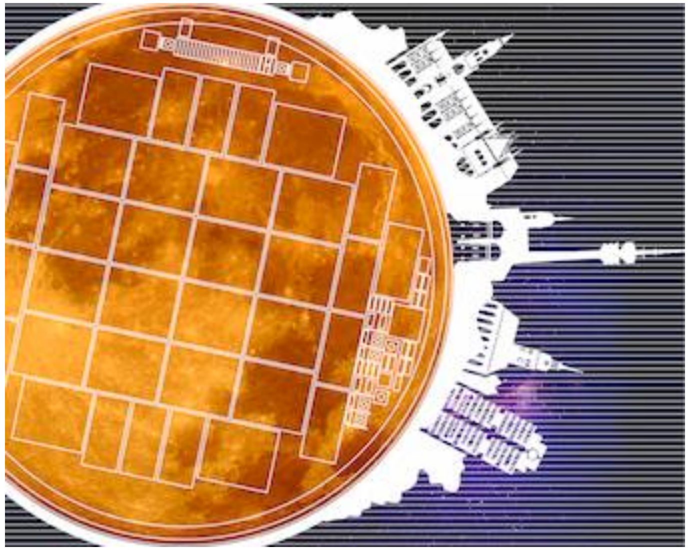

MoVeIT strip silicon detectors for proton beam monitoring: preliminary results

A Vignati[1], V Monaco[1,2], 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], 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

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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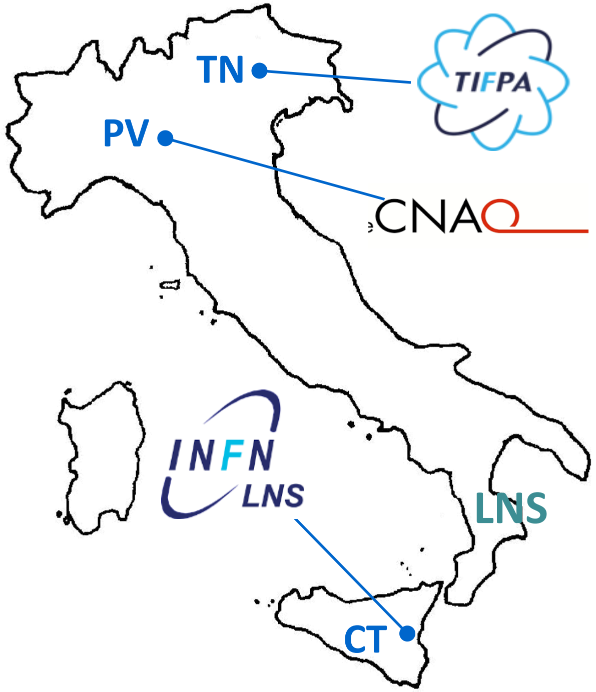

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1. to **directly count** individual protons:
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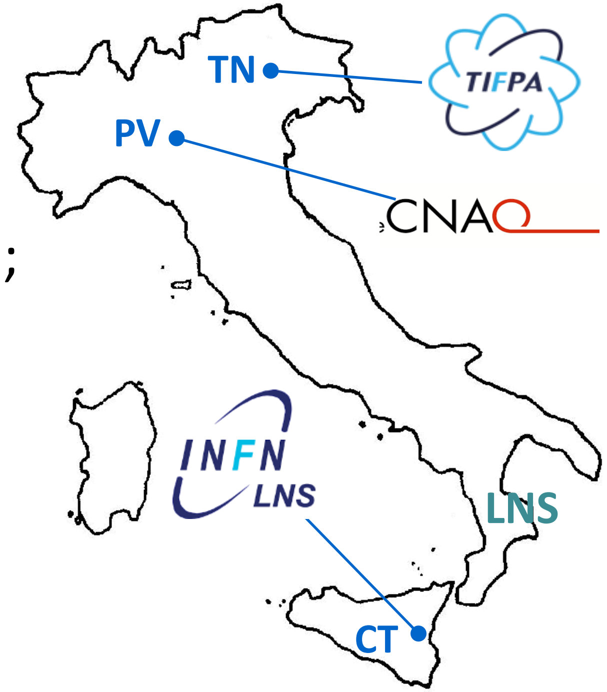
   - segmented in strips → beam projections in two orthogonal directions;



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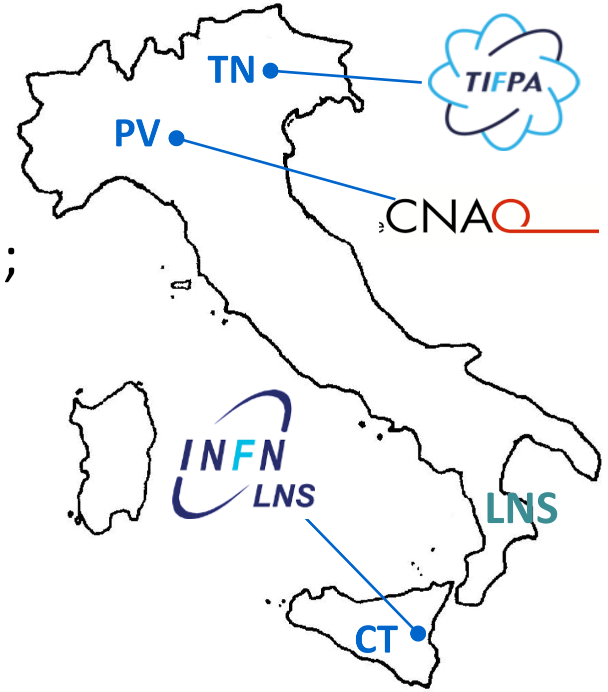
2. to **measure the beam energy** with time-of-flight techniques, using a telescope of two UFSD sensors:
   - error < 1 mm range in water.



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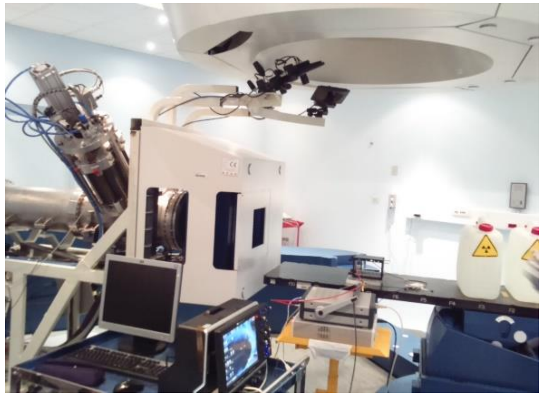
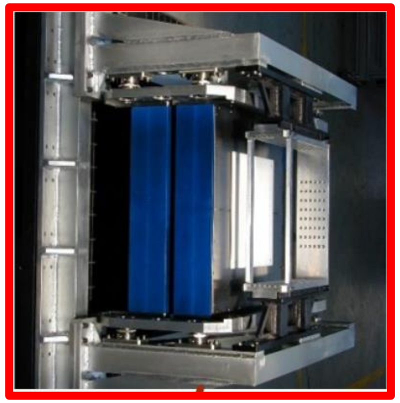
Motivation: beam monitoring in PT

Gas detectors (e.g. ionization chambers)

common choice for existing therapy centers





Large area;
robust and **stable;**
radiation resistant,
limited water equivalent thickness.

Slow charge collection;
limited sensitivity.

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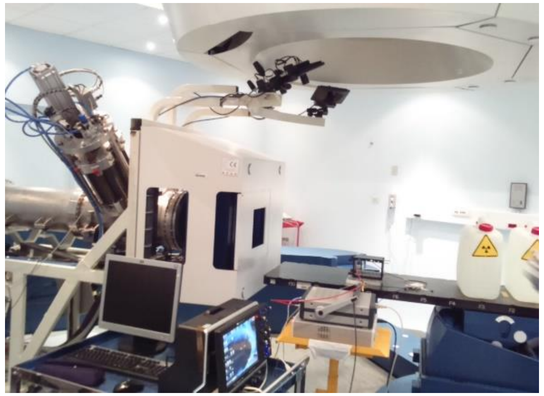
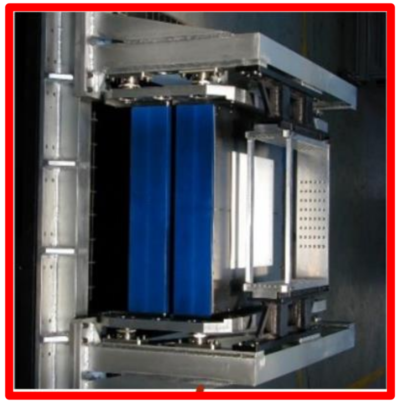
CNAO





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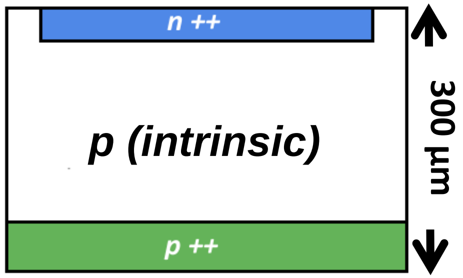
Solid state detectors (e.g. silicon detectors)



Good sensitivity to single particle detection;
Large granularity.

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

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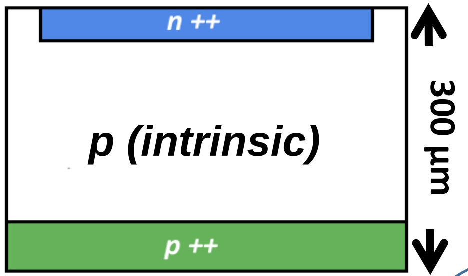

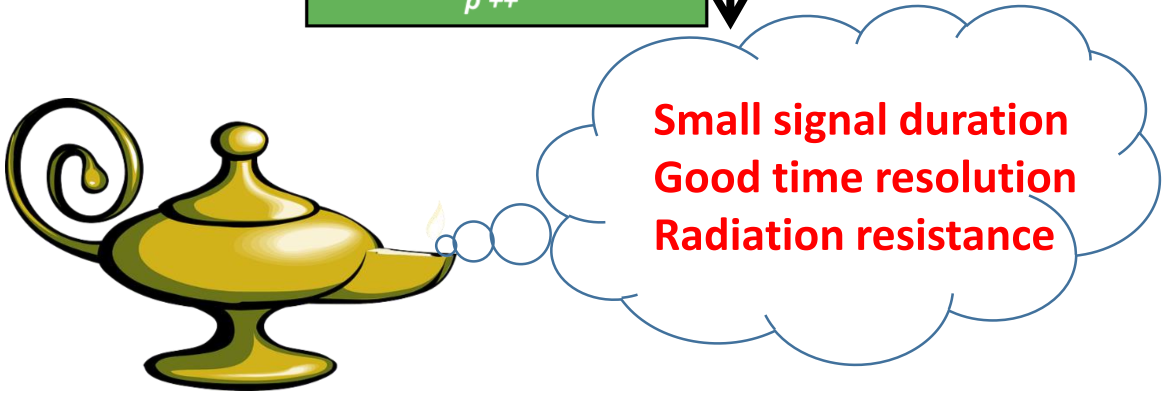

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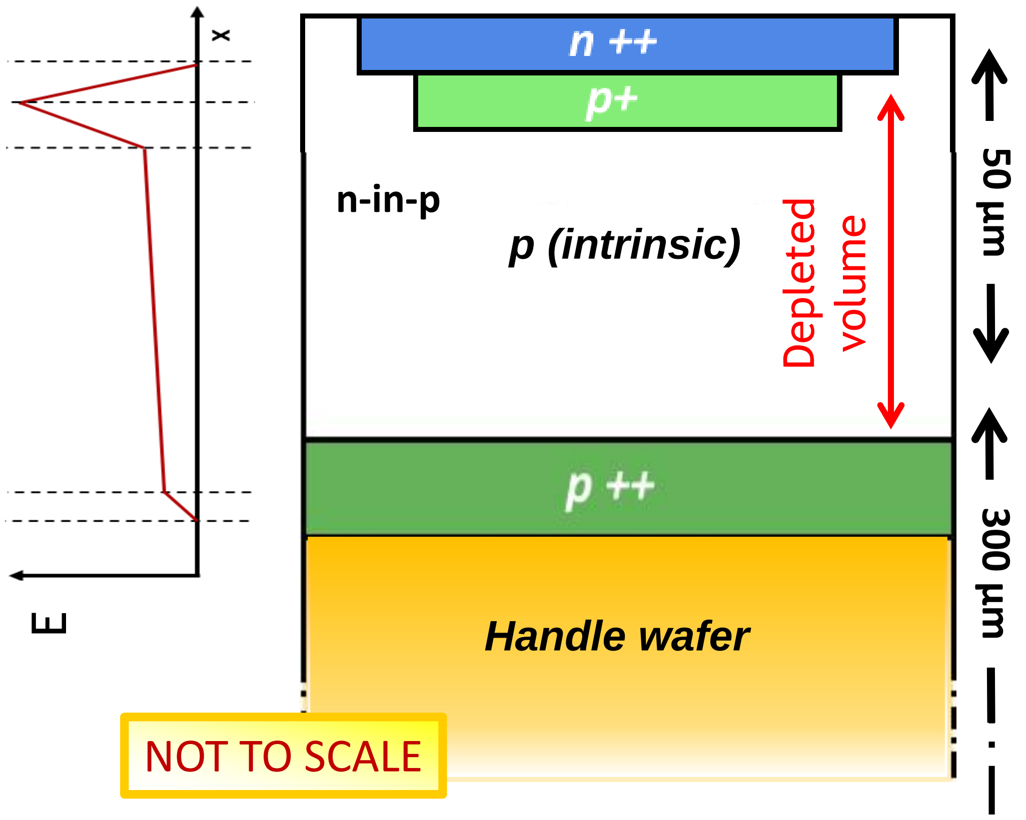
Ultra Fast Silicon Detectors (UFSD)

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



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

small detector thickness;

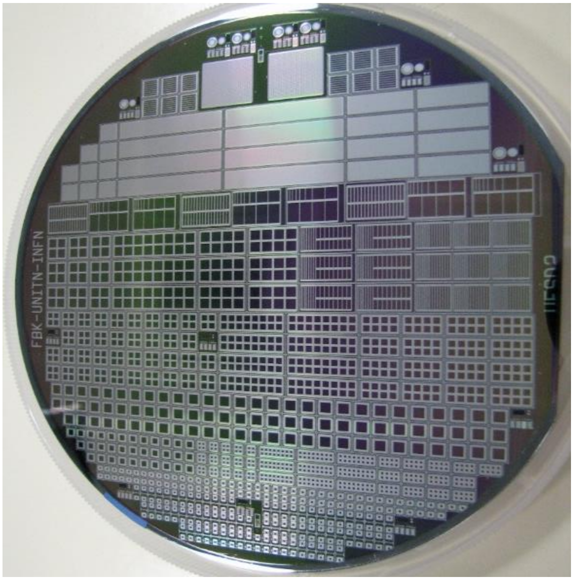
controlled low gain (~ 10), increasing with reverse bias.

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.

Production of 50 µm UFSD prototypes @ FONDAZIONE BRUNO KESSLER



18 silicon-on-silicon wafers

different **doping strategies** for the gain layer to improve **radiation resistance**.

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different **doping strategies** for the gain layer to improve **radiation resistance**.

30 strips, pitch 150 µm
8 per wafer (2 no gain)

30,0 mm

5,6 mm

20 strips, pitch 200 µm
8 per wafer (2 no gain)

15,0 mm

5,6 mm

Same strip area, same capacitance C ~ 5pF;

Gain and no-gain;

Total ~ 250 structures.

Production of 50 µm UFSD prototypes @ FBK

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Same strip area, same capacitance C ~ 5pF;

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Total ~ 250 structures.

Laboratory measurements (probe station + power analyzer and laser beam).

- **IV Curves** (Leakage current, breakdown voltage, bad strips)
- **CV curves** (Depletion voltage & doping profile of the sensor)
- **Laser tests** (dead area between strips)

Beam tests of on a clinical beam (CNAO - Pavia)

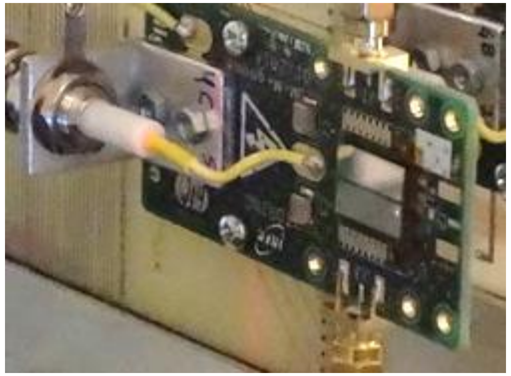
<u>Detectors</u>

2 UFSD pads 50 µm thick

- CNM 1,2 x 1,2 mm^2
- Hamamatsu (HPK) Ø 1 mm

MoveIT strip prototypes (FBK)

- Long and short geometries
- Only 2 ch. (1 gain + 1 no gain)



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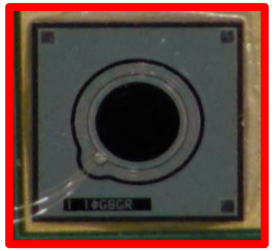
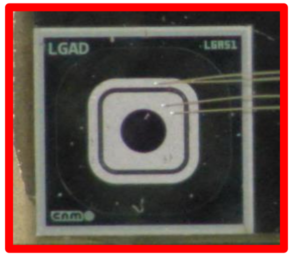
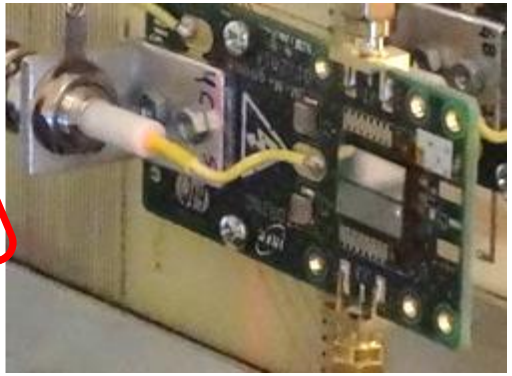
BORON







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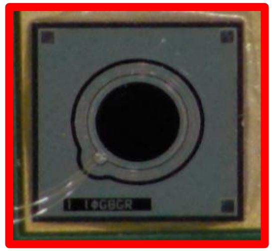

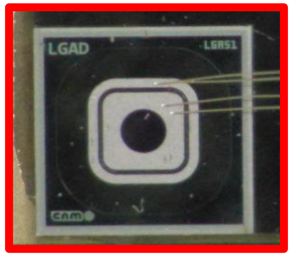

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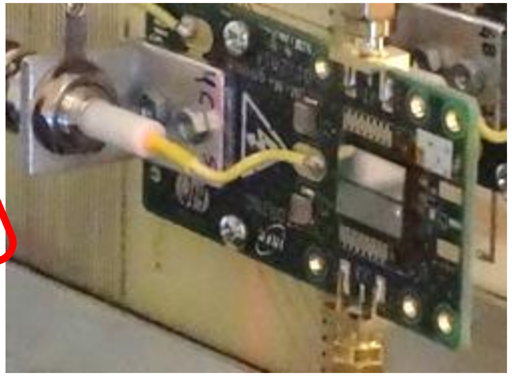

BORON

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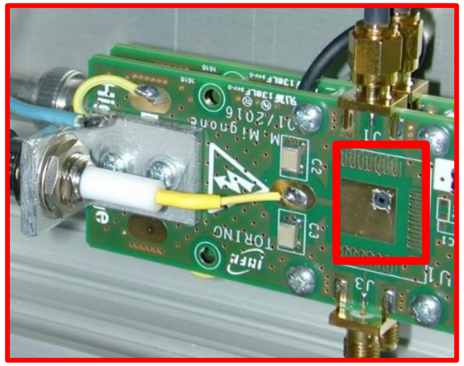
Readout

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



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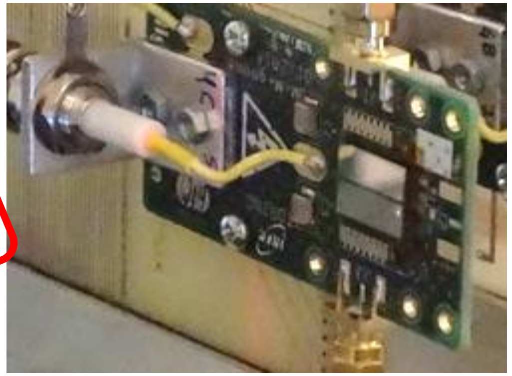

