LGAD enabling technology for 4D tracking and timing measurements in experiments with ions, accelerators and for medical applications

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OUTLINE

- ❑ Problem defined
- ❑ What is LGAD
- ❑ Advantage, disadvantage, limitations of LGAD
- ❑ Selected samples of applications
  - ❑ HEP
  - ❑ Biomedical research
  - ❑ Astrophysics
- ❑ Conclusions

General consideration

The research in frontier science (HEP, astrophysics, space research, cancer therapy etc) requires

- state –of –the –art sensor technology
- state of the art scientifical tools for characterisation of technologies

What are the requested ingredients?

- Excellent timing resolution
- Excellent spatial resolution
- Excellent radiation resistance
- S/N
- Readout electronics
    - vey challenging task!

Excellent timing resolution

- Enabling 4D tracking (completely a new concept!)
    - 4D tracking enabling 5D calorimetery (x,y,z,E,t)!
        - a new paradigm

Excellent spatial resolution requires

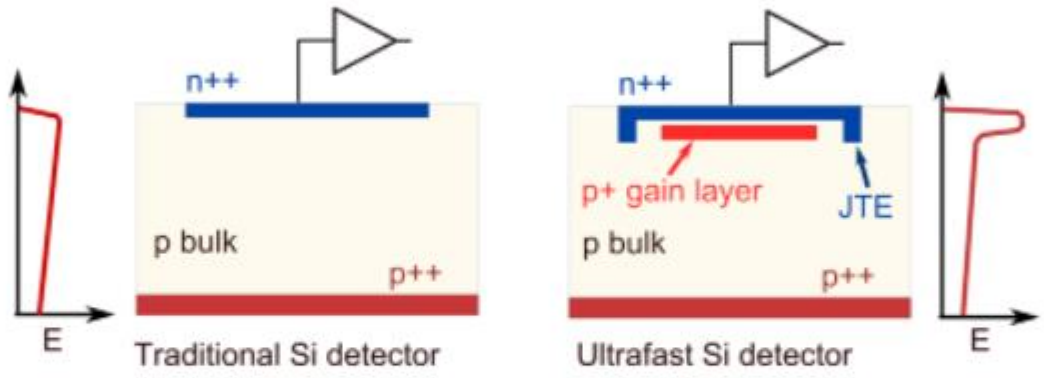
- ✓ segmented detector with a high granularity
    - ✓ small interpixel distance between exceptionally small sensors(50 microns of active region) case of LGAD

What is LGAD

- Low Gain Avalanche Diodes (LGADs) ($n^{++}p^{+}pp^{++}$) are silicon sensors based on p–n junction and provided with an internal signal amplification mechanism (gain).
- Originally designed as technology for timing detectors CMS and ATLAS in order to educe pile-up events at the LHC.
- In this application, the LGADs are used to **measure the time of arrival of minimum ionizing particles** (MIP), providing a time-tagging of the tra reconstructed in the experiments.
- The internal structure is similar to that of silicon Avalanche Photodiodes (APDs), but the gain is much lower (O(10) with respect to O(1000) of APD).
- Gain layer provides gain ~10. – Time resolution for 1 MIP ~10-30 ps.

PIN

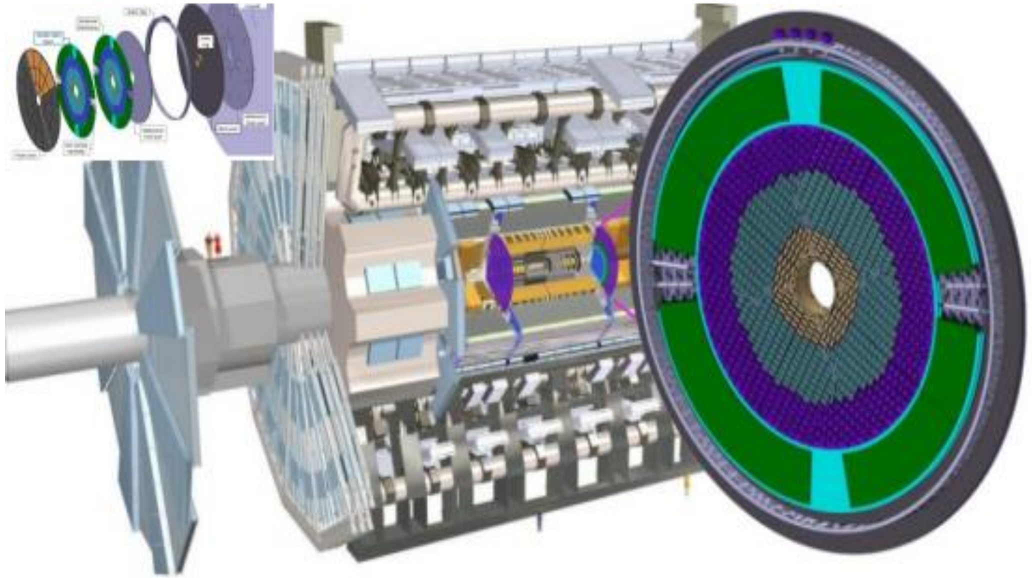
LGAD



Comparison between standard Si-detector (on the left) and LGAD with implemented highly dopped p+ layer in the bulk region (on the right side).

The major limitation for their use is radiation damage manifested as initial acceptor removal
➢The loss of gain layer can be compensated by increase of bias voltage

ATLAS – LGAD based High Granularity Timing Detector

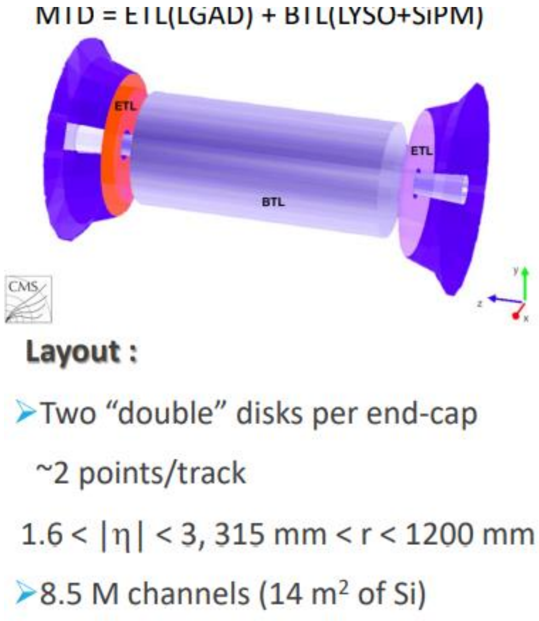


Two double-instrumented disks per end-cap ~2.0 – 2.4 - 2.6 points/track

2.4 < |h| < 4, 120 mm < r < 640 mm , z=350 cm

➢3.6 M channels operating at -30oC (6.4 m2 of Si)

