TCT MEASUREMENTS AND ANALYSES OF PROTON IRRADIATED LGADS

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With CNM-Barcelona and RD50 LGAD Teams

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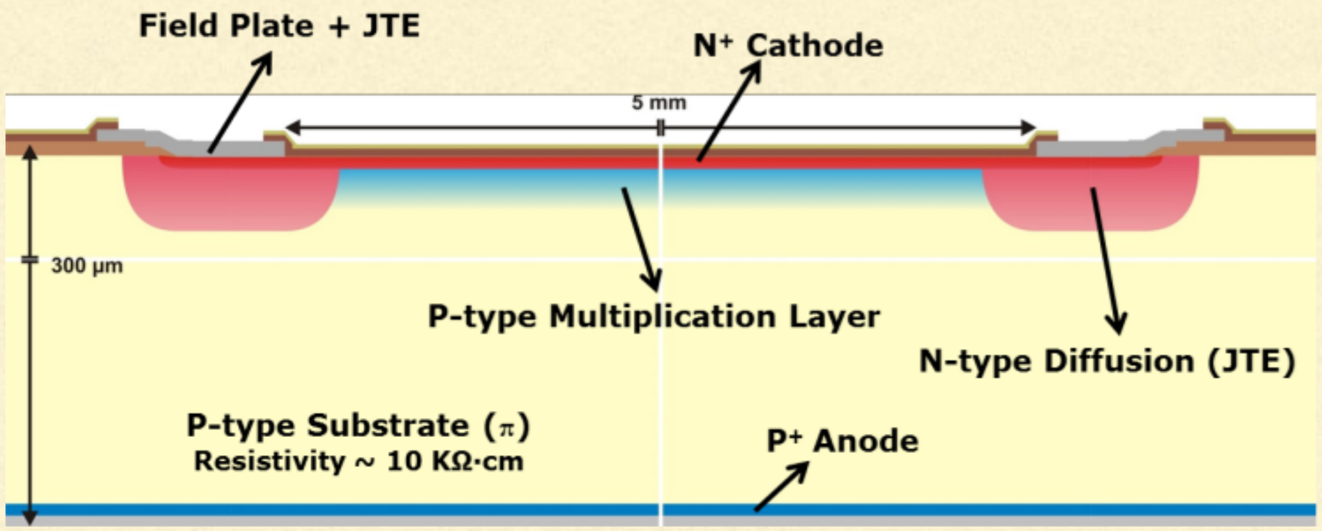
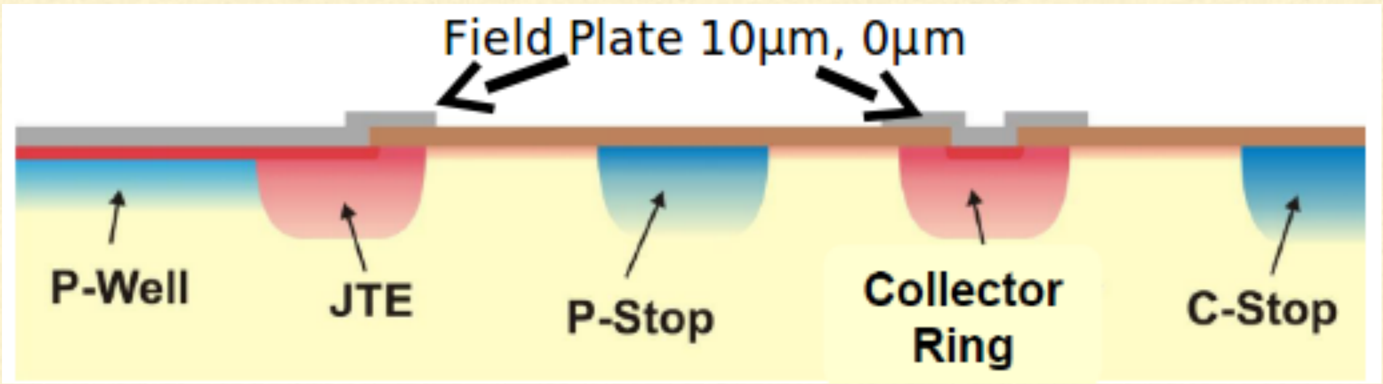
[4]CIEMAT

WAFER CHARACTERISTICS CNM RUN 7859

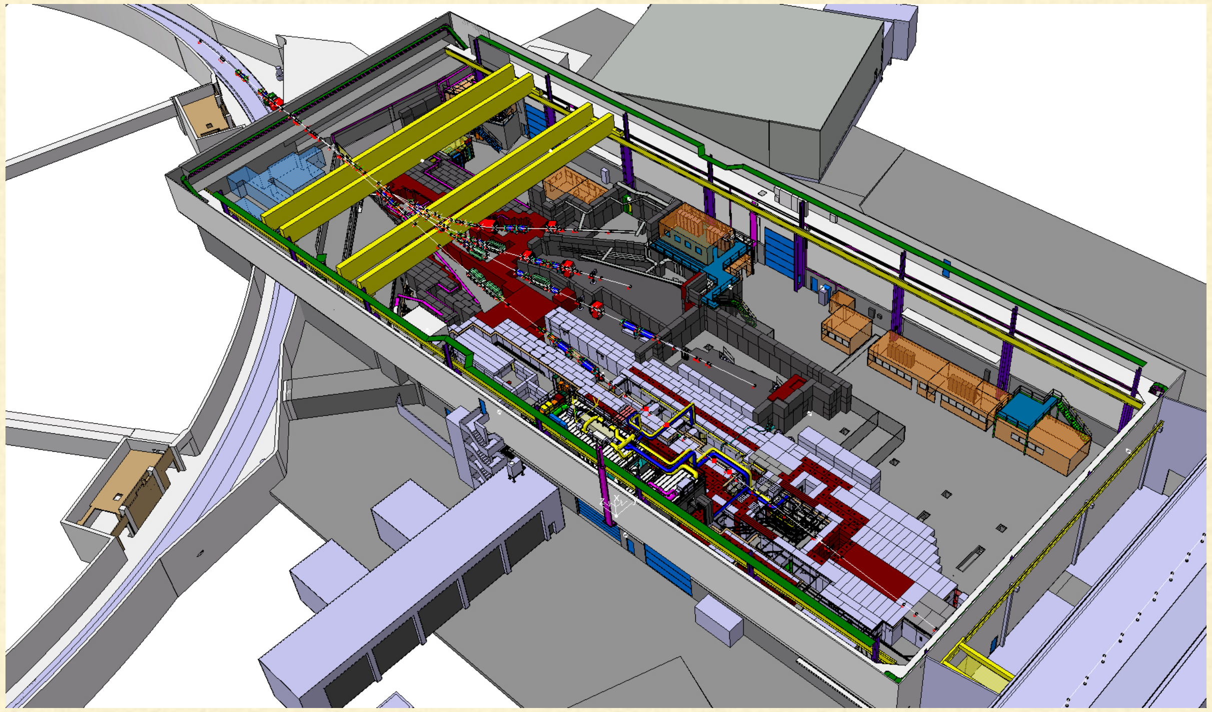
- Multiplication layer dose: 1.8×10^{13} cm^{-2}
  - Wafers 1 and 2.
  - Only one LGAD without JTE.
  - PIN diodes also available.
- Multiplication layer dose: 2.0×10^{13} cm^{-2}
  - Wafers 3 and 4.
  - PIN diodes also available.





IRRADIATION CAMPAIGN

- Irradiation performed at the PS facility
    - 24-GeV protons
- Sets of 4 sensors, formed by
    - 1 PIN + 1 LGAD from W1 or W2
    - 1 PIN + 1 LGAD from W3 or W4
- 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 60°C



References

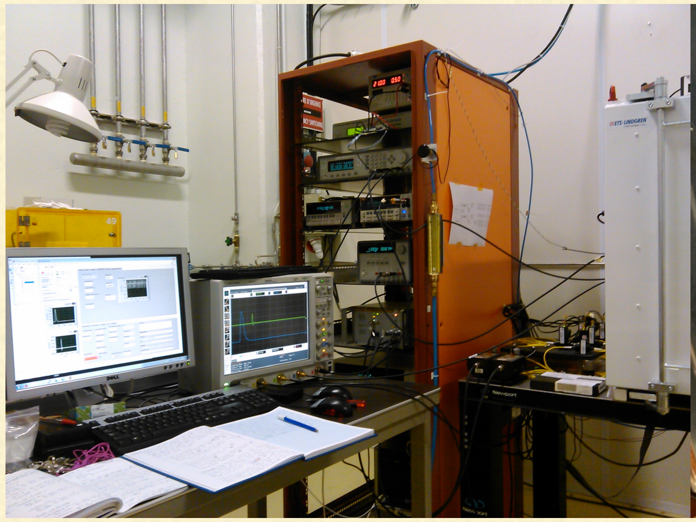
Hardness factor: κ = 0.56

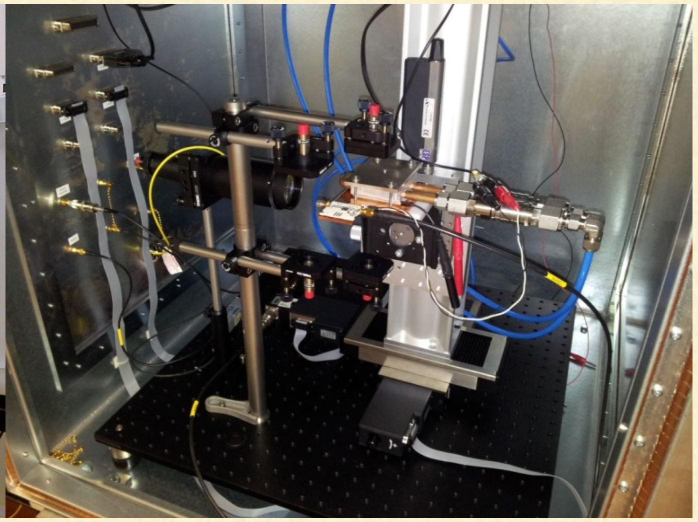
Multiplication layer dose:

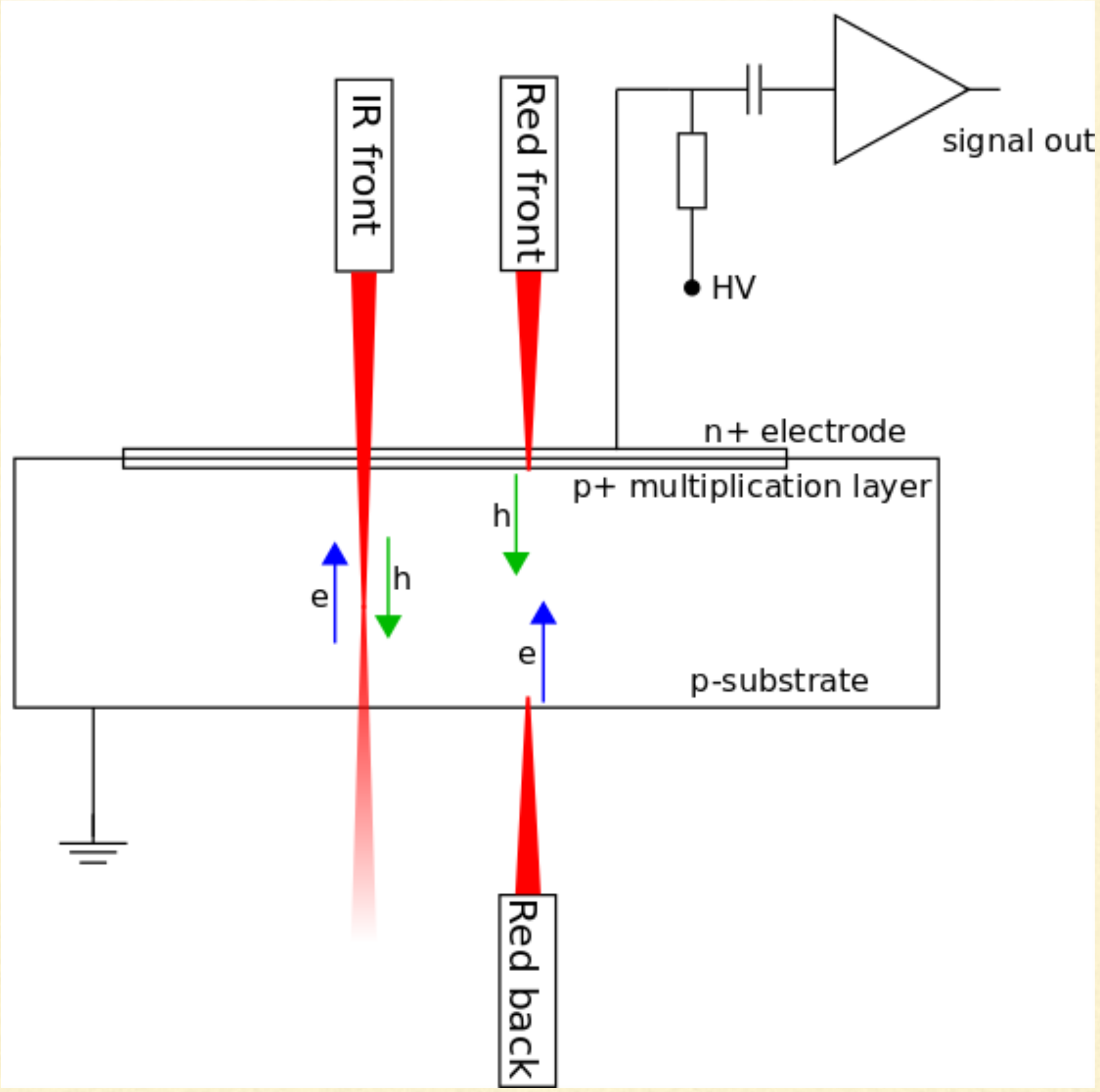
- W1 and W2: 1.8×10^{13} cm^{-2}
- W3 and W4: 2.0×10^{13} cm^{-2}

TCT MEASUREMENTS

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







HOMOGENEITY ANALYSIS

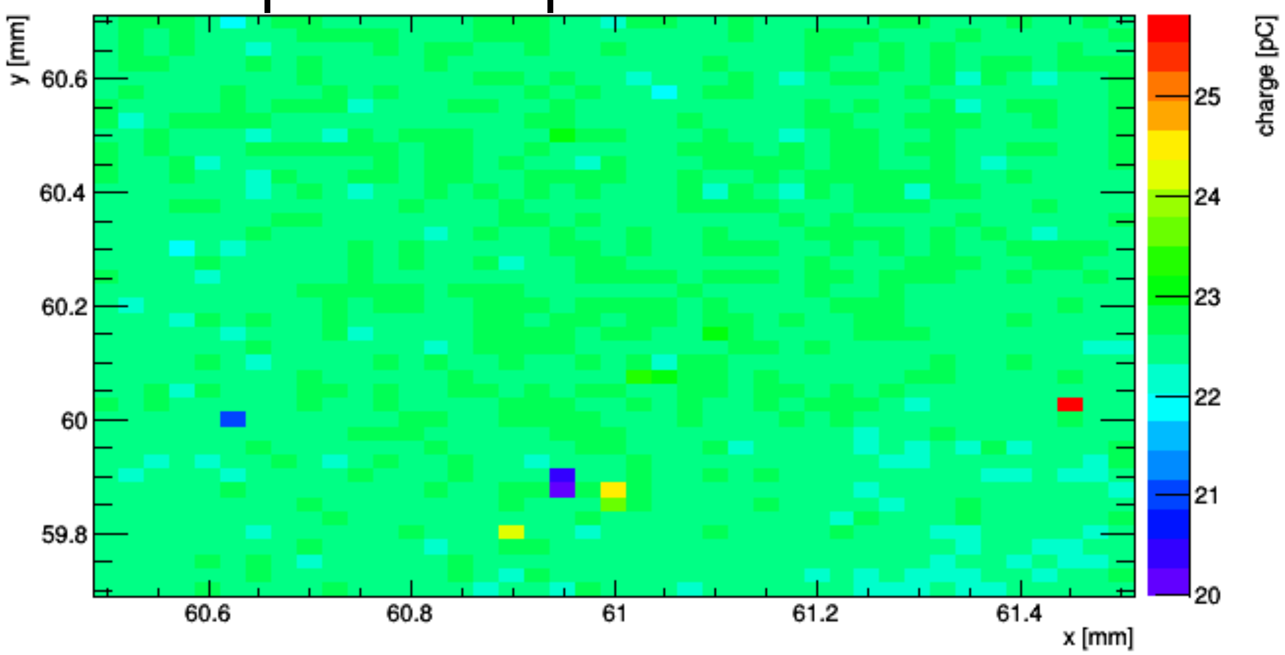
Fluence 10^{12} n_{eq}/cm^2

Sample: LGAD_7859_2.0_4_W4_I3-1

Mult. layer $2.0\times10^{13}cm^{-2}$

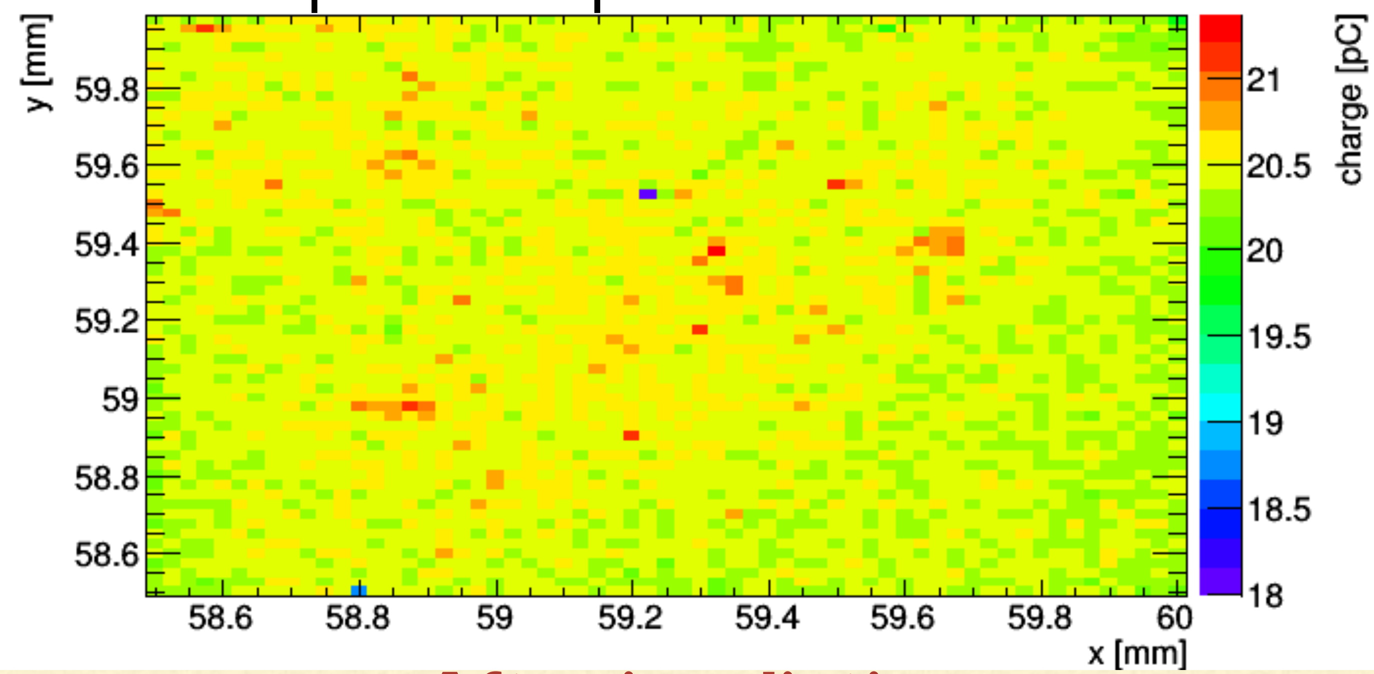
TCT - Red front @ -20°C, 100V

Max. spread ≈ 6 pC



Before irradiation

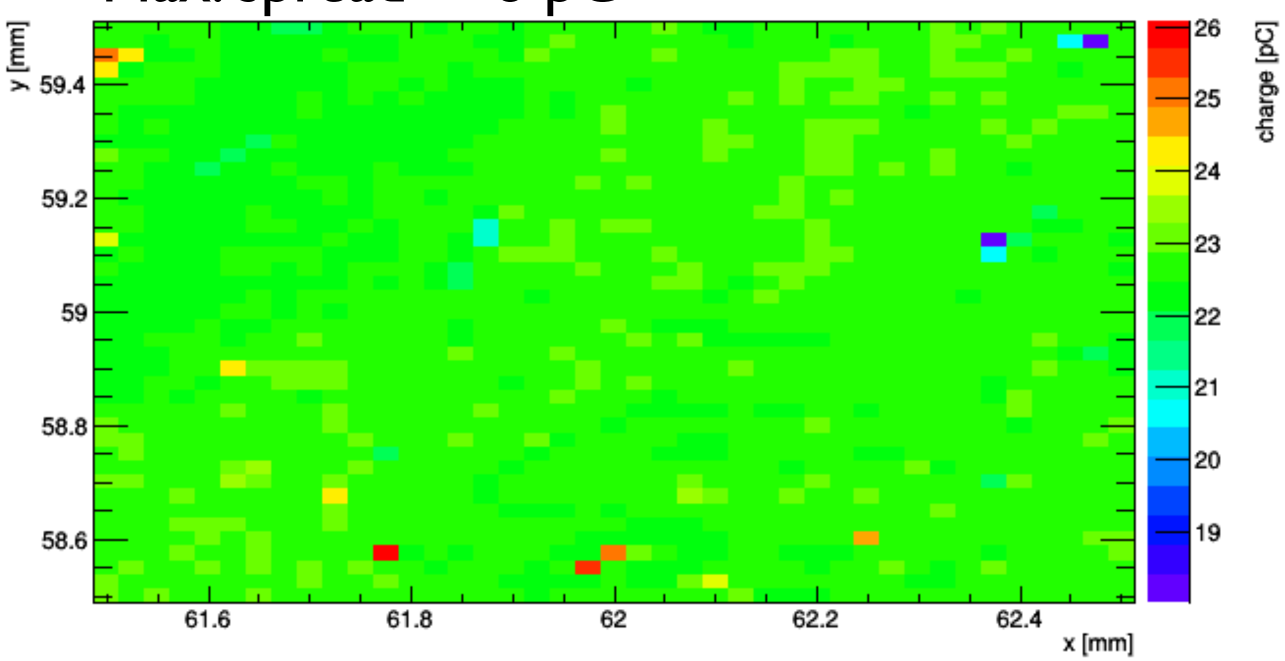
Max. spread ≈ 4 pC



After irradiation

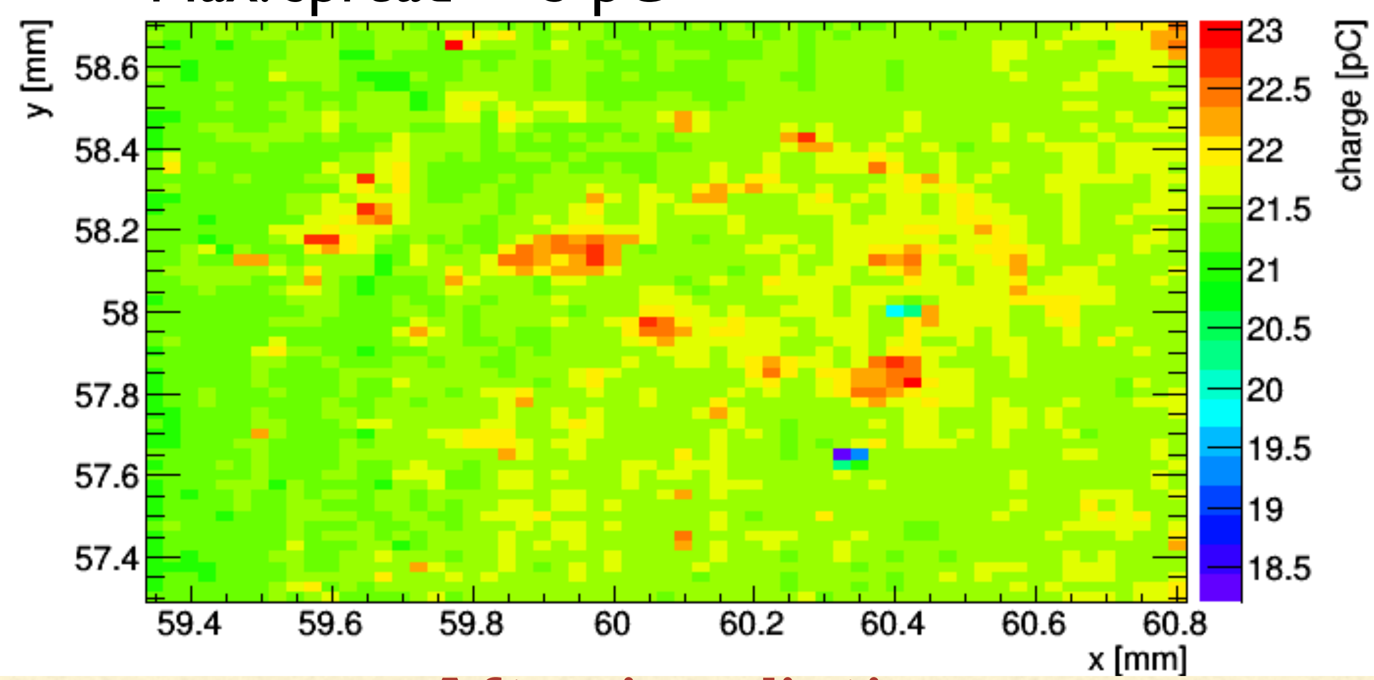
TCT - Red back @ -20°C, 100V

Max. spread ≈ 8 pC



Before irradiation

Max. spread ≈ 5 pC



After irradiation

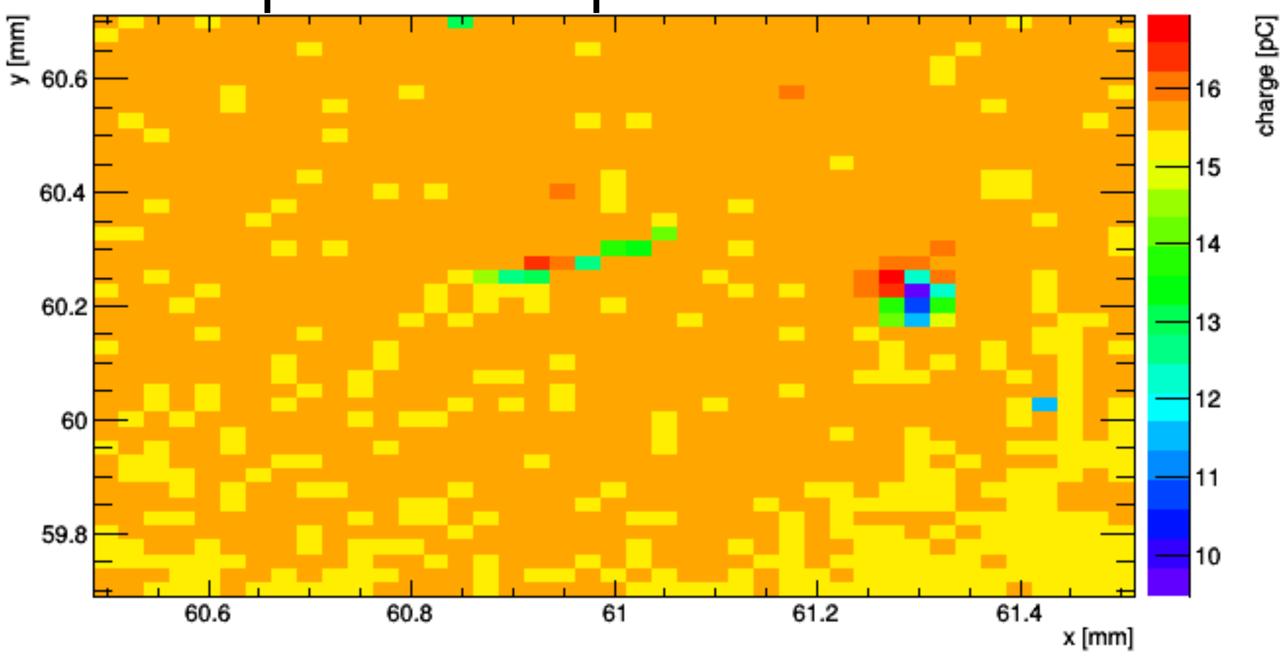
Fluence
$10^{12}\ n_{eq}/cm^2$

Sample: LGAD_7859_1.8_4_W2_E3-1

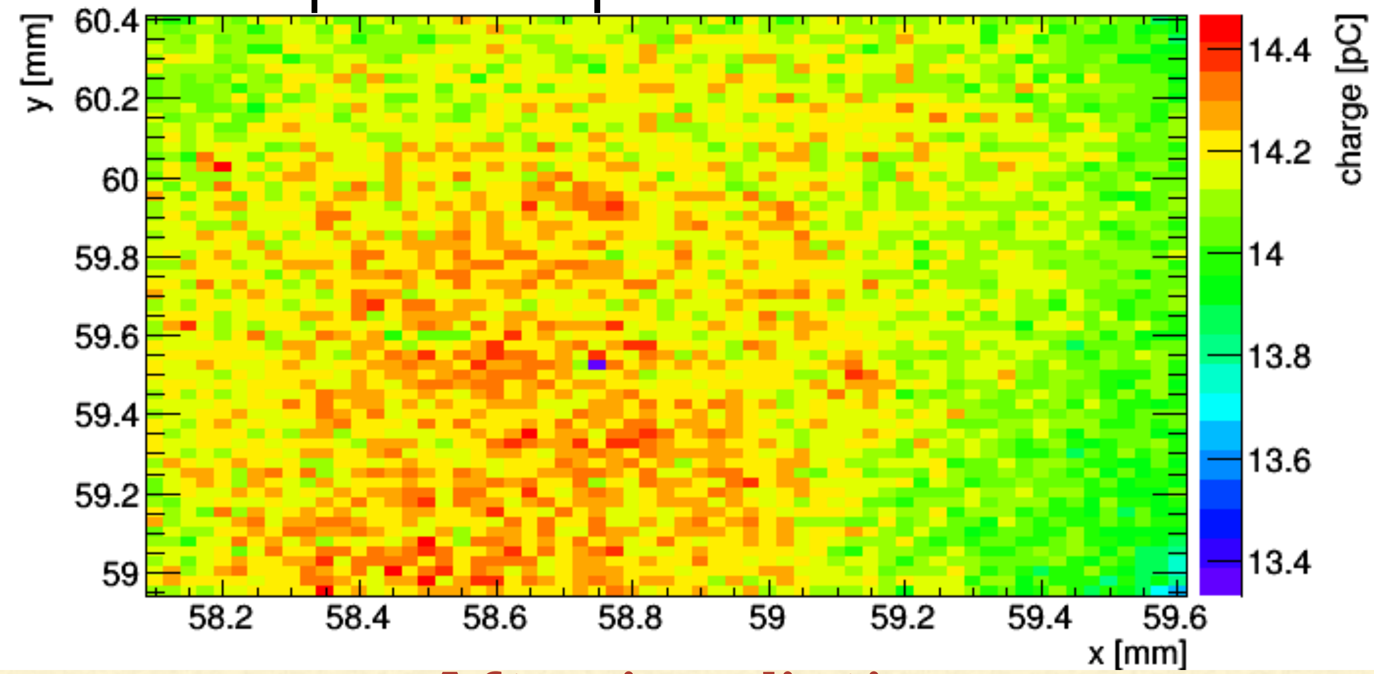
Mult. layer
$1.8 \times 10^{13} cm^{-2}$

