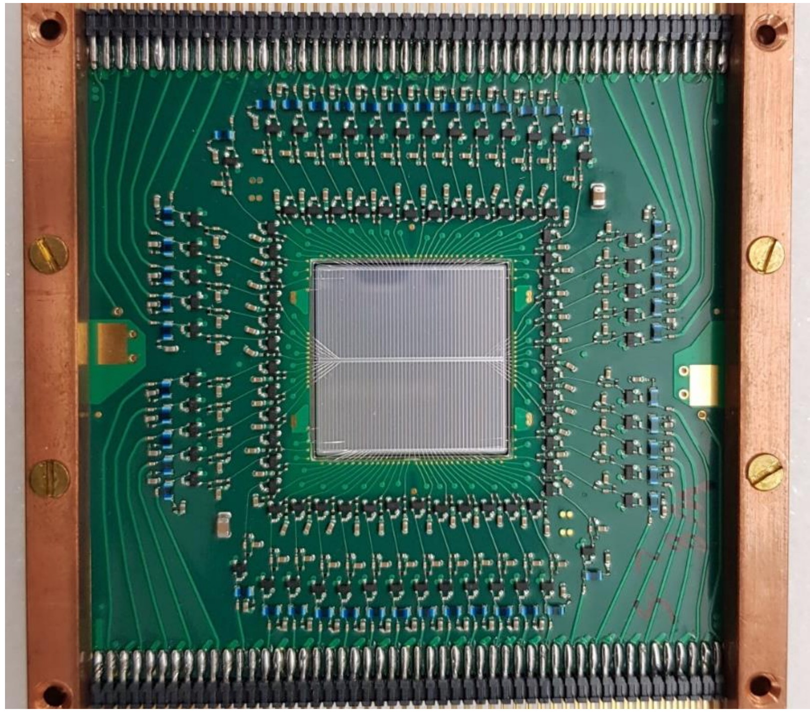
LGAD technology for HADES, accelerator and medical applications

Wilhelm Krüger



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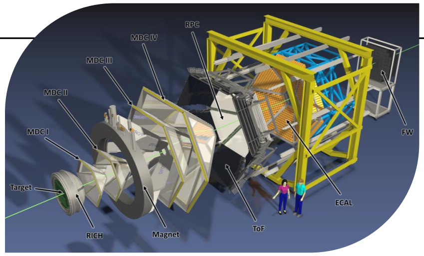
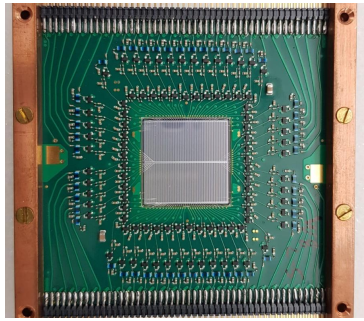
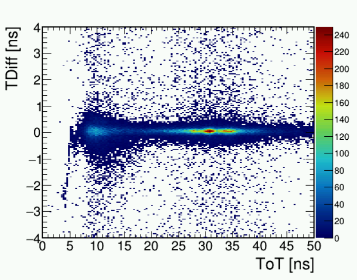
FAIR GmbH: A. Rost
Institut für Kernphysik, Goethe-Universität Frankfurt: J. Michel
Taras Shevchenko National University of Kyiv: V. Svintozelskyi

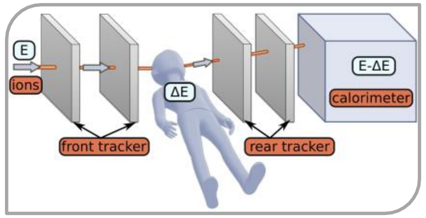
Outline

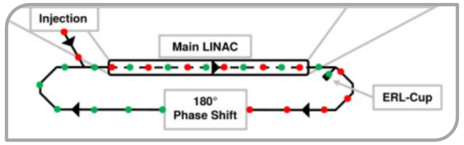






1. The HADES Experiment at GSI/FAIR
2. LGADs for the HADES START Detector
    1. Prototyping using FBK LGADs
    2. Sensor requirements
    3. Dedicated FBK production
    4. Full system test
    5. First glimpse of LGAD performance at HADES
3. LGADs for medical applications (iCT)
4. LGADs for beam time-structure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

