Study of the onset of multiplication in proton irradiated LGADs

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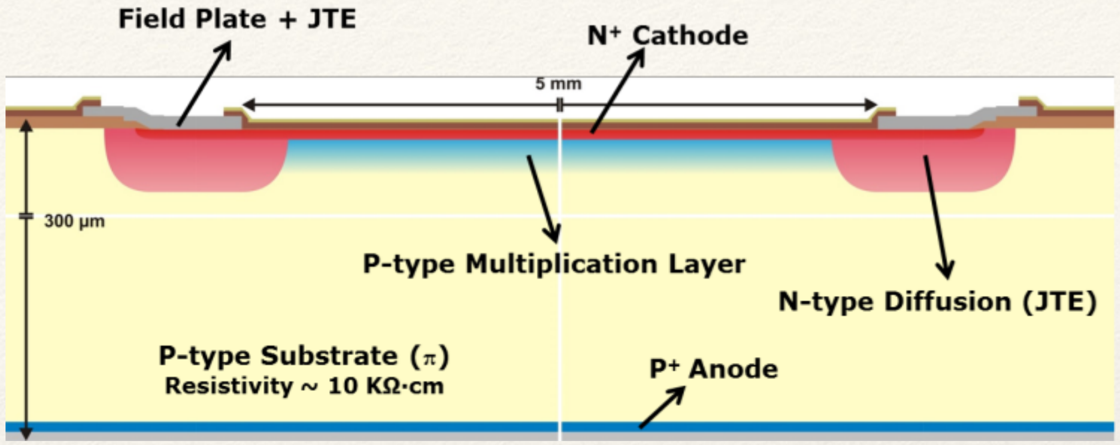
30th RD50 Workshop, Krakow, Poland

Continuation of the work presented in Torino

S. Otero Ugobono, *TCT Measurements and Analyses of Proton Irradiated LGADs*, 28th RD50 Workshop

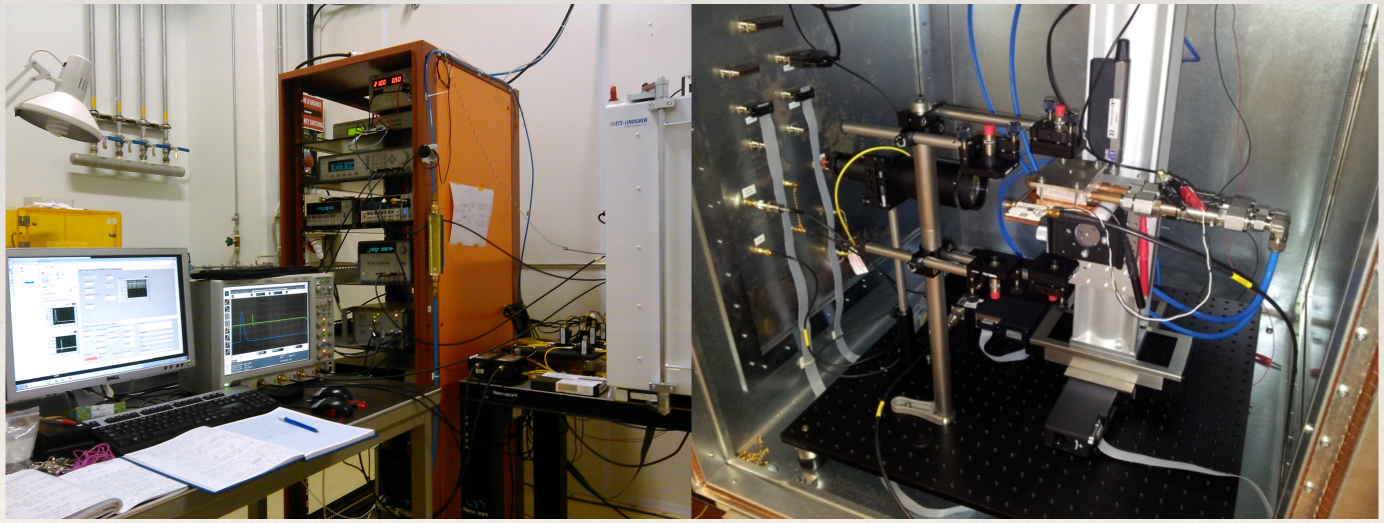
TCT Analyses of Irradiated LGADs

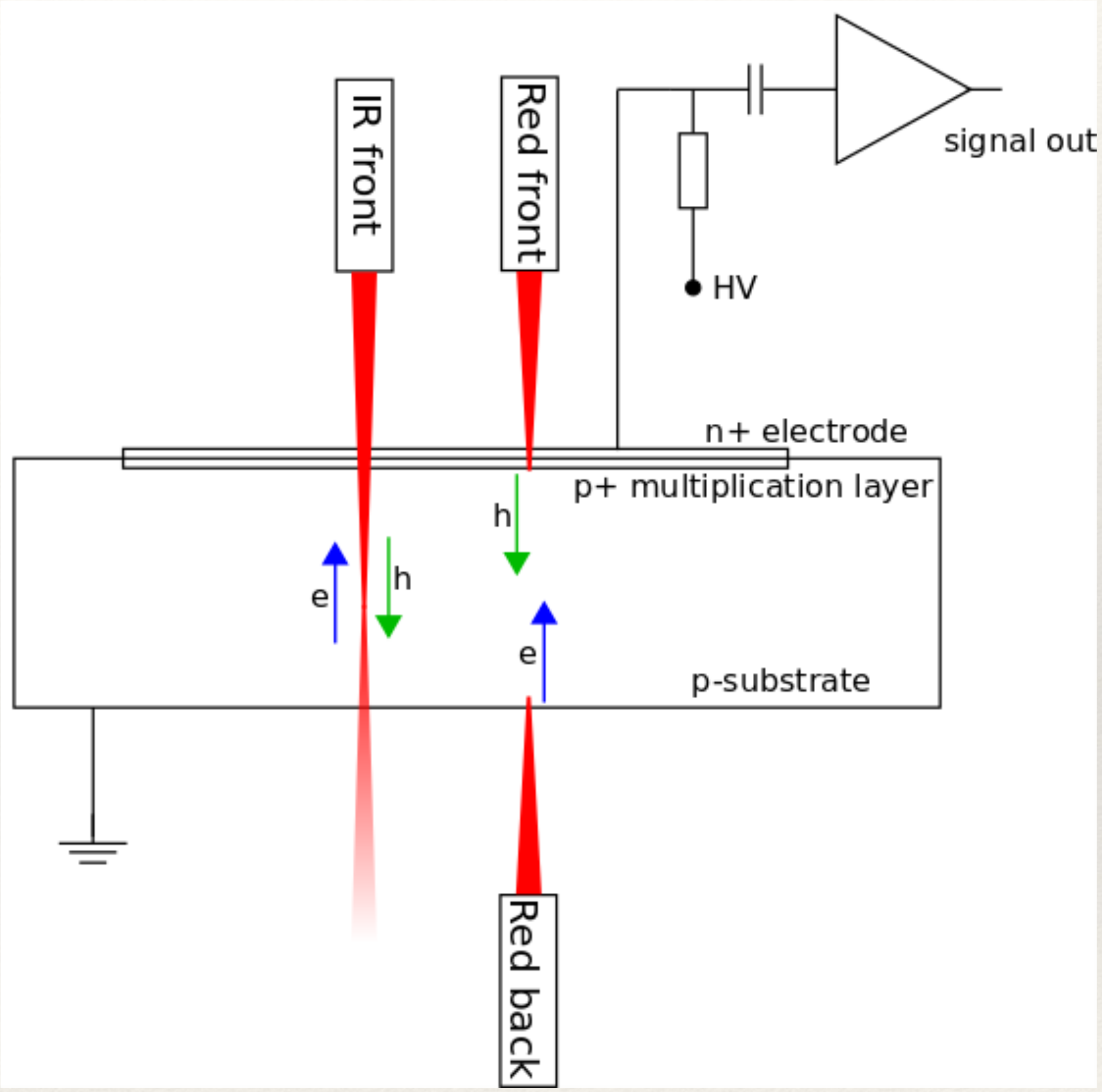


- LGADs from Run 7859.
  - Wafers 1 and 2.
    - Multiplication layer dose: 1.8x10^{13} cm^{-2}.
  - Wafers 3 and 4.
    - Multiplication layer dose: 2.0x10^{13} cm^{-2}.
- Irradiation performed at the PS facility with 24-GeV/c protons.
- Fluences:
  - 10^{12} 1 MeV n_{eq}/cm^2
  - 10^{13} 1 MeV n_{eq}/cm^2
  - 10^{14} 1 MeV n_{eq}/cm^2
  - 10^{15} 1 MeV n_{eq}/cm^2
- Annealing: 80 min at 60ºC.

TCT Analyses of Irradiated LGADs

- Picosecond-pulsed LASER (200 ps).
    - Red front and back (660 nm, 47.4 μW).
    - IR front and back (1064 nm, 29.5 μW).

