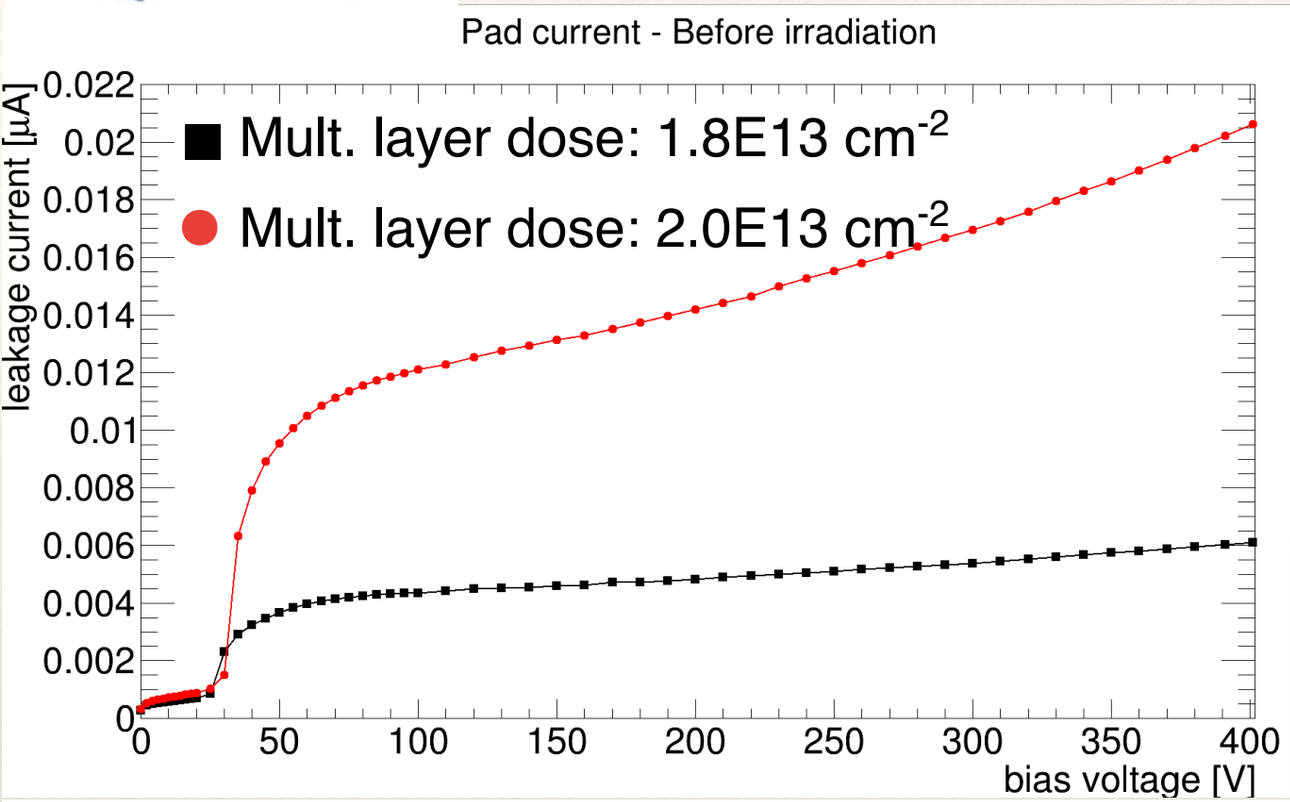


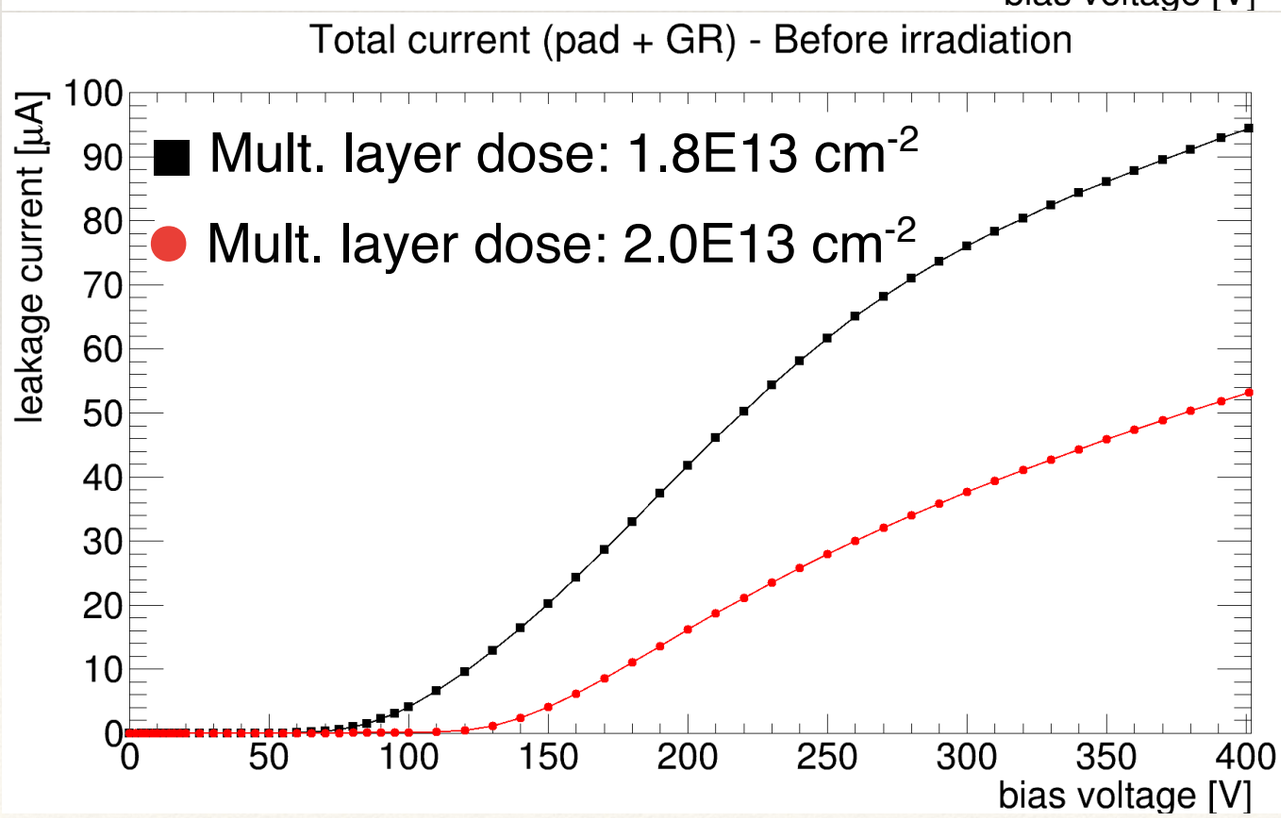
- Because of the occupation probability of traps, the process is highly dependent on temperature.
  - **The lower the temperature, the longer the charges remain trapped.**

Further analyses of the two LGADs irradiated up to $10^{14}\,n_{eq}/cm^2$

The apparent double junction effect is most noticeable at this fluence.

IV Curves at 20°C (before irradiation)





Both sensors qualify as *low current devices* according to the classification employed by G. Kramberger*:

leakage current ≤ 1 µA at V_{fd}, 20°C

*G. Kramberger, Effects of irradiation on LGAD devices with high excess current, 25th RD50 Workshop, CERN, November 2014

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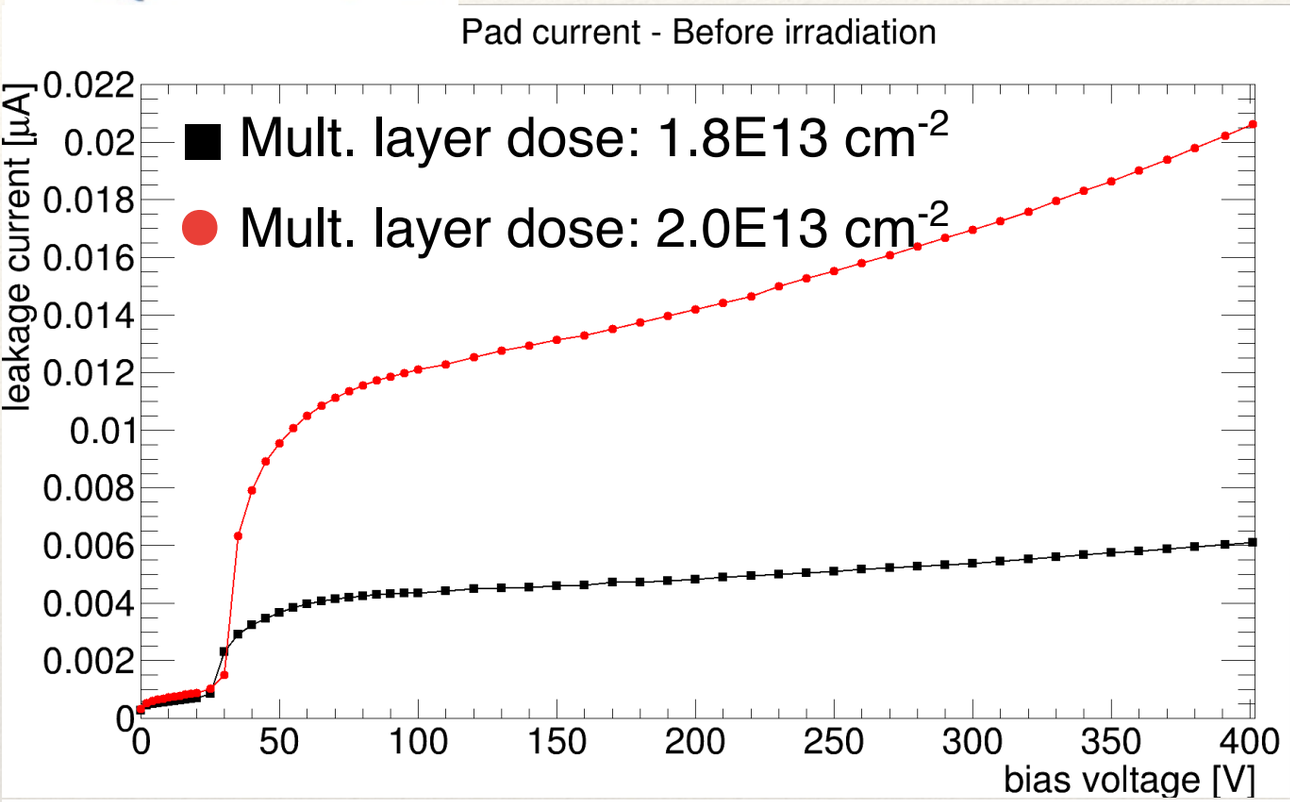

