Proton Energy Dependence of Radiation Induced Gain Layer Degradation in LGADs

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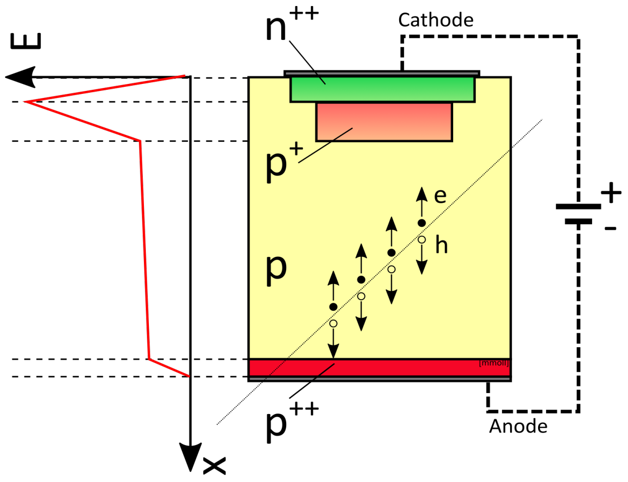
Outline

- **Motivation**
- **Project Overview**
- **Electrical Characterization**
  - Current and capacitance measurements
  - Acceptor removal coefficients in comparison
- **Laser Characterization**
  - Gain studies
  - Gain suppression
  - Timing with comparison to radioactive source measurements
- **Summary & Outlook**

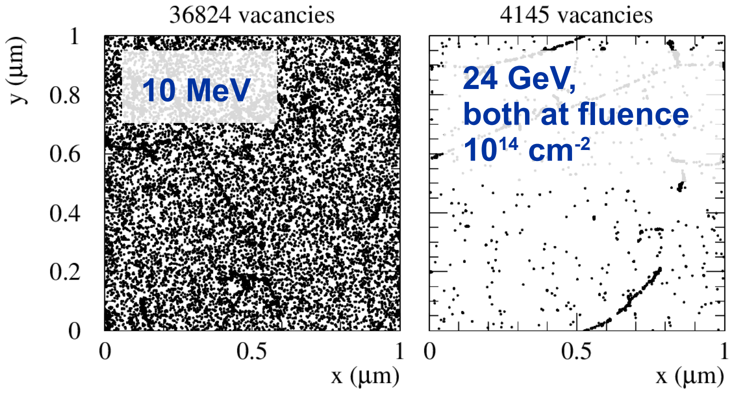
Motivation

- **Low Gain Avalanche Detectors (LGADs):** Gain layer produces an electric field peak → avalanche multiplication of primary e$^-$ → good signal-to-noise ratio and timing capabilities (e.g.: for pile-up at HL-LHC)
- **Radiation damage** in LGADs leads to a degradation of the gain layer due to acceptor removal → **loss of signal amplification**
- Limited literature on the comparison of irradiation induced **LGAD degradation with different proton energies**
- **Of special interest: low energy protons → limits of the Non-Ionizing Energy Loss (NIEL) scaling** (doesn't distinguish between cluster and point displacement)

$$NIEL(T_0) = \frac{N_A}{A} \sum_i \int_{T_{min}}^{T_{max}} Q(T)\, T \left(\frac{d\sigma}{dT} \right)_i dT$$

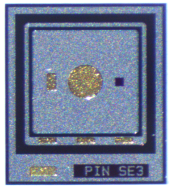


Simulations of radiation damage by M. Huhtinen:



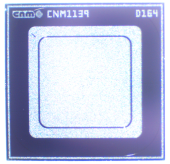
Project Overview

- Proton irradiation of over **100 samples at four irradiation facilities**
- Fluences **$1\cdot10^{13}$ to $2.5\cdot10^{15}$ p/cm²**, depending on energy: up to $7.5\cdot10^{15}$ 1 MeV neutron equivalent fluence (n_{eq})



HPK Prototype 2

- Single LGADs from Wafer 25 and 36
- Active area 1.3 x 1.3 mm², 50 µm epitaxial layer, V_{gl}: 50 - 60 V



CNM Run 15973

- Wafers with different carbon enrichment:
  - W1: no carbon
  - W2: $1\cdot10^{14}$ cm^{-2}
  - W4: $3\cdot10^{14}$ cm^{-2}
- Active area 1.3 x 1.3 mm², active thickness 50 µm, V_{gl}: 30-35 V
- No opening in the topside metallization

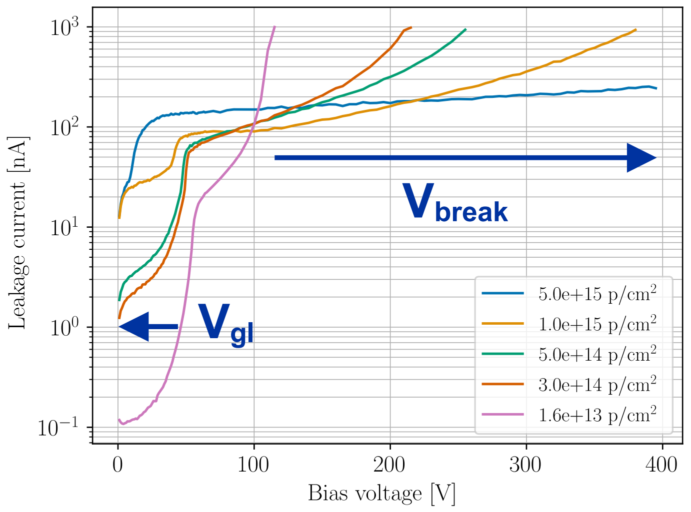
Proton Energy	Samples	Hardness Factor *(M. Huhtinen, G.P. Summers)*
18 MeV (Bern University Hospital)	HKP2 W25	3
24 MeV (University of Birmingham)	HPK2 W25, W36	2.56
400 MeV (Fermilab)	HPK2 W25, W36 CNM W1, W2, W4	0.83
23 GeV (CERN PS-IRRAD)	HPK2 W25, W36 CNM W1, W2, W4	0.62

Electrical Characterization

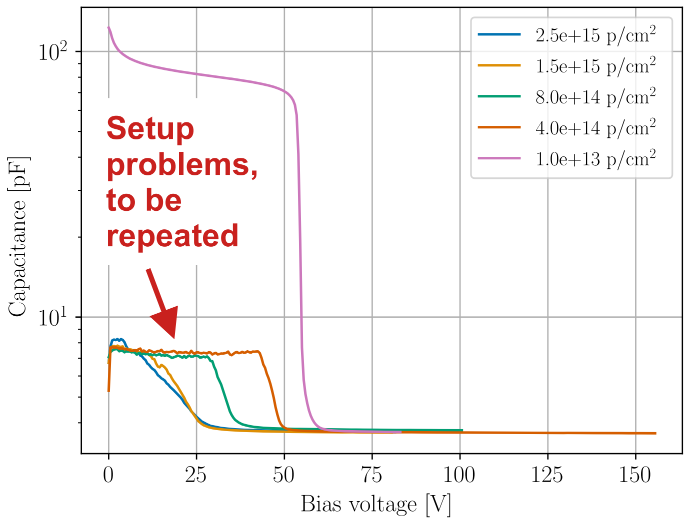
- Exemplary **Current - Voltage (I-V) and Capacitance - Voltage (C-V)** characteristics
  - HPK2 W25, Proton energies of 400 MeV and 23 GeV
  - Measurements at -20°C, 1 kHz, ann. 60 min at 80°C

