Development of a time-of-flight ion computed tomography system based on ultra-fast silicon sensors

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HEPHY and TU WIEN and the HADES LGAD group at GSI

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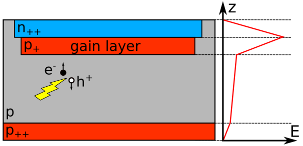
Ultra Fast Silicon Detectors/Low Gain Avalanche Detectors

Low Gain Avalanche Detectors (LGADs)

- thin silicon detector optimized for timing performance
  - gain layer exhibits high electric fields ($> 200\,\text{keV}/\text{cm}$)
    - 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

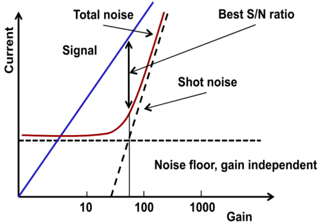


Figure: Sadrozinski et al. 2017

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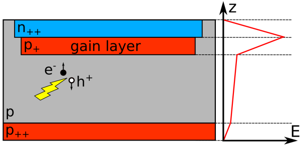

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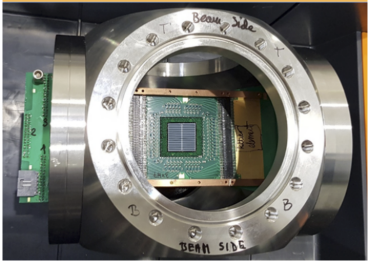
$$\sigma_T^2 \approx \underbrace{\left(\frac{T_{\mathrm{rise}}}{\mathrm{SNR}}\right)^2}_{\sigma_{\mathrm{jitter}}^2} + \underbrace{\sigma_{T,\mathrm{floor}}^2}_{\text{gain indep.}}$$

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
  - large areas $\mathcal{O}(cm^2)$
  - high particle rates (e.g. $10^8\,p/s/cm^2$ at HADES)

- 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 at GSI

HADES T0 detector

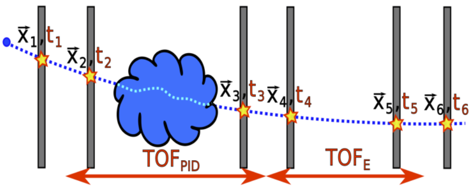


- but also medical applications
  - ion therapy beam quality monitor
  - **ion imaging**

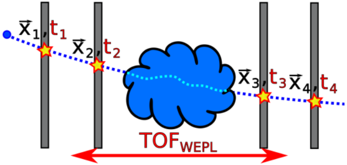
LGAD-based TOF-iCT system

LGAD-based TOF-iCT system - overview

- LGAD-based TOF-iCT system
  - requires 6 4D-tracking layers
  - TOF in air for residual energy determination
  - TOF through object + energy loss for PID (Rovituso et al. 2017)

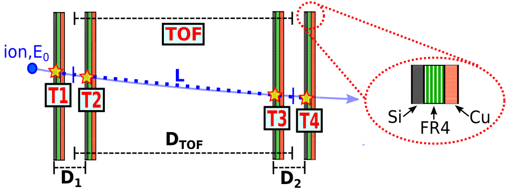


- second approach: “sandwich” TOF-iCT
  - indirect WEPL measurement via TOF through object
  - no need for residual energy detector
  - requires only 4 4D-tracking layers
  - imaging concept has been submitted to JINST (Ulrich-Pur et al. 2022b)



LGAD-based TOF-iCT system - previous work

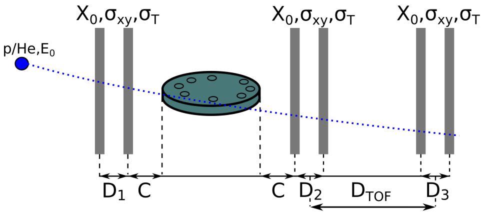
- Monte Carlo feasibility studies (Ulrich-Pur et al. 2022a)
  - performance study of stand-alone TOF calorimeter
    - influence of system parameters on energy resolution and accuracy
    - implementation of dedicated calibration procedure
    - time resolution 30-50 ps required
    - energy modulation, length of the calorimeter and number of LGADs can be adjusted to optimize the time resolution
  - see LLU workshop 2021

