18 MeV Proton Irradiation of Low Gain Avalanche Detectors

Marcos Fernández[1], Veronika Kraus[1,2], Michael Moll[1], Silke Möbius[3], Sebastian Pape[1,4]

[1]CERN, Organisation europénne pour la recherche nucléaire, Geneva, Switzerland
[2]Technische Universität Wien, Vienna, Austria
[3]Universität Bern, Bern, Switzerland
[4]TU Dortmund University, Dortmund, Germany

Last (43rd) RD50 Workshop
30.11.2023

Outline

- Irradiation campaign
- Devices under test
- Electrical characterization
  - IV/CV
  - V_{gl} → Acceptor removal coefficient
- IR Laser TCT
  - Gain
  - Timing
- Outlook

Irradiation campaign

Motivation:

- Limited literature on the comparison of irradiation induced LGAD degradation with different proton energies
- Of special interest: low energy protons (more point-like defects, which contribute differently to some device damage parameters compared to clustered defects) → limits of the Non-Ionizing Energy Loss (NIEL) scaling

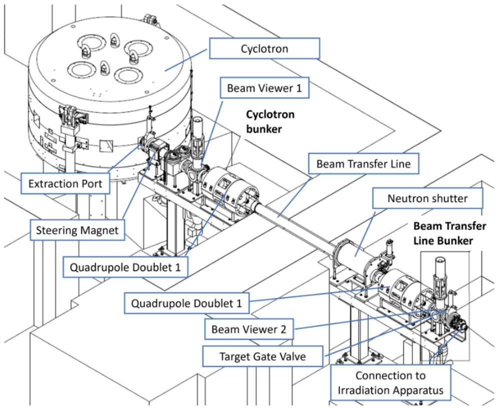
  (For more information take a look at Vendula Subert's work!)
- Comparison to neutron irradiation
- Comparison of samples from different producers

Ongoing irradiation campaign: Proton irradiation at three facilities of over 100 samples (CNM and HPK)

- 23 GeV protons at CERN
- 500 MeV protons at LANSCE
- 18 MeV protons at Bern → This talk is going to cover one part of the study, the 18 MeV p^+

Irradiation with 18 MeV protons:

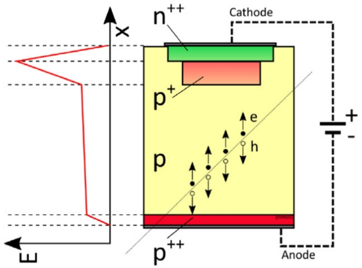
- Medical cyclotron at the Bern University Hospital
- Hardness factor for conversion to 1 MeV neutron equivalent fluence: 1.4
- Five requested fluences: $1 \cdot 10^{13}$, $4 \cdot 10^{14}$, $8 \cdot 10^{14}$, $1.5 \cdot 10^{15}$, $2.5 \cdot 10^{15}$ p/cm^2



Scheme of the Bern University Hospital cyclotron and irradiation bunkers.

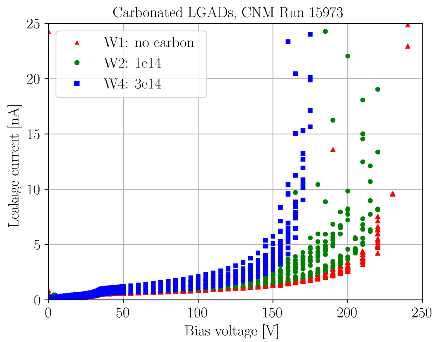
Devices under test

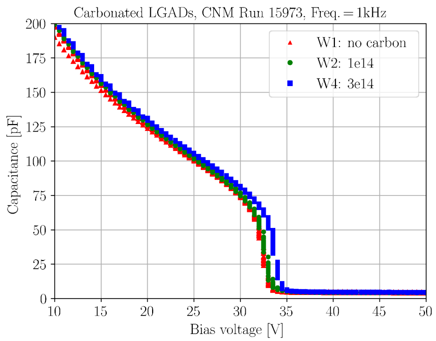
LGADs - Semiconductor detectors with signal amplification:
In a highly-doped p+ layer a high electric field is created → avalanche multiplication of primary electrons → good Signal-to-Noise Ratio and timing capabilities

