HighEnergyPhysics detectors for medical applications

speaker: **Tommaso Isidori**

Nicola Minafra, Patrick McCavana, Brendan McClean,
Ronan McNulty, Naomi Raab, Luke Rock, Christophe Royon

note:
The results presented in this talk can be found at:
https://iopscience.iop.org/article/10.1088/1361-6560/ac0587

Performance of a low gain avalanche detector in a medical linac and characterisation of the beam profile, T.Isidori, N.Minafra, P.McCavana, B.McClean, R.McNulty, N.Raab, L.Rock, C.Royon

Workshop on high energy physics and related topics at Sonora, Mexico -August 18th 2021

Outline

1. Introduction to particle detectors

- principles of detection
- Timing
- sensors and properties
- some HEP examples

2. Fast detector for medical beam monitoring

- Test at the Saint Luke's Hospital
- data acquisition
- integrated charge
- single particle counting
- characterization of the linac

3. What's next?

- dosimetry
- LGAD for X-Rays
- Flash Radiotherapy
- Hadrotherapy

Conclusions

01

Introduction to particle detectors

- principles of detection
- Timing
- sensors and properties
- some HEP examples

From High Energy Physics to commercial, medical, and everyday applications, particle detectors are the “tools” we use to extract crucial information after a particle enters in their acceptance.

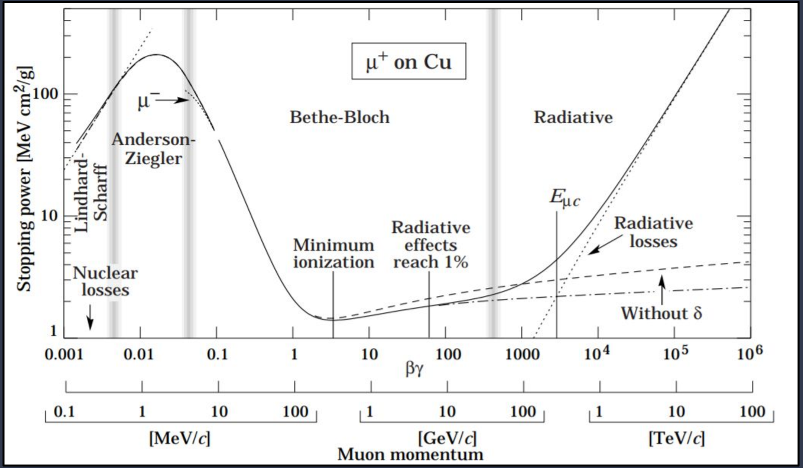
The spectrum of possible technologies to be exploited for this job is incredibly vast and the achievable performance is rapidly improving.

This section introduces the concept of particle detection and provides the basic knowledge to properly understand the functioning mechanics of these commonly used devices.

Introduction to particle detectors

principles of detection

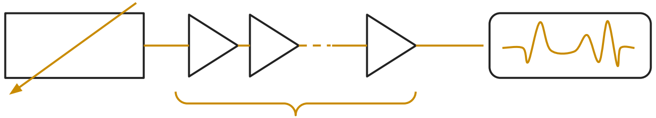
A particle detector works as a transductor, converting in useful information the energy lost by a charged particle passing through its active volume...



$$-\left\langle \frac{dE}{dx}\right\rangle = \frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right)-\beta^2\right]$$

The shape, the duration and the amplitude of the generated pulse give info about the incident particles

Generic particle detector principle of operation (solid state)

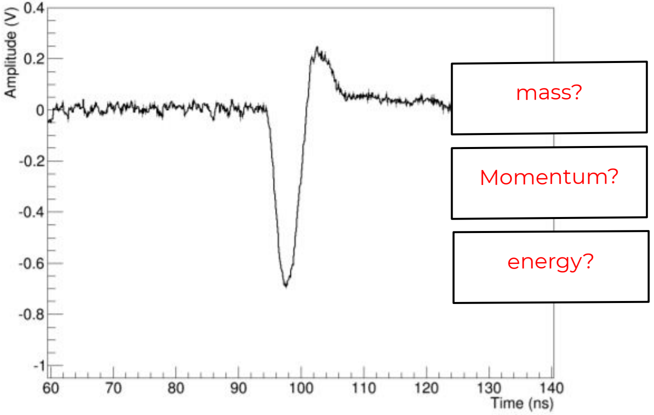


sensor (transductor)

Amplification/shaping chain

sampler/recorder

1. The energy lost by incident particles generates free charges moving through the sensor's **active volume**
2. The **read-out** electronics shapes and amplifies the signals.
3. A fast, high-bandwidth **sampler** records and store the waveforms.



mass?

Momentum?

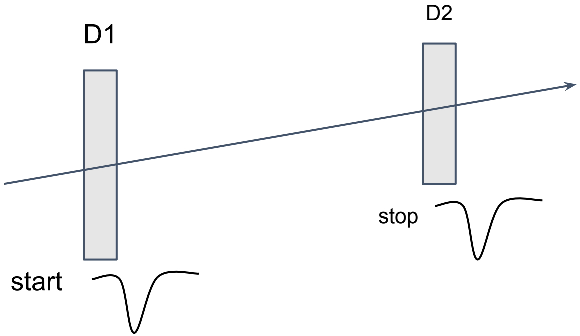
energy?

Introduction to particle detectors

Precise Timing detectors

When we talk about "Timing detectors" we usually refer to detecting devices optimized to accurately reconstruct particles times of arrival when collected from the sensor.

In the example of two devices (D1,D2) detecting the passage of a particle...



$$L \approx |t_{start} - t_{stop}|\, v$$

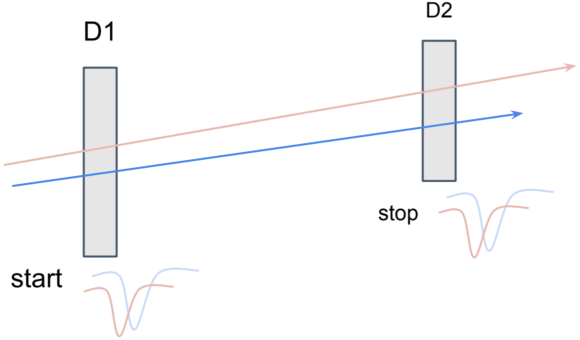
$$\sigma_z = \sqrt{\sigma_{t_1}^2 + \sigma_{t_2}^2} \cdot c$$

$$\sigma_{tot} = \frac{1}{N} \cdot \sqrt{\sigma_{det1}^2 + \sigma_{det2}^2 + ..} \approx \frac{1}{\sqrt{N}} \cdot \sigma_{det}$$

Uncertainty

...When two particles cross the detector the TOF can be used for particle ID

$$\Delta t = t_2 - t_1 = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) \approx \frac{Lc}{2p^2}(m_1^2 - m_2^2)$$



Precise Detector

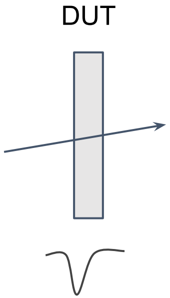
- Output the timestamp of a particle's passage in the active volume with a small uncertainty.
- Suited for **TOF**, **difference of time of arrival**, **time reference for HEP detectors**...
- In new generation detectors, the time uncertainty can go as low as **σ ~ 10ps.**
- The accuracy of the timing measurement affect the spatial reconstruction accuracy $\sigma_L \propto \sigma_t$

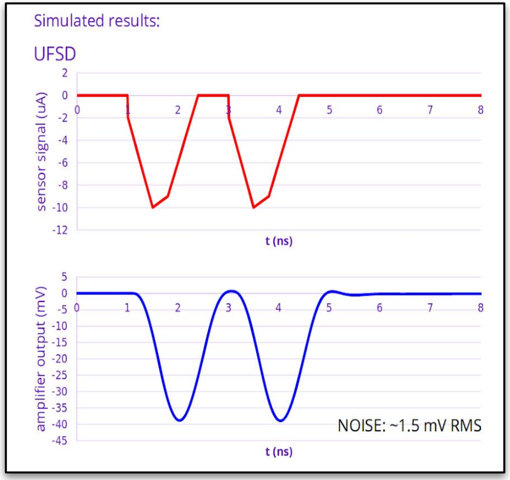
Introduction to particle detectors

Fast timing detectors

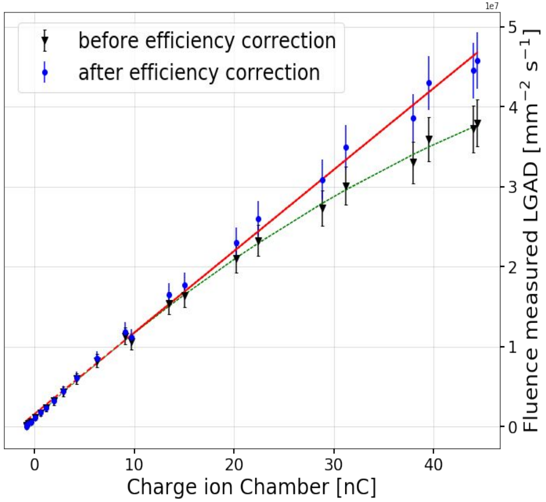
Fast detector

- Output a narrow pulse in response to the passage of a particle.
- Modern electronic components can be combined to develop circuit that outputs pulses as narrow as ~ **few ns.**
- A fast integration of the signal reduces the dead time of the detector: **single particle resolution guaranteed up to high rates**





[1]



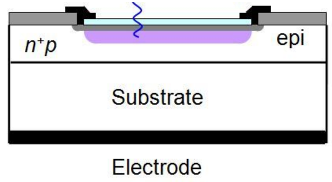
[2]

---

[1] Nicola Minafra - Precision Electron Polarimetry at EIC, EIC User Group Meeting, July 18-22 2017
[2] T.sidori, P. McCavana, B. McClean, R. McNulty, N. Minafra, N. Raab, L. Rock, C. Royon - arXiv:2101.07134

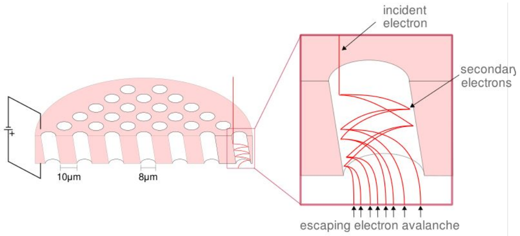
Introduction to particle detectors

sensors and properties



Silicon PhotoMultiplier (SiPM)

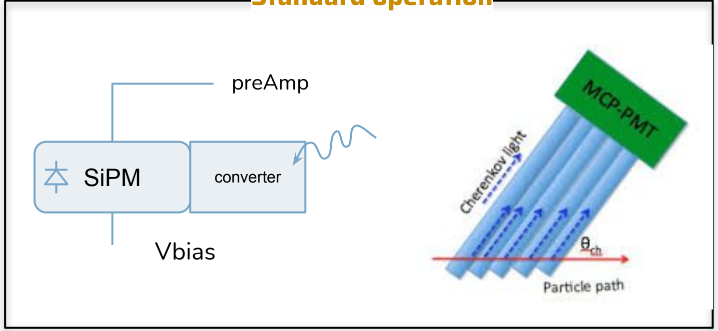
- > Photo detection efficiency (PDE) ranges from 20 to 50%
- > Gain ~ 10^6
- > Low timing jitter
- > not sensitive to external magnetic fields
- > Small dimensions and low voltages required for bias

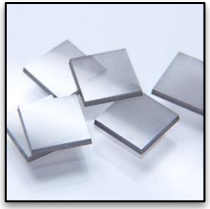


Multi Channel Plate (MCP)

- > avalanche transit time ~100 ps range
- > Gain ~ 10^4 - 10^8
- > fast rise time
- > exceptionally low dark current < 0.5 pA/cm2
- > 0.4-3.0 mm thick plates
- > up to ~1M channels/cm^2 of 5-15 m m diameter

Standard operation

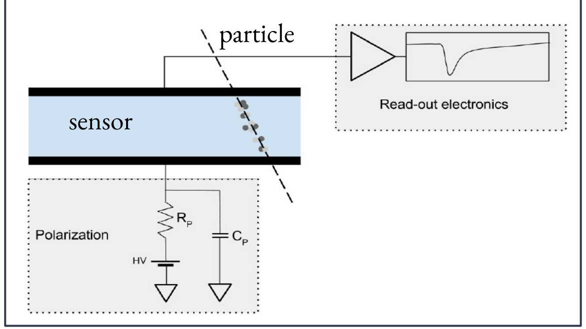


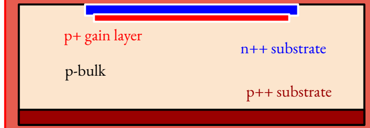


Chemical Vapor Deposition (sCVD) diamond

- > low dielectric constant (low capacitance)
- > high carriers mobility
- > incredibly low dark currents
- > The complicated production process limits the size to few mm^3
- > intrinsically radiation hard

Standard operation





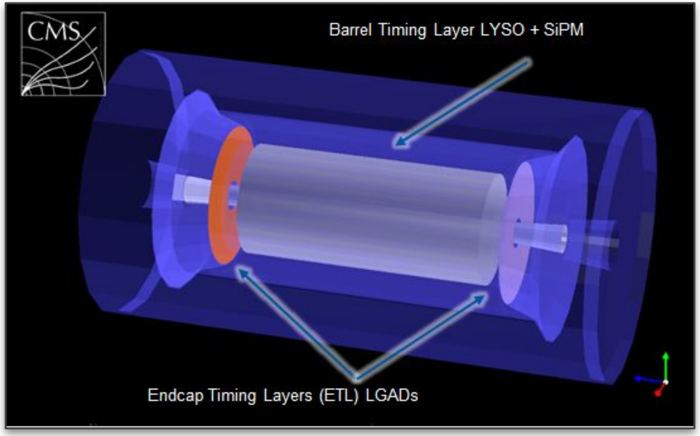
Low Gain Avalanche Diode (LGAD)

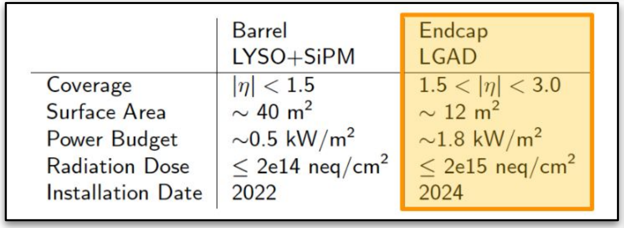
- > low gain(compared to APDs) → necessity to add an additional gain layer
- > fast rise time (dark currents' electron don't cause avalanche processes)
- > low dark currents
- > the thickness is substantially reduced (> 50 μm)
- > Can be produced with Carbon insertion to reduce the radiation damages

