UNIVERSITÀ DEGLI STUDI DI TORINO

CINFAI SCUOLA ALTA FORMAZIONE

INFN TORINO

New Detectors for Beam Monitoring in Particle Therapy - II

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Giornate di Studio sui Rivelatori - Scuola F. Bonaudi

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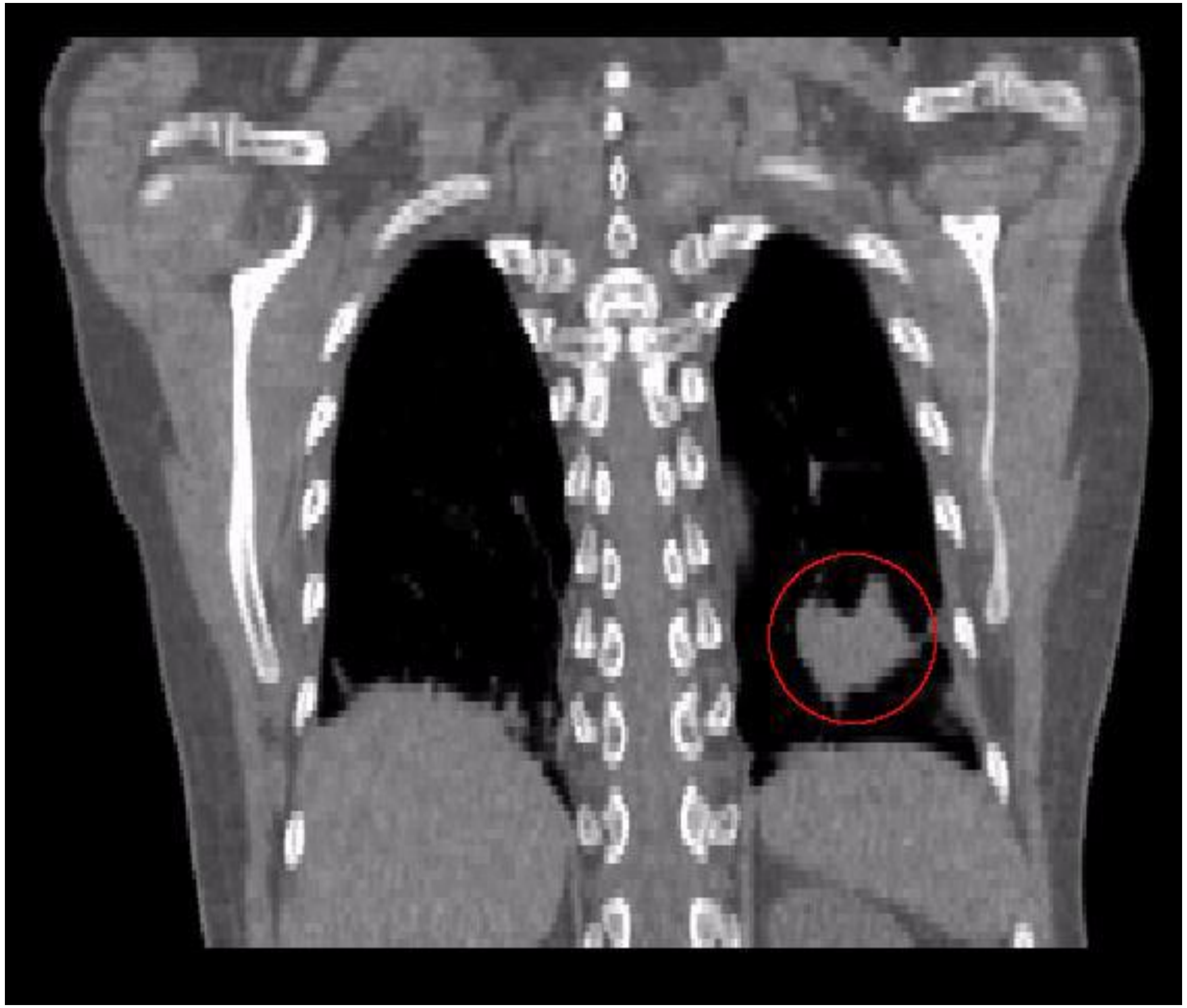
Outline

- Challenges and requirements for next generation of beam monitors
- Thin Low Gain Avalanche Detectors (LGAD) and Ultra Fast Silicon Detector (UFSD)
- LGAD-based online counter of particles
- LGAD-based online beam energy detector

Range uncertainties

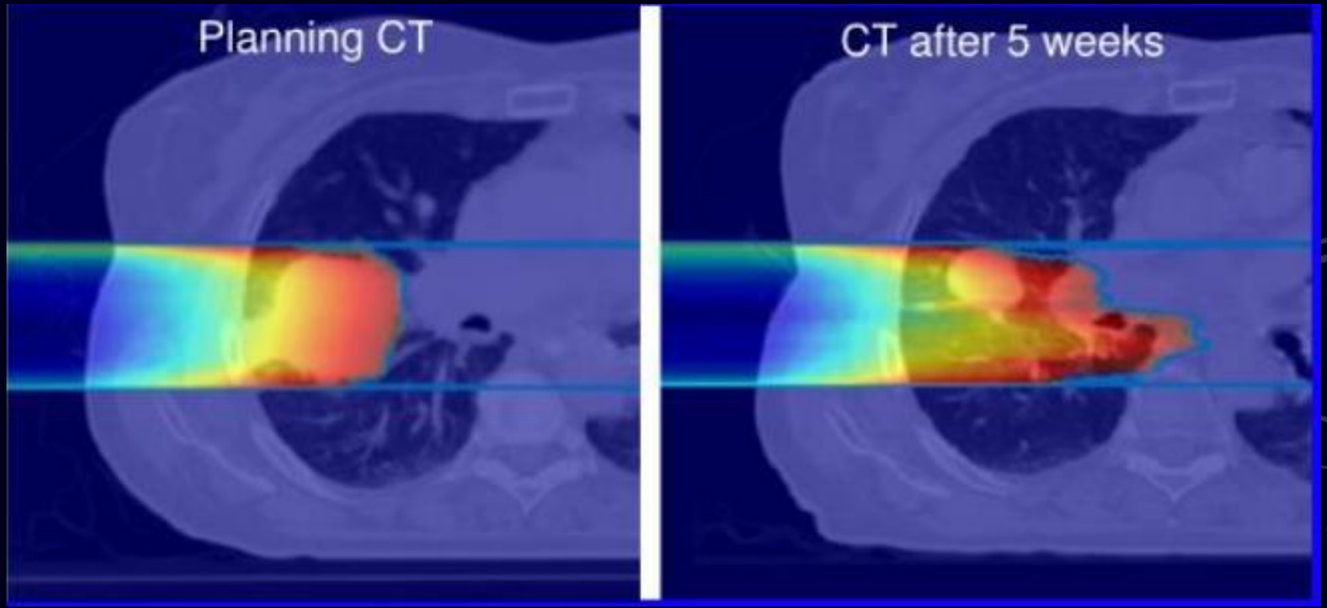
The tumor and surrounding organs move!!



The challenge: minimize range uncertainties

Several sources of range uncertainties in particle therapy lead to dangerous consequences to the patient!!

- *Motion*
  - *Organ position variation*
  - *Breathing motion*
- *Imaging*
- *Dose calculation*
- *Patient Set-up*
- *Tumor shrinkage*
- *Beam delivery errors*
- *……….*



By Tony Lomax, PSI Switzerland

Main motion mitigation strategies

- Gating
- Rescanning
- Tracking
- 4D adaptive radiotherapy

Low fluence rate for multiple-Rescanning

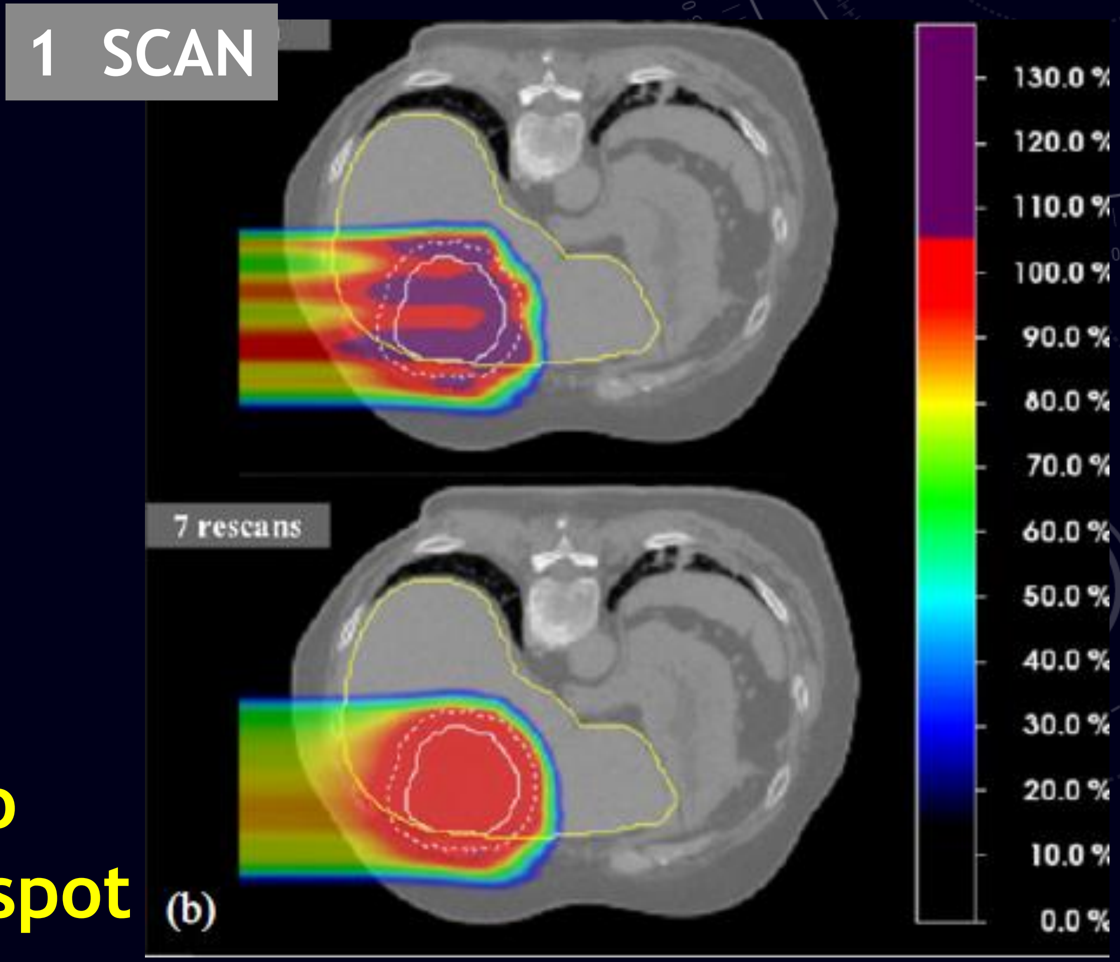
The daily dose is delivered in N consecutive times, the dose delivered during one full volume scan is equal to 1/*N*

A statistical averaging of dose heterogeneity is achieved

Control requirements:

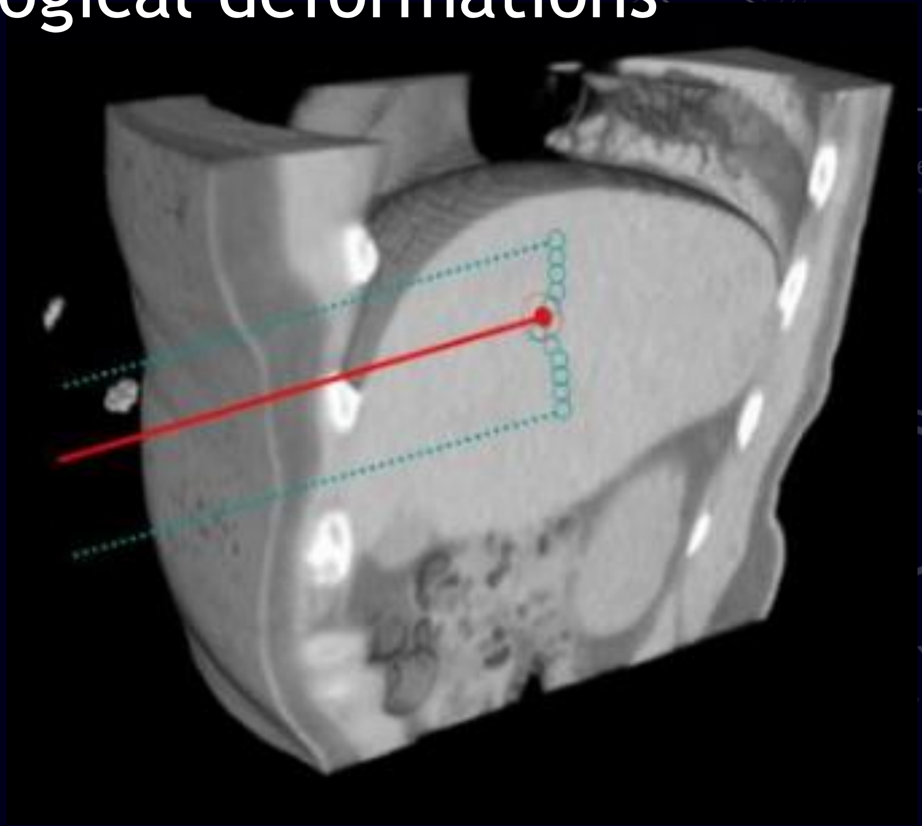
High sensitivity beam flux monitor to deliver low dose (few particles) per spot

N = number of Rescanning



Online energy control for tumor tracking

Tumor tracking aims to follow the motion using online signals from measurements of anatomical/physiological deformations



Control requirements:

Fast beam monitors
to perform feedback on beam position:
(x,y) to the scanning magnets,
(z) to range modulator,
and on fluence to the accelerator

New detector requirements

- HIGH SENSITIVITY
  - GOOD SIGNAL TO NOISE RATIO
  - FAST SIGNAL CREATION
- FINE GRANULARITY
- TRANSPARENT TO THE BEAM
- RESISTANT TO RADIATION
- LARGE AREA (at least 20x20 cm^2)
- DEAD TIME FREE

Increase the charge generated for each proton

$$Q = \frac{S \cdot d \cdot e}{W}$$

⇨

- W small
- Hgher density
- $\rightarrow$ S larger

Short collection time

$$t \approx \frac{d}{\mu \cdot E}$$

⇨

- Reduced thickness
- High Electric field E

For Silicon ….

- $W = 3,6\ \mathbf{eV}$ e $S(120\ \mathbf{MeV}) = 1,2\frac{\mathbf{MeV}}{\mathbf{mm}}$,
- 10^5 e^- /h in 300 μm → Q=16 fC

Sensitivity

MAIN ISSUE of EXISTING Beam Monitors
LOW SENSITIVITY
→ W ~ 30 eV to create 1 e^-/h pair

1 MU ~ 200 fC *

- 7.2×10^3 p (62 MeV)
- 1.9×10^4 p (226 MeV)
- 341 ^{12}C (115 MeV/u)
- 767 ^{12}C (399 MeV/u)

**Values from CNAO beam monitors*

The best sensitivity → particle counter

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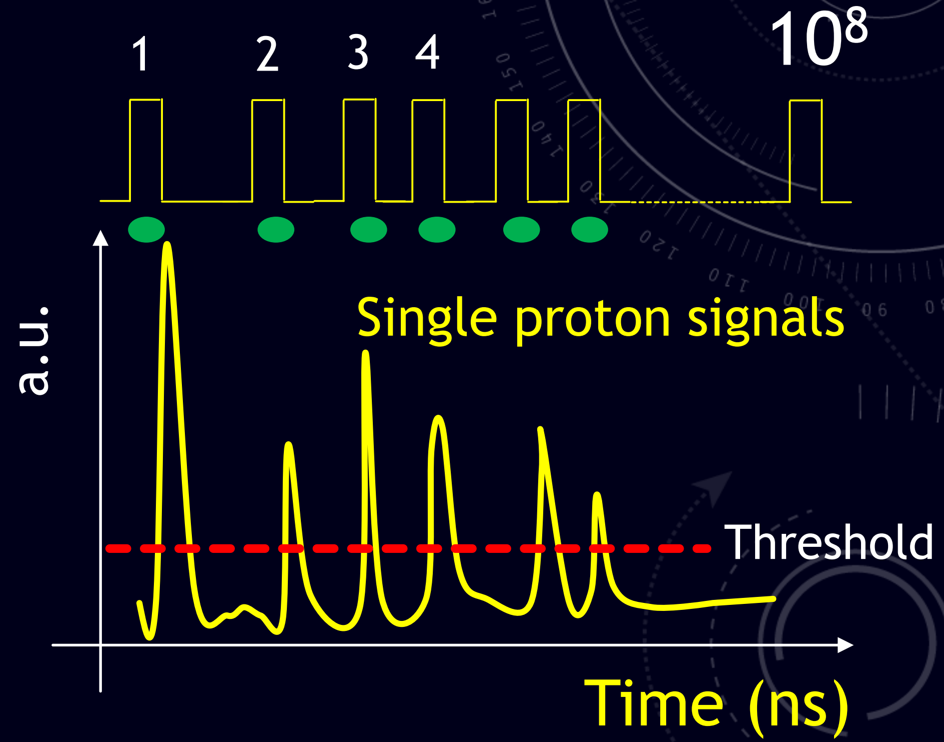
**Values from CNAO beam monitors*



THE IDEAL DETECTOR SHOULD MEASURE ONLINE THE NUMBER OF PARTICLE with 1% of accuracy

The promising candidate: silicon sensor

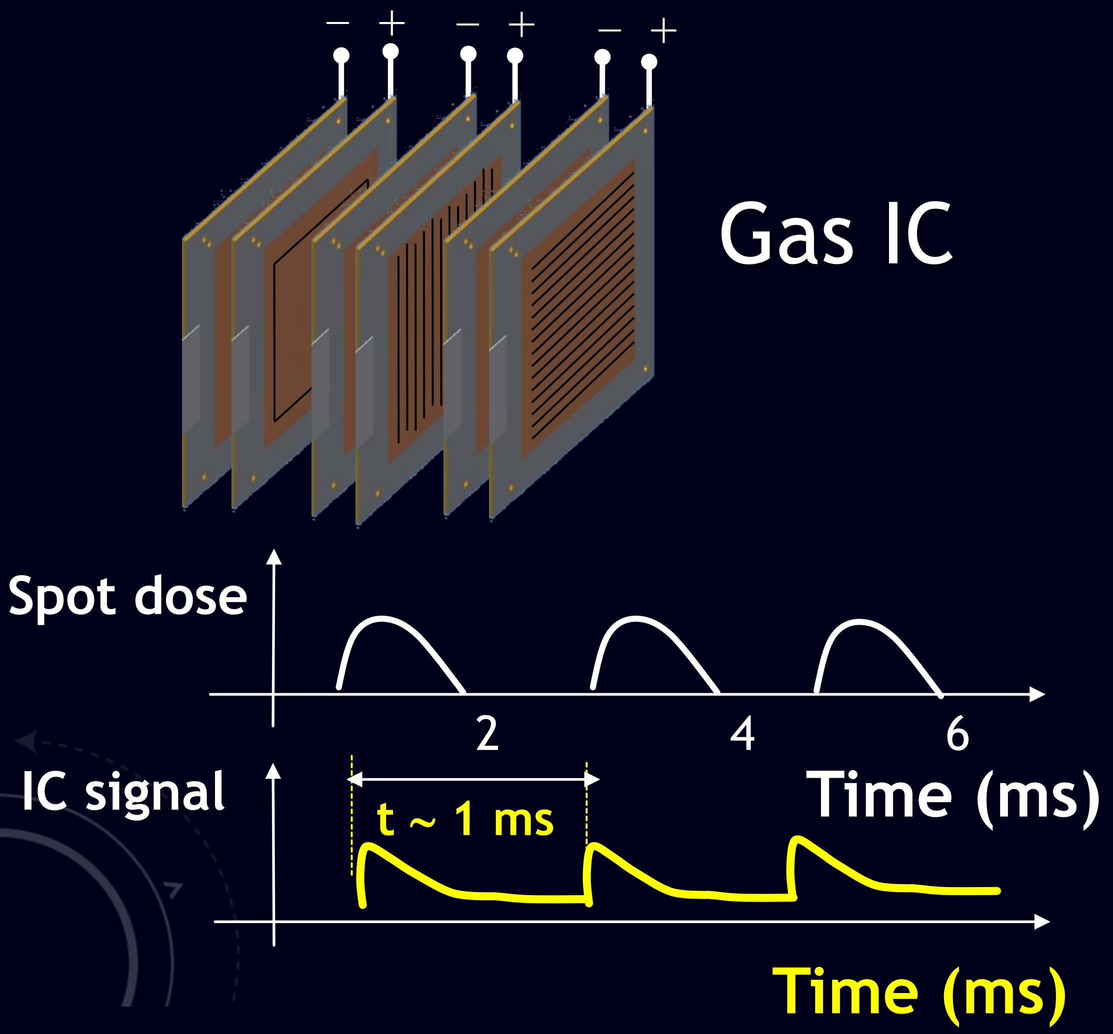
The promising candidate: silicon sensor

At present, silicon sensors are the ONLY detector able to provide excellent timing capability (~ 30 ps) , good radiation hardness (fluence ~ 1E15 n/cm2), good pixelation (10um – 1 mm), and large area coverage (many m^2)

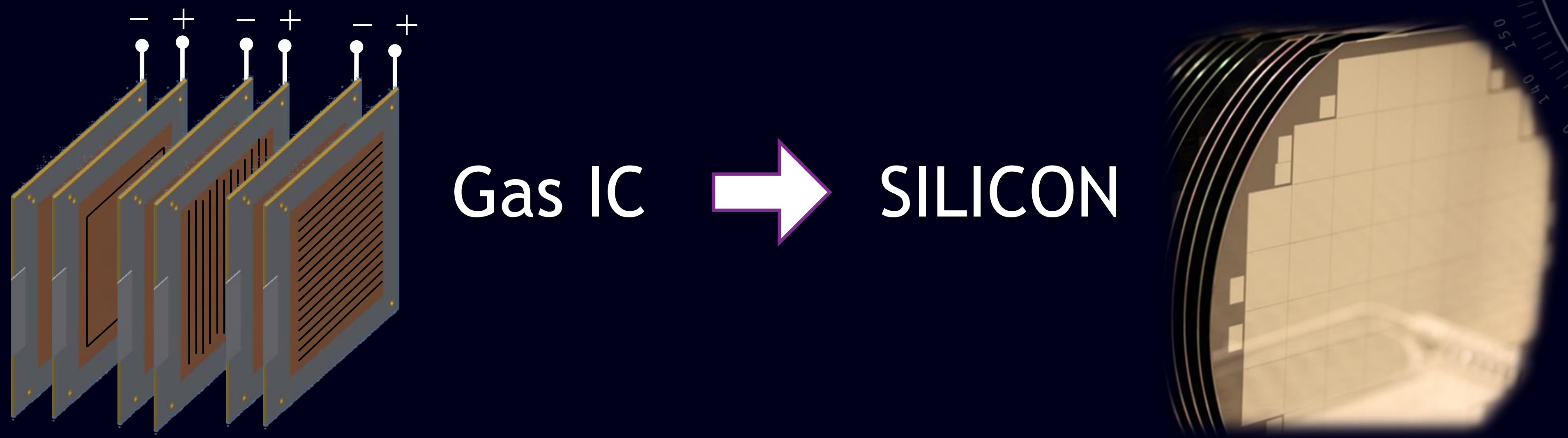
N. Cartiglia, INFN. Terascale meeting - 27-Nov-2019

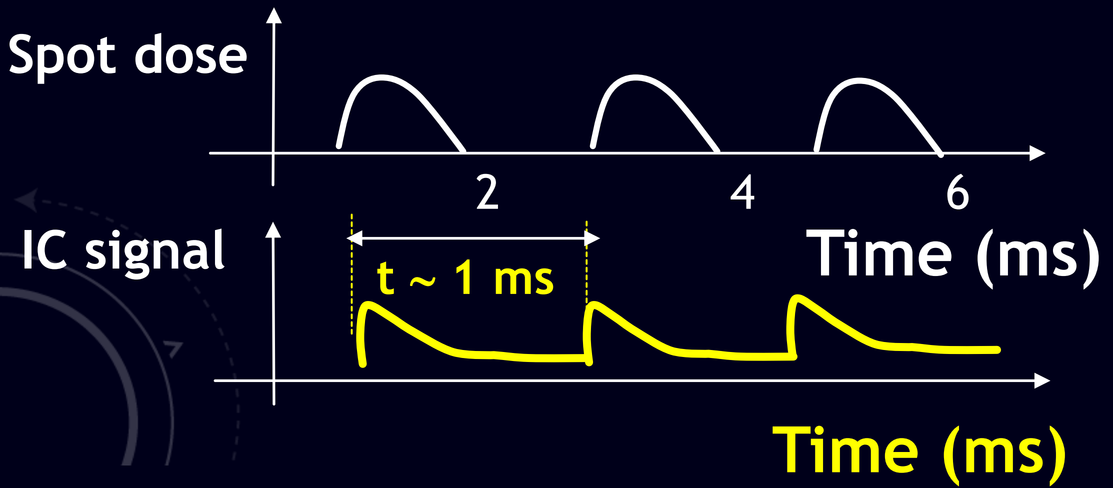
Additionally: optimized read-out chain (ASIC + FPGA) is mandatory

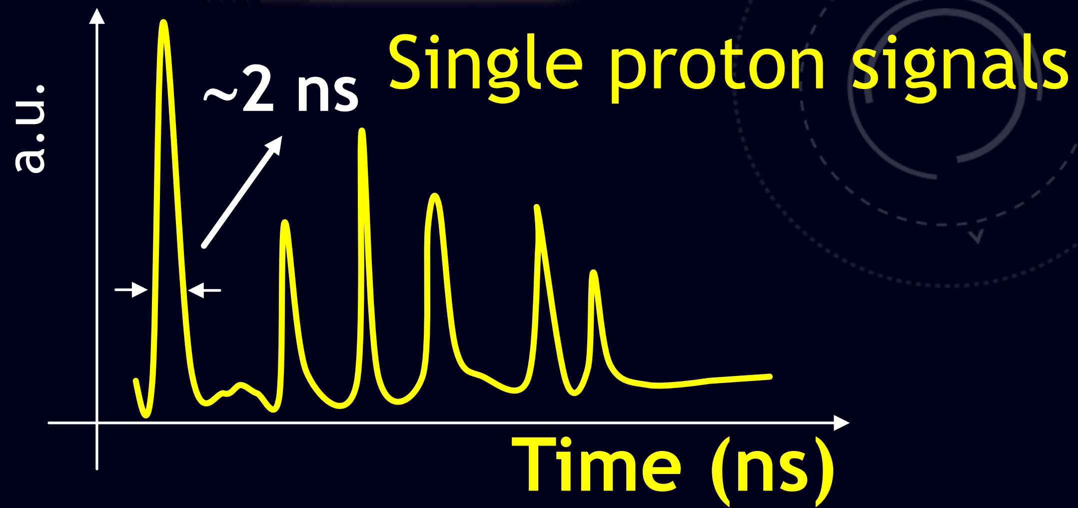
From *Integrated charge* with GAS IONIZATION CHAMBERS