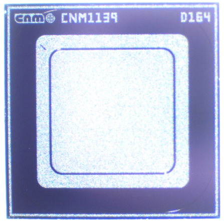


Samples included in the study: CNM run 15973

- Three wafers with different carbon enrichment (to mitigate degradation of gain layer)
  - W1: no carbon
  - W2: $1 \cdot 10^{14}$ /cm^2
  - W4: $3 \cdot 10^{14}$ /cm^2
- Boron dose: $1.9 \cdot 10^{13}$ /cm^2
- Active area: 1.3x1.3 mm^2
- Active volume 50 µm, support wafer 350 µm







IV/CV curves before irradiation (measured at 20°C, CV 1 kHz):
- Slight differences in the average V_{gl} value for the three wafers with different carbon content
- W1:~31.4 V, W2:~32 V, W4:~32.7 V
- Boron content in the gain layer is the same for all wafers, slightly different gain comes from different carbon concentrations acting as diffusion suppressor for boron during fabrication

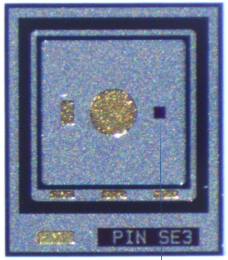
Devices under test

Samples included in the study: HPK prototype 2

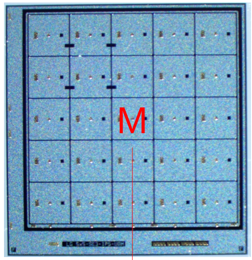
- Single LGADs from W25 and W36 (Tray 5)
- Active area: 1.3x1.3 mm^2
- 50 µm epitaxial layer
- 150 µm low resistivity support wafer

- 5x5 LGAD grid from W33, W37 and W42 with similar properties

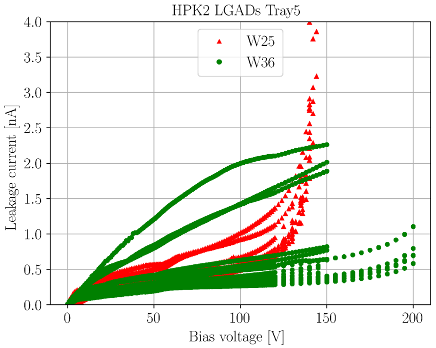
(all these samples are part of a large study comparing irradiation with different proton energies, in the 18 MeV proton irradiation only 5x5 LGADs of W37 are included due to limited sample numbers)

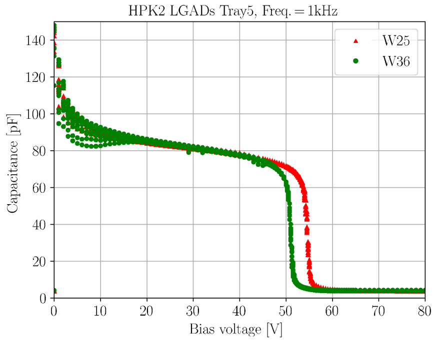


Opening for TCT measurements

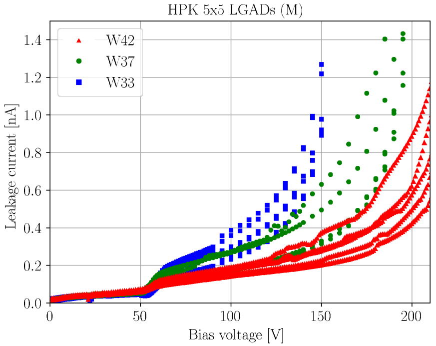


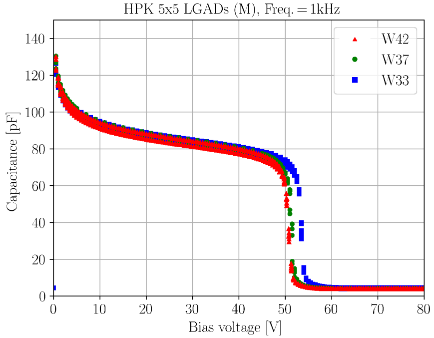
Middle LGAD shown in plot





- W25: lower breakdown voltage (indication for higher gain)
- V_{gl} between 50 and 60 V



