Section 5: Biophysics and Medical Physics
107° Congresso Nazionale- Società Italiana di Fisica
Milan, 13-17 September 2021

Innovative thin silicon detectors for online beam monitoring in particle therapy applications.

Names:

M. Abujami[1,2], C. Galeone[2], S. Garbolino[1], S. Giordanengo [1], F. Mas Milian[1,2,3] G. Mazza[1], M. Mignone[1], V. Monaco [1,2], A. Vignati [1,2], R. Cirio [1,2], O. A. Martì Villarreal [1,2], R. Sacchi [1,2]

Affiliations:

(1) National Institute for Nuclear Physics INFN, Turin division, Turin, Italy

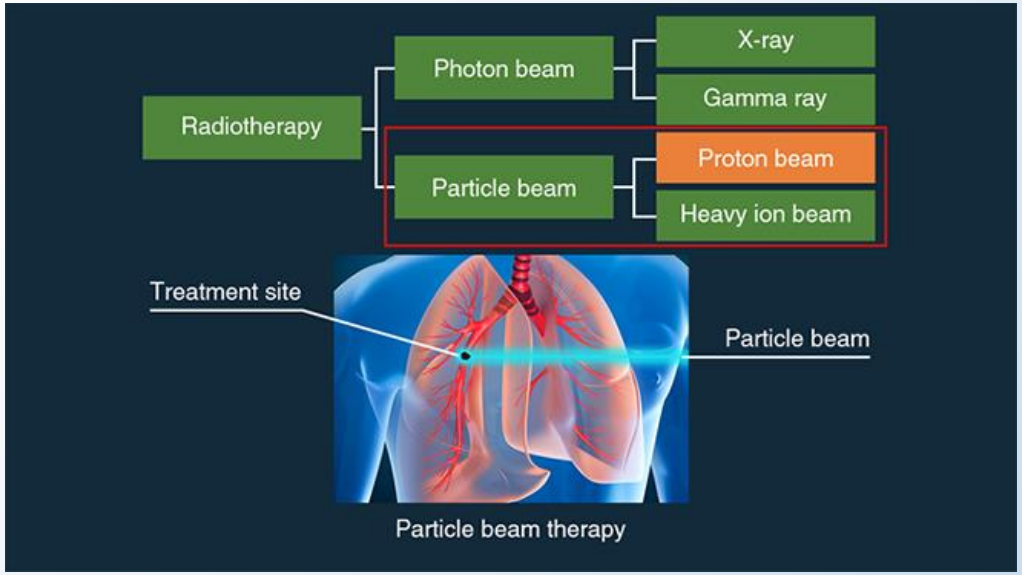
(2) Università degli Studi di Torino, Physics Department, Turin, Italy

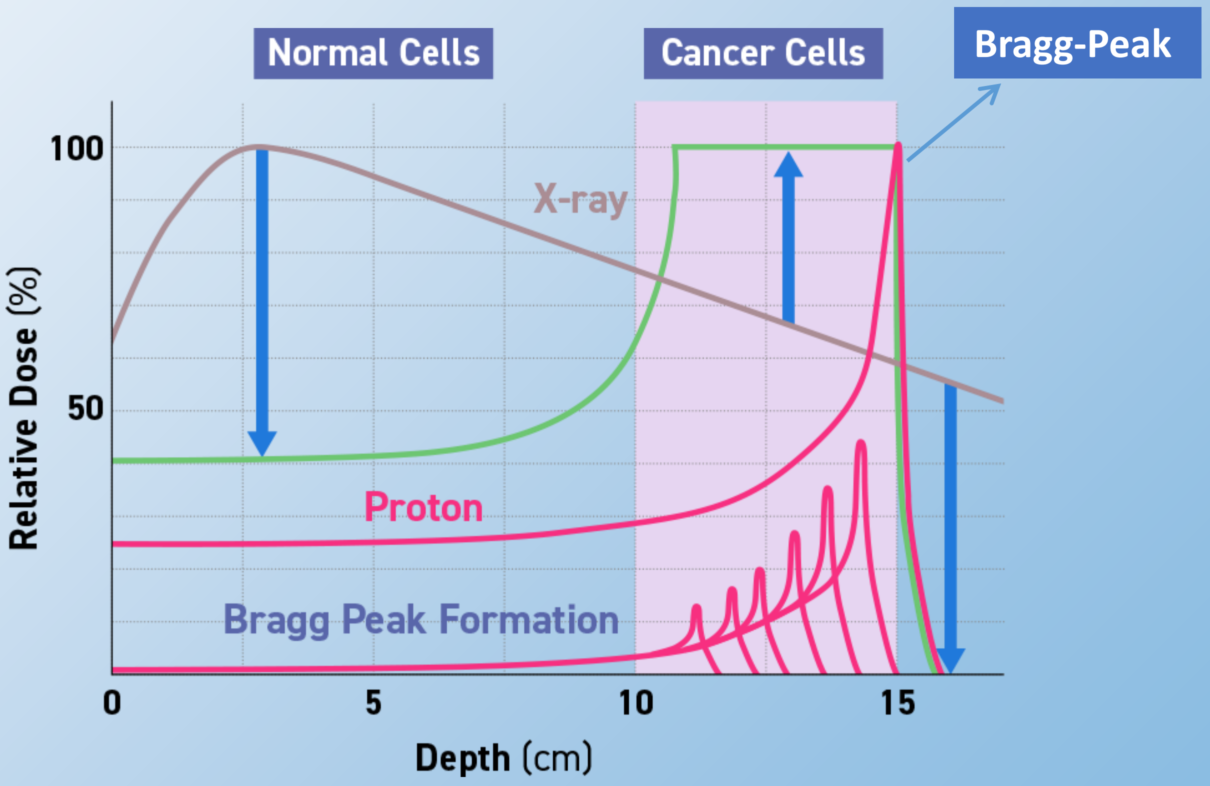
(3) Universidade Estadual de Santa Cruz, Ilheus, Brazil

mohammed.abujami@unito.it

Charged Particle Therapy: Introduction

Particle Therapy is a form of external beam radiation therapy which uses beams of radiation to be adjusted for the depth of the treatment site, giving it the ability to deliver a concentrated dose of radiation inside the tumor.