TCT - Red front @ -20°C, 100V

Max. spread ≈ 7.5 pC



Max. spread ≈ 1 pC

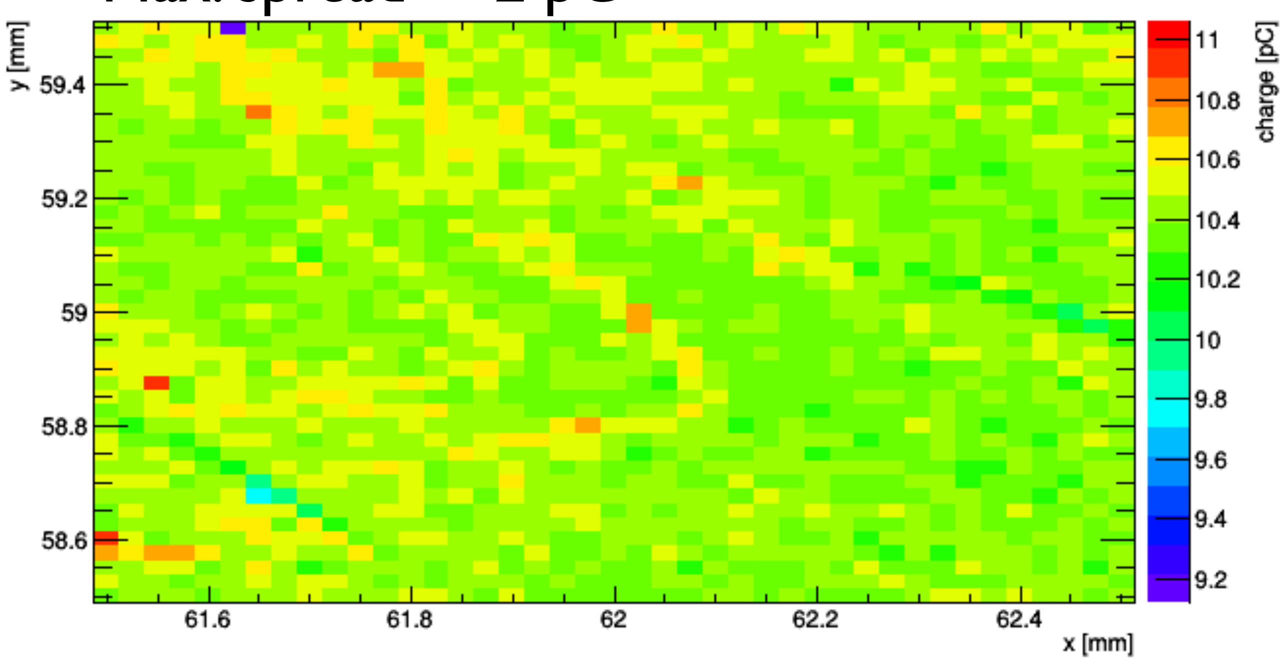


Before irradiation

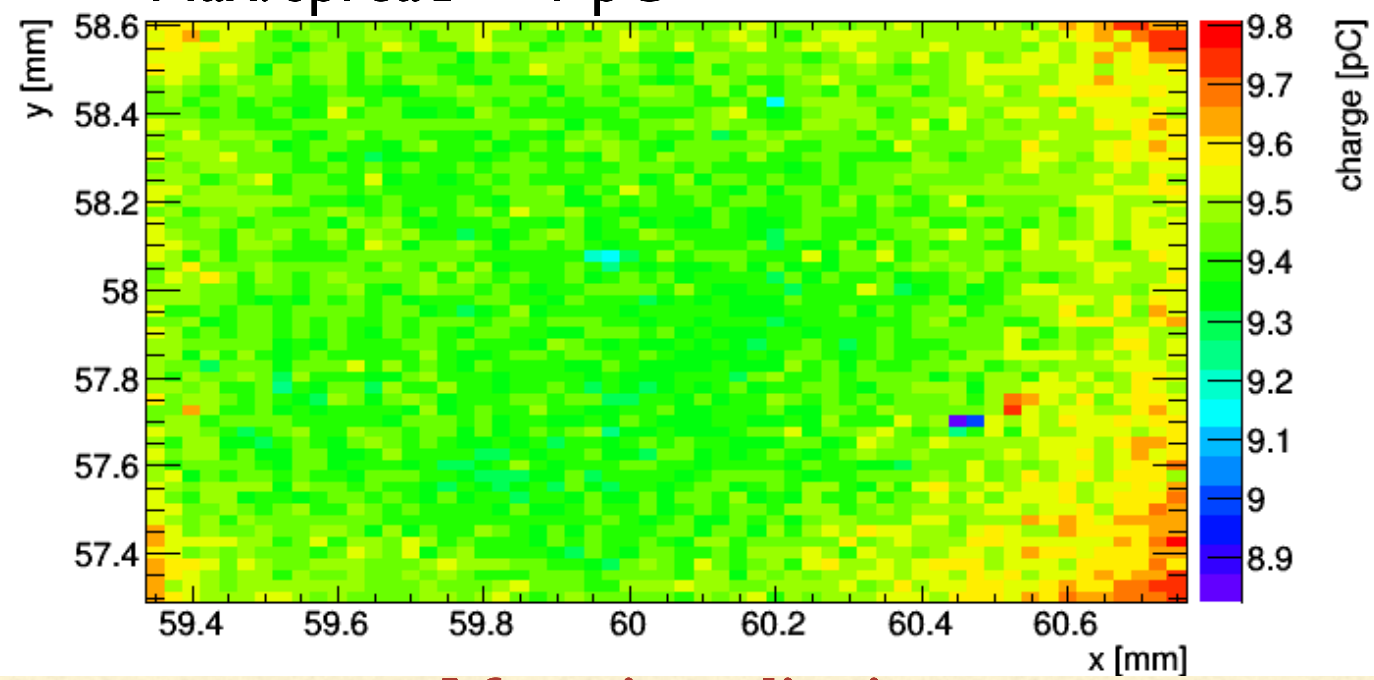
After irradiation

TCT - Red back @ -20°C, 100V

Max. spread ≈ 2 pC



Max. spread ≈ 1 pC



Before irradiation

After irradiation

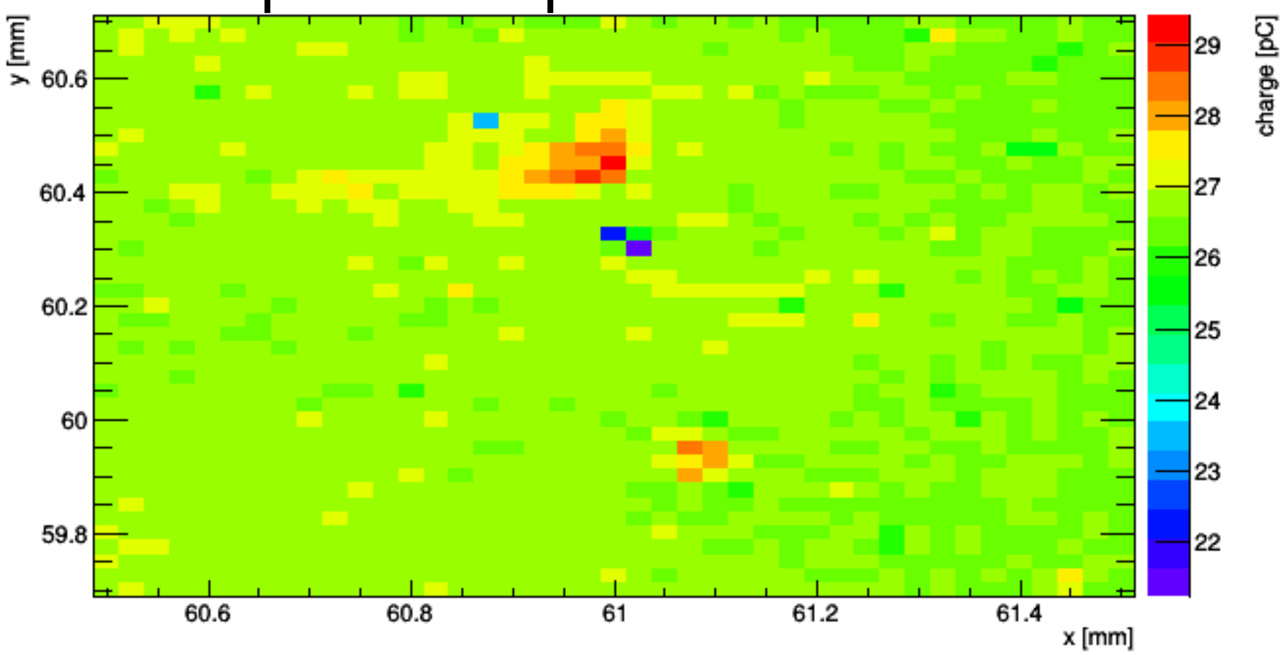
Fluence
$10^{14}\ n_{eq}/cm^2$

Sample: LGAD_7859_2.0_7_W3_C2-3

Mult. layer
$2.0\times10^{13} cm^{-2}$

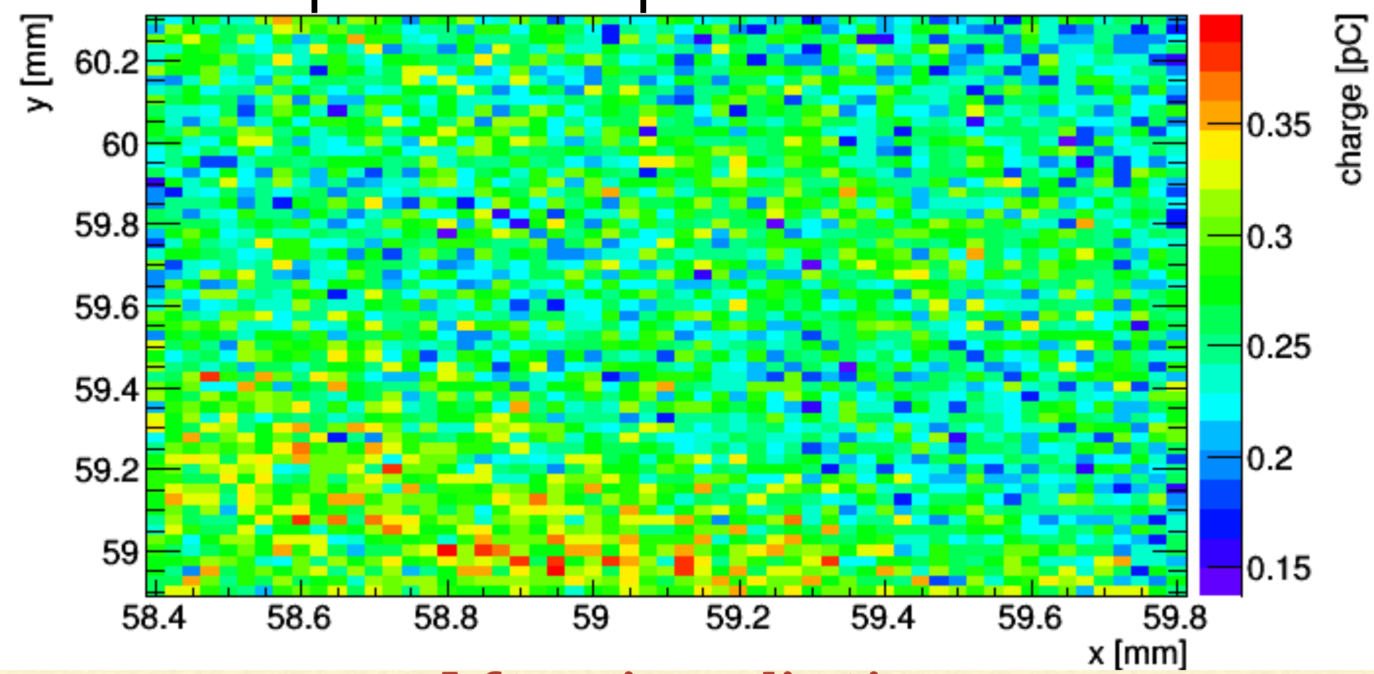
TCT - Red front @ -20°C, 100V

Max. spread ≈ 8 pC



Before irradiation

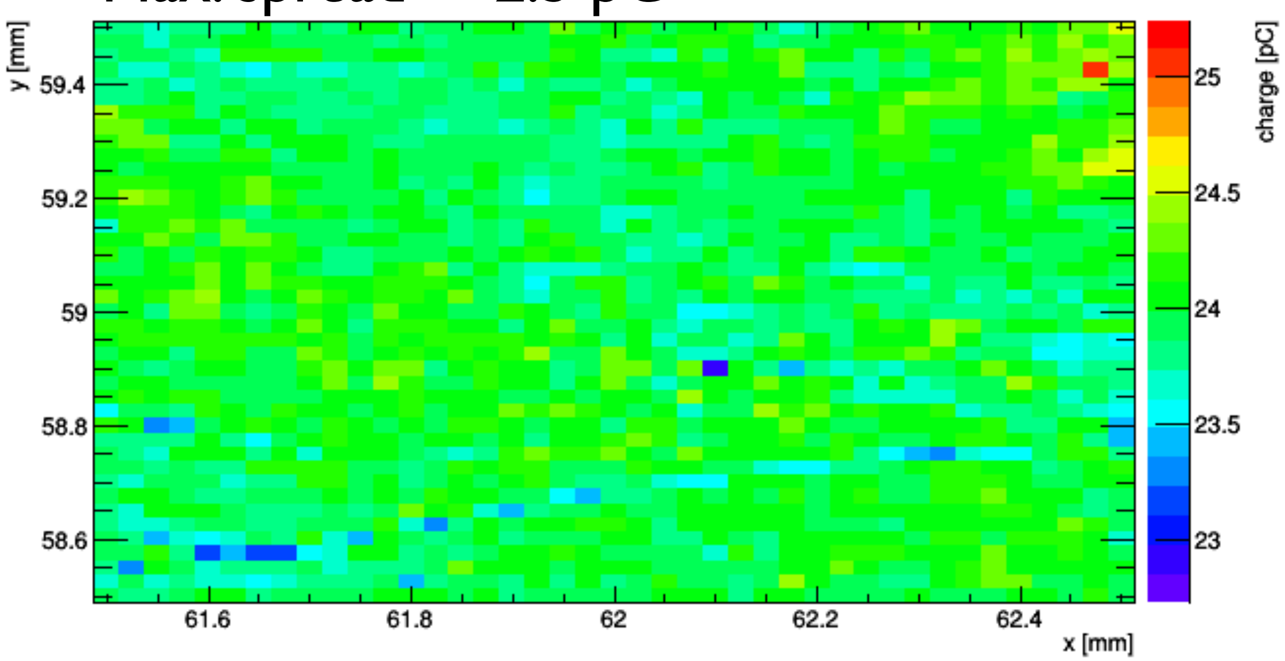
Max. spread ≈ 0.3 pC



After irradiation

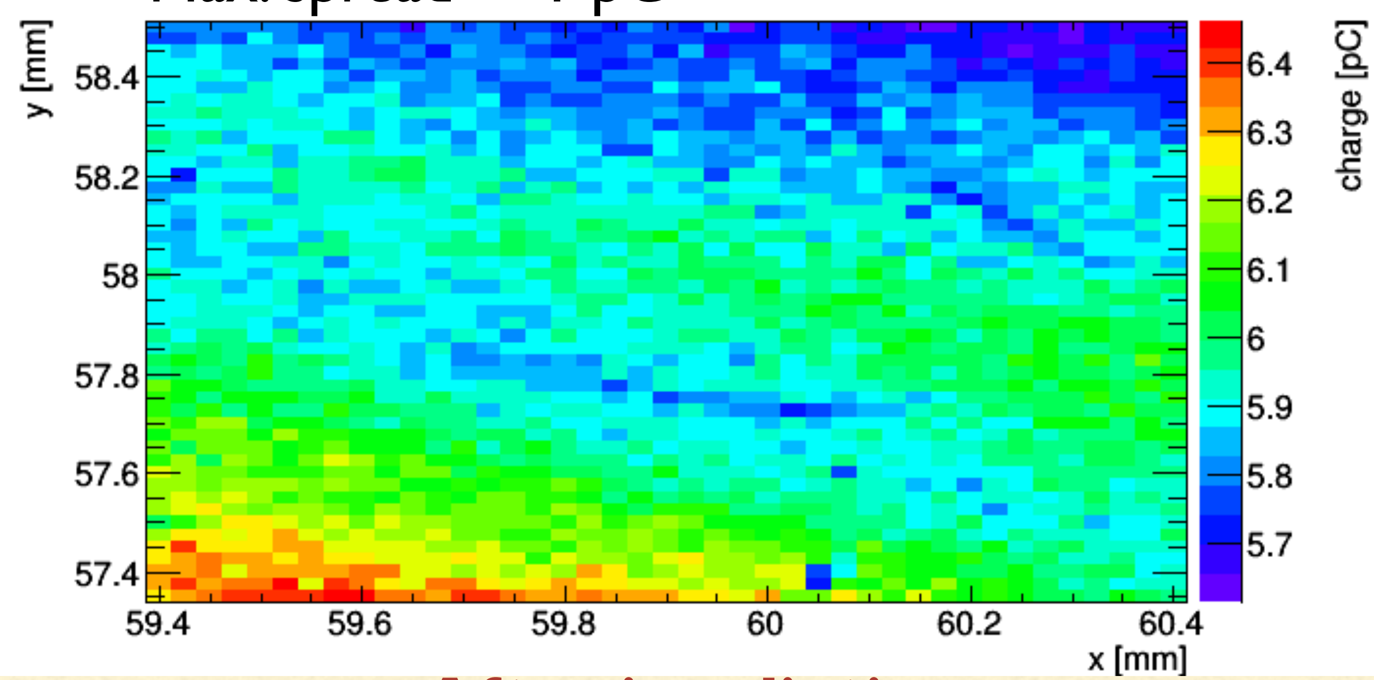
TCT - Red back @ -20°C, 100V

Max. spread ≈ 2.5 pC



Before irradiation

Max. spread ≈ 1 pC



After irradiation

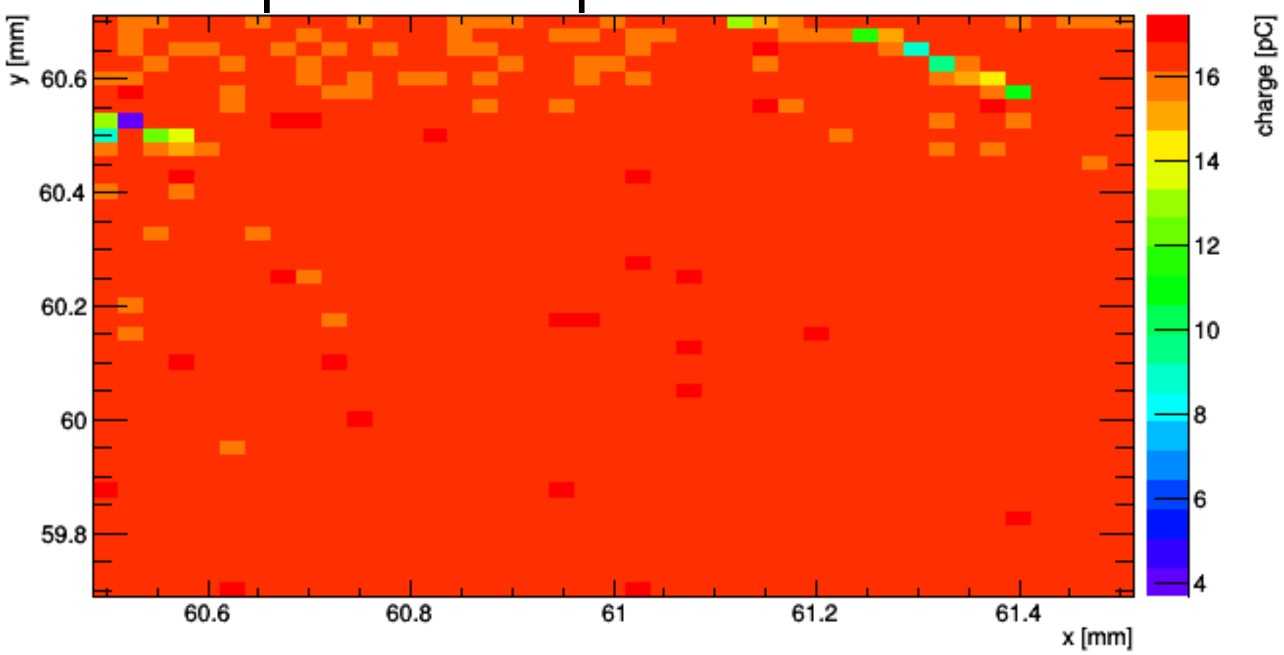
Fluence $10^{15} n_{eq}/cm^2$

Sample: LGAD_7859_1.8_9_W1_F10-3

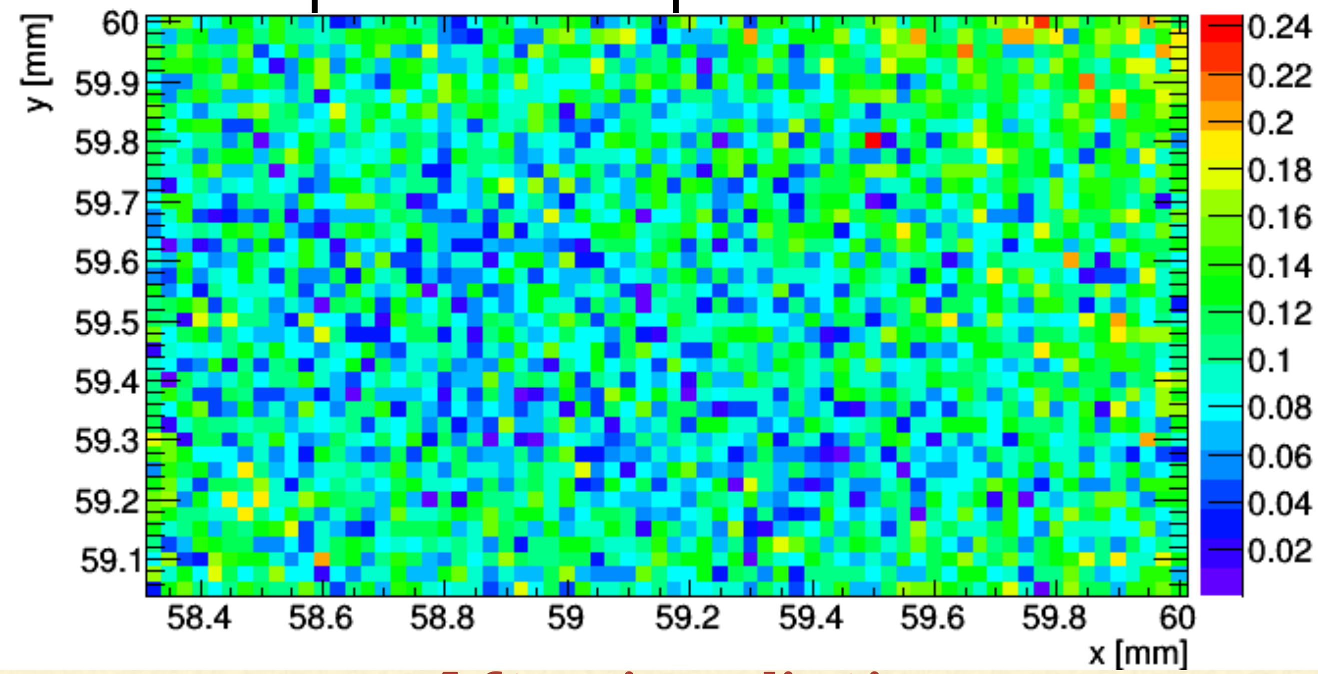
Mult. layer $1.8 \times 10^{13} cm^{-2}$

TCT - Red front @ -20°C, 100V

Max. spread ≈ 14 pC



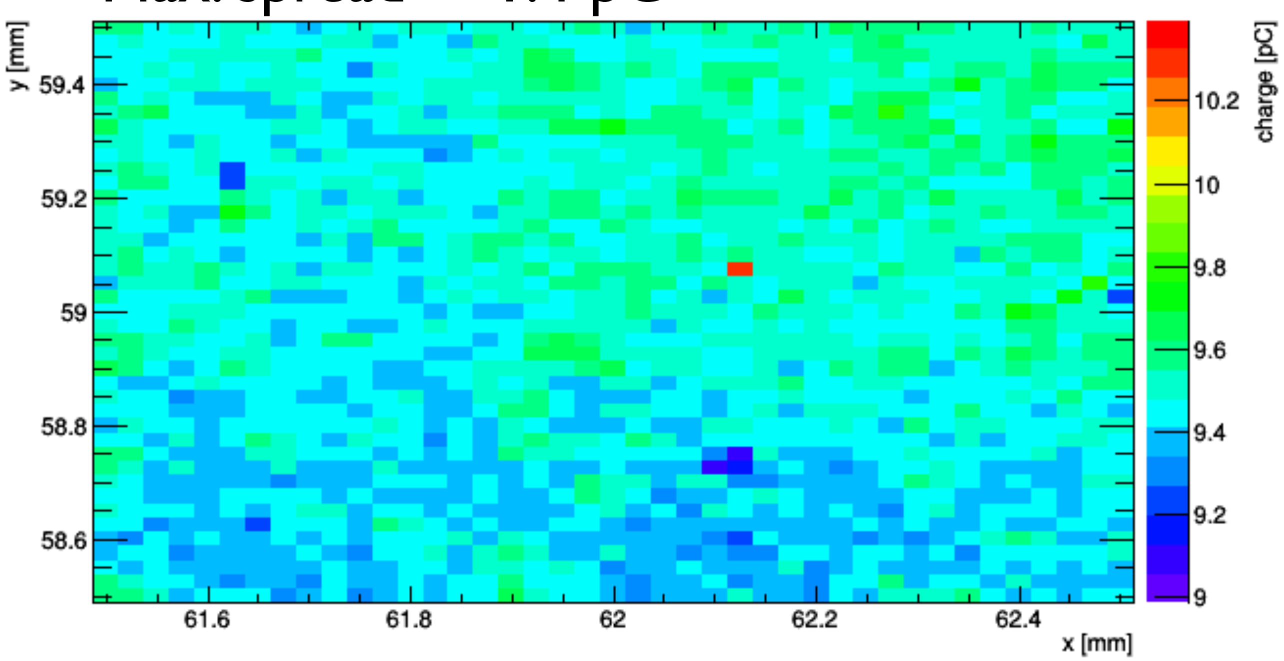
Max. spread ≈ 0.23 pC



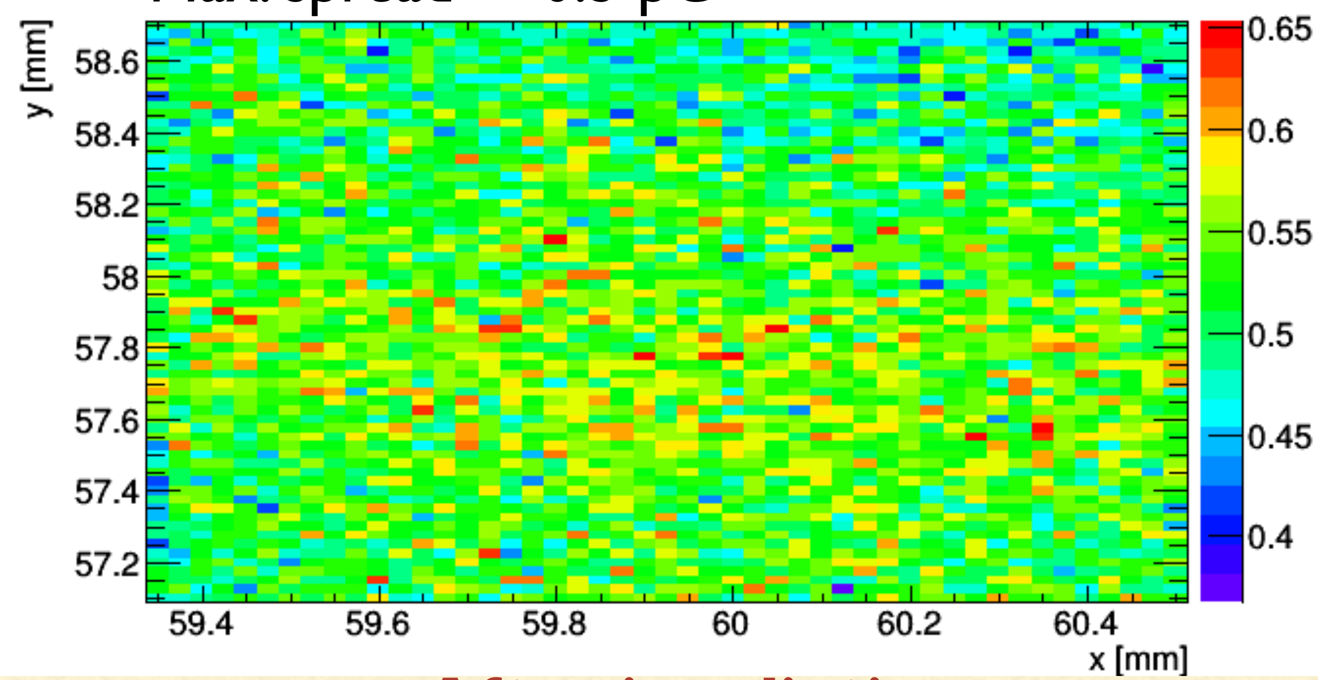
Before irradiation **After irradiation**

TCT - Red back @ -20°C, 100V

Max. spread ≈ 1.4 pC



Max. spread ≈ 0.3 pC



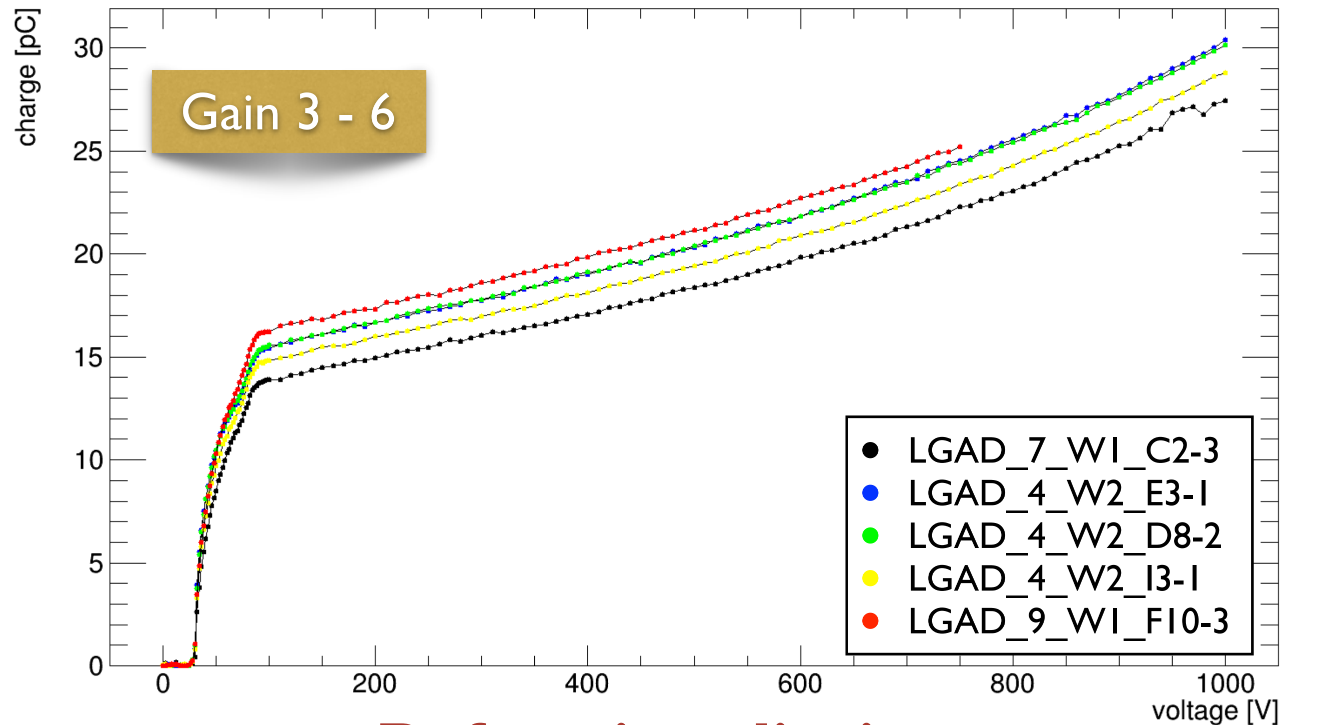
Before irradiation **After irradiation**

