LGAD technology for HADES, accelerator and medical applications

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Outline

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2. LGADs for the HADES START Detector
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   2. Sensor requirements
   3. Dedicated FBK production
   4. Full system test
   5. First glimpse of LGAD performance at HADES
3. LGADs for medical applications (iCT)
4. LGADs for beam time-structure monitoring at S-DALINAC
5. Summary & Outlook
The HADES Experiment at GSI/FAIR

High Acceptance Di-Electron Spectrometer (HADES) at SIS18 GSI, Darmstadt (Germany)


Exploring the phase diagram of strong-interaction matter in the high-$\mu_B$ region


- Diagnostic tools: rare and penetrating probes (e.g. di-electrons, subthreshold strangeness production …)

- Fixed target experiment with large acceptance
- Heavy-ion, proton and secondary $\pi$ beams with energies of few GeV (per nucleon)
- Low $x/X_0$, excellent momentum precision and particle identification
HADES START Detector

Applications:
- Precise $T_0$ determination
  - Crucial for particle identification by means of velocity
- Particle flux measurement
  - Luminosity monitoring
- Beam quality monitoring
  - Detector stability, higher interaction rate

Requirements:
- Radiation hardness
- Large radiation length material - low $Z$
- Time precision < 100 ps
- Position information better than 0.5 mm

Replacement of diamond based START detector using LGADs

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See also:
Nicolo Cartiglia: 4d-tracking, LGADs, and fast timing detectors
Feb 25, 2022, 9:00 AM
https://indico.cern.ch/event/1044975/contributions/4566014/
Prototyping Phase-1

Prototype LGAD detector

- LGADs from UFSD2 production by FBK
- Protons at 1.92 GeV kinetic energy (MIPs) @ COoler SYnchrotron (COSY), in Jülich
- 2 sensors with form factor of 5 x 4.3 mm², 16 channels of each sensor connected
- Active thickness 50 µm, total thickness 570 µm
- ~150 µm pitch, 90 µm gain to gain distance, 20 µm metal to metal
- 2 amplification stages on PCB
- Operated in air without cooling
- Signal rate of several kHz per channel

Recorded data

- Analog signals on Oscilloscope
  - MPV at ≈ 200 mV
  - Noise level at 5 mV
- Time over Threshold (ToT) measurements with FPGA based TDCs (trb.gsi.de)
  - Signal discrimination based on NINO ASIC and PaDiWas
  - Time of Arrival (ToA) and ToT recorded
- Significant Time Walk in the order of 2 ns
  - Offline corrections needed to get excellent timing performance
- Time Difference (TDiff) defined as difference between ToA of signals in both detectors

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Prototyping Phase-2

- Time Walk correction based on ToT
- After Time Walk correction **no residual dependence** of TDiff on ToT
- Time Walk correction crucial to reach excellent timing precision

\[ \sigma_{T_0} = \frac{66.4}{\sqrt{2}} \text{ ps} \approx 47 \text{ ps} \] timing precision per channel reached after full calibration
HADES START Detector LGADs

Requirements

- Sensor size of **2 cm x 2 cm**
- Single particle detection at **10^8 protons/s/cm^2**
- Radiation hardness
  - \( \sim 10^{14} n_{eq} / \text{cm}^2 \)
- Timing precision below **100 ps for MIPs**
- Fill factor close to **100%**
- Low material budget
  - Below 500 \( \mu \text{m} \) silicon
  - \( x/X_0 < 0.55 \%

Tasks

- Precise reaction time measurements to assist particle identification
- Beam quality monitoring

HADES LGAD production by FBK

- Sensor production at Fondazione Bruno Kessler
  - Five sensor geometries
  - 14 \( \mu \text{m} \) metal-metal, 24 \( \mu \text{m} \) gain-gain distance
  - Thinning to **total thickness of 200 \( \mu \text{m} \)**

1. Sensor size: 2 cm x 2 cm
   - 2 x 48 half strips (9.28mm long)
   - Pitch about 387 \( \mu \text{m} \), Die size 19.9 x 19.9 mm^2
   - Fill Factor \( \approx 94 \%
   - Capacitance \( \approx 9 \text{ pF} \)

2. Sensor size 1cm x 1cm pitch about 192 \( \mu \text{m} \)
3. Sensor size 1cm x 1cm pitch 150 \( \mu \text{m} \)
4. Sensor size 1cm x 1cm pitch 100 \( \mu \text{m} \)
5. Sensor size 1cm x 0.5 cm pitch 50 \( \mu \text{m} \)

R&D sensors for various applications
START Detector Full System Test @ COSY

Set-up

- 2 LGADs with HADES geometry tested
  - 50 µm active thickness
  - 200 µm total thickness
  - Up to 5 MHz/channel signal rate
  - PaDiWa and NINO discriminators tested
- 2 LGADs with 100 µm pitch for reference

Performance

Final test of LGADs for HADES p+p beam-time
- After Time Walk corrections timing precision **below 85 ps per channel reached**
- Extracted from two independent LGAD sensors

\[ \frac{121}{\sqrt{2}} \, \text{ps} = 83 \, \text{ps} \]
HADES START Detector in p+p @ 4.5 GeV Run Feb.-Mar. 2022