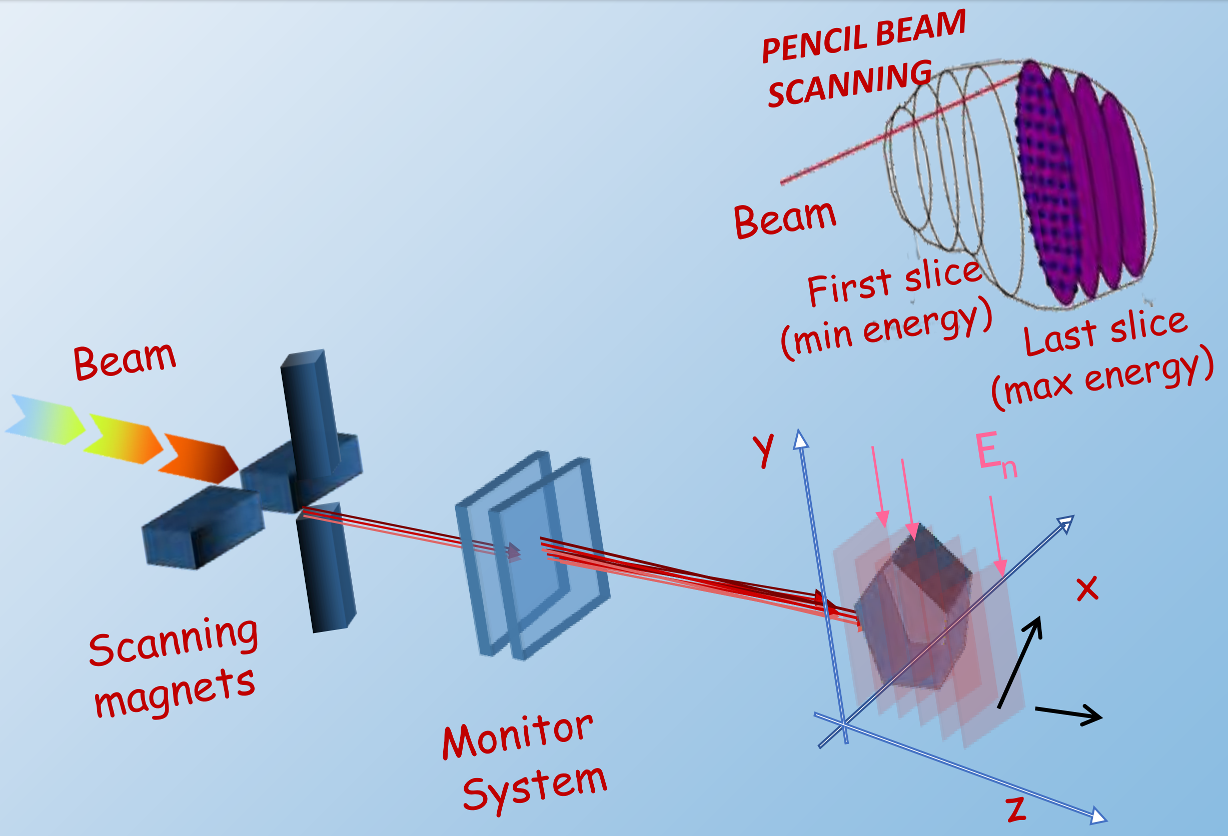
With proton therapy, dose is released mostly at the end of the path in the tissue, in the so-called Bragg peak.

Proton therapy is a type of radiation treatment that uses a beam of protons to deliver radiation directly to the tumor given effective to deliver minimal dose in front of the tumor, maximum dose to the tumor region.

A single Bragg Peak isn't very useful clinically because it is thin. By modulating the beam energy, we can add multiple Bragg peaks at different depths. By taking the sum of these individual Bragg Peaks, we get the **SOBP**.

Beam Delivery System / Pencil beam scanning

Pencil beam scanning (PBS) is the generic name for delivering the dose to a target using individually controlled small pencil beams (spot) to cover the target in 3 dimensions. And to reduce even more the dose to surrounding organs.



Potential Benefits of PBS Delivery:

- Confirm tumor control radiation.
- Avoid irradiate normal tissue .
- Shorter treatment times.
- Increased treatment options for certain tumor types.

Technical issues

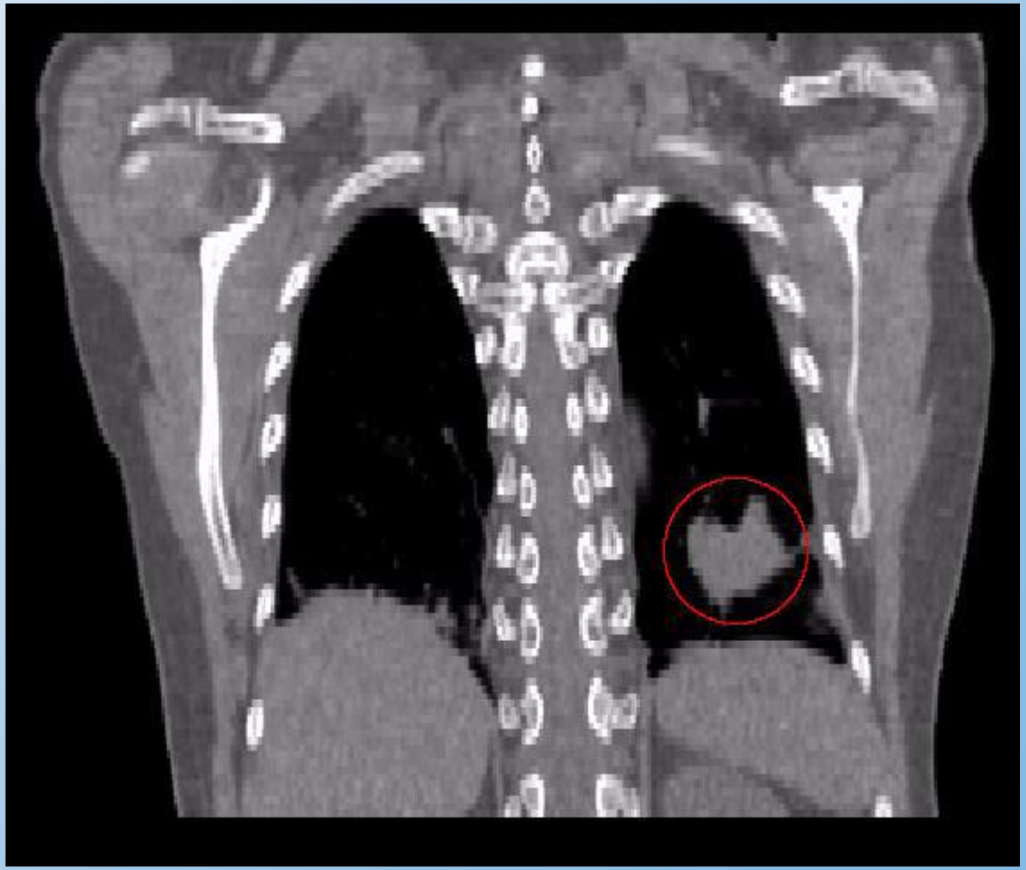
- Ability to change the beam energy.
- Monitor on-line the beam (fluence, position and dimension).
- Correct on-line the beam position (feed-back operations).

Problem!!!!

The main challenge in particle therapy is to treat tumors that moves or surrounded by organs that moving by breathing and heart beats.

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

Lung cancer



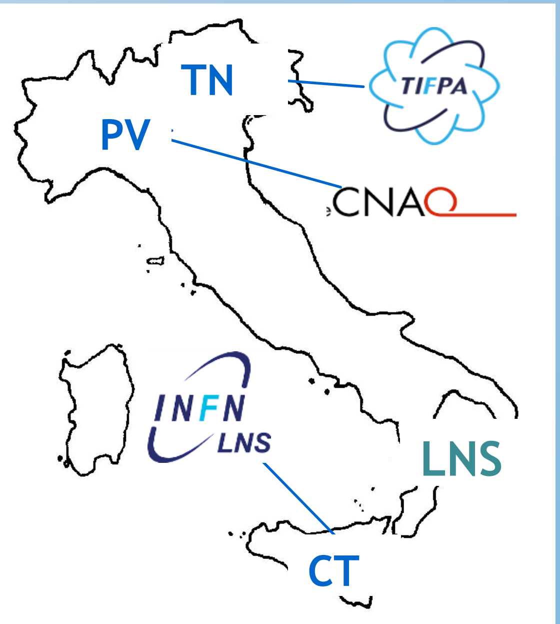
Aim of the MoVe IT INFN project

Modeling and **Ve**rification for **I**on beam **T**reatment planning → Implementation of advanced radiobiological models in ion TPS, experimental verification in-vitro and in-vivo.