Introduction to particle detectors

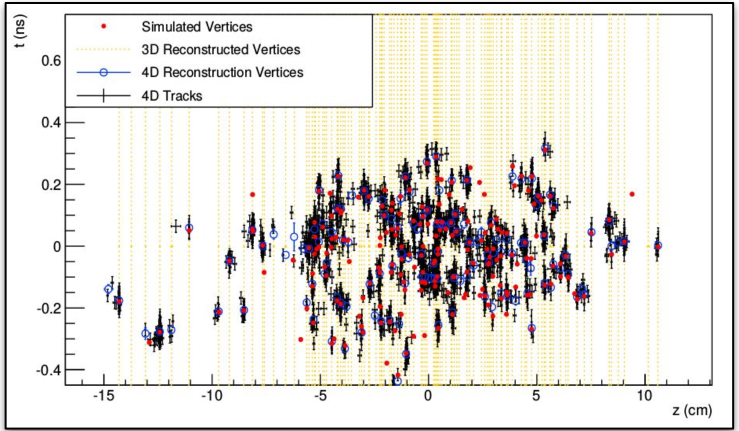
Some HEP examples: precise

The CMS MTD - ETL & BTL





	Barrel LYSO+SiPM	Endcap LGAD
Coverage	$\lvert\eta\rvert < 1.5$	$1.5 < \lvert\eta\rvert < 3.0$
Surface Area	$\sim$ 40 m^2	$\sim$ 12 m^2
Power Budget	$\sim$0.5 kW/m^2	$\sim$1.8 kW/m^2
Radiation Dose	$\leq$ 2e14 neq/cm^2	$\leq$ 2e15 neq/cm^2
Installation Date	2022	2024



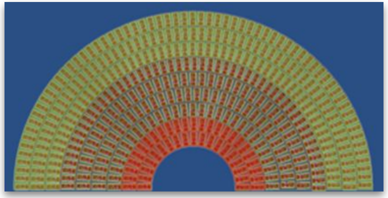
MIP Timing Layer with 40 ps of time precision is required

impact on the physics program:

> improved track and vertex reconstruction abilities
> lepton reconstruction efficiency
> diphoton vertex location
> missing transverse momentum resolution
> reduction of the pile up jet rate

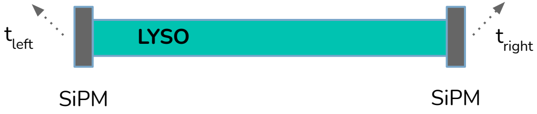
selected technologies

ETL - LGAD



- Pad size: 1.3 x 1.3 mm²
- High fill factor (>85% per layer)
- 16624 sensors of 2x4 cm²

BTL - LYSO + SiPM



- Lutetium-yttrium orthosilicate crystals activated with cerium
- active volume (per strip) = 3 × 3 × 57 mm³
- SiPM active area = 9 mm²,
- SiPM light collection efficiency (LCE) ~ 15%

[1] Precision timing at CMS for HL-LHC - Artur Apresyan | TREDI 2017
[2] Test Platform for Automated Scan of Multiple Sensors - N.Minafra
[3] Timing detectors in the CMS experiment - T.Isidori

Introduction to particle detectors

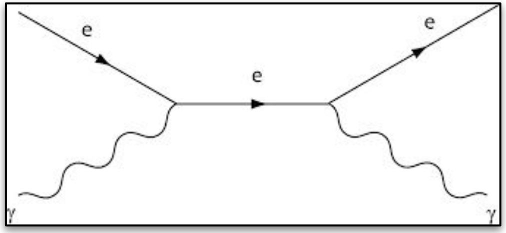
Some HEP examples: fast

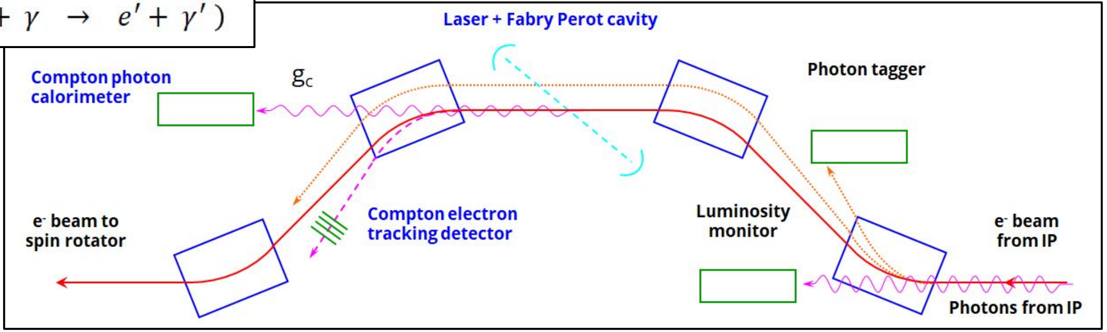
Compton polarimeters represent the best option for measuring the polarization asymmetry of high energy particle beams.

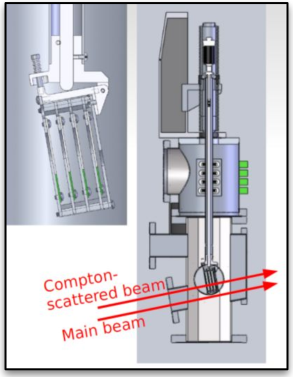
After every interaction @ the EIC, the level of polarization is verified using on-beam detectors. Starting from the photons polarization coming from the laser+Fabry Perot cavity (measurable) and estimating the predicted QED asymmetry, the apparatus constraints the electrons polarization:

$$\sigma(\vec{e} + \gamma \rightarrow e' + \gamma') \neq \sigma(\overleftarrow{e} + \gamma \rightarrow e' + \gamma')$$

[1]







$$A_{EXP} \equiv \frac{N^+ - N^-}{N^+ + N^-} = \boldsymbol{P_e} * P_\gamma * A_{QED}(E_e, k_\gamma, k_{\gamma'})$$

Roman pots: solid state detectors (in the primary vacuum) approaching the beam using a movable support

Resolves the shape of the expected asymmetry by measuring the strip-by-strip asymmetry.
> Compton edge and zero needed to fit $\mathbf{P_e}$ to $\mathbf{A}_{\text{measured}} = \mathbf{P_e A_{\text{theory}}}$

High luminosity
560 MHz RF
1320 bunches
10 ns between bunches
Electron current up to 2.4 A
Ion current up to 0.92 A

!! Need a fast, efficient and precise detector capable of single particle resolution for 10 ns spaced bunches (uniquely associate a detected particle with the correct bunch crossing) !!

[1] N. Minafra- Precision Electron Polarimetry at EIC, July 18-22 2017

02

Fast detector for medical beam monitoring

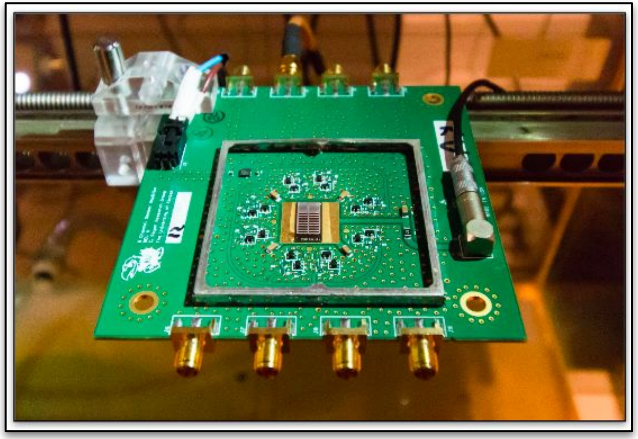
- Test at the Saint Luke’s Hospital
- data acquisition
- integrated charge
- single particle counting
- characterization of the linac

This section will describe the work performed for the test and characterization of a medical Linac used for Radiotherapy treatments at the Saint Luke’s hospital in Dublin.

The KU group collaborated with the University College of Dublin (UCD) in a single test beam campaign where an Ultrafast Silicon Detector prototyped at the university of Kansas was used to monitor the radiation fluences output from the machine

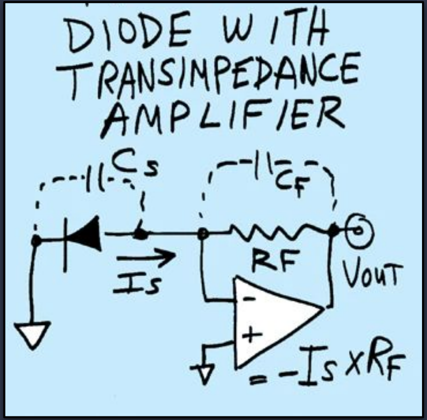
...Everything starts with the KU electronic board *(designed by Nicola Minafra)*

This is a plug and play hybrid board (hosts the sensor and the read-out electronics), designed for operating in test beams



Technical details:

- discrete components
- 8 identical two-stages transimpedance* amplifiers w/ adjustable gain
- adjustable input RC to adapt it to different solid state sensors
- control over integration time and time resolution
- $20mm^2$ x $20mm^2$ HV pad with stable bias up to ~ 500V



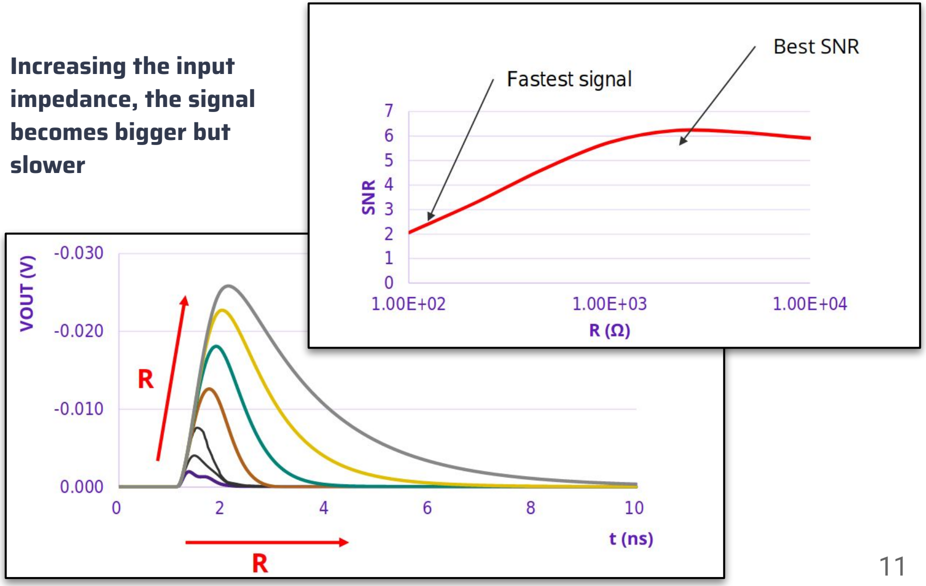
* Designed to convert a current input into a voltage output.
The Input resistance decides the gain of the amplification stage.
The sensor capacitance have to be adapted in order to have a decent SNR and/or a low integration time

$$V_{OUT} = -(I_S \times R_F)$$

$$t = R_{Load} \times C_S$$

$$C_F = \frac{C_S}{2\left(\frac{R_F}{R_{IN}}+1\right)}$$

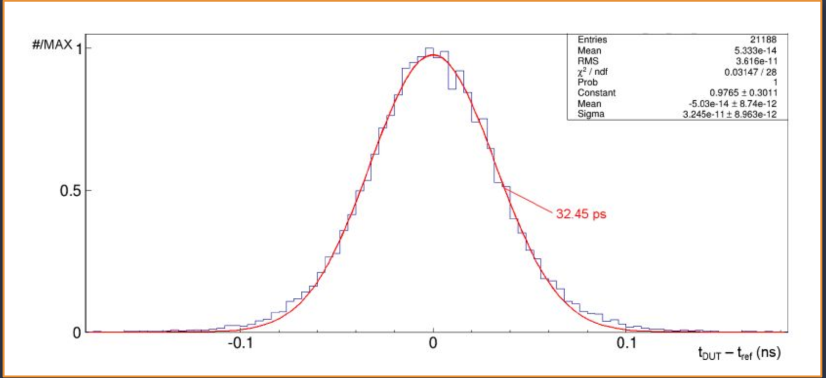
Increasing the input impedance, the signal becomes bigger but slower



https://www.electronicdesign.com/technologies/analog/article/21801223/whats-all-this-transimpedance-amplifier-stuff-anyhow-part-1

…Its performance were verified in previous tests

CF can be selected to provide the best rise time and SNR.
During the test beams performed at the CERN North Area the board was optimize to read-out a LGAD [1].
The results, obtained with a 180 GeV pions beam (MIP), show a time resolution smaller than **30 ps.**

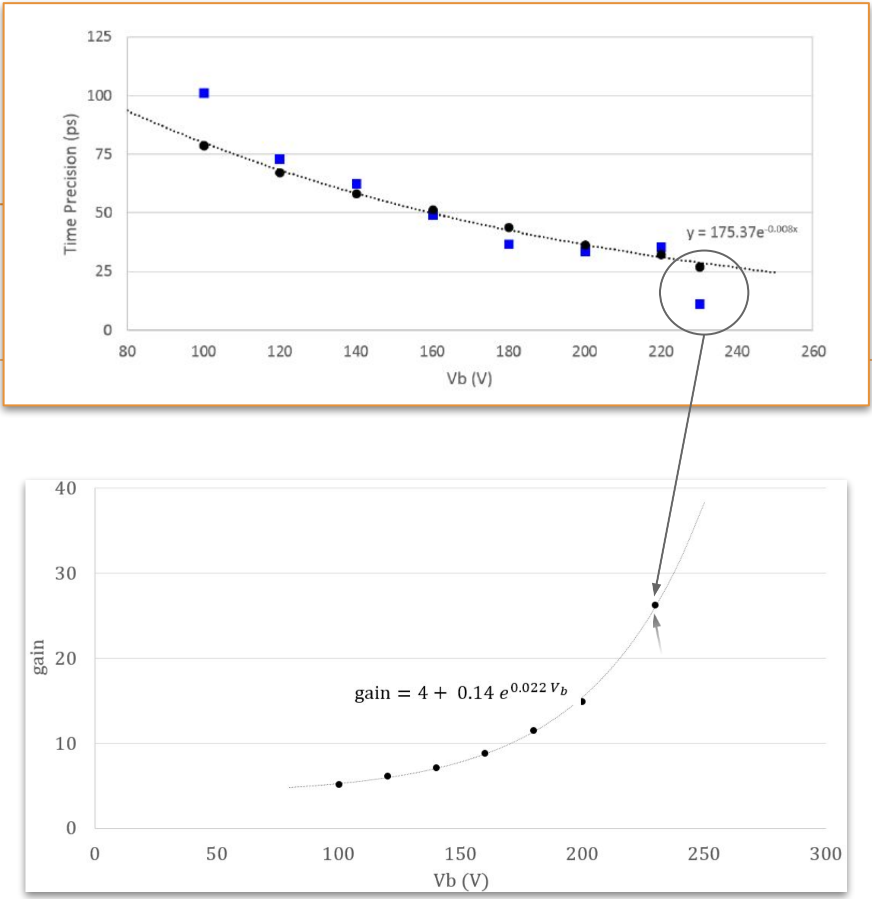


Entries	21188
Mean	5.333e-14
RMS	3.616e-11
χ^2 / ndf	0.03147 / 28
Prob	1
Constant	0.9765 ± 0.3011
Mean	-5.03e-14 ± 8.74e-12
Sigma	3.245e-11 ± 8.963e-12

Time difference between the DUT and the time reference

$$\sqrt{\sigma^2 - \sigma_{ref}^2} \approx 27\ \mathrm{ps}$$

blue circle measured using a Constant Fraction Discriminator (CFD) algorithm
black circles are computed using the formula displayed in the plot.