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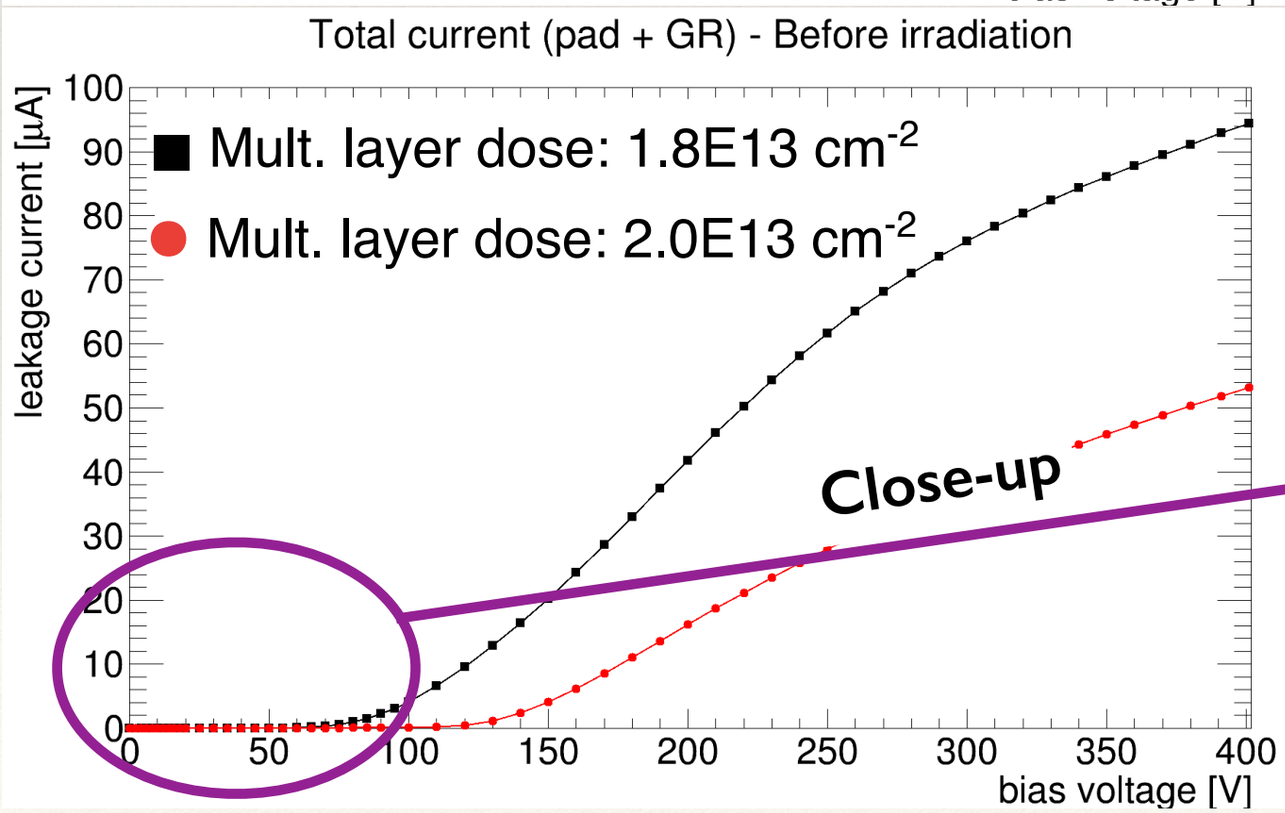
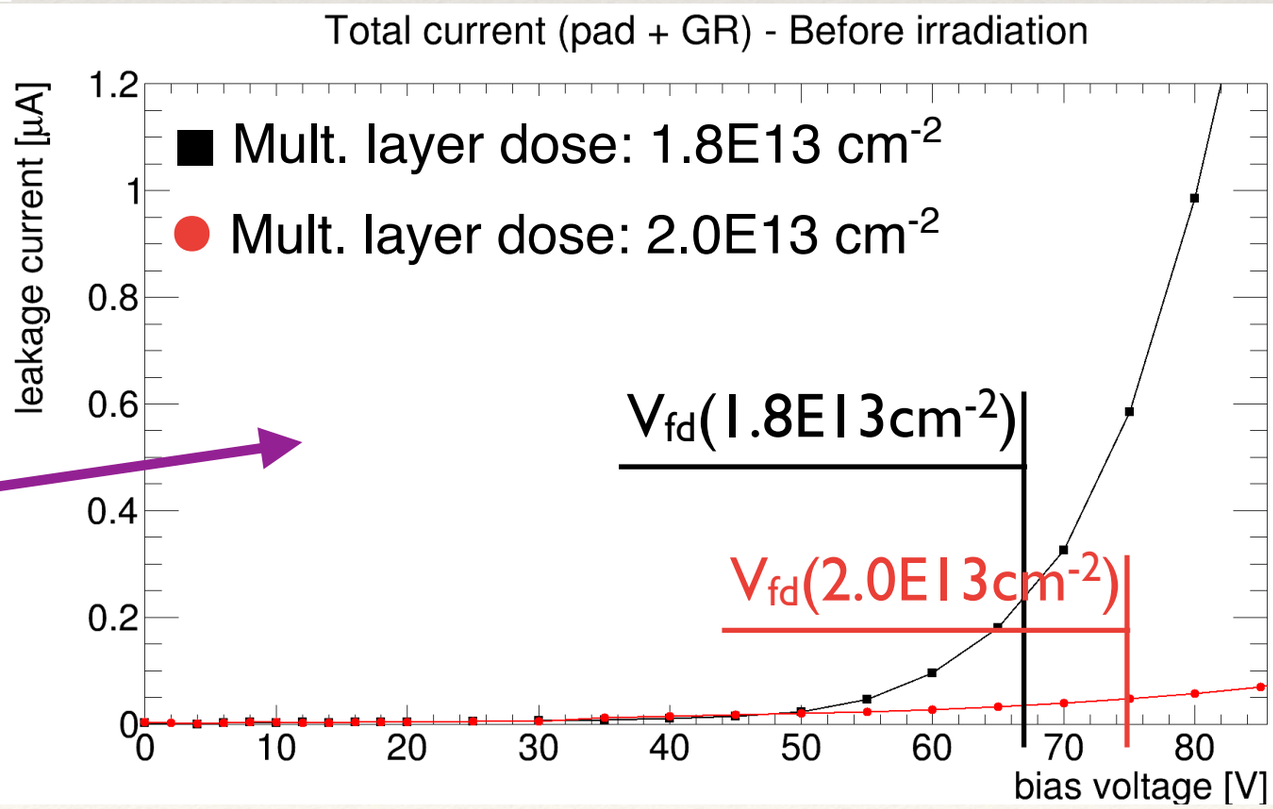




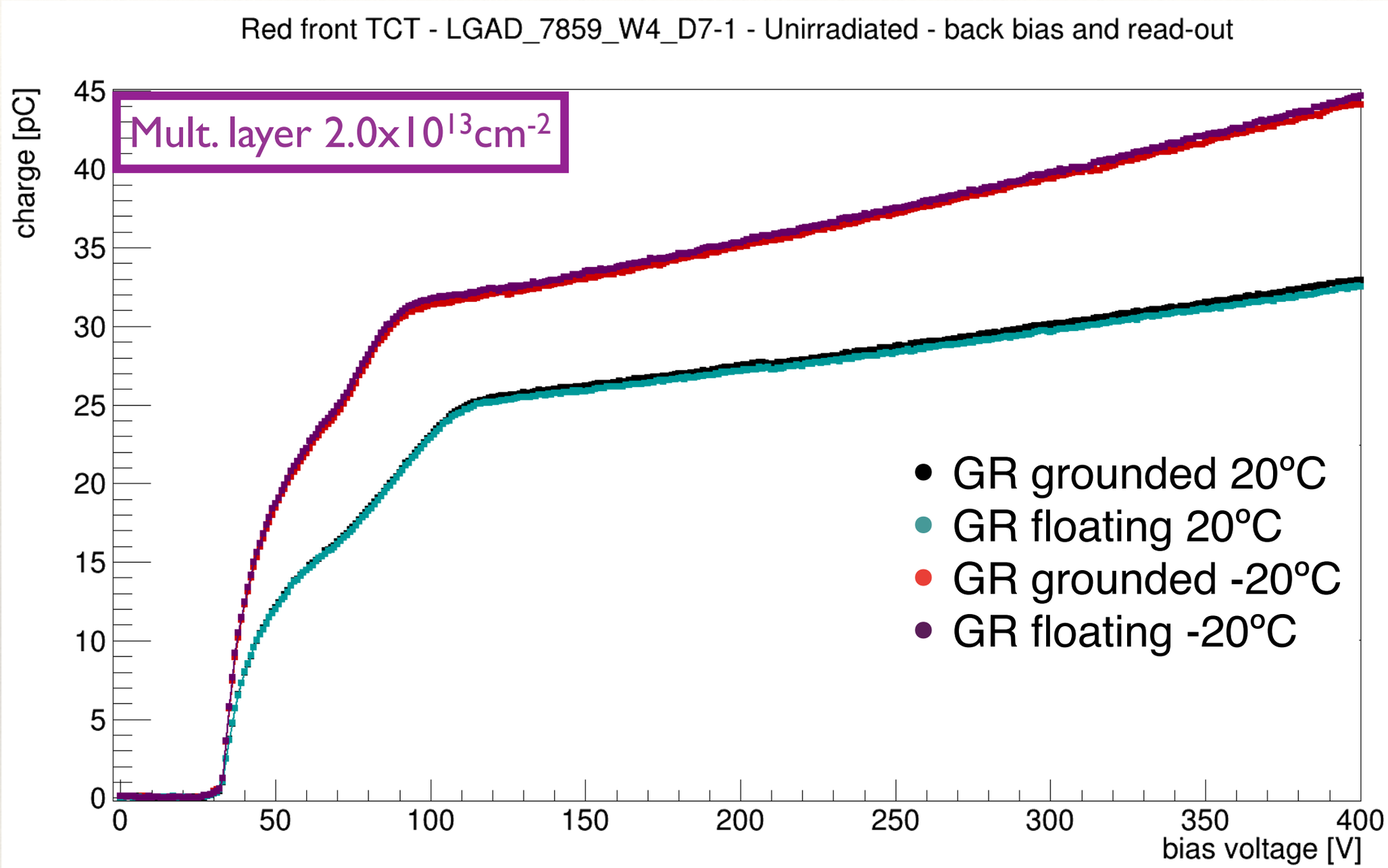
TCT Charge Collection vs. Bias

- TCT voltage scans performed on:
  - One unirradiated LGAD used as reference (mult. layer 2.0×10^{13} cm^{-2}).
  - Both LGADs irradiated up to 10^{14} n_{eq}/cm^2.

- Conditions:
  - Two temperatures: 20ºC and -20ºC.
    - To see the effects of temperature on the multiplication onset (double junction effect).
  - The measurements were performed
    - with the guard ring (GR) floating (usual procedure),
    - with the GR connected to ground (to assess any possible differences).