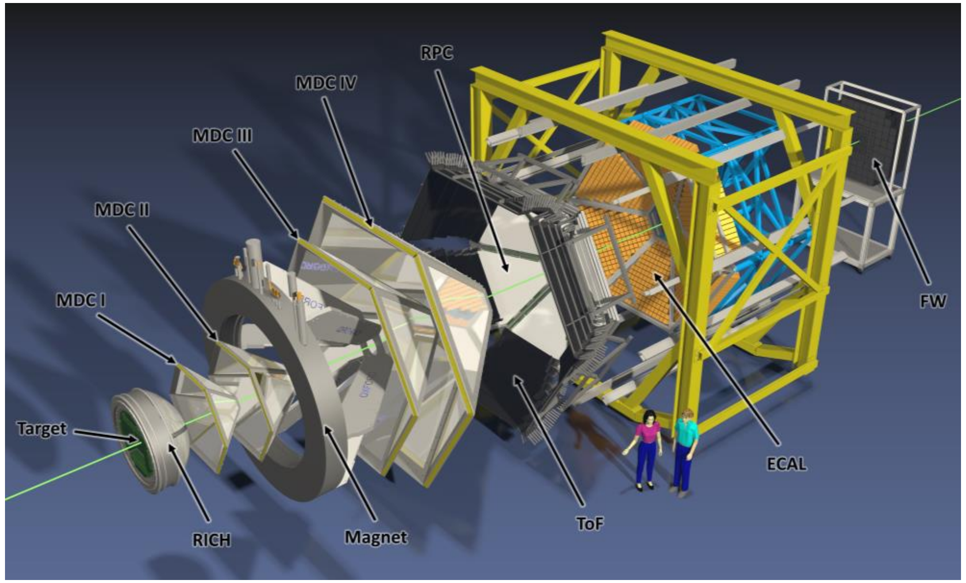




The HADES Experiment at GSI/FAIR

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

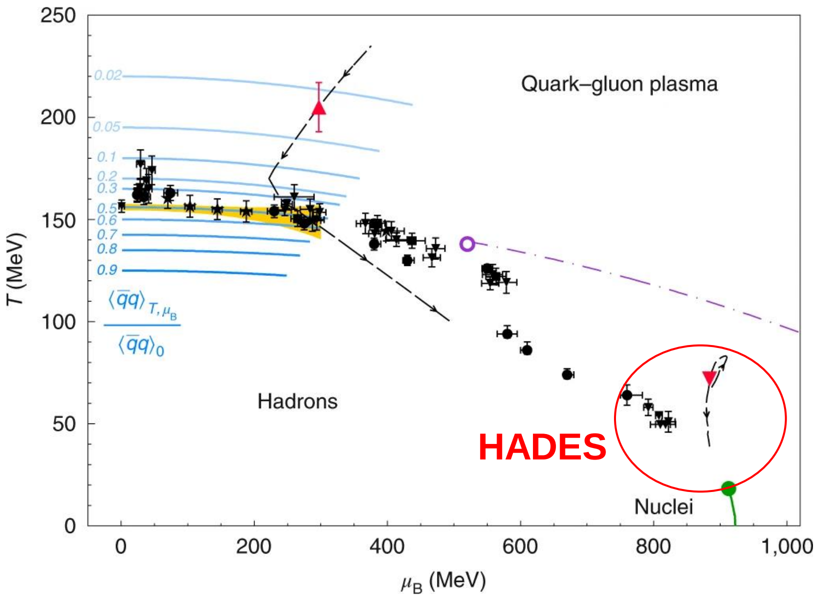
HADES, Eur.Phys.J.A 41 (2009) 243-277



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

Exploring the phase diagram of strong-interaction matter in the high-μ_B region

HADES, Nature Phys. 15 (2019) 10

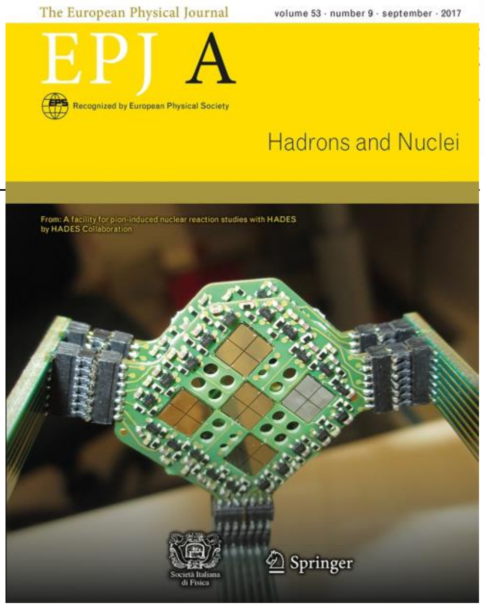


- Diagnostic tools: rare and penetrating probes (e.g. di-electrons, subthreshold strangeness production …)

HADES START Detector

Diamond based START detector

J. Adamczewski-Muschet et al.,
Eur. Phys. J. A (2017) 53: 188

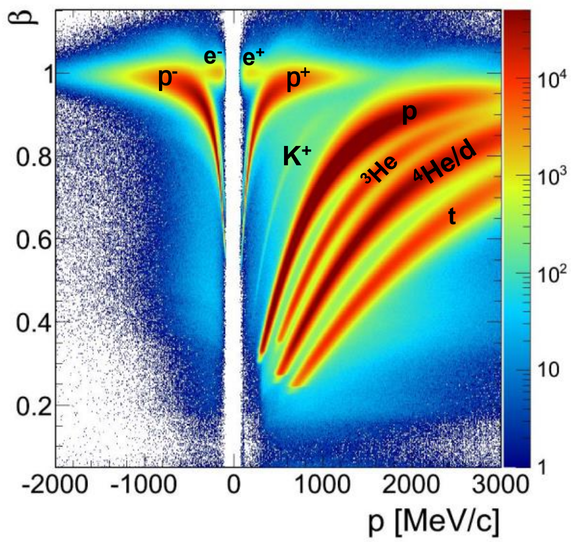

The European Physical Journal
volume 53 · number 9 · september · 2017
EPJ A
Recognized by European Physical Society
Hadrons and Nuclei
From: A facility for pion-induced nuclear reaction studies with HADES by HADES Collaboration
Società Italiana di Fisica
Springer

Applications:

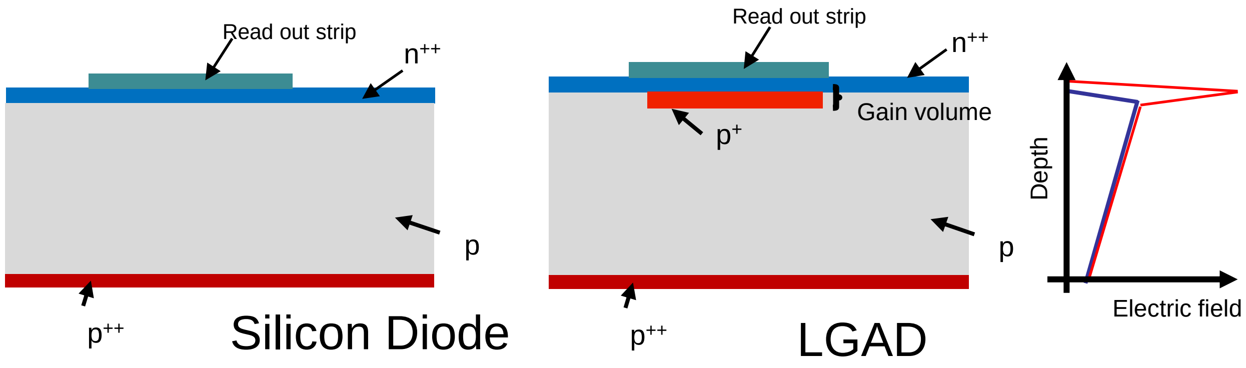
- Precise T_0 determination
  - ○ Crucial for particle identification by means of velocity
- Particle flux measurement
  - ○ Luminosity monitoring
- Beam quality monitoring
  - ○ Detector stability, higher interaction rate

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



See also:

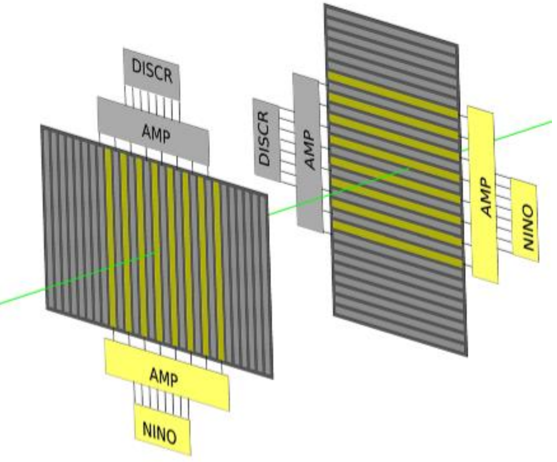
Nicolo Cartiglia: **4d-tracking, LGADs, and fast timing detectors**
Feb 25, 2022, 9:00 AM

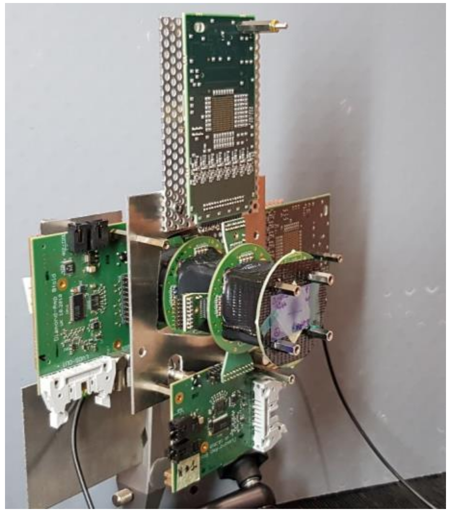
https://indico.cern.ch/event/1044975/contributions/4566014/

