PRAE International Workshop
Platform for Research and Applications with Electrons

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LAL-IPNO-IMNC, Orsay

INFN Istituto Nazionale di Fisica Nucleare

FONDAZIONE BRUNO KESSLER

MoVe IT INFN project

Fast Silicon Detectors for beam monitoring in proton therapy: preliminary results

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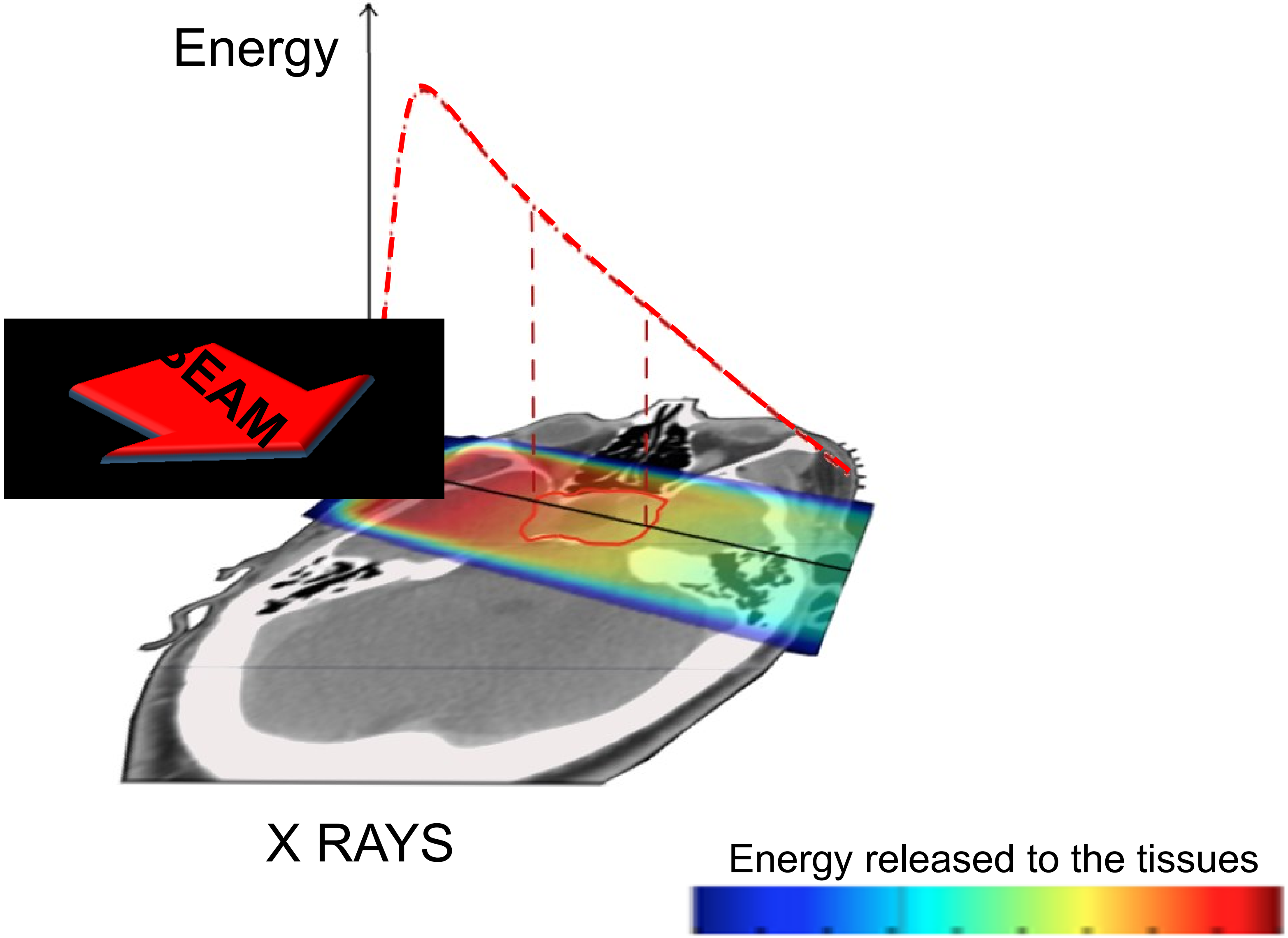
Introduction – Charged Particle Therapy



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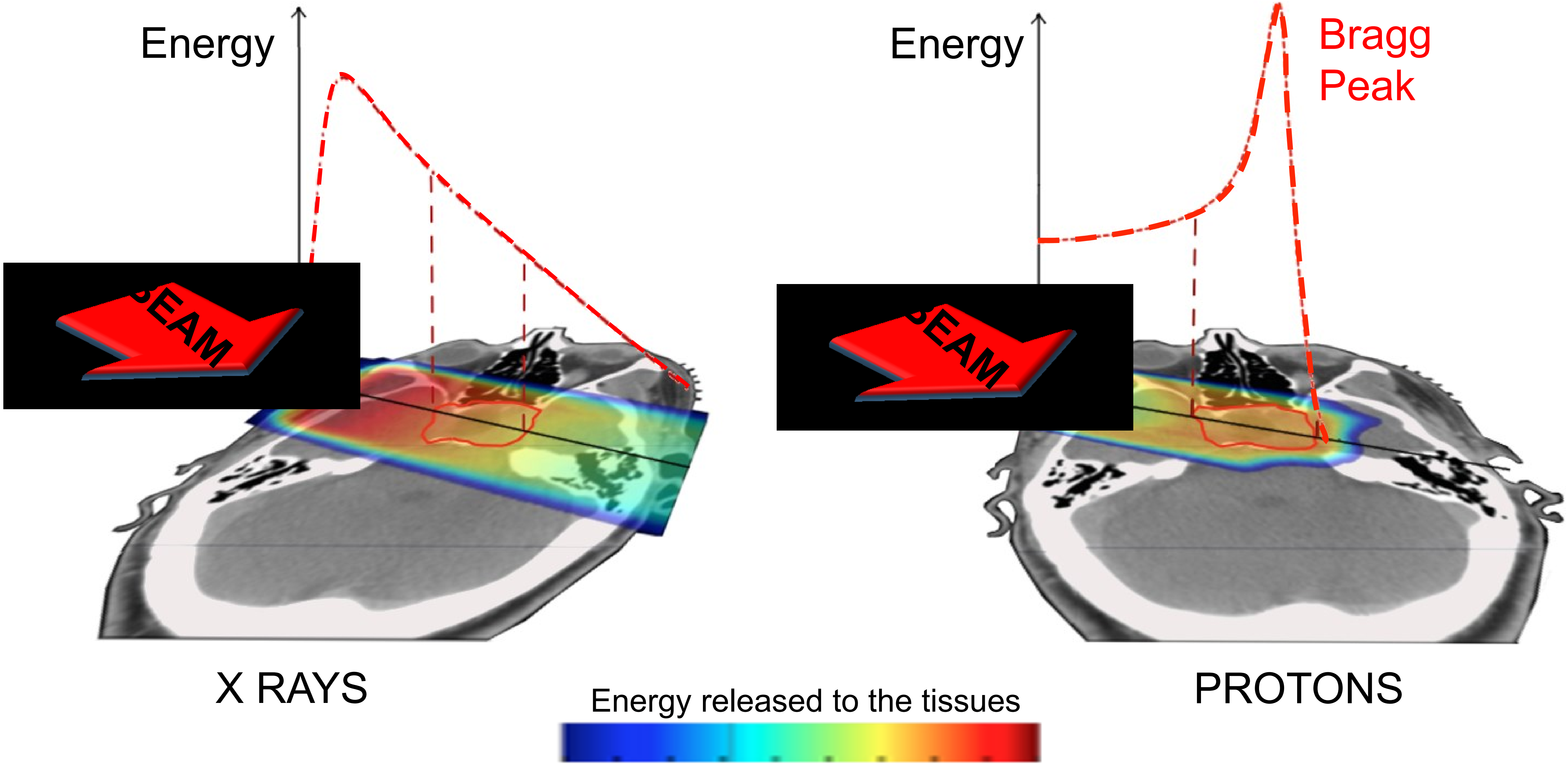

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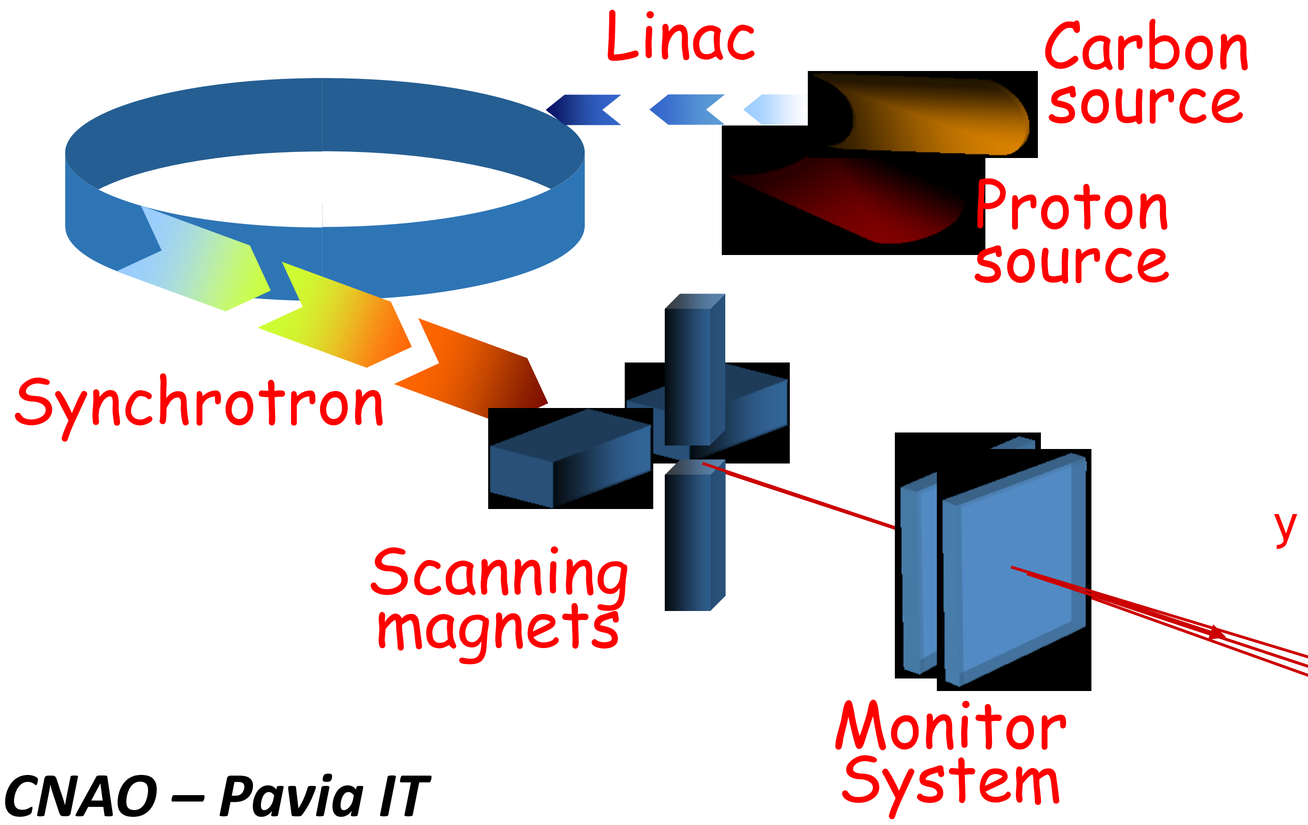

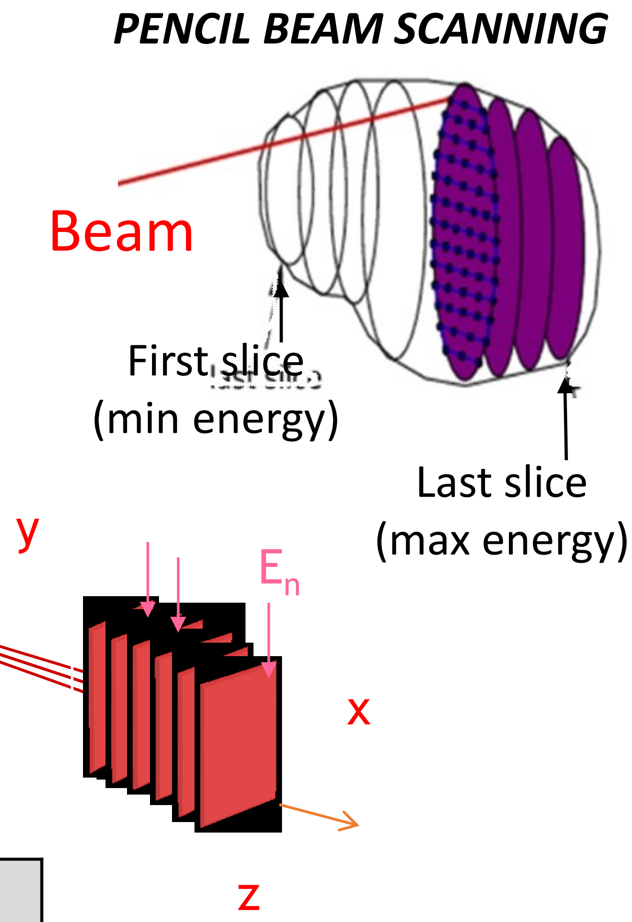

CNAO – Pavia IT

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

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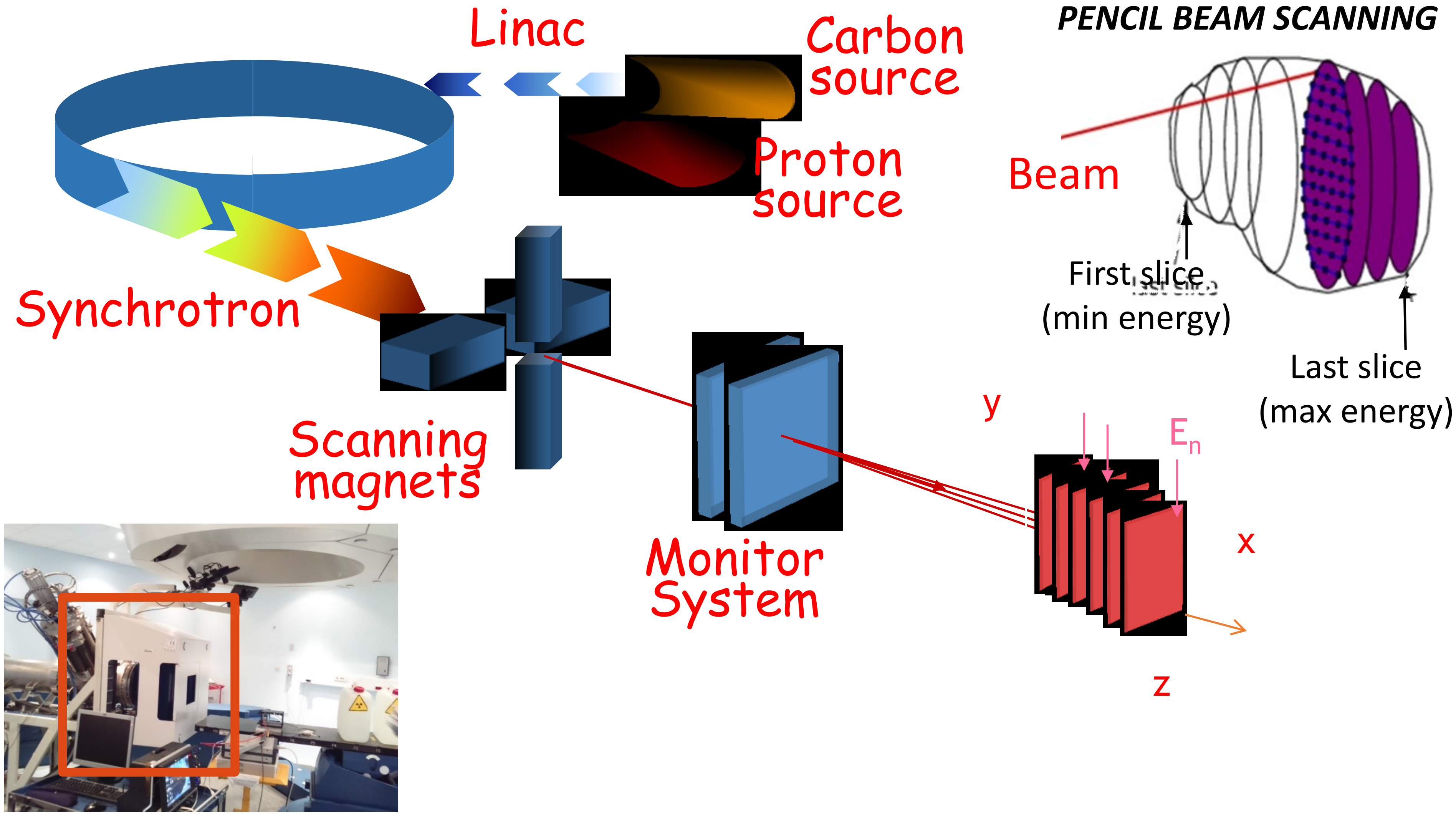

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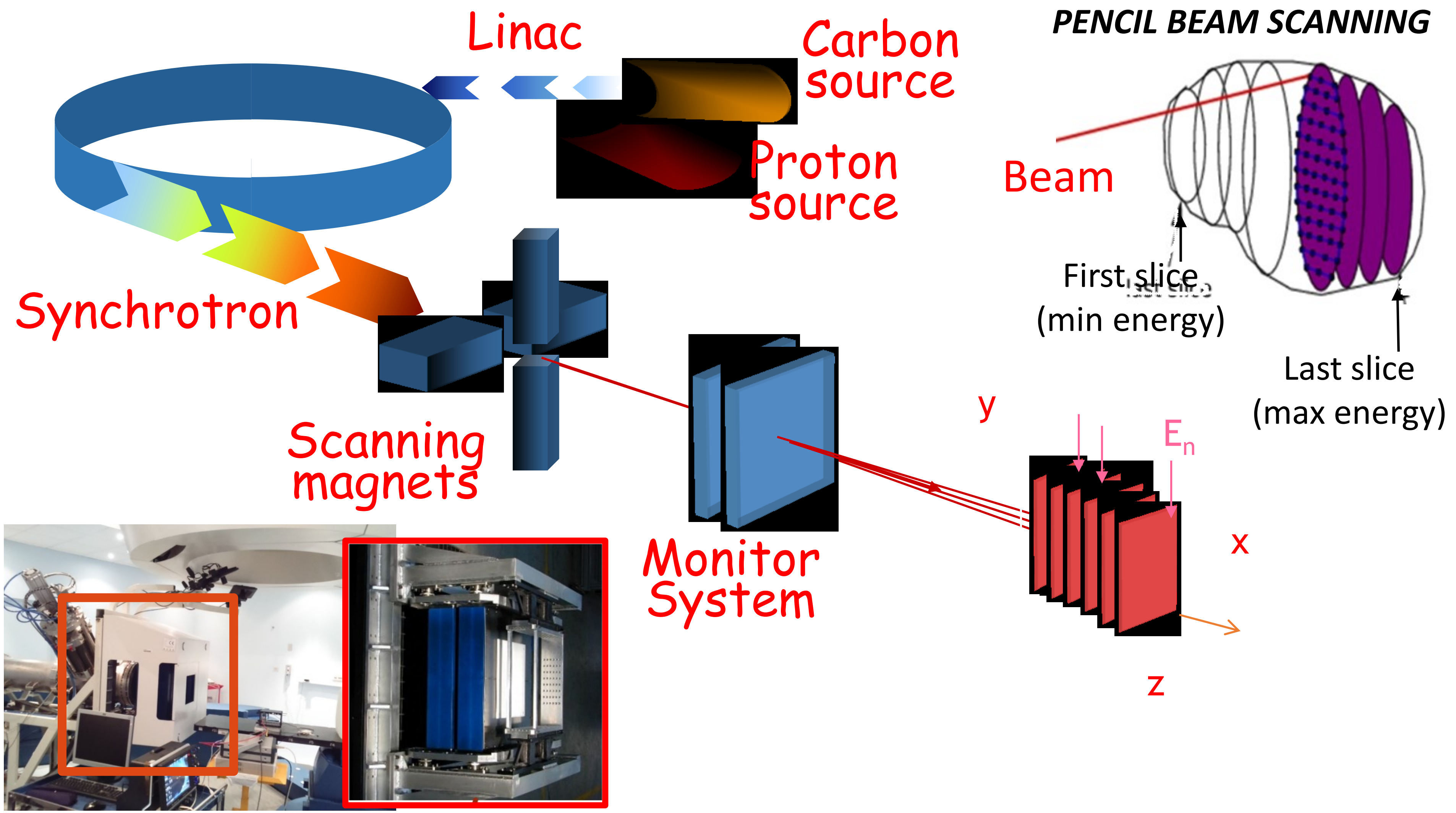