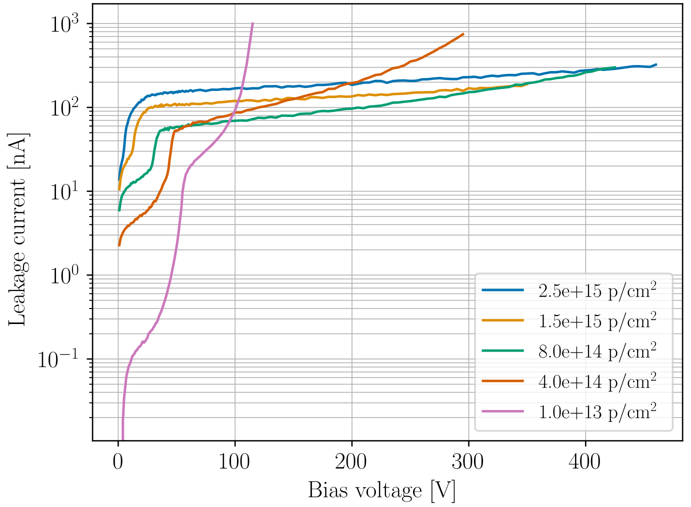
- Expected trends with increasing fluences: **V_{break} and V_{gl} shift** due to degradation of the gain layer, **leakage current increases**
- Indication: **400 MeV protons less damaging** than higher energy (contrary to expectation)

400 MeV:



23 GeV:



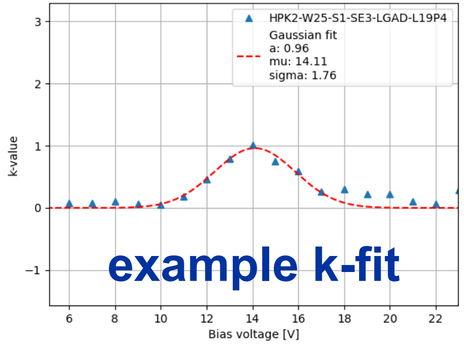


Acc. Removal Coeff.: HPK2 LGADs

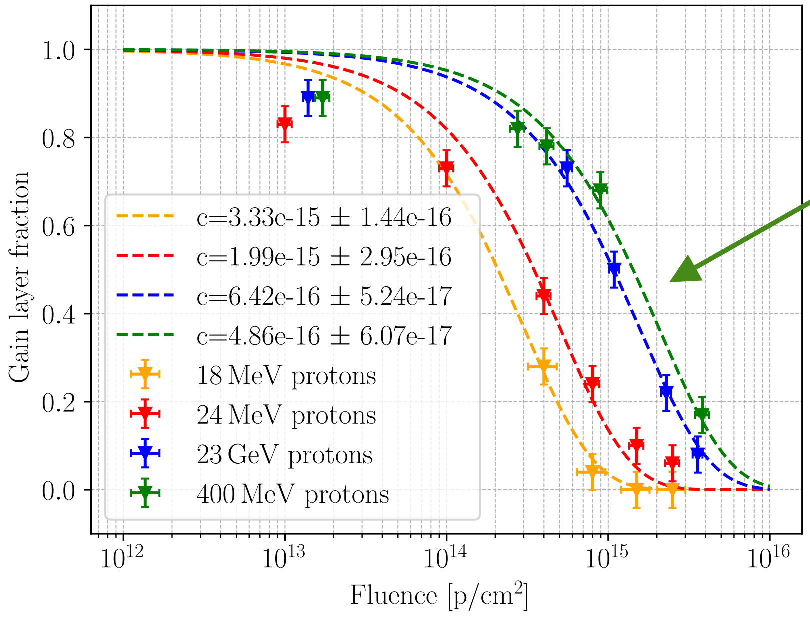
- **V_{gl} obtained from IV curves** with the k-fit method, then normalized to the non-irradiated sample and plotted over fluence: acceptor removal coefficient *c* can be fitted
- Expected trend: **lower-energy protons more damaging**

$$k(I,V)=\frac{\Delta I}{\Delta V}\frac{V}{I}$$

$$\frac{V_{gl}(\Phi_{eq})}{V_{gl}(0)}\approx e^{-c\,\Phi_{eq}}$$

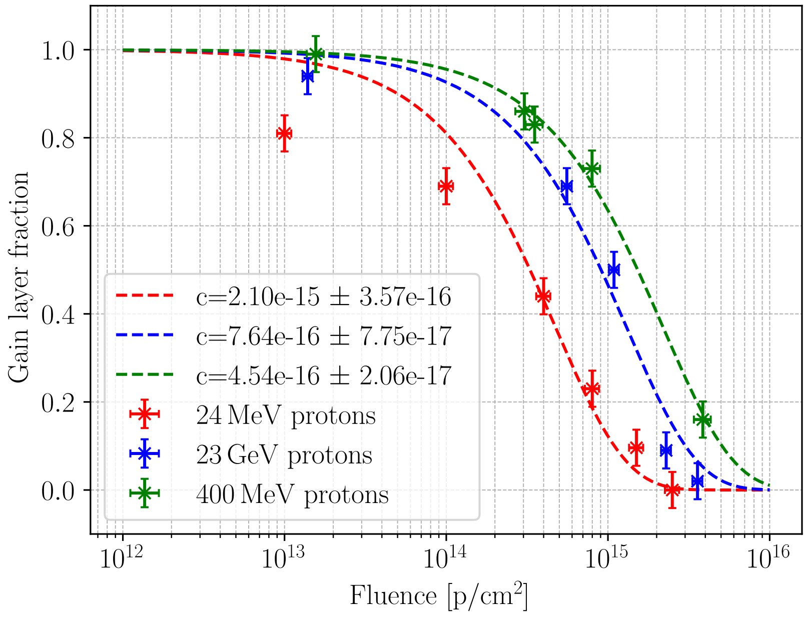


HPK2 W25:



400 MeV protons appear to be the least damaging!

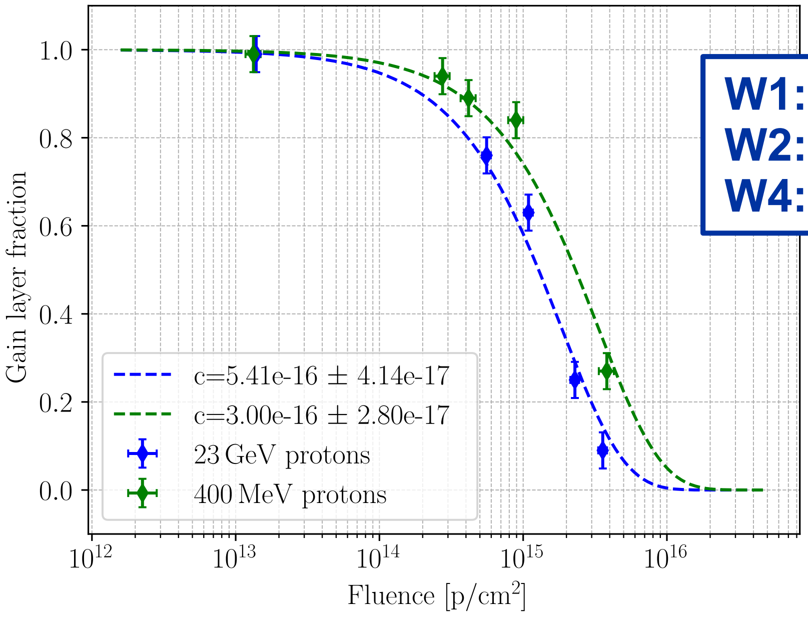
HPK2 W36:



Acc. Removal Coeff.: CNM LGADs

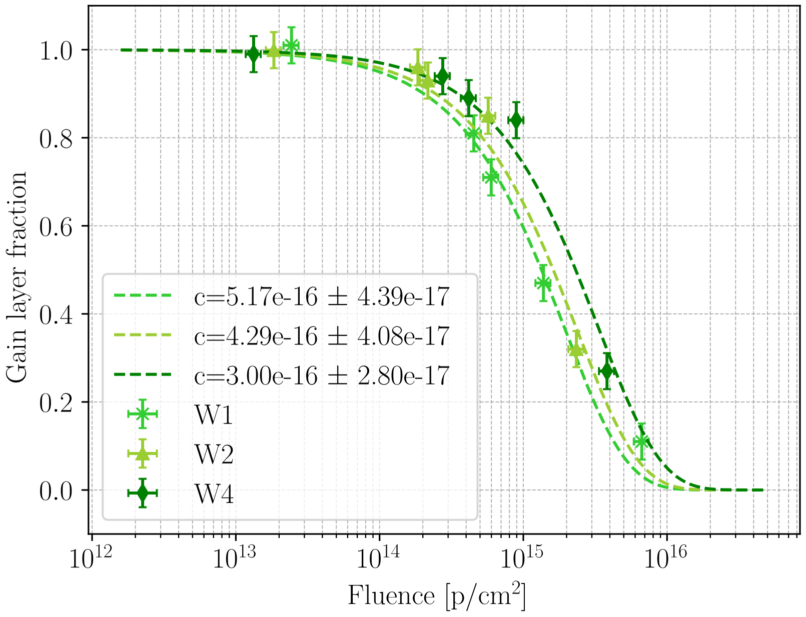
- **Different p-Energies & Same Wafer: 400 MeV** irradiation again results in less acceptor removal than **23 GeV**; Bigger difference between the two energies for carbonated LGADs
- **Different Wafers & Same p-Energy:** Carbon implantation mitigates gain layer degradation

Comparing p-Energies: W4



W1: no carbon
W2: $1 \cdot 10^{14}$ cm^{-2}
W4: $3 \cdot 10^{14}$ cm^{-2}

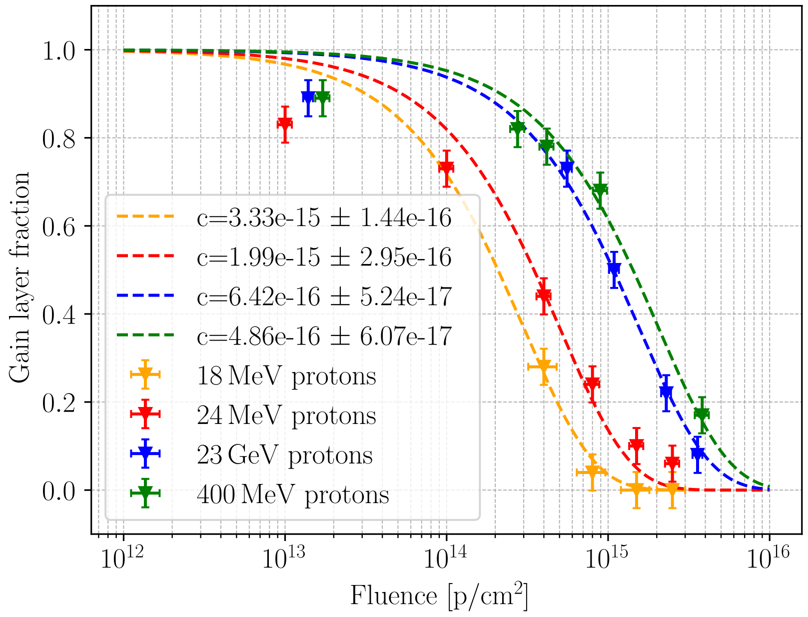
Comparing Wafers: 400 MeV



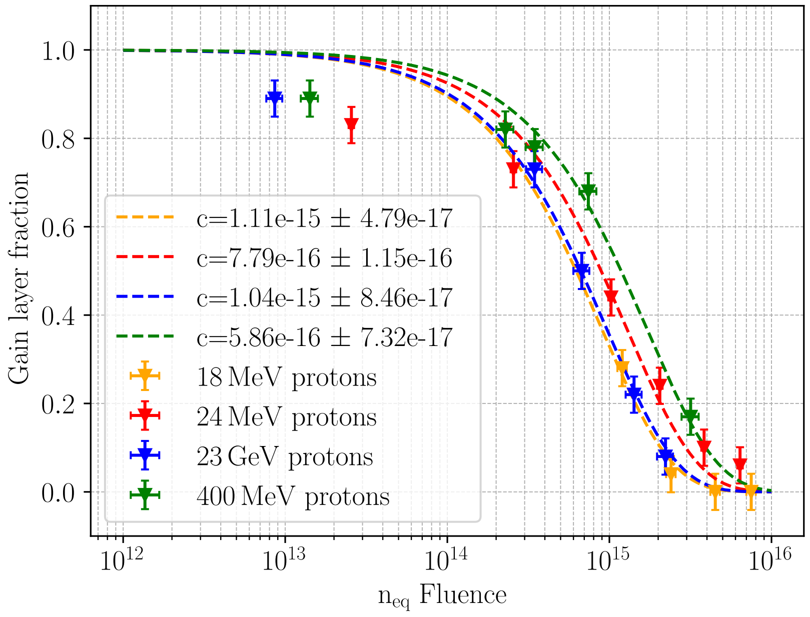
Acc. Removal Coeff. Comparison

- **Converting to 1 MeV n_{eq} fluence:** curves appear closer and their relative order changes
- **Difference in *c* values remains,** indicating that NIEL scaling only partially compensates for different proton energies!

HPK2 W25 with p fluences:

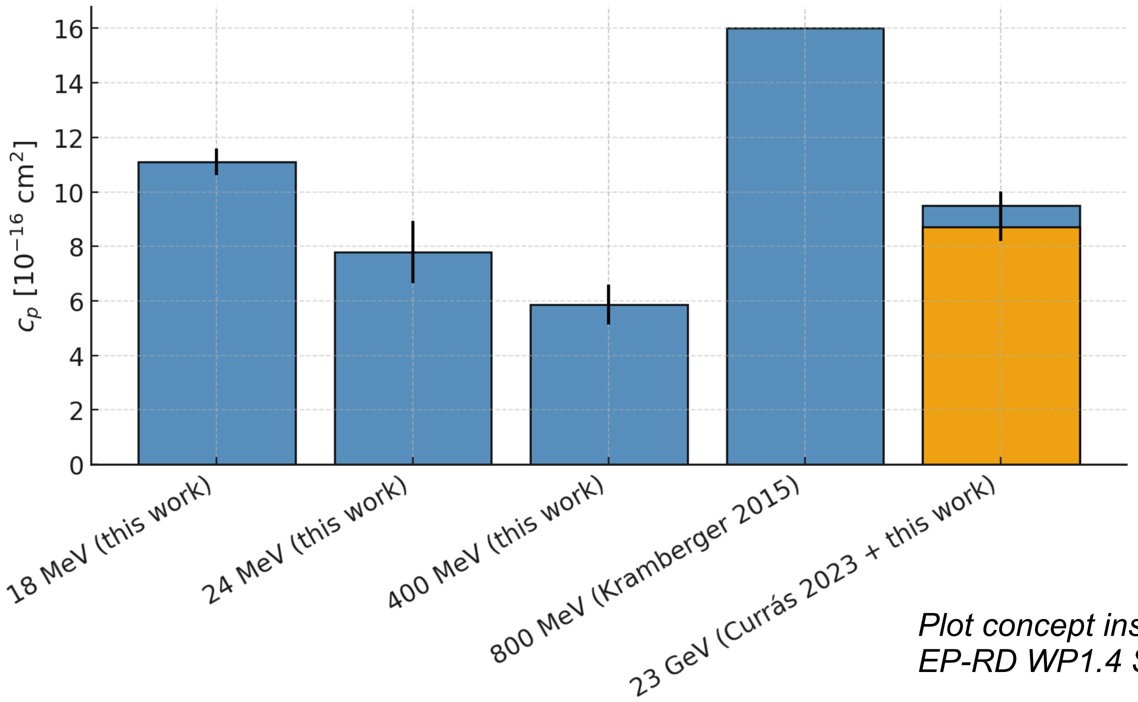


Converting the x-axis to 1 MeV n_{eq} fluence:



Acc. Removal Coeff. Literature Comparison

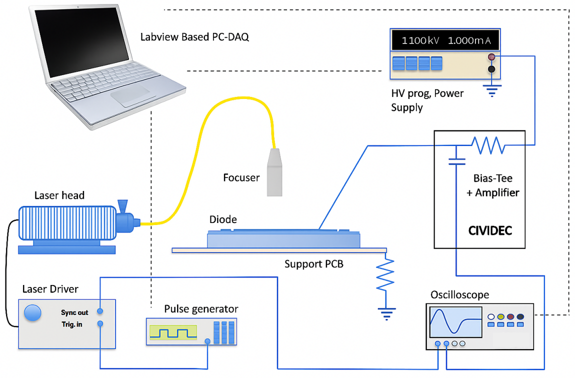
- **LGADs used in HL-LHC timing layer upgrades, some studies available for comparison**
  - Acceptor-removal coefficients for HPK2 LGADs (no carbon) irradiated with protons of different energies
  - *c values* plotted here from V_{gl} fits versus n_{eq} fluence

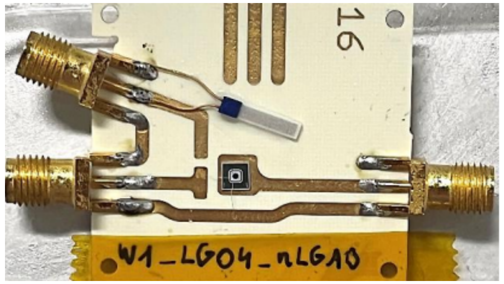


Plot concept inspired by Bojan Hiti, EP-RD WP1.4 Seminar

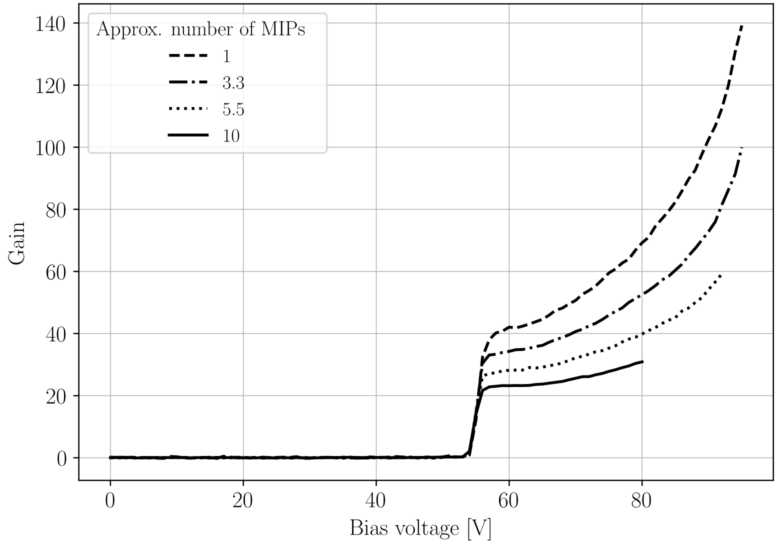
Laser Characterization

- Performed with an **IR laser with λ = 1064 nm ≈** 1.17 eV, spot size 10 µm, SSD laboratory (CERN)
- Tested intensities **~ 10 Minimum Ionizing Particles (MIPs) down to 1 MIP**
- Waveforms for HPK2 (W25) LGADs and diodes measured → Calculation of Collected Charge (CC) → Comparing the CC of LGADs to respective diodes allows to determine the sensor gain





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

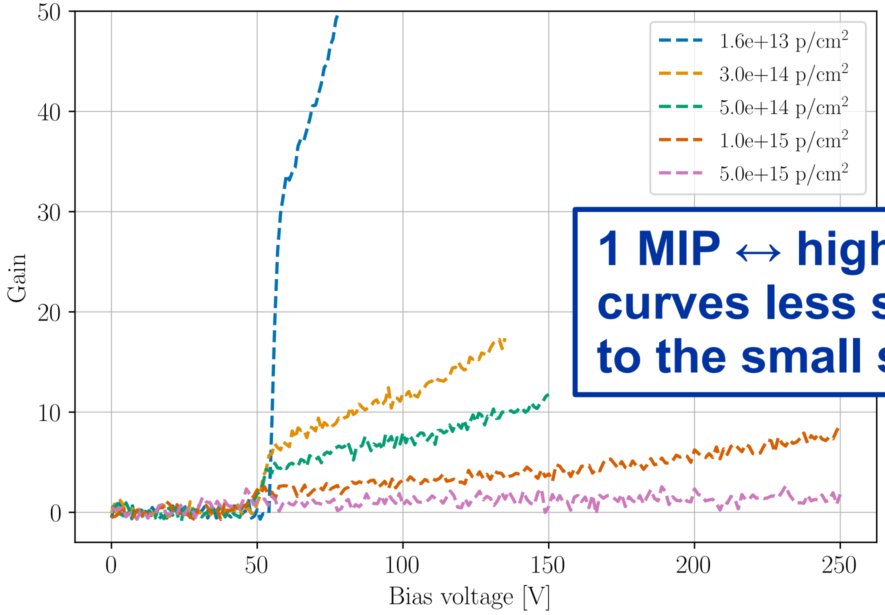


HPK2 W25:
Gain measurements of non-irrad. LGAD for different laser intensities (MIPs);
Gain suppressed for higher number of MIPs