From *Integrated charge* with GAS IONIZATION CHAMBERS To *number of particles* with SILICON DETECTORS





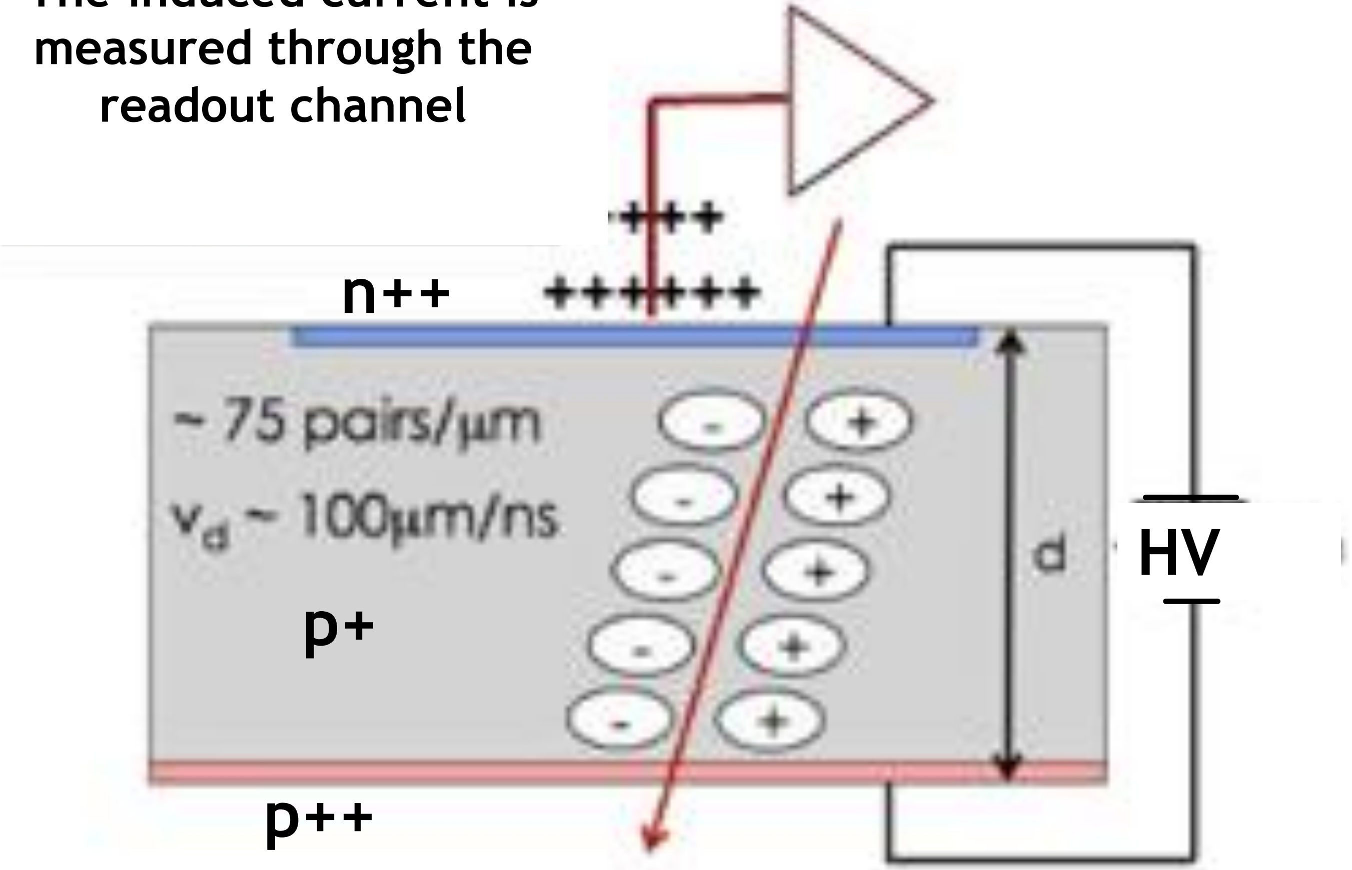


Traditional n-on-p silicon detectors

External bias voltage (HV) inversely polarizes the p-n junction, creating a large depleted volume where charged particle creates free electron-hole pairs (e-h) by ionization

The electric field (~30 kV/cm) determines the electrons drift toward the n++ contact, and the holes toward the p++ contact, creating an induced current on the electrodes

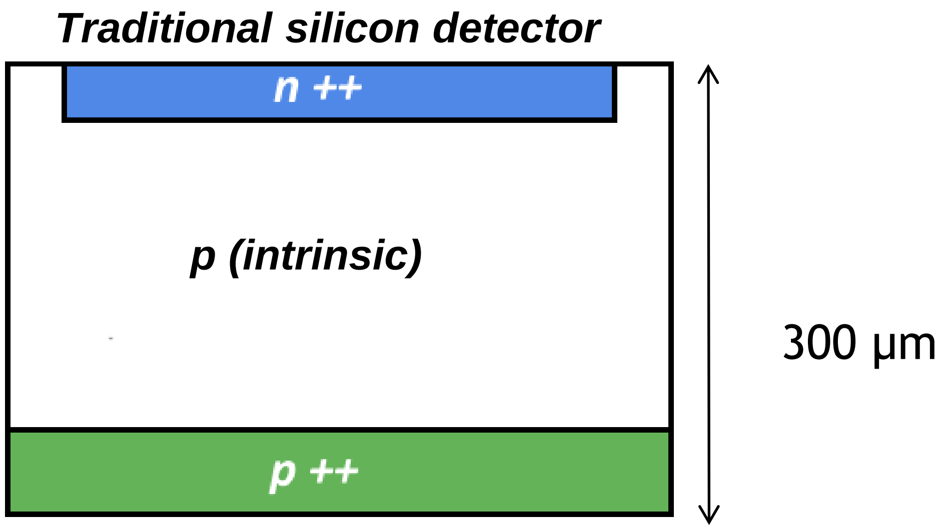
The induced current is measured through the readout channel



Traditional n-on-p silicon detectors

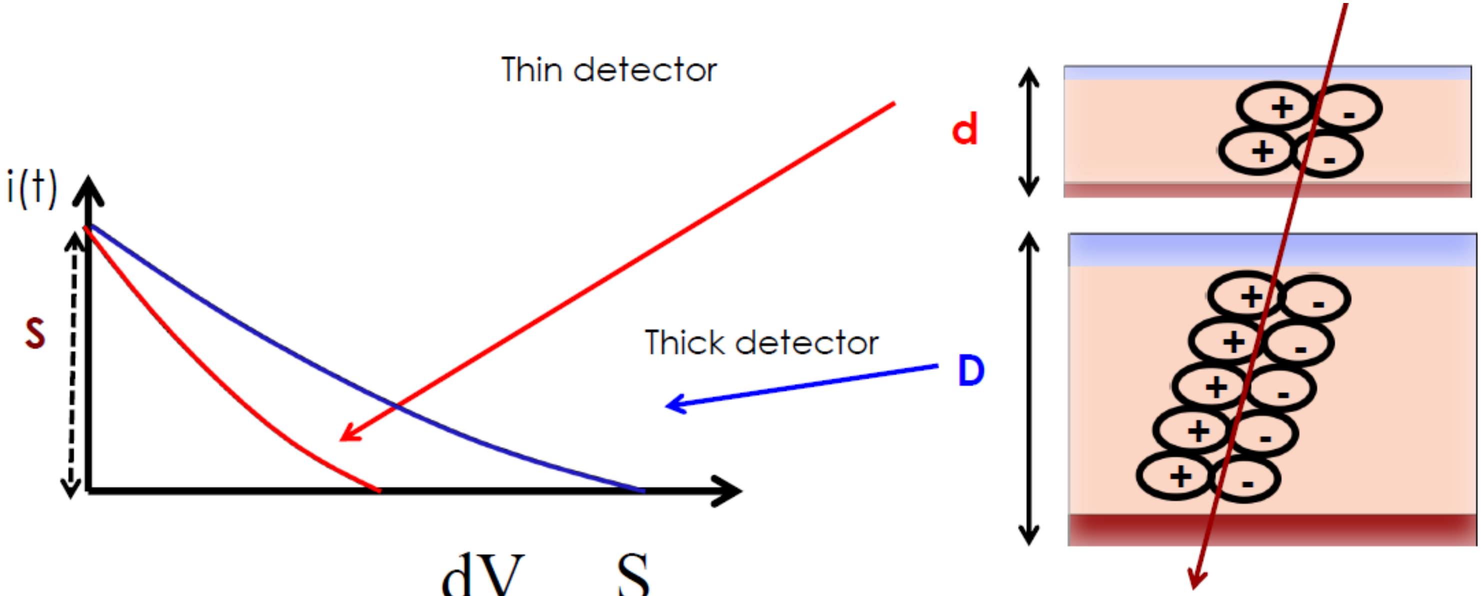
W = 3.6 eV to create 1 pair e-/h in silicon

- Good sensitivity
- Fast response
- Fine granularity
- Good spatial resolution
- Good Signal/Noise ratio



Signal duration ~ 10 ns → too large to discriminate particles with a beam flux of 10^8-10^9 p/cm^{2}sec

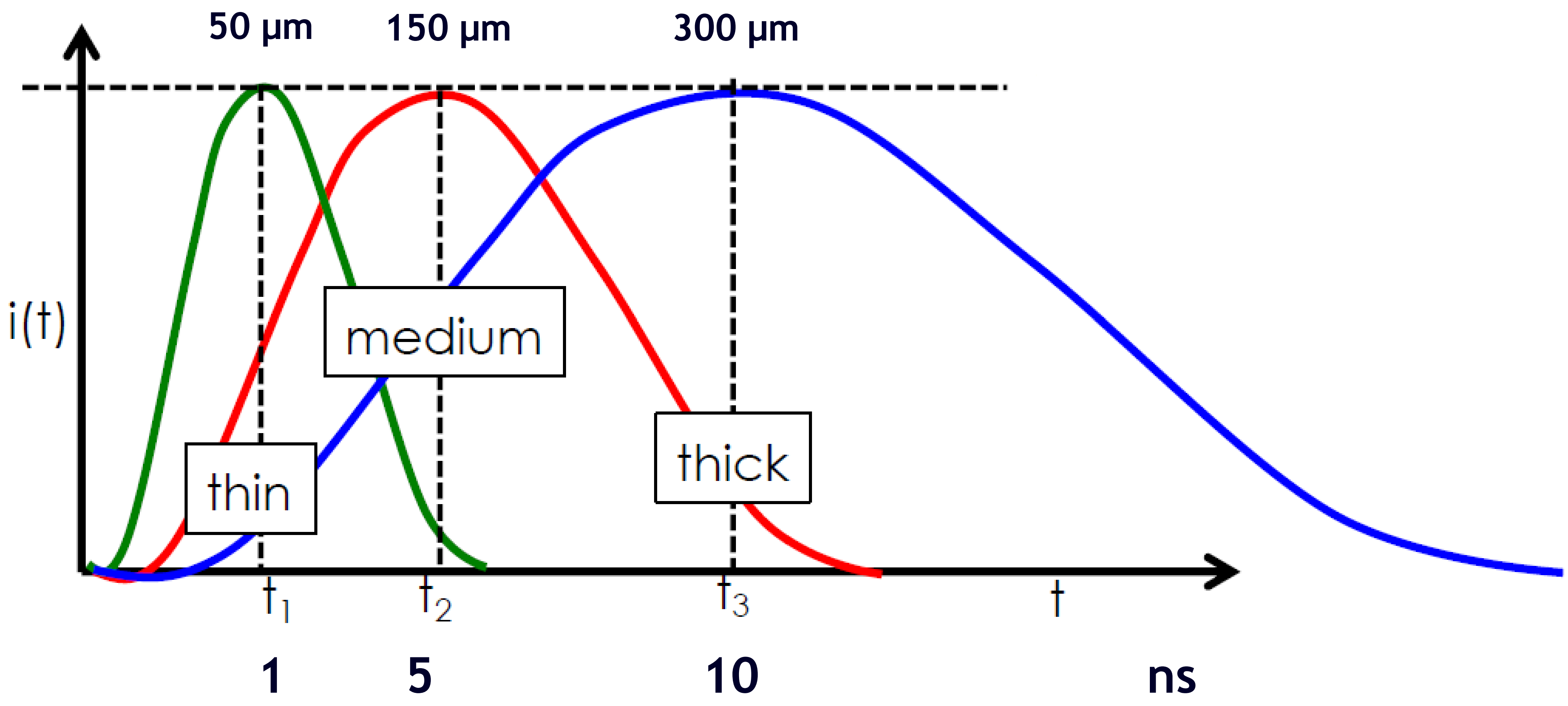
Shorten the signal by reducing the thickness



$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$

The effect of reducing thickness is to obtain a **shorter signal**,
not higher signal

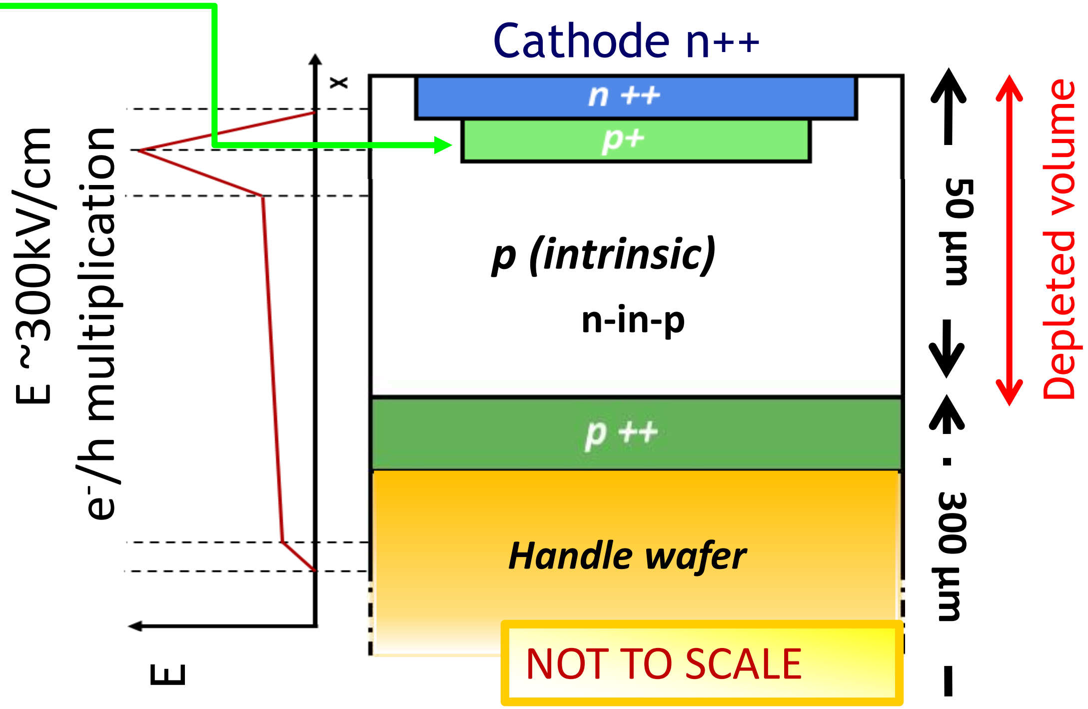
Signal length for different thicknesses



Increase the amplitude by adding a Gain

- **Thin p+ gain layer implanted under the n++ cathode**

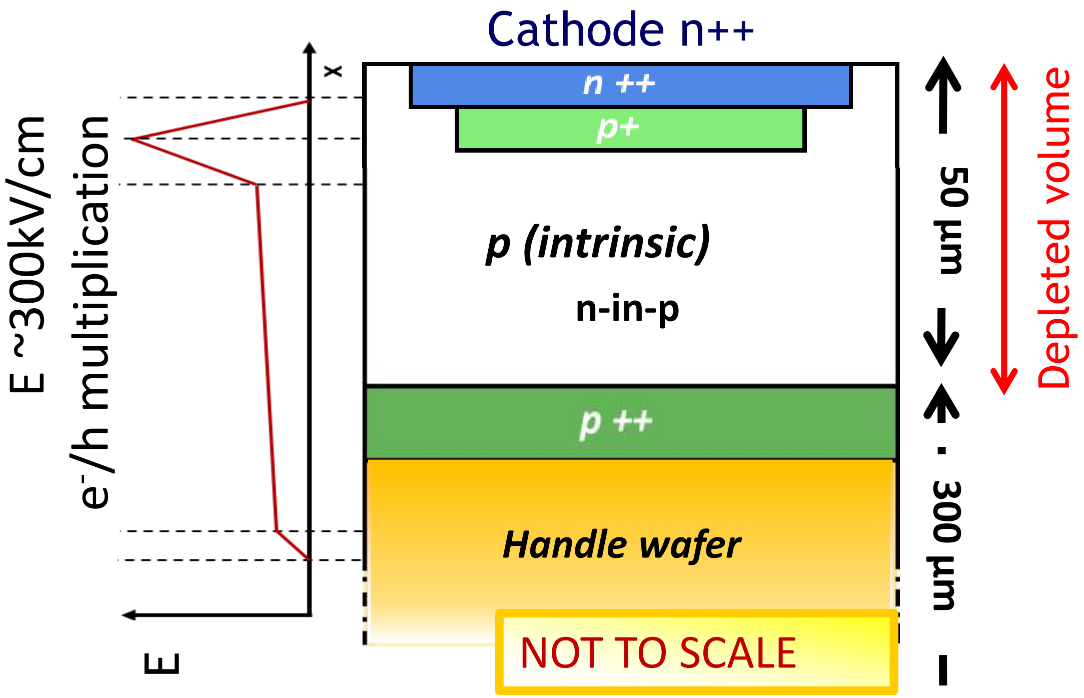
- Controlled low gain (10~30)
- Gain increases with bias voltage



ADVANTAGE

- **GAIN INCREASES THE SIGNAL→ Enhanced signal-to-noise ratio**
- **GAIN IMPROVES RISE TIME → Better time resolution (few tens of ps)**

Thin Low Gain Avalanche Diodes



Small thickness of active volume → 50 µm

Reduced number of charge

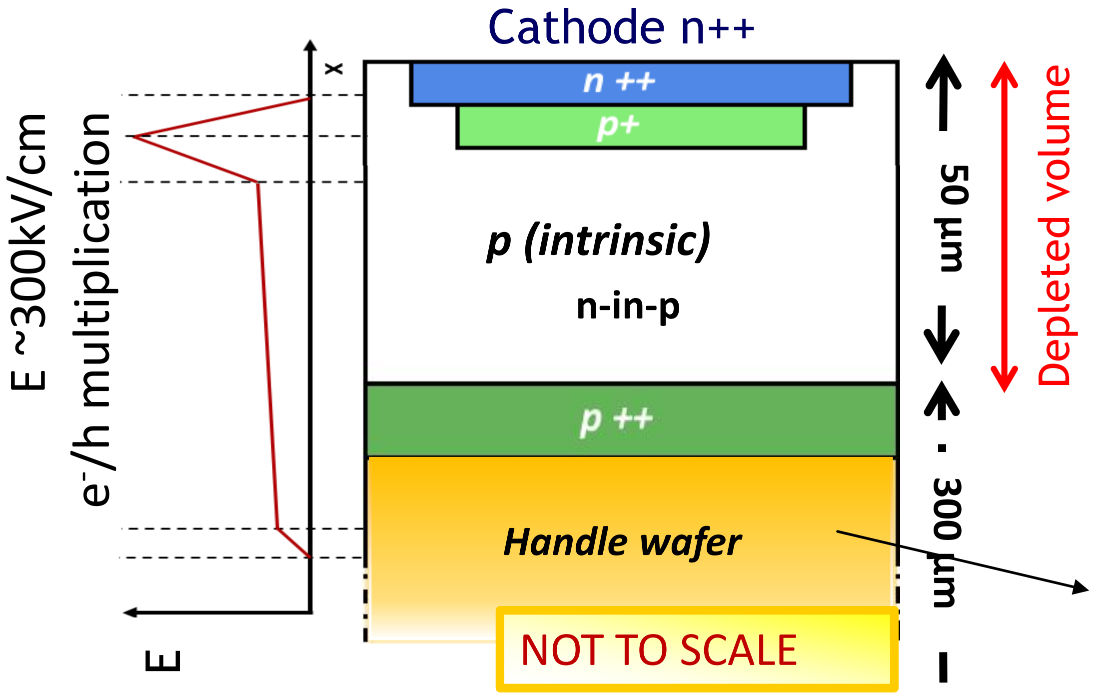
$$Q_{tot} \sim 75\ q*d$$

The internal gain compensates for the loss of signal due to reduced thickness

ADVANTAGE

- Short signal duration (1,5-2 ns in 50 µm)

Thin Low Gain Avalanche Diodes



Handle wafer can be safely thinned down to 20 µm to reduce material budget

ADVANTAGE

- **High density segmentation possible**
- **Good spatial resolution (~100 µm pitch)**

EXAMPLE of LGAD application: UFSD

- **Ultra Fast Silicon Detectors (UFSD)**
  LGAD sensors optimized for high time resolution
  - **Excellent time resolution (30 ps in 50 μm)**

RD50 Collaboration

H.F. W. Sadrozinski et al., Nucl.Instrum. Meth. A831 (2016) 18-23.

V. Sola et al. Ultra-Fast Silicon Detectors for 4D tracking. Journal of Instrumentation (2017), Volume 12.

Dependences of Time resolution

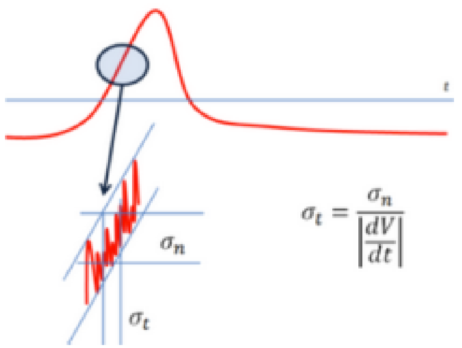
$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2 + (\Delta shape)^2 + (TDC)^2$$

Sensor design

Subleading, ignored here

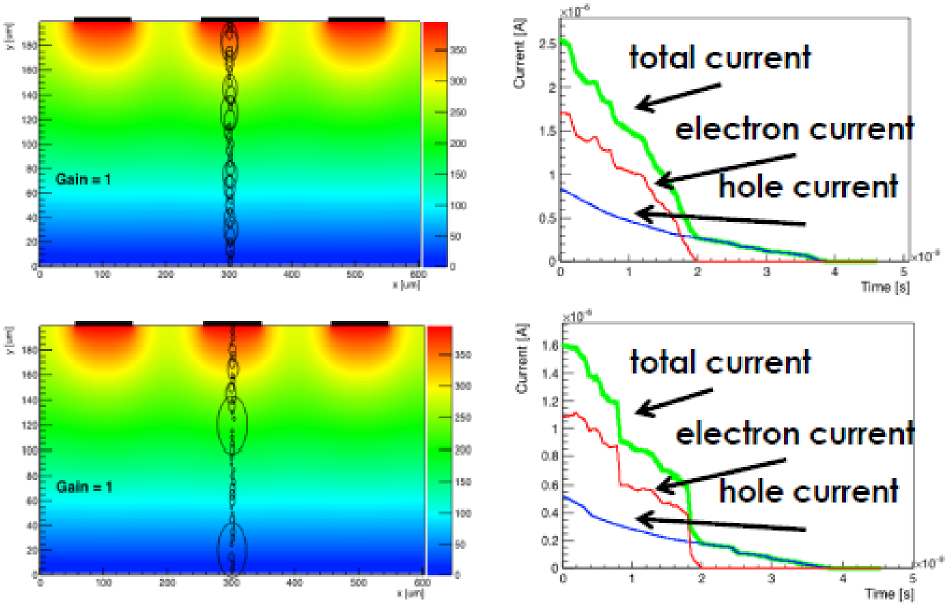
Usual "**Jitter**" term
Here enters everything that is "Noise" and the steepness of the signal

Amplitude variation:
variation in the total charge
Shape distortion:
non homogeneous energy deposition



$$\sigma_t = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|}$$

Need large dV/dt



Courtesy of N. Cartiglia

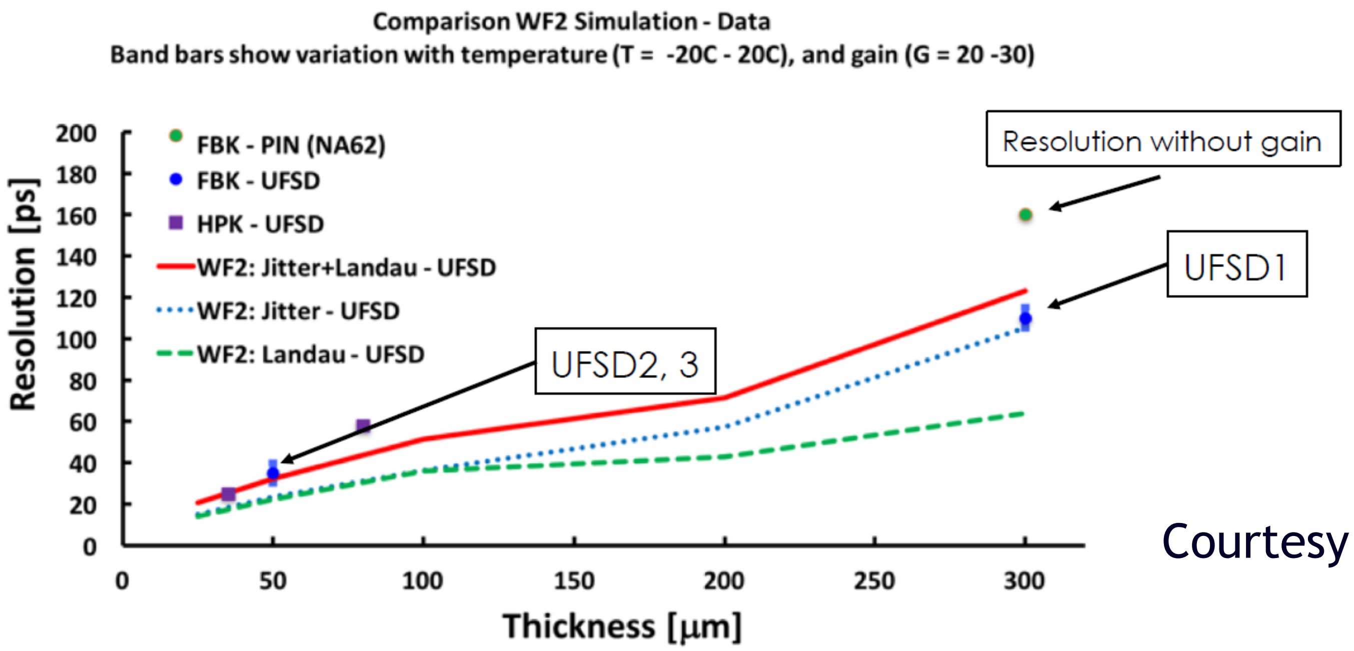
UFSD time resolution

Summary of the results achieved by the INFN Torino UFSD group

For each thickness, the goal is to obtain the intrinsic time resolution

Achieved:

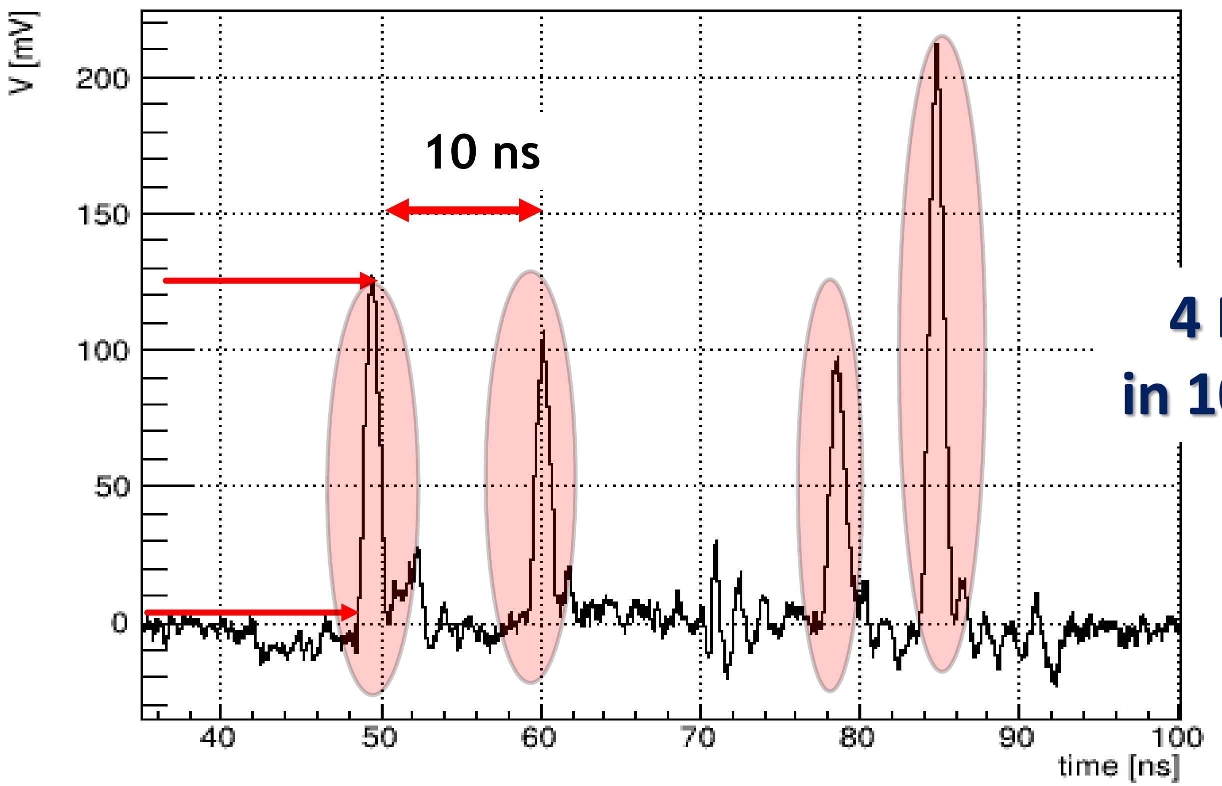
- **20 ps for 35 micron**
- **30 ps for 50 micron**



Courtesy of N. Cartiglia

Example of UFSD output

The output we have with UFSD for $5x10^8$ protons/sec



4 PROTONS DETECTED
in 100 ns signal waveform

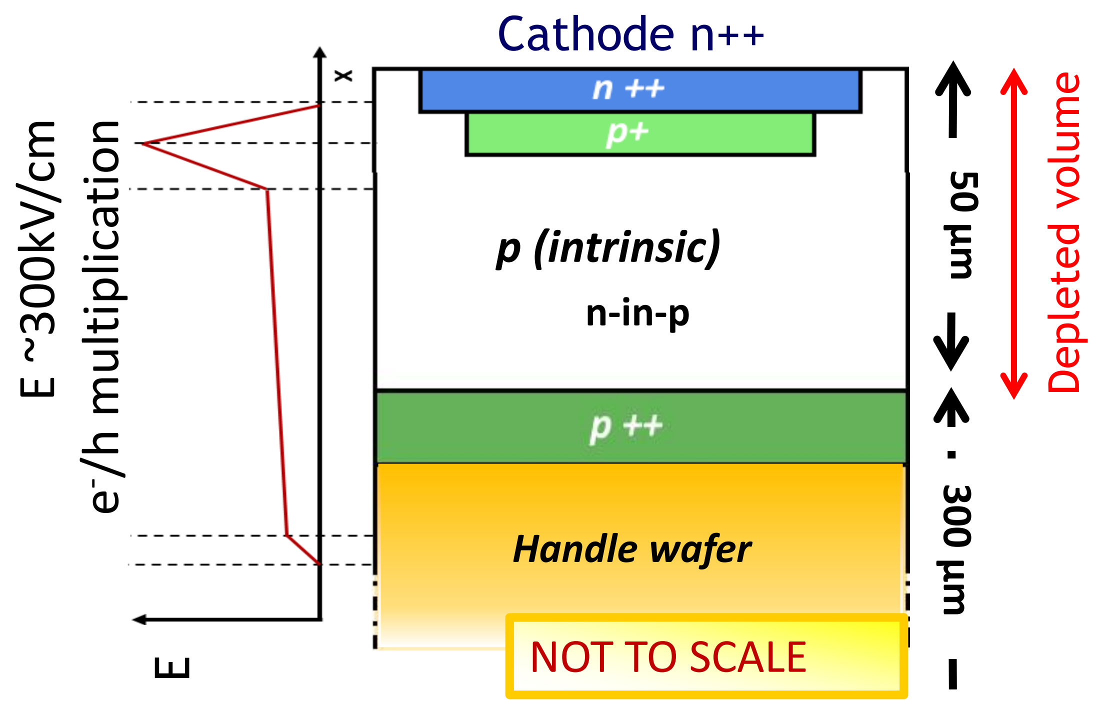
Thin UFSD sensors (50 μm)

Small signal duration (~1 ns) → single particle detection capability

Main issues of UFSD

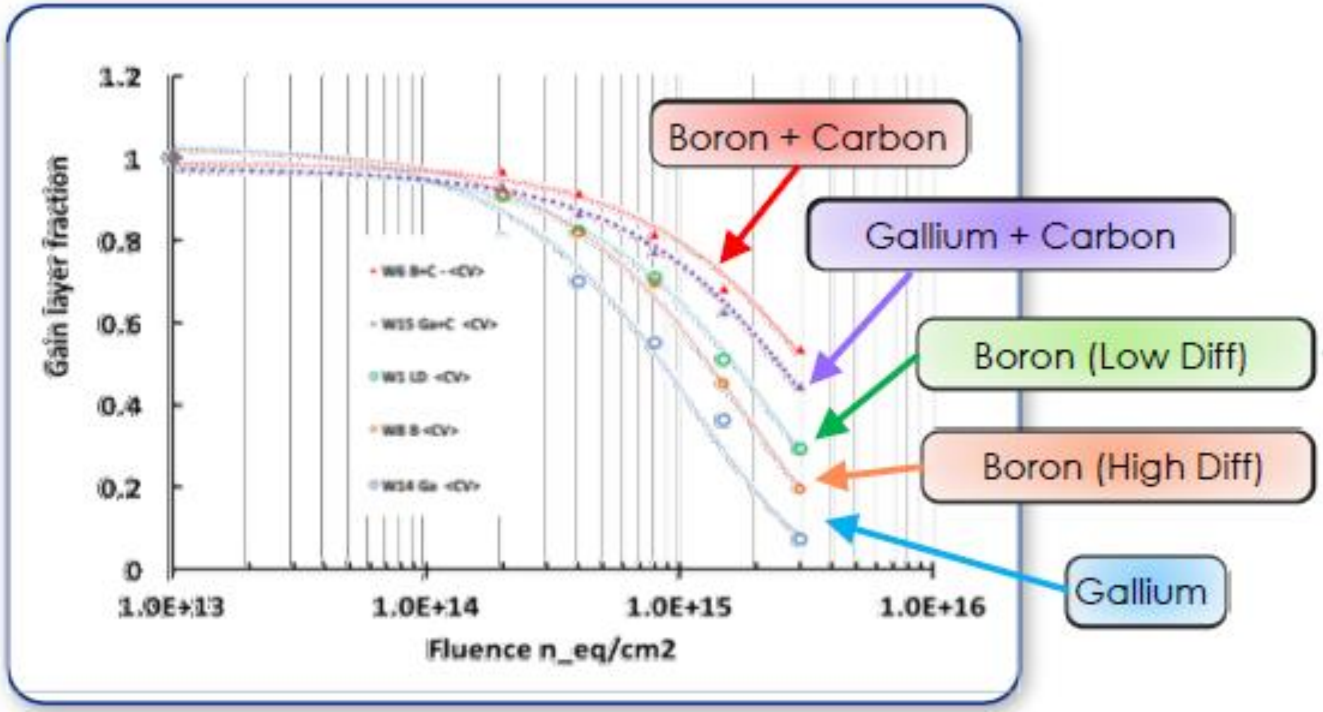
ISSUES for a UFSD-based MEDICAL DEVICE

- Higher readout complexity (efficiency and dead time)
- Radiation damage
- Pile-up effects
- Dead area



R&D on LGAD radiation hardness

Radiation reduce the gain layer → up to 10^{15} n_eq/cm^2 it is possible to compensate with bias voltage



Defect Engineering of the gain implant

- **Carbon** co-implantation mitigates the gain loss after irradiation
- Replacing Boron by **Gallium** did not improve the radiation hardness

Modification of the gain implant profile

- **Narrower Boron doping profiles** with high concentration peak (Low Thermal Diffusion) are less prone to be inactivated

MoVe IT

INFN project (2017-2019)

Modeling and **Ve**rification for **I**on beam **T**reatment planning
http://www.tifpa.infn.it/projects/move-it/

Implementation of advanced radiobiological models in ion TPS, **experimental verification** in-vitro and in-vivo.

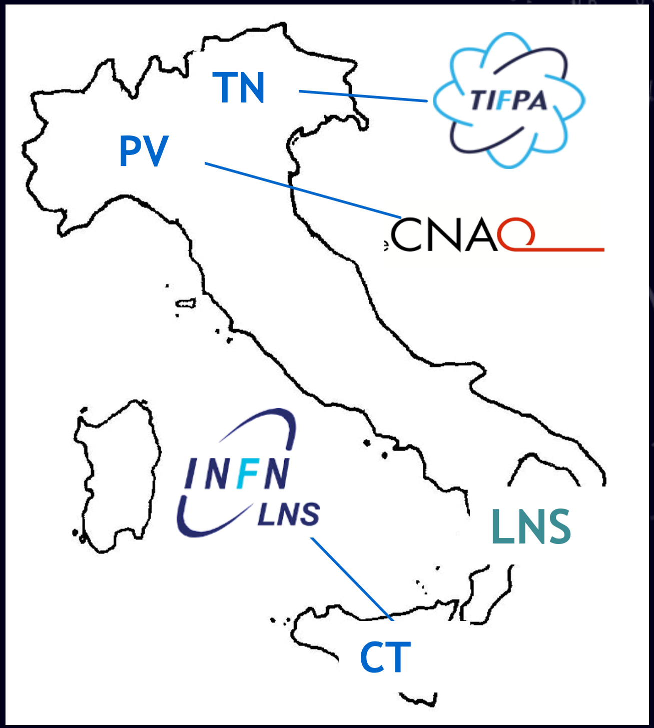
Physics → **Treatment Planning System** ← Radiobiology

↓

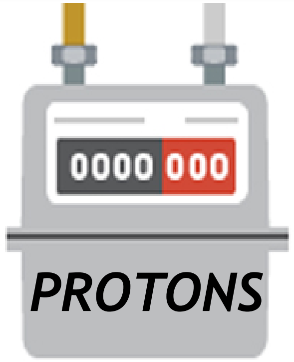
Delivered Dose Verification

↓

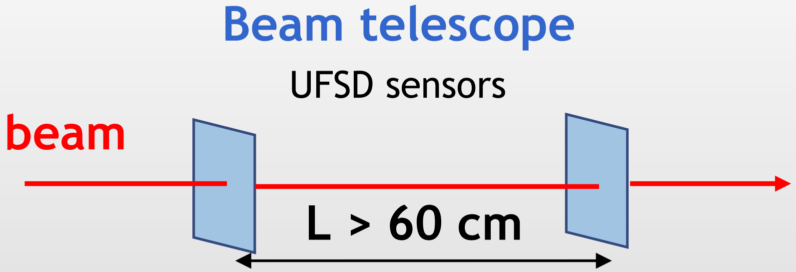
We are developing 2 new detectors based on THIN LGAD to overcome the limits of ICs



2 new UFSD-based DETECTORS

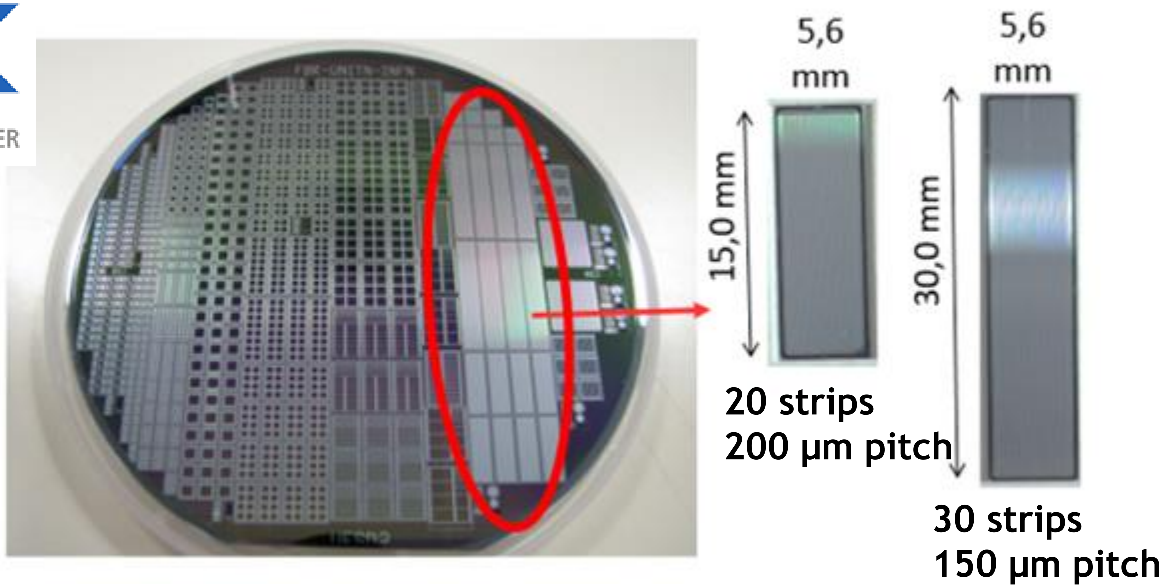


Particle counter as beam fluence monitor

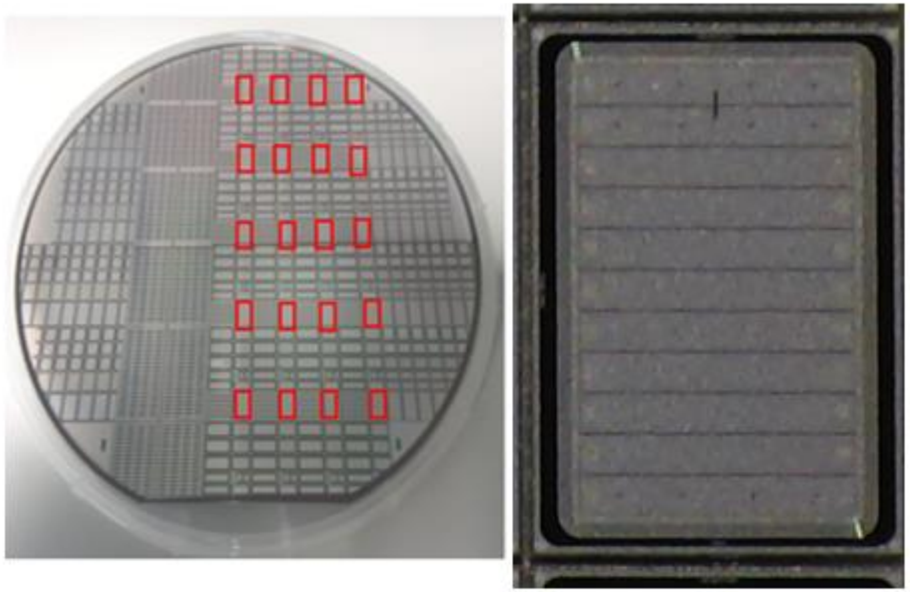


Beam energy monitor based on Time of Flight

UFSD sensors for beam monitors



MoveIT Strip detectors prototypes for the beam flux detector (UFSD2 production-2017)



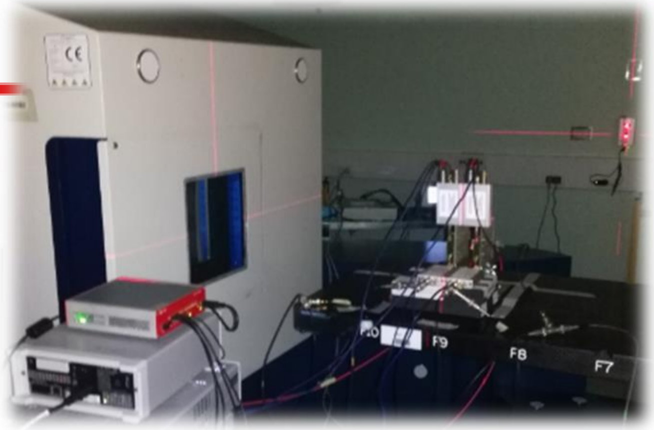
Strip sensors for the energy measurement (UFSD3 production-2018)

18 silicon-on-silicon wafers
different **doping strategies** for the gain layer
to improve **radiation resistance**

SENSORS DEVELOPED AND TESTED
with the clinical beams

Preliminary tests with clinical beams

CNAO



Proton Beam

from synchrotron

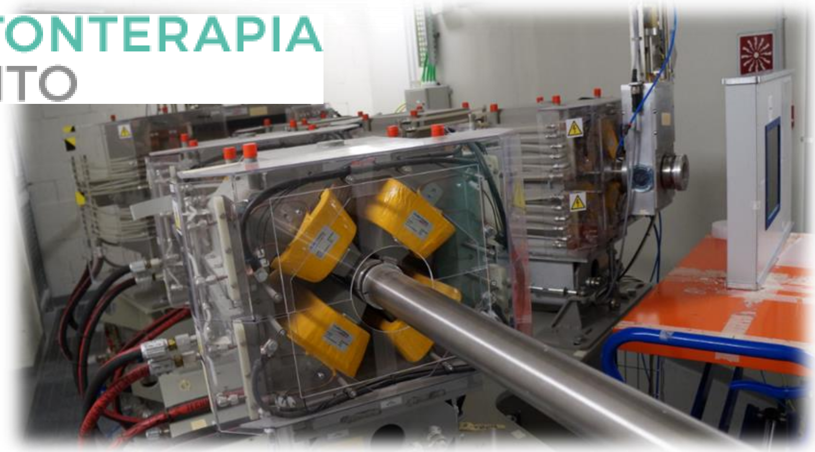
Beam FWHM ~ 10 mm

Max flux ~ 10^9 p/s delivered in spills

Beam flux range: 20% - 100% of max flux

Beam energy range: 62 – 227 MeV (5 – 2 MIPs)

TIFPA PROTONTERAPIA TRENTO



Proton Beam

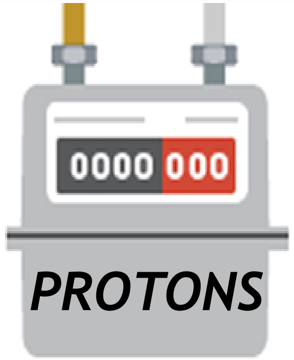
from cyclotron

Beam FWHM 3-7 mm

Beam flux 10^6 - 10^{10} p/s

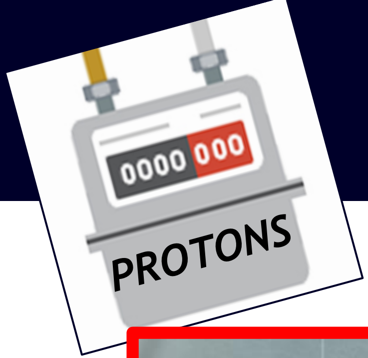
Beam current range: 1 nA – 320 nA

Beam energy range: 70 – 228 MeV



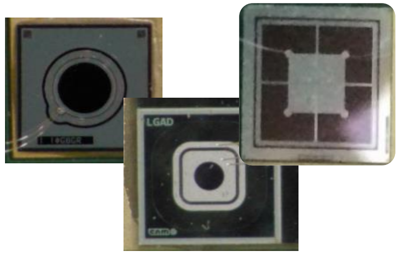
Particle counter as beam fluence monitor

Particle counter - preliminary test

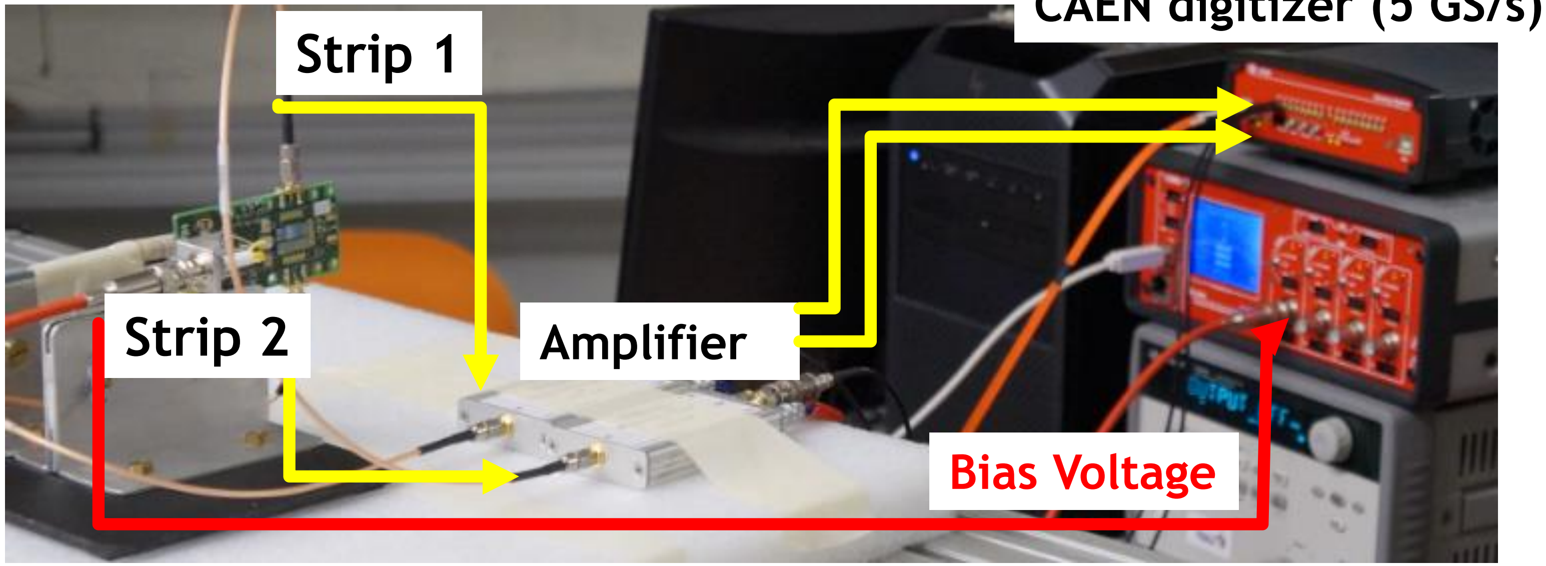


Passive Frontend boards with sensors aligned to the beam

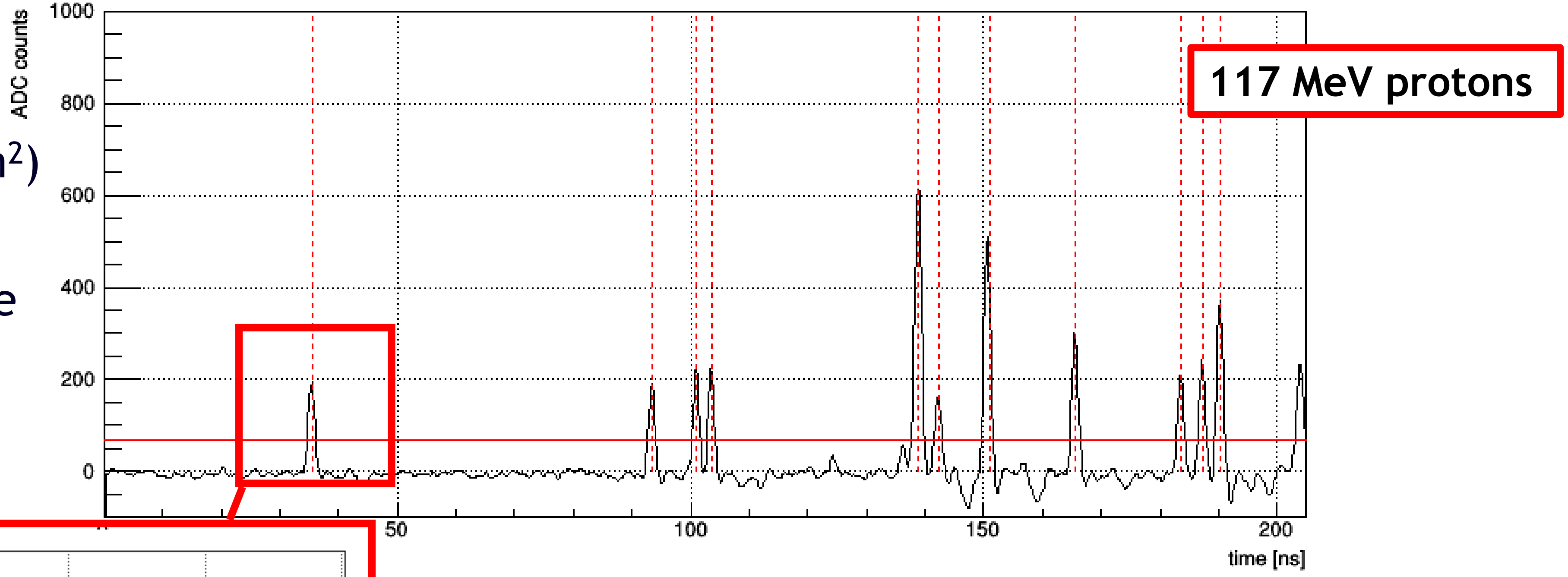
We tested the UFSD counting capability first with a preliminary readout setup and single pad