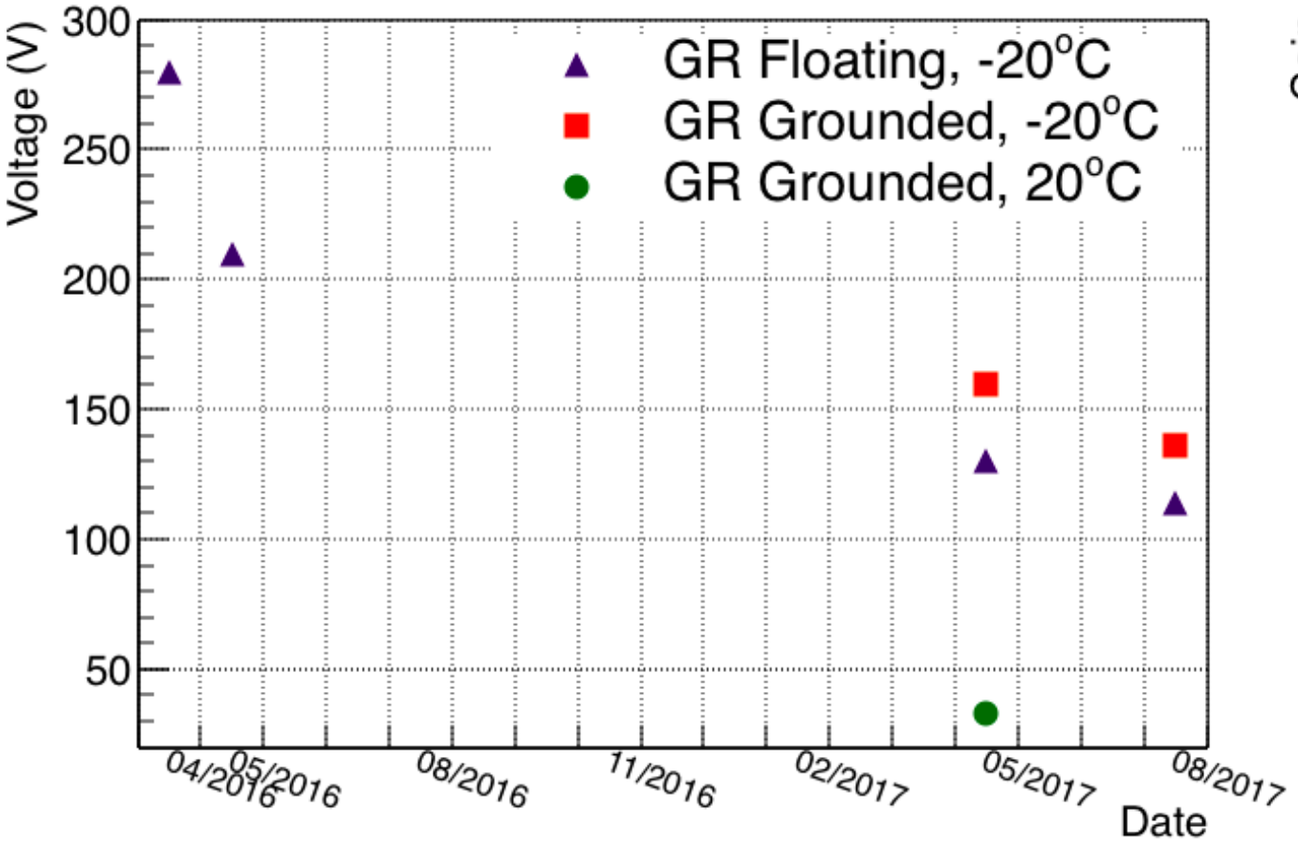
- The scans were compared to those measured in 2016 and presented at the 28th RD50 Workshop.

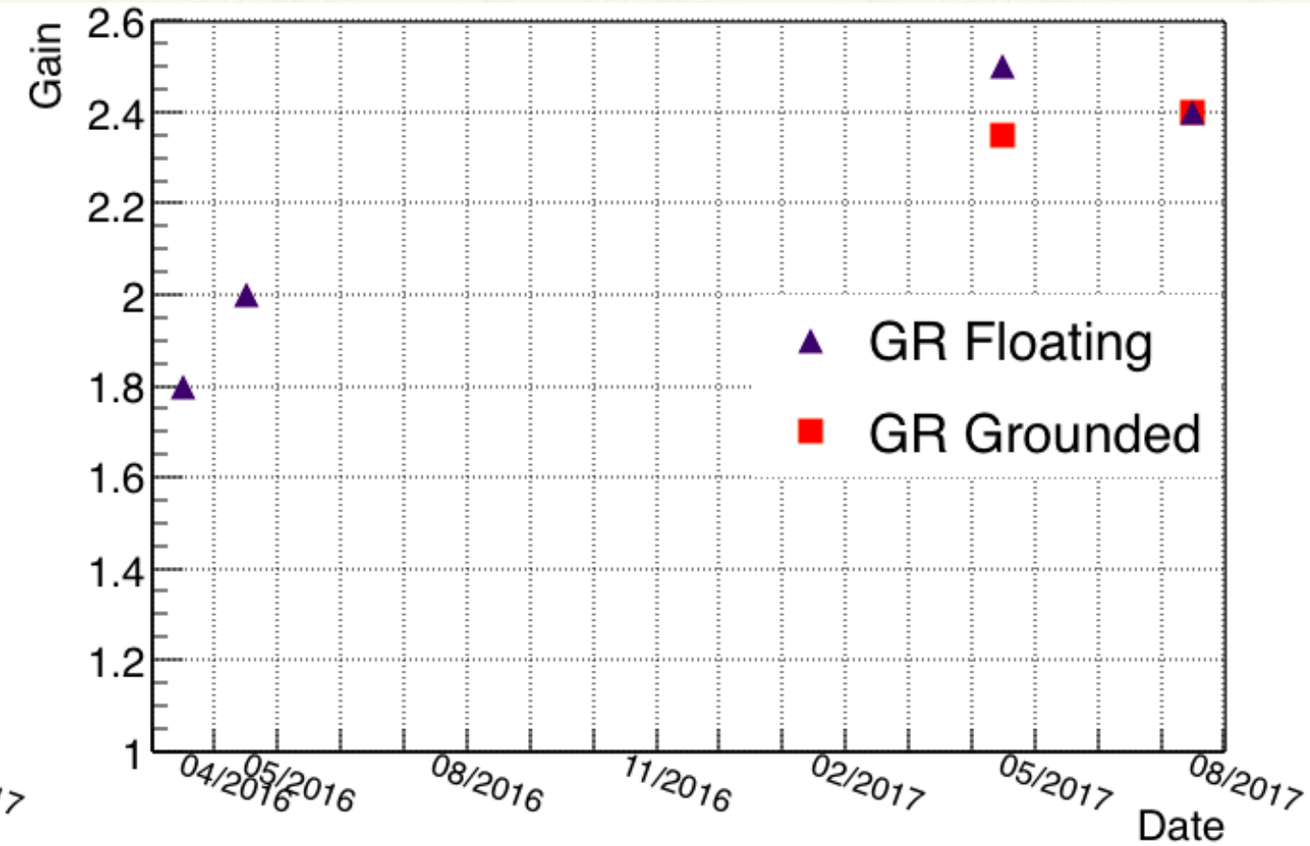
Unirradiated LGAD



- The GR connection scheme causes no significative changes.
- The multiplication onset does not depend on temperature.