CMS: LGAD based ETL(Endcap Timing Layer)



MTD = ETL(LGAD) + BTL(LYSO+SiPM)

Layout :

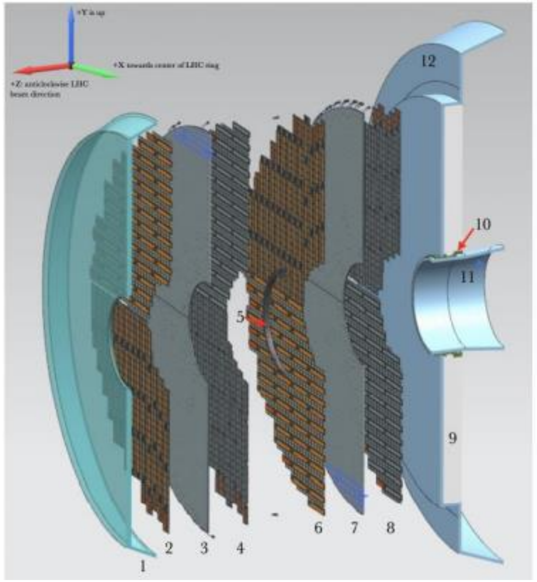
- ➢Two “double” disks per end-cap

  ~2 points/track

  1.6 < |η| < 3, 315 mm < r < 1200 mm

- ➢8.5 M channels (14 m^2 of Si)

CMS-MTD TDR (cern.ch)

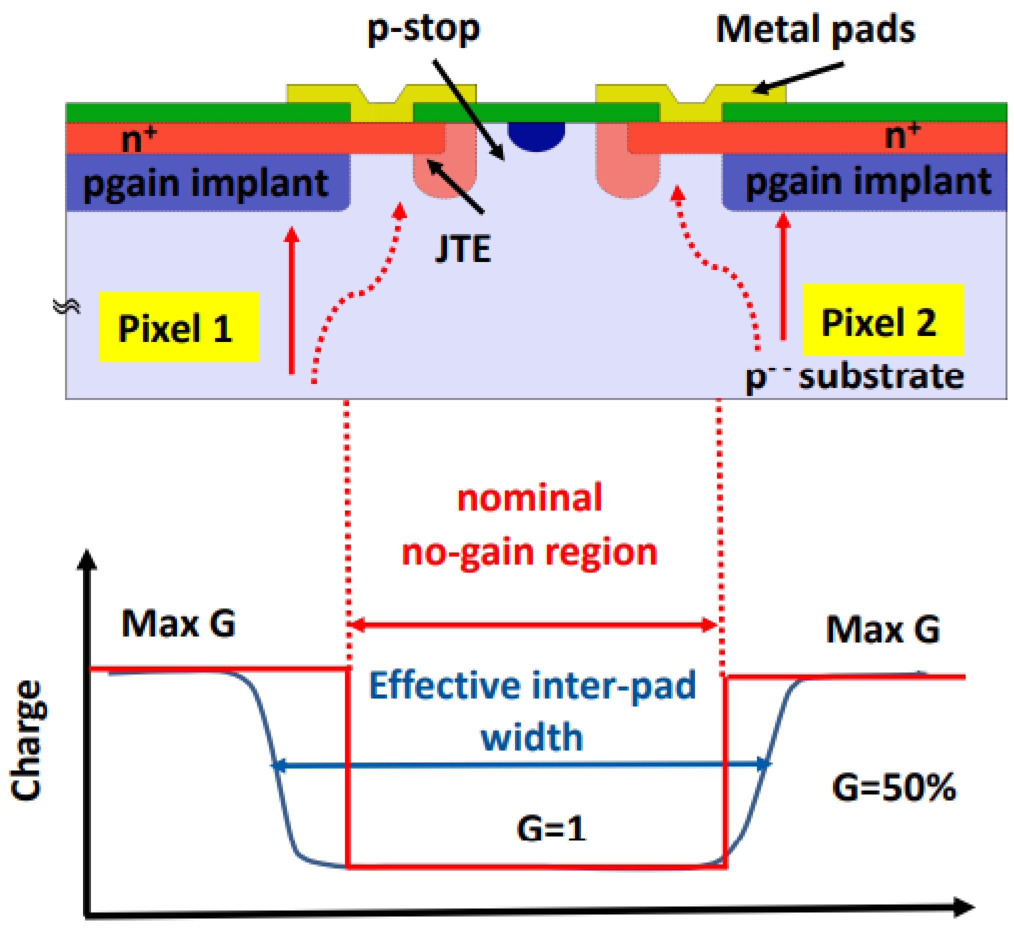


Different module arrangement and connectivity as ATLAS but essentially also “pixel” module

Issue: Segmentation in standard LGAD

[G. Paternoster et al., Novel strategies for fine-segmented Low Gain Avalanche Diodes, NIM A 987 (2021) 164840]

The collection and drift mechanisms also play a role in the no-gain region.



- Some carriers, generated at the periphery of the gain implant, are collected by the JTE and do not pass through the gain layer.
- **These carriers are multiplied with reduced gain**

Effective interpad width
>=
nominal no-gain

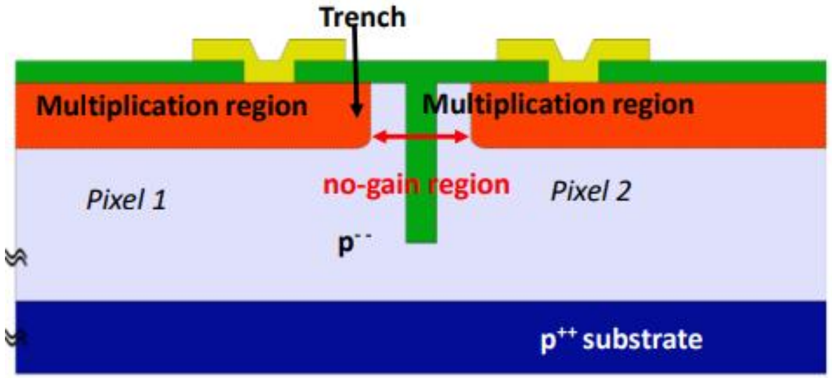
JTE-Junction termination extension

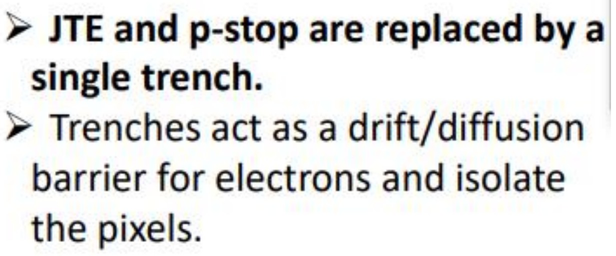
Inter-pad distance in LGADs determines the "fill factor" of the sensors – sensitive area irradiation

