Istituto Nazionale di Fisica Nucleare

FONDAZIONE BRUNO KESSLER

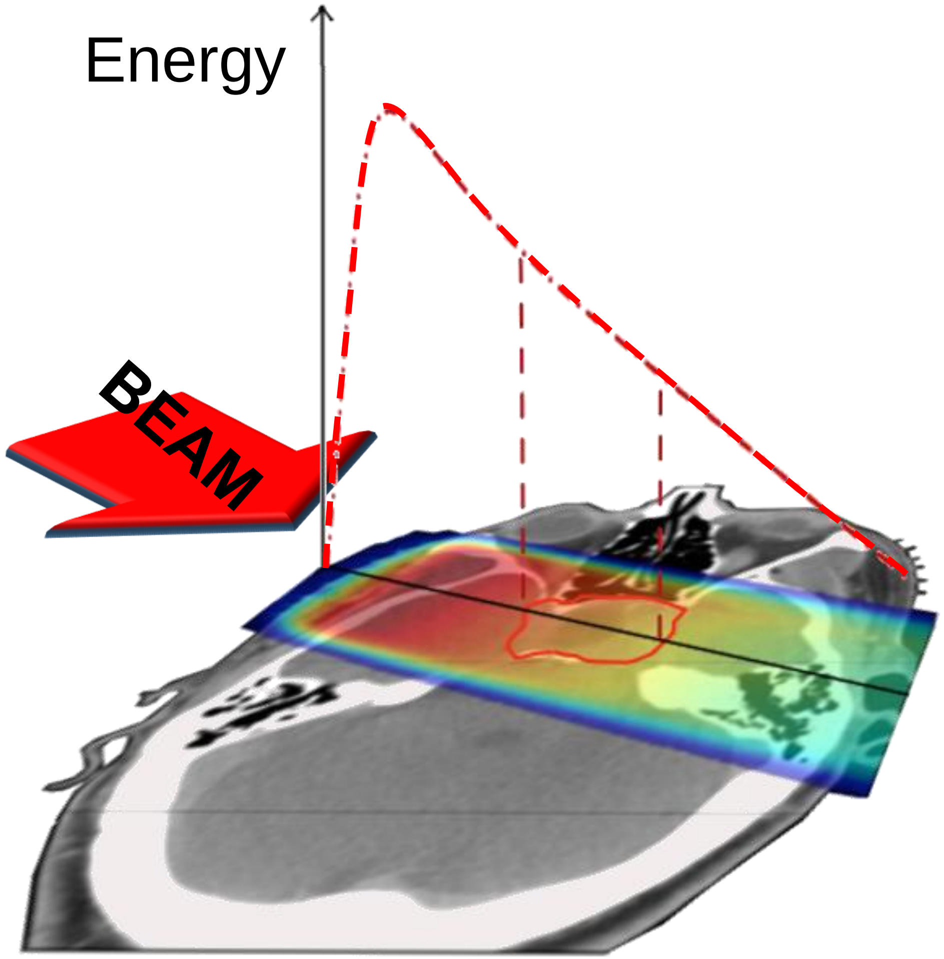
MoVe IT INFN project

Silicon Detectors for beam monitoring in proton therapy: MoVeIT preliminary results.

A Vignati[1], Z. Ahmadiganeh, A Attili[1], M Boscardin[3], N Cartiglia[1], GF Dalla Betta[4], M Donetti[5], F Fausti[1,6], M Ferrero[1], F Ficorella[3], S Giordanengo[1], O Hammad Ali[1,2], M Mandurrino[1], L Manganaro[1,2], G Mazza[1], V Monaco[1,2], L. Pancheri[4], G Paternoster[3], R Sacchi[1,2], Z Shakarami[2], V Sola[1], A Staiano[1], R Cirio[1,2]

1 – INFN - National Institute for Nuclear Physics - Torino, 2 – Università degli Studi di Torino, 3 – Fondazione Bruno Kessler (FBK), 4 – Università degli Studi di Trento, 5 – Fondazione CNAO, 6 – Polytechnic University of Turin

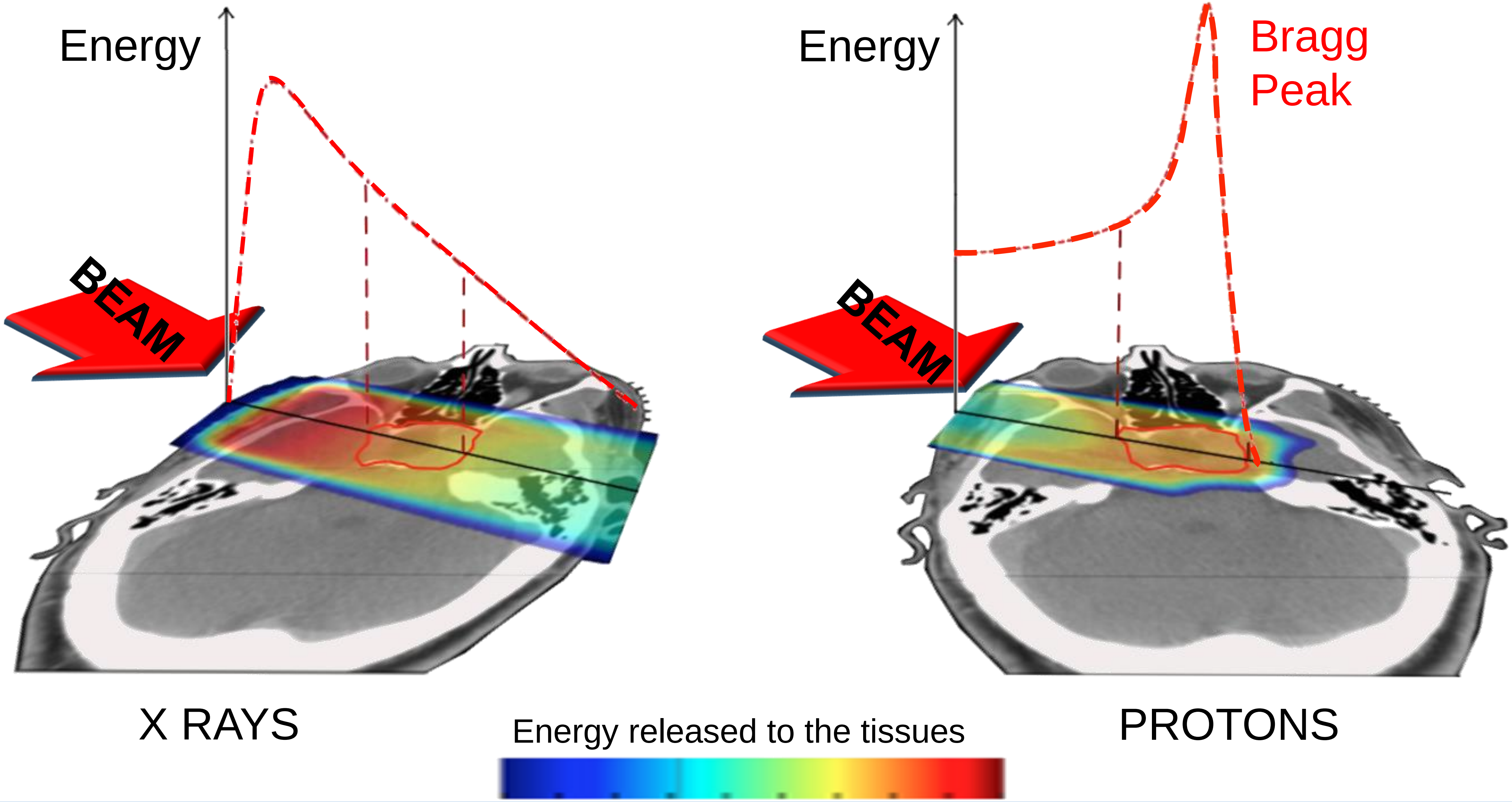
Introduction – Charged Particle Therapy



X RAYS

Energy released to the tissues

Introduction – Charged Particle Therapy



Aim of the MoVe IT INFN project

Modeling and **Ve**rification for
Ion beam **T**reatment planning

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

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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.

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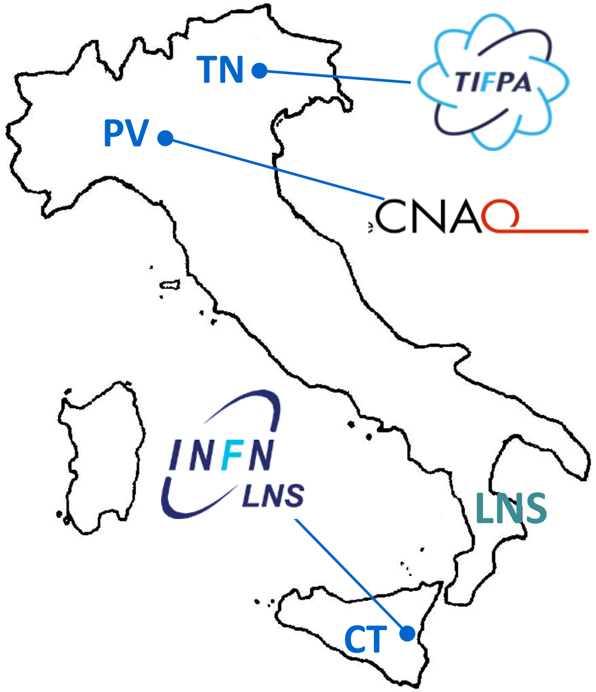
Two prototypes of UFSD for radiobiological applications @ three irradiation facilities:



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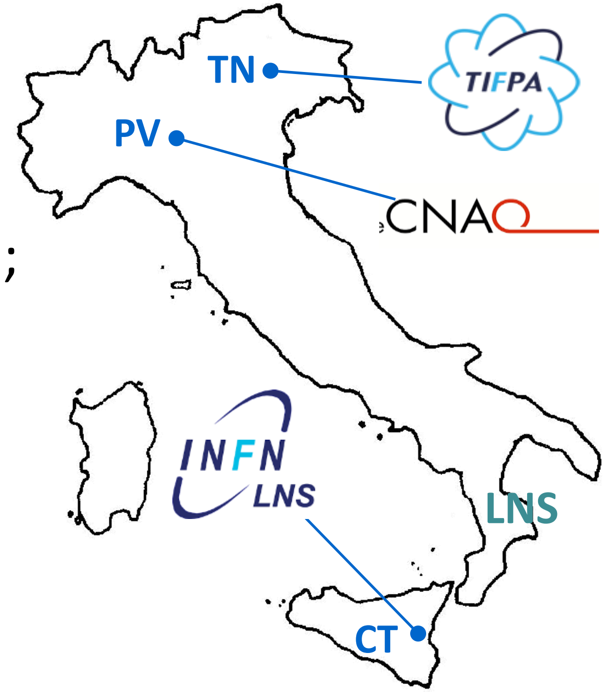
1. to **directly count** individual protons:
   - area 3x3 cm^2;
   - up to fluence rate of **10^8 p/s cm^2** (with error < 1% - clinical requirement);
   - segmented in strips → beam projections in two orthogonal directions;



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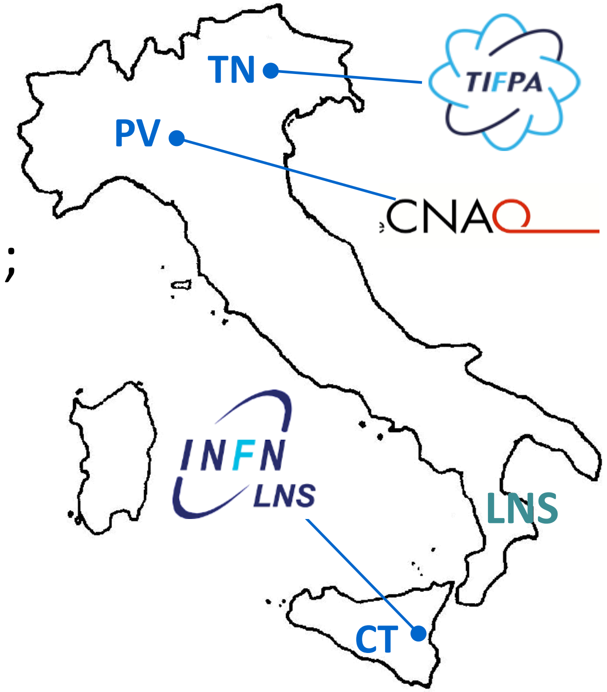

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   - area 3x3 cm^2;
   - up to fluence rate of **10^8 p/s cm^2** (with error < 1% - clinical requirement);
   - segmented in strips → beam projections in two orthogonal directions;

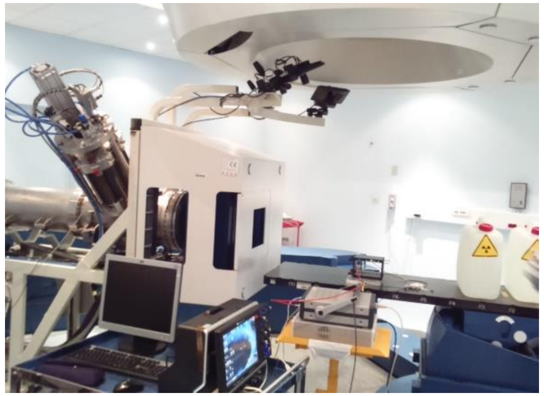
2. to **measure the beam energy** with time-of-flight techniques, using a telescope of two UFSD sensors:
   - error < 1 mm range in water.

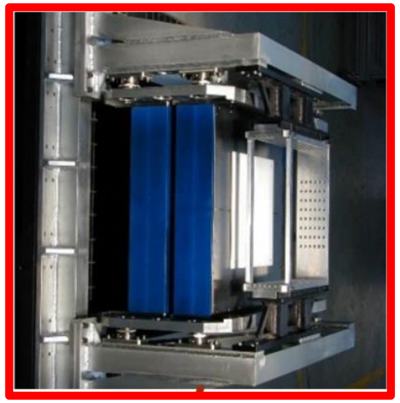
For additional details http://www.tifpa.infn.it/projects/move-it/

Motivation: beam monitoring in PT

Gas detectors (e.g. ionization chambers)

common choice for existing therapy centers





Large area;
robust and **stable;**
radiation resistant.

