Observations from operating Strip-LGAD detectors as in-beam start detector for a TOF system

4. High-D Consortium Meeting 2024

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on behalf of the HADES LGAD group

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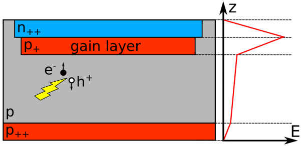
Low Gain Avalanche detectors

Low Gain Avalanche Detectors (LGADs)

- Thin silicon detector optimized for timing performance
  - gain layer exhibits high electric fields ($> 300\,\mathrm{keV/cm}$)
    - leads to intrinsic signal amplification
    - results in large signals with short rise times (< 1 ns)



- Why low gain?
  - high gain also amplifies noise
    - leads to temporal signal fluctuations (time jitter)
    - deteriorates time resolution
  - LGADs are operated at controlled low gain ($\approx$ 10-30)
    - to optimize SNR and time resolution

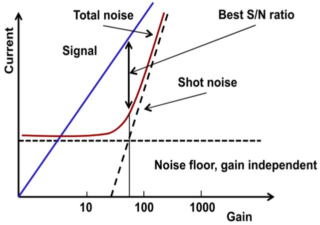
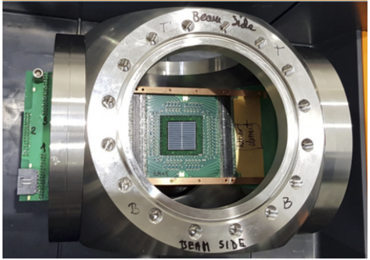


Figure: Sadrozinski et al. 2017

Low Gain Avalanche Detectors (LGADs)

- LGADs are promising candidates for 4D-tracking
  - time resolutions down to 30-50 ps possible
  - high spatial resolution ($< 100\,\mu$m)
  - low material budget ($X/X_0 \ll 1\,\%$)
  - radiation hard ($\approx 10^{15} n_{eq}/cm^2$)
  - large areas $\mathcal{O}(cm^2)$
- High interest in high energy physics community
  - CERN high luminosity upgrade
    - ATLAS High-Granularity Timing Detector (HGTD)
    - CMS Endcap Timing Layer (ETL)
  - RD50
  - **HADES T0 detector**
  - **S-DALINAC** beam monitor

HADES T0 detector



- but also medical applications
  - ion therapy beam quality monitor
  - **ion imaging**

Beam monitoring system for the S-DALINAC

S-DALINAC

- **S**uperconducting **DA**rmstadt **LIN**ear **AC**celerator

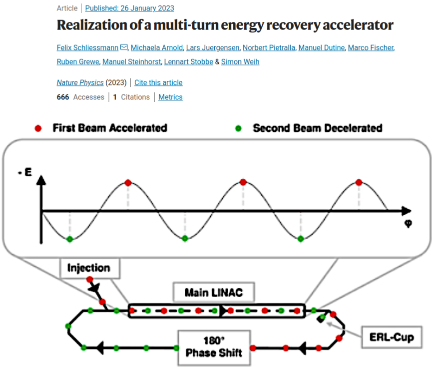
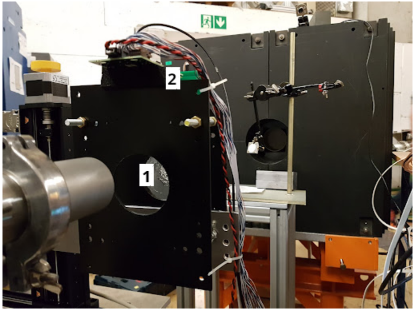


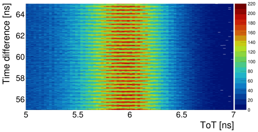
Figure: ERL mode principle

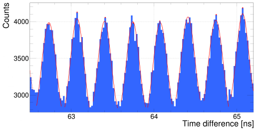
- S-DALINAC properties:
  - e-beams up to 130 MeV
  - 3 GHz time structure ($\approx$ 333 ps between bunches)
  - also energy recovery mode is possible (ERL mode)
    - published in Nature Physics (Schliessmann et al. 2023)
    - applying 180° phase shift on the beam
    - energy is put back in RF field
    - 6 GHz time structure ($\approx$ 167 ps between bunches)

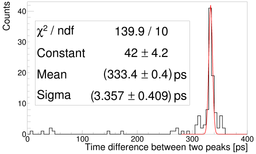
Beam monitor for the S-DALINAC in Darmstadt

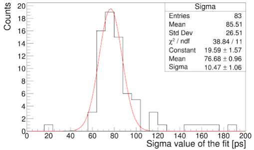


- Analysis of time difference of subsequent events
  - 3 GHz time-structure could be successfully resolved