Two prototypes of UFSD for radiobiological applications @ three irradiation facilities:

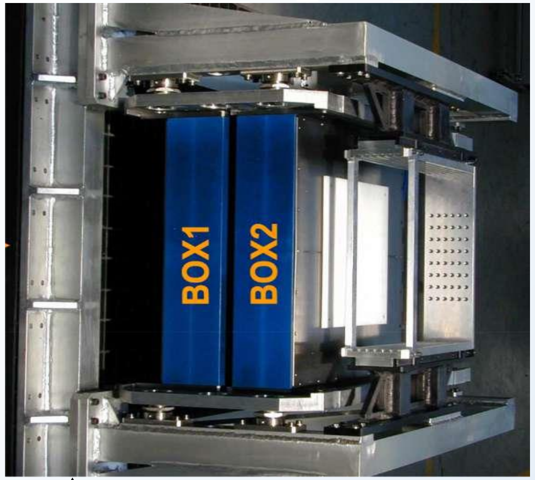
1. **Directly count individual protons:**
   - Cover area 3x3 cm^2.
   - Measure up to fluence rate of **10^8 p/s cm^2** (with error < 1% - clinical requirement).
   - Sensitivity to single particles at very low fluxes.
   - Provide the beam shape in two orthogonal directions.

2. **Measure the beam energy** with time-of-flight techniques, using a telescope of two UFSD sensors:
   - Error < 1 mm range in water.

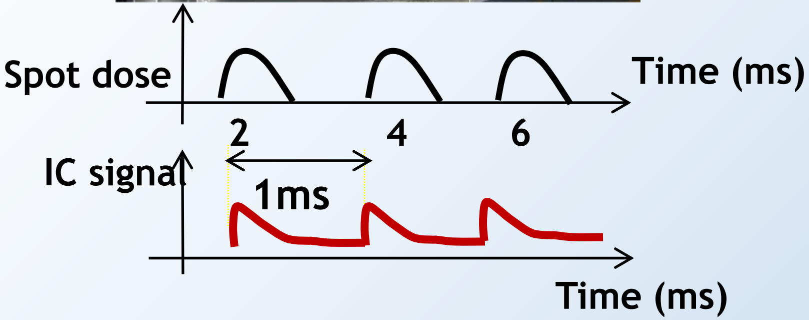


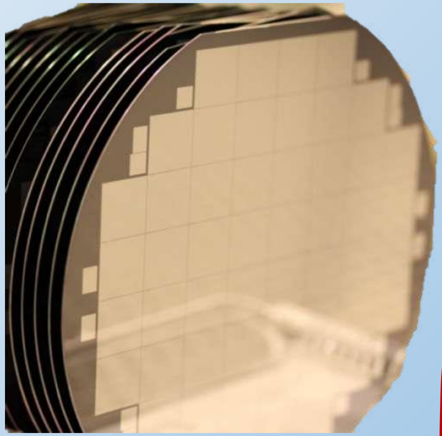
For additional details http://www.tifpa.infn.it/projects/move-it/

From Integrated Charge with Gas Ionization Chambers to Number of Particles with Silicon Detectors.

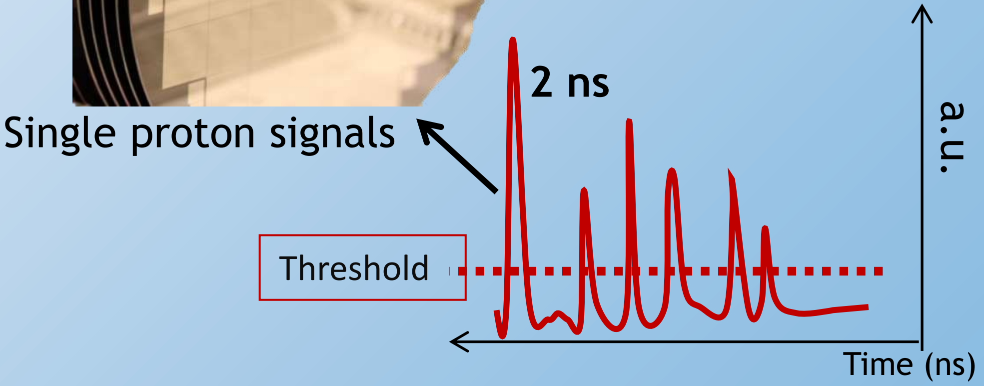


Ionization Chambers
Indirect Measurement





Silicon Detectors
Direct Measurement



- Robust
- Simple construction and readout
- Large area
- Radiation resistance
- Low thickness

- Slow response time
- Limited sensitivity

- Fast response time
- High time resolution
- Large granularity (spatial resolution)
- Sensitivity to single particles

- Radiation resistance
- Pile-up effects
- High readout complexity

The ideal detector should measure online the number of particle with 1% of accuracy

Ultra Fast Silicon Detector (UFSD)

Requirements for sensor signal:

- **Fast** → **Reduce pile-up effect and enhance time resolution.**
- **Large** → **Achieve good SNR→ Improve the sensitivity.**

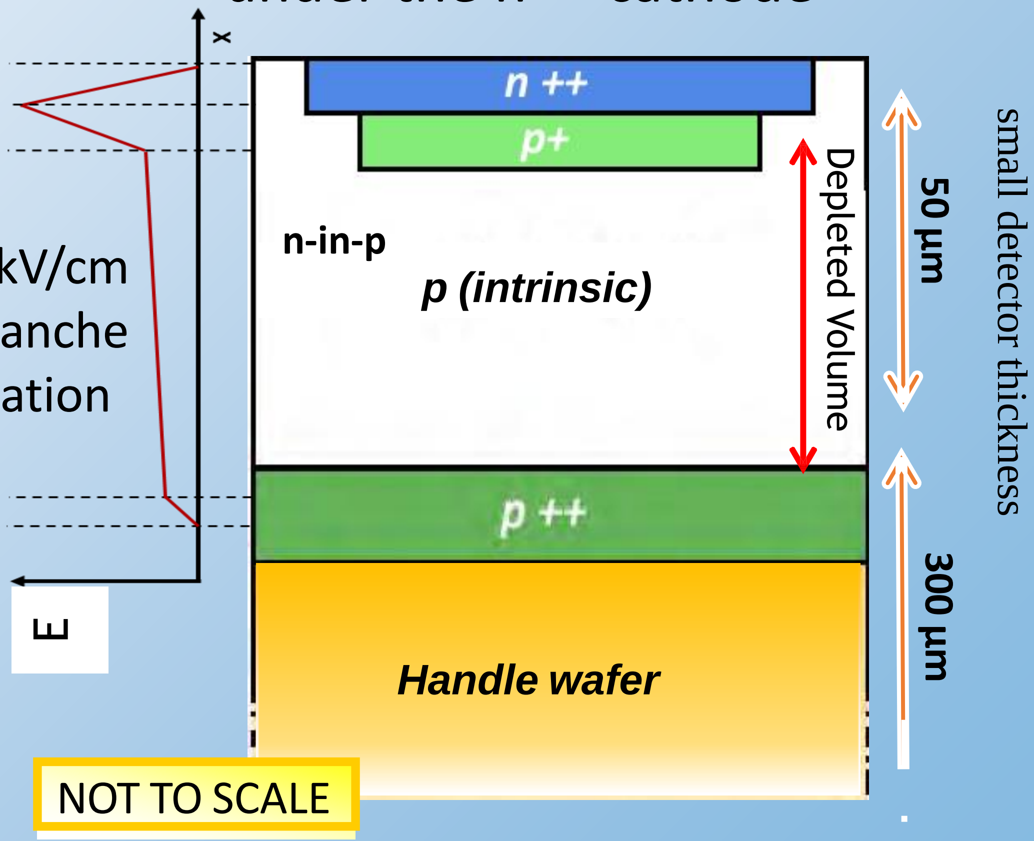
✓ **Small signal duration (1 ns)** →
Single particle detection capability.