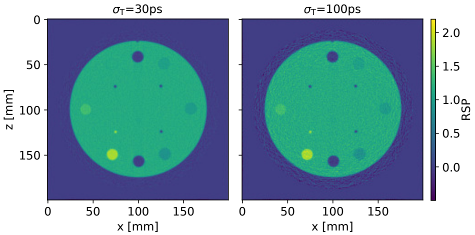


$$E_{kin} = m_0 c^2 \left(\frac{1}{\sqrt{1 - \frac{L^2}{c^2} \mathrm{TOF}^2} - 1} \right)$$

LGAD-based TOF-iCT system - previous work

- Monte Carlo feasibility studies (Ulrich-Pur et al. 2022a)
  - realistic model of LGAD-based TOF-iCT system
    - assessment of image quality using the CTP404 phantom
    - study of RSP accuracy and resolution
    - RSP MAPE down to 0.12 %
    - time resolution $\leq$ 30-50 ps required
  - see also Krah et al. 2022

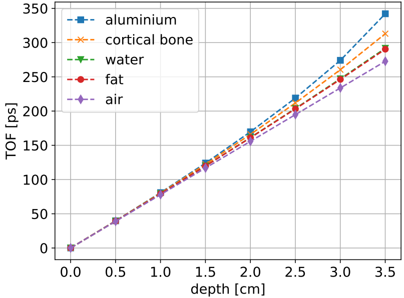




Sandwich TOF-iCT

“Sandwich” TOF-iCT - motivation

- main idea:
  - particles loose energy along their path
    - TOF increases depending on traversed material and beam energy
  - find method to exploit increase in TOF through object for WEPL estimation
    - define “new” material dependent quantity, i.e. slowing down power (SDP)
    - define imaging problem
    - find method to map the SDP to the stopping power (SP)

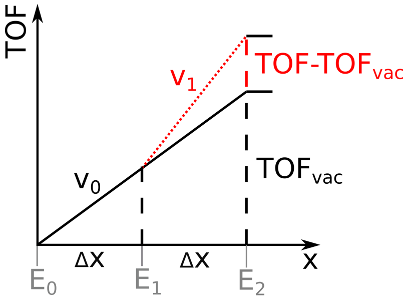


$$\mathrm{TOF} = \int_0^L \frac{\mathrm{d}s}{v(\mathbf{x}(s))} \neq \frac{L}{v}$$

"Sandwich" TOF-iCT - concept

- definition of "slowing down power"
  - increase in TOF with respect to the TOF in vacuum per unit path length

$$\mathrm{SDP}(E_{\mathrm{kin}}(\mathbf{x}(s)) := \frac{\mathrm{TOF}-\mathrm{TOF}_{\mathrm{vac}}}{\Delta s}(E_{\mathrm{kin}}(\mathbf{x}(s))$$



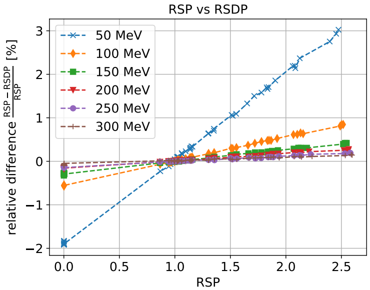
- SDP is directly related to SP

$$\mathrm{SDP}(E(x)) \approx -\frac{\Delta x}{2v^2(E(x))} v'(E(x)) \cdot \mathrm{SP}(E(x))$$

“Sandwich” TOF-iCT - concept

- define relative slowing down power (RSDP)
  - RSDP is approximately equal to the RSP
  - WEPL definition stays the same

$$\text{RSDP} := \frac{\text{SDP}_{\text{mat}}(E(x))}{\text{SDP}_{H_20}(E(x))} \approx \text{RSP}$$