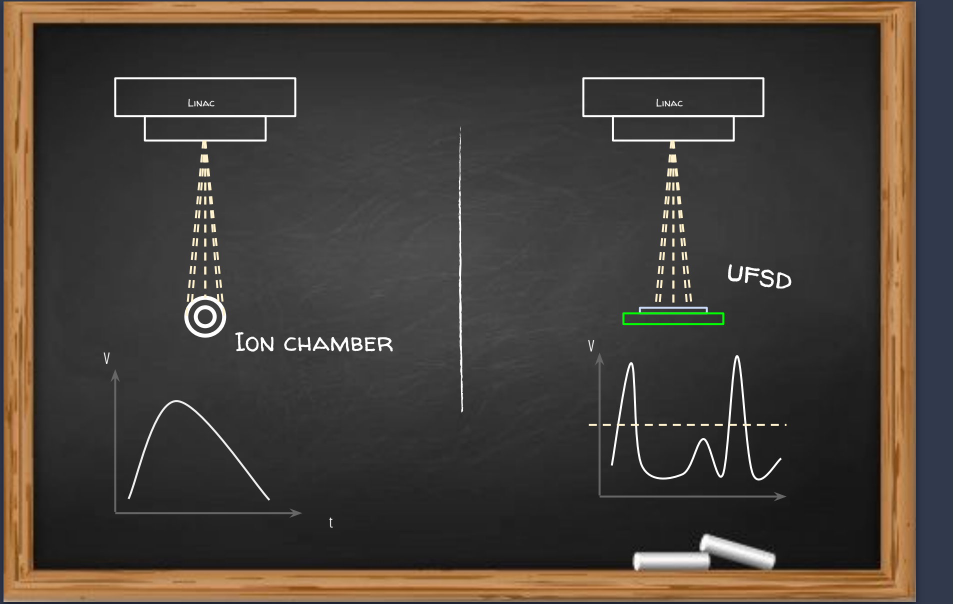


---

[1] N. Minafra et al.- Test of Ultra Fast Silicon Detectors for Picosecond Time Measurements with a New Multipurpose Read-Out Board - DOI: 10.1016/j.nima.2017.04.032

Fast detector for medical beam monitoring

Test at the Saint Luke’s Hospital



!! In both cases, the integral of the amplitude spectrum outputs the total charge generated in the sensor... But the ion chamber is too slow to resolve single events, therefore it’s adding the contribution of all the incident particles !!

PROBLEM:

During standard radiological exams and diagnostic procedures, the differential dose provided to the patient is usually measured using gas detectors (ion chamber detectors).

The measurement relies on the integration over time of the current produced by the particles passage... Intrinsically, this procedure **doesn’t allow to keep track of the fast variation of the particle fluxes.**

In the case of a charged particles beam:

The dose absorbed by a single pixel (renormalized to the area) can be calculated integrating over time the equation:

$$\dot{D} = \frac{\dot{\varphi}\, A(-dE/dx)\,\Delta x}{\rho\, A \Delta x} = \dot{\varphi}\left(-\frac{dE}{\rho\, dx}\right)$$

$\dot{D}$ = dose rate
$\dot{\varphi}$ = fluence rate (cm^{-2} s^{-1})
ρ= density
A = area

Idea:

What if we can develop a detector fast (and efficient) enough to count the incident particles up to high rate?

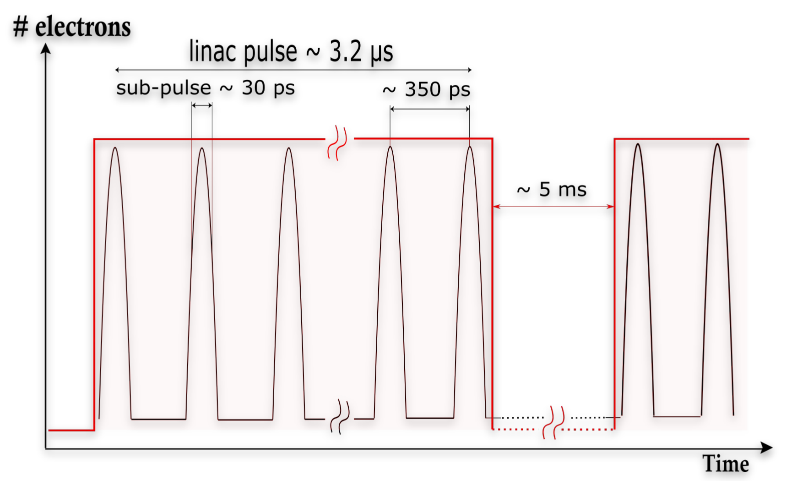
pro:
- intrinsically **extremely precise measurement**
- **no** need for **energy calibrations**
- **high granularity** (spatial resolution ~ **mm^2**)
- **Sensitive** to small **variations in dose-rates**

cons:
- The probability of photoconversion in Silicon is ~ **0.001%.**
- Requires more computing power and expensive samplers
- Dealing with high rate means operating with minimal detector’s dead time

Fast detector for medical beam monitoring

Test at the Saint Luke’s Hospital

A collaboration between the University of Kansas and the UCD Dublin organized a week of data taking using a dismissed high rate Linac machine provided by the Saint Luke’s Hospital, in Dublin (Ireland) to assess the single particle resolution capabilities of a LGAD.

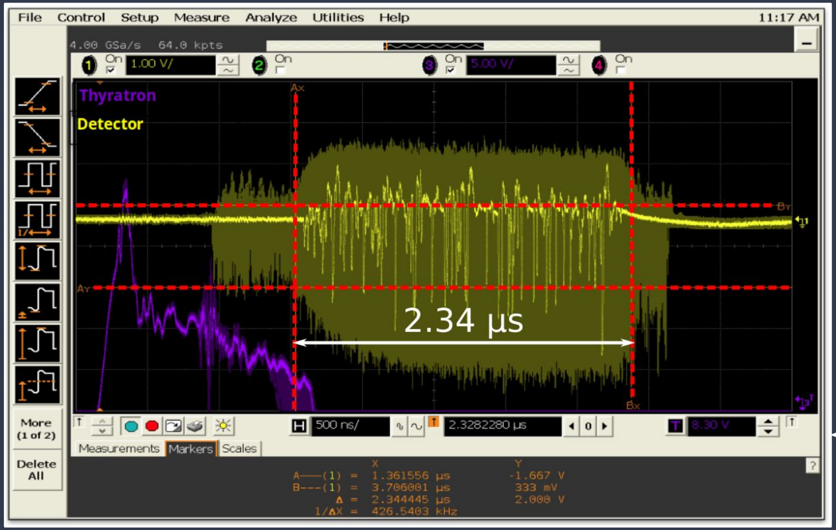


ELEKTA™ Precise (Elekta AB, Sweden)Dual modality Linac

- equipped with a **multileaf collimator (MLC)** and an **electronic portal imaging device (EPID)**
- **pulse length ~ 3.2 μs long**
- each pulse sequences contains **thousands of 30 ps sub-pulses** separated by **350 ps (frequency of 2.858GHz)**
- **photon beam:**
  - energy 6 MV
  - dose rates up to 600 MU/min
  - pulse repetition frequency of 400 Hz
- **electron beam:**
  - energy 4-18 MeV
  - dose rates up to 600 MU/min
  - pulse repetition frequency of 200 Hz

Fast detector for medical beam monitoring Test at the Saint Luke’s Hospital

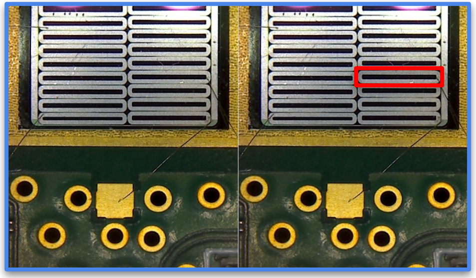
The DUT performance were measured using a standard medical ion chamber to compare the obtained results…



```
                X               Y
A——(1) =  1.361556 µs      -1.667 V
B---(1) =  3.706001 µs       333 mV
      Δ =  2.344445 µs       2.000 V
   1/ΔX =  426.5403 kHz
```

PTW Semiflex Ion Chamber 31010

- cylinder of **radius 2.75 mm** and **height 6.5 mm**
- **0.55 mm PMMA** and **0.15 mm graphite**
- **bias = +400 V**
- **resolution = 10 fA**
- **minimum measuring intervals = 10 ms**



LGAD

- **intrinsic gain = 5-20**
- **thickness = 50 micron**
- **pixel active area = 2.9×0.5 mm2**
- **bias = 150 V**
- **time resolution ~ 50 ps**
- **signal rise time ~ 600 ps**
- **signal width = 5 – 10 ns**

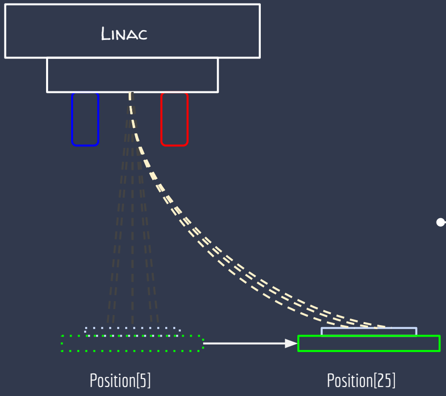
Front-end

Agilent™DSO8104A Infiniium oscilloscope
- bandwidth 1 GHz
- sampling rate of 4 GSa/s.

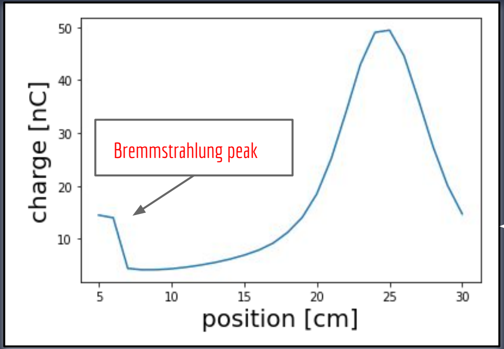
…The acquisition was triggered by a **signal from the thyratron (electron injection inside the first acceleration stage)** in the linac (in purple)

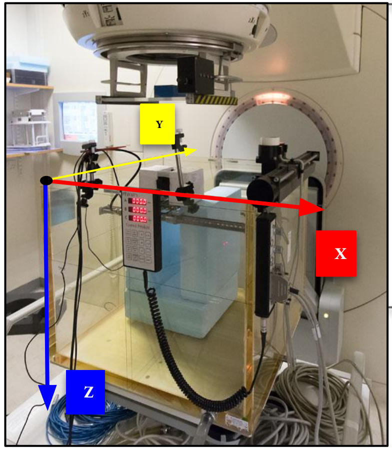
Fast detector for medical beam monitoring Data acquisition

The detector was mounted on a moving support to provide the monitoring of the beam as a function of its location relative to the Linac's head....



...For each position of the sensor, the response of the detector to 200 pulses of the linac was recorded



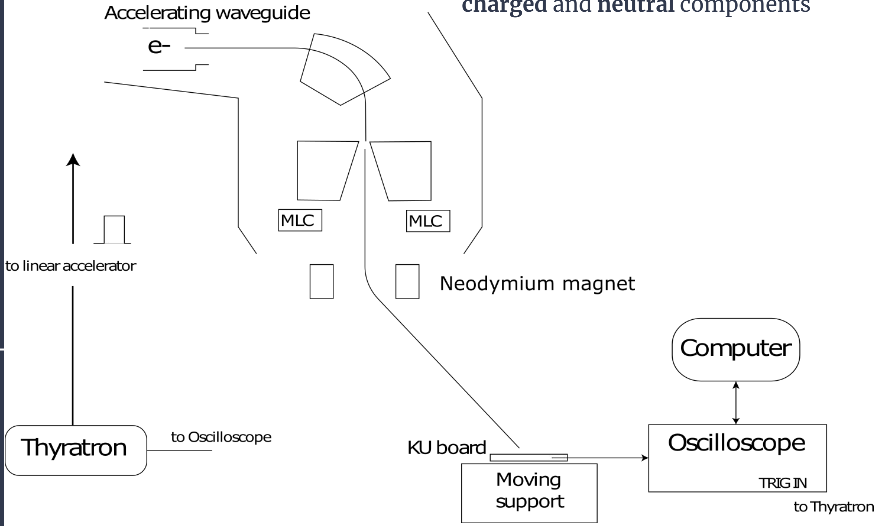


PTW 3D scanning water tank with remote position control
(the data presented were obtaining scanning the x-axis)

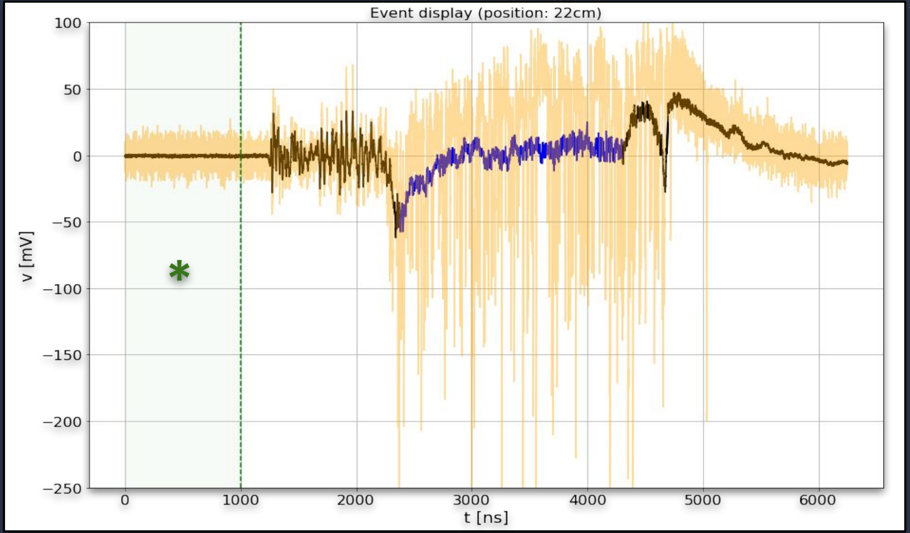
note: sensor aligned vertically using the in-room positioning lasers and horizontally using the linac's light-field crosshair

Linac operation during data taking:

- **6 MeV electron** beam
- Neodymium **N40 permanent magne**t 12 cm below the collimator faceplate to **isolate** the **charged** and **neutral** components



Fast detector for medical beam monitoring Integrated charge

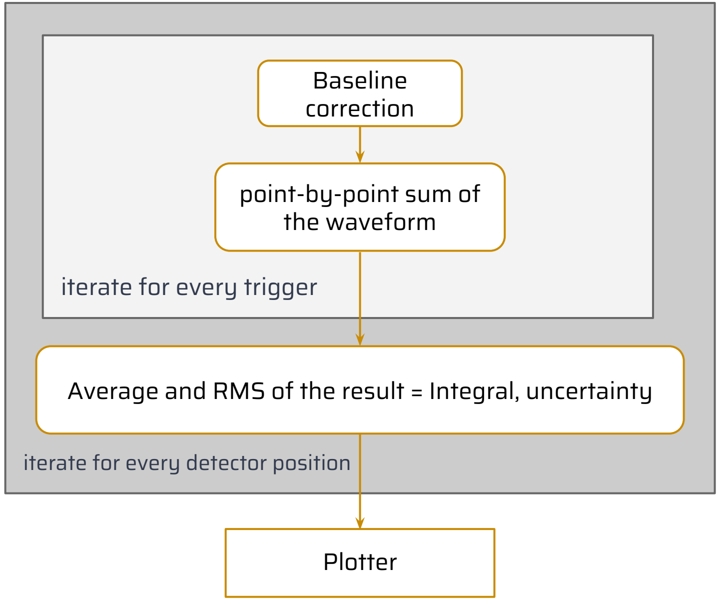


*** Baseline correction (DC Offset):**
average of the data from 0.5 to 1.5 μs before the pulse for each one of the waveforms.