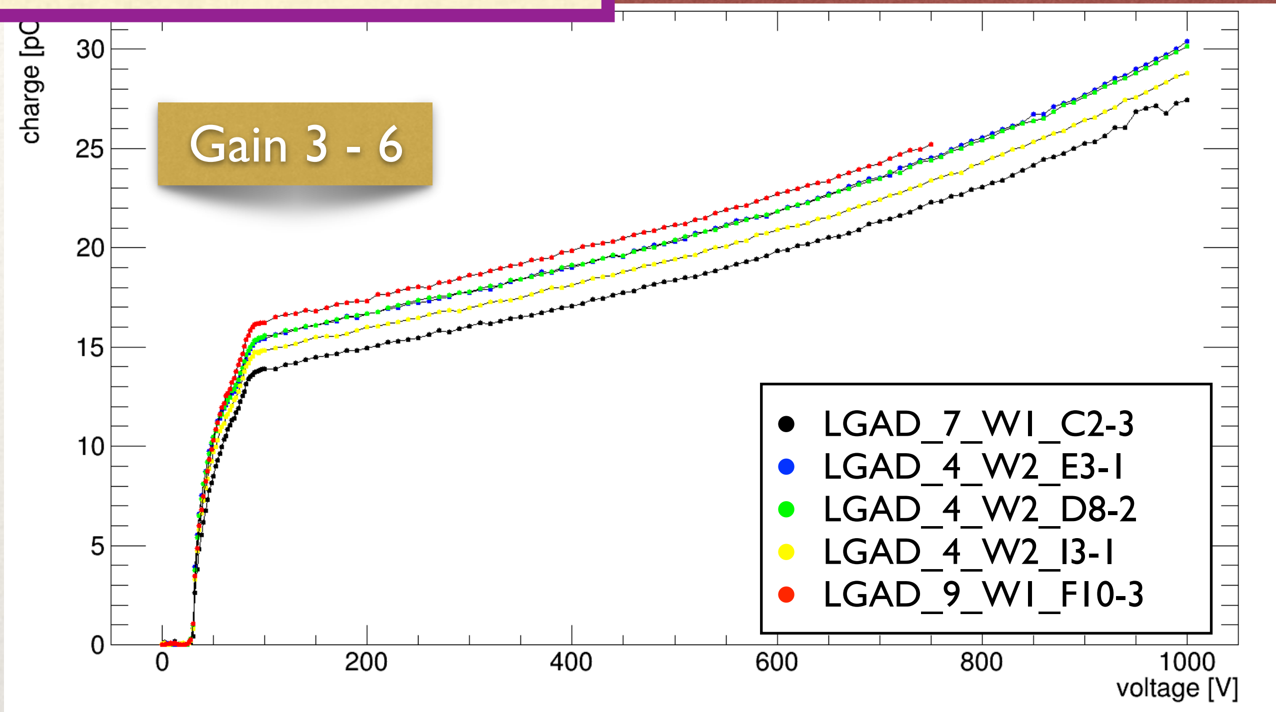




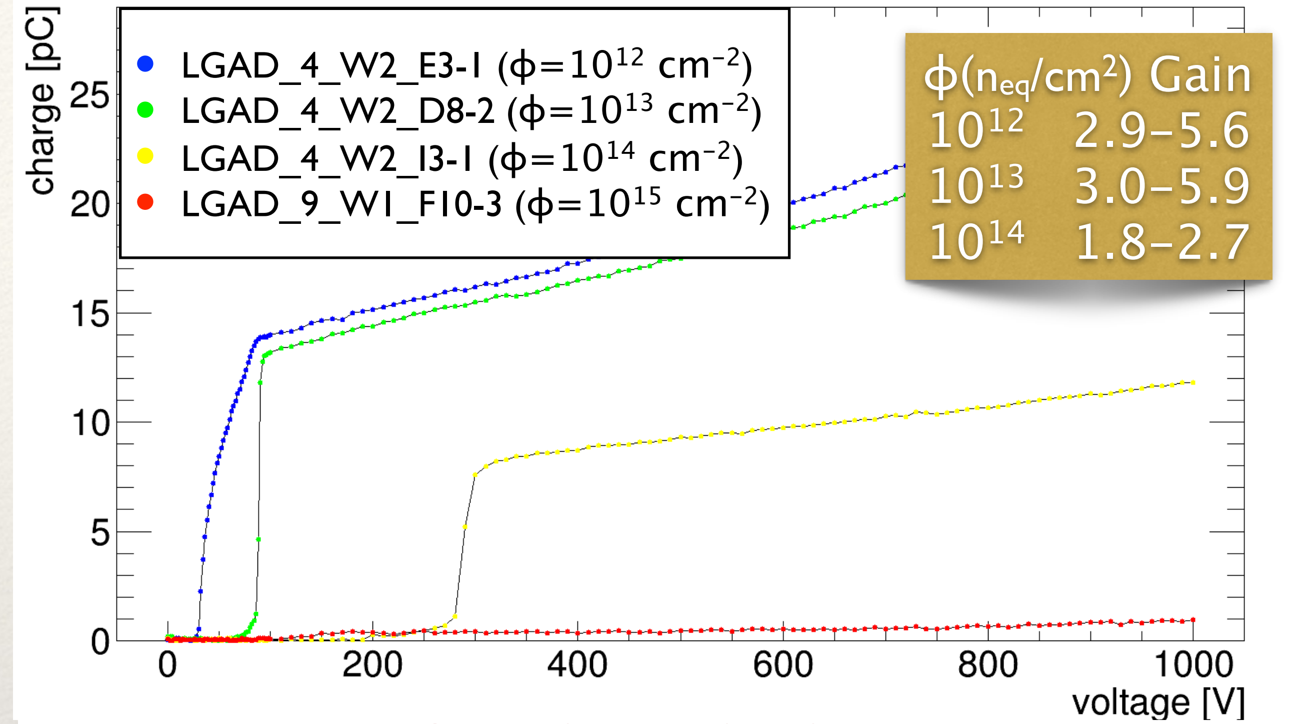
Charge Collection with Voltage

LGAD - TCT - Red front @ -20°C

Mult. layer 1.8×10^{13} cm^{-2}

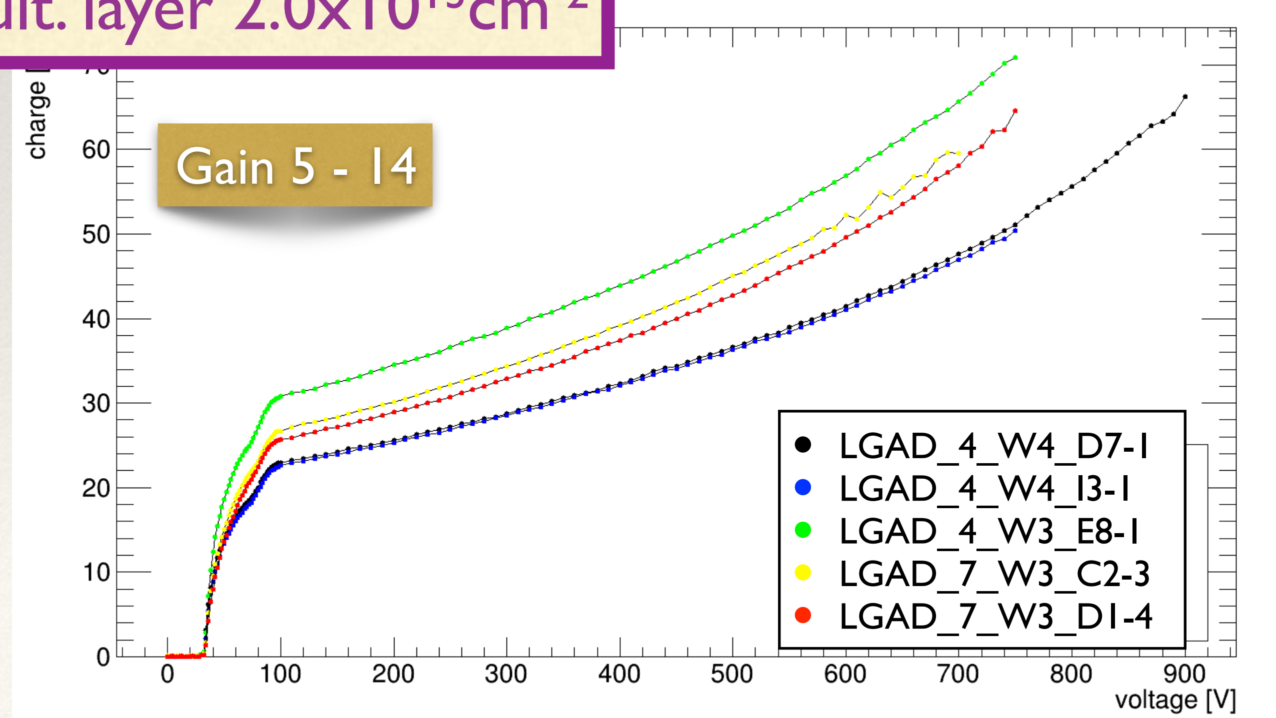


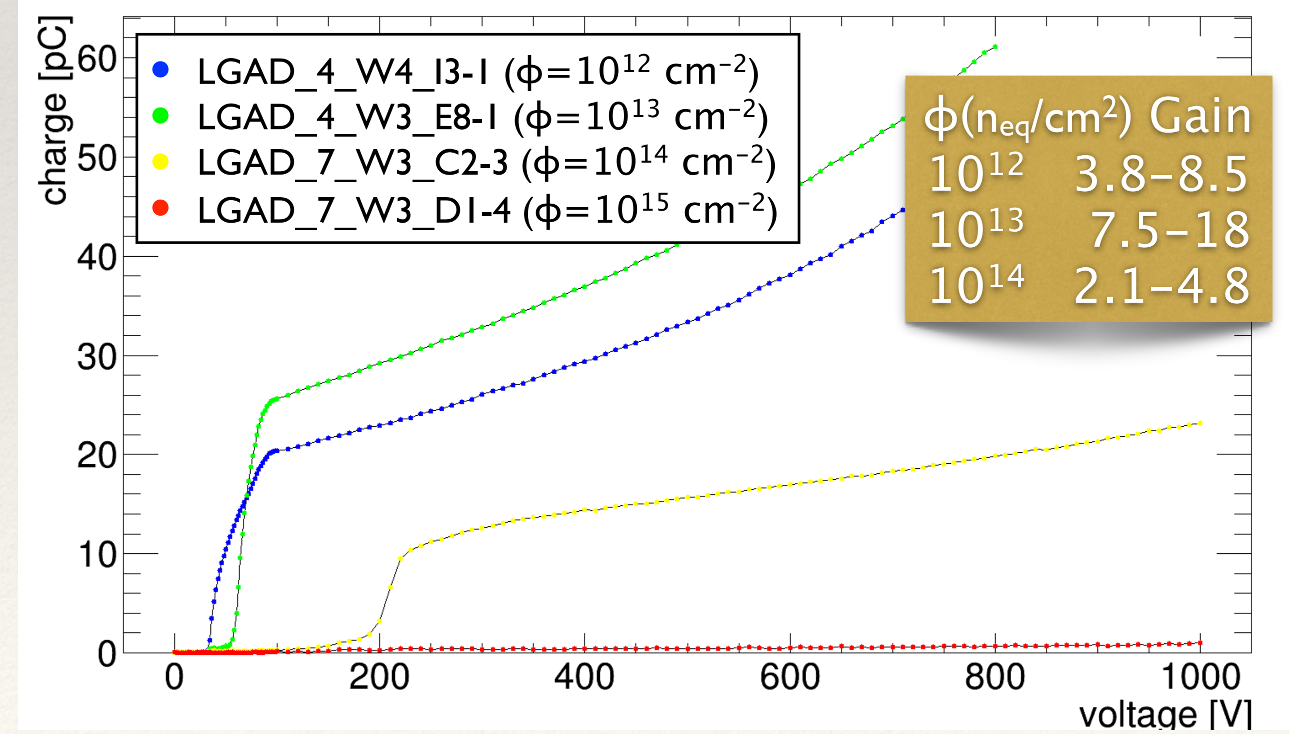
Before irradiation



After irradiation

Mult. layer 2.0×10^{13} cm^{-2}

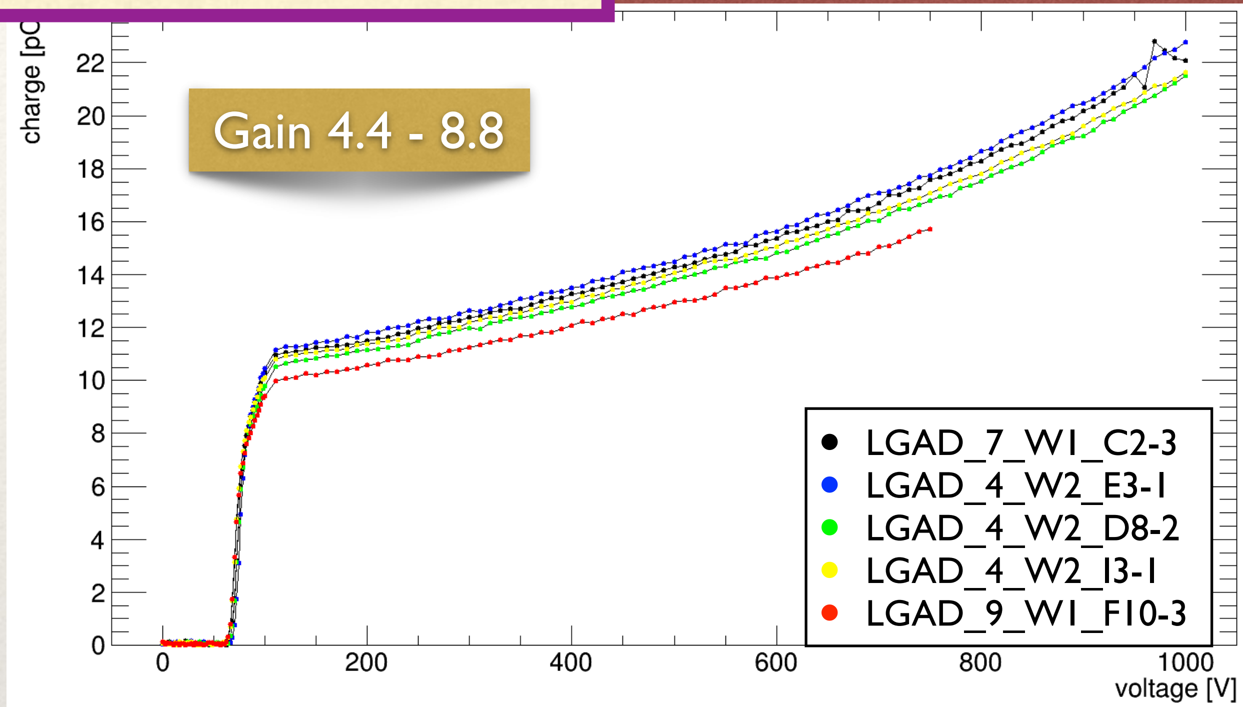


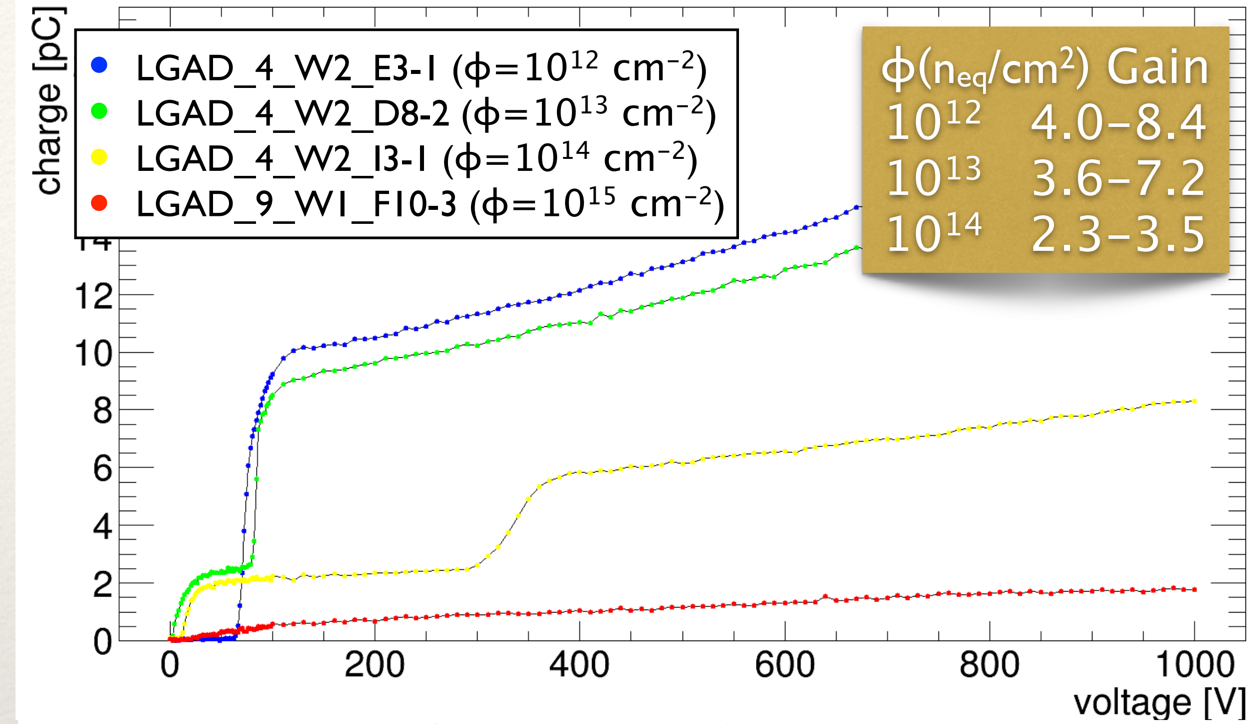


Charge Collection with Voltage

LGAD - TCT - Red back @ -20°C