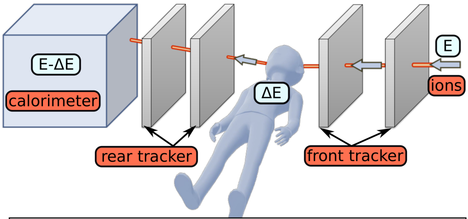




LGAD-based ion imaging system

Ion computed tomography (iCT)

- **i**on **C**omputed **T**omography allows determining the relative stopping power (RSP) distribution inside a patient directly
  - improves treatment planning accuracy
  - requires tracking and energy measurement

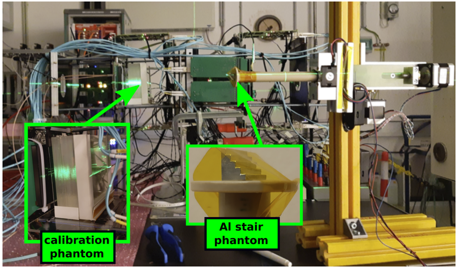


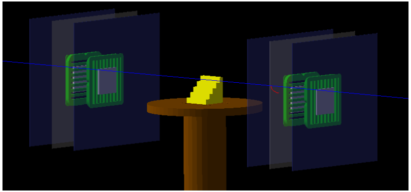
$$\int_L \mathrm{RSP}\left(\vec{x}(s)\right) \mathrm{d}s = \mathrm{WEPL}(E, \Delta E)$$

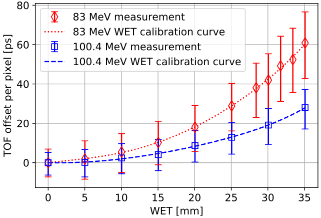
- Several prototypes have been developed (Johnson 2018)
  - still no clinical system exists so far
- Meeting all clinical requirements at once is challenging
  - RSP accuracy $< 1\,\%$
  - energy resolution $< 1\,\%$
  - DAQ rate $> 10^6$-10^7 Hz
- LGADs are perfect detector candidates (Ulrich-Pur et al. 2022)
  - 4D-tracking iCT system
  - incorporate time-of-flight (TOF) measurements into imaging process

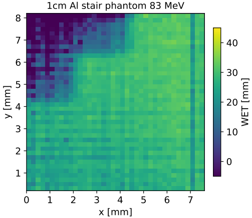
LGAD-based iCT system - first experiment

- MedAustron testbeam in April 2023
  - 10^5 p/s protons with 83 MeV and 100.4 MeV
  - 1.6 mm PMMA slabs for calibration
  - pRad of Al stair phantom was recorded
- **First TOF-based pRad** (Ulrich-Pur et al. 2023)
  - e-Print: 2312.15027 [physics.med-ph]
- More tests will follow with upgraded setup









HADES reaction START Detector

HADES experiment

- **H**igh **A**cceptance **D**i-**E**lectron **S**pectrometer
  - fixed target experiment at GSI, Darmstadt
  - heavy ion, proton or secondary π beams $\mathcal{O}$ (GeV)

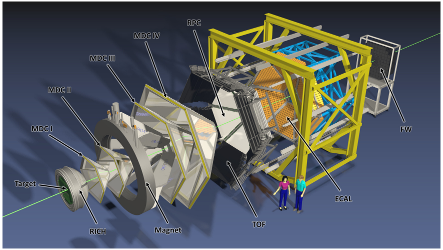


Figure: Spies 2022

- Investigation of phase diagram of strongly interacting matter at high μ_B and moderate T using rare, penetrating probes (e.g. dileptons)

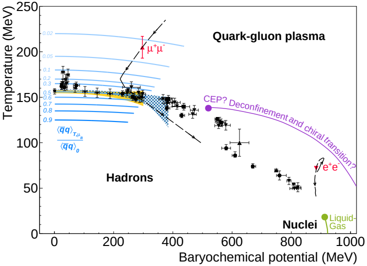


Figure: Adamczewski-Musch et al. 2019

HADES T_0 detector - overview

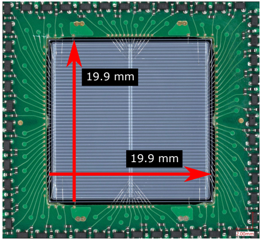
- T_0 detector
  - placed 2 cm in front of the target
  - defines start reaction time
    - TOF used for particle identification (PID)
  - can also be used for beam monitoring
    - e.g. luminosity monitoring

requirements for the T_0 detector	
sensor size	$\approx 2 \times 2\,\mathrm{cm}^2$
material budget	$X/X_0 < 0.55\,\%$
time resolution	$< 100\,\mathrm{ps}$
spatial resolution	$< 500\,\mu\mathrm{m}$
fill factor	$\approx 100\,\%$
particle rates	$\mathcal{O}\left(10^8\,\mathrm{protons/s/cm^2}\right)$
radiation hardness	$\approx 10^{14}\,\mathrm{n_{eq}/cm^2}$