Prototyping Phase-1

Pietraszko, J., Galatyuk, T., Kedych, V. *et al.*, Low Gain Avalanche Detectors for the HADES reaction time (T0) Detector upgrade, Eur. Phys. J. A 56, 183 (2020)

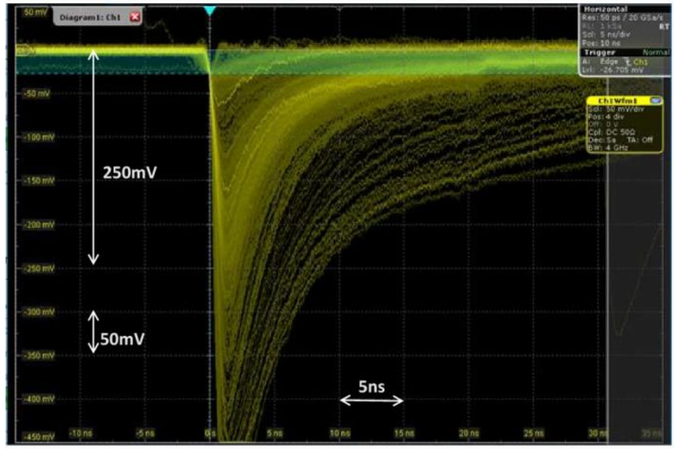
Prototype LGAD detector

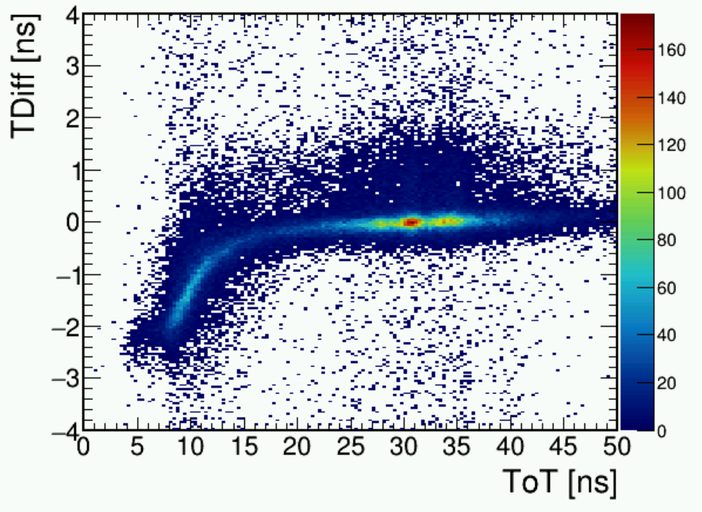




- LGADs from **UFSD2** production by **FBK**
- Protons at 1.92 GeV kinetic energy (**MIPs)** @ COoler SYnchrotron (**COSY**), in Jülich
- 2 sensors **with form factor of 5 x 4.3 mm²**, 16 channels of each sensor connected
- **Active thickness 50 µm**, total thickness 570 µm
- ~**150 µm pitch**, 90 µm 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 Oszilloscope
  - **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 **PaDiWa**s
  - 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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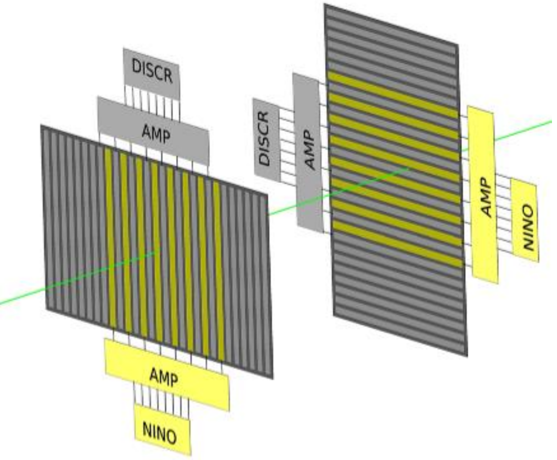

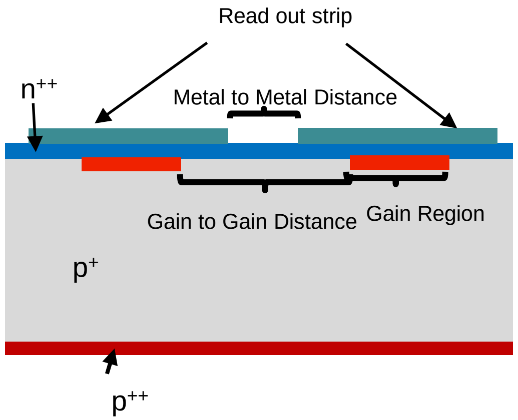

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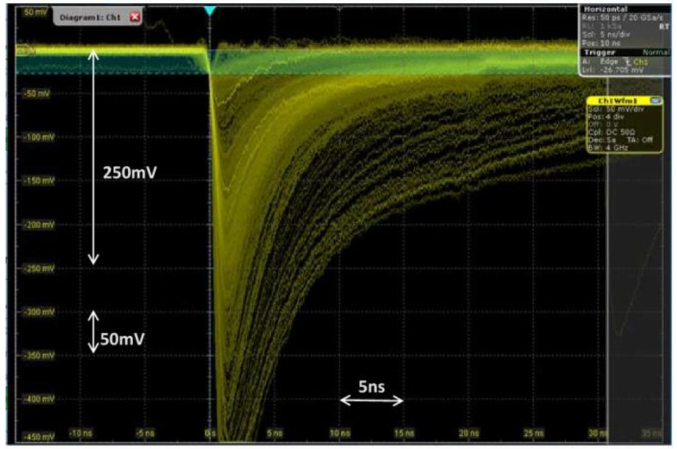