VOLTAGE SCANS

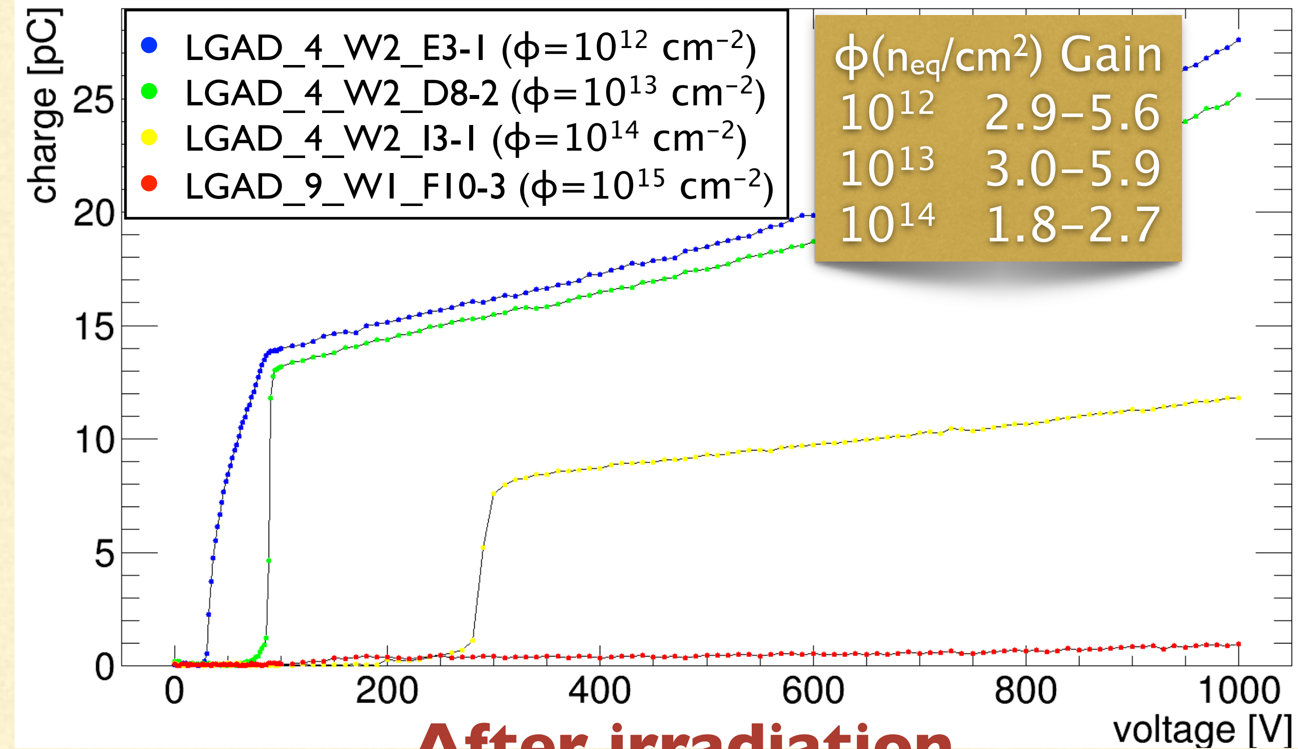
Charge collection with voltage

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

LGAD - TCT - Red front @ -20°C

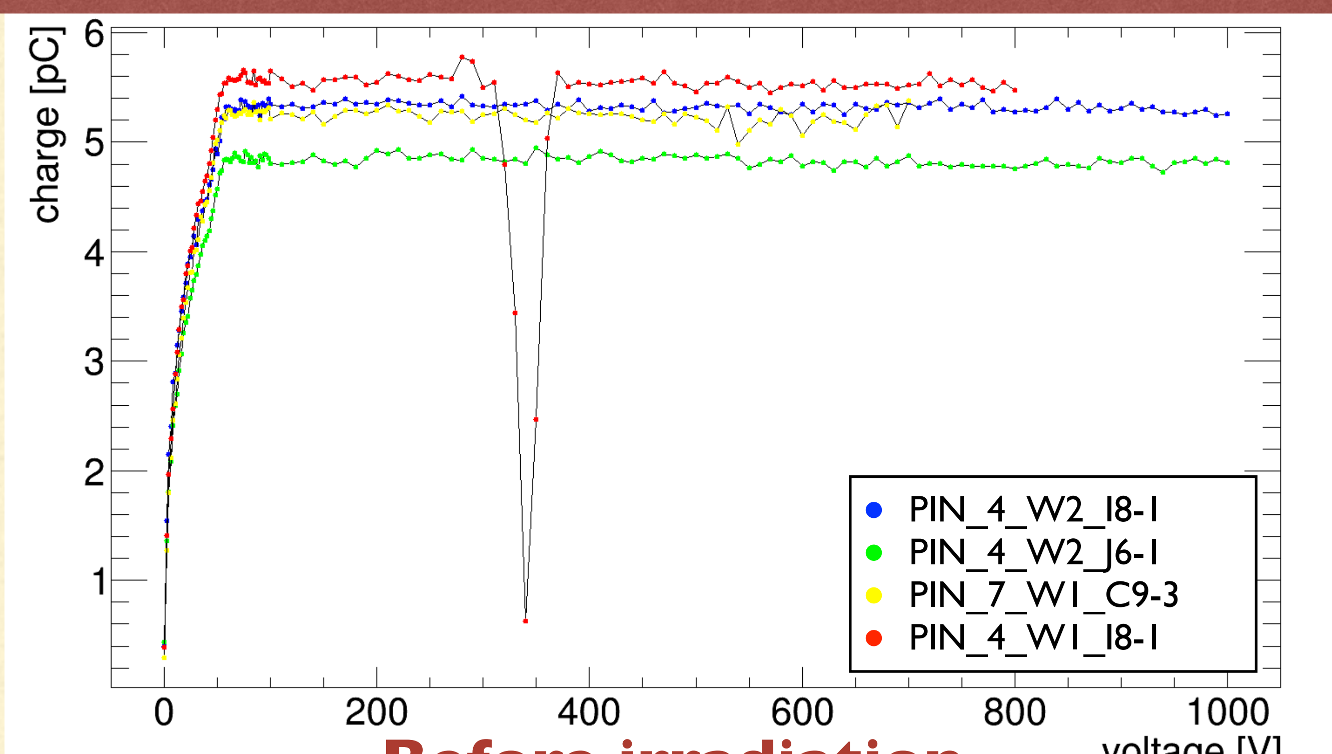


Before irradiation

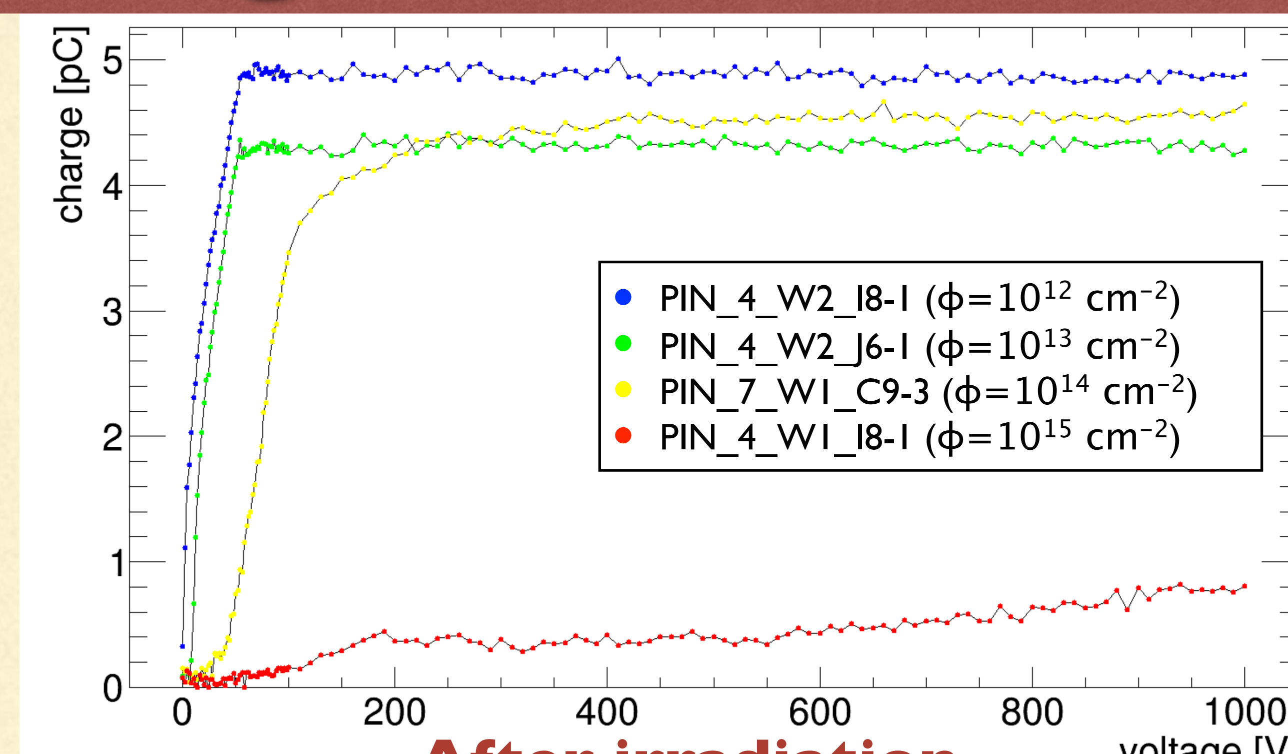


After irradiation

PIN - TCT - Red front @ -20°C



Before irradiation

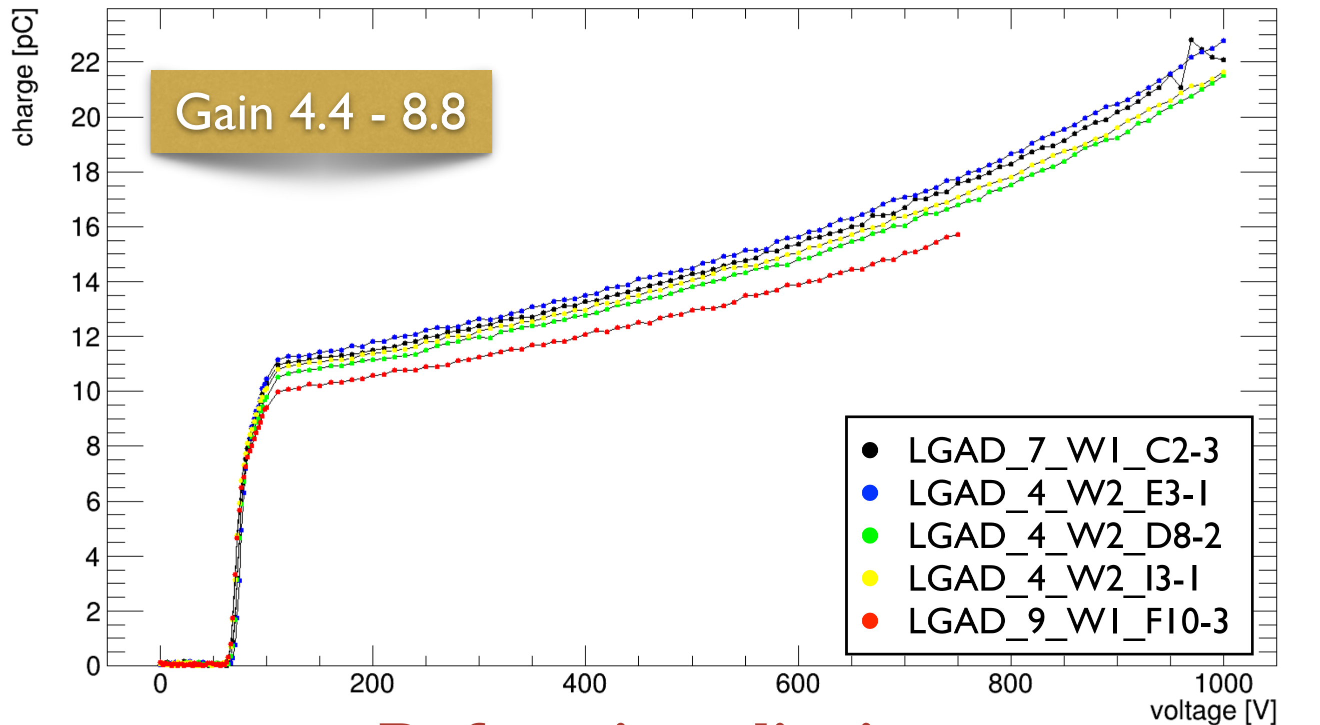


After irradiation

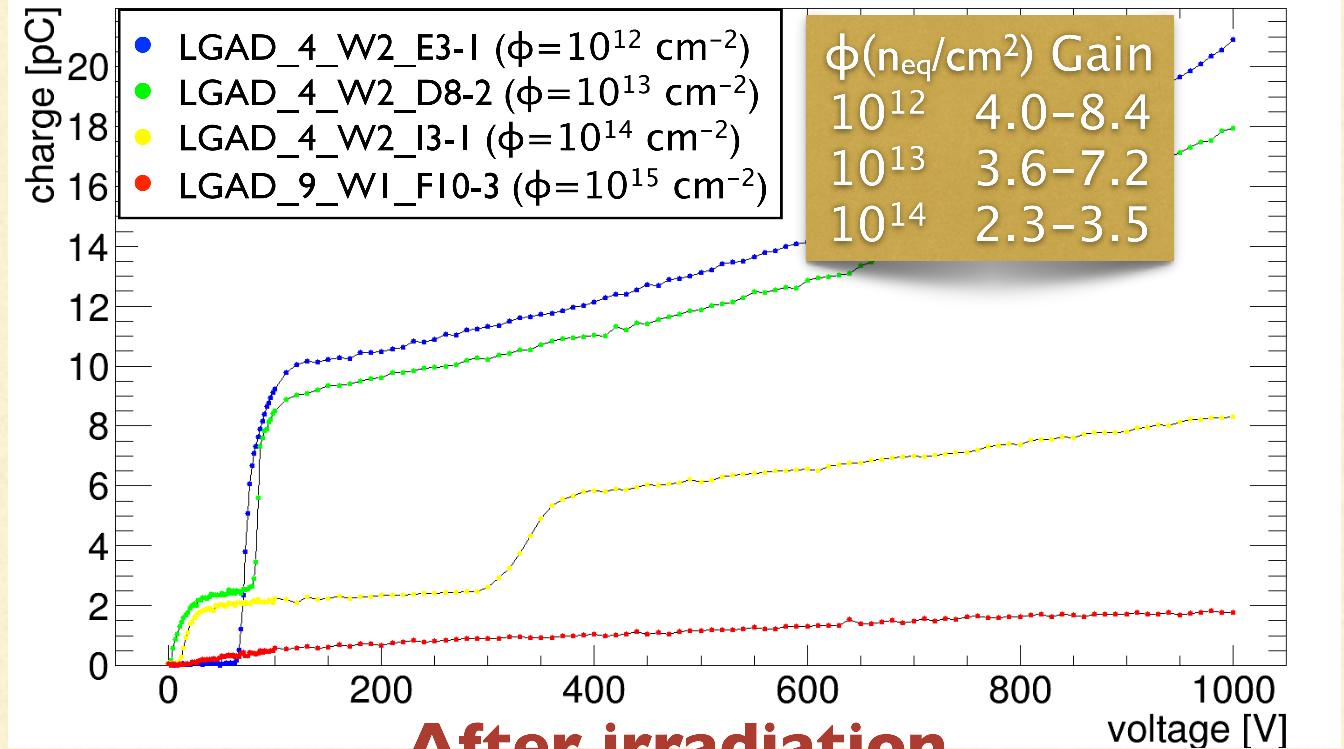
Charge collection with voltage

Mult. layer
$1.8\times10^{13}\,\text{cm}^{-2}$

LGAD - TCT - Red back @ -20°C

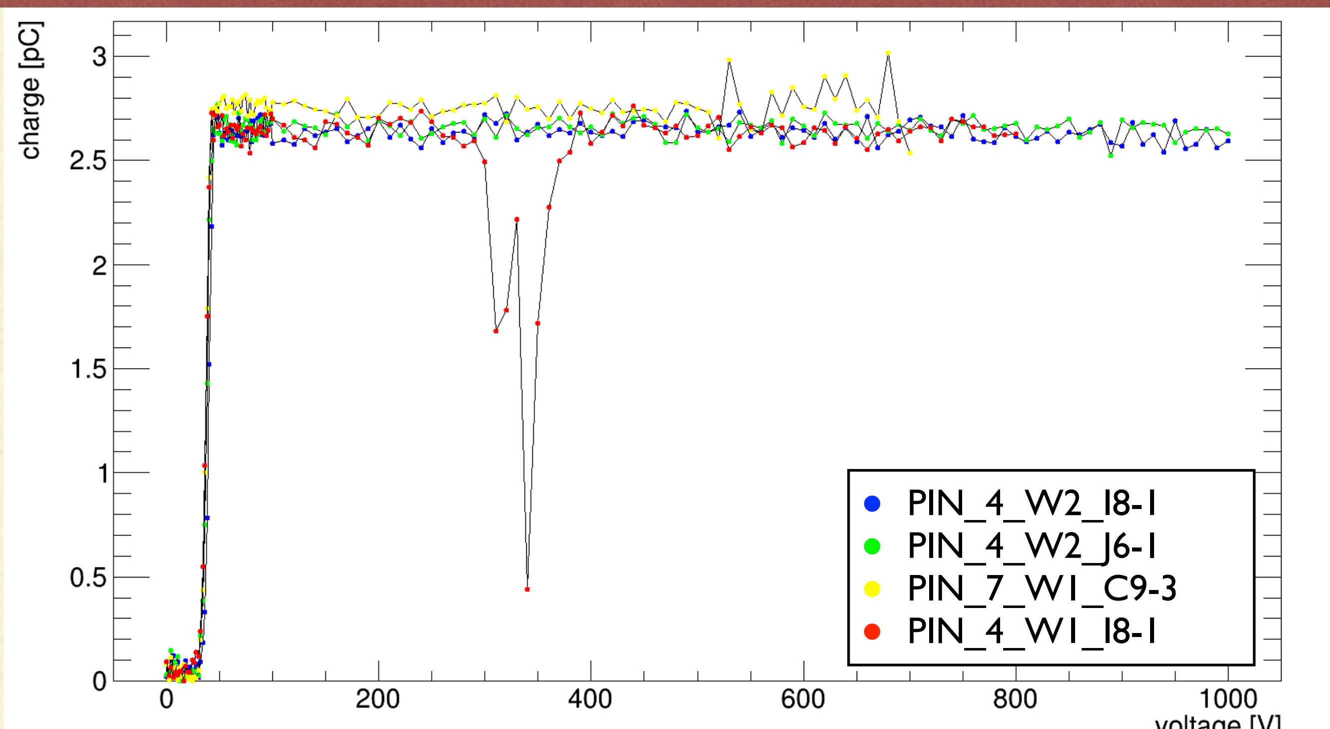


Before irradiation

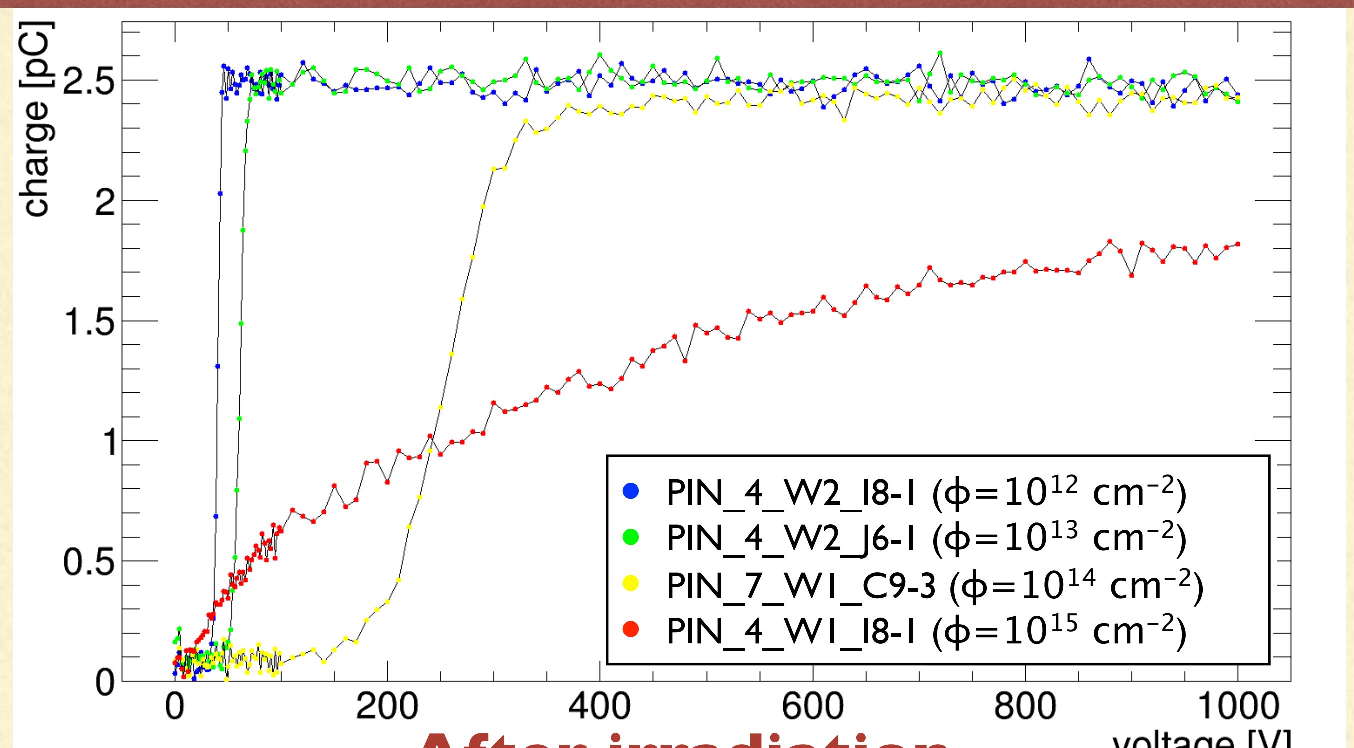


After irradiation

PIN - TCT - Red back @ -20°C



Before irradiation

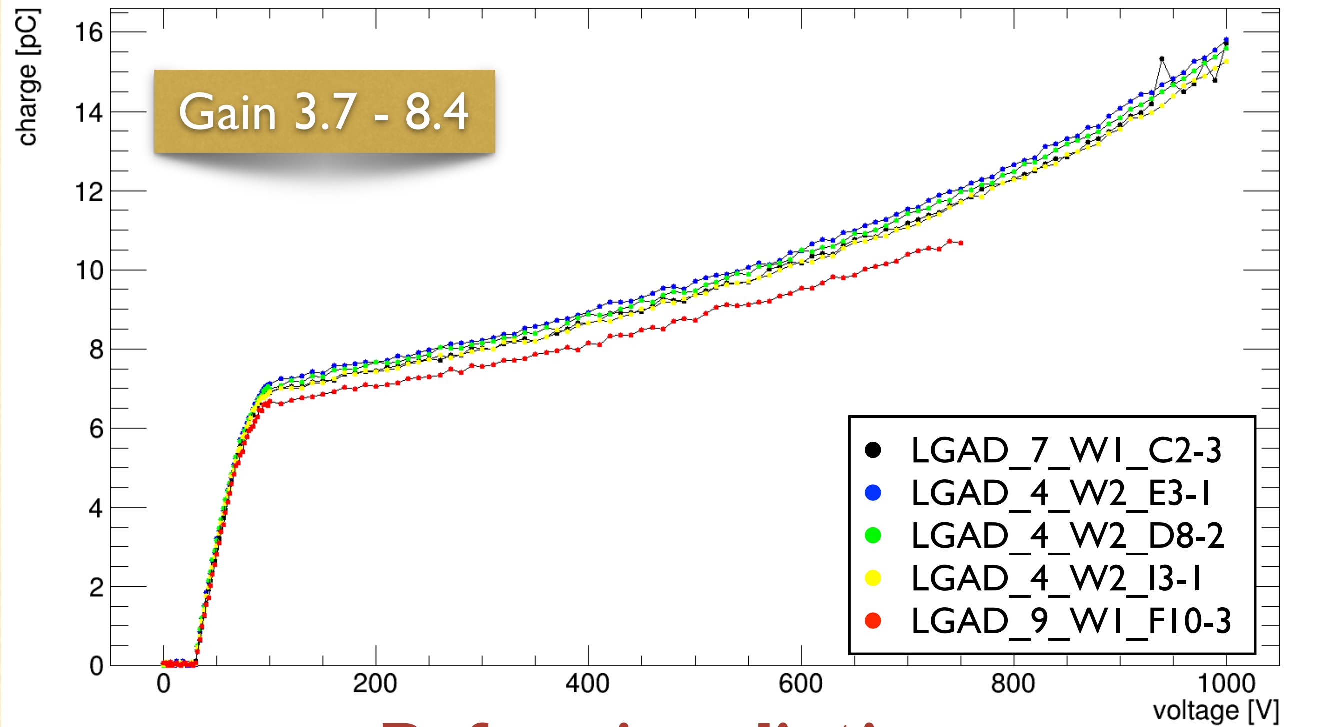


After irradiation

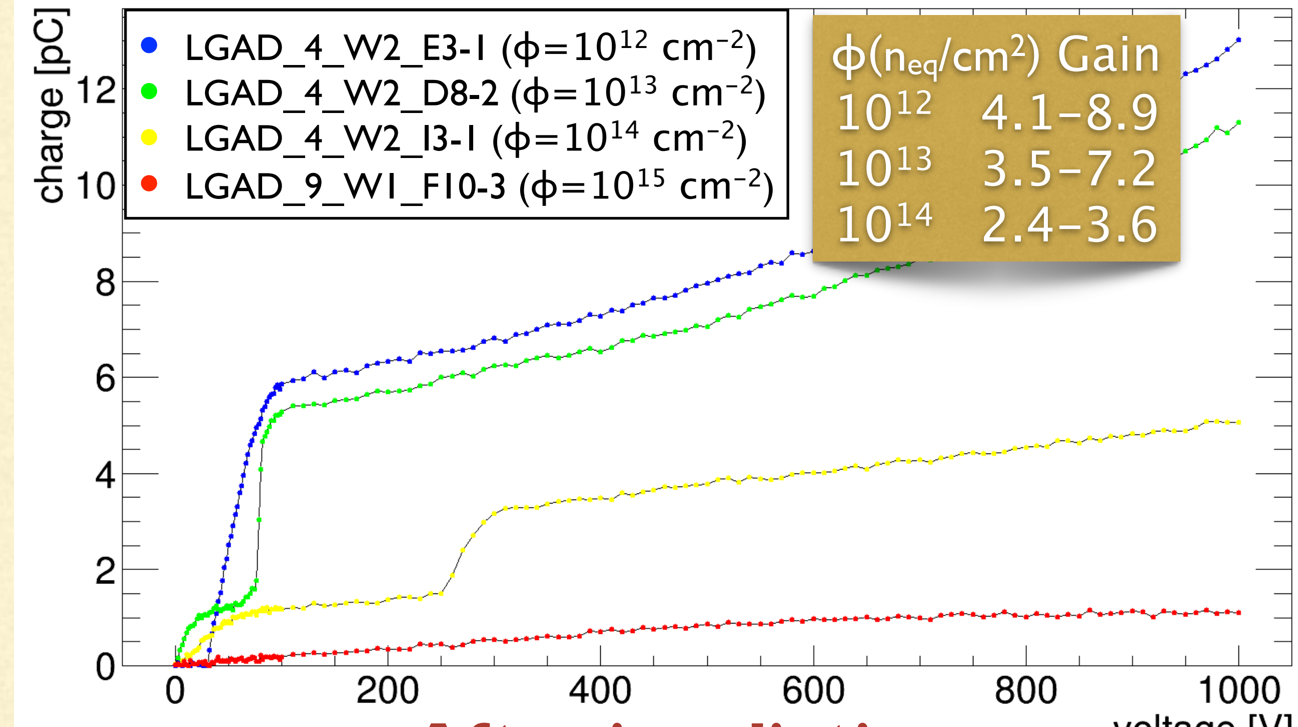
Charge collection with voltage

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

LGAD - TCT - IR back @ -20°C

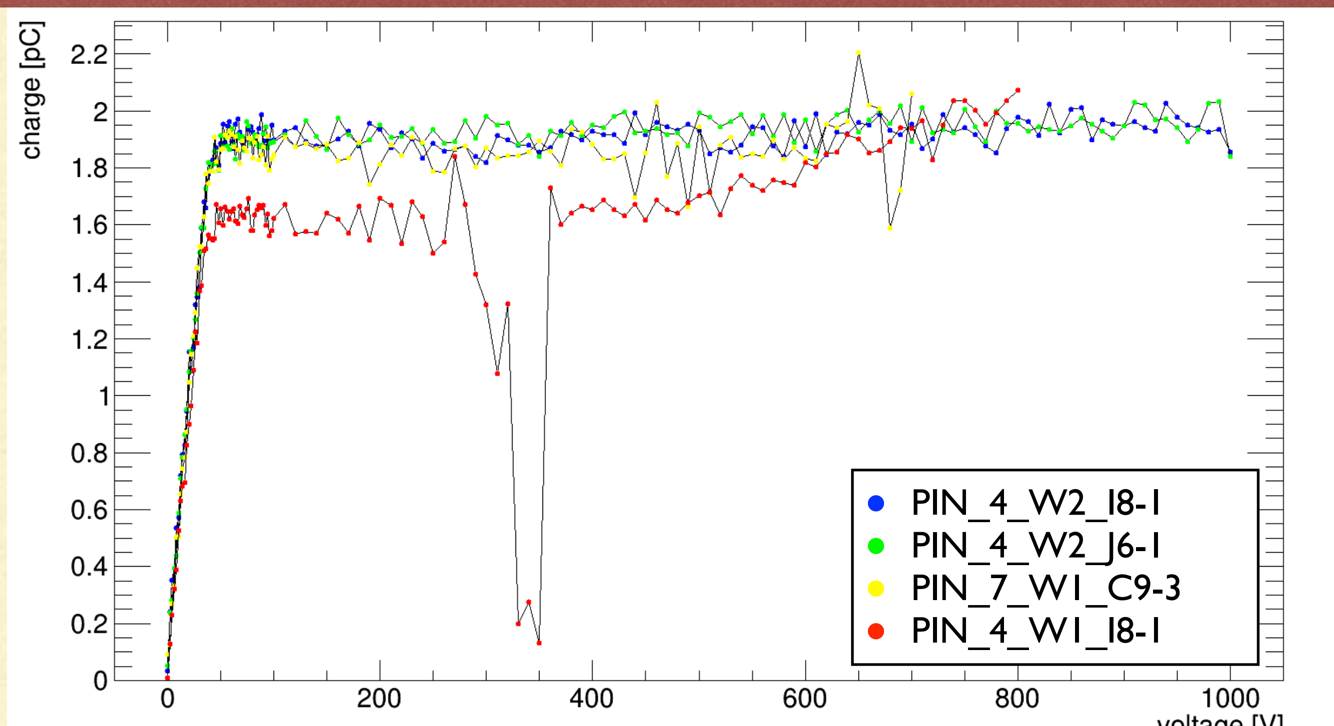


Before irradiation

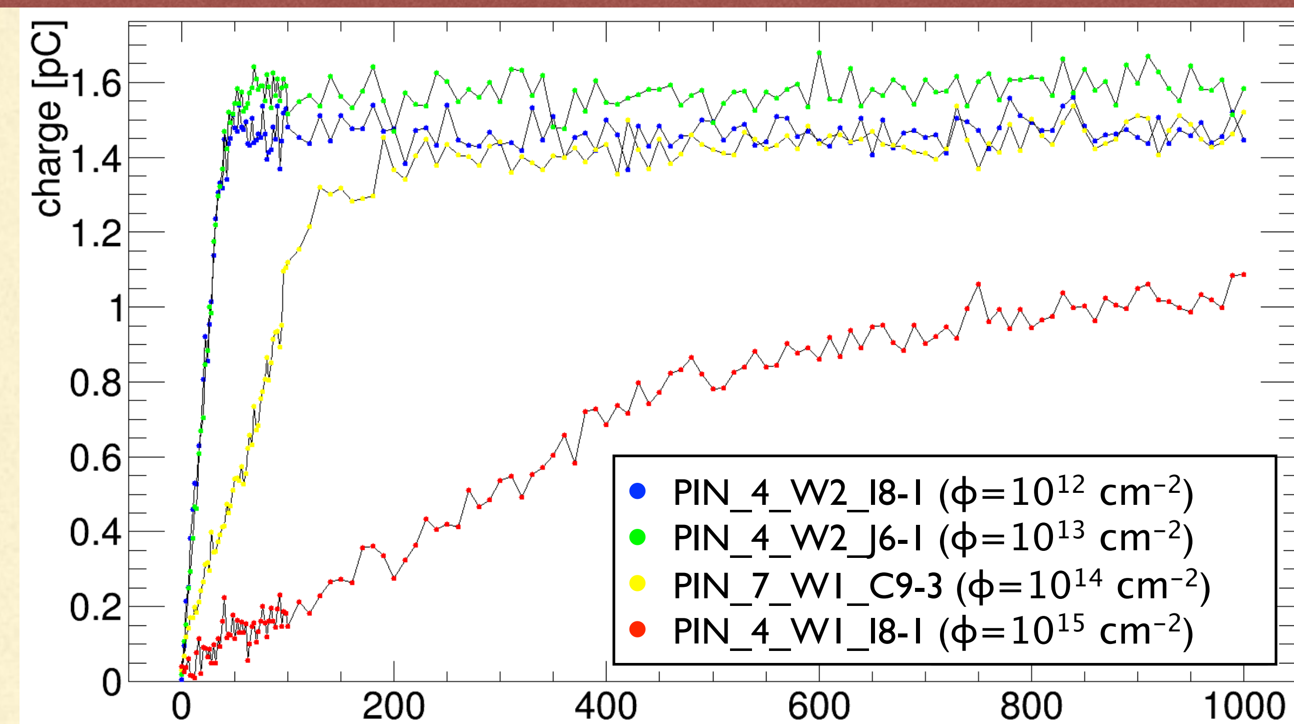


After irradiation

PIN - TCT - IR back @ -20°C



Before irradiation

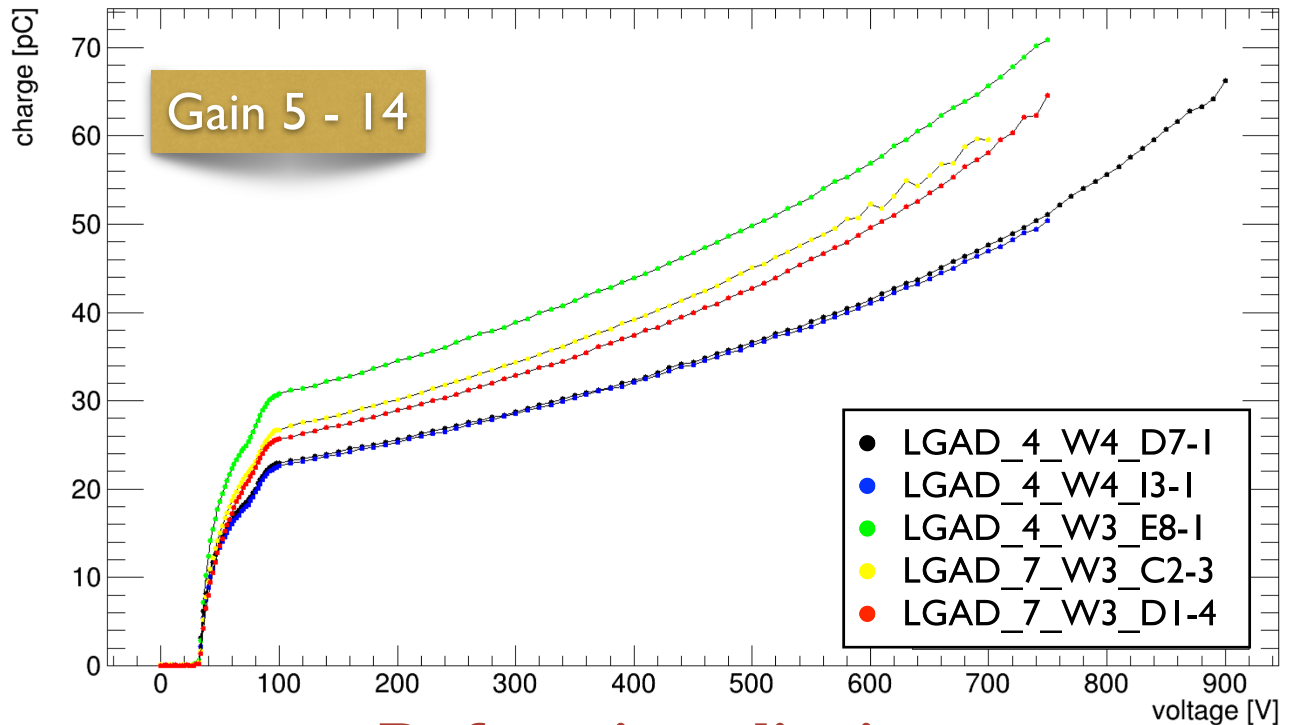


After irradiation

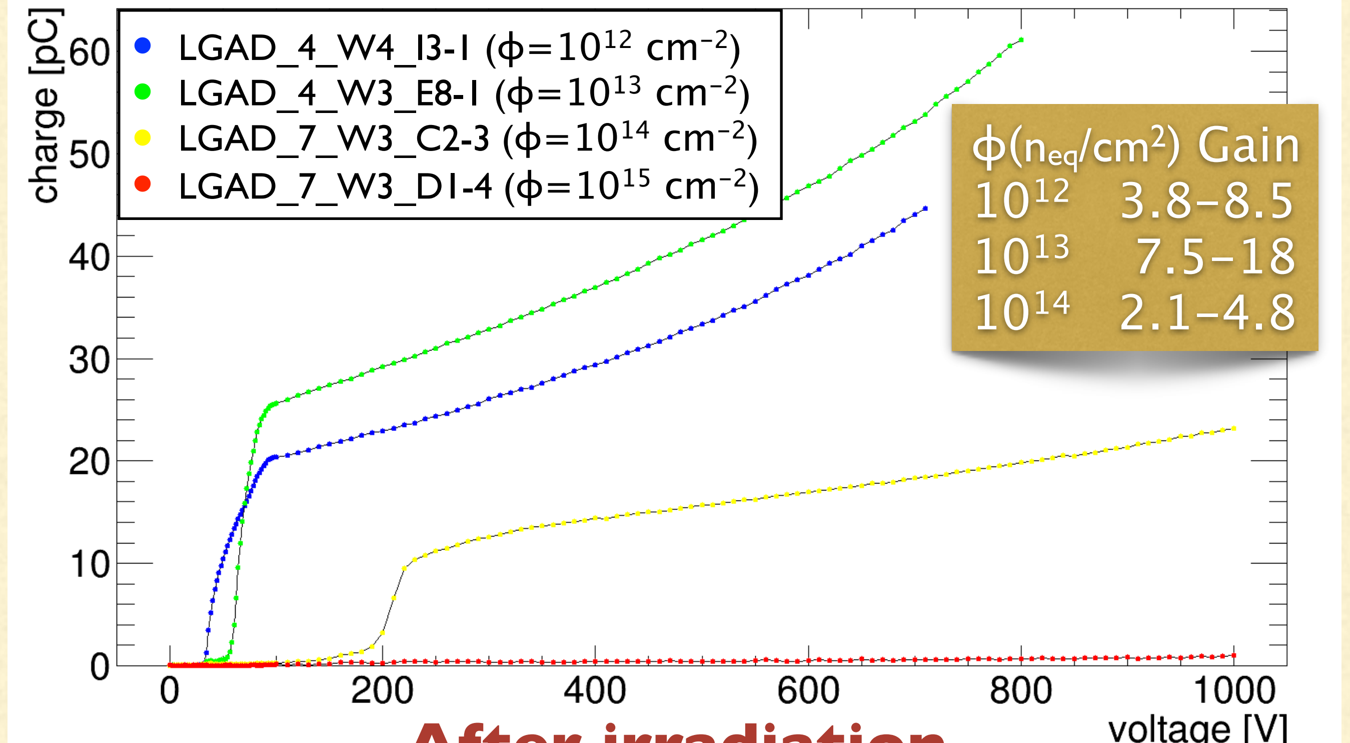
Charge collection with voltage

Mult. layer $2.0\times10^{13}cm^{-2}$

LGAD - TCT - Red front @ -20°C

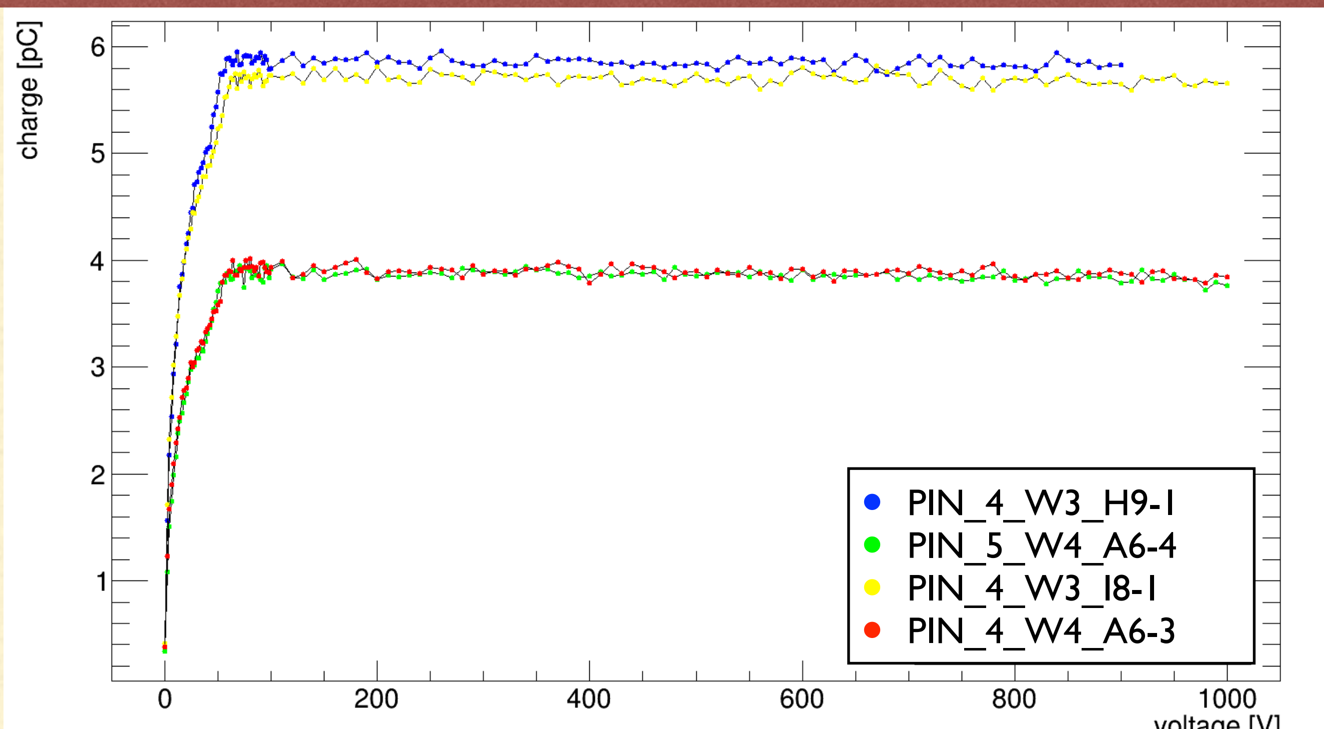


Before irradiation

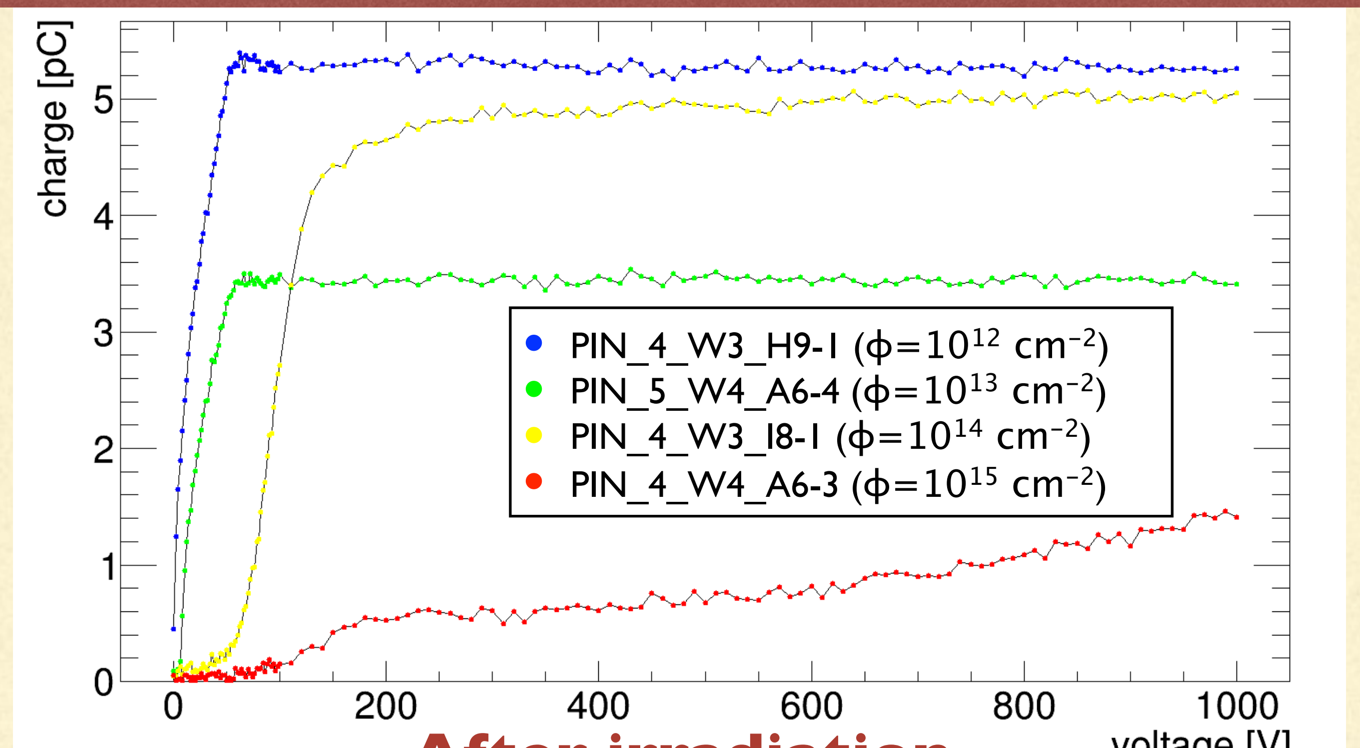


After irradiation

PIN - TCT - Red front @ -20°C



Before irradiation

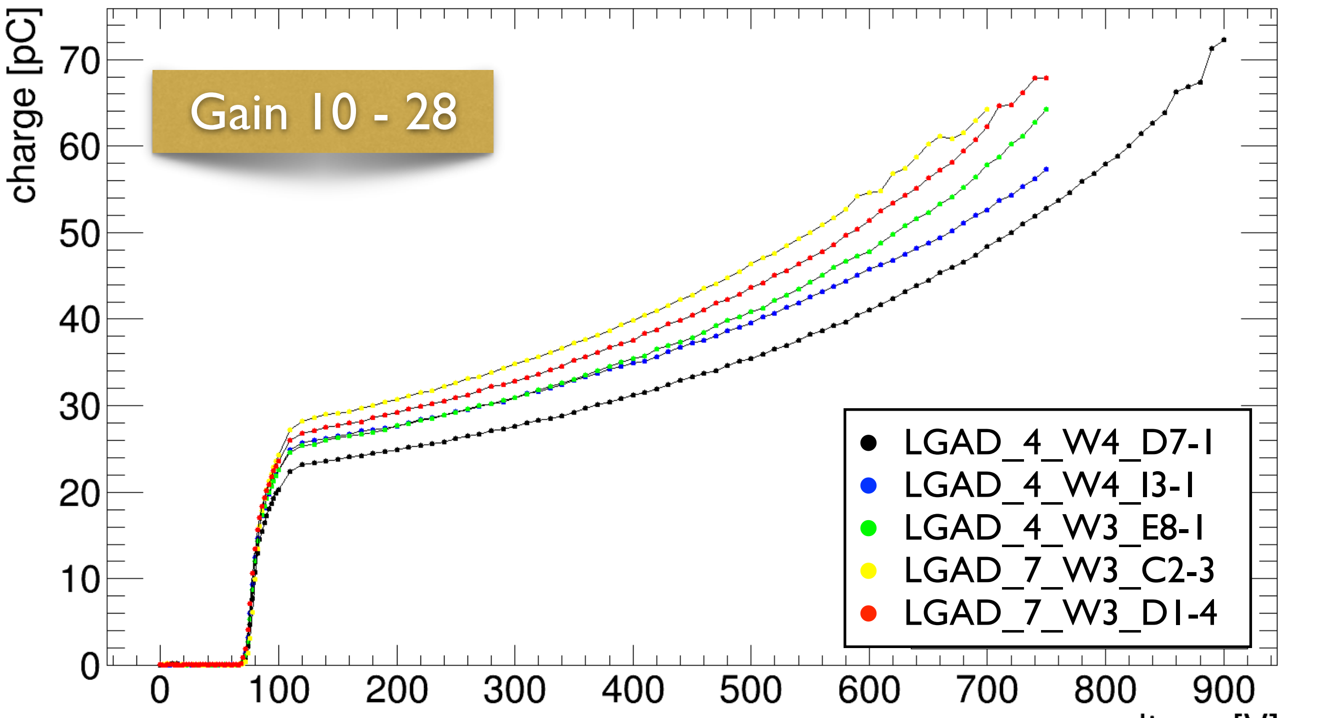


After irradiation

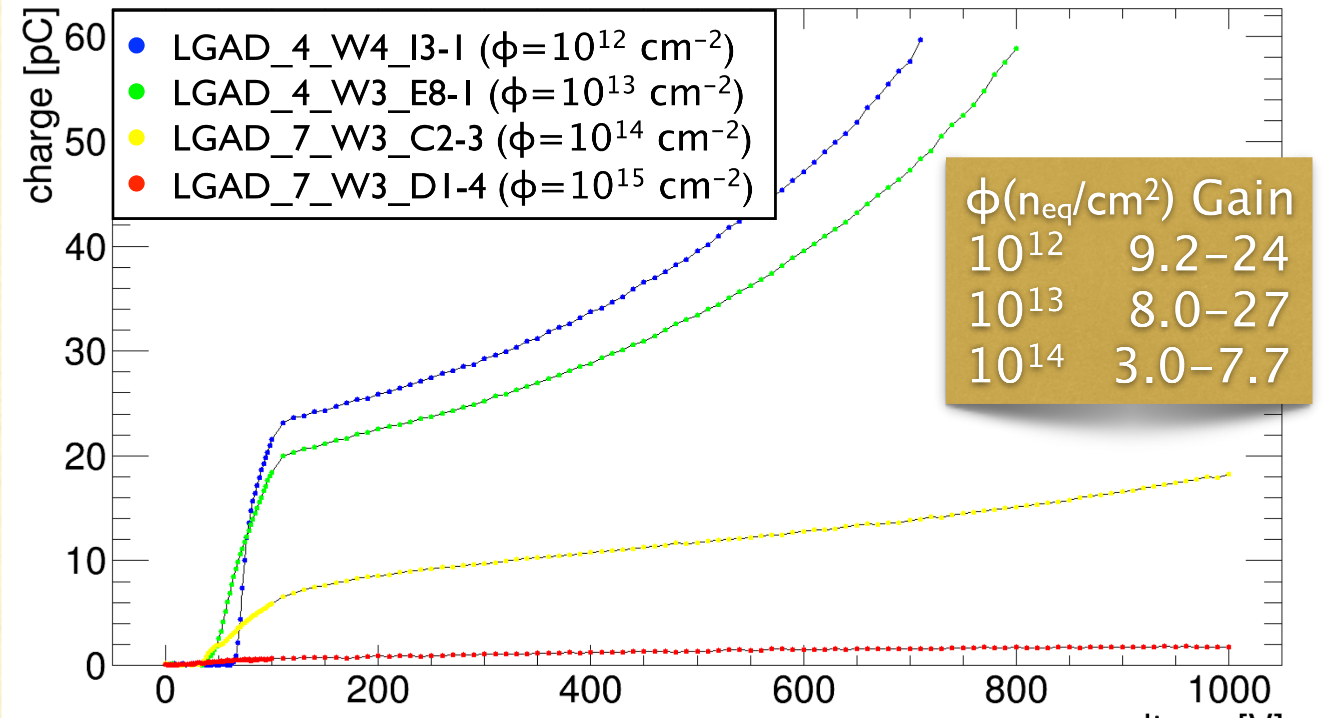
Charge collection with voltage

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

LGAD - TCT - Red back @ -20°C

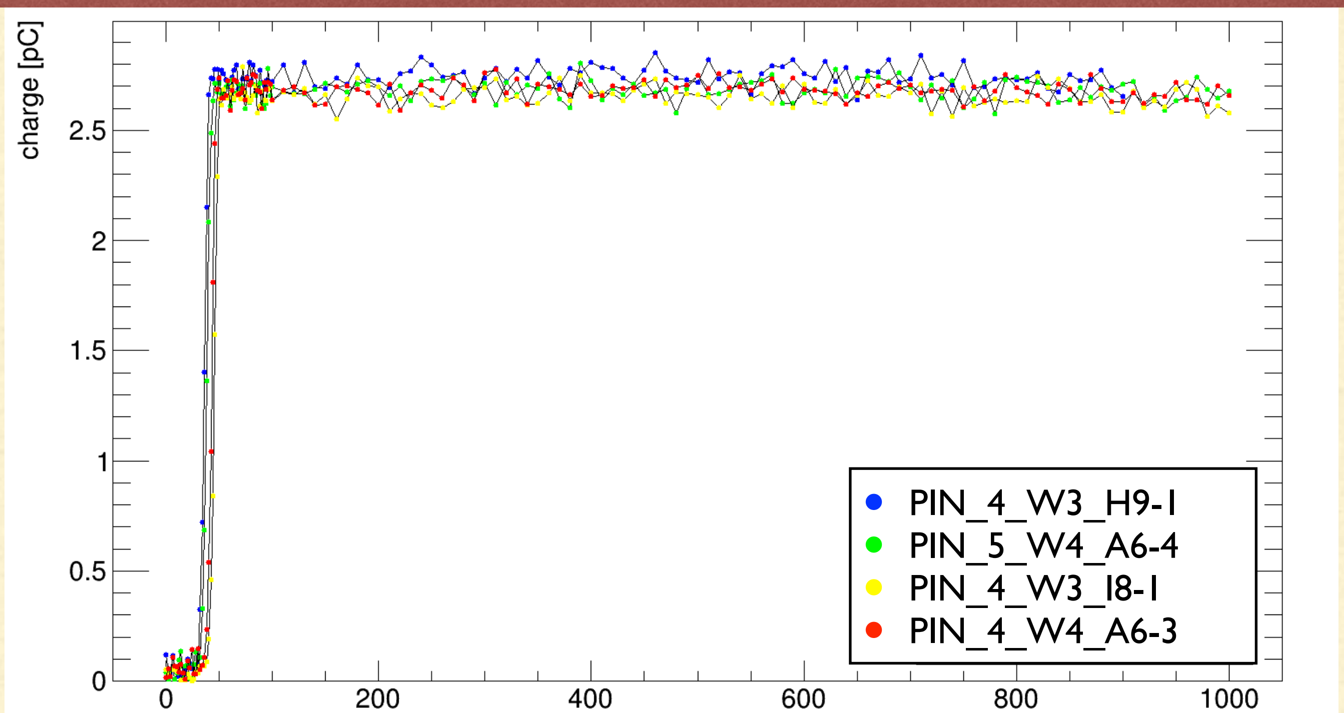


Before irradiation

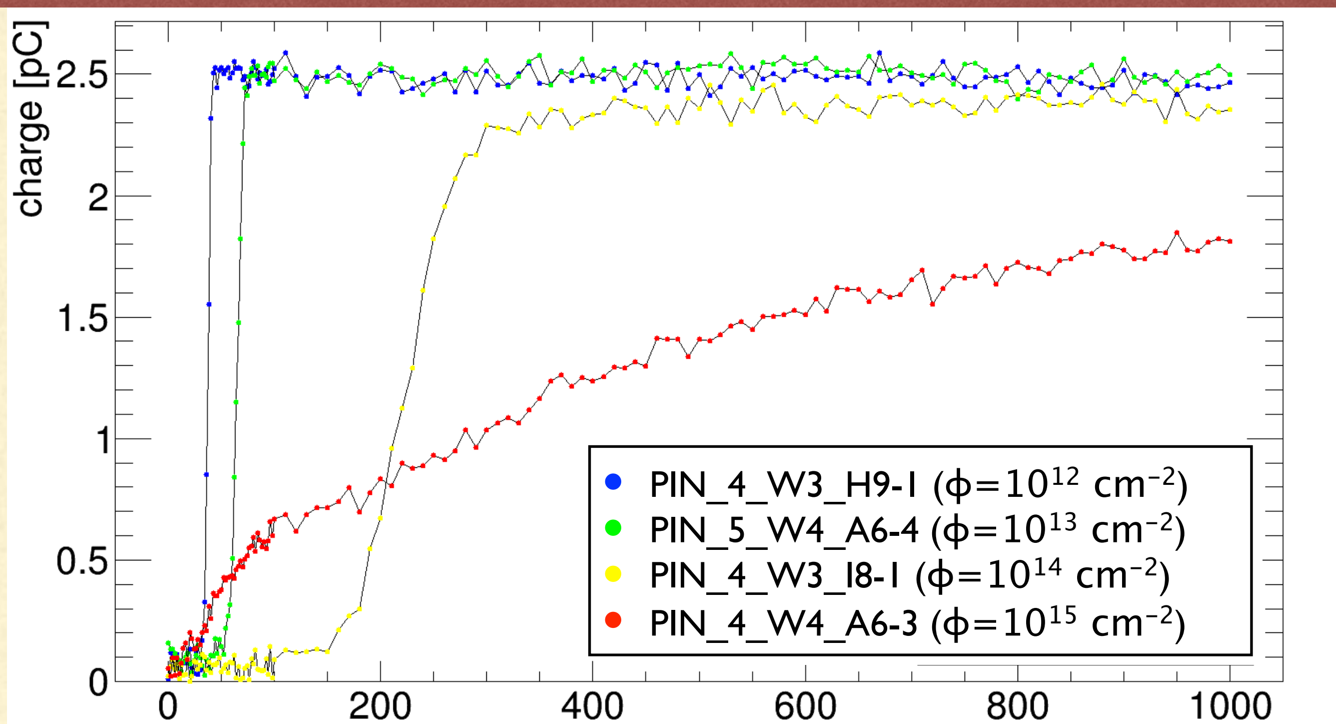


After irradiation

PIN - TCT - Red back @ -20°C



Before irradiation

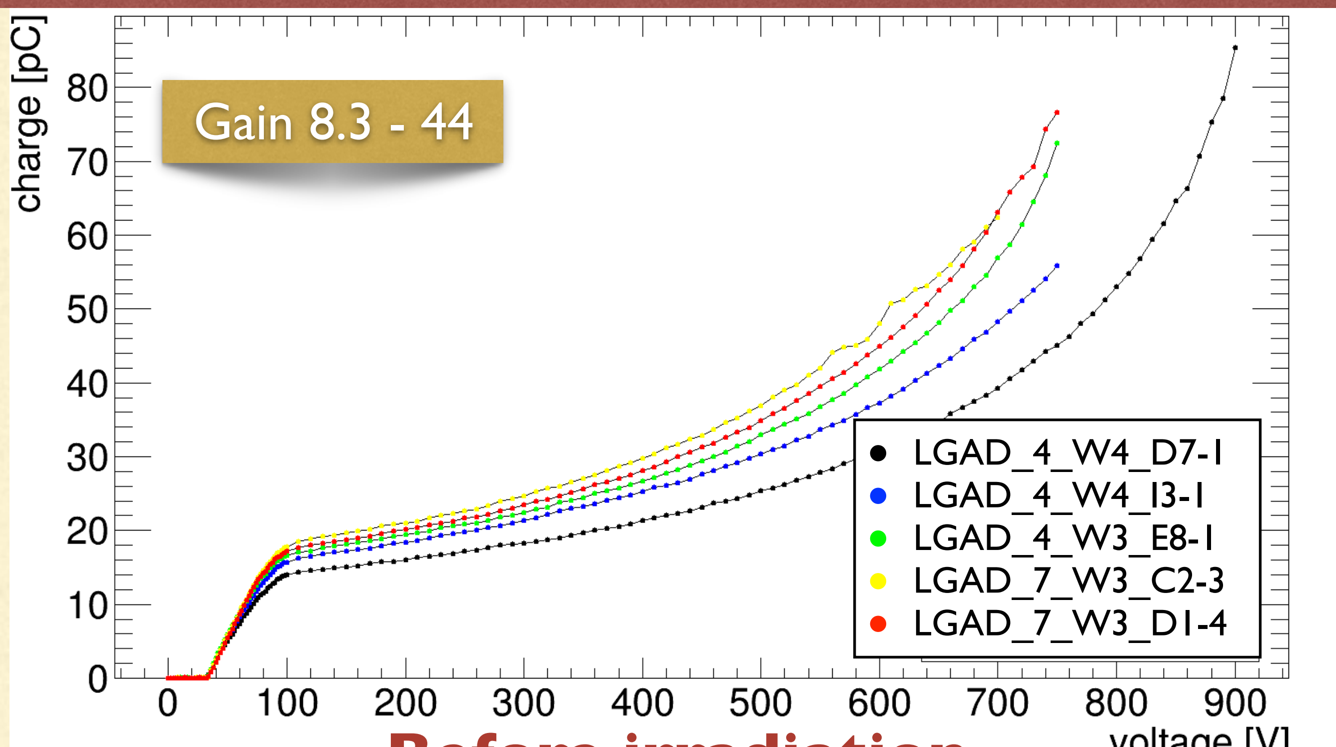


After irradiation

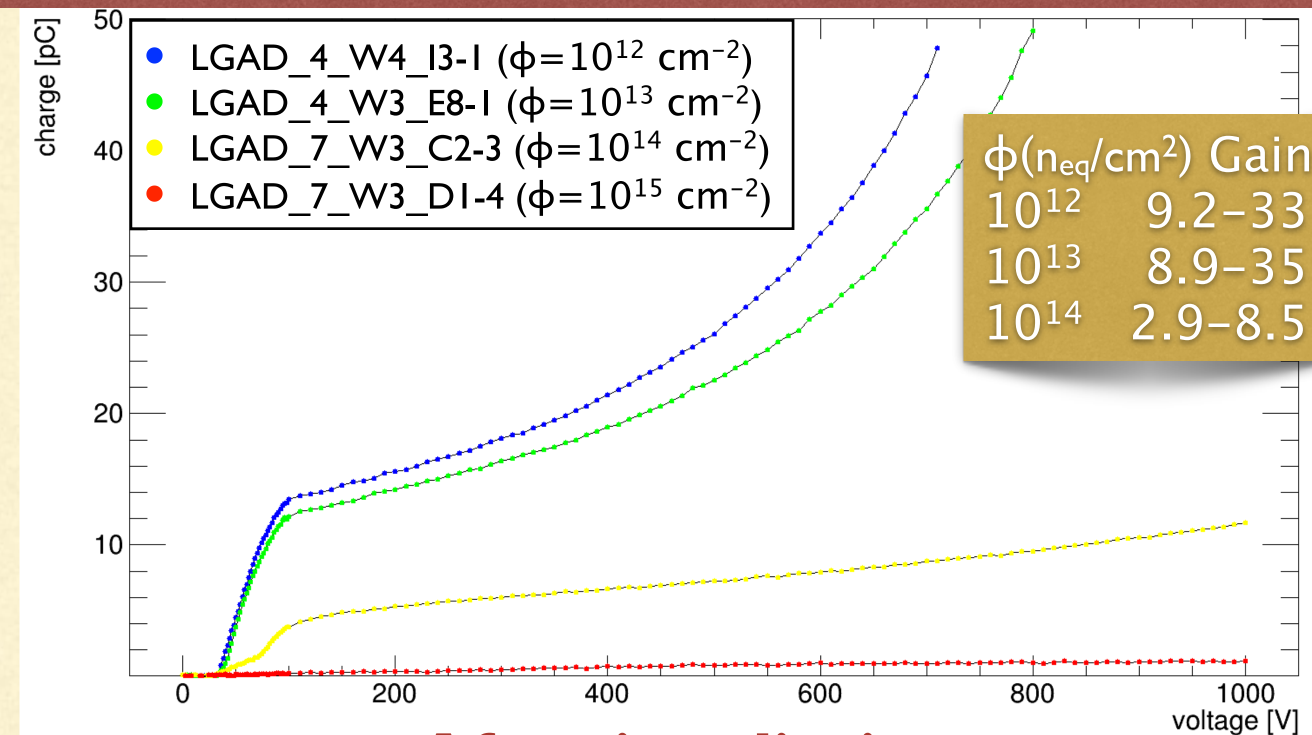
Charge collection with voltage

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

LGAD - TCT - IR back @ -20°C