- LGAD are perfect candidates
  - first proof-of-principle test with LGAD prototype sensors at COSY in 2020
  - new sensor production with different sensor geometries was launched at FBK
    - first test as T_0 detector during a p-p shift at GSI in Feb 2022

HADES T_0 detector - current setup

- LGAD strip sensor
  - $2 \times 2\,\mathrm{cm}^2$
  - thinned to 200 µm
  - strips arranged in 2 columns
  - fill factor ≈ 94 %
  - 387 µm pitch



- Readout electronics developed at GSI trb.gsi.de
  - custom 2 stage preamplifier board
  - FPGA-based signal discrimination (PaDiWa)
  - FPGA-based TDC for time-over-threshold (ToT) and time-of-arrival (ToA) measurements

- Measurement and analysis
  - two sensors were used for the time measurement
  - arranged orthogonal to each other to retrieve spot size
  - time-walk and offset correction was implemented

HADES T_0 detector - results

- Particle fluence estimation
  - trigger count and window
    - factor for total passed particles
  - beam spot fit yields area
  - calculate neutron equivalent fluence for 4.5 GeV protons

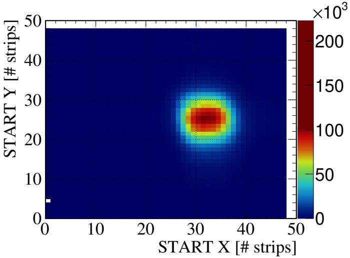
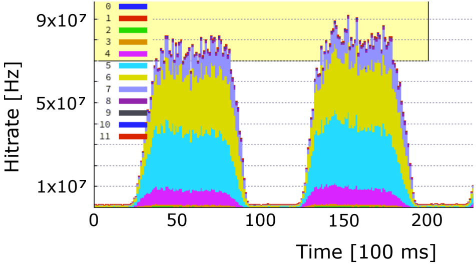


Figure: (Krüger et al. 2022)

- Example sensor timing precision 124 ps
  - worsens by up to 88 ps after full fluence of $\approx 10^{14}\, n_{eq}/cm^2$
- Radiation damage estimated from timing precision deterioration



HADES T_0 detector - results

- LGADs for PID
  - T_0 defines collision time
    - needed for e.g. velocity measurement
- Time precision of single channel $> 100\,\text{ps}$
- At Jülich testbeam $\approx 90\,\text{ps}$ was reached
  - expected $\approx 80\,\text{ps} - 90\,\text{ps}$
    - strip capacitance ($\approx 10\,\text{pF}$) limits time precision
    - no cooling at higher temperatures
    - DC coupled FEE instead of AC coupled
- No radiation damage compensation possible
  - beam spot smaller than detector area
  - undamaged strips prohibit voltage increase

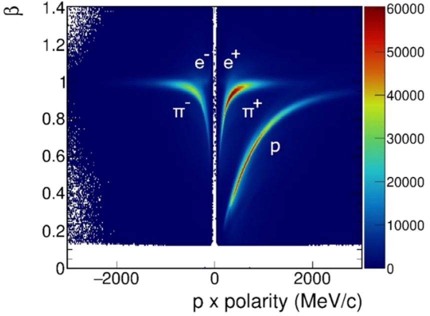


Figure: velocity vs. momentum times polarity for particle identification

Summary and outlook

Summary and outlook

- LGADs are promising 4D-tracking detectors with many applications

- Several R&D scenarios have been tested
  - beam monitor and start reaction time detector for the HADES experiment
  - beam monitor for S-DALINAC
  - ion beam therapy (ion imaging)

- Next generation of LGAD detector
  - new sensors with higher fill factor
  - will be combined with upgraded electronics able to read out large area sensors with hundreds of readout channels
  - dedicated low-mass module design for large-area 4D tracking system planned

Thank you for your attention!

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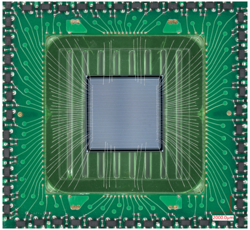
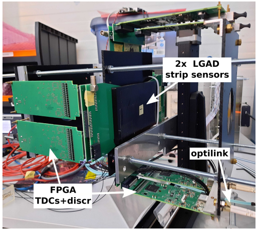
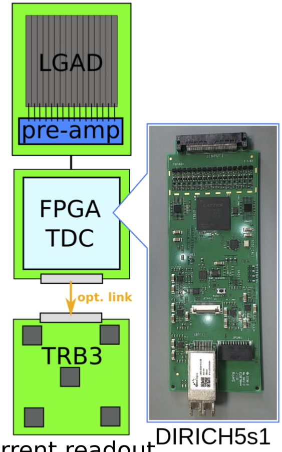
Backup slides

