Test of thin Ultra-Fast Silicon Detectors (UFSD) for monitoring of high flux charged particle beams

V.Monaco (Università di Torino and INFN, Italy)

Z.Amadi, R.Arcidiacono, A.Attili, N.Cartiglia, M.Donetti, F.Fausti, M.Ferrero, S.Giordanengo, O. Hammad Ali, M.Mandurrino, L.Manganaro, G.Mazza, R.Sacchi, V.Sola, A Staiano, A Vignati, R. Cirio

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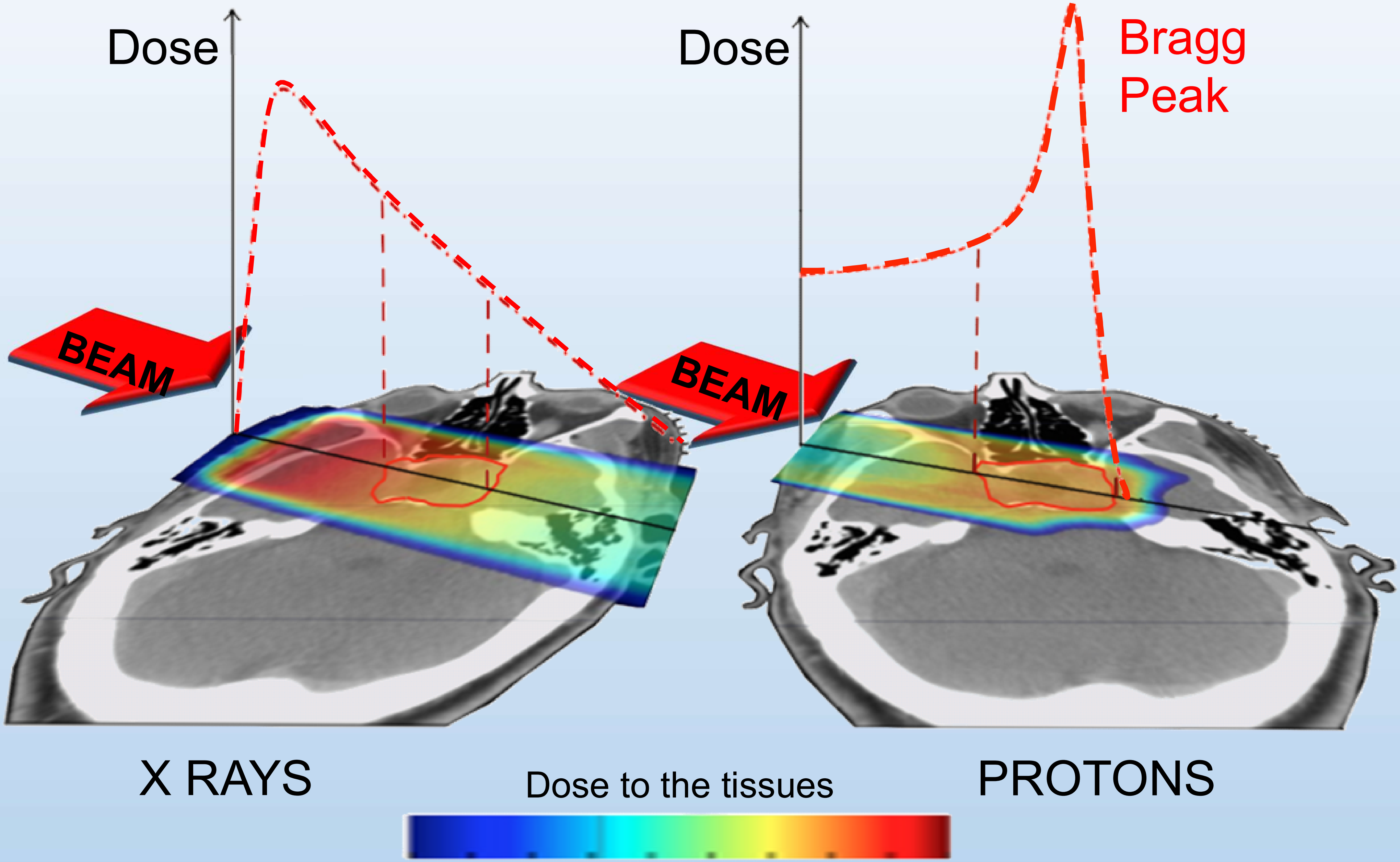
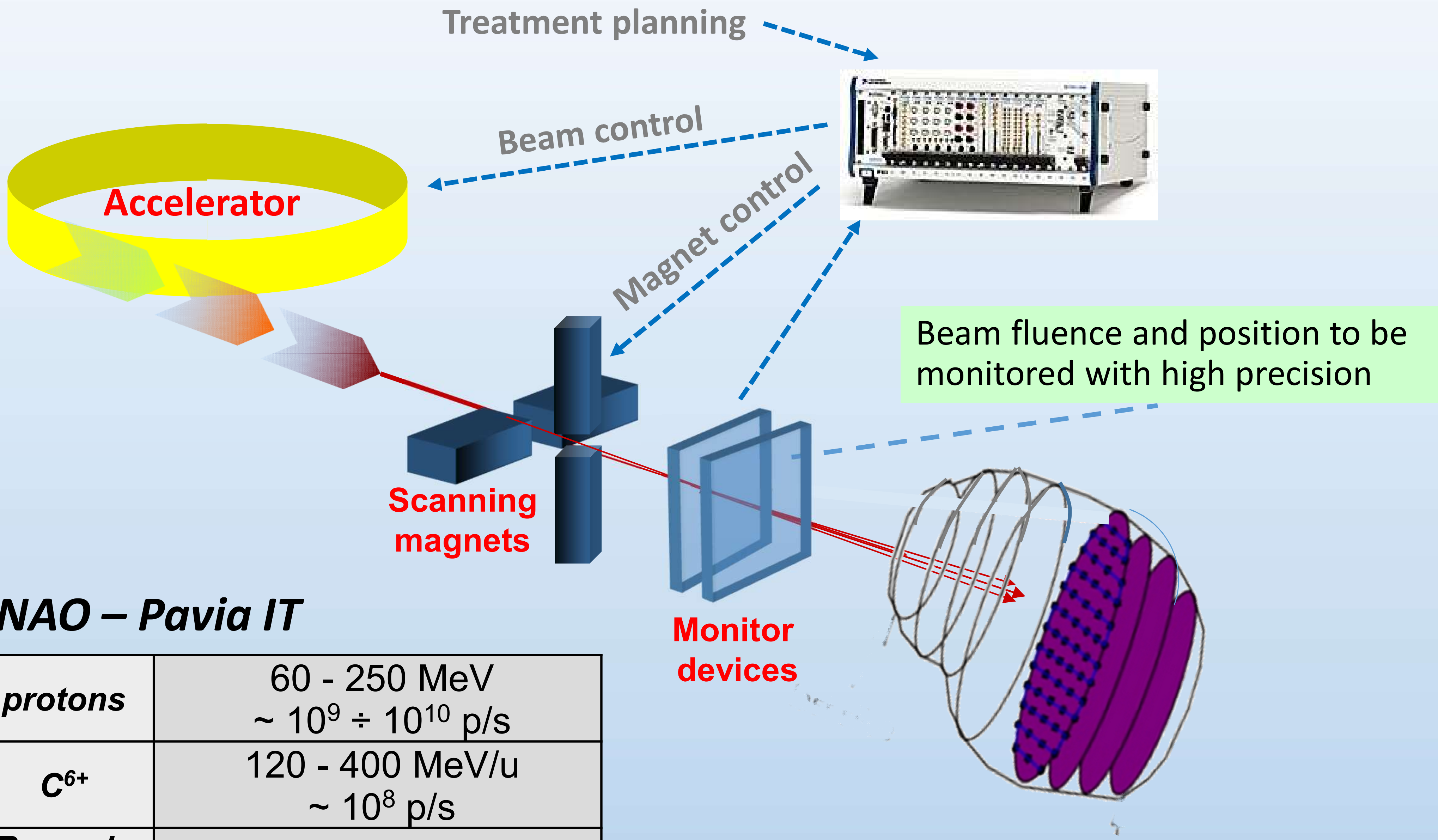
Charged Particle Therapy



Active Spot Scanning: beam monitoring



Treatment planning

Beam control

Magnet control

Accelerator

Scanning magnets

Monitor devices

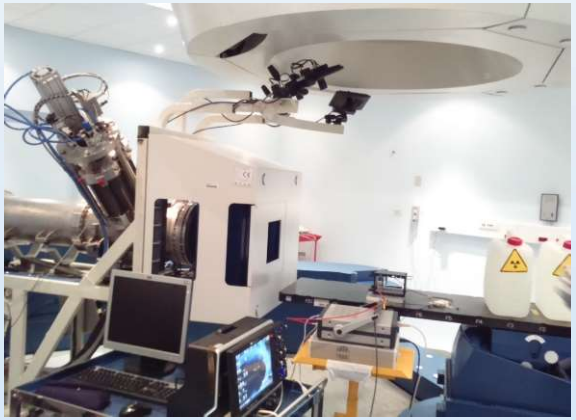
Beam fluence and position to be monitored with high precision

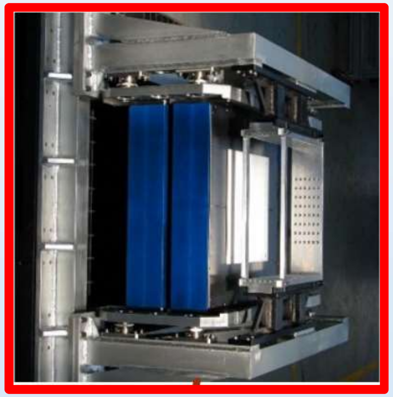
CNAO – Pavia IT

protons	60 - 250 MeV ~ $10^9 \div 10^{10}$ p/s
C^{6+}	120 - 400 MeV/u ~ 10^8 p/s
Range in water	3 - 27 cm

Beam monitoring in charged particle therapy

Parallel-plate ionization chambers





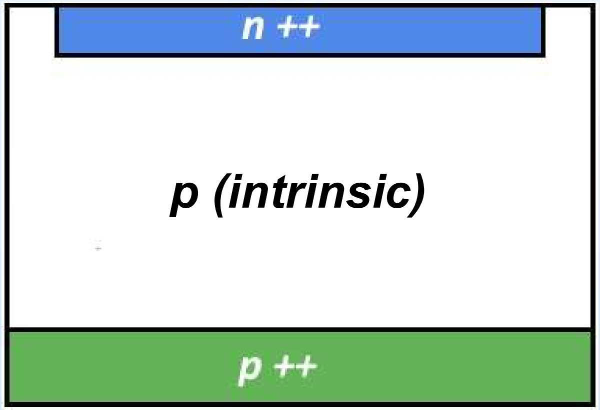
PROS:

- Robust, stable, radiation resistance

CONS;

- Slow response time
- Limited sensitivity
- Measurement of number of particles from the produced charge depends on energy
- Daily QA and calibration measurements.