Advanced segmentation: Deep Trench Isolation Technology

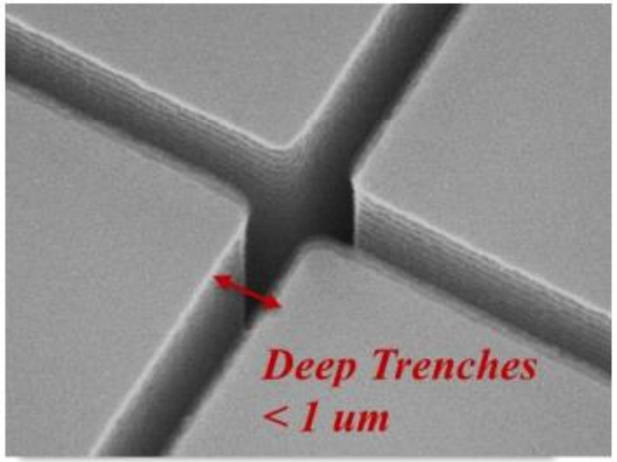
- ✓ DC readout
- ✓ Patterned p-gain
- ✓ Compact isolation structure based on Deep Trench Isolation technology

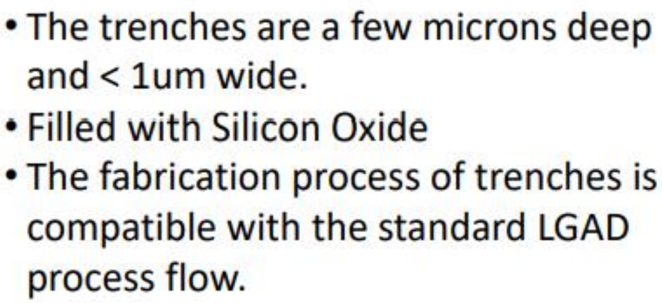
- ➢ Developed by FBK





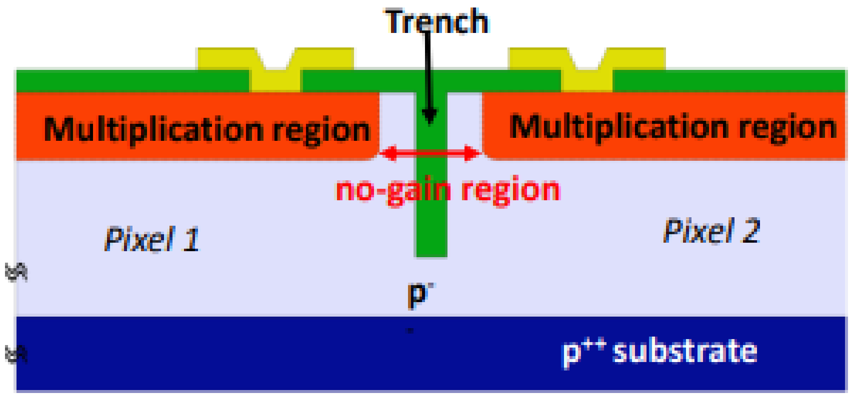
- ➢ **JTE and p-stop are replaced by a single trench.**
- ➢ Trenches act as a drift/diffusion barrier for electrons and isolate the pixels.



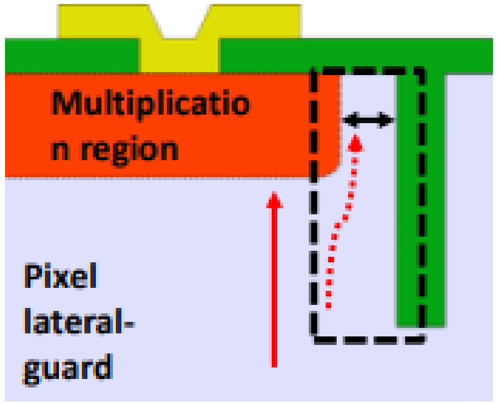


- The trenches are a few microns deep and < 1um wide.
- Filled with Silicon Oxide
- The fabrication process of trenches is compatible with the standard LGAD process flow.

Two – fold advantage with respect to standard LGADs



- Trenches are much smaller wrt JTE and p-stop => smaller nominal no-gain region **(from 20-60 um to 4-6um)**
- The E-field at the pixel border could be optimized to reduce the transition region width

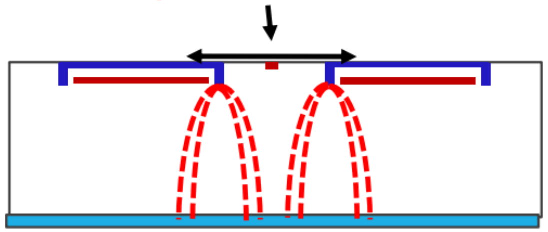


Multiplication Region to Trench distance

Smaller gain-loss region is expected

Standard LGAD

No gain area ~ 50 um



JTE + p-stop design

Image: -IEEEE Elec. Dev. Lett. 41 (2020) p. 884]

- CMS & ATLAS choice (many details in TDR)
- Signal in a single pixel: little charge sharing
- Not 100% fill factor (FF)
- FF has a strong function of IP
- JTE makes the effective IP significantly larger than geometrical
- Very well tested
- Suited for very high occupancy
- Rate ~ 50-100 MHz

Radiation hardness ~ 2.5E15 n/cm2 (limited by gain removal and SEB)

Standard segmentation

TI-LGAD

No gain area ~ 5 um

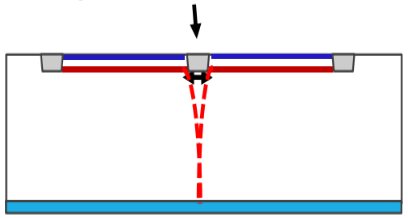


Image: -IEEEE Elec. Dev. Lett. 41 (2020) p. 884]

- Signal in a single pixel
- almost 100% fill factor (suitable for pixels ~100x100 mm2)
- time resolution similar to JTE-p-stop design
- suited for very high occupancy
- Rate ~ 50-100 MHz

Radiation hardness: to be studied (in addition to JTE-p stop also break-down at the IP, loss of isolation)