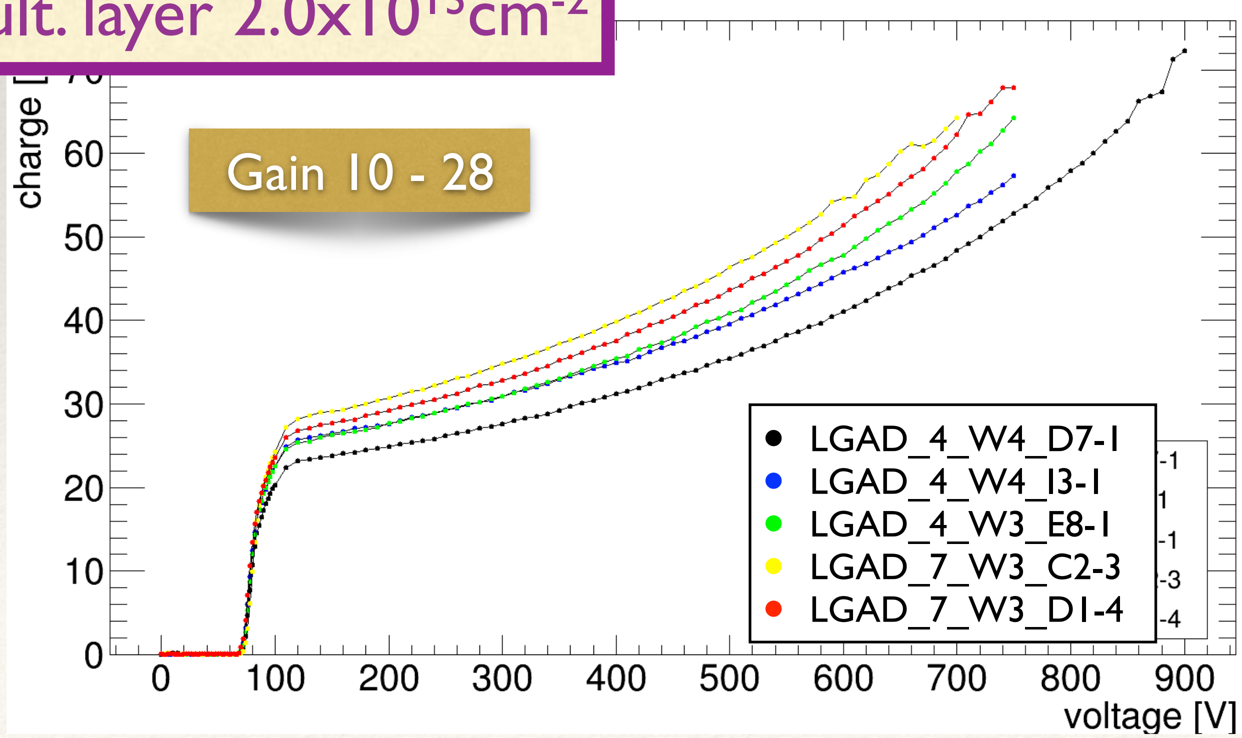
Mult. layer 1.8×10^{13} cm^{-2}

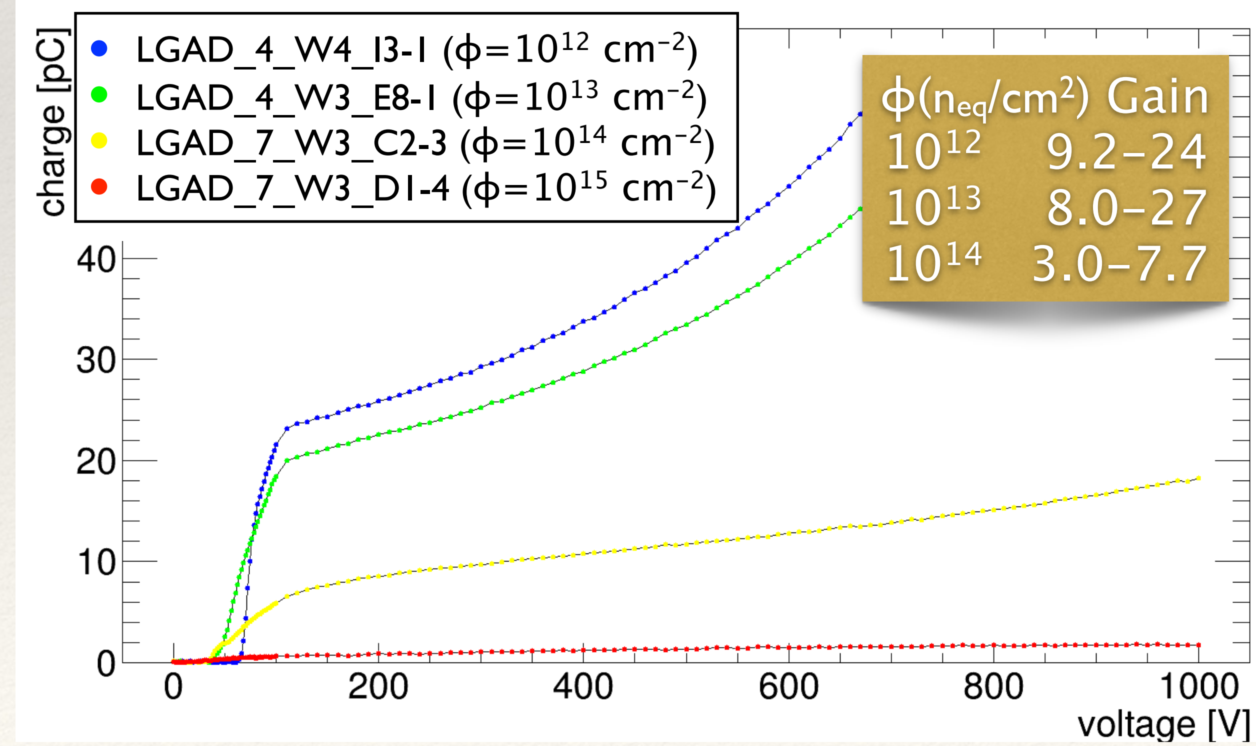




Before irradiation **After irradiation**

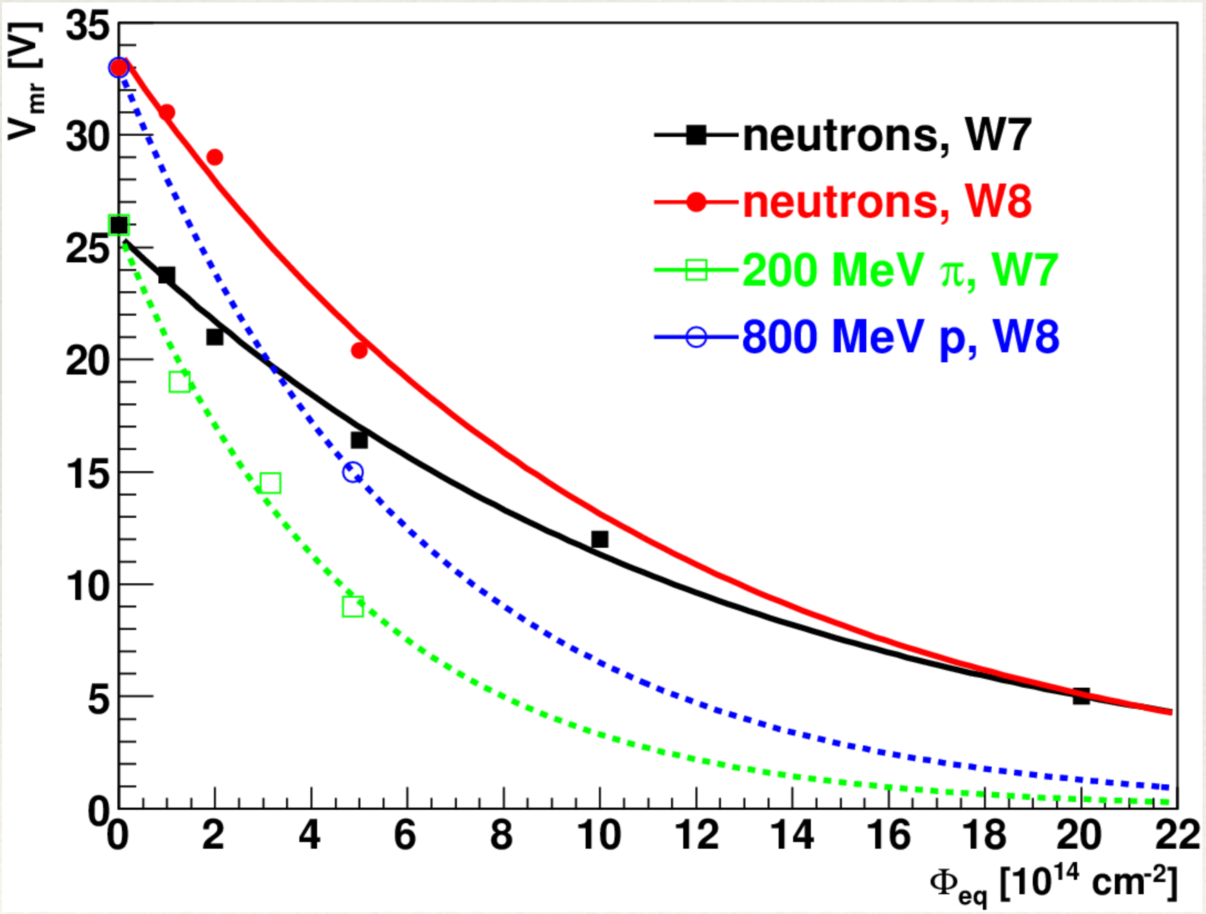
Mult. layer 2.0×10^{13} cm^{-2}

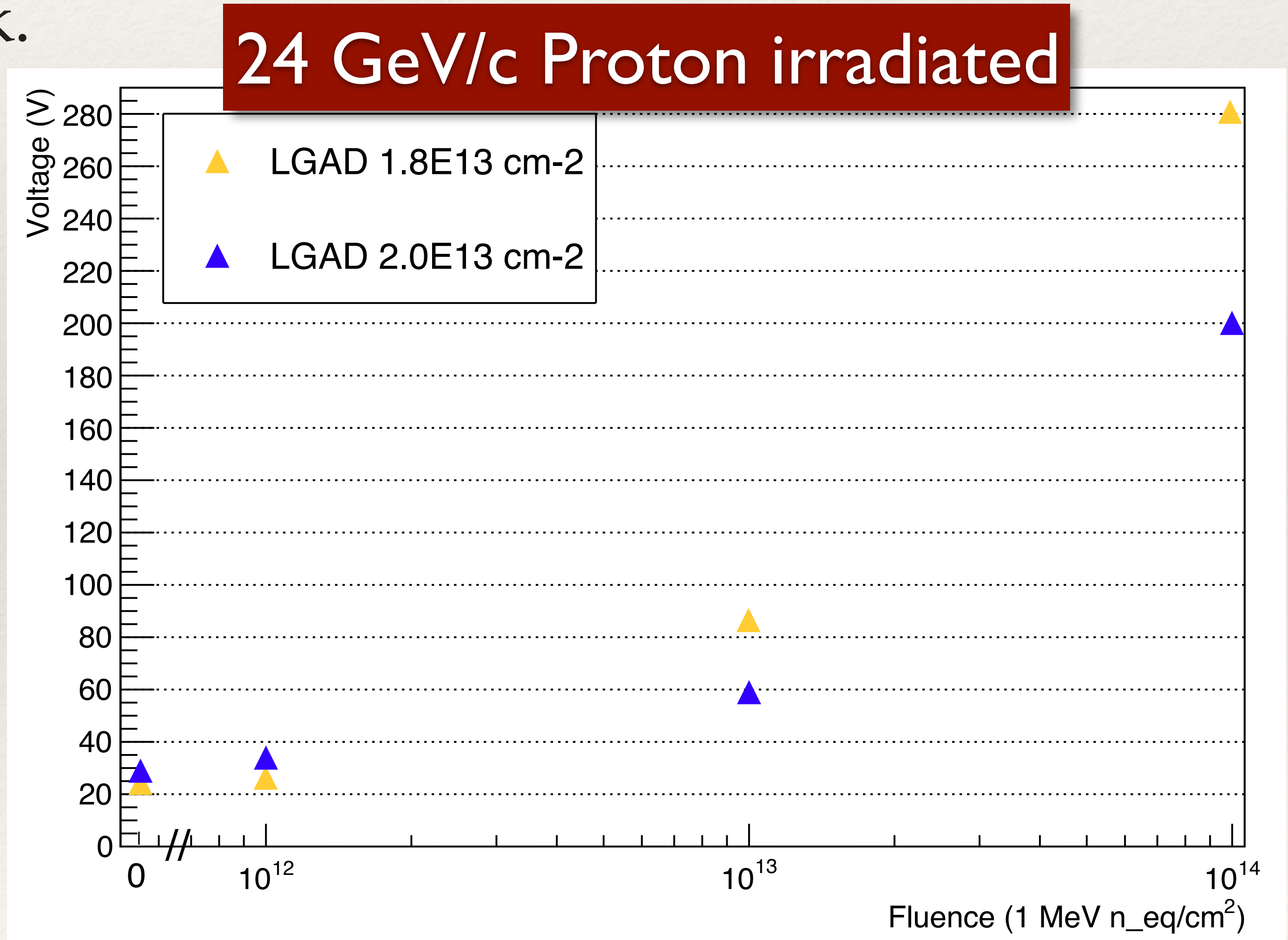




Onset Voltage and Fluence

- According to Gregor's results* (CNM run 6474), the threshold voltage decreases with fluence.
- 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.

