Investigating LGAD Degradation with Proton Irradiation and the Novel nLGAD Technology

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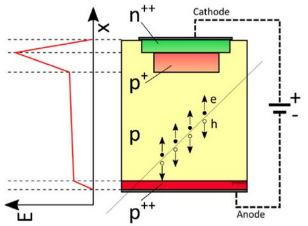
Outline

The talk will be split into two parts:

Proton irradiation study
- Overview
- 24 MeV protons (Birmingham)
- Comparison with other proton energies

Investigating the novel nLGAD technology
- Difference to HEP LGADs
- El. characterization
- Characterization with TPA-TCT
- Gain measurements with UV laser

Proton irradiation campaigns



Motivation:

- **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** (<30 ps)
- **Current challenges:** LGADs suffer from radiation induced performance degradation (loss of signal gain)
- 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** *(For more information take a look at Vendula Subert's soon coming PhD thesis and DRD3 talk on 19.06.)*

Ongoing irradiation campaigns: Proton irradiation at four facilities of over 100 samples (CNM and HPK)

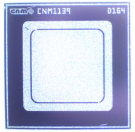
- 23 GeV protons at CERN: *irradiation completed, measurements in progress*
- 500 MeV protons at LANSCE: *irradiation delayed, now planned for Q3/24*
- 24 MeV protons at the University of Birmingham: *irradiation completed, measurements in progress*
- 18 MeV protons at Bern: *irradiation completed, measurements completed, Due to unexpected results, measurements for dosimetry calibration ongoing.*

24 MeV proton irradiation

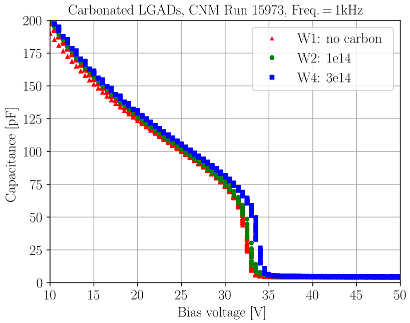
Facility: University of Birmingham's MC40 cyclotron facility,
Typically runs with 27 MeV proton beam → 24 MeV seen at the sample

Samples:

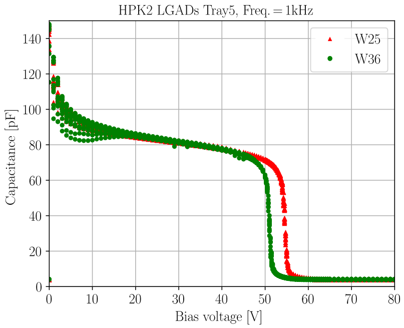
CNM run 15973
- Three wafers with different carbon enrichment (to mitigate degradation of gain layer): W1: no carbon, W2: $1\cdot10^{14}$ /cm², W4: $3\cdot10^{14}$ /cm²
- Boron dose: $1.9\cdot10^{13}$ /cm²
- Active area: 1.3 x 1.3 mm²
- Active volume 50 µm, support wafer 350 µm



HPK prototype 2
- Single LGADs from W25 and W36 (Tray 5)
- Active area: 1.3 x 1.3 mm²
- 50 µm epitaxial layer
- 150 µm low resistivity support wafer



El. tests before irrad.:
- Slight differences in V_{gl} for the three wafers with different carbon content
- W1:~31.4 V, W2:~32 V, W4:~32.7 V



El. tests before irrad.:
V_{gl} between 50 and 60 V

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.

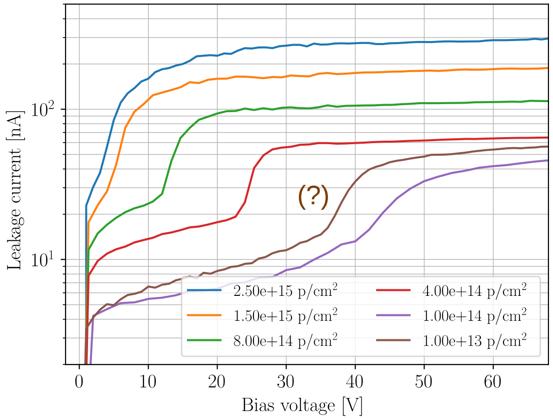
24 MeV protons: Electrical characterization