CNM, HPK pads (50 μm * 1 mm^2, 80 μm * 9 mm^2) and FBK strips (50 μm, 2 mm^2)

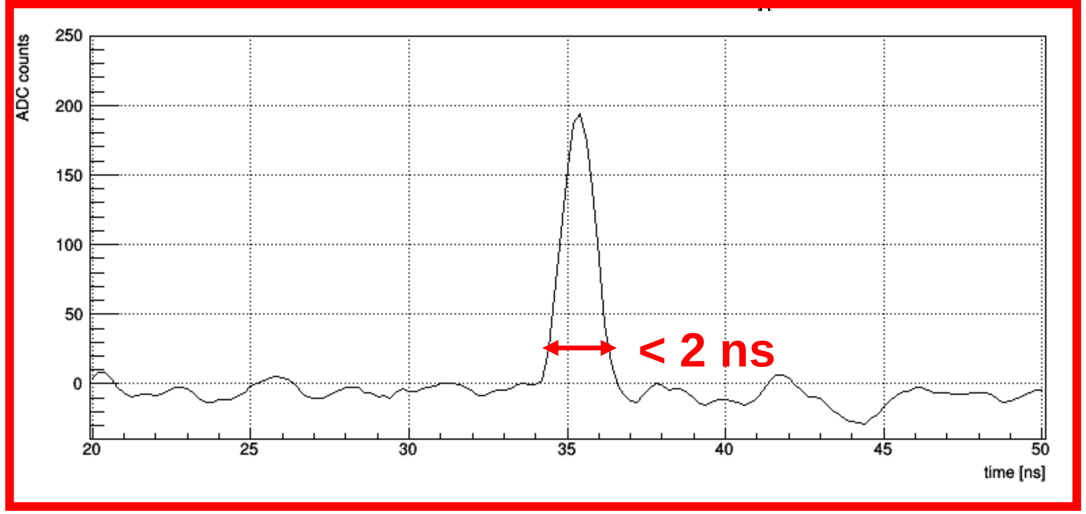


Example of signal waveform



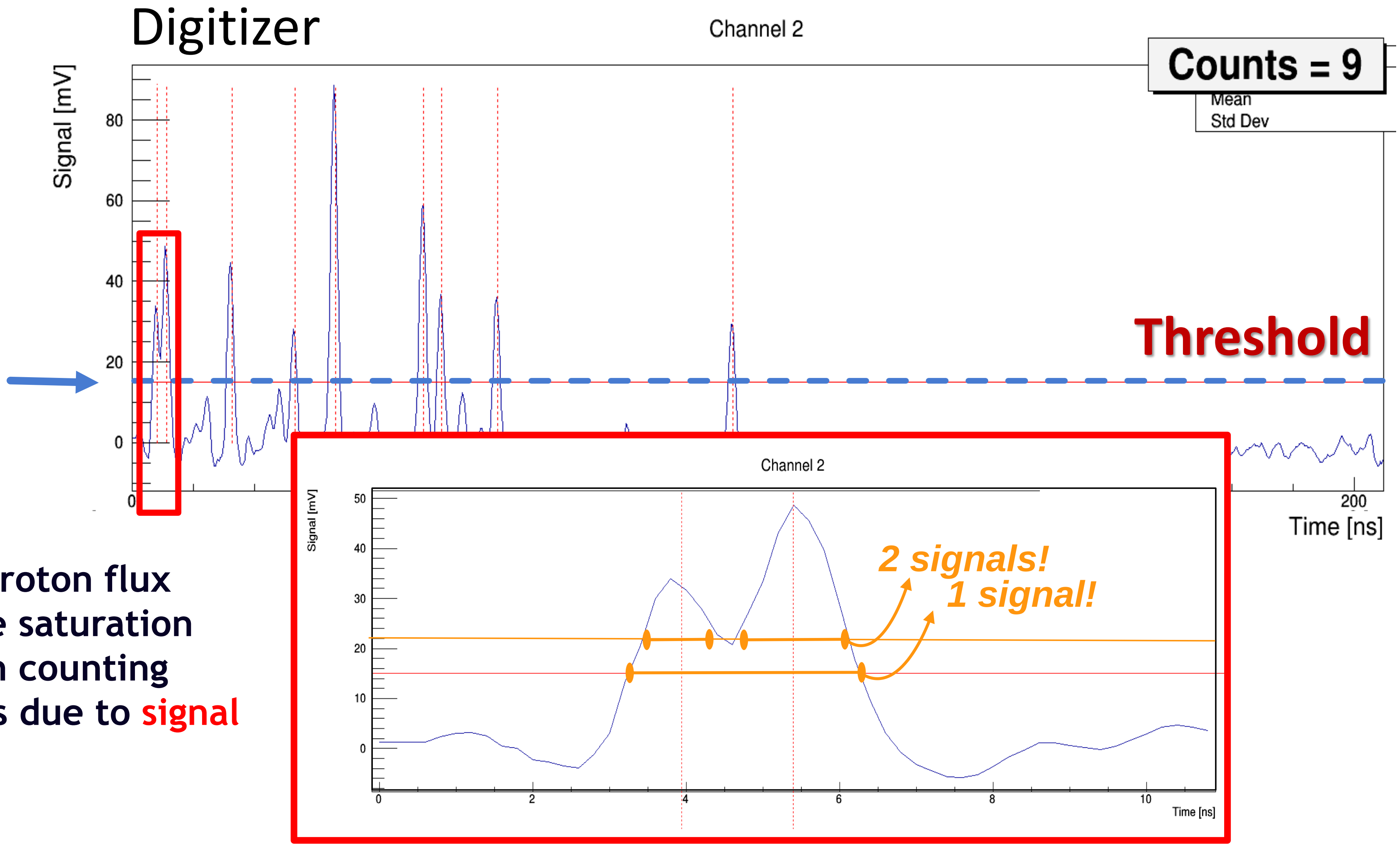
- ✓ UFSD pad by CNM (1,4 mm^2) centered on the beam
- ✓ Average beam fluence rate $\sim 10^9\ \mathrm{p/cm^2 \cdot s}$

Test with the CNAO beam



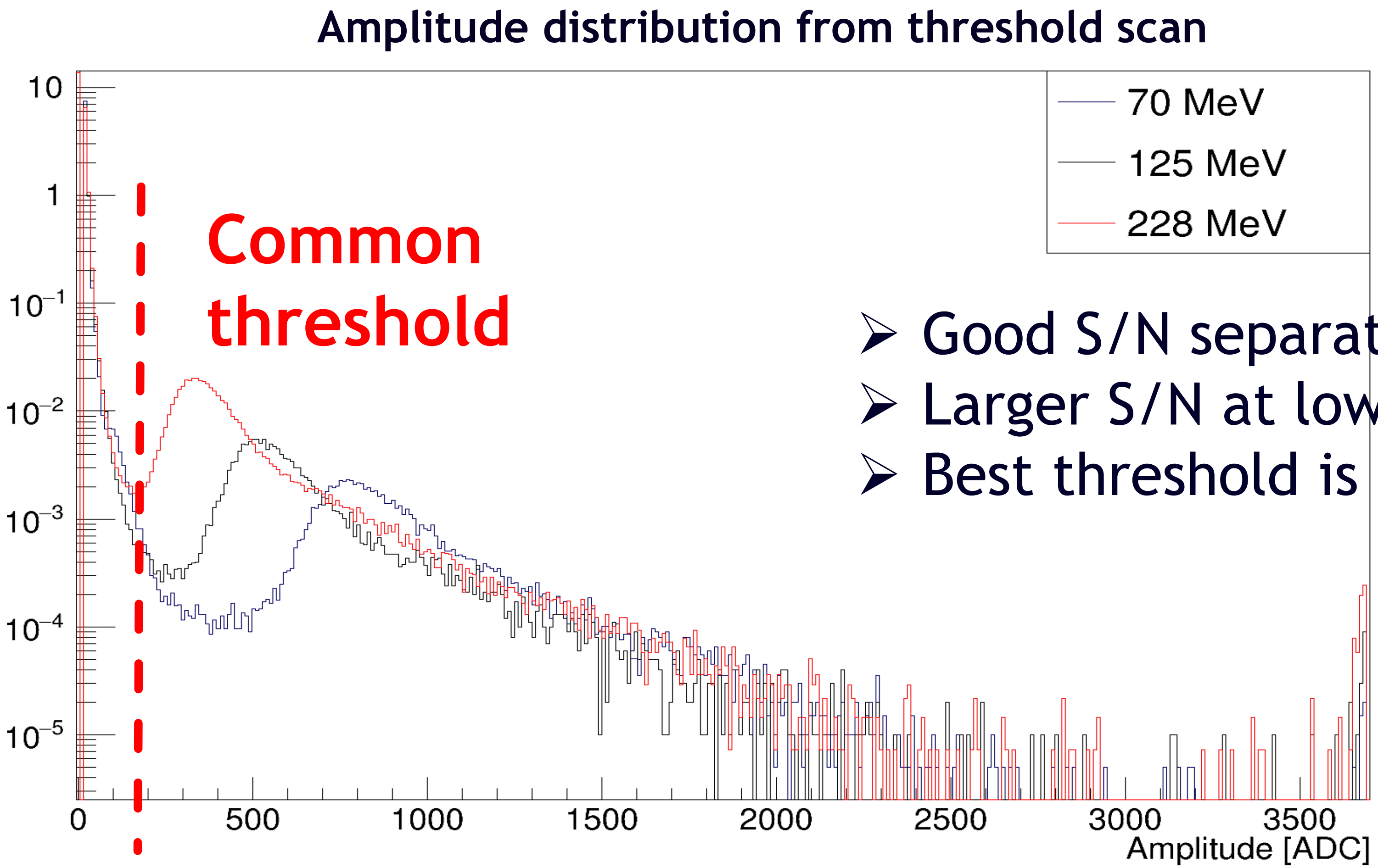
- ➢ Peaks corresponding to individual protons can be easily distinguished
- ➢ Large amplitude fluctuations
- ➢ Short peak duration

Signal pile-up affects the counter efficiency



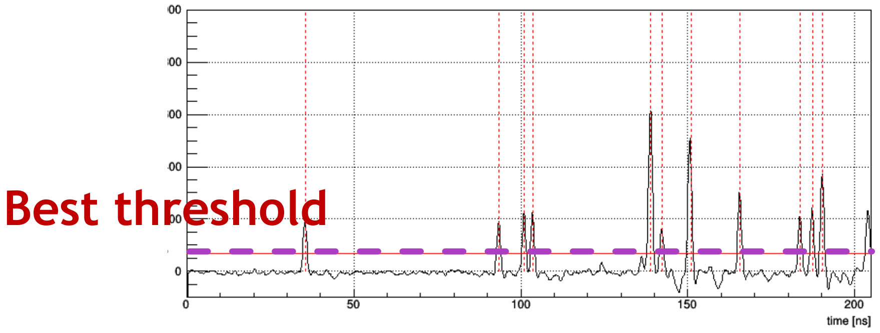
At high proton flux there are saturation effects in counting measures due to signal pile-up

Best threshold by amplitude distribution



Signal amplitude distribution for proton beams at 3 different energies

- Good S/N separation;
- Larger S/N at lower beam energies;
- Best threshold is beam energy dependent.

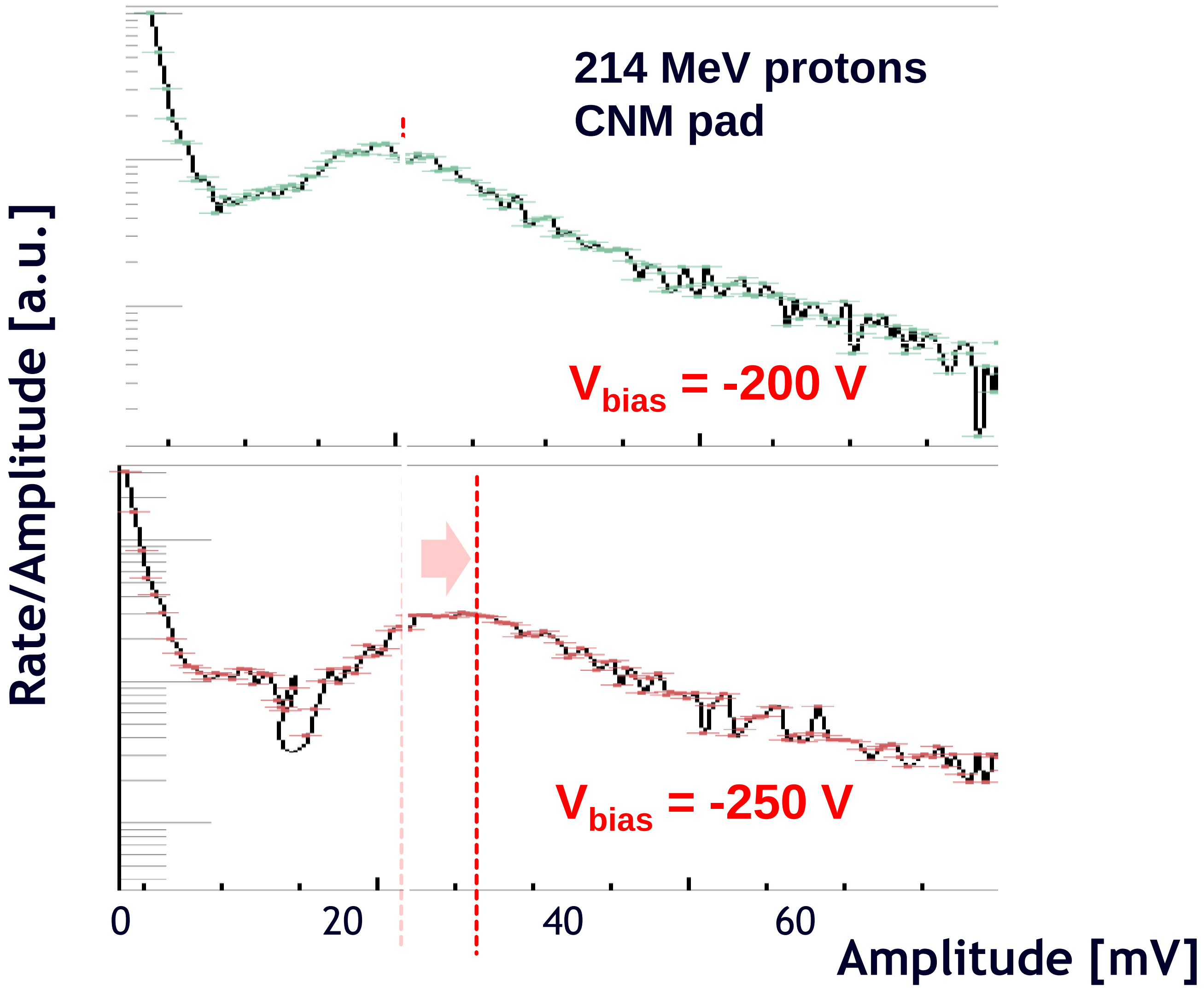


Bias voltage & gain effect on signal amplitude

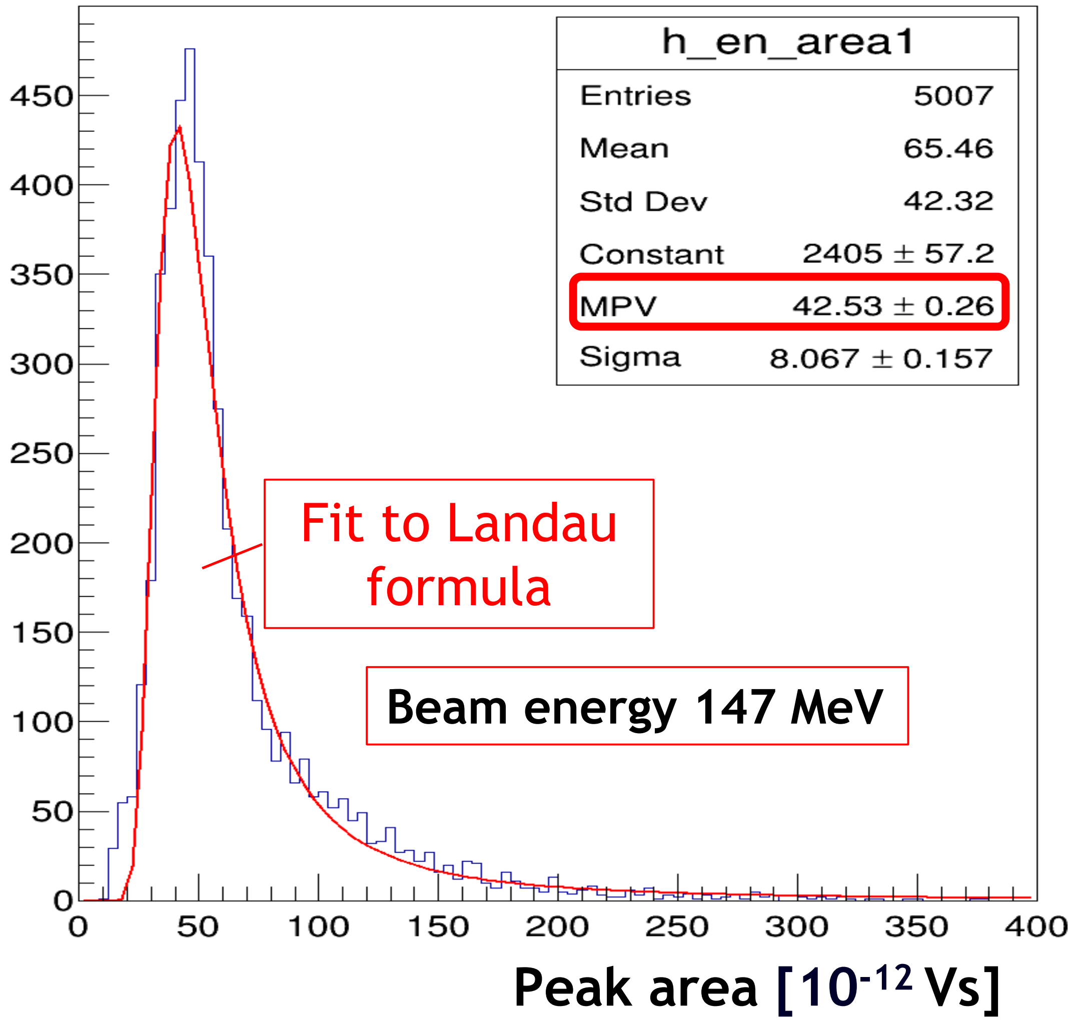
Increasing the bias voltage

⇓

Gain increase in the sensor



Peak area & Landau distributions



- Area of peaks proportional to collected charge;
- well described by Landau formula.

Landau's MPV vs Beam Energy

described by Bethe-Bloch formula

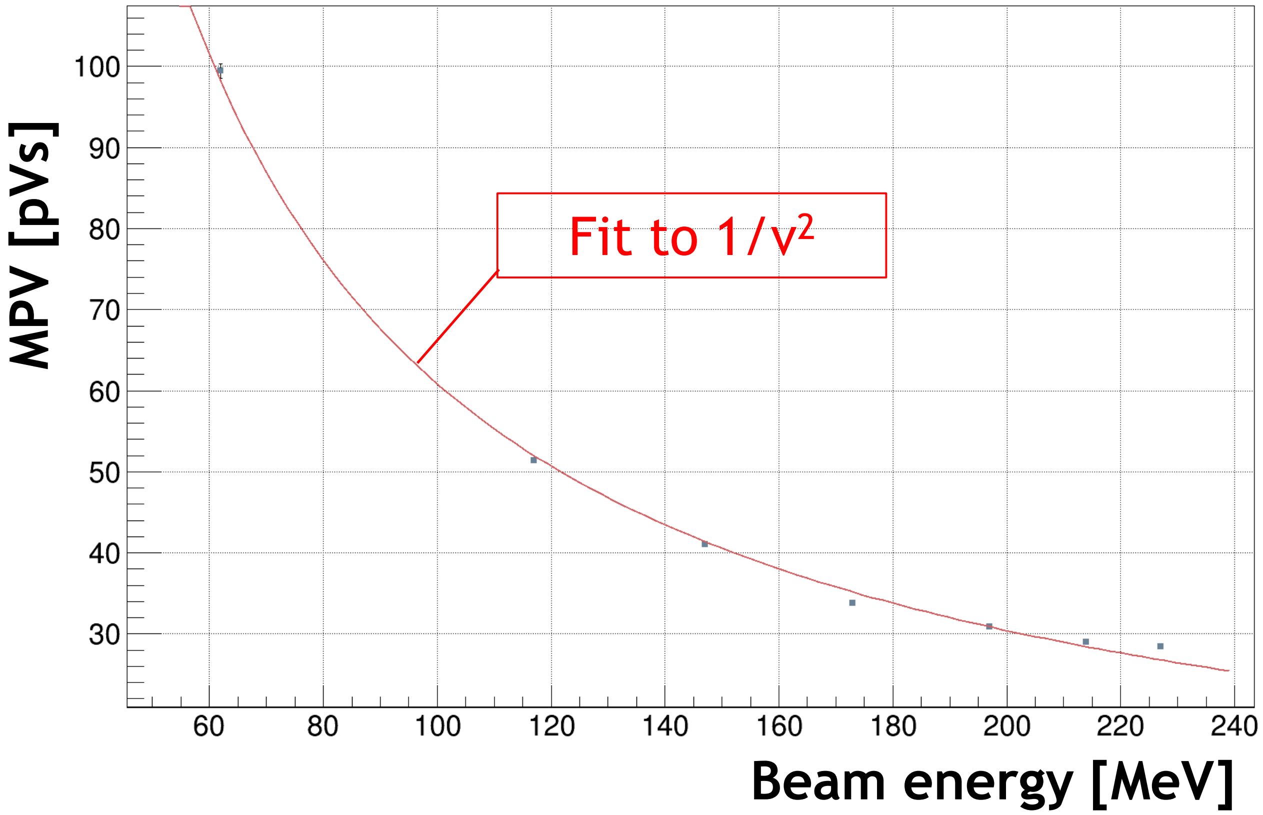
$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 NZ}{(4\pi\varepsilon_0)^2 M_e v^2}\left[\ln\left(\frac{2M_e v^2}{I}\right) - \ln(1-\beta^2) - \beta^2\right]$$

Bethe-Bloch $1/v^2$ dependence

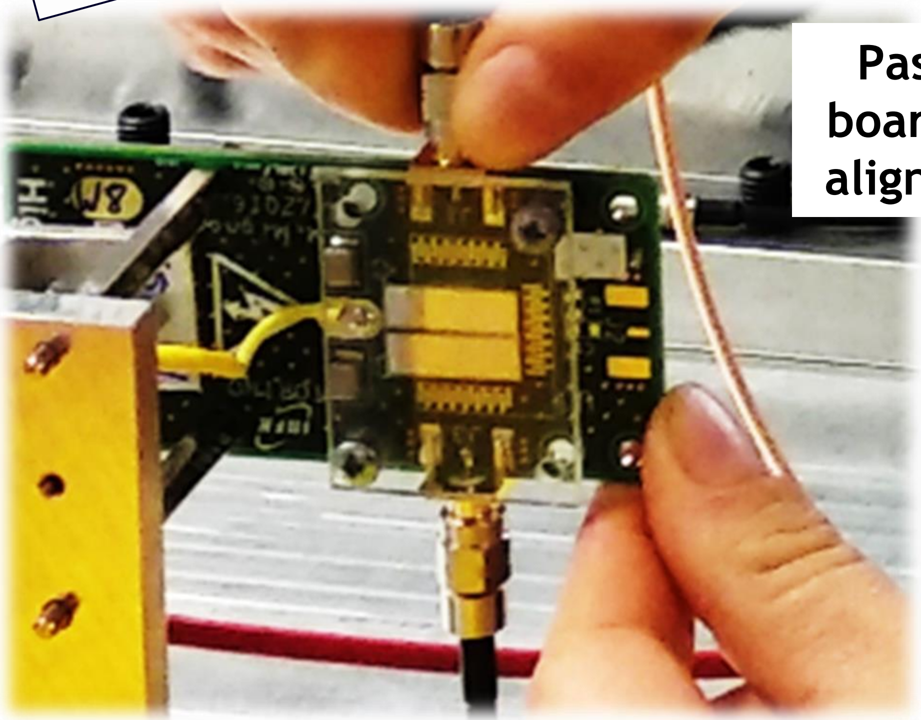
Measurements with proton beams at 5 energies in the clinical range at the CNAO

- **Landau's MPV** dependence on **beam energy** well described by Bethe-Bloch $1/v^2$ dependence