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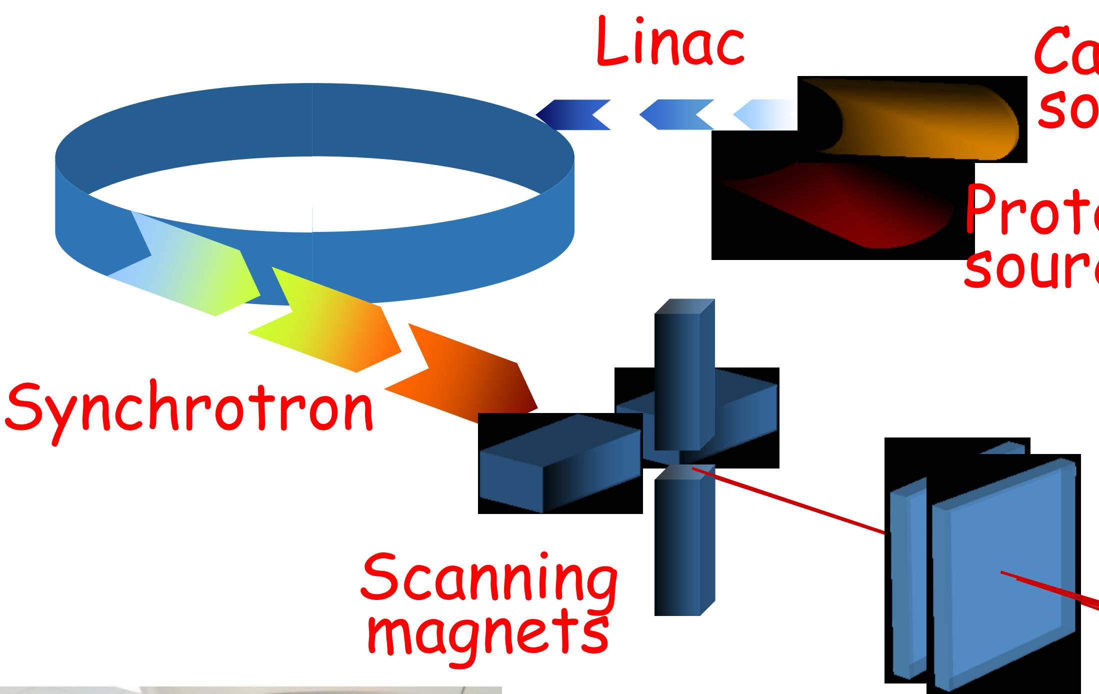
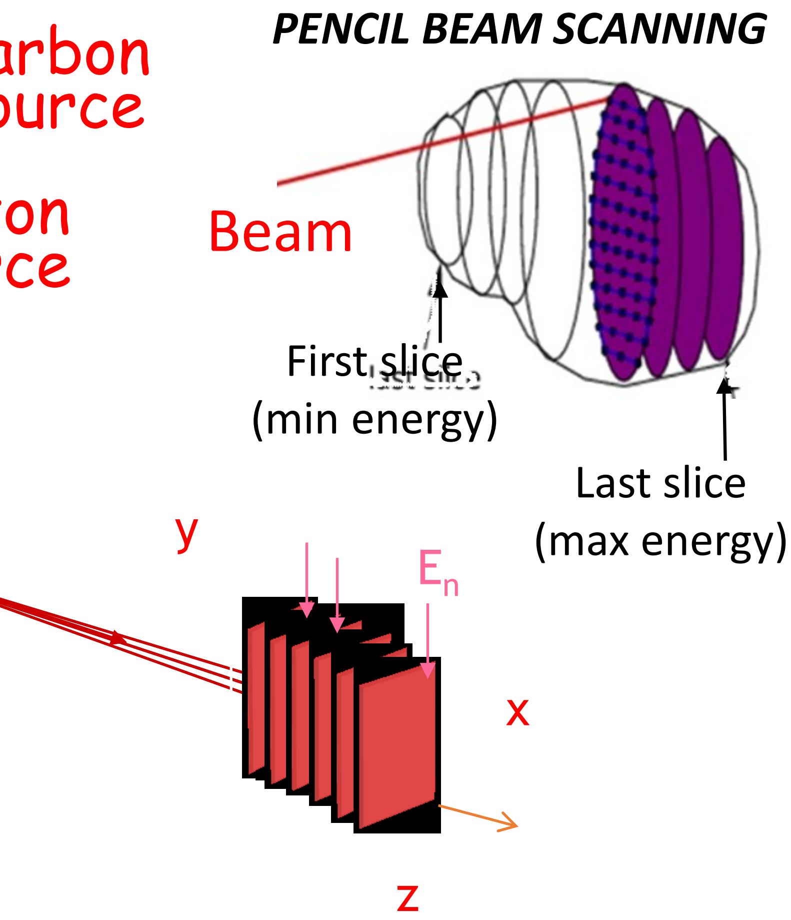




IONIZATION CHAMBERS

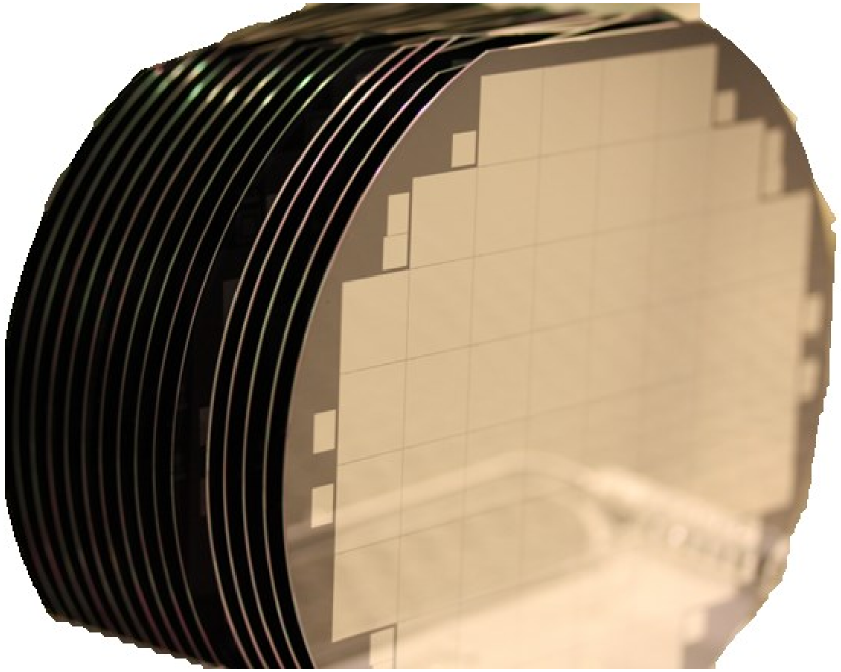
Response dependence on beam energy, slow collection time, reduced sensitivity.

Motivation: beam monitoring in PT

Solid state detectors

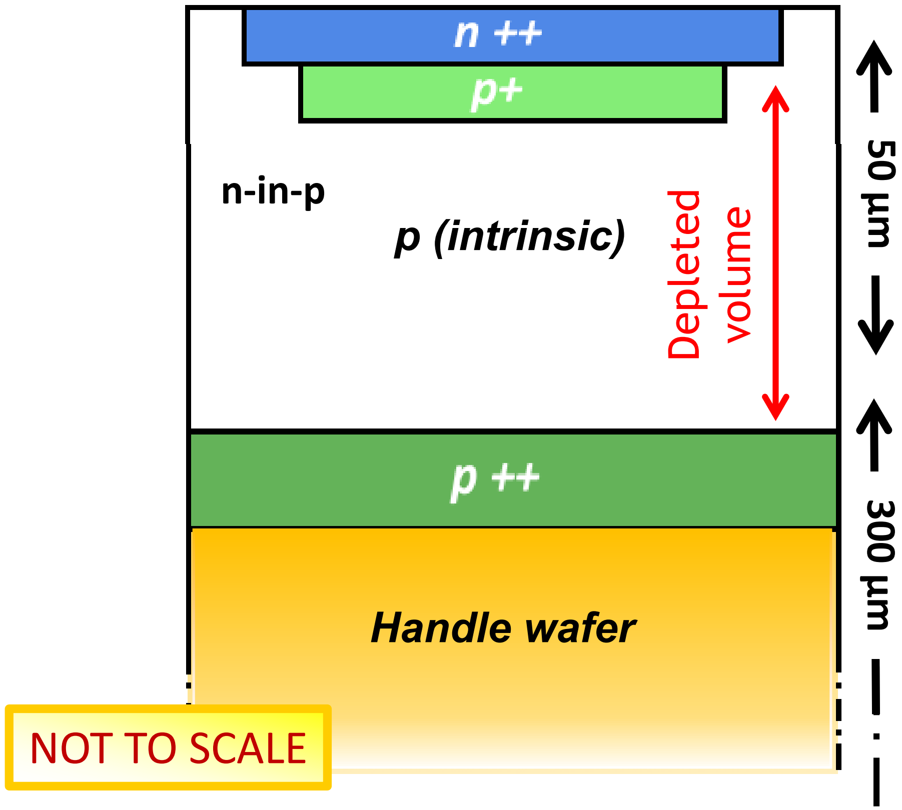
t response time,
time resolution,
large granularity.

Radiation damage,
Pile-up effects,
High readout complexity.



Ultra Fast Silicon Detector (UFSD)

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



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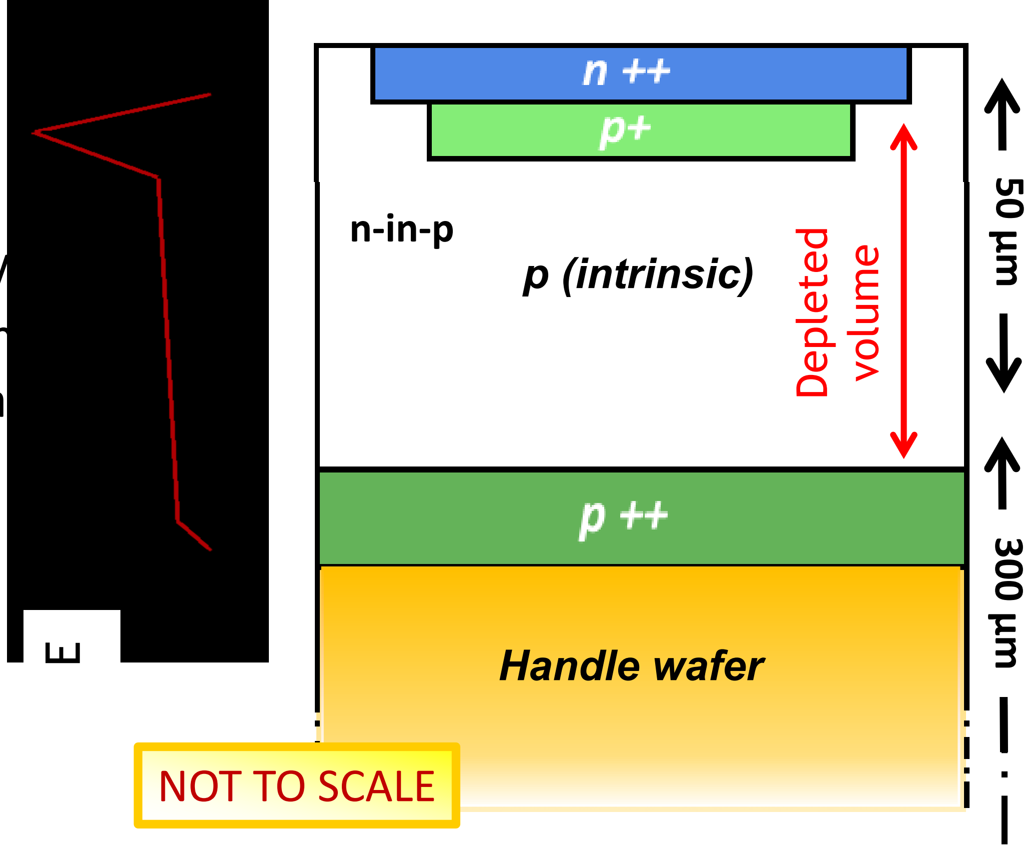
E ~300kV
e^-/h avalan
multiplica



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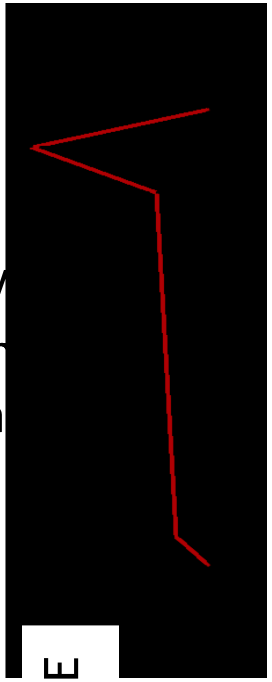

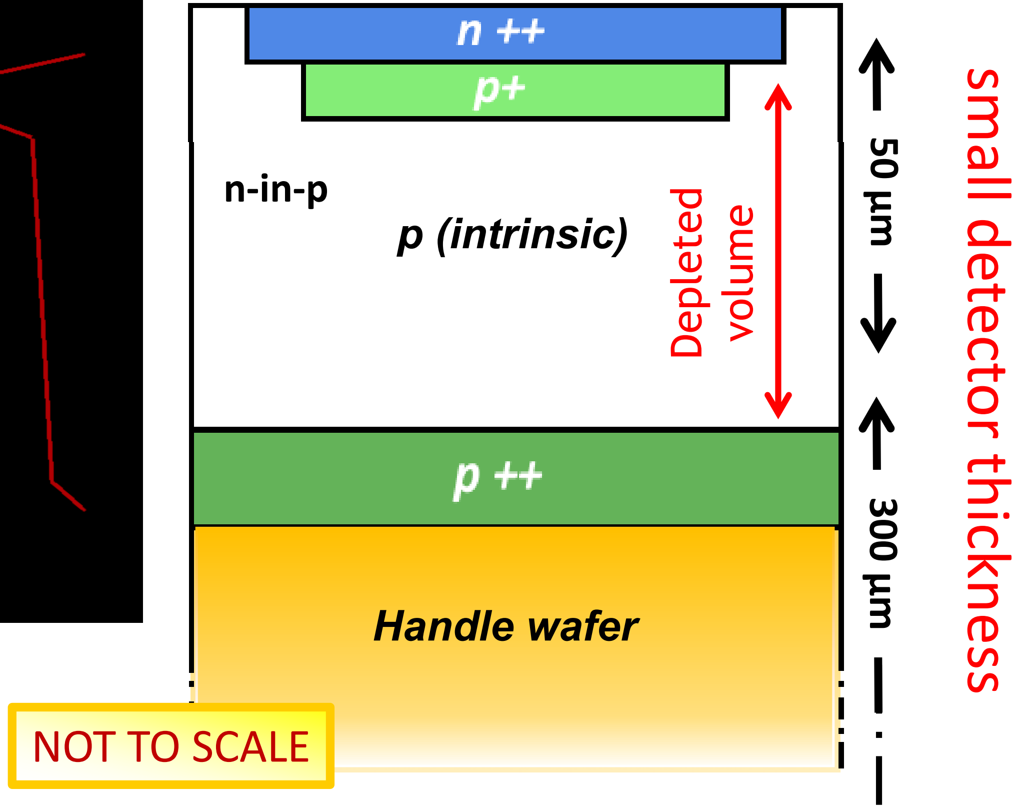

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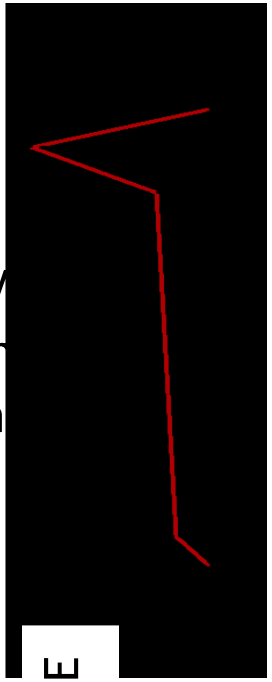

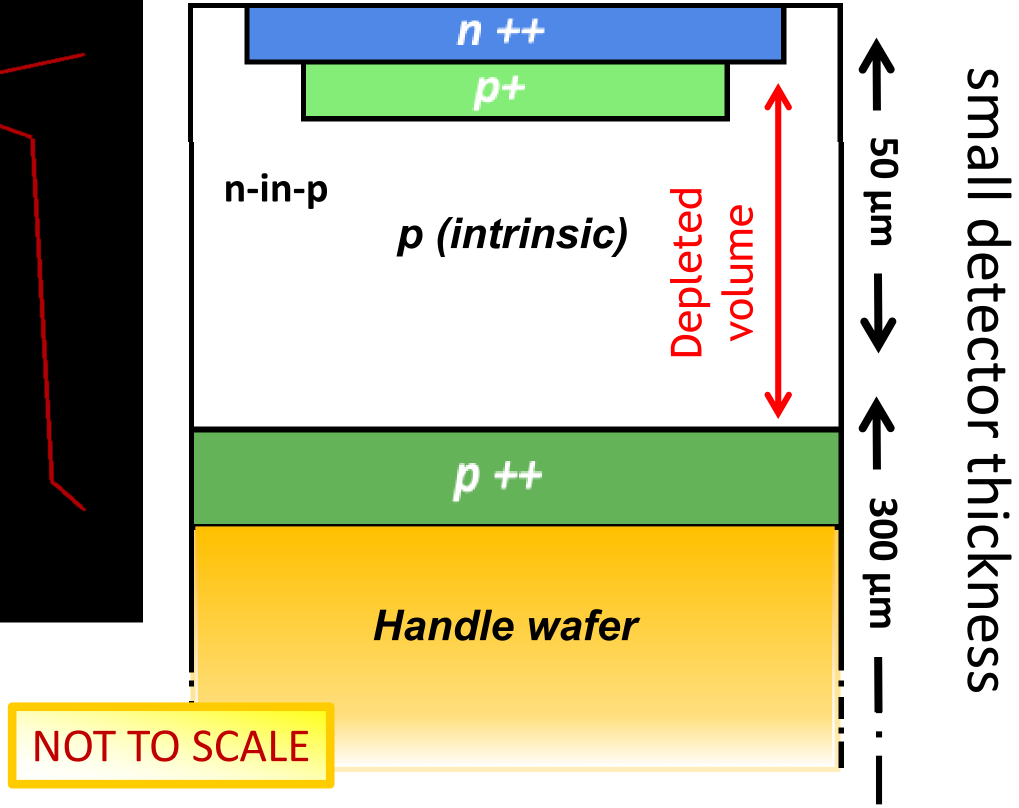

controlled low gain (~ 10), increasing with reverse bias

Ultra Fast Silicon Detector (UFSD)