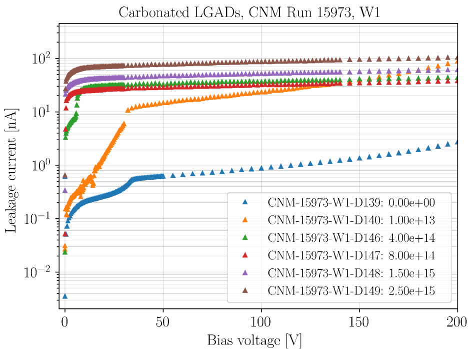


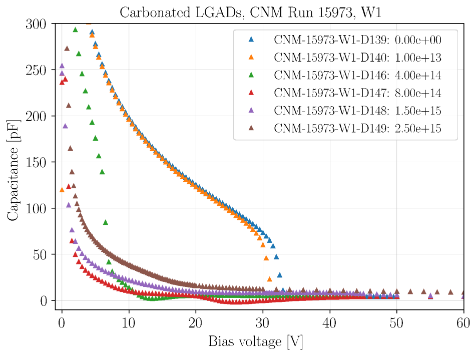
- V_{gl} for three different wafers also between 50 and 60 V

IV/CV characteristics: CNM

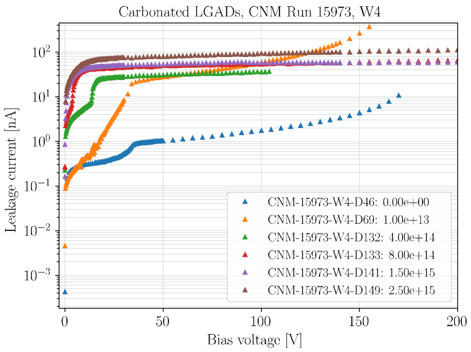
Annealing after irradiation: 80 min, 60°C
IV measured at -20°C, CV at 10°C and 100 Hz

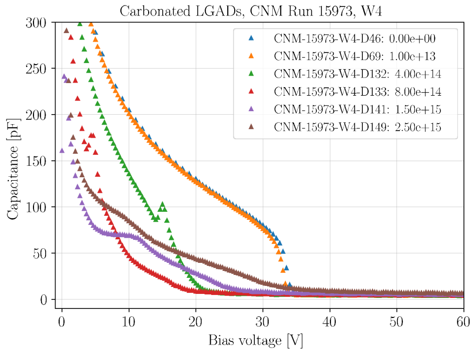
W1 (no carbon): IV and CV curves with increasing fluence





W4 ($3 \cdot 10^{13}$/cm^2): IV and CV curves with increasing fluence

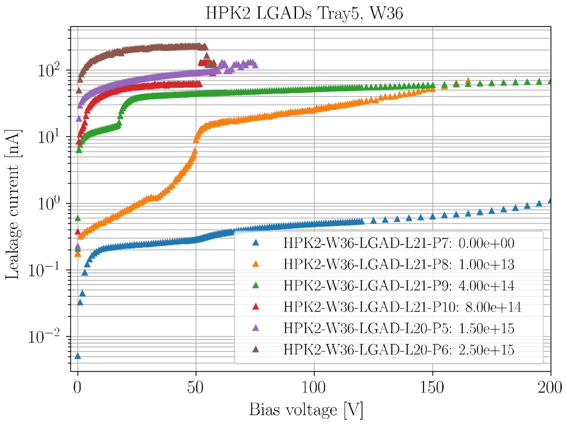


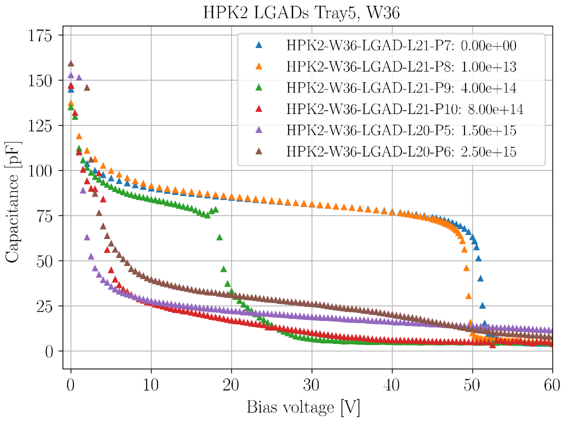


- Small shift in V_{gl} between the not irrad. sample and first fluence ($1 \cdot 10^{13}$ p/cm^2), increase in leakage current
- $8 \cdot 10^{14}$ p/cm^2 and higher fluences: pin-like behavior
- Comparing W1 and W4: carbon implantation seems to improve the irradiation induced degradation of the gain layer