Irradiated LGAD - Mult. Layer: 1.8×10^{13} cm^{-2}



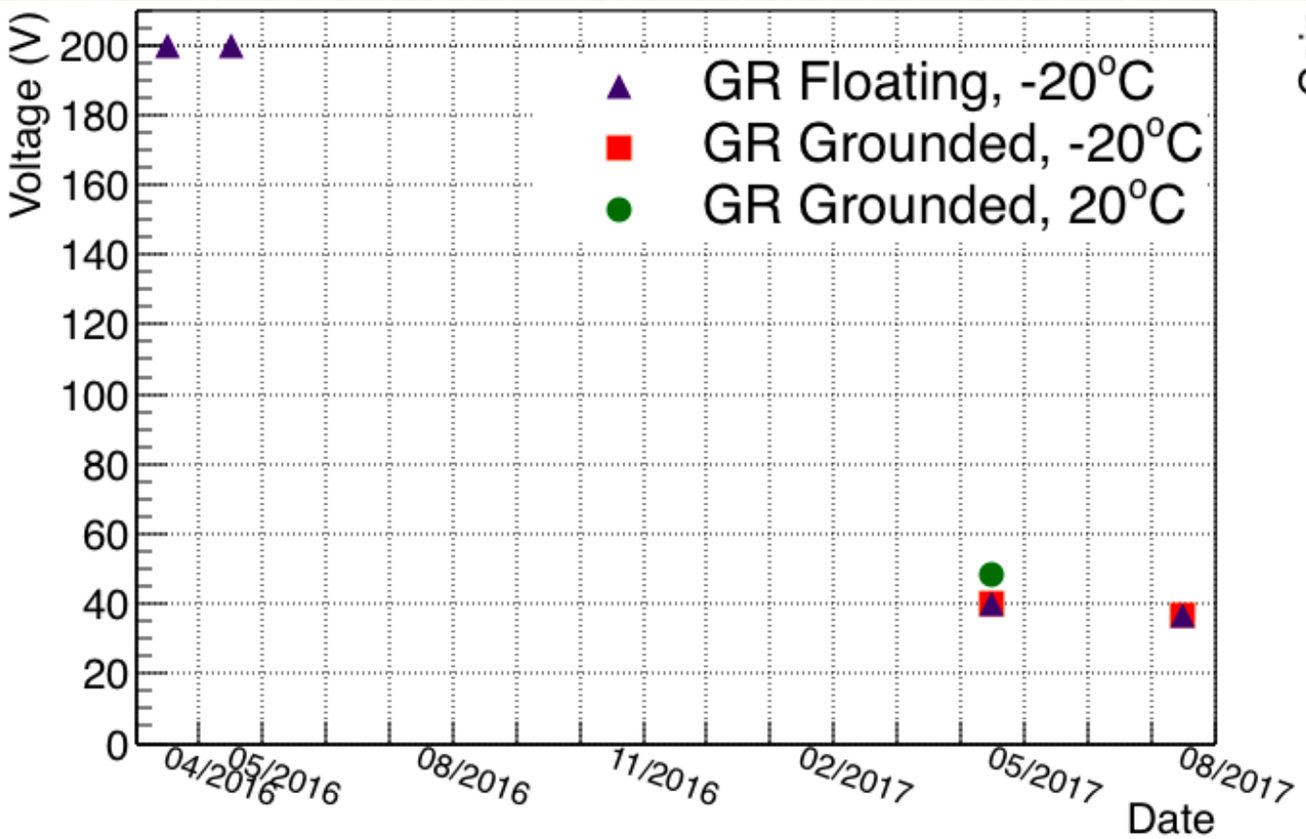


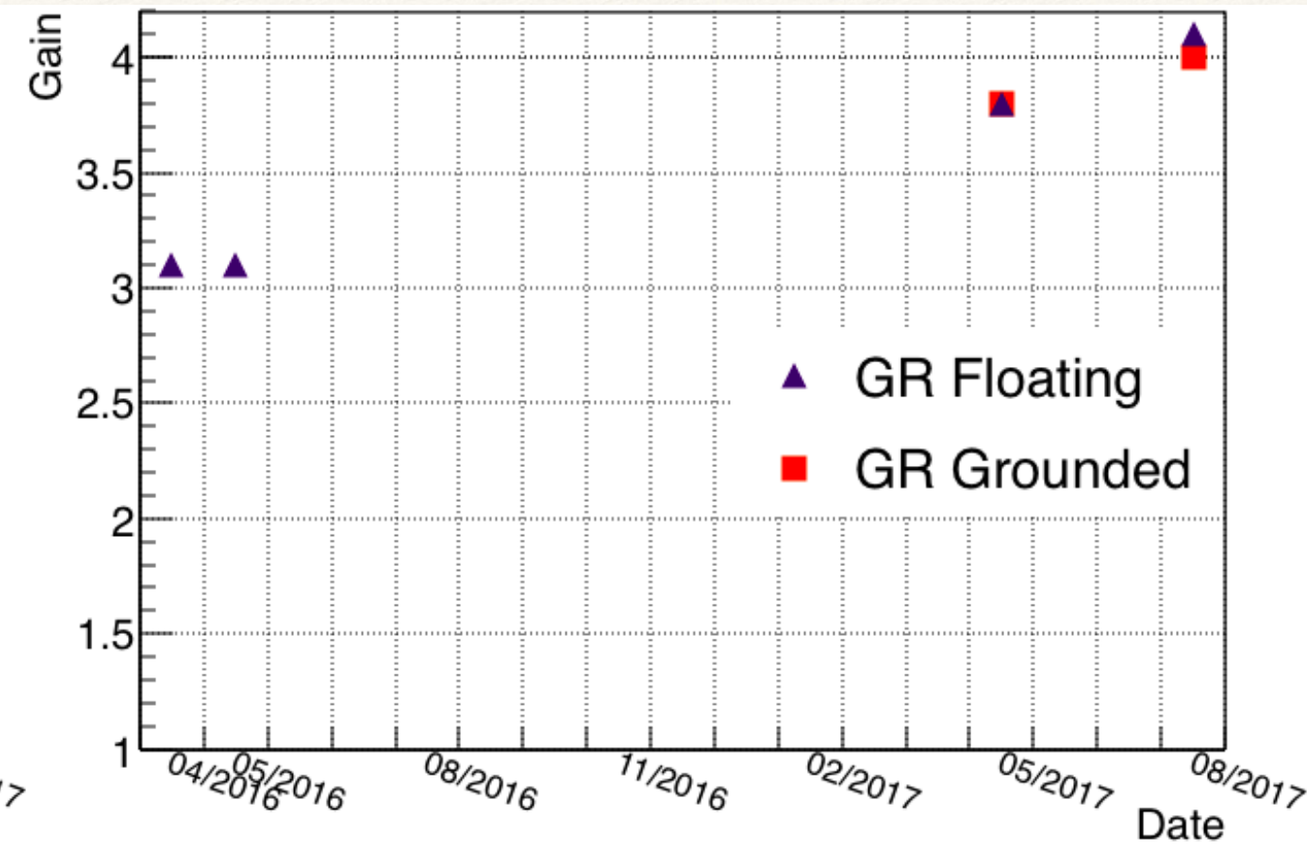
Onset voltage before irradiation: ~30 V
Gain before irradiation at 400V and -20°C: ~3.45

Gain at 400 V, -20°C. Calculated w.r.t a PiN. Normalised by laser power.

- At -20°C the GR shifts the onset of multiplication.
- The multiplication-onset voltage is lower at high temperatures.
- The multiplication-onset voltage decreased with time. ↴
- Recovery of gain with time. ➔ Possible cause: **annealing**.

Irradiated LGAD - Mult. Layer: 2.0×10^{13} cm^{-2}





Onset voltage before irradiation: ~32 V
Gain before irradiation at 400V and -20°C: ~6.83

Gain at 400 V, -20°C. Calculated w.r.t a PiN.
Normalised by laser power.

- The GR connection causes no significative changes.
- The multiplication onset does not change significantly with temperature now.
- Significantly large shift in the multiplication-onset voltage with respect to 2016.
- Recovery of gain with time/annealing.

Results from Irradiated LGADs

- **Device with a multiplication layer dose of 1.8×10^{13} cm^{-2}.**
  - Multiplication onset dependant on temperature.
    - Consistent with double junction effect.
- **Device with a multiplication layer dose of 2.0×10^{13} cm^{-2}.**
  - In 2016 this sample presented clear signs of double junction effect.
  - In 2017 the multiplication onset ceased to be affected by temperature.
    - Just as before irradiation.

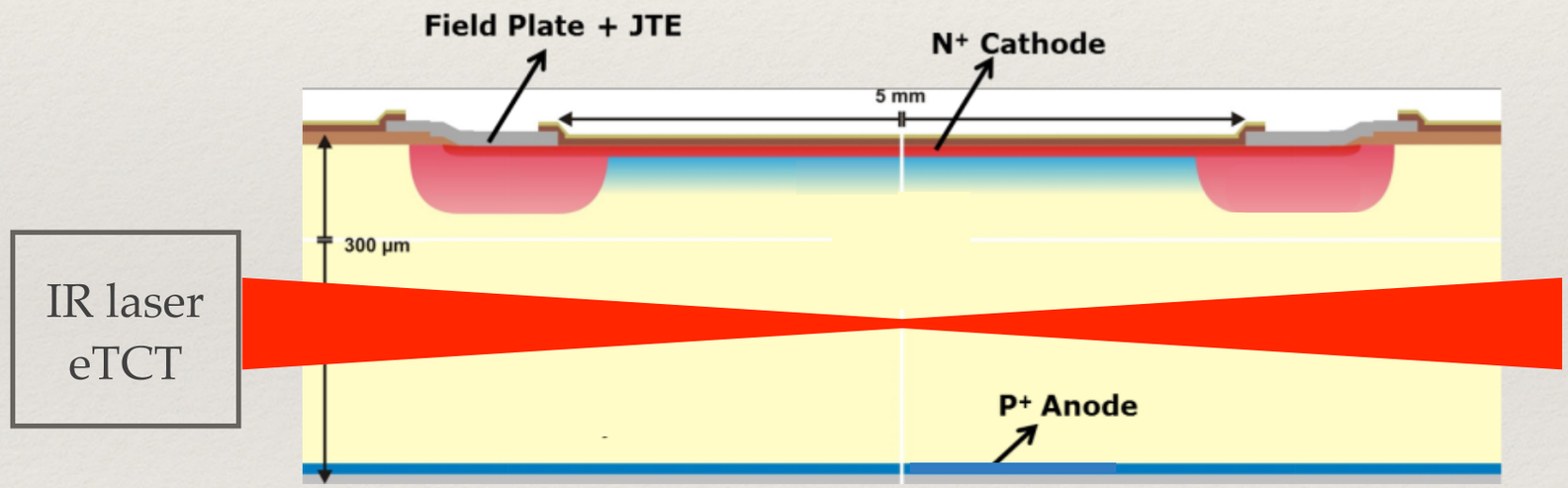
Double Junction Effect?

- How does the electric field evolve with voltage?
- How does the electric field change with temperature?

Measurements Performed

Edge Transient Current Technique (eTCT)

- **IR edge illumination.**
  - ~1 mm absorption length in Si.
  - Probing of the electric field profile.



eTCT Diagram

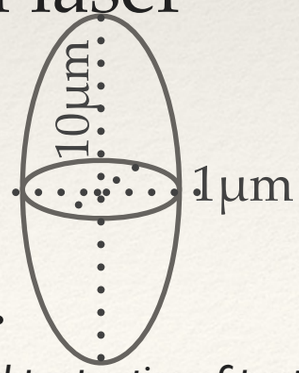
Measurements Performed

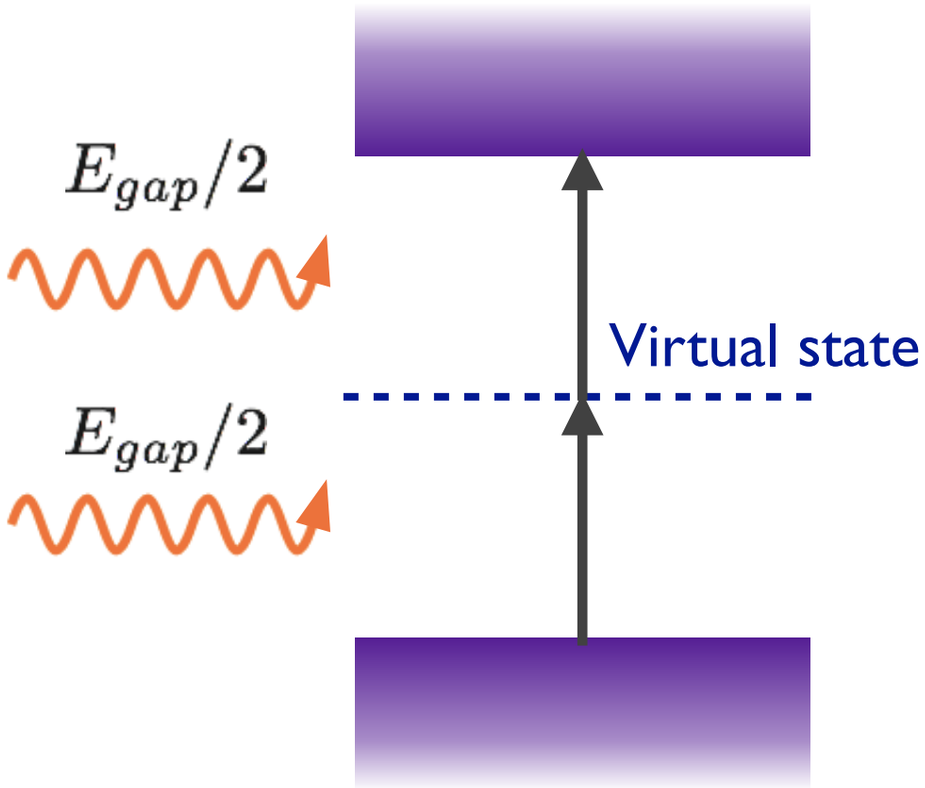
Two Photon Absorption TCT (TPA)

- **The energy of each individual photon is smaller than the bandgap.**
- Sum of energies from 2 photons ≥ bandgap.
- **If the Δt between photons is smaller than ~0.1 fs, both photons are absorbed.**

$$\tau \approx \frac{\hbar}{E_{gap}/2} \approx 0.1 \text{ fs}$$

  - Transition via an intermediate virtual state.
  - **An e-h pair is produced.**
- Femtosecond pulsed mode-locked laser required.
- Beam spot volume: ellipsoid of ~1 μm section and ~10 μm length.