✓ **Excellent time resolution (tens of ps)→**
Beam energy measurement

✓ **Fast Electronics with low power consumption**

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

E ~300kV/cm
e^-/h avalanche multiplication



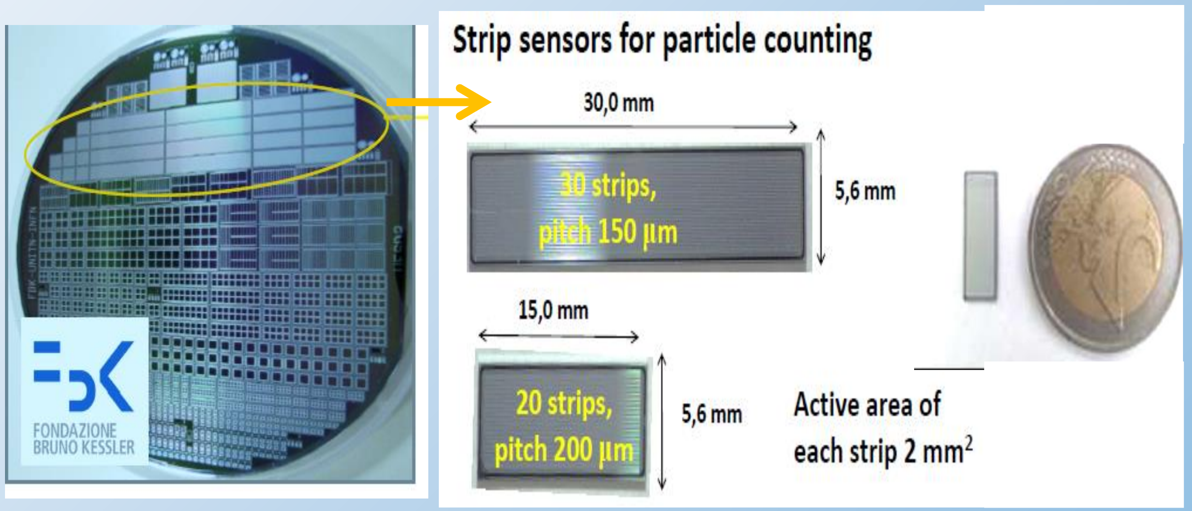
controlled low gain (~ 10), increasing with reverse bias

Sensor and Readout

18 silicon-on-silicon wafers were produced with different doping modalities for the gain layer to study the optimal strategy in terms of radiation resistance.

A two sets of 50 µm thick strips, are tested:

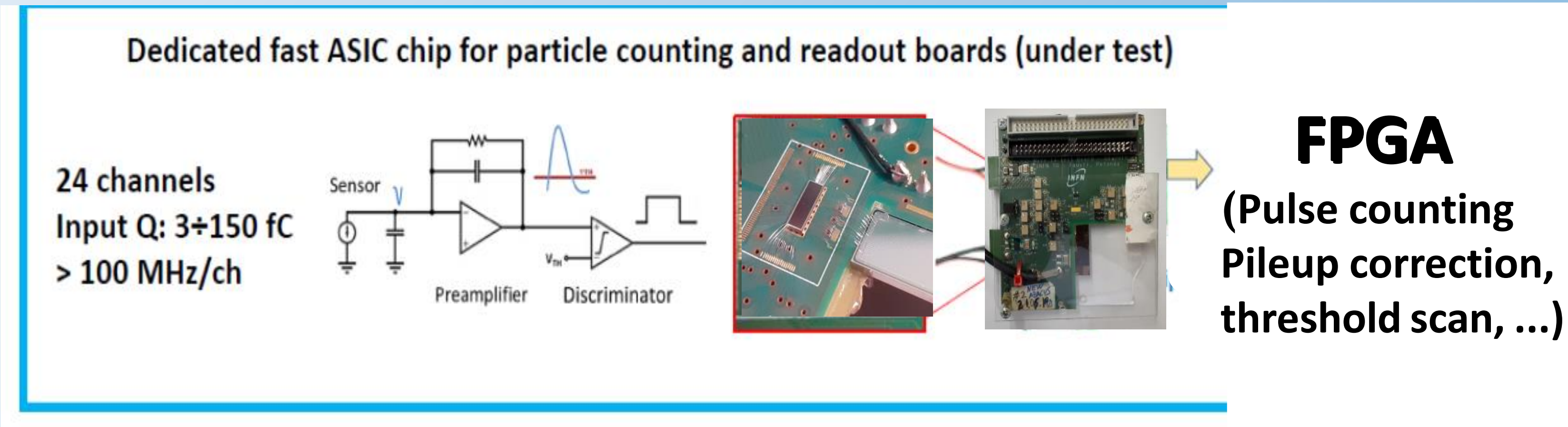
- 30 strips→30 mm long → 150 µm pitch
- 20 strips → 15 mm long → 200 µm pitch



Front-end electronics has to provide short signal duration to minimize pile-up counting inefficiencies.

– Dead time → ~ 10 ns.

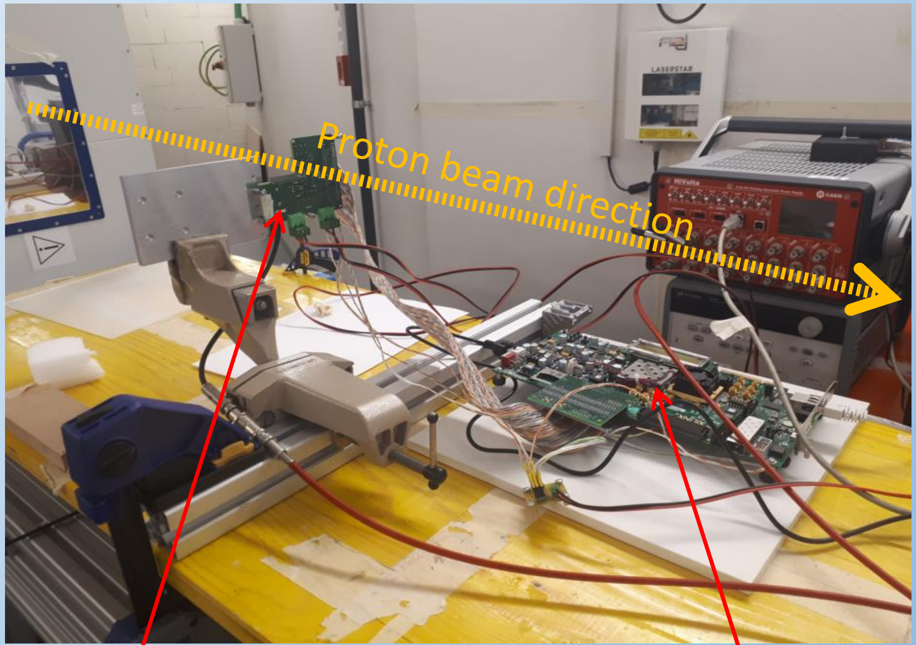
– Counting efficiency > 98 % up to 100 MHz.



The role of the electronics is to amplify the current signals from each strip and compare the amplified signal with a fixed threshold to provide a logical pulse for each particle

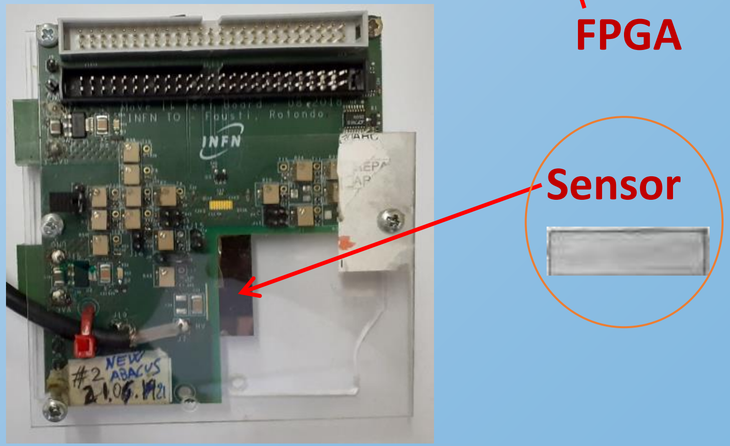
Test beams set-up at TIFPA (Trento, Italy - Feb 2021)

The experimental setup was configured by placing a planar and a pin point ionization chamber in front of the strip sensor.
The sensor connected to FPGA was in connection with a PC.