Silicon detectors



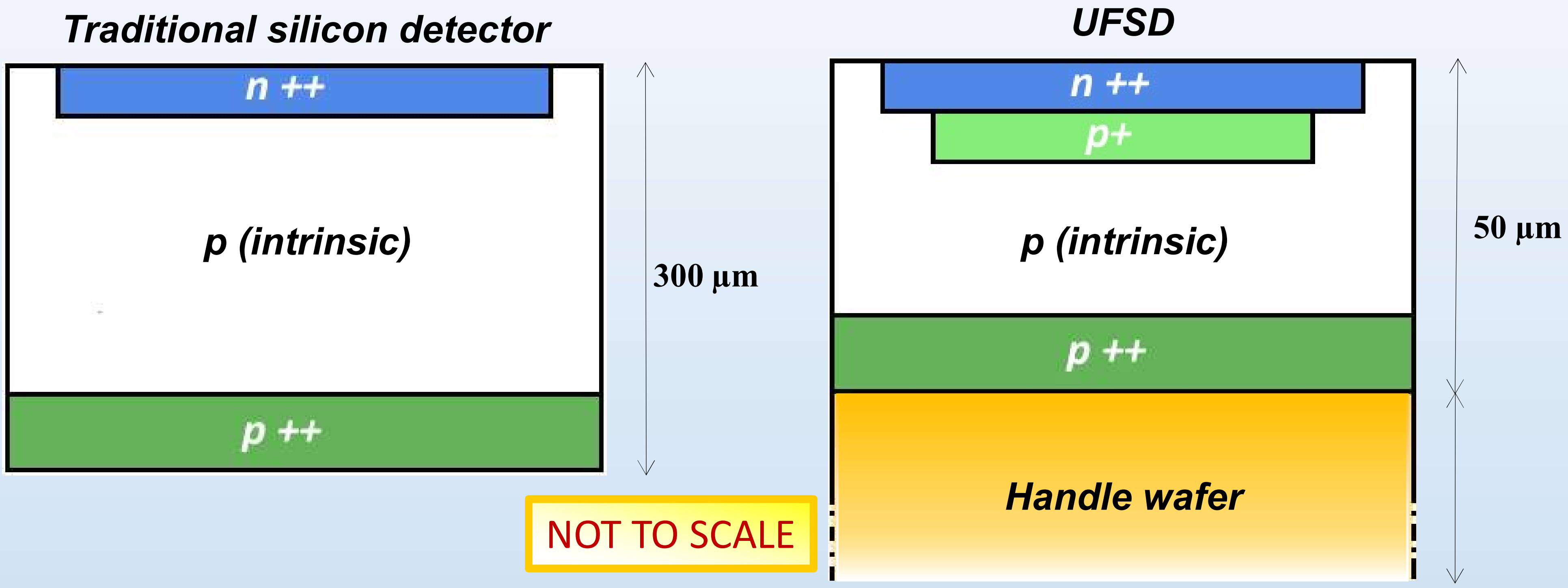
PROS:

- Good sensitivity (single particle detection)
- Small signal duration (direct count of number of particles)
- Fine segmentation -> beam profile
- Time resolution (measurement of beam energy with time-of-flight techniques)

CONS:

- Pile-up effects at high frequencies
- Radiation resistance.

Ultra-Fast Silicon Detectors (UFSD)



- ✓ controlled low gain (based on LGAD, Low-Gain Avalanche Detectors)
- ✓ Enhanced signal -> smaller thickness -> smaller signal durations;
- ✓ excellent time resolutions;

H.F.-W. Sadrozinski et al. Ultra-fast silicon detectors (UFSD) Nucl. Instrum. Meth. A831 (2016) 18-23.

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

Aim of the project …

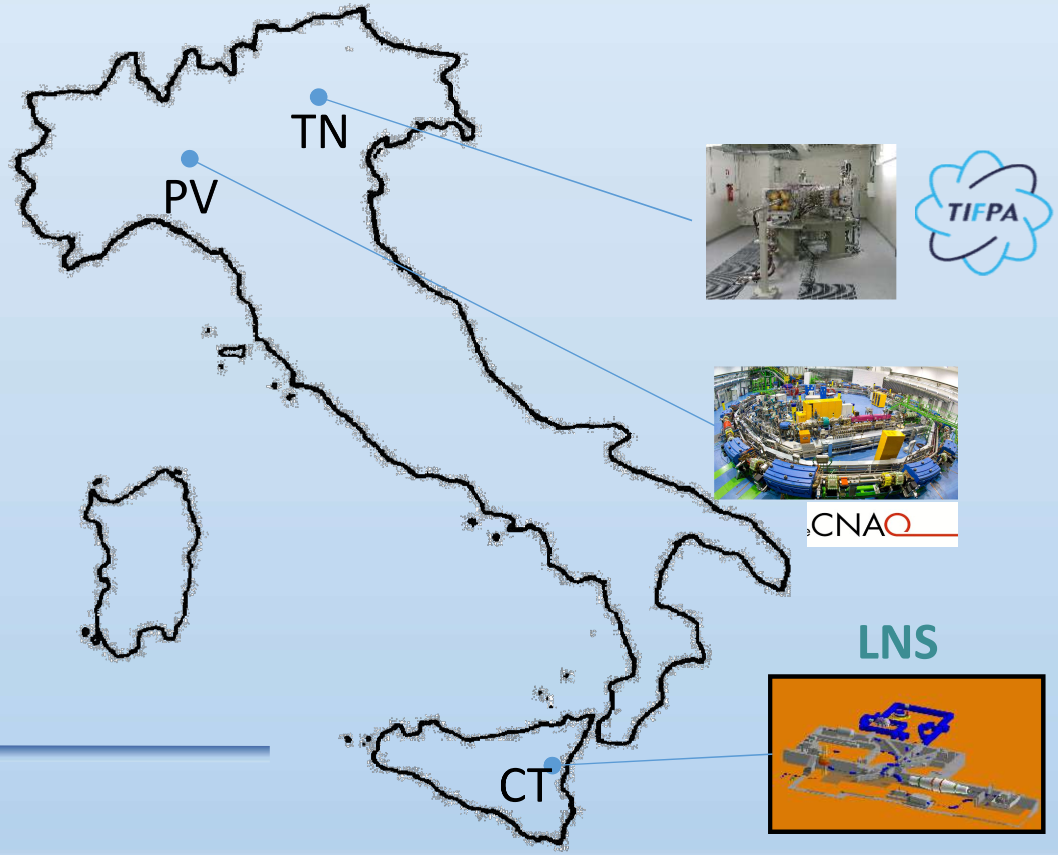
Development of two UFSD prototype devices:

- ✓ **to directly count individual protons at high rates and (thanks to the segmentation in strips) and to measure the beam profiles in two orthogonal directions;**
- ✓ **to measure the beam energy with time-of-flight techniques, using a telescope of two UFSD sensors**

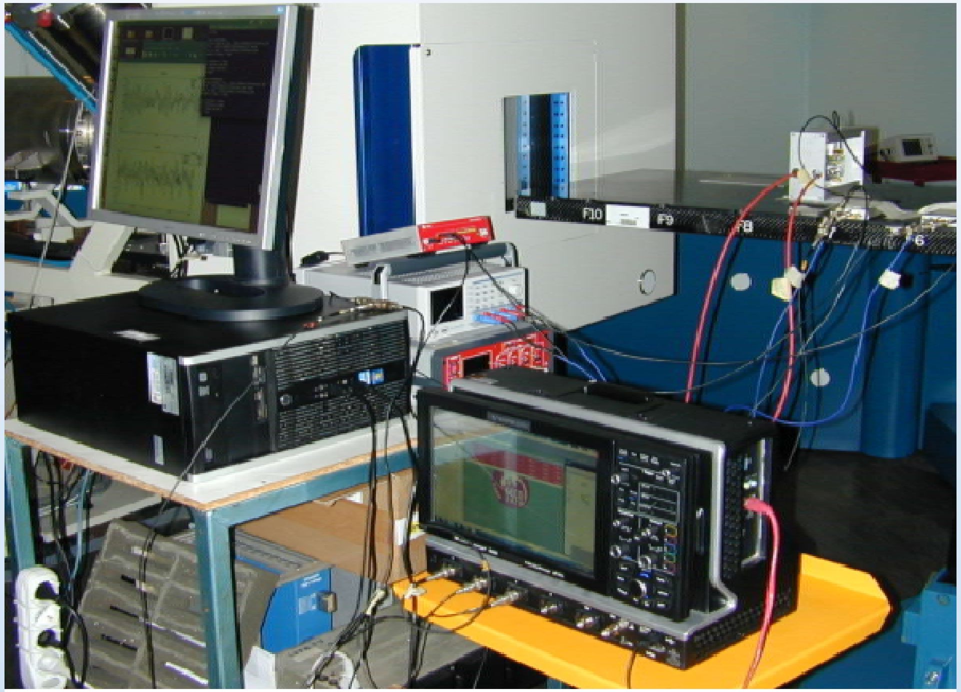
Prototypes will be developed for radiobiological applications and used in the three italian therapy facilities

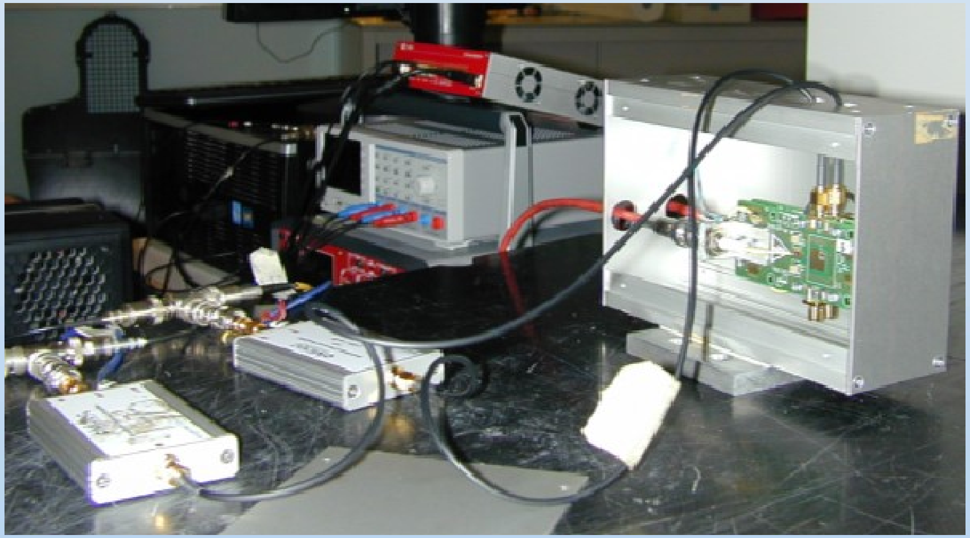
FOV = 3x3 cm^2;

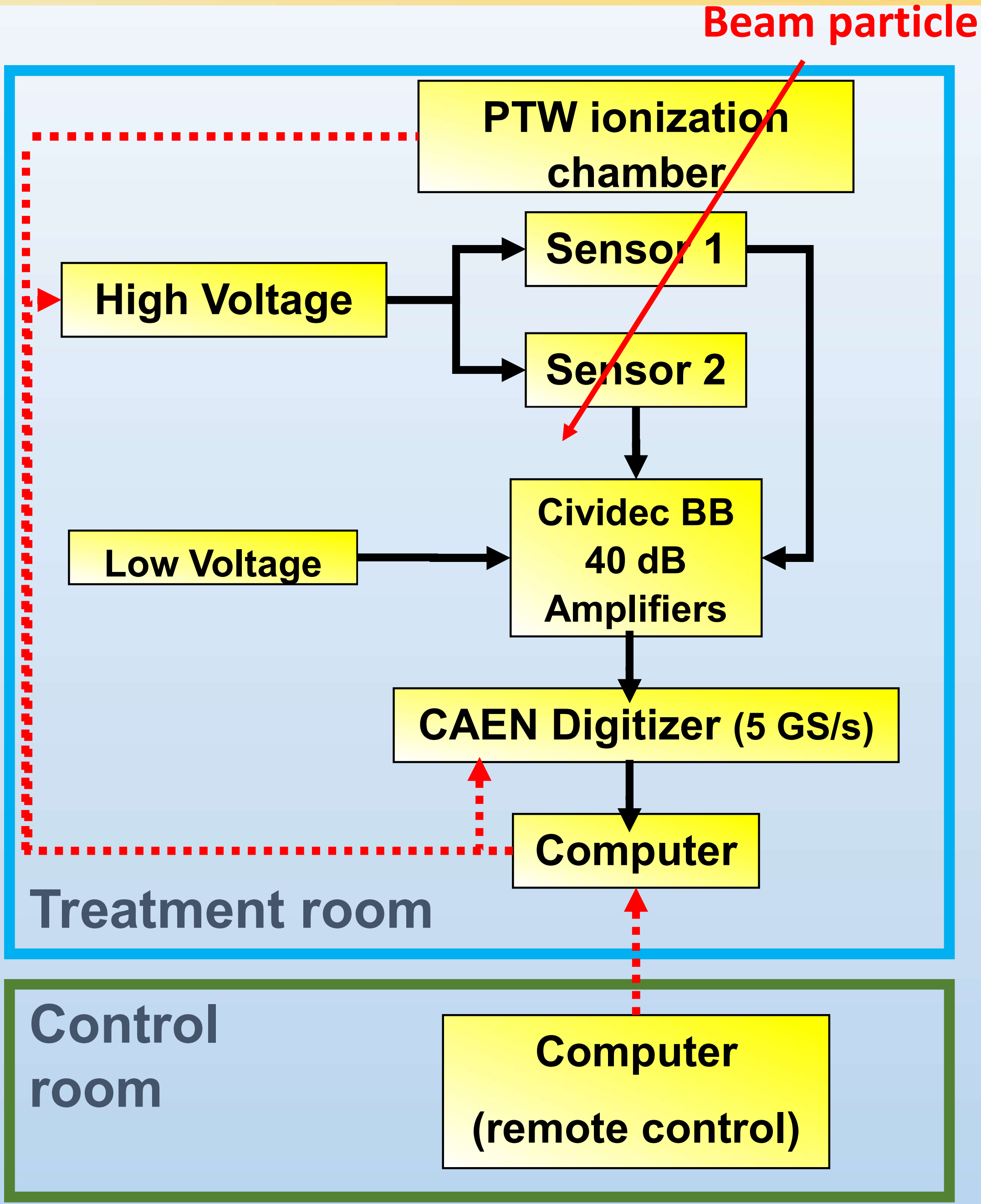
Flux > 10^8 p/s cm^2 (error < 1%)