Proton irrad. Study: Overview - **24 MeV protons** - Comparison

Exemplary measurement results of HPK2 W36:

- The MC40 cyclotron facilities hardness factor is given by κ = 2.13
- The gain layer depletion voltage V_{gl} of the LGADs is used as indicator for the acceptor removal in the gain layer. For the non-irradiated samples V_{gl} is between 50 and 60 V
- V_{gl} is obtained after annealing at 60ºC for 80 min

Sample	Fluence [p/cm^2]	n_{eq} with κ = 2.13	V_{gl} [V]
HPK2-W36-LGAD-L19-P7	$1 \cdot 10^{13}$	$2.13 \cdot 10^{13}$	36.5 (?)
HPK2-W36-LGAD-L19-P8	$1 \cdot 10^{14}$	$2.13 \cdot 10^{14}$	40.7
HPK2-W36-LGAD-L19-P9	$4 \cdot 10^{14}$	$8.52 \cdot 10^{14}$	23.6
HPK2-W36-LGAD-L19-P10	$8 \cdot 10^{14}$	$1.7 \cdot 10^{15}$	12.3
HPK2-W36-LGAD-L19-P11	$1.5 \cdot 10^{15}$	$3.2 \cdot 10^{15}$	5.1
HPK2-W36-LGAD-L19-P12	$2.5 \cdot 10^{15}$	$5.32 \cdot 10^{15}$	not recognizable (~0)



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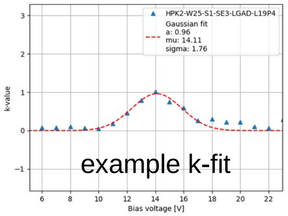
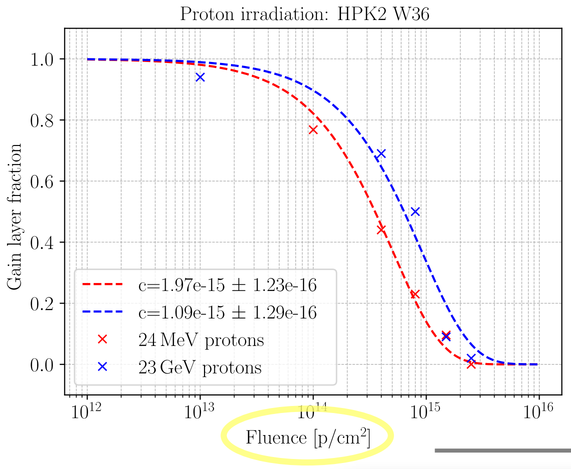
24 MeV protons: Acc. removal coefficient in comparison

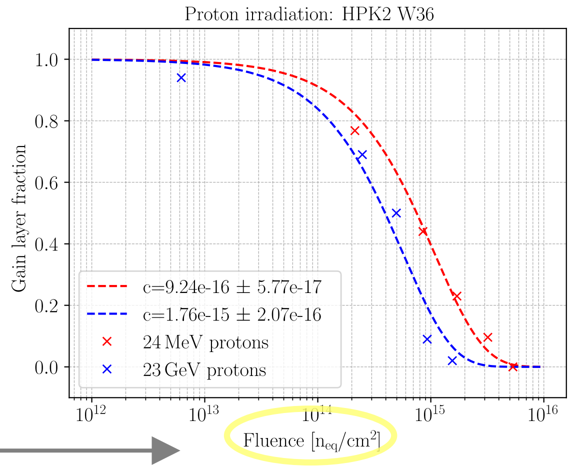


Results: 24 MeV (κ = 2.13) compared to 23 GeV (κ = 0.62) proton irradiation

- 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: acceptor removal coefficient (c) can be fitted $\frac{V_{gl}(\Phi)}{V_{gl}(0)} \approx e^{-c\Phi}$



Calculating the neutron equivalent fluence (n_{eq})



Fitting an acceptor removal coefficient (c) gives different ratios between the two proton energies depending on whether the original or the n_{eq} fluence is used: With n_{eq} the 24 MeV protons seem to be less damaging (contrary to expectations)

Very recent, first results! Measurements of further samples and proton energies must be obtained to establish a trend