Small signal duration (1 ns)
→ **particle counting**
Excellent time resolution (tens of ps)
→ beam **energy measurement**

E ~300kV
e^-/h avalan
multiplica

ingle particle detection
apability

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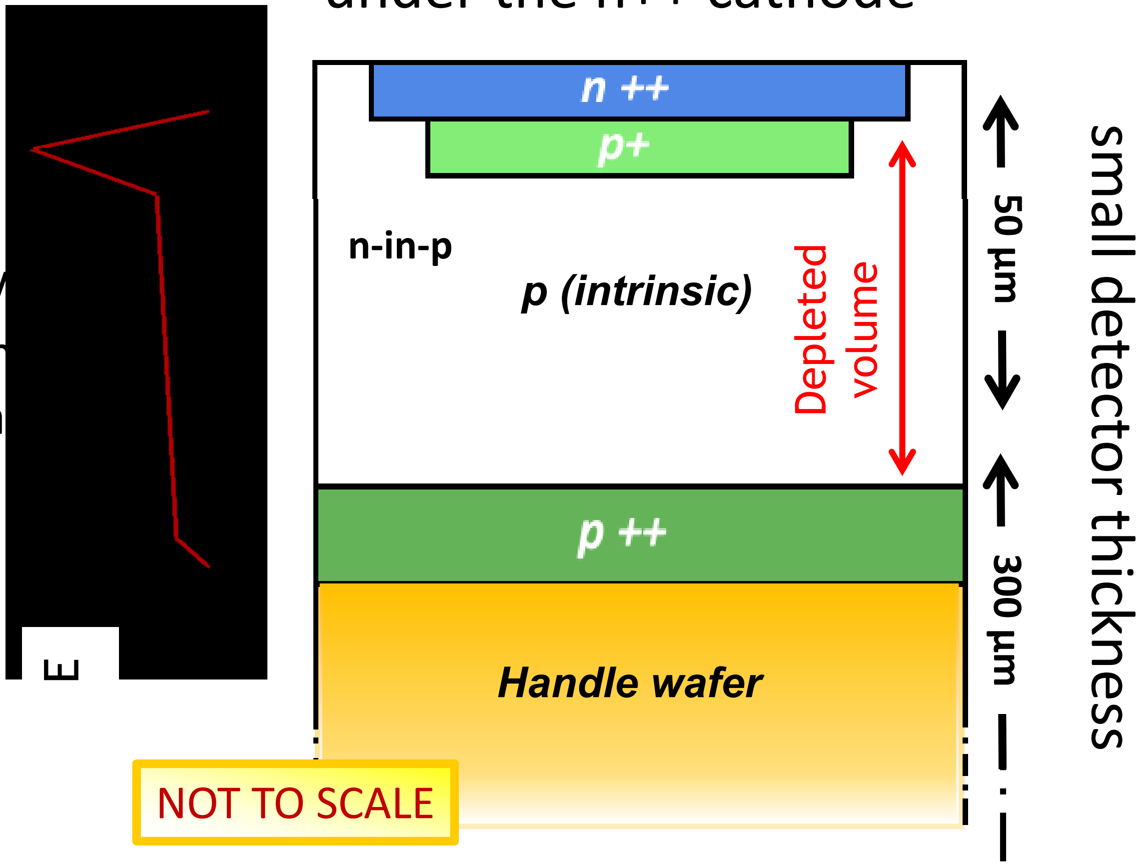


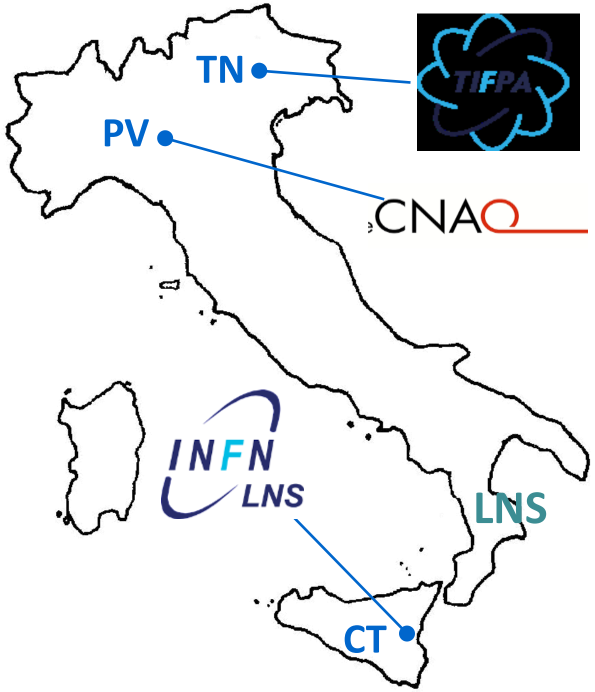
controlled low gain (~ 10), increasing with reverse bias

Aim of the MoVe IT INFN project

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

1. to **directly count** individual protons:
   - ➢ area 3x3 cm^2;
   - ➢ up to fluence rate of $\mathbf{10^8}$ **p/s** $\mathbf{cm^2}$ (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/

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.

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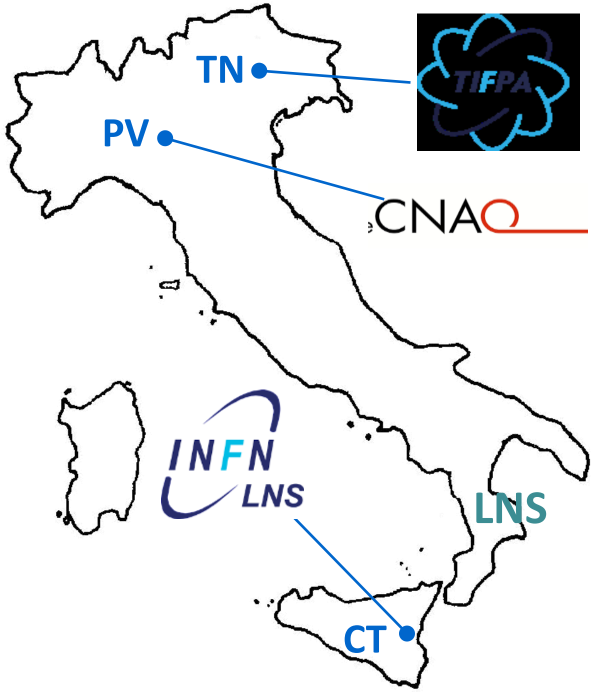

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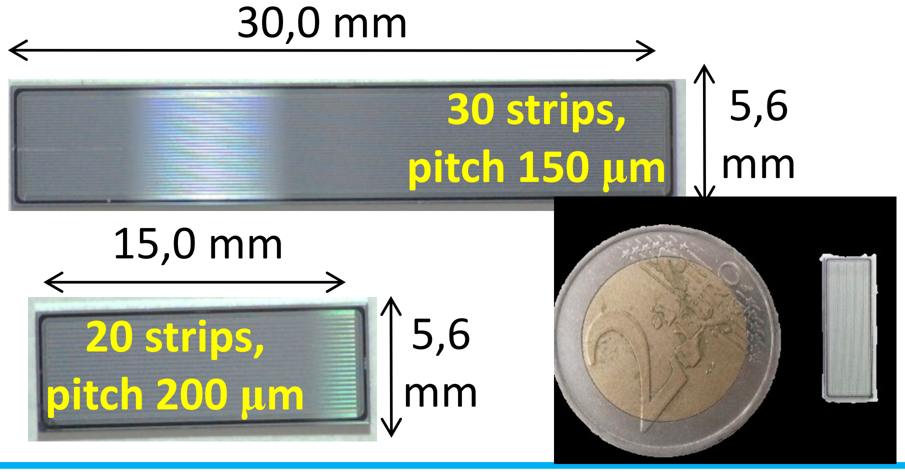
Particle Counting

Test of 50 µm UFSD prototypes @ CNAO (protons)



18 silicon-on-silicon wafers

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

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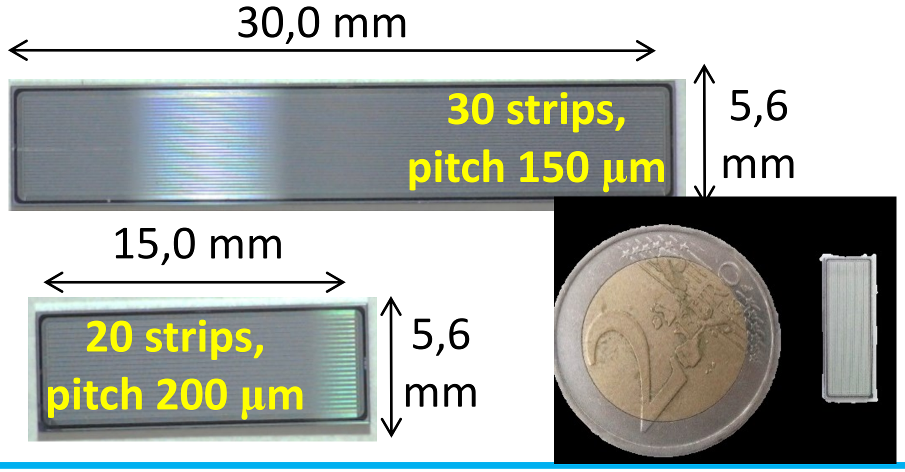

Readout

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

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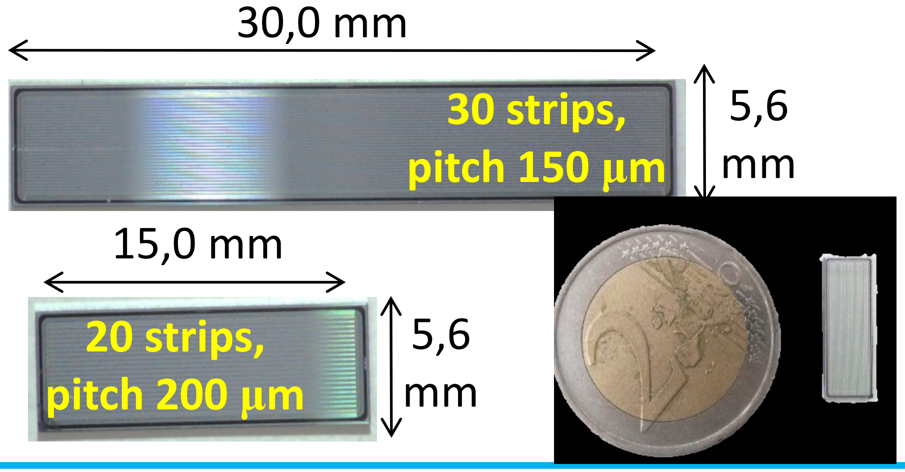

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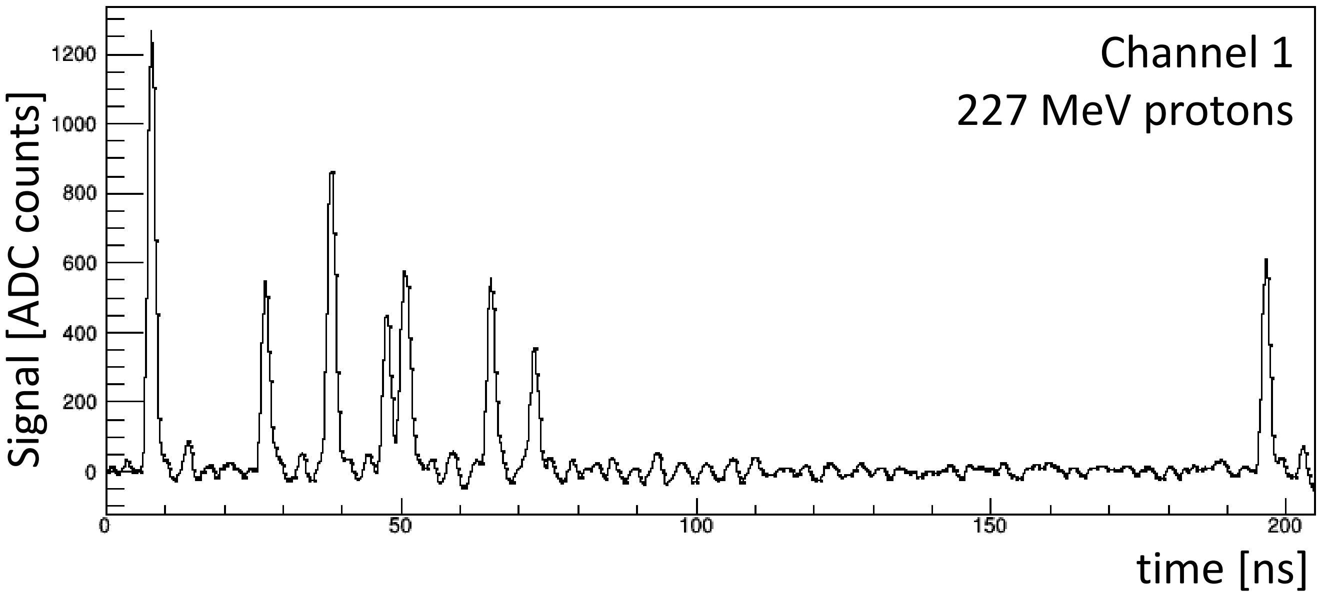
CNAO [redacted]hical Proton Beam

- **Beam FWHM** ~ 10mm
- **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)

Signal waveform acquired on a clinical proton beam

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



Signal waveform acquired on a clinical proton beam

- Peaks corresponding to **individual protons** can be easily distinguished;
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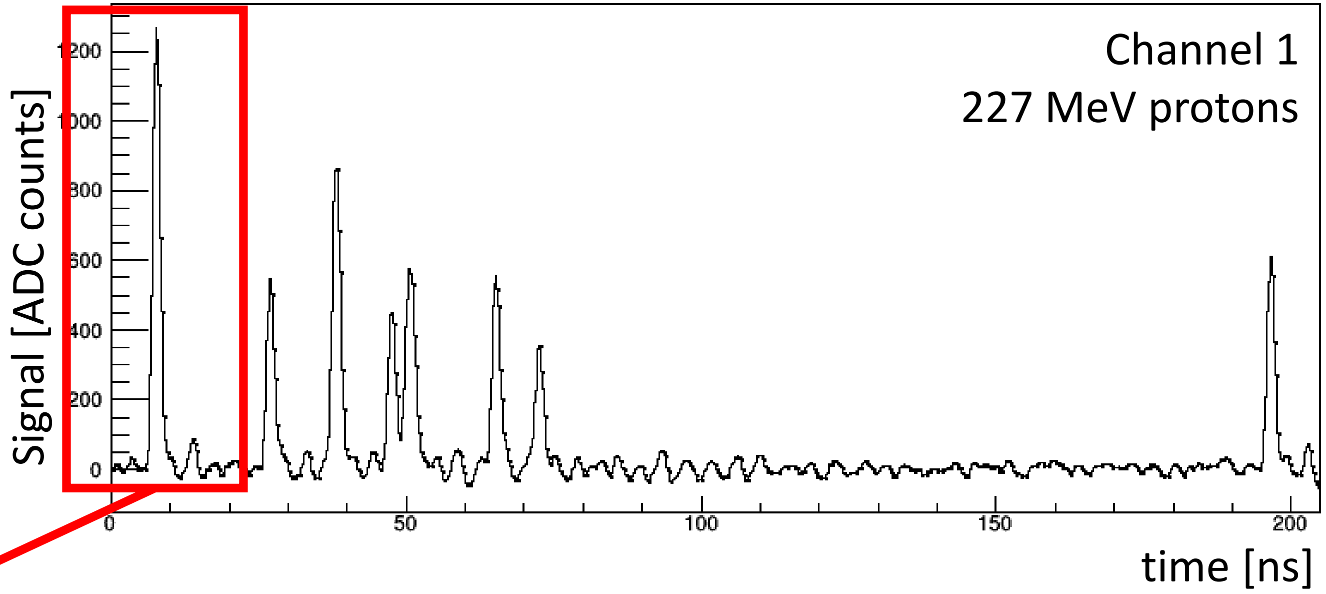
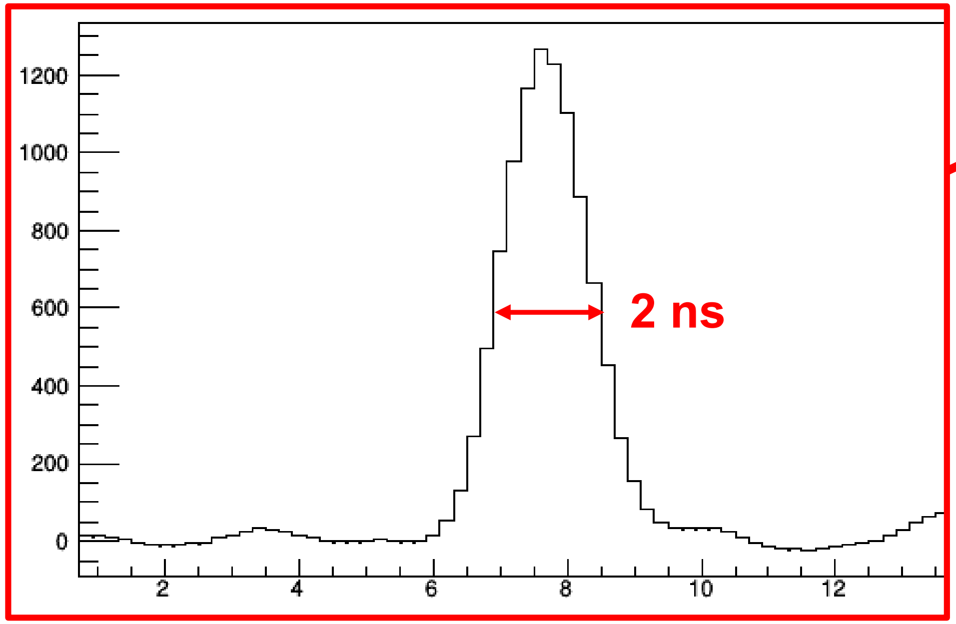
- short peak duration;





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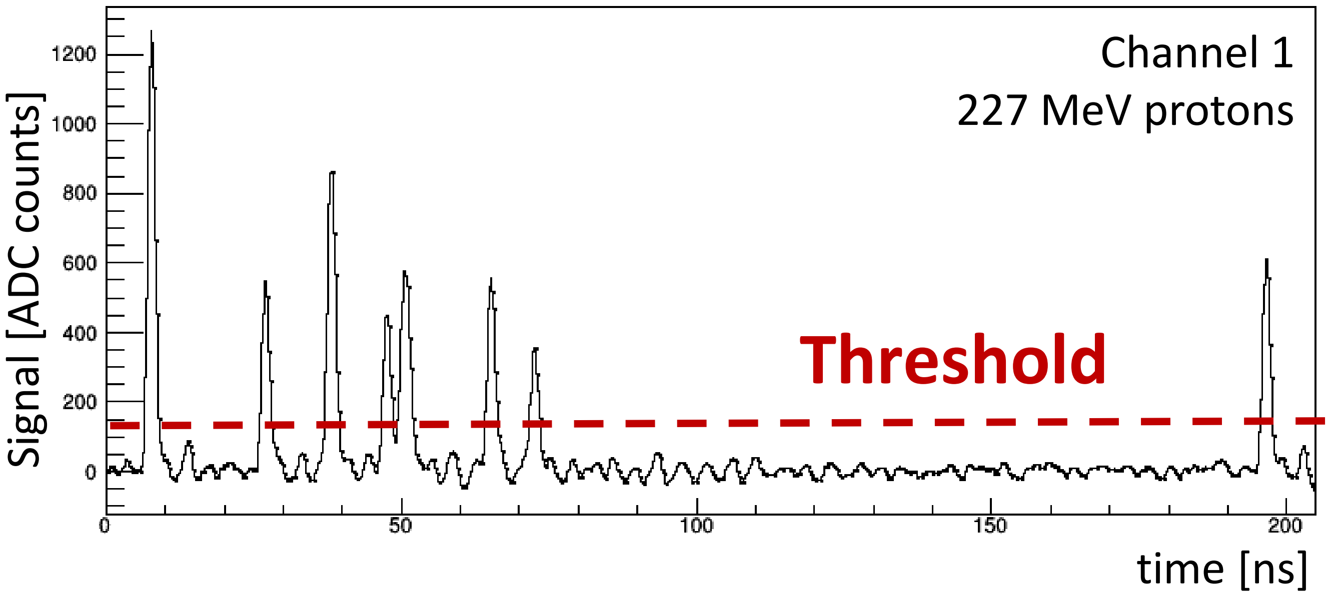