- 2 LGAD sensors installed in vacuum in beam line
  - X and Y position measurements
- Read out using PaDiWa discriminators and FPGA based TDCs (trb.gsi.de)
- Preliminary timing precision around 114 ps per channel
  - Affected by noise situation in HADES
  - Pencil like beam → too high intensity in middle of detector
- Possibility to measure each particle twice and average measured times
  - Improve timing precision by an additional factor $\sqrt{2}$
Medical Applications - Ion Imaging

Objective

- Ion computed tomography (iCT) allows to directly measure the stopping power distribution within the patient
  - Improves treatment planning accuracy
  - Requires path estimation and residual energy measurement of single particles
  - No clinical system exists so far

Conventional iCT system
(adapted from F. Ulrich-Pur, 10.34726/HSS.2018.52042)

Concept

- Requirements for a clinical iCT scanner
  - Relative stopping power accuracy < 1%
    - Spatial resolution (image) < 1 mm
    - Energy resolution < 1%
    - DAQ rate > $10^6 - 10^7$ p/s

- 4D-tracking system could potentially fulfill all requirements iCT system solely based on LGADs
  - LGADs both for path estimation and residual energy measurements
  - TOF through object can also be exploited e.g. for particle identification (particle fragmentation)
  - LGADs with 30-50 ps timing precision required

iCT system based on 4D-tracking with LGADs

G. Poludniowski et al., 10.1259/bjr.20150134
R. Schulte et al., 10.1109/TNS.2004.829392
(F. Ulrich-Pur et al., arXiv:2109.05058)

M Rovituso et al., 10.1088/1361-6560/aa5302
Medical Applications - Ion Imaging

**Setup at MedAustron**

- Proof-of-principle measurement at MedAustron using 100.4 MeV protons with ~5*10^6 p/s
- Polymethyl methacrylate (PMMA) slabs with 1 cm thickness were used as a phantom
- The TOF through the phantom was measured using the two innermost LGAD sensors

**Preliminary results**

- First measurement with LGADs in an iCT scenario
  - Fast 4D tracking of single particles in a clinical environment possible
- Further applications of TOF in ion computed tomography are currently under investigation

Preliminary results compared to a Geant4 simulation of the experimental setup
LGAD at S-DALINAC

ERL concept

- Reduced power consumption
- Higher injector brightness
- Lower dumping energy

S-DALINAC

- 3 times recirculating superconducting linear electron accelerator
- ~130 MeV maximum electron energy
- 3 GHz time structure (~333 ps between bunches)
- Operated in two fold energy recovery mode in August 2021
- LGADs foreseen for time structure monitoring

Establishment of Multi-Turn Energy Recovery Mode at the S-DALINAC

In August 2021, TU Darmstadt’s superconducting electron linear accelerator, S-DALINAC, has been operated in a stable, twofold energy-recovery mode. The main linac was used twice to accelerate the electron beam to 99.99% of the speed of light at the interaction point and then to decelerate it afterwards. Beam currents of up to 8 µA at an energy of 41 MeV have been studied. Recovery of more than 80% of the required beam-load power has been observed. This represents the world-wide first demonstration of a multi-turn, superconducting energy recovery linac (ERL) with significant recovery effect. Technological challenges, such as the phase-
LGAD at S-DALINAC Preliminary Results

LGAD set-up at S-DALINAC

- Multipurpose test set-up at S-DALINAC (in air, not cooled)
- Sensor form factor of 0.5 x 1 cm²
- 50 μm pitch
- 50 μm active thickness
- Produced by Fondazione Bruno Kessler

Measurement Principle
- Measure ToA of two electrons from different bunches
- Time Walk correction crucial to see 3 GHz time structure

LGAD Performance

Time difference between signals in the same channel versus ToT of the first signal

Raw data

Time walk calibrated data
LGAD @ S-DALINAC Preliminary Results 2/2

- After Time Walk correction 3 GHz time structure is visible
- Fit function is "Gaussian + const" used to fit every sub-peak
- Mean time difference between two consecutive peaks ≈ 333 ps
- Timing precision: $\sigma_T \approx \frac{76}{\sqrt{2}} \approx 54$ ps
- Further improvements of results ongoing
- Set-up improvements:
  - Install a second LGAD
  - Install LGADs in vacuum
  - Re-scatter electrons from beam with a thin wire
Summary and Outlook

Summary

- LGADs are successfully used as a beam monitoring tool in HADES in a high rate pp experiment
  - Tuning of beam position and spill shape
  - Approx. $10^7$ p/s signal rate on channels in beam focus
  - Preliminary timing precision about 114 ps per channel, expected timing precision about 85 ps per channel
- Proof of principle measurement to use LGADs in the context of iCT successful
  - Time of Flight increase due to phantom agree withings error with simulations
- Proof of principle measurements to use LGADs for beam structure monitoring at S-DALINAC in the context of ERL operation successful
  - 3 GHz time structure of the beam could be resolved

Outlook

- Precise analysis of LGAD performance w.r.t. timing precision and radiation hardness
- Installing LGADs in vacuum at S-DALINAC to measure electrons scattered by a wire in beam
- Building large area tracking detectors for further feasibility studies regarding applications of LGADs in iCT
- Foreseen LGAD projects at HADES
  - Use LGADs in heavy-ion experiments
  - Large area barrel detector for 4D-tracking
  - LGAD based mini Forward Wall for event plane reconstruction
- Employing ASIC readout designed for LGADs (e.g. ETROC)

Acknowledgements

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M. Centis Vignali, M. Boscardin, F. Ficorella, G. Borghi, G. Paternoster, O. Hammad Ali