Beam tests of UFSD sensors (CNAO 2017)

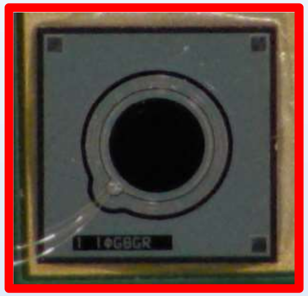


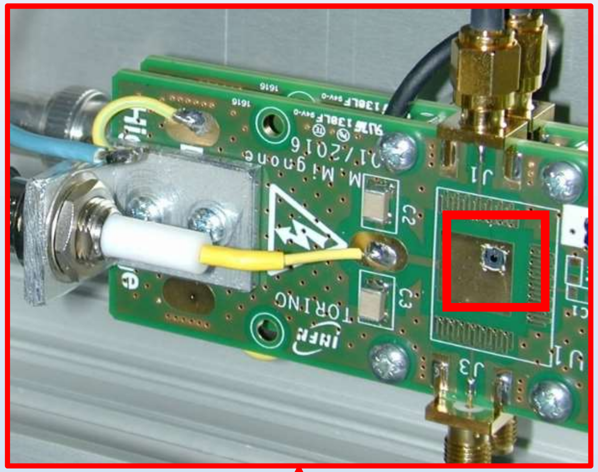


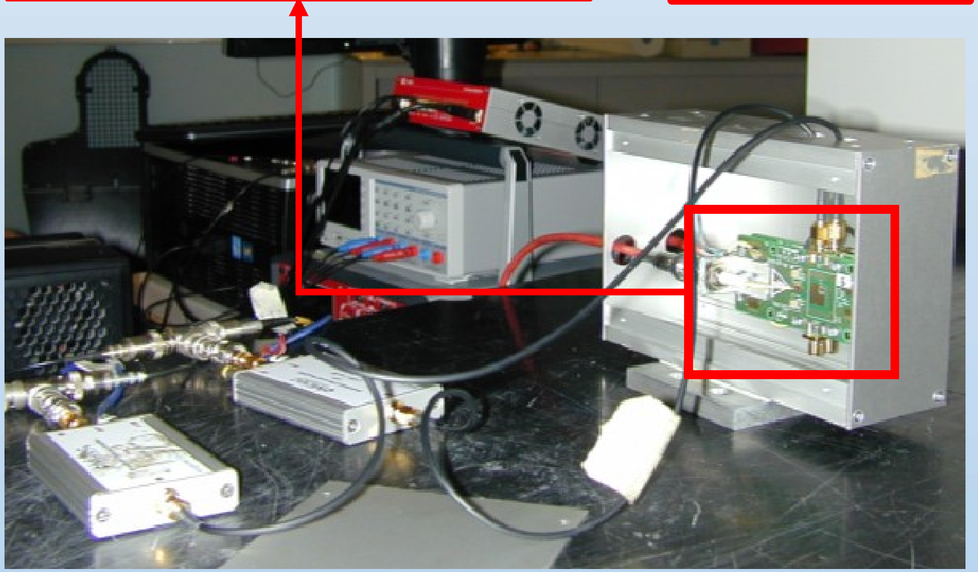


Beam tests of UFSD pads (CNAO 2017)

2 detectors of 50 µm:
1. CNM 1,2 x 1,2 mm^2;
2. Hamamatsu Ø 1 mm.

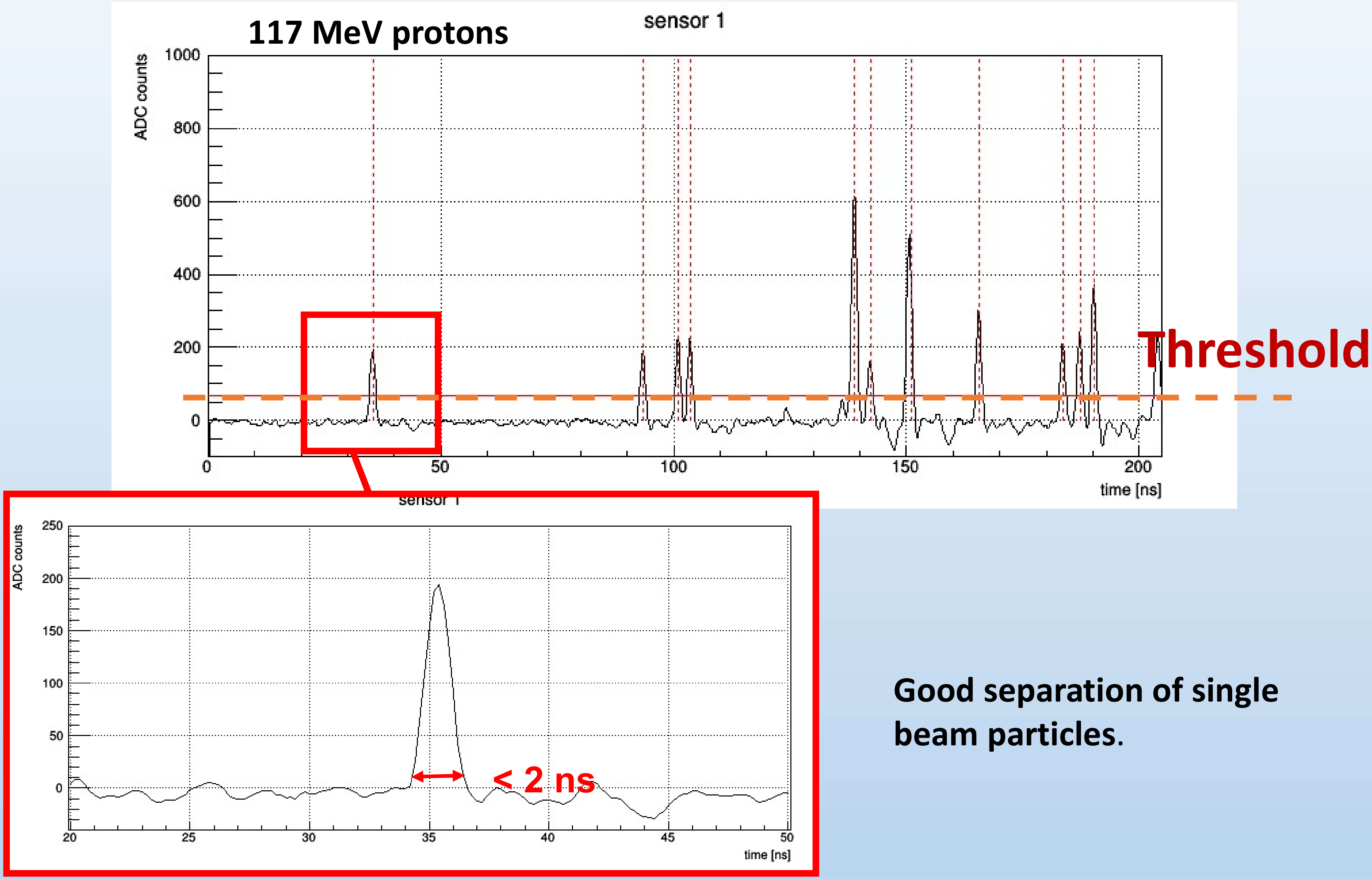






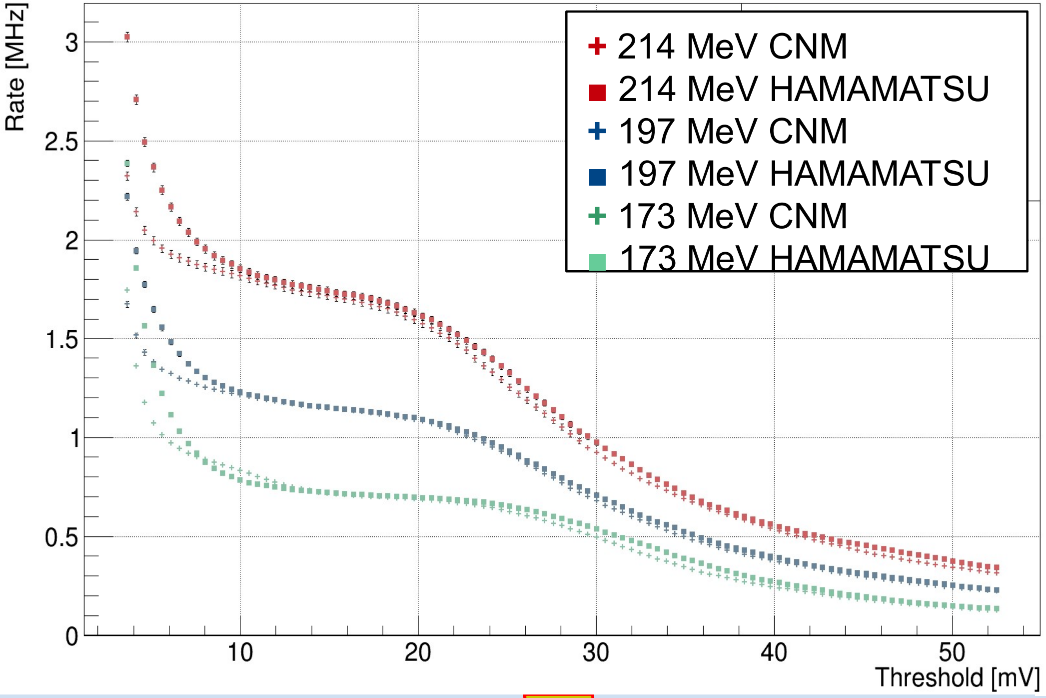
- ✓ CNAO (Pavia);
- ✓ 32 runs;
- ✓ ~ 2*10^{10} p each run (FWHM 1 cm);
- ✓ 20 spills/run (1 sec/spill)
- ✓ protons (62-227 MeV);
- ✓ Different beam intensities (20-100 % of max flux).