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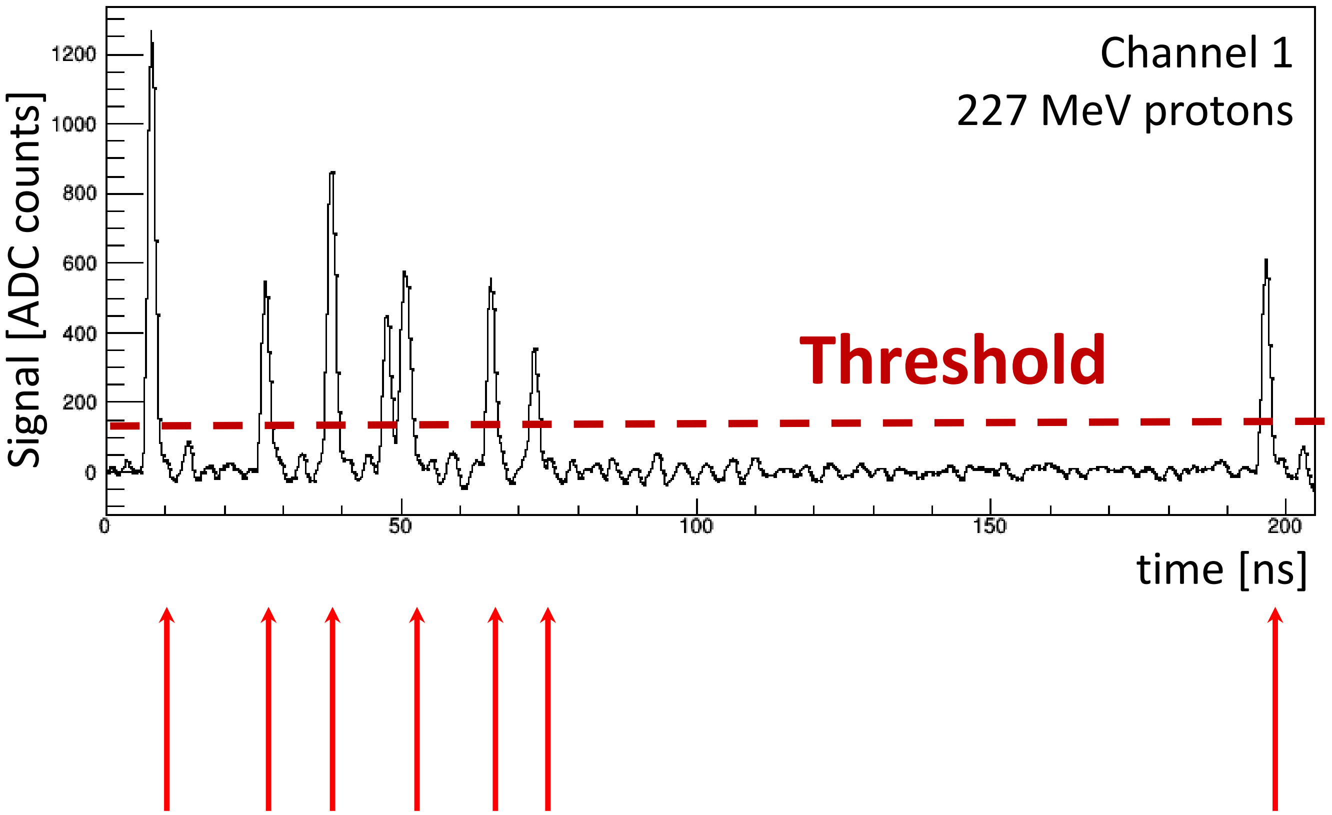
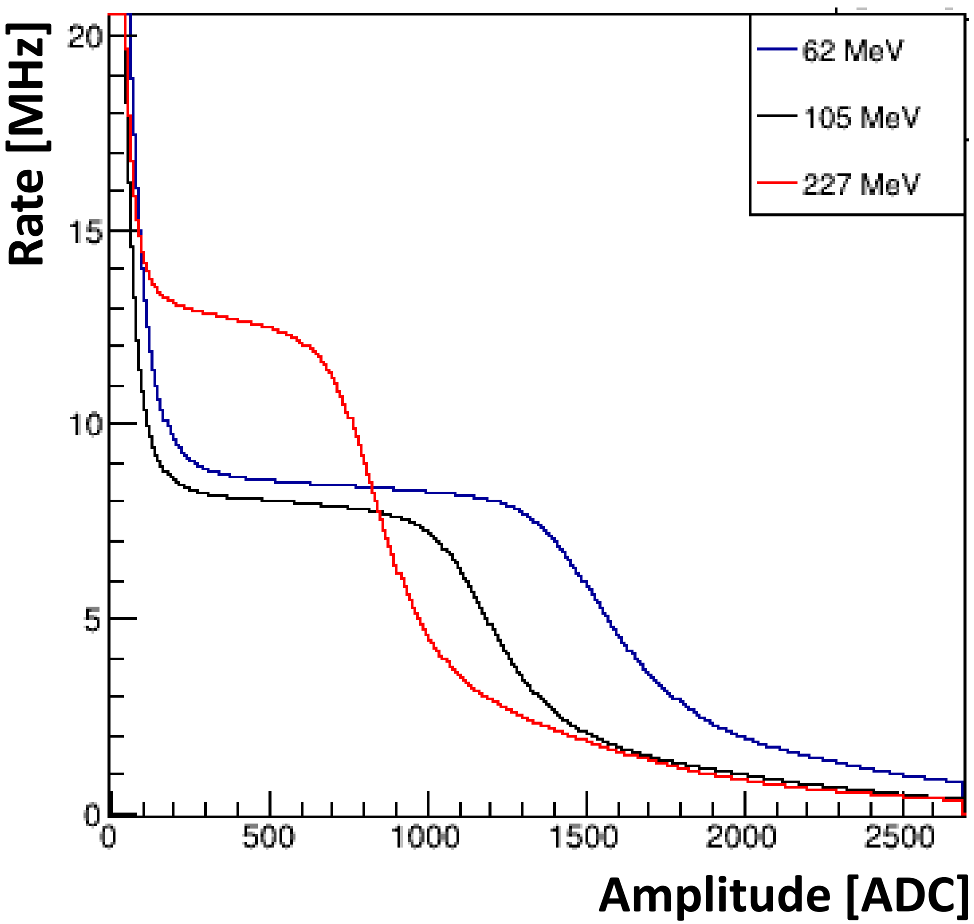


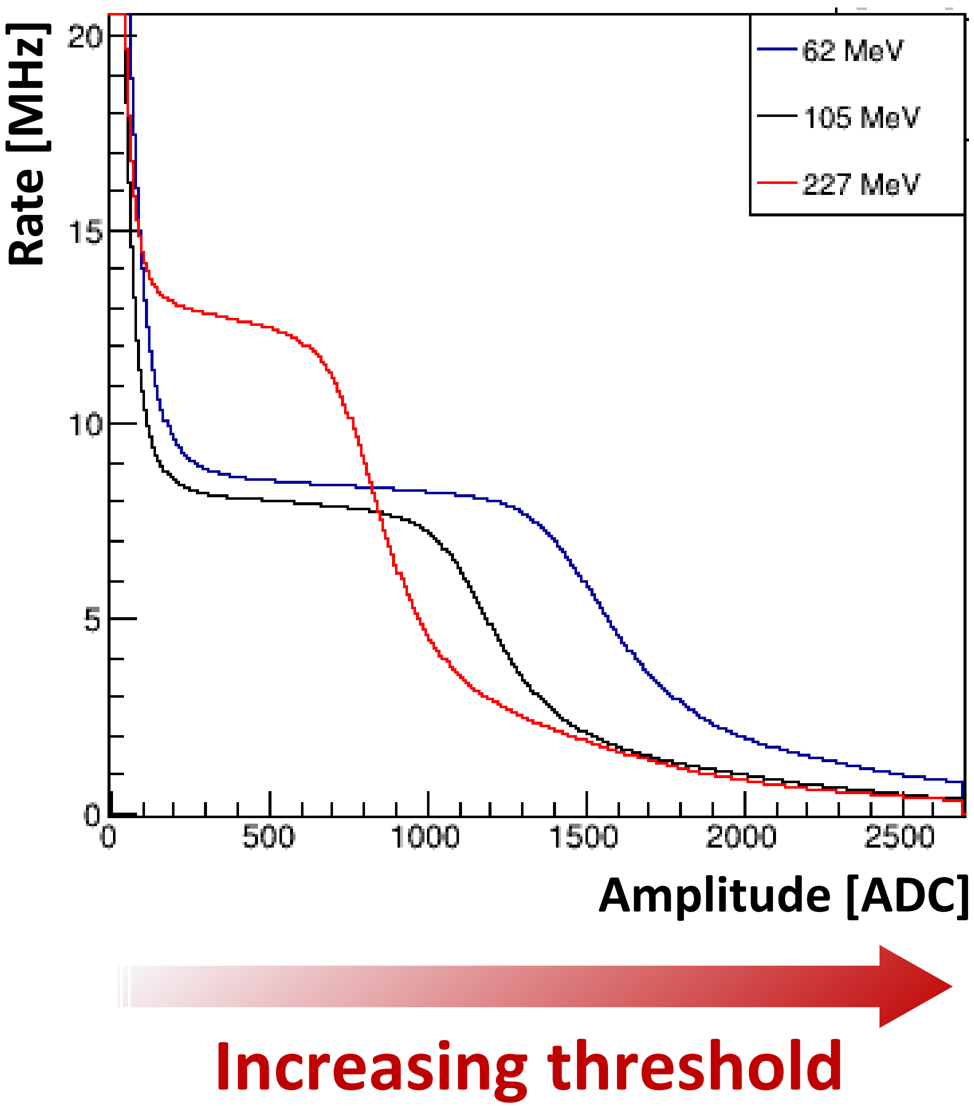
Count protons

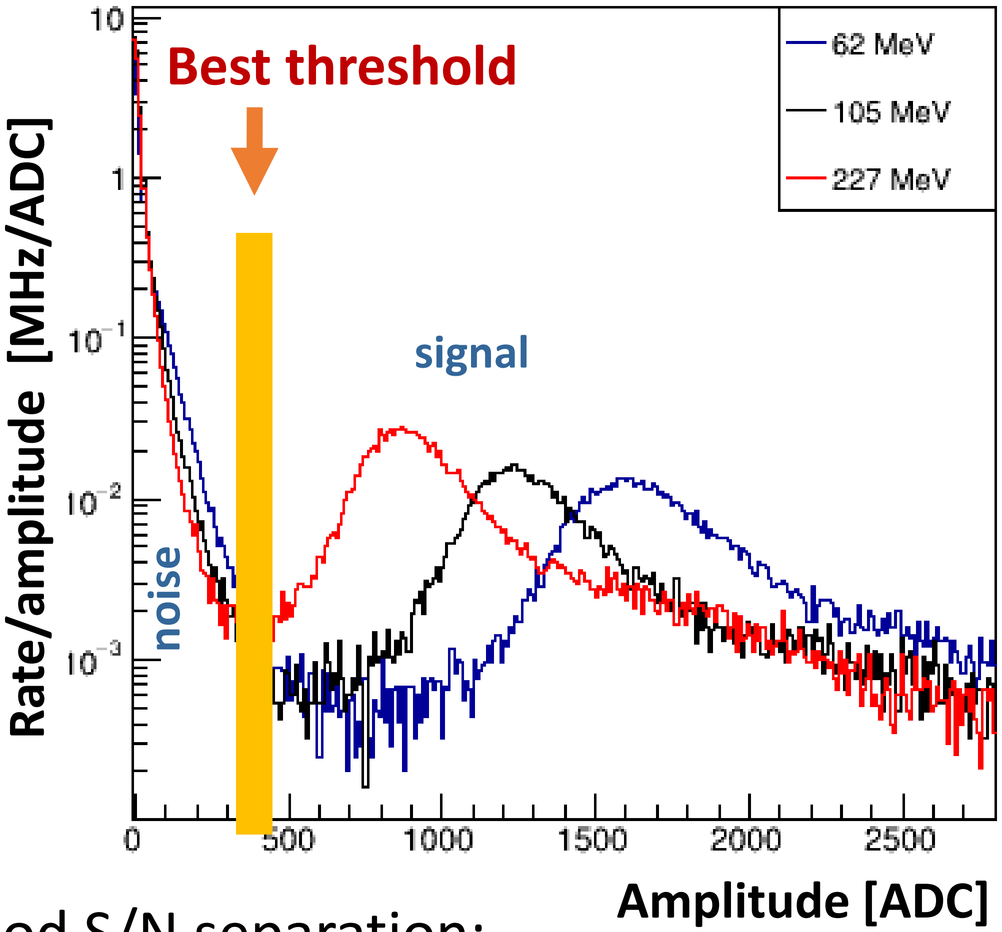
Signal distribution



Increasing threshold

Signal distribution

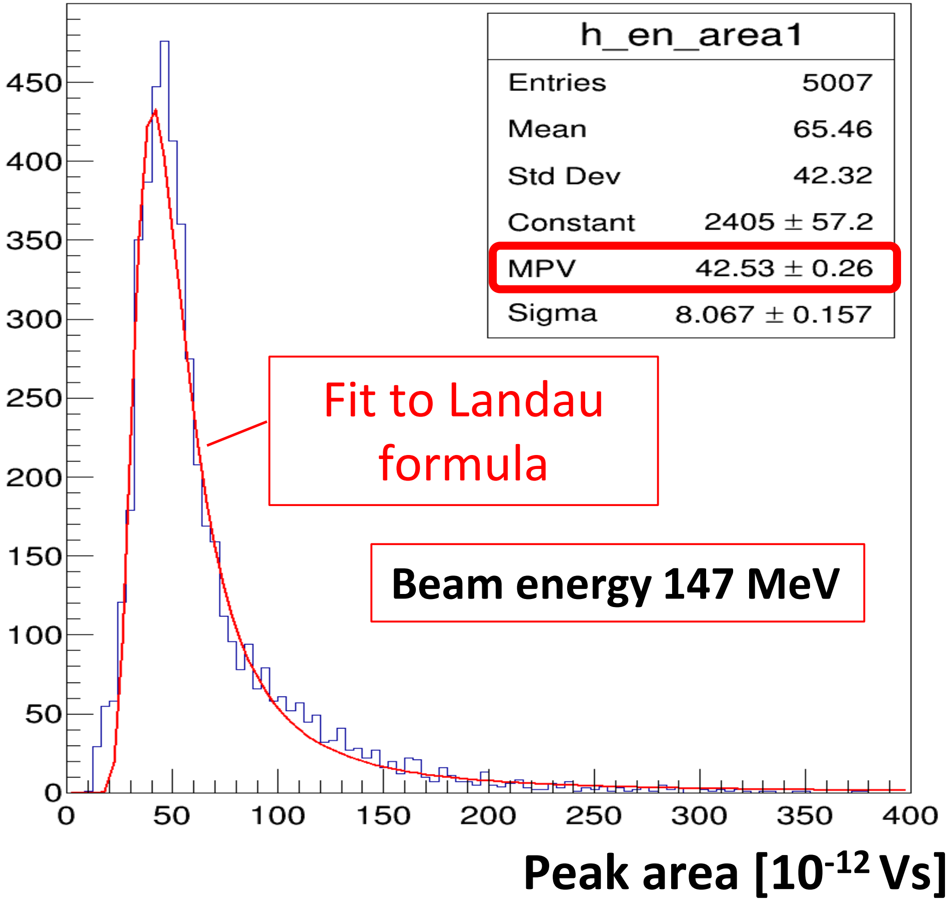




- ➢ Good S/N separation;
- ➢ Larger S/N at lower beam energies;
- ➢ Best threshold is beam energy dependent.