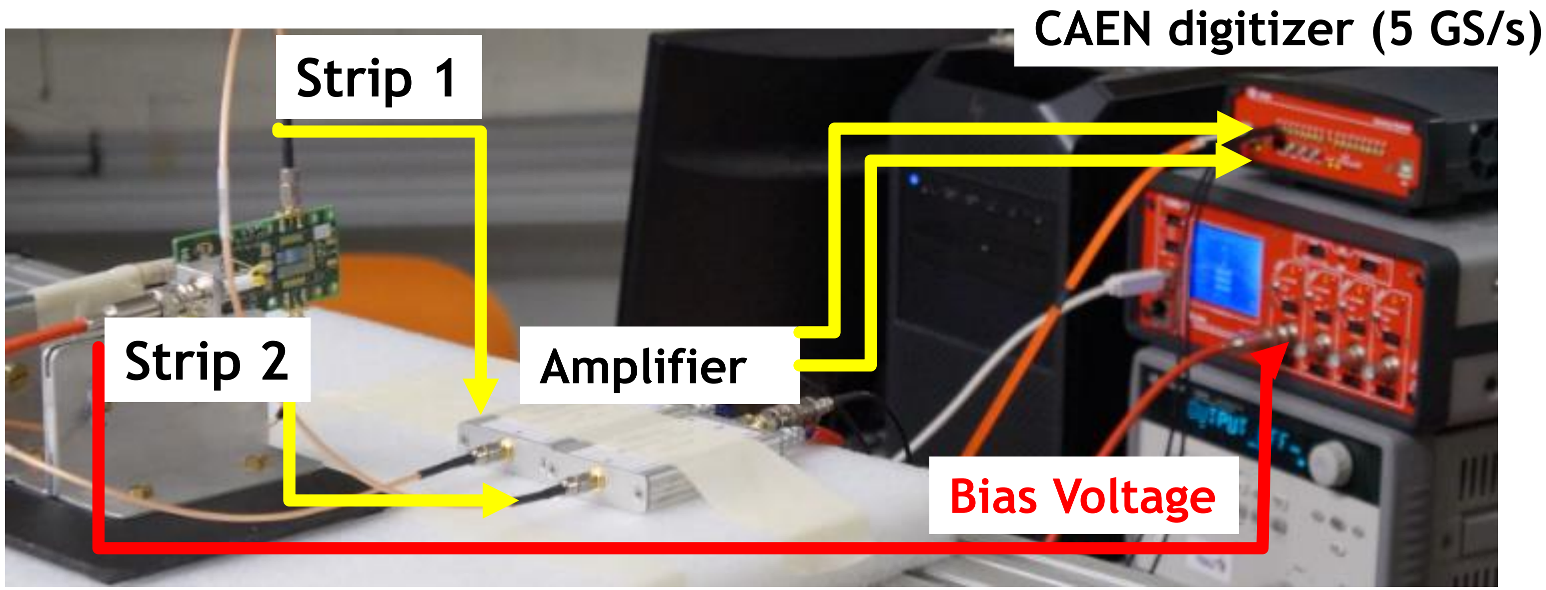
Protons dE/dx
from 60 to 240 MeV

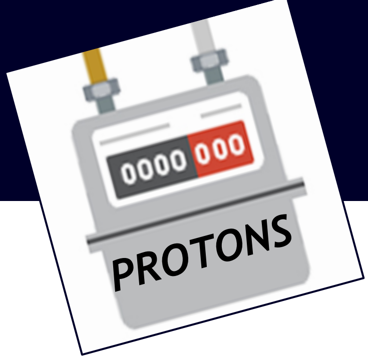


Beam test with strip detectors



Passive Frontend boards with sensors aligned to the beam

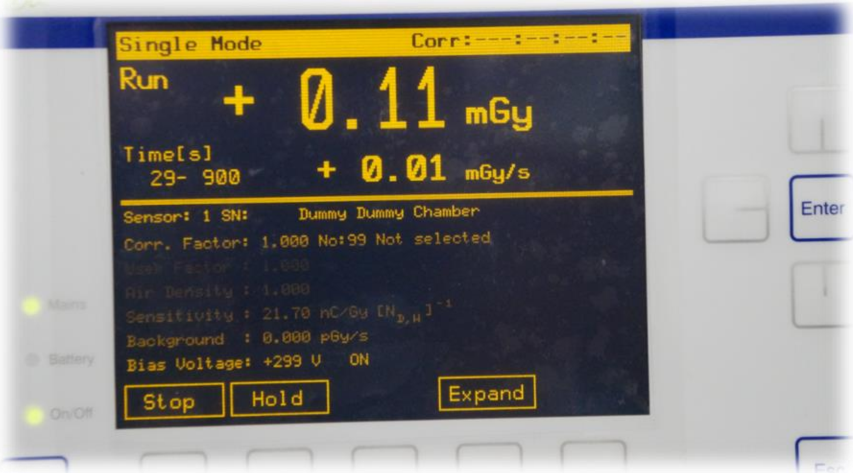


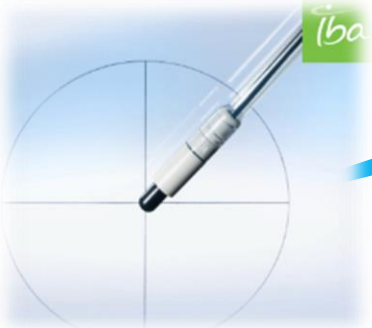


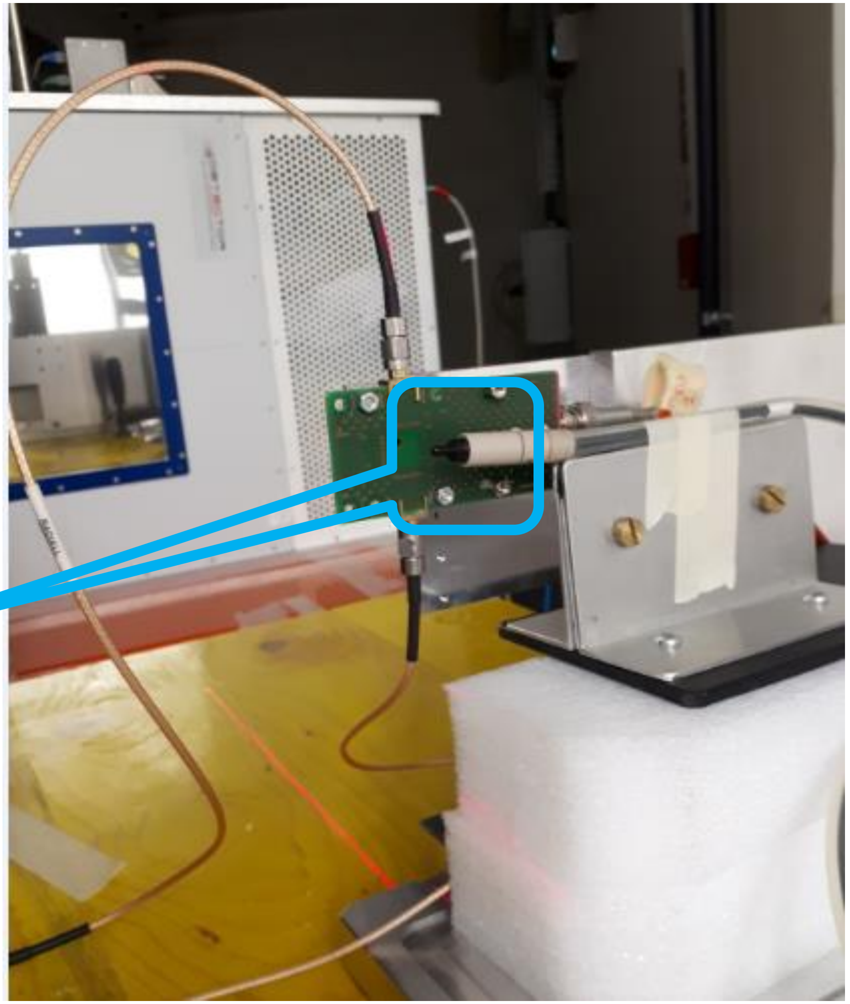
Pile-up study - beam test setup

Relative Reference measurement of the fluence rate with a
Pinpoint Ionization Chamber
(dose measurement in air)

Front panel of the Pinpoint Electrometer

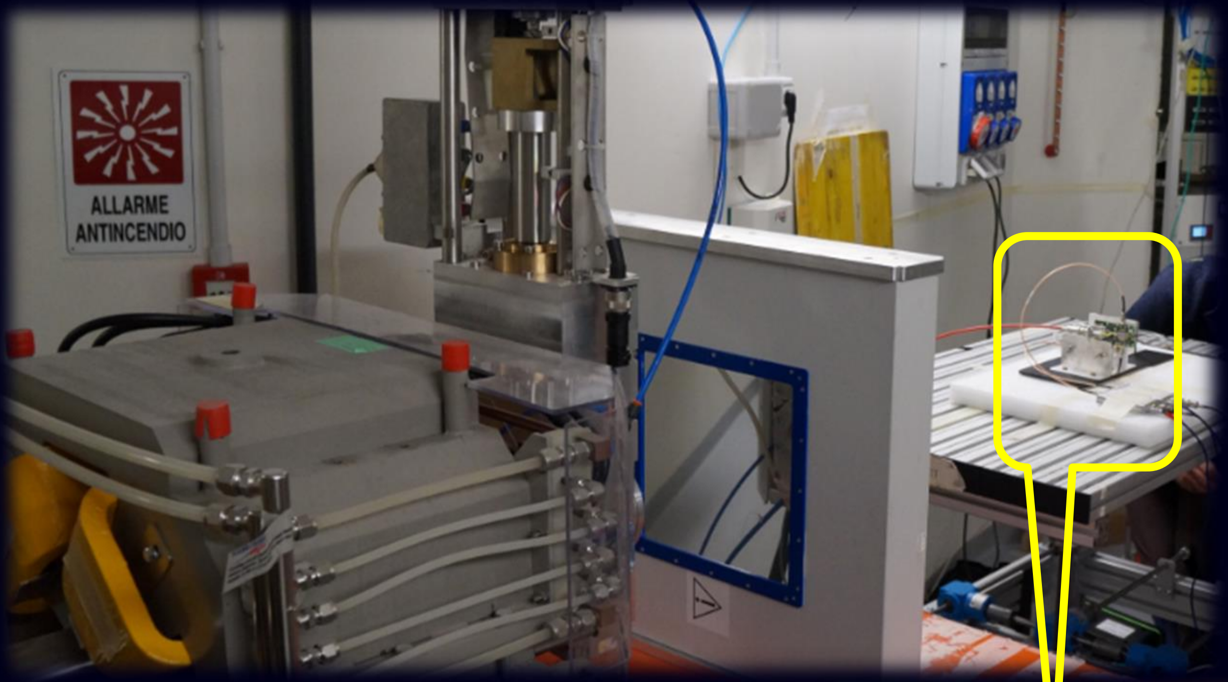


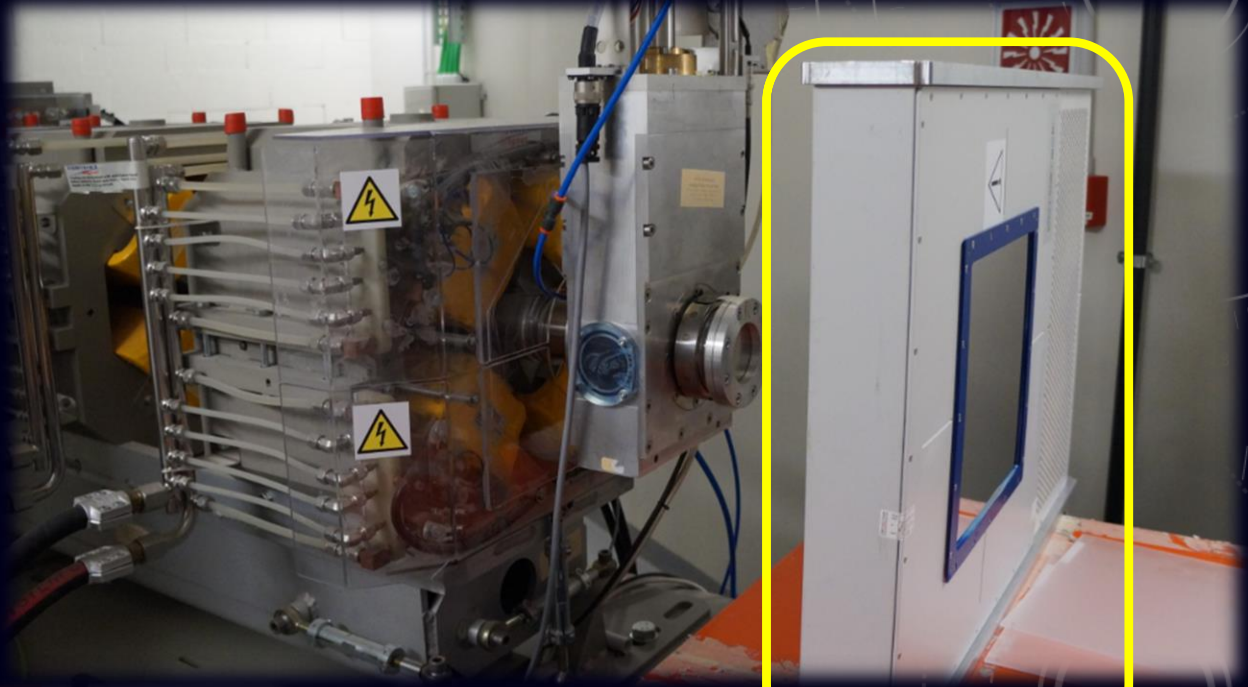


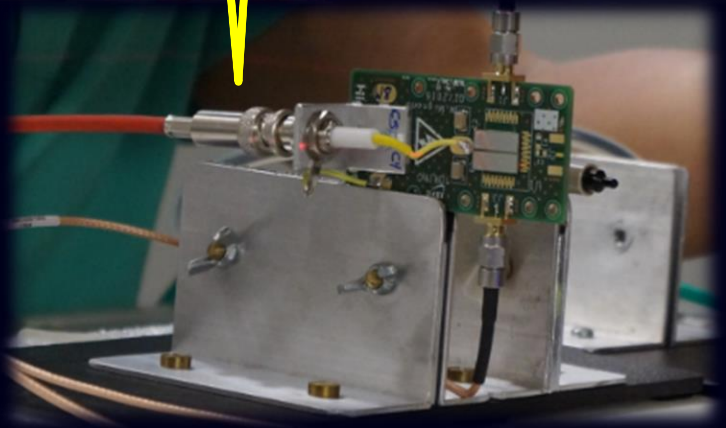


Pinpoint active volume: 0.13 cm^3

Beam test in Trento (experimental room)





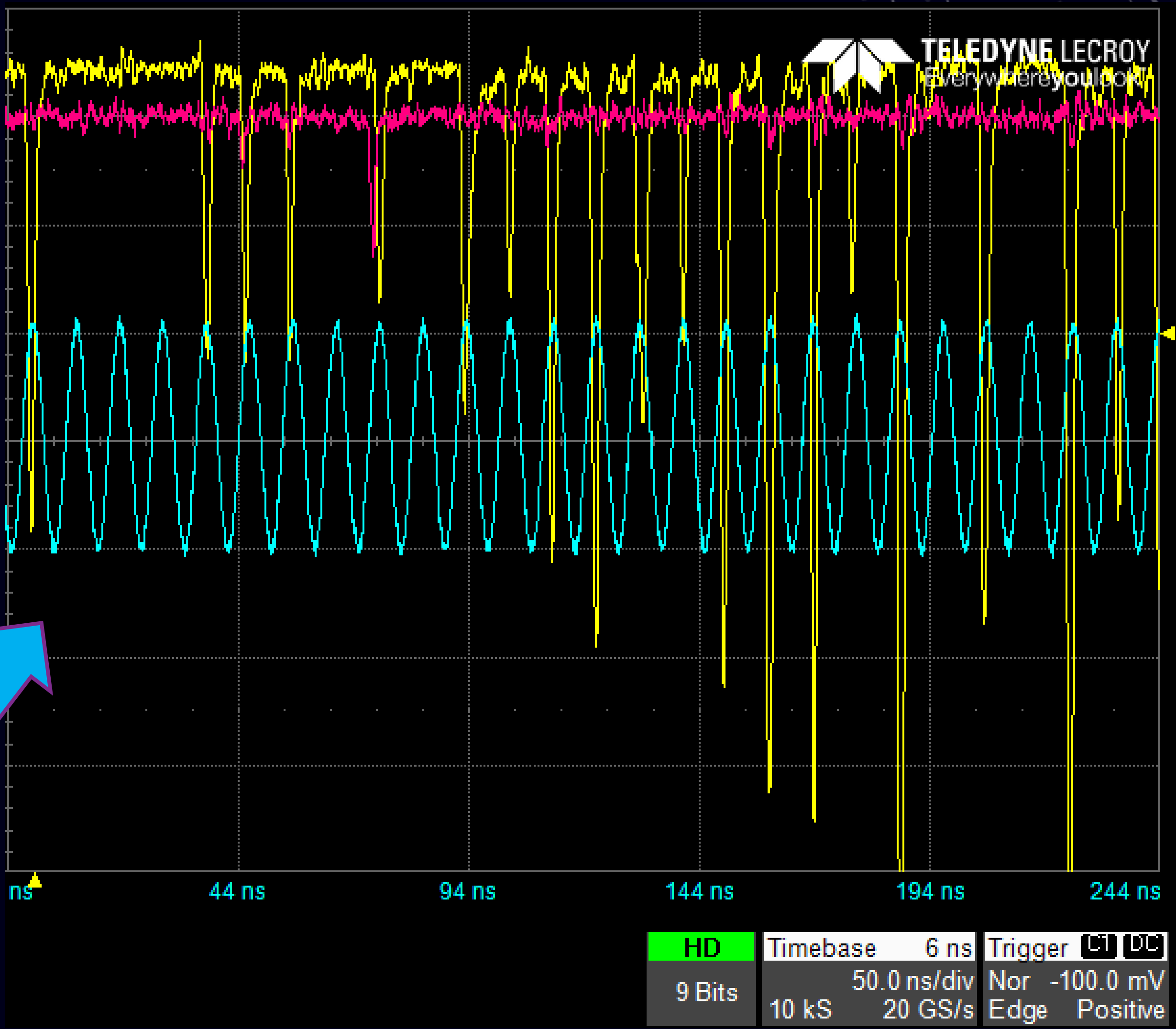


Beam monitors:
2 large area ionization chambers
By De.Tec.Tor Torino

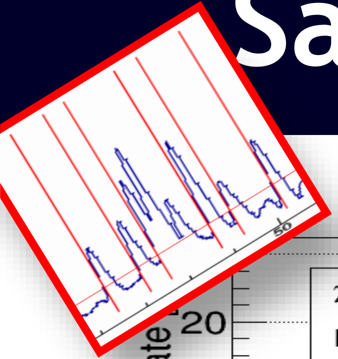
UFSD signals in Trento with proton beam

Particles are delivered in bunch due to the Cyclotron radiofrequency

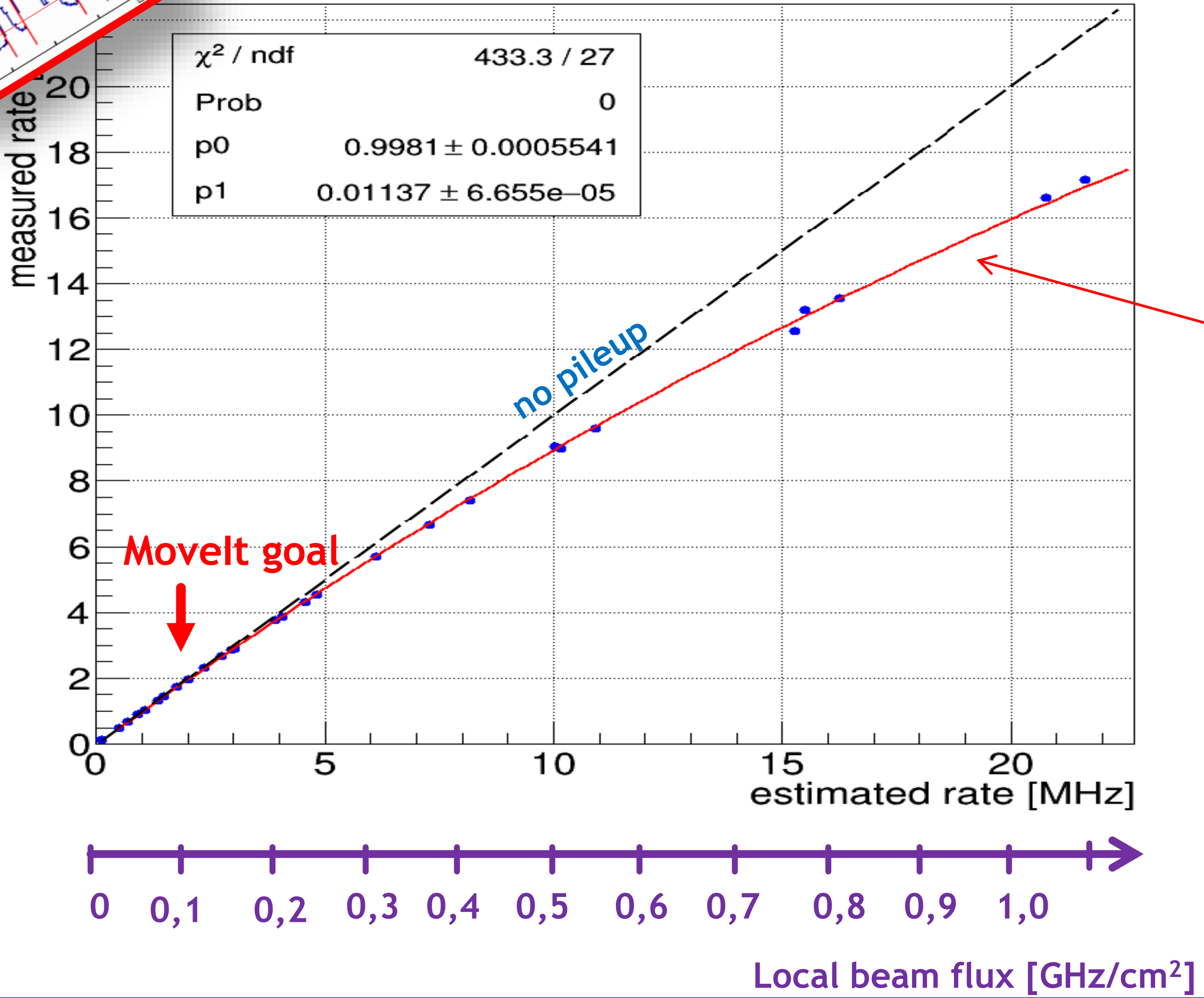
106 MHz Cyclotron RF frequency

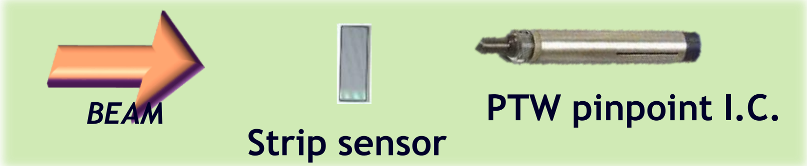


Saturation effects at high fluence rate



- (Trento, July 2019)





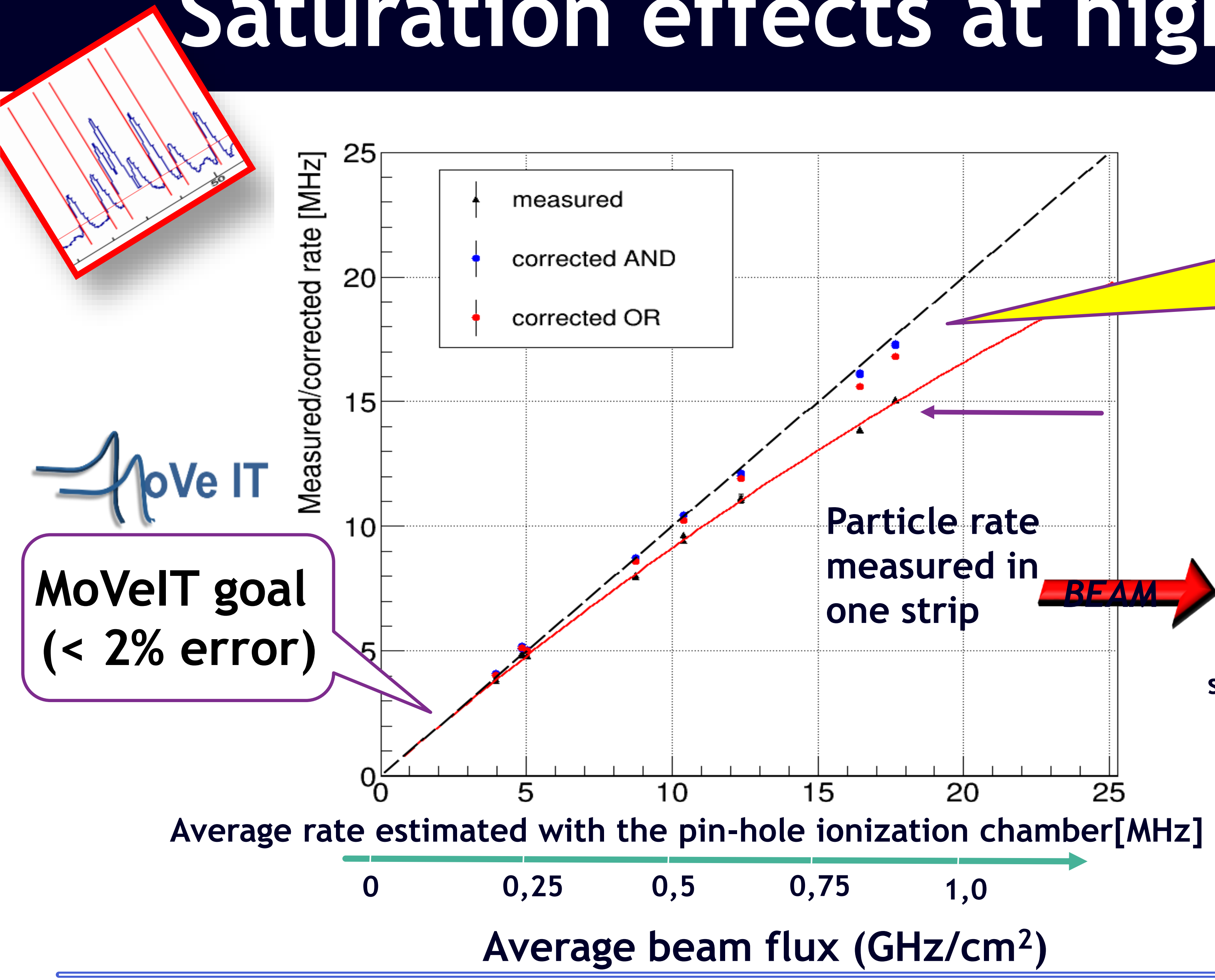
Particle rate estimated using the charge measured with a PTW pin-hole ionization chamber and assuming a paralyzable saturation model

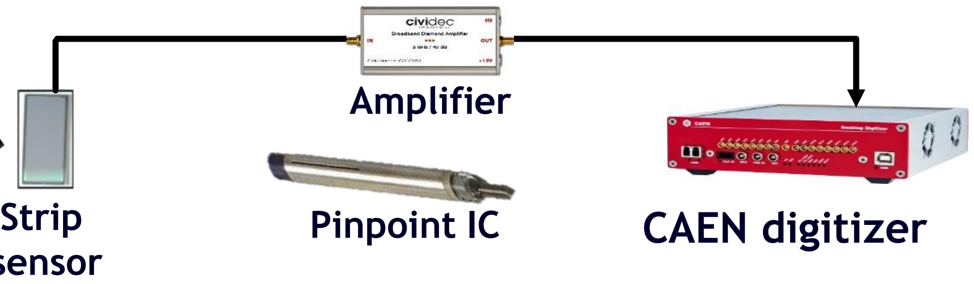
$$f_{meas} = \frac{Q}{C} e^{-\frac{Q}{C}\tau} \qquad f_{estim} = \frac{Q}{C}$$

f_{meas} = particle rate measured with LGAD strip
Q = charge rate in I.C.
C = effective charge in I.C. for each proton at fixed energy
τ = deadtime

C and τ estimated from a fit of data collected for each beam energy at different beam currents.