Intrinsic noise
the RMS of the data in this region defines the intrinsic noise, σ_{noise}.

In order to compare the LGAD response with the one of the ion chamber

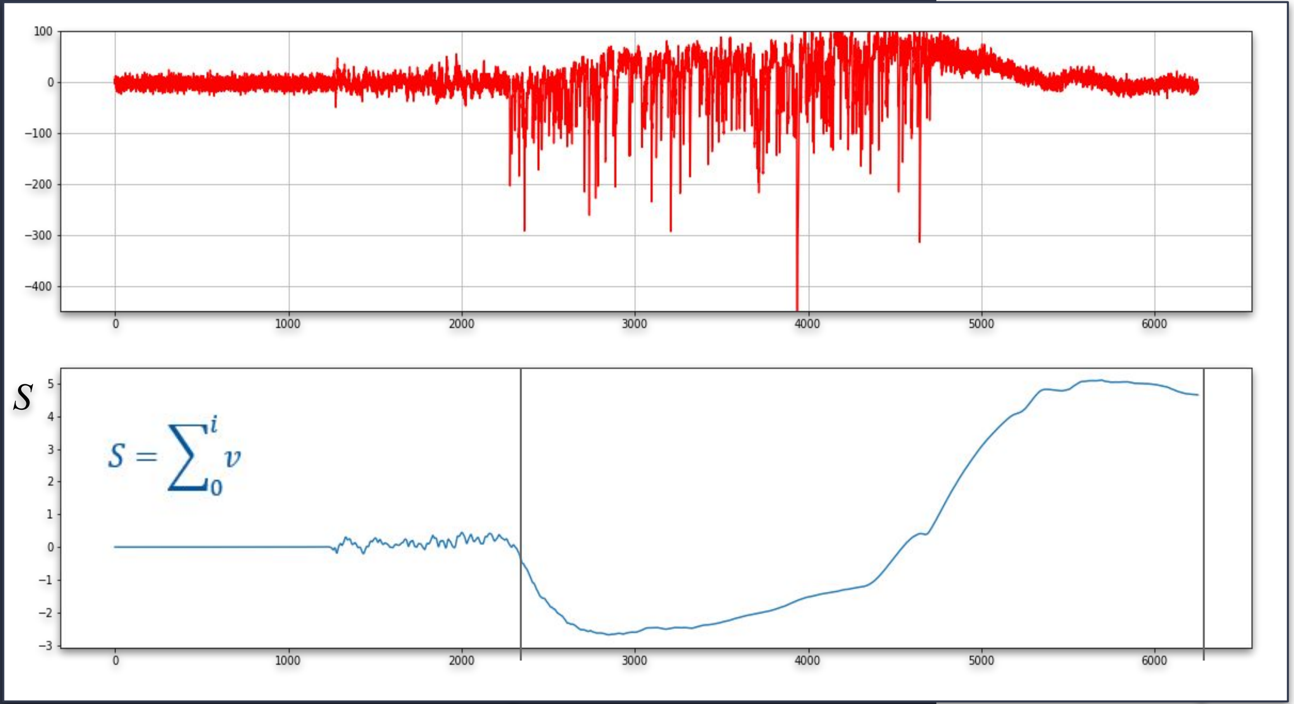
The first measurement performed is the charge integrated by the silicon sensor as a function of the detector position



Charge collected:
The charge collected is estimated adding the height of every samples from the beginning of the particle spill to the end of the trigger (Integral) for each detector position.

Fast detector for medical beam monitoring Integrated charge

Note:
The amplifier is collecting all the (negative) charge, then (since it is AC coupled and the output has to be with null average) the same charge is injected back.



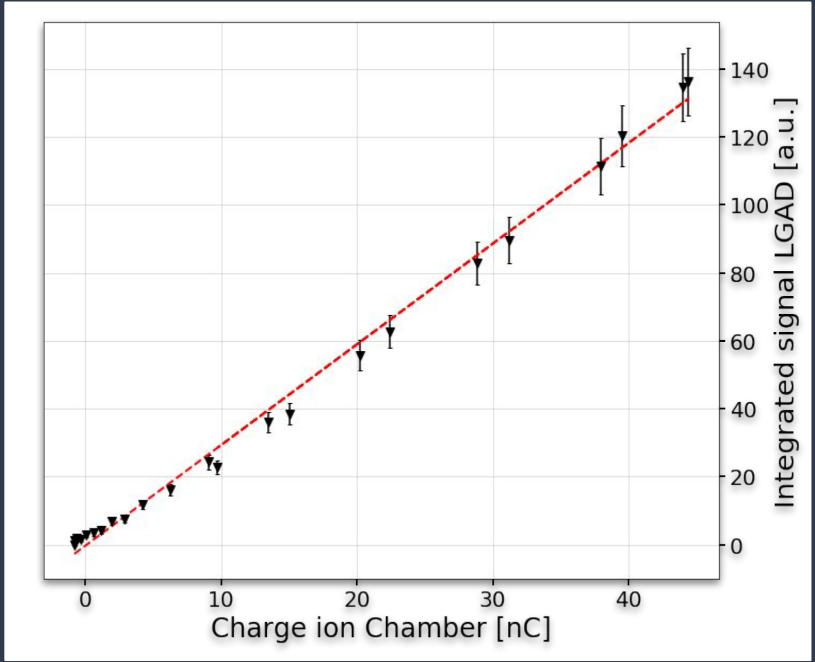
It depends on the intrinsic nature of the amplifier design (The input decoupling capacitors “shunt” the energy from the signals right to the return path).

BUT

The “abs(minimum)” and the “maximum” value of this integral will be both proportional to the charge.

Note: the integration procedure stops when it reaches its maximum....
...This grants that the entire produced charge to be collected by the amplifier

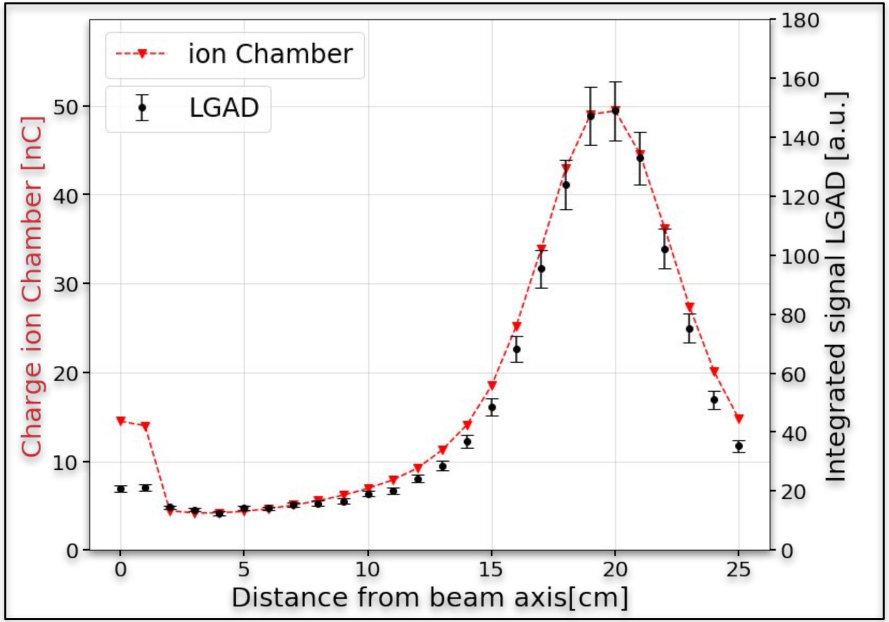
Fast detector for medical beam monitoring Integrated charge



...Excluding the region on the beam-axis, the average signal in the LGAD correlates well with the ion-chamber signal!

Charge recorded in the LGAD and with an ion chamber as a function of distance from the beam axis

(data points are calculated as the average and RMS of the integrated charge in the LGAD)

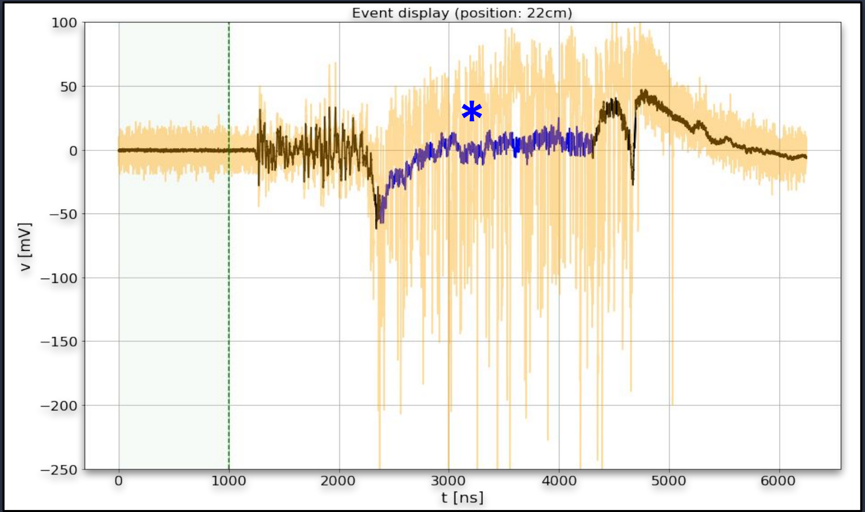


Note:

- We observe the **principal difference** under the (undeflected) beam position where there is a **large flux of photons** (more photons may be interacting in the ion chamber and its housing than in the silicon).

- The rest of the spectrum can is broadly similar, beside some effects due to the non-linearities in the read-out response

Fast detector for medical beam monitoring single particle counting



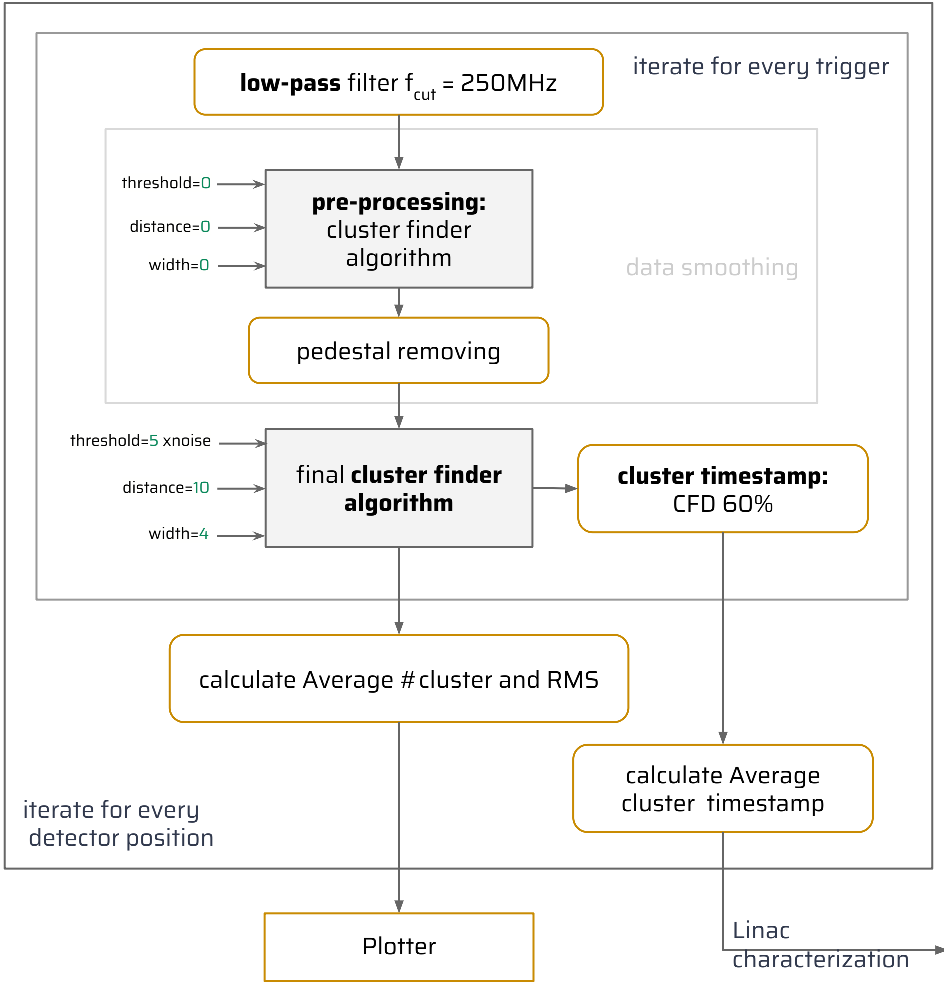
*

data smoothing:

average of the data from 0.5 to 1.5 ns before every pulse for each one of the waveforms.