IV/CV characteristics: HPK

Annealing after irradiation: 80 min, 60°C
IV measured at -20°C, CV at 10°C and 100 Hz





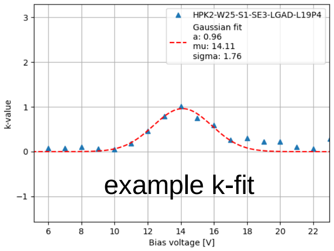
Exemplary for HPK2 LGADs: W36 IV and CV curves with increasing fluence

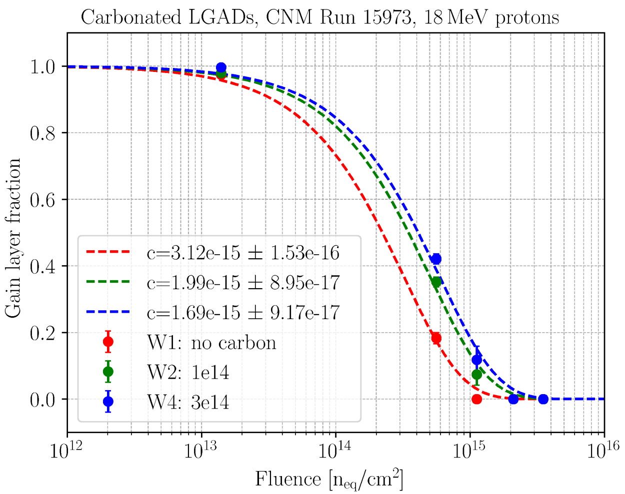
Same trends as for CNM samples:

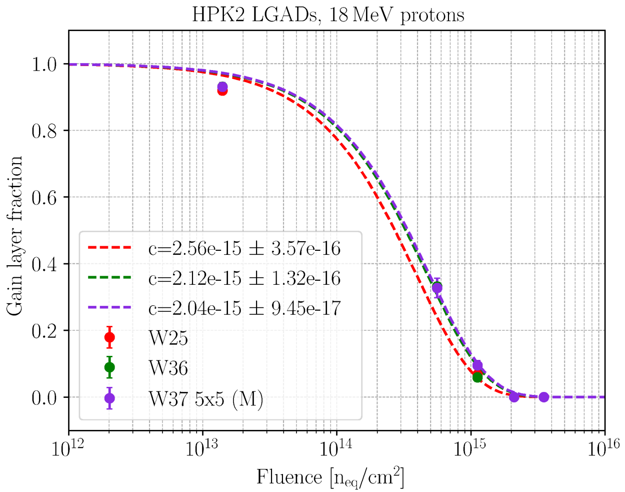
- Small shift in V_{gl} between the not irrad. sample and first fluence ($1 \cdot 10^{13}$ p/cm^2)
- Increase in leakage current with irradiation
- $8 \cdot 10^{14}$ p/cm^2 and higher fluences: pin-like behavior

Acceptor removal coefficient

- V_{gl} obtained from IV curves with the k-fit method $k(I,V)=\frac{\Delta I}{\Delta V}\frac{V}{I}$
- V_{gl} normalized to the non-irradiated sample and plotted over the neutron-equivalent fluence (κ = 1.4): acceptor removal coefficient (c) can be fitted $\frac{V_{gl}(\Phi_{eq})}{V_{gl}(0)} \approx e^{-c\Phi_{eq}}$





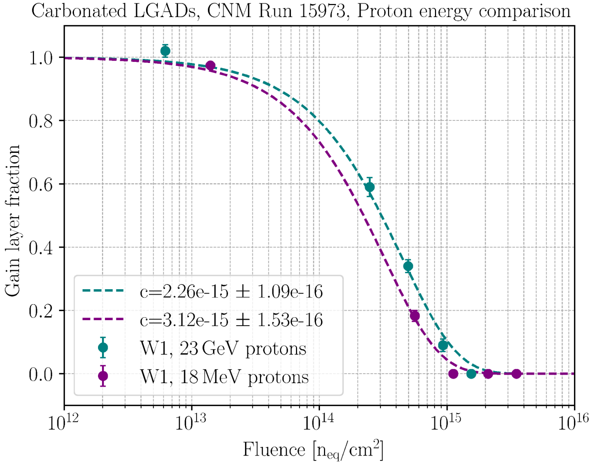


Difference in c-value visible for CNM samples with increasing carbon implantation