Slow charge collection;
poor time resolution;
limited sensitivity

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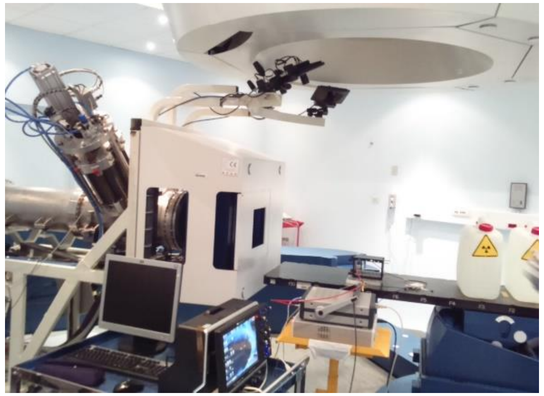
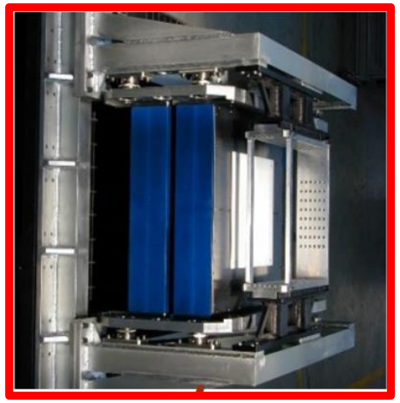
CNAO





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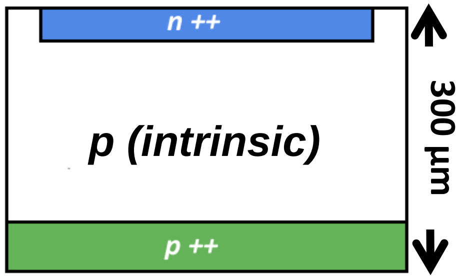
Solid state detectors (e.g. silicon detectors)



Good sensitivity to single particle detection;
Large granularity;
ToF energy measurement.

Higher readout complexity;
Radiation damage;
Pile-up effects.

Motivation: beam monitoring in PT

Gas detectors (e.g. ionization chambers)

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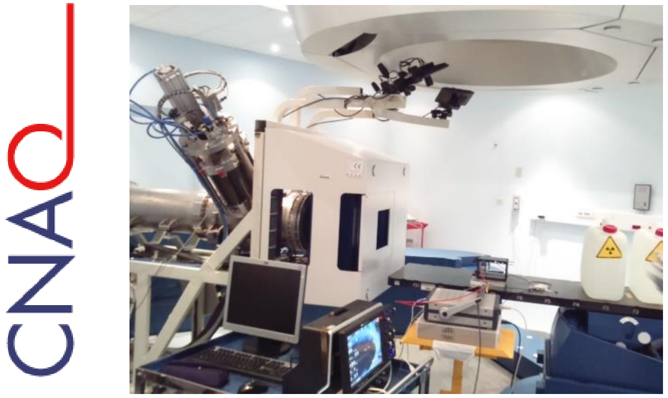

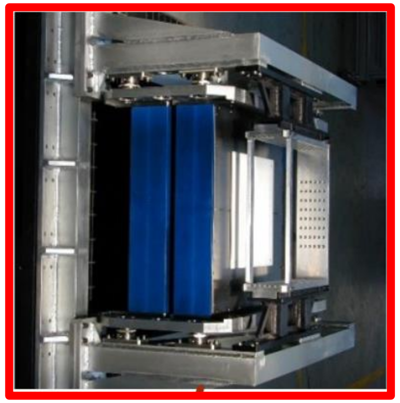

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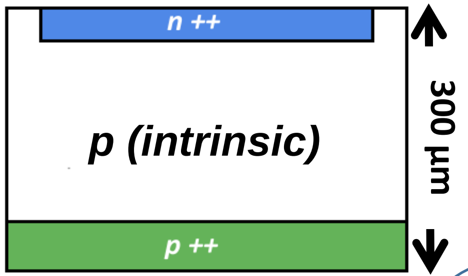

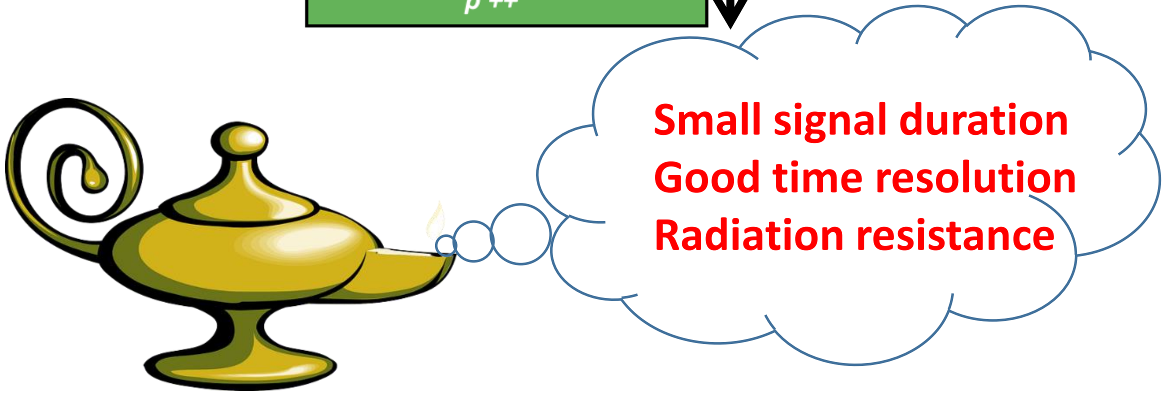

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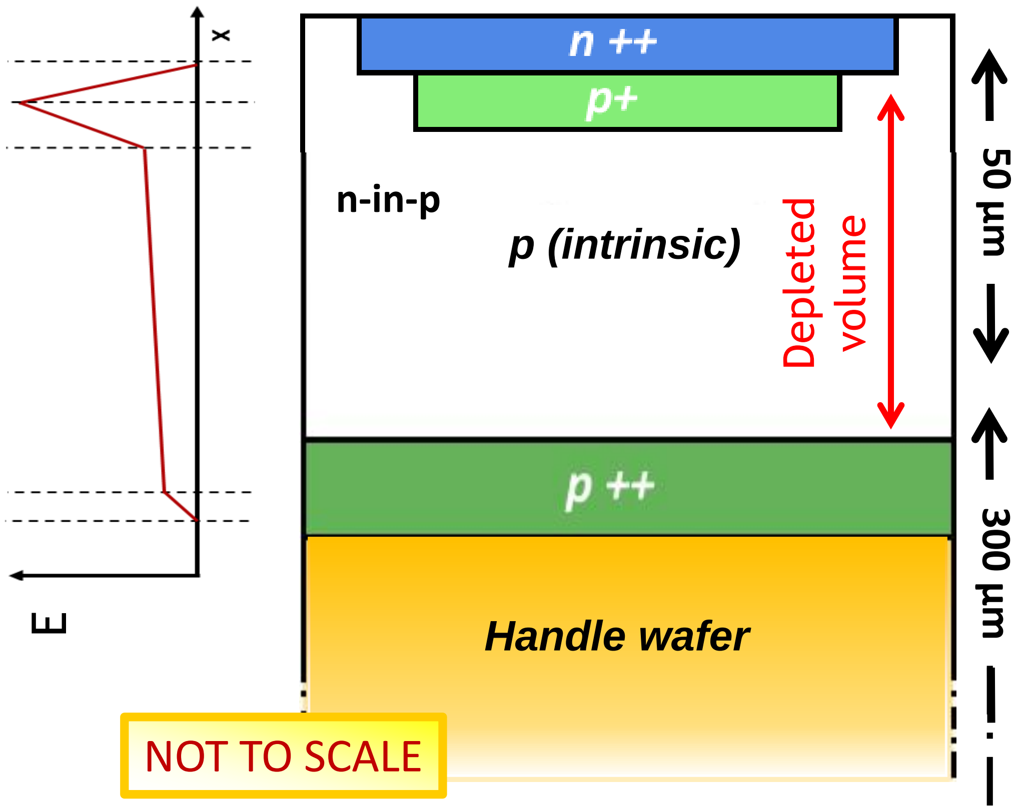
Ultra Fast Silicon Detectors (UFSD)

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



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

small detector thickness;

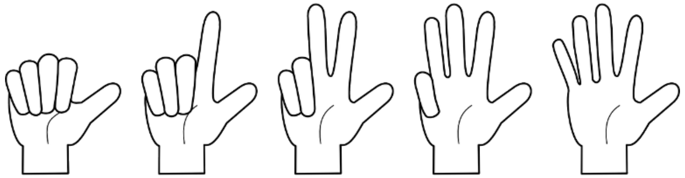
controlled low gain (~ 10), increasing with reverse bias.

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

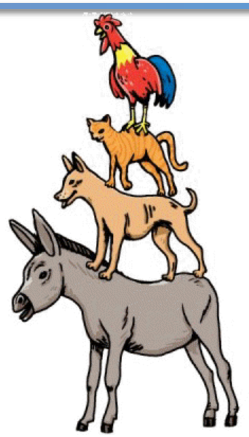
V. Sola et al. Ultra-Fast Silicon Detectors for 4D tracking. Journal of Instrumentation (2017), Volume 12.

fast signal collection (~ ns) and excellent time resolution with S/N ratio of conventional Si detectors.

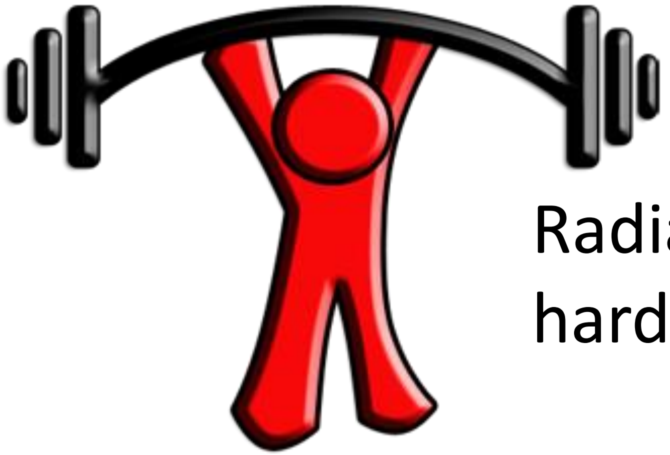
Beam Tests – sensors characterization



Counting



Pile up

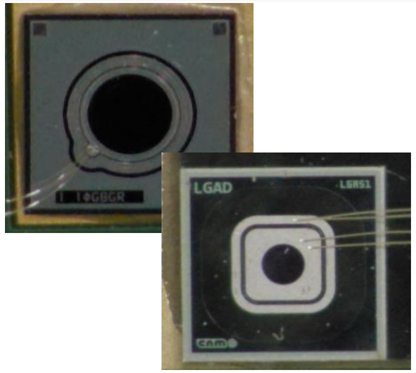


Radiation hardness

Timing properties

Beam Tests – sensors characterization

<u>**Detectors**</u>



2 UFSD pads (50 µm thick active area)
- CNM 1,2 x 1,2 mm^2
- Hamamatsu (HPK) Ø 1 mm

30,0 mm

5,6 mm

UFSD MoveIT strip prototypes (FBK)
- Long (30 strips) and

short (20 strips) geometries

15,0 mm

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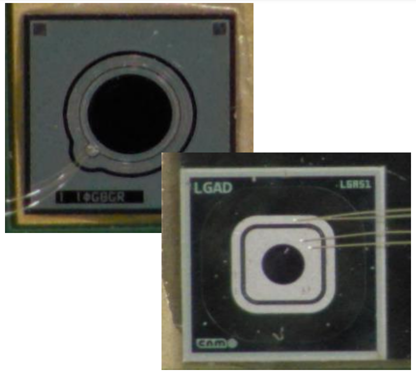
2 UFSD pads (80 µm thick active area)
- Hamamatsu (HPK) 3x3 mm^2

Beam Tests – sensors characterization

Detectors



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CNAO Beam

- Clinical proton beam
- **Beam FWHM** ~ 10mm
- **Max flux** ~ 10^9 p/s delivered in spills (~ 1s duration)
- **Beam flux** range: 20% - 100% of max flux.
- **Beam energy** range: 62 – 227 MeV (5 – 2 MIP)

Beam Tests – sensors characterization

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UFSD MoveIT strip prototypes (FBK)
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2 UFSD pads (80 µm thick active area)
- Hamamatsu (HPK) 3x3 mm^2