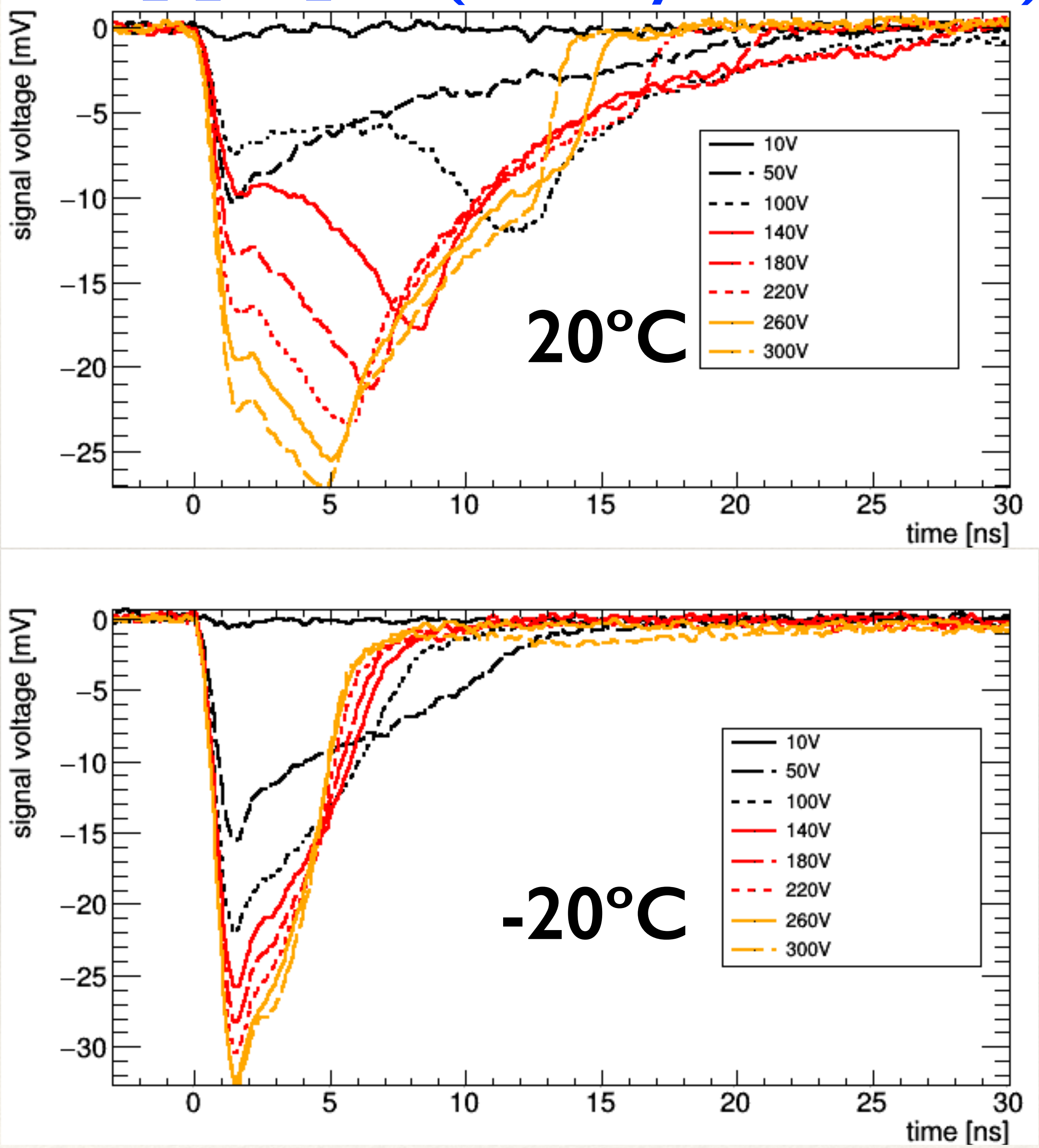
Double Junction Effect

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

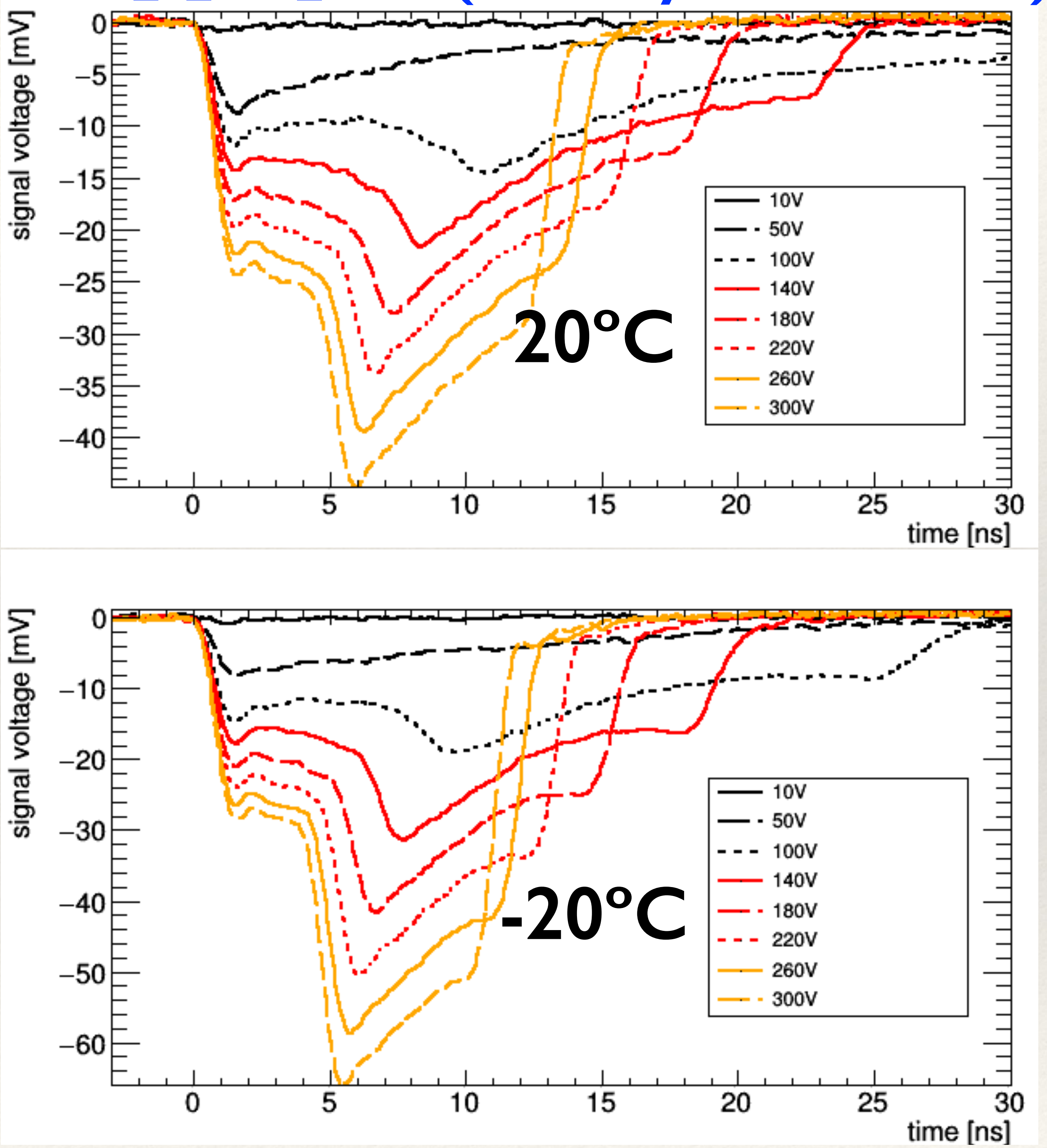
TCT - Red back

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

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

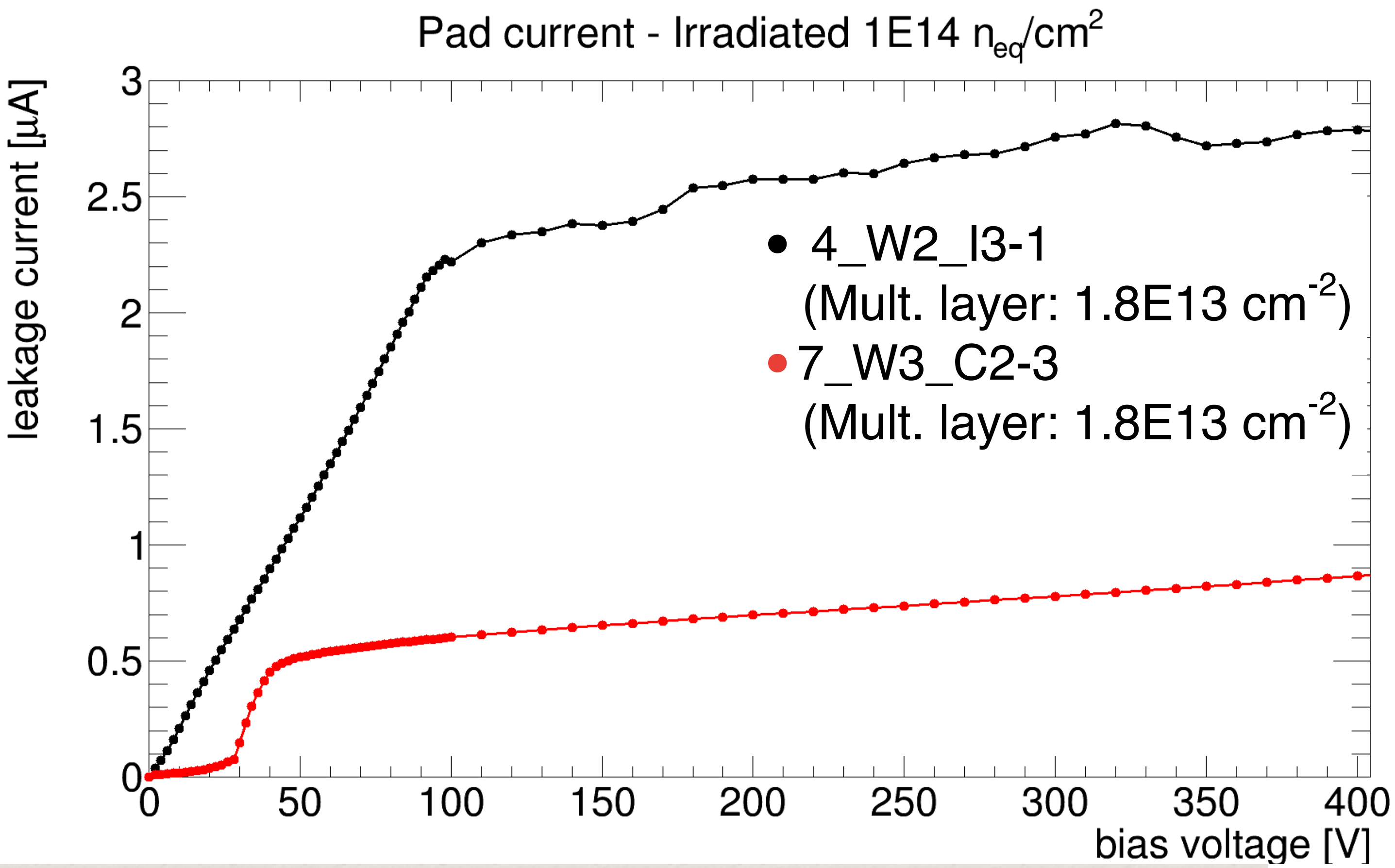


LGAD_7_W3_C2-3 (Mult. layer: 2.0E13 cm²)

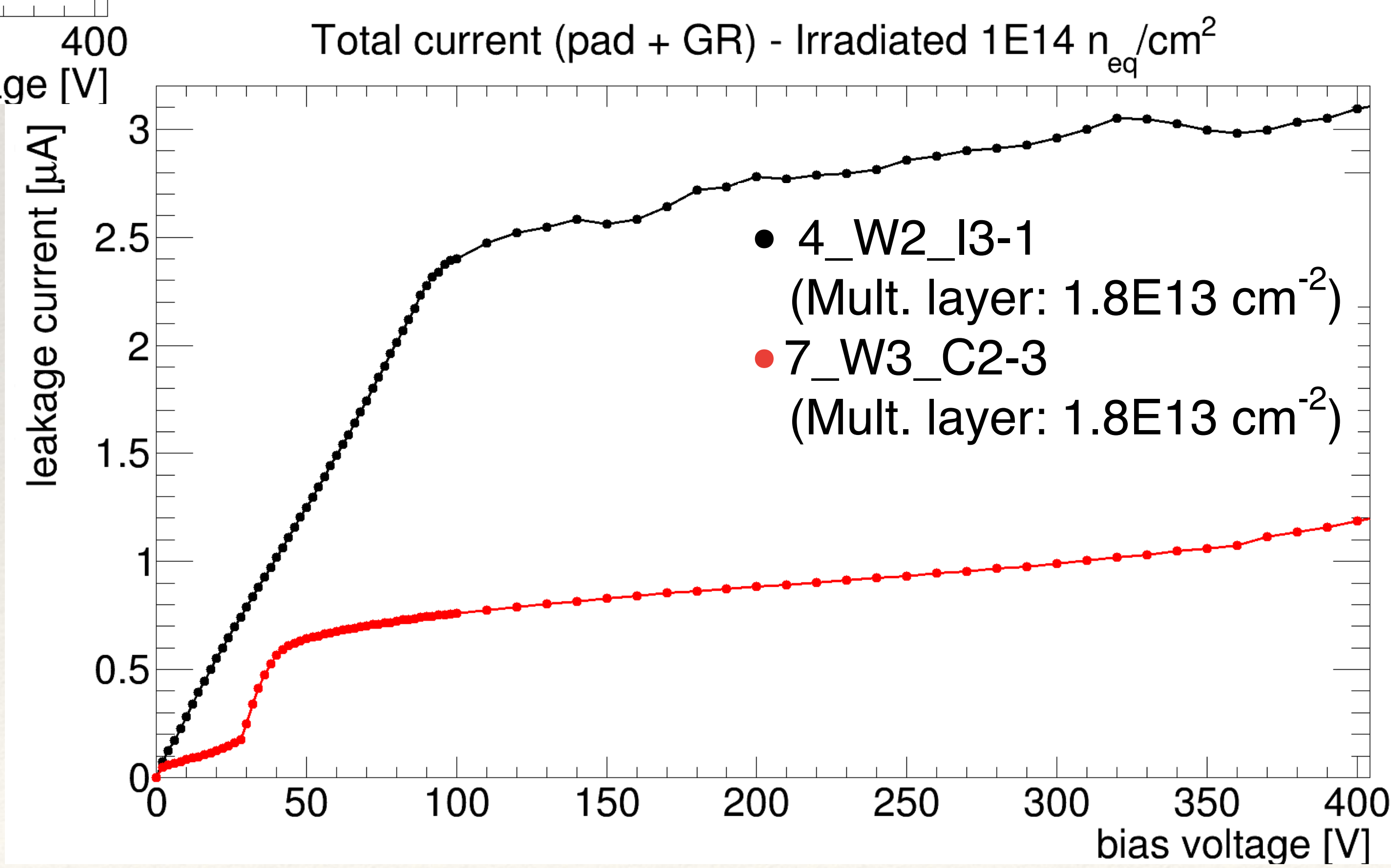


Further analyses of the two LGADs irradiated up to $10^{14}\ n_{eq}/cm^2$

IV Curves at -20°C



- At voltages within the range of the multiplication onset, the current through the Guard Ring is negligible.



- Both sensors qualify as *low current devices* according to the classification employed by Gregor.* (Order of nA)

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

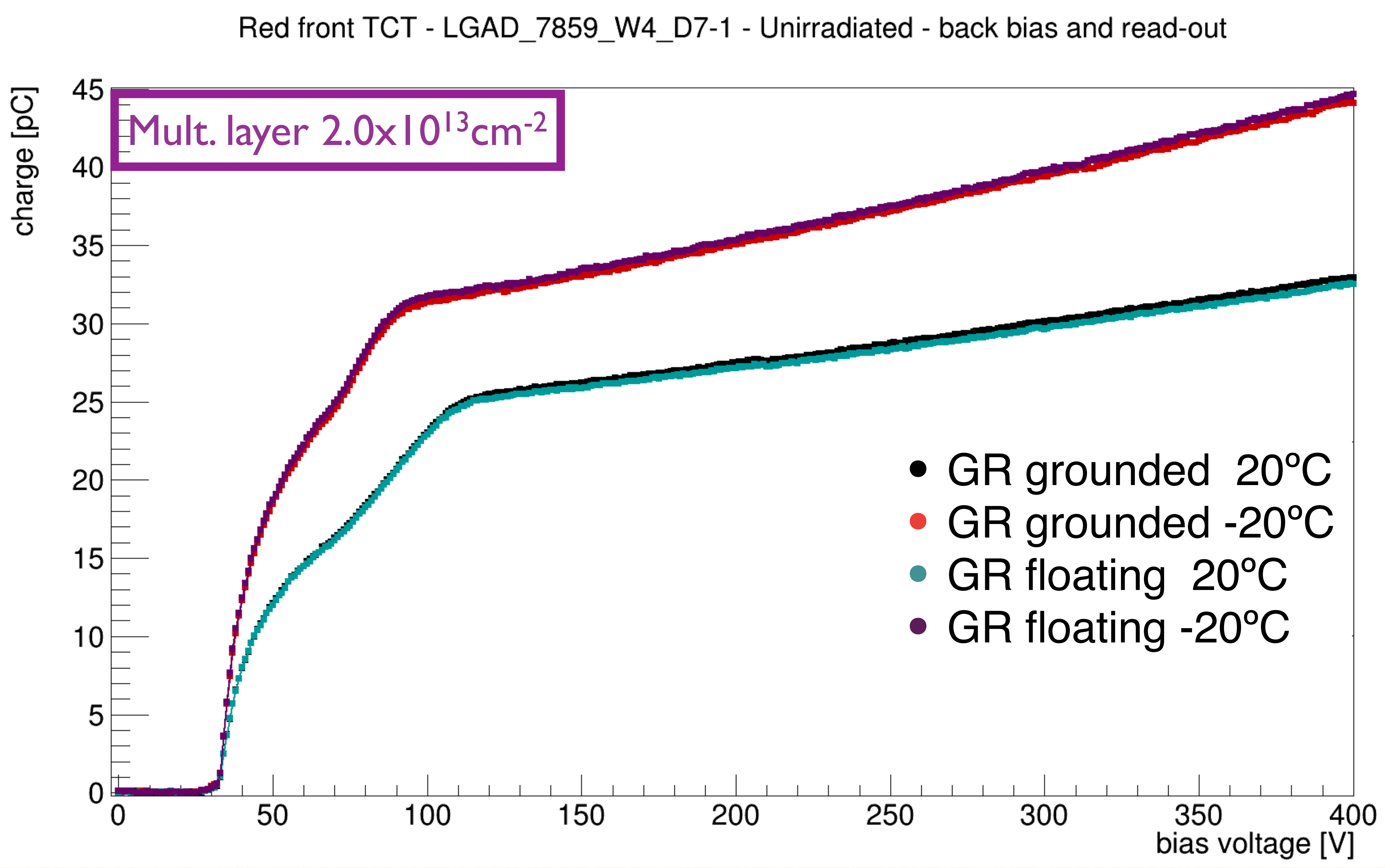
TCT Voltage Scans

- TCT voltage scans performed on:
  - one unirradiated LGAD used as reference (mult. layer $2.0\text{x}10^{13}\ \text{cm}^{-2}$)
  - 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).
  - Different bias and read-out schemes were tested.

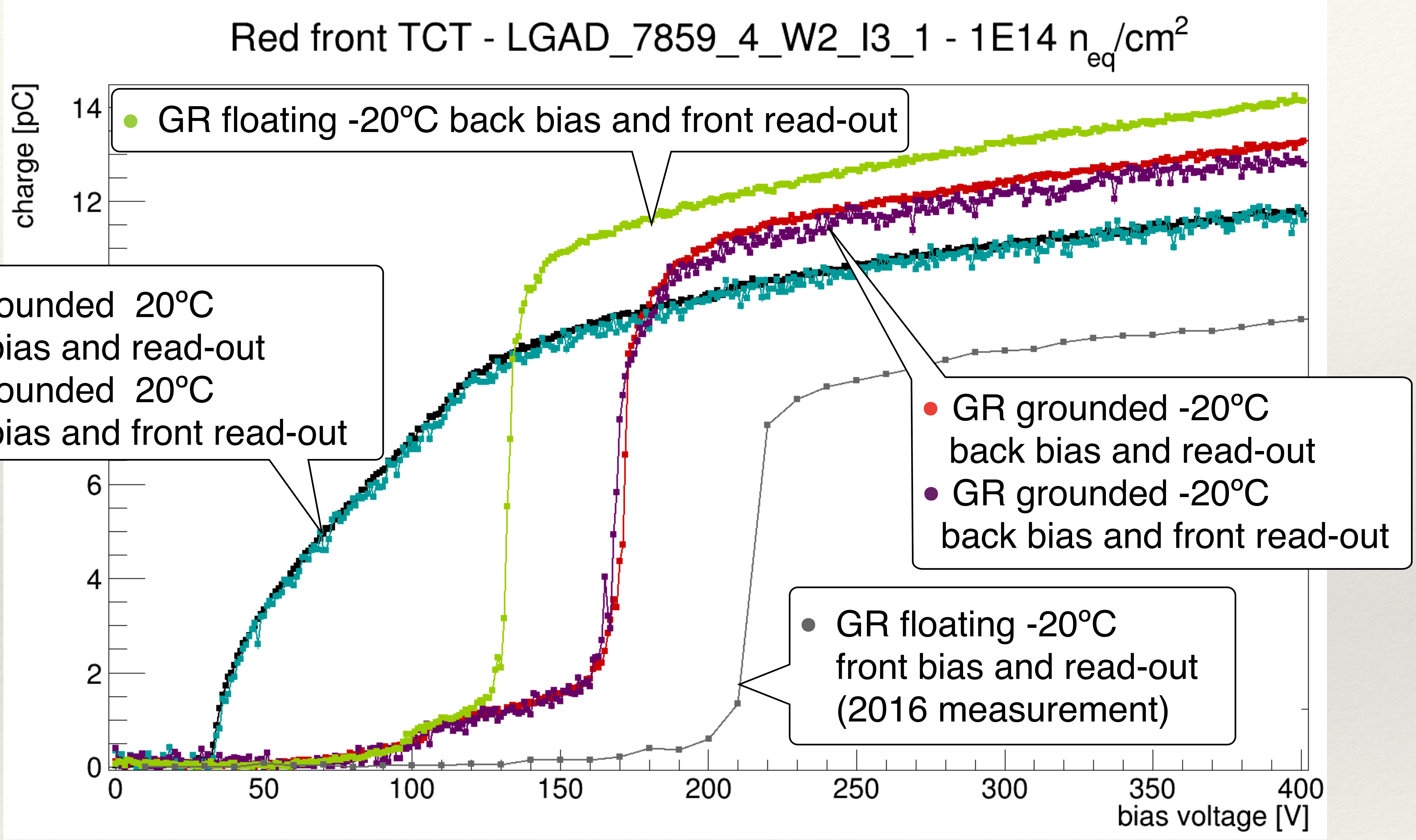
- The scans were compared to those measured in 2016 and presented at the 28th RD50 Workshop.