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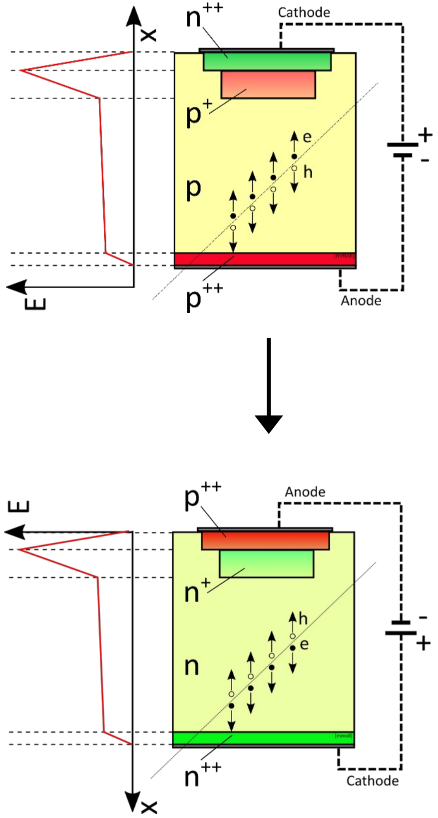
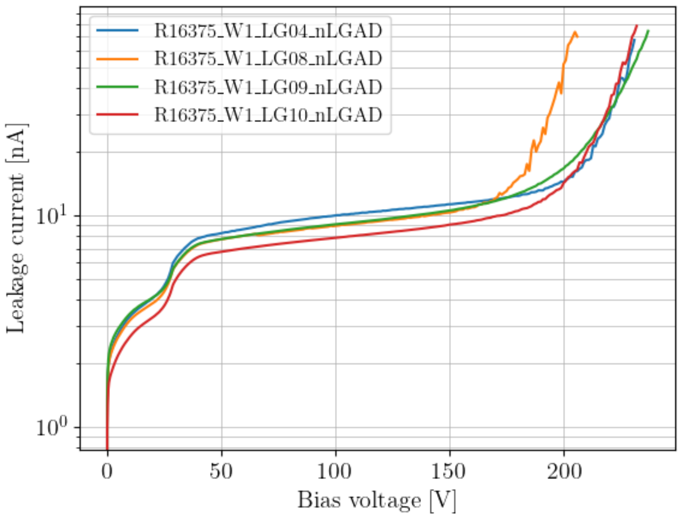
The novel nLGAD concept

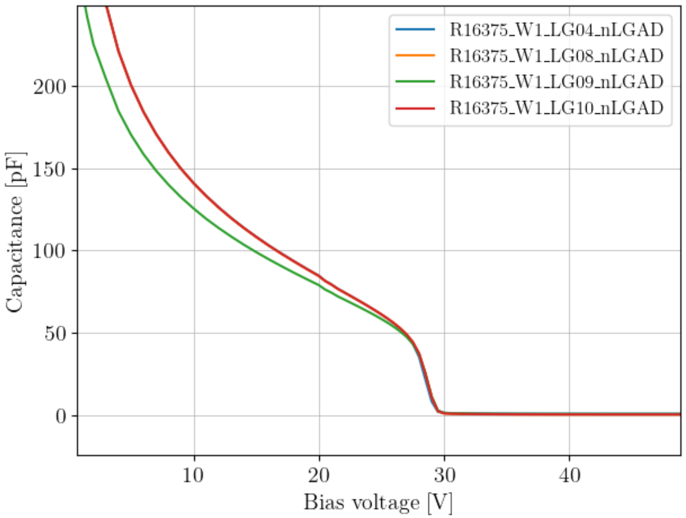
- LGADs implemented as $n^{++}{-}p^{+}{-}p$, show outstanding performance when detecting high-energy charged particles
- HEP LGADs show poor detection performance for low penetrating particles. Thus, the novel nLGAD concept was designed and fabricated at CNM and tested at the CERN SSD group
- The concept is also interesting for HEP R&D: first ever tests in such a structure! We want to study general properties of the devices like impact ionization and donor-removal ↔ acceptor removal with irradiation



Sample info:
- n-type
- Thickness 275 µm
- Active area 1.3 x 1.3 mm^2
- Resistivity > 1 kΩcm