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

CNAO Beam

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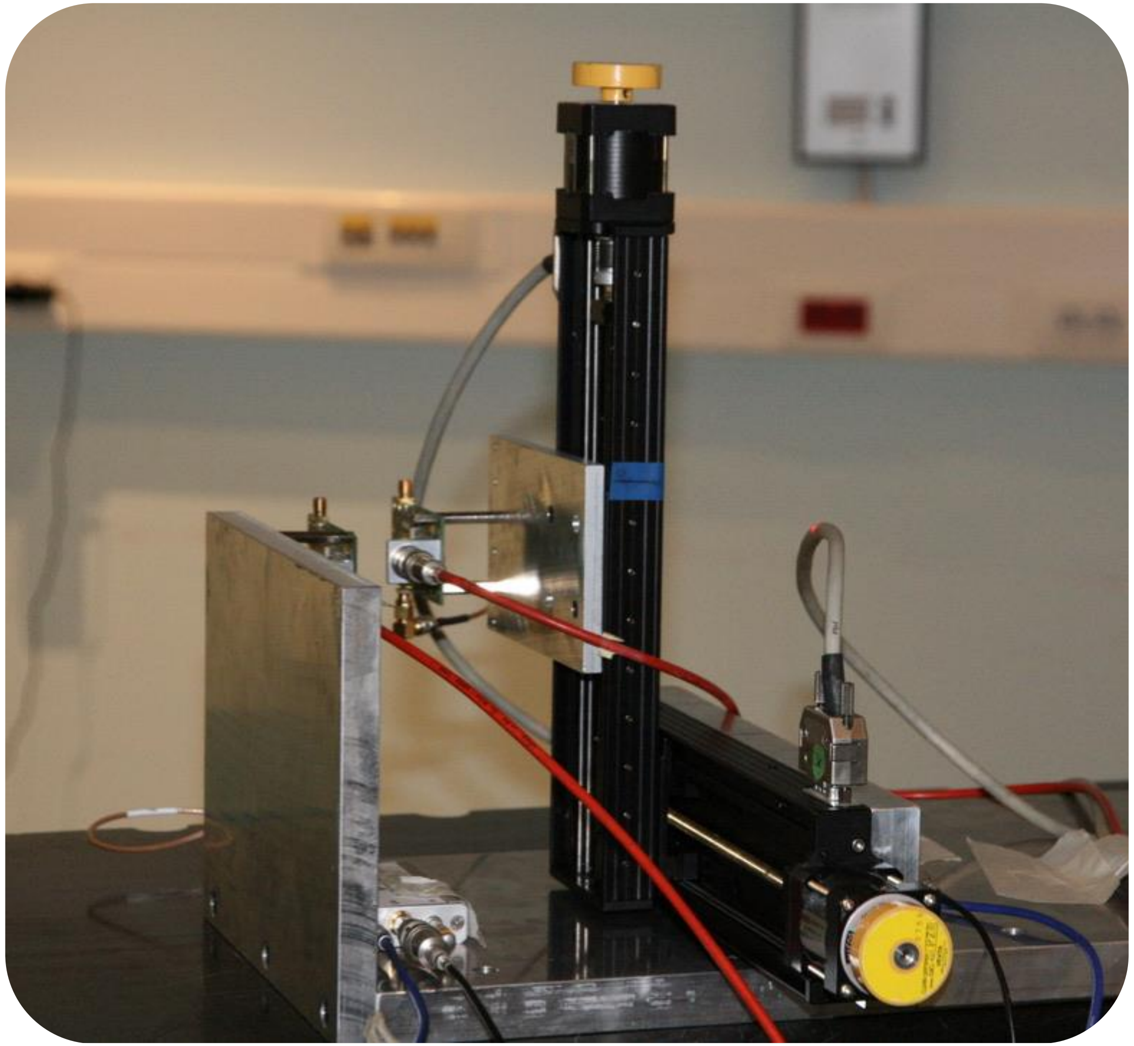
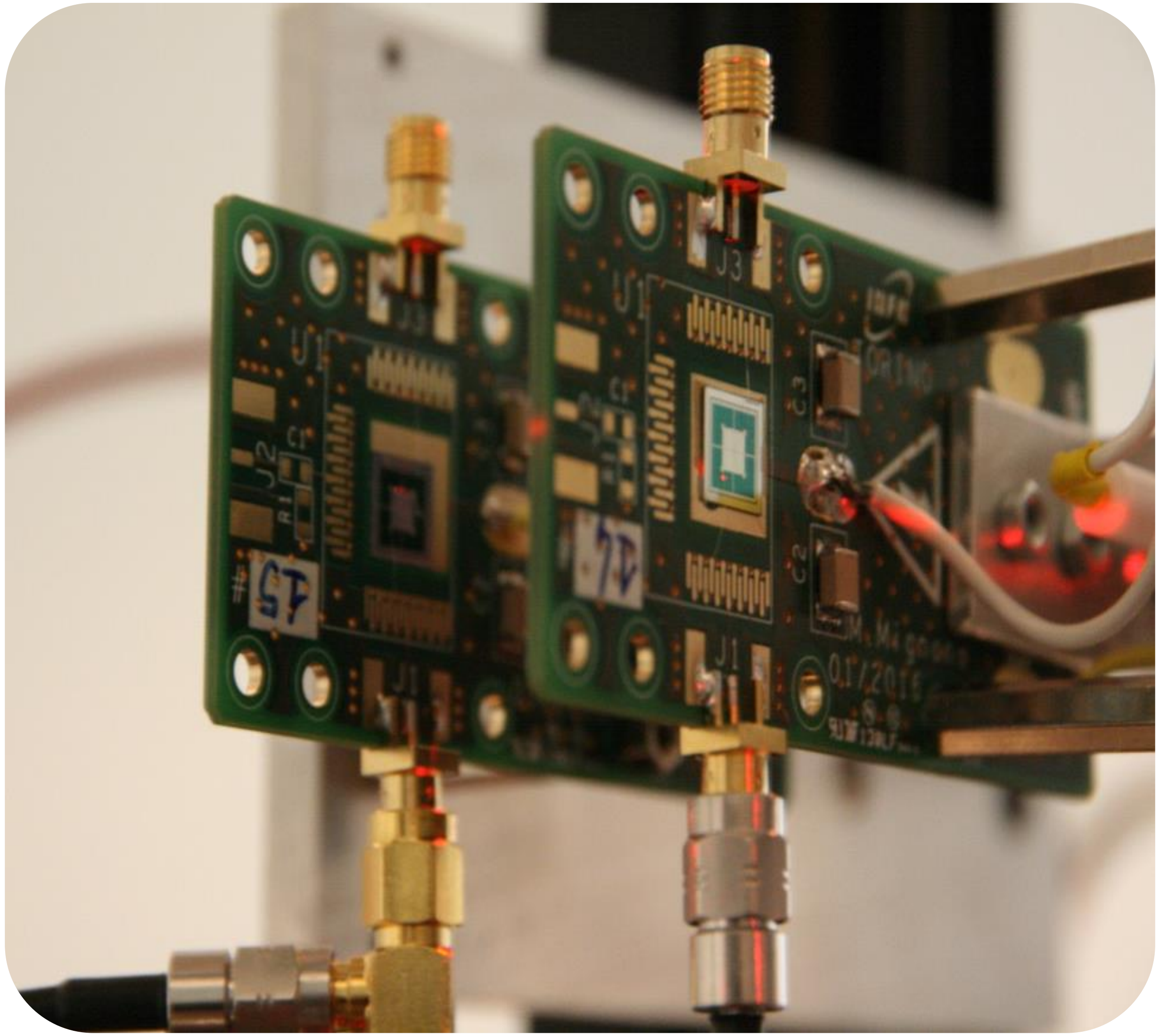
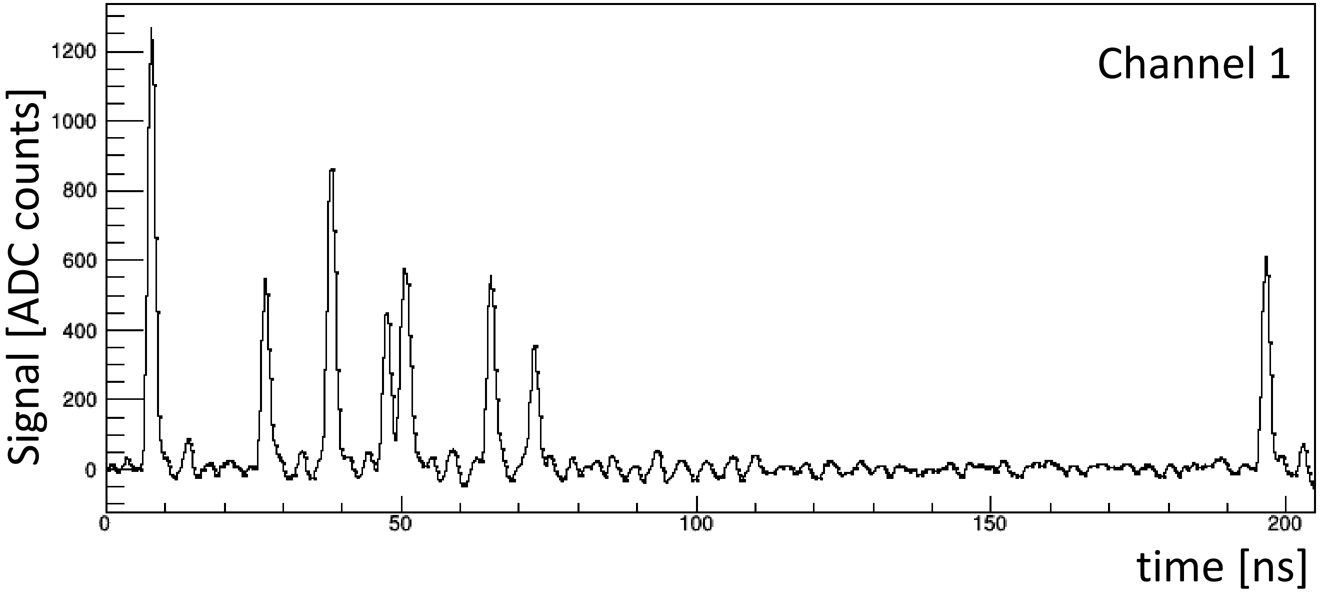
Timing Tests – Set Up





Signal waveform acquired on the CNAO beam

- ✓ HPK pad (80 um, 9 mm^2)
- ✓ 227 MeV protons
- ✓ average beam fluence rate $10^8 - 10^9$ p/cm$^2 \cdot$ s



- ➢ Peaks corresponding to individual protons can be easily distinguished;
- ➢ large amplitude fluctuations;

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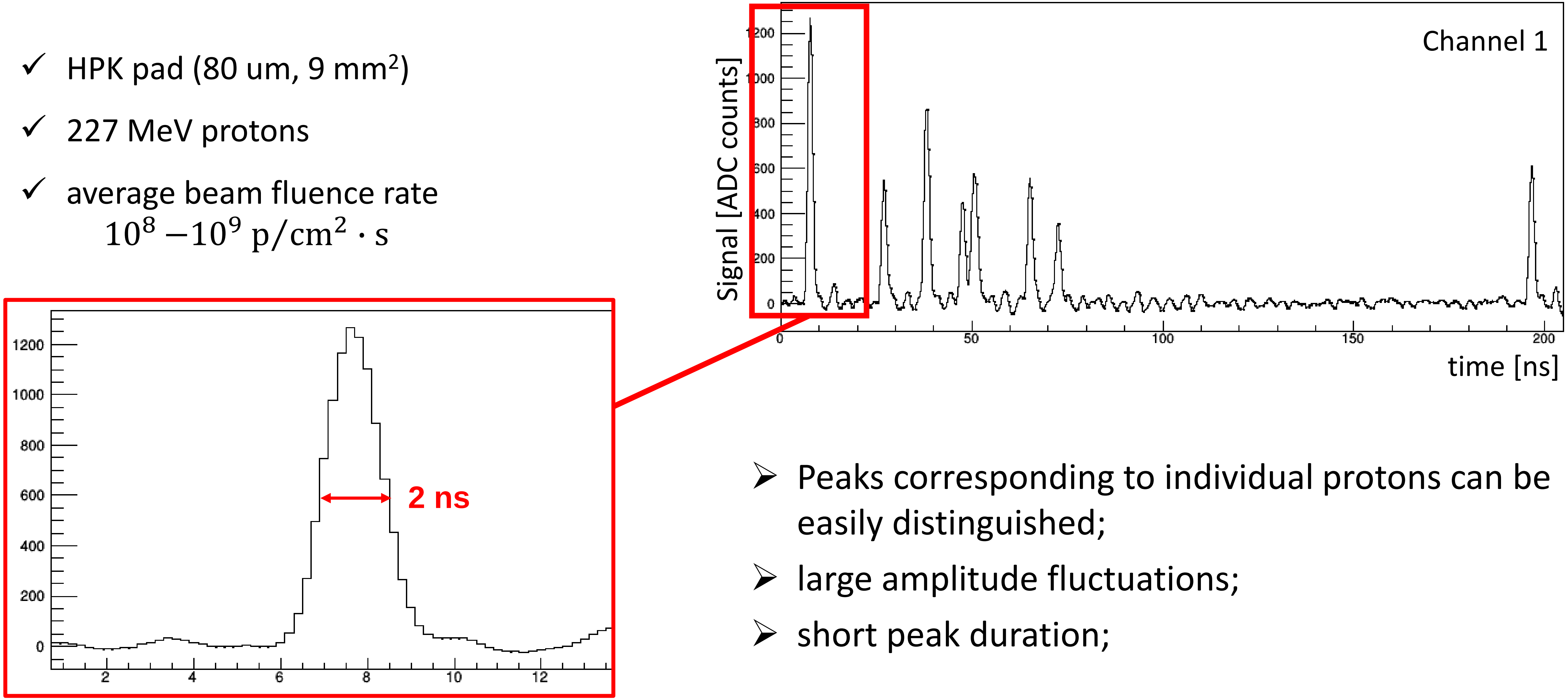
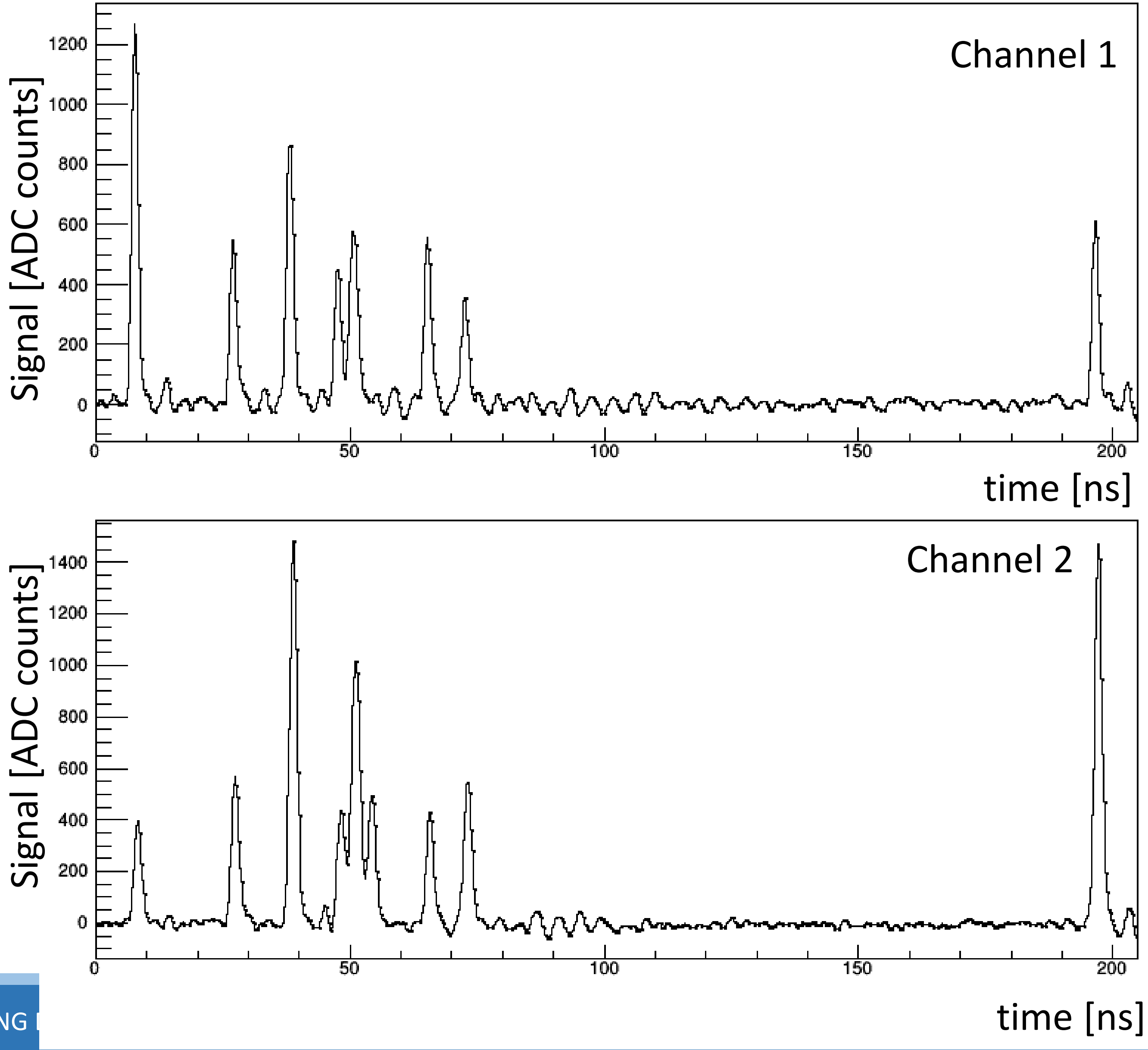


- ➢ Peaks corresponding to individual protons can be easily distinguished;
- ➢ large amplitude fluctuations;
- ➢ short peak duration;

Signal waveform - Coincidences

- ✓ HPK pads (80 um, 9 mm^2)
- ✓ 227 MeV protons
- ✓ average beam fluence rate
  $$10^8 - 10^9 \ \mathrm{p/cm^2 \cdot s}$$