Advanced segmentation

iLGAD

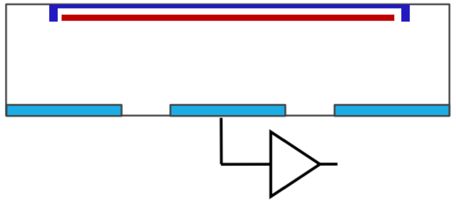


Image: iLGAD [JINST 11 (2016) C12039; NIM A958 (2020) 162545]

- p-side segmentation (no need for p-spray/stop)
- Multiplication in a non-segmented layer
- 100% fill factor except at the edges
- Thin i-LGAD with single side processing (conventional is double sided) under development at CNM
- Suitable for high occupancy
- Rate ~ 50-100 MHz

Radiation hardness: in addition to gain loss and SEB – more influence of trapping (hole collection), unknown possible effects at p+ segmented electrodes

AC coupled

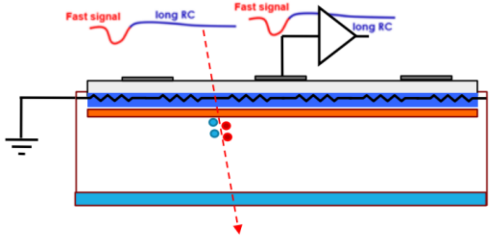


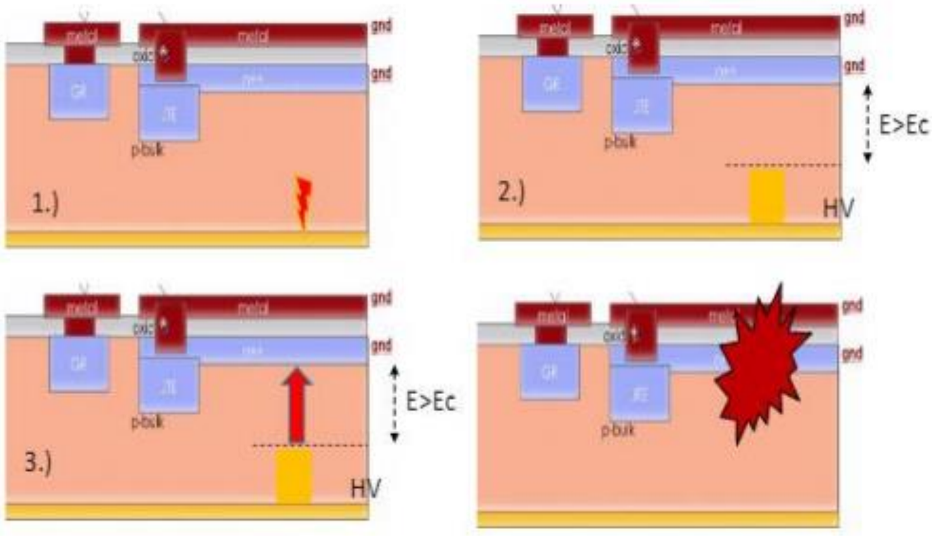
Image: [M. Mandurrino et al., NIM A959 (2020) 163479]

- Signal in many pixels – capacitive coupling similar to AC strip detectors
- 100% fill factor
- Excellent position resolution: ~ 5 mm with large pixels – resistive charge sharing (CoG/extrapolation methods)
- Temporal resolution (50 mm) : 35-40 ps
- Rate is limited by the RC constant - pileup

Radiation hardness: in addition to gain loss and SEB, large changes of n+ resistivity (RC), charging of the layer

ISSUE: Single Event Burnout (SEB) induced by Highly Ionized Particle

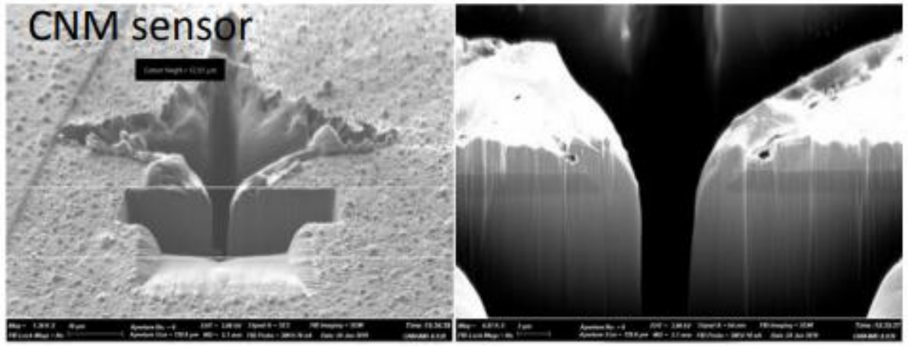
This field collapse in the presence of high concentration of free carriers is the probable cause. Electric field (Vbias/thickness) is the key parameter determining the fatality.



hypotheses

- 1.) larger deposition of the charge (fragments producing deposition in few mm as large as 1000 mips are possible) in few mm (not possible with lab sources)
- 2.)larger density of carriers leading to collapse of the field (screening prevents the carriers from being swept away
- 3.) once the field collapses the HV is brought closer to the pad which leads to very high field strength and to avalanche breakdown causing full discharge of sensors and bias capacitor
- 4.) the discharge leaves a crater behind if enough energy is stored to melt the silicon (~10 nF) The process of large current in narrow path is called “Single Event Burnout” – SEB

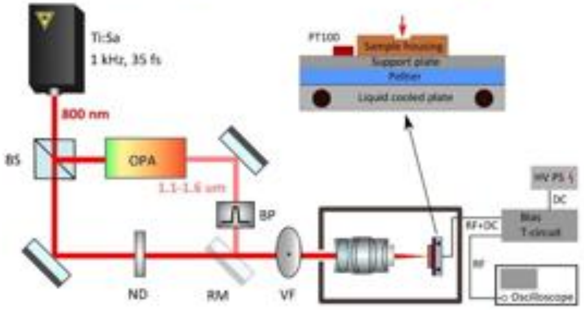
Burning mark:



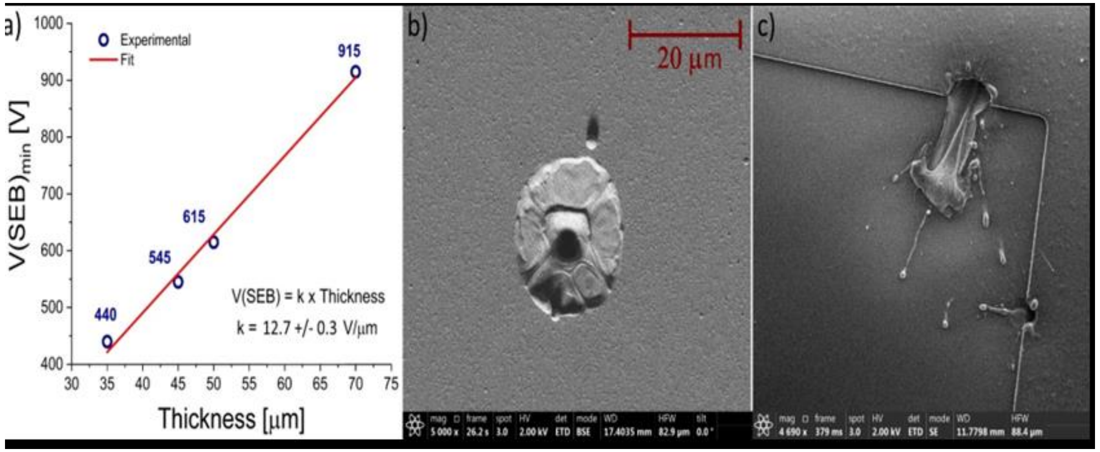
“courtesy of CNM (ATLAS TB sensor)”

Laser tests at ELI Beamlines was used to simulate SEB

Experimental station:
SEB testing facility developed at ELI Beamlines in Czechia

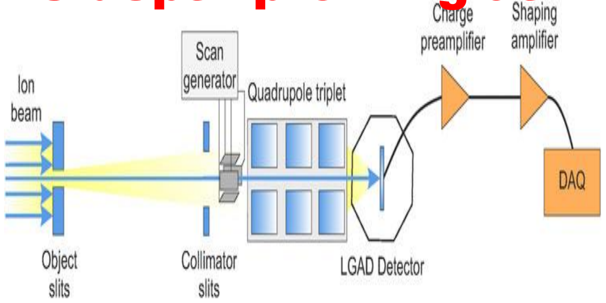


Gordana Laštovička-Medin et al., Femtosecond laser studies of the Single Event Effects in Low Gain Avalanche Detectors and PINs at ELI Beamlines, recently published to NIM A, 2022.

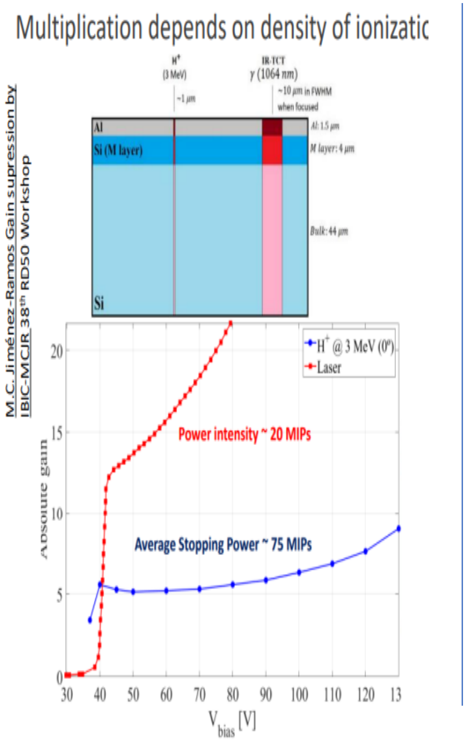


Issue: Density Induced Gain suppression

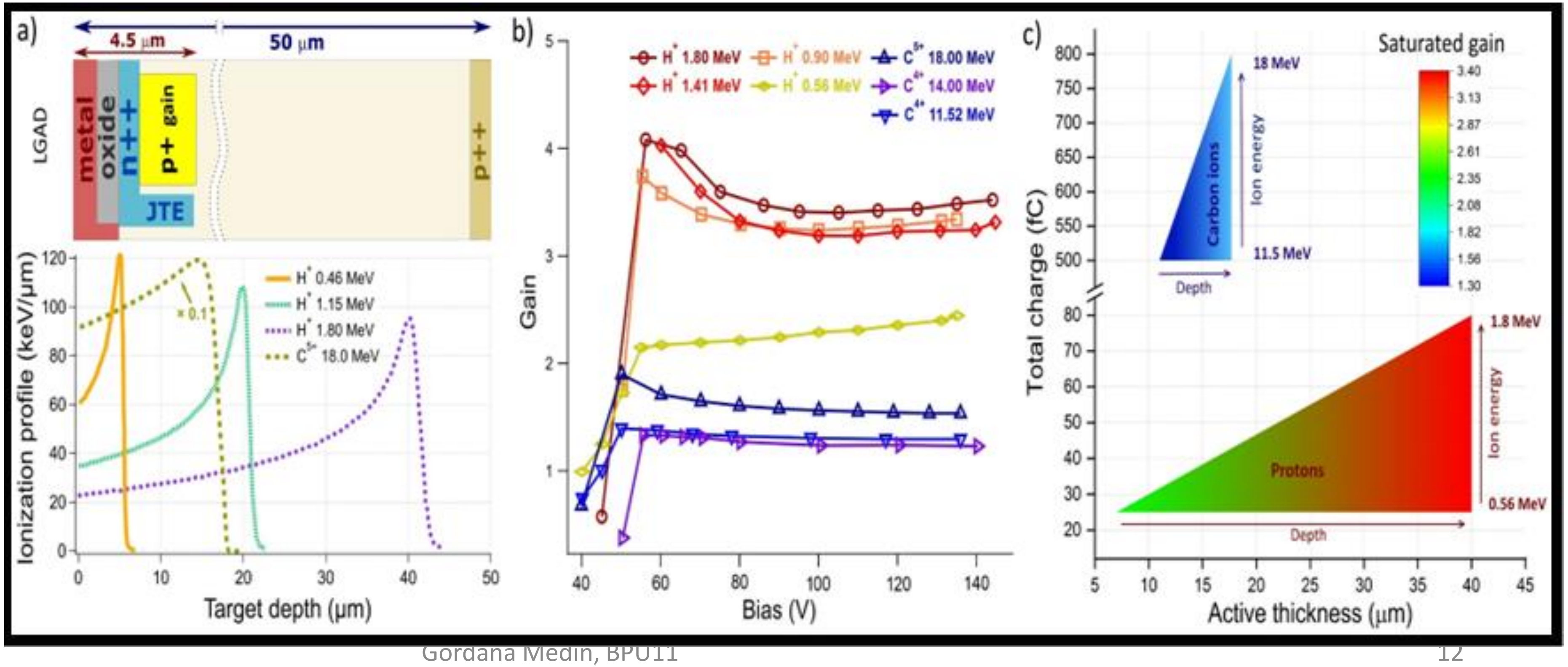
tested by IBIC depth profiling at RBI



Milko Jaksic, Andreo Crnjac, Gregor Kramberger, Milos Manojlovic,Gordana Lastovicka-Medin, M.R, Ramos et al. "Ion Microbeam Studies of Charge Transport in Semiconductor Radiation Detectors With Three-Dimensional Structures: An Example of LGAD." *Frontiers in Physics* (2022): 415