Peak Area and Landau distribution

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



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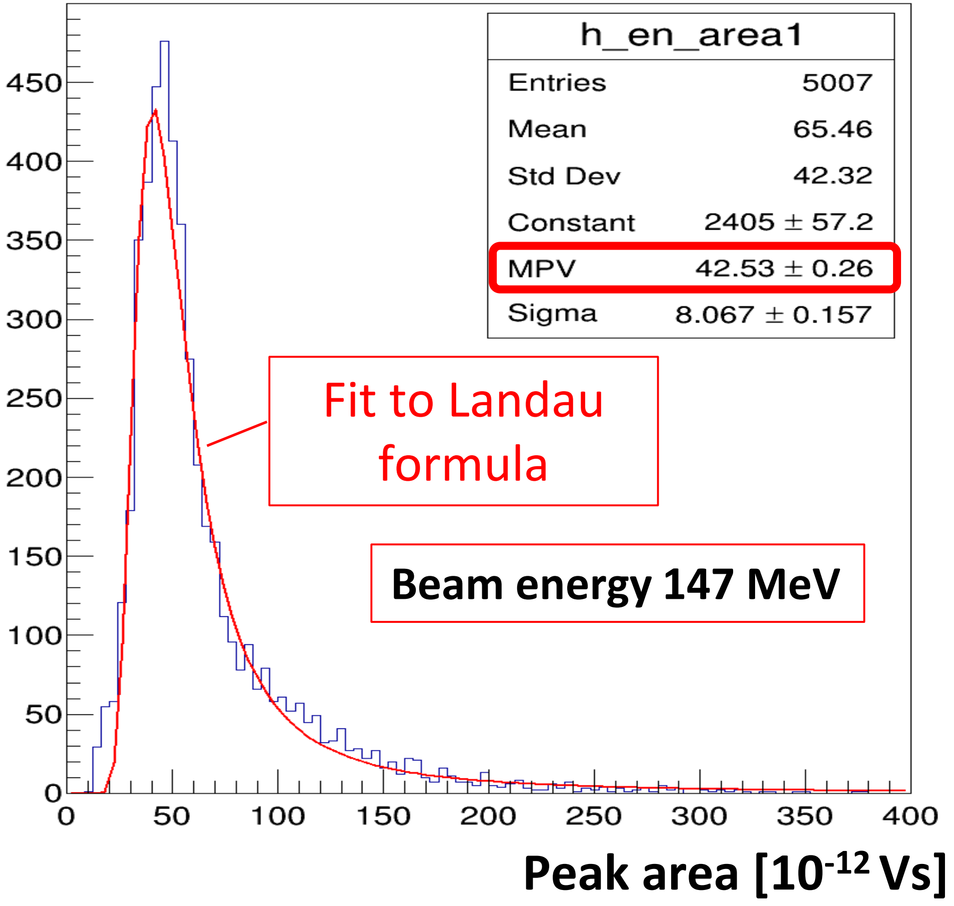
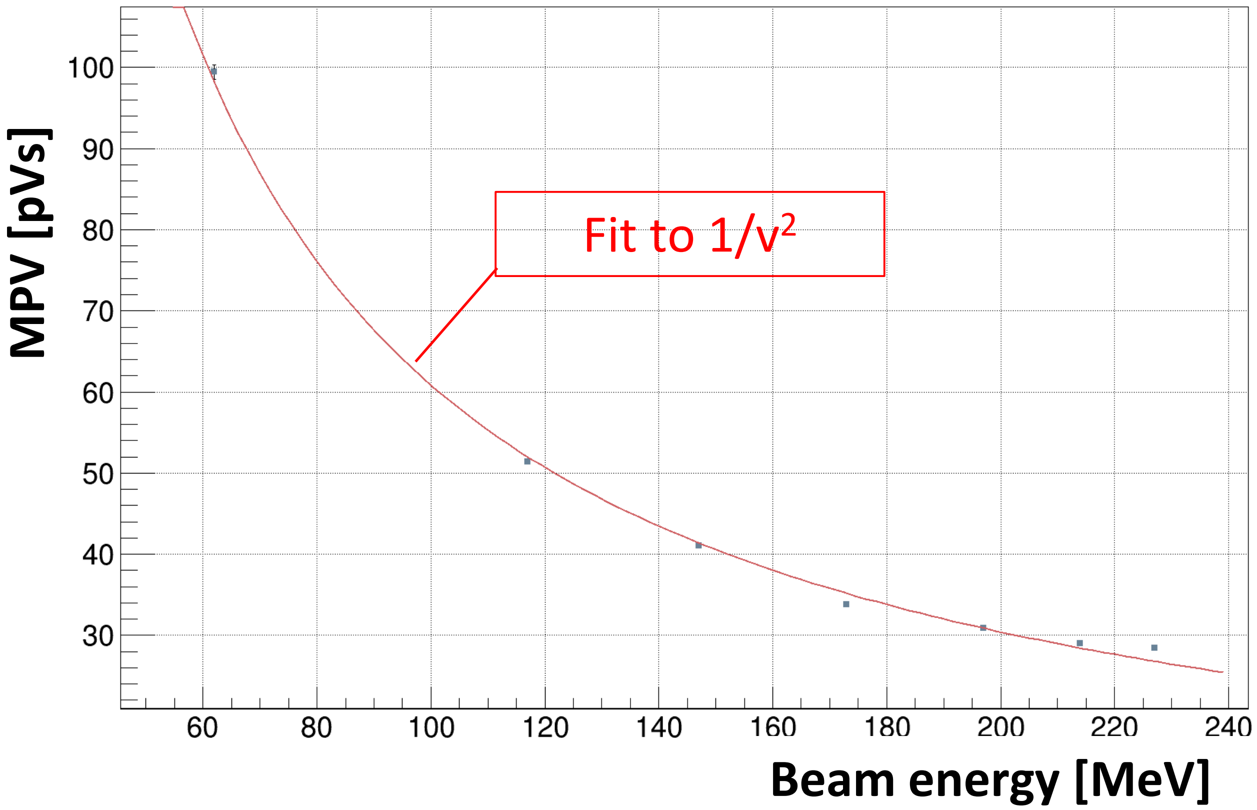
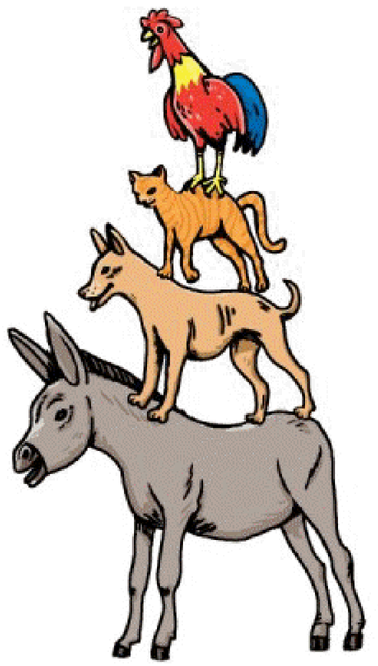


- **Landau's MPV** dependence on **beam energy** well described by Bethe-Bloch $1/v^2$ dependence

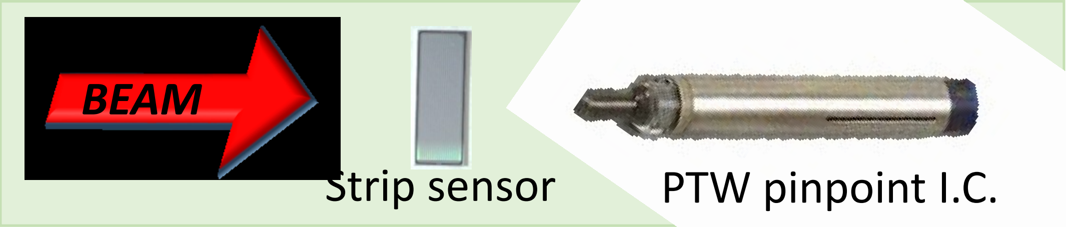


Particle Counting

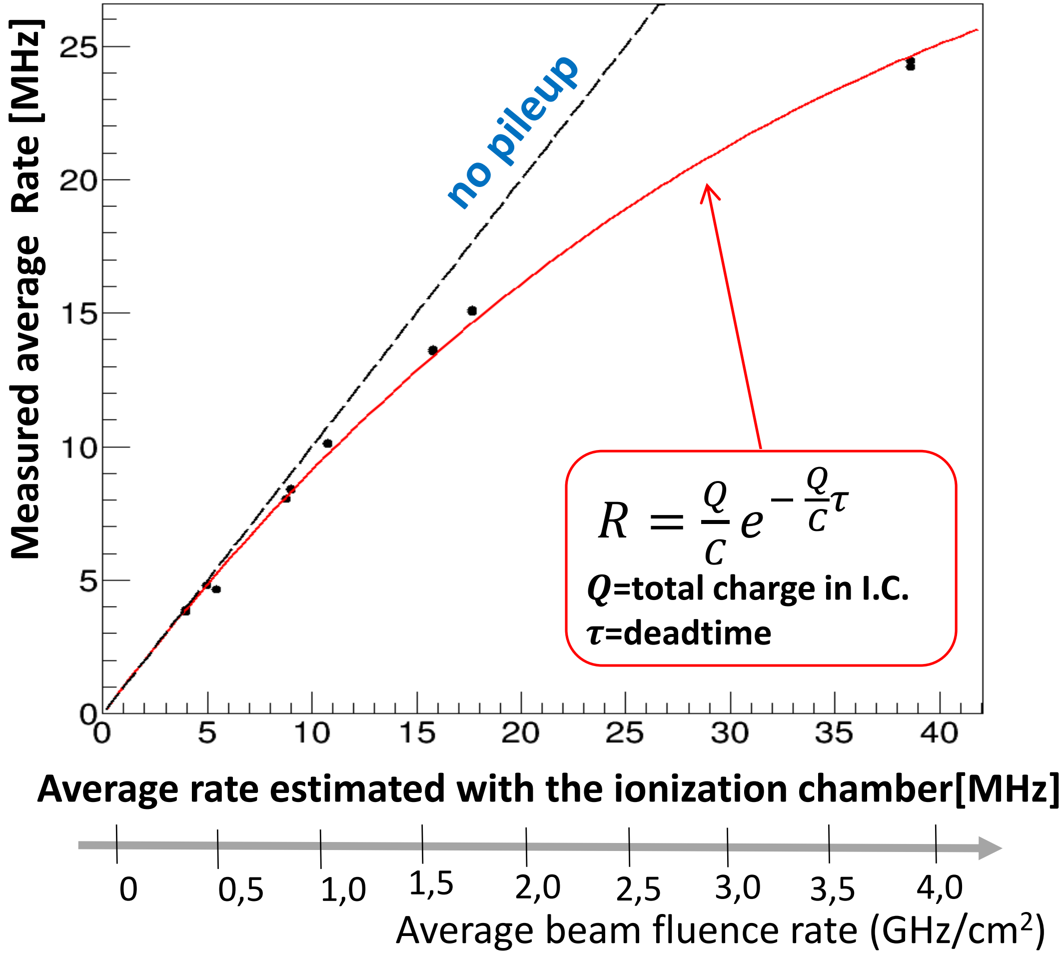


Pile-up inefficiency

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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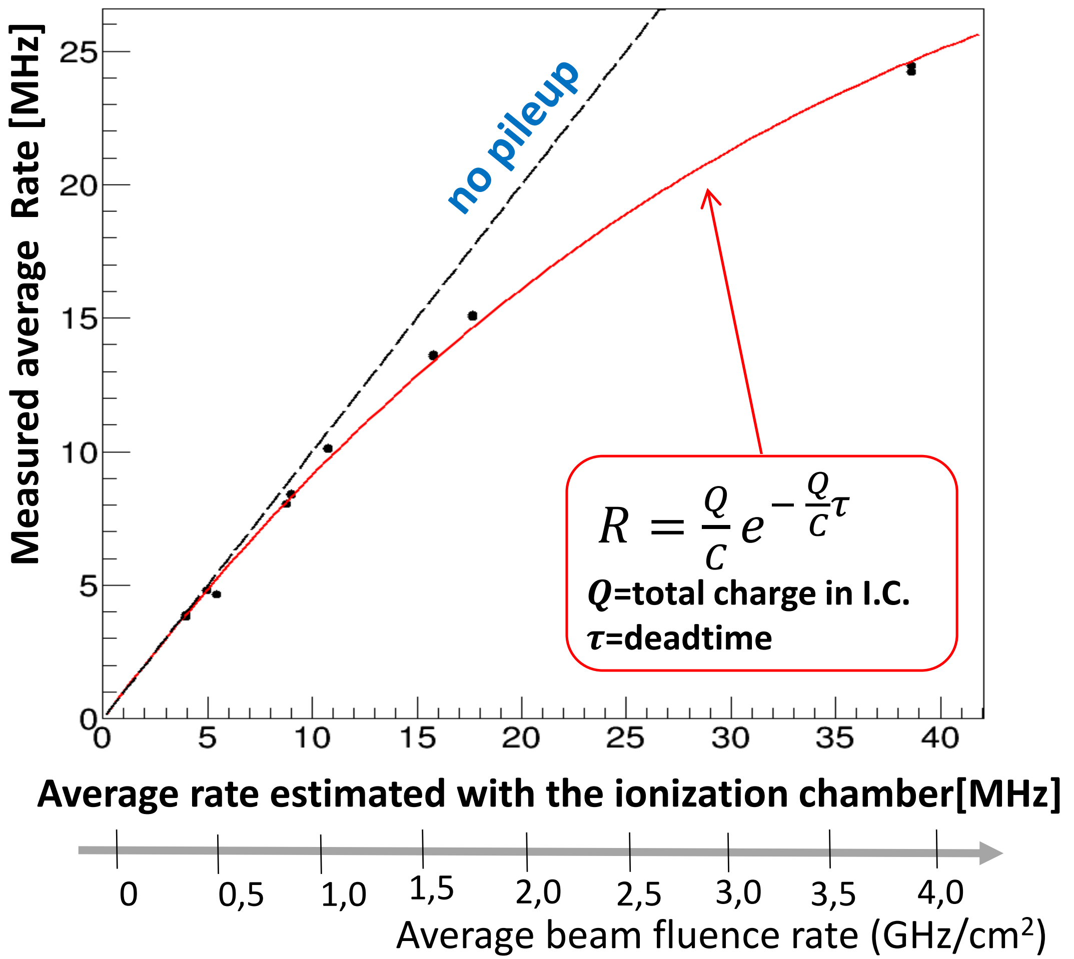

- Large inefficiency observed (up to 25% at largest clinical fluxes) ⇒ Correction required
- Data well described by paralyzable pileup model

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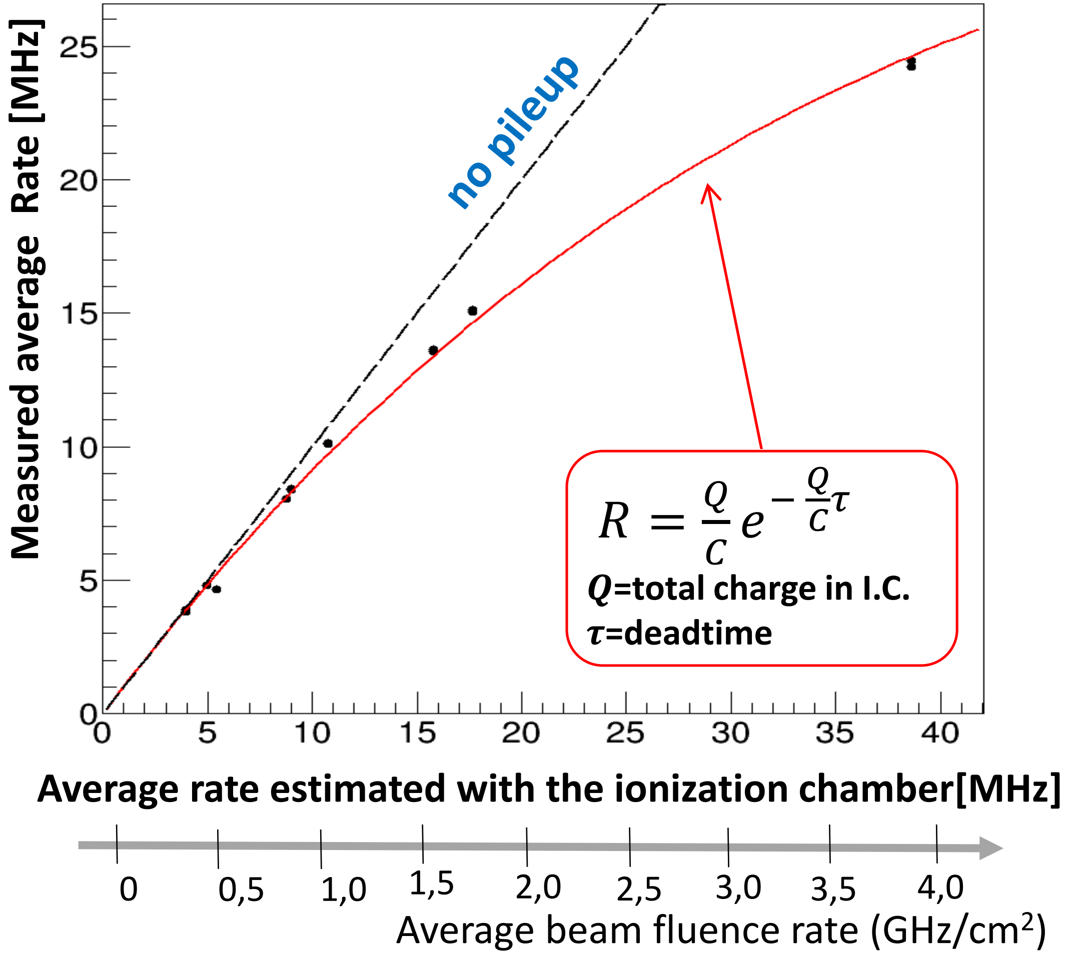

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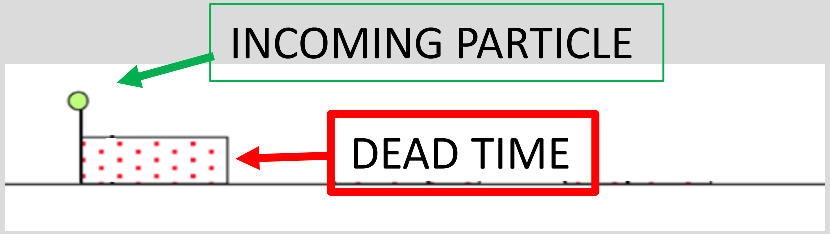

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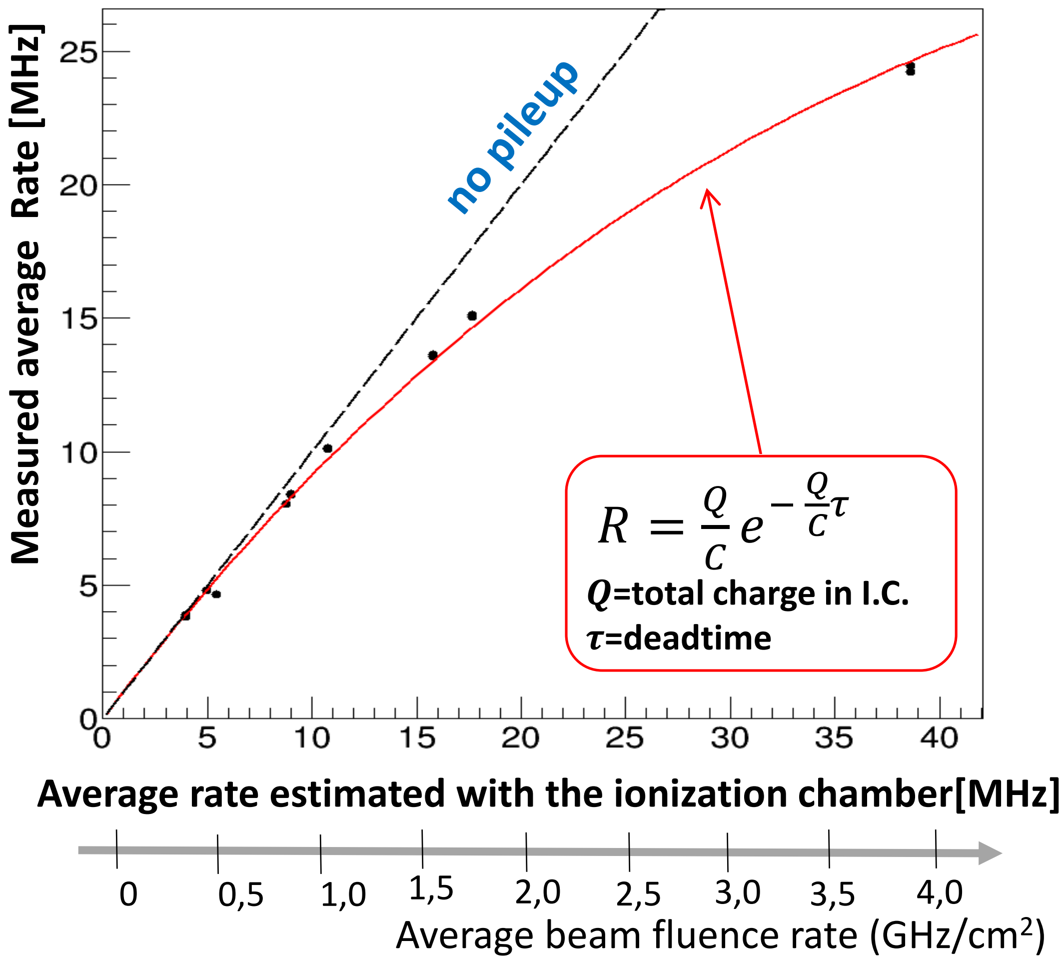

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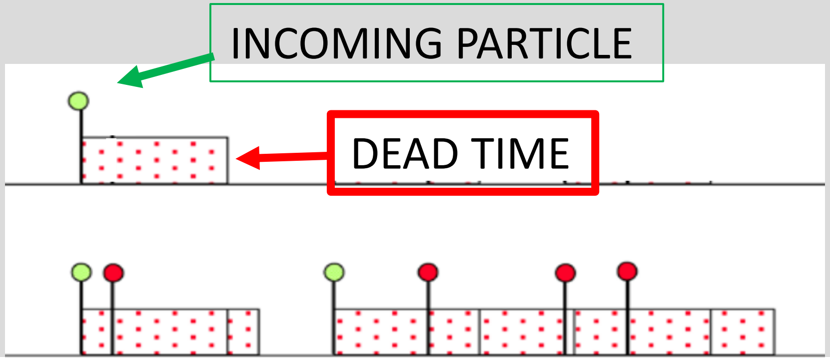