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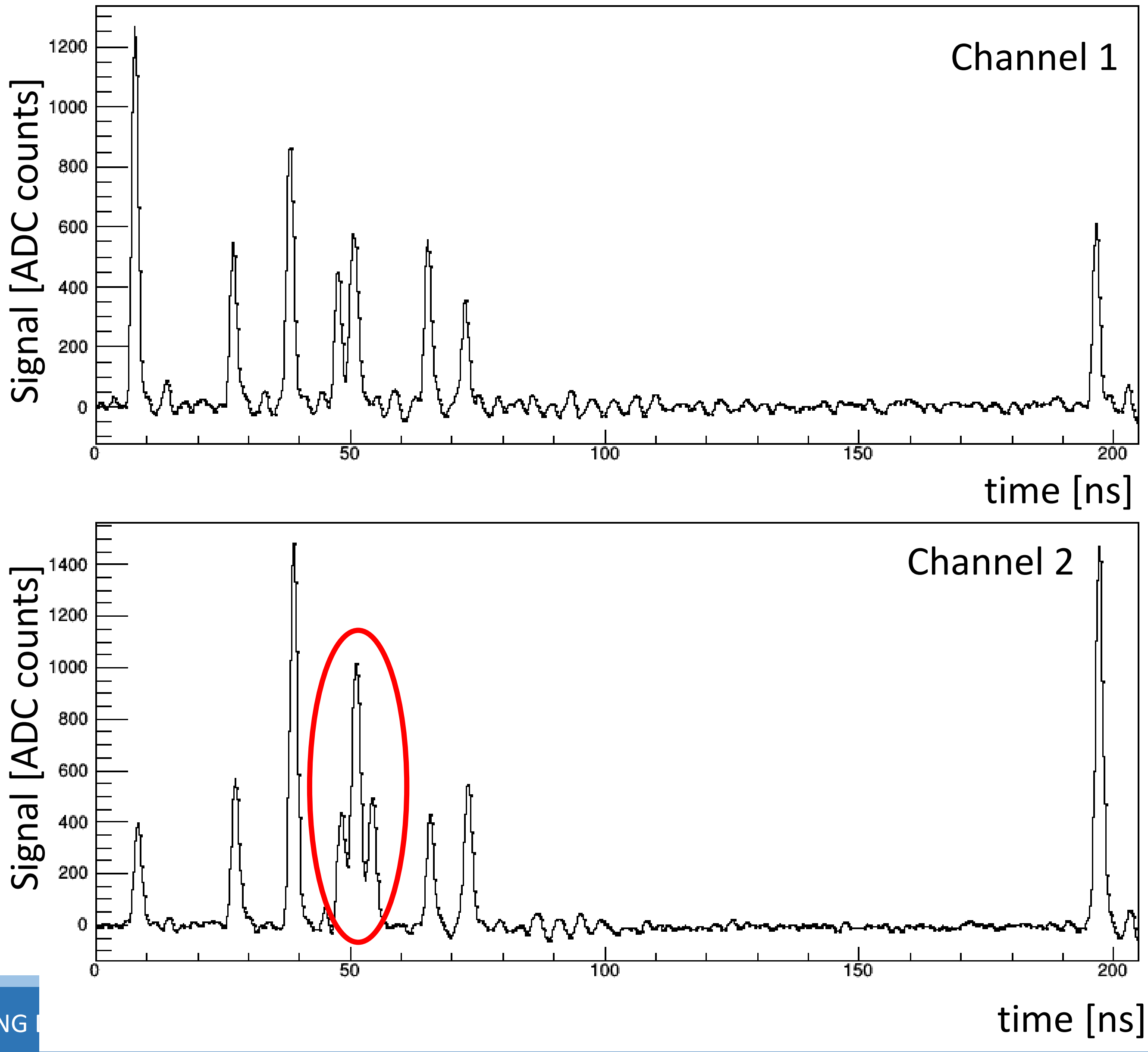

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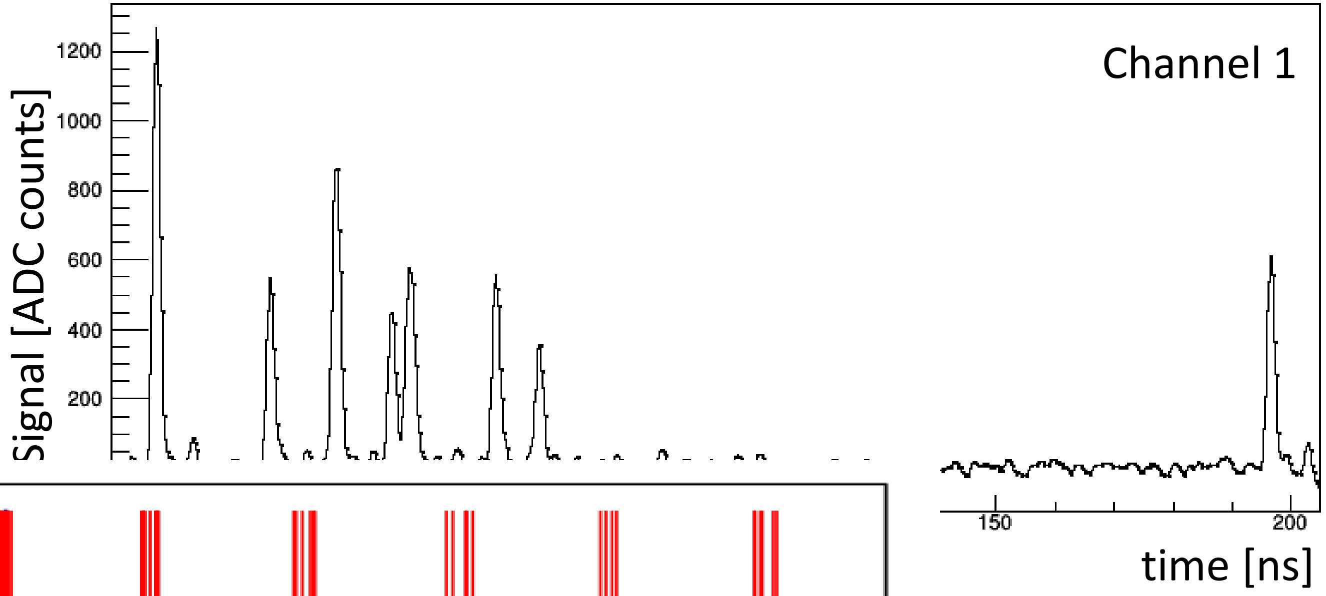
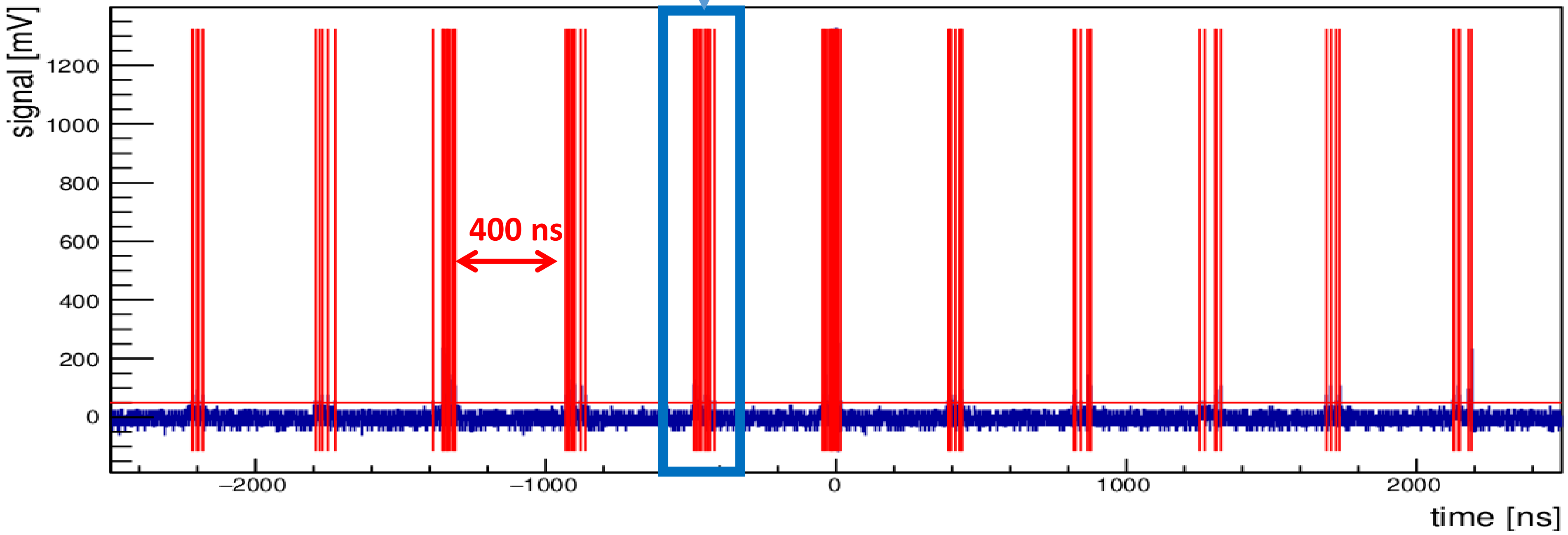
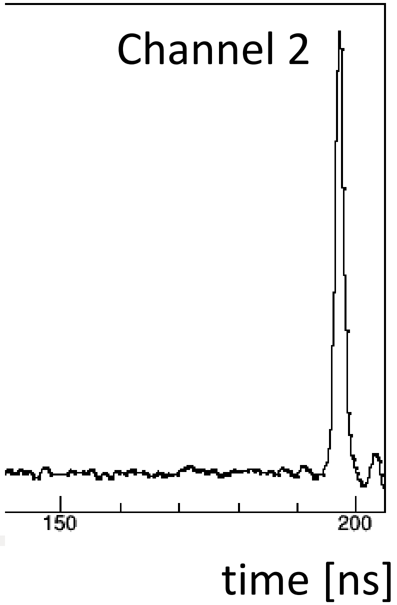
~10^{10} p/s cm^2







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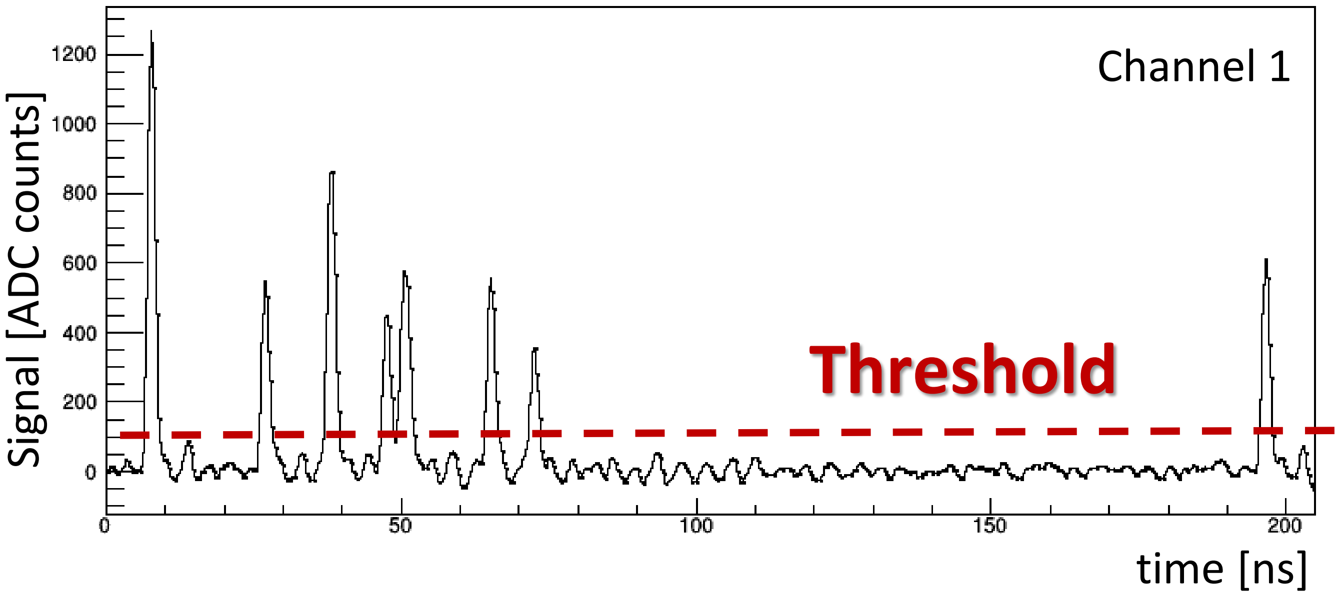
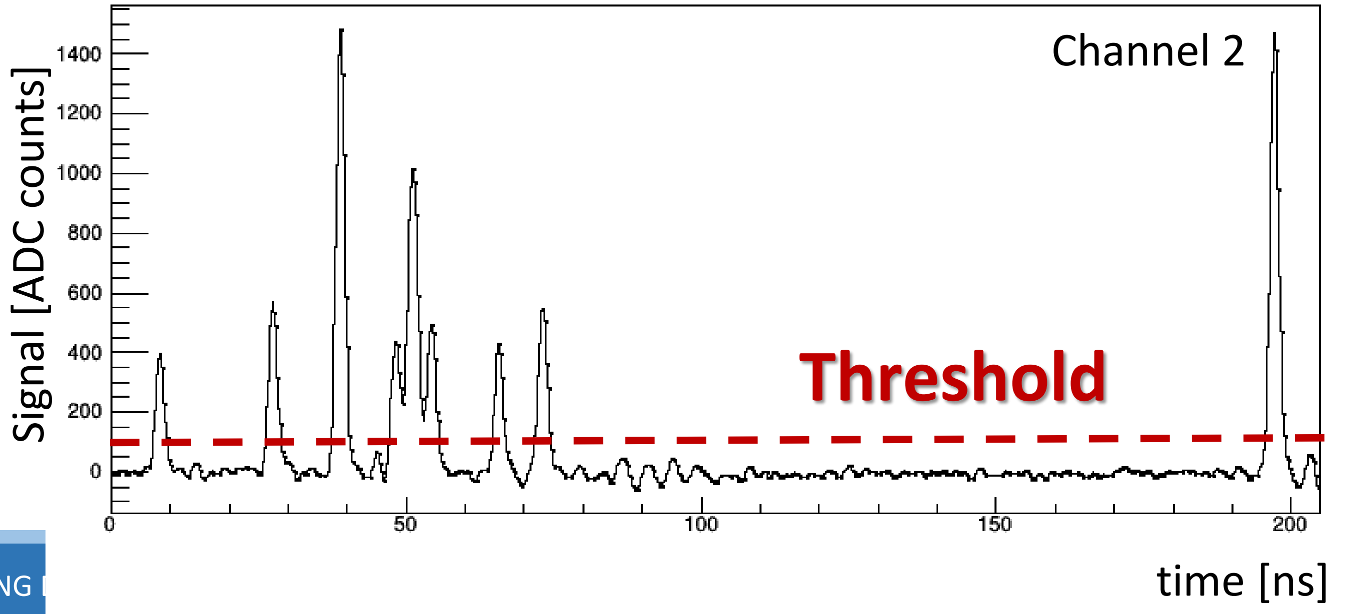
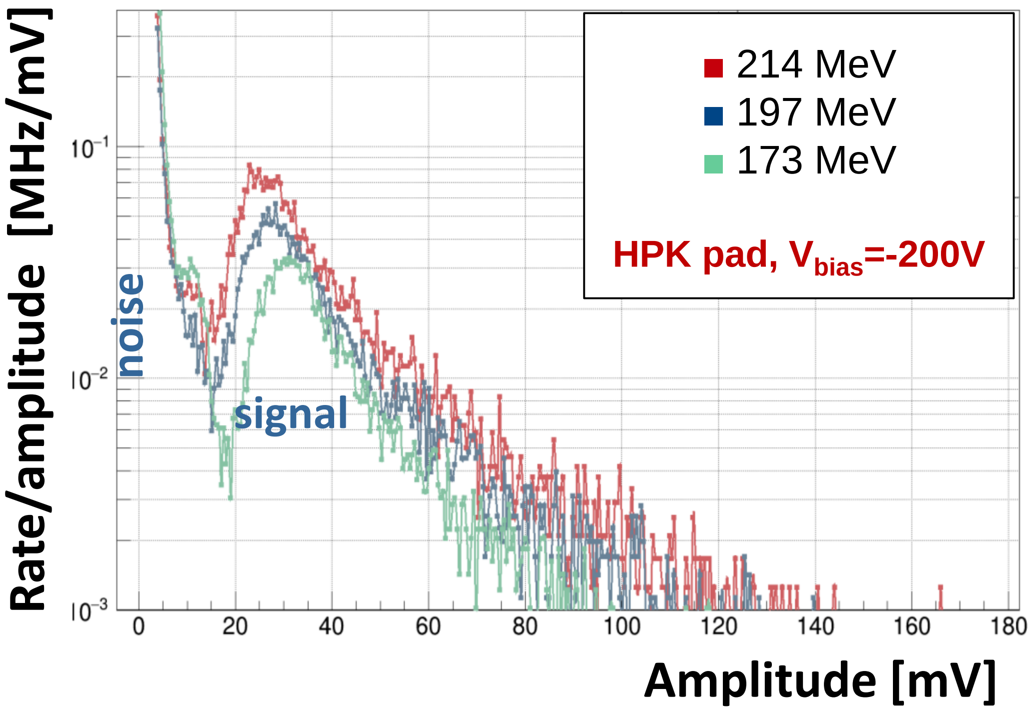