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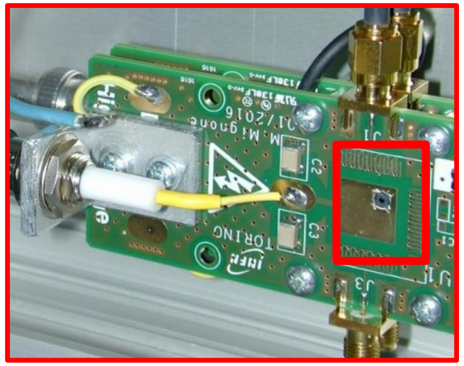
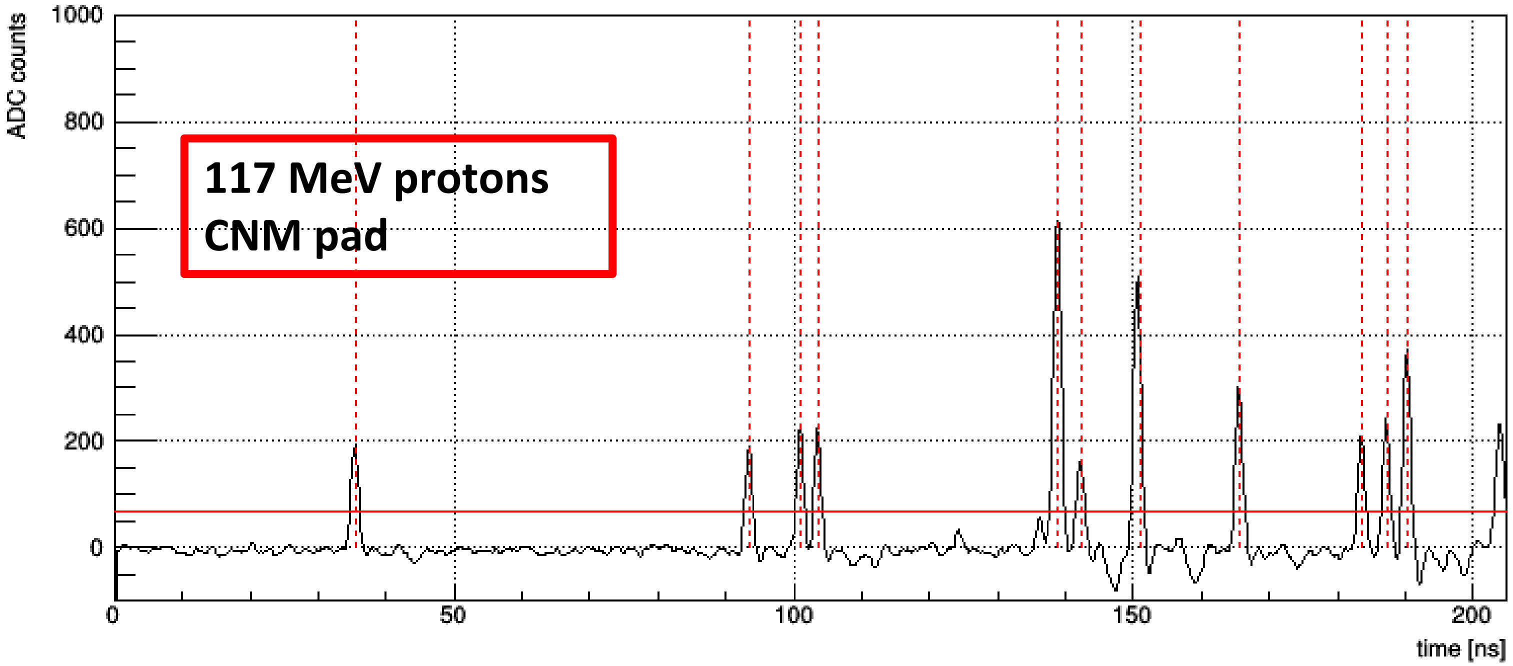


CNAO Beam

- 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)

Signal waveform acquired on the CNAO beam

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



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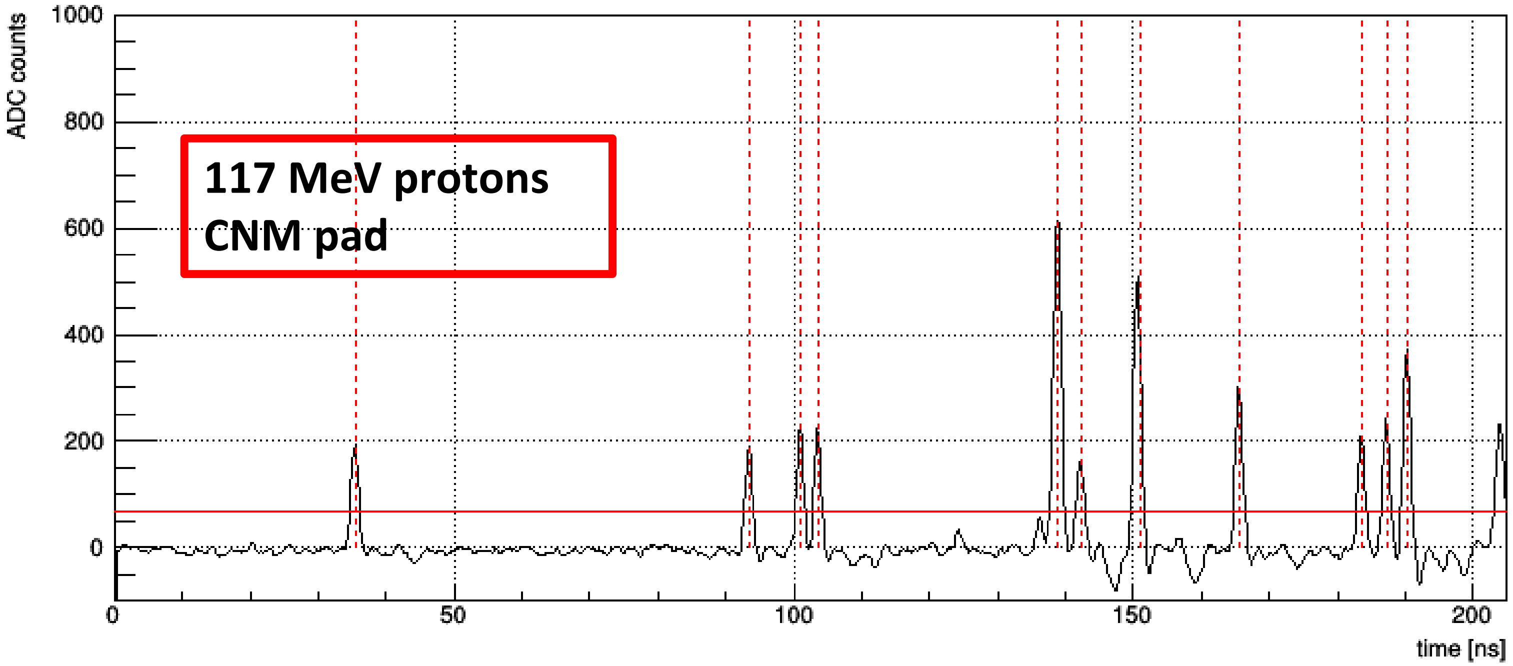

- ➢ Peaks corresponding to individual protons can be easily distinguished;
- ➢ large amplitude fluctuations;

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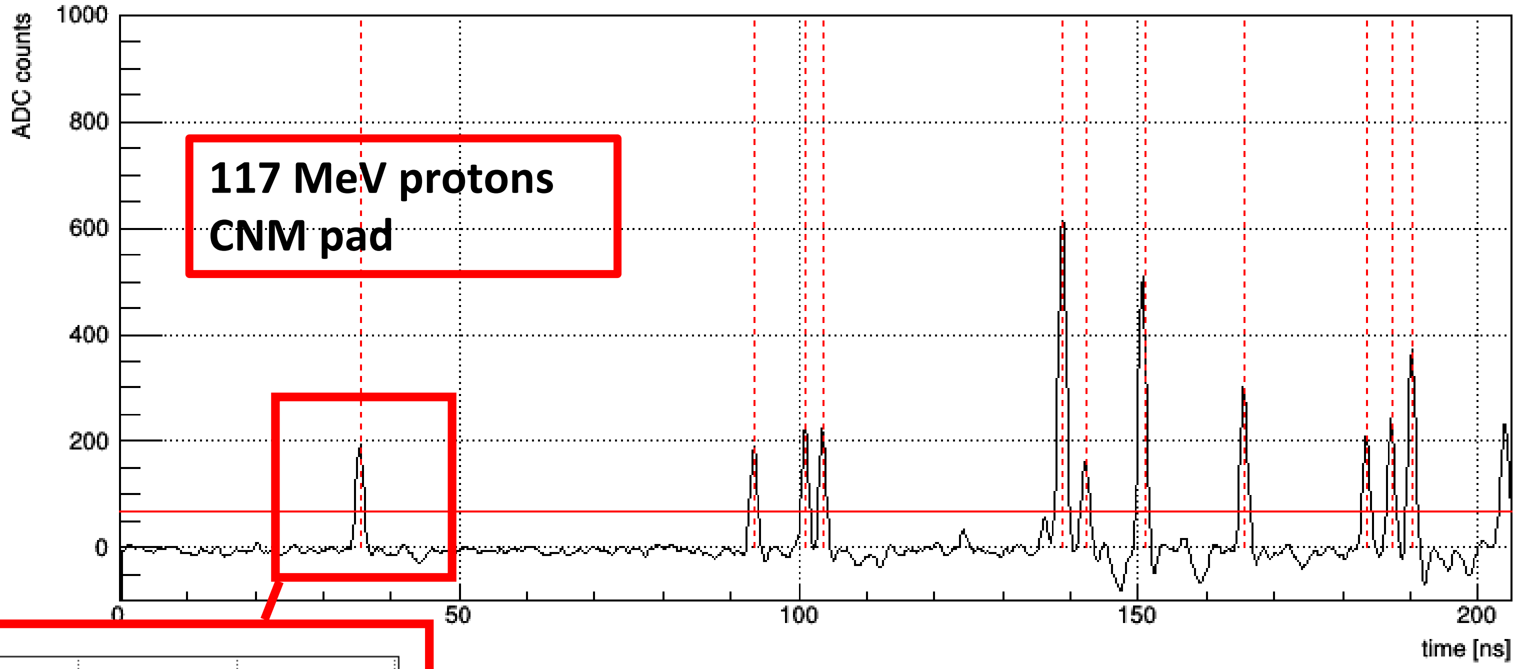

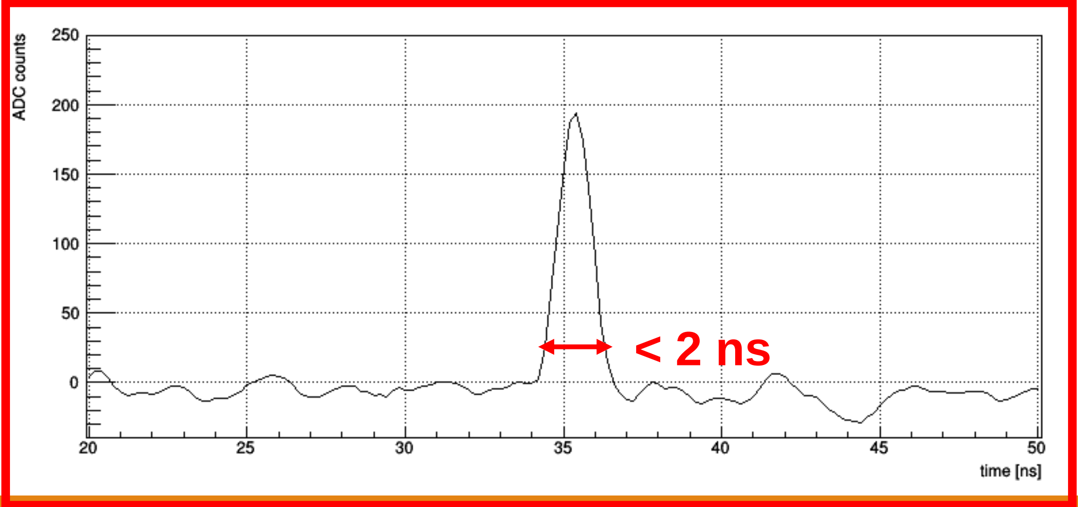

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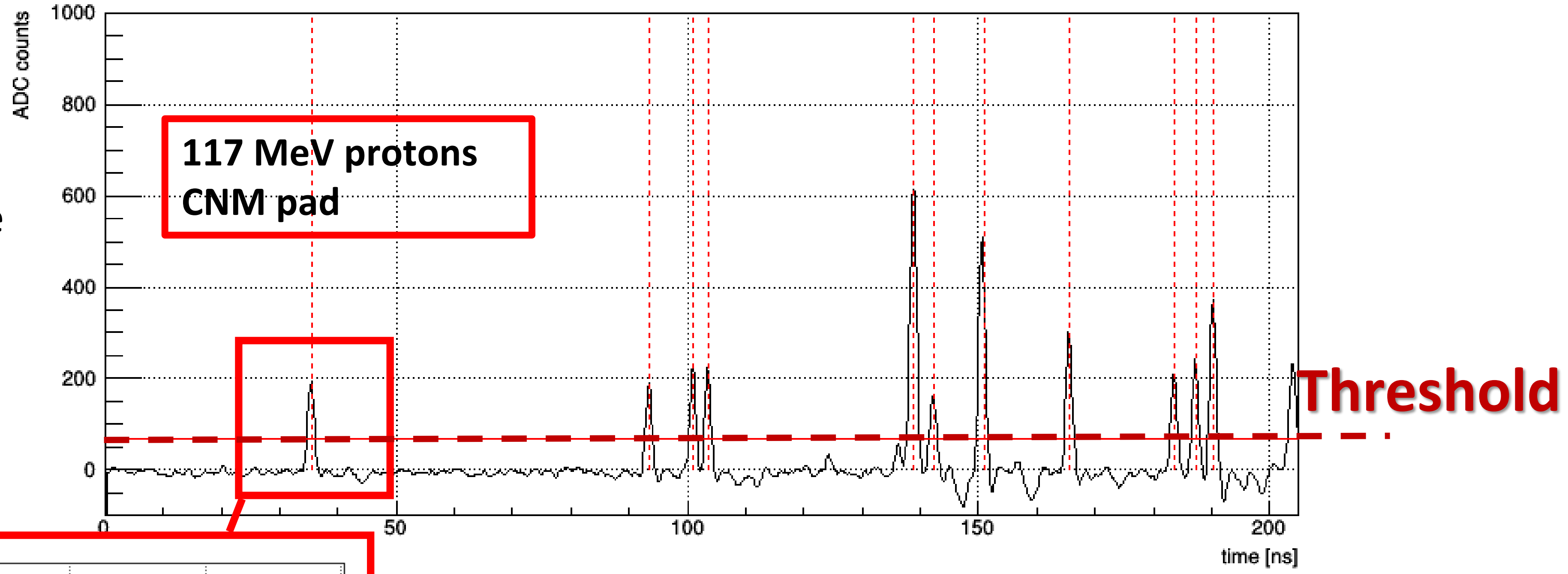
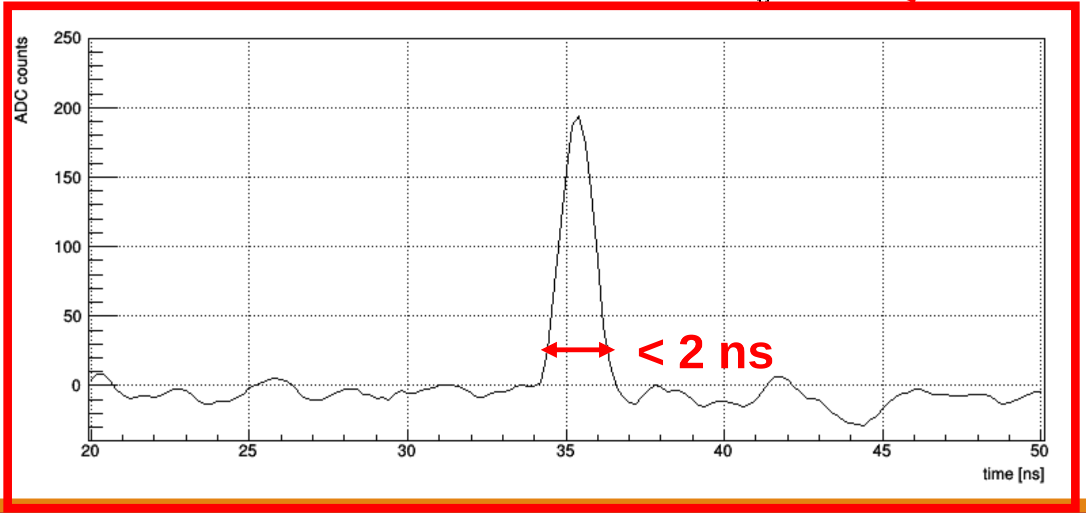
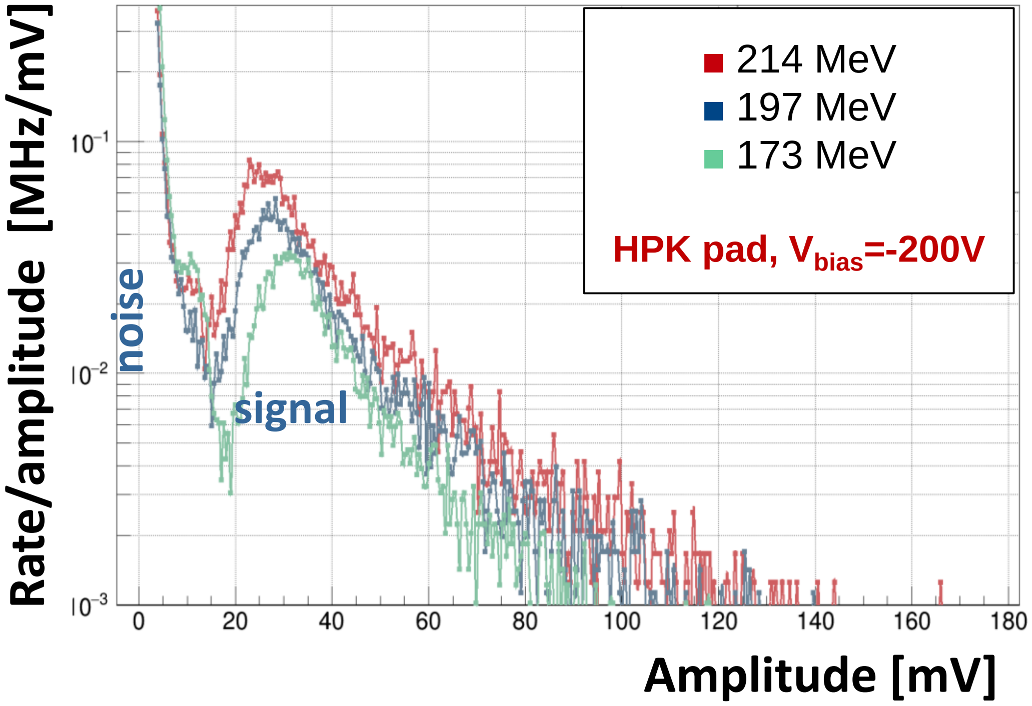




- Peaks corresponding to individual protons can be easily distinguished;
- large amplitude fluctuations;
- short peak duration;
- fixed threshold can be applied to count the pulses.

Signal & noise distribution

Signal amplitude distribution



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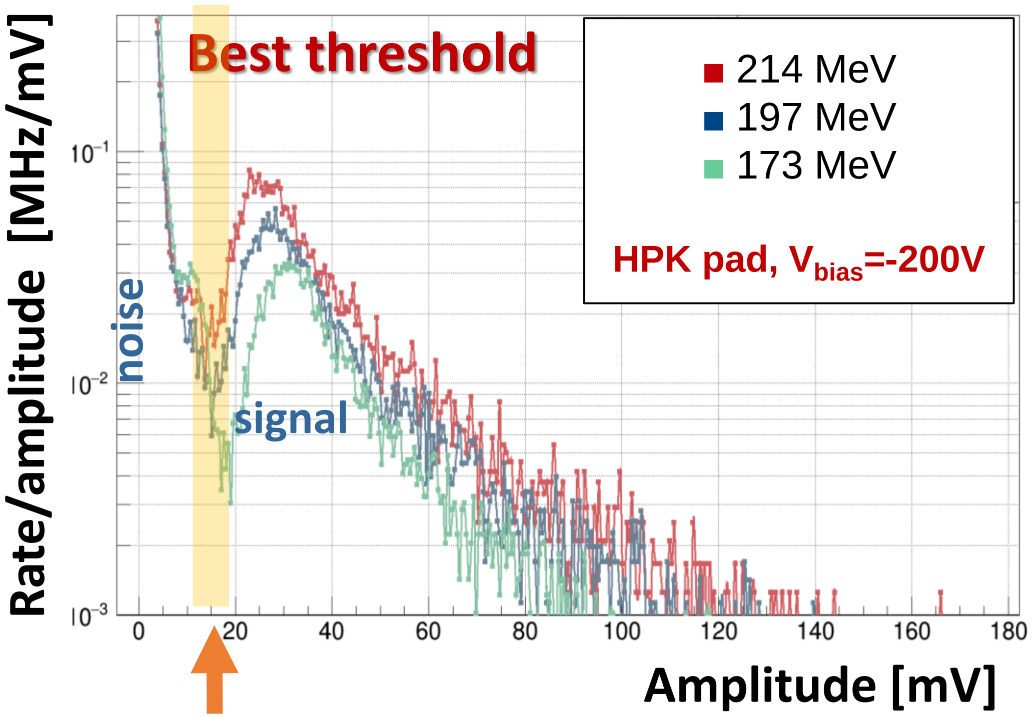
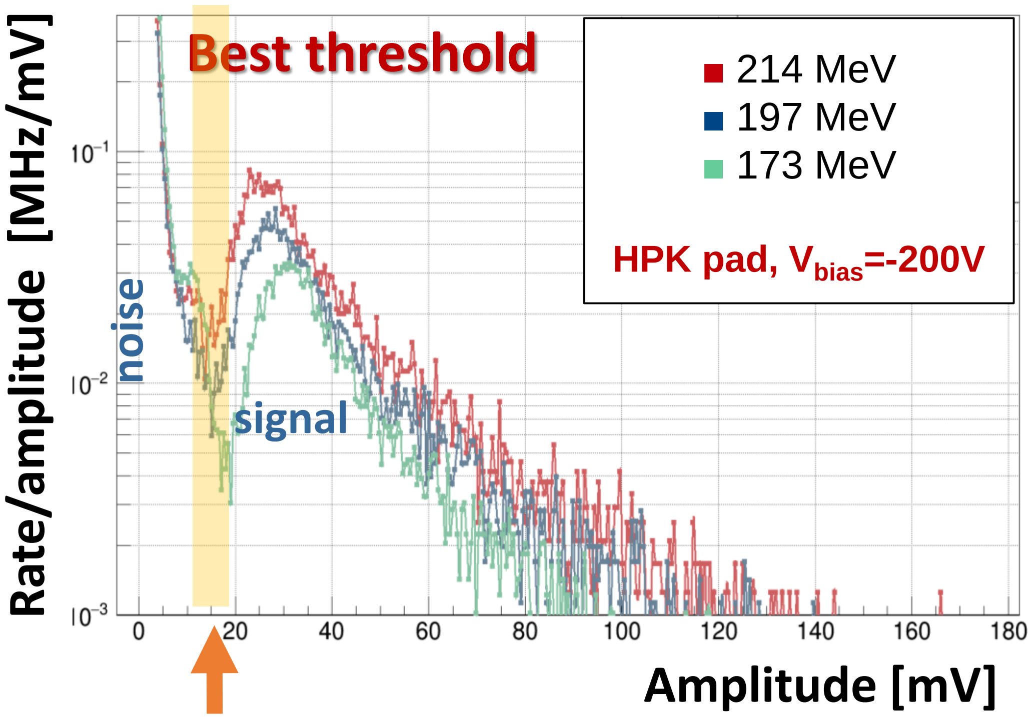
Signal amplitude distribution