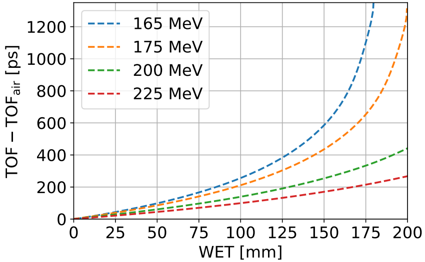


- inverse problem

$$\text{WEPL} := \int_0^{\text{TOF}-\text{TOF}_{\text{vac}}} \frac{d\Delta\text{TOF}}{\text{SDP}_{H_20}(\Delta\text{TOF}(E(\mathbf{x}(s))))} = \int_0^L \text{RSDP}\,(\mathbf{x}(s))\,ds \approx \int_0^L \text{RSP}\,(\mathbf{x}(s))\,ds$$

“Sandwich” TOF-iCT - concept

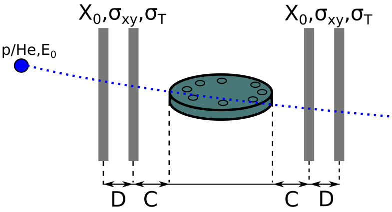
- measuring increase in TOF w.r.t vacuum is challenging
  - requires accurate velocity map to determine TOF in vacuum
  - can be obtained e.g. via MC simulations
- simpler approach
  - measure TOF increase w.r.t TOF in air and calibrate against WEPL
  - use e.g. 5th-order polynomial for calibration

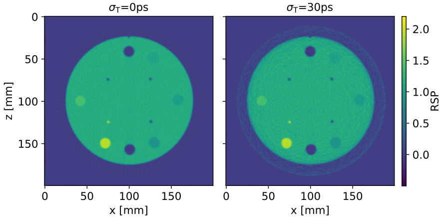


$$\mathrm{TOF} - \mathrm{TOF}_{\mathrm{air}}(\mathrm{WEPL}, \mathrm{E}_0) \approx \sum_{i=0}^{5} a_i(E_0) \cdot \mathrm{WEPL}^i$$

“Sandwich” TOF-iCT - MC study

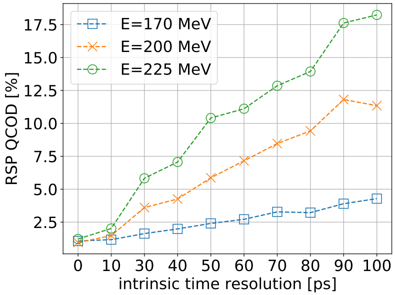
- Monte Carlo feasibility study (Ulrich-Pur et al. 2022b)
  - same MC model as in “standard” TOF-iCT study
  - determine influence of different system parameters on image quality
    - influence on RSP accuracy and resolution
    - measured with CTP 404 phantom
  - first study based on simple WEPL calibration approach

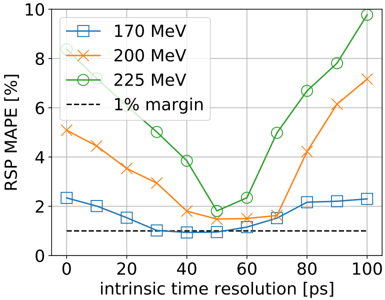




‘Sandwich” TOF-iCT - MC study

- RSP resolution (QCOD) shows similar dependence on time resolution and beam energy when compared to standard TOF-iCT system
- RSP accuracy $\geq 0.91\ \%$
  - still shows systematic dependence on system parameters
    - more dedicated calibration procedure/model is currently under investigation