Beam monitor for the S-DALINAC in Darmstadt

- new system with upgraded read-out electronics was tested in December 2022
  - $1 \times 1\,\mathrm{cm}^2$ LGADs from **F**ondazione **B**runo **K**essler (FBK) production
  - same discrete FEE (pre-amps) as for HADES experiment
  - new FPGA-based TDC+discriminator (DiRICH5s1) with 32 channels each (trb.gsi.de)



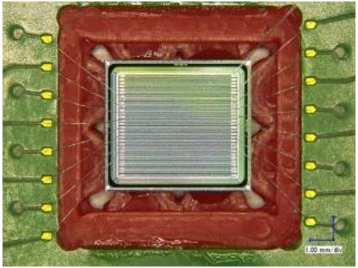




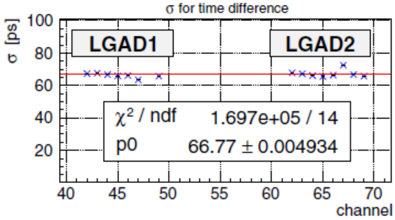
current readout system

Proof-of-principle measurement at COSY in 2020

- test of 2 different LGAD prototype strip sensors from FBK (Pietraszko et al. 2020)
  - $5 \times 4.3\,\mathrm{mm}^2$
  - $50\,\mu\mathrm{m}$ thickness
  - 16 channels with $146\,\mu\mathrm{m}$ pitch



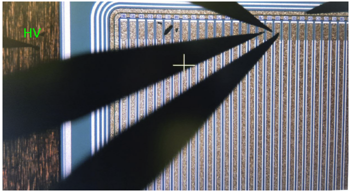
- NINO leading-edge discriminator and FPGA-based TDC
- excellent intrinsic time resolution could be shown at COSY:



$$\boxed{\sigma_t = 66.8\,\mathrm{ps}/\sqrt{2} \approx 47.2\,\mathrm{ps}}$$

Future system - large area 4D-tracking system

- novel LGAD sensors with increased fill factor will be investigated
  - trench-isolated (TI) and AC-coupled LGADs
  - new sensor production planned
- new sensors can be characterised in clean room at GSI
  - IV and CV curve measurements established



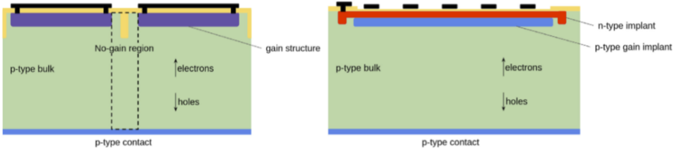
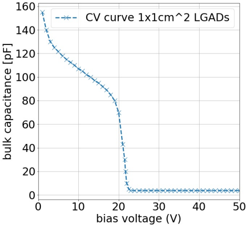


Figure: TI LGAD (left) AC LGAD (right) (Bisht et al. 2022)



Additional Figures

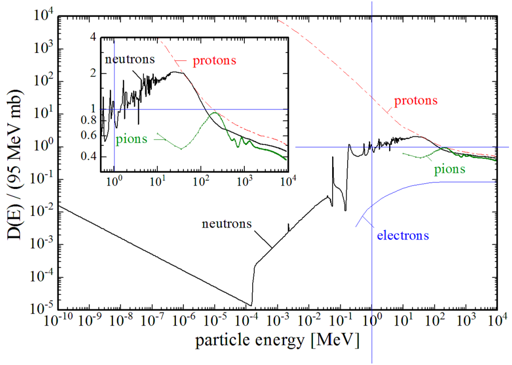


Figure: displacement damage cross-sections (Donegani 2017)

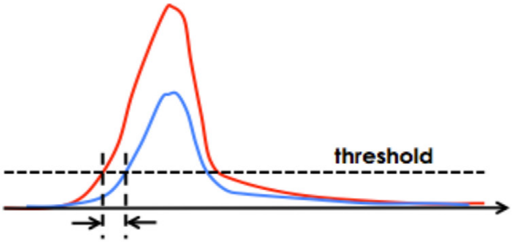


Figure: Time walk effect (Sadrozinski et al. 2017)

Additional figures

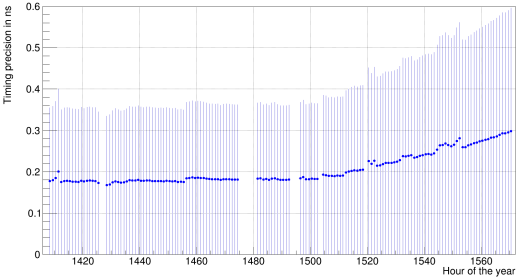


Figure: Timing precision deterioration