Unirradiated LGAD



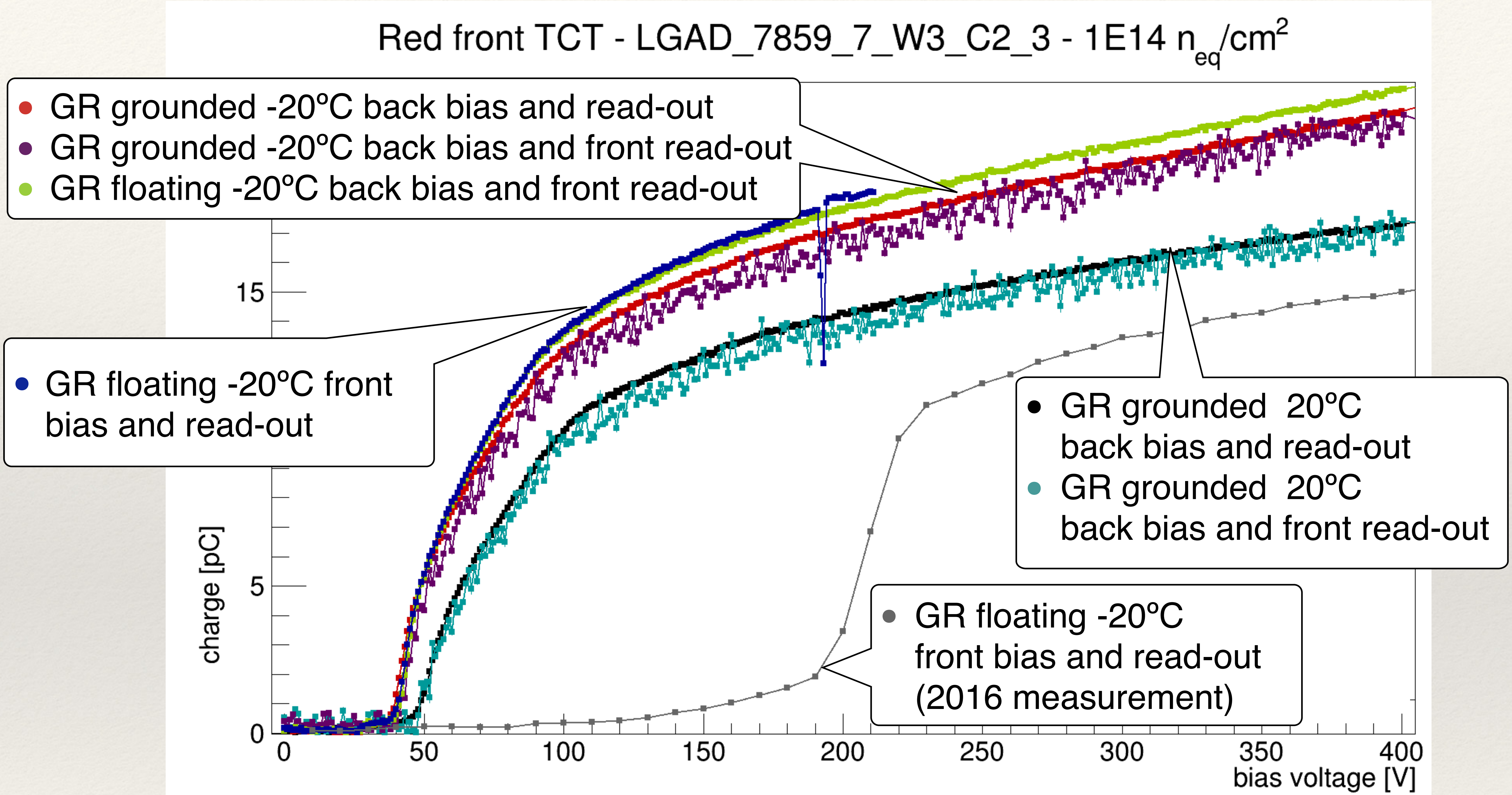
- The GR connection scheme causes no significative changes.
- The multiplication onset does not depend on temperature.

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



- At -20ºC the GR shifts the onset of multiplication.
- The multiplication-onset voltage is higher for lower temperatures.
- Shift in the multiplication-onset voltage with respect to the value seen in 2016.

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



- Significantly large shift in the multiplication-onset voltage with respect to 2016.
- The multiplication onset does not change significantly with temperature.
- The bias and read-out scheme causes no significative changes.

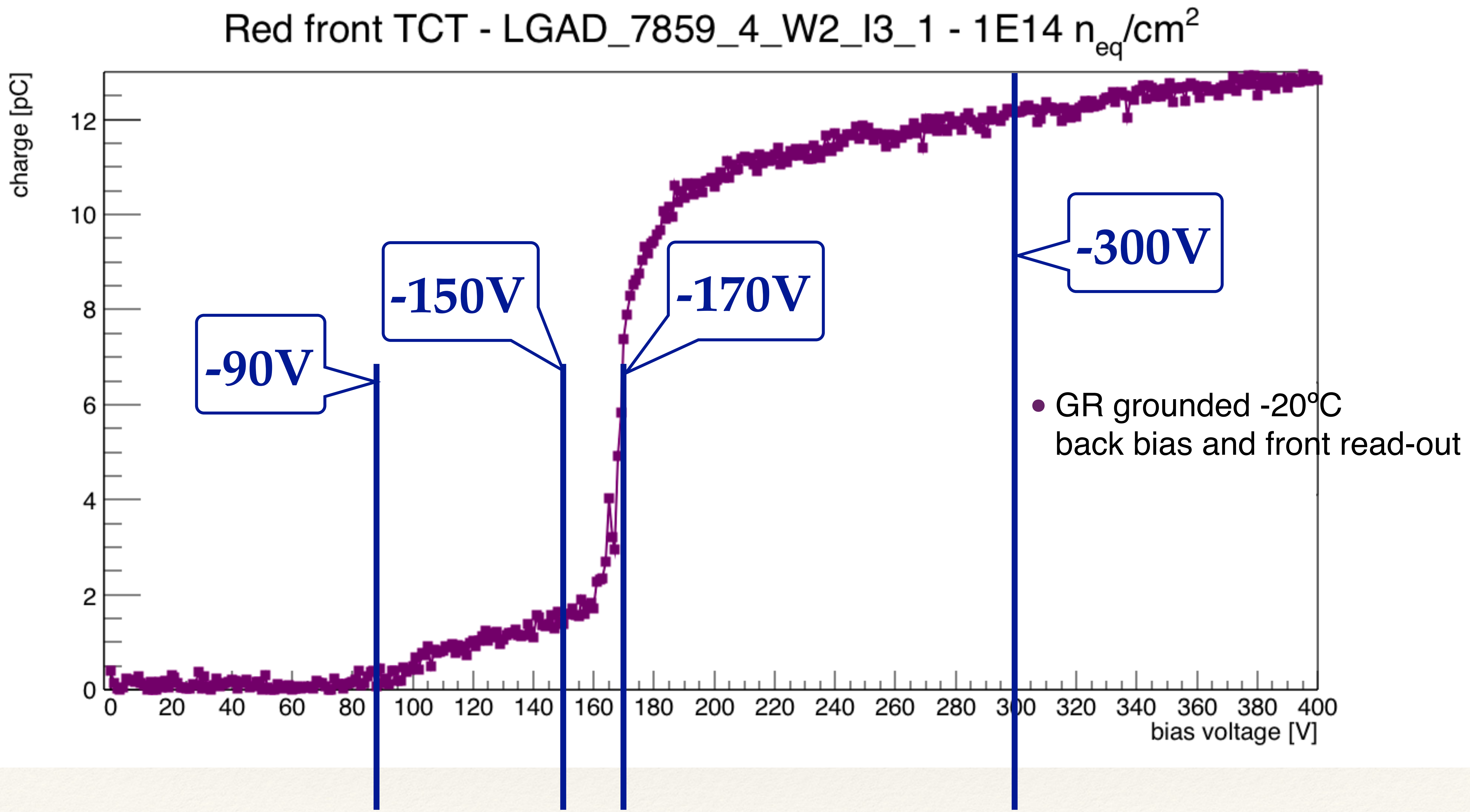
Edge TCT

- In order to better understand the results, eTCT scans were performed on both irradiated samples.
- The objective is to better comprehend the distribution of the electric field inside the devices.
- Conditions:
  - Two temperatures: 20ºC and -20ºC.
  - Several voltages (before, during and after the multiplication onset).
  - All the plots were obtained by integrating the signals up to 0.6 ns.
  - The edge was not polished (time constraints).

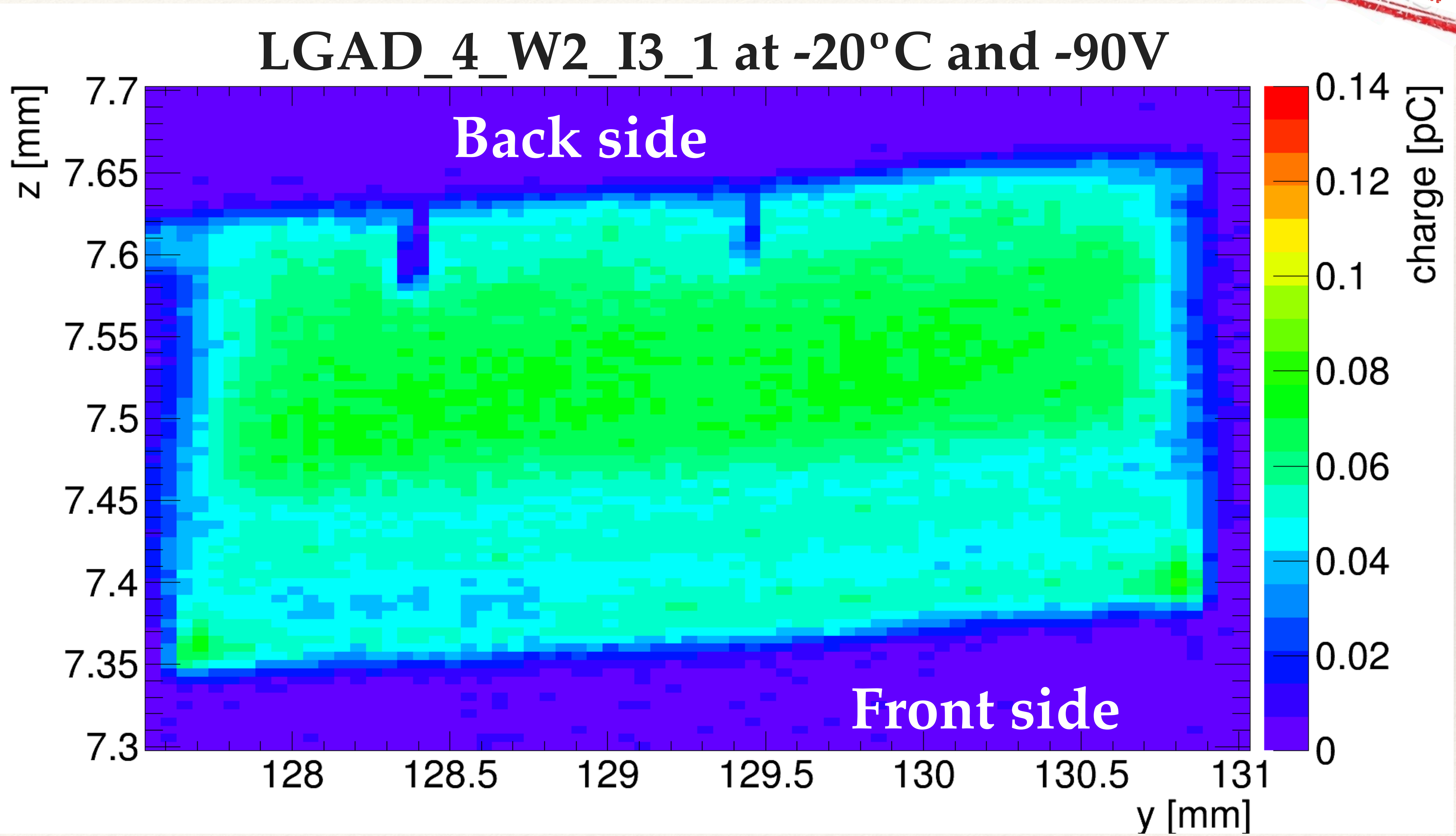
PRELIMINARY RESULTS

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

Voltages for eTCT



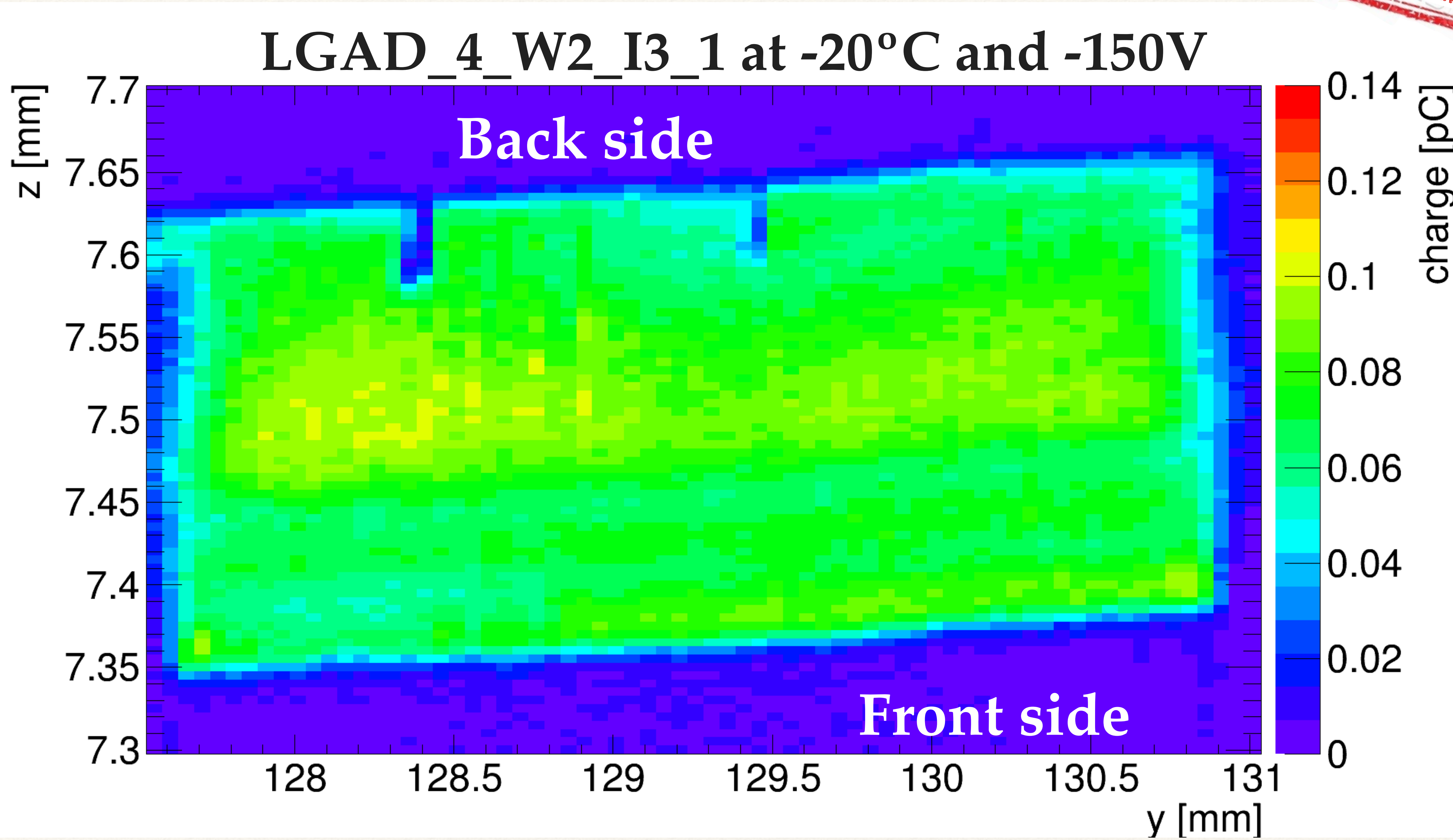
eTCT - Mult. Layer $1.8x10^{13}cm^{-2}$



Integrated charge in 0.6 ns [Q(0.6 ns)]