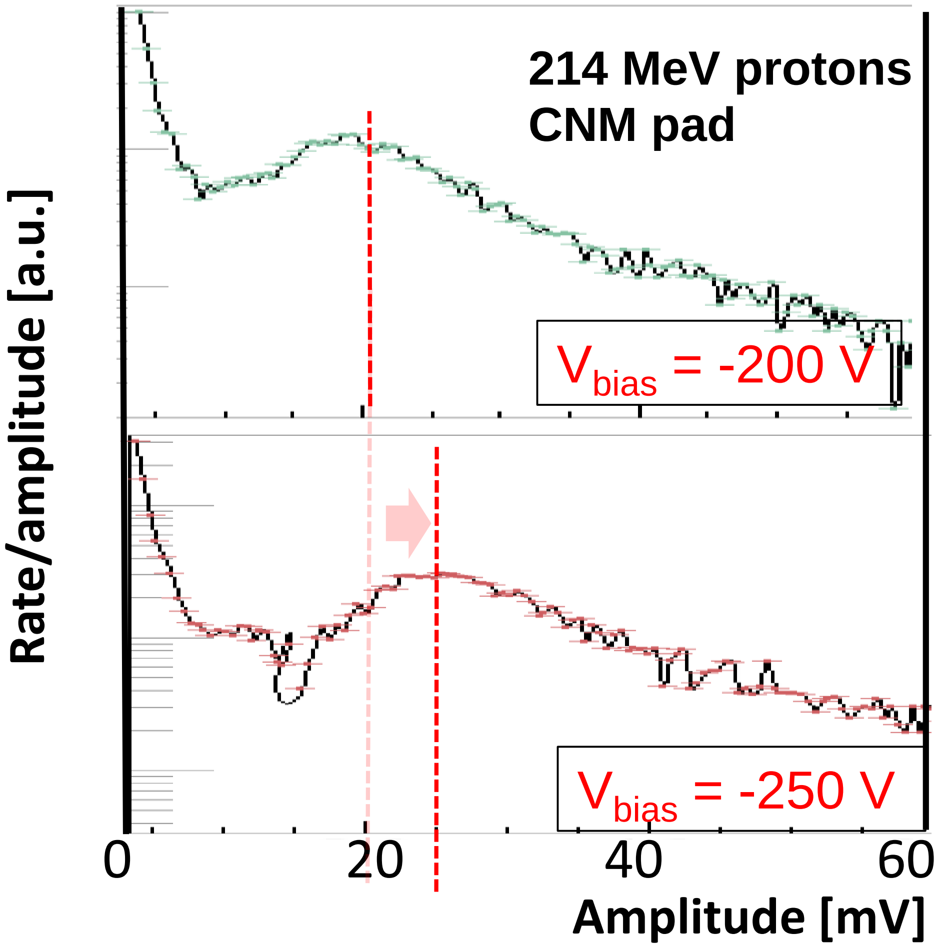
- Good S/N separation;
- Larger S/N at lower beam energies;
- Best threshold is beam energy dependent.

Signal & noise distribution

Signal amplitude distribution



The S/N can be enhanced by increasing the bias voltage ➡ gain increase in the sensor



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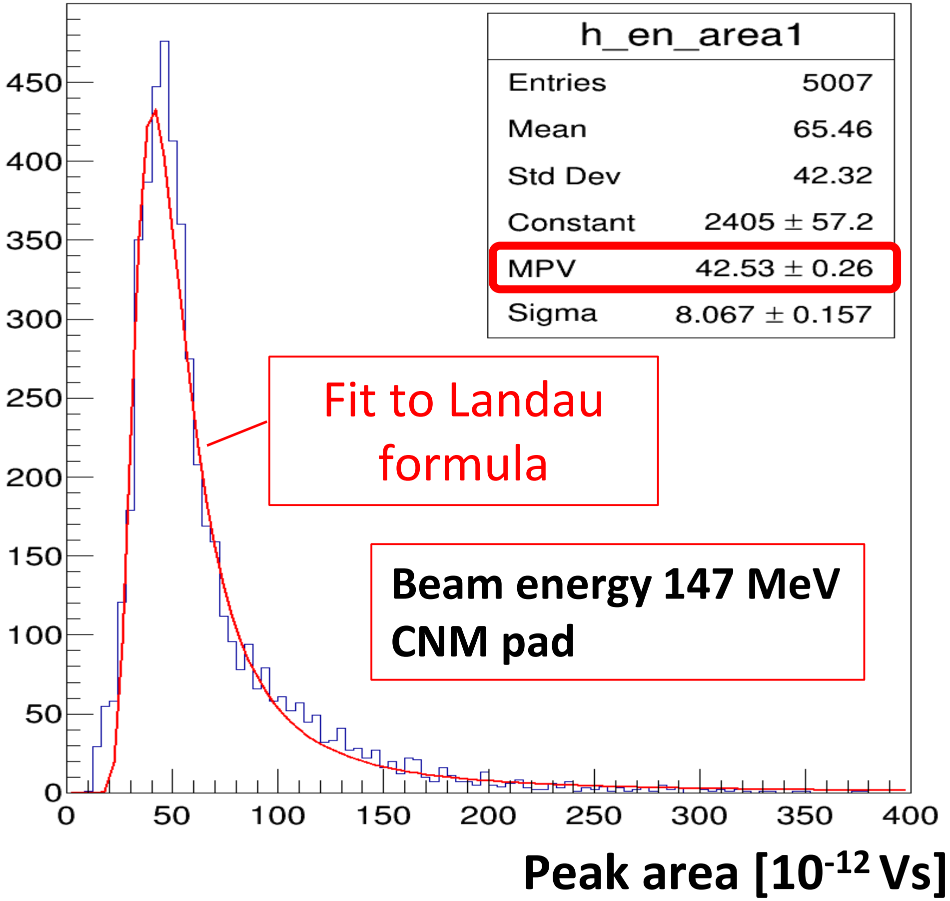
Peak area & Landau distributions

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



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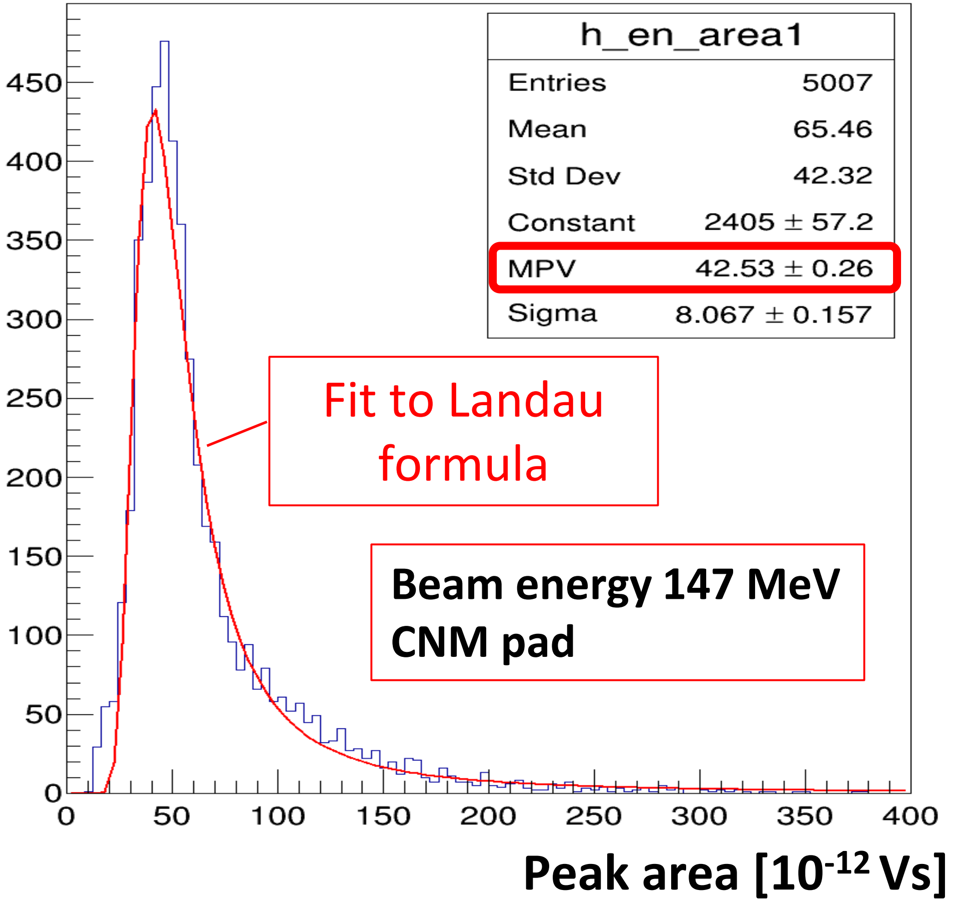
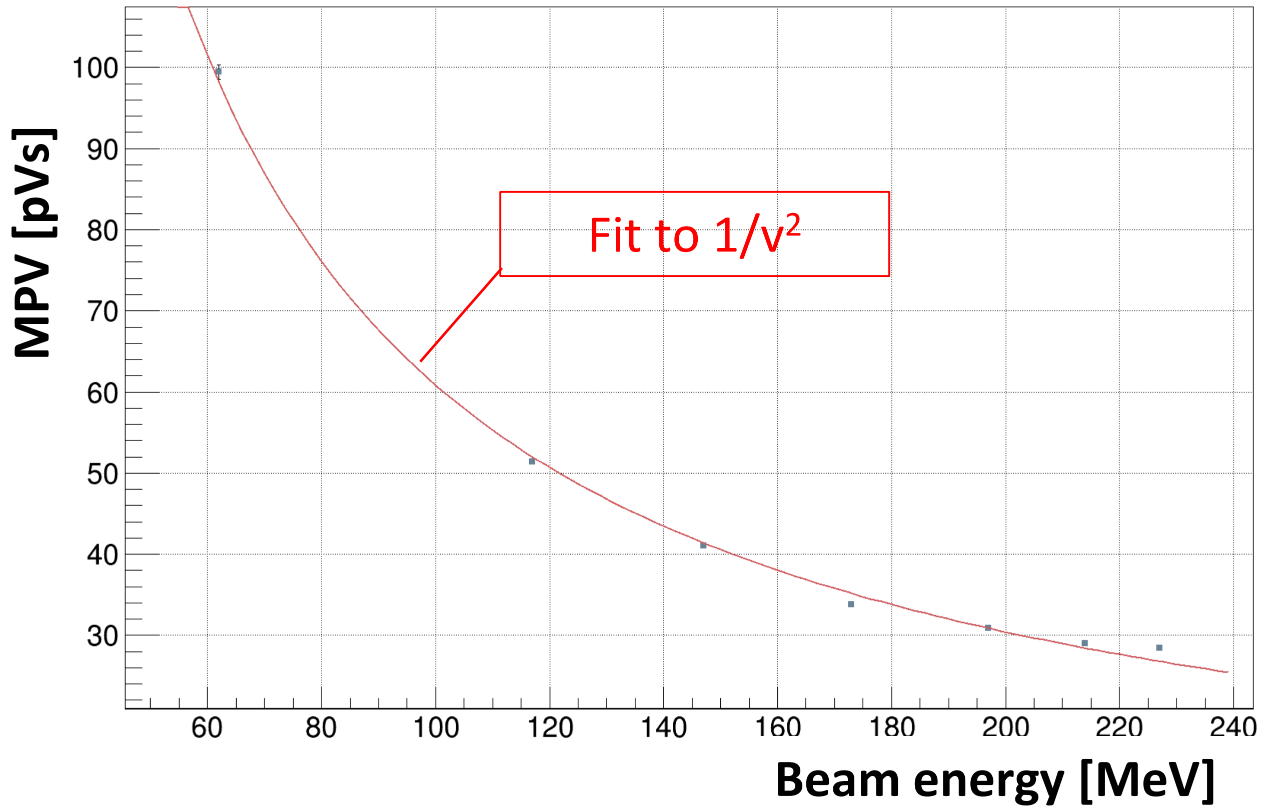
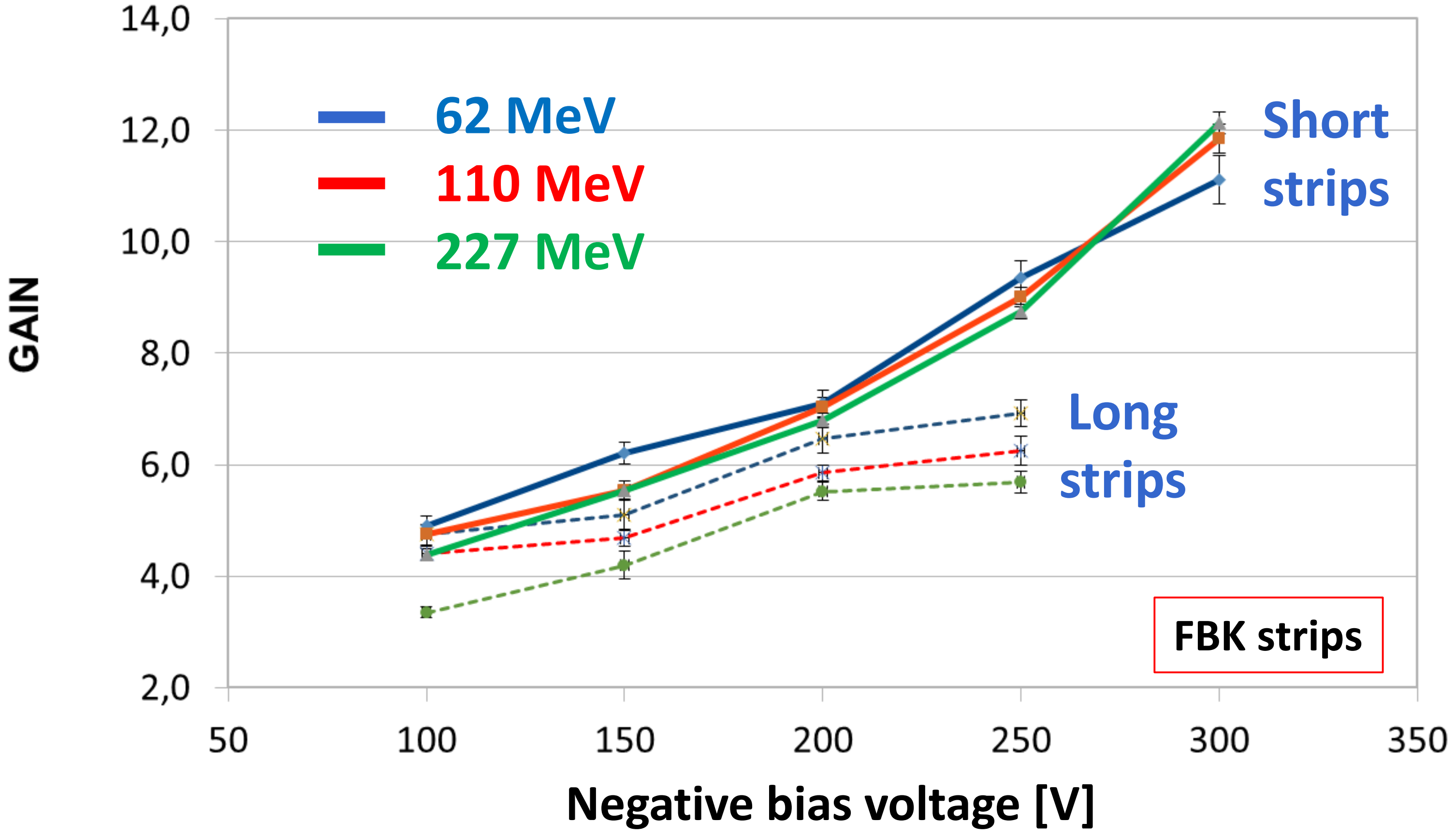


- **Landau's MPV** dependence on **beam energy** well described by Bethe-Bloch $1/v^2$ dependence



Gain of strip detectors

$$\text{Gain}(V) = \frac{\text{MPV}_{\text{gain}}\ (V)}{\text{MPV}_{\text{no gain}}(V)}$$



- Gain increase with V_{bias}

Gain of strip detectors

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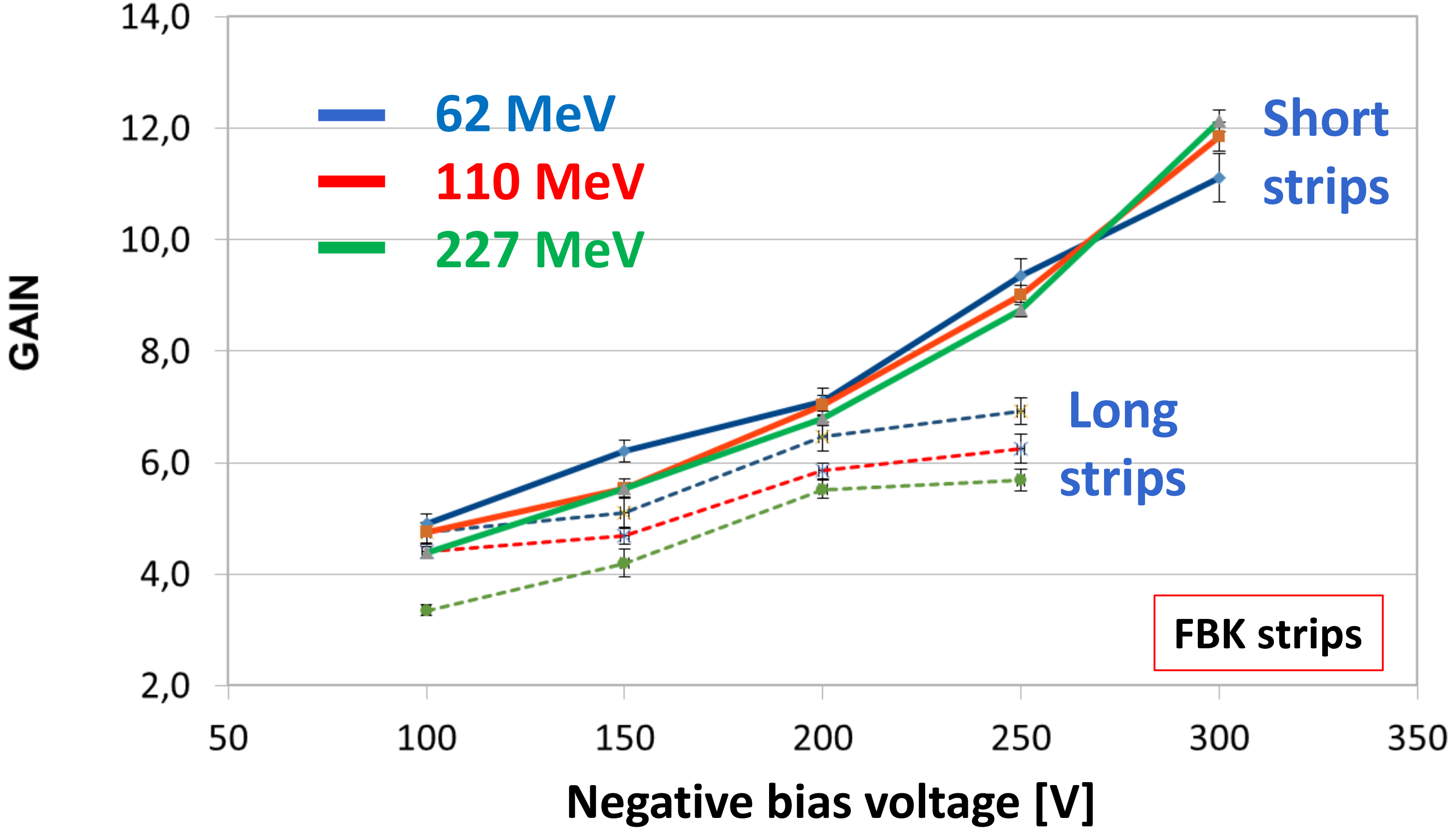
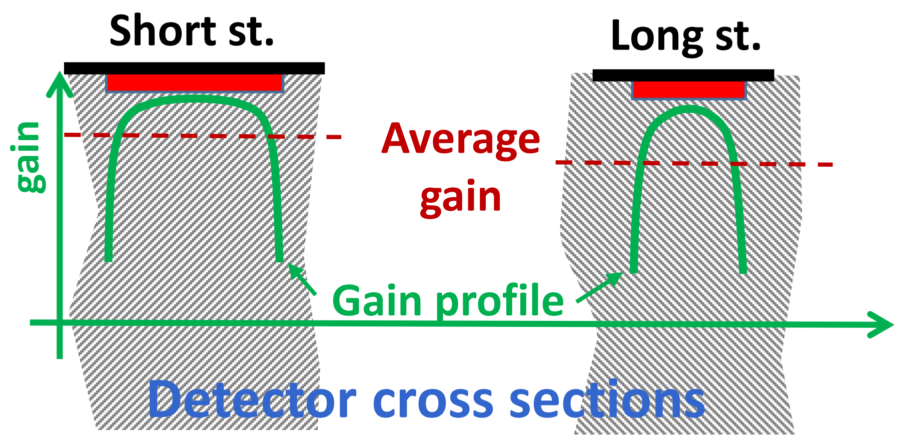
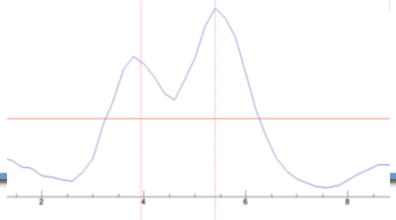