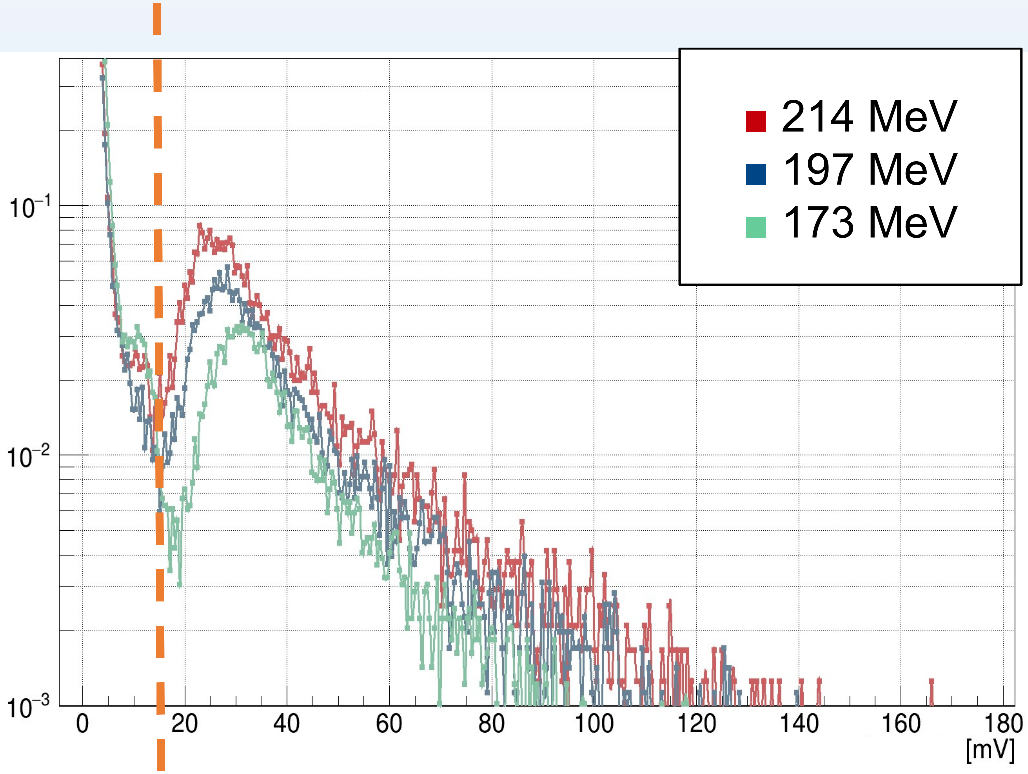
Signal shape (digitizer)



Good separation of single beam particles.