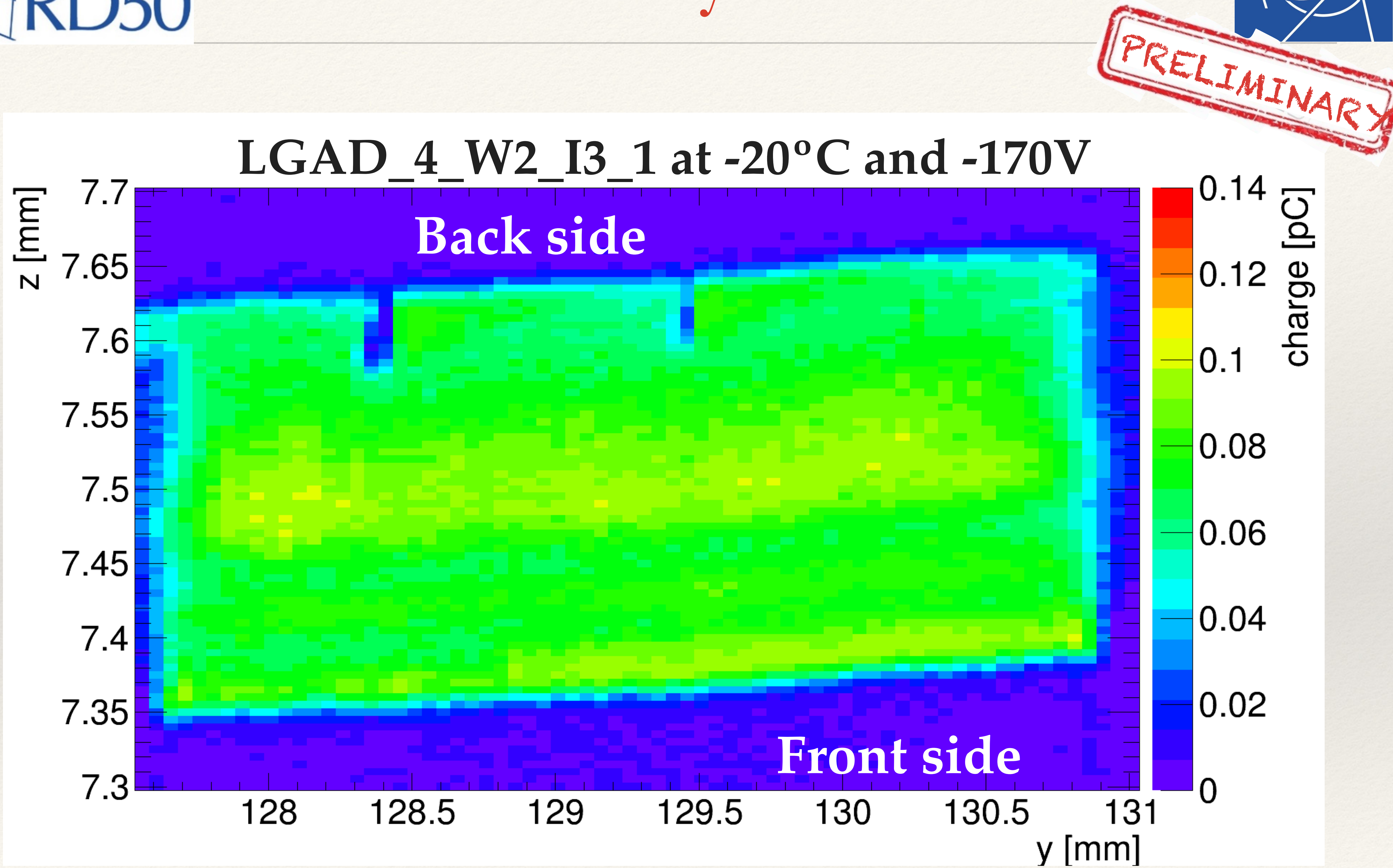
eTCT - Mult. Layer $1.8x10^{13}cm^{-2}$

PRELIMINARY



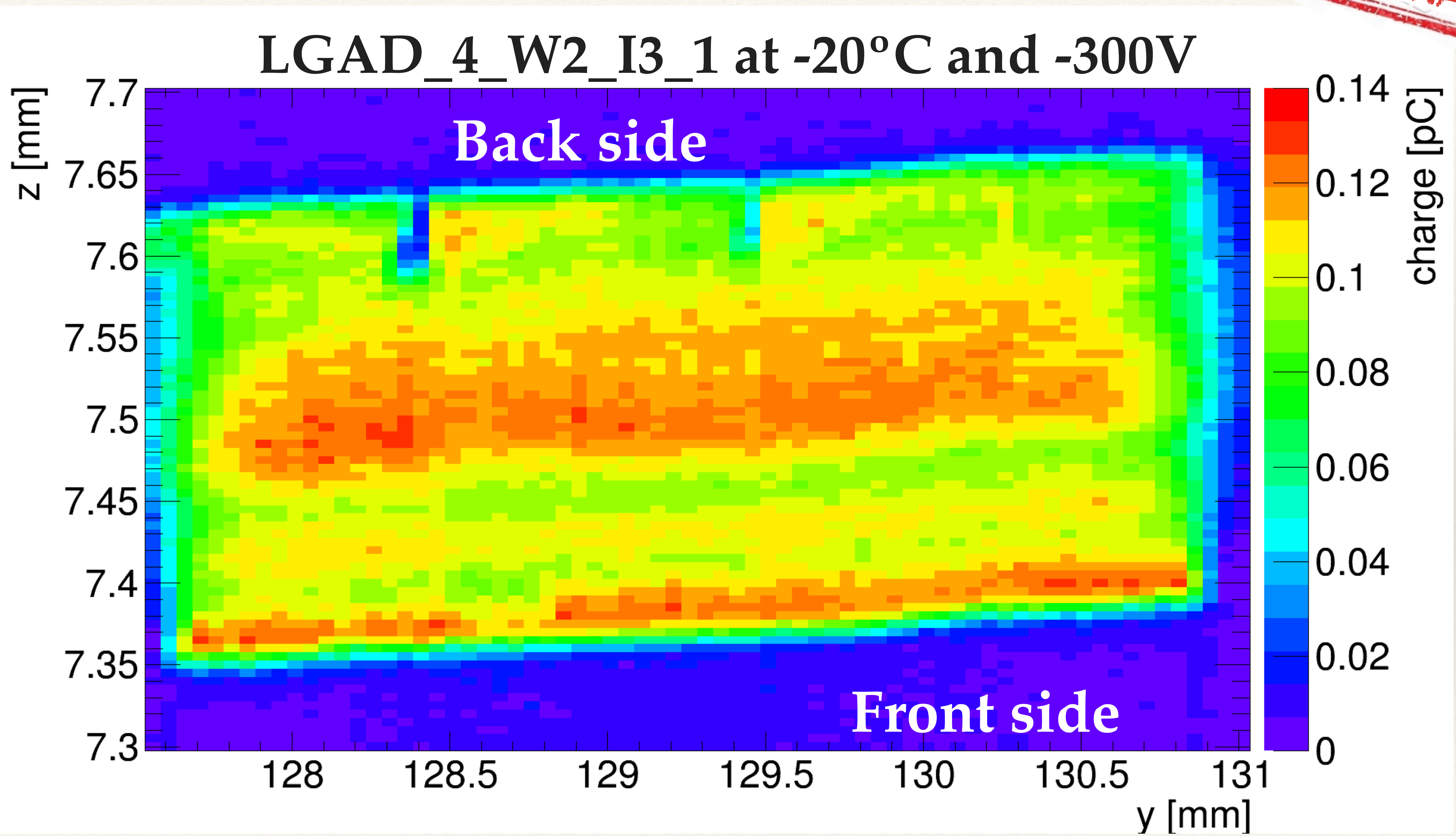
Integrated charge in 0.6 ns [Q(0.6 ns)]

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



Integrated charge in 0.6 ns [Q(0.6 ns)]

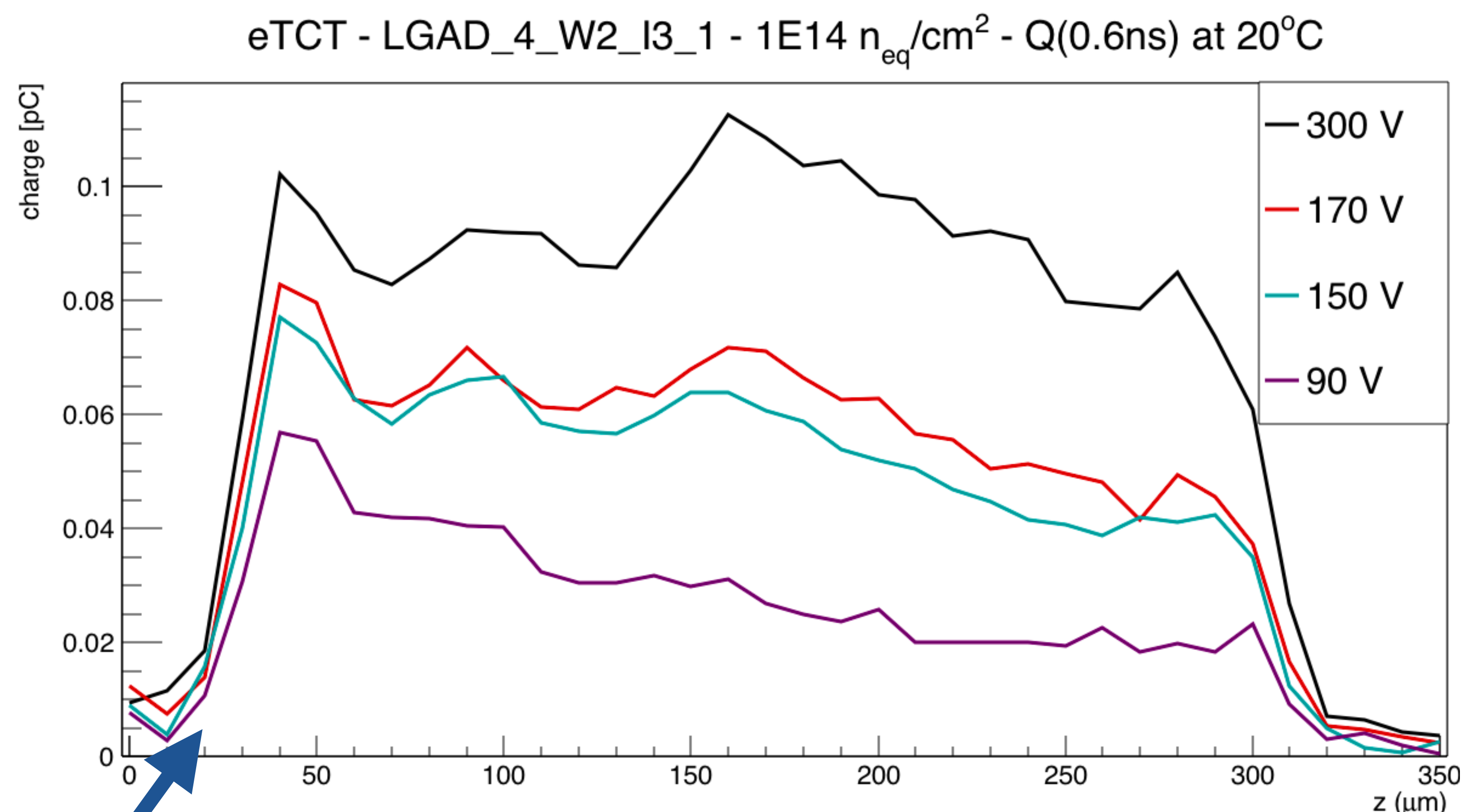
eTCT - Mult. Layer $1.8x10^{13}cm^{-2}$



Integrated charge in 0.6 ns [Q(0.6 ns)]

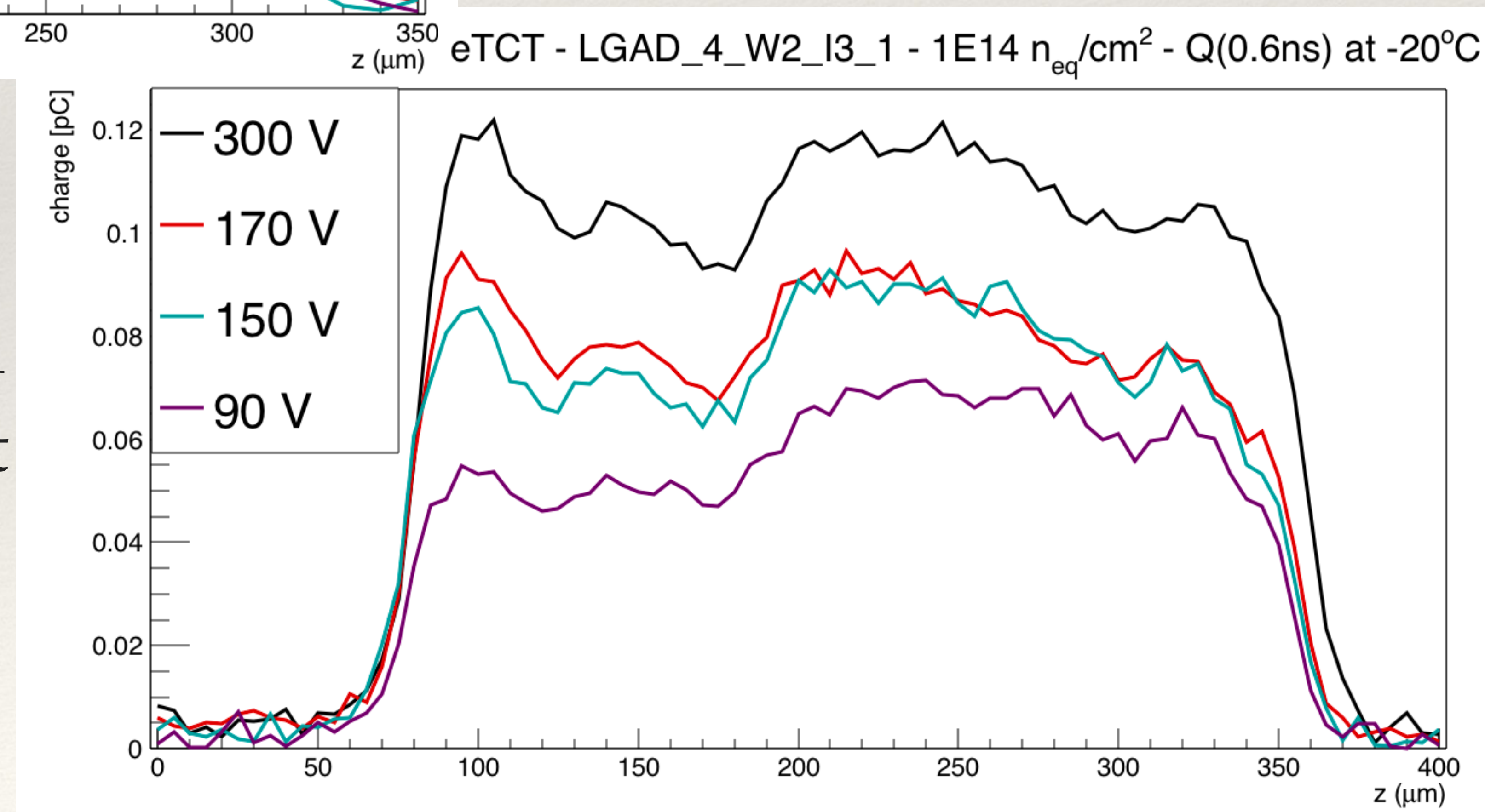
eTCT - Mult. Layer $1.8x10^{13}cm^{-2}$

PRELIMINARY



Front side

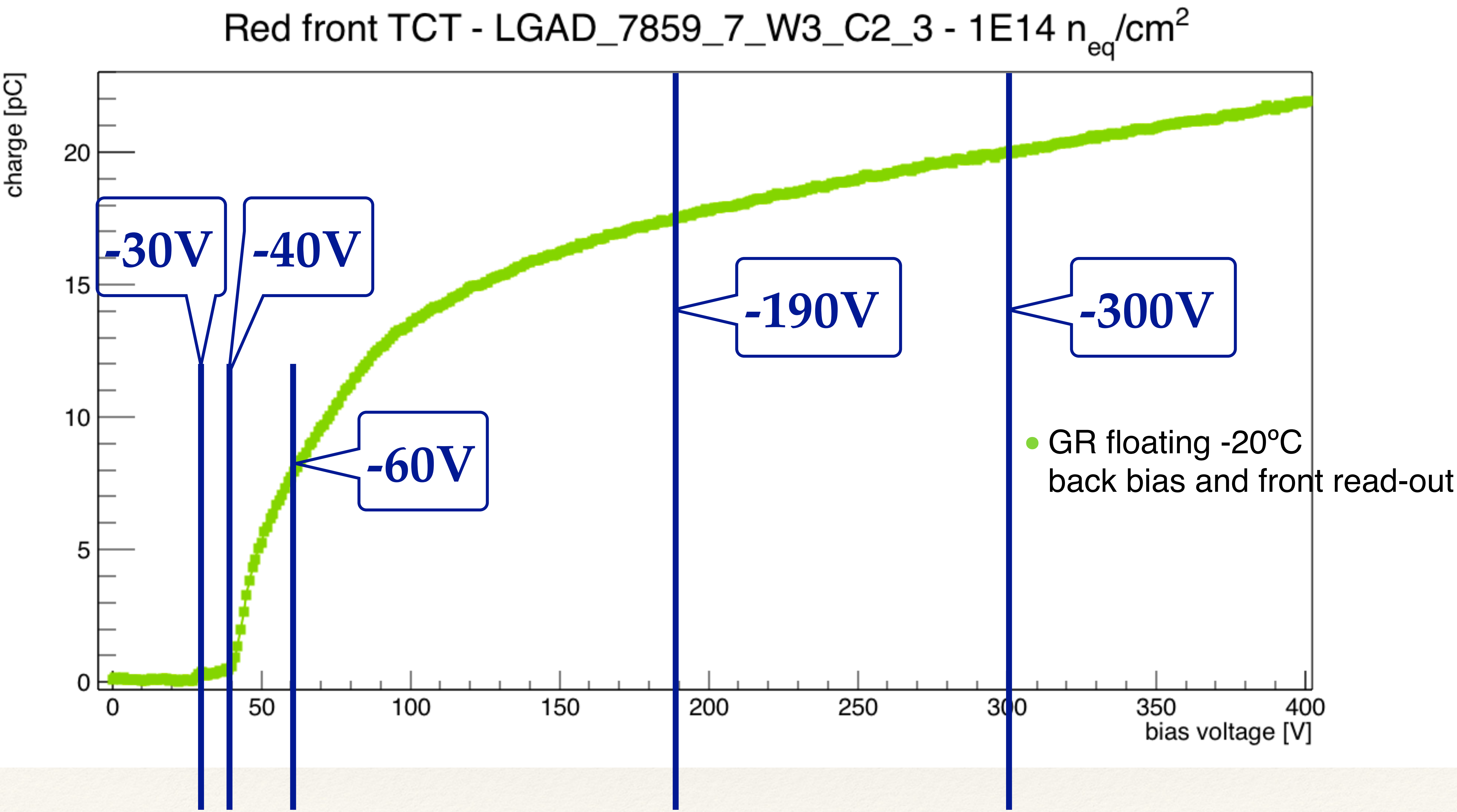
- 20ºC: More charge collected close to the front electrode at low voltages.