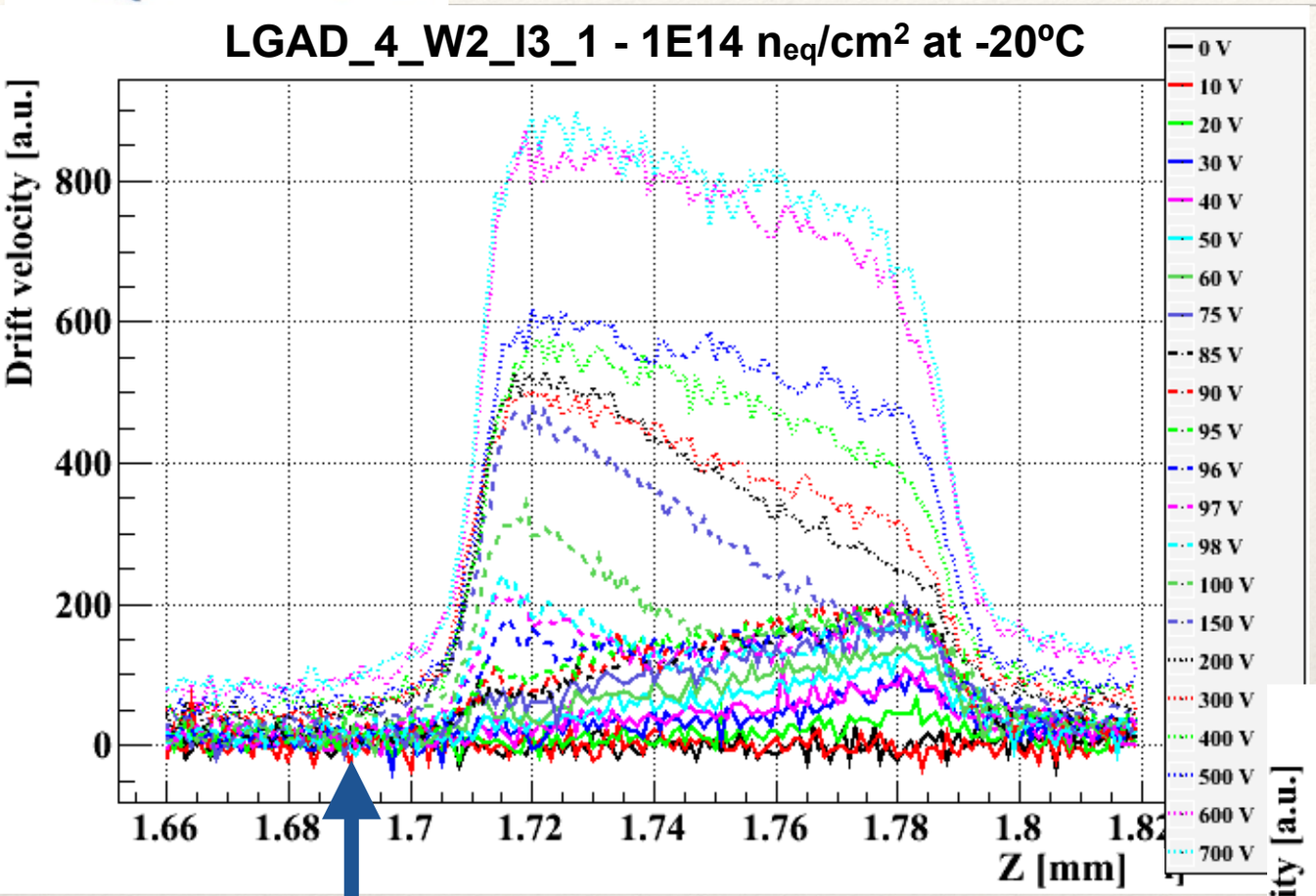




Edge TCT and TPA

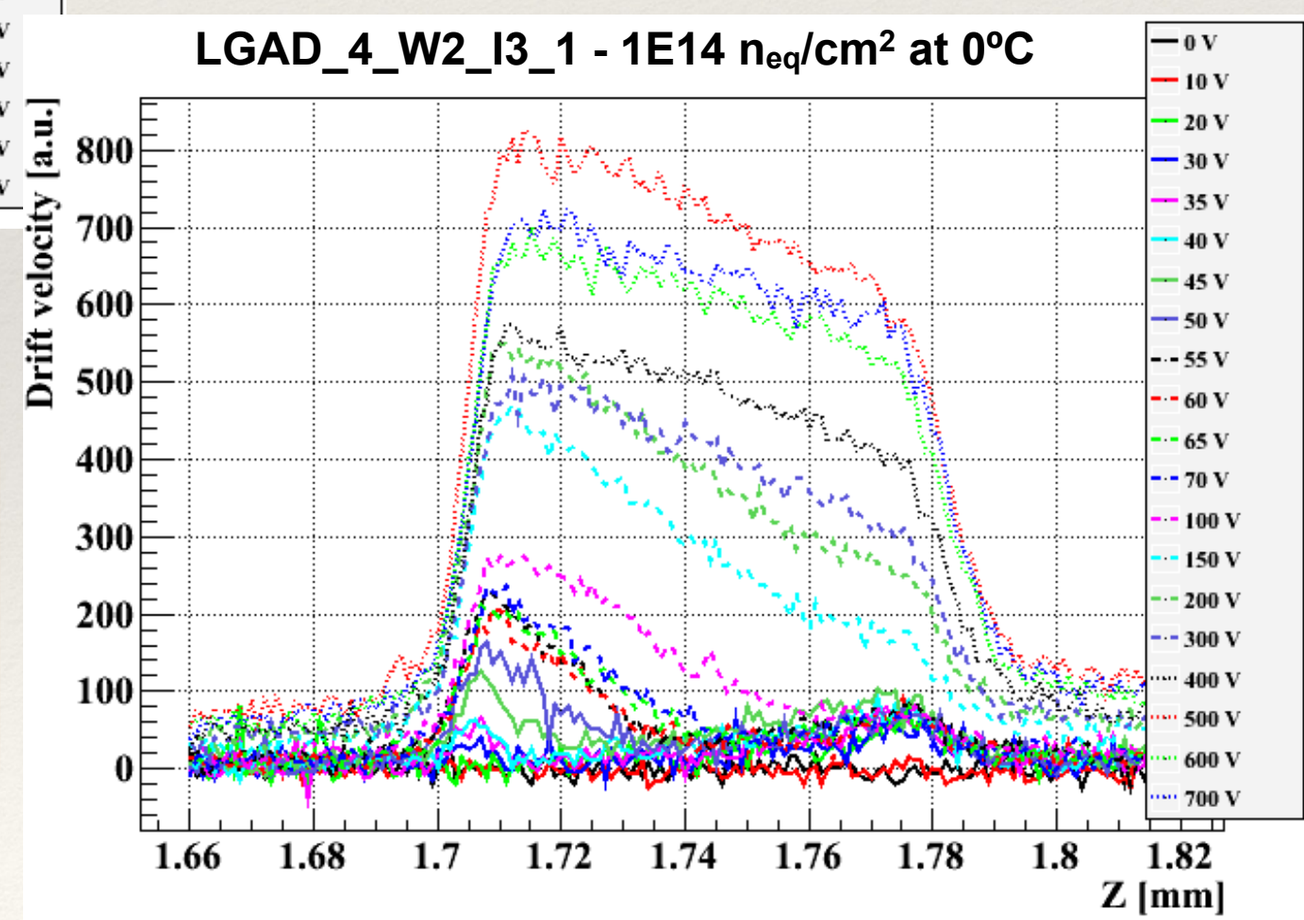
- TPA-TCT was performed on one sample (mult. dose: $1.8 \times 10^{13} cm^{-2}$).
- eTCT scans were performed on both irradiated samples.
- The objective is to better comprehend the distribution of the electric field inside the devices.
- Conditions:
  - Temperatures: 20ºC, -20ºC, and 0ºC (only for TPA).
  - Several voltages.
  - The edge was polished.

TPA - Mult. Layer $1.8x10^{13}cm^{-2}$



Front side

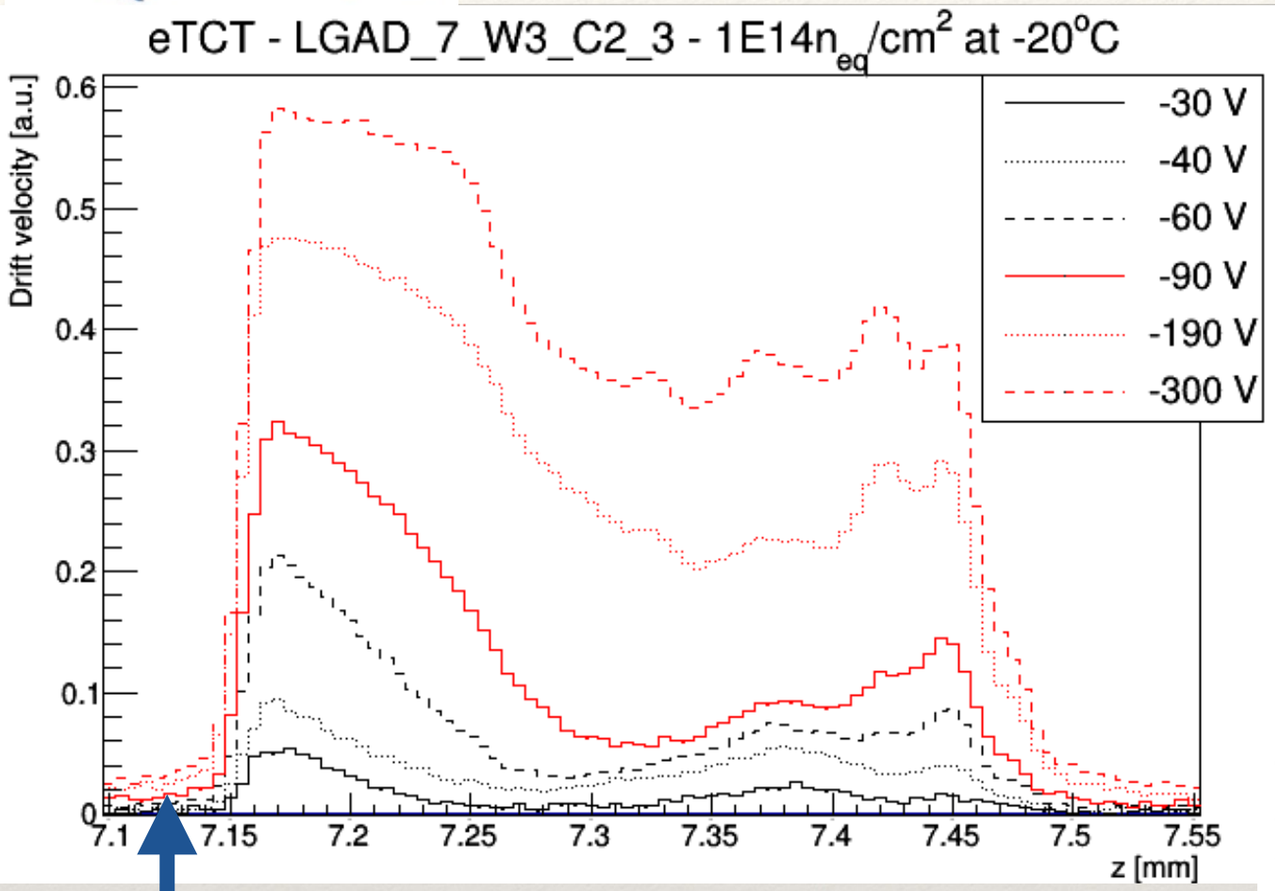
- The electric field grows from the back of the device.
- The electric field begins to increase in the front side at:
  - ~96 V for -20ºC,
  - ~45 V for 0ºC.