Multiplication depends on density of ionizatic

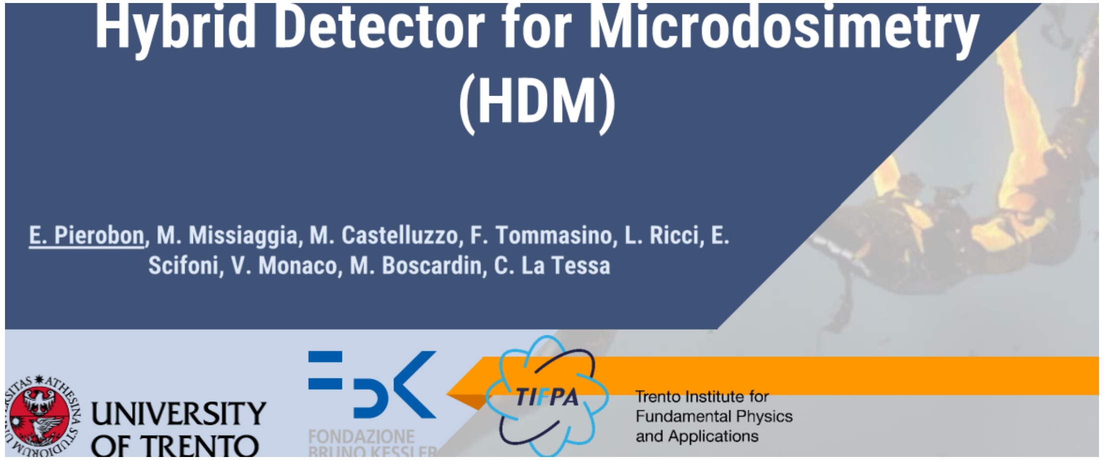
M.C. Jiménez-Ramos Gain supression by IBIC-MCJR 38th RD50 Workshop



Applications/Selected examples

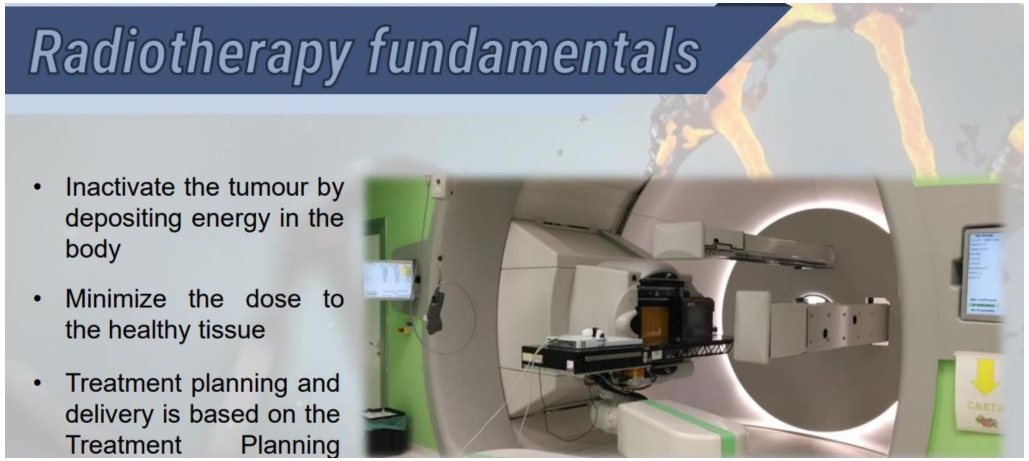
Biomedical research

An example of Hybrid detector for dosimetry exploring the LGAD potential



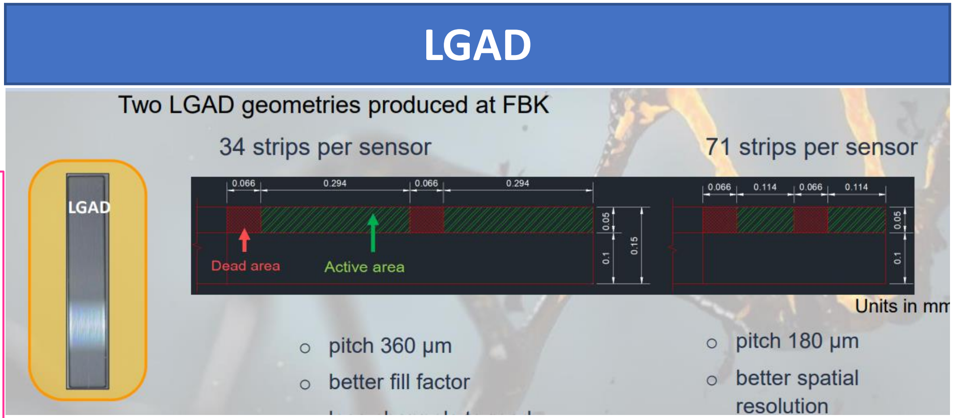
Hybrid Detector for Microdosimetry (HDM)

E. Pierobon, M. Missiaggia, M. Castelluzzo, F. Tommasino, L. Ricci, E. Scifoni, V. Monaco, M. Boscardin, C. La Tessa



Radiotherapy fundamentals

- Inactivate the tumour by depositing energy in the body
- Minimize the dose to the healthy tissue
- Treatment planning and delivery is based on the Treatment Planning