- ➢ fixed threshold can be applied to count the pulses.

Signal & noise distribution

Signal amplitude distribution



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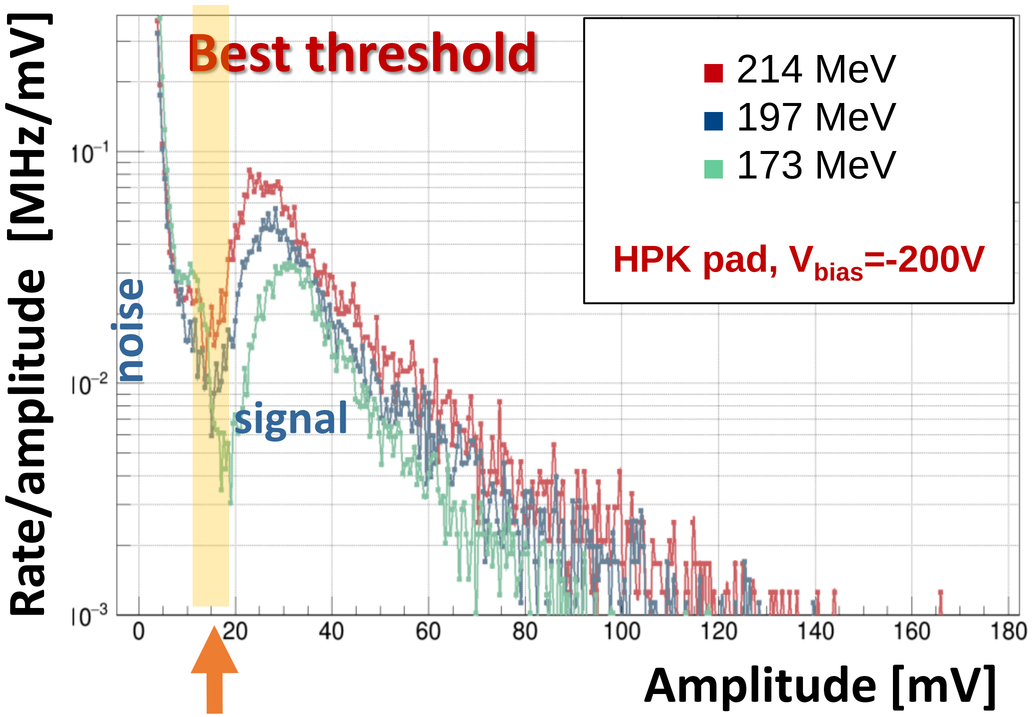
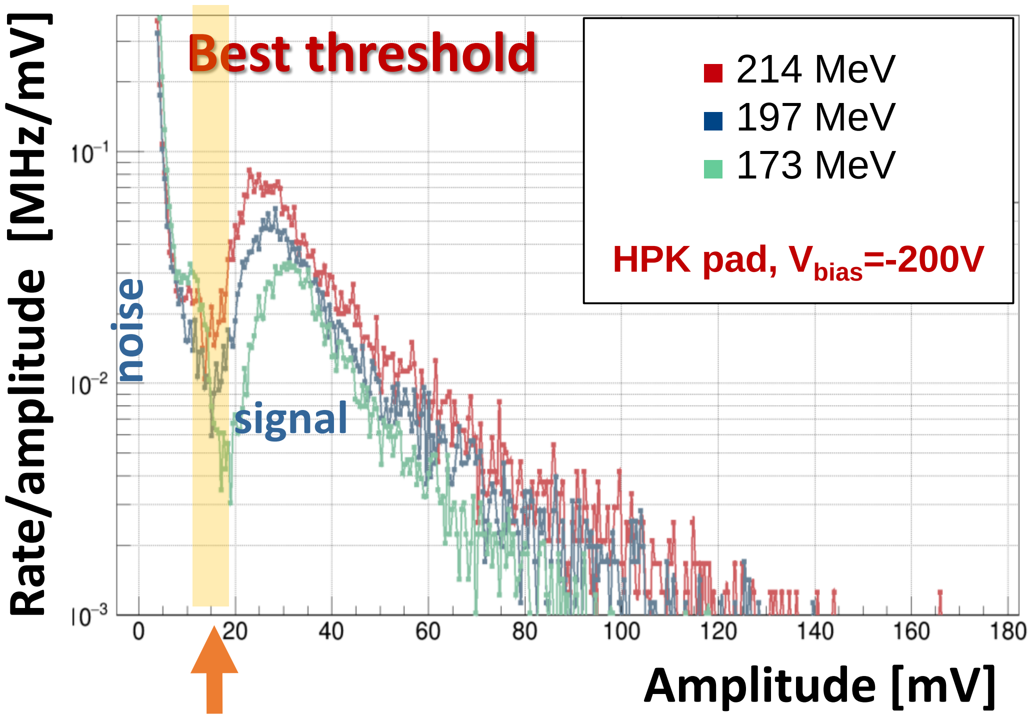


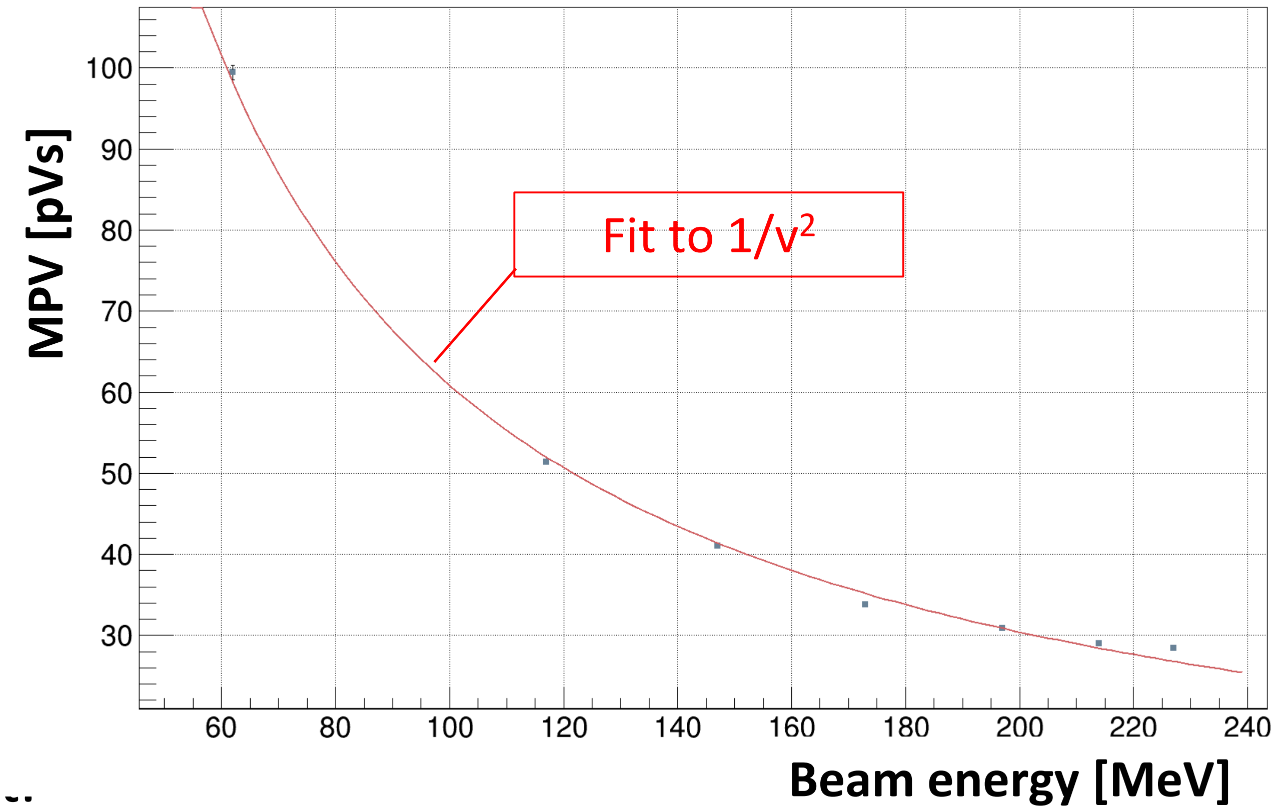
- Good S/N separation;
- Larger S/N at lower beam energies;
- Best threshold is beam energy dependent.

Signal & noise distribution

Signal amplitude distribution



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



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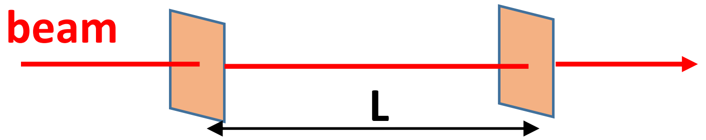
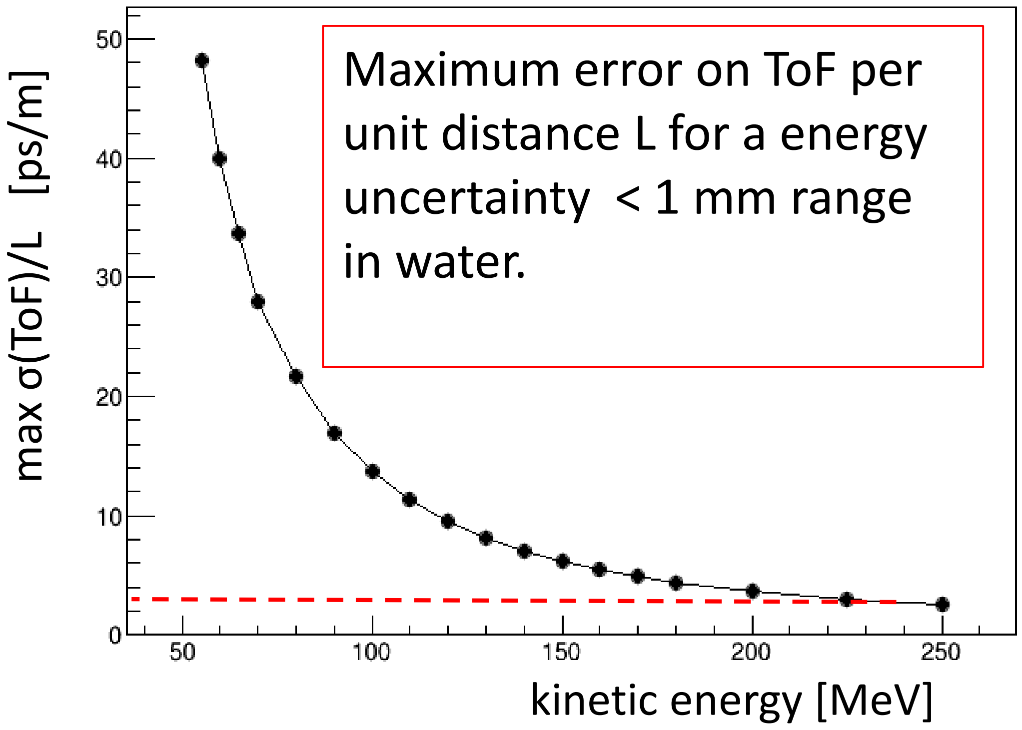
Timing requirements