Laser Characterization: Gain

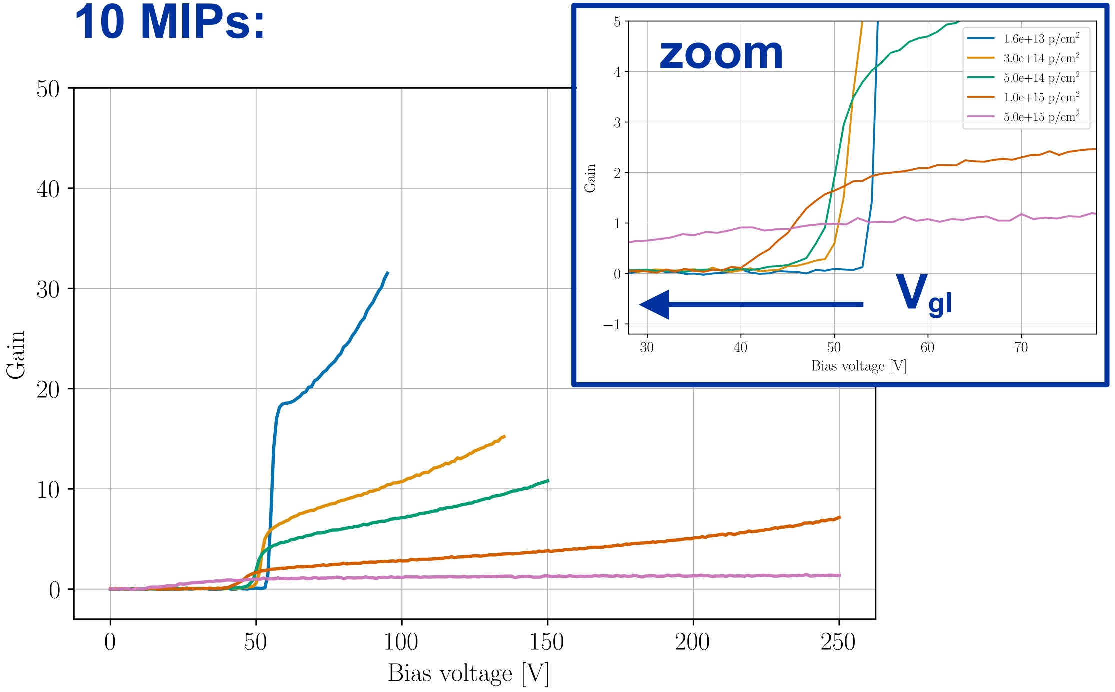
- Comparing the **LGAD gain for different laser intensities** (→ Number of MIPs):
  - Exemplary plots for **400 MeV**
    - All gain measurements for irradiated samples taken at -20°C

1 MIP:



1 MIP ↔ higher gain; curves less smooth due to the small signals

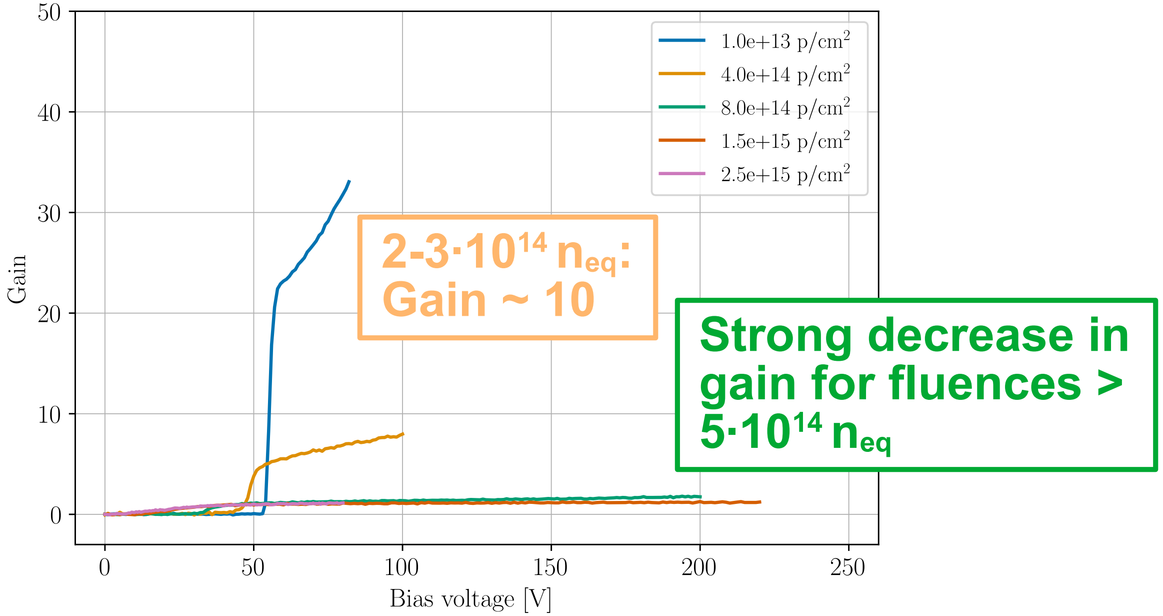
10 MIPs:



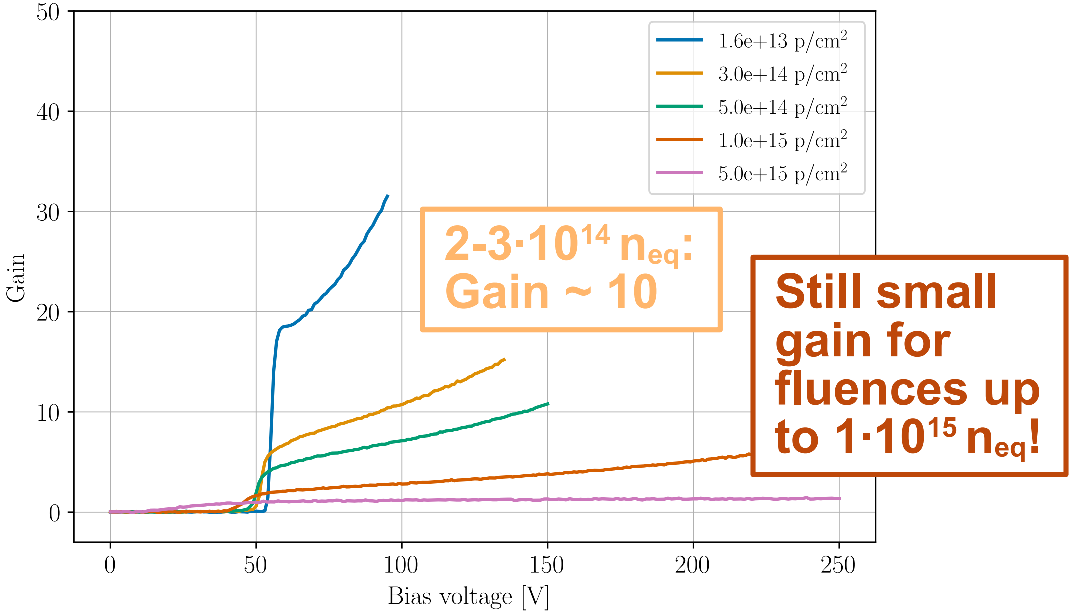
Laser Characterization: Gain

- Comparing the **LGAD gain for different proton energies** (at same laser intensity): **23 GeV vs. 400 MeV**
  - For lower fluences: similar behavior, 23 GeV shows even slightly higher gain
  - **400 MeV proton LGADs** still exhibit **measurable gain after fluences ~ $1 \cdot 10^{15}$ n_{eq}**