El. characterization: IV, CV

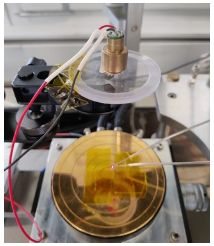




- Breakdown of the nLGADs starts at ~200 V
- V_{gl} between 25 and 30 V

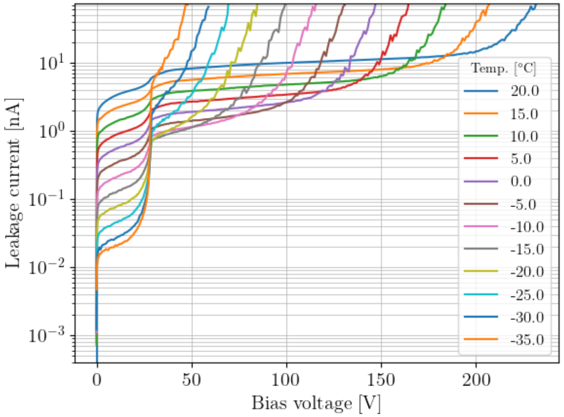
El. characterization: impact ionization

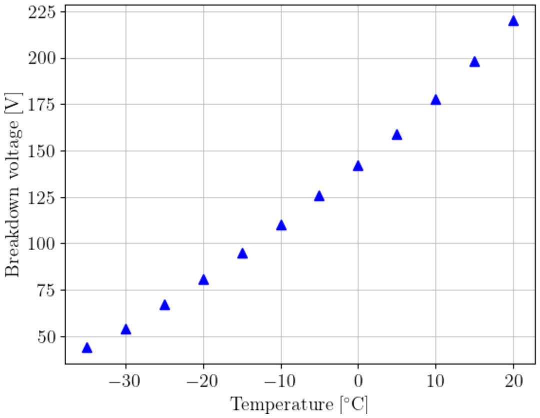
- Temperature dependent IV measurements
- The temperature dependence of the breakdown voltage indicates the temperature dependence of impact ionization in the n^+ gain layer
- To verify that the effect really comes from the gain layer, measurements with red light exposure were carried out: shift of break down also visible with light source

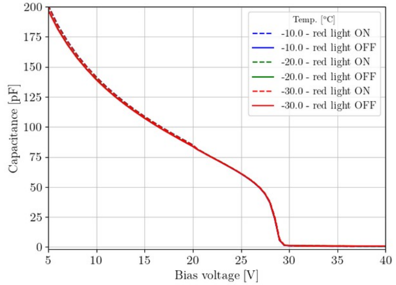


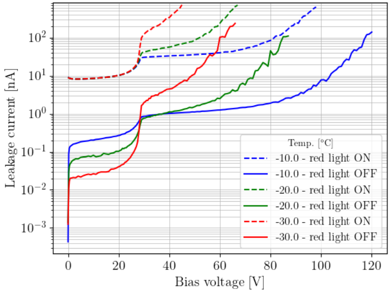
Red light source in IVCV setup with switch on the outside

decreasing temp.





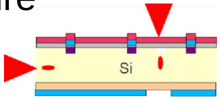




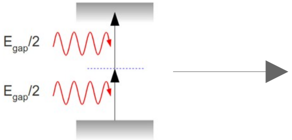
Shift of break down voltage also visible with light source,
effect seems to come from gain layer
→ impact ionization!

TPA-TCT with nLGADs

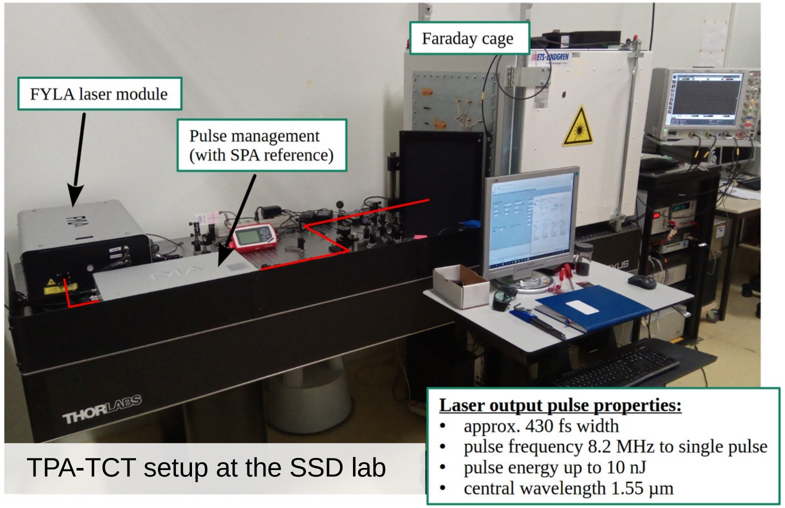
Two **P**hoton **A**bsorption – **T**ransient **C**urrent **T**echnique:
- Two photons produce one electron-hole paire
- Point-like energy deposition in focal point
- 3D spatial resolution (1 x 1 x 10 µm)