Acceptor removal coefficient

- V_{gl} obtained from IV curves with the k-fit method $k(I,V)=\frac{\Delta I}{\Delta V}\frac{V}{I}$
- V_{gl} normalized to the non-irradiated sample and plotted over the neutron-equivalent fluence (κ = 1.4): acceptor removal coefficient (c) can be fitted $\frac{V_{gl}(\Phi_{eq})}{V_{gl}(0)} \approx e^{-c\,\Phi_{eq}}$

- Comparison 18 MeV proton results to other studies with different energies and particles (neutron-equivalent fluence): Higher c-values → more damaging!
- 18 MeV protons demonstrate the limits of NIEL scaling
- More point- than cluster-defects induced



eg. comparison to first results of CNM W1, SAME SAMPLES but 23 GeV proton irradiation (κ = 0.62): c-value difference ~38%

Wafer #	c [10^{-16} cm²] (no annealing)	c [10^{-16} cm²] (80 min @ 60C)
W1	6.40	7.08
W2	4.07	4.31
W3	3.55	3.91
W4	3.45	3.66
W5	3.53	3.82
W6	3.51	3.76

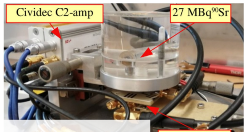
eg. comparison to RD50 talk by Alissa Howard: measurements of CNM samples from the same run, n irradiated
https://indico.cern.ch/event/1270076/contributions/5450203/attachments/2670347/4629062/RD50_Tivat_CNM_FirstMeasurements.pdf

→ Protons more damaging than neutrons

TCT

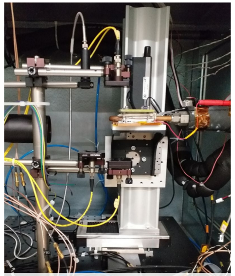
Laser characterization with Transient Current Technique (TCT)

- Pulsed IR-Laser (1060 nm) from top
- Only HPK2 single LGADs included in the laser characterization study because CNM samples have no opening window (CNM samples will be studies with ^{90}Sr source)
- First ^{90}Sr source measurements performed to confirm TCT results



^{90}Sr setup


Electrical and readout system

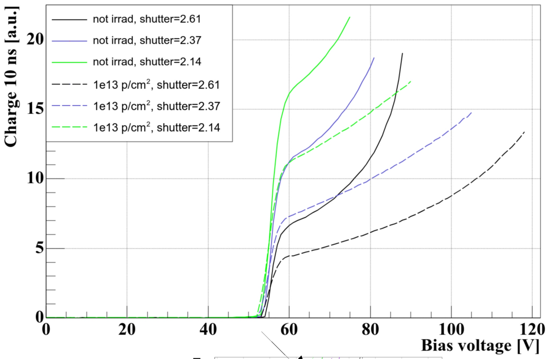

Optical system and linear stage

TCT setup SSD lab, CERN

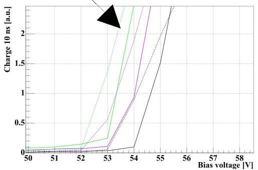
Preliminary results:

Comparing not irradiated sample to first fluence ($1{\cdot}10^{13}$ p/cm^2):
Difference in V_{gl} ~1-2 V but strongly pronounced difference in charge!