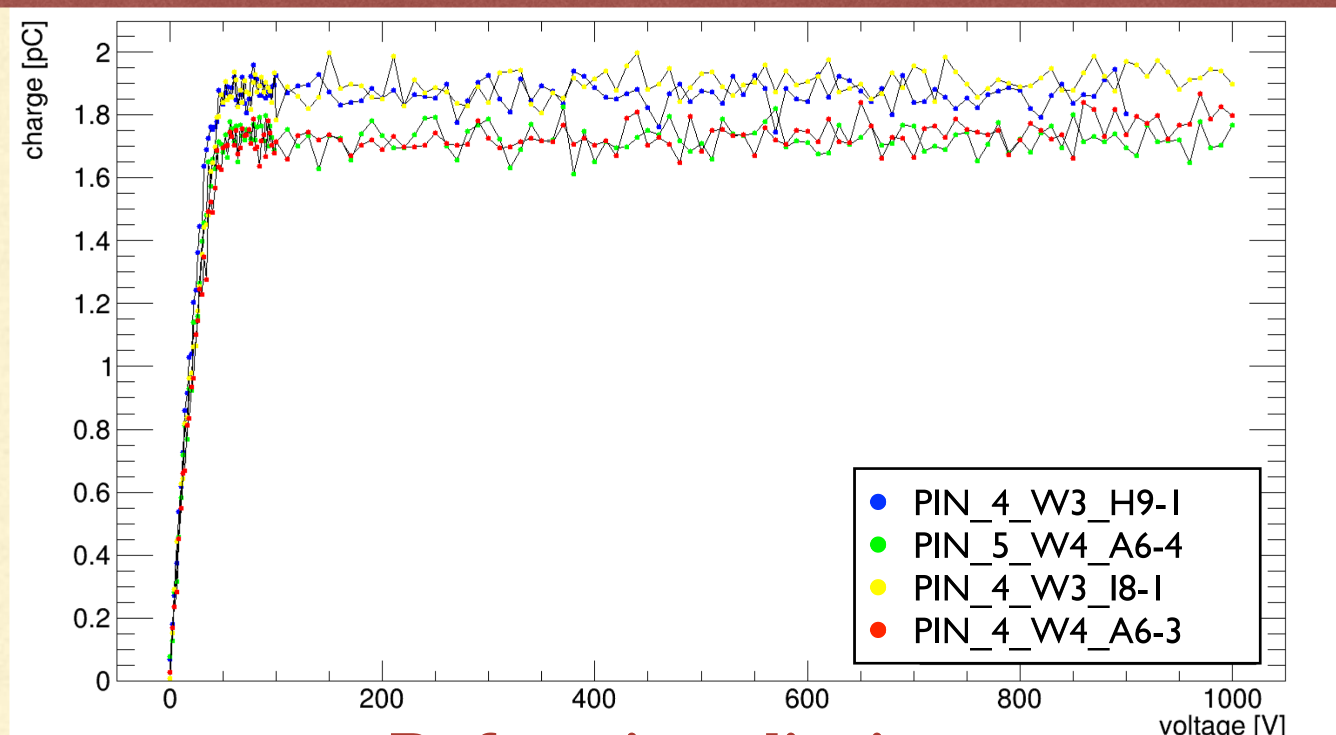


Before irradiation

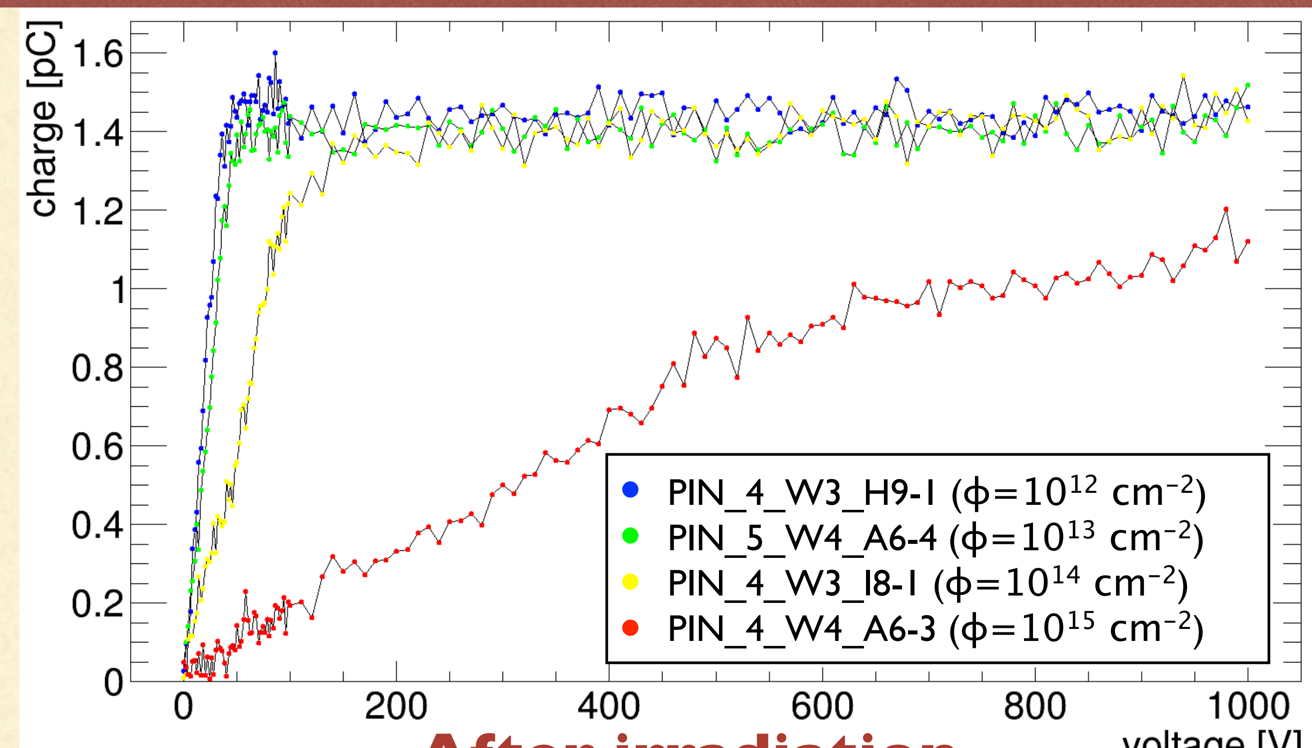


After irradiation

PIN - TCT - IR back @ -20°C



Before irradiation



After irradiation

GAIN VALUES

- "Type-1 Gain":
  - Ratio between the charge collected, after full depletion, in the LGAD and its respective PIN diode.
  - This ratio should be obtained between sensors from identical wafers.
  - If the samples were irradiated, in order to calculate the gain, the LGAD and the PIN must have been exposed to the same fluence.

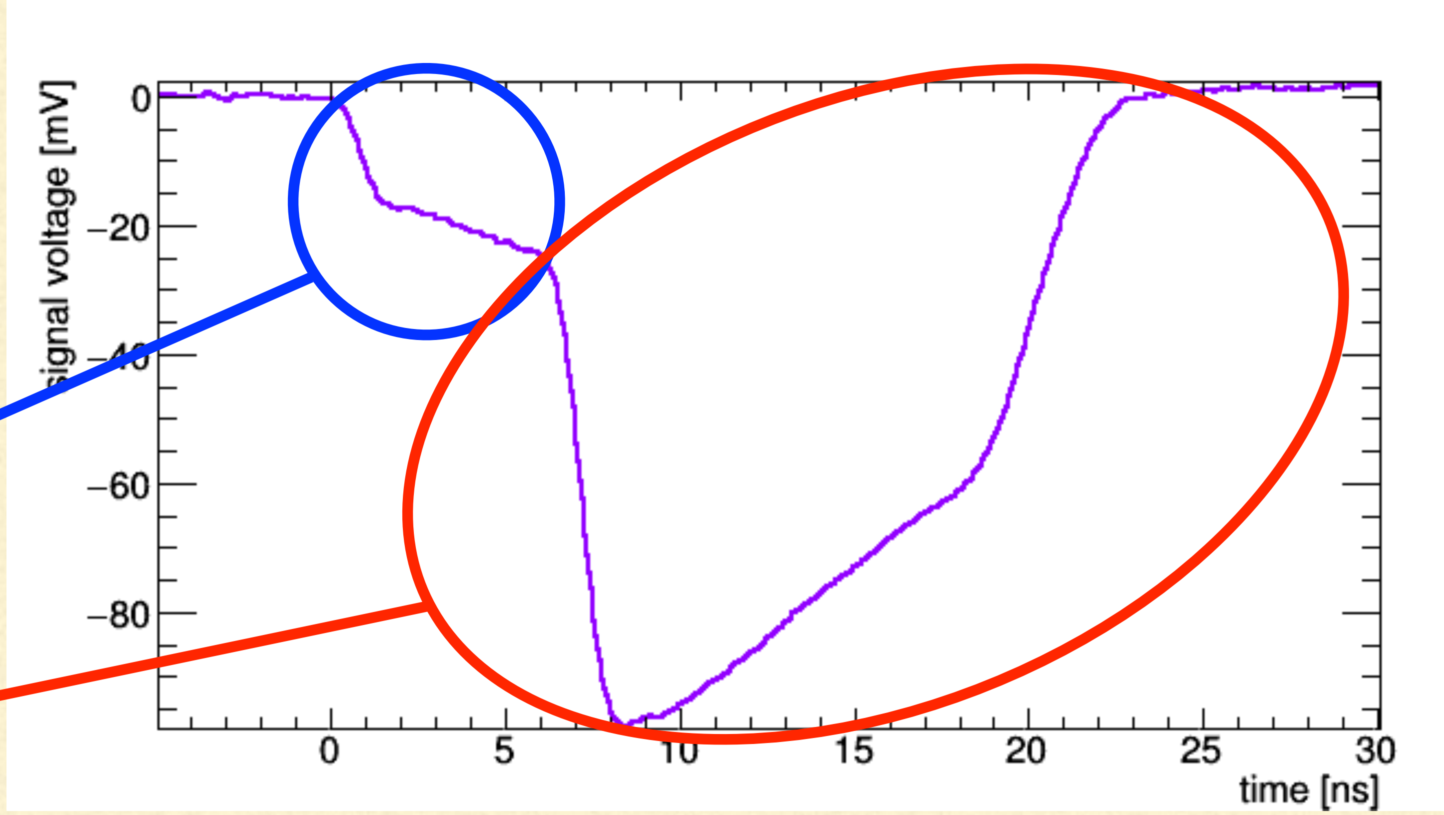
Type-I gain values at 700 V

Multiplication layer doping	IR back			Red back			Red front		
	Before Irrad.*	After Irrad.		Before Irrad.*	After Irrad.		Before Irrad.*	After Irrad.	
		ϕ (n_{eq}/cm^2)			ϕ (n_{eq}/cm^2)			ϕ (n_{eq}/cm^2)	
1.8×10^{13} cm^{-2}	5.7	10^{12}	6.6	6.2	10^{12}	6.0	4.3	10^{12}	4.3
		10^{13}	5.3		10^{13}	5.7		10^{13}	4.7
		10^{14}	3.1		10^{14}	2.8		10^{14}	2.3
		10^{15}	1.1		10^{15}	0.9		10^{15}	1.0
2.0×10^{13} cm^{-2}	W3 = 31.9 W4 = 25.7	10^{12}	31.5	21.4	10^{12}	23.1	W3 = 10.6 W4 = 12.9	10^{12}	8.3
		10^{13}	24.6		10^{13}	18.9		10^{13}	15.3
		10^{14}	6.2		10^{14}	7.7		10^{14}	3.7
		10^{15}	0.97		10^{15}	0.97		10^{15}	0.6

**The gain values before irradiation correspond to the mean between the type-I gain values at 700 V of all the corresponding sensors.*

GAIN VALUES

- "Type-2 Gain":
  - Ratio between the electrons injected and the holes created in the multiplication layer.
  - Obtained by integration of the waveform.



Type-2 gain values at 700 V

Multiplication layer doping	Before Irradiation*	After Irradiation - ϕ (n_{eq}/cm^2)			
		10^{12}	10^{13}	10^{14}	10^{15}
1.8×10^{13} cm^{-2}	7.4	7.7	6.9	3.0	Not possible to calculate
2.0×10^{13} cm^{-2}	29.6	33.2	26.3	7.3	Not possible to calculate

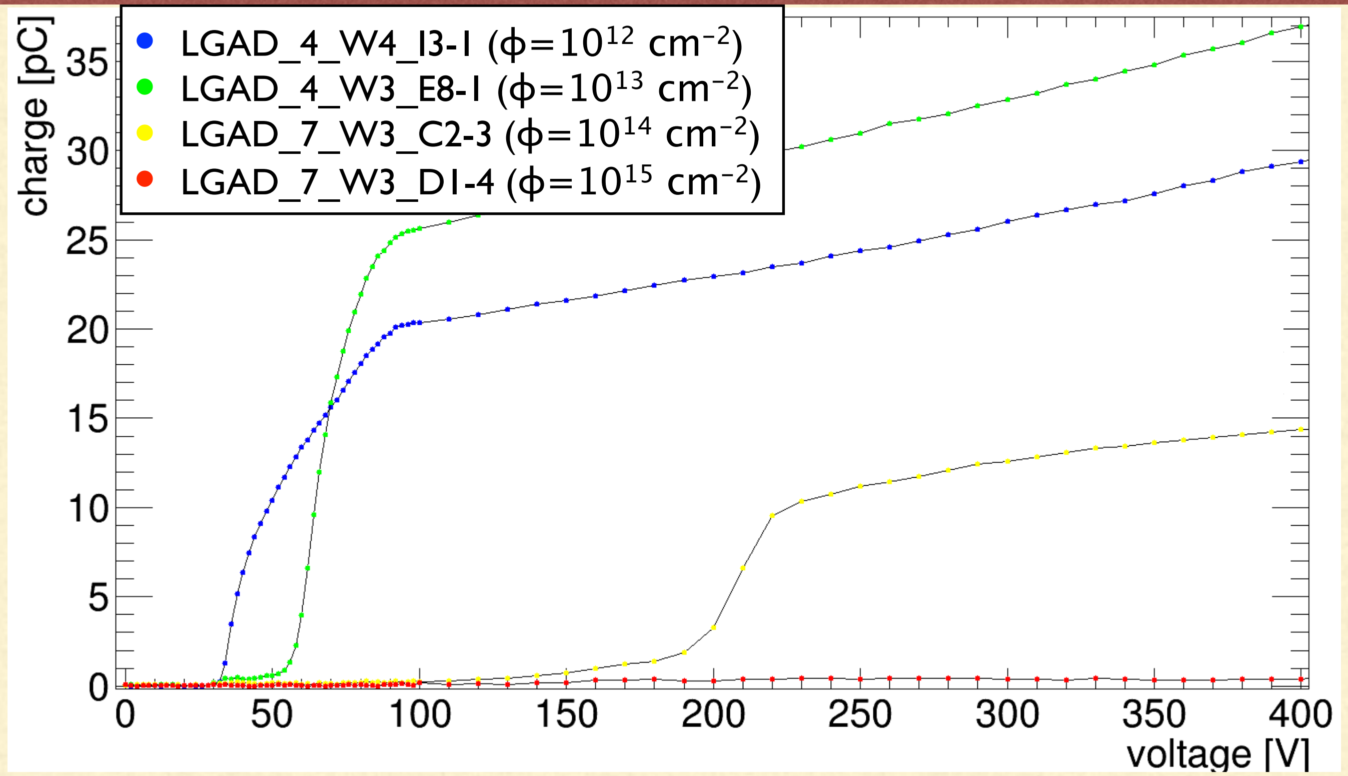
Type-1 gain values with red back TCT at 700 V

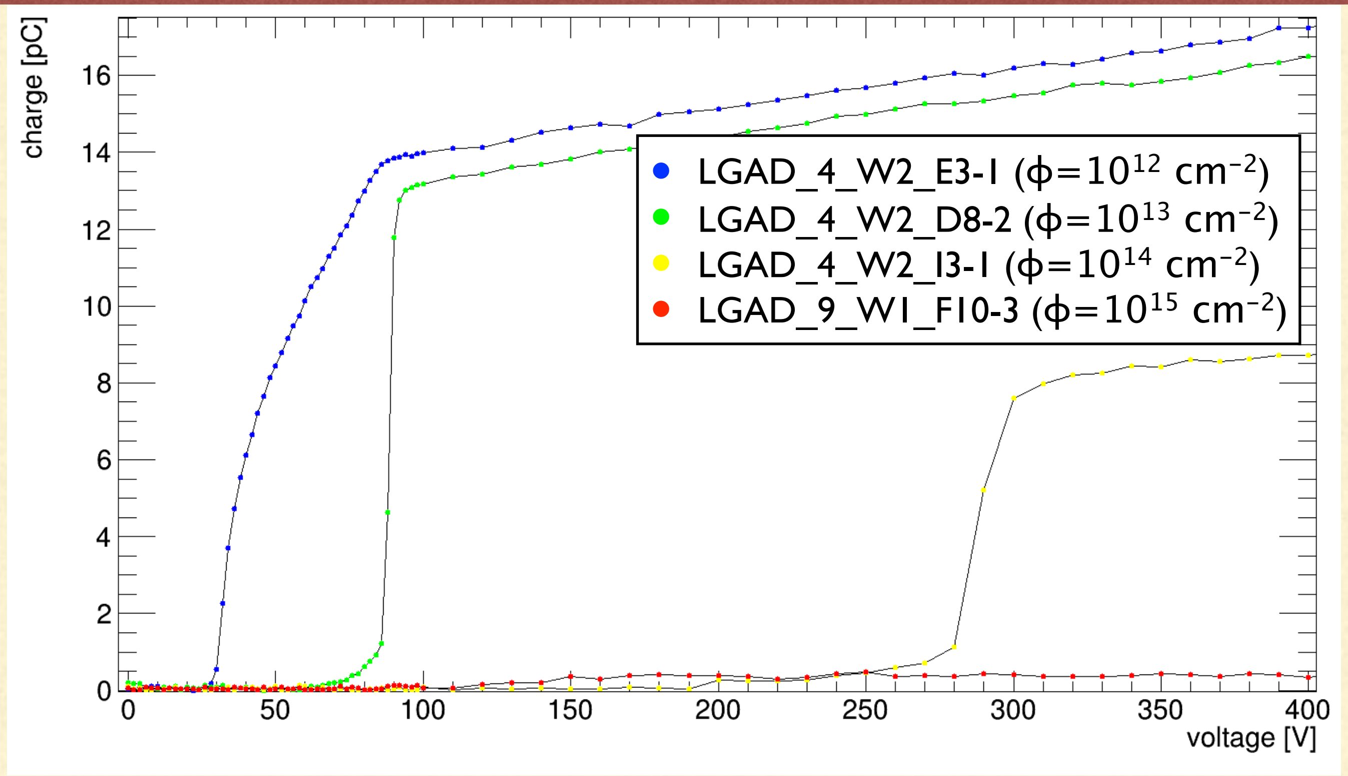
Multiplication layer doping	Before Irradiation*	After Irradiation - ϕ (n_{eq}/cm^2)			
		10^{12}	10^{13}	10^{14}	10^{15}
1.8×10^{13} cm^{-2}	6.2	6.0	5.7	2.8	0.9
2.0×10^{13} cm^{-2}	21.4	23.1	18.9	7.7	0.97