Saturation effects at high fluence rate



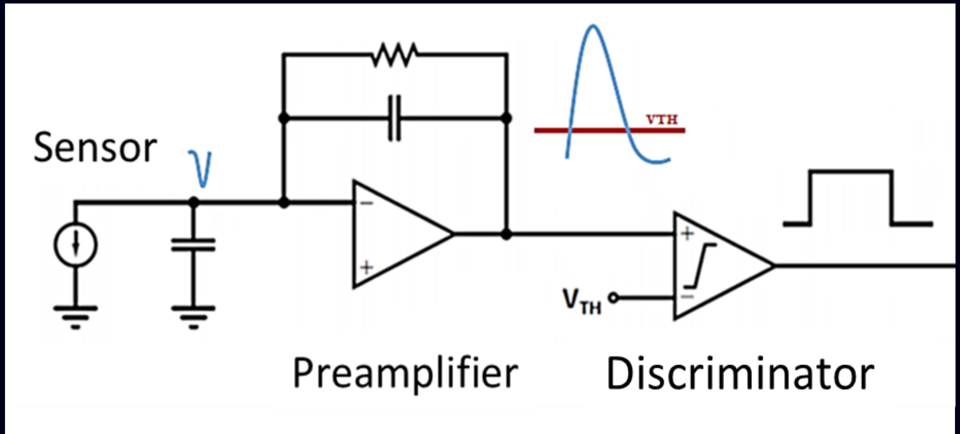


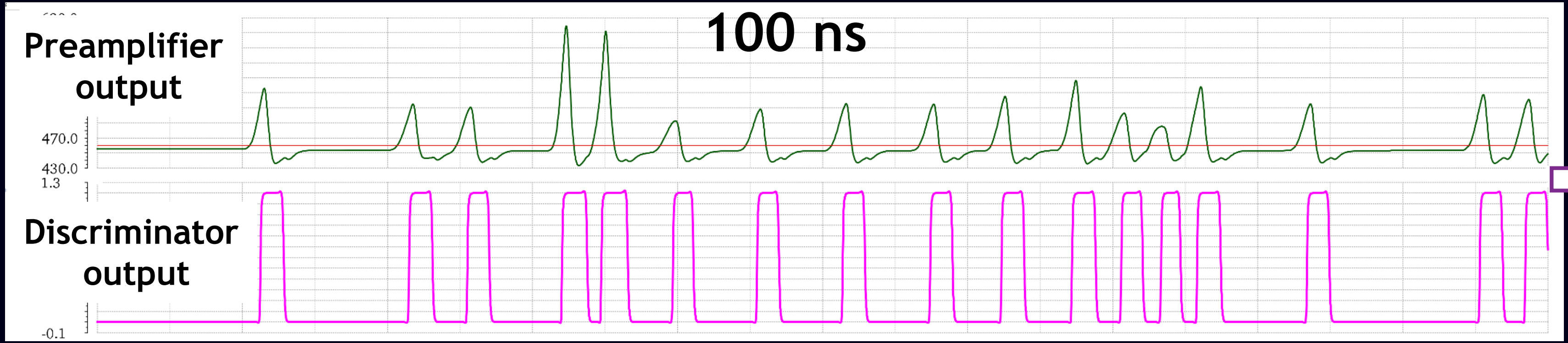
Pinpoint IC = Reference

Readout electronics for the particle counter

Requirements

Input Q range: 3 fC ÷ 140 fC
Rate/channel: up to 200 MHz
Inefficiency < 1 %.



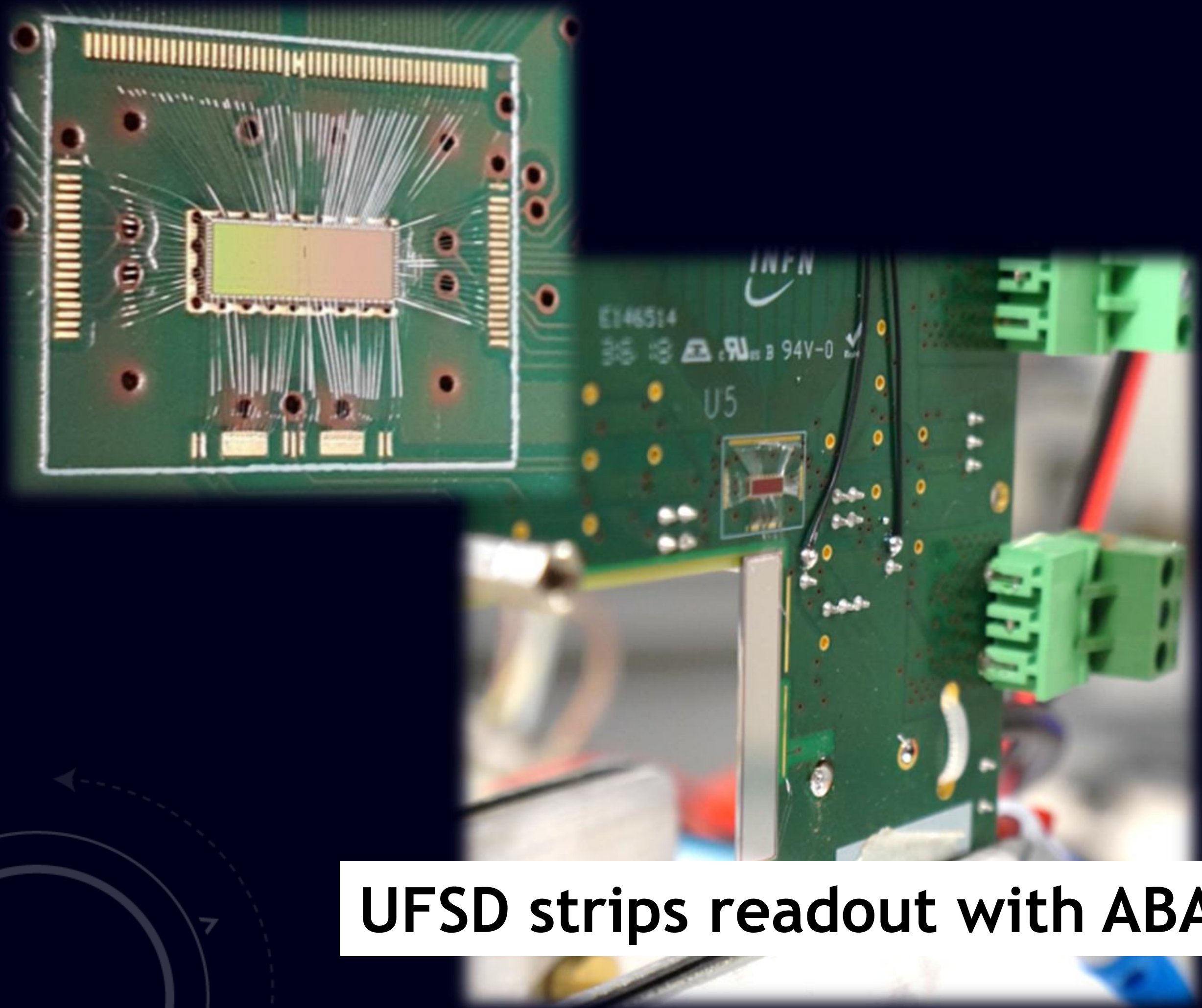


FPGA

- FE inizialization
- Pulse counting
- Pileup correction

Prototypes (24 ch) of 2 different architectures in UMC110 technology ready to be tested

Custom front-end ASIC → ABACUS



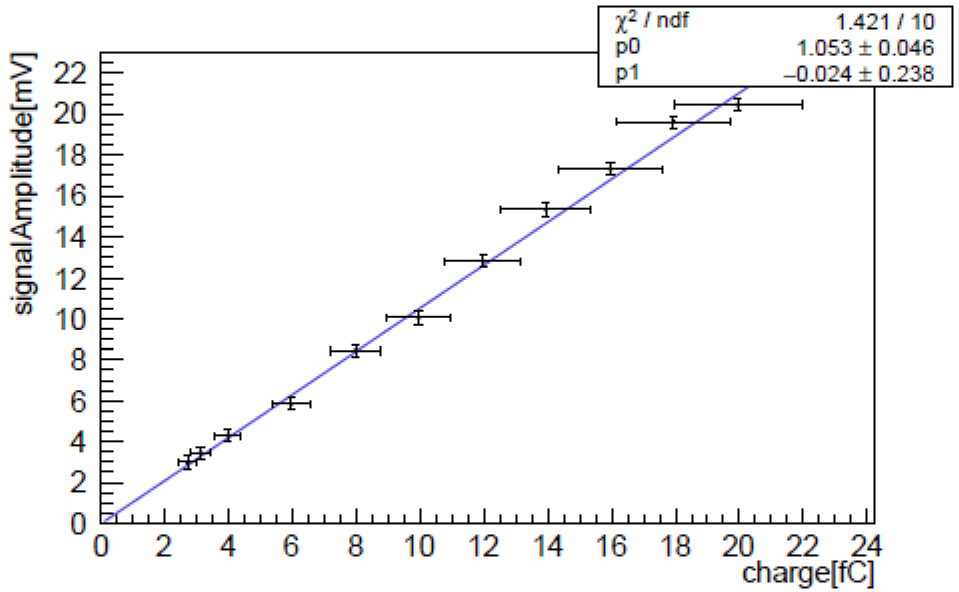
UFSD strips readout with ABACUS

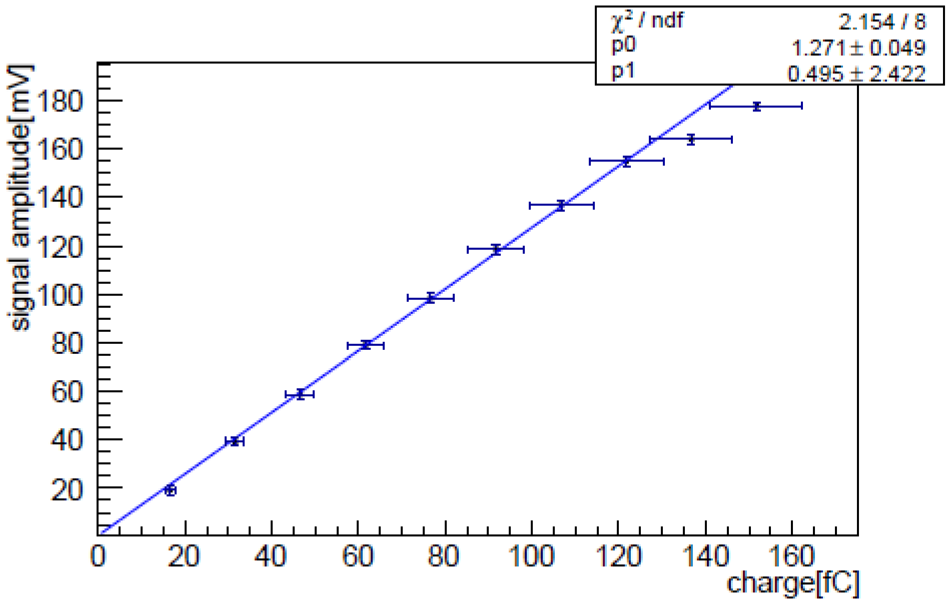
Custom front-end ASIC (ABACUS) developed and characterized at clinical facilities

- 24 channels
- Adjustable threshold for pulse discrimination
- Discrimination efficiency 100 % up to 100 MHz per channel

ABACUS signal amplitude vs input charge

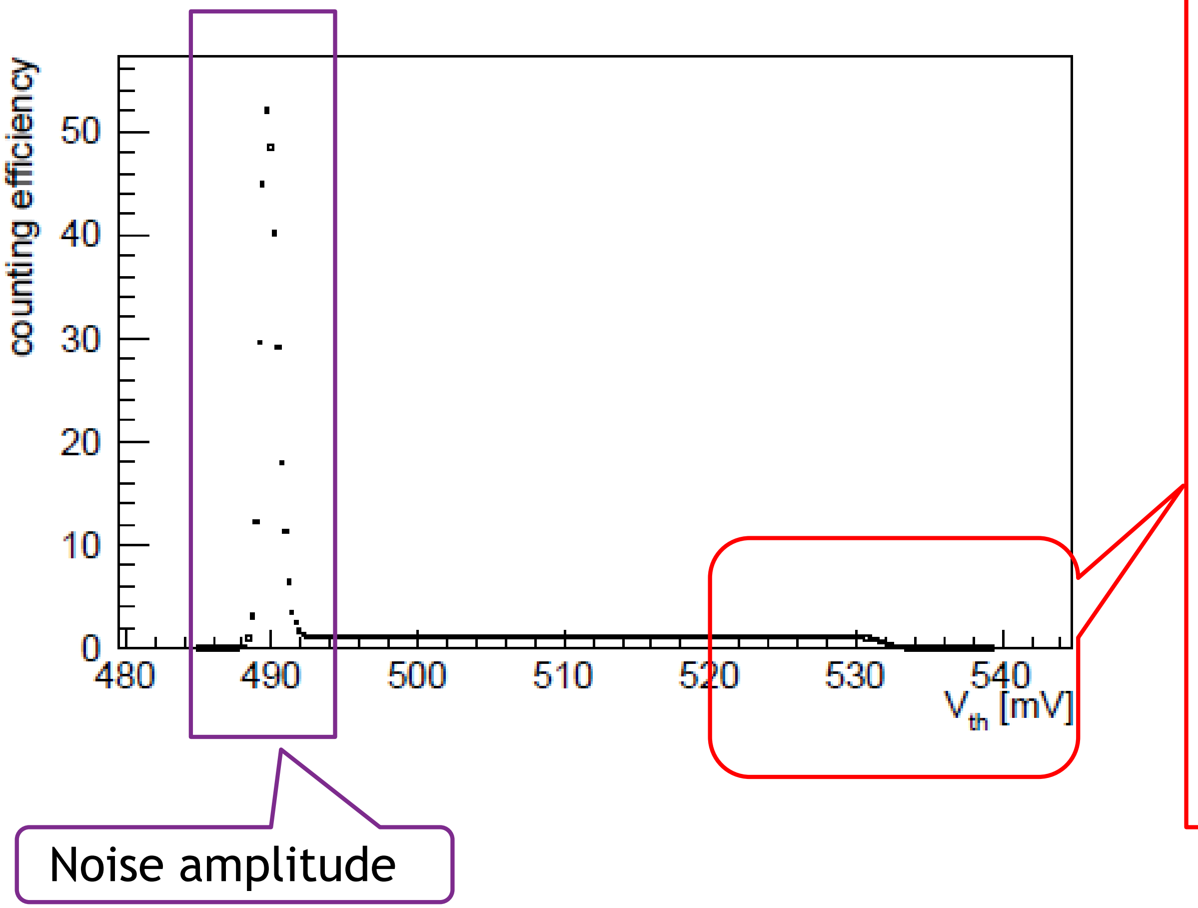
RANGE OF CHARGE → 3 fC ÷ 150 fC



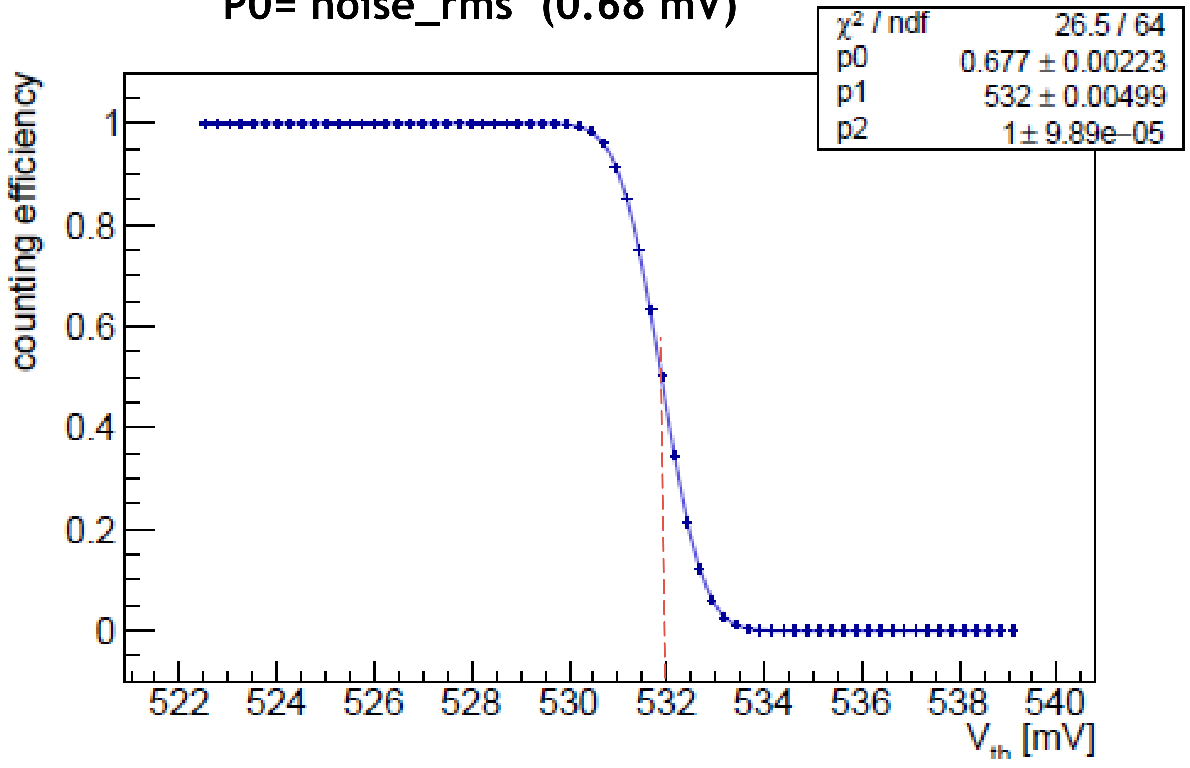


AMPLITUDE of AMPLIFIER output → 3 mV ÷ 180 mV

Threshold scan and noise

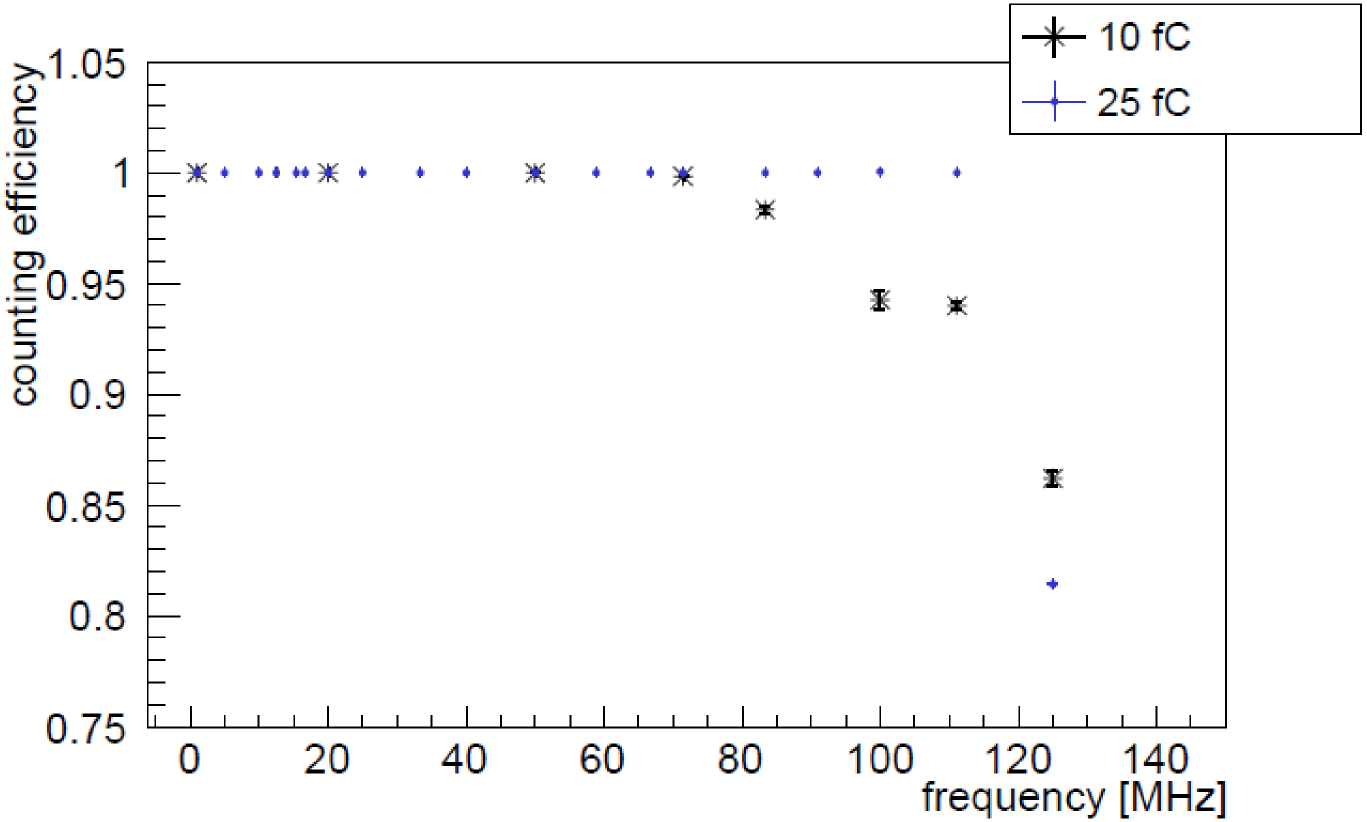


P1 = value at 50% (532 mV)
P0= noise_rms (0.68 mV)



Counting efficiency

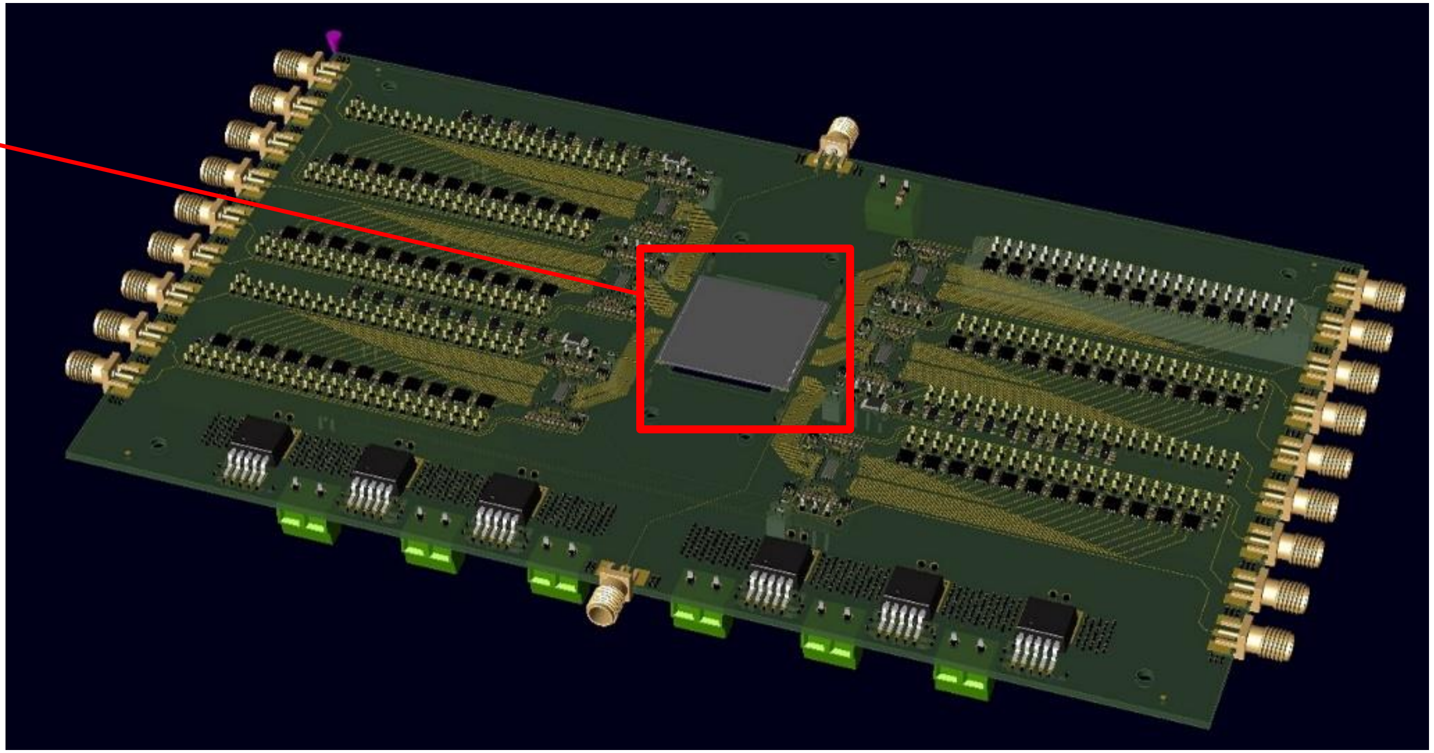
Discrimination efficiency 100 % up to 100 MHz per channel with 20 mV signal (25 fC)