- Gain increase with V_{bias}
- **Long strips** (thinner) show a **lower average gain** than short strips

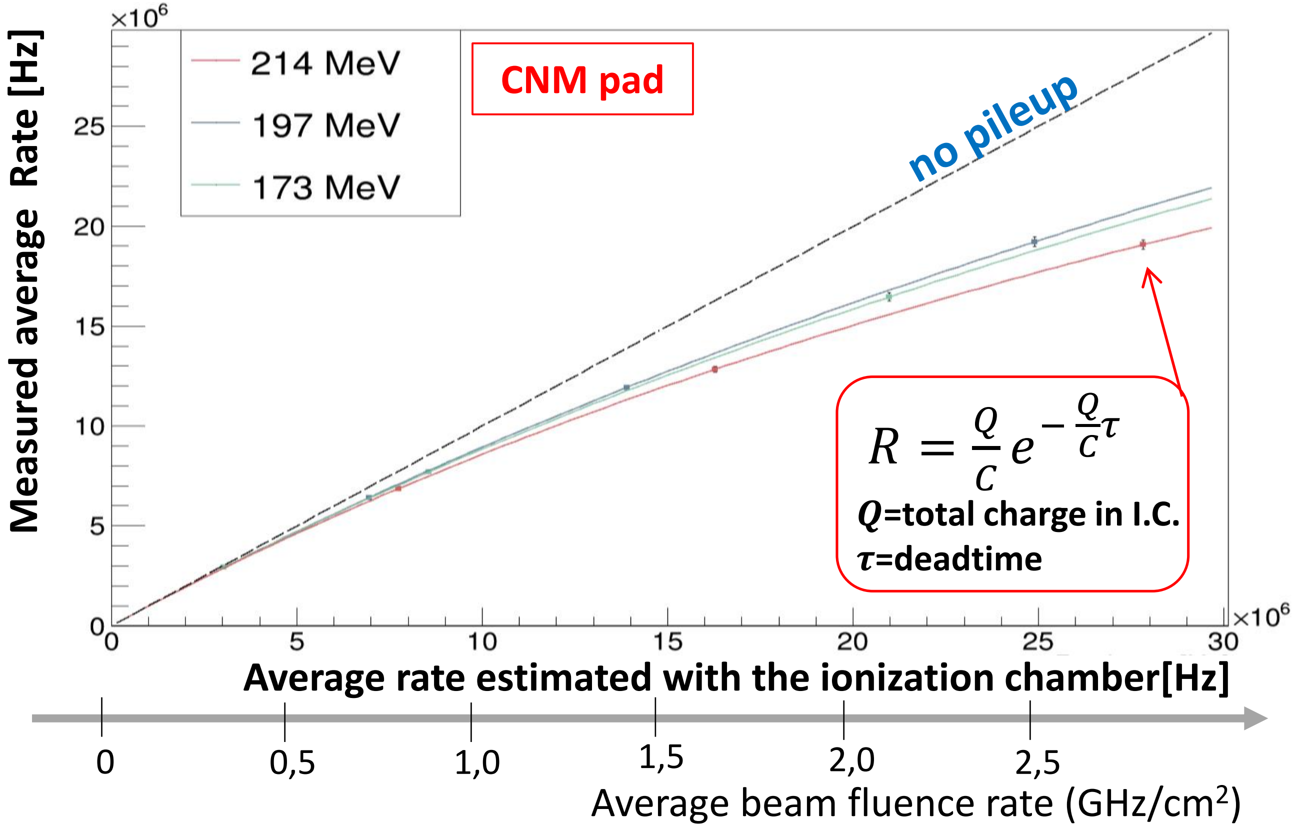
geometrical effect



Concern: pile-up inefficiency



Measured vs. estimated rate, using a PTW pinpoint I.C. and a varied beam flux (20 – 50 – 100% of max)



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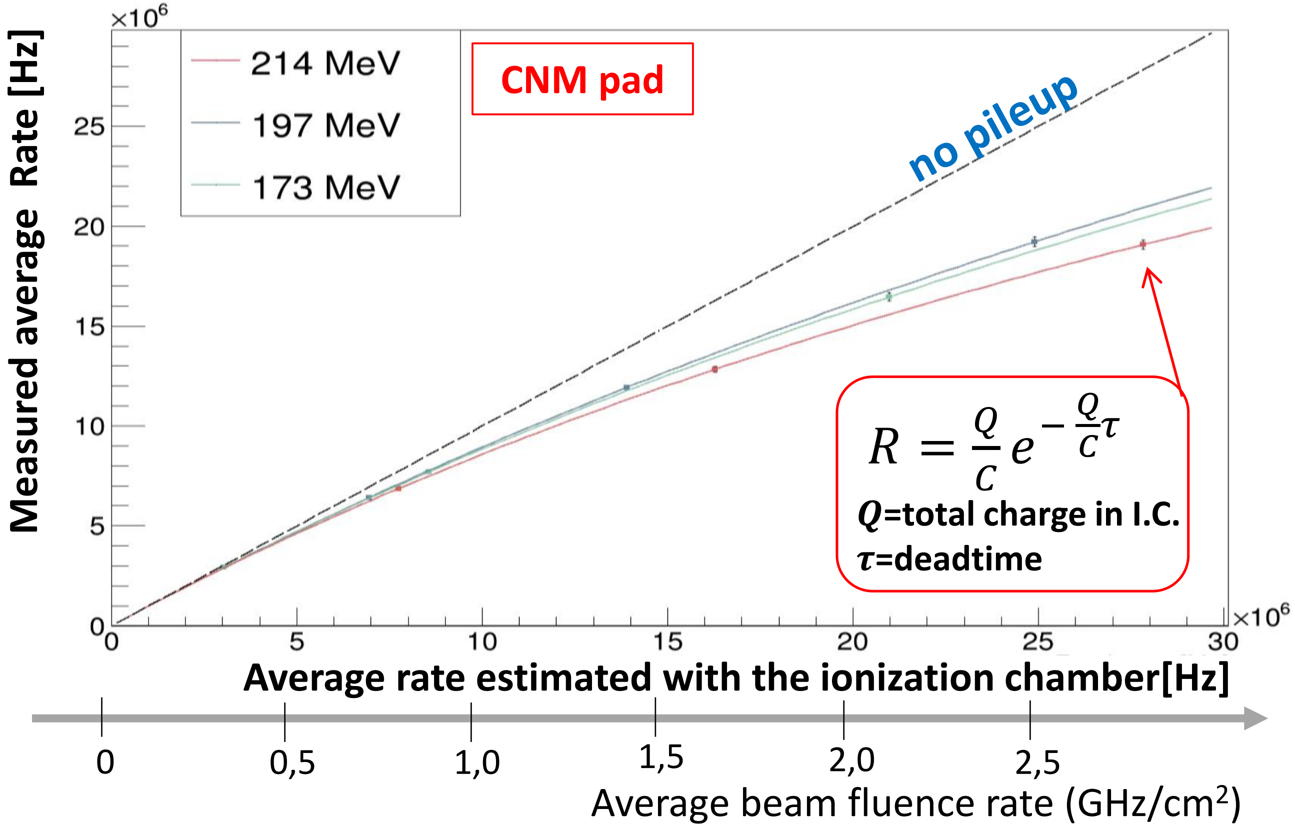
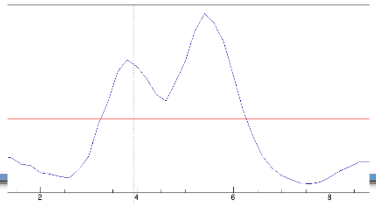


- Large inefficiency observed (up to 25% at largest clinical fluxes) ⇒ Correction required
- Data well described by paralyzable pileup model

Concern: pile-up inefficiency



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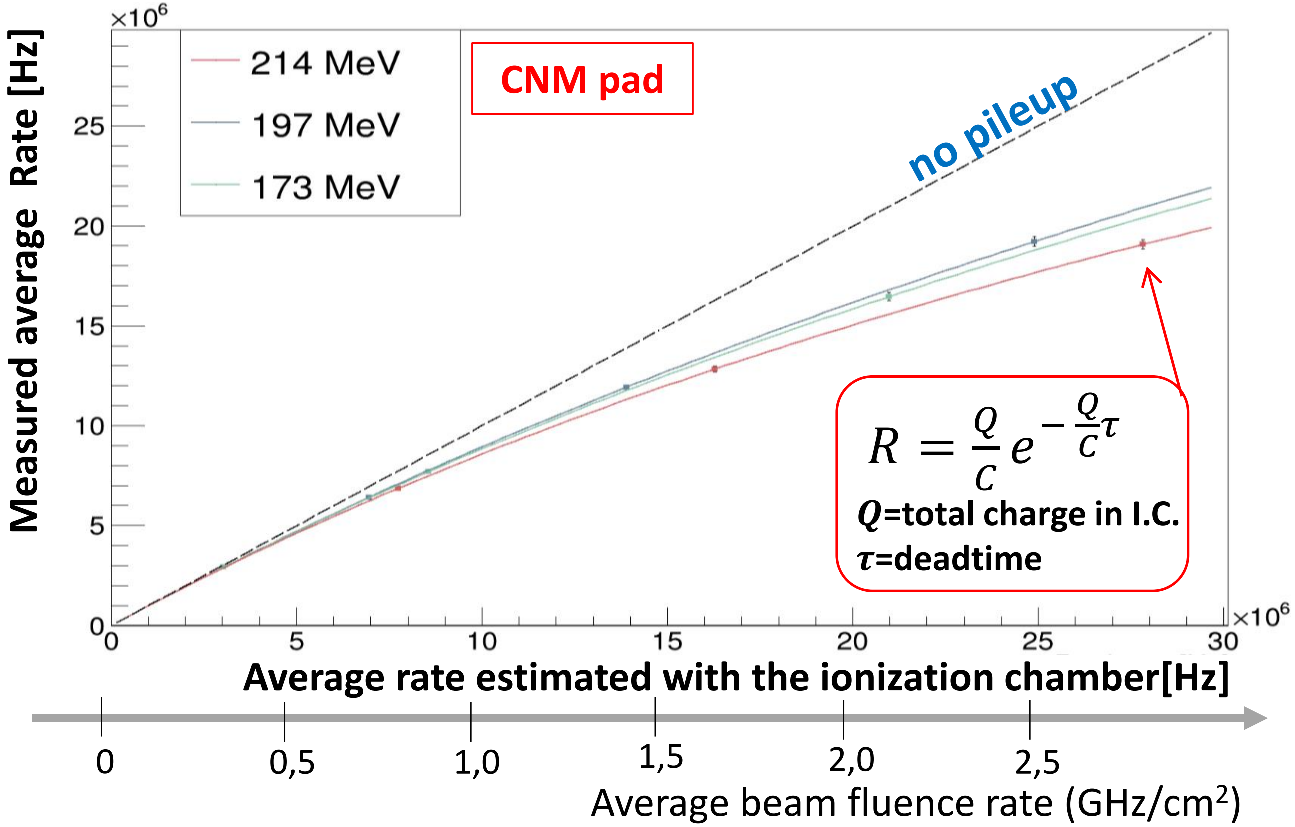

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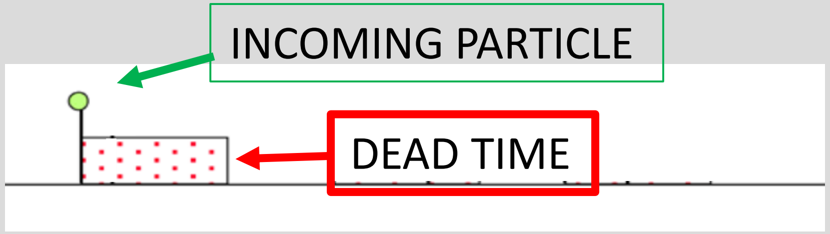

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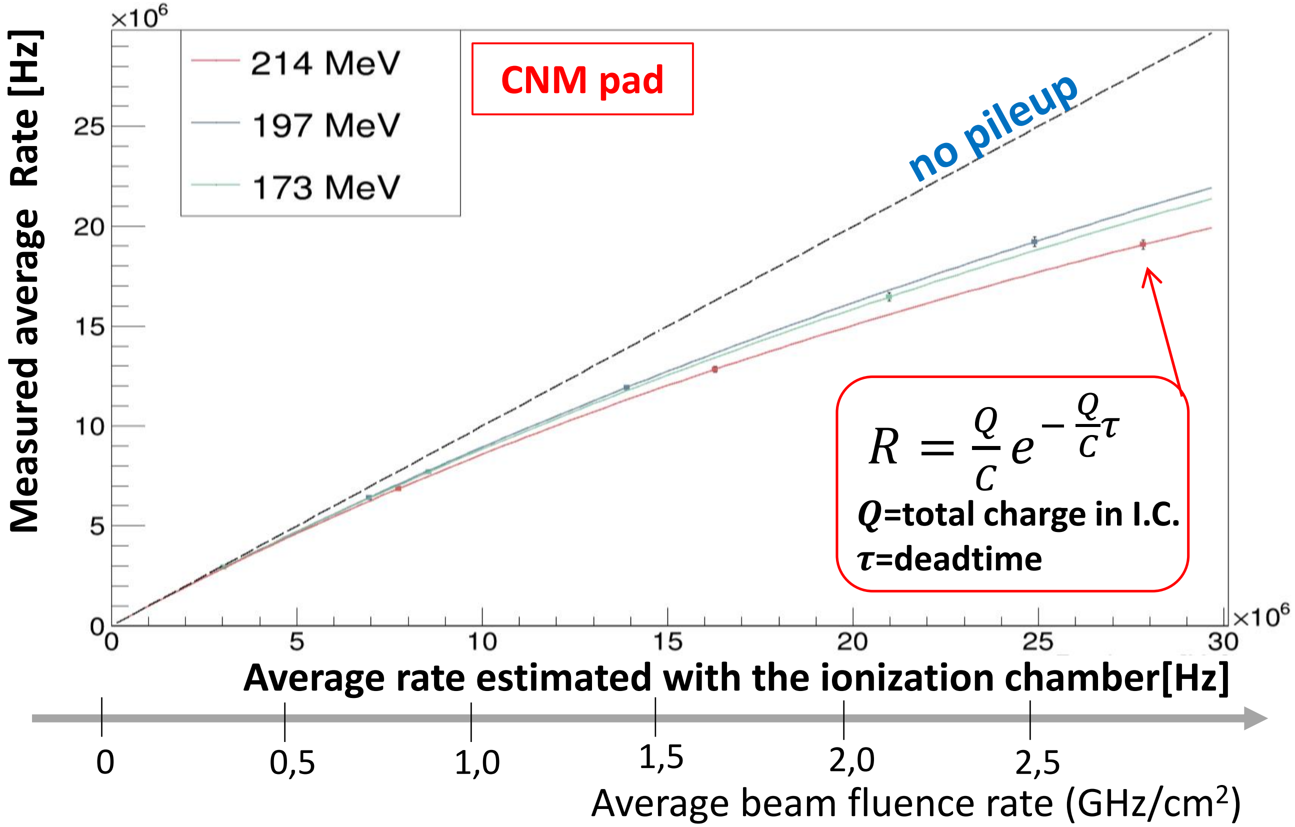

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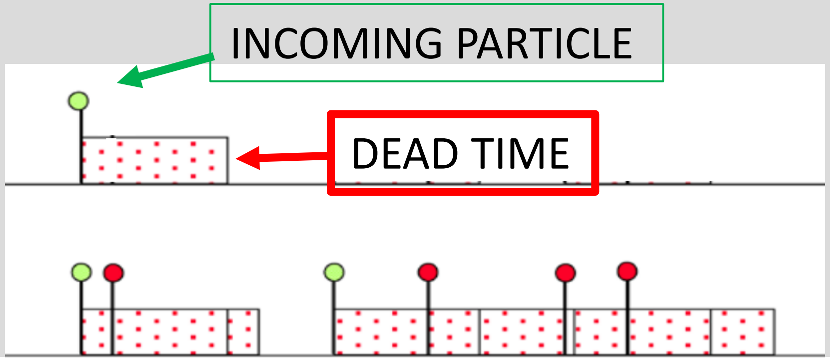
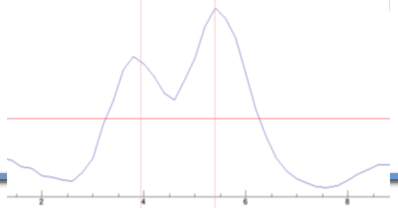
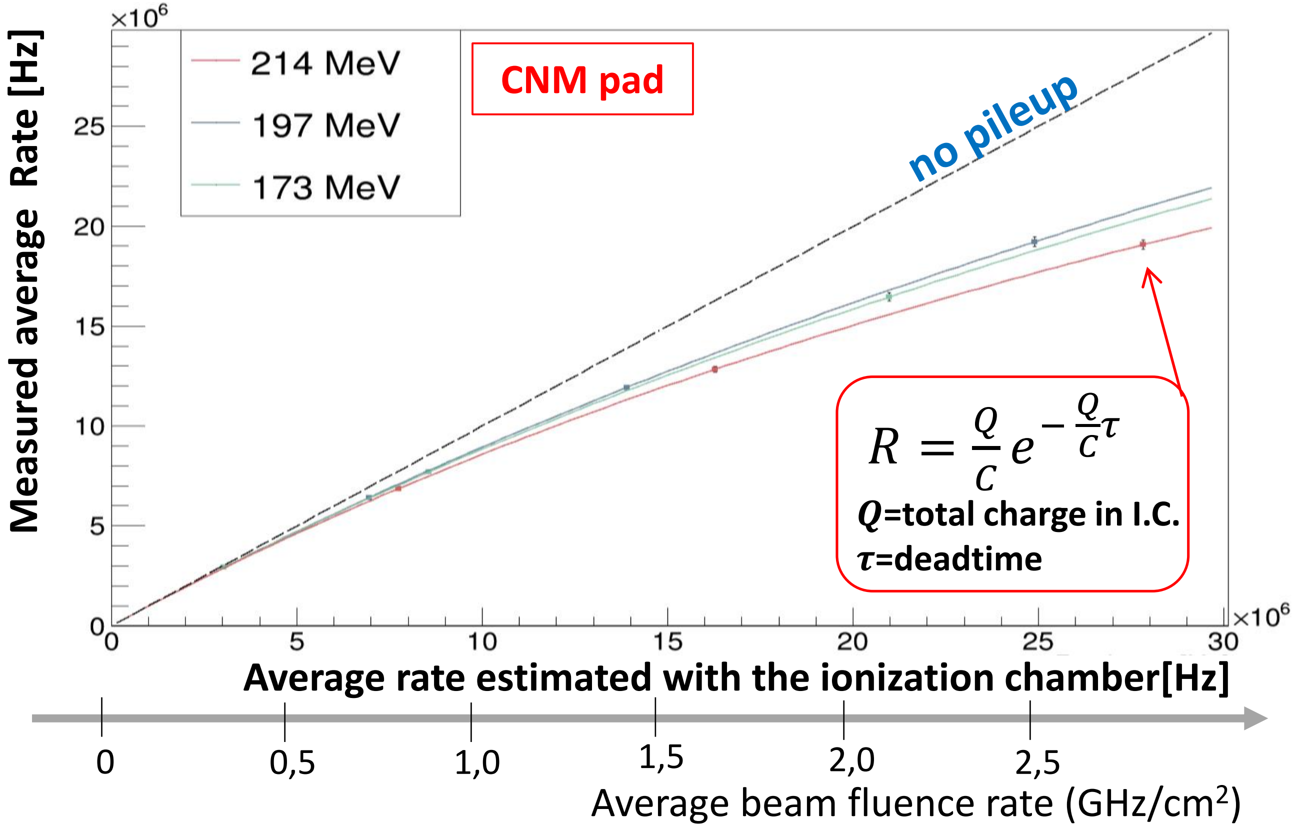


Concern: pile-up inefficiency

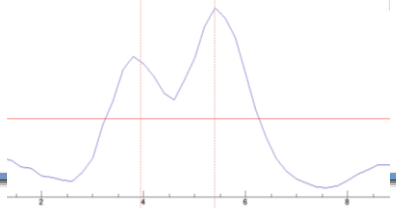


Measured vs. estimated rate, using a PTW pinpoint I.C. and a varied beam flux (20 – 50 – 100% of max)



- Large inefficiency observed (up to 25% at largest clinical fluxes) ➡ Correction required
- Data well described by paralyzable pileup model ➡ deadtime **much larger than expected**