**The gain values before irradiation correspond to the mean between the gain values at 700 V of all the corresponding sensors.*

THRESHOLD VOLTAGE

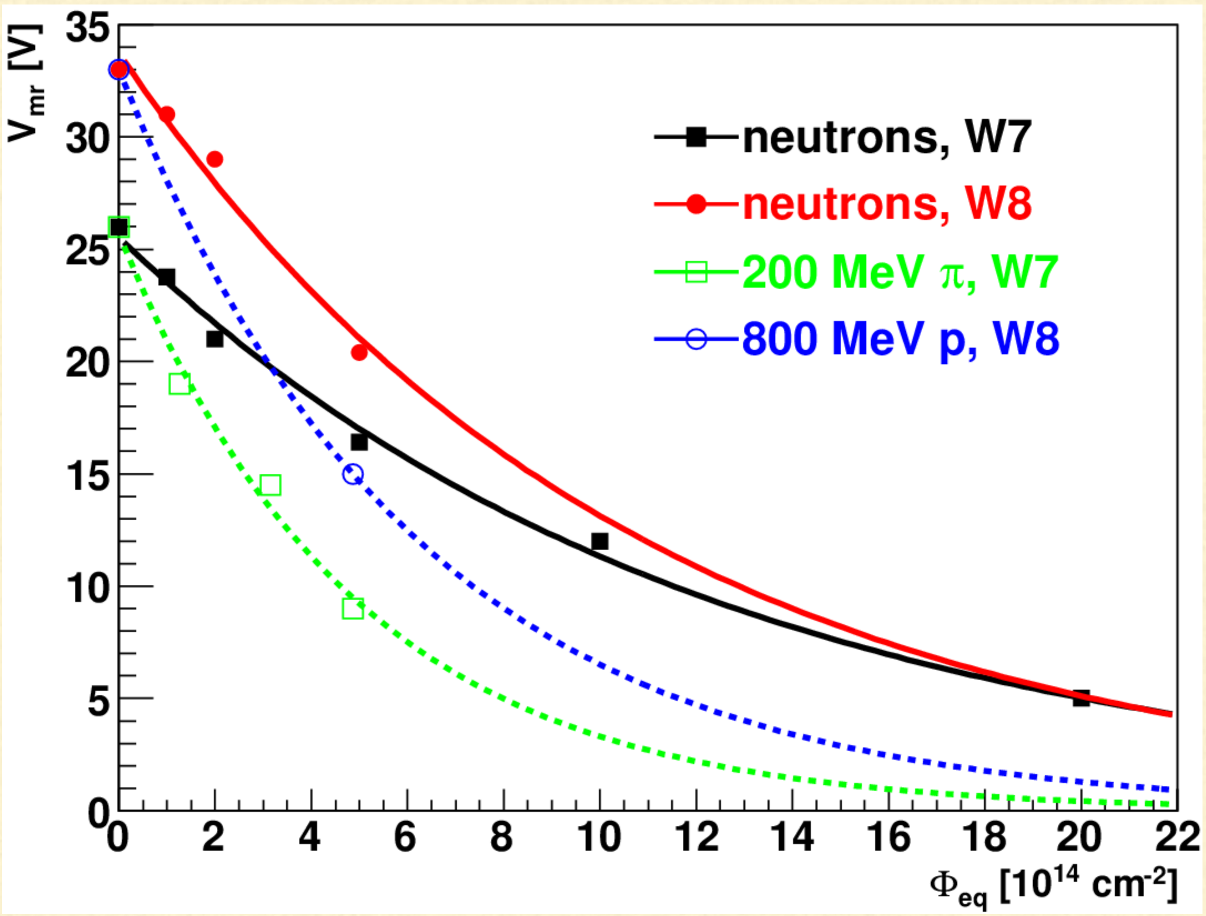
LGAD - TCT - Red front @ -20°C



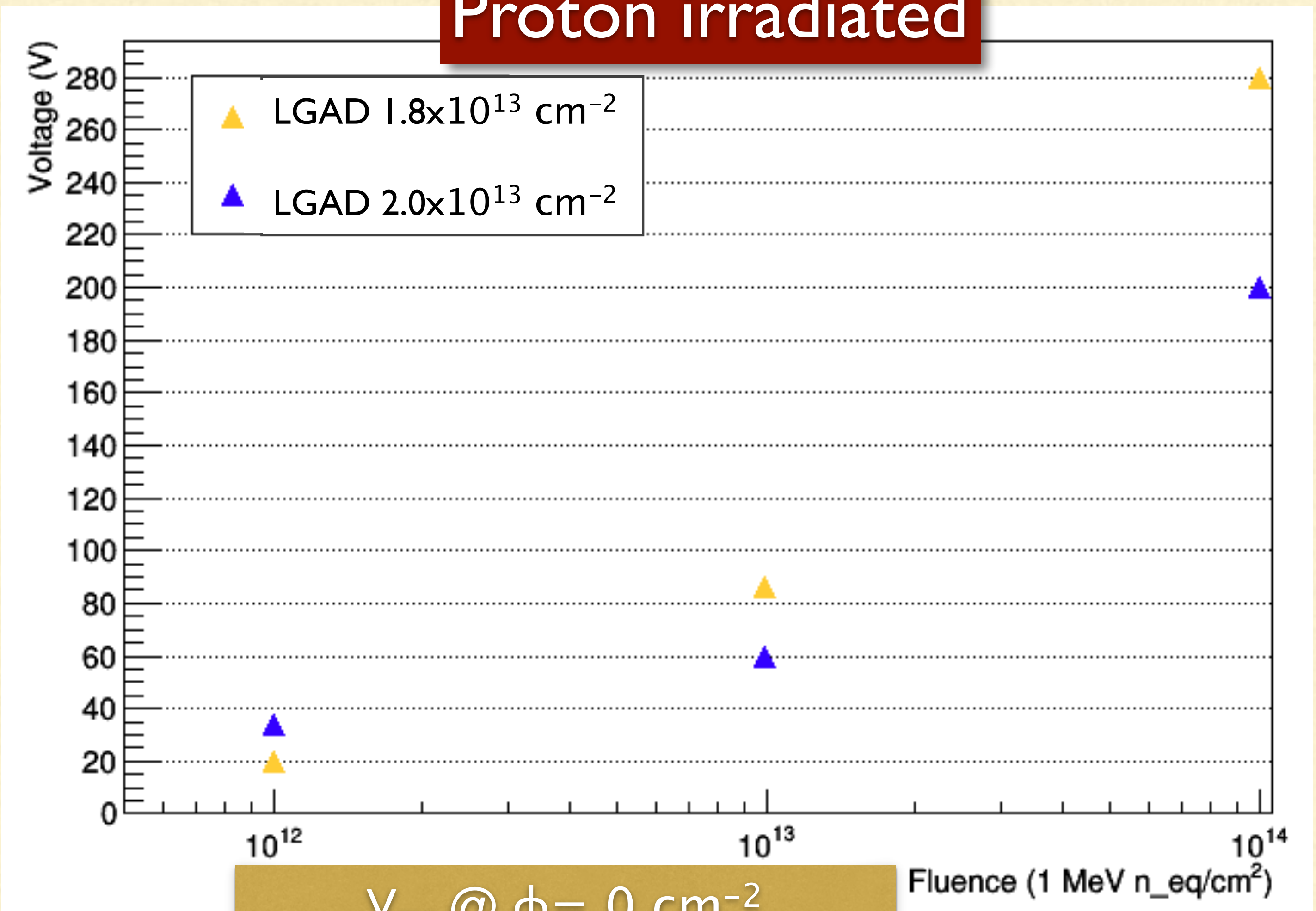


- To actually have gain the multiplication layer must be depleted.
- The threshold voltage indicates as from which voltage the multiplication layer is depleted.
- The threshold voltage can be determined by red front TCT.

- According to Gregor's results* 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.



Proton irradiated



V_{mr} @ ϕ= 0 cm^{-2}
LGAD 1.8x10^{13} cm^{-2}: 30 V
LGAD 2.0x10^{13} cm^{-2}: 74 V

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

DOUBLE JUNCTION EFFECT

HOLE TRAPPING

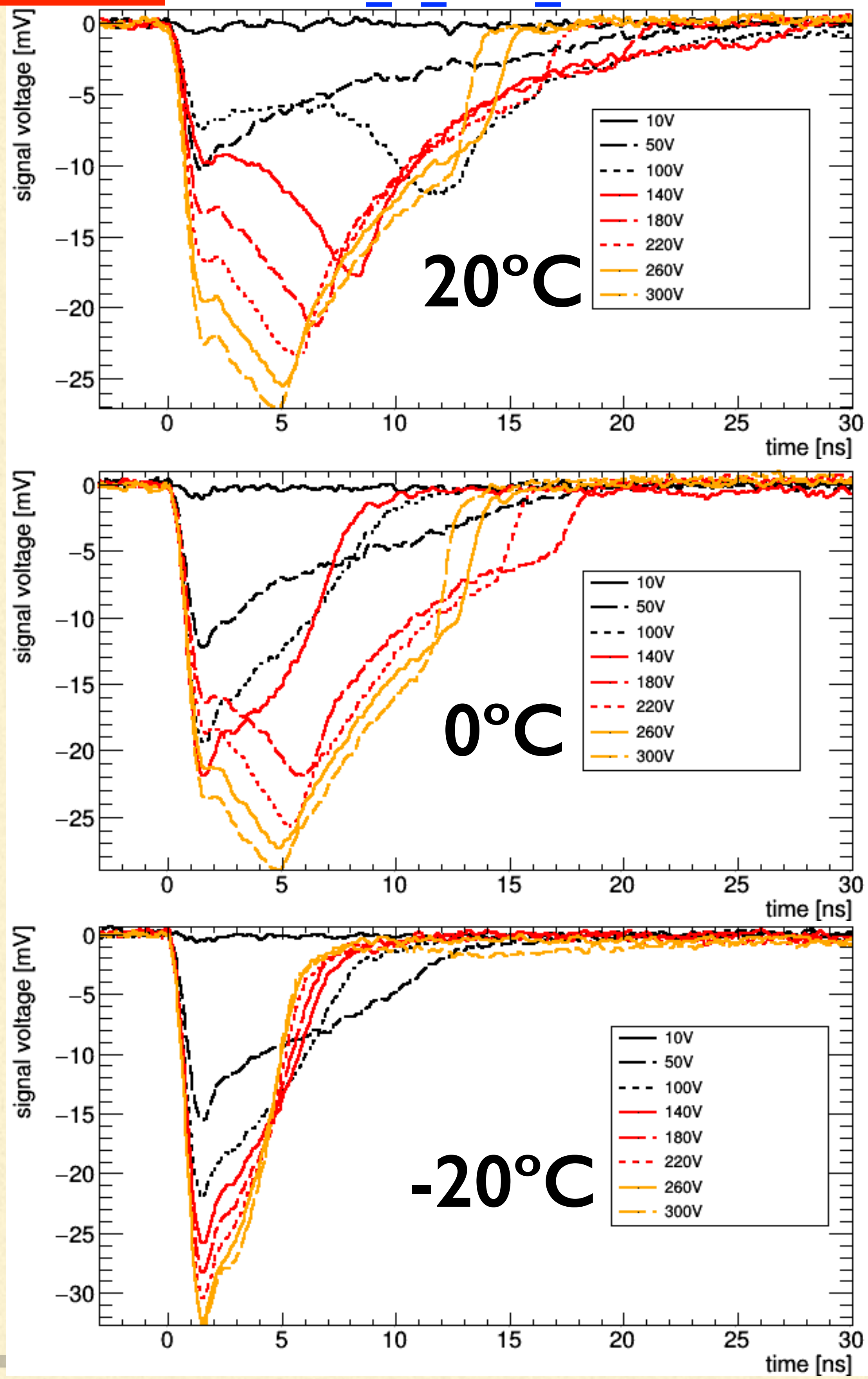
- Before irradiation there are no deep traps => the depletion region grows from the front.
- After irradiation trapping is significant.
- Excess holes + multiplication holes can get trapped and thus change the space charge.
- Because of the occupation probability of traps, the process is highly dependent on temperature
    - The lower the temperature, the longer charges remain trapped.

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

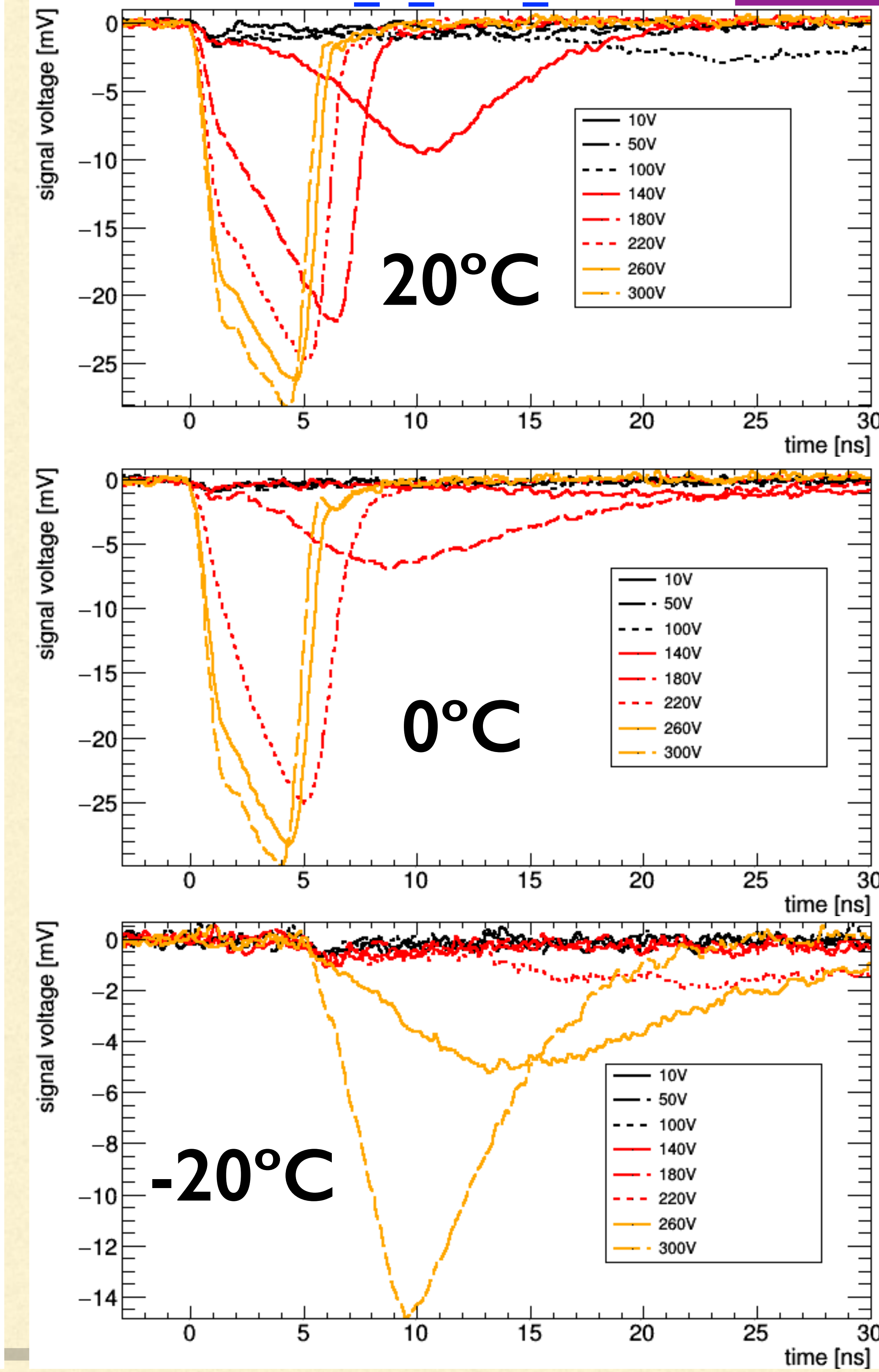
TCT - Red back

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

LGAD_4_W2_I3-1



PIN_7_W1_C9-3

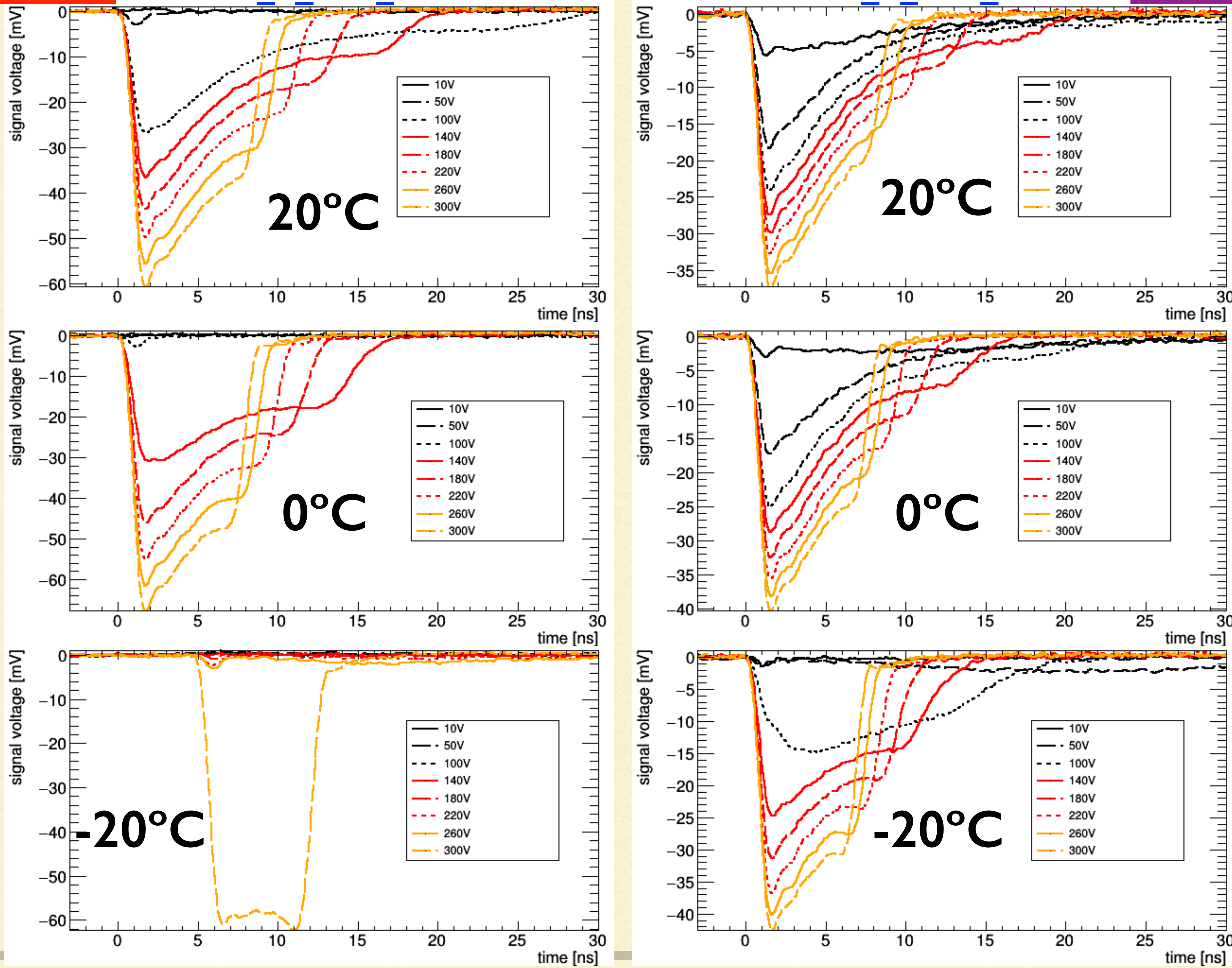


Fluence $10^{14}\ n_{eq}/cm^2$

TCT - Red front

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

LGAD_4_W2_I3-1 **PIN_7_W1_C9-3**

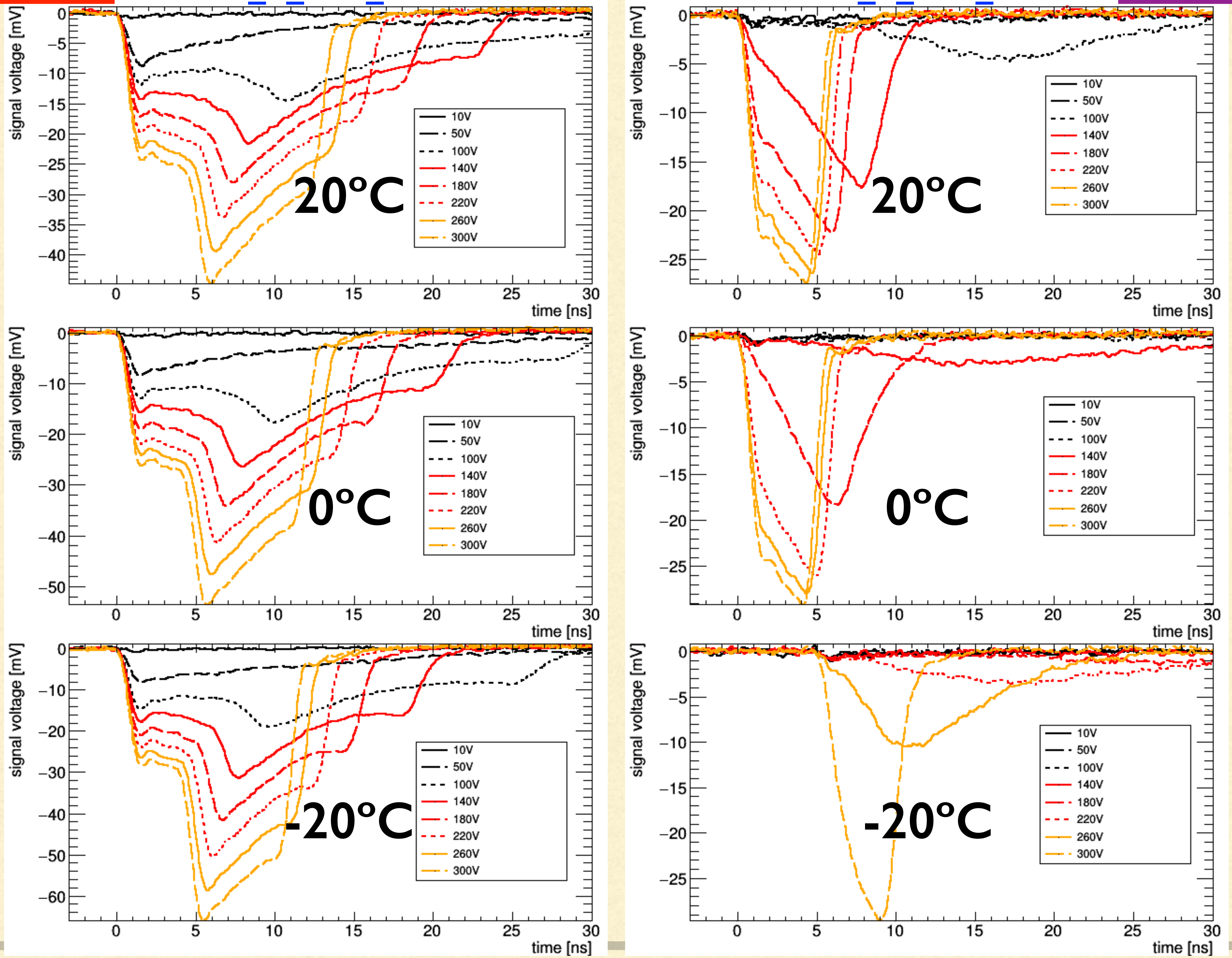


Fluence
$10^{14}\ n_{eq}/cm^2$

TCT - Red back

Mult. layer
$2.0\times10^{13}cm^{-2}$

LGAD_7_W3_C2-3 **PIN_4_W3_I8-1**

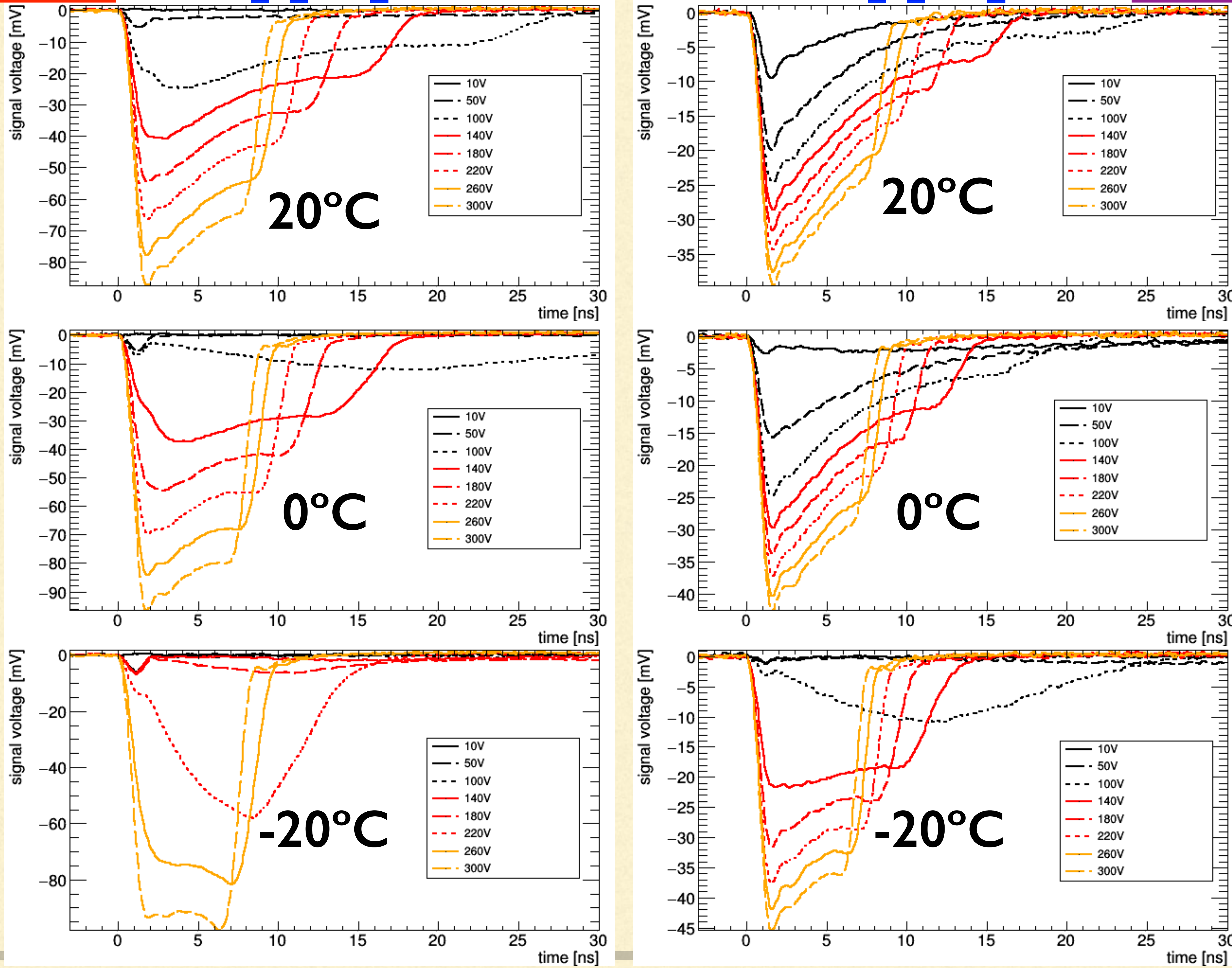


Fluence
$10^{14}\ n_{eq}/cm^2$

TCT - Red front

Mult. layer
$2.0\times10^{13} cm^{-2}$

LGAD_7_W3_C2-3 | **PIN_4_W3_I8-1**



CONCLUSIONS

- Homogeneous charge collection before and after irradiation.
- Charge collection and gain decrease after irradiation.
  - At a fluence of 10^{14} n_{eq}/cm^2 the gain is
    - ≈ 2 times smaller than before irradiation, for W1 and W2,
    - ≈ 4 times smaller than before irradiation, for W3 and W4.
  - At 10^{15} n_{eq}/cm^2 there is no difference in charge collection between PIN diodes and LGADs.
- The voltage required to deplete the multiplication layer increases with fluence, when the irradiation is with protons.
  - This is a direct consequence of the double junction effect caused by hole trapping.