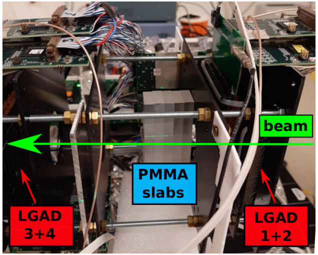


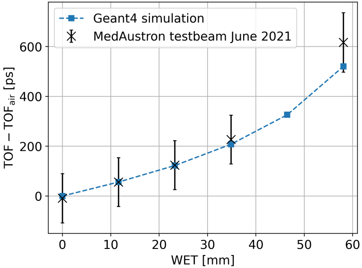


Hardware development efforts towards a TOF-iCT demonstrator system

TOF-iCT demonstrator - previous work

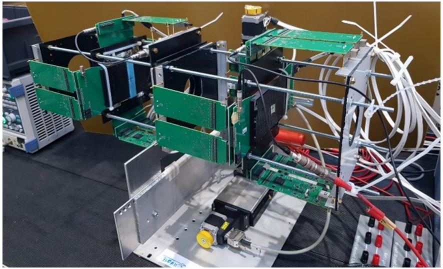
- first proof-of-principle measurement at MedAustron in 2021 (Krüger et al. 2022)
  - 4 LGAD strip sensors (HADES) with different geometries
    - total active area: $0.5 \times 0.5\,\mathrm{cm}^2$
  - $100.4\,\mathrm{MeV}$ protons with $\approx 5 \times 10^6\,\mathrm{p/s}$
  - increase in TOF for different PMMA absorbers

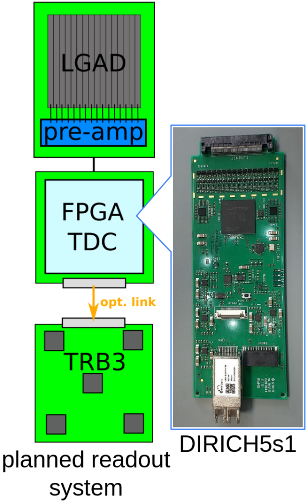




TOF-iCT demonstrator - current setup

- TOF-iCT demonstrator at GSI
  - four $1 \times 1\,\mathrm{cm}^2$ HADES strip LGADs with 100 µm pitch
  - discrete front-end electronics
  - FPGA-based TDCs with leading-edge discriminator
    - 4x DIRICH5s1 (32 channels per DiRICH)
  - plan to image small objects $\mathcal{O}(< 1\,\mathrm{cm}^2)$





Summary and outlook

Summary and outlook

- LGADs are promising 4D-tracking detectors with many applications
  - well-suited for ion imaging
- two scanner concepts have been studied via MC simulations
  - “standard” TOF-iCT system with TOF calorimeter
  - sandwich TOF-iCT system without a residual energy detector
- TOF-iCT demonstrator system
  - first demonstrator system based on LGAD strip sensors
  - plan to image small objects $< \mathcal{O}(cm^3)$
- future system
  - requires dedicated ASIC which can handle high rates and large number of channels
  - dedicated module design to build low-mass large area system
  - funding

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Backup slides

- LGADs for beam monitoring (Krüger et al. 2022)

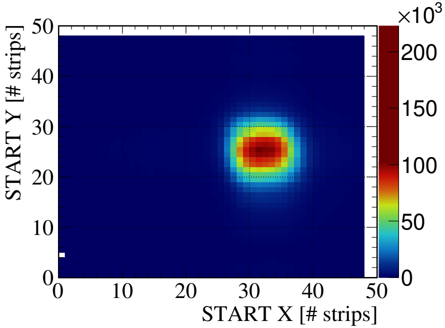

Figure: beam spot measurement

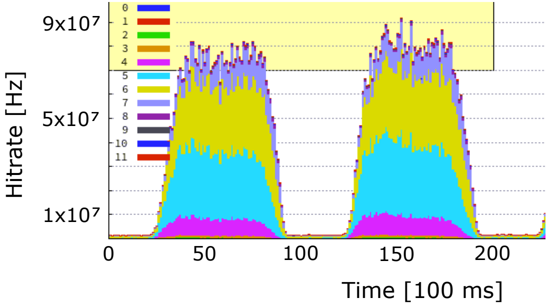

Figure: macro spill structure of p beam

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