Low pass filter:

remove from the data the high frequency fluctuations, reducing the uncertainty on the threshold crossing definition



iterate for every trigger

low-pass filter f_{cut} = 250MHz

data smoothing

threshold=0
distance=0
width=0

pre-processing:
cluster finder algorithm

pedestal removing

threshold=5 xnoise
distance=10
width=4

final **cluster finder algorithm**

cluster timestamp:
CFD 60%

calculate Average #cluster and RMS

calculate Average cluster timestamp

iterate for every detector position

Plotter

Linac characterization

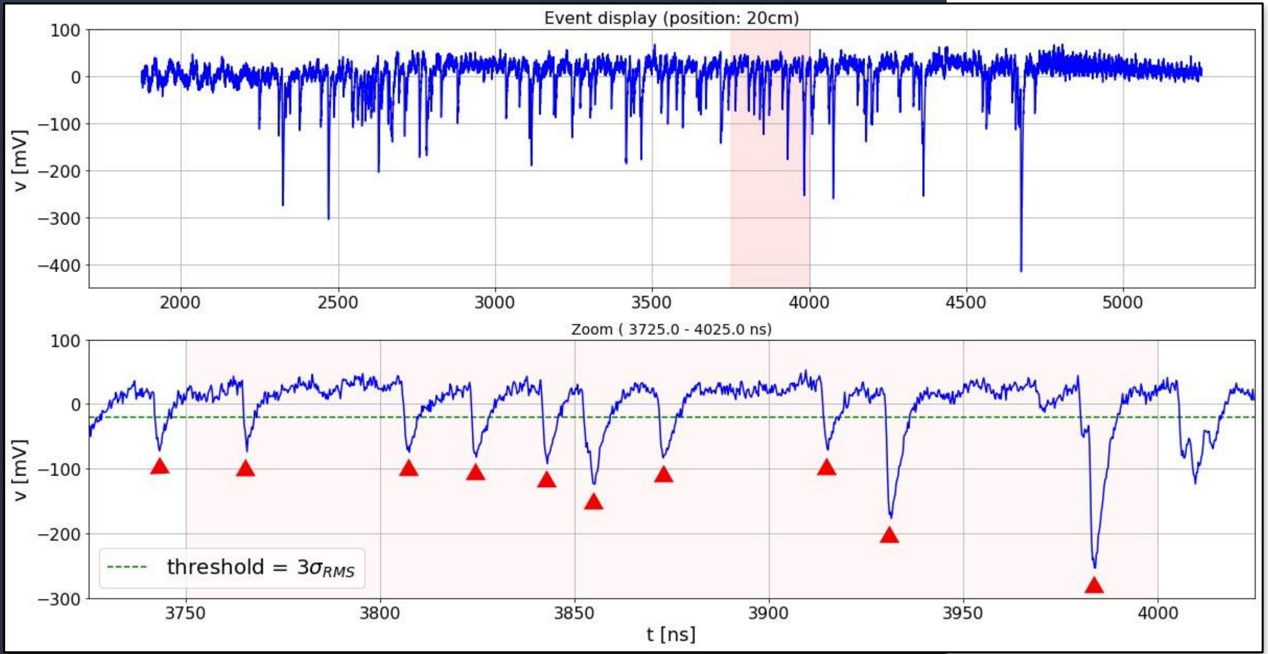
Fast detector for medical beam monitoring single particle counting


threshold=5 xnoise

distance=10

width=4

final **cluster finder algorithm**



The cluster finder algorithm selects a signal if it fulfills a series of condition (1 AND 2 AND 3):

1. exceeds by 5 sigma the noise level (rms ~ 8mV)

2. is isolated (rejects at least one, if the peaks are closer than 3ns)

3. 10 ns separation between consecutive peaks (algorithm fully efficient)

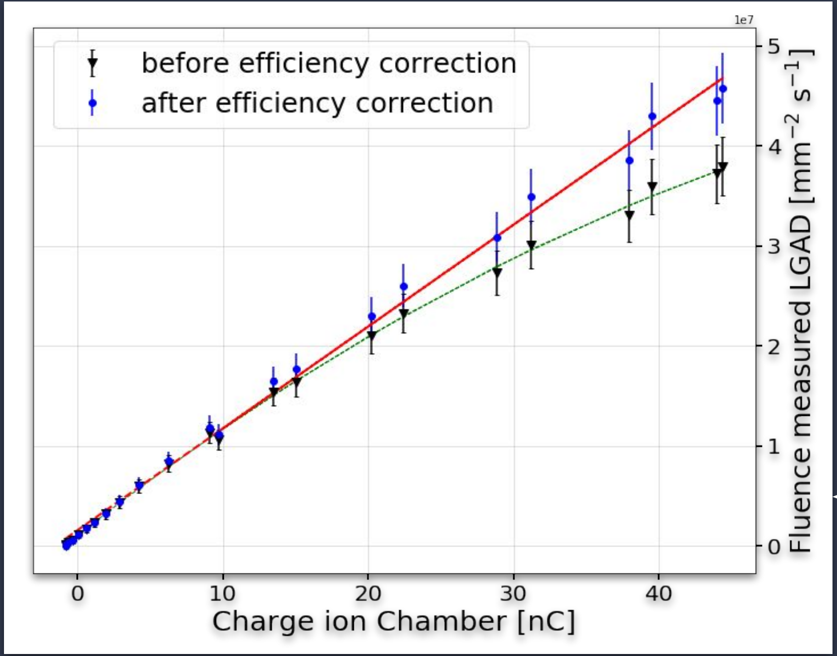
Thanks to the high signal-to-noise of the LGAD the algorithm is extremely efficient for isolated peak…

…However…

…The efficiency drops as the time spacing between consecutive particles crossing the detector becomes significantly lower than the width of the average pulse length (~ 10 ns).

Fast detector for medical beam monitoring single particle counting

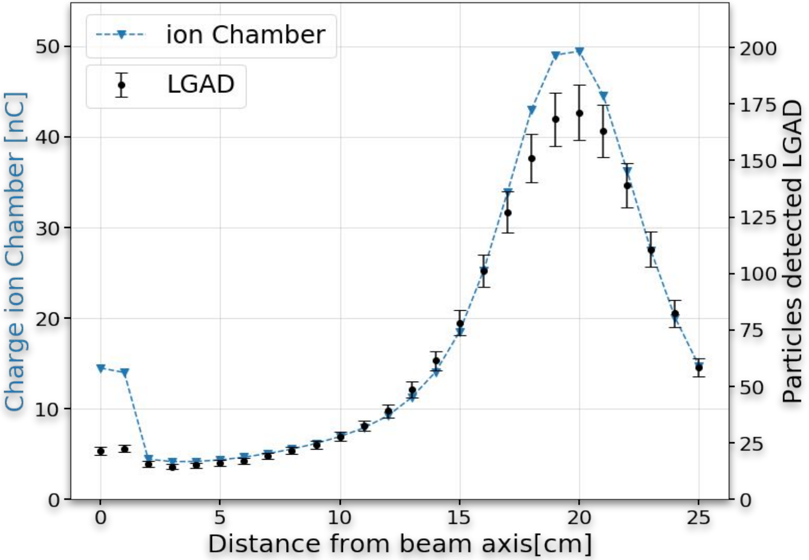
On average, the algorithm fails when two particles pass through the detector within 6.5 ns of each other…



Average # of particles in a linac cycle as a function of detector position

The effects of the intrinsic limit to the algorithm can be observed at high fluence rates

…Probability of this occurring = exp(-6.5 . μ)
μ = incident particle rate [GHz]



Counting particles gives equivalent results to integrating the charge **BUT** the LGAD is operating as a single-quantum detector.

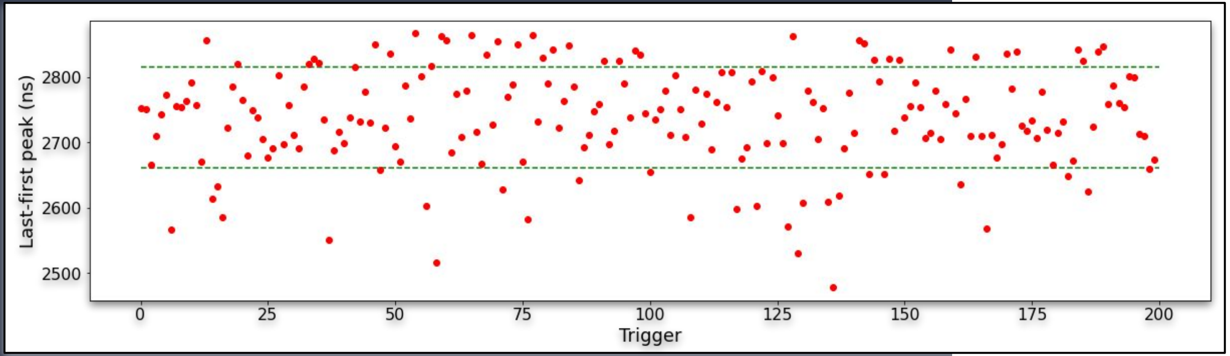
if the **rate of incident particles < 200MHz**:

the LGAD resolves single electrons with a time resolution of about 50 ps (precision leading edge).

Fast detector for medical beam monitoring Characterization of the Linac

A first, important feature of the cluster identification using single particle ID (thanks to the excellent time resolution and linearity of the LGAD)...

...The Linac's spill effective duration and the distribution of particles emitted over time

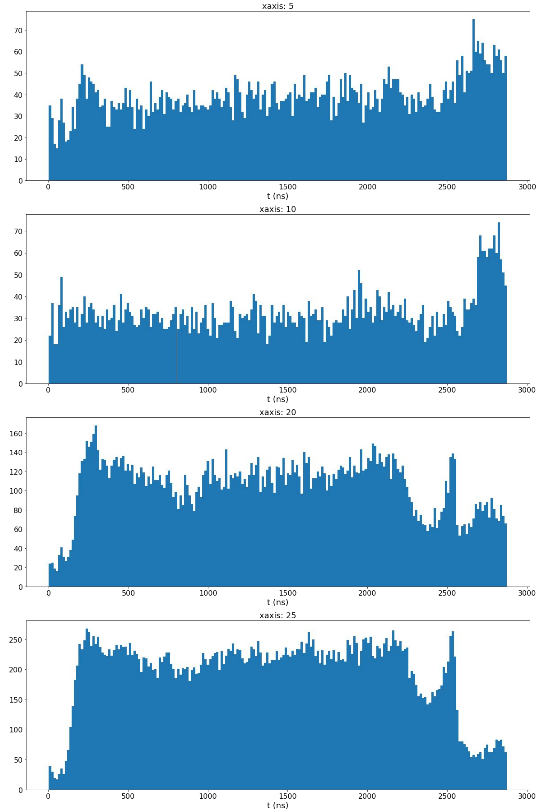


These feature provide a better understanding of the collateral radiation dose coming from an unperfect technical understanding of the machine

Cluster distribution as a function of the time for different detector's positions.

Provides a better understanding of the dose provided as a function of the time within the spill duration!

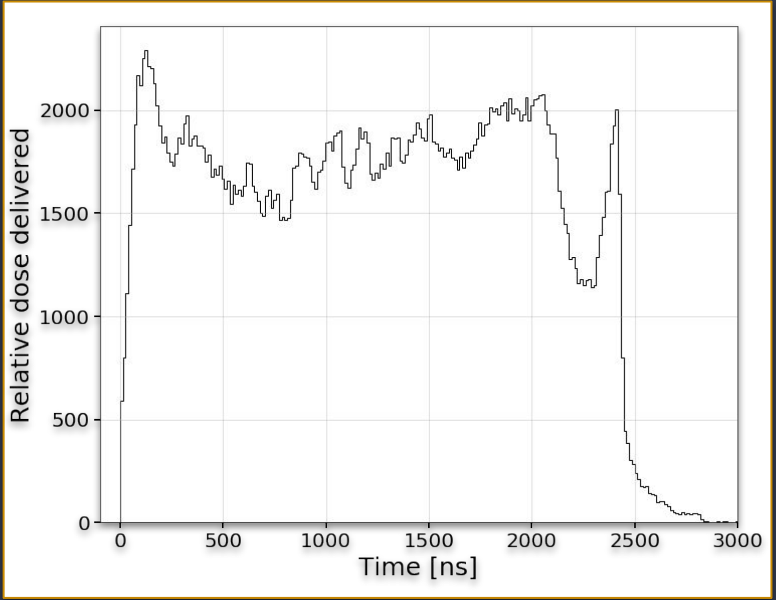
Note: the irregular behaviour around the spill end is due to artifact generated by the (old versions) of the code



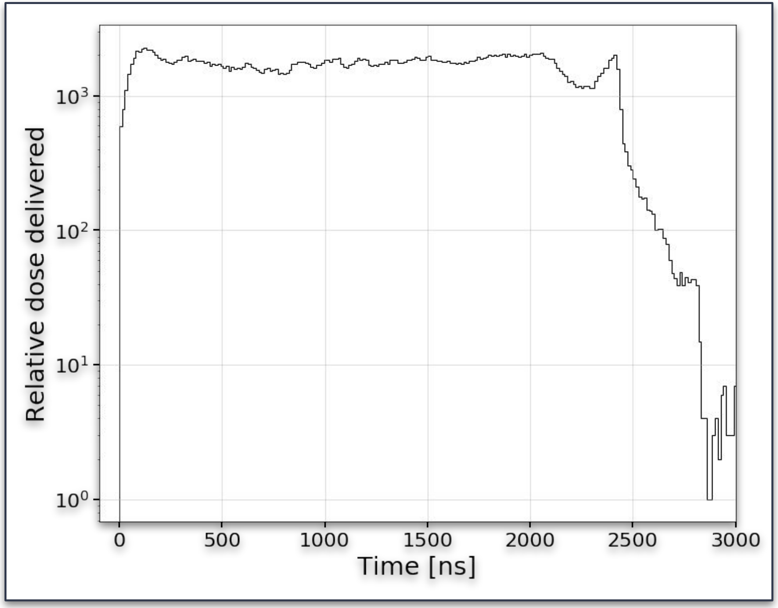
Fast detector for medical beam monitoring Characterization of the Linac

Sum of the # of particles recorded at all detector positions as a function of time

The number of particles recorded is proportional to the dose delivered...this allows the temporal prole of the beam to be seen.



Approximation to the idealised square pulse shown in the previous slides...



...And the width of the pulse is seen to be smaller than nominal at 2.85 ± 0.01 μs.

Fast detector for medical beam monitoring Characterization of the Linac

Can we investigate the train of sub-pulses that make up the microsecond pulse?

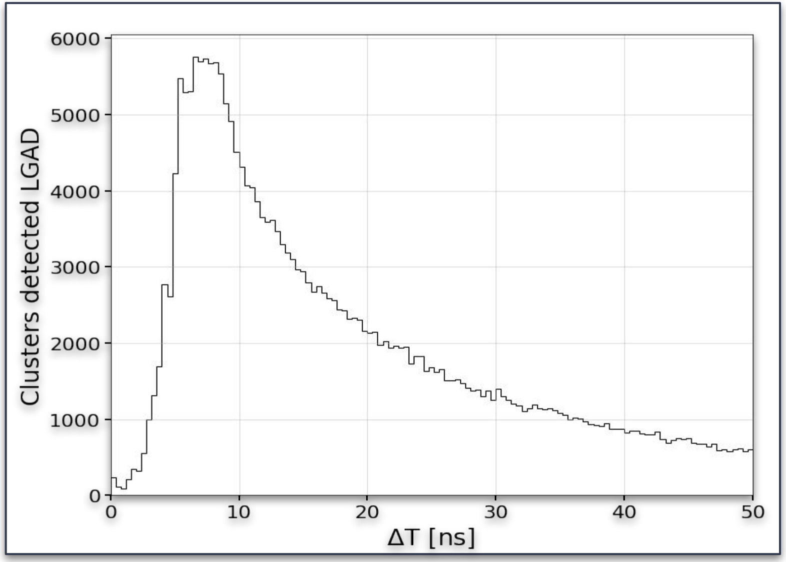
The LGAD time resolution is about 50 ps …The sub-pulses should be visible!