What's next? 3x3 cm^2 PARTICLE COUNTER

MAIN CHARACTERISTICS of UFSD sensors for a prototype of particle counter

- Sensitive area = 3x3 cm^2
- N of strips =146
- Sensor thickness = 50 µm

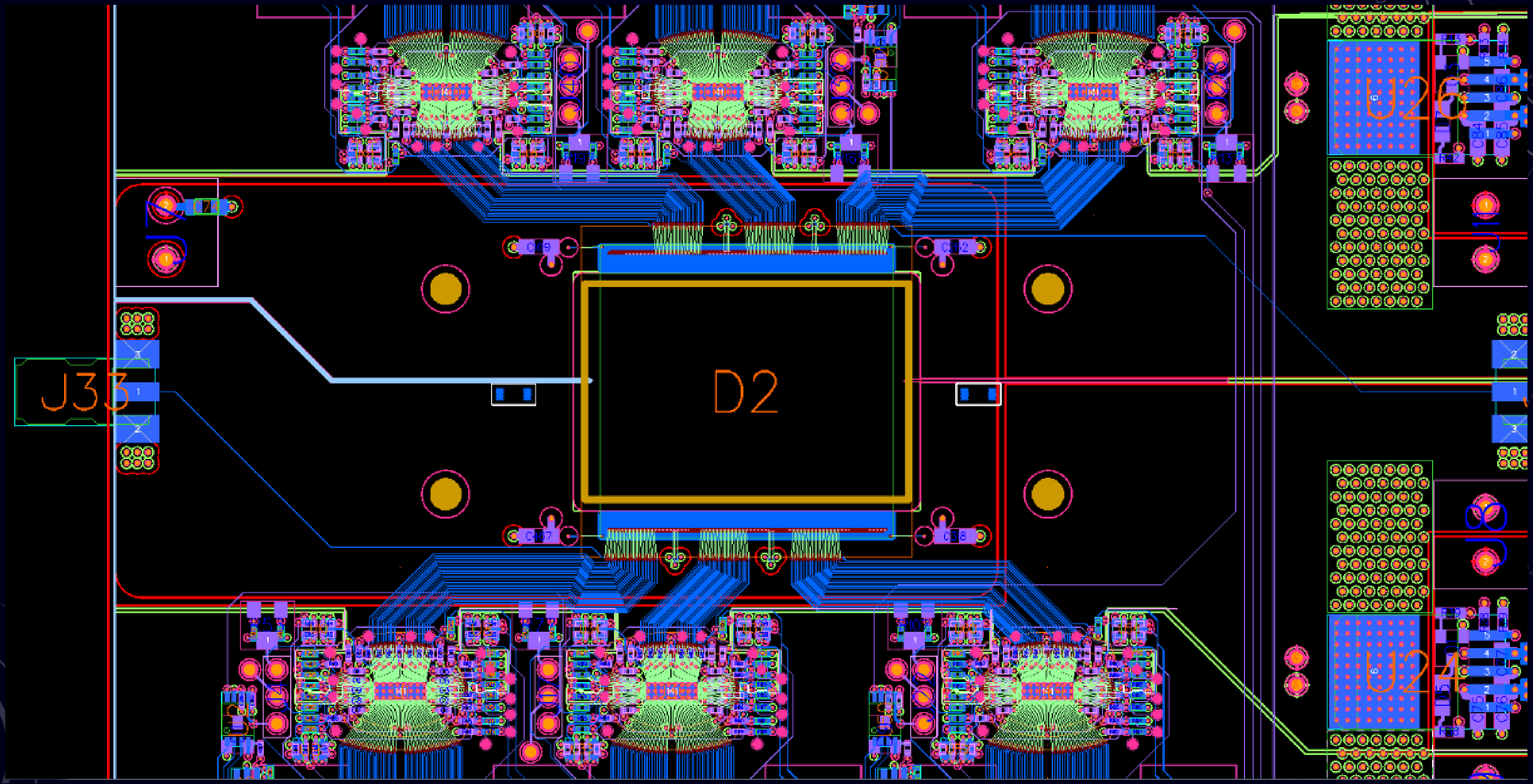


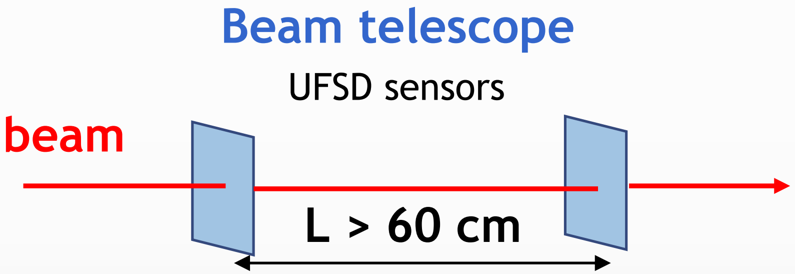
Design and production ongoing @ FBK-Trento

FONDAZIONE BRUNO KESSLER

ABACUS v.2

PCB design to readout 6 ABACUS chips





Beam energy monitor based on Time of Flight

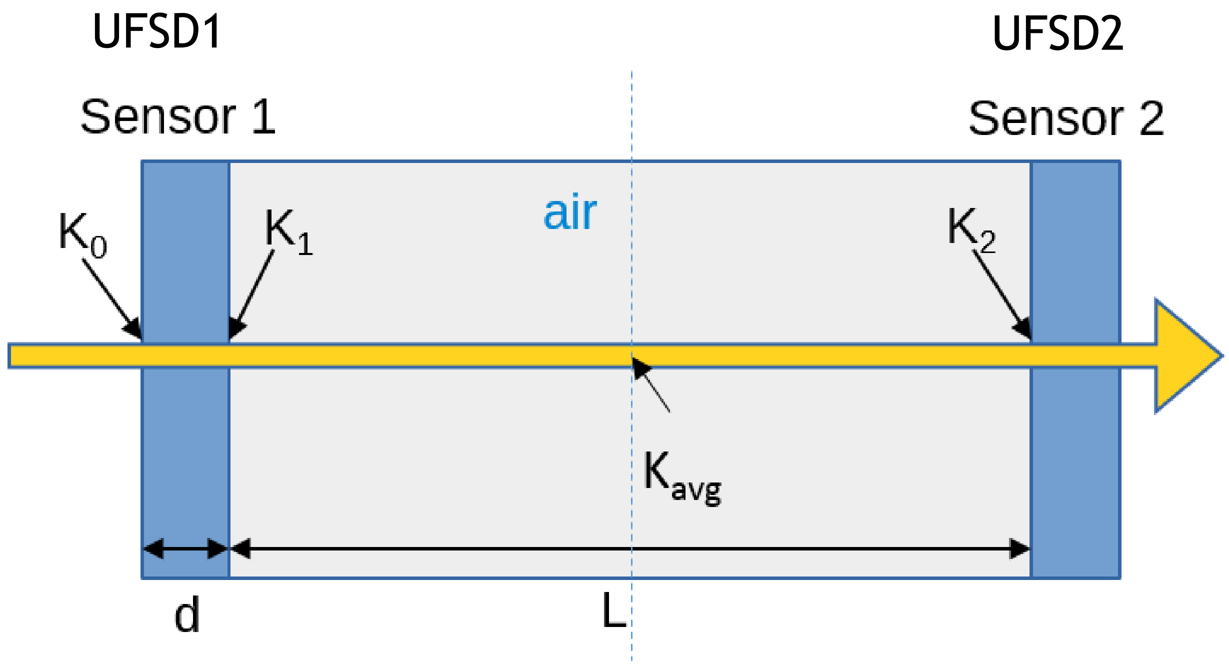
Beam kinetic energy from Time of Flight

$$v = \frac{L}{\Delta t} = c \cdot \sqrt{1 - \frac{E_0^2}{(E_0 + K)^2}} \quad ,$$

$$K = E_0 \cdot \left(\frac{c\Delta t}{\sqrt{c^2 \Delta t^2 - L^2}} - 1 \right)$$

$$K_1 \approx K_0 - \left(\frac{S_{Si}}{\rho\_Si} \right) \cdot \rho_{Si} \cdot d$$

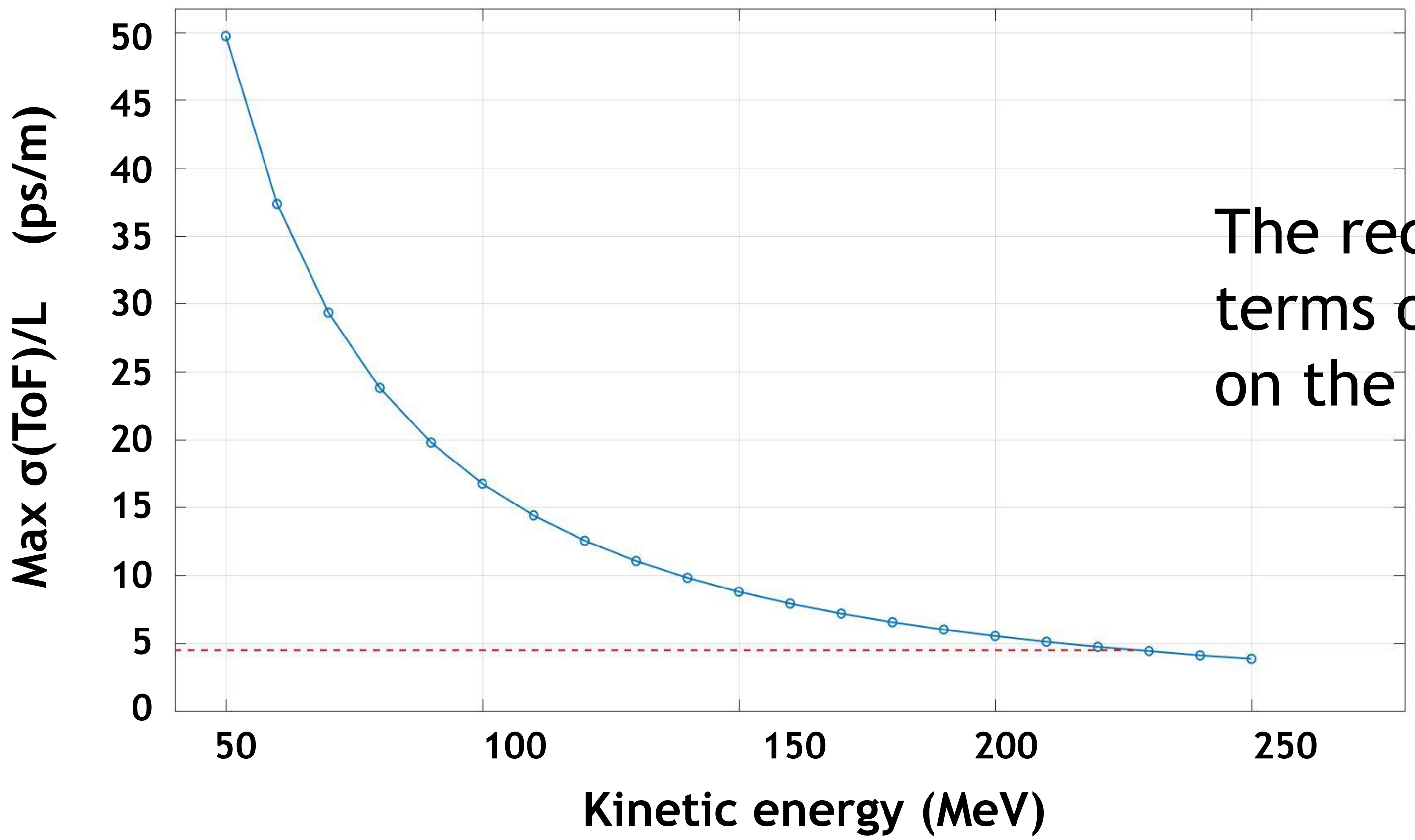
$$K_2 \approx K_1 - \left(\frac{S_{air}}{\rho\_air} \right)_{avg} \cdot \rho_{air} \cdot$$



$$K_{avg} = \frac{K_1 + K_2}{2}$$

The challenge: σ_{range} < 1 mm & σ(ToF) 3 ps

Maximum error on ToF per unit distance L
corresponding to an uncertainty **< 1 mm range in water.**



Four different distances between sensors

The required precision in terms of time of flight depends on the particle kinetic energy

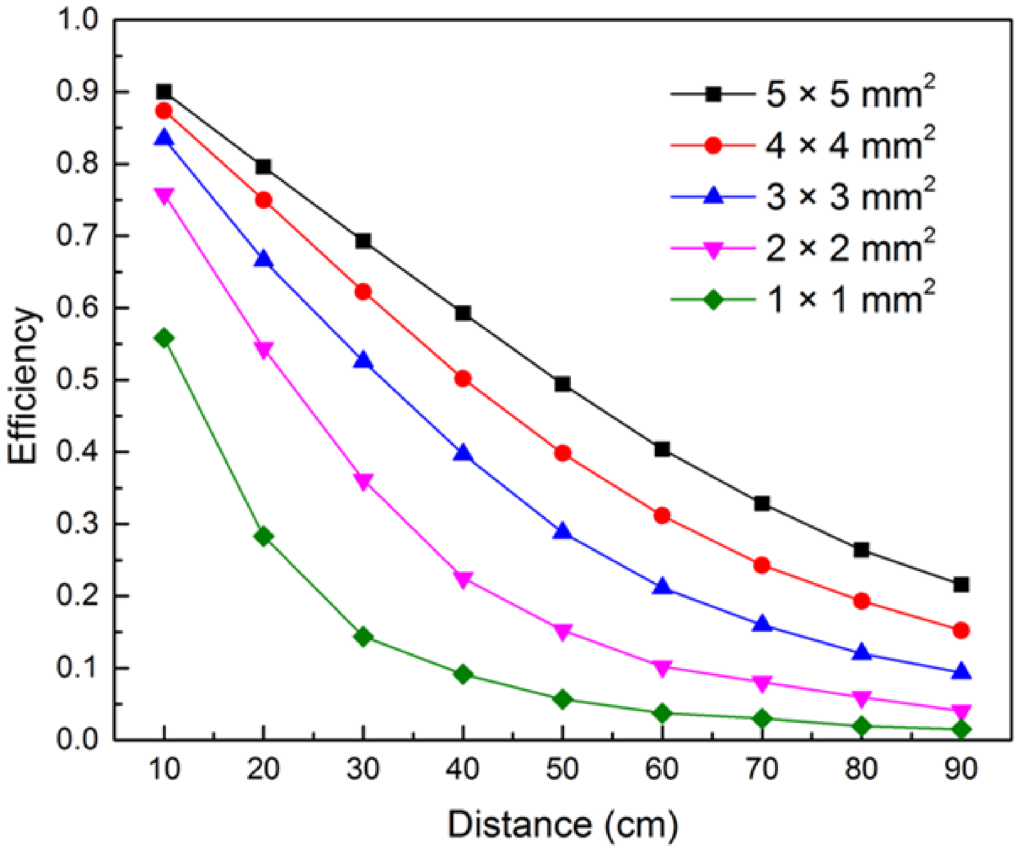
The challenge is to find the right trade-off between distance L and number of coincidences

Efficiency vs distance

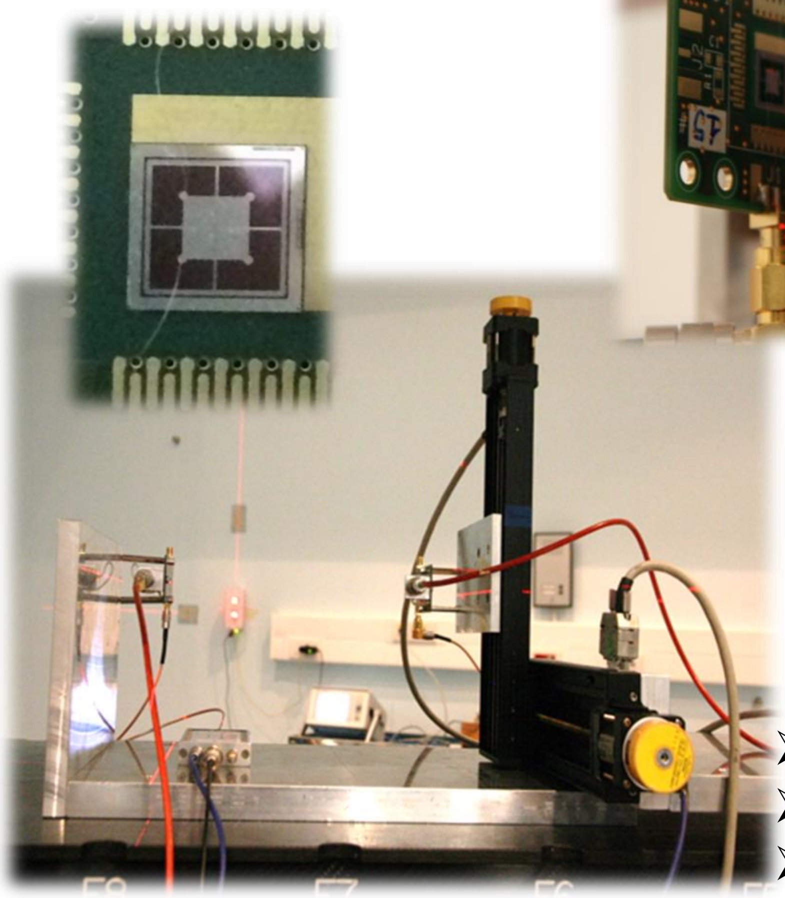
Telescope system efficiency

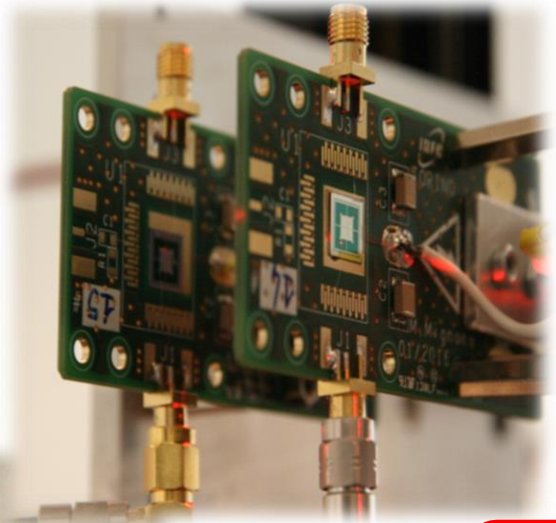
Probability that a proton crossing the first sensor hits the second one

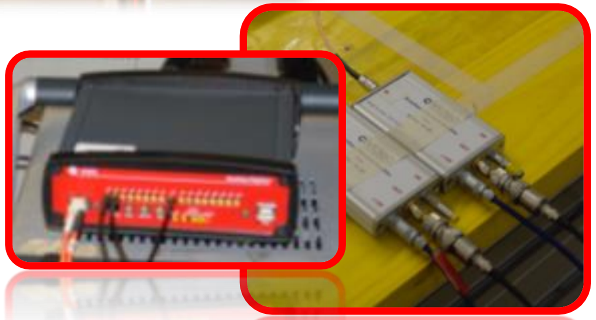
Results from Geant4 simulations for 50 μm thick sensors of different areas and a Gaussian beam of 10 mm FWHM

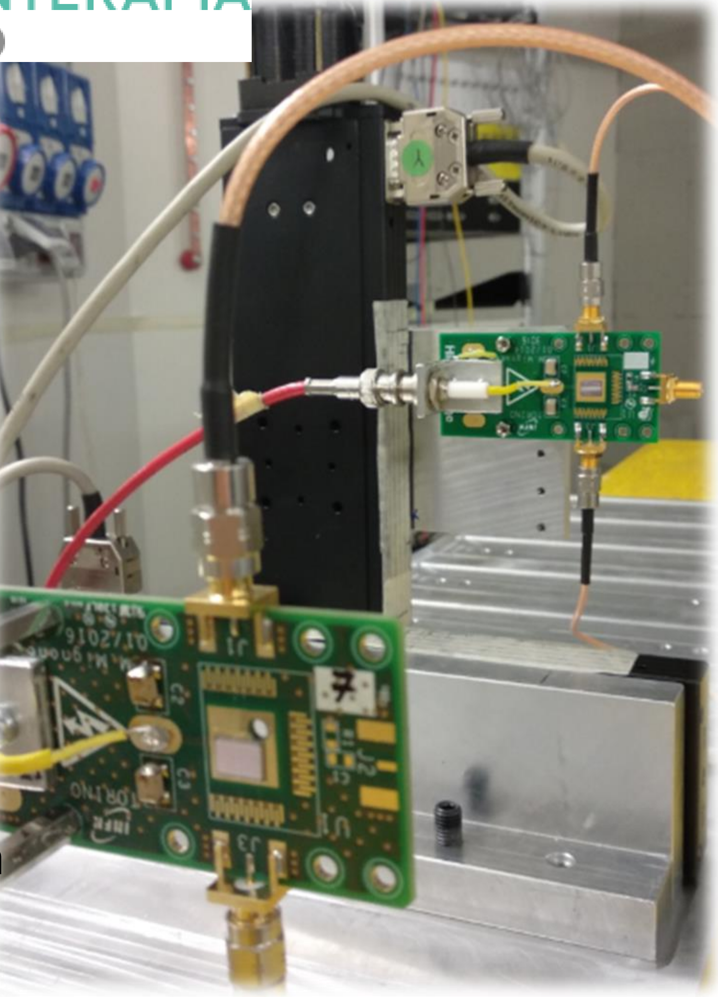


Beam energy detector - beam test setup







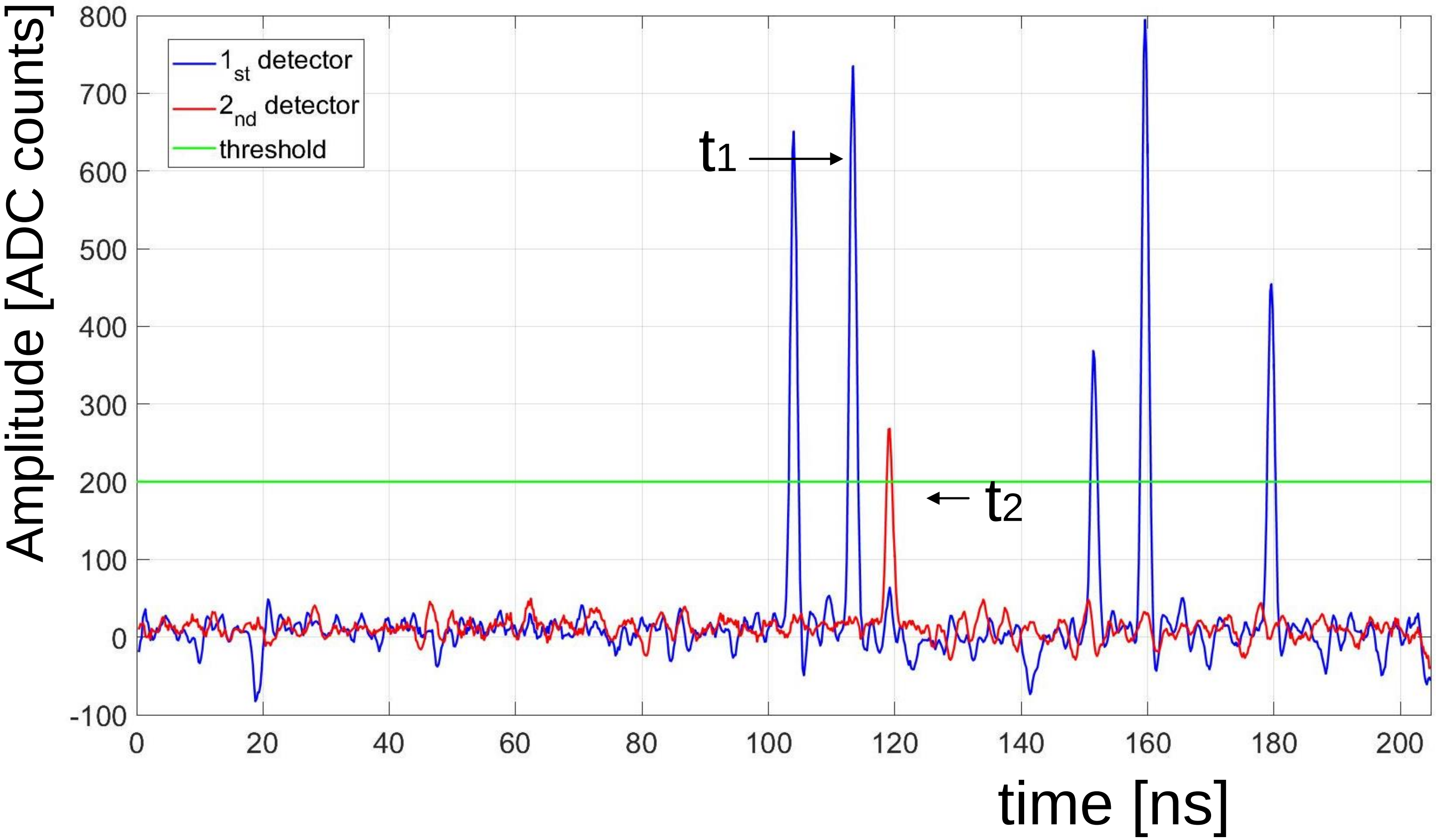


- Passive FE boards aligned to the beam
- CIVIDEC broadband 40 dB amplifiers
- CAEN digitizer (5 Gs/s)

Synchronous signals from 2 aligned sensors

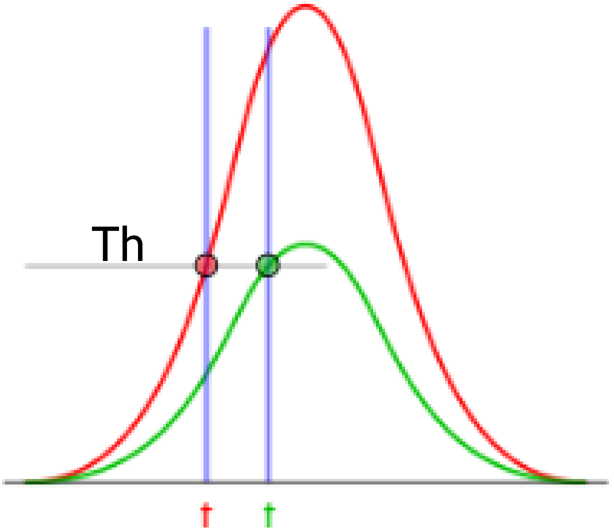
TOF = t2-t1

Example of 2 waveforms with signals from 2 aligned sensors



Signal time measurements

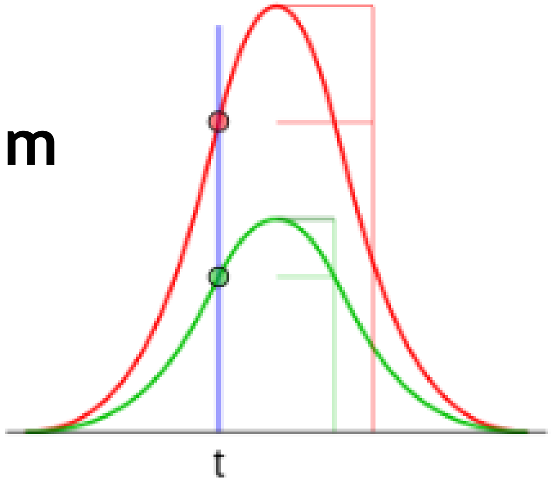
TIME WALK EFFECT



The time of arrival depends on signal amplitude

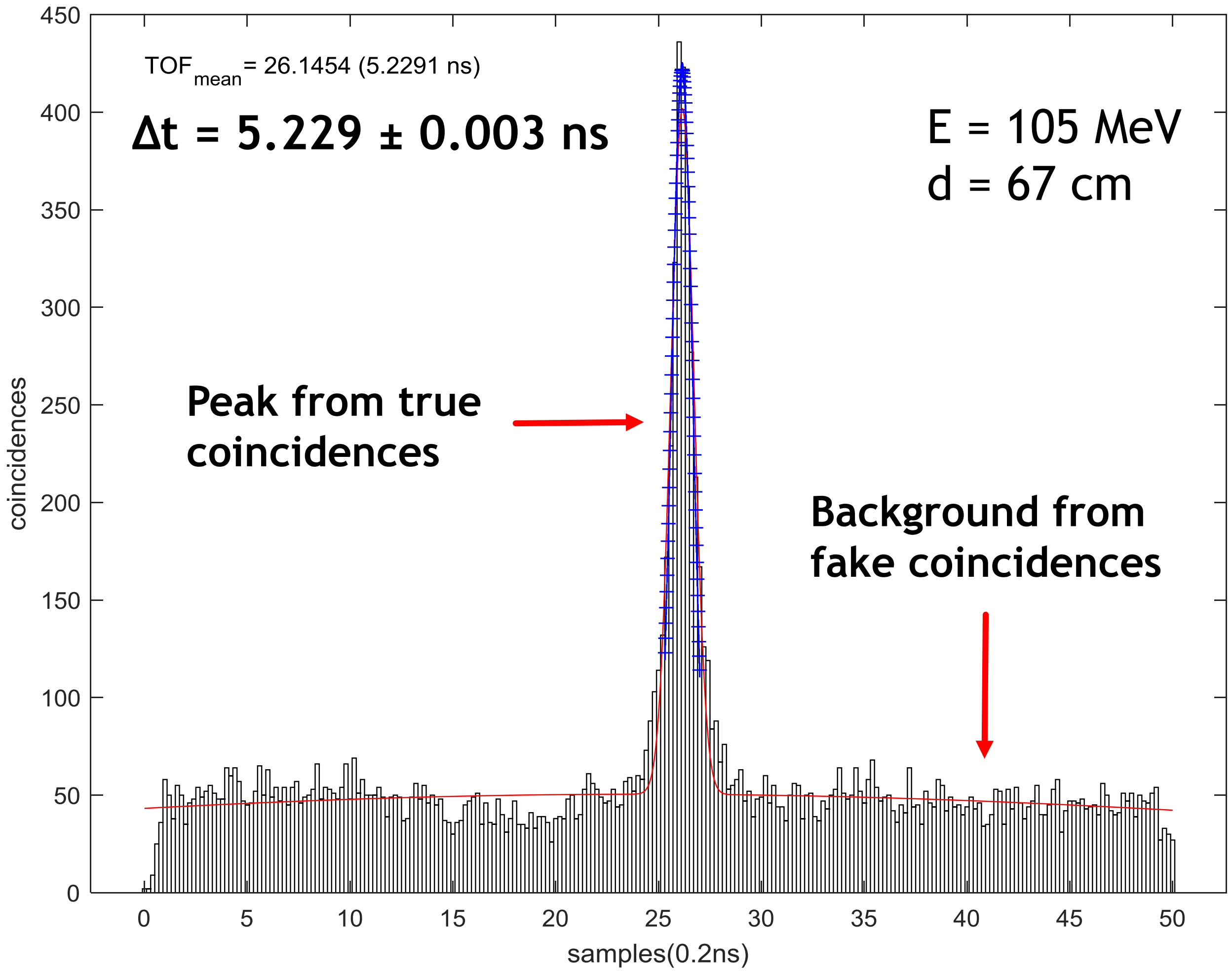
Using a fixed threshold to trigger the time selection
the difference between two times is affected by time walk