23 GeV, 10 MIPs:

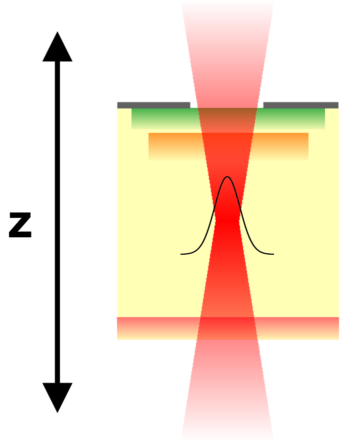


400 MeV, 10 MIPs:



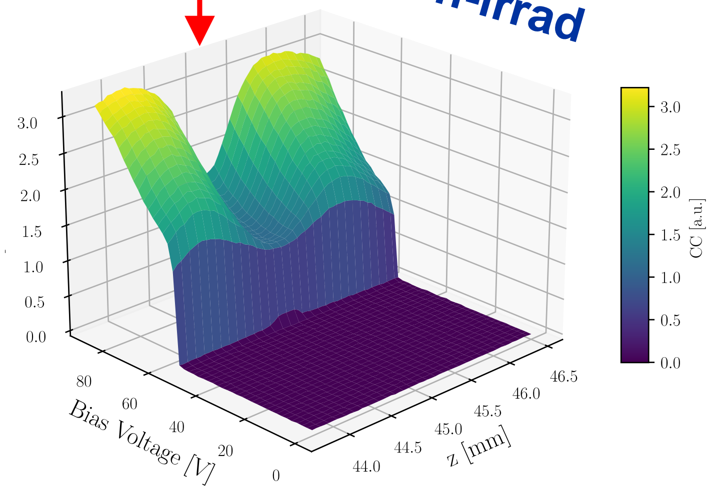
Gain Suppression

- **Two ways:**
  - **Changing the position of the focus (z-V_{bias} scan)**
  - Changing the laser intensity



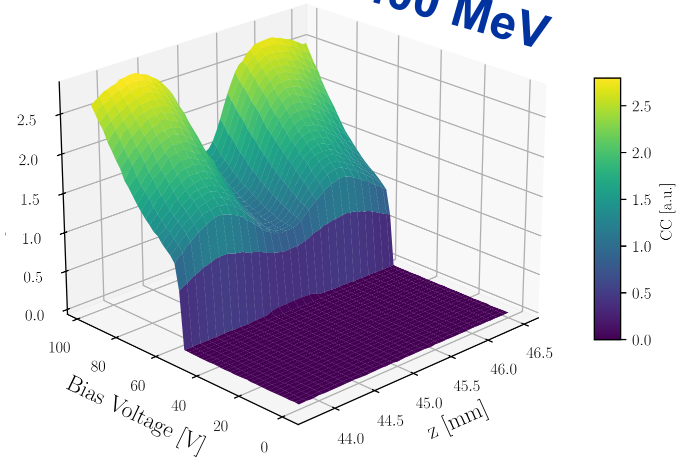
Laser focus

Non-irrad

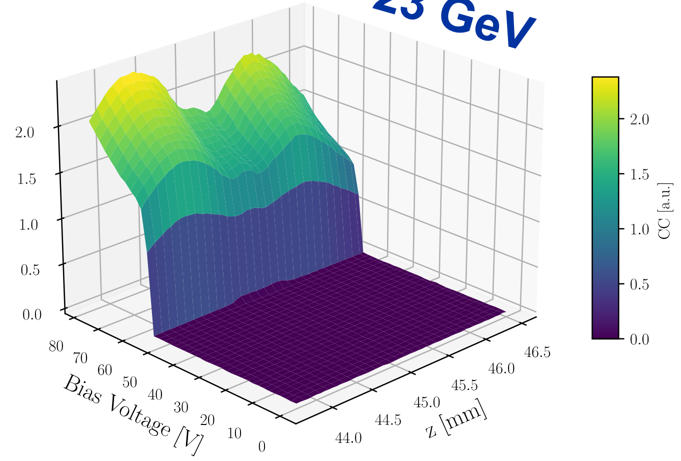


Lowest fluences: 1-2·10^{13} n_{eq}

400 MeV



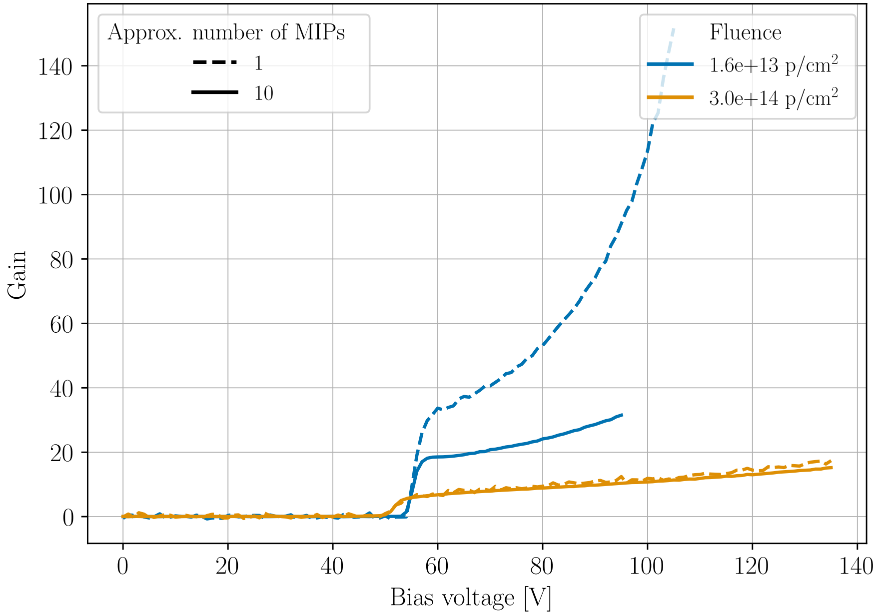
23 GeV



Gain Suppression

- **Two ways:**
  - Changing the position of the focus (z-V_{bias} scan)
  - **Changing the laser intensity**

400 MeV, two lowest fluences ($1.5 \cdot 10^{13}$ – $3 \cdot 10^{14}$ n_{eq}), 1 vs 10 MIPs:

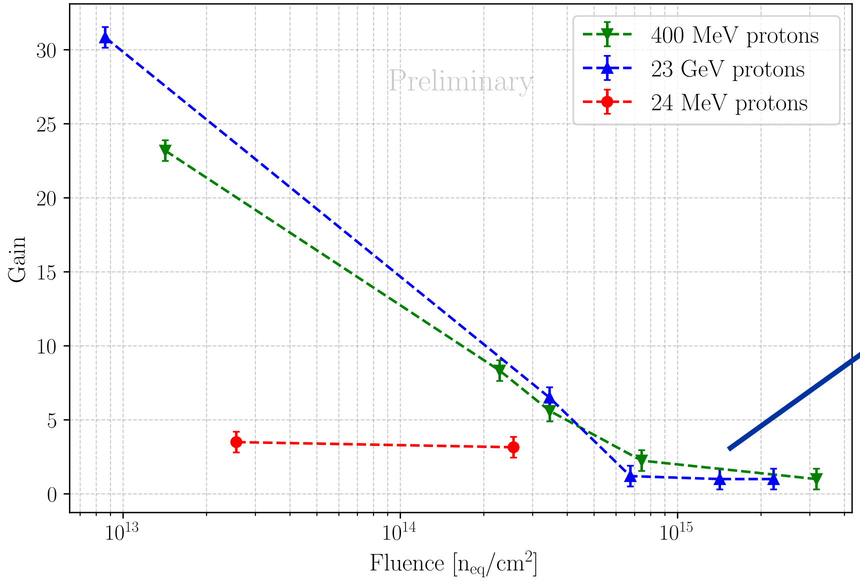


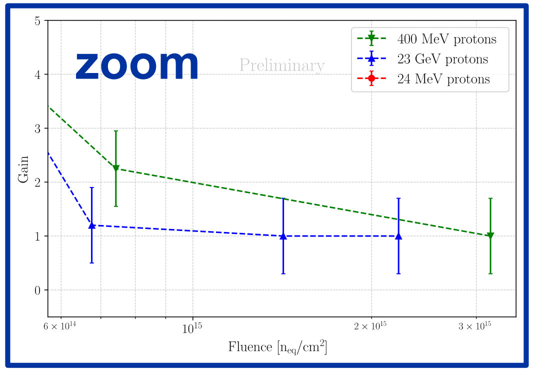
- Gain suppression at 80 V between 1 and 10 MIPs:
  - 400 MeV **lowest fluence: ~ 45% suppression**
  - Non-irrad LGAD (see plot slide 10) and 23 GeV lowest fluence sample show comparable values
- For **next highest tested fluences** around $3 \cdot 10^{14}$ n_{eq} (Gain < 15): **Gain suppression is almost negligible**