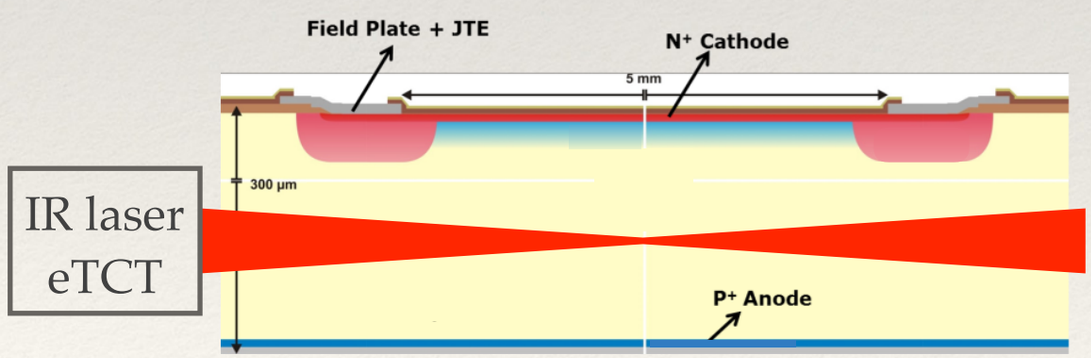
Consistent with double junction effect.

- The lower the temperature the more noticeable the effect.

eTCT - Mult. Layer $2.0 \times 10^{13} cm^{-2}$

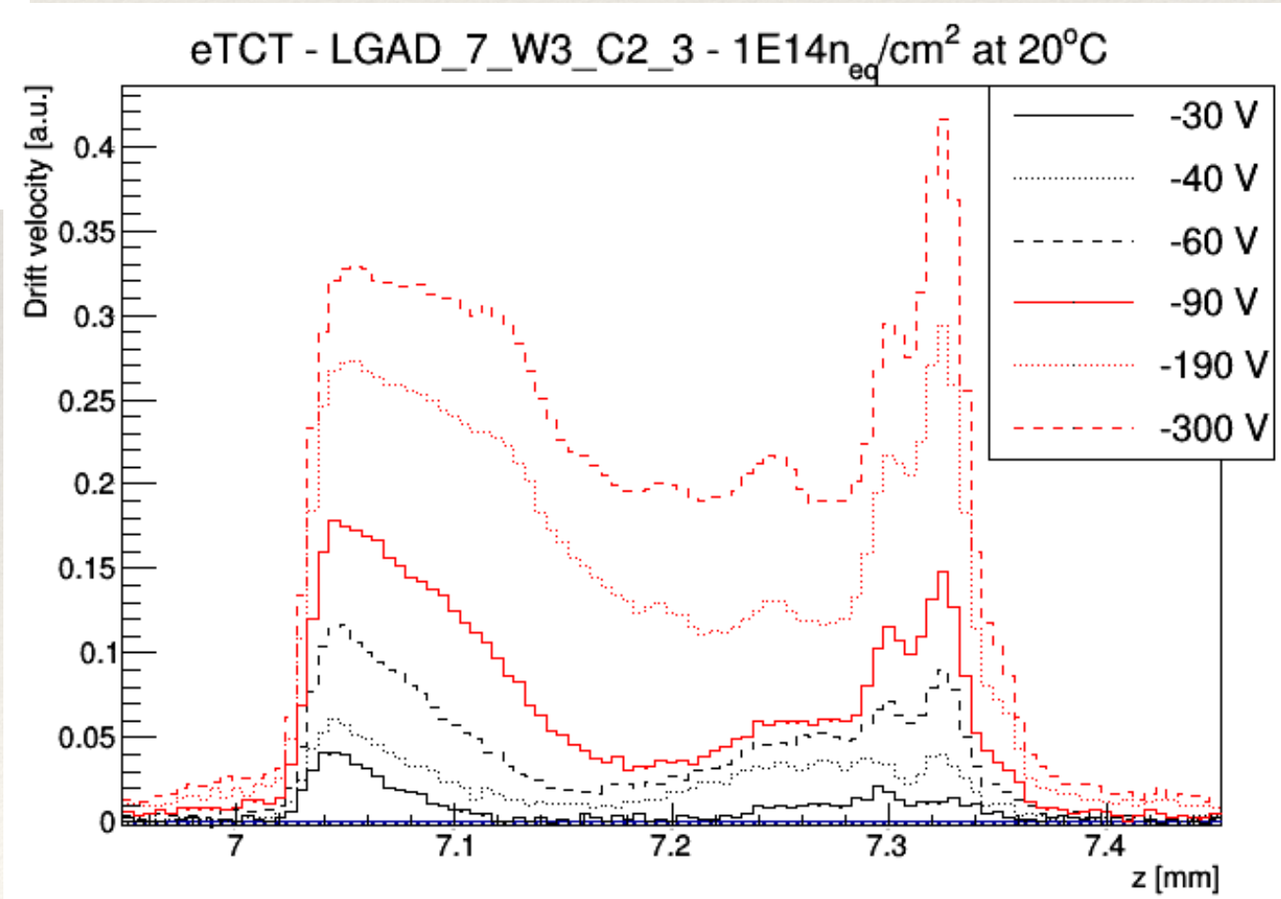


Front side



eTCT Diagram

- Temperature does not seem to affect dramatically the profile of the electric field (**unirradiated-like**).
- At 20°C the electric field on the back of the device is higher than at -20°C.



Conclusions

- Good quality samples
  - i.e. low leakage current before irradiation < 1 μA at V_{fd}, and 20ºC.
- Devices irradiated up to 10^{14} 1 MeV n_{eq}/cm^2.
- Double junction effect observed in TCT measurements (TCT, eTCT and TPA-TCT).
  - The electric field starts growing from the back of the device.

Open question: why are our results different from previous measurements on similar devices?

Conclusions

- Devices irradiated up to 10^{14} 1 MeV n_{eq}/cm^2.
- Measurements show that with annealing
  - the multiplication-onset voltage decreases,
  - the gain is recovered to 60-70% of the value before irradiation.
- Sample with a multiplication layer dose of $2.0 \times 10^{13} cm^{-2}$: no temperature dependance of the onset voltage (as before irradiation) in 2017.

The double junction effect shows a dependance on the annealing history.

As samples get annealed, they tend towards an unirradiated-like state.

Annealing is playing an important role for LGAD performance and might be exploitable for LGAD long term operation.

Further Studies

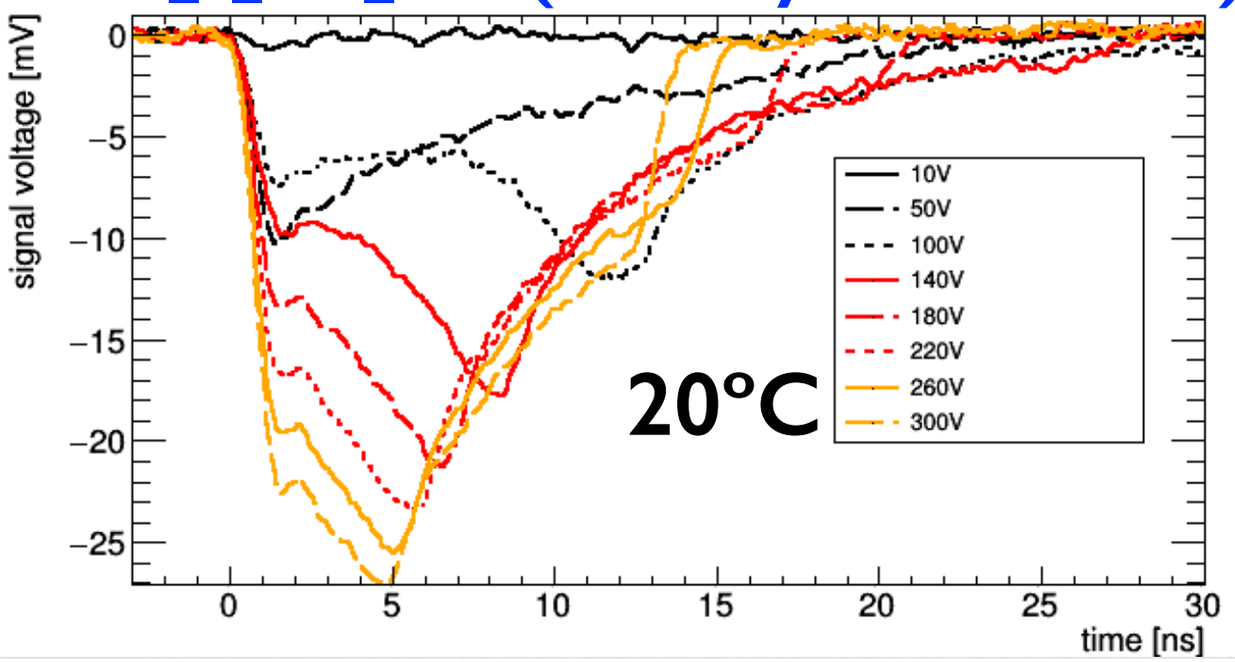
- Perform an annealing study on the devices presented today.
- Perform TPA on sample LGAD_7859_7_W3_C2-3 (mult. layer dose: $2.0 \times 10^{13} cm^{-2}$).
- Irradiate to 10^{14} 1 MeV n_{eq}/cm^2 the LGAD kept unirradiated for reference.
  - Perform CV/IV, TCT and eTCT.
  - Do an annealing study on the device.
- Irradiate a new set of LGADs of similar characteristics and compare the results.
  - The devices have already been characterised before irradiation.
  - To be irradiated at the CERN IRRAD facility with 24-GeV/c protons.
- Analyse if the behaviour of the other irradiated devices (fluences between 10^{12} and 10^{15} 1 MeV n_{eq}/cm^2) has changed.