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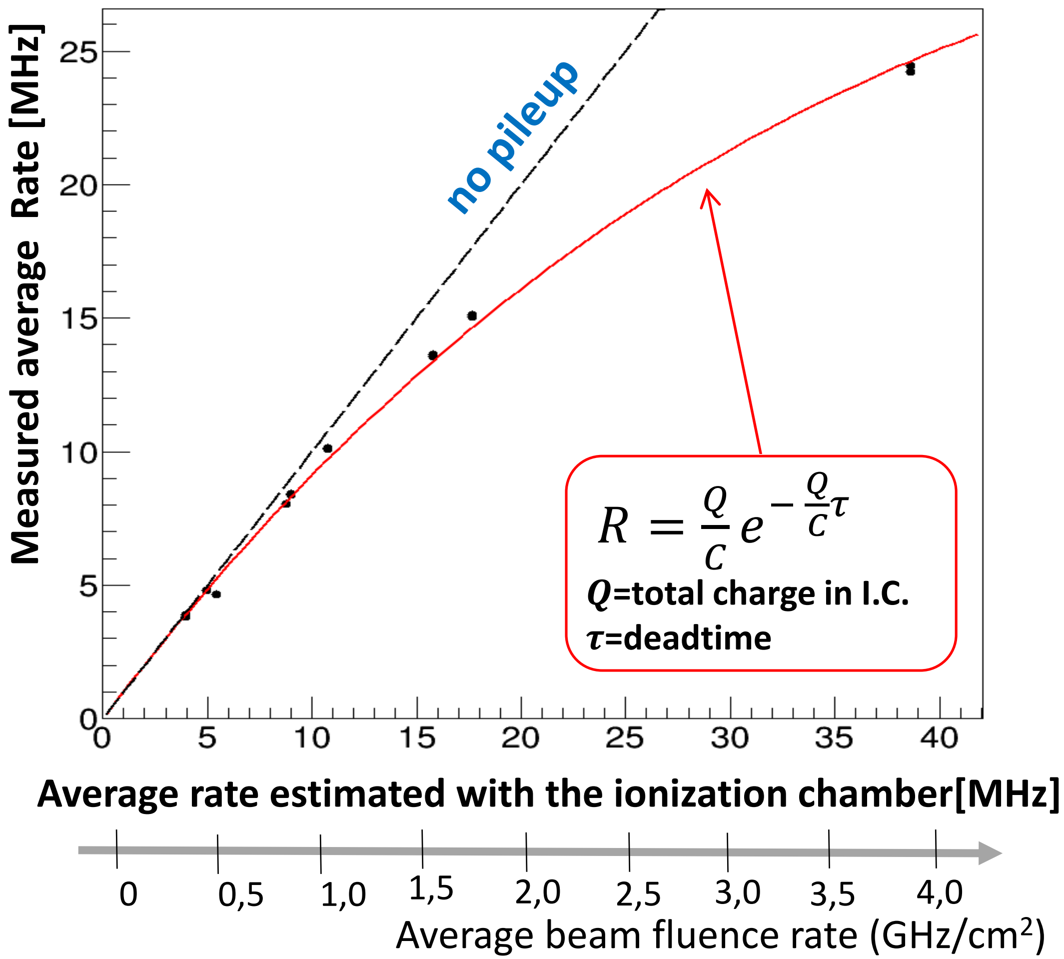

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- Data well described by paralyzable pileup model → deadtime **much larger than expected**

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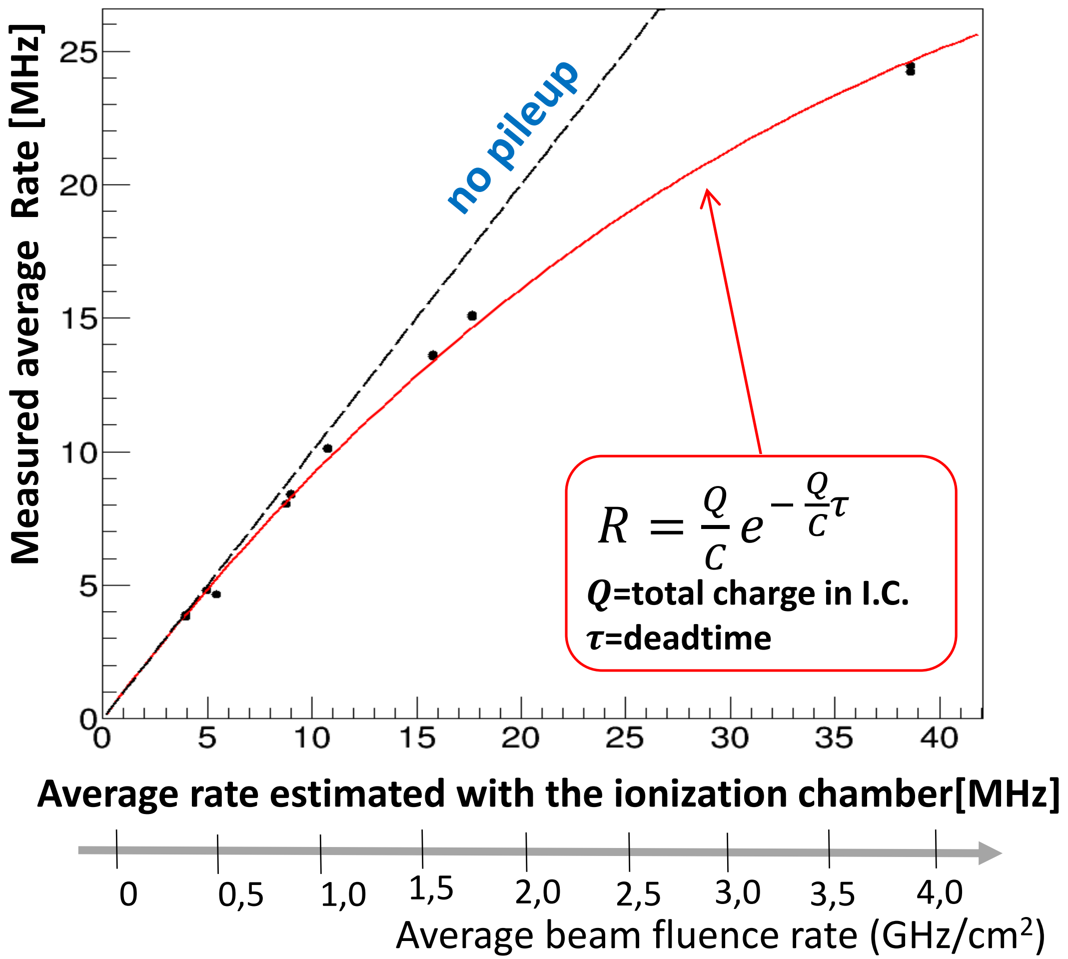
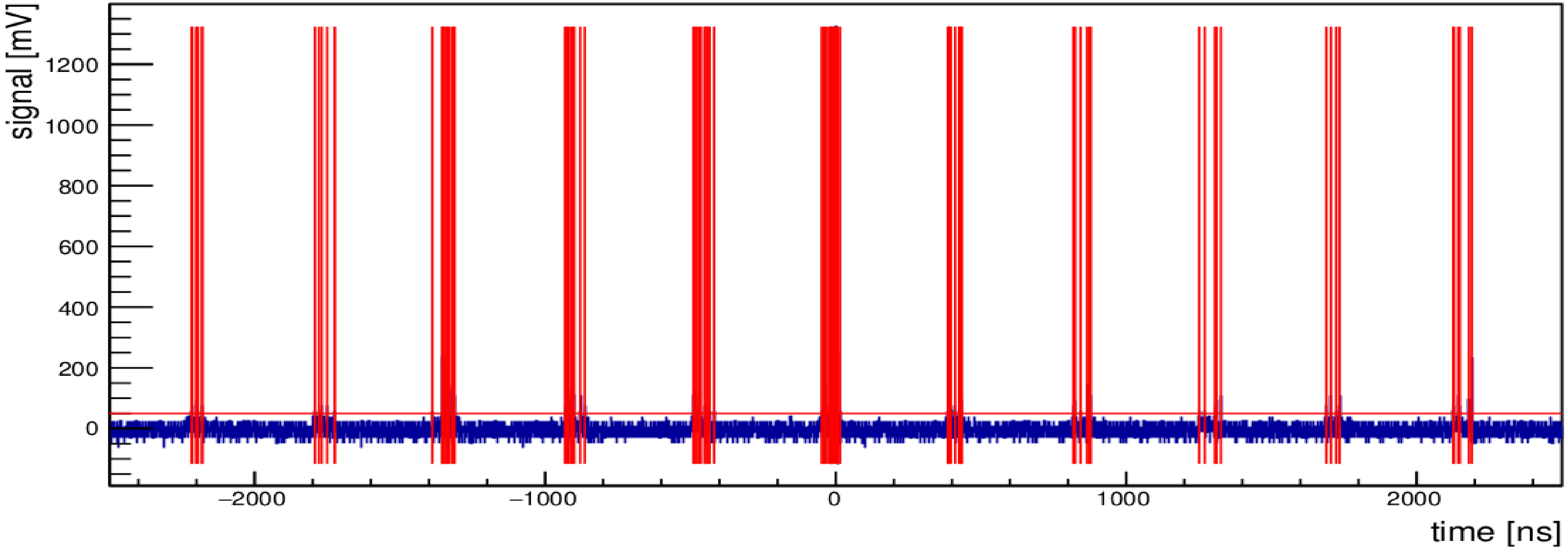


- Large inefficiency observed (up to 25% at largest clinical fluxes) ⇒ Correction required
- Data well described by paralyzable pileup model ⇒ deadtime **much larger than expected**
- Reason relies on the bunched structure of the CNAO beam (istanteneous flux ~ 10 X average)

Concern: pile-up inefficiency



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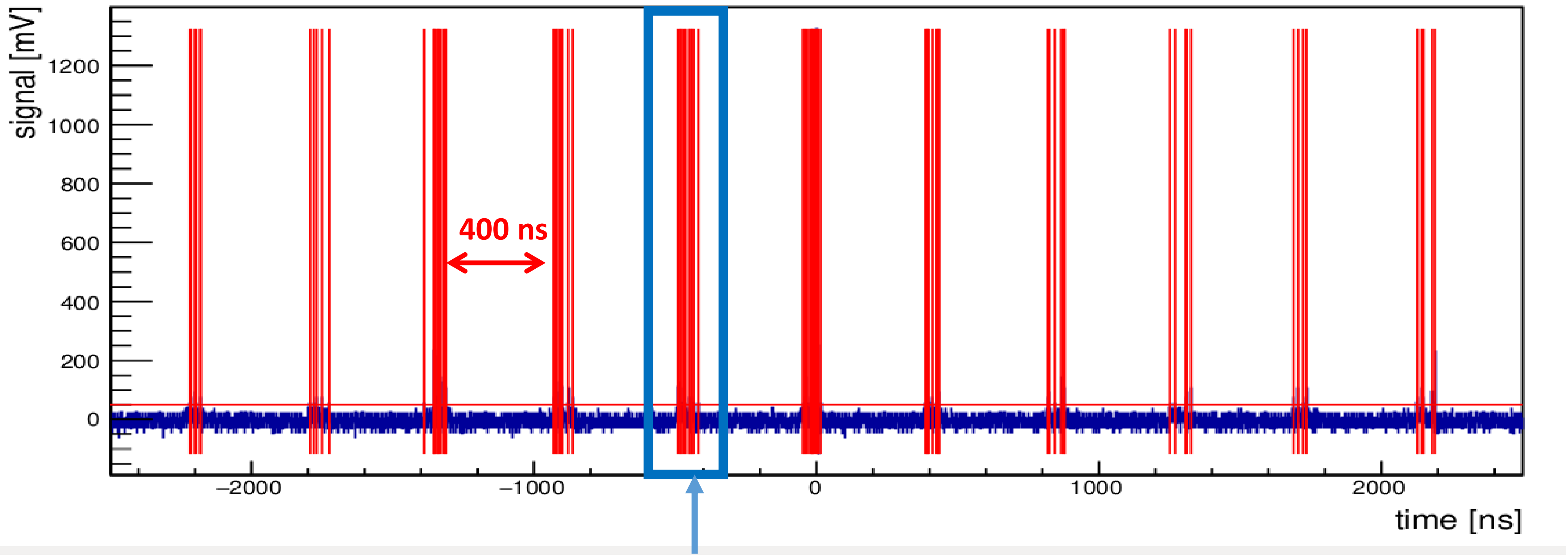
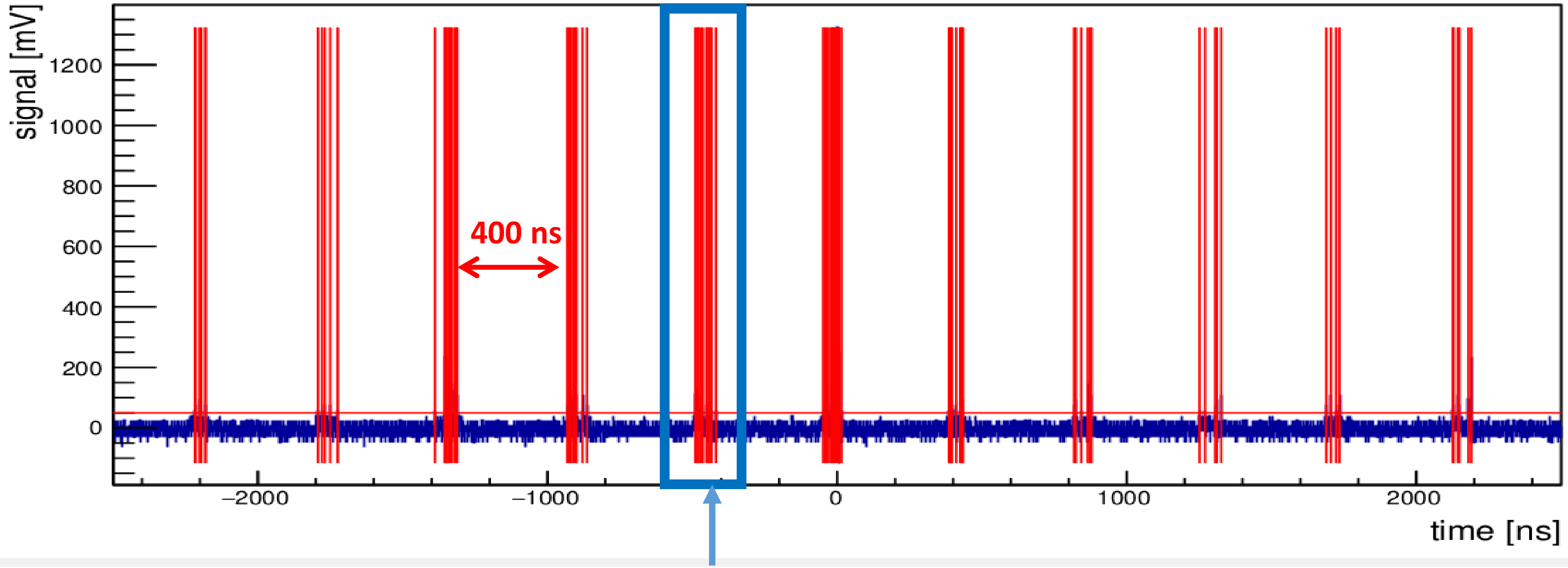


~10^{10} p/s cm^2 !!

- Measurement of CNAO proton beam structure.

Concern: pile-up inefficiency



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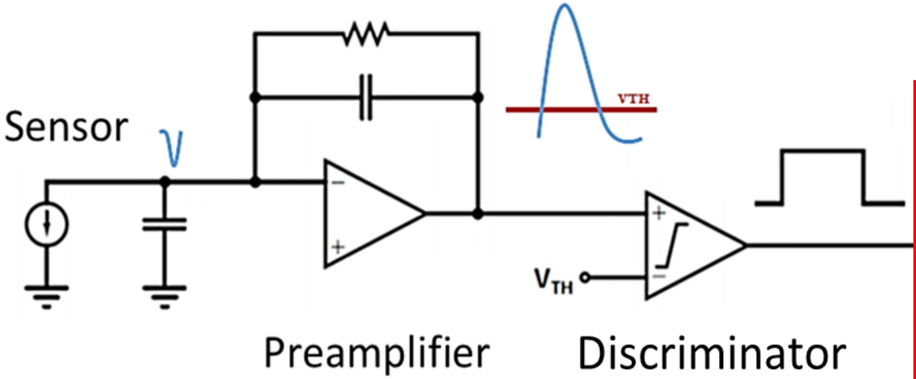
Fast read-out electronics



FPGA

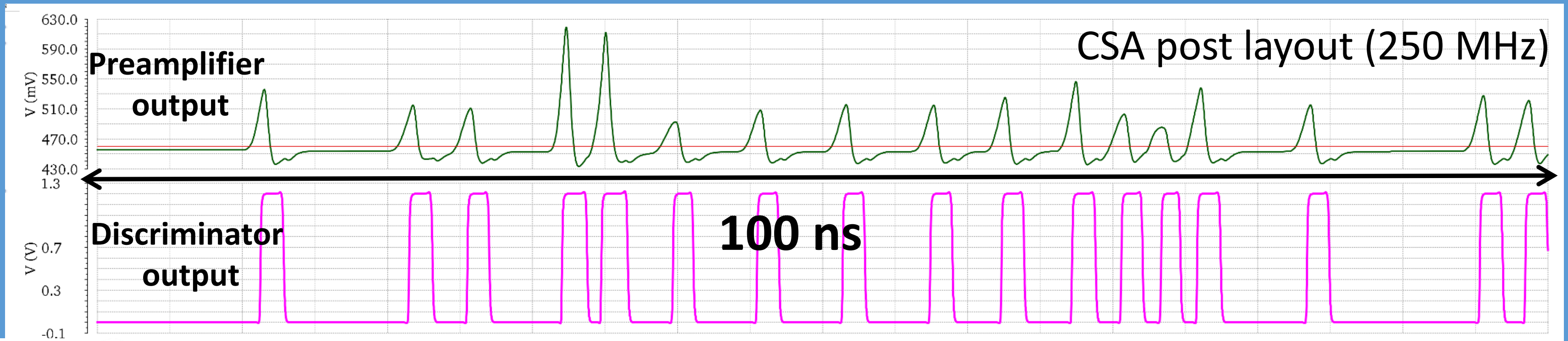
- FE inizialization
- Pulse counting
- Pileup correction

+ Additional functionalities (threshold scan, ...)