Concern: pile-up inefficiency



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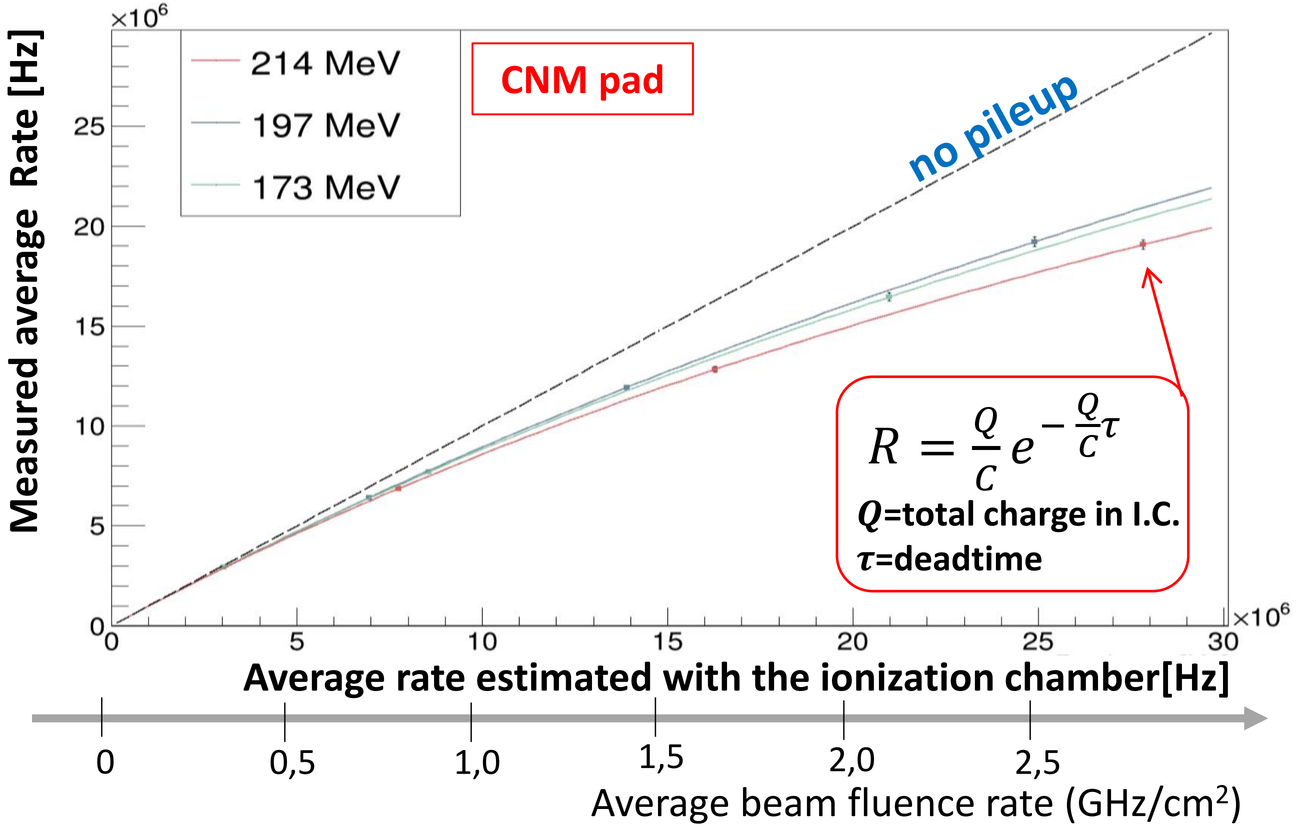
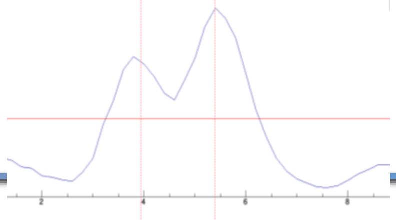
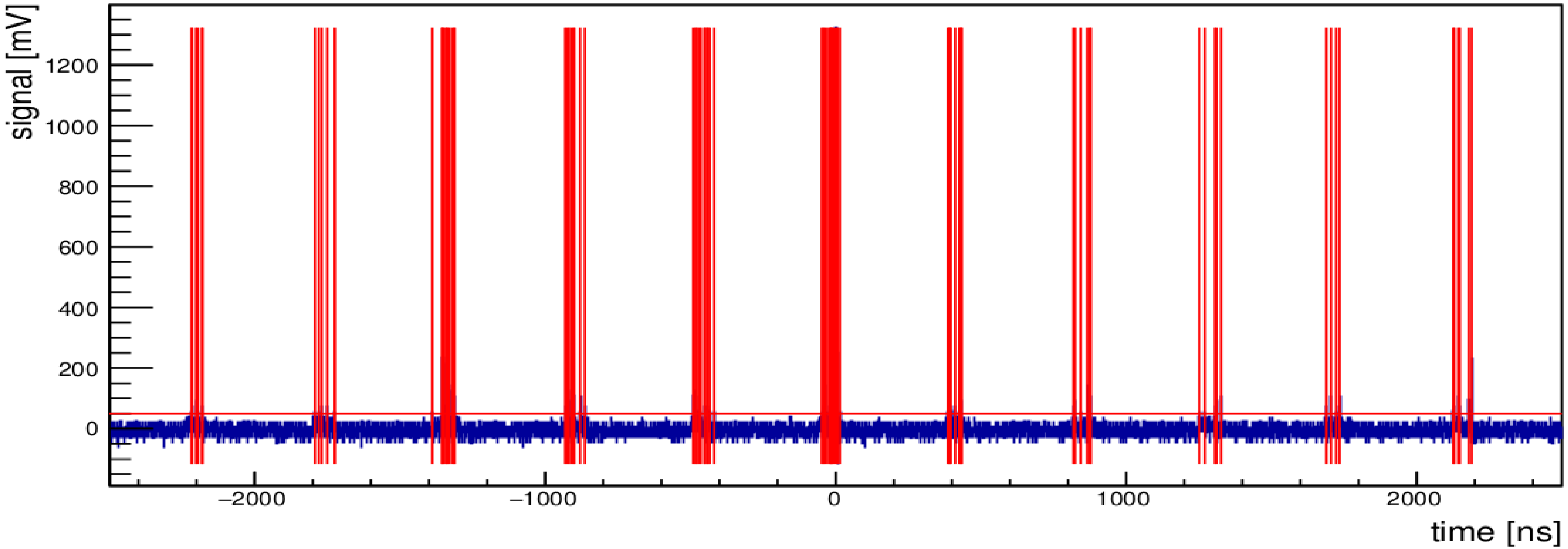


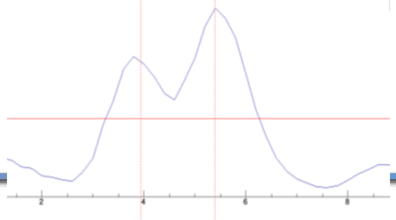
- Large inefficiency observed (up to 25% at largest clinical fluxes) → Correction required
- Data well described by paralyzable pileup model → deadtime **much larger than expected**
- Reason relies on the bunched structure of the CNAO beam (istanteneous flux ~ 10 X average)

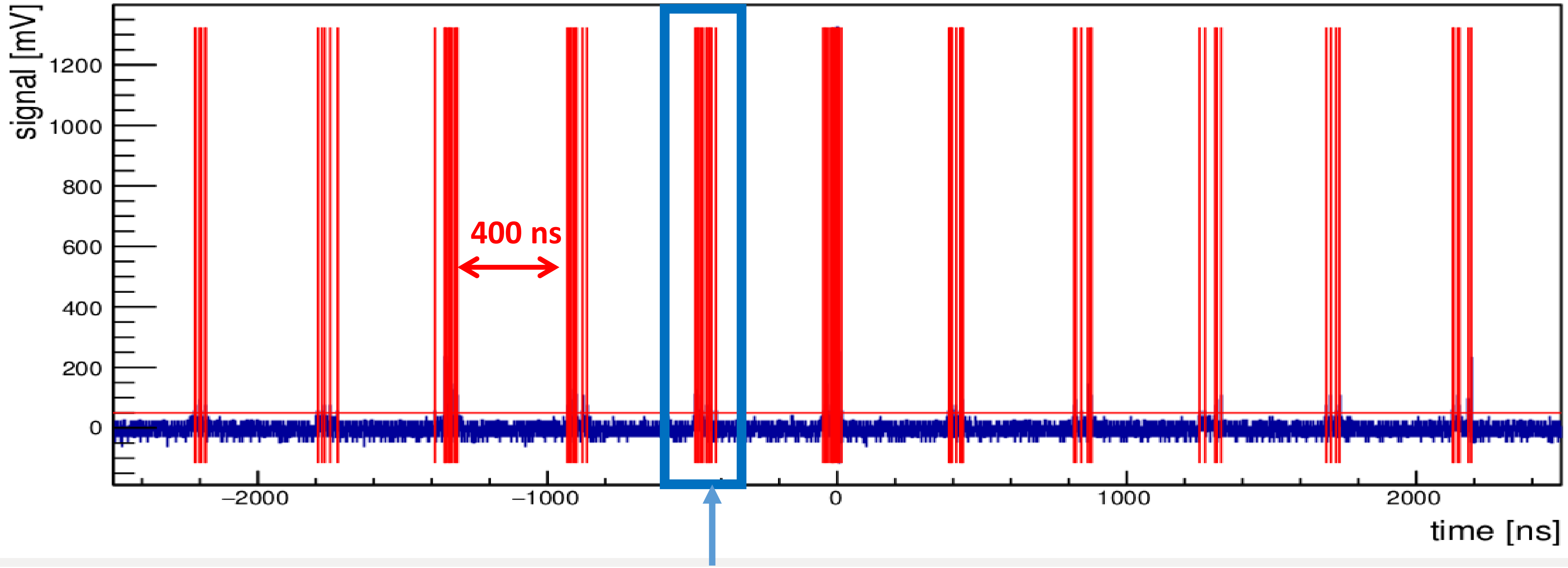
Concern: pile-up inefficiency





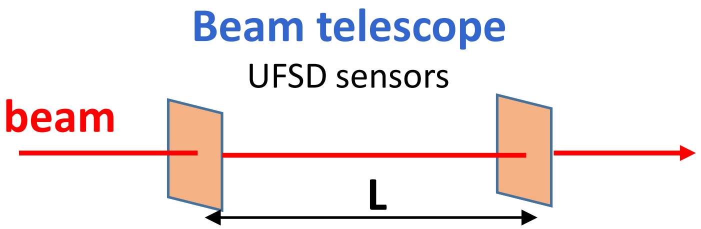
Concern: pile-up inefficiency

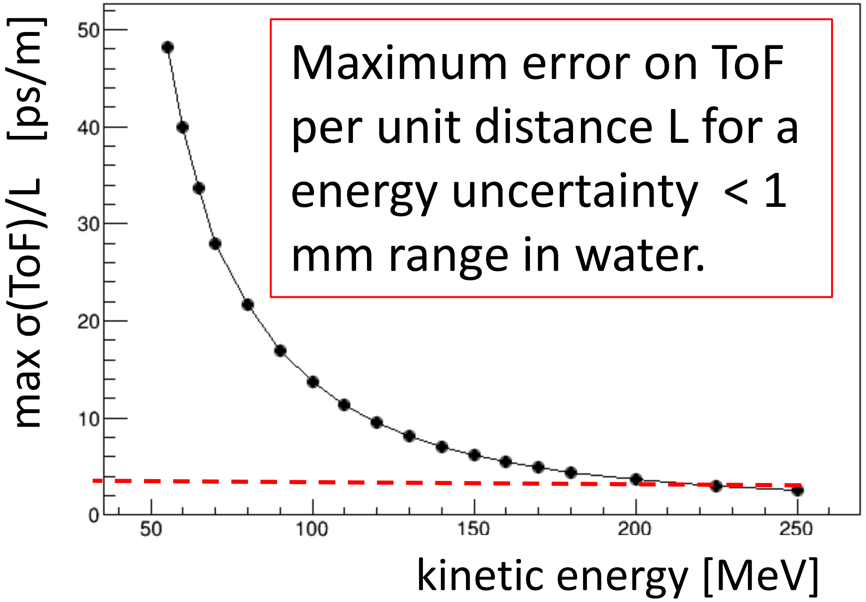




~10^{10} p/s cm^2 !!

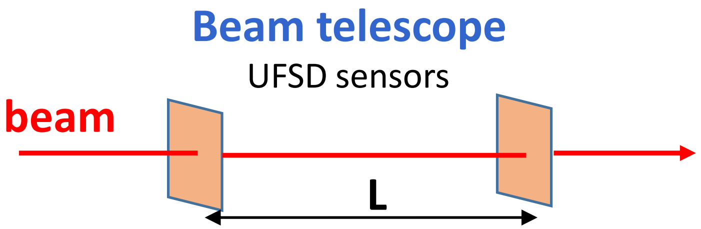
Beam energy measured from Time-of-Flight

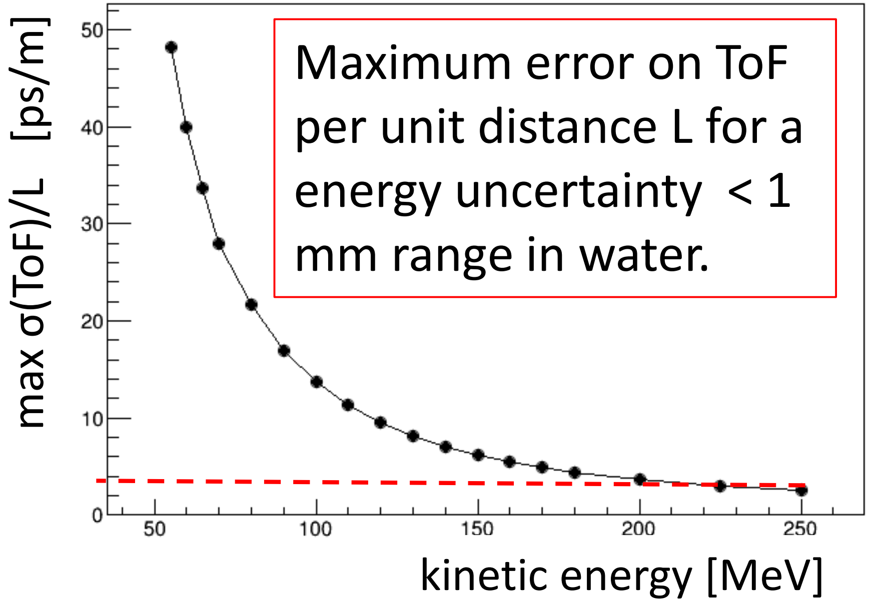




- For 1m distance the **max error on TOF < 4 ps**
- Large number of coincidences are needed

Beam energy measured from Time-of-Flight





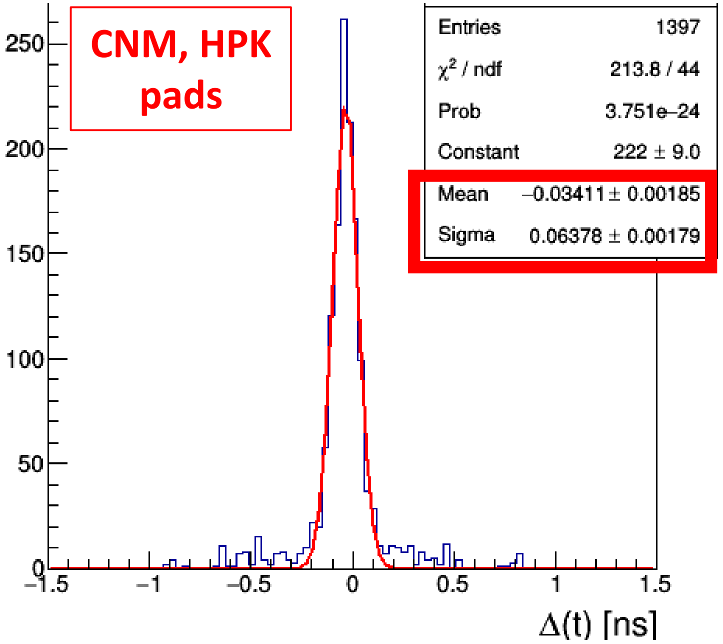
- For 1m distance the **max error on TOF < 4 ps**
- Large number of coincidences are needed

Time difference for pulses in coincidence in 2 pads

- Beam **E = 114 MeV, total acquisition time 300 μs** (less than average spot duration), CFD algorithm applied on pulses signals

Stat error on <ToF>
2 ps

Time resolution of single hit
$\sigma(t) = 64ps/\sqrt{2} = 43$ ps



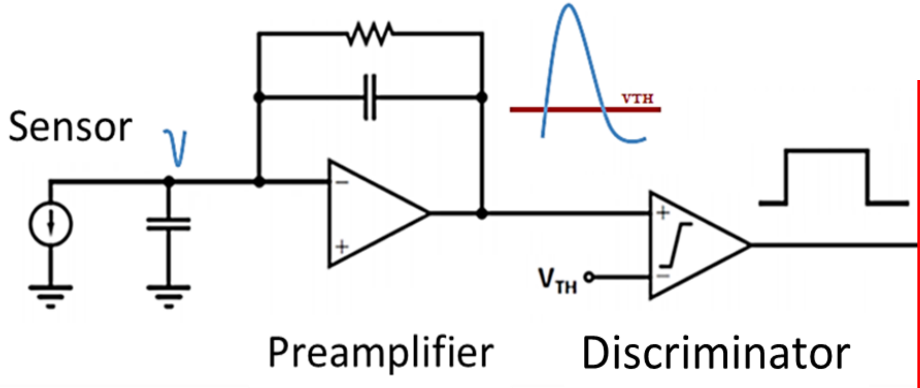
Remarks

- Sensors at 2cm distance (favorable condition)
- Ongoing simulations for optimizing the geometry and the ToF reconstruction method

Fast readout electronics (TERA10)

Requirements

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

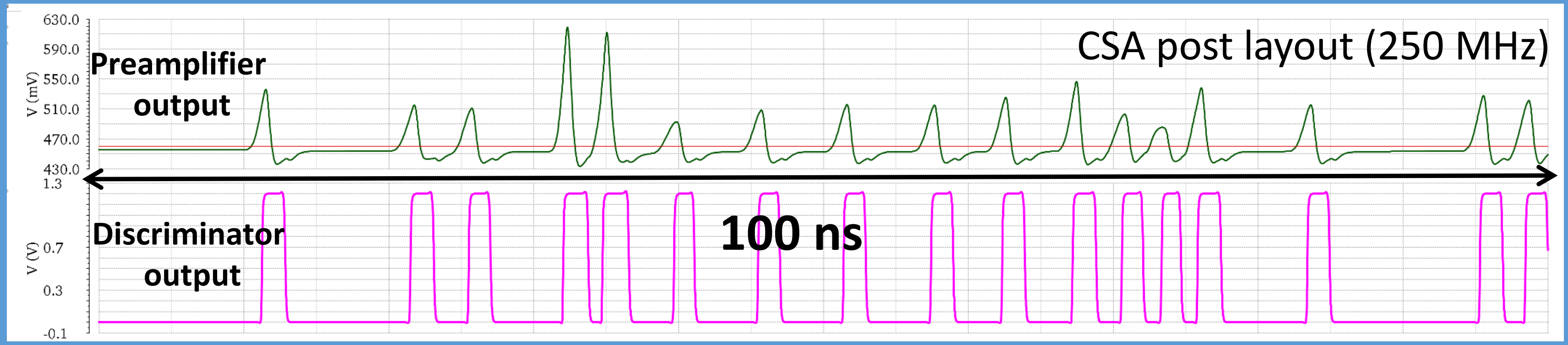


FPGA

- **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 April

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

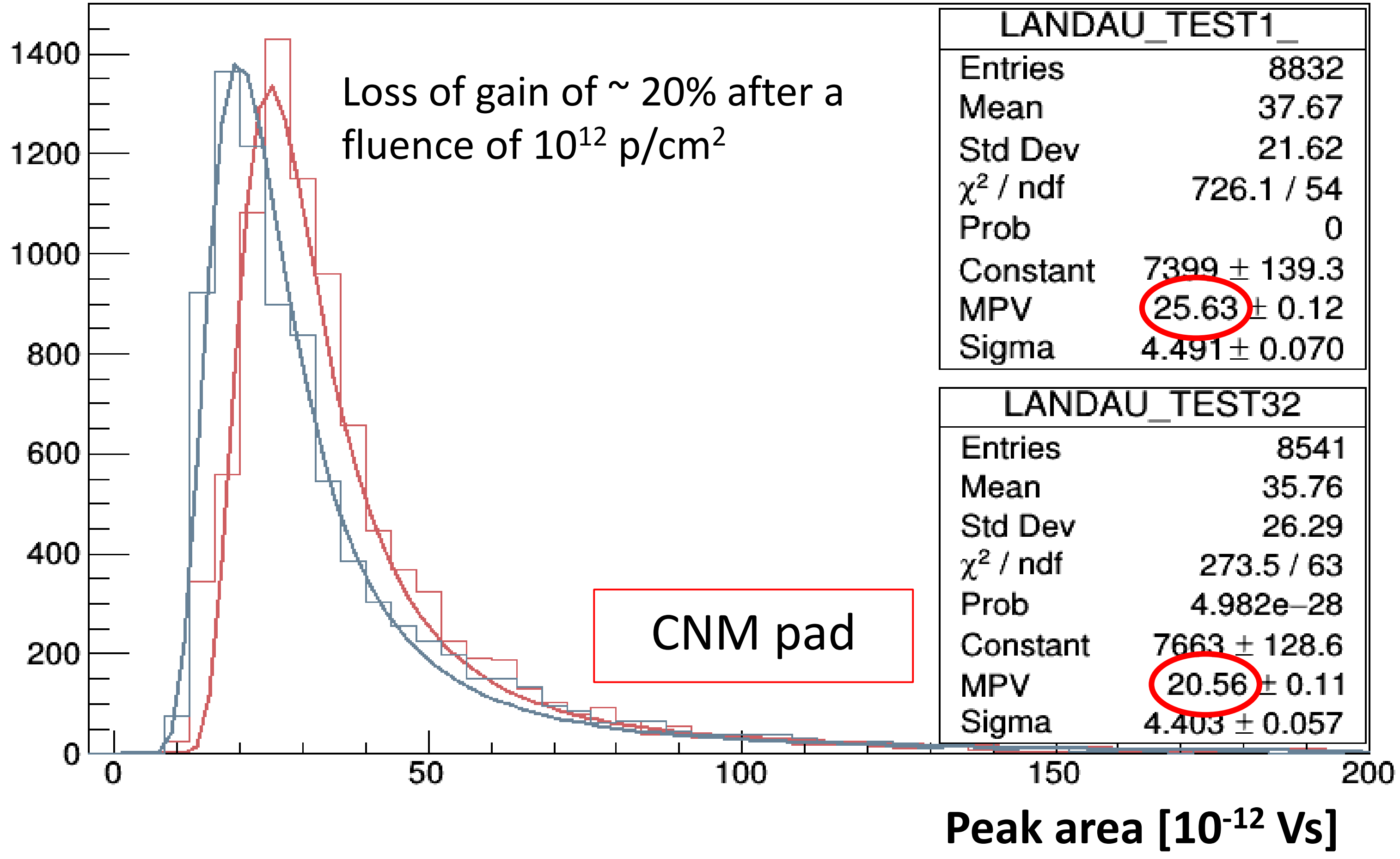
- **How to scale to an area 20x20 cm^2**
  - Beyond the scope of this project