THANK YOU

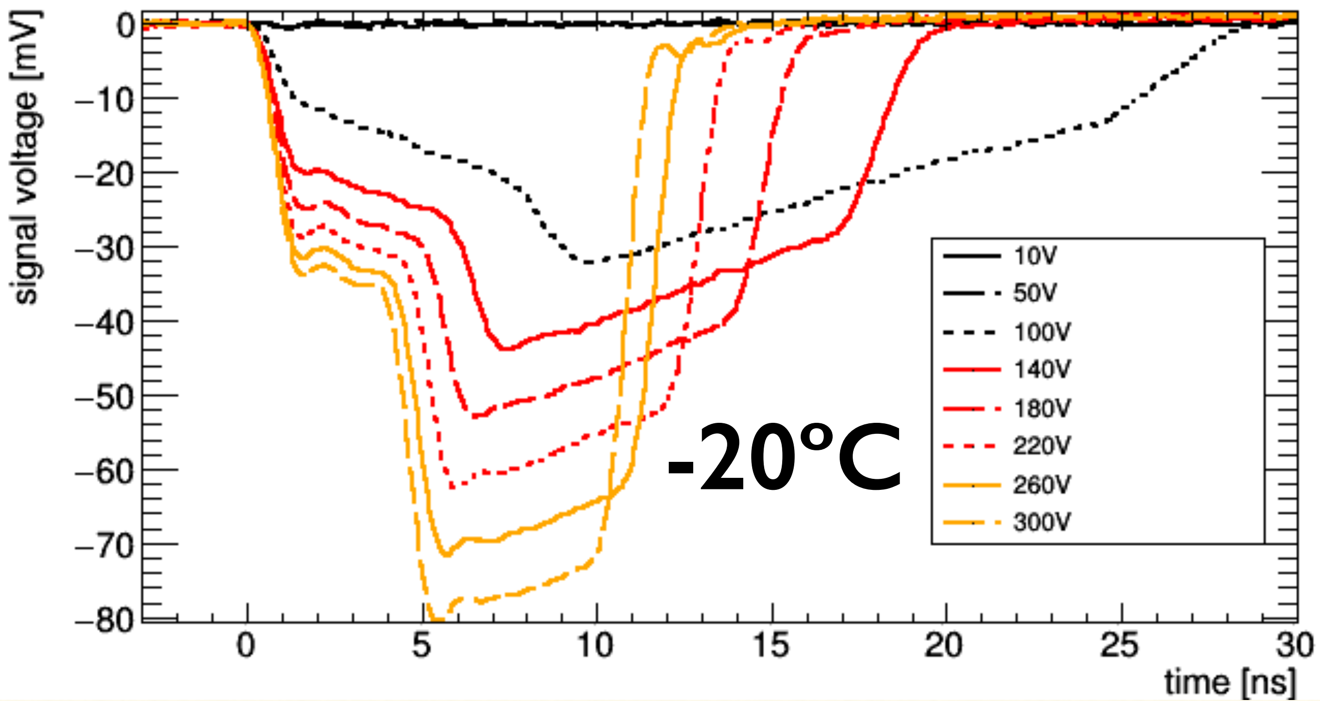
BACKUP SLIDES

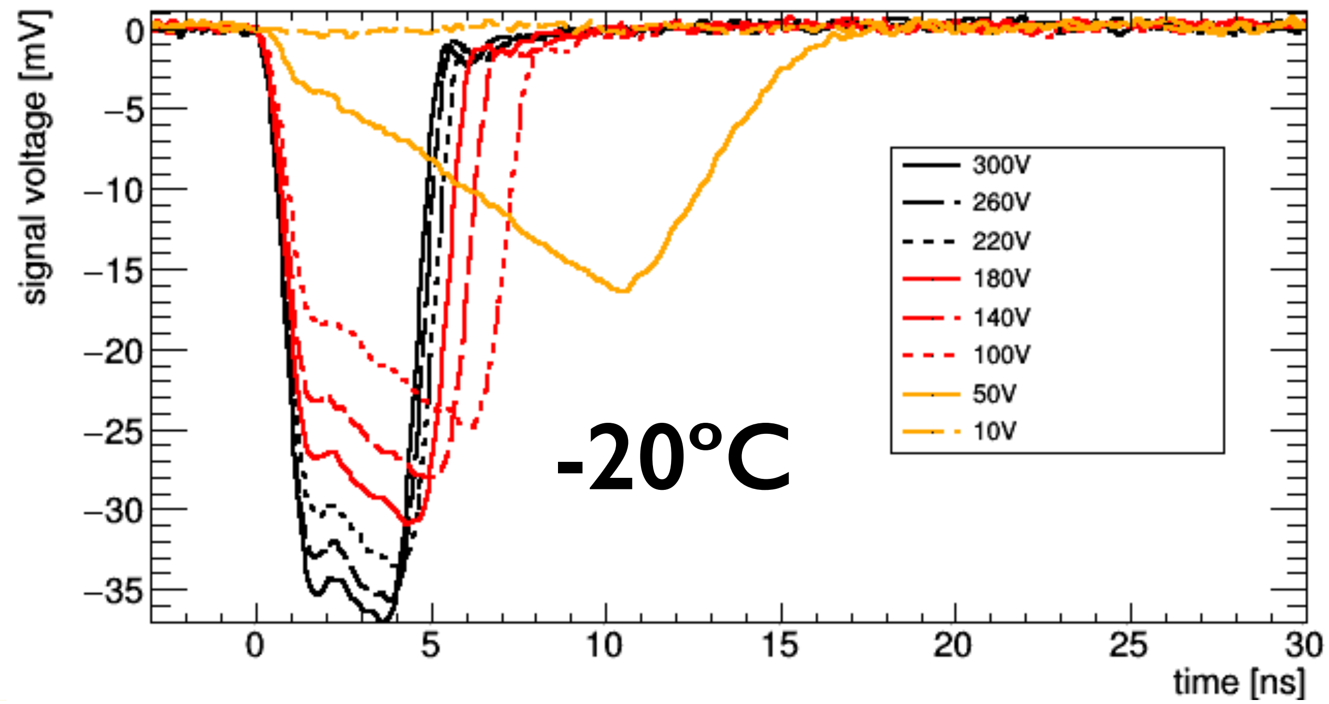
Fluence
$10^{14}\ n_{eq}/cm^2$

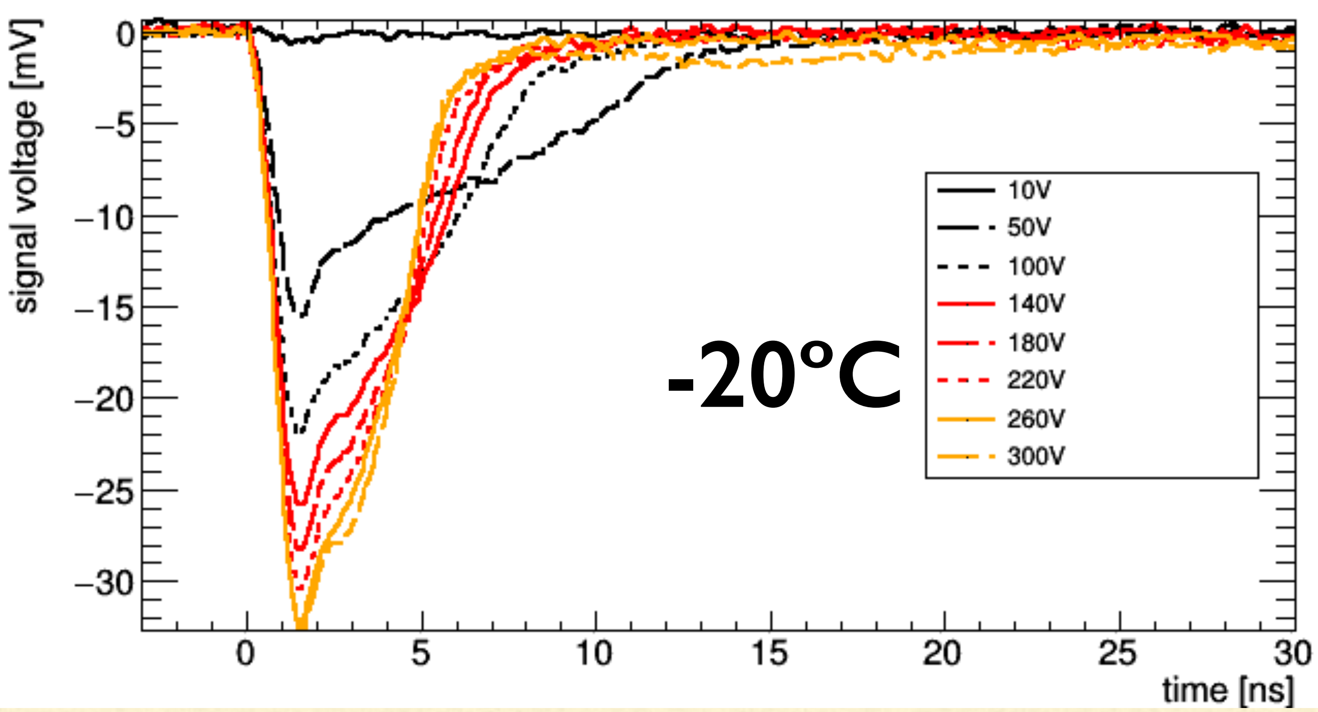
TCT - Red back

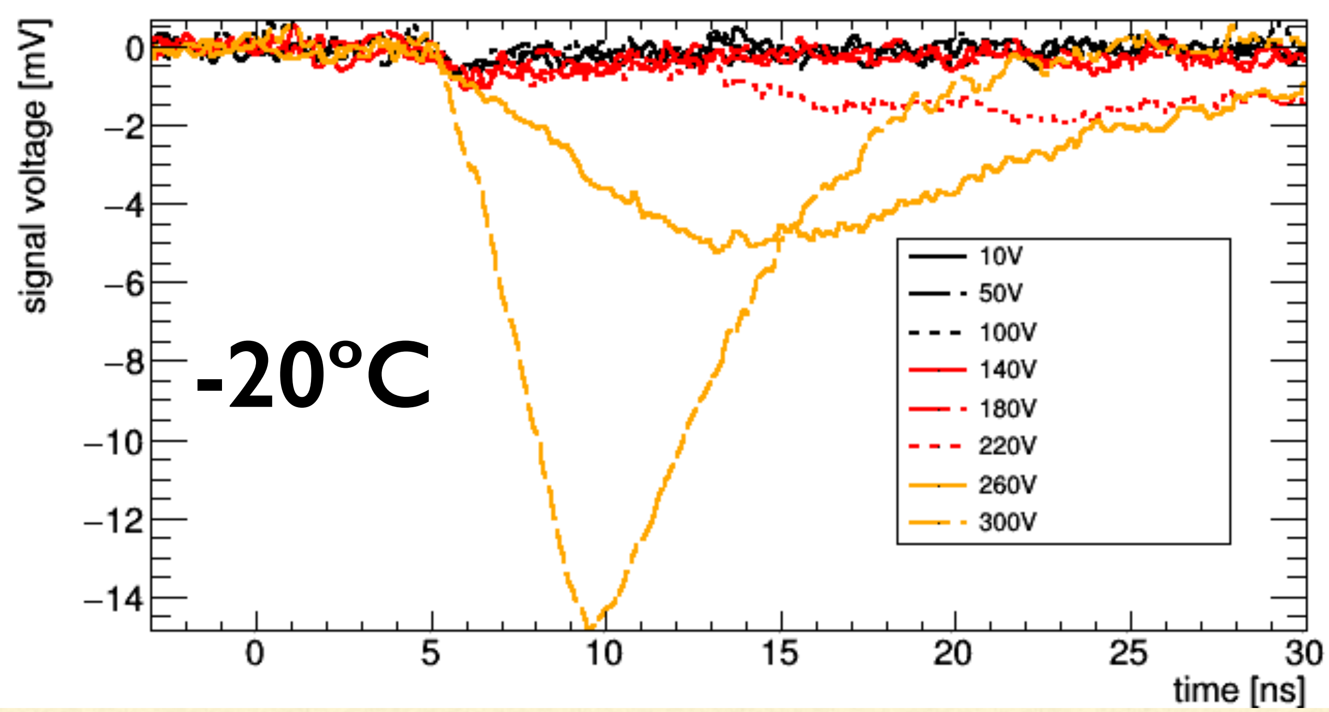
Mult. layer
$1.8\times10^{13} cm^{-2}$

LGAD_4_W2_I3-1 **PIN_7_W1_C9-3**







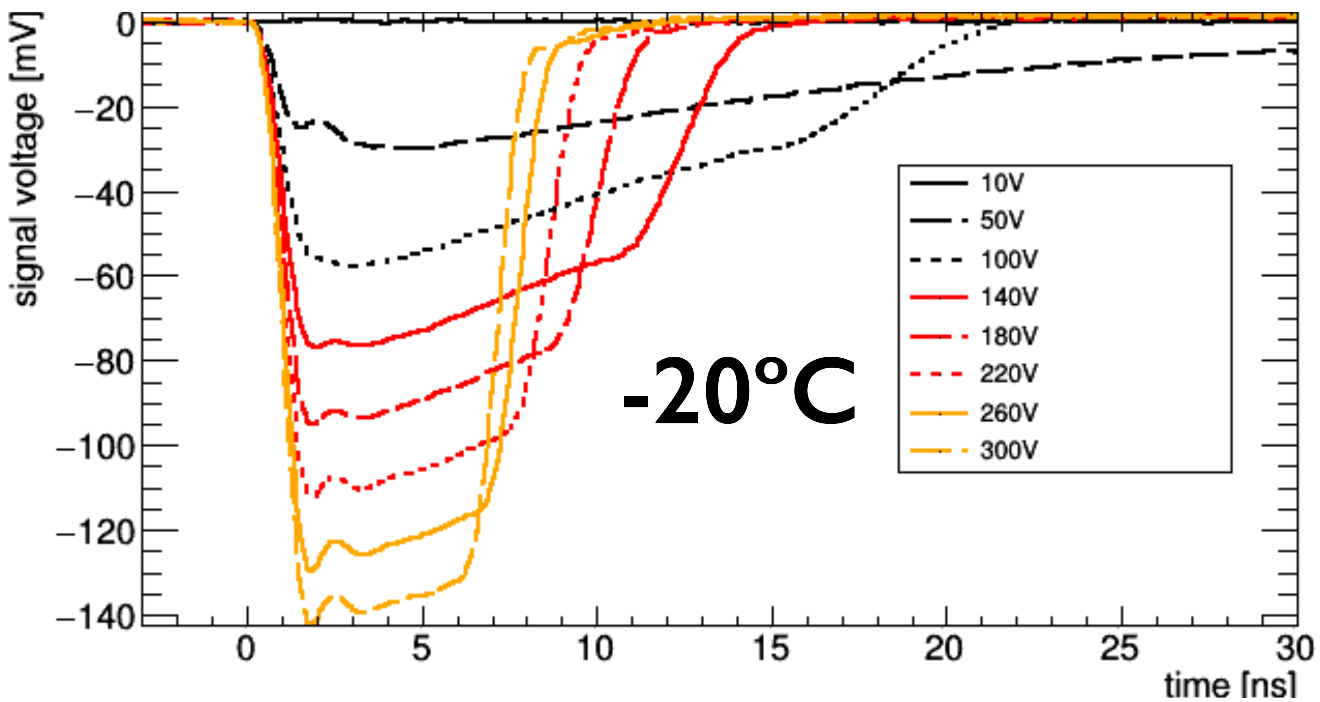


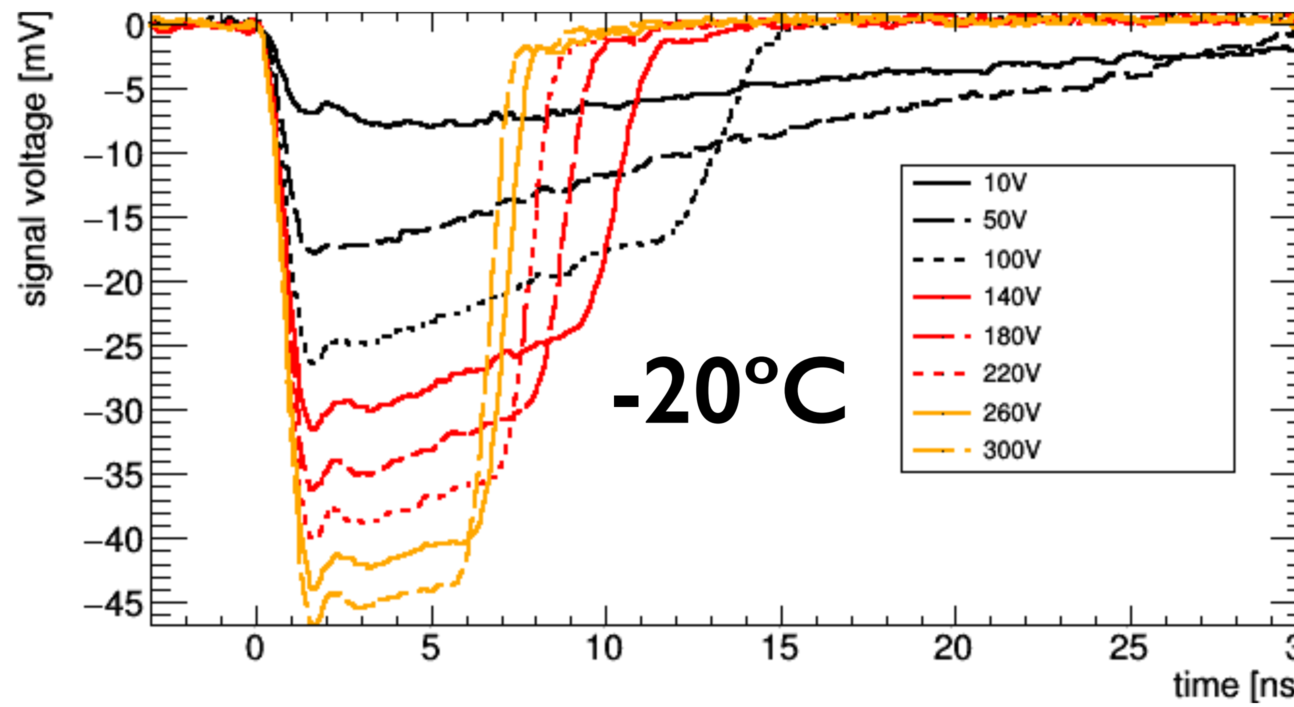
Fluence
10^{14} n_{eq}/cm^2

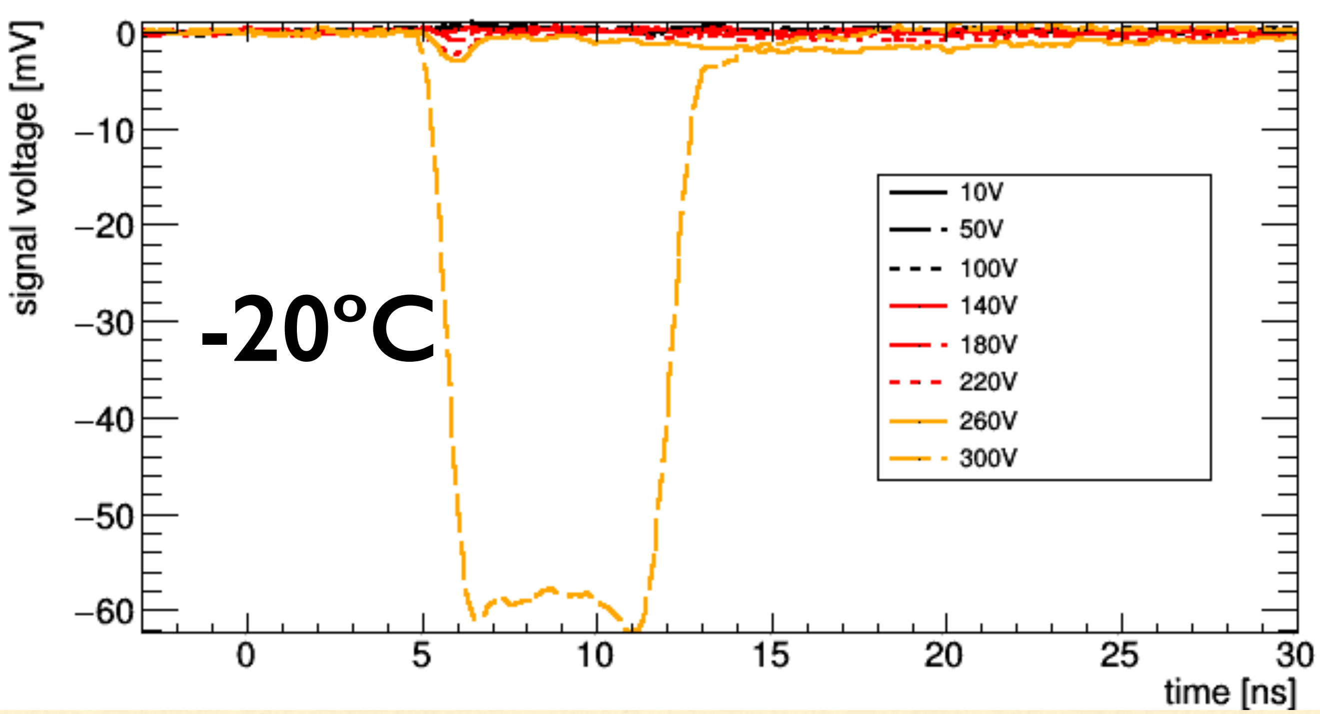
TCT - Red front

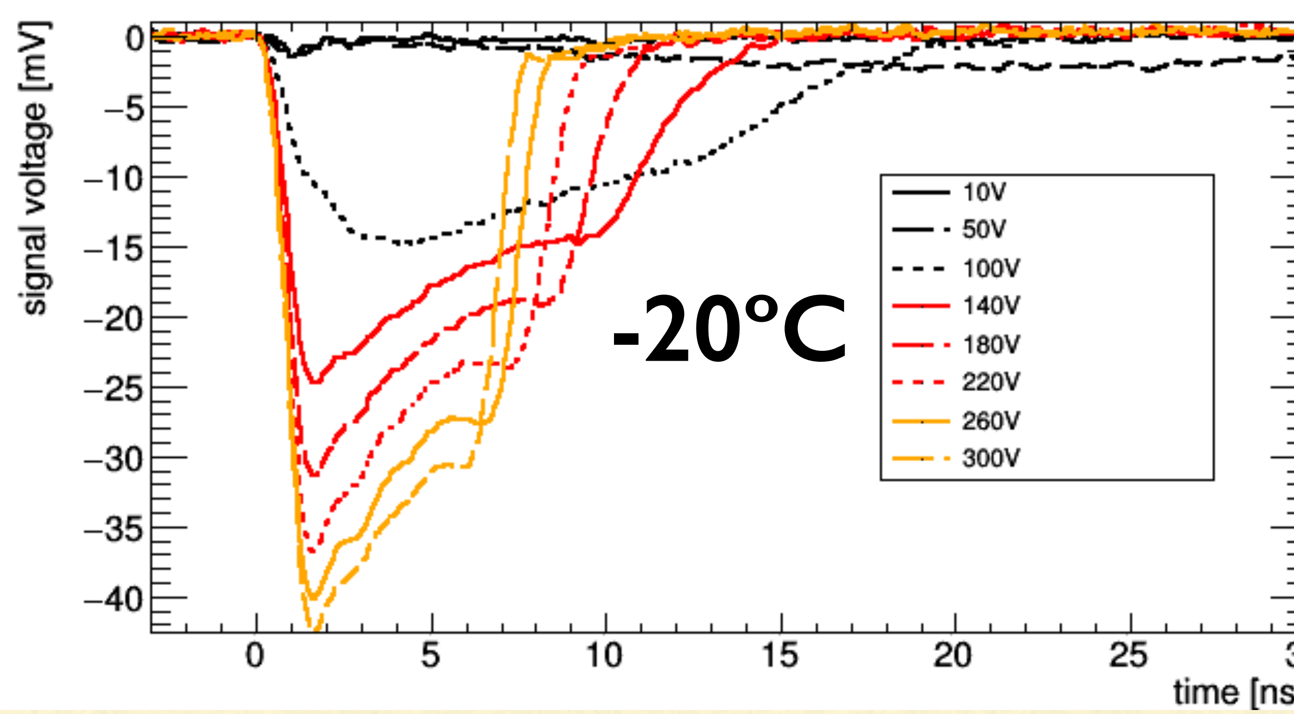
Mult. layer
$1.8\times10^{13} cm^{-2}$

LGAD_4_W2_I3-1 | **PIN_7_W1_C9-3**









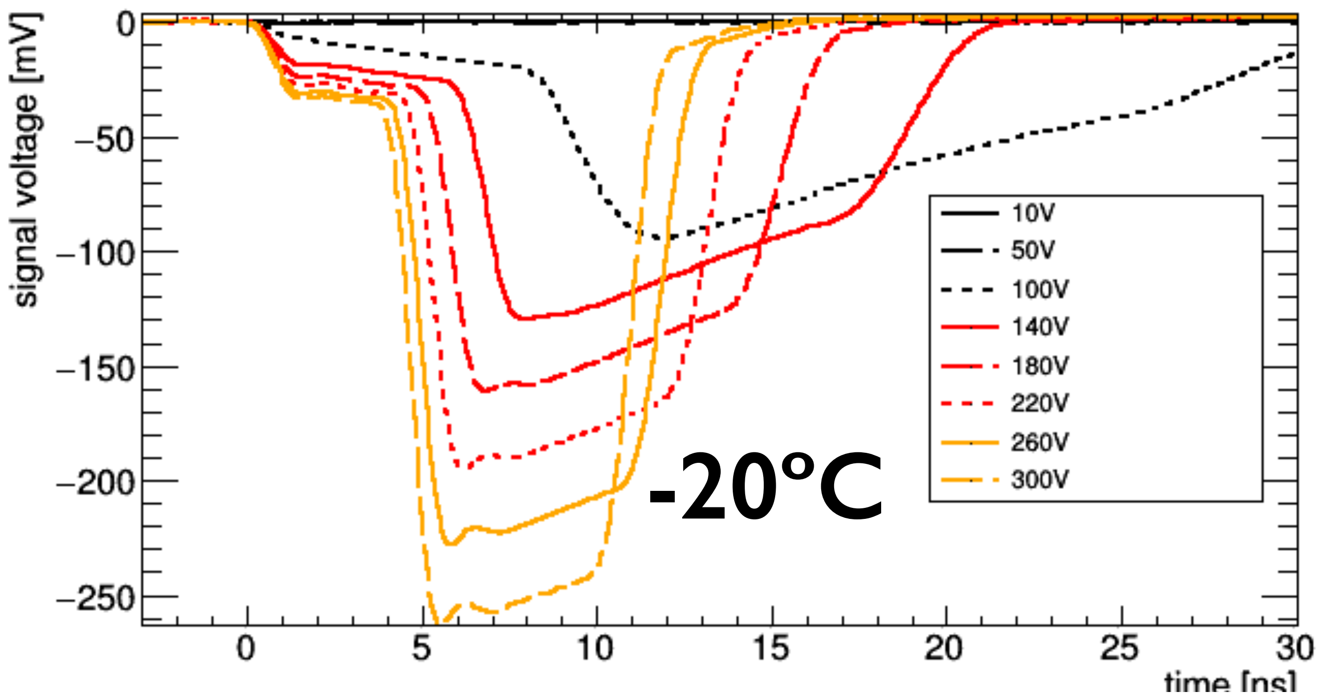
Fluence
10^{14} n_{eq}/cm^2

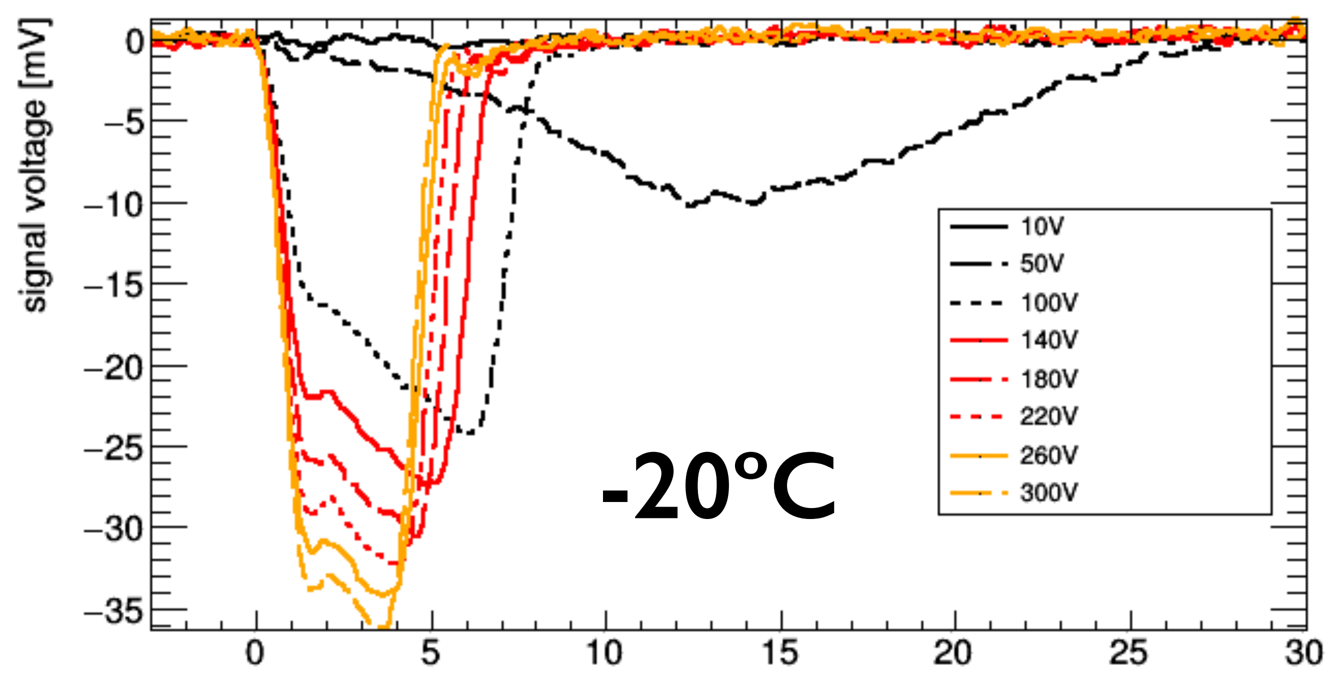
TCT - Red back

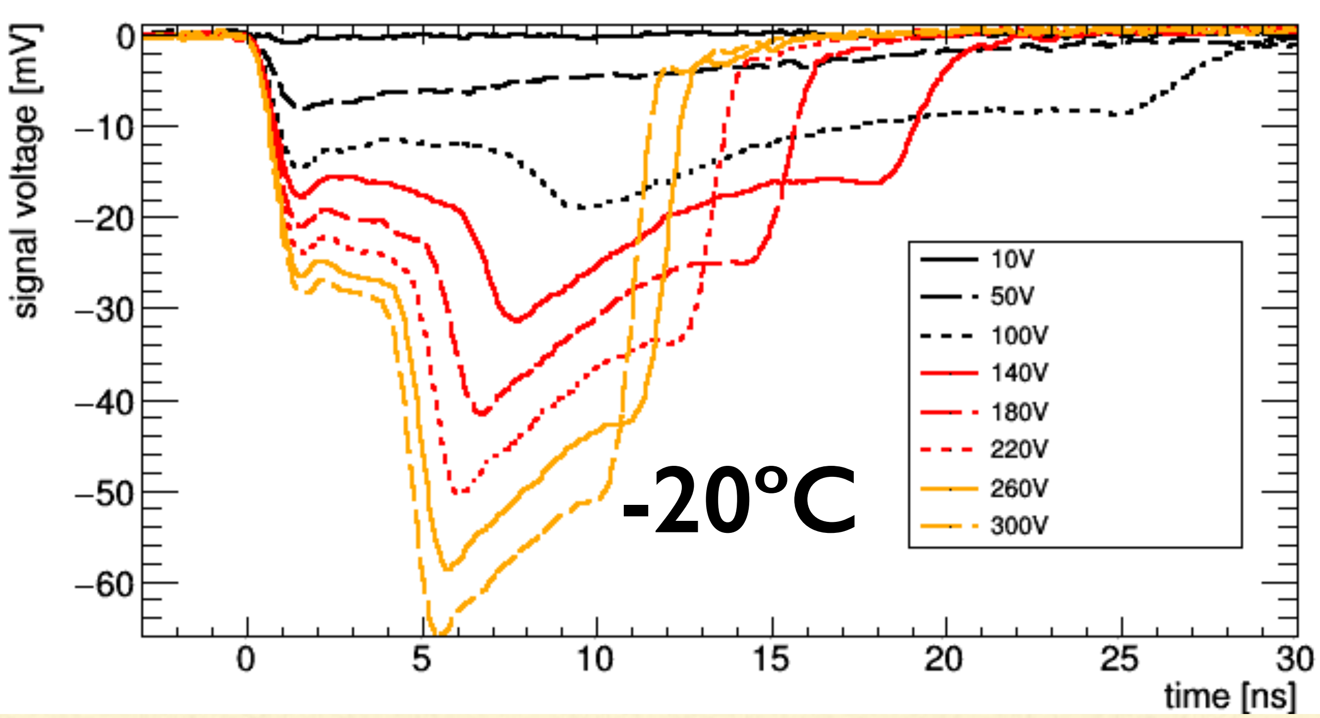
Mult. layer
$2.0\times10^{13} cm^{-2}$

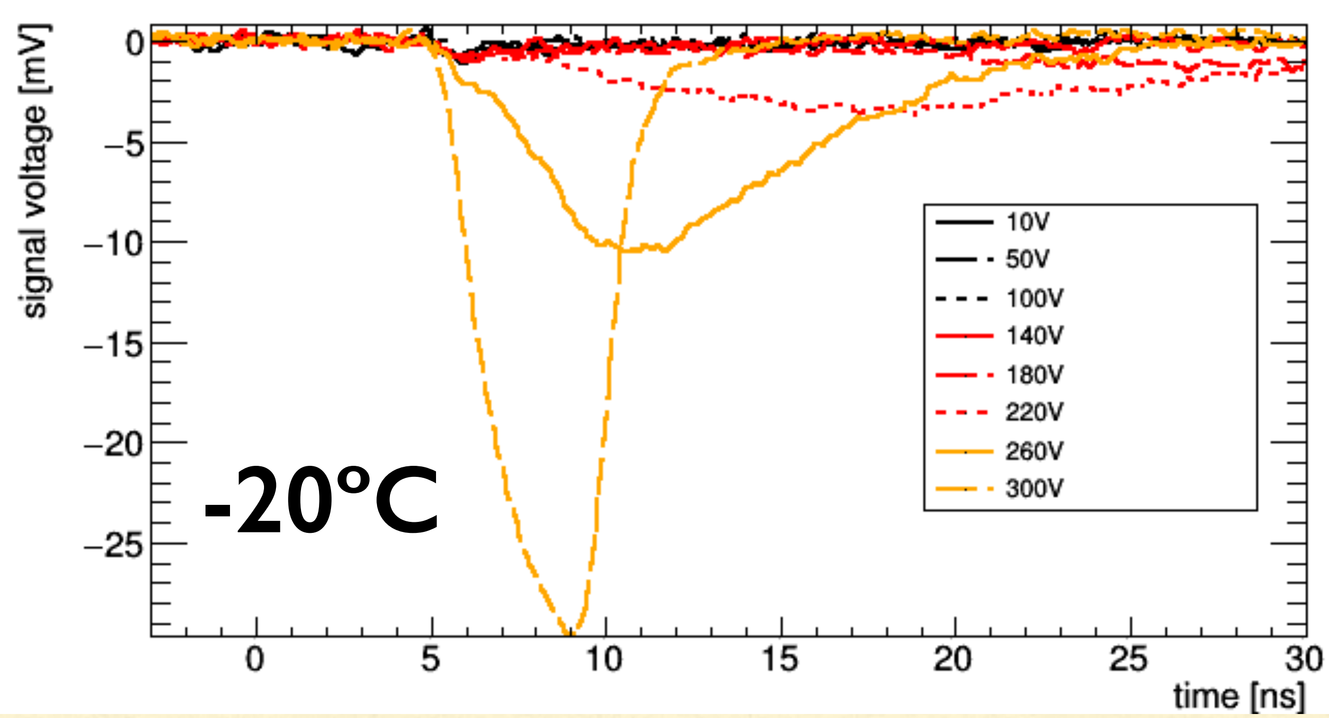
LGAD_7_W3_C2-3

PIN_4_W3_I8-1