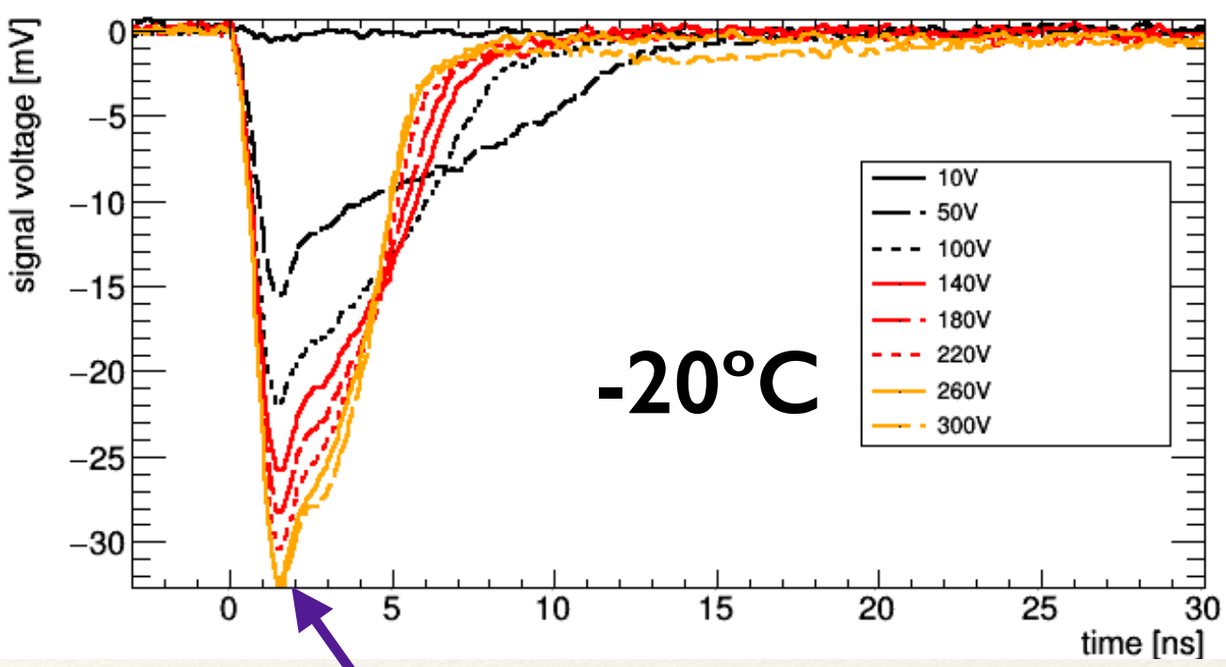
Backup Slides

Fluence
10^{14} n_{eq}/cm^2

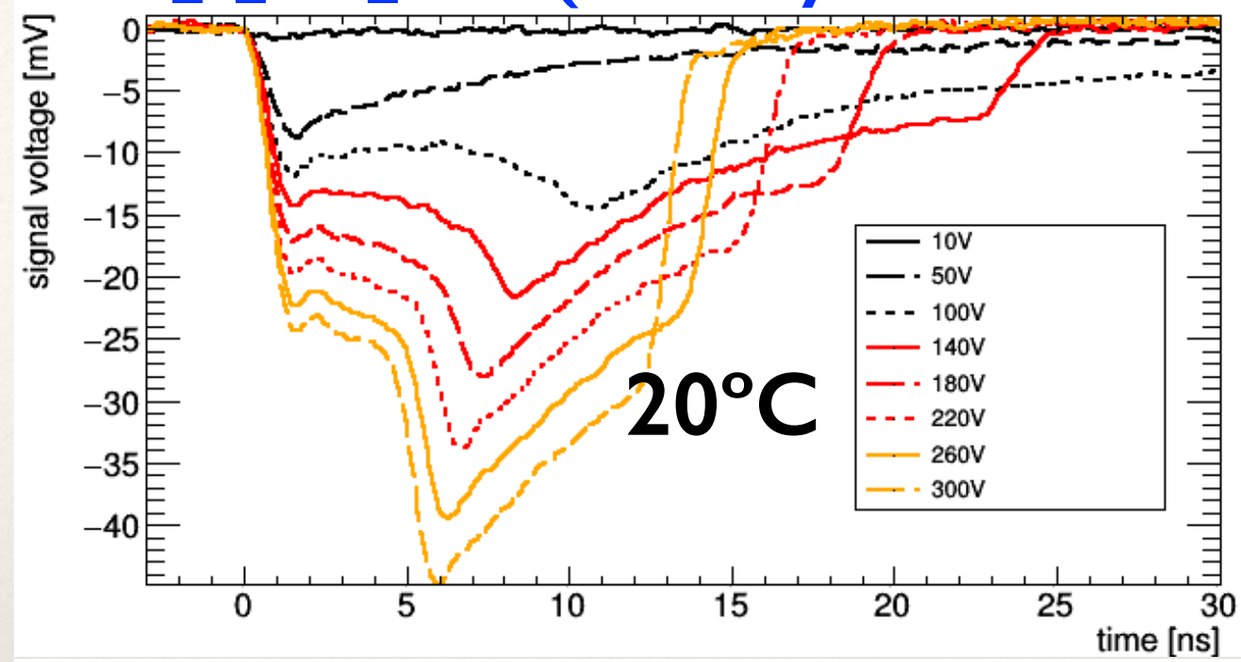
TCT - Red back illumination

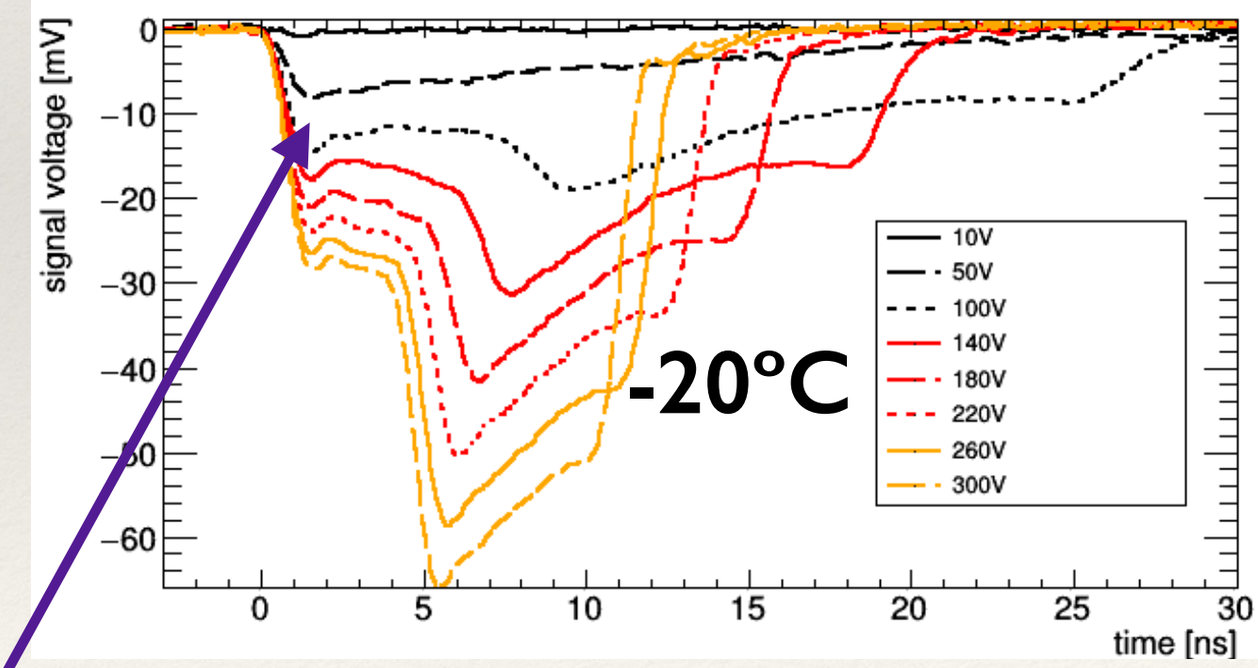
LGAD_4_W2_I3-1 (Mult. layer: 1.8E13 cm²)





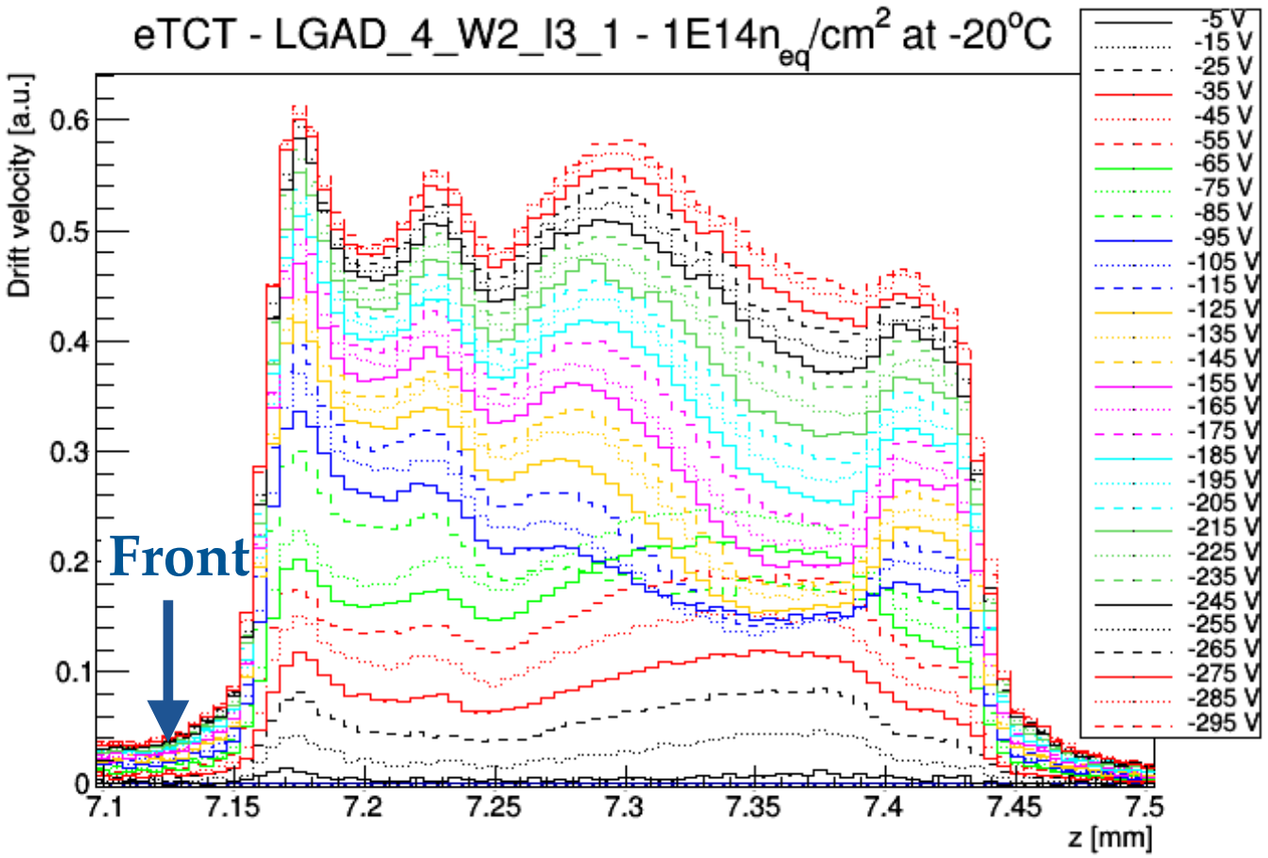
LGAD_7_W3_C2-3 (Mult. layer: 2.0E13 cm²)





The electric field grows from the back.