Threshold scan

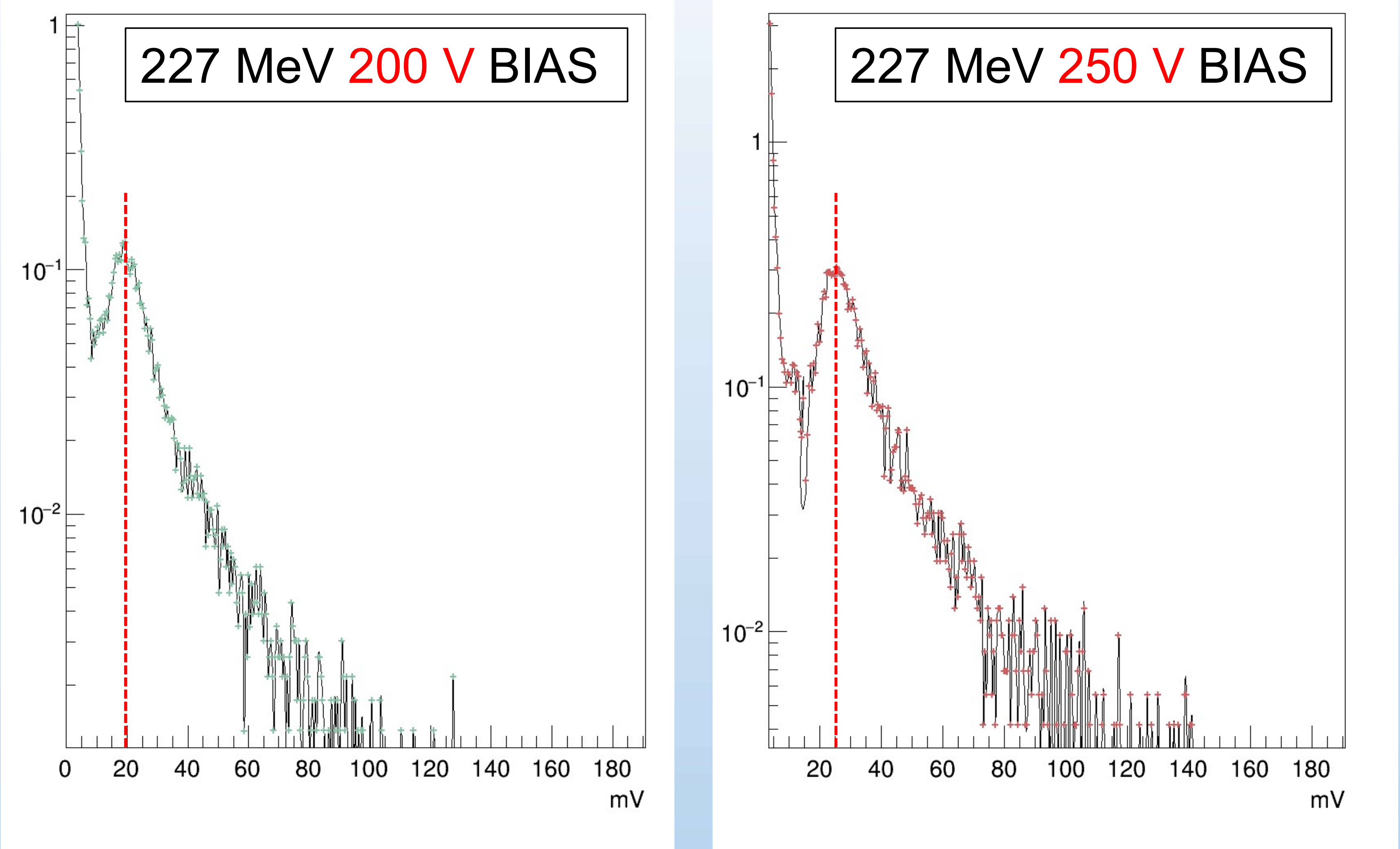




Derivating

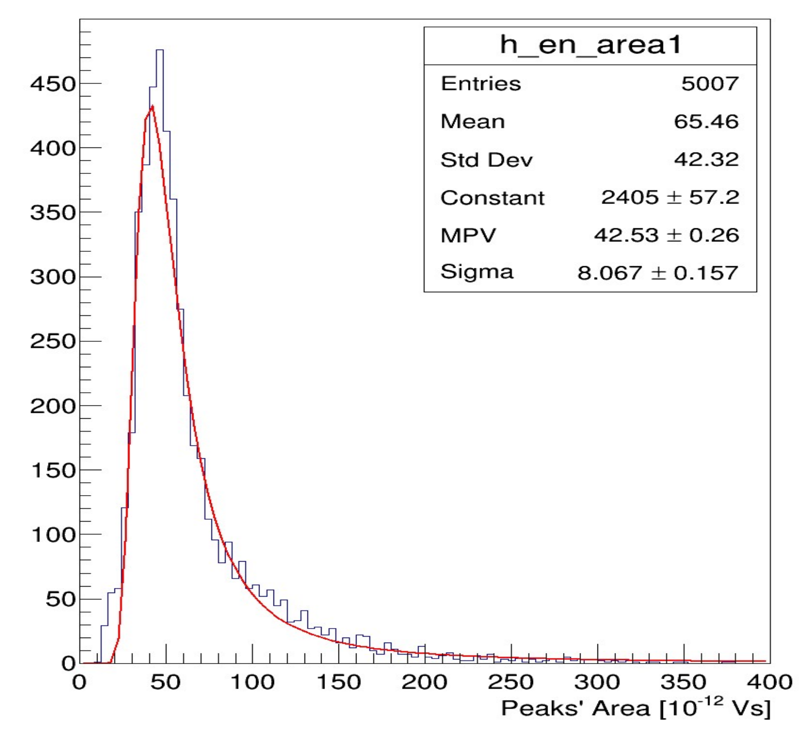
Best threshold

Control of Signal to Noise Ratio

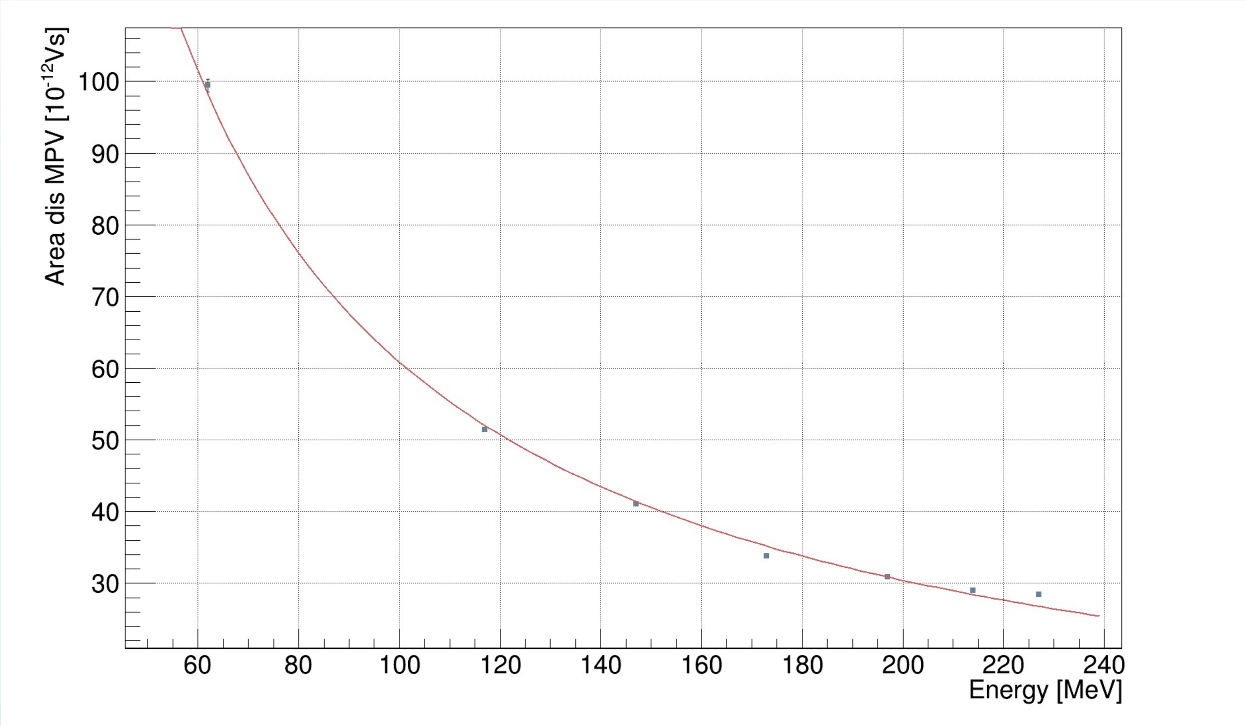


Landau distributions

Proton energy 143 MeV

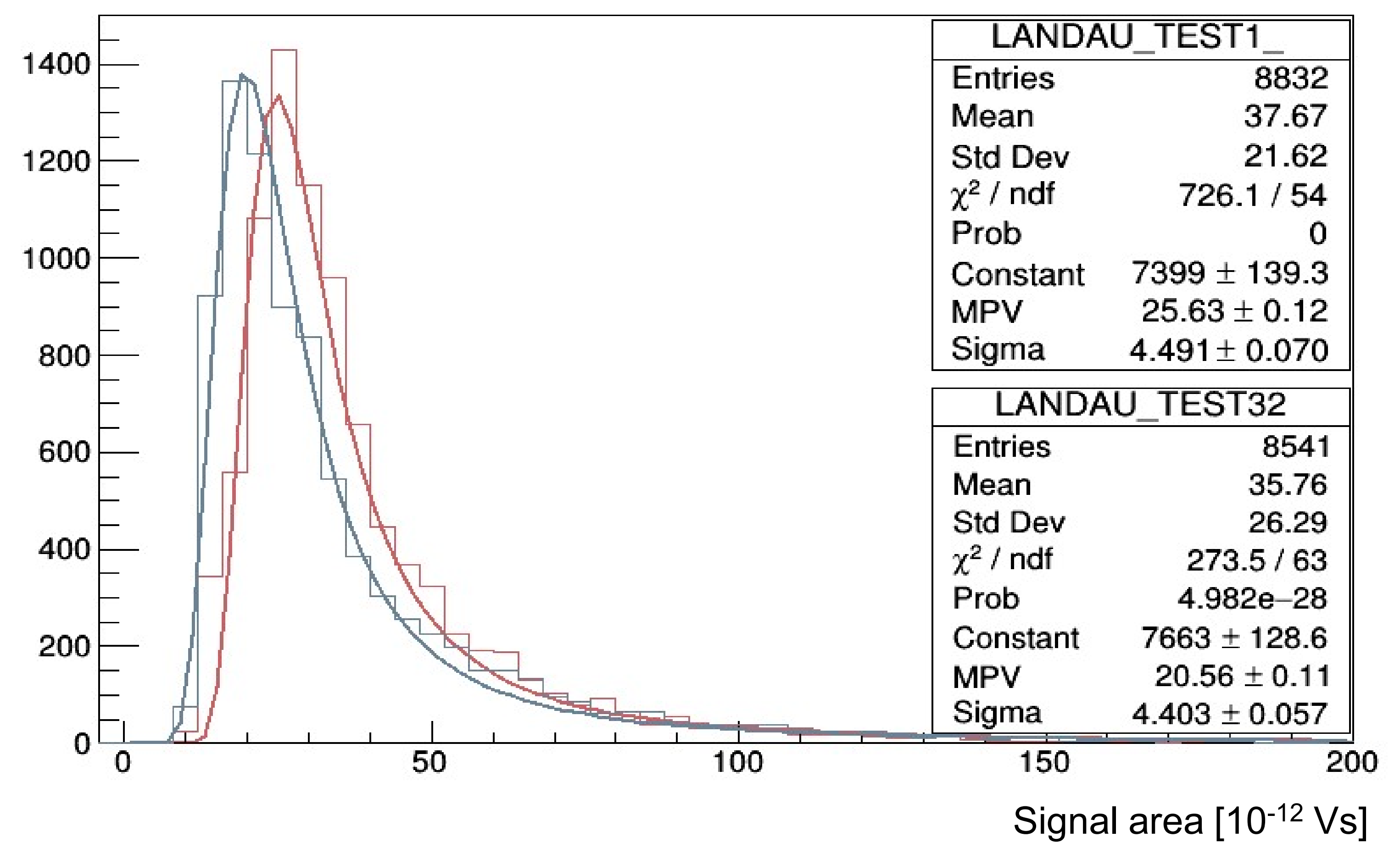


MPV vs energy



Bethe-Bloch curve’s trend

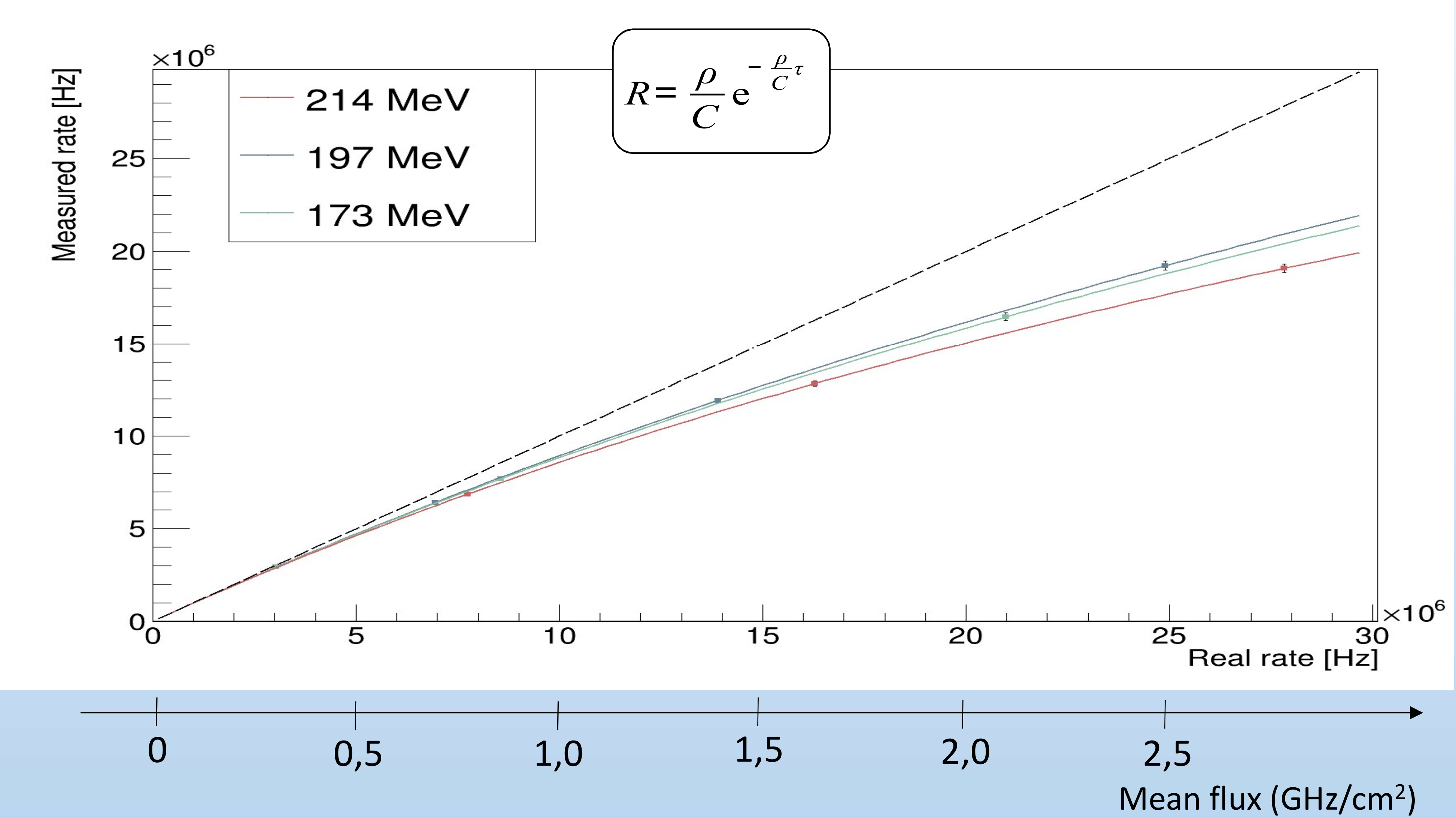
Radiation damage



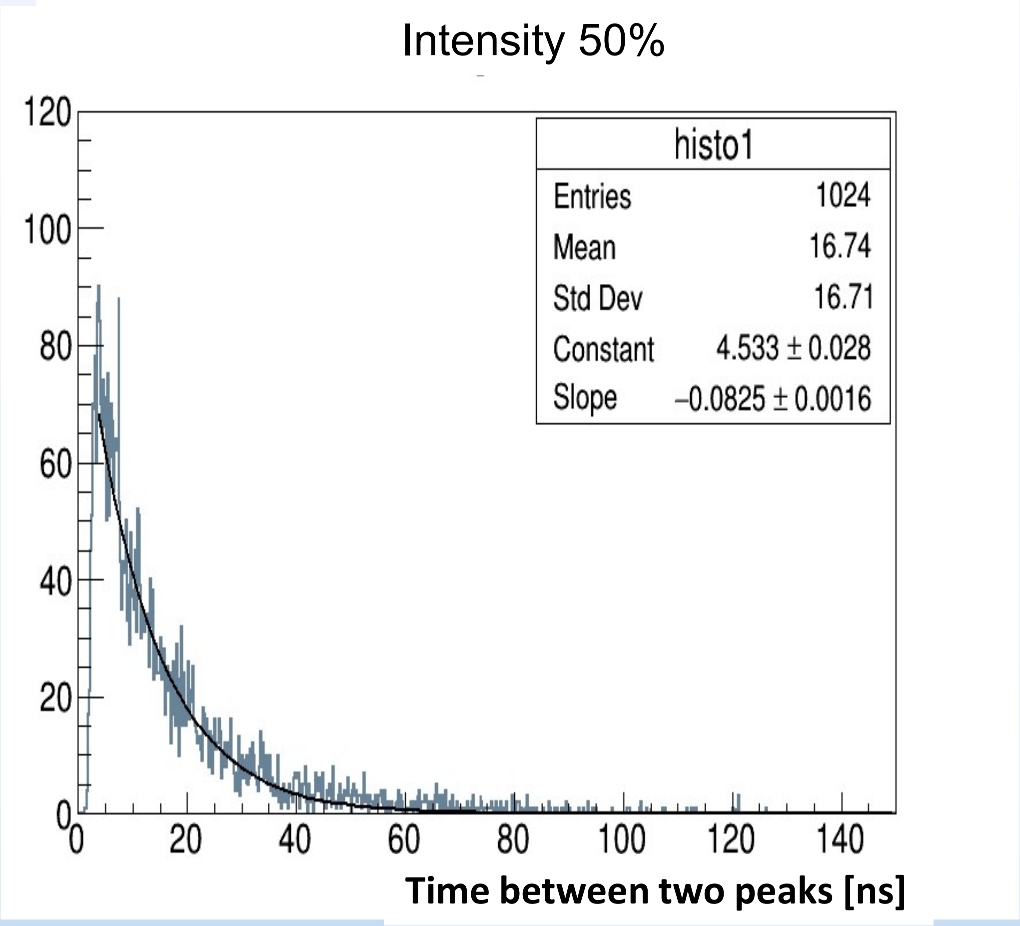
20% signal loss after ~ 10^{12} protons/cm^2

Pile-up and saturation effects

Fit to a paralyzable pile-up model, usign the PTW ionization chamber to estimate the real particle rate.