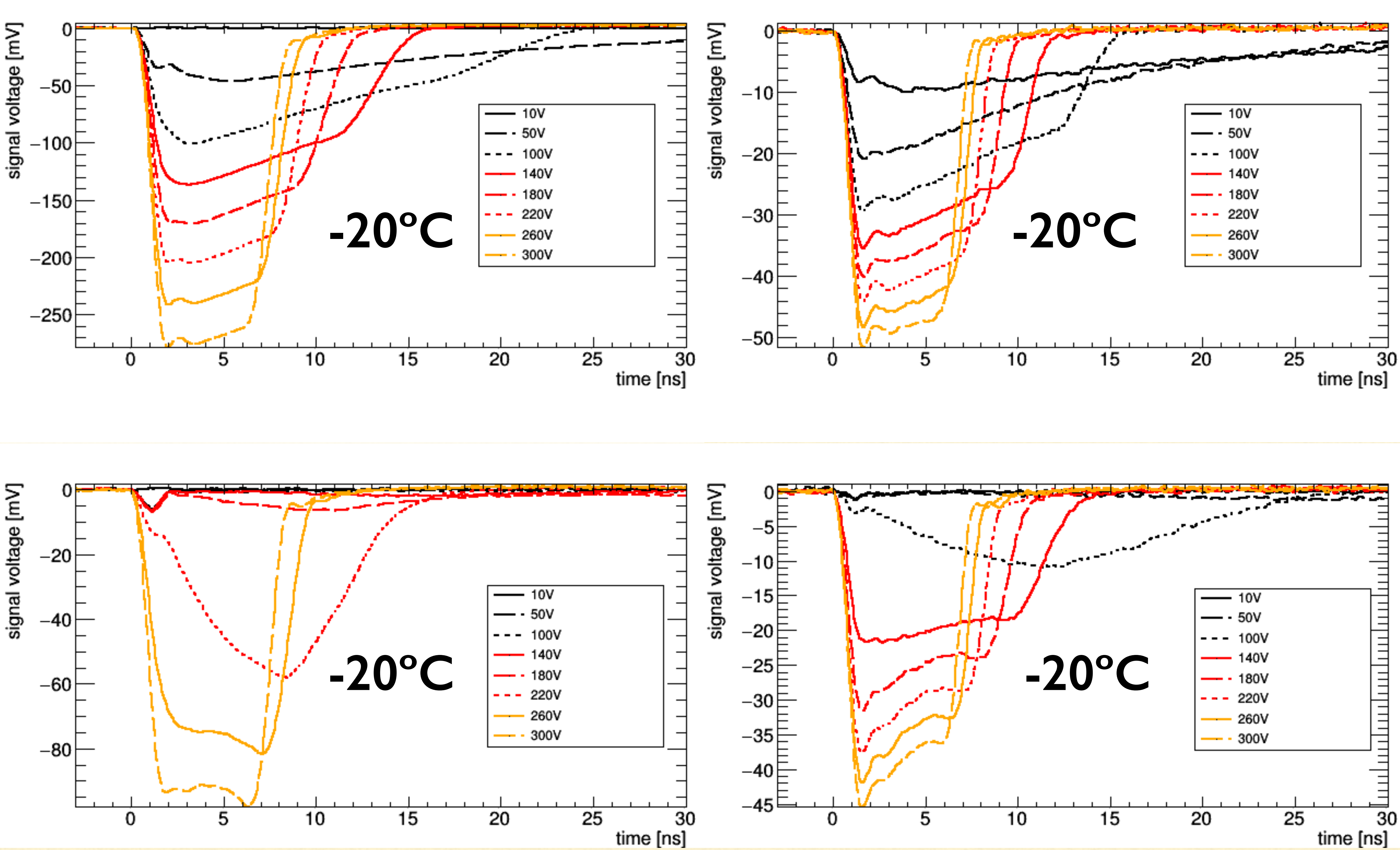


TCT - Red front

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

Mult. layer $2.0\times10^{13}cm^{-2}$

LGAD_7_W3_C2-3 **PIN_4_W3_I8-1**

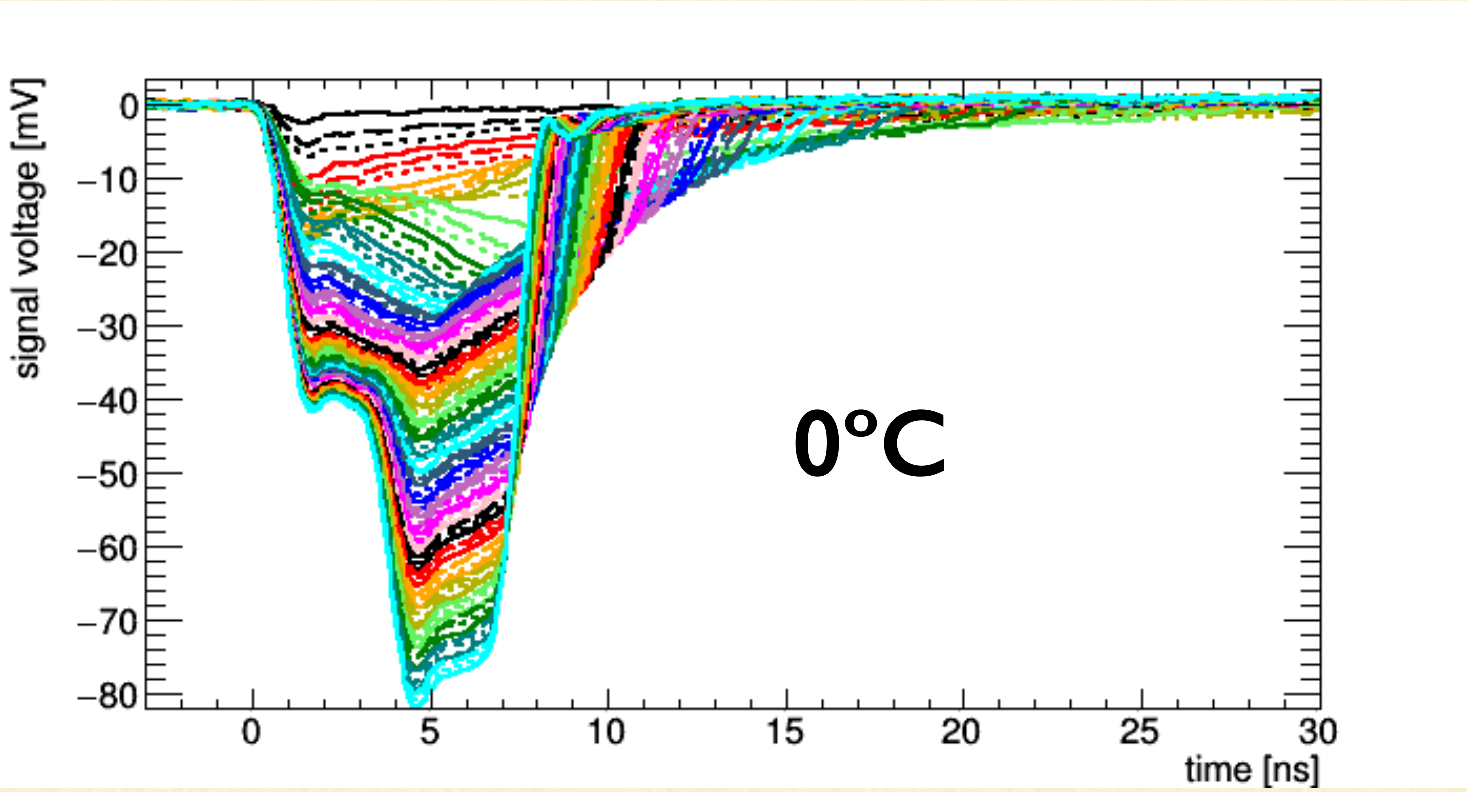


Fluence $10^{14}\ n_{eq}/cm^2$

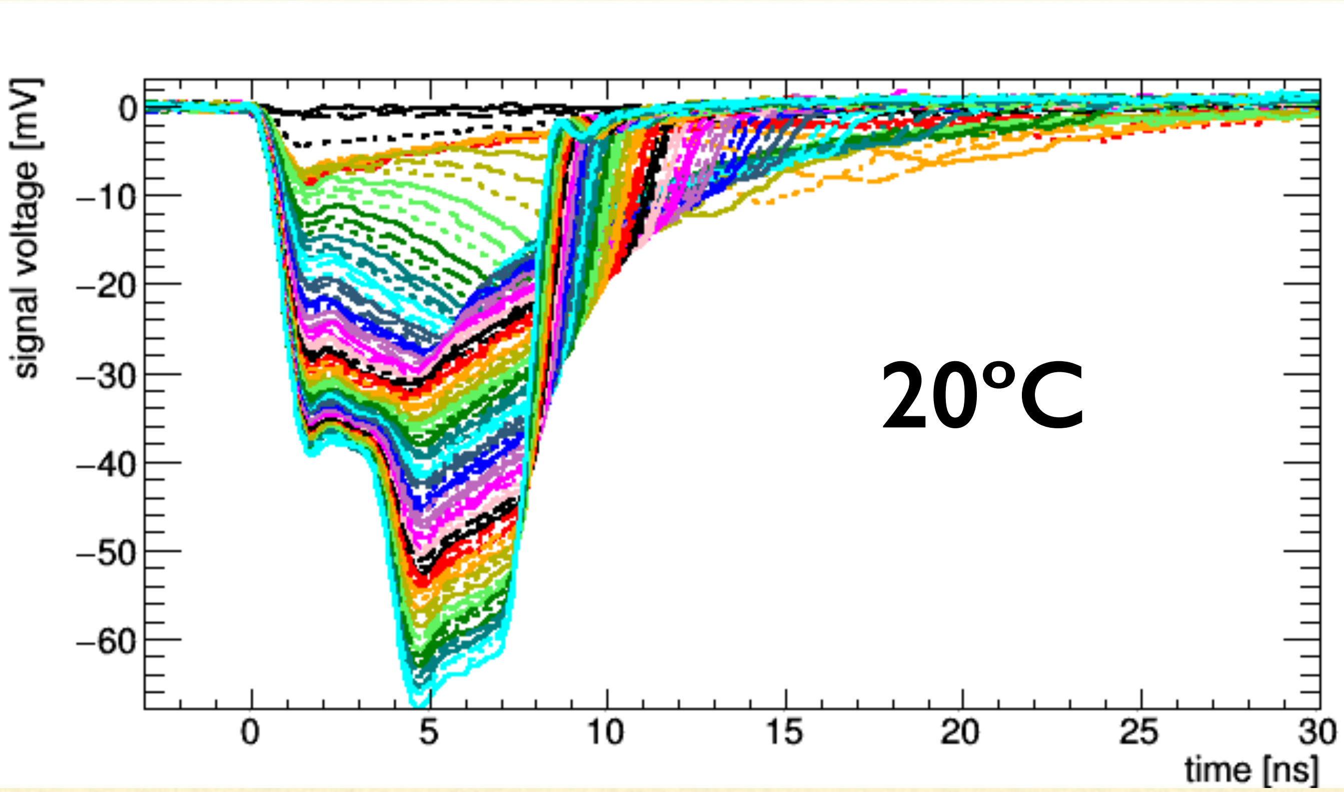
TCT - Red back

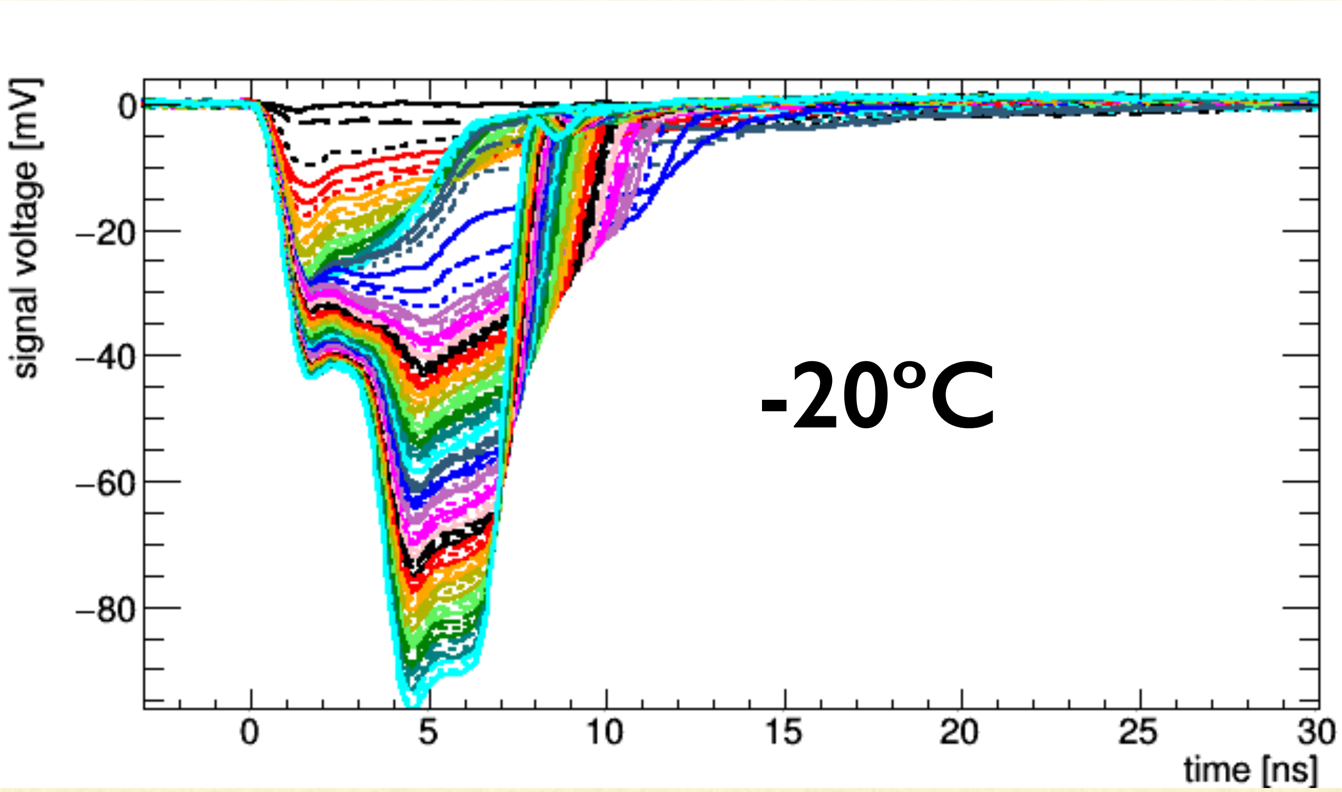
Mult. layer $1.8 \times 10^{13} cm^{-2}$

LGAD_4_W2_I3-1



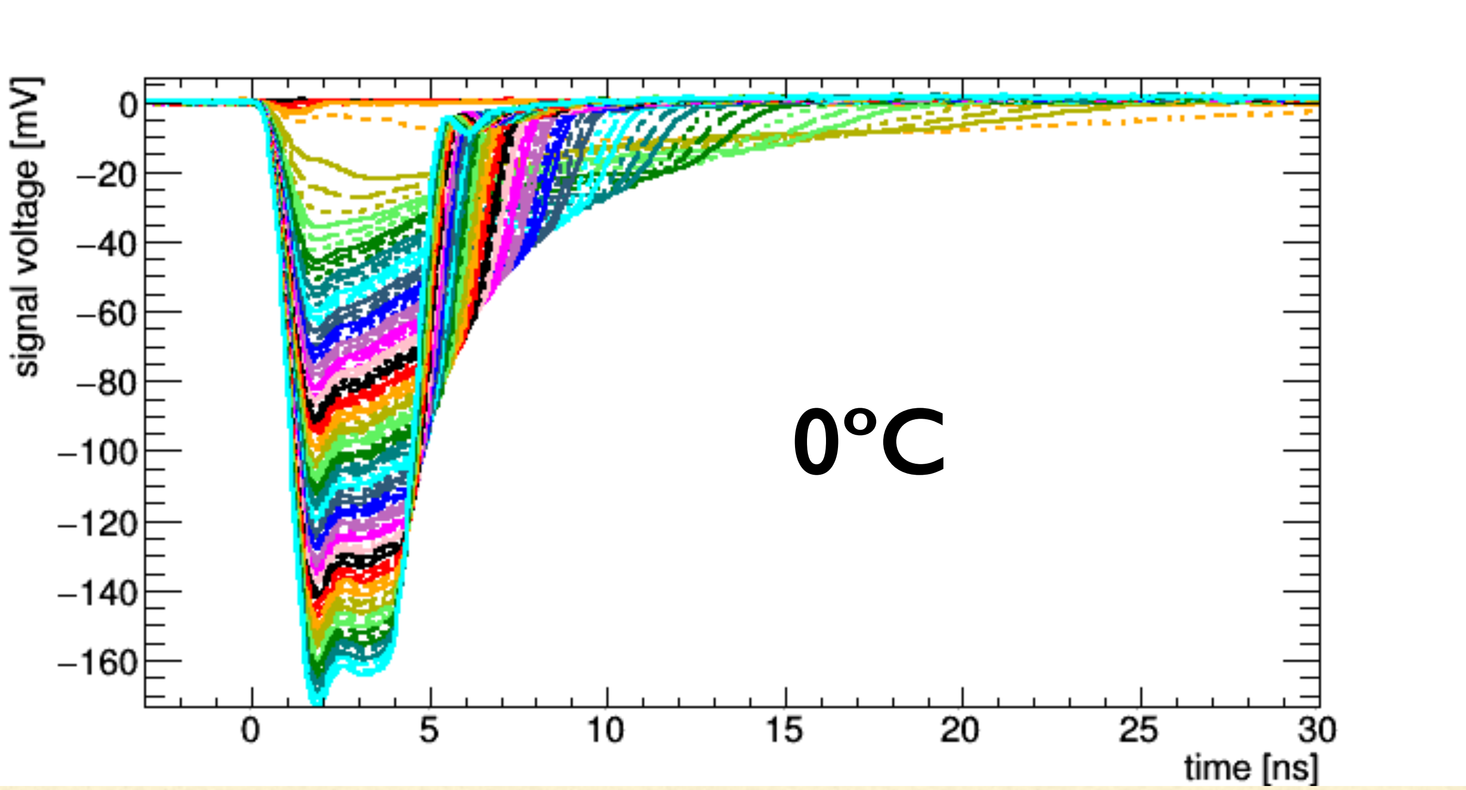
Voltage range: 10V to 1000V, 10V steps



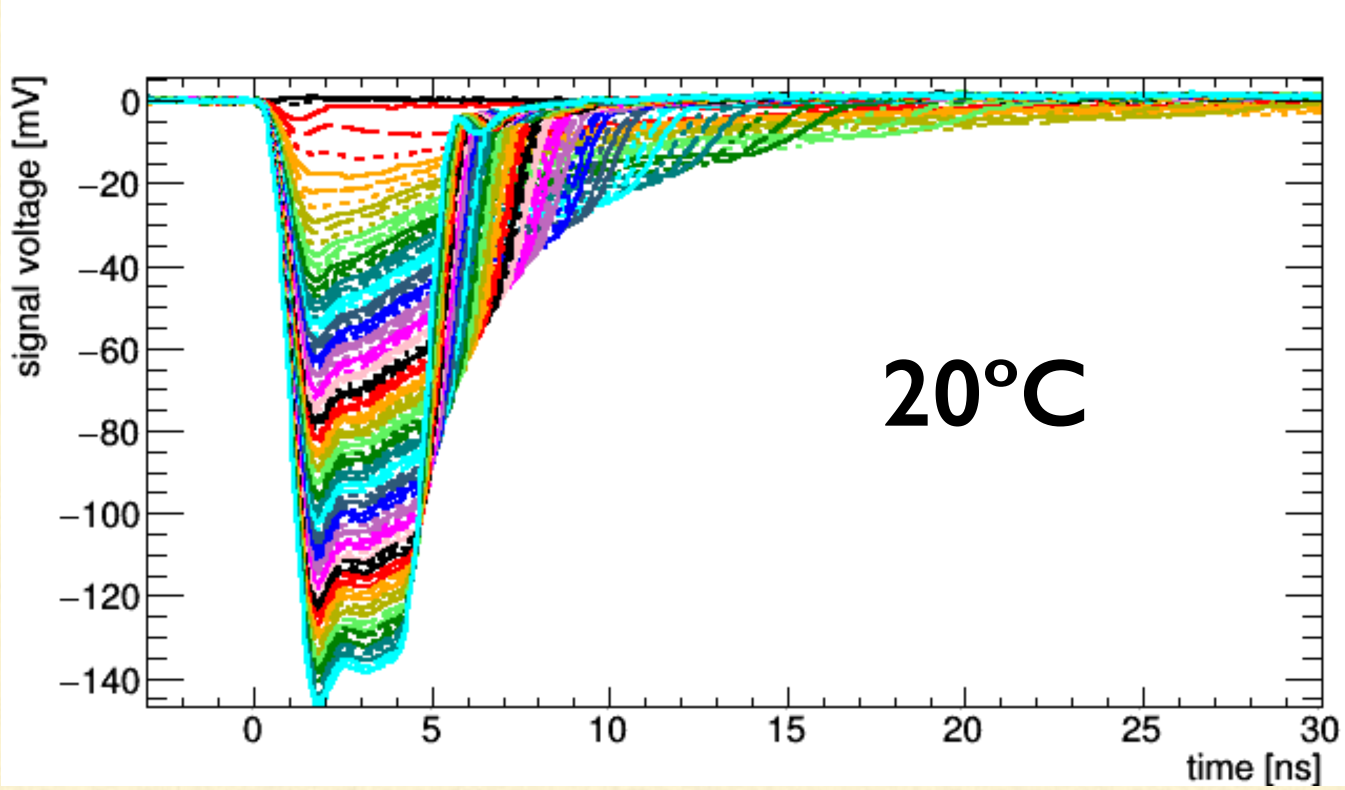


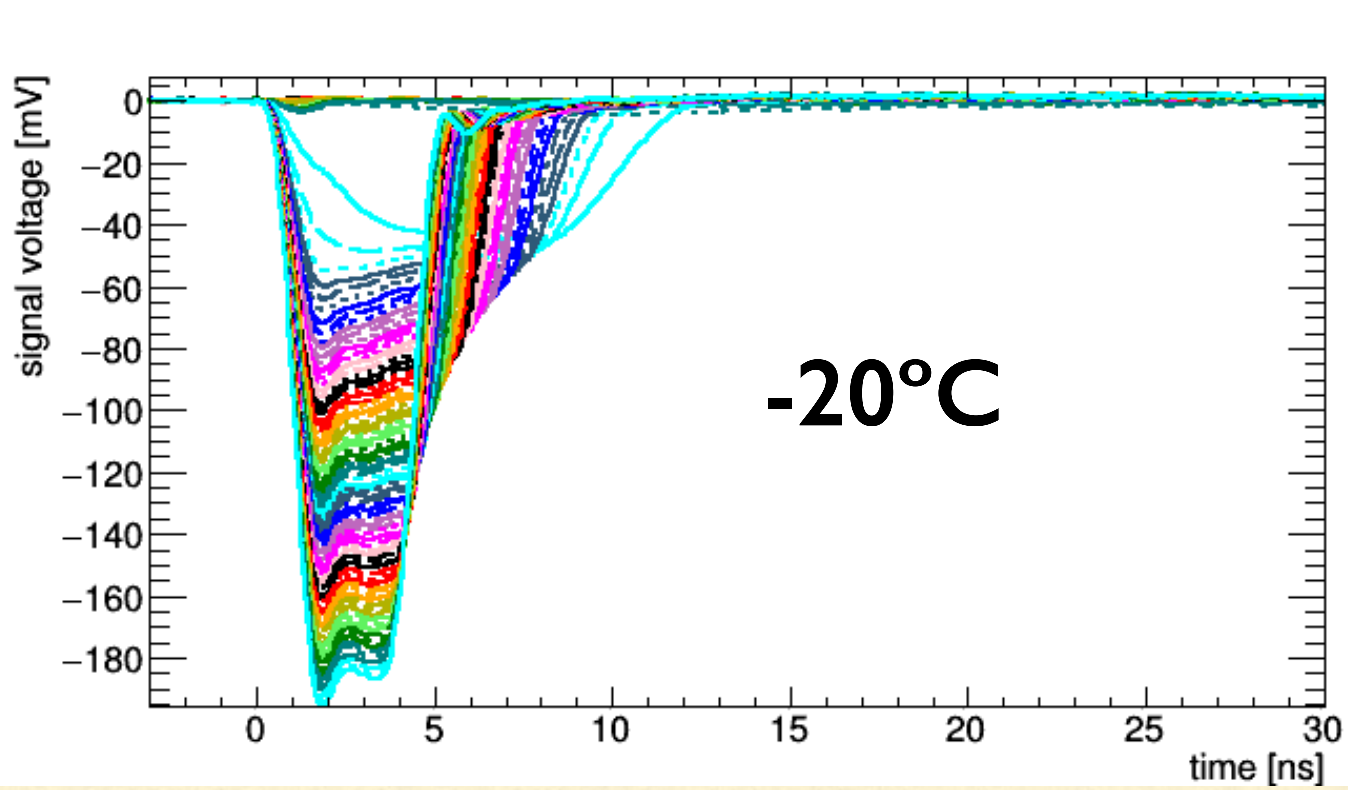
TCT - Red front

LGAD_4_W2_I3-1



Voltage range: 10 V to 1000 V, 10 V steps



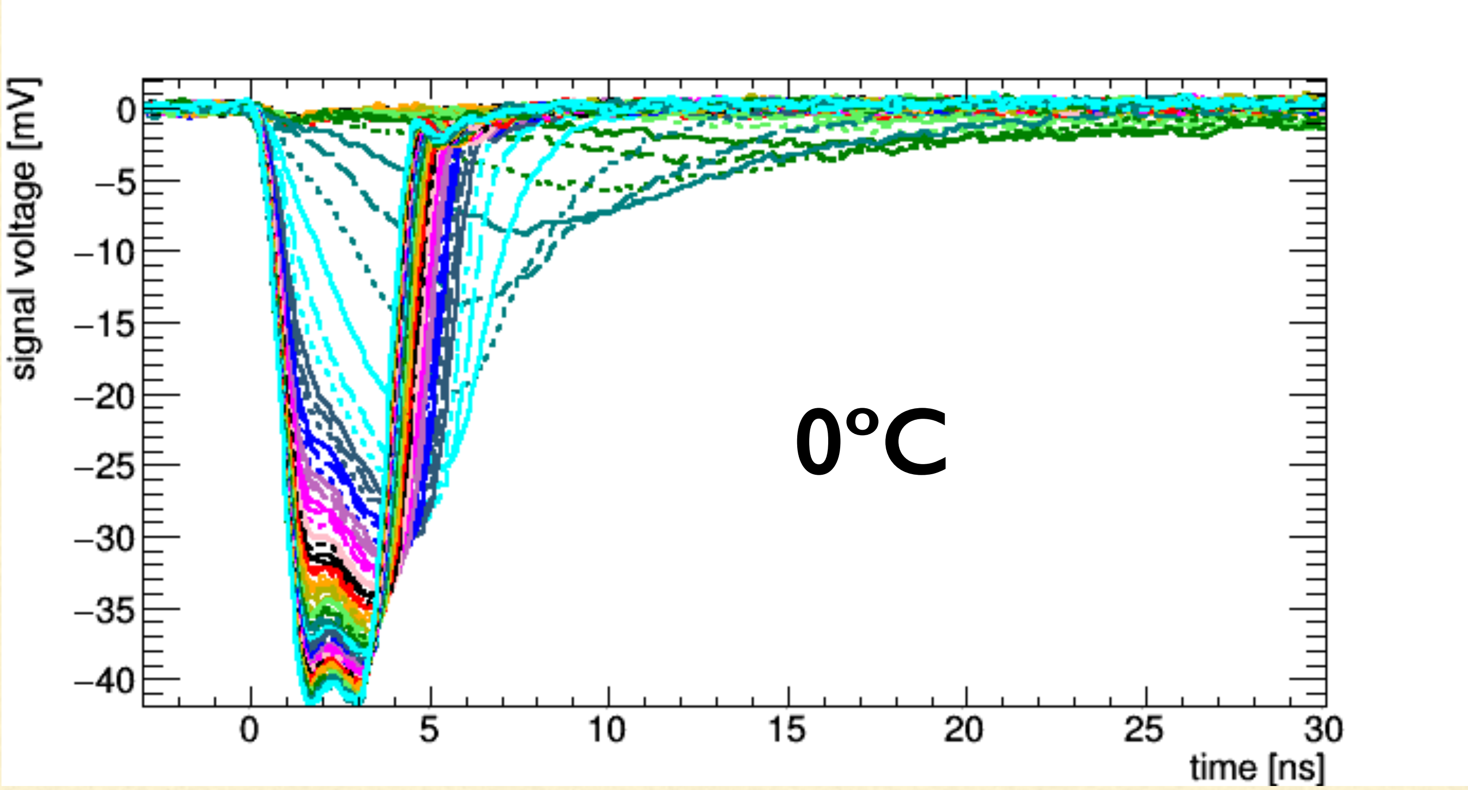


Fluence
10^{14} n_{eq}/cm^2

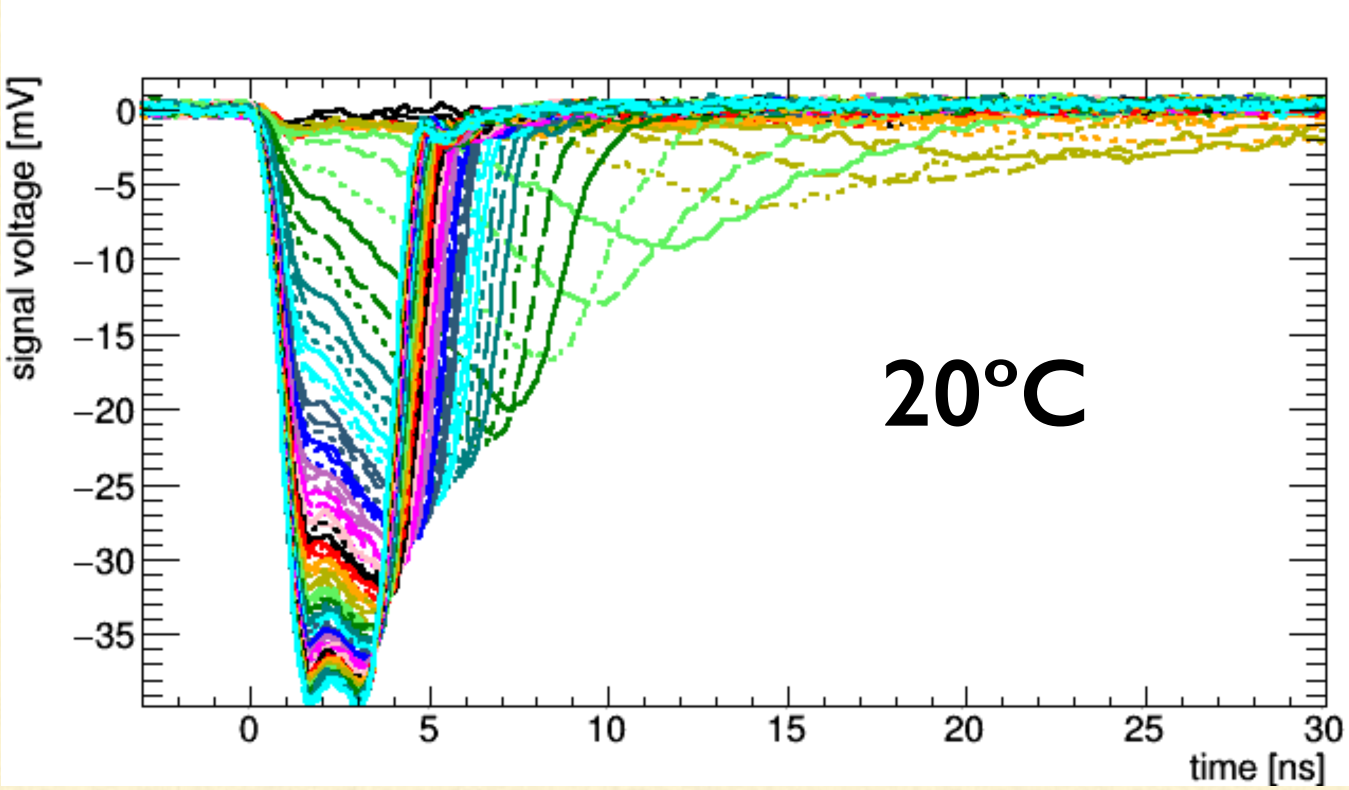
TCT - Red back

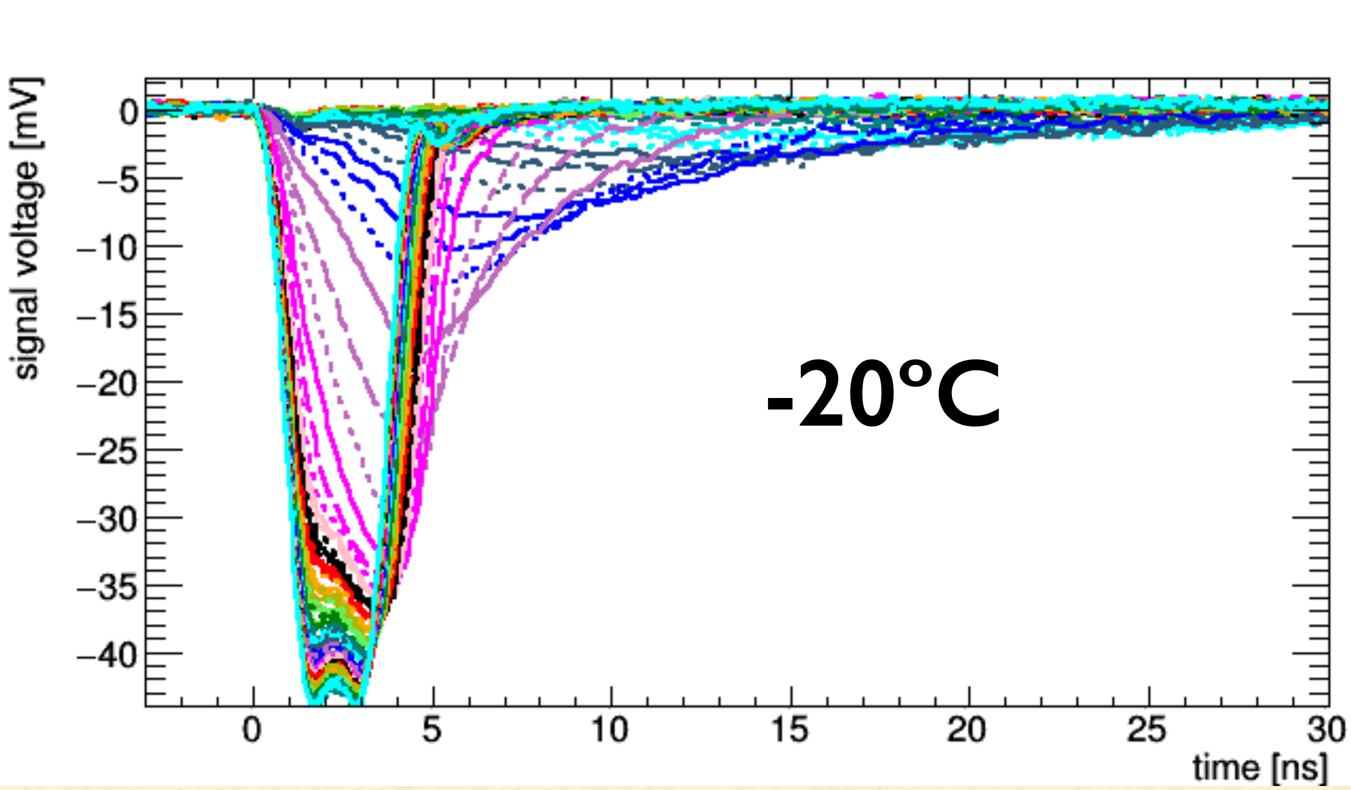
Mult. layer
$1.8 \times 10^{13} cm^{-2}$