BUT

..A large timing uncertainty was found in the thyraton trigger signal…

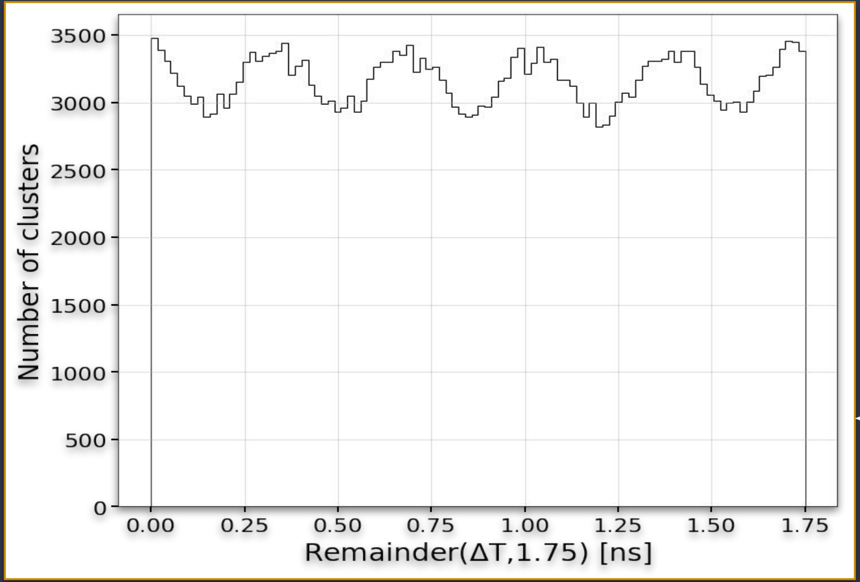
… We decided to use the distribution of the difference between the time-stamps for consecutive particles

The expected exponential behaviour is affected by the algorithm inefficiencies when consecutive peaks are closer than 10ns!

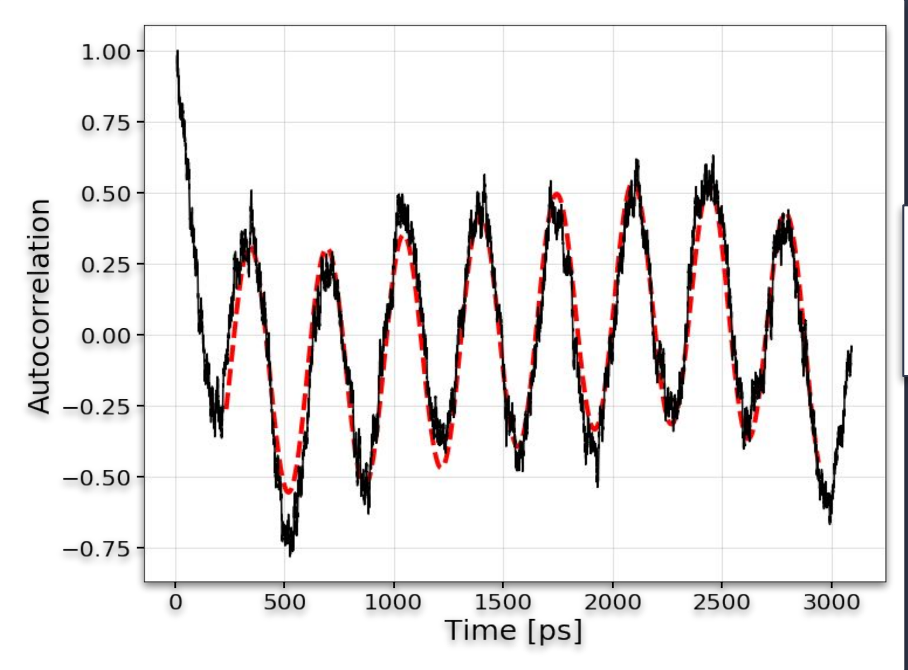


Preventively, to highlight the periodic substructure of the pulses,we can plot the reminder of the ΔT

The plots displays a periodic behaviour within the single linac's spills



Fast detector for medical beam monitoring Characterization of the Linac



R as a function of τ, after the coarse-grained structure has been subtracted

To search for the expected modularity we can plot the Autocorrelation* (of the signals timestamp differences)

The algorithm divides the data in steps of **10 ps** and it calculates the equation:

$$\boxed{R(\tau) = \frac{1}{N-\tau}\sum_{i=1}^{N-\tau} y_i y_{i+\tau}}$$

y_i = number of entries in bin i

Note:

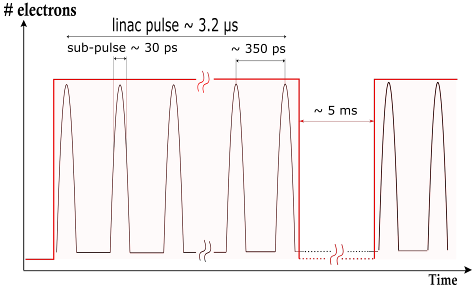
...The coarse-grained structure of ΔT results in a **roughly exponential shape** to R(τ), **superimposed on top of which is a fine-grained sinusoidal pattern.**

A modulated sine is used then to fit the Autocorrelation function

The period of the sine was measured to be:

Period = 346 ± 3 ps

!! consistent with the nominal frequency of the linac 2856 MHz !!



***Autocorrelation**
correlation of a signal with a delayed copy of itself as a function of delay

03

What’s next?

- dosimetry
- LGAD for X-Rays
- Flash Radiotherapy
- Hadrotherapy

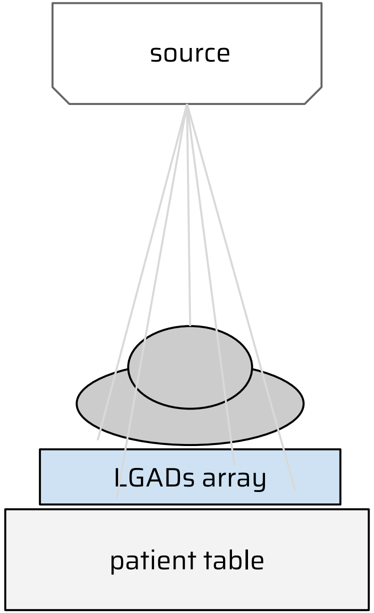
What are the next goals the physics community can achieve using this technology? How can timing detector help in the medical and commercial environment?

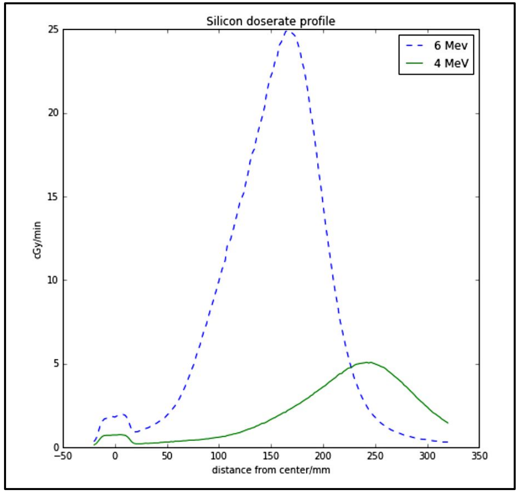
In this chapter we present some example where the medical fields can benefit from exploiting the HEP knowledge of fast detection, radiation tolerance, time precision…

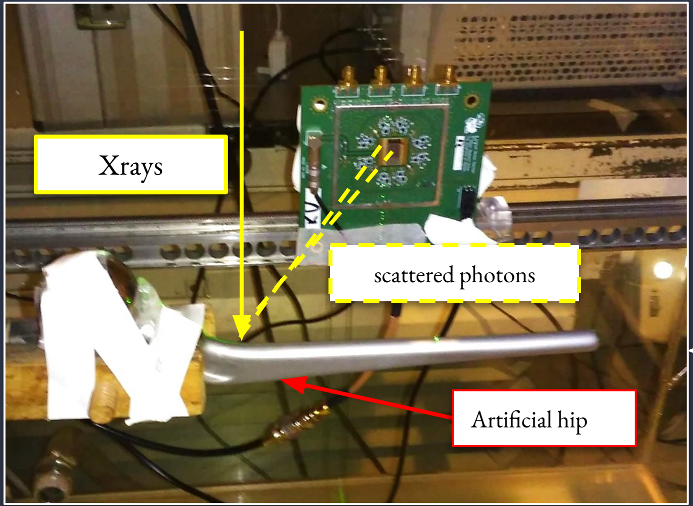
What’s next? dosimetry

The newly discovered possibility to resolve single particles interaction opens new horizon on the studies of radiation doses detection:

Although a simulation of the full apparatus is required to connect the number of particles detected to the effective dose collected, the detector could be used to measure the differential dose delivered by high-rate medical facilities







The sensitivity of a particle counter is not limited by a minimum amount of collected charge!

LGADs can be used to evaluate low amount of doses deposited in the affected tissues!

Example:
in the picture we can observe one of the configuration used during the tests at the Saint Luke’s hospital of dublin

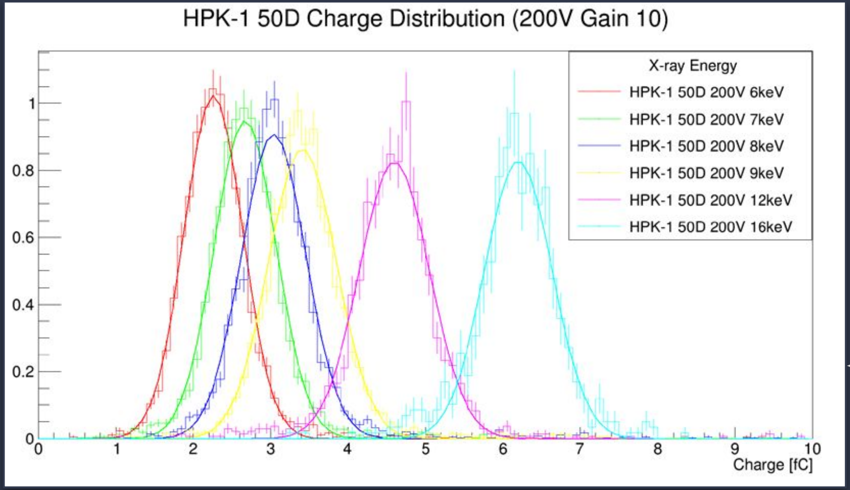
What's next? LGAD for X-Rays

The operation of LGADs for soft (<20 KeV) X-rays detection is currently under study

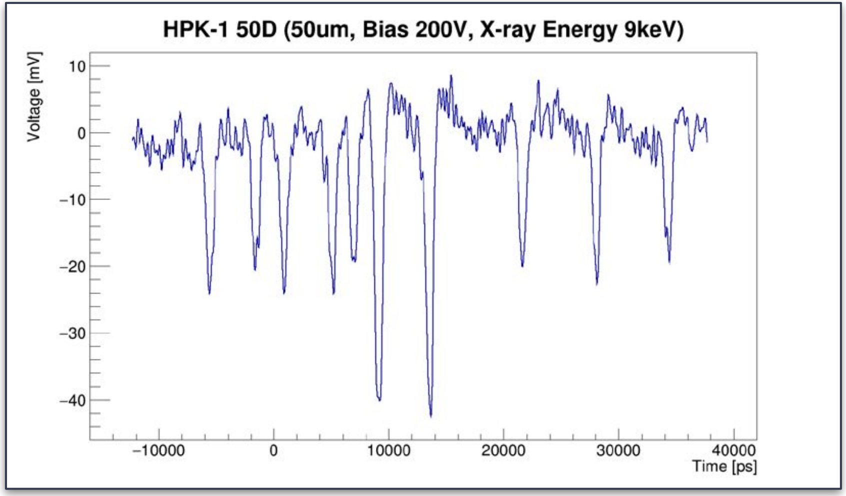
the project can provide interesting insights in the use of LGADs for photodetection.

A 50 µm LGAD sensor was tested at SLAC SSRL for the range [6, 16] KeV:

- time resolution ~100ps
- Single pulses resolution with a **2ns beam separation**



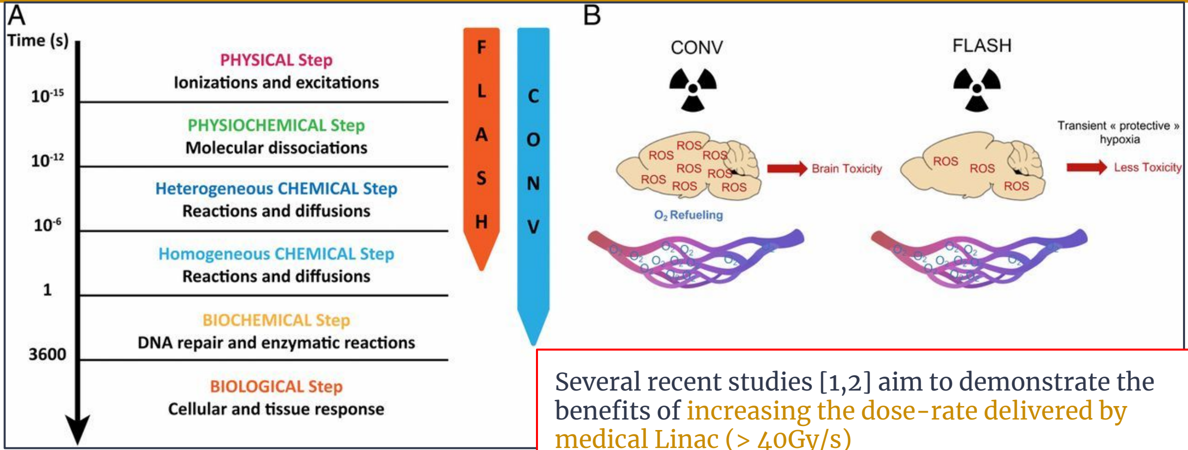
S.M. Mazza, X-ray detection with Low Gain Avalanche Detectors (LGAD), RD50



Response of the LGAD to photons from different X-rays transitions: the detector displays promising capabilities in energy discirimination!

(the group also proved the detector to be able to distinguish between 1,2,3... photons)

What’s next? Flash Radiotherapy



Several recent studies [1,2] aim to demonstrate the benefits of increasing the dose-rate delivered by medical Linac (> 40Gy/s)

Tissue toxicity
Studies in the 1960s reported that **healthy human tissues** were **less affected from high instantaneous doses** of radiation compared to standard ones. At the same times, during the treatments, **the cancerous cells seemed** to react **independently from the rate of radiation delivered!**

Possible causes [3]:

Oxygen depletion
Hypoxic tissues (tissues that are deprived of oxygen) are more resistant to radiation than well-oxygenated tissues. The level of hypoxia at ultra-high dose rates and subsequent radioresistance transferred to the irradiated tissue might be one of the factors.

Immune modification
As it involves a shorter treatment time, the response of the immune system is not as efficient, resulting in less lymphocytes are affected by the radiation.

Current technology
The current instrumentation for measuring doses level often relies on self-developing radiochromic films [1] which can be read-out once the dose is delivered...

... exactly like the ion chamber used in our studies, this method can’t provide any information about the beam profile.