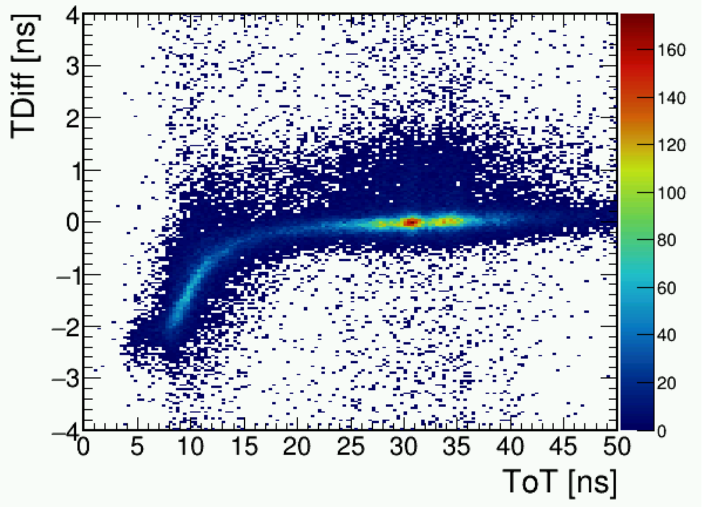

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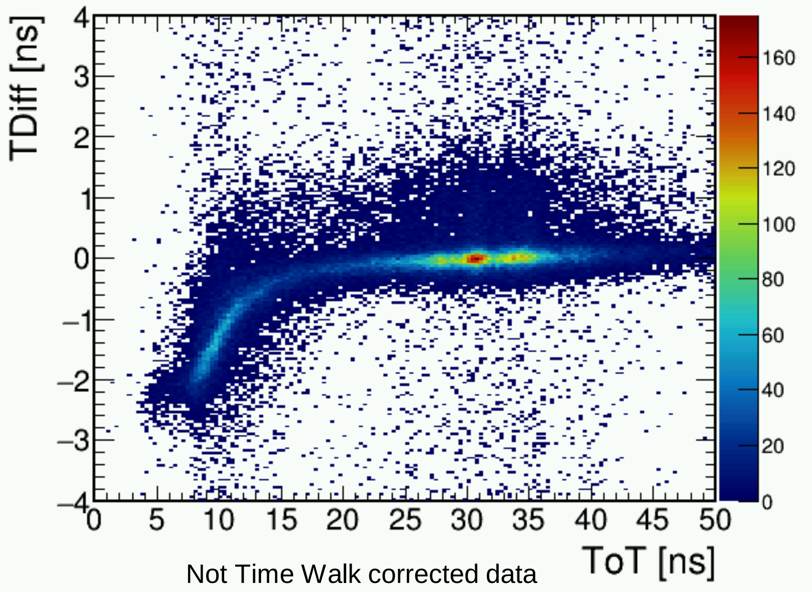
Prototyping Phase-2

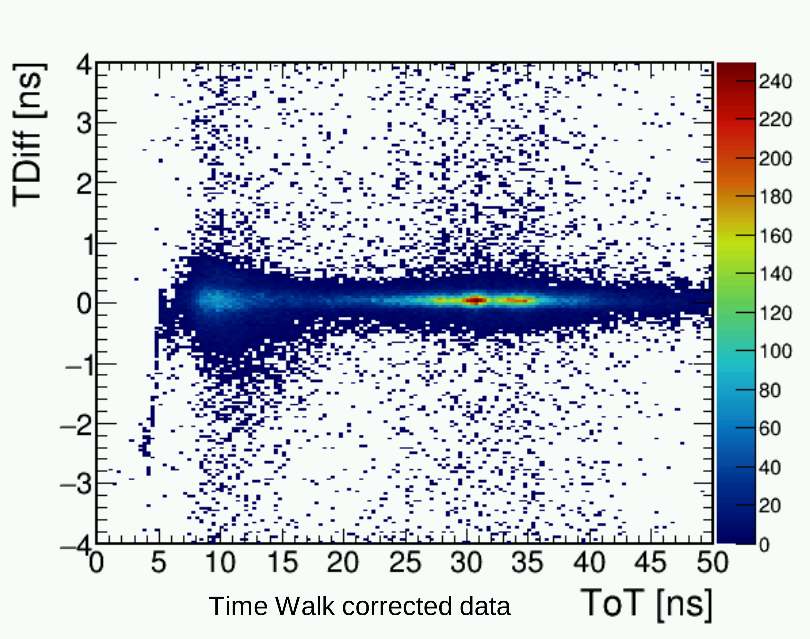
Pietraszko, J., Galatyuk, T., Kedych, V. et al., Low Gain Avalanche Detectors for the HADES reaction time (T0) Detector upgrade, Eur. Phys. J. A 56, 183 (2020)

Calibrated Data

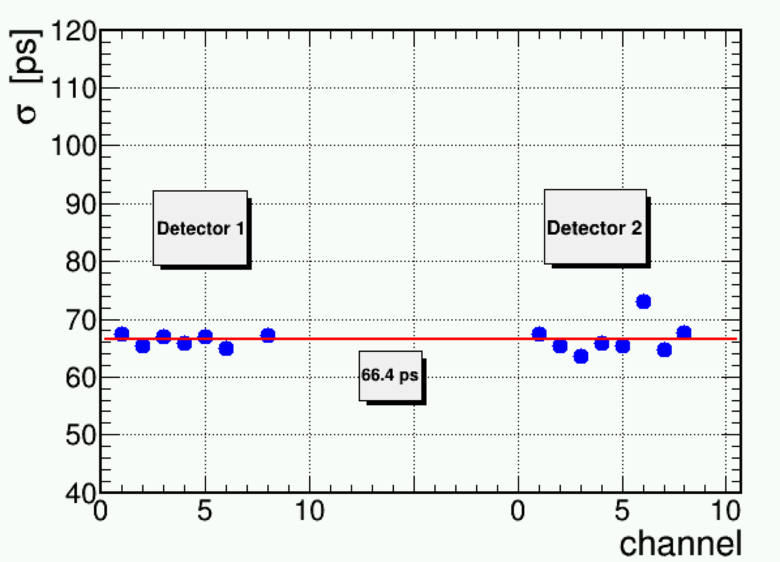
Final Performance



Not Time Walk corrected data



Time Walk corrected data



- 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

$\sigma_{T_0} = \frac{66.4}{\sqrt{2}}\, ps \approx \mathbf{47\ ps}$ 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
  - **~ 10^{14} n_{eq} / cm^2**
- Timing precision below **100 ps for MIPs**
- Fill factor close **to 100%**
- Low material budget
  - Below 500 µm 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 µm metal-metal, 24 µm gain-gain distance
- Thinning to **total thickness of 200 µm**

1. Sensor size: 2 cm x 2 cm

  - **2 x 48 half strips (9.28mm long)**
  - **Pitch about 387 µm, Die size 19.9 x 19.9 mm^2**
  - **Fill Factor ≈ 94 %**
  - **Capacitance ≈ 9 pF**

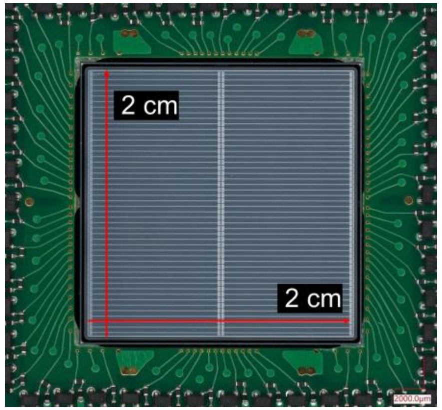
2. Sensor size 1cm x 1cm pitch about 192 µm
3. Sensor size 1cm x 1cm pitch 150 µm
4. Sensor size 1cm x 1cm pitch 100 µm
5. Sensor size 1cm x 0.5 cm pitch 50 µm