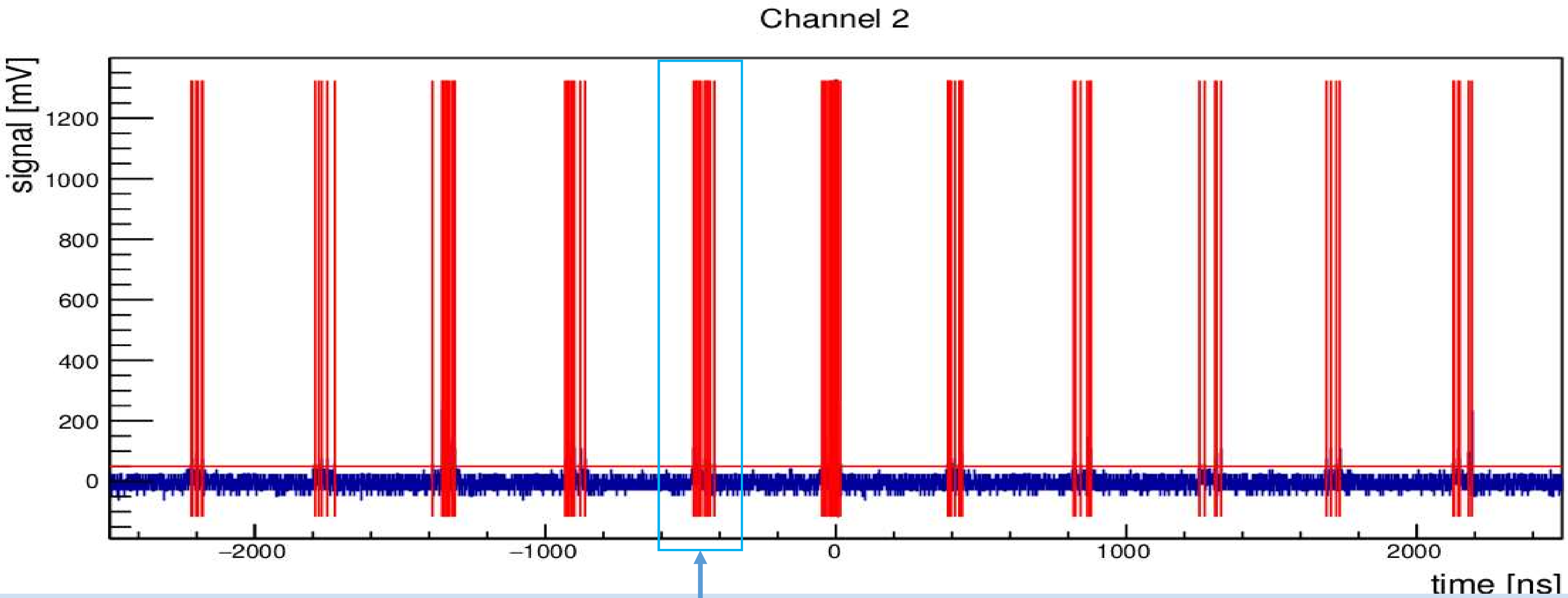
Beam structure



Intensity	Rate (counts) [MHz]	Rate (Poissonian fit) [MHz]
20%	2.92 ± 0.03	50.7 ± 1.1
50%	7.70 ± 0.09	82.5 ± 1.6
100%	13.57 ± 0.21	127.3 ± 2.6

The distribution of time difference between neighbouring peaks is compatible with a Poissonian distribution but with a pulse frequency one order of magnitude higher than the mean frequency measured with counts.

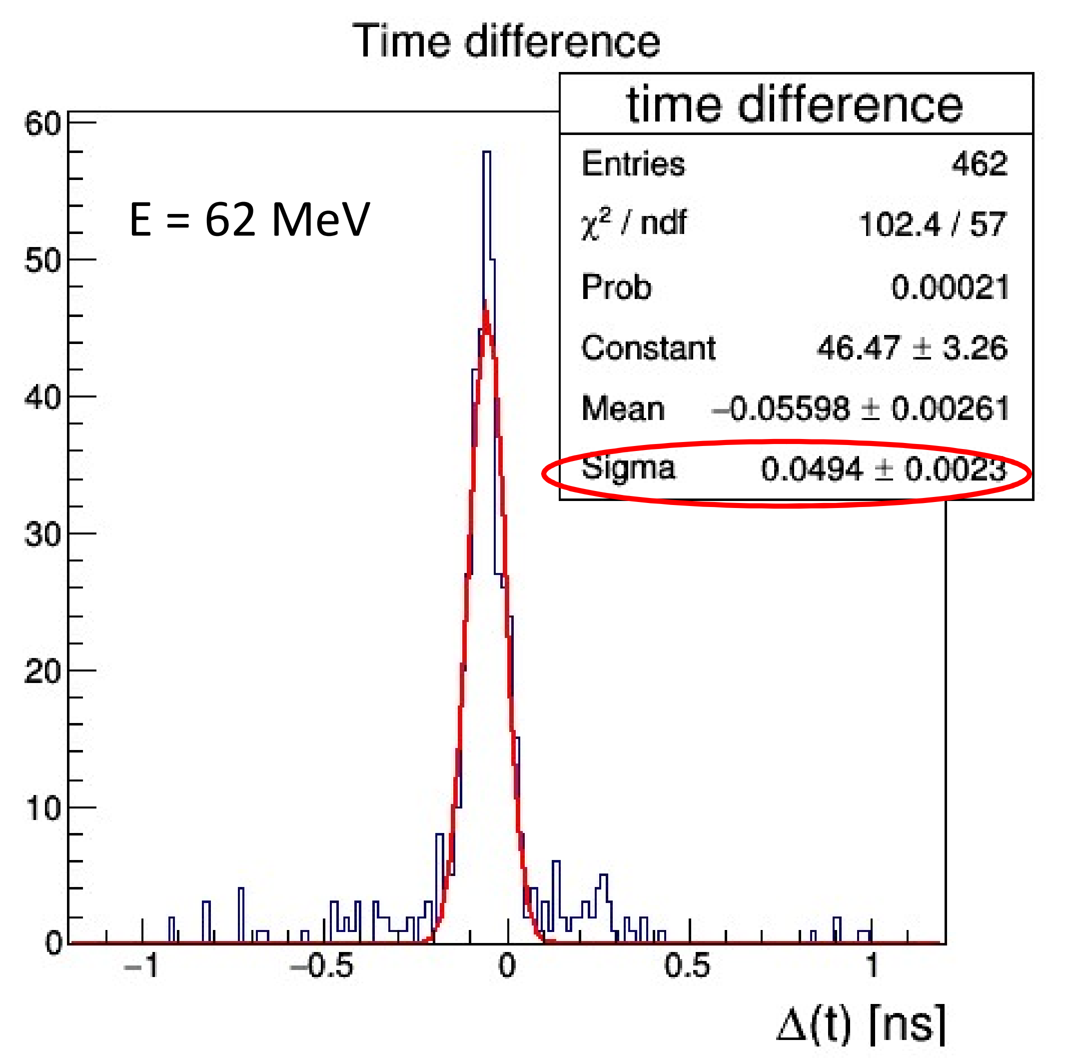
Beam structure



Instantaneous flux
~10^{10} p/s cm^2 !!

Mitigation techniques of saturation effects due to pile-up under investigation !!

Timing



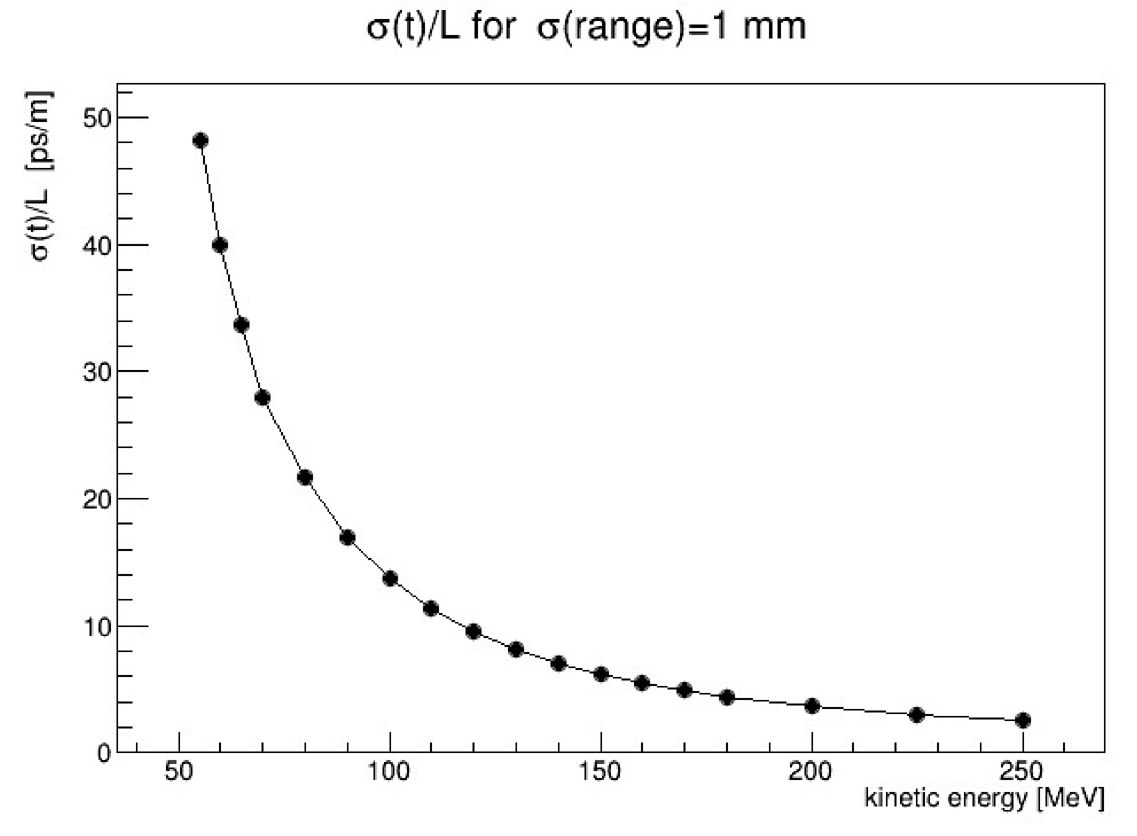
CFD algorithm applied on signals waveforms collected with digitizer

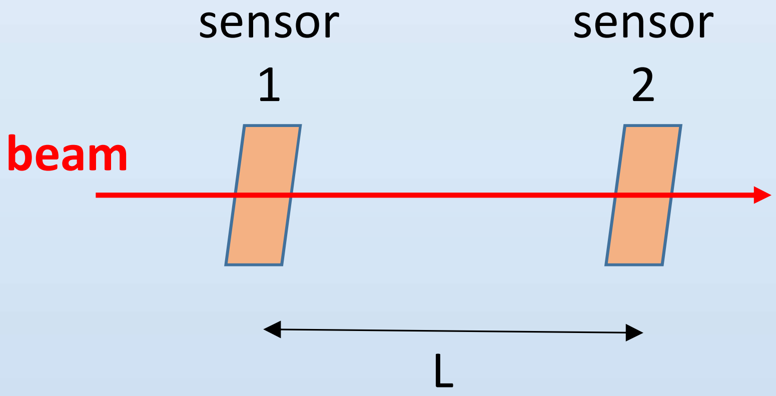
Time resolution of single crossing

$\sigma(t) = 35$ ps !!

Timing requirements for energy measurement

Error on time difference corresponding to a range uncertainty < 1 mm in water.

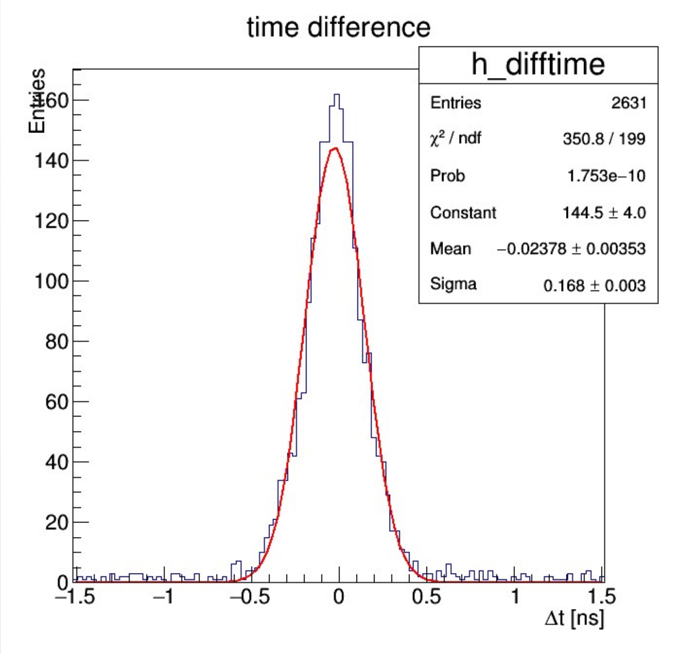




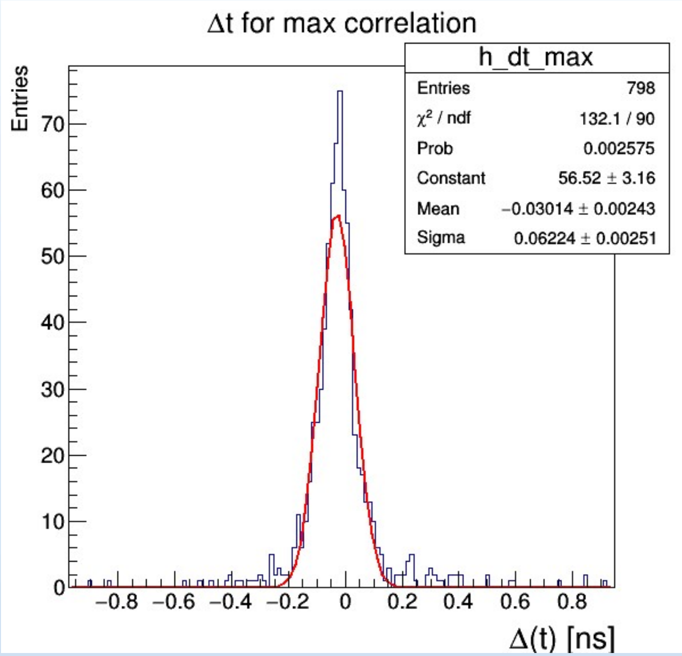
To reach such an error on the mean time difference a large number of measurements Is needed !!