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.**
- **Measurements with proton beams at 4 energies in the clinical range at TIFPA (70 MeV 125 MeV 179 MeV 228 MeV).**
- **Data analyzed by MATLAB.**



Test beams at TIFPA (Trento, Italy)

First treatments → end of 2014

1000 Patients → end of 2019

TIFPA

Trento Institute for Fundamental Physics and Applications

Two treatment rooms with gantry

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

https://protonterapia.provincia.tn.it/

One experimental room for research


Results

Signal Amplitude Distributions

The count rate distributions depends on the noise level and signal distributions,

$$N(x > x_{thr}) = \int_{x_{thr}}^{\infty} f(x)dx = 1 - \int_{-\infty}^{x_{thr}} f(x)dx$$

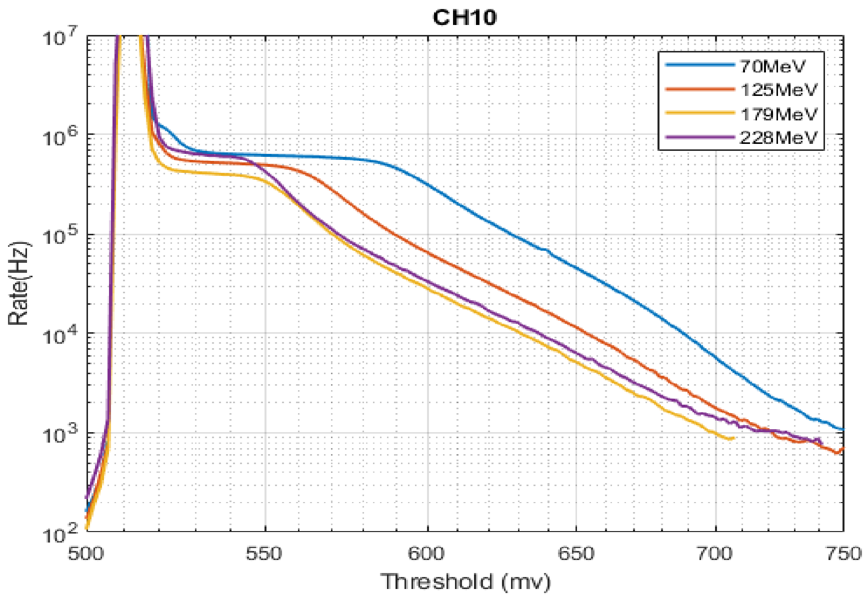
N=Rate of counts detected at a fixed value of threshold (x_{thr}).
$f(x)$= probability density function of Amplitude of signal x.

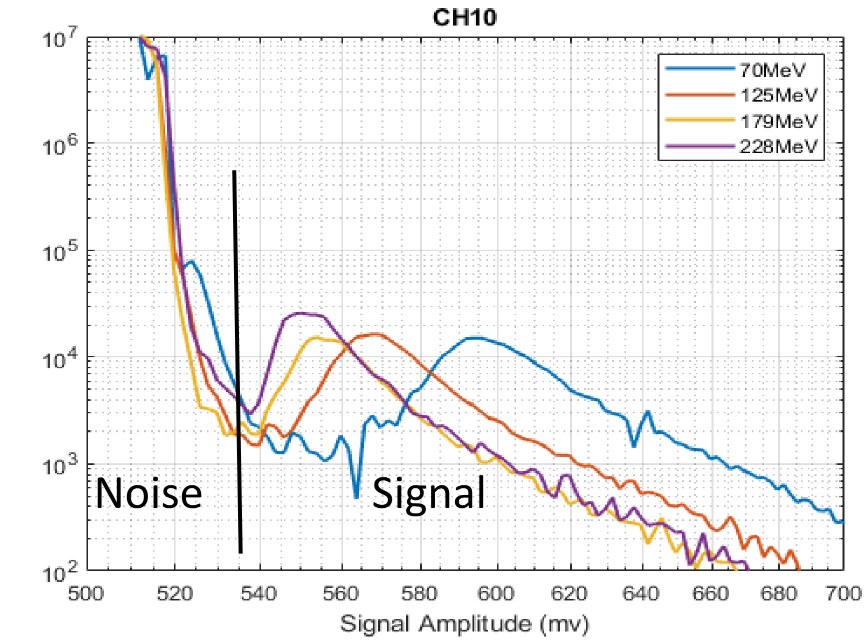
Signal amplitude distribution can be estimated using the discrete derivative of the rate as a function of the threshold