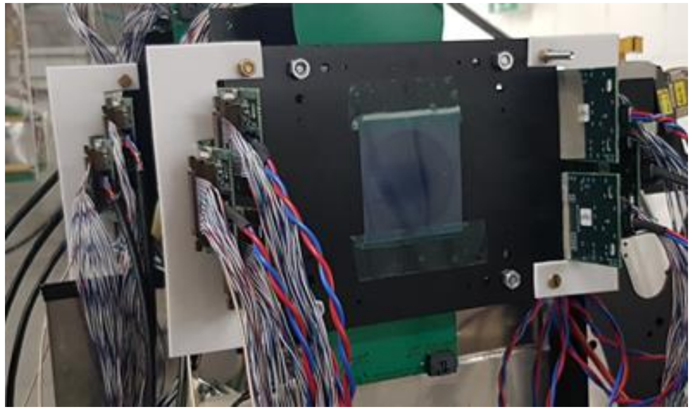
$\underbrace{\hphantom{xxxxxxxxxxxxxxxxxxxxxx}}$

R&D sensors for various applications

START Detector Full System Test @ COSY

Set-up



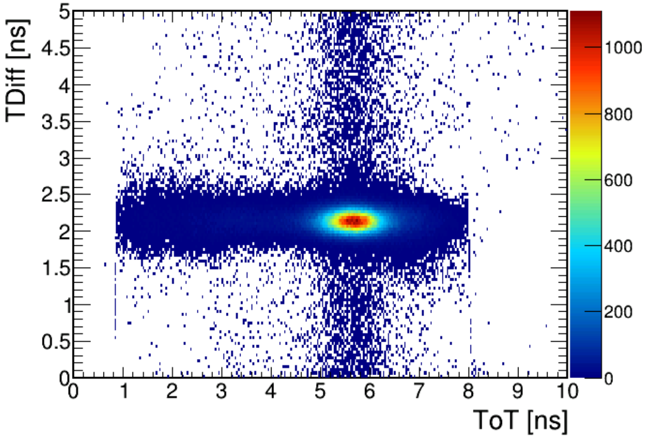


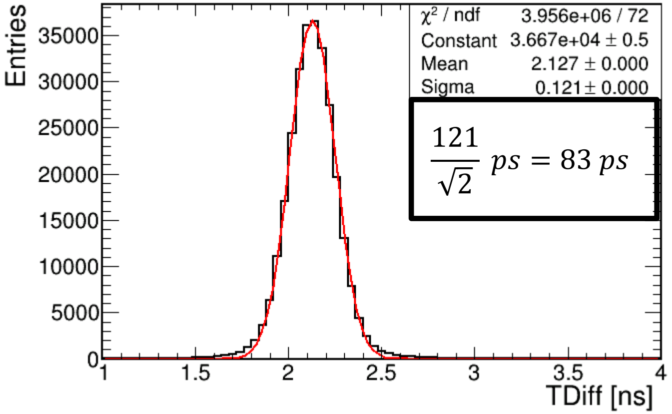
- 2 LGADs with HADES geometry tested
    - 50 µm active thickness
    - 200 µm total thickness
    - Up to 5 MHz/channel signal rate
    - PaDiWa and NINO discriminators tested
- 2 LGADs with 100 μm pitch for reference

Performance

Final test of LGADs for HADES p+p beam-time

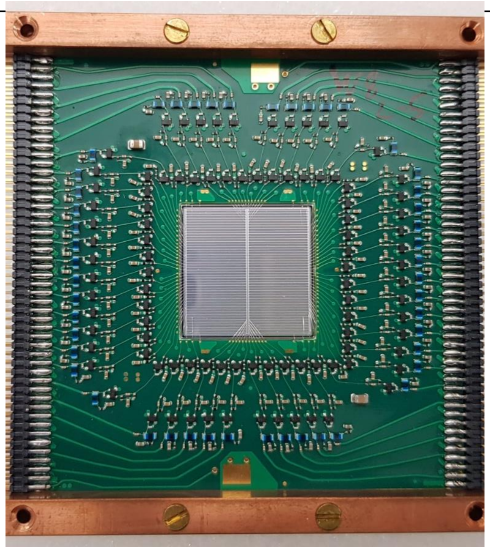
- After Time Walk corrections timing precision **below 85 ps per channel reached**
- Extracted from two independent LGAD sensors

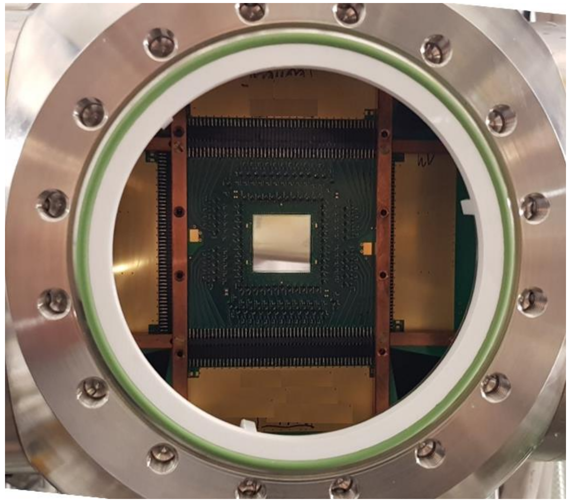




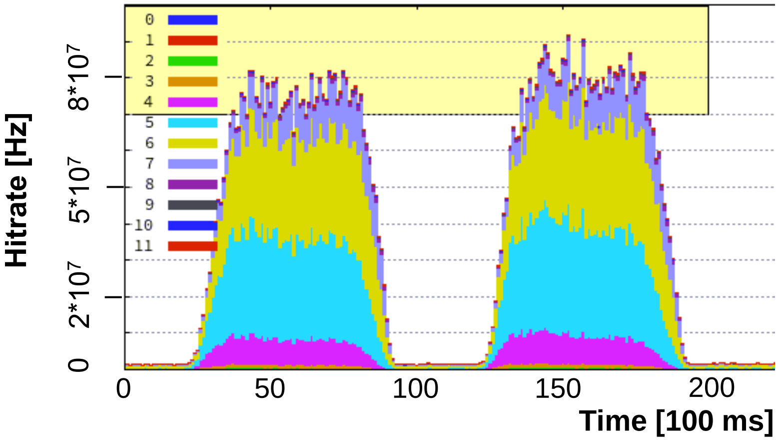
$$\frac{121}{\sqrt{2}}\,ps = 83\,ps$$

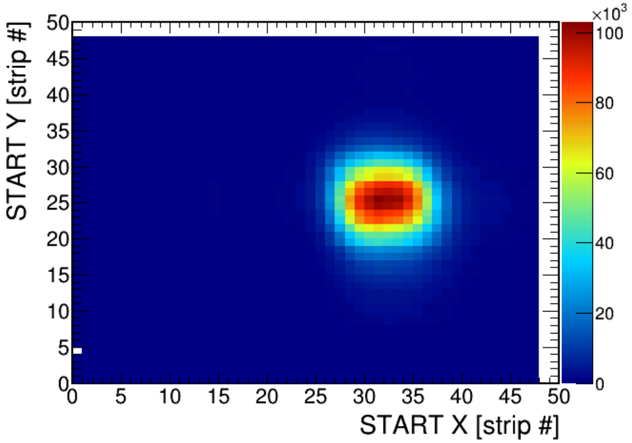
HADES START Detector in p+p @ 4.5 GeV Run Feb.-Mar. 2022