PIN_7_W1_C9-3



Voltage range:
10 V to 1000 V,
10 V steps



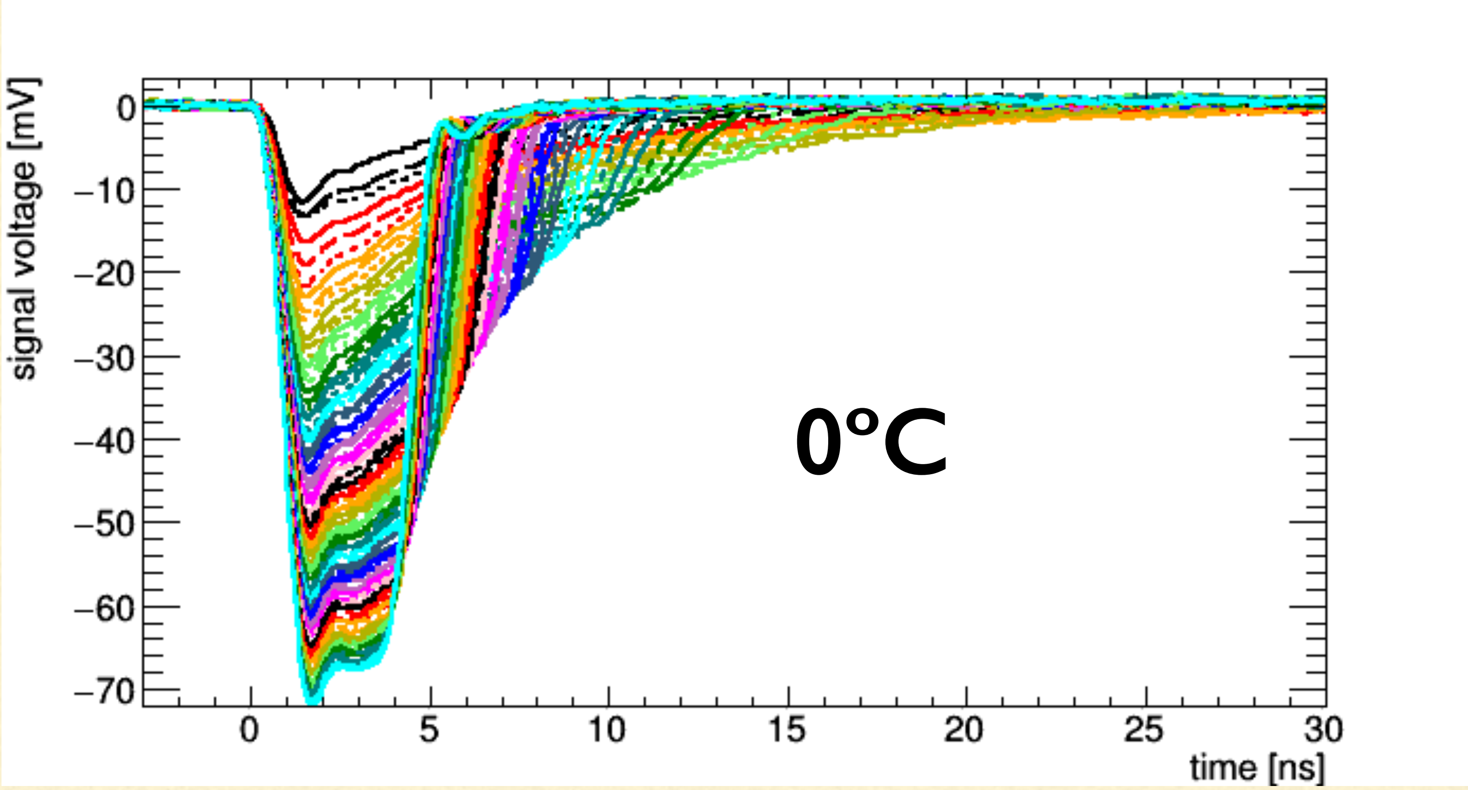


Fluence
$10^{14}\ n_{eq}/cm^2$

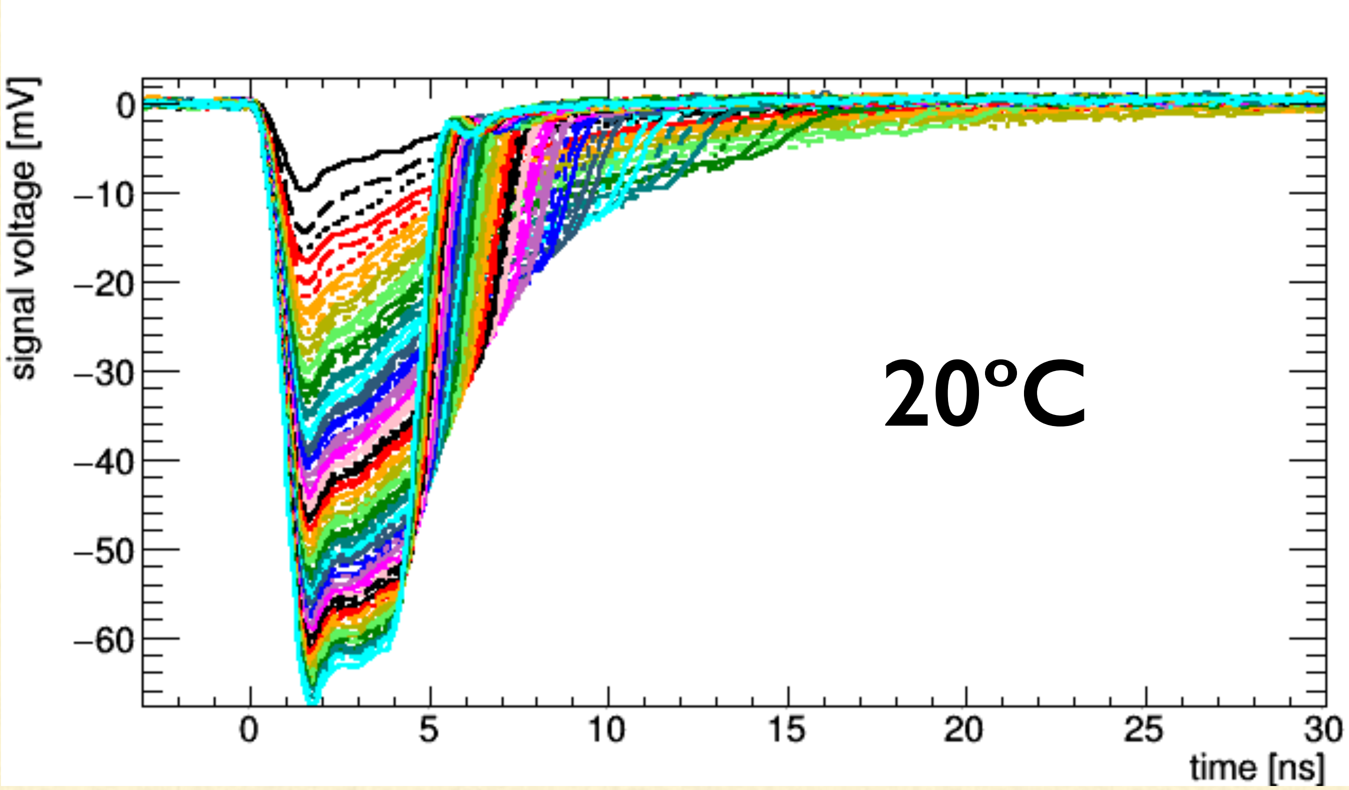
TCT - Red front

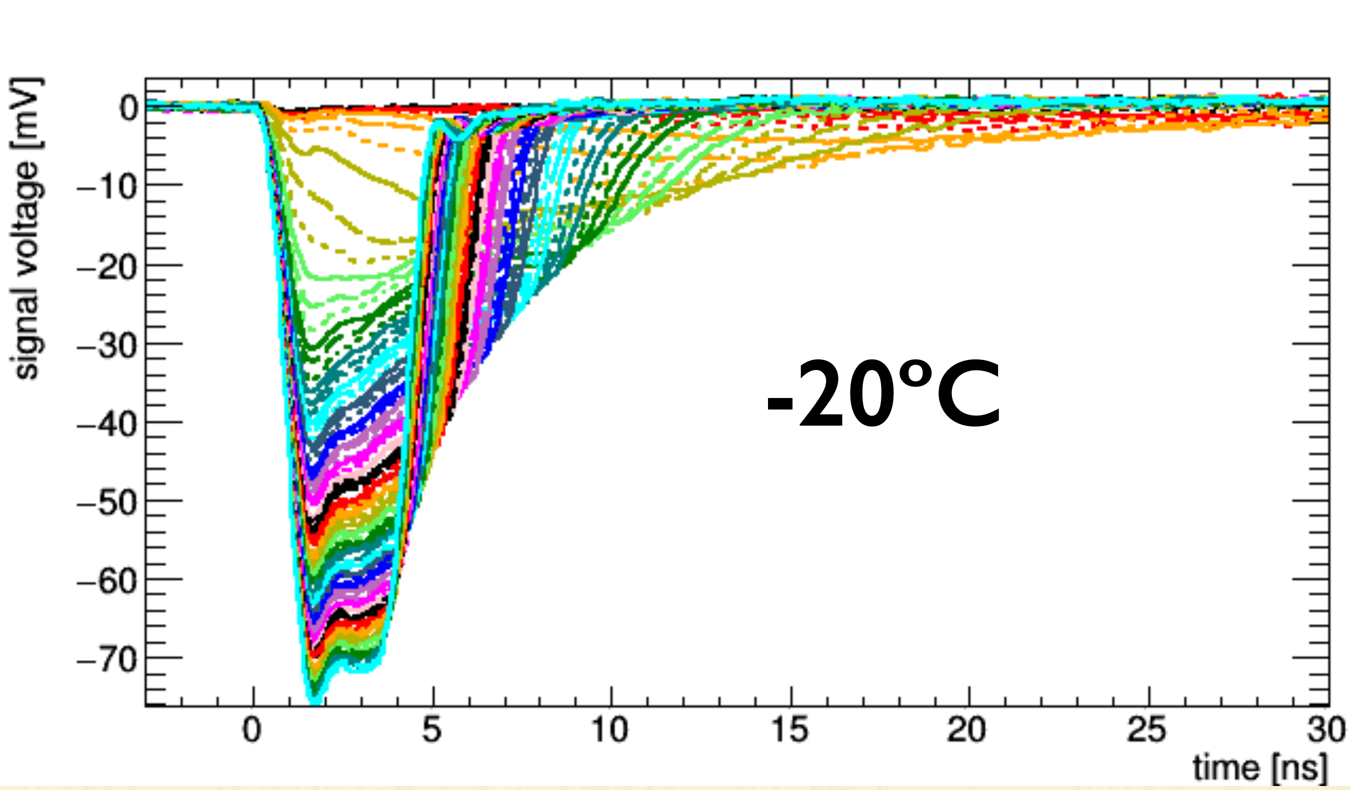
Mult. layer
$1.8\times10^{13} cm^{-2}$

PIN_7_W1_C9-3



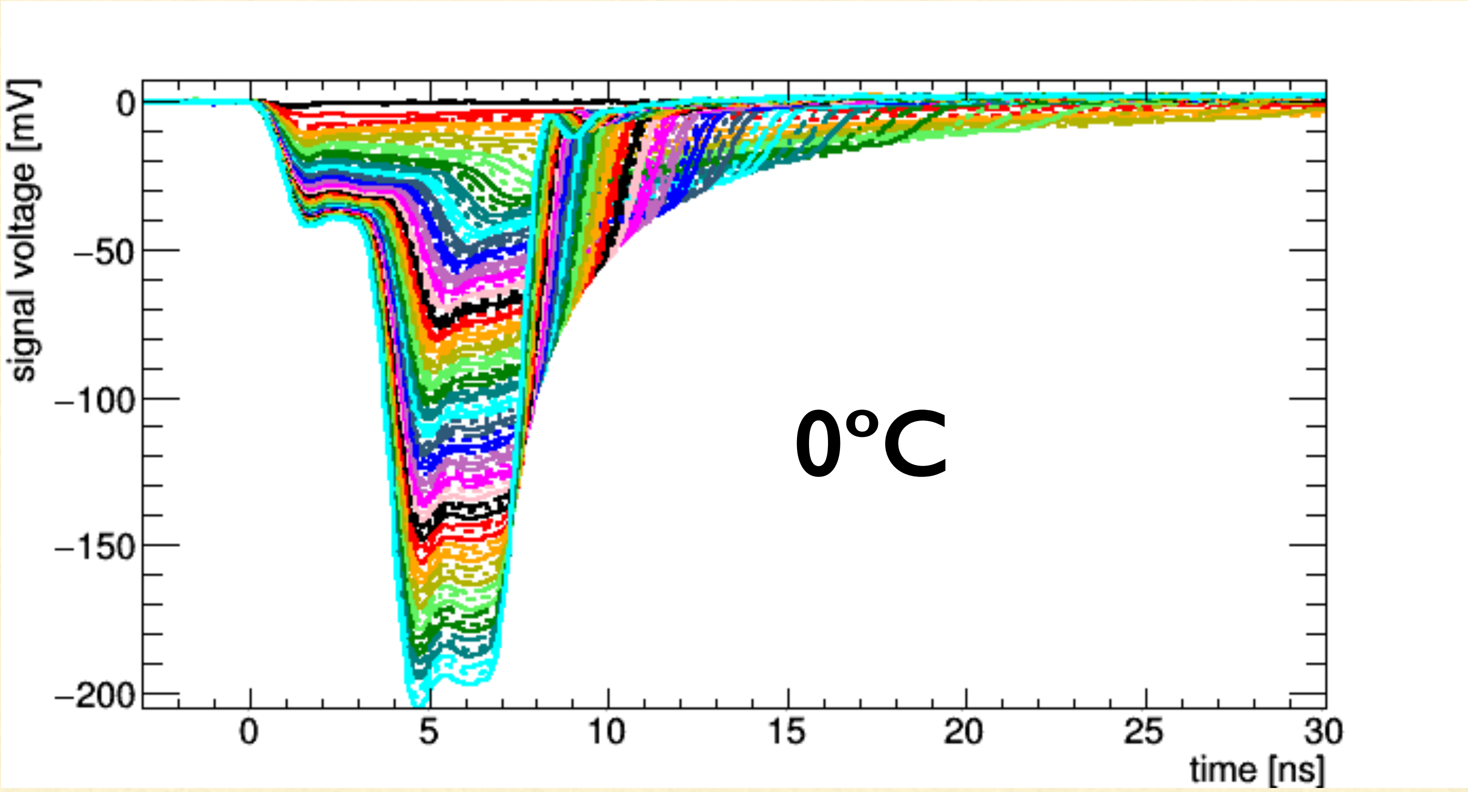
Voltage range:
10V to 1000V,
10V steps



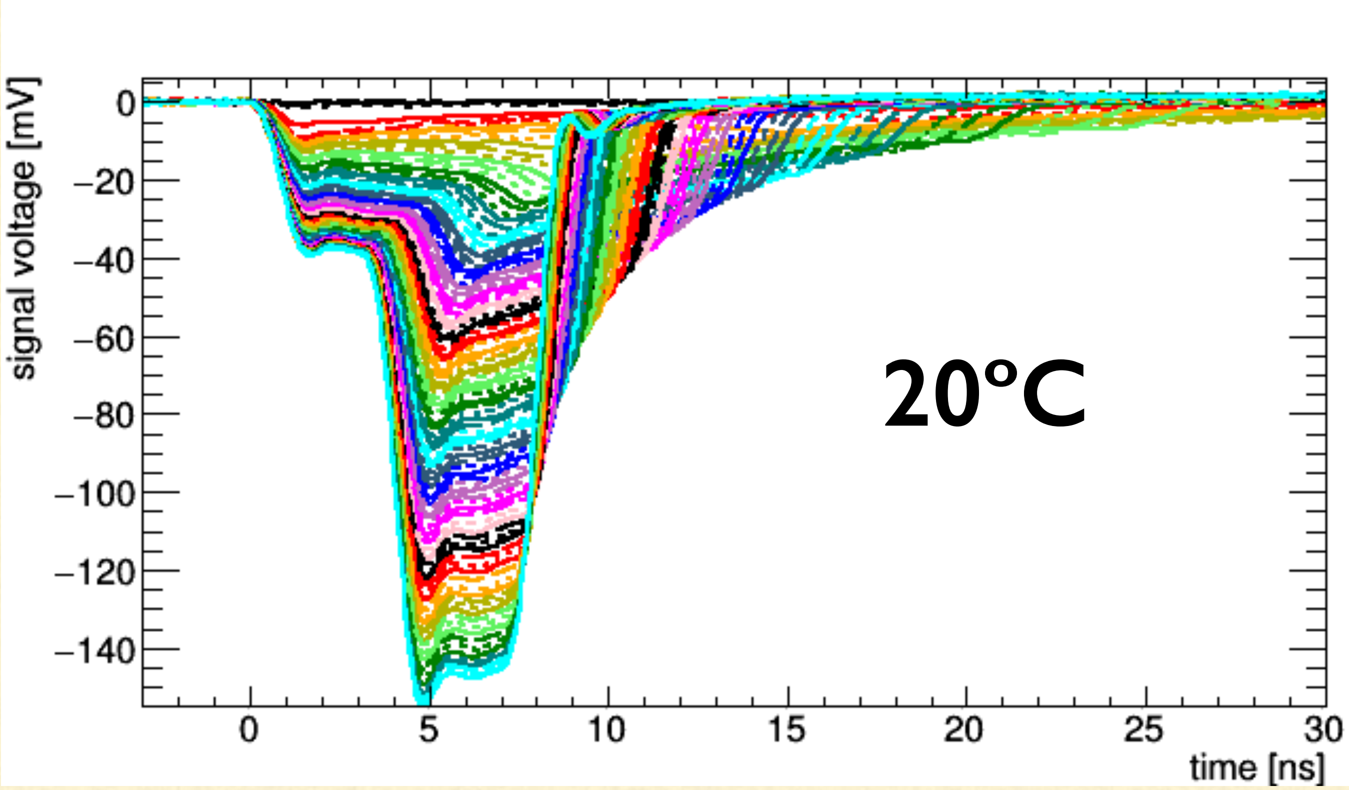


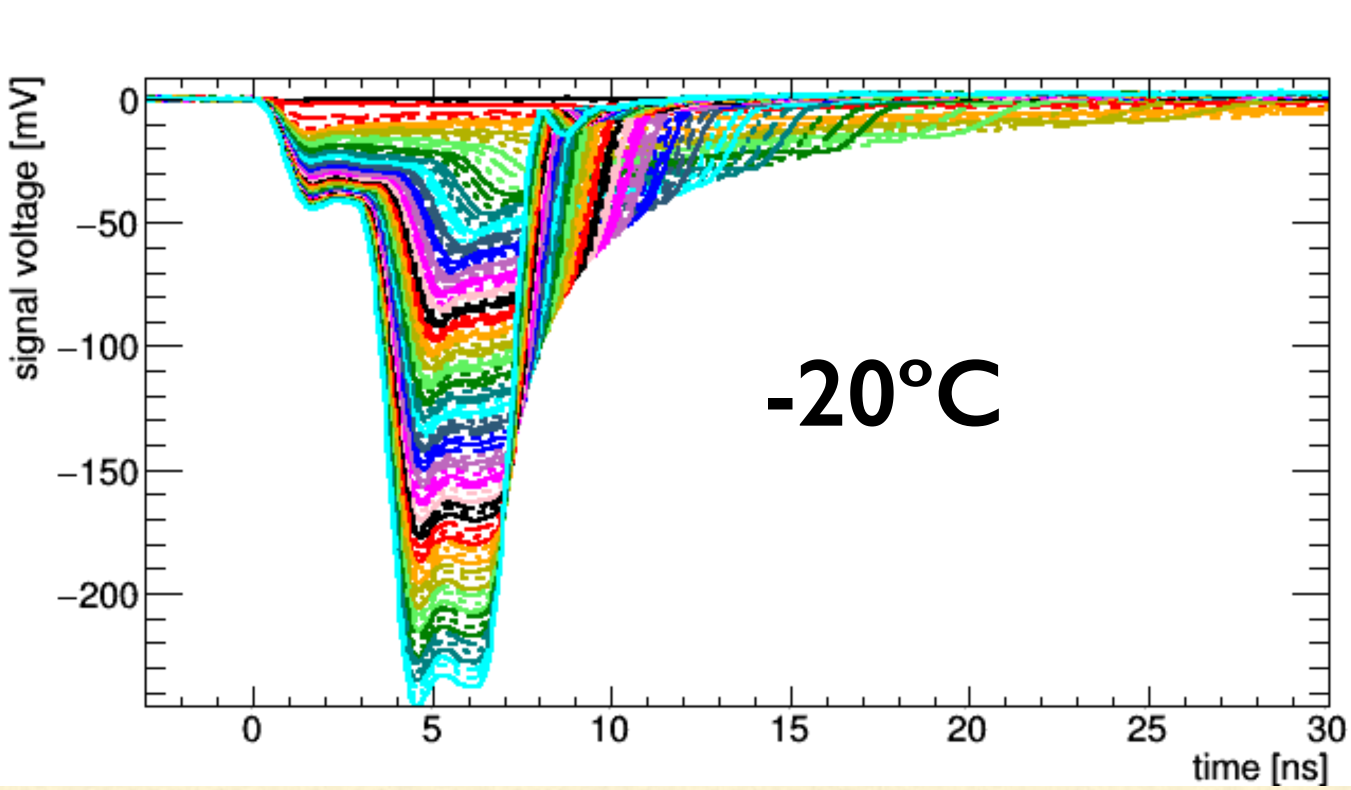
TCT - Red back

LGAD_7_W3_C2-3



Voltage range: 10V to 1000V, 10V steps



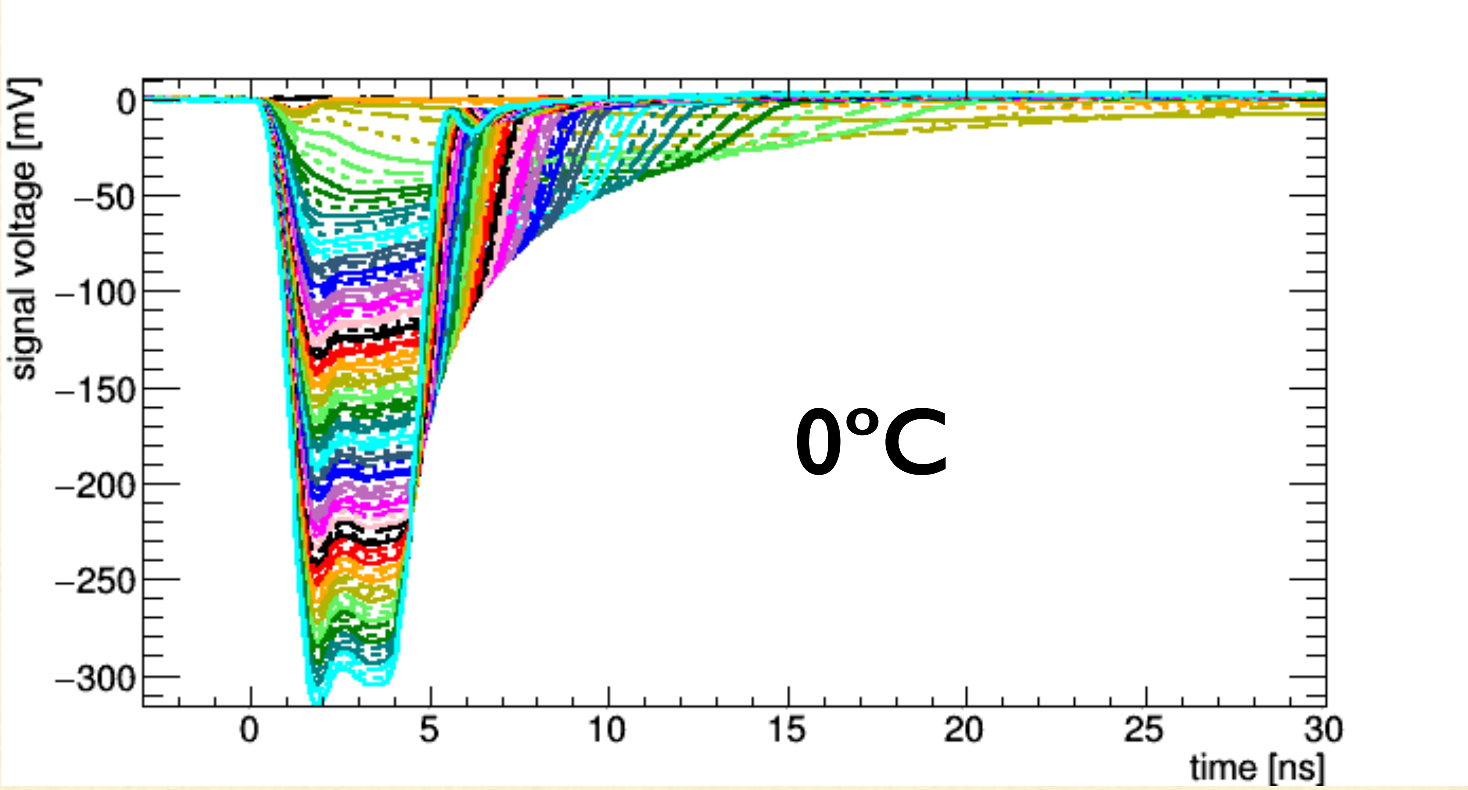


Fluence
$10^{14}\ n_{eq}/cm^2$

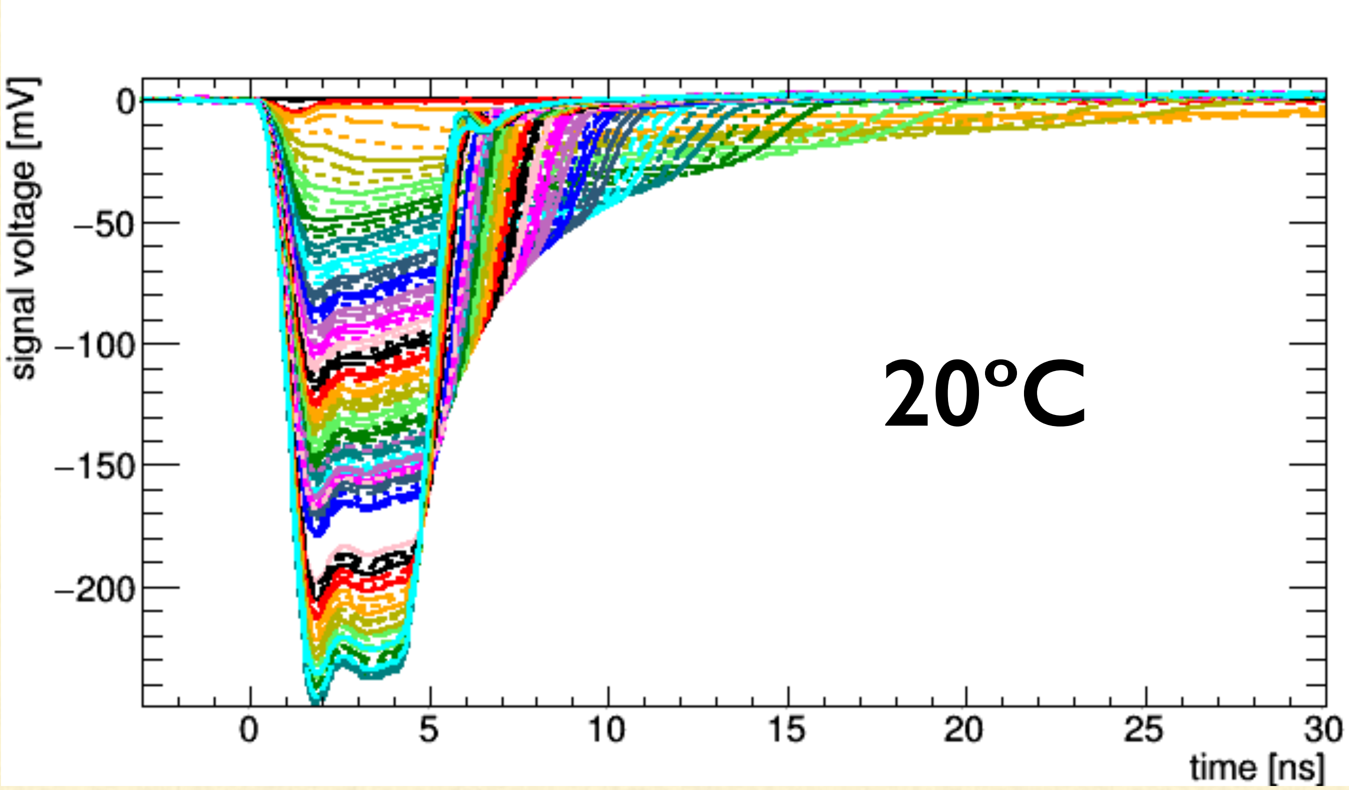
TCT - Red front

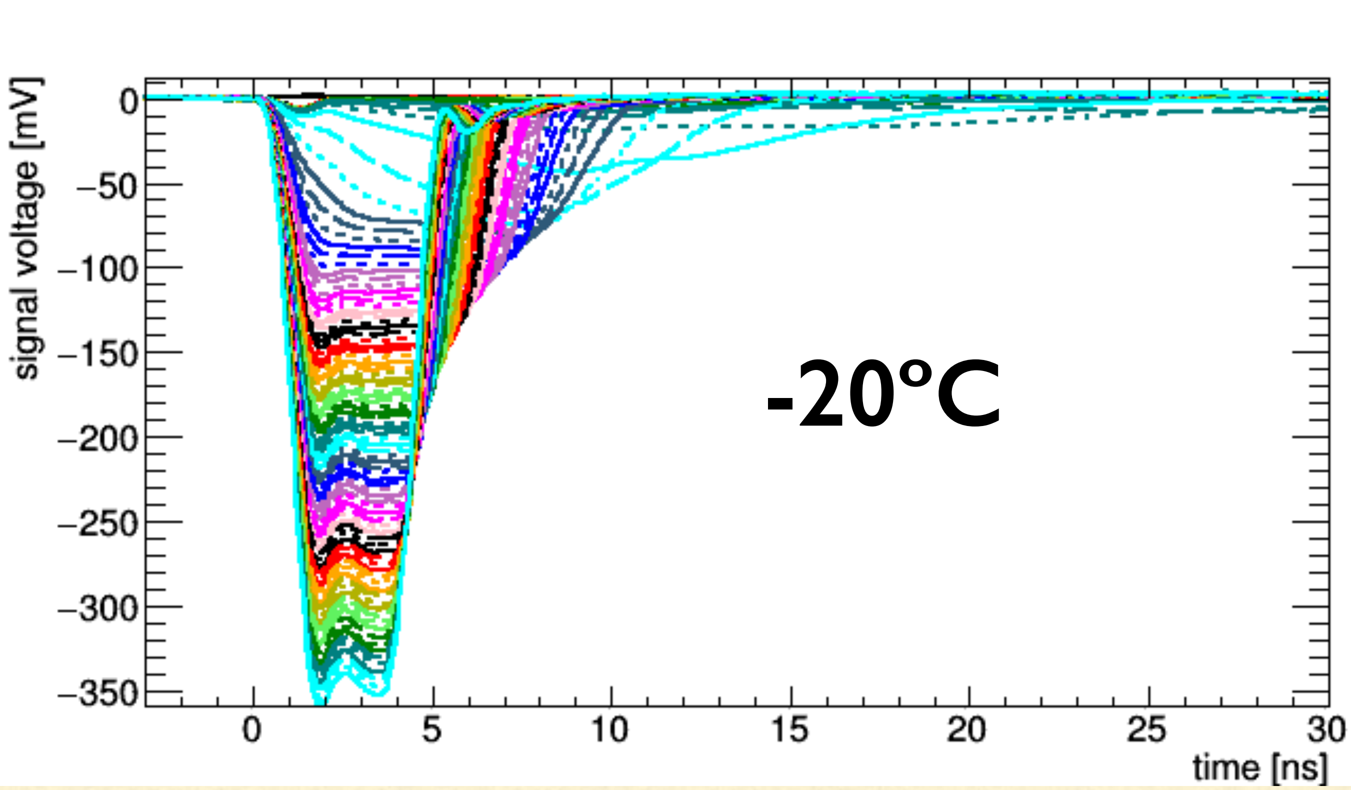
Mult. layer
$2.0\times10^{13} cm^{-2}$

LGAD_7_W3_C2-3



Voltage range:
10 V to 1000 V,
10 V steps



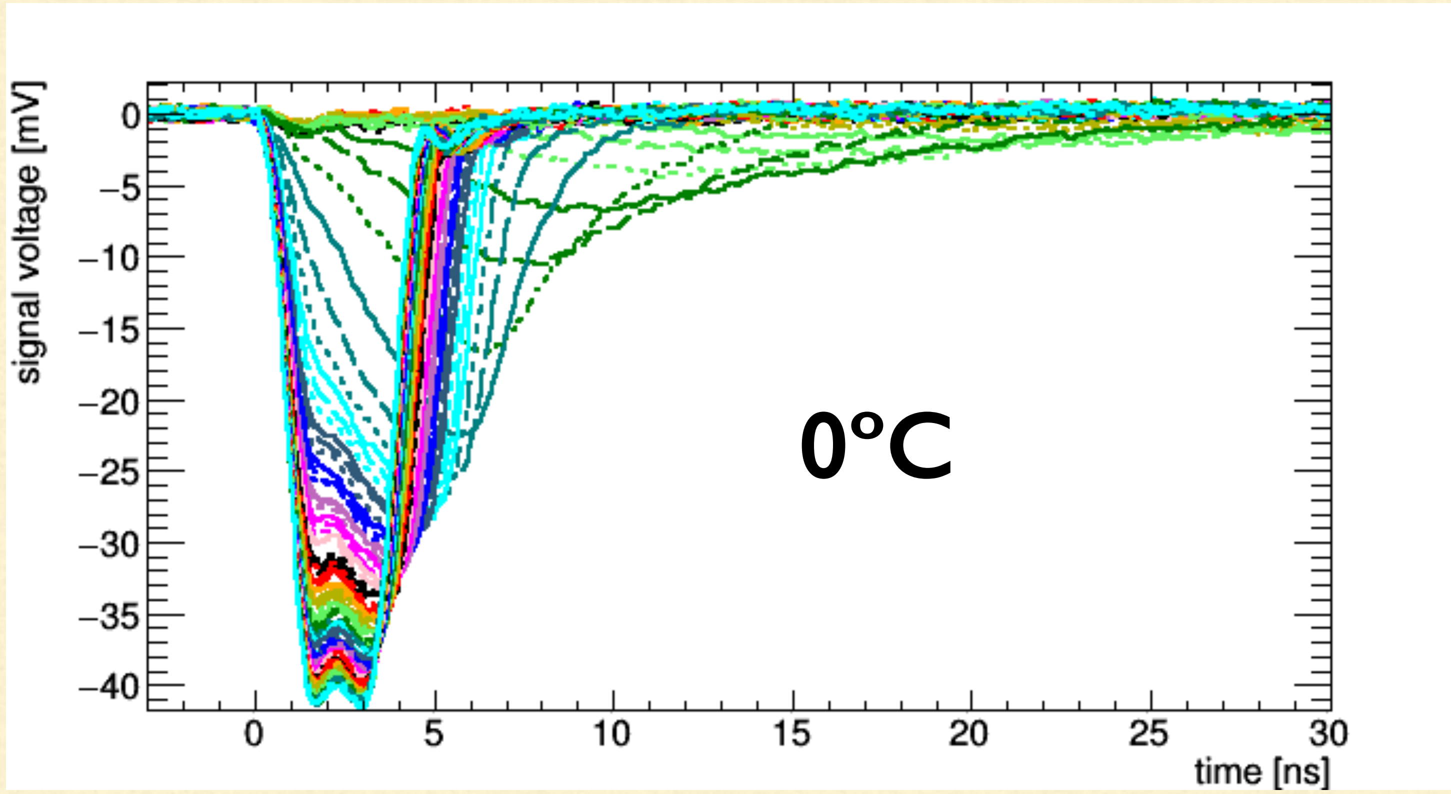


Fluence 10^{14} n_{eq}/cm^2

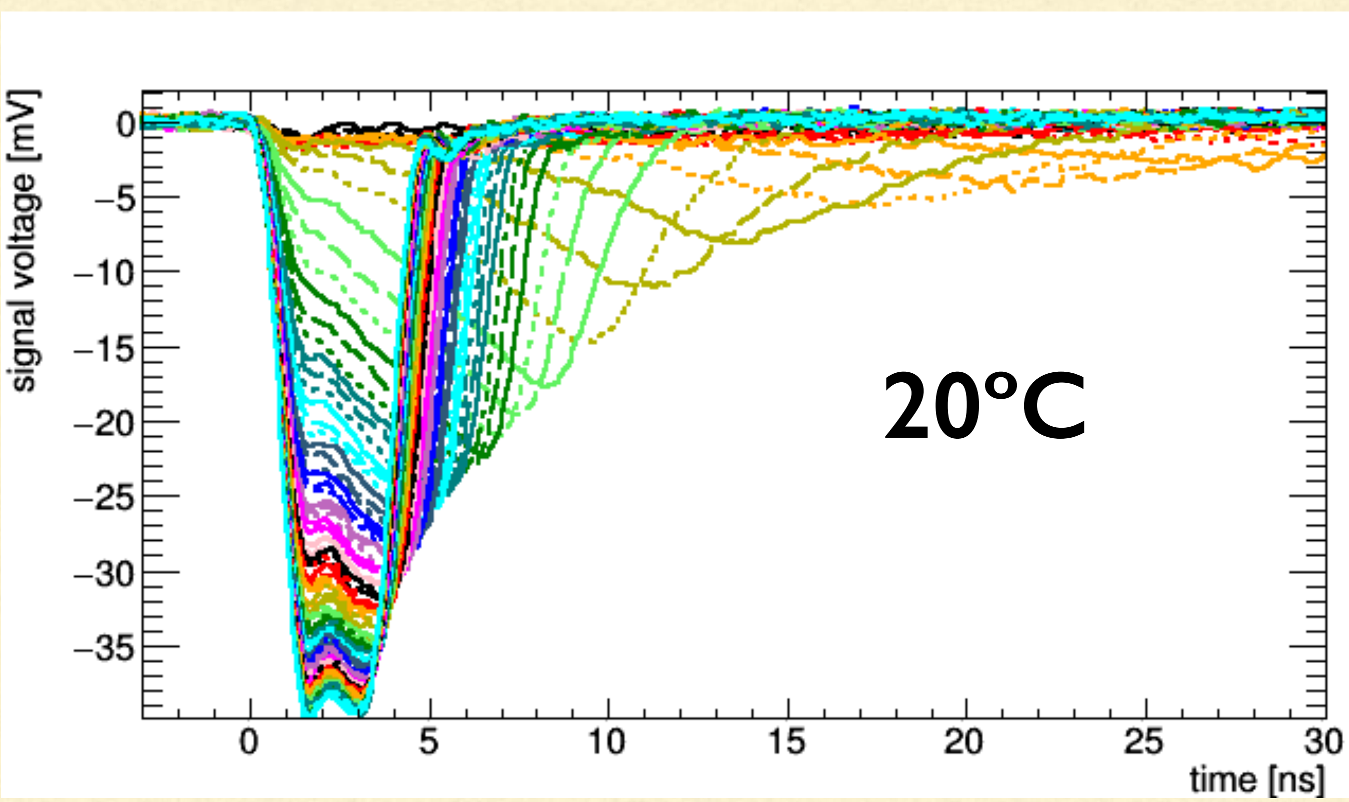
TCT - Red back

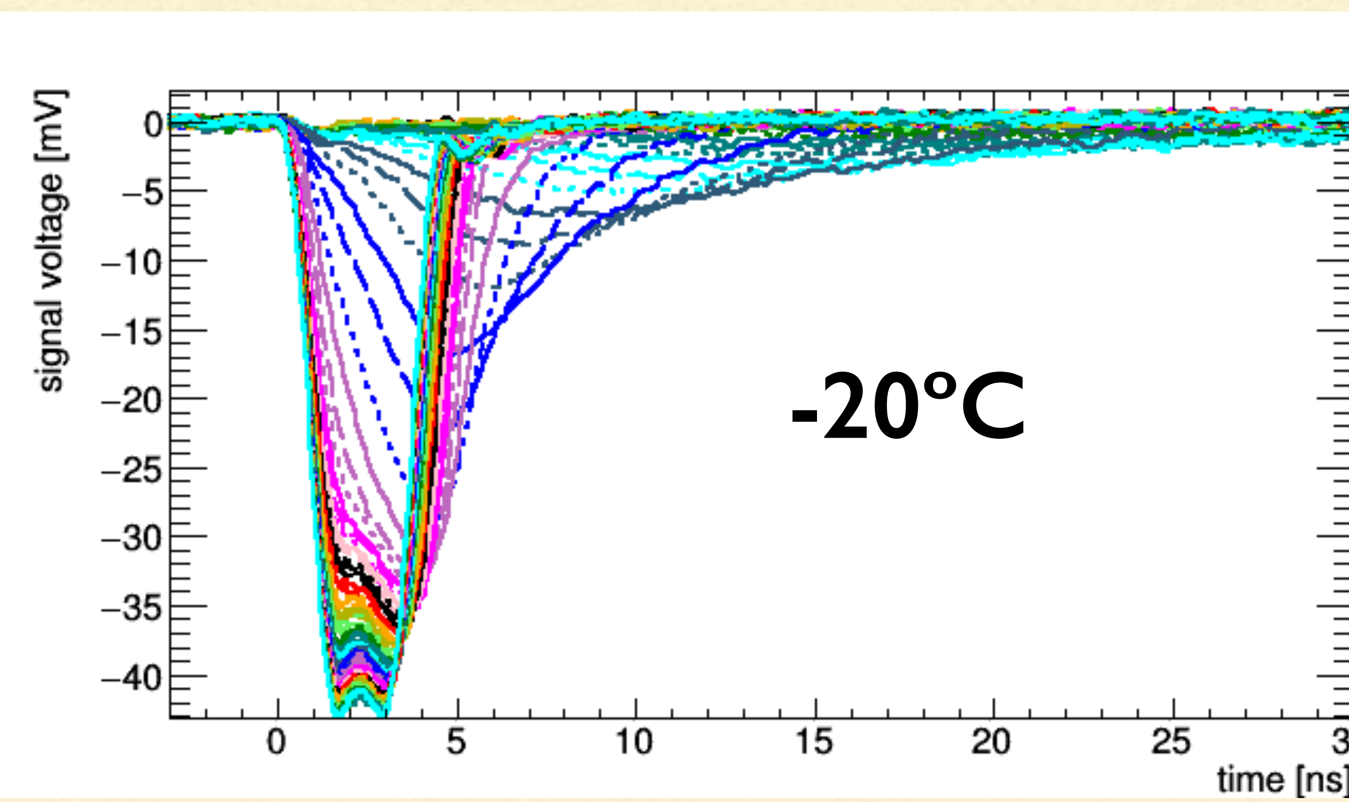
Mult. layer $2.0\times10^{13}cm^{-2}$

PIN_4_W3_I8-1



Voltage range: 10V to 1000V, 10V steps



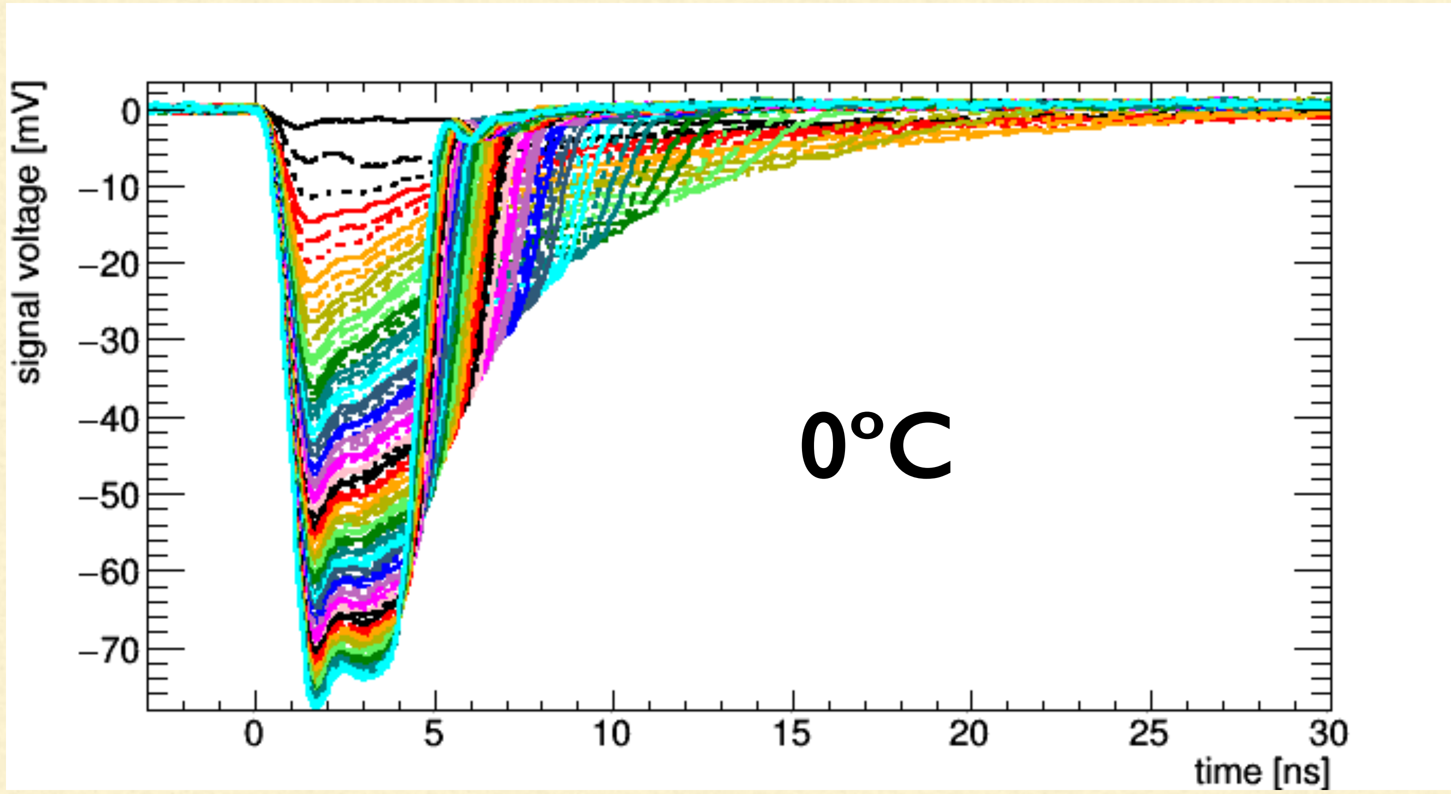


Fluence
$10^{14}\ n_{eq}/cm^2$

TCT - Red front

Mult. layer
$2.0\text{x}10^{13}cm^{-2}$

PIN_4_W3_I8-1



Voltage range:
10V to 1000V,
10V steps