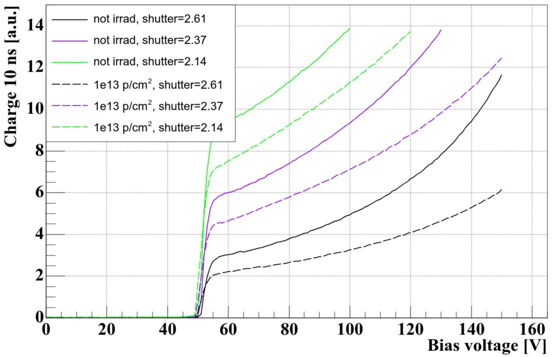
HPK2-W25: not irrad vs lowest fluence



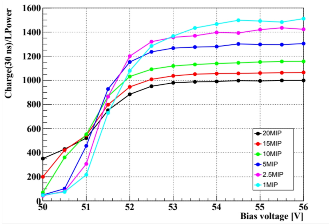
zoom



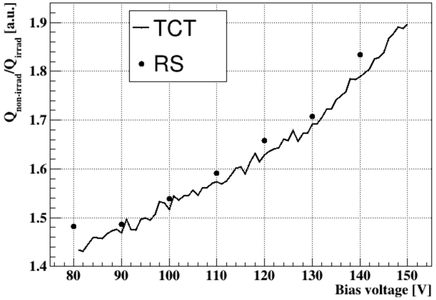
HPK2-W36: not irrad vs lowest fluence



Measurements at -20°C, lowest tested laser power (shutter=2.16) corresponds to ~ 7 MIPs



HPK2-W36: measurement of not irrad. LGAD at different laser powers: V_{gl} shift

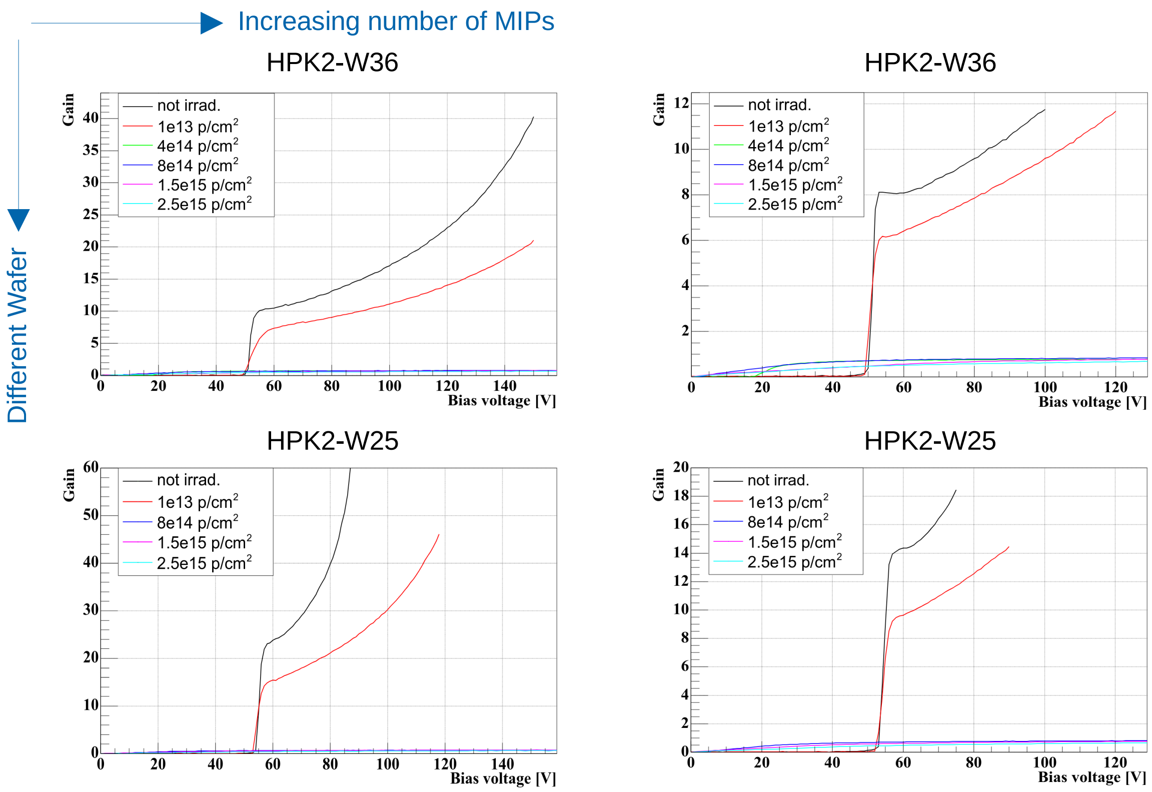


Comparison with ^{90}Sr source measurements: ratio between not irrad LGAD and first fluence are the same!