- 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 $\sqrt{2}$

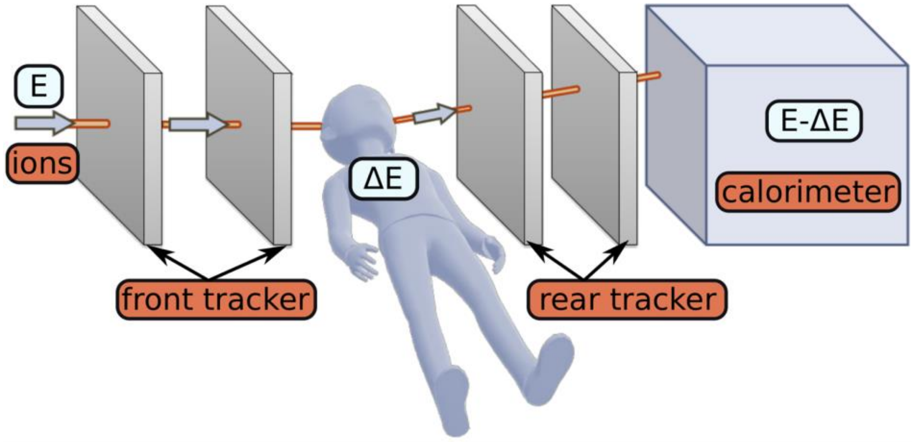




Medical Applications - Ion Imaging

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



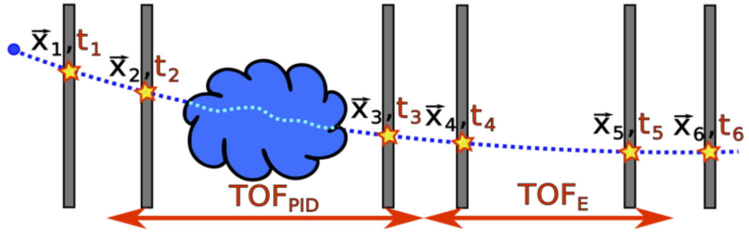
Conventional iCT system

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

Concept

G. Poludniowski et al. ,10.1259/bjr.20150134
R. Schulte et al., 10.1109/TNS.2004.829392

- 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 (F. Ulrich-Pur et al.,arXiv:2109.05058)
    - LGADs both for path estimation and residual energy measurements
    - TOF through object can also be exploited e.g. for particle identification (particle fragmentation) M Rovituso et al., 10.1088/1361-6560/aa5302
    - LGADs with 30-50 ps timing precision required