After the conversion of a IORT Linac Into a FLASH Research Machine, in [1] Giuseppe Felici, et al. conclude:

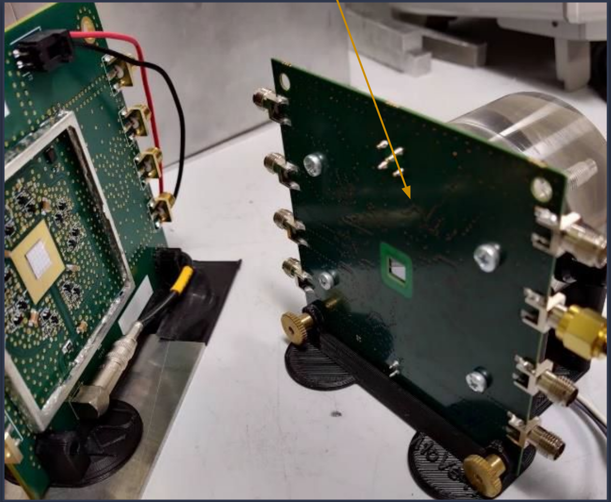
A commercial ionization chamber was found to saturate, even for the low dose first pulse. Dosimetry under FLASH conditions remains a challenging task; dosimetric tools that can offer real-time, pulse resolved, dose-rate independent dosimetry are required so that machine output can be monitored and controlled in real-time. [...]

[1] Transforming an IORT Linac Into a FLASH Research Machine: Procedure and Dosimetric Characterization
[2] Electron FLASH Delivery at Treatment Room Isocenter for Efficient Reversible Conversion of a Clinical LINAC
[3] https://researchoutreach.org/articles/flash-radiotherapy-what-how-why/

What’s next? Hadrotherapy

Reduction of the material budget behind the sensor’s active area:

This trick helps reducing the stopping power of MIP produced by radiation sources, allowing the user to setup desk-top experiment for the characterization of the sensors using a second detector as a time reference

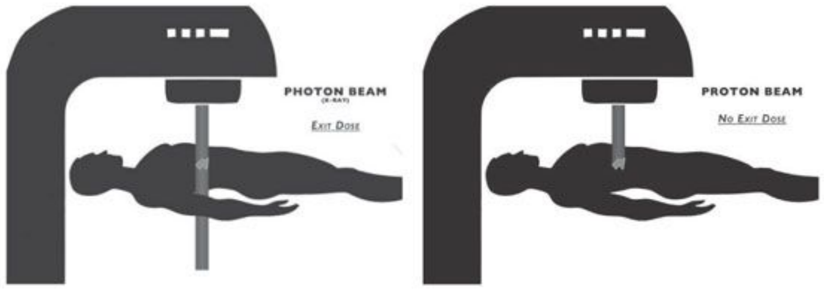


Use of thin LGADS for MIPs:

Thickness ~150 um (tot)
linearity up to 10 MIPs and for high rates (>200MHz)
optimized for single particle ID

Improve detector for beam characterization:

The most immediate transition is the development of fast detectors for **Hadrotherapy** accelerators.



Treating cancerous cell with the use of hadrons helps minimizing damages to the healthy tissues.

This technique exploits a better focus of the particles energy loss, using the propriety of the Bragg peak proper of protons interacting with matter.

[1] N.Minafra, Test Platform for Automated Scan of Multiple Sensors
[2] Hadrontherapy for cancer. An overview of HTA reports and ongoing studies - Tom Jefferson, et all - DOI: 10.1701/3278.32516

Conclusions

Timing detectors

> recent results in the field of fast timing detector show incredibly promising performance in silicon detectors of new generation

> The choice of the sensor, read-out and sampler are crucial steps to develop a performing timing detector.

Fast detector for medical beam monitoring

> The KU detector proved to be able to replicate the results obtained with standard medical detectors in a much shorter timescale (~ µs instead of s)

> The LGAD displayed single particle identification up to high-rates, using a 6 MeV electron beam output from the medical linac

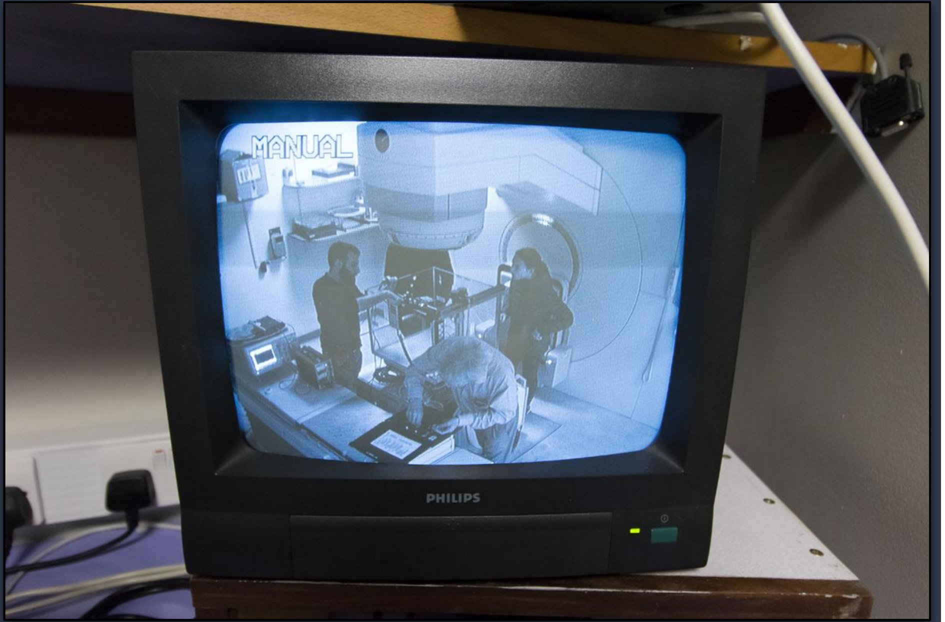
> The capabilities of the LGAD detector opened the possibility to further the studies of the beam profile. The 2.85 GHz substructure of the linac pulses was resolved.

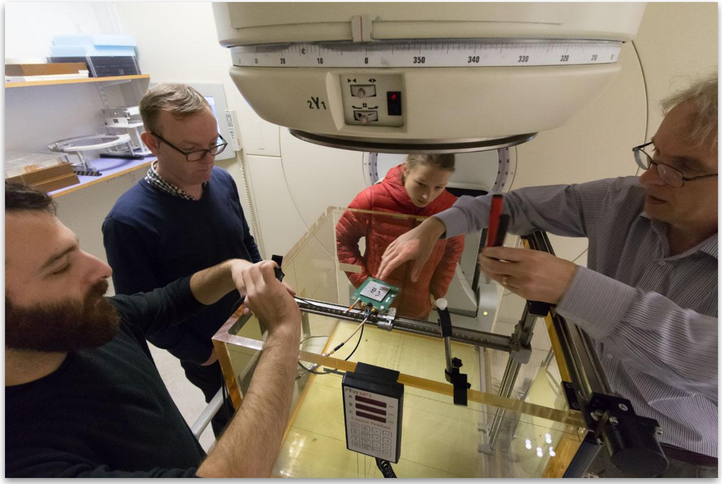
The next step

> The demanding requests coming from HEP experiments accelerate the production of top of the line LGADs and, in turns, broaden the spectrum of applications

> Interesting results could be found testing LGAD as beam monitor in Hadrotherapy facilities or FLASH Linac machines.

Thank you for your attention!





Backup

Timing detectors: sensors and properties

First step: choosing the sensor

$$\sigma^2_t \sim \overset{*}{\sigma}^2_{jitter} + \overset{*}{\sigma}^2_{Landau} + \sigma^2_{TimeWalk} + \sigma^2_{Distorsion}$$

*

Sensor's contributions:

Jitter = Variation in time caused by the noise of the system.

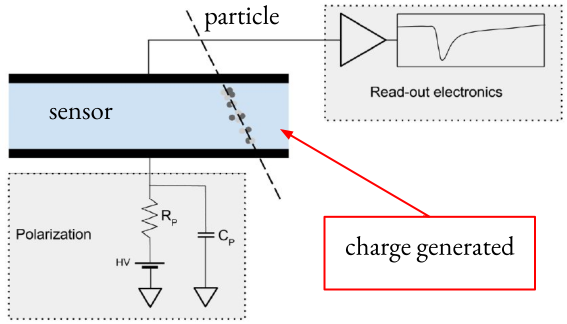
Landau = local stochastic fluctuations of the energy loss spatial distribution

The quality of the sensor, the production process, the material used ... Decide the performance of the detector, drastically influencing properties such as:

- Charge Collection Efficiency (CCE)
- radiation tolerance
- gain due to multiplication processes
- ...

Solid state detectors are the most commonly used for timing

The polarization circuit connected to one of the electrodes, **provides the E-field** needed **to drift the** free **charges** inside the bulk, hence **generating the current collected by the read-out**



Solid state sensors

- **μ > 1000 (cm2/V)s** High **mobility** of the carriers
- **v_s > 10^7 cm/s** - High **saturation velocity**
- **$C_{sensor} \propto \varepsilon_0\varepsilon_d$ (S/d)** the sensor capacitance is proportional to the dielectric constant (low capacitance means shorter integration time)
- The **Displacement energy** in sensors of new generation drastically improved (lifespan up to **10^{15} n_{eq}**)
- **Low thickness** and **material budget.** Sensor size down to ~**50μm**
- **High granularity** on the active area

Timing detectors: Low Gain Avalanche diodes

During the last decade the promising technology of Low Gain Avalanche Diodes has been heavily exploited in the design of timing detectors for High Energy Physics experiments

Low Gain Avalanche Diode (LGAD)

> low gain(compared to APDs) → necessity to add an additional gain layer
> fast rise time (dark currents' electron don't cause avalanche processes)
> low dark currents
> the thickness is substantially reduced (> 50 µm)
> Can be produced with Carbon insertion to reduce the radiation damages

σ^2_{jitter} *affects (not exclusively! Next slides) the intrinsic rise time*

- Reduce the sensor's thickness, maintaining the same gain!
- Same pulse height but faster rise time!

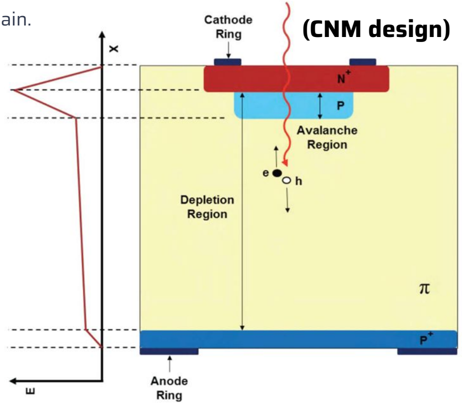
BUT

σ^2_{Landau} becomes dominant in a thin sensor

- Increase the gain
- post-processing the data correctly (CFD, next slides)

Main LGAD producers:

- Centro Nacional de Microelectrónica (**CNM**) in Spain.
- Fondazione Bruno Kessler (**FBK**) in Italy.
- Hamamatsu Photonics (**HPK**) in Japan.



Example LGAD structure

- Highly doped n-type thin layer (n++-p+-p structure).
- A moderately doped p-type gain layer.
- resistive p-bulk (in yellow)
- High E-feld region in the gain layer
- Gain ~10 -70 without (no breakdown to increase SNR)
- Timing resolution ~ 20ps for MIPs (before irradiation).

$$\sigma^2_t \sim \overset{*}{\sigma}{}^2_{jitter} + \overset{*}{\sigma}{}^2_{Landau} + \sigma^2_{TimeWalk} + \sigma^2_{Distorsion}$$

* **Sensor's contributions:**

Jitter = Variation in time caused by the noise of the system.

Landau = local stochastic fluctuations of the energy loss spatial distribution

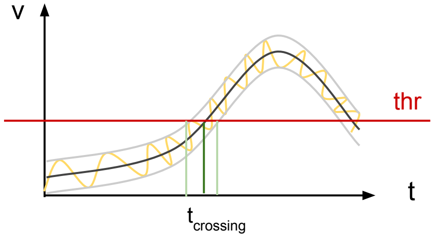
Yuzhan Zhao, Timing Performance of Thin Low-Gain-Avalanche-Diodes (LGAD), ULITIMA 2018 Workshop

Timing detectors: Front End and post-processing

$$\sigma^2_t \sim \overset{*}{\sigma^2_{jitter}} + \sigma^2_{Landau} + \overset{*}{\sigma^2_{TimeWalk}} + \sigma^2_{Distorsion}$$

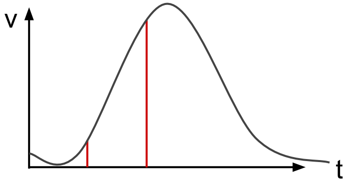
* contribution of the FE

* post-processing corrections



read-out

The predominant contribution introduced by the shaping and amplifying chain comes from the **noise fluctuations** that, in turn affect the Signal to Noise Ratio (SNR)



front-end

The choice of a performing sampler directly influence the timing precision of the instrument as the jitter depends on the slope of the signal's rising edge. The bottleneck of the rising time for fast detectors comes from the **sampler's bandwidth.**

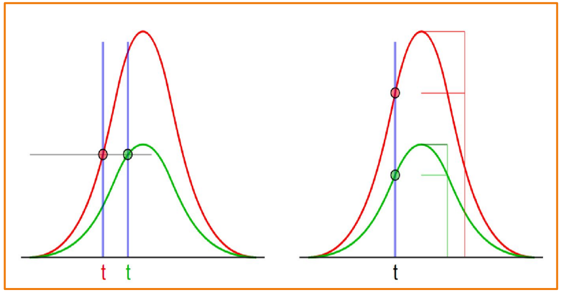
$$\boxed{\sigma_{jitter} \simeq \frac{noise}{dV/dt} = 1.25\frac{\tau_{0.1} - \tau_{0.9}}{SNR} = 1.25\frac{t_{rise}}{SNR}}$$

With

$$\boxed{t_{rise} = \frac{0.35}{Bandwidth}}$$

Note (post-processing data):

Some of the contributions come from effects that are intrinsic to the nature of the measurement and can only be corrected during the analysis procedure.
The **Time Walk** is the mis-reconstruction of the timestamp of simultaneous pulses with **different amplitudes**.



Timing detectors: read-out and front-end

The uncertainty to be attributed to a timing measurement is expressed as the sum (in quadrature) of many contributing factors:

$$\sigma^2_t \sim \overset{*}{\sigma^2_{jitter}} + \sigma^2_{Landau} + \sigma^2_{TimeWalk} \overset{*}{+} \sigma^2_{Distorsion}$$

*

read-out/front-end contributions:

jitter = variation in time caused by the noise of the system

Distortions = variation in the amplifier chain response due to changes of the work point (Temperature, humidity, degradation of the electronic components..)