Timing measurements with different algorithms

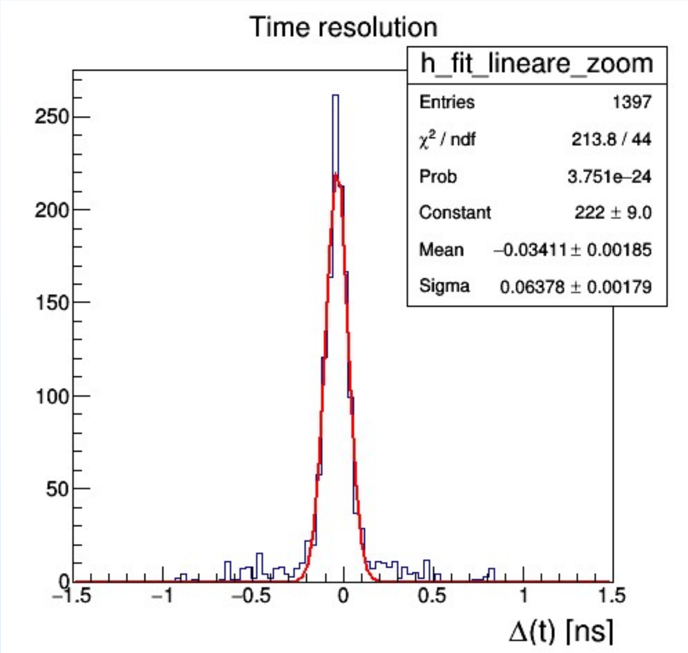
LE - leading edge
(fix threshold)



CC - Maximization of cross-correlation
function of two digitizer waveforms



CFD



1400 digitizer snapshots
($T_{acquisition}$ = 300 μs)
E = 114 MeV

Algorithm	Mean Δt	Δt resolution
LE	**- (24 ± 3) ps**	**170 ps**
CC	**- (30 ± 2) ps**	**62 ps (snapshot)**
CFD	**- (34 ± 2) ps**	**64 ps**

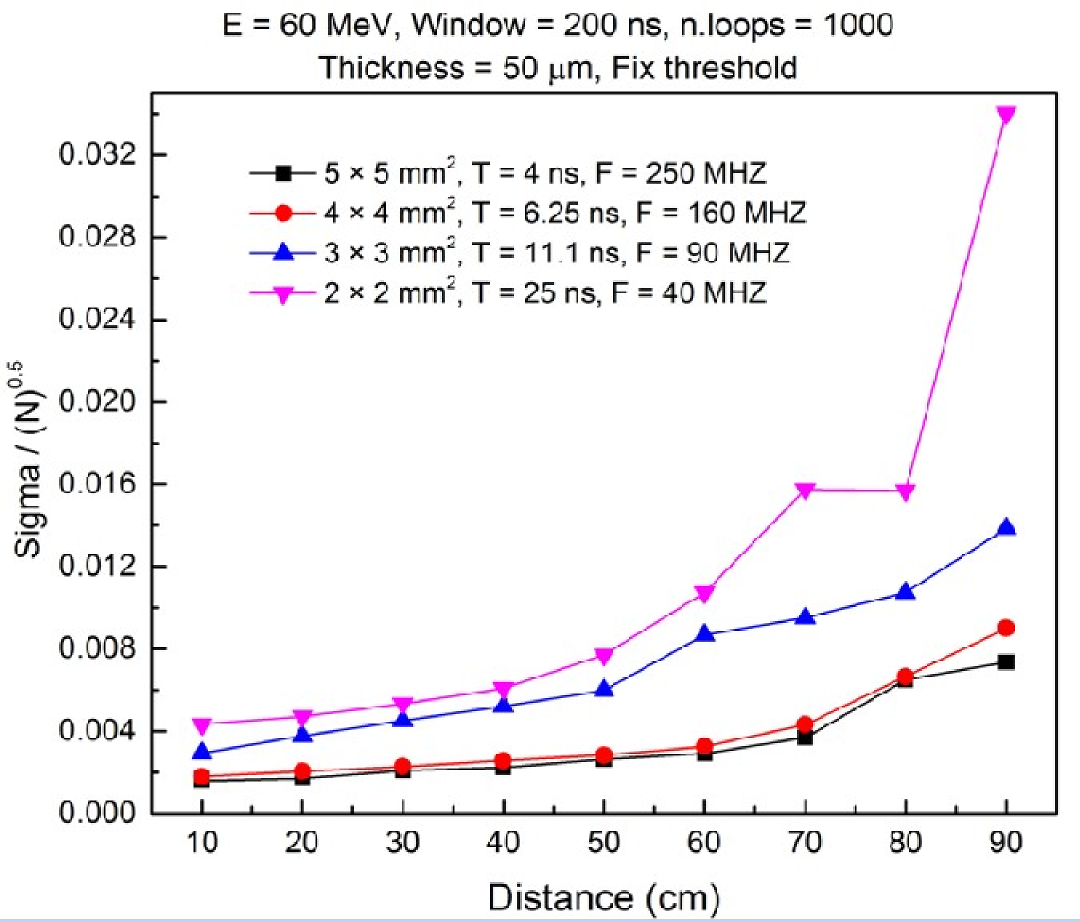
Simulation of UFSD beam telescope

GEANT4 simulation of material effects (energy loss and multiple scattering)
WEIGHTFIELD2 simulation of the UFSD response.

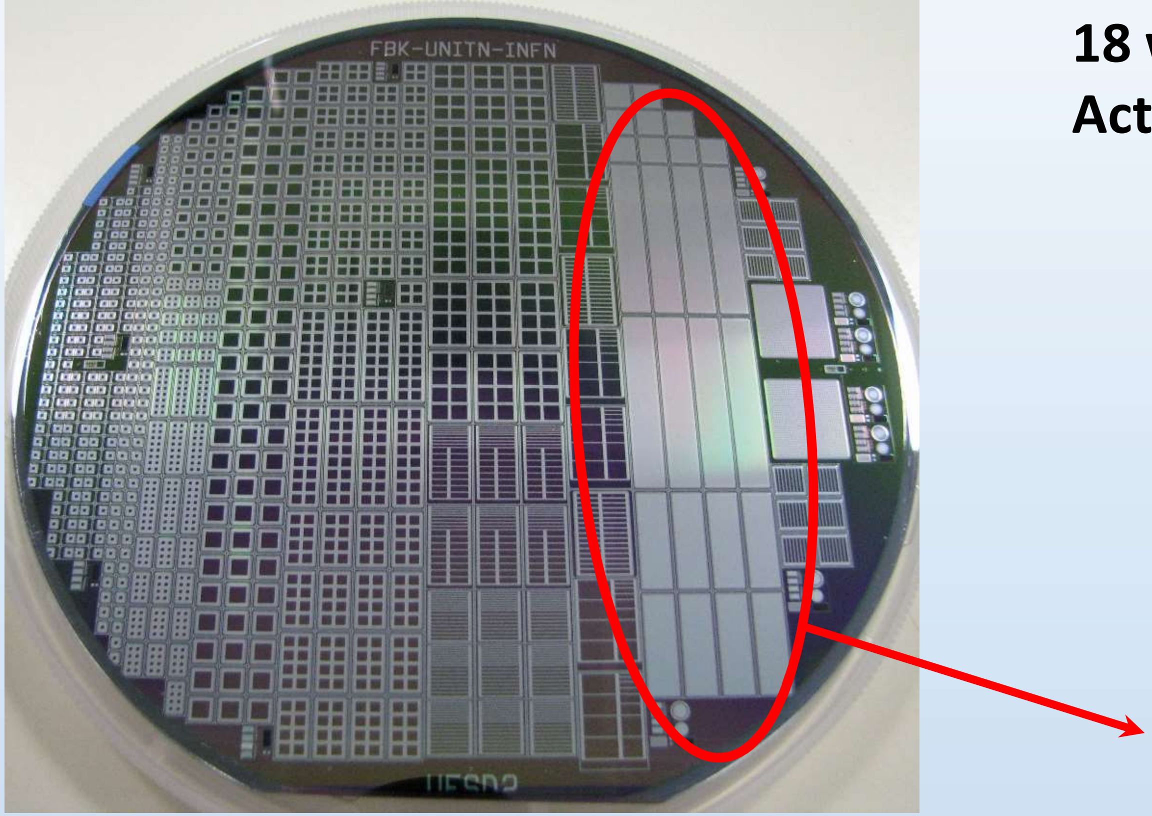
f = 10^9 p/(s·cm^2)