$$f(Amp = x_{thr}) = \frac{-dN}{dx_{thr}}(x_{thr})$$

The noise appears as the fast decreasing curves at small threshold values

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

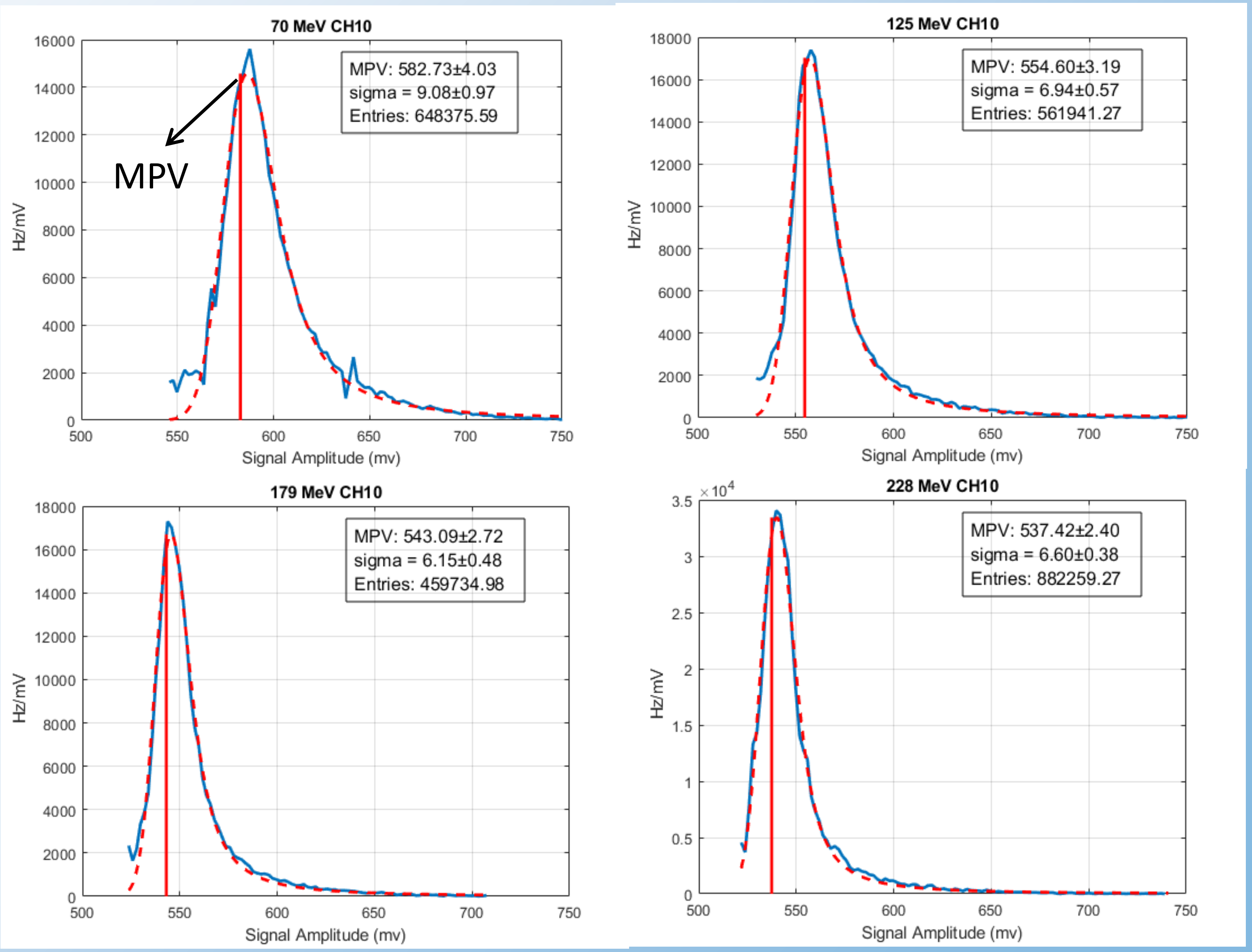




LANDAU*GAUSS fit: example for a channel

Expected Amplitude distribution→
Convolution of a Landau with a gaussian

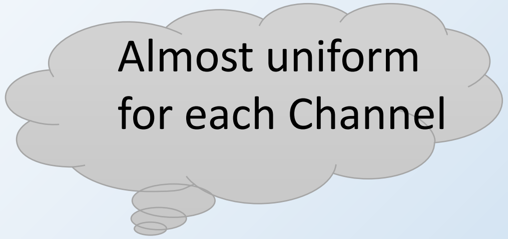
Landau → Probability density function of the energy loss by a charged particle in a certain thickness of a medium.
Gaussian→ Noise.

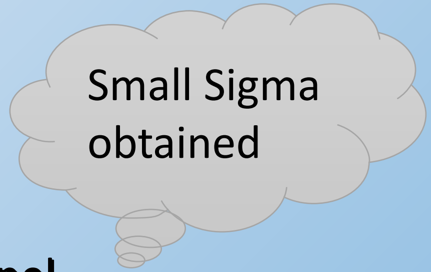


The amplitude distributions show the expected Landau distribution, with a long tail and an decreasing Most Probable Values (MPV) with increasing the of the proton energy.

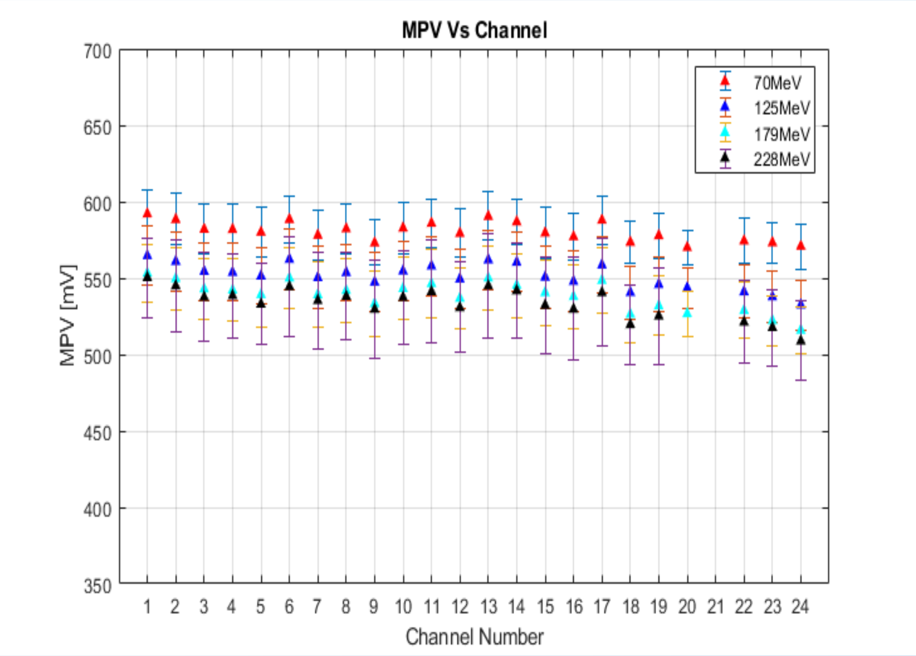
Parameter Sigma and MPV for each Channel