Thank you

Spares

Concern n.1: effects of radiation damage

Loss of gain of LGADs with radiation reported in literature[1] → Inactivation of the gain layer caused by *acceptor removal* mechanism



1 Kramberger G, *et al.* 2015 *JINST* **10** P07006

Concern n.1: effects of radiation damage

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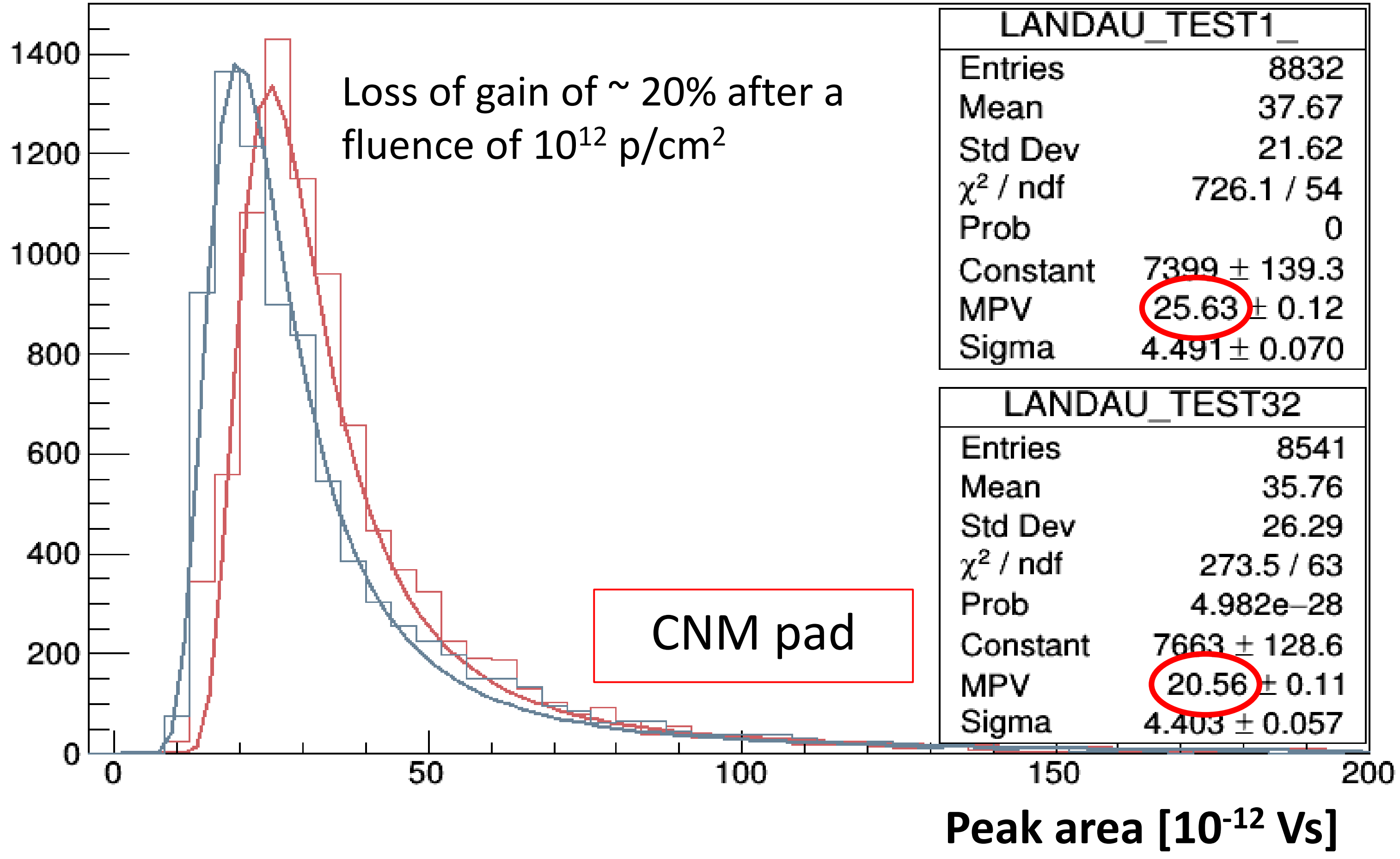
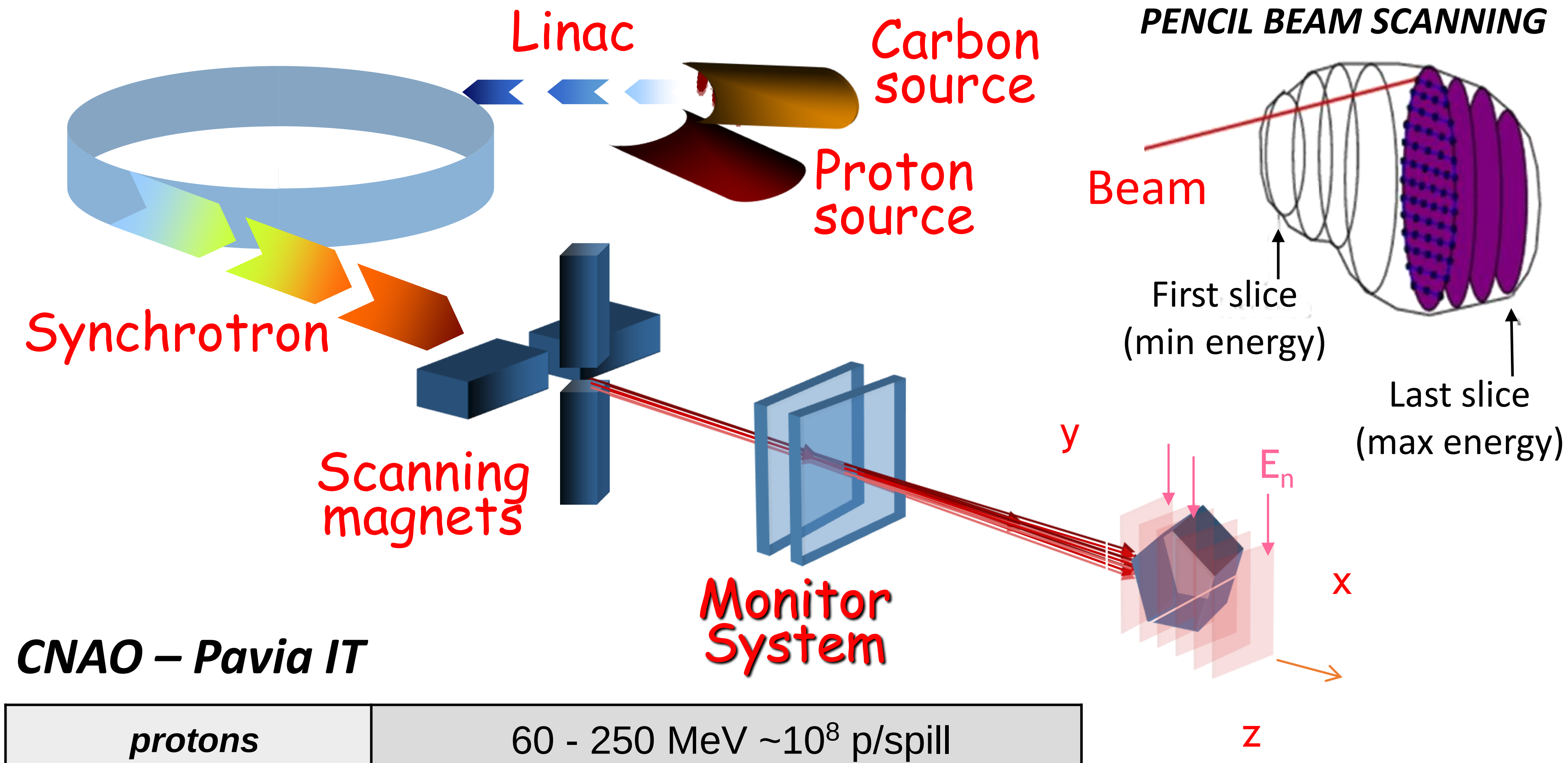


Note:

- Pad not optimized for radiation resistance, no annealing attempted
- No similar loss observed with MoveIt strips

1 Kramberger G, *et al.* 2015 *JINST* **10** P07006

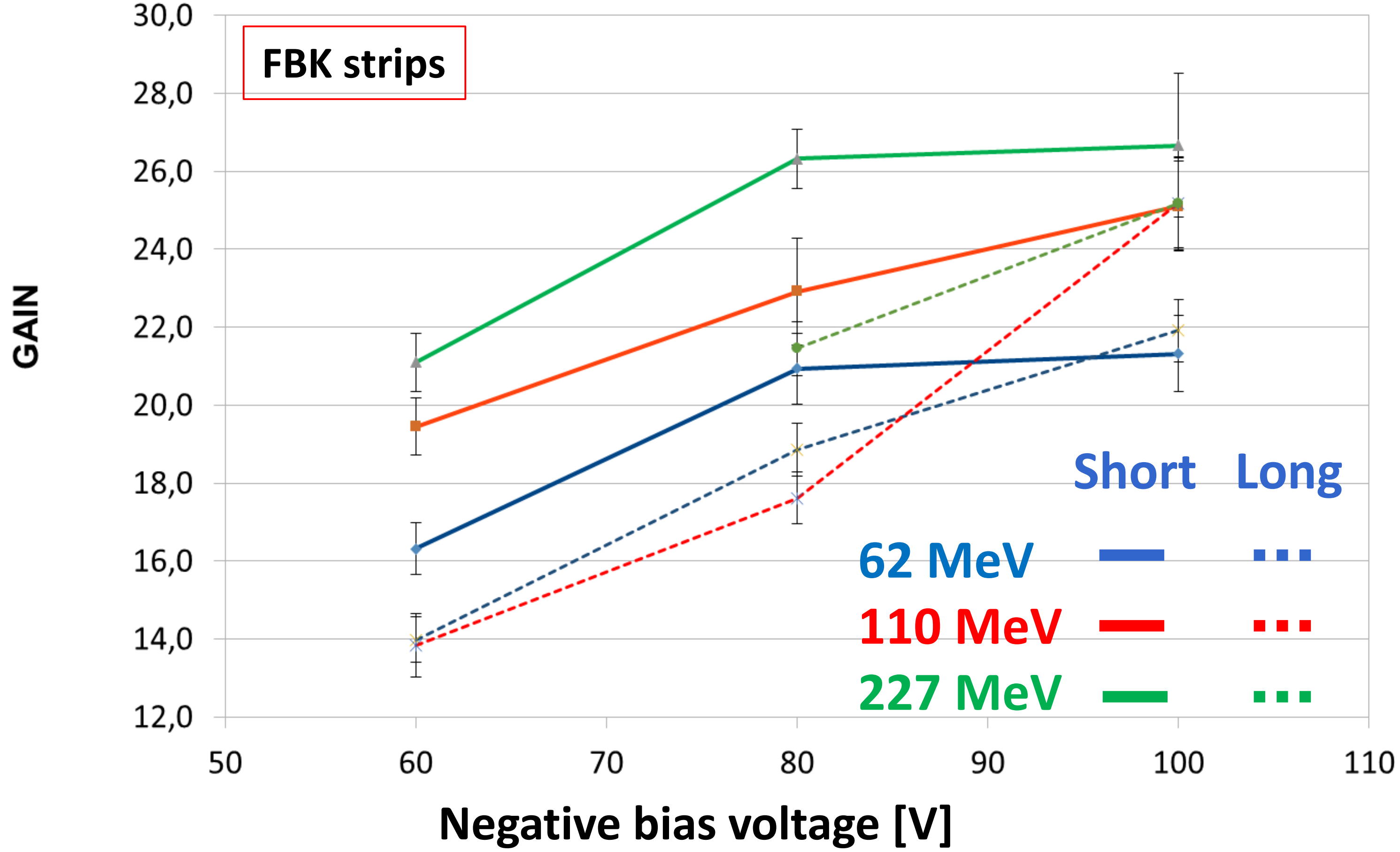


CNAO – Pavia IT

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

Gain of strip detectors – Gallium doped

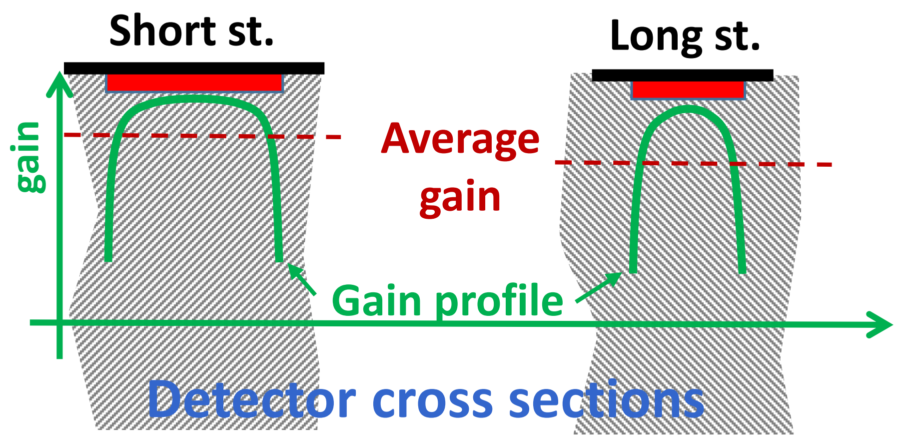
$$\text{Gain}(V) = \frac{\text{MPV}_{\text{gain}}\ (V)}{\text{MPV}_{\text{no gain}}(V)}$$



- Gain increase with V_{bias}
- Similar trend observed with laser source on test pads

- **Long strips** (thinner) show a **lower average gain** than short strips

→ geometrical effect



A Graphycal summary of MoVe IT

Physics

- Depth dose distributions
- Nuclear fragment spectra (including target – FOOT exp)
- Stopping power data

TPS

Radiobiology

(= Biological effects + micro/nanoscale physics)

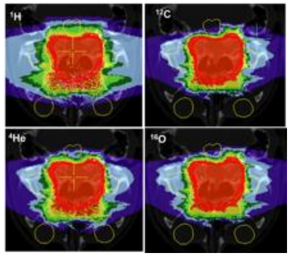
- RBE (eg. LEMx, MKM)
- OER
- DEF

Beamline specifics

Patient Imaging data

Including intratumor heterogeneity

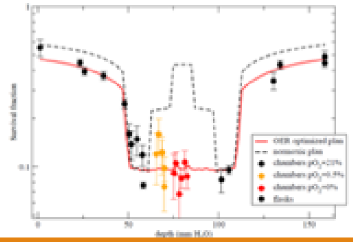
Effective Dose profile



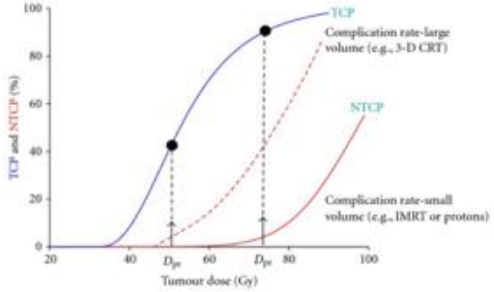
Verification

advanced beam monitoring

“Bio”-dosimetry



Clinical Impact



TCP/NTCP

Slide from E. Scifoni

MoVe IT - WP Structure and Tasks

WP1 – RB modeling for TPS
Sebastian Hild (TIFPA)

- ***T1.1:*** *RBE modeling for protons*
- ***T1.2:*** *OER and ITH modeling*

WP2 – NTCP/TCP
L. Cella (NA)

- ***T2.1:*** *NTCP models on proton patient data including RBE*
- ***T2.2:*** *TCP/NTCP including hypoxia for different ions*

WP3 – Biological Dosimetry
Giorgio Russo (LNS)

- ***T3.1:*** *Devices for spatially resolved proton RBE measurement*
- ***T3.2:*** *Hypoxic, Coculture and Stem cells devices*
- ***T3.3:*** *In vivo and Molecular biomarkers*

WP4 – Facilities and beamline simulations
Pablo Cirrone (LNS)

- ***T4.1:*** *CNAO/TIFPA/LNS lines development for beam delivering*
- ***T4.2:*** *MC Simulations for beamlines/target stations for in vitro/in vivo exp*
- ***T4.3:*** *Detectors for beam flux and beam energy measurement*

WP0 – Coordination& Dissemination
Emanuele Scifoni (TIFPA)

Motivation for the doping strategy of UFSD2 production

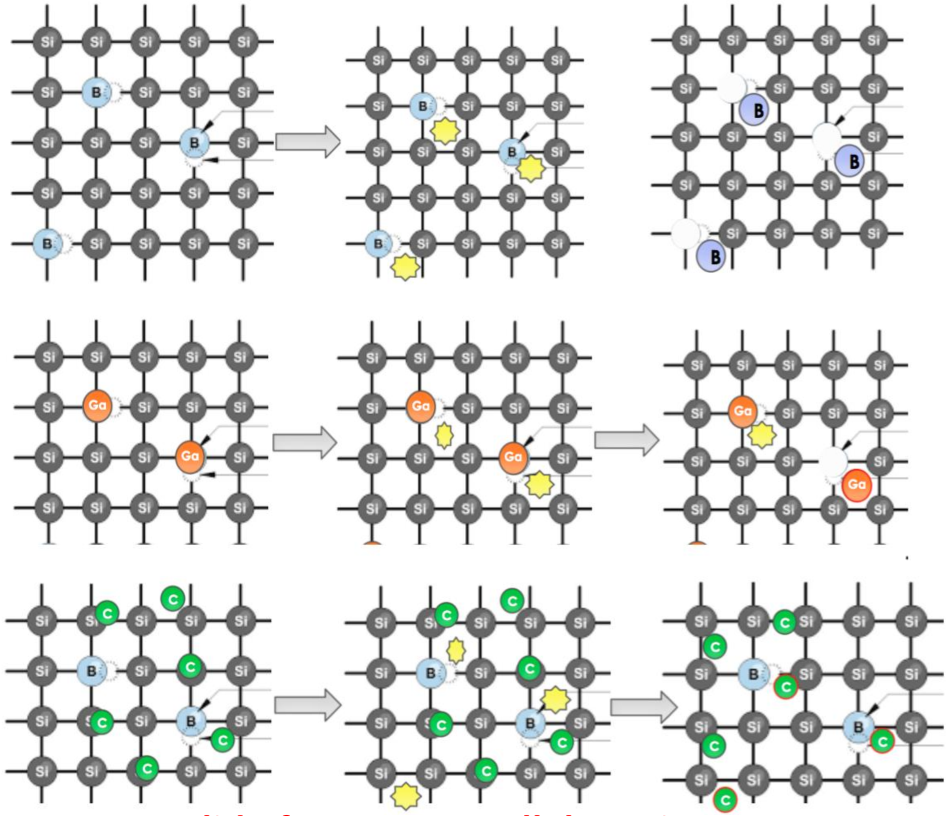
Main effect of the irradiation is the inactivation of the dopant in the gain layer

- Substitutional → interstitial (acceptor removal)
- Effect: reduction of gain

Boron
Radiation creates interstitial defects that inactivate the Boron

Gallium
From literature, Gallium has a lower possibility to become interstitial

Carbon
Interstitial defects filled with Carbon instead of with Boron and Gallium



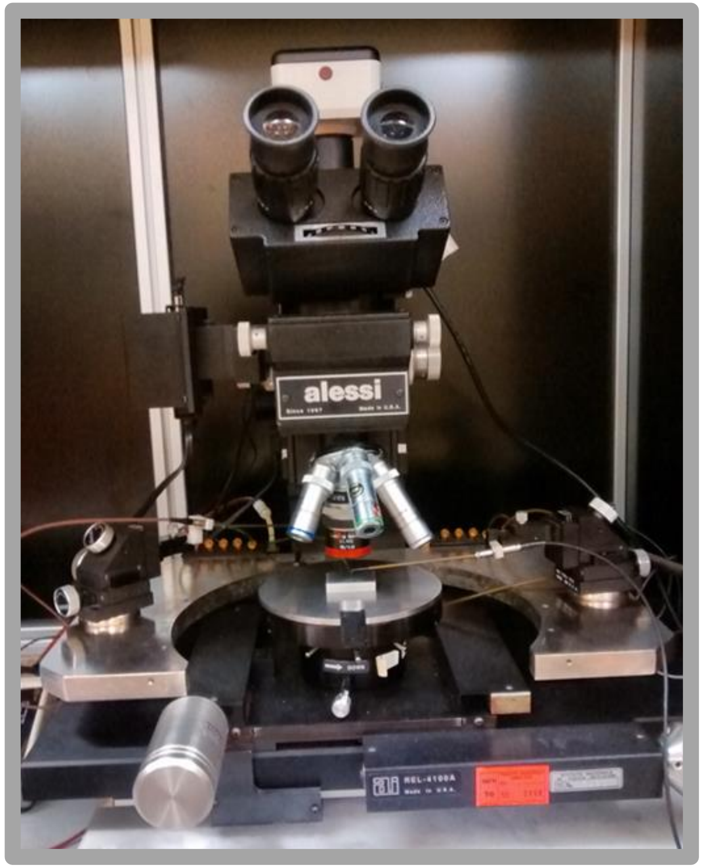
Slide from RD50 Collaboration

<u>UFSD2 production @ FBK</u>:

- 4 different gain layer strategies:
  - **Boron** (Low & High diffusion)
  - **Carbonated Boron** (High diffusion)
  - **Gallium** (Low diffusion)
  - **Carbonated Gallium** (Low diffusion)
- 4 (3) different **doping concentration** for Boron (Gallium) implants
- 2 different diffusion temperatures for Boron
- 2 carbon concentration (Low & High)

LAB setup for IV and CV curves

MANUAL PROBE STATION ALESSI



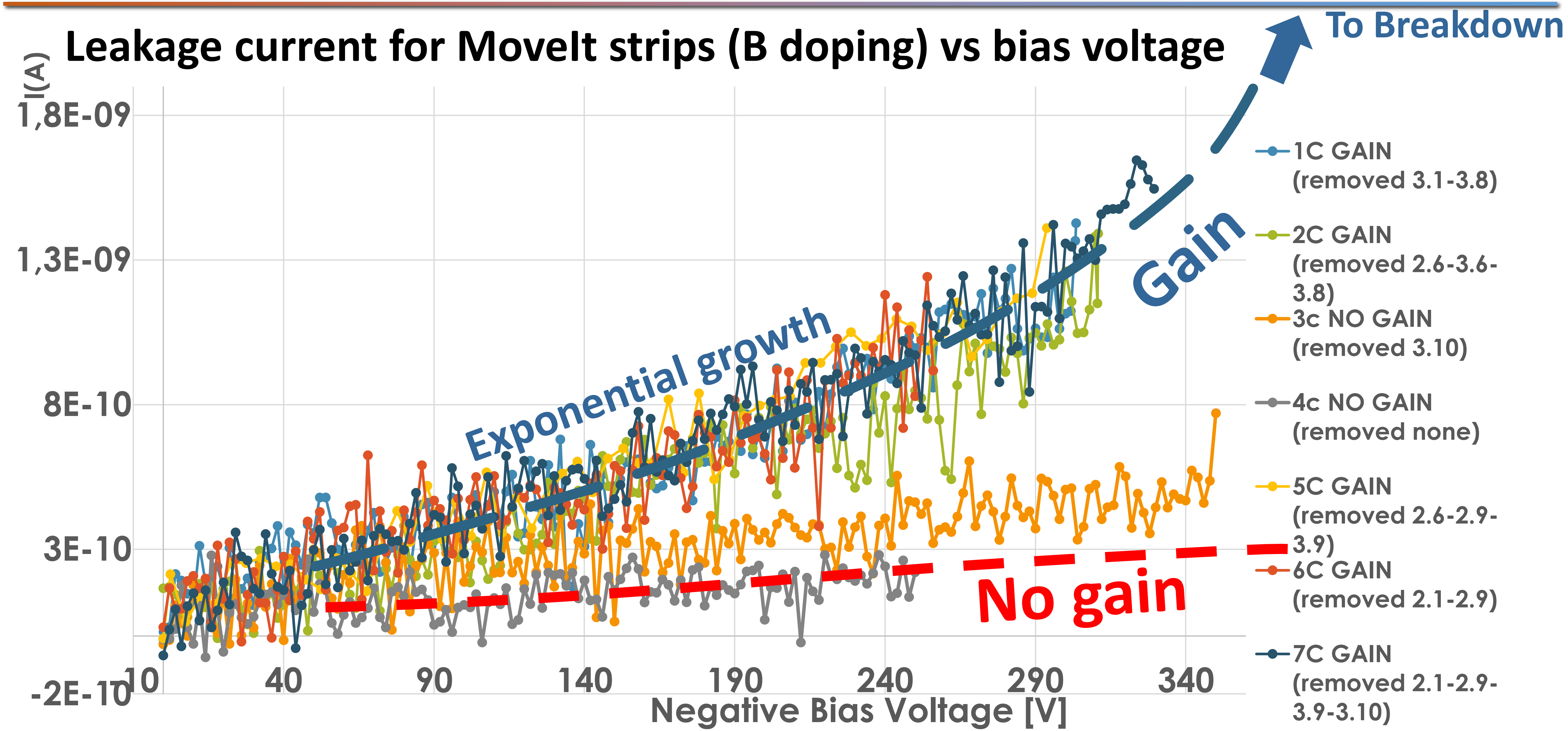
CUSTOM PROBE CARD FOR SIMULATANEOUS CONTACT TO ALLSTRIPS + GUARD RING

POWER DEVICE ANALYZER/CURVE TRACKER

MODEL : KEYSIGHT B1505A

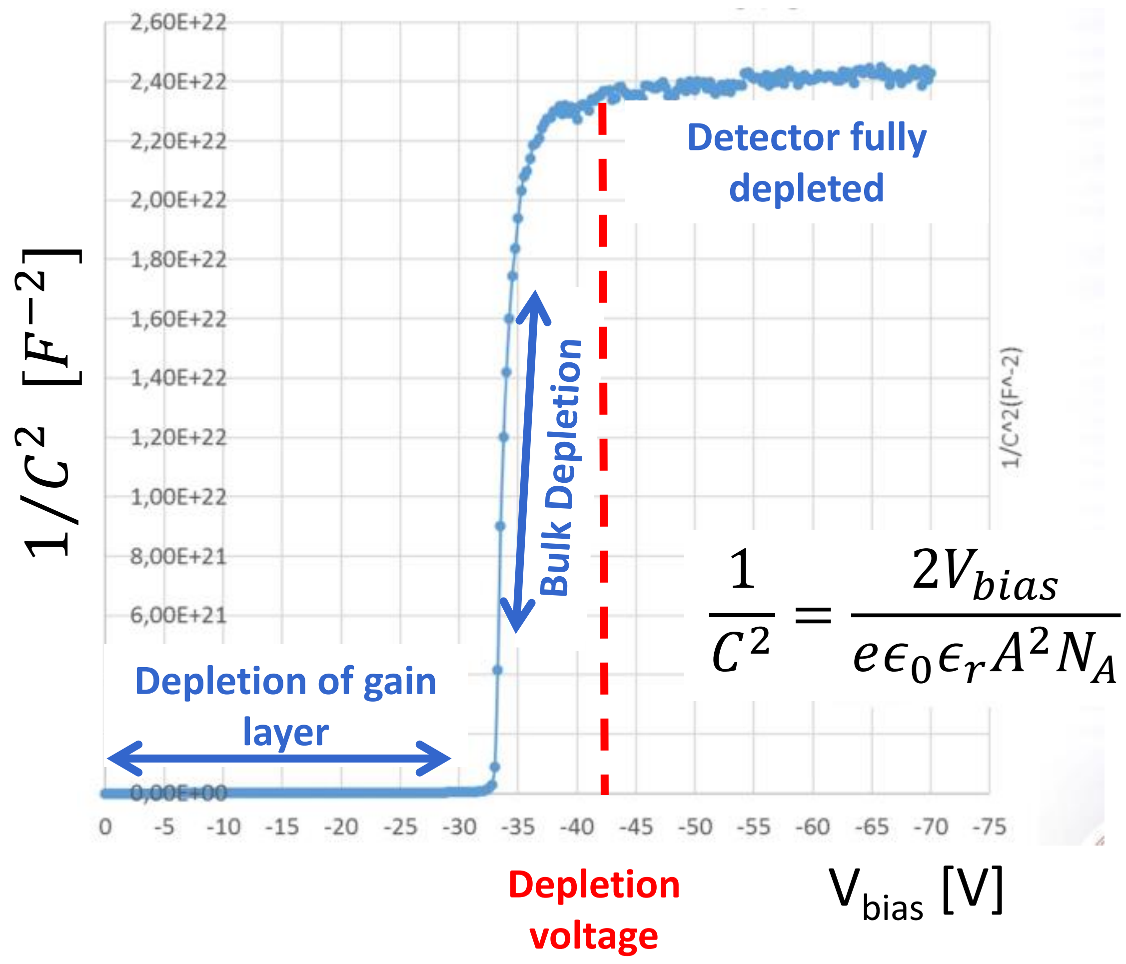
IV Curves

Leakage current for MoveIt strips (B doping) vs bias voltage

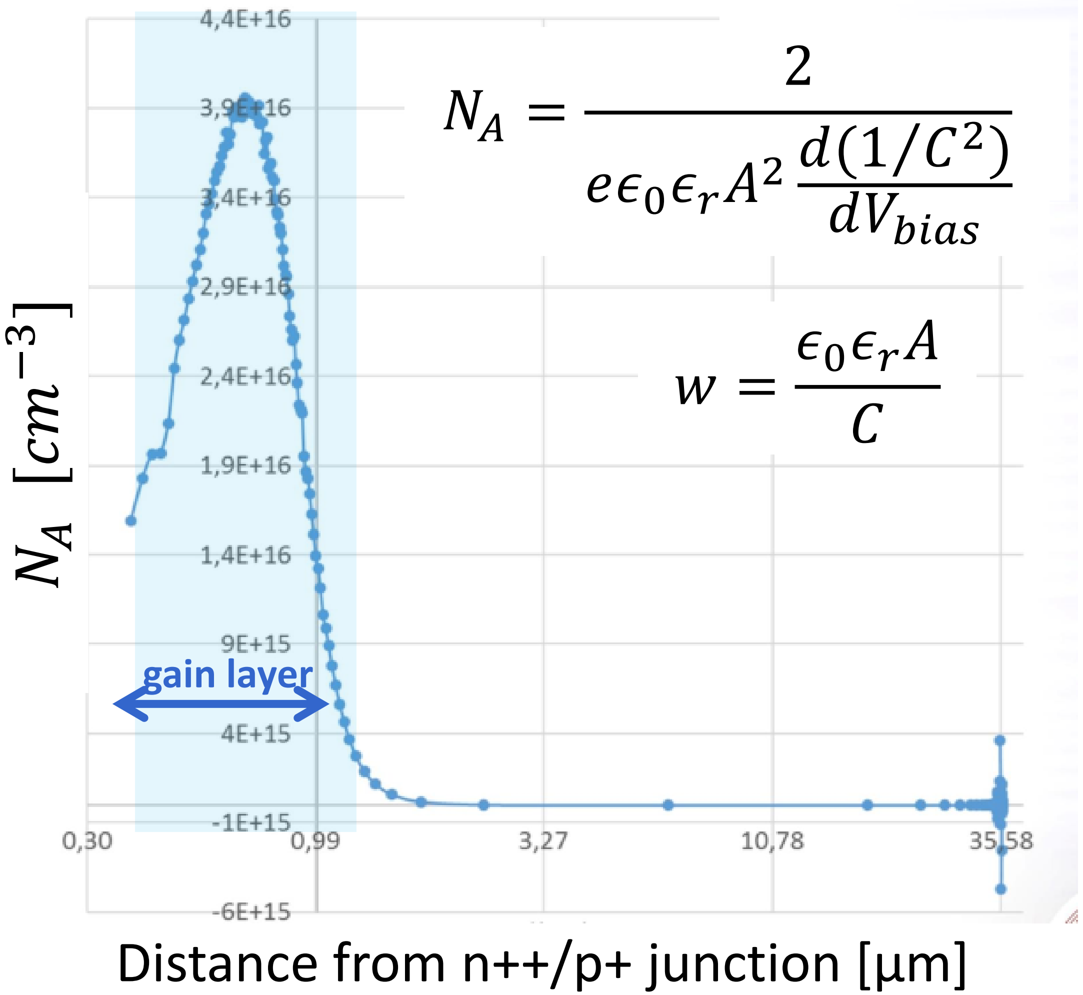


CV Curves

Allow to determine the doping profile: example a short MoveIt strip (B doped)



$$\frac{1}{C^2} = \frac{2V_{bias}}{e\epsilon_0\epsilon_r A^2 N_A}$$



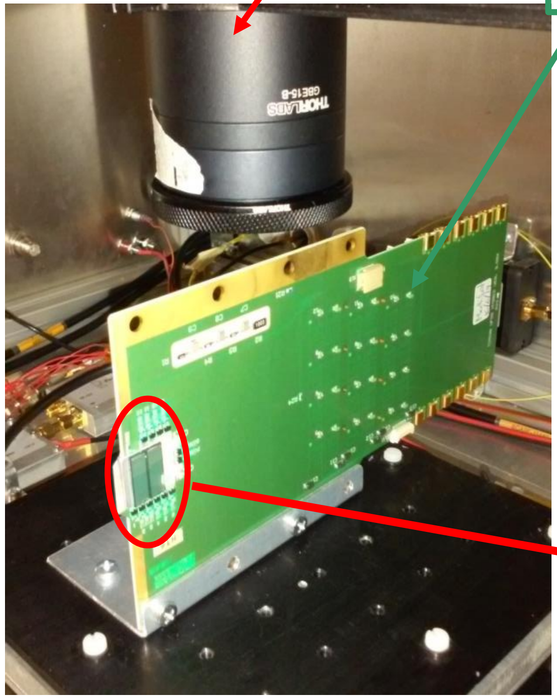
$$N_A = \frac{2}{e\epsilon_0\epsilon_r A^2 \frac{d(1/C^2)}{dV_{bias}}}$$

$$w = \frac{\epsilon_0\epsilon_r A}{C}$$

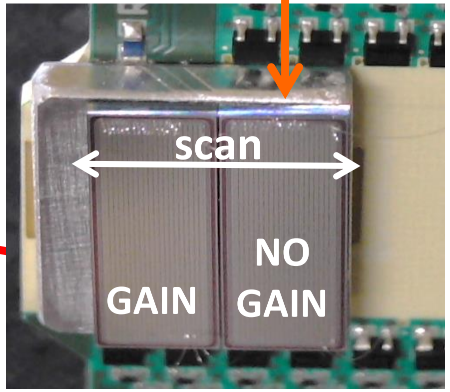
Strip characterization with laser scan

Picosecond Pulsed IR laser:
λ = 1060 nm, Spot size ~ 20 µm

Multichannel Amplifier/Shaper board (CMS CT-PPS)



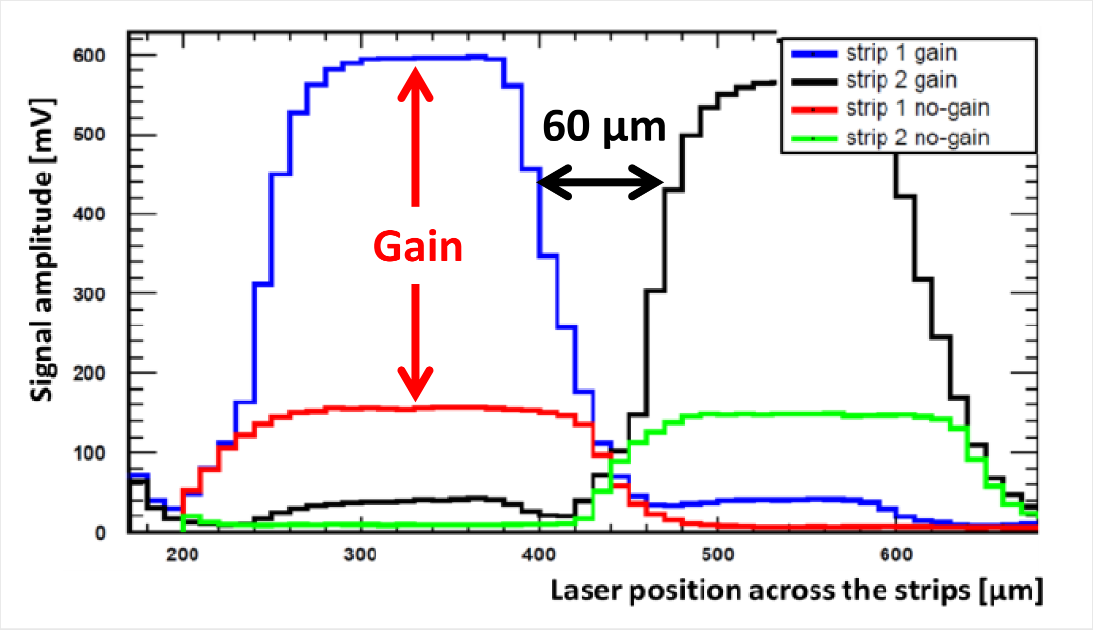
Front and back metallization: sensor mounted to allow laser scan along the strip edge



Short strips of (B doped)

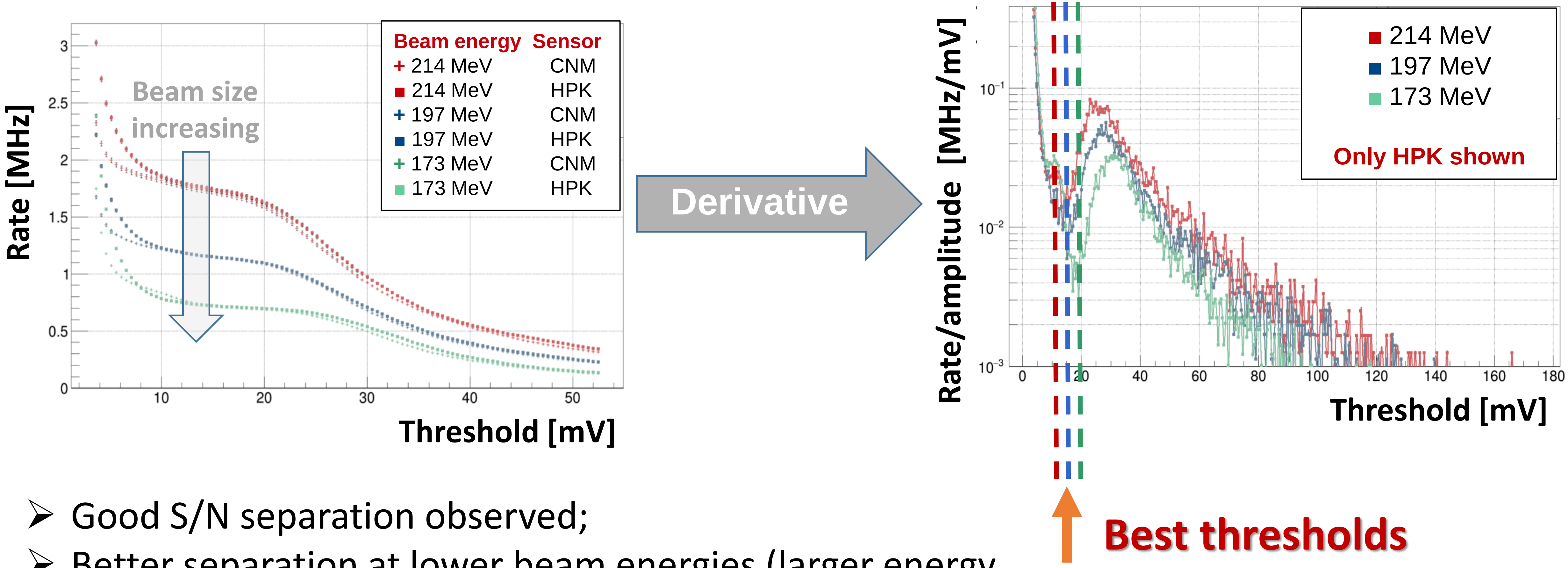
Results

Signal amplitude scan between adjacent strips



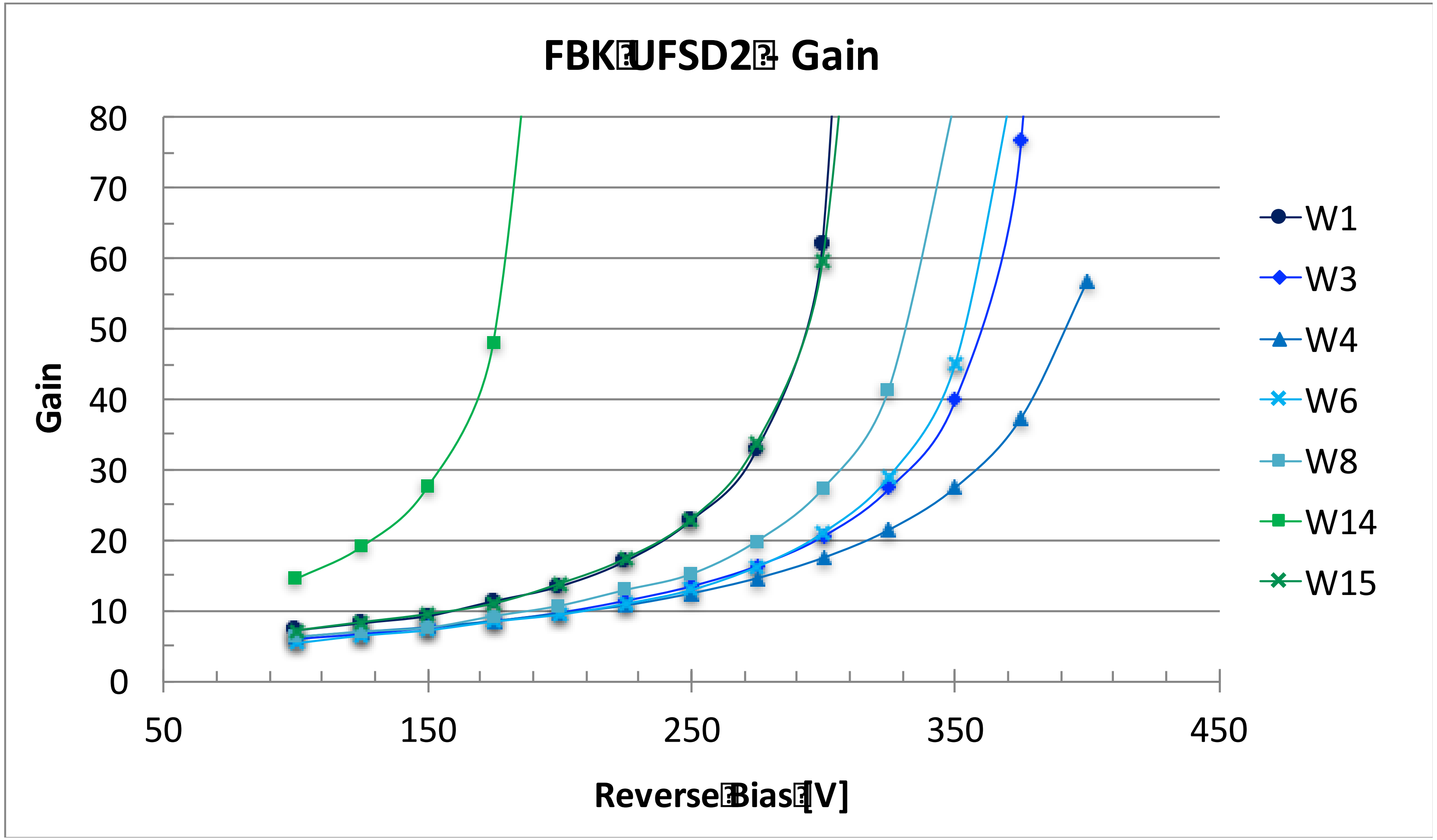
- **Gain** ≈ 4 at V_{bias}= -230 V
- **Dead area** ~ 60 µm
  - expected by sensor layout and by the production technology, in agreement with TCAD simulations
  - **possibly reduced in next UFSD production**