Gain measurements

Gain gets evaluated as the ratio between the LGAD collected charge and the equivalent unirradiated PIN collected charge after full depletion

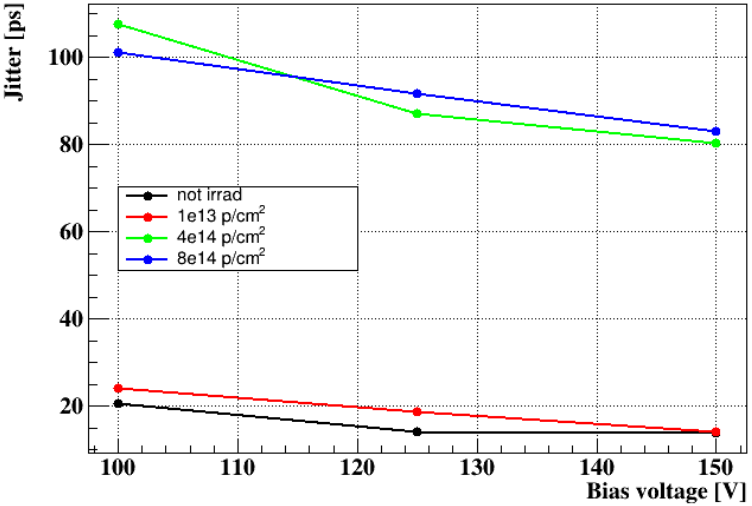
$$Gain[V] = \frac{CC_{LAGD}[V]}{CC_{PIN}[V \geq V_{FD}]}$$



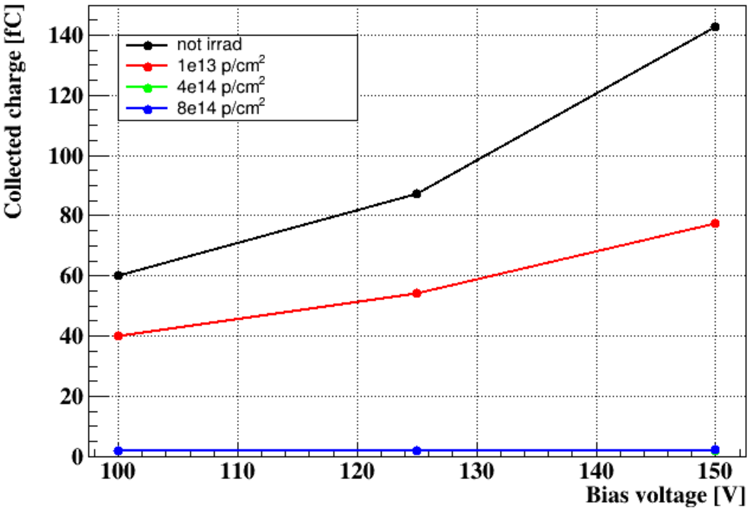
- Already after irradiation with 18 MeV protons, $4 \cdot 10^{14}$ p/cm^2: LGAD gain heavily reduced
- More MIPs show less gain: gain suppression
- W25 has higher gain compared to W36 (as already seen in IV/CV measurements)

Timing

- Timing studies for subset of HPK2-W36 LGADs (not irrad. to fluence $8 \cdot 10^{14}$ p/cm^2) to show trends in behavior after 18 MeV proton irradiation
- Presented timing results for IR top laser illumination in two-pulse configuration, laser power ~ 7 MIPs, measured at -20°C



Time resolution contributions:
1) Landau fluctuations, not given with lasers measurements
2) Timing differences due to amplitude fluctuations (Time Walk), can be corrected by constant fraction discrimination
3) Sensor jitter
→ results underestimate LGAD time resolution



Sample $4 \cdot 10^{14}$ p/cm^2 and $8 \cdot 10^{14}$ p/cm^2 around 2 fC, as comparison Q(Pin) = 0.54 fC

As seen in gain measurements: LGAD degradation already far advanced after irradiation with 18 MeV protons, $4 \cdot 10^{14}$ p/cm^2

Outlook

18 MeV proton irradiation:

- IV/CV characteristics:
  - HPK and CNM samples show pin-like behavior for $8 \cdot 10^{14}$ p/cm^2 and higher fluences
  - CNM LGADs: Comparing **different carbon doses** in gain layer shows least irradiation induced degradation for highest tested dose of $3 \cdot 10^{14}$ /cm^2: c(W1) = $3.12 \cdot 10^{-15}$ vs c(W4) = $1.69 \cdot 10^{-15}$ (wafers were selected as the sweet spot based on previous studies of same samples also including higher carbon doses)

- **Gain and timing** measurements of HPK2 samples **agree**: LGAD degradation already significant after $1 \cdot 10^{13}$ p/cm^2 and far advanced after irradiation to a fluence of $4 \cdot 10^{14}$ p/cm^2 with 18 MeV protons

- 18 MeV protons **more damaging** compared to higher proton energies!