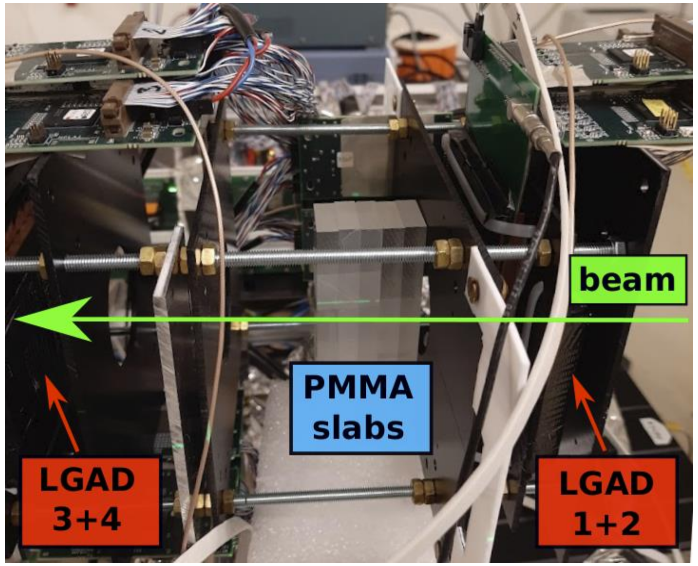


iCT system based on 4D-tracking with LGADs

Medical Applications - Ion Imaging

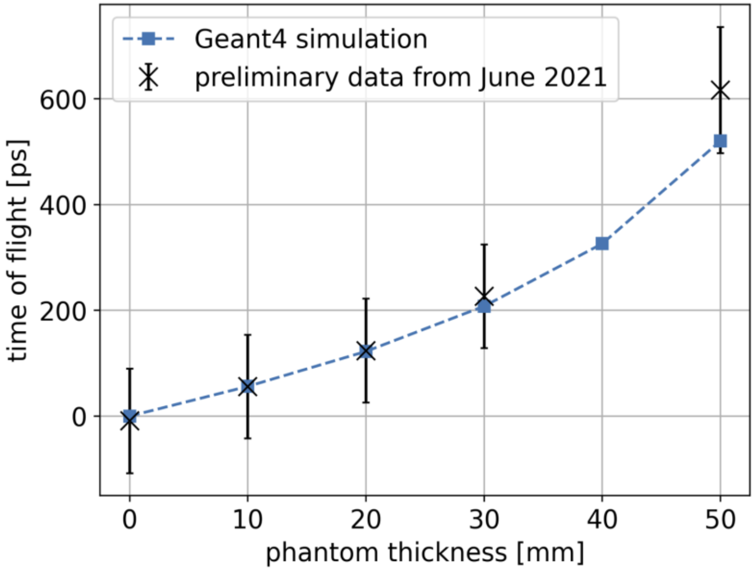
Setup at MedAustron

- 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

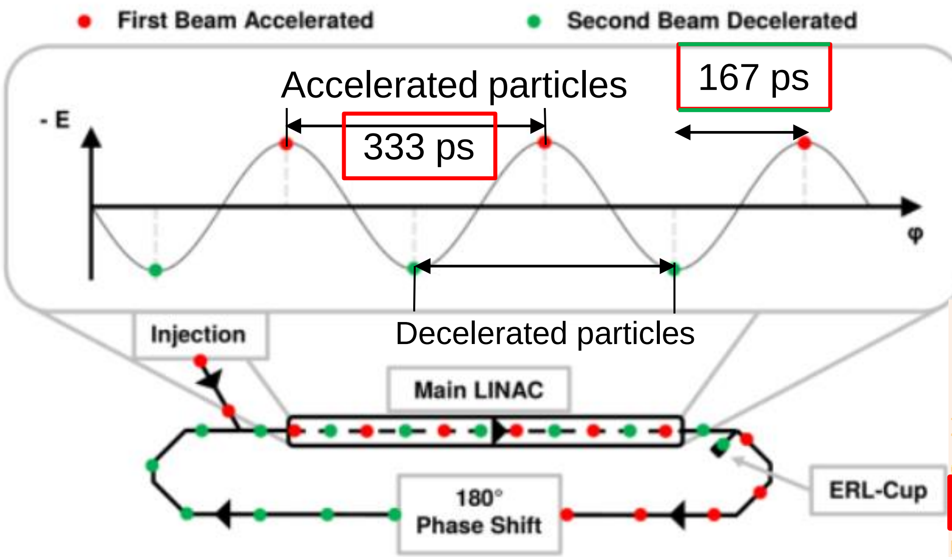


Preliminary results compared to a Geant4 simulation of the experimental setup

LGAD at S-DALINAC

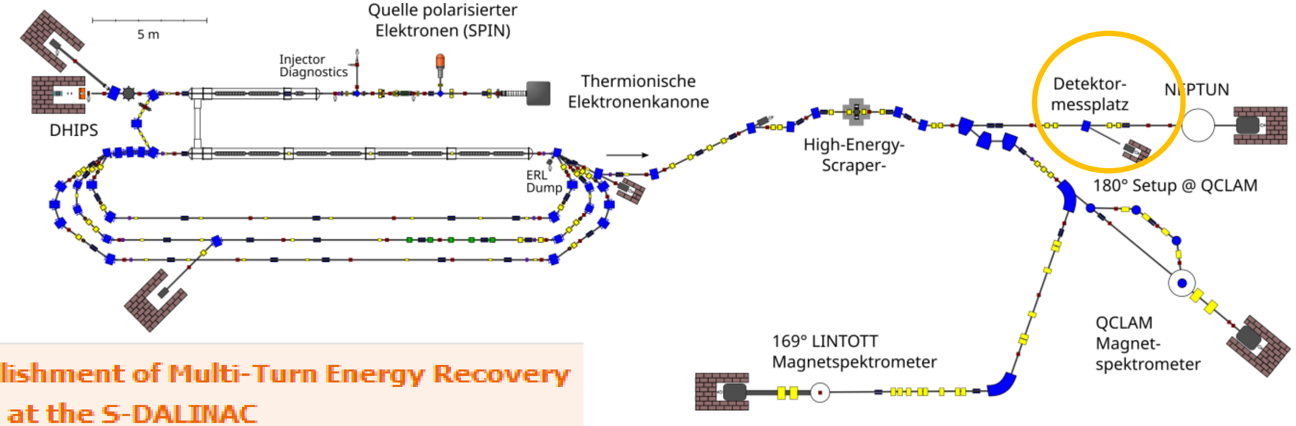
TECHNISCHE UNIVERSITÄT DARMSTADT

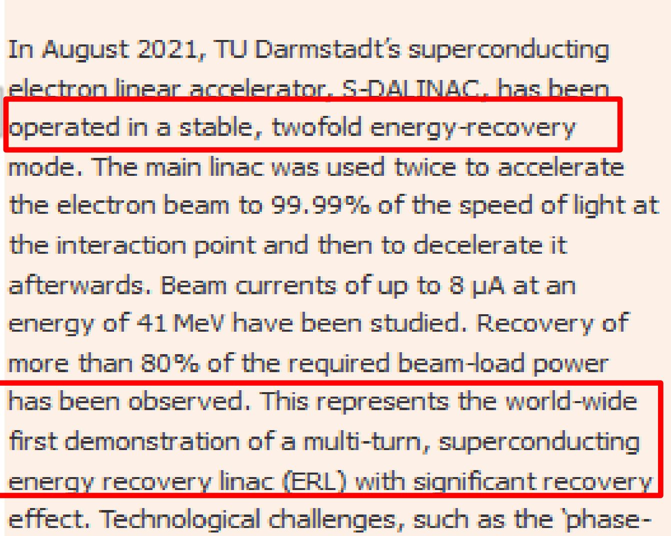
ERL concept



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

S-DALINAC





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

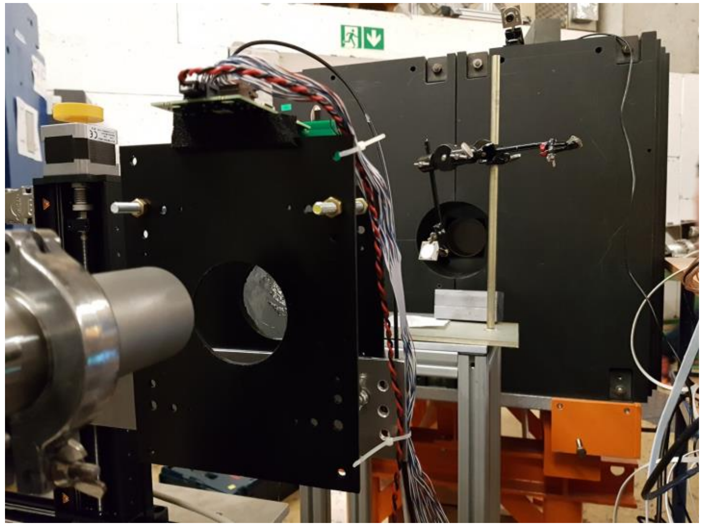
In August 2021, TU Darmstadt's superconducting electron linear accelerator, S-DALINAC, has been operated in a stable, twofold energy-recovery mode. The main linac was used twice to accelerate the electron beam to 99.99% of the speed of light at the interaction point and then to decelerate it afterwards. 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-

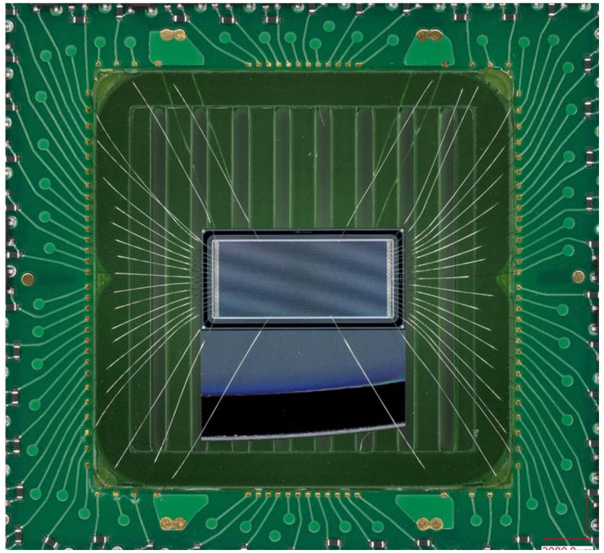
- 3 times **recirculating super conducting** linear electron accelerator
- ~ 130 MeV maximum electron energy
- **3 GHz time structure** (~333 ps between bunches)
- Operated in **two fold energy recovery mode** in August 2021
- LGADs foreseen for time structure monitoring

https://www.ikp.tu-darmstadt.de/nachrichten_2/home_3.de.jsp

LGAD at S-DALINAC Preliminary Results

LGAD set-up at S-DALINAC



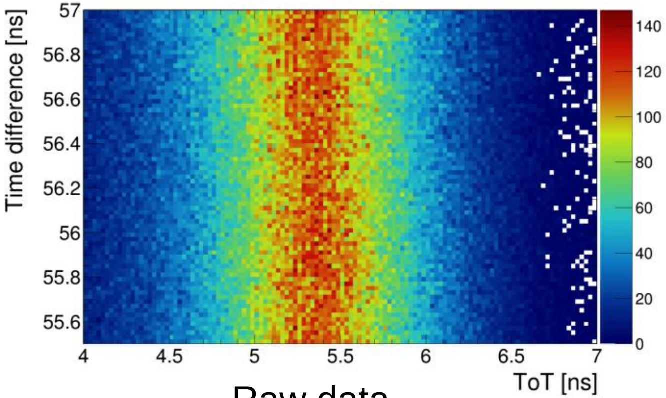


- Mulitpurpose test set-up at S-DALINAC (in air, not cooled)
- **Sensor** form factor of 0.5 x 1 cm^2
- 50 µm **pitch**
- 50 µm **active thickness**
- Produced by Fondazione Bruno Kessler