$T_{acquisition}$ = 200 μs

Error on mean Δt vs distance

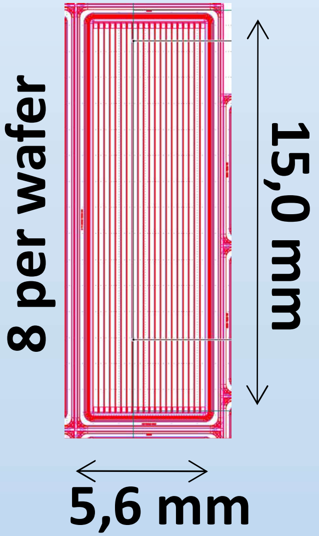


Production of UFSD strip sensors

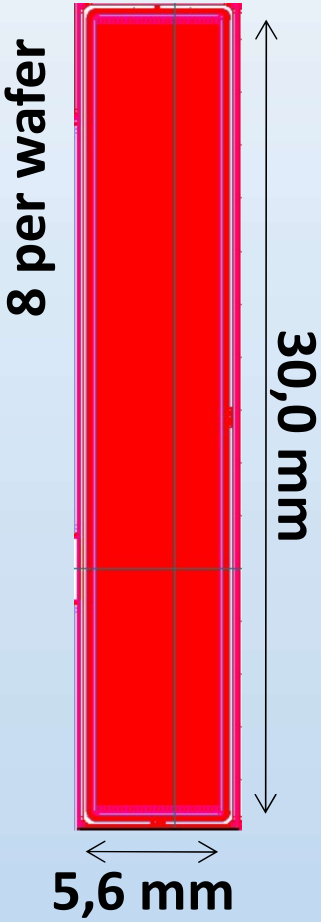


18 wafers

Active sensor thickness 50 μm



20 strips
pitch 200 μm



30 strips
pitch 146 μm

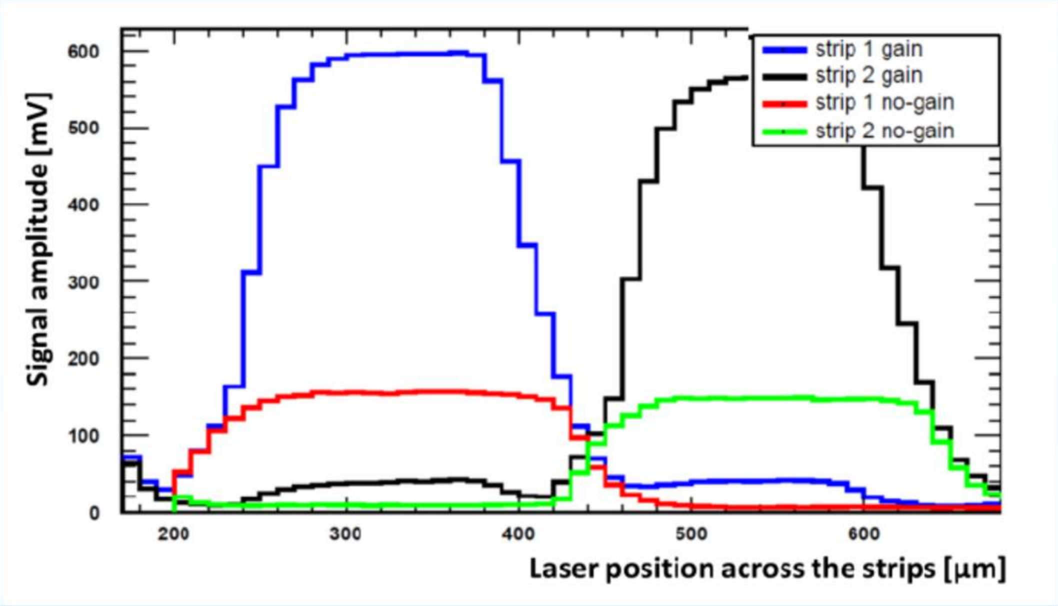
Optimization for radiation resistance

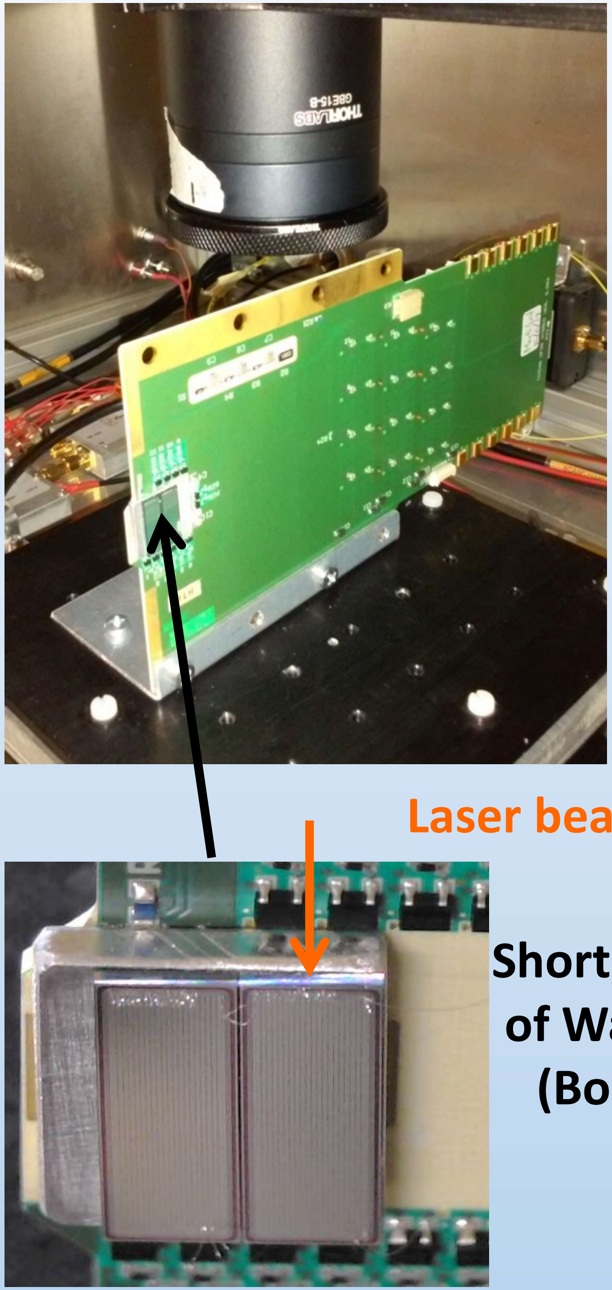
- ✓ **Different doping doses;**
- ✓ **Doping with gallium instead of boron;**
- ✓ **Treatment with a carbon spray;**
- ✓ **Varying the thermal cycle for activation.**

UFSD strip sensors

2 sensors, one with gain and the neighbour without.
Amplifier Pilsen Board (CMS CT-PPS)
Sensor shifted to allow laser scan along the strip edge

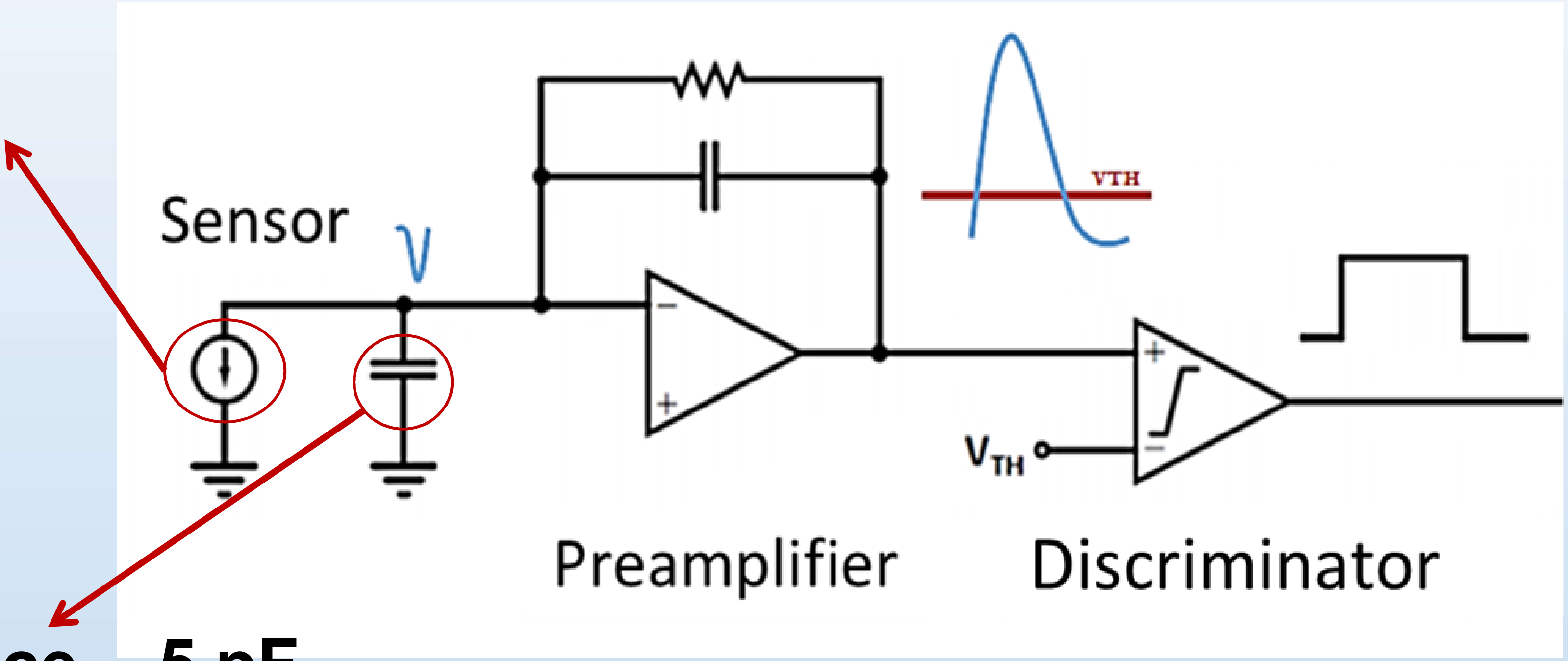
λ = 1060 nm
Spot size = 20 µm





Short Strips of Wafer 8 (Boron)

Fast readout electronics



Sensor Signal

Sensor Capacitance ~ 5 pF

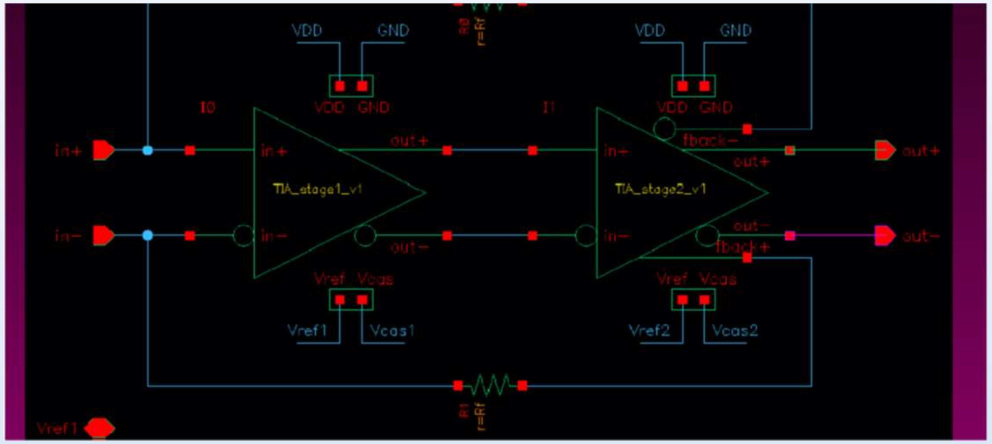
Proton beam energy range: 60÷250 MeV (6-2 MIPs)
Front-End Input charge range: 3 fC ÷ 140 fC
Fluxes measurements: up to 10^8 p cm^{-2} s^{-1}
Pile-up probability kept < 1 %.

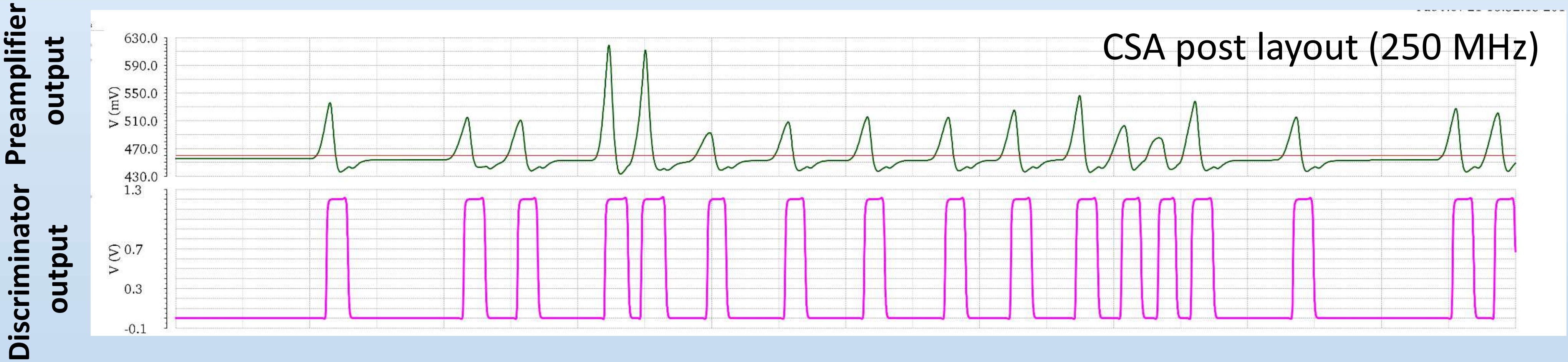
Readout electronics

Design based CSA with capacitive feedback and fast reset of the input capacitance

Design based on TIA with differential architecture.

TIA architecture




CSA post layout (250 MHz)

ASIC design ready for both the architectures (24 channels/chip)
sLVS output and readout in external FPGA.
Submission for chip production this week.

Conclusions

UFSD in charge particle therapy could open new perspectives:

Directly count the number of particles → exploiting the large UFSD S/N ratio and fast collection time in small thicknesses;

Measure the energy of the beam → exploiting the outstanding time resolution.