LGAD

Two LGAD geometries produced at FBK

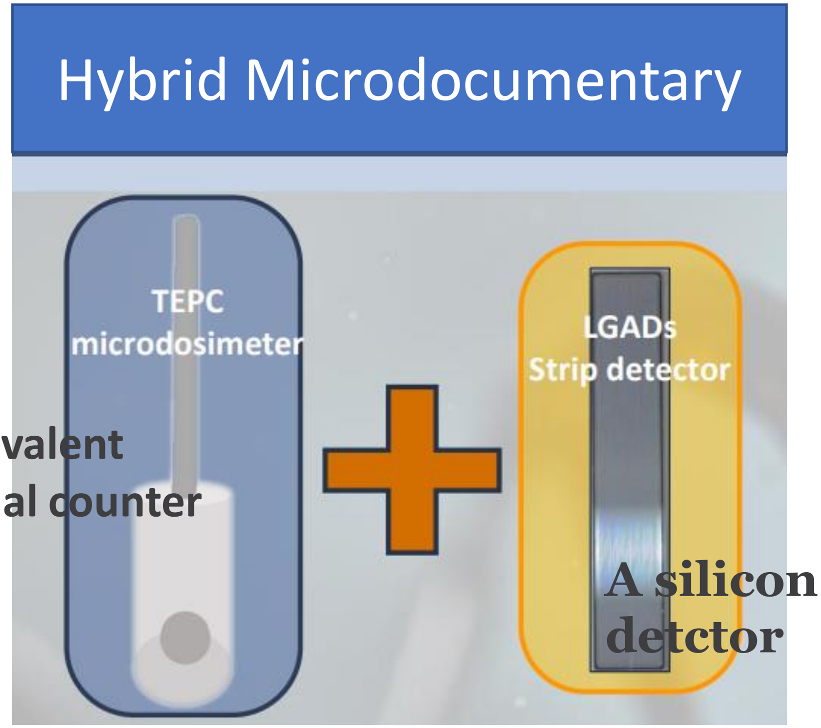
34 strips per sensor

71 strips per sensor

Units in mm

- pitch 360 μm
- better fill factor

- pitch 180 μm
- better spatial resolution

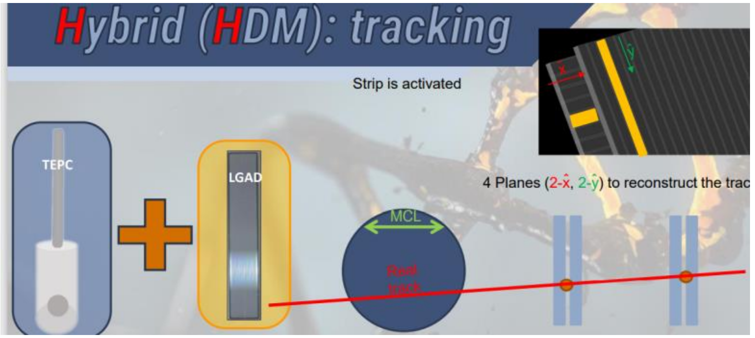


Hybrid Microdocumentary

tissue equivalent proportional counter

A silicon detctor

This design provides a direct measurement of energy deposition in tissue as well as particles tracking with a submillimetre lateral spatial resolution.



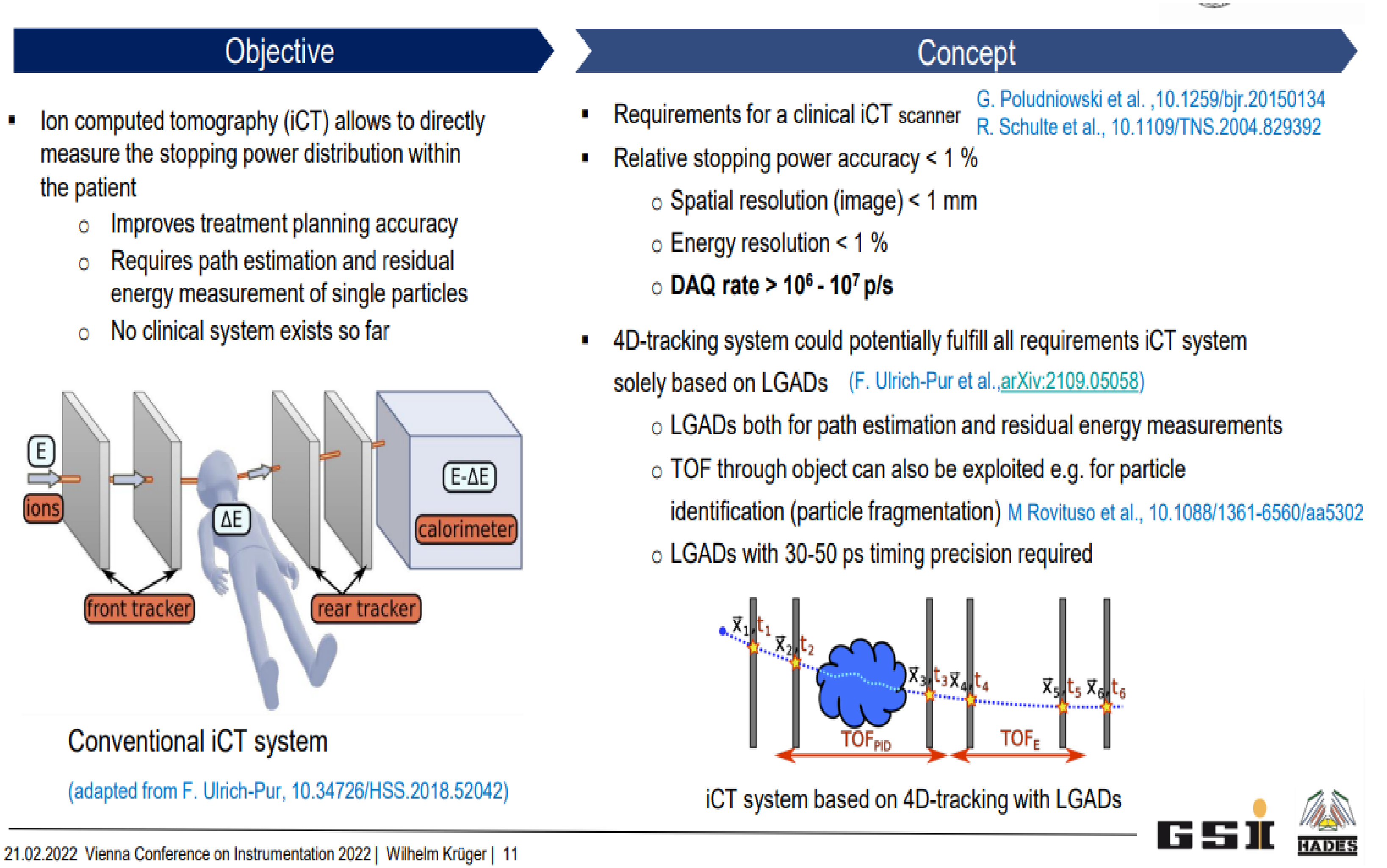
Hybrid (HDM): tracking

Strip is activated

4 Planes (2-$\hat{x}$, 2-$\hat{y}$) to reconstruct the trac

An example of LGAD application in medical Ion imaging

https://indico.cern.ch/event/1044975/contributions/4663687/attachments/2394423/4093740/LgadTechnologyForHADES_AcceleratorAndMedicalApplications.pdf