For 24 Channels we extract MPV & Sigma

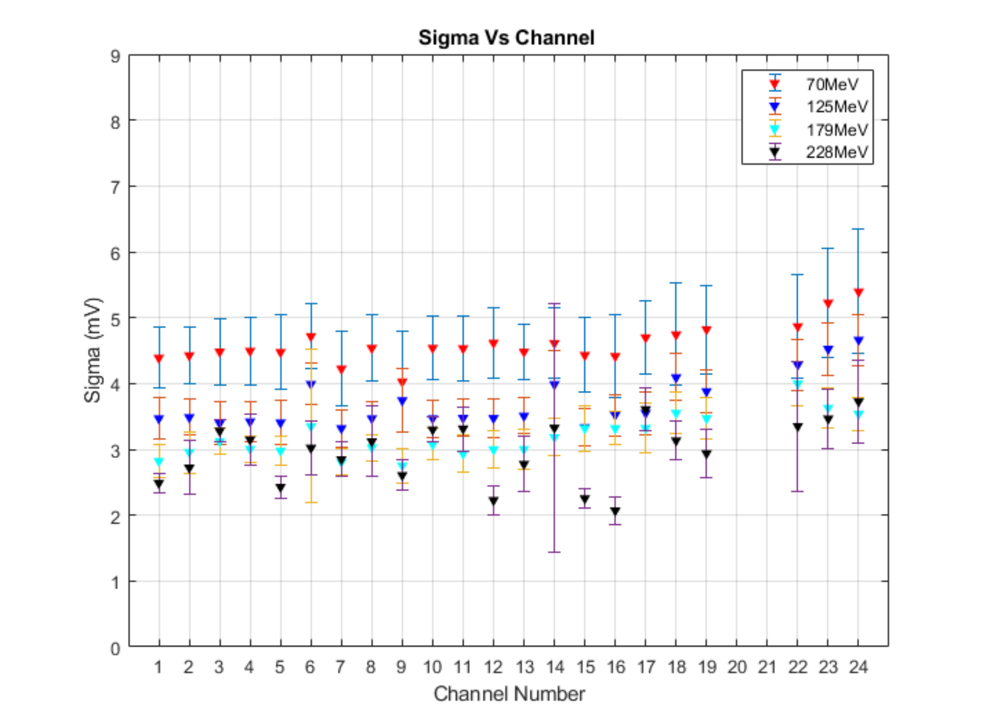




MPV For each Channel



Sigma For each Channel

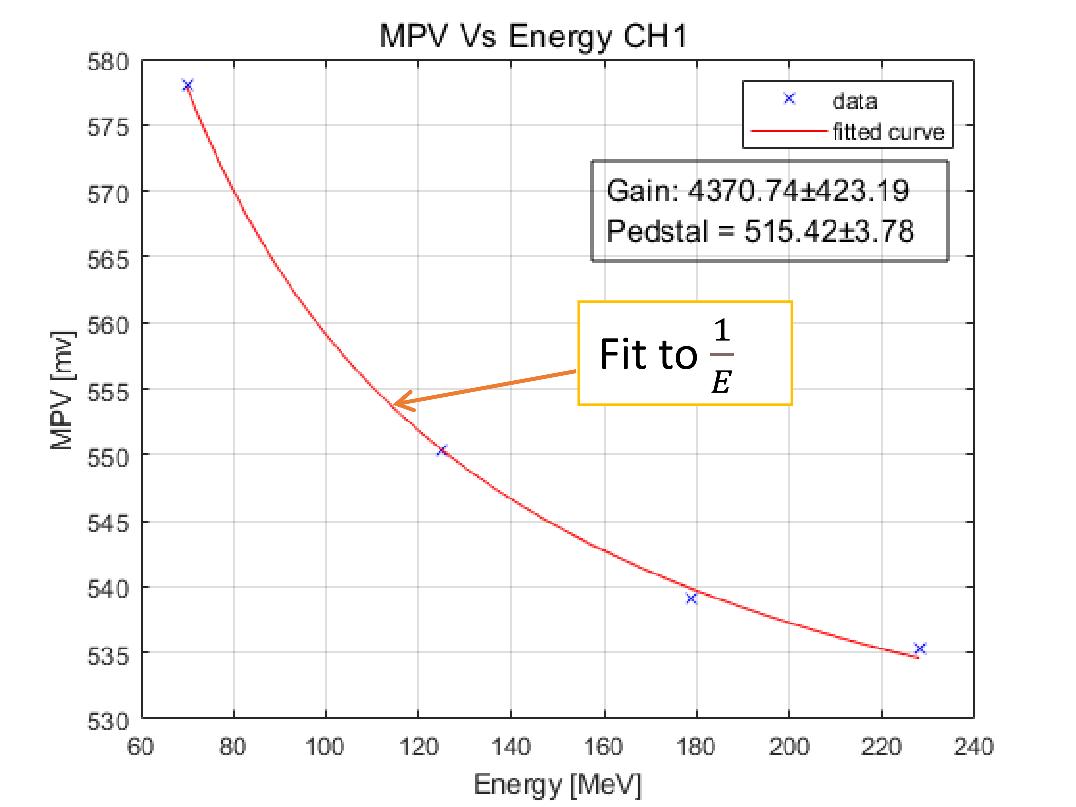


Estimated with the corresponding uncertainties (again using 95% c.l.).

Bethe-Bloch formula

Bethe-Bloch formula calculates average/mean amount of energy lost due to ionization per unit of distance in the media).

MPVs are expected to follow the Bethe-Bloch function:



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

$$\frac{\partial E}{\partial x} \propto \frac{1}{v^2} \propto \frac{1}{E}$$

$$MPV \sim \frac{1}{E}.\Delta x$$

$$\boxed{f(E) = \frac{a}{E} + b}$$

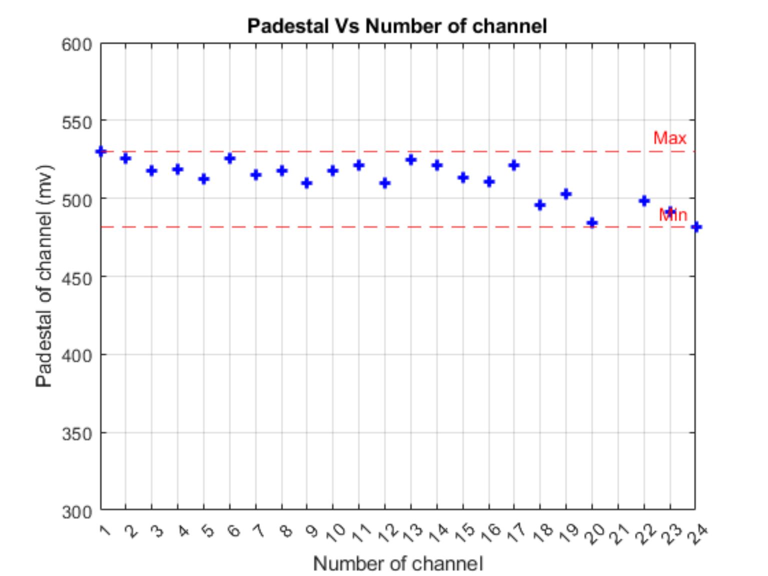
$a =$ **Depends on Gain of the channel** (units mV.MeV).

$b =$ **Pedestal of the channel** (units in mV).