CONSTANT FRACTION DISCRIMINATOR (CFD) algorithm



REMOVE TIME WALK EFFECT

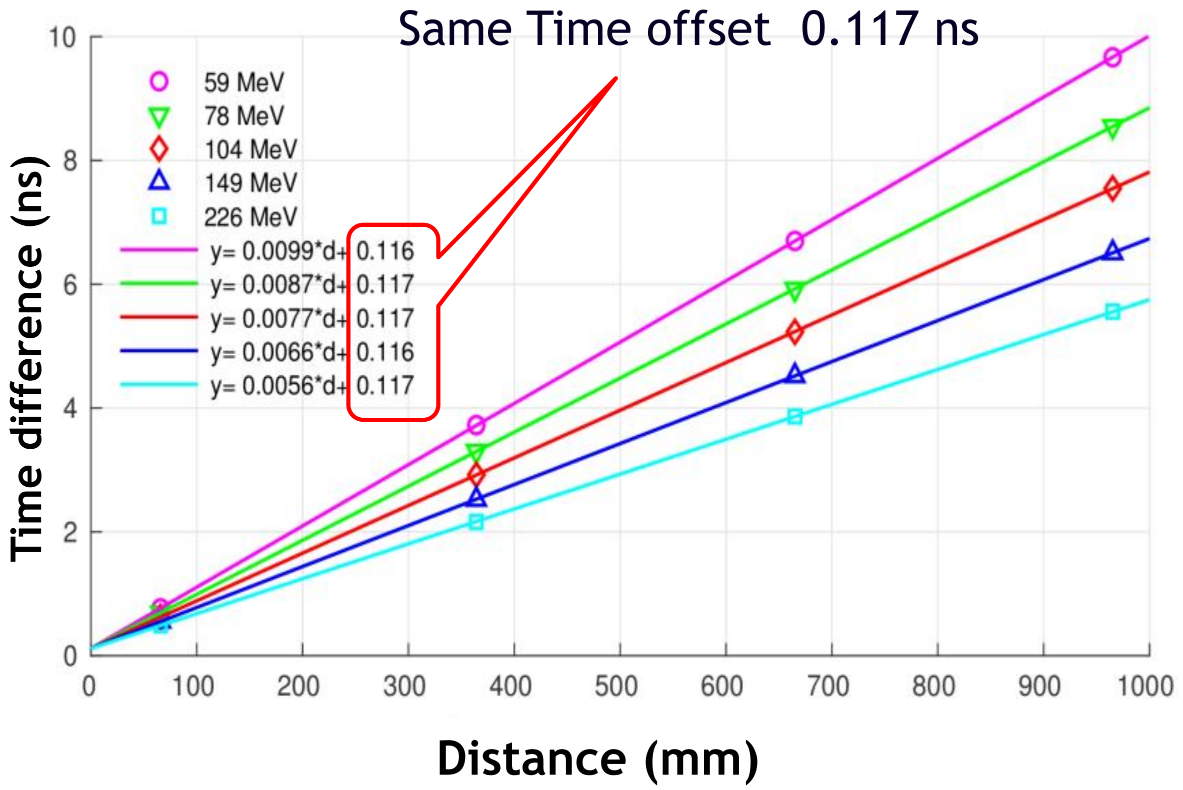
Example of ToFs distribution with CFD



- proton beam of 105 MeV nominal energy
- distance of 67 cm between the sensors
- The red blue line shows the fit performed on the values within ΔT ± 3σ
- First fit (red line) used to found ΔT

Times vs distance measurements

CNAO

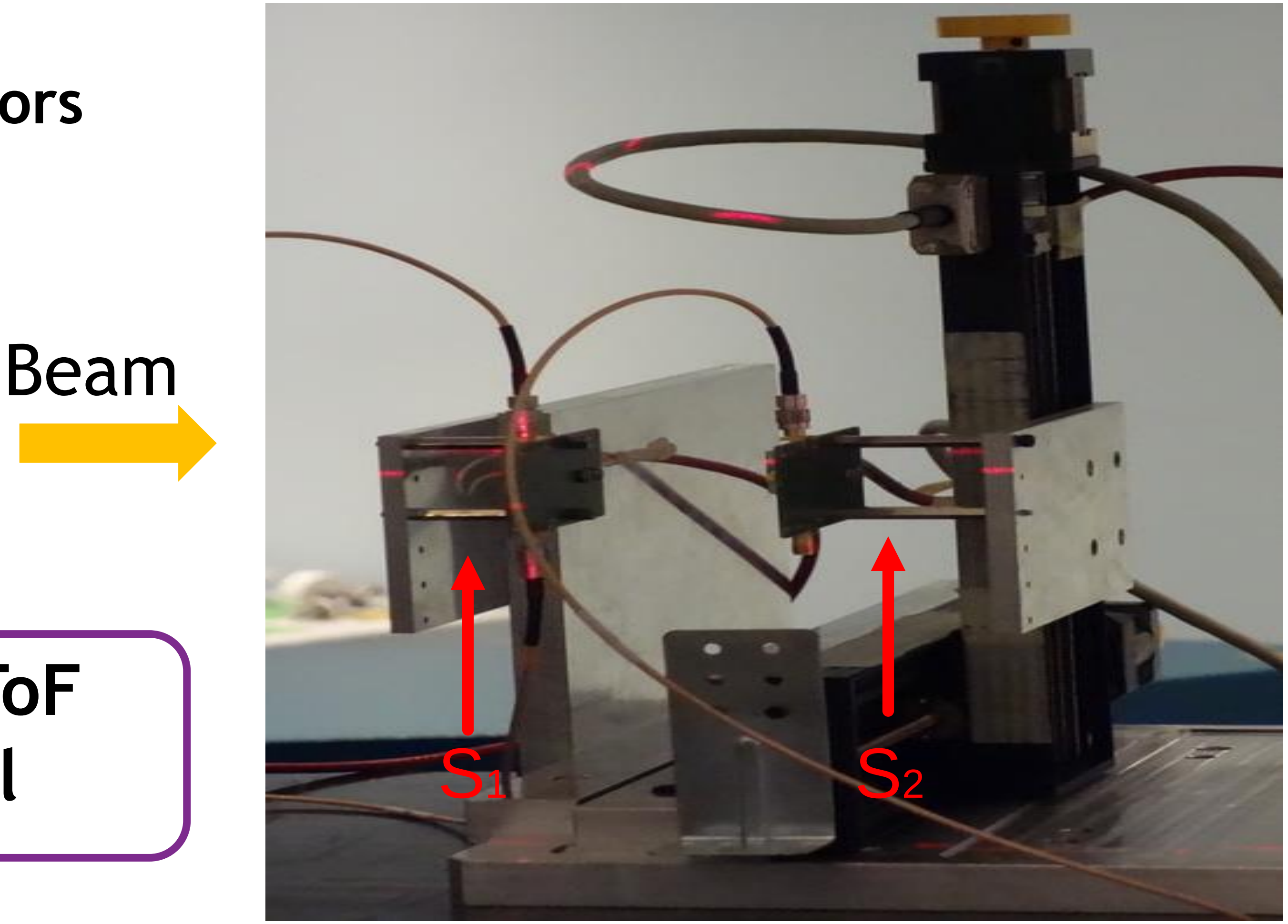


σ(Δt) < 5 ps

System Calibration

Calibration needed to remove systematic errors on

- time offset and
- distance between the sensors



All systematic errors on ToF must be kept at 3 ps level

Calibration: Relative approach using N distances

i = energy index
j = distance index

Global fit

Δt = measured time;
$\boldsymbol{E_i}$ = nominal energies of the beam (corrected for energy loss in silicon and air)

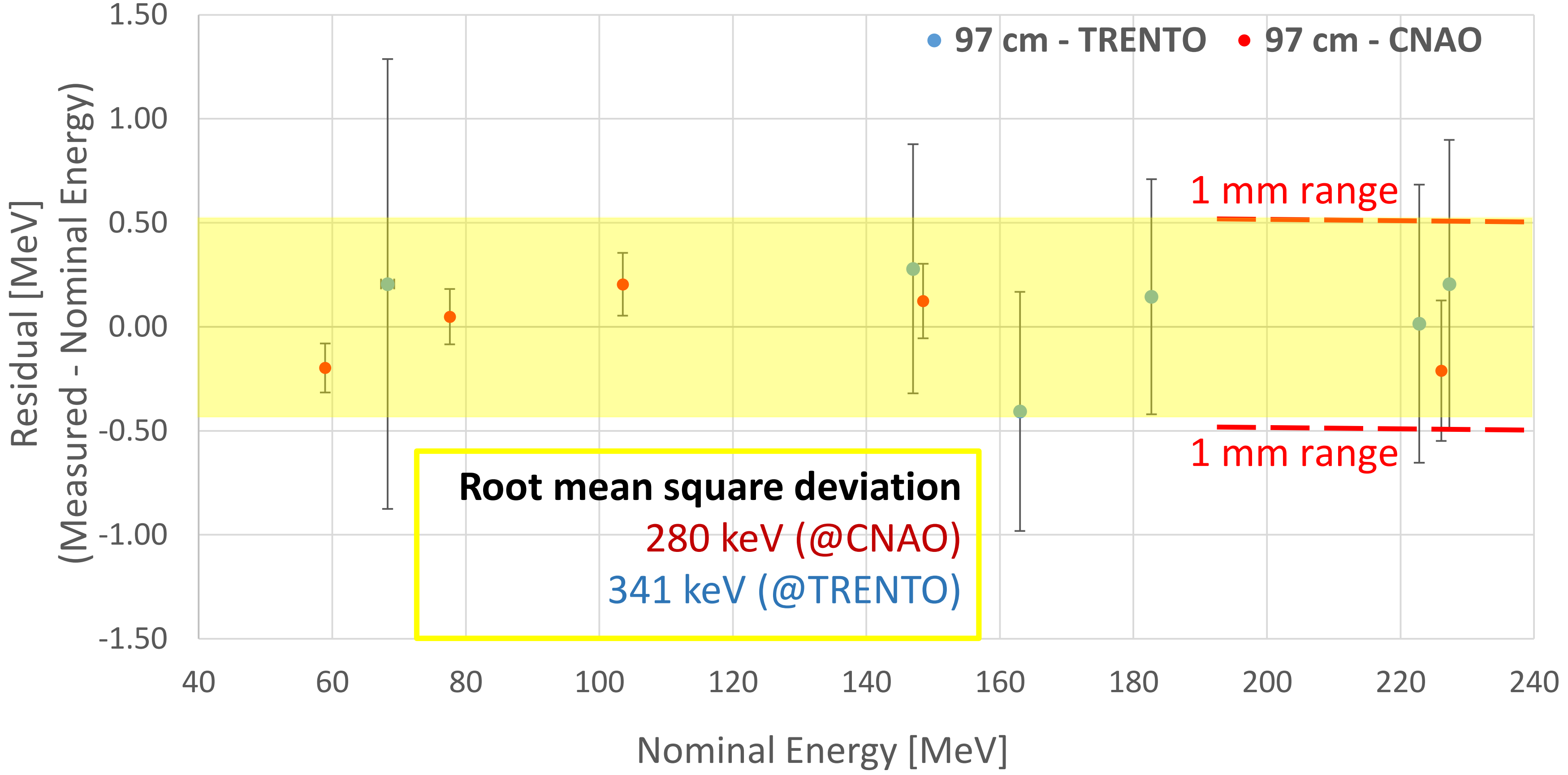
Output PARAMETERS:
$\boldsymbol{d_j}$ (distance between the two detectors);
Offset (time difference due to the different signal path for the two sensors).

$$\chi^2(offset, d_j) = \sum_{i,j} \left\{ \frac{(\Delta t_{ij} - offset) - ToF(E_i, d_j)}{\sigma_{ToF_{ij}}} \right\}^2$$

$$ToF(E, d) = \frac{Ed}{c\sqrt{E^2 - m^2c^4}}$$

Measured residual energy

Tests performed at CNAO and TRENTO therapy facilities



What’s next ? (I): Absolute approach

To measure the beam energy without any beam information.
The needed quantities are Δt and ΔX for 2 energies

time difference, t1 and t2, between sensors at a distance X1 for two energies, E1 and E2.

time difference, t1 and t2, between sensors at a distance X2 for the same two energies, E1 and E2.

Δx = X1-X2 (distance between the two detectors);

Offset (possible time offset of the signals);

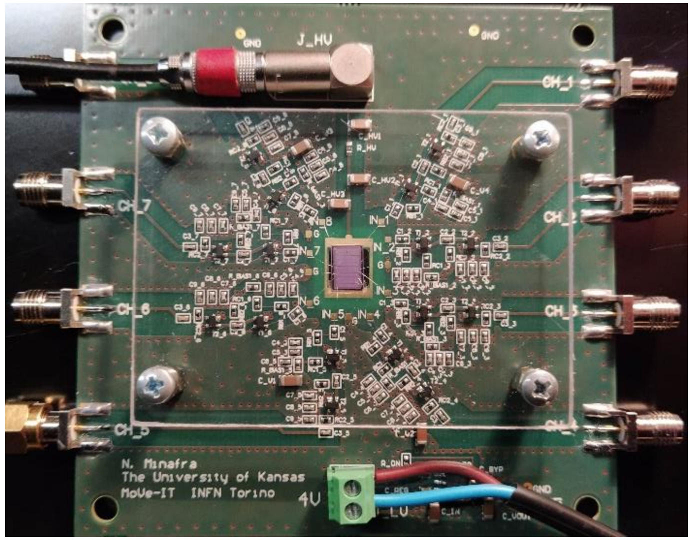
Speed v1 and v2 → Beam Energies

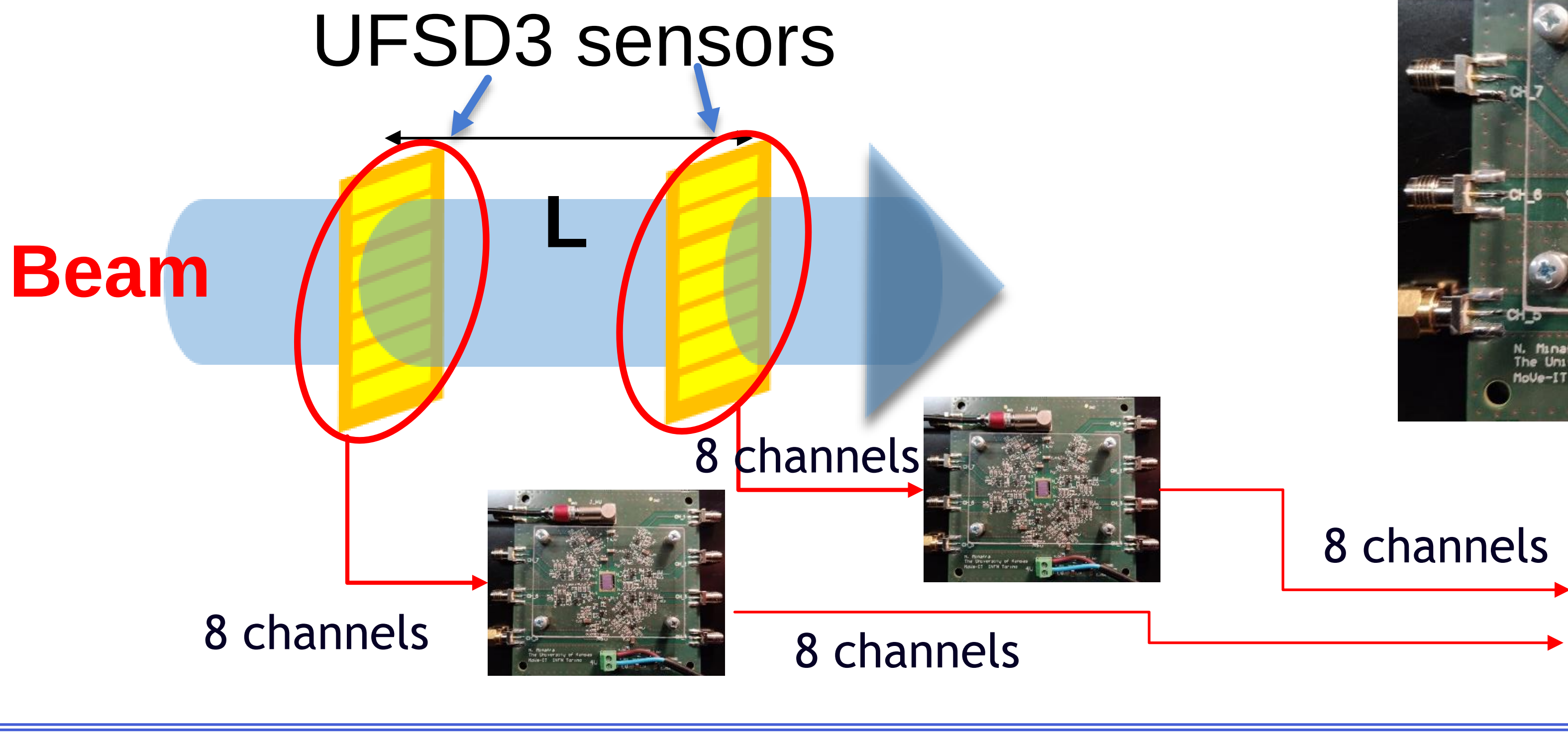
What’s next? (II) : final sensors and front-end readout

Next step: Beam test with 8 strips and dedicated readout board

- Custom UFSD sensors (11 strips) designed and produced @ FBK (UFSD 3)
- Thinned at 70 and 120 um

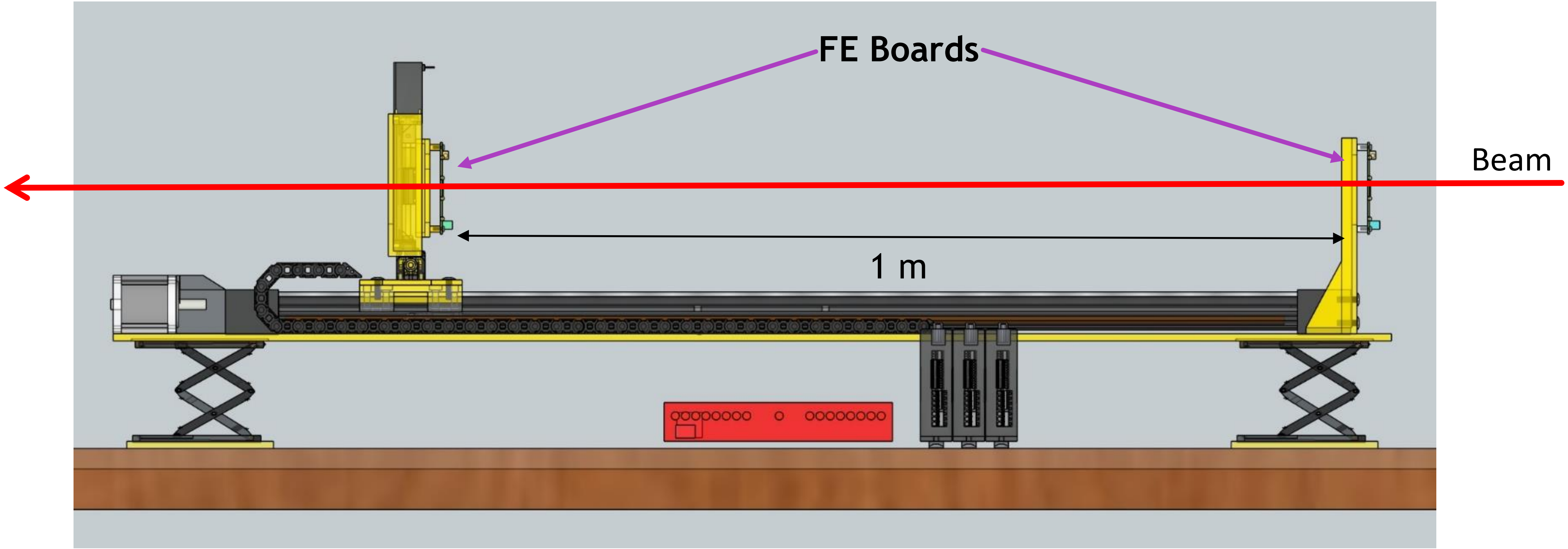
- 8 channels dedicated front-end board
- Optimized for timing
- ready





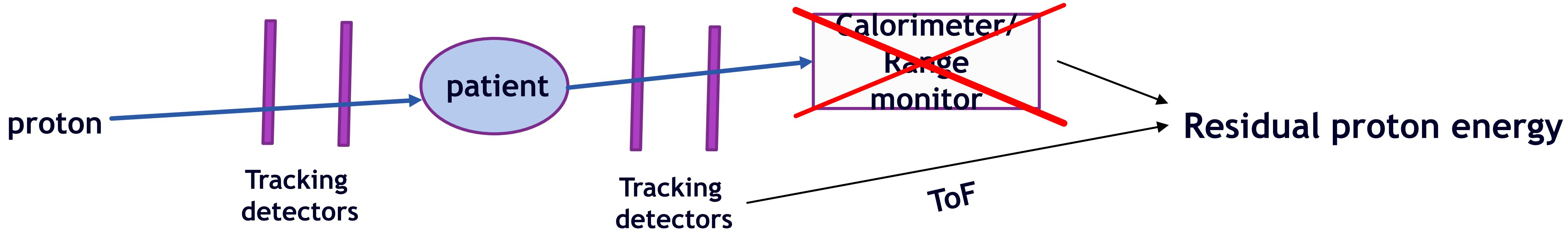
What's next? (III)

Portable mechanical system under construction



Other possible applications of LGAD detectors in PT

Measurement of residual proton energy from ToF in pCT applications



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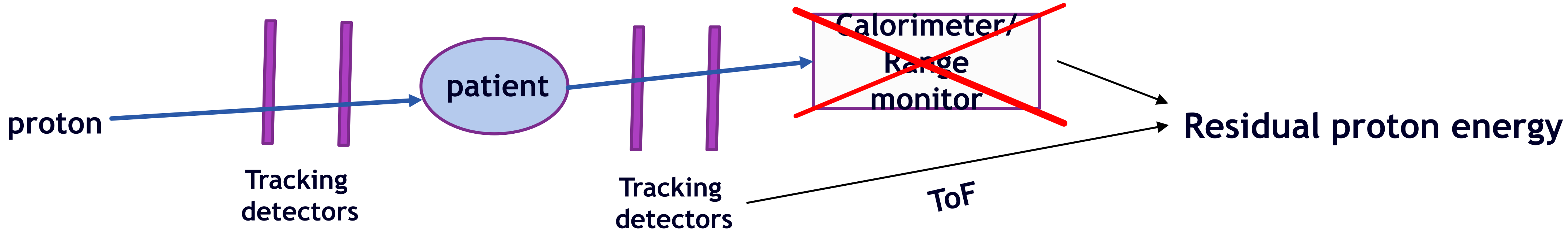


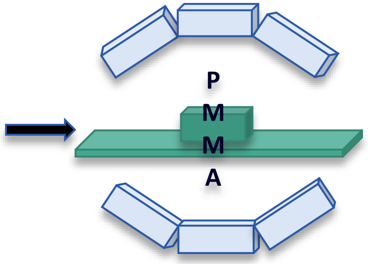
In-sensors PET measurement of fast decay β⁺ isotopes

UFSD sensors used for fast on-line monitoring of the beam erogation for in-spill PET acquisition of gamma's from short time-life β^+ isotopes (^{12}N $T_{1/2}$=0,011 s; ^{8}B $T_{1/2}$=0,770 s)

Range assesment with prompt-gamma timing

UFSD detectors provide the time reference for p-γ ToF measurements

Experimental validation on-going within the I3PET INFN project



V. Ferrero et al., Nucl.Instr.Meth.A,986 (2018) 48 .

Summary

ULTRA FAST SILICON DETECTORS are one of the promising new technology for next generation of beam qualification and monitoring in Particle Therapy

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ULTRA FAST SILICON DETECTORS are one of the promising new technology for next generation of beam qualification and monitoring in Particle Therapy

TORINO UNIVERSITY AND INFN ARE DEVELOPING NEW DETECTORS FOR PARTICLE THERAPY BASED ON UFSD

→ A PARTICLE COUNTER and → A FAST BEAM ENERGY MONITOR

The big challenge for the future is to build a 24x24 cm^2 particle counter

UNIVERSITÀ DEGLI STUDI DI TORINO

CINFAI SCUOLA ALTA FORMAZIONE

INFN TORINO

Thanks for your attention!

Simona Giordanengo

INFN Torino

Giornate di Studio sui Rivelatori - Scuola F. Bonaudi

February 10-14, 2020 Cogne

Acknowledgments