Further steps:

- 18 MeV protons: in-depth studies with ^{90}Sr source, TCT red light, …

- Analysis and comparison with same type of samples after 500 MeV and 23 GeV proton irradiation

- Completing the study with TCAD simulations

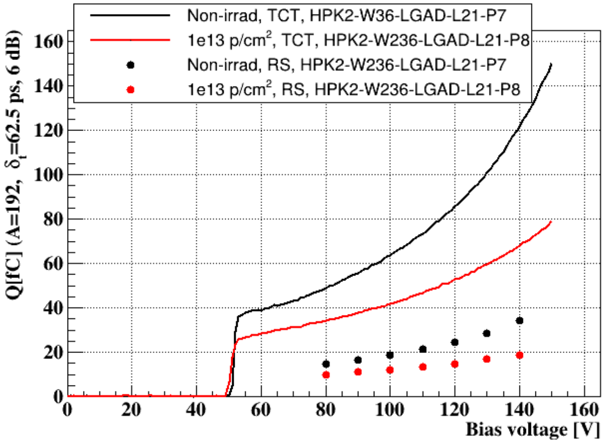
Backup

TCT

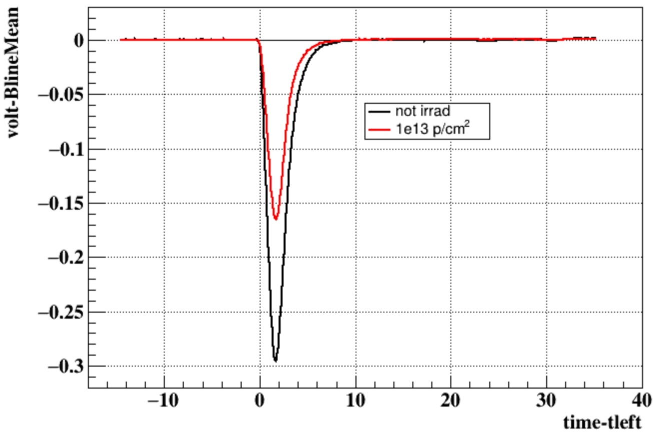
Preliminary results:

Comparing not irradiated sample to first fluence ($1 \cdot 10^{13}\ p/cm^2$):

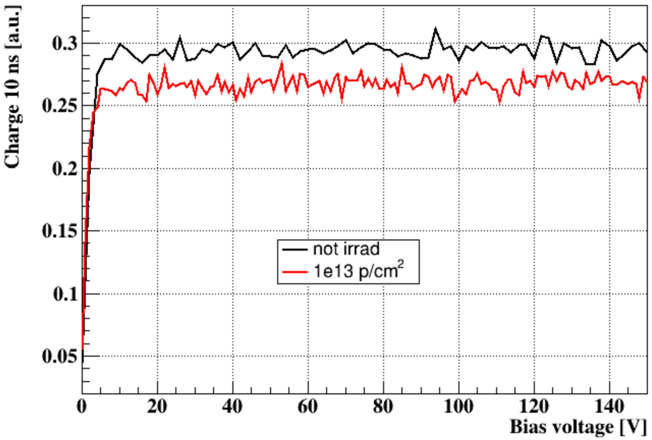
Difference in V_{gl} ~1-2 V but strongly pronounced difference in charge!



Ratio between non-irradiated and irradiated in TCT(line) with the same ratio for RS (markers). Despite the gain reduction being different for both, the relative variation is still the same.



Comparison of waveforms HPK2-W25, ~7 MIPs, at 80 V (after full depletion): difference in amplitude, which is the only parameter that changes



Comparison of charge in the corresponding not irrad and lowest fluence pins