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

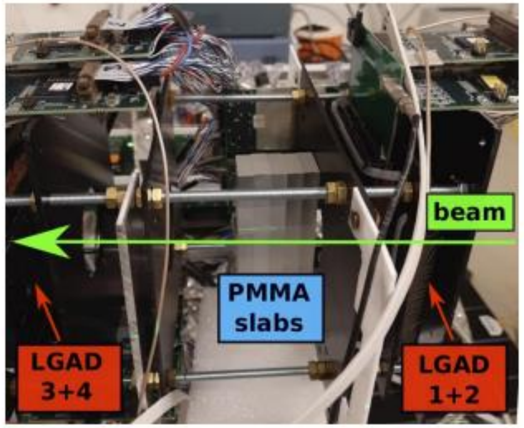
- Requirements for a clinical iCT scanner G. Poludniowski et al. ,10.1259/bjr.20150134 R. Schulte et al., 10.1109/TNS.2004.829392
- Relative stopping power accuracy < 1 %
  - Spatial resolution (image) < 1 mm
  - Energy resolution < 1 %
  - **DAQ rate > 10^6 - 10^7 p/s**
- 4D-tracking system could potentially 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

21.02.2022 Vienna Conference on Instrumentation 2022 | Wilhelm Krüger | 11

Setup at MedAustron

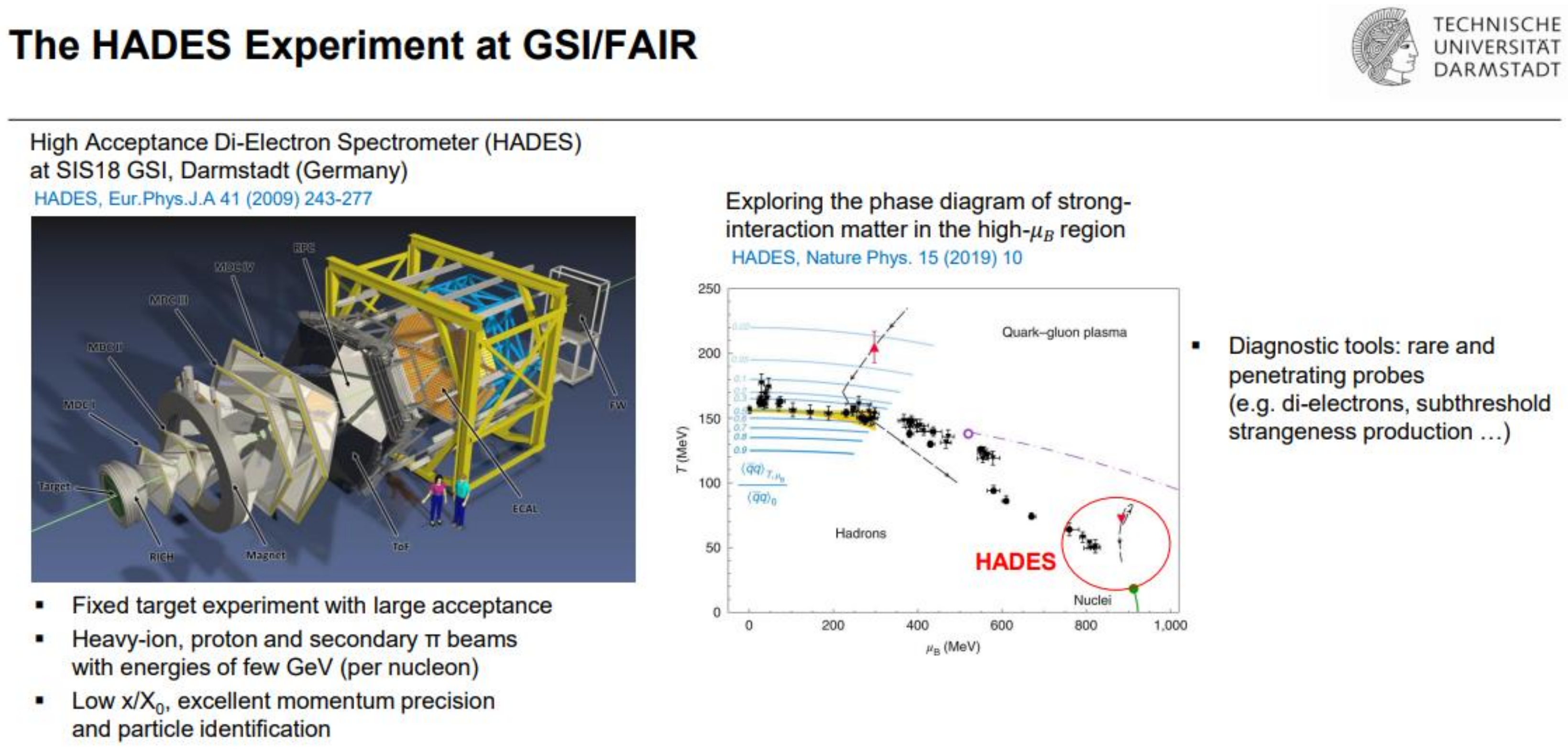
- Proof-of-principle measurement at MedAustron using 100.4 MeV protons with ~$5*10^6$ p/s
- Polymethyl methacrylate (PMMA) slabs with 1 cm thickness were used as a phantom
- The TOF through the phantom was measured using the two innermost LGAD sensors



Applications

Astrophysics

Application in astrophysics: search for dark mater by HADES & T0 Detector



The HADES Experiment at GSI/FAIR

TECHNISCHE
UNIVERSITÄT
DARMSTADT

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 …)

- The **HADES LGAD based T0** (detector is used for **reaction time determination as well as for beam monitoring purposes, e.g. time structure, position, beam spot size and intensity.**

- The fill-factor of the sensors should be close to 100 % in order to ensure high detection efficiency.
- The sensor size should be around 2 × 2 cm2 , to detect beam and halo particles.
- As the T0 detector is placed directly in beam, the sensors should be as radiation-hard as possible, i.e. fluences above 10^{14} neq/cm2 should not significantly affect the detector performance

Conclusion

LGADs have come long way and are now a major choice for timing detectors for HL-LHC

➢being a planar technology it is accessible by many vendors

➢it is now the only mature technology that can offer intrinsic limit for timing resolution of ~few tens ps

Operation of LGADs on the other hand is much more complex than ordinary planar sensors as they are sensitive to operation conditions, density of ionization, very small fluence variations…

➢The major limitation for their use is radiation damage manifested as initial acceptor removal

➢The loss of gain layer can be compensated by increase of bias voltage

➢The bias voltage is limited by so called Single Event Burnout in the highly energetic particle beam to

➢ 4D tracking is a new paradigm (enabled by LGAD based UFSD)

➢ Excelling timing and spatial resolution, simple fabrication made LGAD and possible 4D tracking made LGAD to become very attractive solution as timing technology for many experiments (from HEP to biomedical research)

➢ A lot of activities all around the world are now going to adjust LGAD's application in biomedical research; some feasibility studies has ben already successfully approved!

THANK YOU!