- -20ºC: More charge collected close to the back electrode at low voltages.

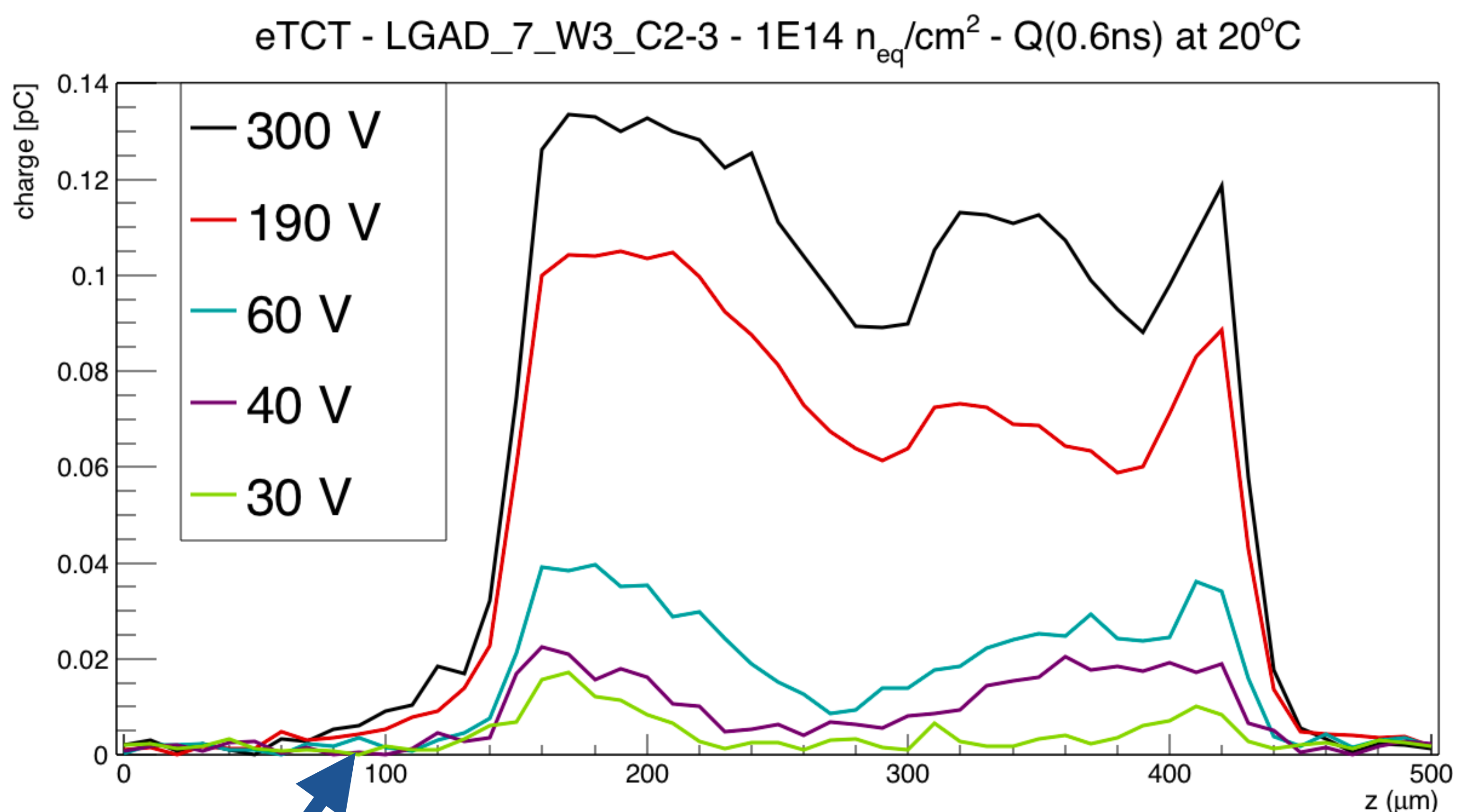
eTCT - Mult. Layer $2.0 \times 10^{13} cm^{-2}$

Voltages for eTCT



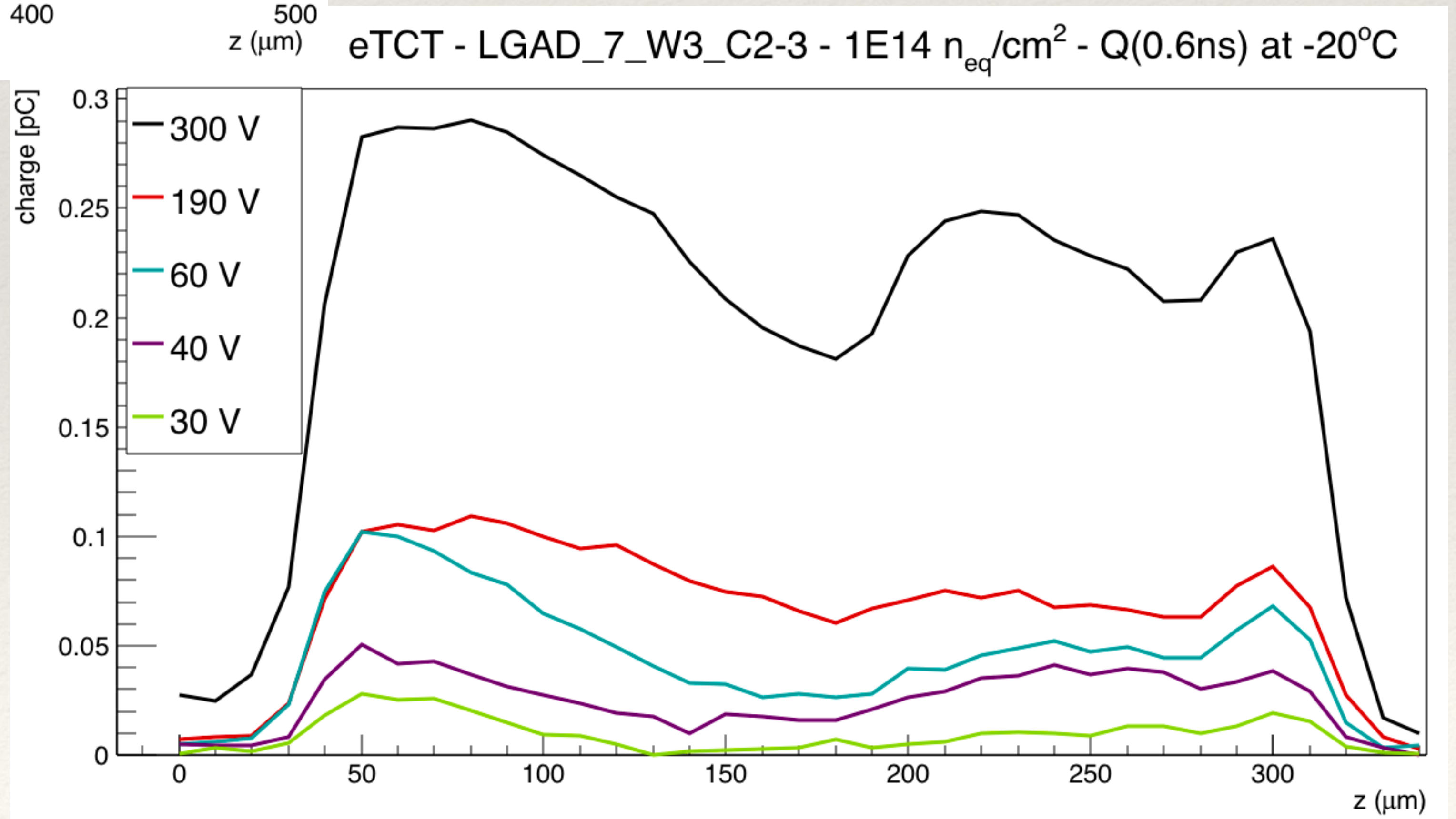
eTCT - Mult. Layer $2.0x10^{13}cm^{-2}$

PRELIMINARY



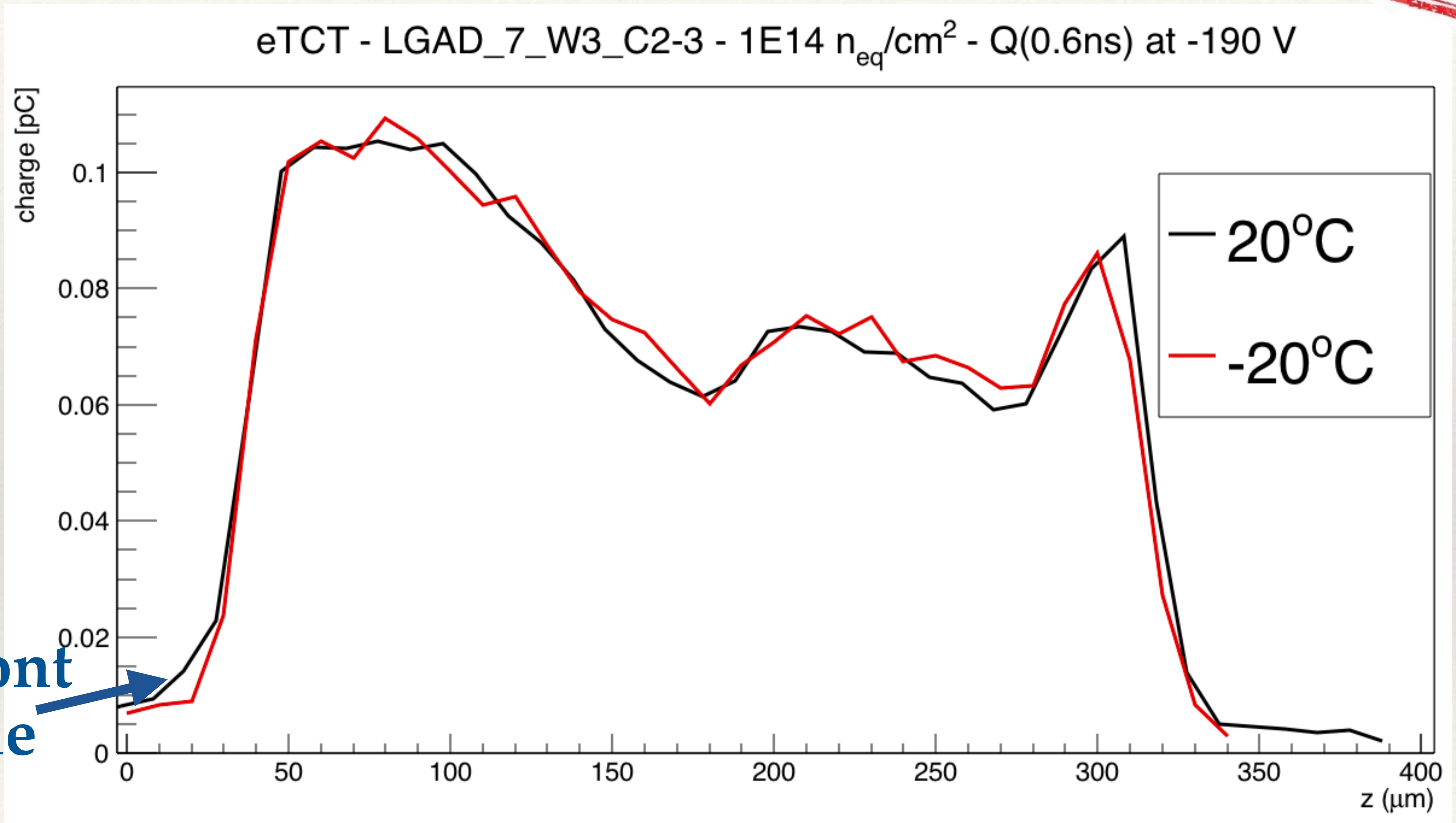
Front side

- Temperature does not seem to affect the charge collection profile.



eTCT - Mult. Layer $2.0x10^{13}cm^{-2}$

PRELIMINARY



Front side

Conclusions

- LGAD_7859_4_W2_I3-1 - Multiplication layer dose: $1.8x10^{13}cm^{-2}$.
  - Irradiated up to 10^{14} 1 MeV n_{eq}/cm^2.
  - Low leakage current device.
  - TCT voltage scans and eTCT seem to confirm the hypothesis of the double junction effect.
  - The electric field grows from the back of the device.
  - Open question: why is this effect present in low leakage current devices?
- LGAD_7859_7_W3_C2-3 - Multiplication layer dose: $2.0x10^{13}cm^{-2}$.
  - Irradiated up to 10^{14} 1 MeV n_{eq}/cm^2.
  - Low leakage current device.
  - Same annealing history as sample LGAD_7859_4_W2_I3-1.
  - In 2016 it showed clear signs of double junction effect.
  - In 2017 the multiplication-onset voltage went down to an unirradiated-like value.

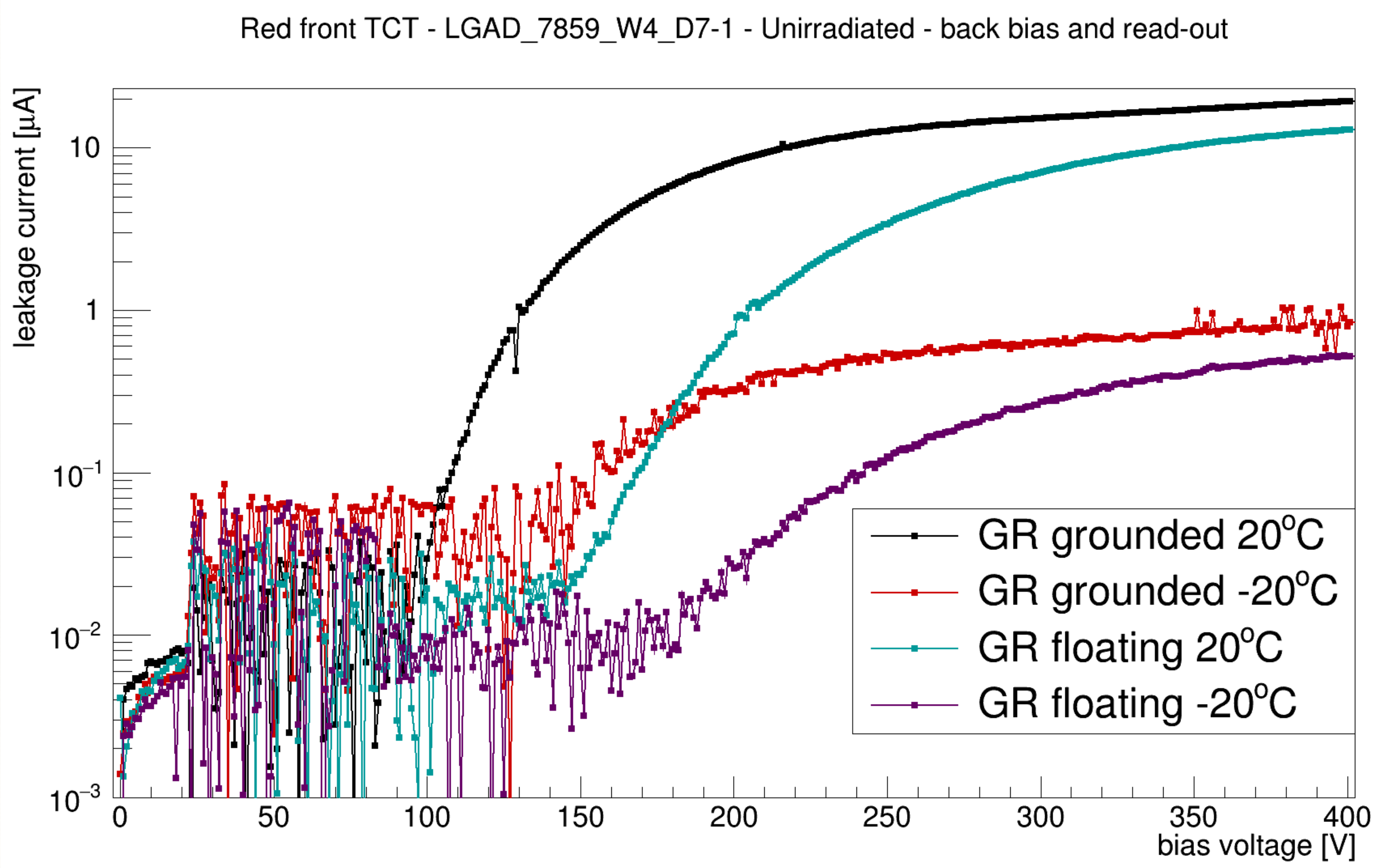
Further Studies

- Repeat the measurements on all the irradiated devices (fluences between 10^{12} and 10^{15} 1 MeV n_{eq}/cm^2).
    - With and without illumination by a LED.
- Perform a detailed temperature dependance study on the samples:
    - TCT voltage scans at several temperatures between 20ºC and -20ºC.
- Carry out new eTCT scans on the samples with a polished edge for better resolution.
    - eTCT scans at different voltages.
    - eTCT scans at several temperatures between 20ºC and -20ºC.
- Irradiate to 10^{14} 1 MeV n_{eq}/cm^2 the LGAD we had kept unirradiated for reference.
    - Perform the aforementioned analyses.
    - Do an annealing study on the device.