TPA (1550 nm):
No excitation if $E_{photon} < E_{gap}$ ~ 1 eV. But, if **two** photons arrive in ~100 attoseconds:



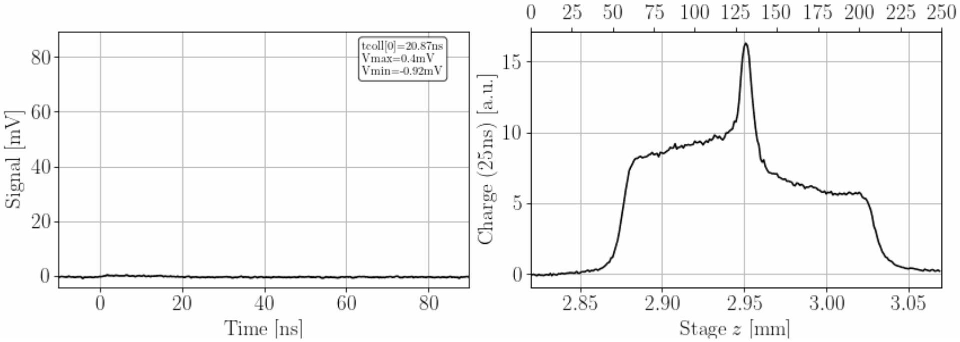
$$\tau_{virtual} \approx \frac{\hbar}{E_{gap}/2} \approx 0.1\ fs$$



TPA-TCT setup at the SSD lab

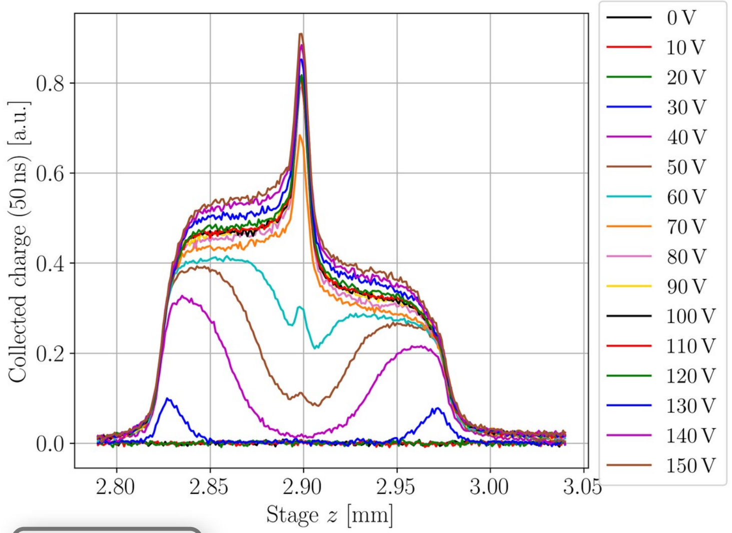
Laser output pulse properties:
- approx. 430 fs width
- pulse frequency 8.2 MHz to single pulse
- pulse energy up to 10 nJ
- central wavelength 1.55 µm

For more information: see PhD thesis M. Wiehe (2021), S. Pape (2024)



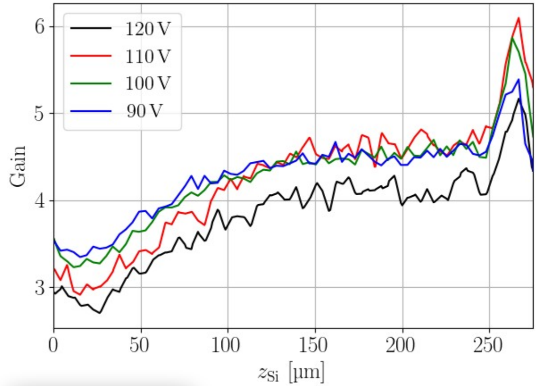
Exemplary TPA-TCT measurement of an nLGAD: Generated charge profile along z-direction (right) and corresponding signal (left). The separation between hole and electron contribution to the signal is nicely visible.