Requirements

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

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

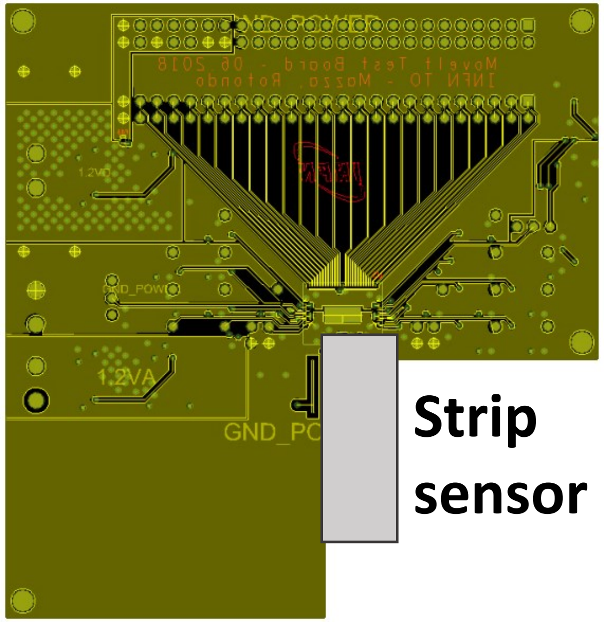


ʼrotoypes (24 ch) of the 2 ırchitectures (UMC110 technology)

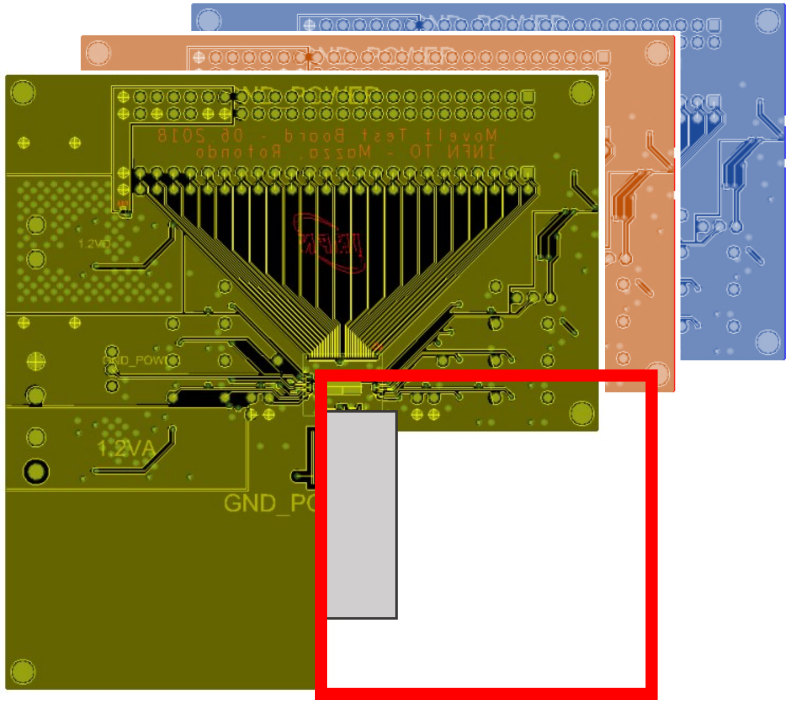
ːst Board

Counting - outlook

Test of complete chain…



Test Board



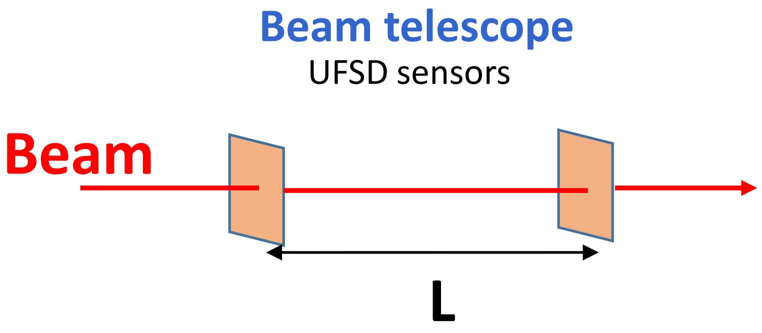
3 x 3 cm^2

FPGA

Energy Measuremen

Energy measurement - coincidences

Beam energy measured from Time-of-Flight



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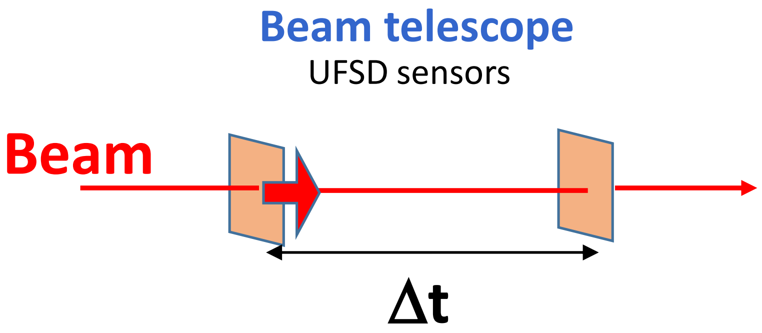

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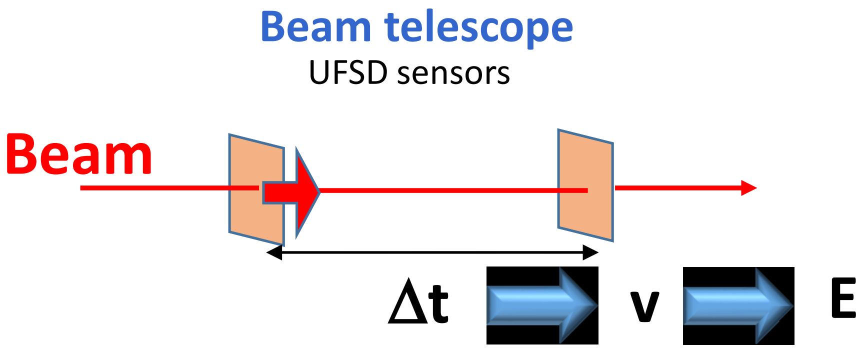
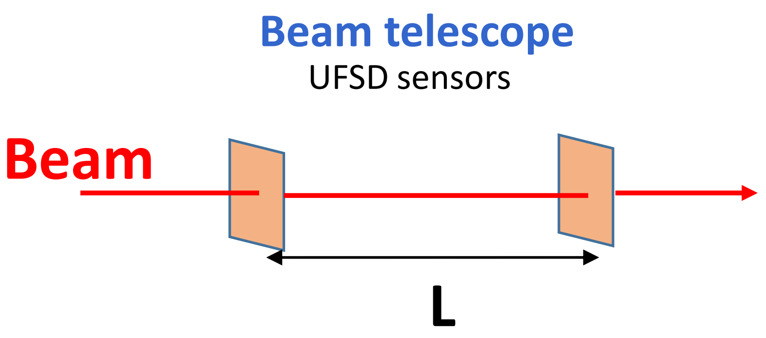
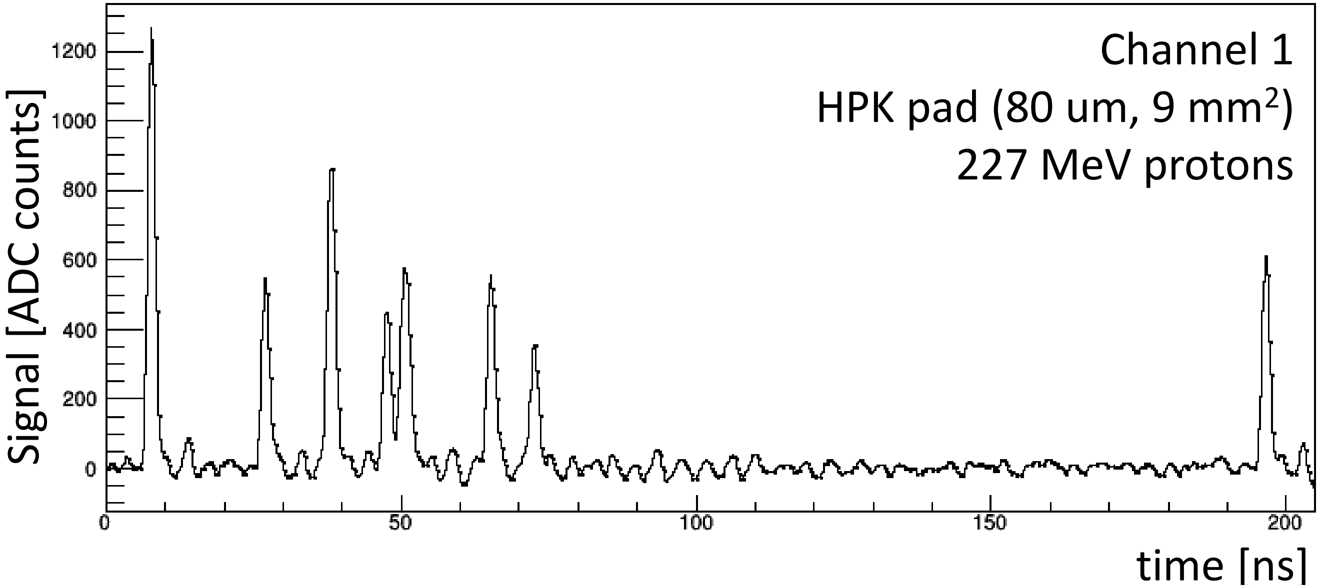
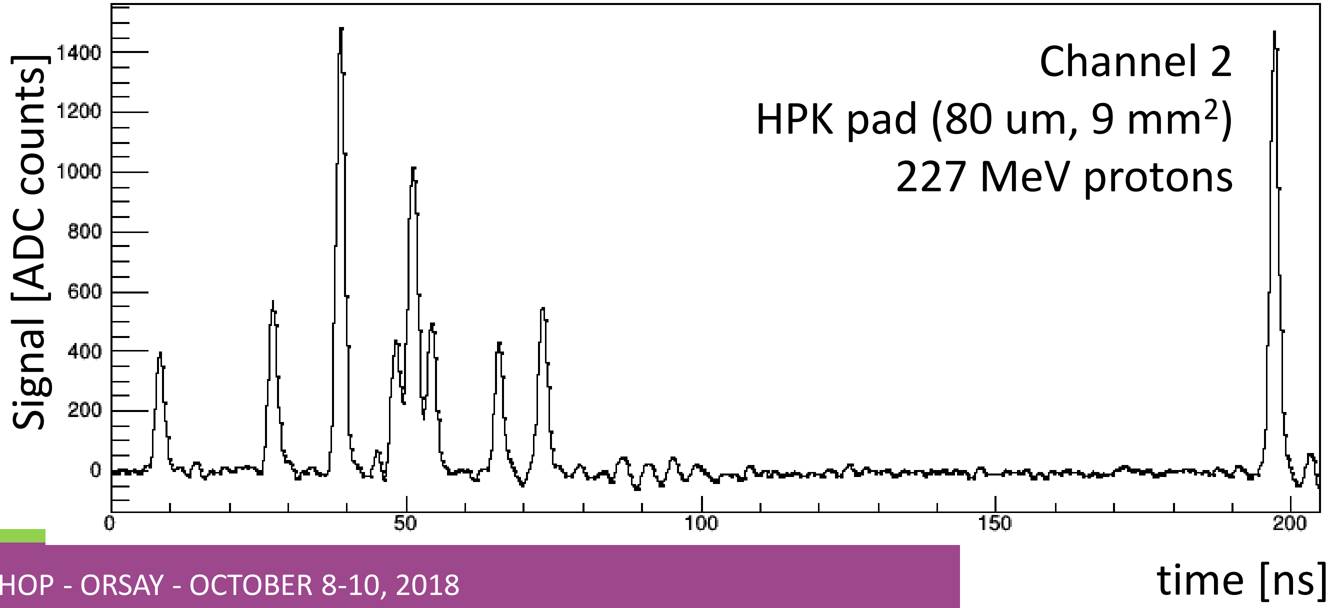


Energy measurement - coincidences

Beam energy measured from Time-of-Flight







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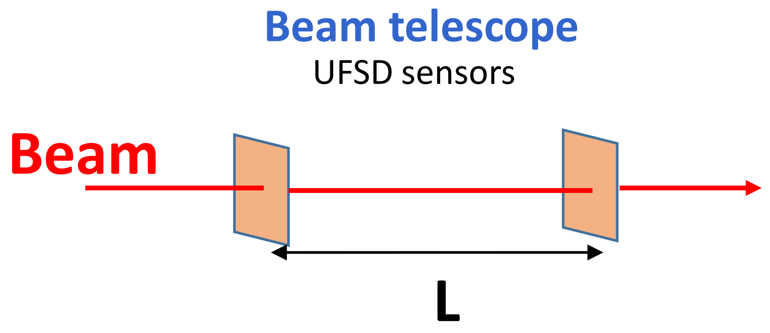
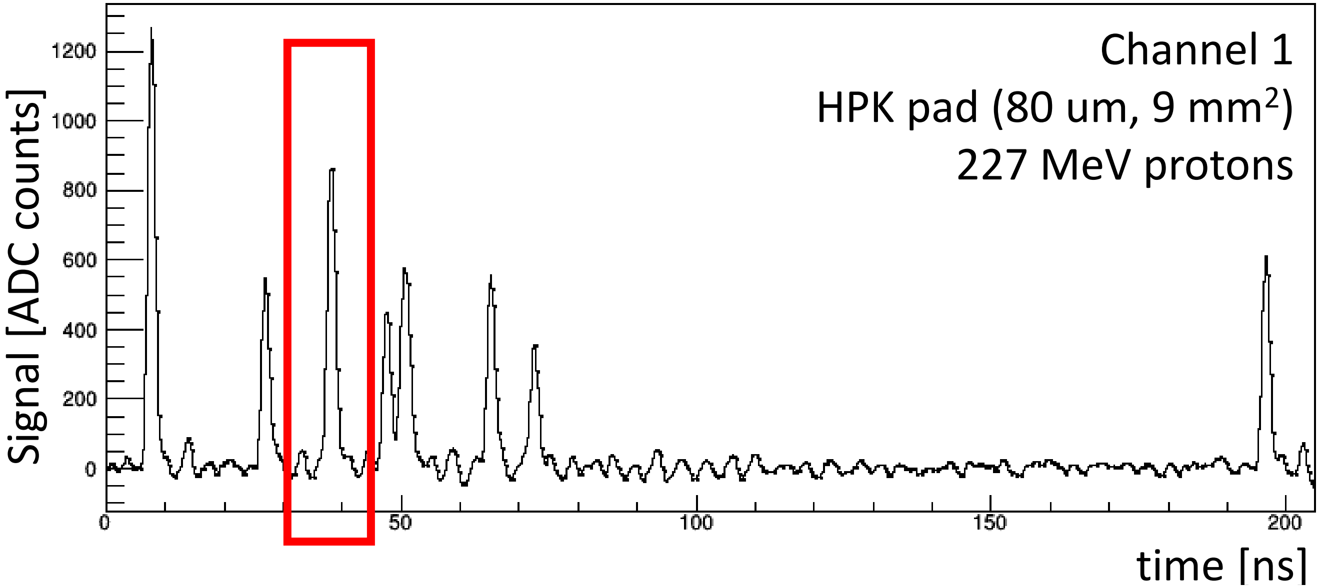
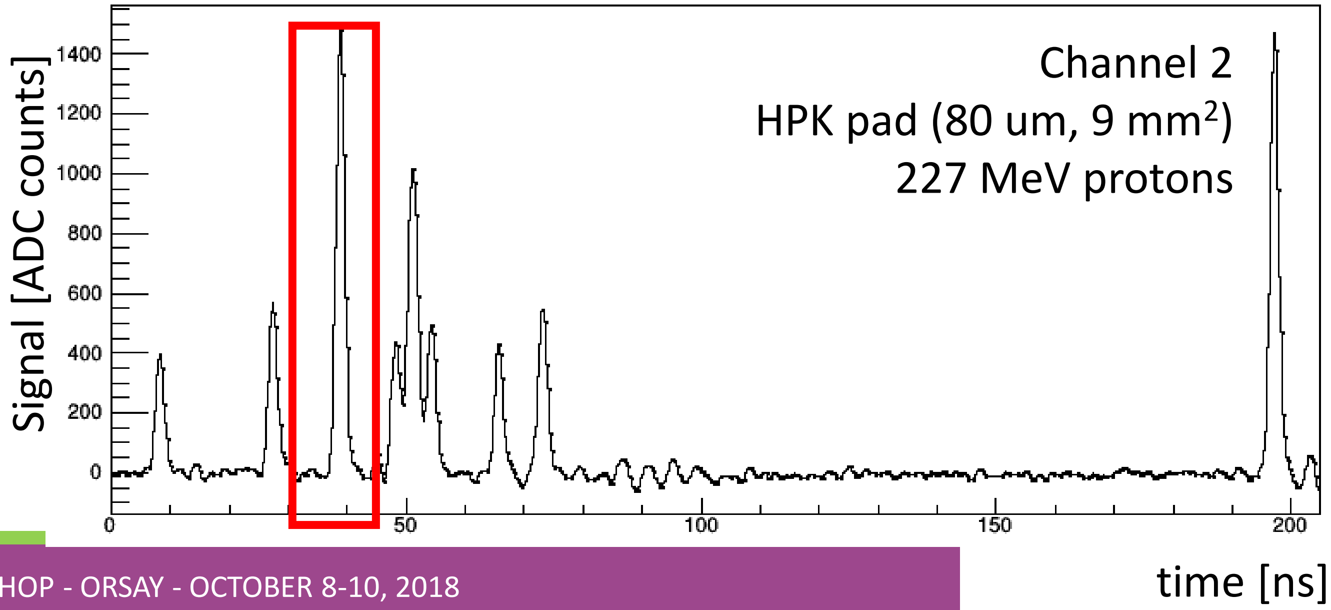