Beam energy measured from Time-of-Flight

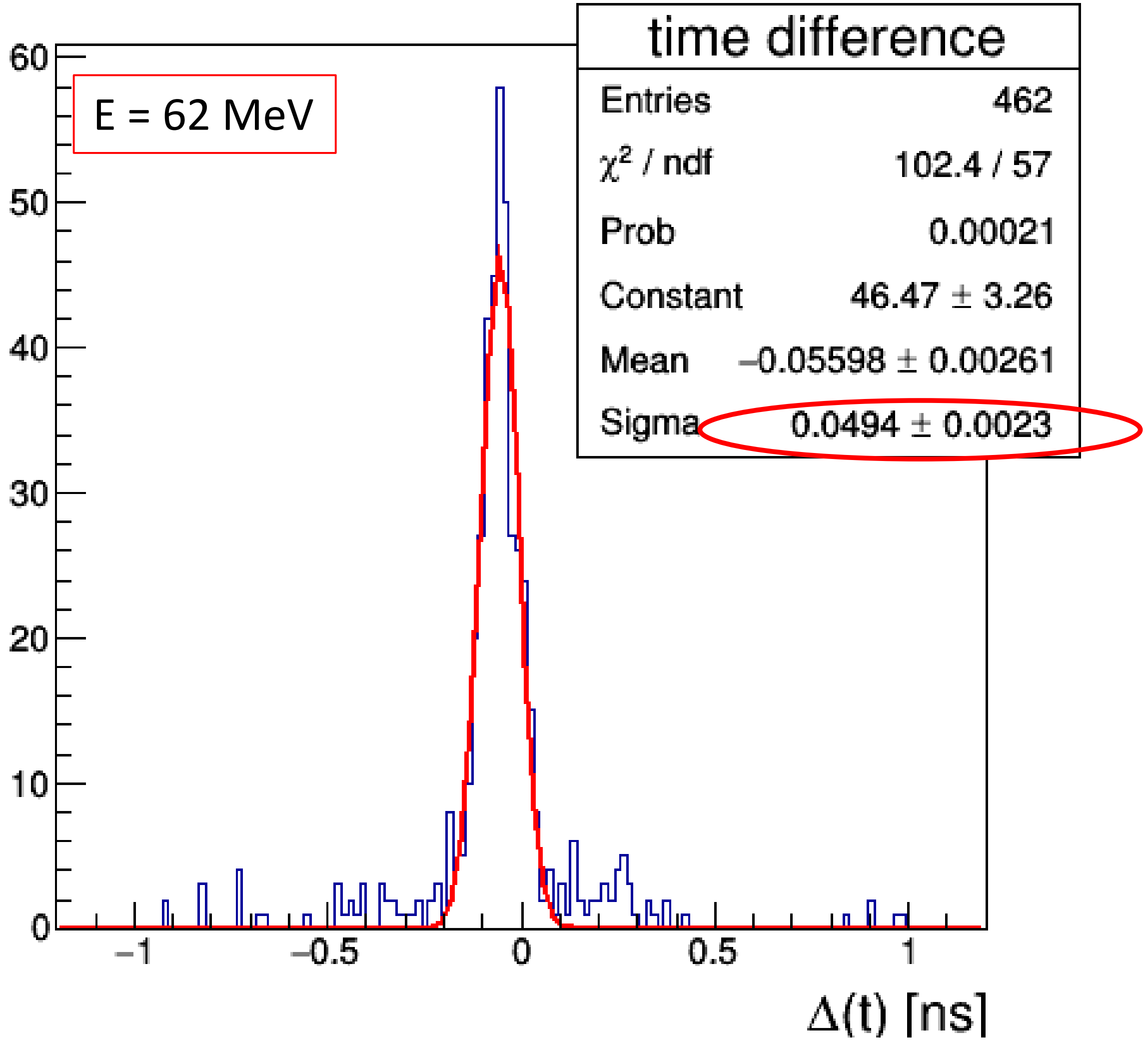


Range



For 1m distance the **max error on TOF < 4 ps**

Preliminary results (50 µm sensors)

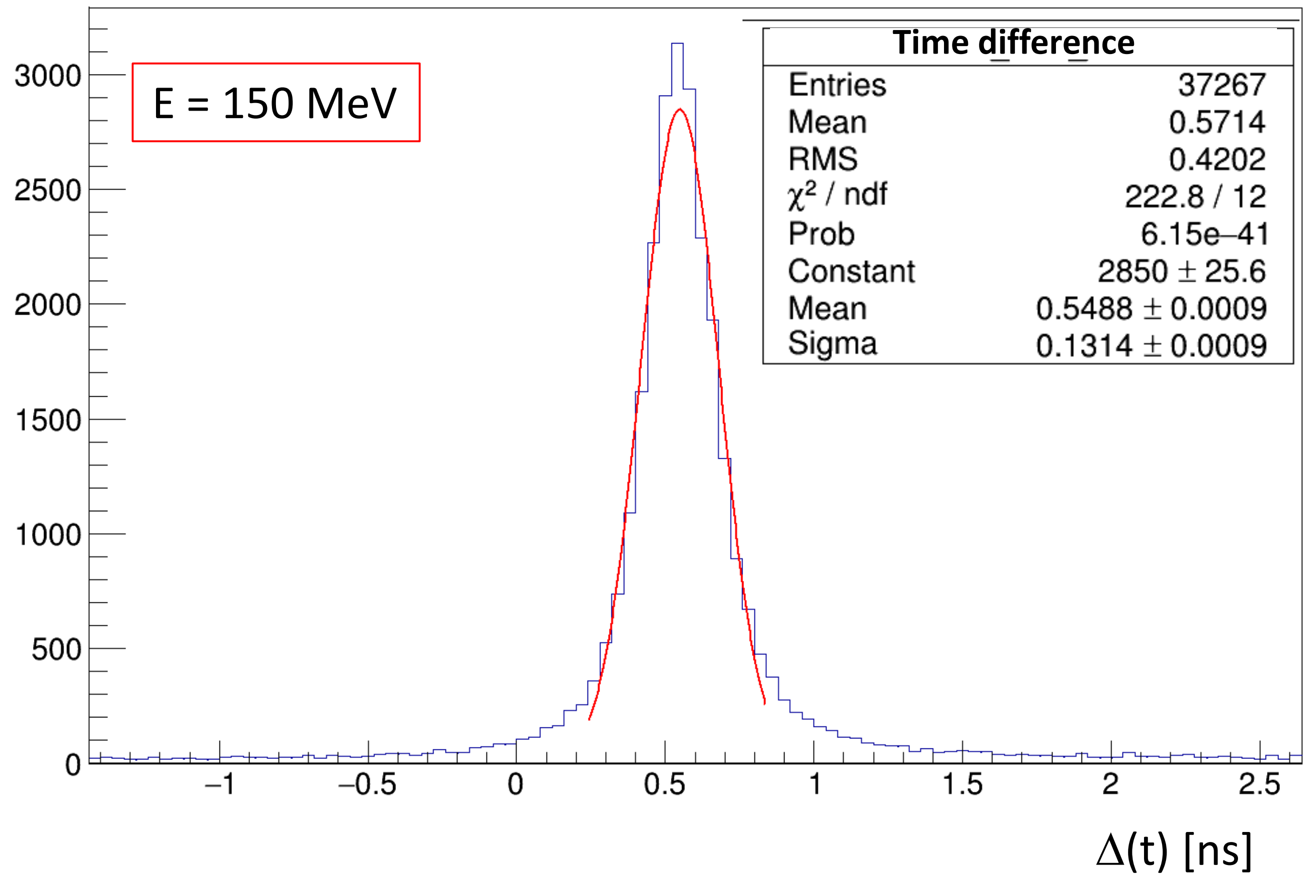


Stat error on <ToF>
3 ps

Time resolution of single crossing
$\sigma(t) = 50ps/\sqrt{2} = 35$ ps

- Time difference measured for pulses in coincidence in the 2 pads (HPK, CNM → 50 µm)
- Sensors at 2 cm distance
- CFD algorithm applied on pulses signals
- Total acquisition time 300 µs (less than average spot duration).

Preliminary results (80 um sensors)



Stat error on <ToF>

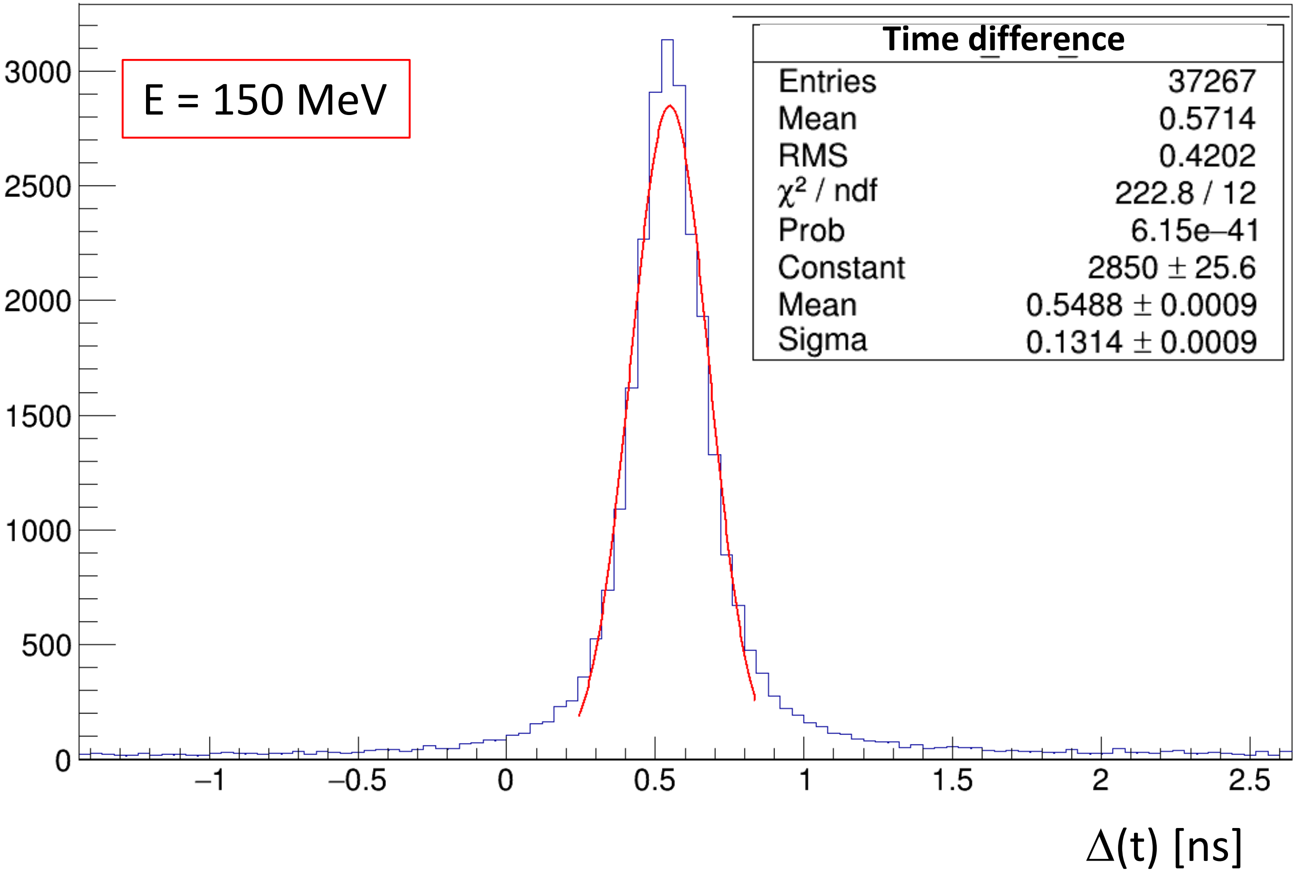
1 ps

Time resolution of single crossing

$\sigma(t) = 130ps/\sqrt{2} = 90$ ps

- Time difference measured for pulses in coincidence in the 2 pads (HPK → 80 μm)
- CFD algorithm applied on pulses signals
- Sensors at 3.5 cm distance…

Preliminary results (80 um sensors)



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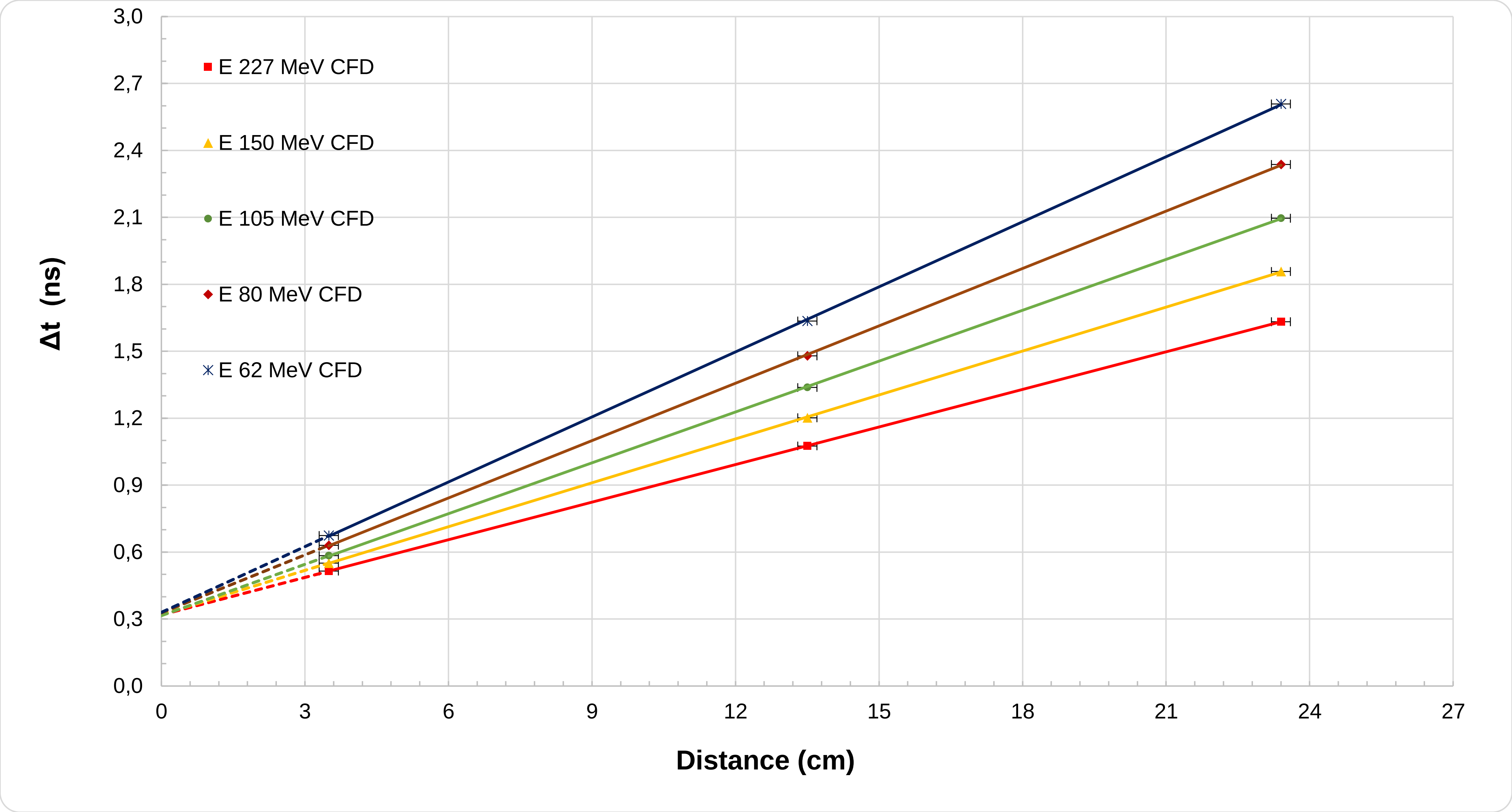
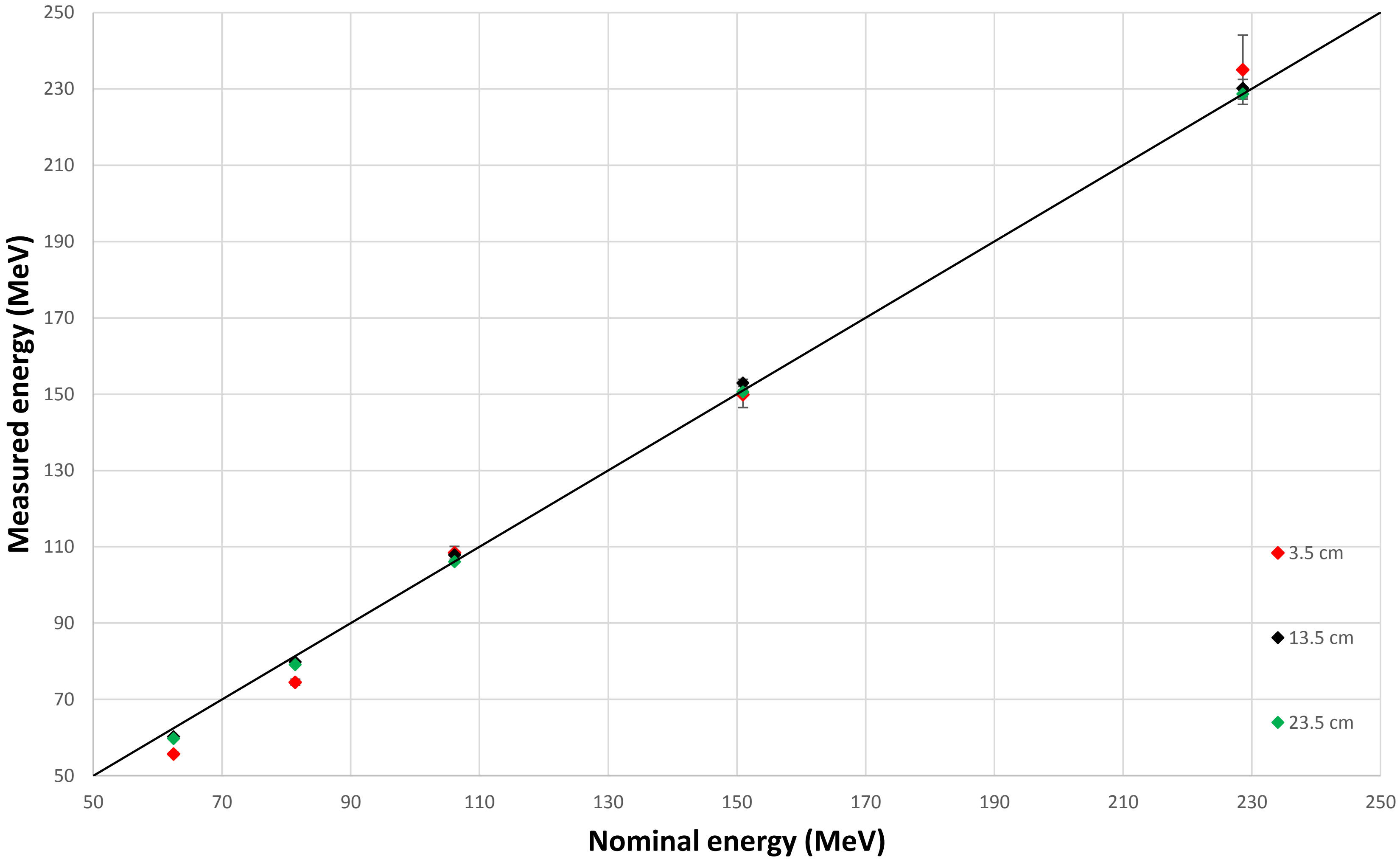
- Time difference measured for pulses in coincidence in the 2 pads (HPK → 80 μm)
- CFD algorithm applied on pulses signals
- Sensors at 3.5 cm distance…
- …at 13.5 cm and 23.4 cm distances