Threshold scan

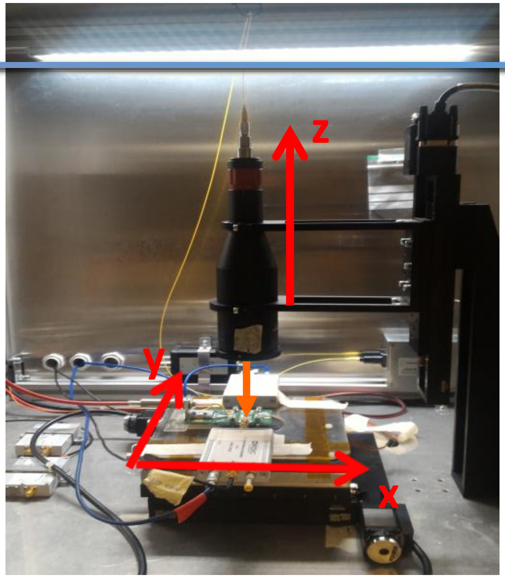


- Good S/N separation observed;
- Better separation at lower beam energies (larger energy loss in Silicon):
- Best threshold is beam energy dependent

Gain Measurement with PS laser



GAIN = (Signal area LGAD)/(Signal area PiN)



TCT Setup from Particulars

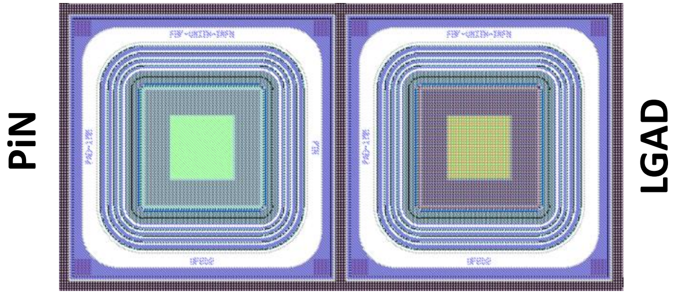
Pico-second IR laser at 1064 nm

Laser spot diameter ~ 50 µm

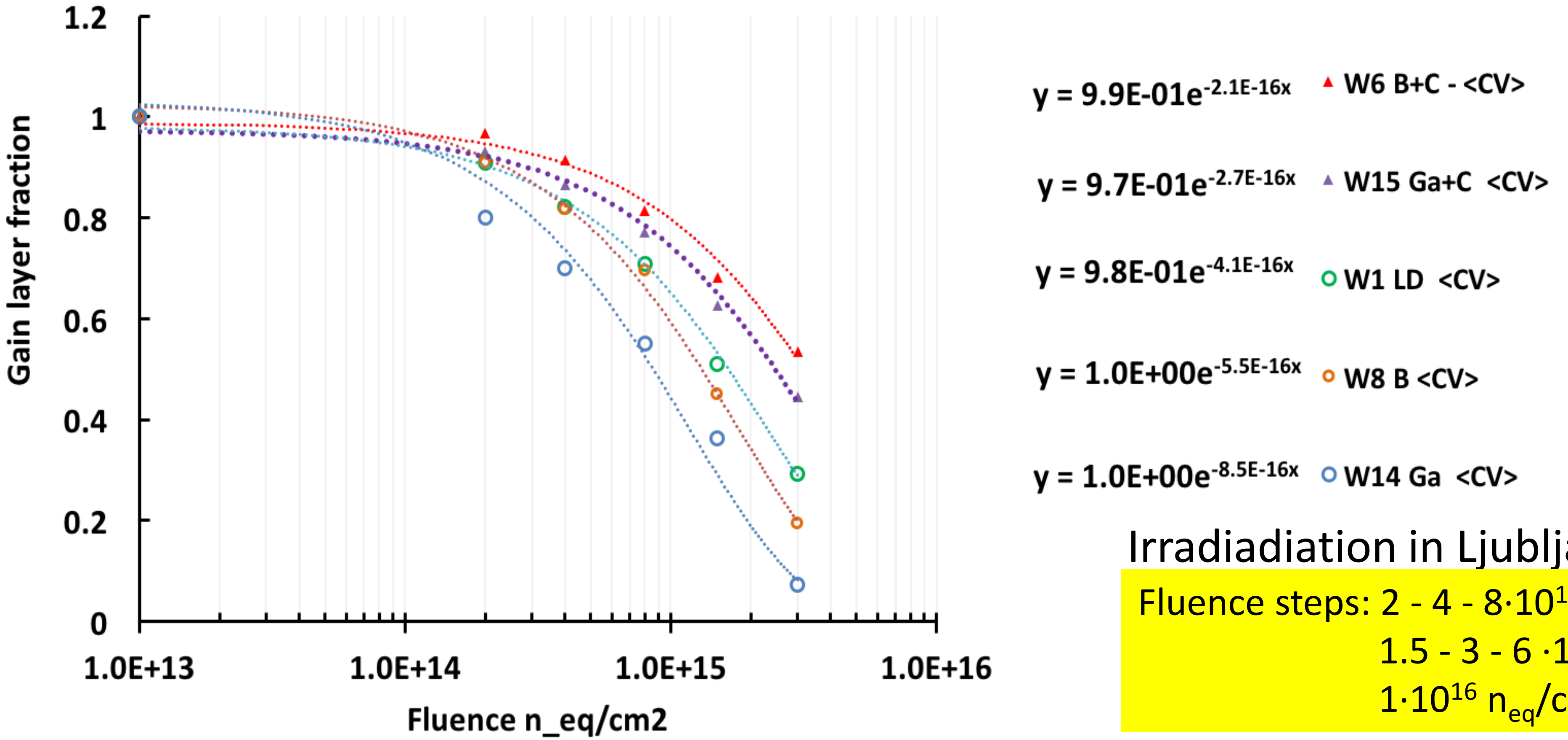
Cividec Broadband Amplifier (40dB)

Oscilloscope Lecroy 640Zi

Room temperature



Irradiation with neutrons



Irradiadiation in Ljubljana

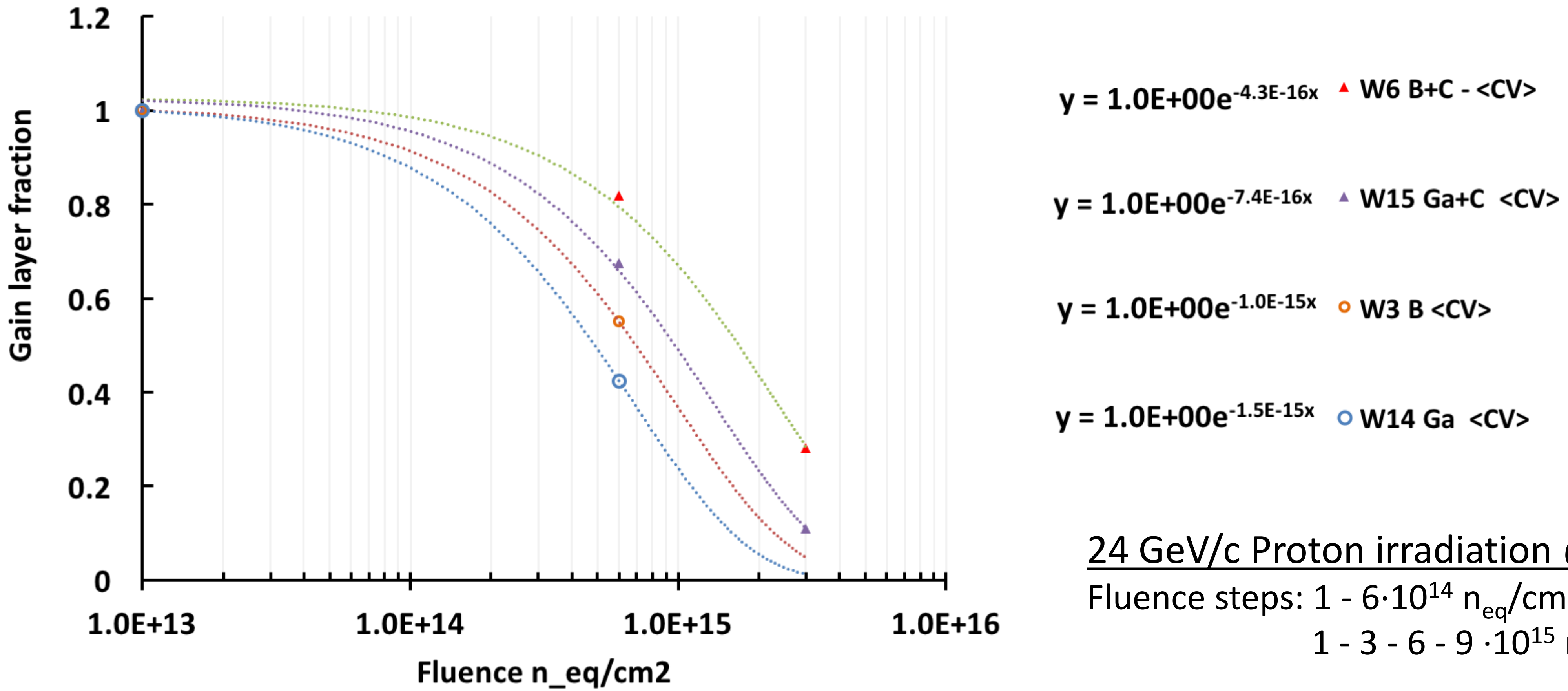
Fluence steps: $2 - 4 - 8 \cdot 10^{14}\ n_{eq}/cm^2$

$1.5 - 3 - 6 \cdot 10^{15}\ n_{eq}/cm^2$

$1 \cdot 10^{16}\ n_{eq}/cm^2$

- Carbonated sensors have a factor ~ 3 better acceptor removal coefficient
- Among not carbonated sensors, low diffusion Boron has the better response to irradiation

Irradiation with protons



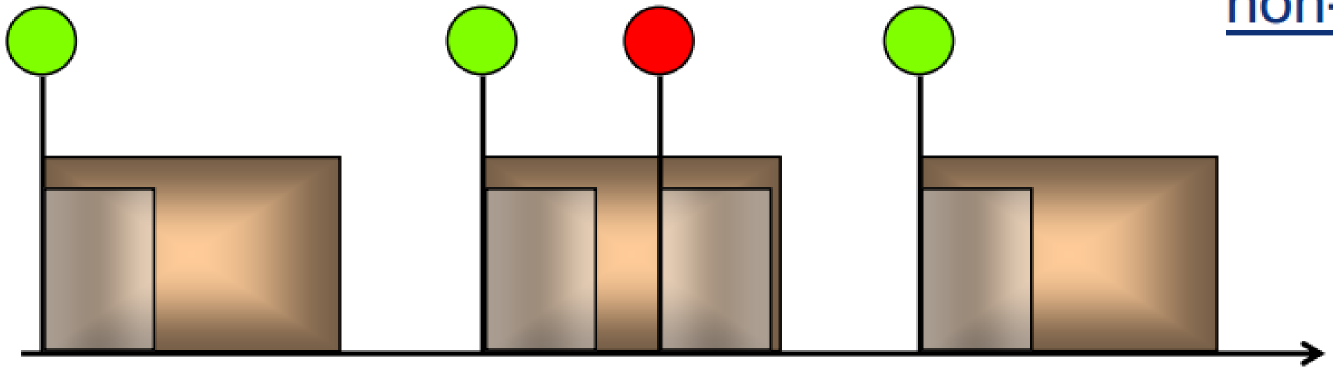
24 GeV/c Proton irradiation @ CERN PS

Fluence steps: $1 - 6 \cdot 10^{14}$ n_{eq}/cm^2

$1 - 3 - 6 - 9 \cdot 10^{15}$ n/cm^2

Pileup Models

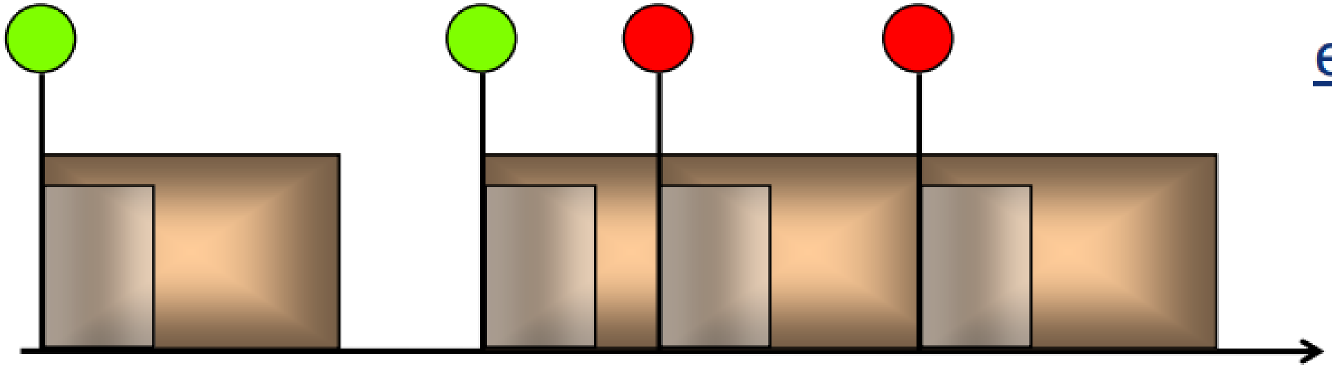
Non- paralyzable model



non-extending dead time

$$R = \frac{\rho}{1+\rho\tau_{ne}}$$

Paralyzable model

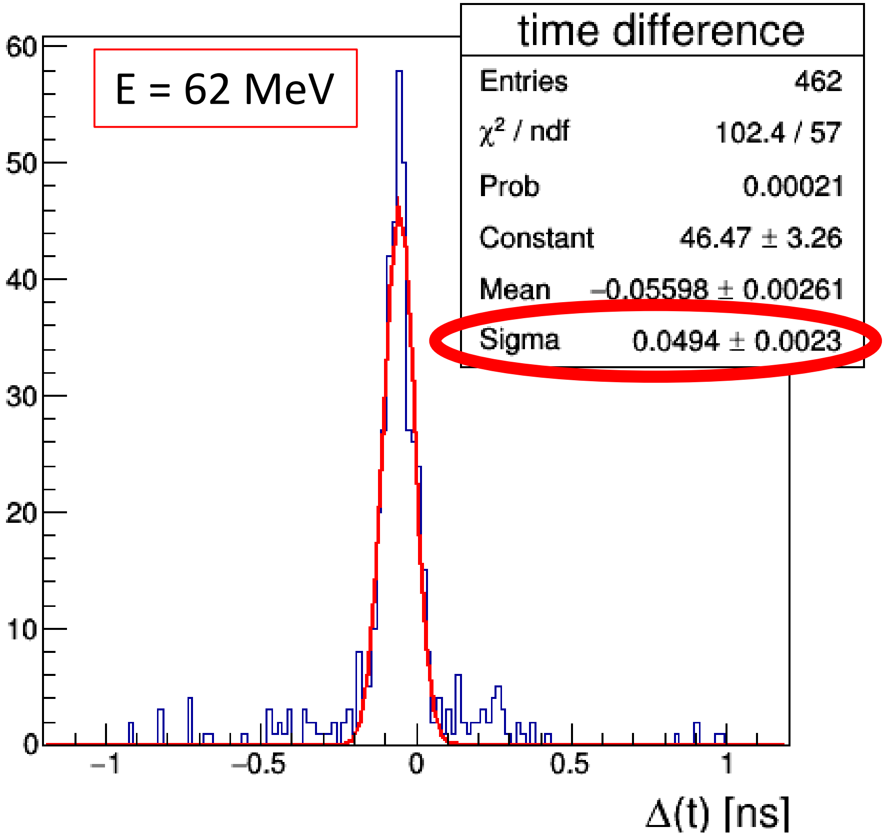


extending dead time

$$R = \rho\, e^{-\rho\tau_e}$$

Best time resolution

- CFD algorithm applied on pulses signals
- Time difference measured for pulses in coincidence in the 2 pads



Time resolution of single crossing

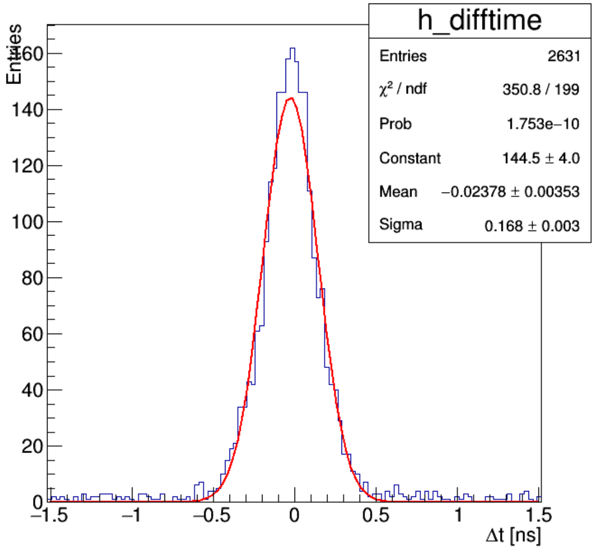
σ(t) = 35 ps !!

ToF measurement with different algorithms

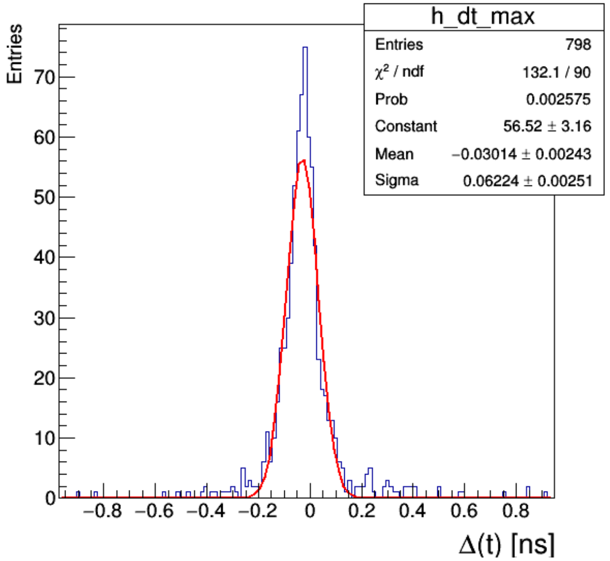
From test beam data:

- Beam **E = 117 MeV**
- **total acquisition time 300 μs** (less than average spot duration)
- 3 ToF reconstruction methods

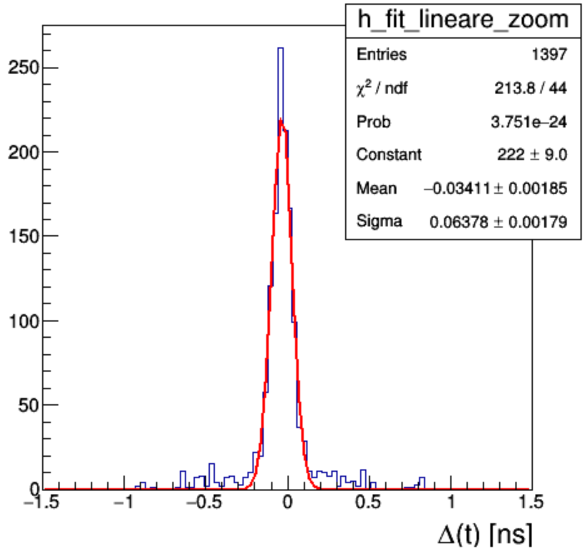
LE - **leading edge (fixed threshold)**



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



CFD – **Constant Fraction Discriminator**



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

Remarks

- Sensors at 2cm distance (favorable condition)
- Ongoing simulations for optimizing the geometry

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)

$T_{acquisition} = 200\ \mu s$

Error on mean Δt vs distance