TPA-TCT with nLGADs



Sample topside

Collected charge in a nLGAD for increasing V_{bias} values. The peak corresponds to reflections on the backside metal of the sample. No “shark-fins” (signs for gain suppression) visible.



Sample topside

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

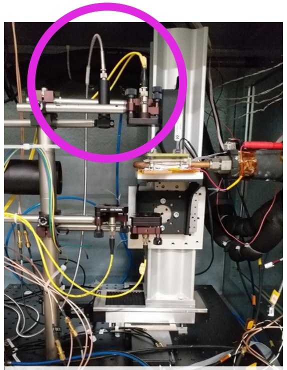
Gain of nLGADs (Q_{nLGAD}/Q_{PiN}) against depth: comparing different V_{bias} up to 120V, measured at -20ºC

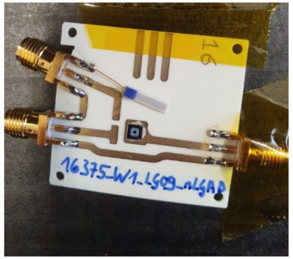
- Results of gain measurements with the TPA-TCT laser (λ=1550 nm) indicate effects of gain suppression
- Due to the difference in multiplication mechanisms for electrons and holes, the gain values are relatively low measured with this laser → tests with UV laser

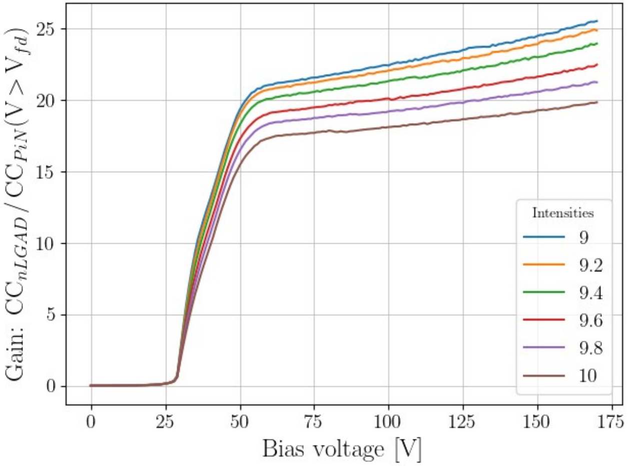
M. Moll, 43rd RD50 Workshop

Gain measurements with UV laser

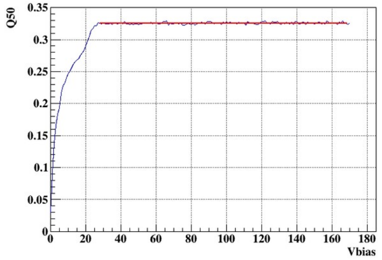
- In nLGADs: Gain (IR) < Gain (UV) because electrons mainly trigger the avalanche mechanism for UV and holes for IR (impact ionization rate is higher for electrons than for holes)
- UV laser installed at the TCT setup at SSD lab (CERN)
- Wavelength: λ = 375 nm


Optical system and linear stage





- Gain suppression with increasing intensity clearly visible!
- Min. intensity ~ 30 fC to max. intensity ~ 59 fC deposited in the detector



Charge fitted from corresponding PiN measurements

Outlook

Proton irradiation study: extensive study stared with the ultimate goal of a comparison of irradiation induced LGAD degradation with different proton energies of four facilities

Further plans:

- In depth characterization of the 24 MeV proton irradiated samples (TCT, Sr-90 measurements)
- Obtain correct fluences for the 18 MeV proton campaign (Bern), reference detectors currently get irradiated
- Still waiting for the 500 MeV samples

Investigating the novel nLGAD technology: nLGADs are subjected to temperature-dependent impact ionization and gain suppression like HEP LGADs

Further plans:

- Irradiation of nLGADs with protons (23 GeV at CERN) → samples already irradiated, characterization within the scope of a summer student project starting in July
- Irradiation of nLGADs with neutrons (JSI Ljubljana)
- Donor removal ↔ acceptor removal