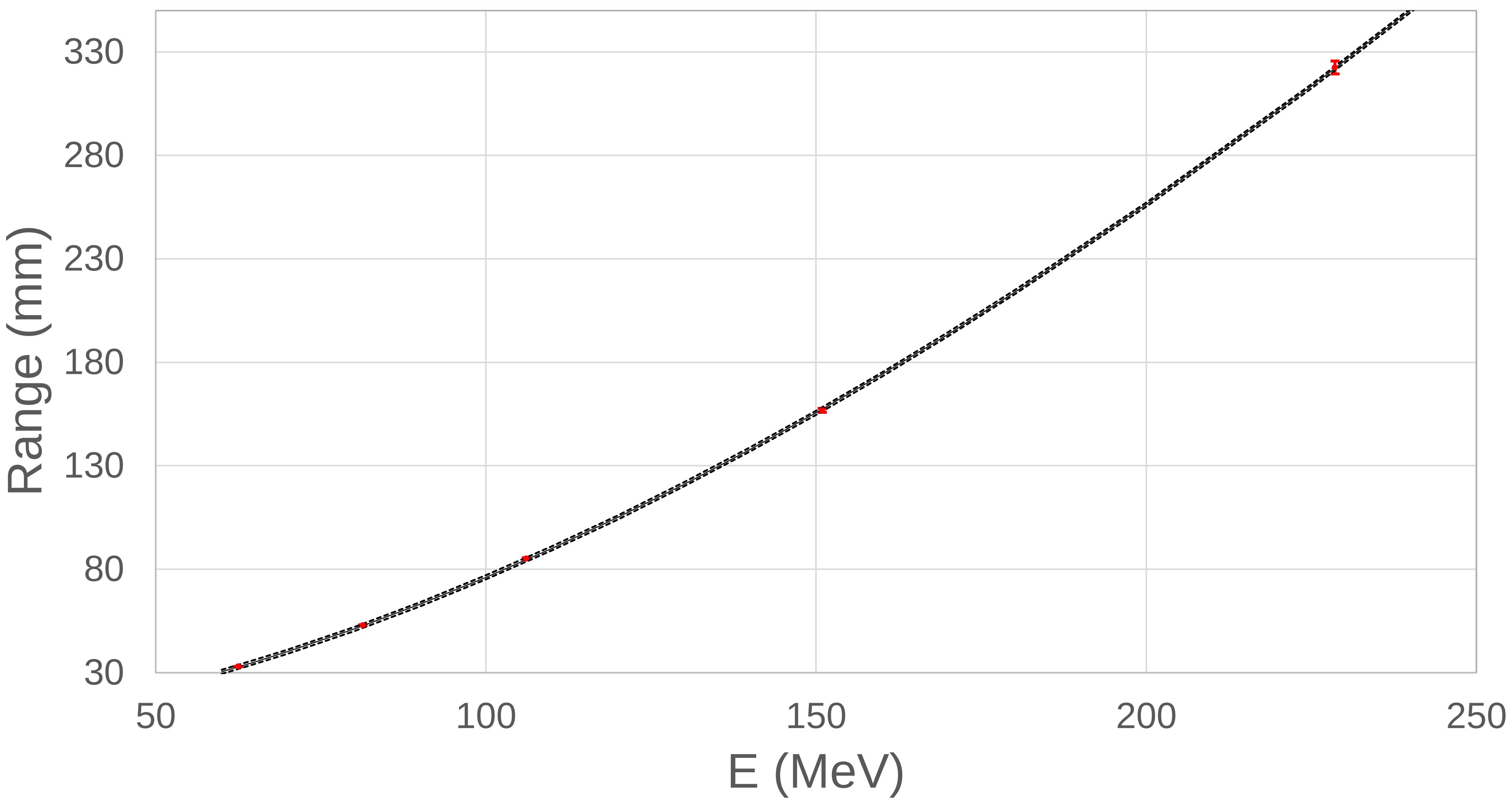
Preliminary results (80 um) – Δt vs distance



Measured Energy vs Nominal Energy



Range vs Energy (from 23.4 cm measurements)



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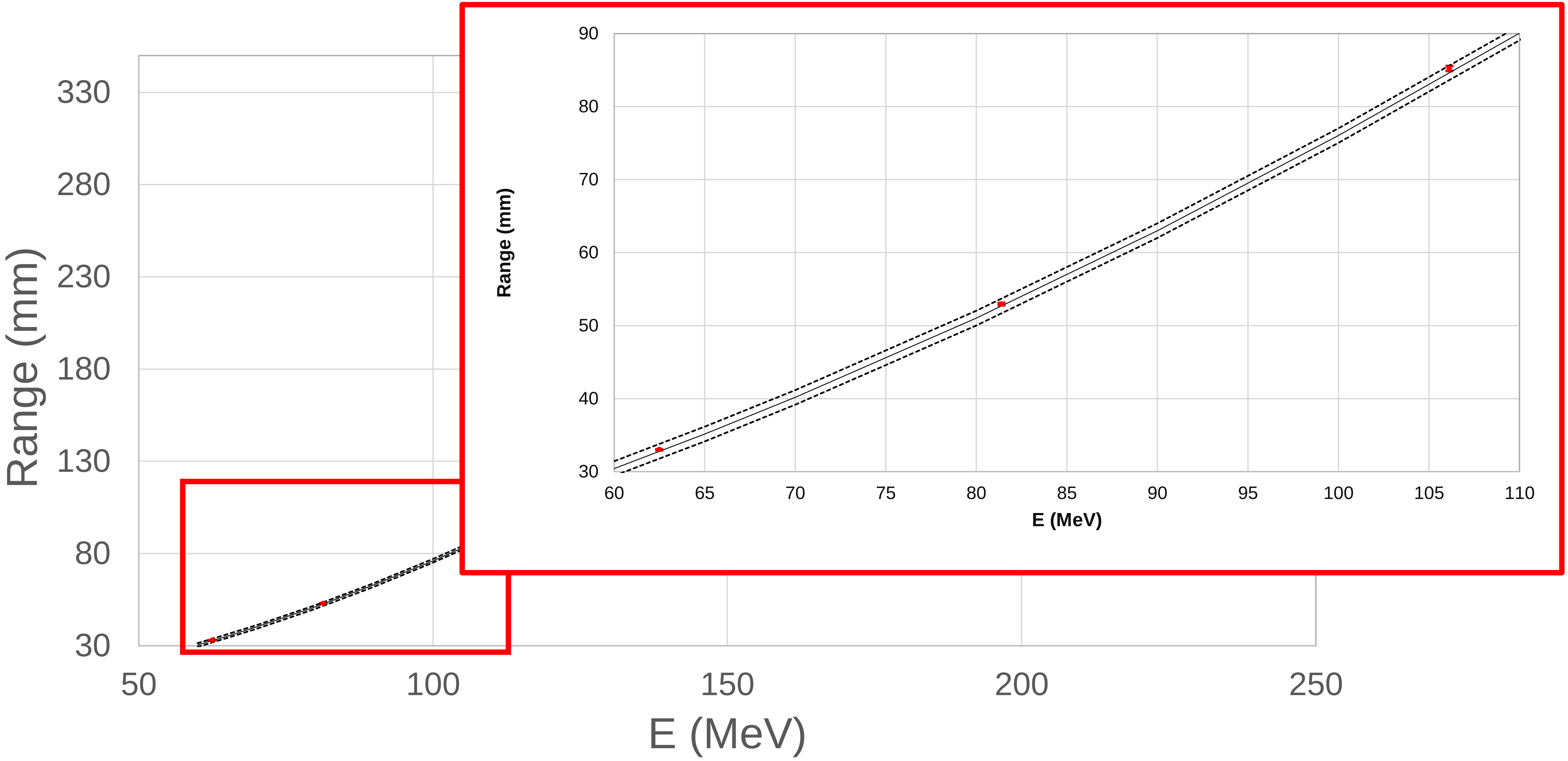

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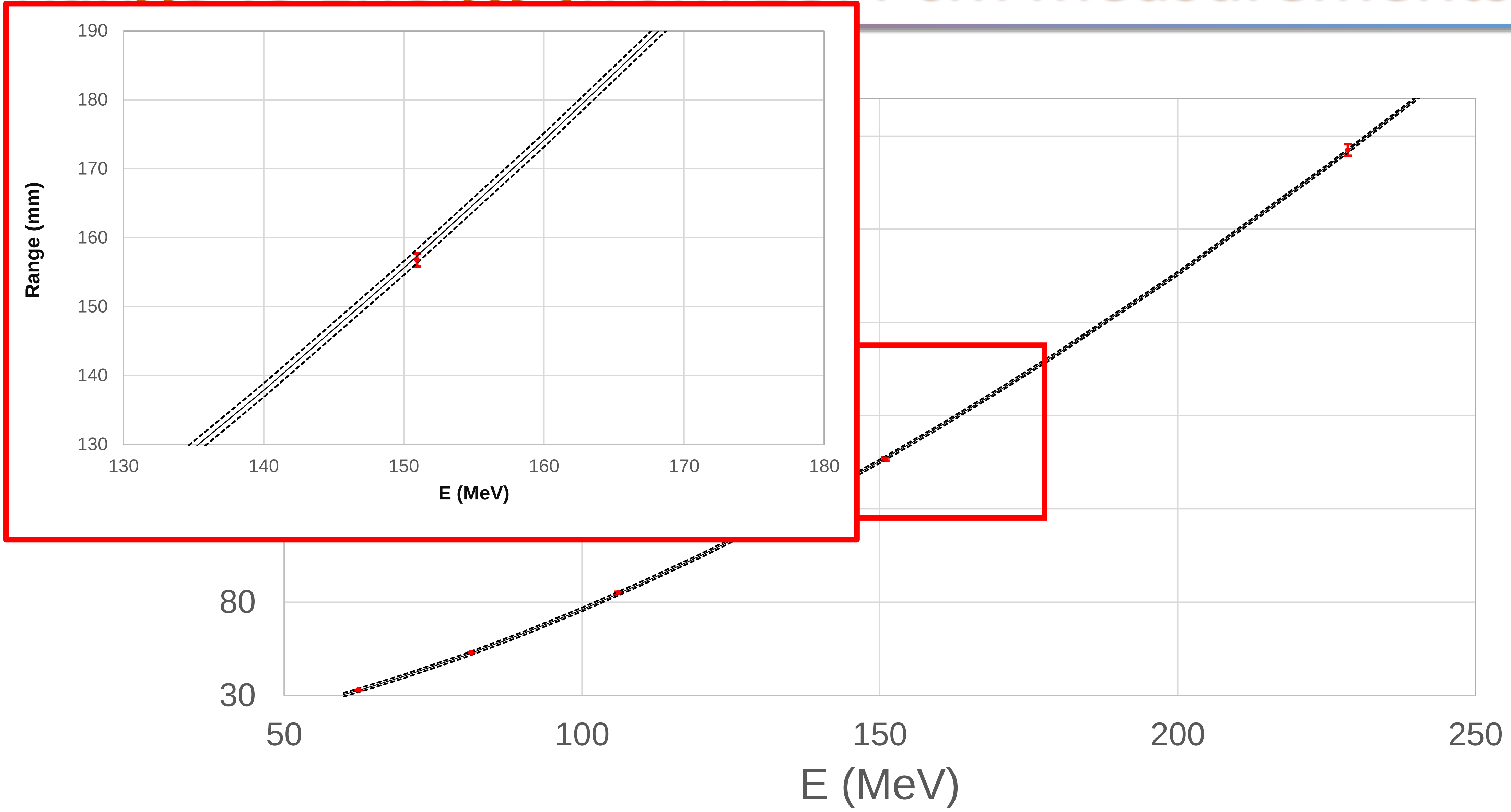