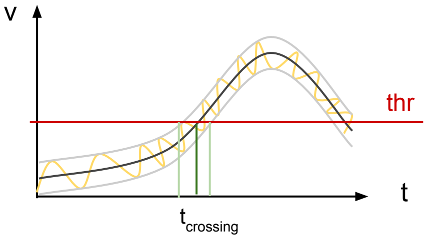
$$\sigma_{jitter} \simeq \frac{noise}{dV/dt} = 1.25\frac{\tau_{0.1} - \tau_{0.9}}{SNR} = 1.25\frac{t_{rise}}{SNR}$$

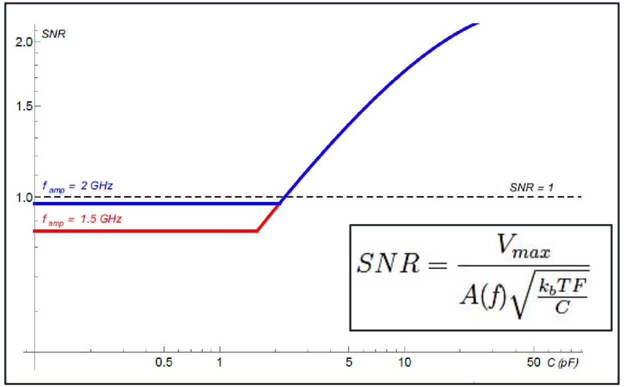
where $t_{rise} = \dfrac{0.35}{Bandwidth}$

Need to maximize the slew rate!!
- low readout noise
- Large amplitude and fast rise time

Read-out

The noise fluctuations introduced by the amplification stages, in turns affect the Signal to Noise Ratio (SNR)





$$SNR = \frac{V_{max}}{A(f)\sqrt{\frac{k_b T F}{C}}}$$

For commercial circuit: the noise of a High-bandwidth amplifier can be expressed as...

$$\sigma_V \propto \sqrt{B}$$

Front-end

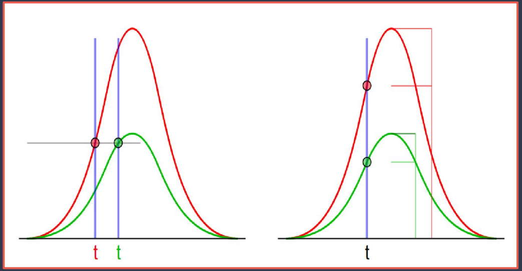
The performance of a timing detector can be heavily affected by the choice of the recording sampler: an important contribution comes from the **uncertainty affecting the reconstruction of the signal rise time**.

The bottleneck of the rise time for fast detectors comes from the **sampler's bandwidth.**

Timing detectors: post-processing

As we gonna observe during the course of this presentation, the post-processing reco algorithms play a major role in a precise timing measurement...

$\sigma^2_{TimeWalk}$

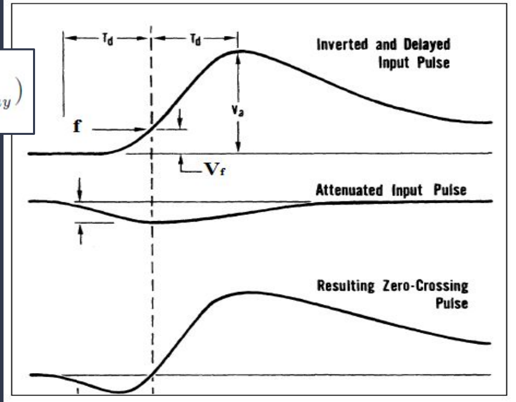


Time Walk
incorrect reconstruction of the particles timestamp due to simultaneous pulses with **different amplitudes** (static threshold).

$$V_F = f \cdot V_0$$

$$f \cdot \frac{V_0}{t_M} t_{cross} = \frac{V_0}{t_M}(t_{cross} - t_{delay})$$

$$t_{cross} = \frac{t_{delay}}{1-f}$$



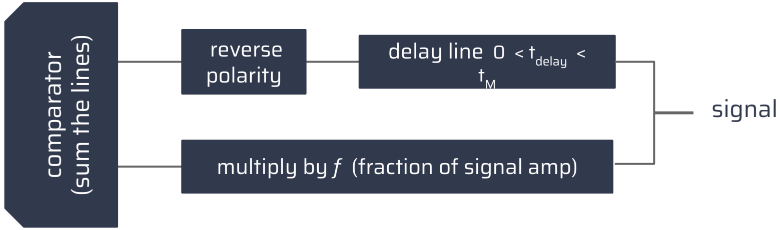
How to correctly reconstruct the timestamp of an incident particle?

To correct for the ambiguity of the measurement, we can use a number of different algorithms (it often depends on the sampler architecture):

Constant Fraction Discriminator (CFD)
The method used for our studies records the particles crossing time whenever the pulse amplitude is > than a certain fraction of the max. The CFD acts like a dynamic threshold tailored over every single pulse.

The analog implementation of the CFD can be used to understand its functioning:

1. split the waveform in two lines
2. delay the first line by **$0 < t_{delay} < t_M$** , **reverse the polarity** (t_M time to reach the signal max)
3. multiply the second line by a fraction *f* of the signal amplitude
4. Add the lines and find the zero crossing point


comparator (sum the lines)

reverse polarity

delay line $0 < t_{delay} < t_M$

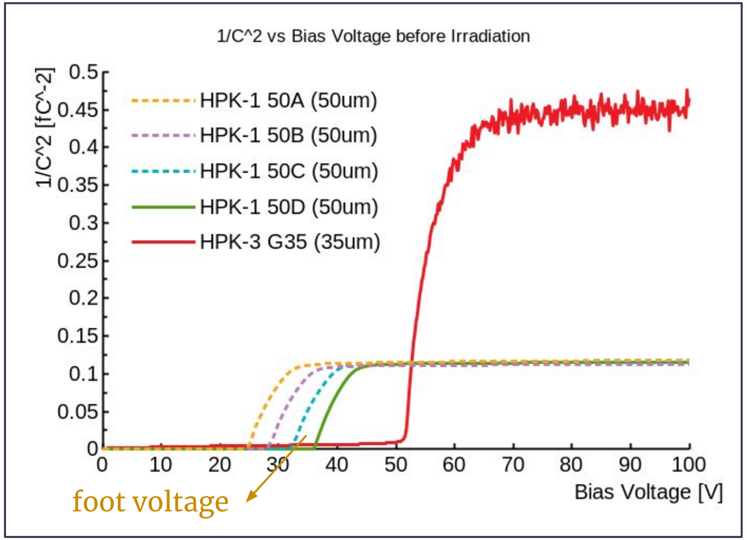
multiply by *f* (fraction of signal amp)

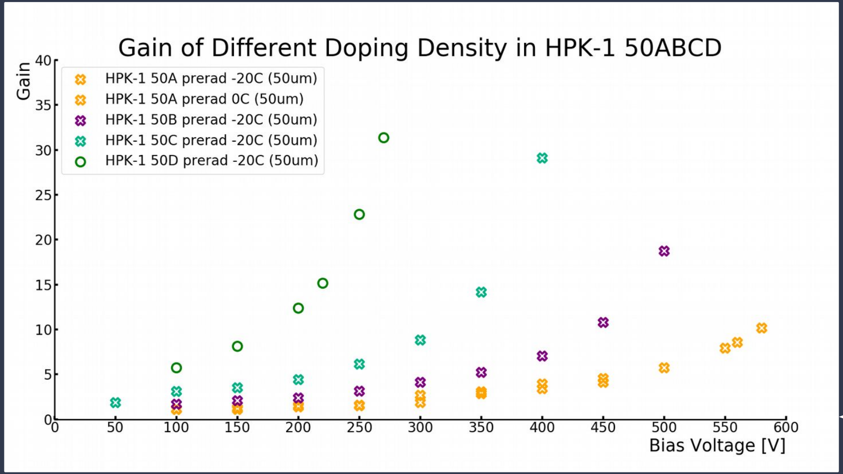
signal

Timing detectors: Low Gain Avalanche diodes

The effects of the doping density in the gain layer decides the bias voltage needed to fully deplete the gain layer

A C-V scan of the pixel under test describes the relationship between the quantities: the “foot voltage” is proportional to the doping density of the gain layer





The sensor total gain varies as a function of the bias AND the doping
the multiplication of the free charges generated in the sensor happens within the gain layer. The gain increases with the gain layer doping density.

In the plot:

from L to R: Higher to lower gain layer doping densities

Yuzhan Zhao, Timing Performance of Thin Low-Gain-Avalanche-Diodes (LGAD), ULITIMA 2018 Workshop

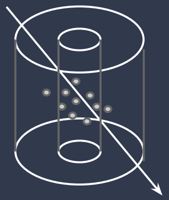
The collaboration with UCD Dublin and the Saint Luke’s Hospital: *idea*

Current technology: ion Chambers

Gas detectors used in radiotherapy exams to monitor the radiation delivered by the linac and its distribution. The beam monitoring operations are performed before and after the patients are treated or during special research runs.

1. These detectors work integrating the charge deposited...

Incoming particles produce free charges which in turn generate an avalanche process

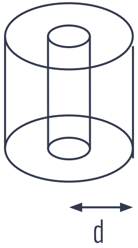


...And the timescales are long

> Usually every measurement takes tens of second (up to minutes).

> cannot be sensitive to small/fast variations since integrating we lose track of single events

2. The spatial resolution is not optimal (if we want to use them at the top of their performance)



> The reduction of the active area is limited by the distance between the electrodes:

These devices would require high voltage to be have a fast response.. But that reflects on the minimum ’ d ’ we can chose

PROBLEM:

During standard radiological exams and diagnostic procedures, the differential dose provided to the patient is usually measured using gas detectors (ion chamber detectors).

The measurement relies on the integration over time of the current produced by the particles passage... Intrinsically, this procedure **doesn’t allow to keep track of the fast variation of the particle fluxes output by a medical machine.**

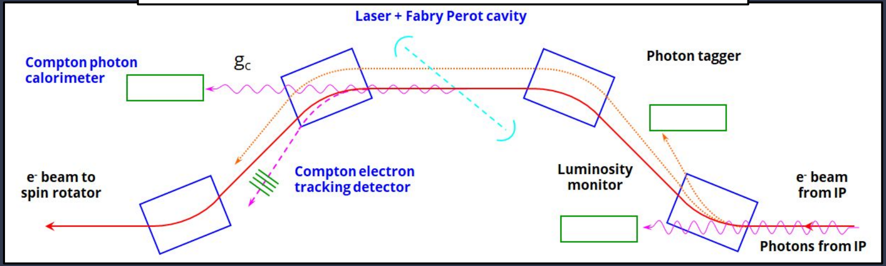
The next step: improvements on the current technology and expanding the horizon of applications

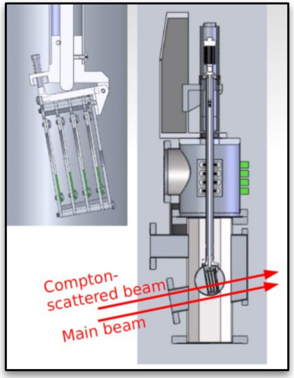
Polarimetry

Compton polarimeters represent the best option for measuring the polarization asymmetry of high energy particle beams.

After every interaction @ the EIC, the level of polarization is verified using on-beam detectors. Starting from the photons polarization coming from the laser+Fabry Perot cavity (measurable) and estimating the predicted QED asymmetry, the apparatus constraints the electrons polarization:

$$\sigma(\vec{e} + \gamma \rightarrow e' + \gamma') \neq \sigma(\overleftarrow{e} + \gamma \rightarrow e' + \gamma')$$





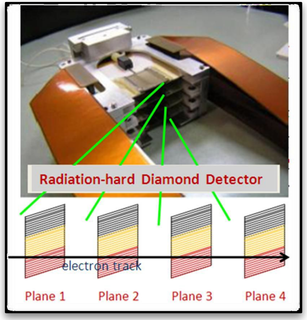
$$A_{EXP} \equiv \frac{N^+ - N^-}{N^+ + N^-} = \boldsymbol{P_e} * P_\gamma * A_{QED}(E_e, k_\gamma, k_{\gamma'})$$

Roman pots: solid state detectors (in the primary vacuum) approaching the beam using a movable support

Resolves the shape of the expected asymmetry by measuring the strip-by-strip asymmetry.
> Compton edge and zero needed to fit $\boldsymbol{P_e}$ to
$A_{\text{measured}} = P_e A_{\text{theory}}$

Current technology…The electron detector

> set of four diamond planes each with 96 “microstrips” of metal alloy etched on the Surface.
> Each strip is 0.180 mm wide separated by 0.02 mm.



LGAD could provide for new electron detectors

…Fast

> Single particle every bunch crossing per channel

> expected rate for 10 kW laser power >3 GHz per 5 cm^2

> Sensor, amplifier, digitizer, DAQ to be designed

… And Precise

> Increased segmentation

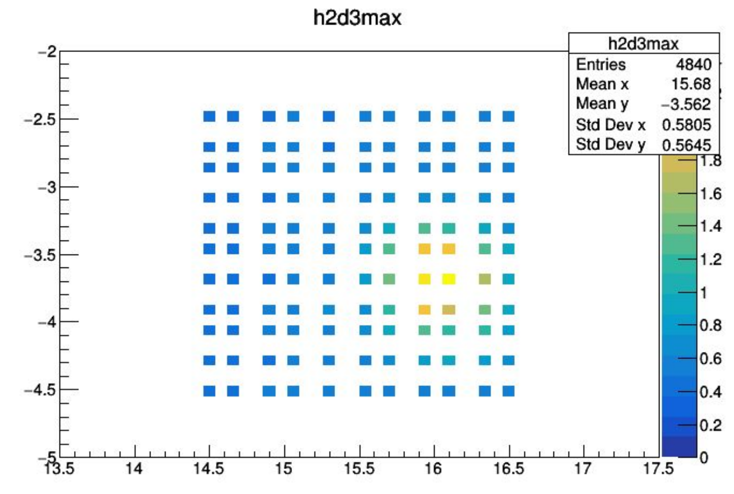
> Less challenging detector requirements, but more channels

> Digitizer, DAQ to be designed

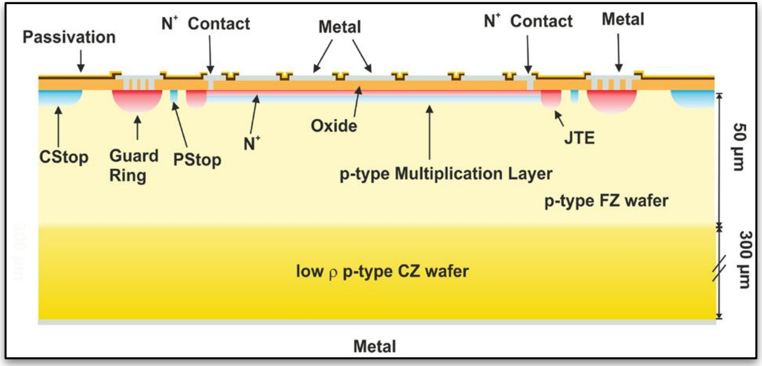
The next step: improvements on the current technology and expanding the horizon of applications

In order to achieve extremely high granularity on the silicon wafers…

…The CNM company developed new prototypes where the signal is AC-coupled into the metal pads by another continuous sheet of coupling oxide.



Continuous sheets of multiplication layer and n+ layer and only segments the metal connected to the readout…



Note : N+ layer crucial parameter to optimize for a correct ohmic contact

First prototype:

large detector (0.84 x 0.84 cm)

50μm thin , 14 strips, 49 pixels

Pixels of 200x200μm with 500 μm pitch