Measurement Principle

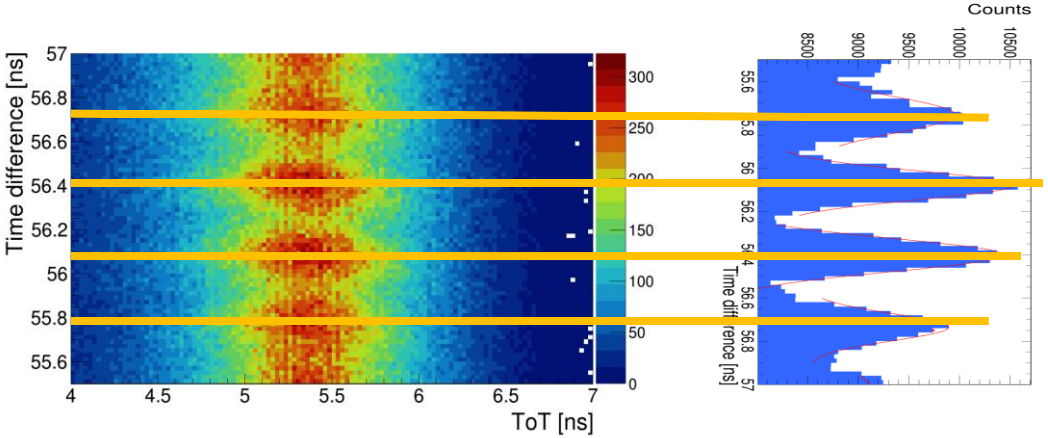
- Measure ToA of **two** electrons from different bunches
- **Time Walk correction** crucial to see 3 GHz time structure

LGAD Performance



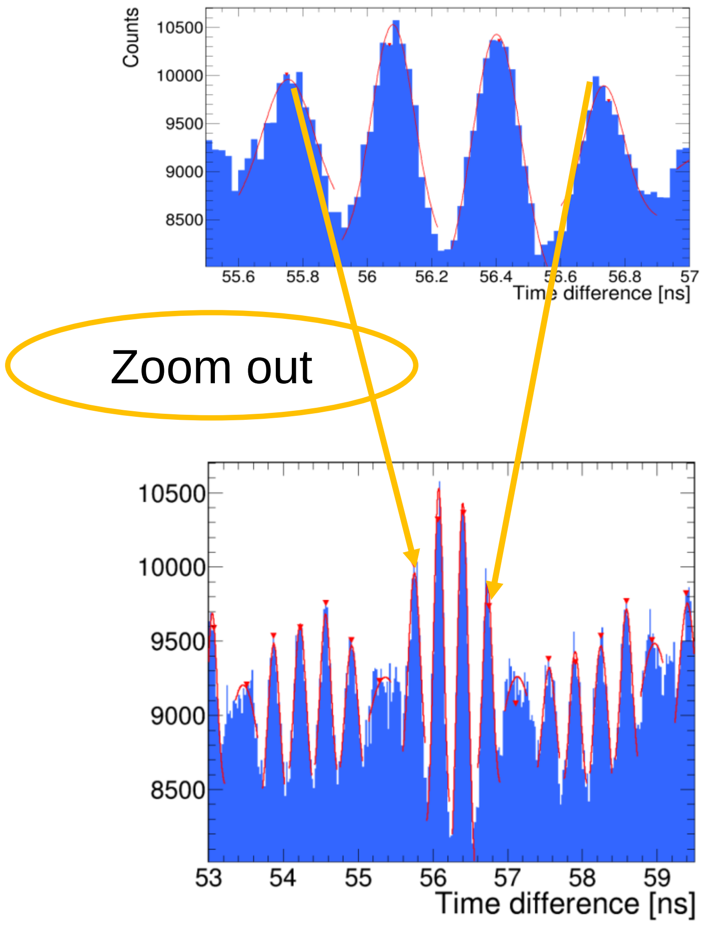
Raw data

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

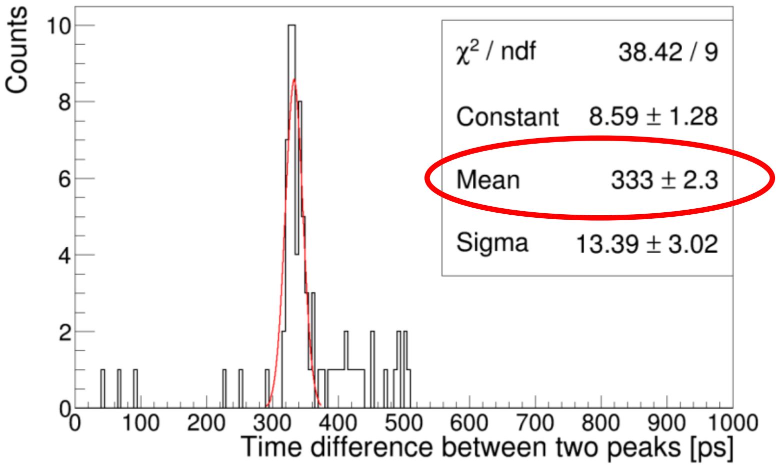


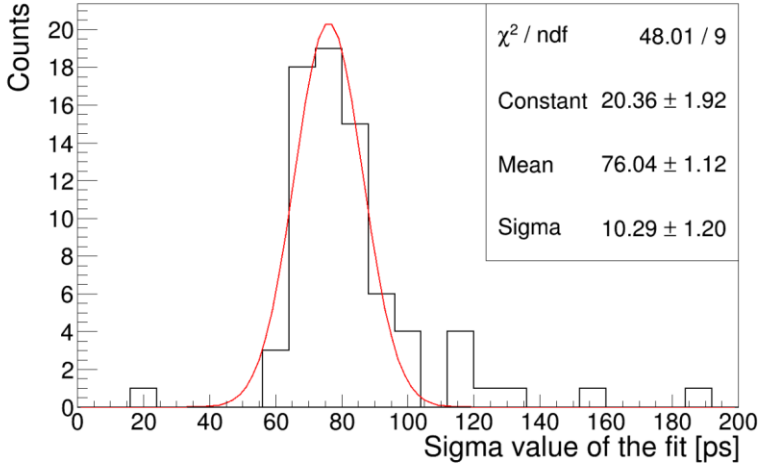
Time walk calibrated data

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 withing 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)

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