Gain Comparison

- **Comparison of gain at same relative V_{bias}** (V_{gl} + 20 V to account for irradiation induced shifts) **and intensity (10 MIPs)** for increasing fluences and different proton energies
  - I-V and C-V analysis (acceptor removal): sensitive to gain-layer deactivation
  - Laser characterization: also more sensitive to charge collection and trapping
- Comparing **energy dependence** qualitatively: **Similar trends in electrical and laser characterization**

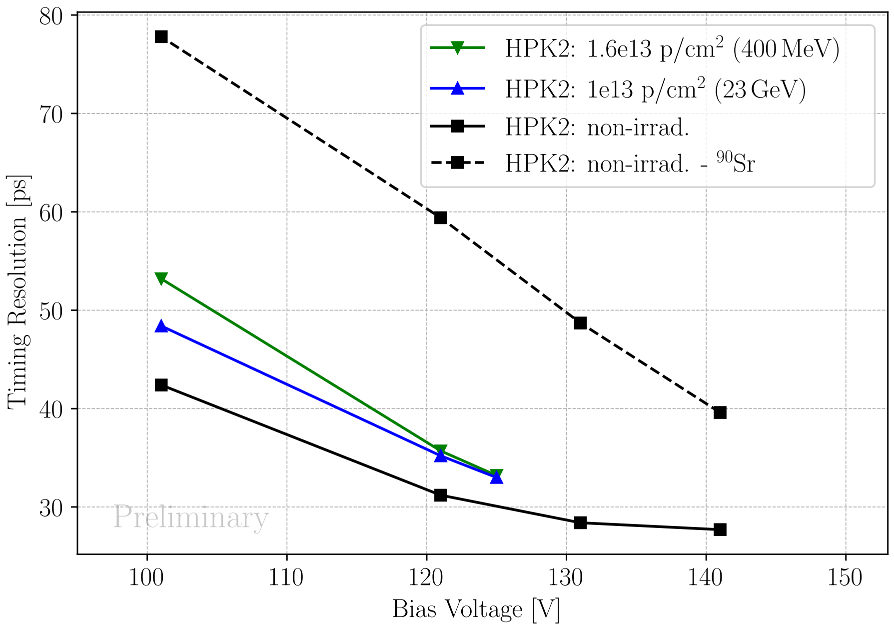
- **400 MeV** and **23 GeV** gain seems to have the same trend
- Lower fluences: **23 GeV** samples exhibit a slightly higher gain; Higher fluences: **400 MeV** samples maintain gain longer
- Lower energy protons (here **24 MeV**) more damaging → way faster gain degradation

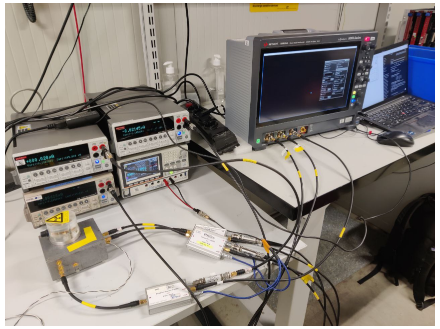




Timing and Comparison to ^{90}Sr Source

- **HPK2 W25 samples** tested with laser timing configuration (two pulses) and ^{90}Sr
  - **Laser:** comparison of non-irrad. LGAD with lowest **400 MeV** and **23 GeV** fluence
  - **^{90}Sr:** first test for non-irrad. LGAD shows worse timing (expected due to Landau fluctuation)





Interim ^{90}Sr setup

(Source from the CMS ETL System Test group)

https://github.com/icosivi/BetaAnalysis
Code used for timing analysis

Timing and Comparison to ^{90}Sr Source

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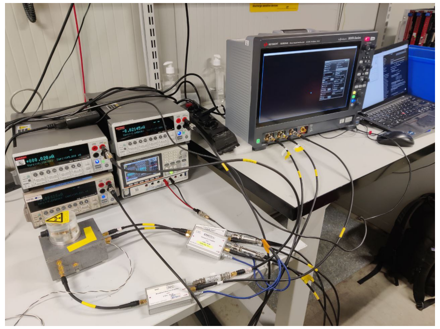
  - **Laser:** comparison of non-irrad. LGAD with lowest **400 MeV** and **23 GeV** fluence
  - **^{90}Sr:** first test for non-irrad. LGAD shows worse timing (expected due to Landau fluctuation) → **systematics measurements of CNM LGADs planned!**



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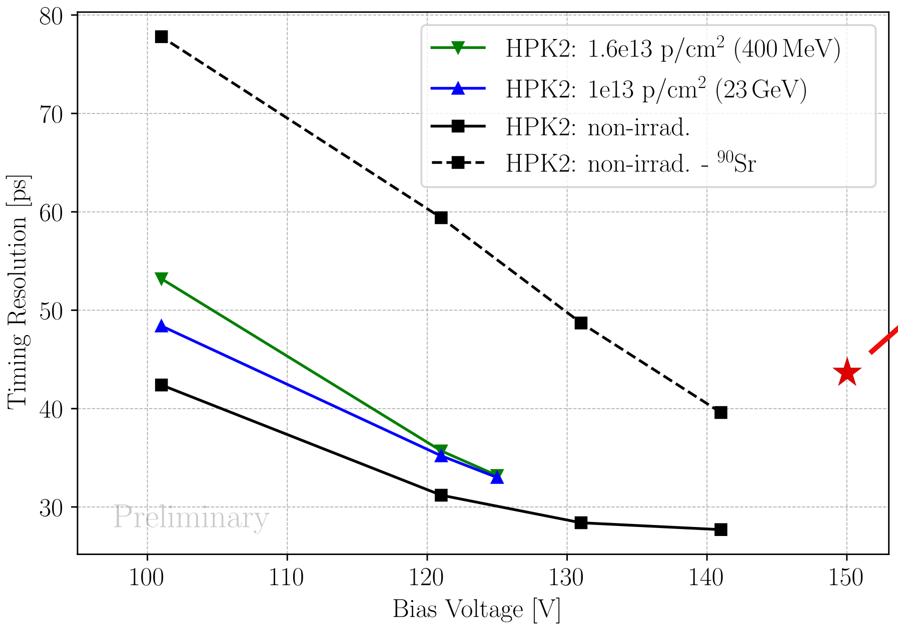

Preview of timing with S^{90} CNM W4, non-irrad. at max. V_{bias}: 44 ps

https://github.com/icosivi/BetaAnalysis
Code used for timing analysis

Summary & Outlook

- **HPK2 and CNM LGADs** irradiated with protons from **18 MeV to 23 GeV** and studied by **electrical, laser and radioactive source measurements**
- **Lower-energy protons** induce **faster degradation,** whereas the **400 MeV proton damage deviates from** an otherwise systematic **energy-dependent trend**
- Electrical and laser/source measurements **show a comparable energy dependence**
- **CNM samples** without opening in the topside metallization to be tested with ^{90}Sr
- **While NIEL scaling offers a valuable baseline, it requires revision to account for different particle types and energies!**

Thank you for your attention!