eTCT - Mult. Layer $1.8 \times 10^{13} cm^{-2}$

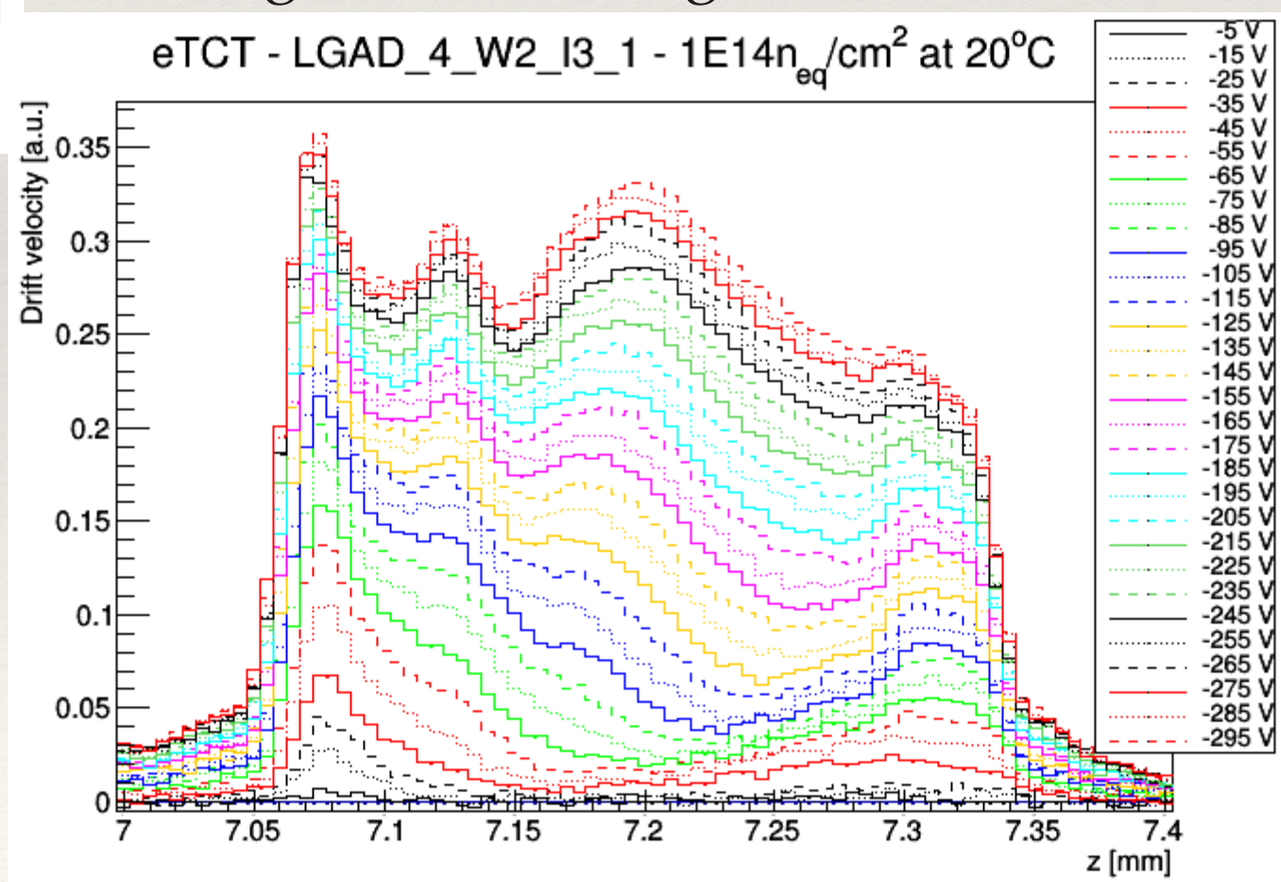


-20°C:

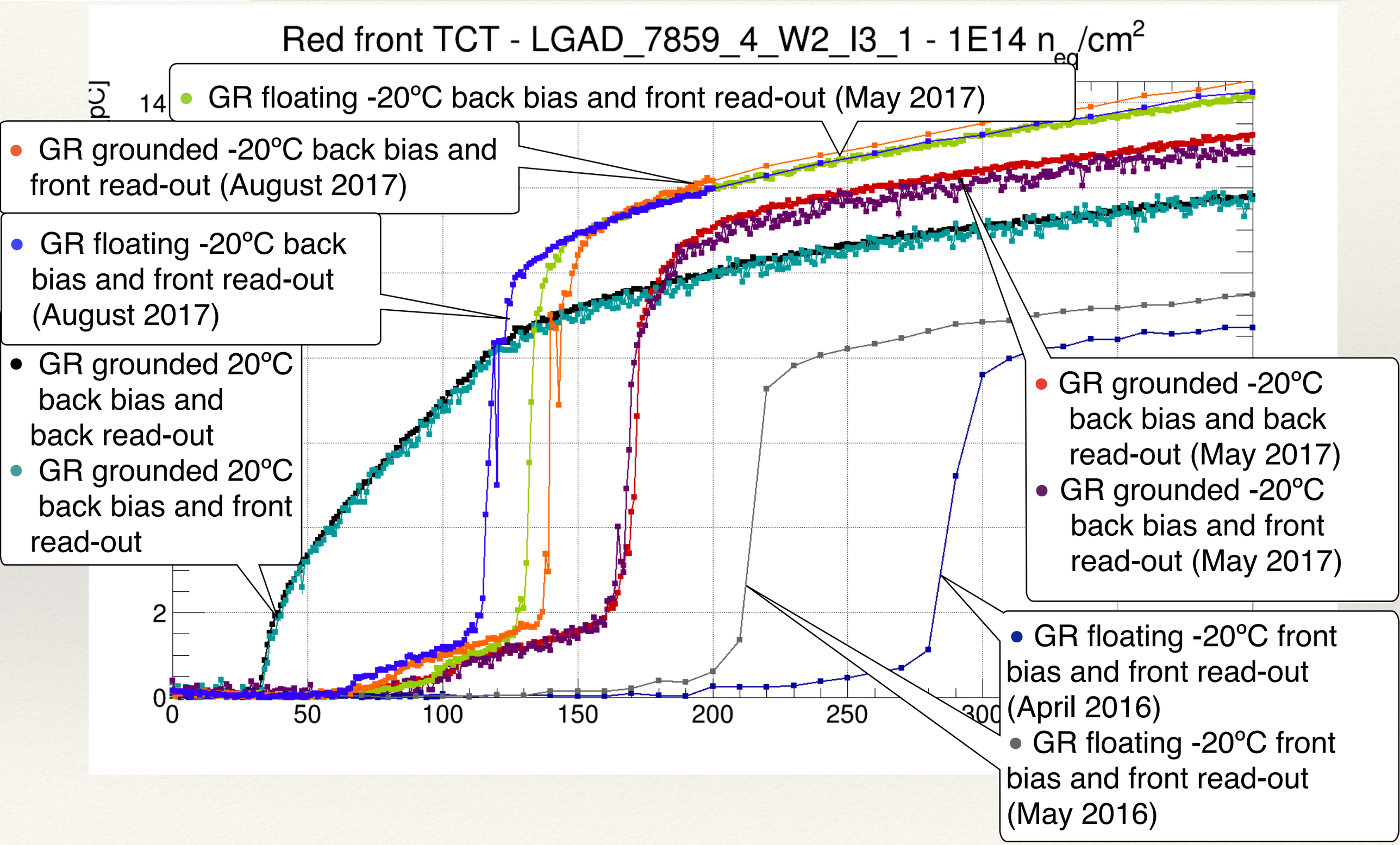
- V < 85 V: drift velocity on the back is either higher or comparable to that on the front.
- V > 85 V: drift velocity peaks at the front.
- V >> 85 V: drift velocity tends to be more homogeneous throughout the device.

20°C:

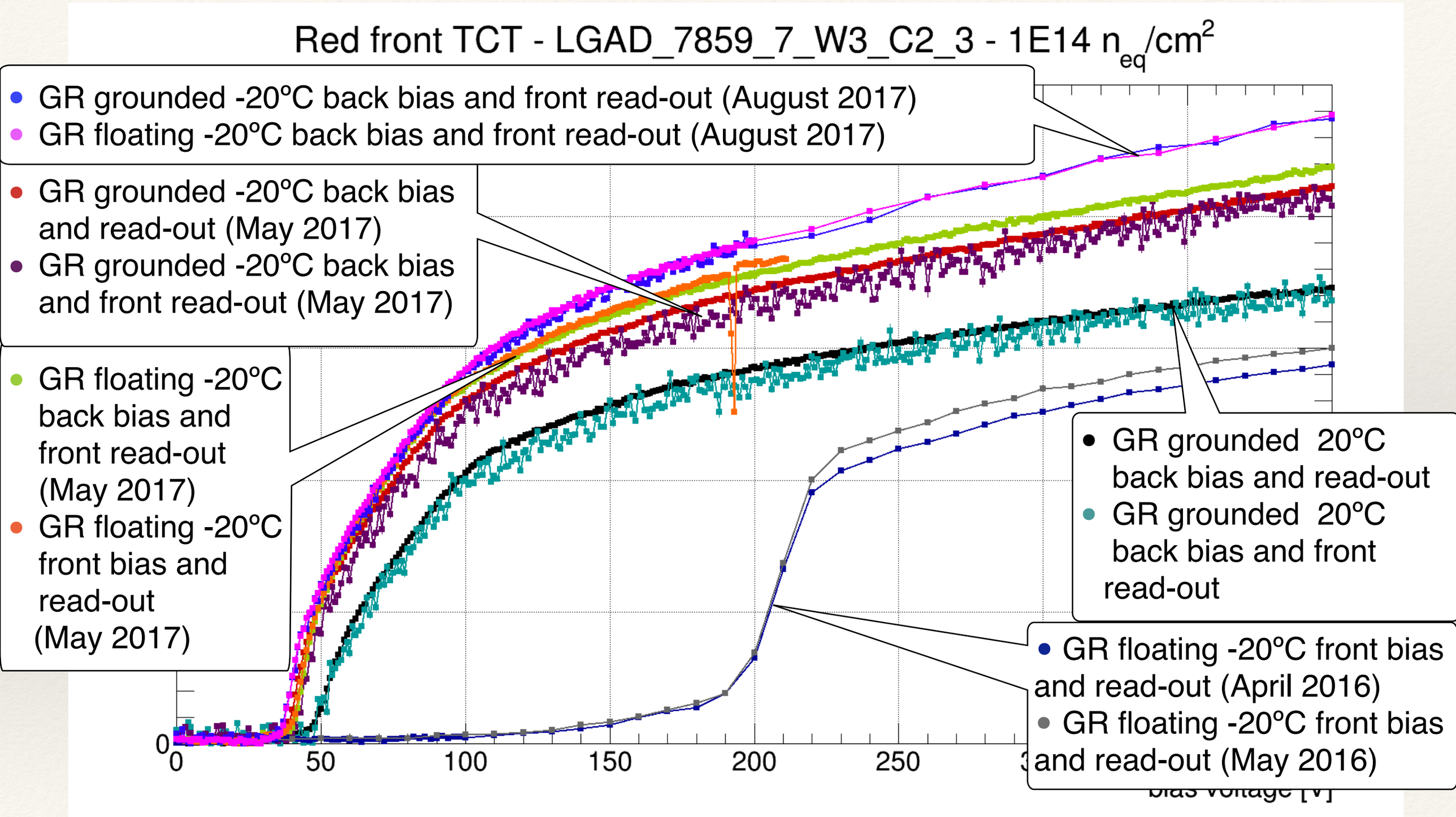
- The drift velocity is higher on the front of the device.
- At higher voltages the velocity tends to be more homogeneous throughout the device.



Irradiated LGAD - Mult. Layer: 1.8×10^{13} cm^{-2}



Irradiated LGAD - Mult. Layer: 2.0×10^{13} cm^{-2}



Irradiated LGAD - Mult. Layer: 2.0×10^{13} cm^{-2}

- GR grounded -20ºC back bias and front read-out (August 2017)
- GR floating -20ºC back bias and front read-out (August 2017)