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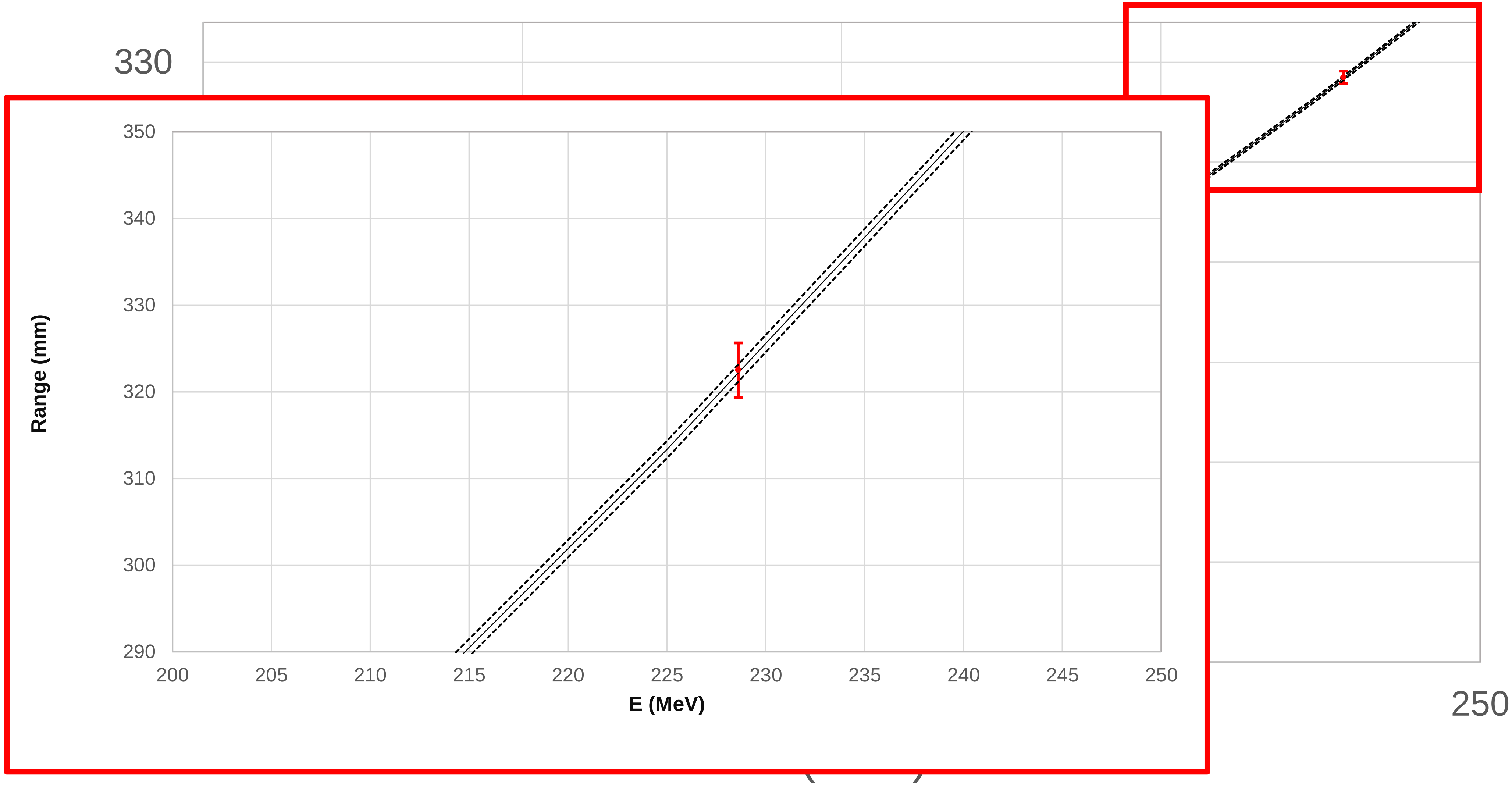

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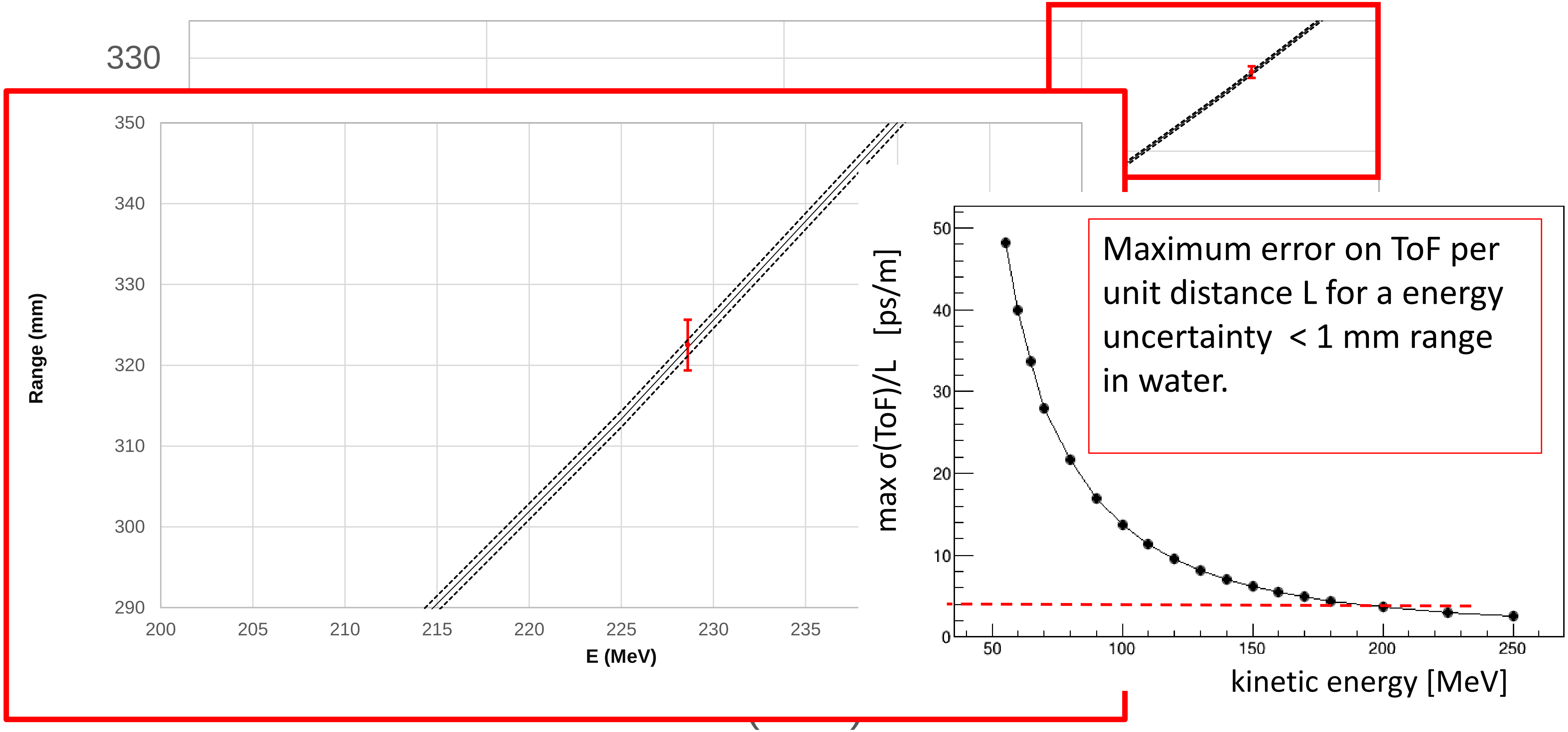
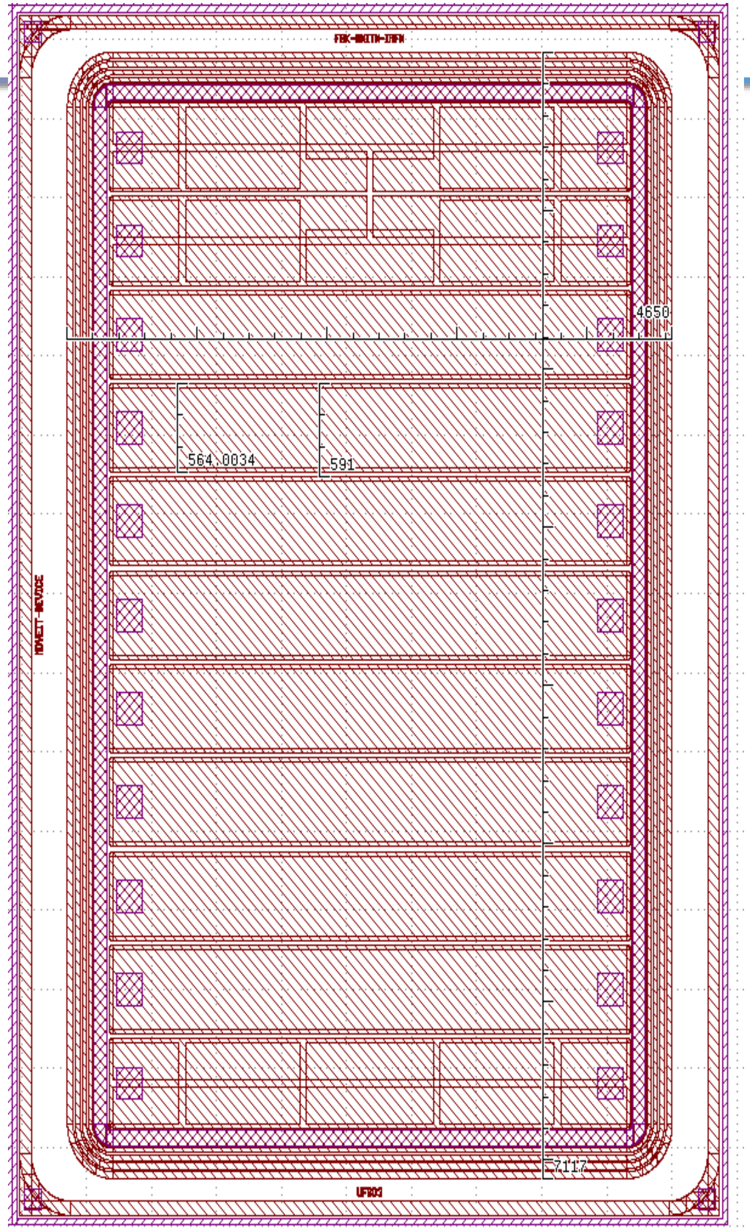


Maximum error on ToF per unit distance L for a energy uncertainty < 1 mm range in water.

Dedicated sensor @ FBK



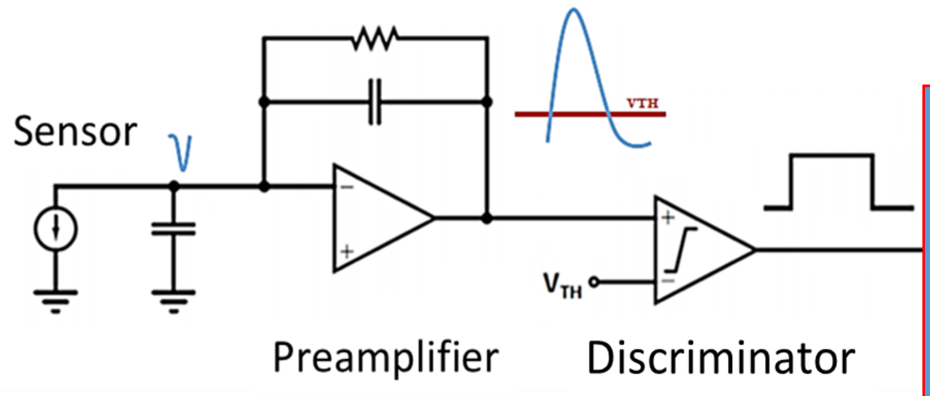
11 strips of 2.2 mm^2 (3993 um x 550 um; Pitch = 590 um):

2 gain with optical windows;

8 gain (NO optical windows)

1 no gain with optical windows.

Fast readout electronics (TERA10)



Requirements

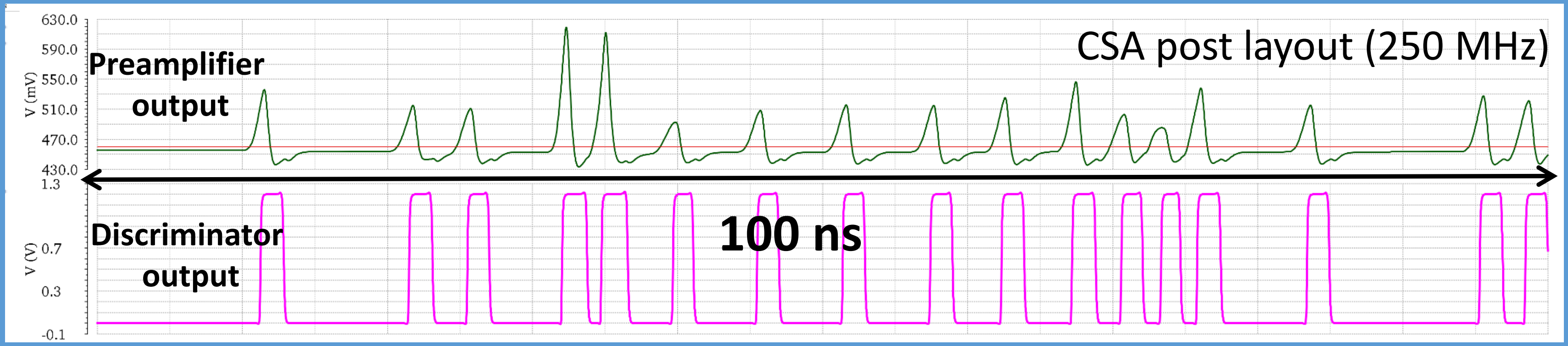
Input ch. range: **3 fC ÷ 140 fC**
Rate/channel: **up to 200 MHz**
Inefficiency **< 1 %.**

FPGA

- **FE inizialization**
- **Pulse counting**
- **Pileup correction**

+ Additional functionalities (threshold scan, ...)

2 alternative designs (CSA & TIA) of the amplifier developed and compared



Protoypes (24 ch) of the 2 architectures submitted in UMC110 technology, available in June

Conclusions

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

- Fast collection time + Large S/N ratio
  ➡ directly count of number of ions of a clinical beam

- Excellent time resolution
  ➡ measurement of the beam energy

Open issues for clinical applications

- **Radiation resistance:**
  - large effort in HL-LHC community for achieving resistance up to $\Phi > 10^{15}\ \mathrm{n/cm^2}$
  - Extensive radiation tolerance tests have been carried on with pads of the same USFD production of the strips:
    - gain can be recovered up to 10^{15} n/cm^2 for some of the options tested;
    - protons worse than neutrons by factor 2.

- **Pileup inefficiency**
  - Many correction methods are proposed in literature.
  - Additional complication for a higly non-uniform beam flux vs. time
  - Detailed simulations ongoing, first results are encouraging

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Thank you