Backup Slides

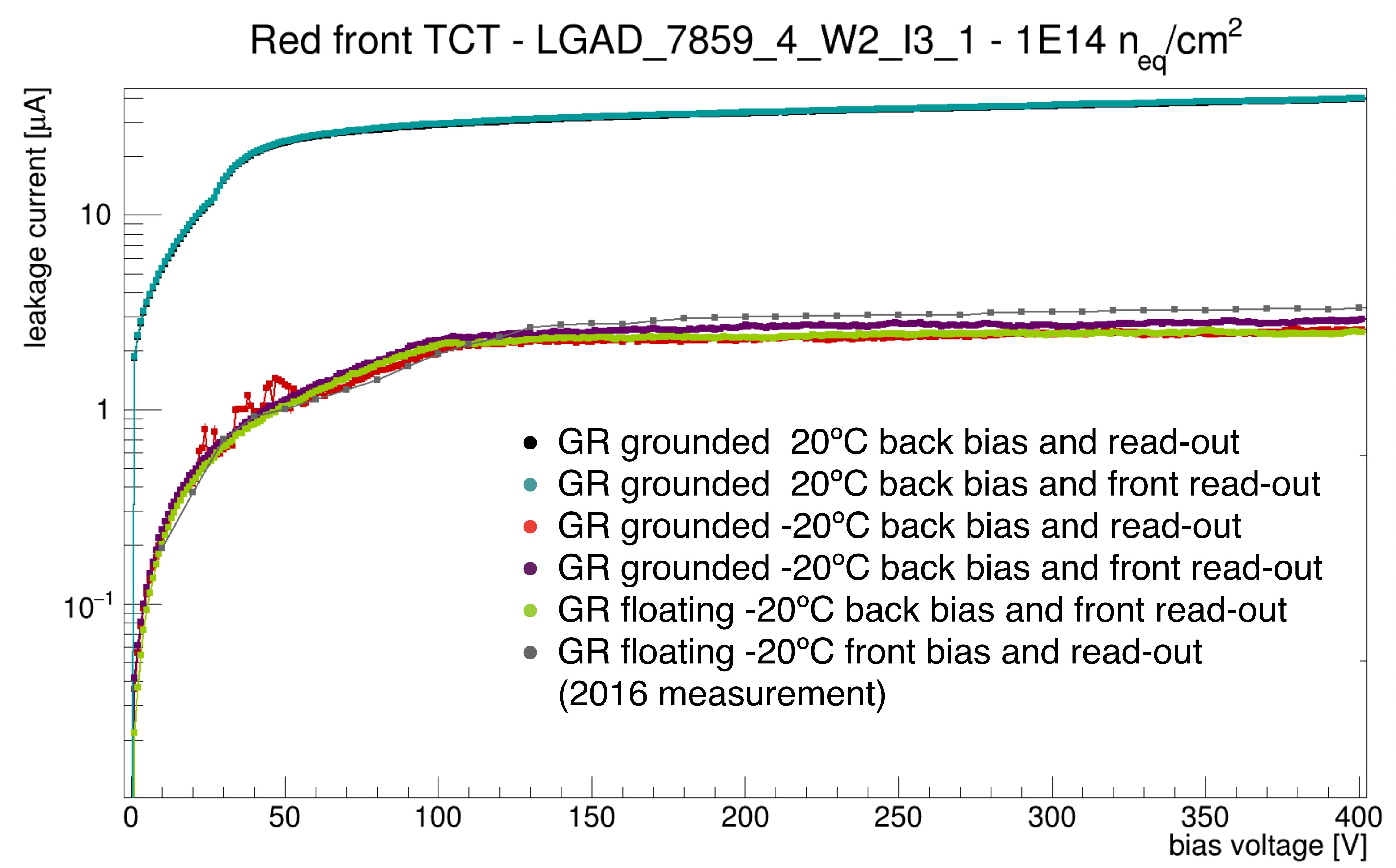
Unirradiated LGAD

- IV curves obtained during the Red Front TCT measurements.



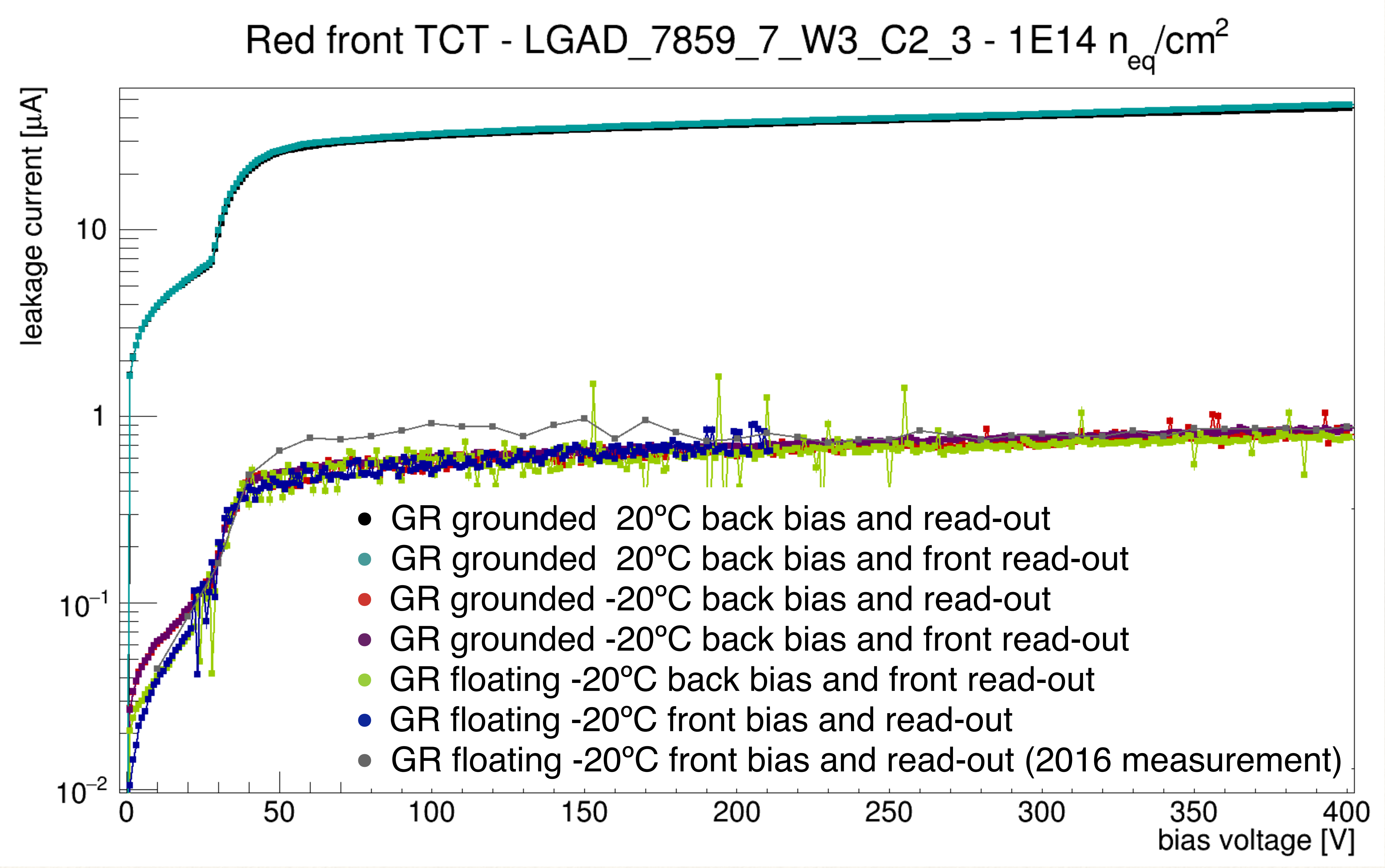
Irradiated LGAD - Mult. Layer: 1.8x10^{13}cm^{-2}

- IV curves obtained during the Red Front TCT measurements.



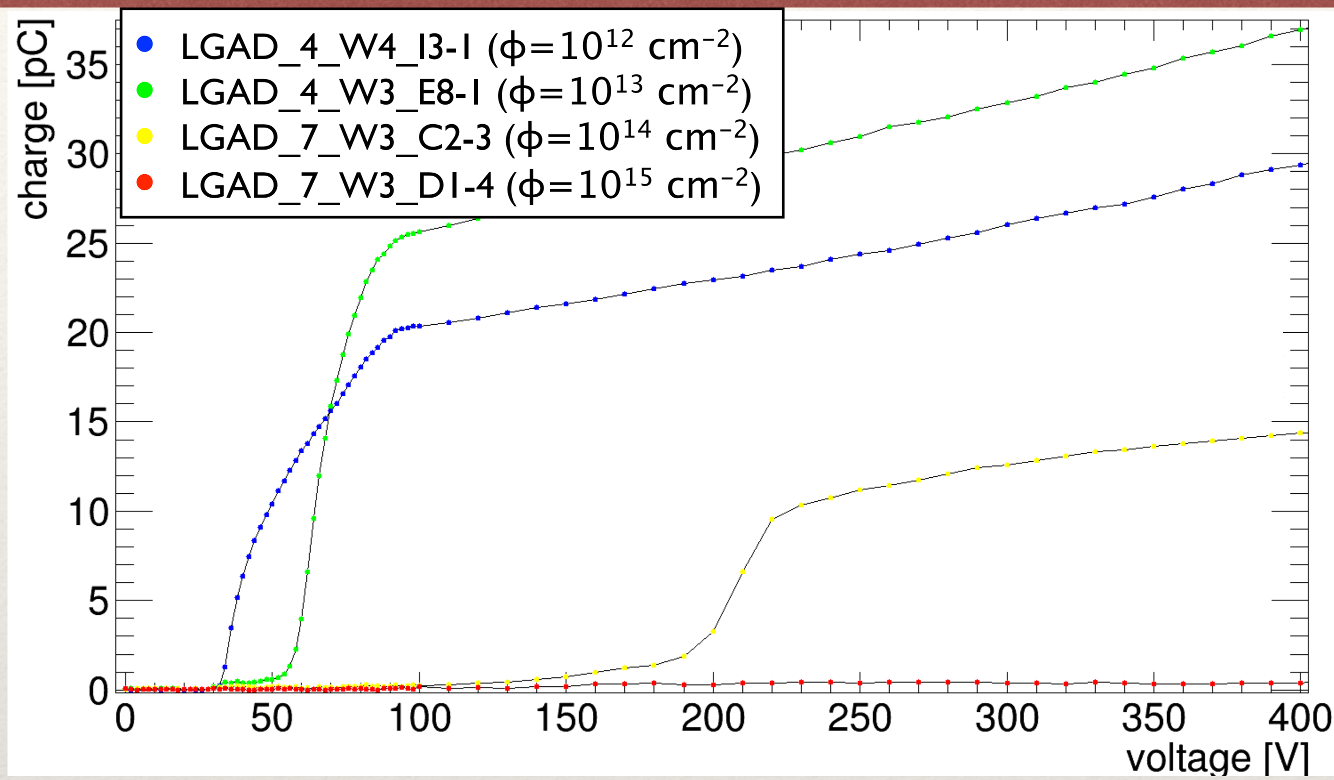
Irradiated LGAD - Mult. Layer: $2.0x10^{13}cm^{-2}$

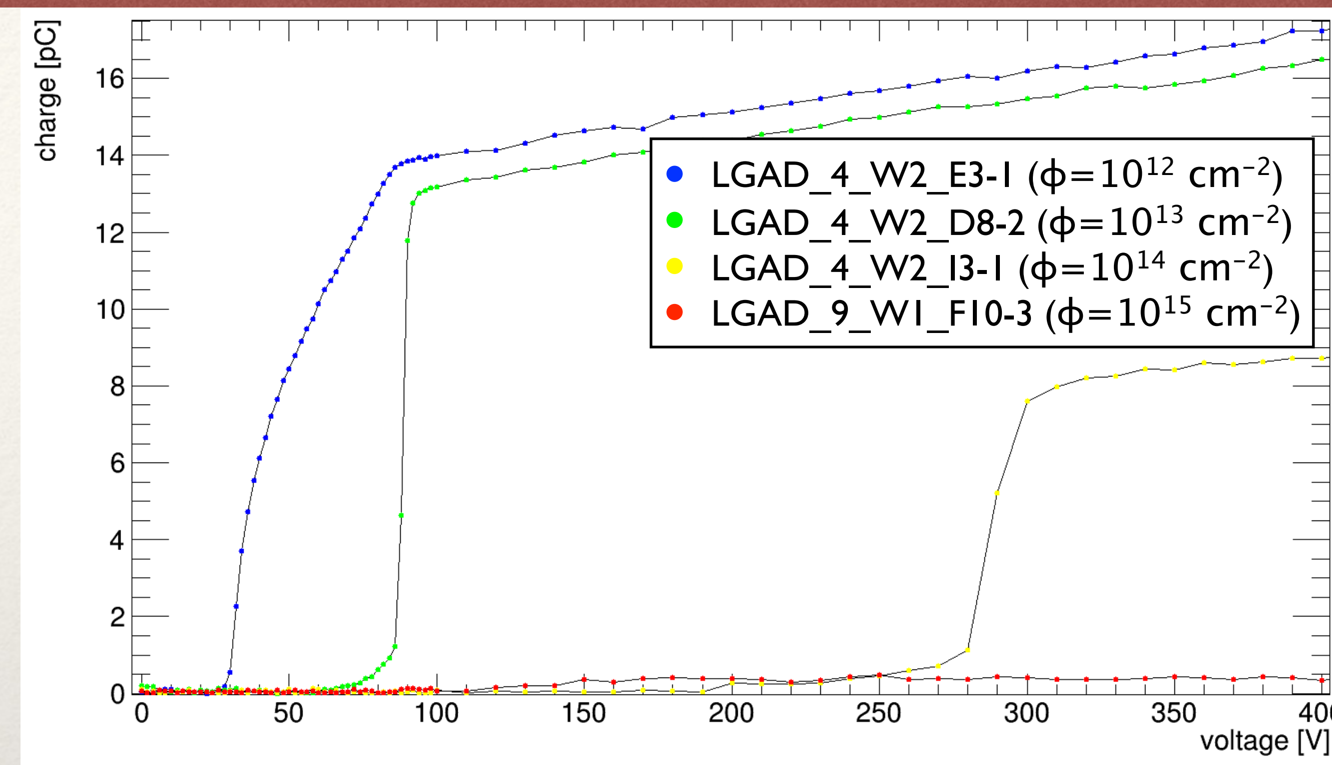
- IV curves obtained during the Red Front TCT measurements.



Multiplication Onset

LGAD - TCT - Red front @ -20°C





- To actually have gain, the multiplication layer must be depleted.
- The threshold voltage indicates as from which voltage the multiplication layer is depleted.
- The threshold voltage can be determined by red front TCT.