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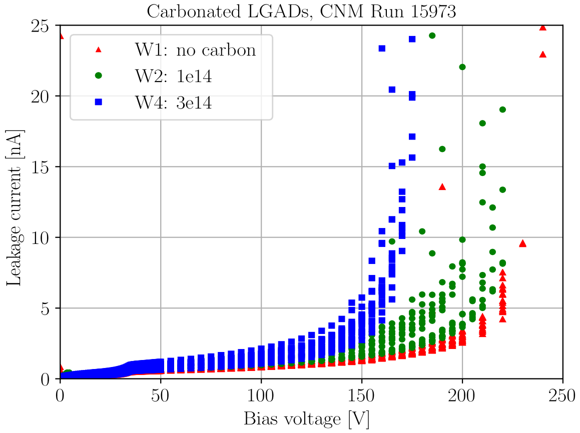
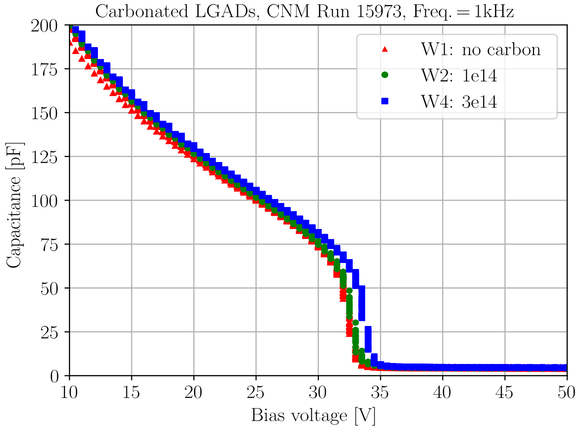
Backup Slides

I-V and C-V Characteristics (Before Irradiation)

CNM:

@ +20°C, 1 kHz

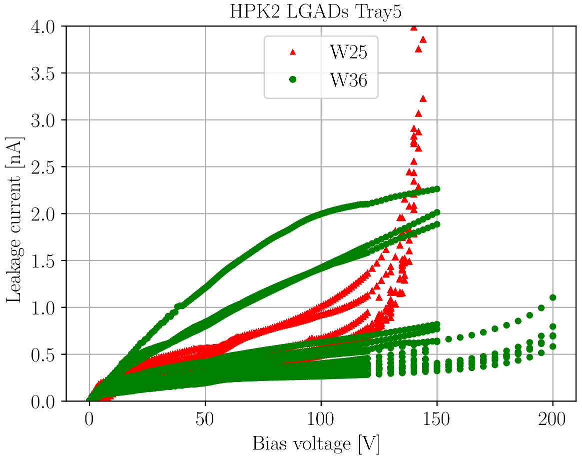


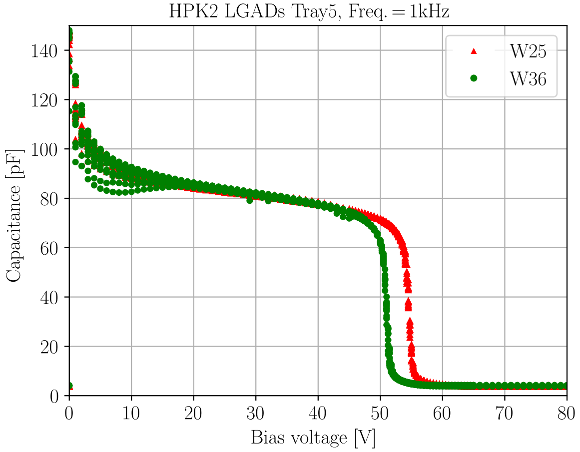


- Boron content the same in all Wafers; Carbon content influences V_{break} (carbon acting as diffusion suppressor for boron during fabrication)
- Influences the breakdown
- V_{gl} between 30 and 35 V

HPK:

@ +20°C, 1 kHz



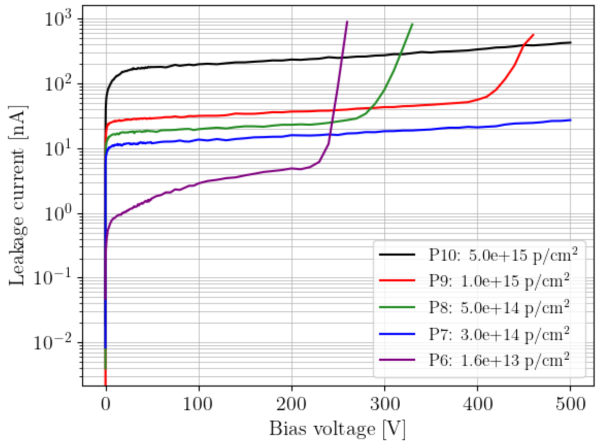


- W25: lower breakdown voltage (indication for higher gain)
- V_{gl} between 50 and 60 V

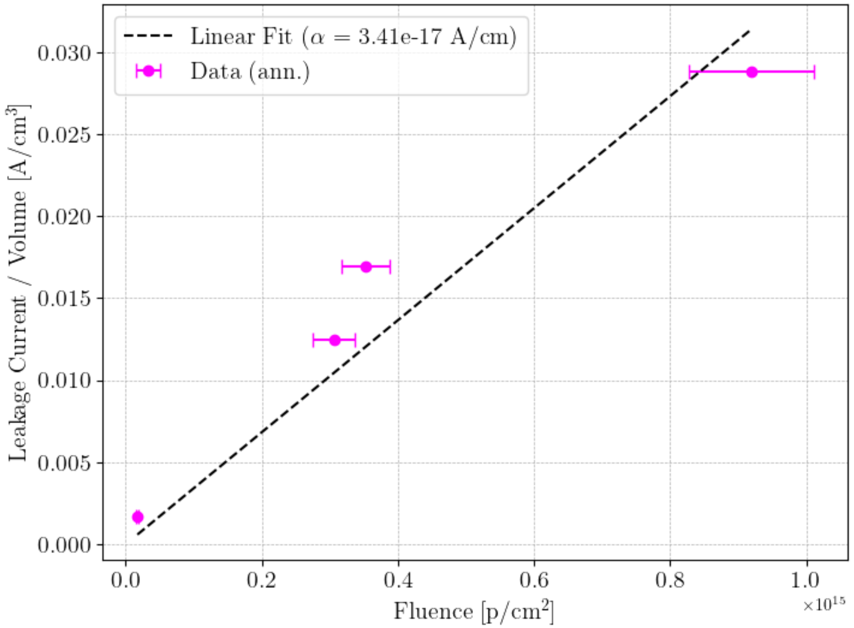
Fluence Confirmation

- 400 MeV protons (Fermilab) look less damaging than all other tested proton energies
  - Cross check fluences with annealed reference diodes (80 min at 60ºC)
  - α_{nq} = 3.99·10^{-17}

HPK2 ref. diodes:



Fit leakage currents



$$\frac{\Delta I}{V} = \alpha \cdot \phi_p \rightarrow \kappa = \frac{\alpha}{\alpha_{nq}}$$

Hardness factor κ approx. 0.85