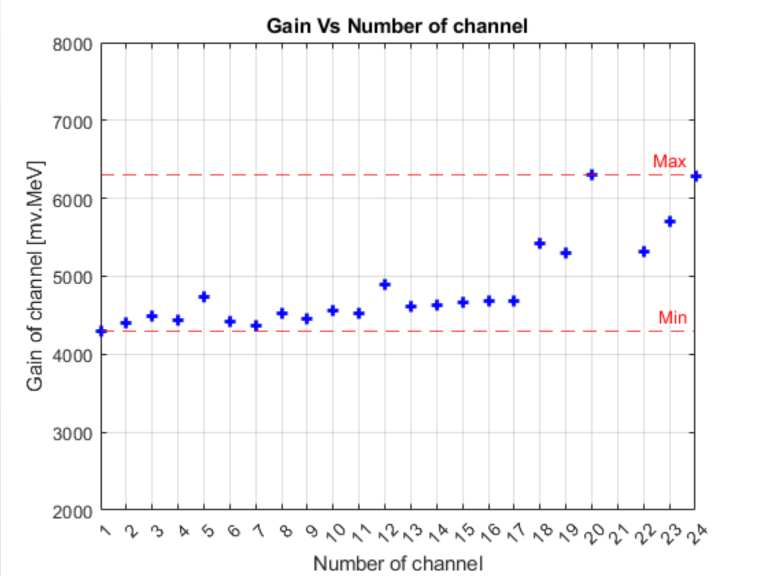
Pedestal and gain distributions

Pedestal and Gain plot for 24 channels

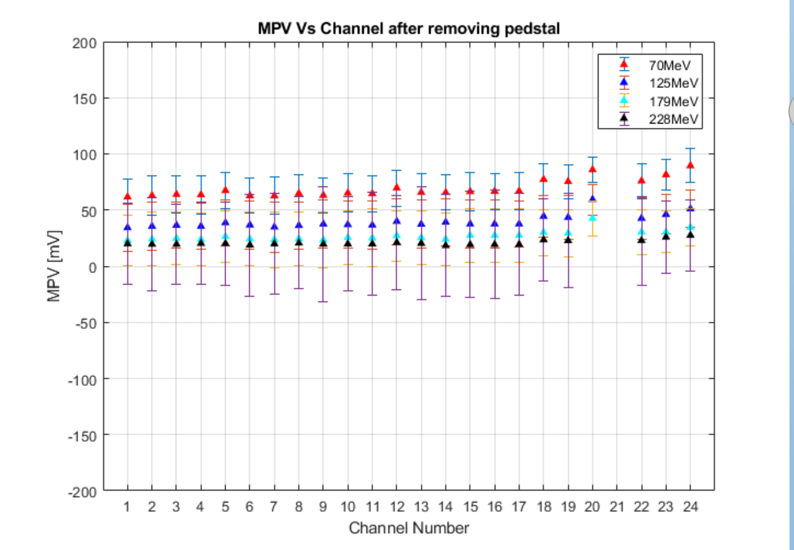
Pedestal For each Channel



Gain For each Channel



After removing Pedestal from threshold we replot MPV for each Channel



More uniform for each Channel after removing Pedestal

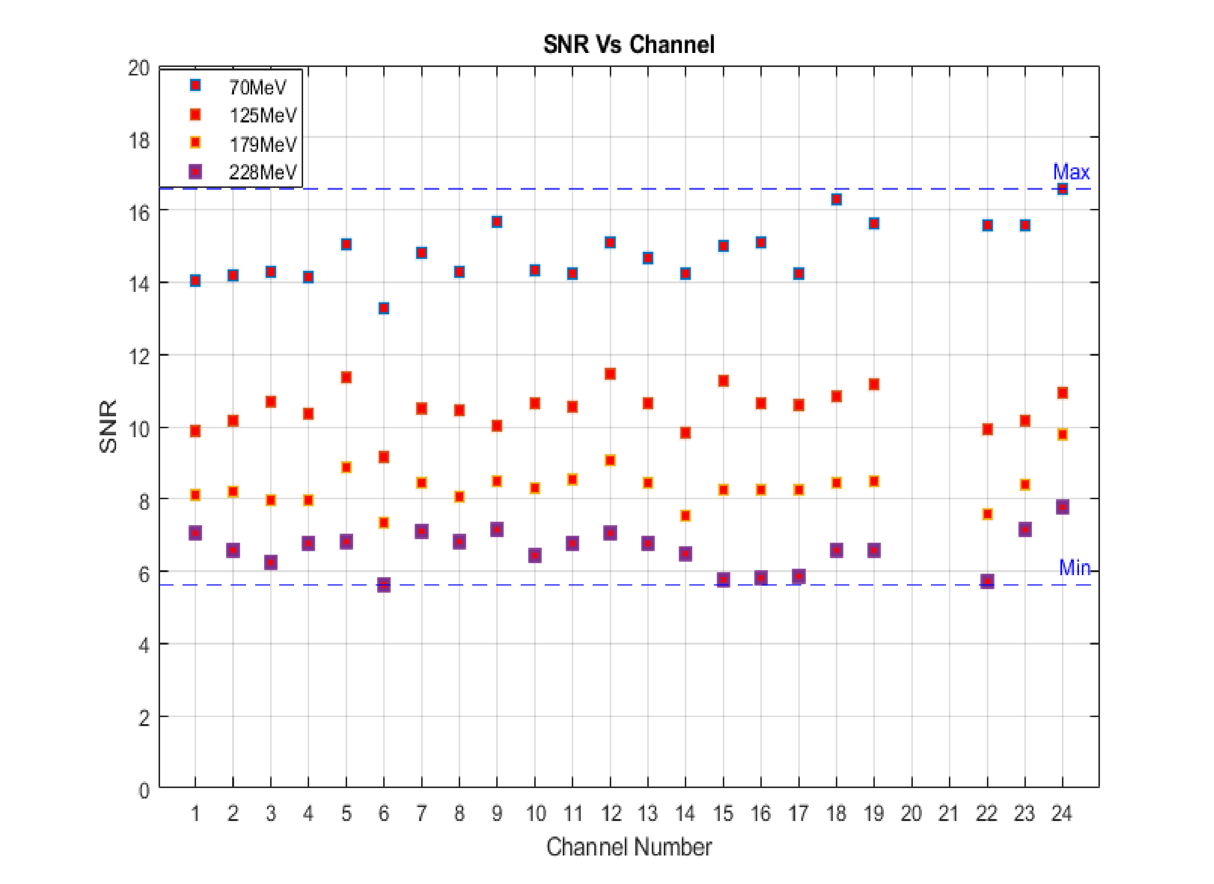
The Signal-to-Noise Ratio (SNR)

Signal-to-noise ratio (SNR) is a widely used metric for the ability of a detector to distinguish between an incident signal and its absence. While SNR is frequently involved to classify detector sensing capabilities (how well an object is measured).

$$\mathbf{SNR} = (\mathbf{MPV_i} - \mathbf{b_i})/\mathbf{SIGMA_i}$$

This require choose the precise determination of threshold as the function of

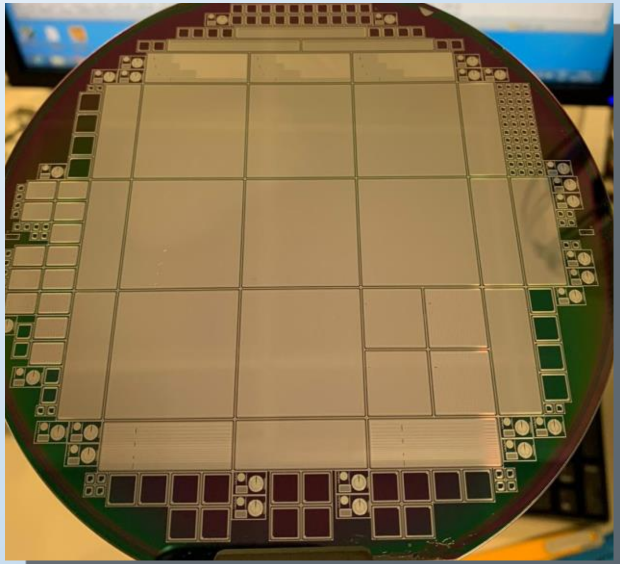
- Beam energy
- Channel



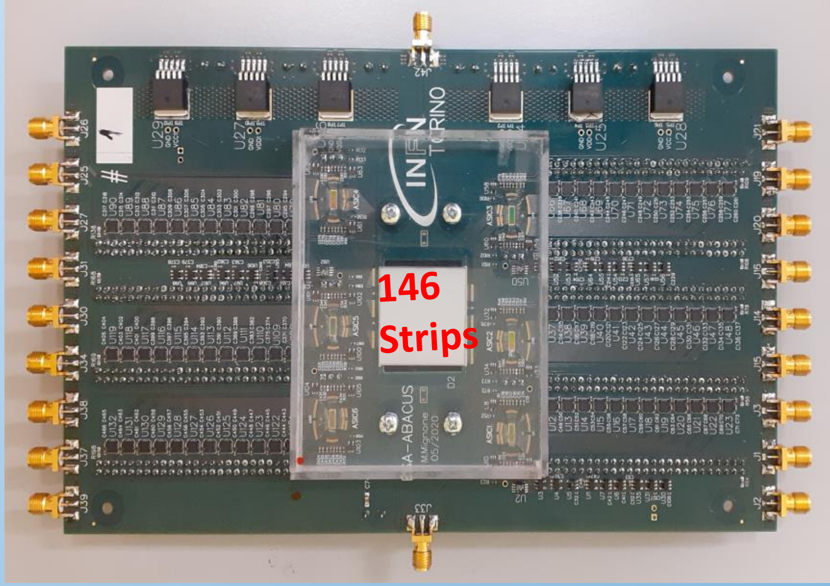
What's next?

Final characteristics of UFSD sensors for a prototype of particle counter

- **Area 3 ⨯ 3 cm ^{2} (Full Beam coverage).**
- **146 strips (144 with gain, 2 no gain).**
- **Internal gain → 5 – 20.**
- **Capacitance → ~ 9 pF.**
- **Total Thickness of sensitive volume → ~ 50 µm.**
- **Strip segmentation (strip area ~ 3 mm^2).**



Design and production ongoing @ FBK-Trento



ESA_ABACUS frontend board
ABACUS V.2

Conclusion

UFSD are a promising new technology for beam qualification and monitoring in Particle Therapy

- Fast collection time + Large S/N ratio

Directly count number of beam ions.

OPEN ISSUE: pile-up inefficiency, radiation hardness.

- Prototype for proton counting (3x3 cm^2 area, strip sensors).

Radiobiological experiments

Aiming at clinics!

A first step towards tumor tracking in charged particle therapy

Ackowledgments

This work was supported by the INFN Gruppo V (MoVe-IT project) and by the European Union's Horizon 2020 Research and Innovation funding program (Grant Agreement no. 669529 - ERC UFSD669529). We acknowledge the proactive collaboration of the Fondazione Bruno Kessler to this project. We also thank the CNAO Foundation (Pavia) and the Centro di Protonterapia (Trento) for the beam time accorded.

Istituto Nazionale di Fisica Nucleare

MoVe IT

FONDAZIONE BRUNO KESSLER