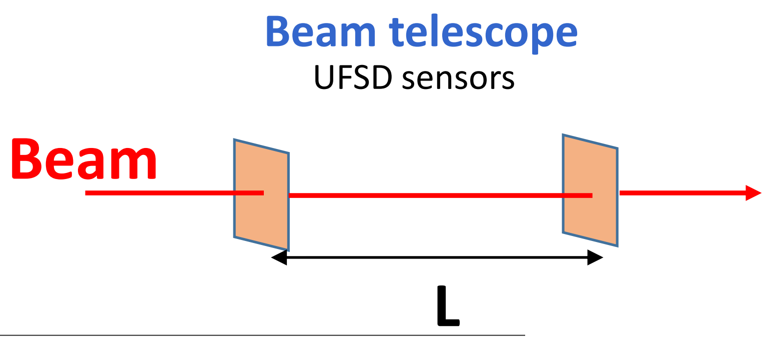


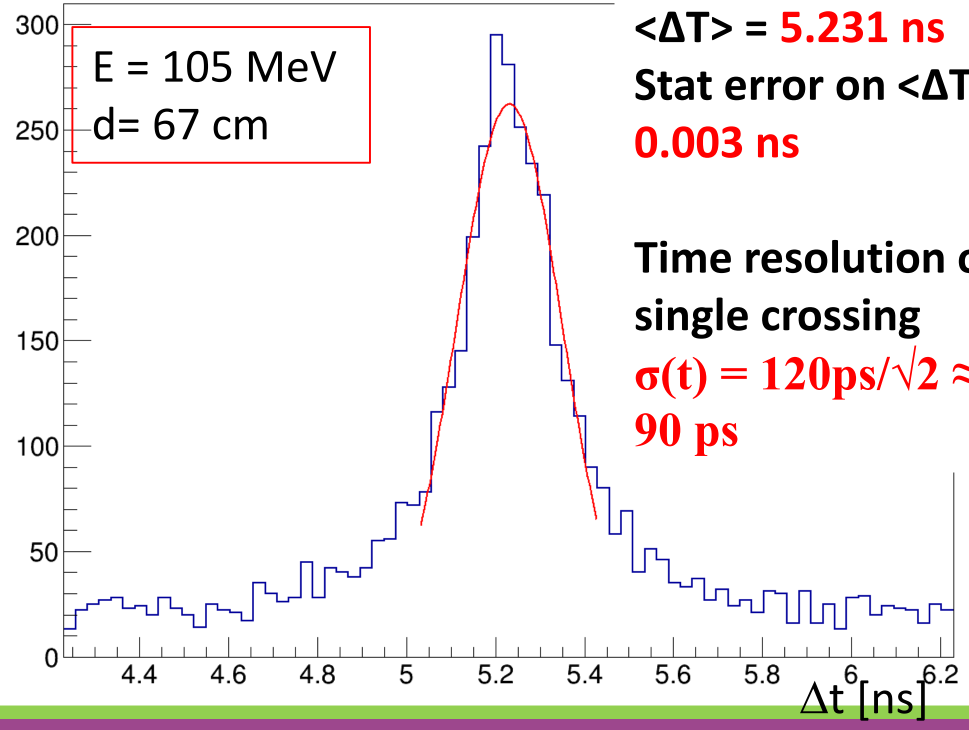


- Constant fraction discriminator algorithm applied on pulses signals

Energy measurement - coincidences

Beam energy measured from Time-of-Flight



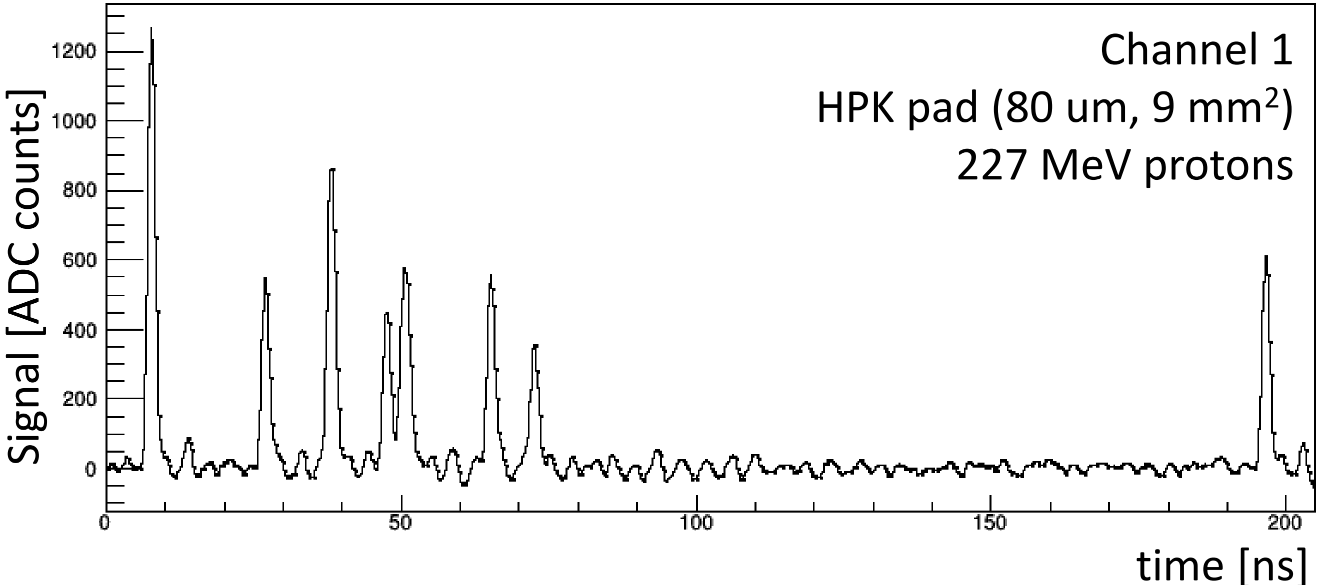


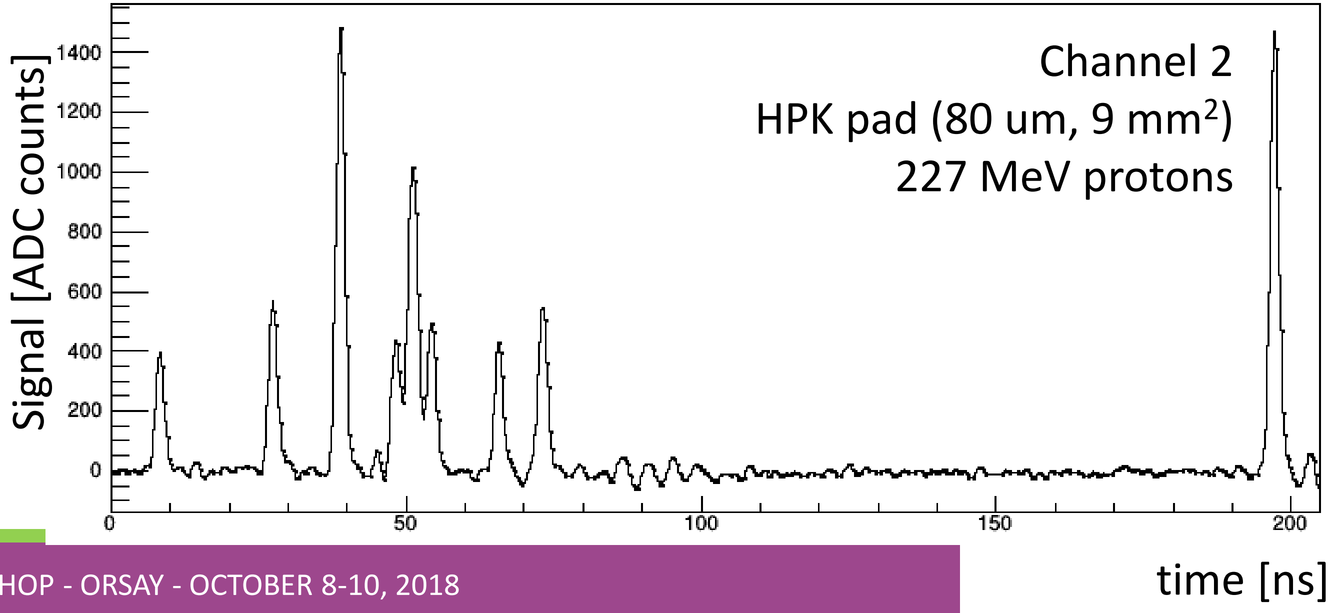
<ΔT> = 5.231 ns

Stat error on <ΔT>= 0.003 ns

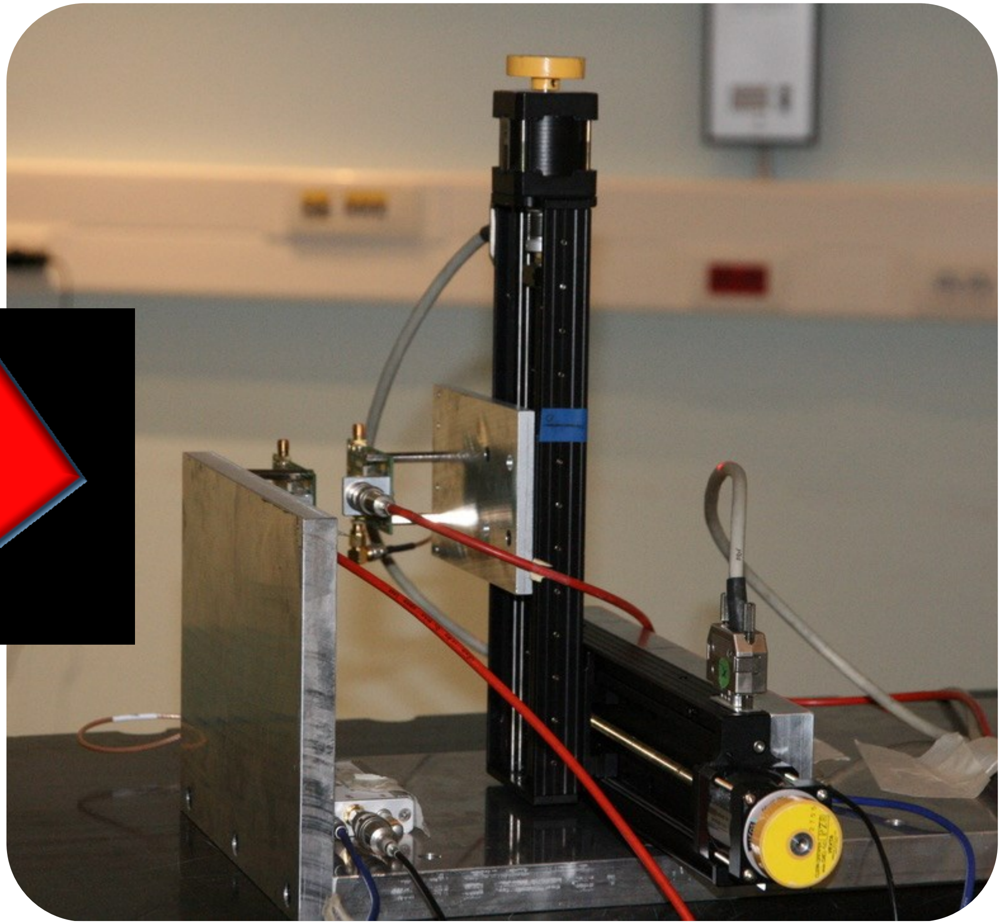
Time resolution of single crossing

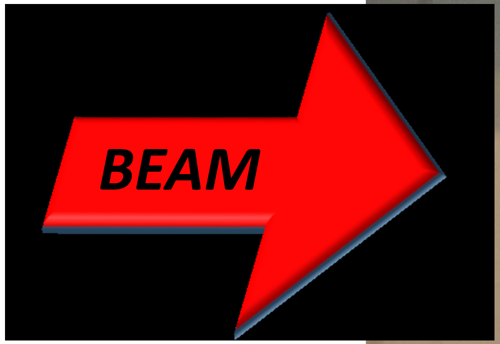
σ(t) = 120ps/√2 ≈ 90 ps





Energy measurement - test

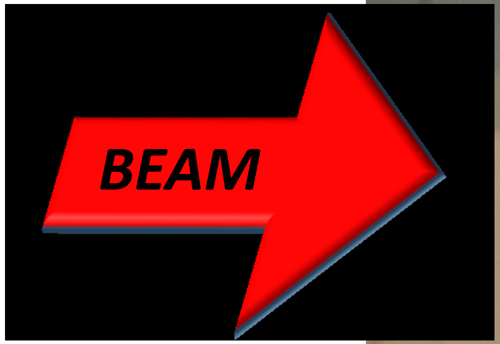


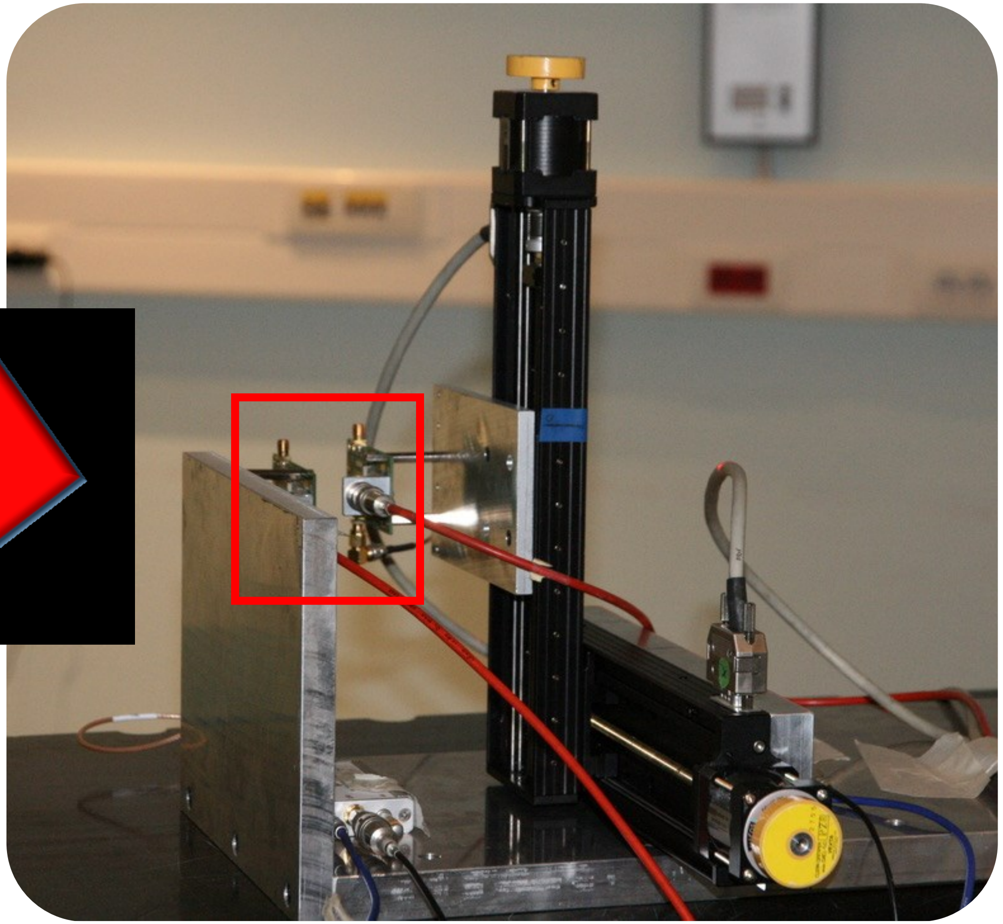


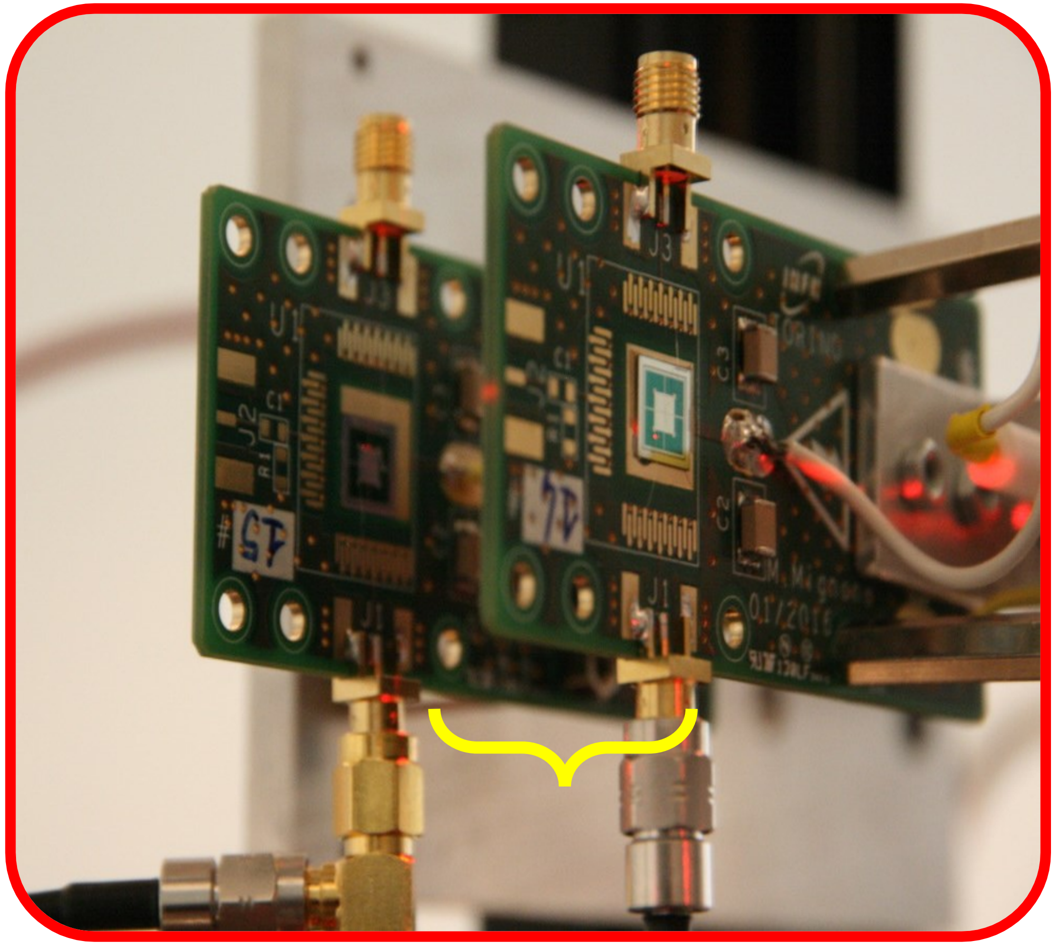
4 distances= 7, 37, 67, 97 cm

5 energies= 62.73, 80.70, 106.24, 150.99, 228.56 MeV

Energy measurement - test







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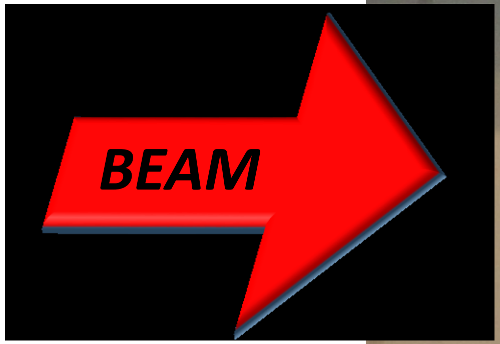
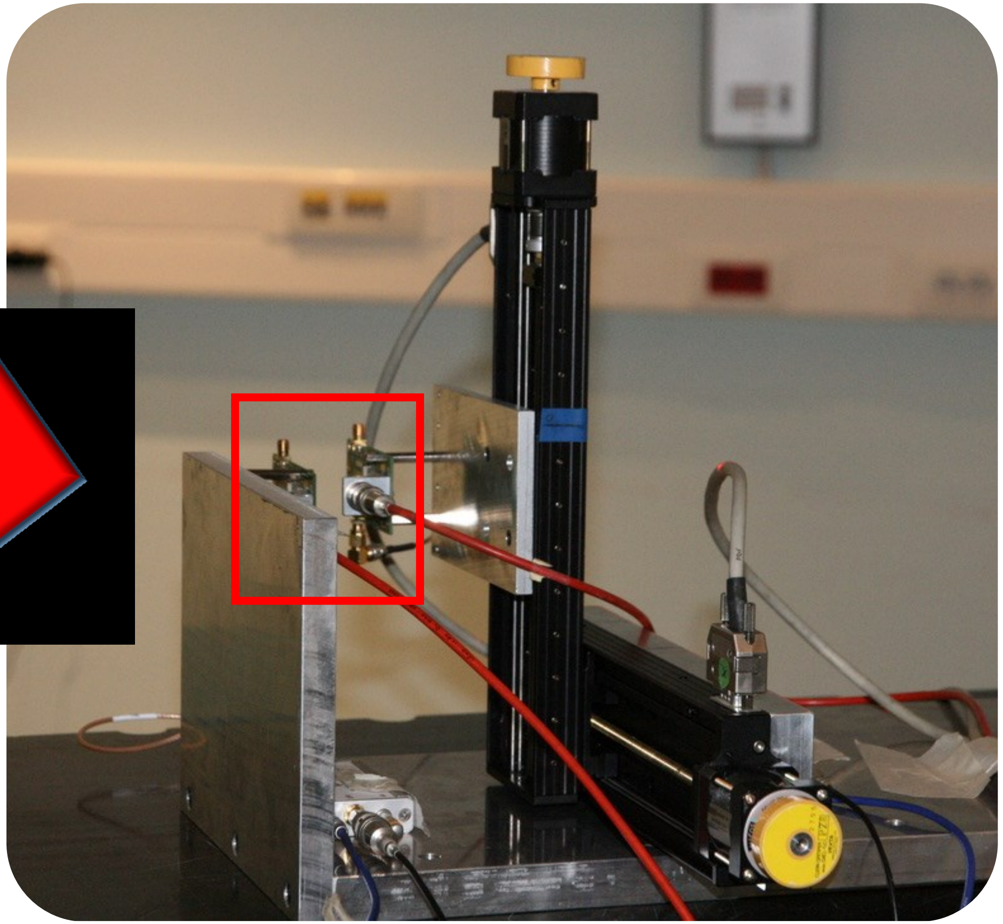
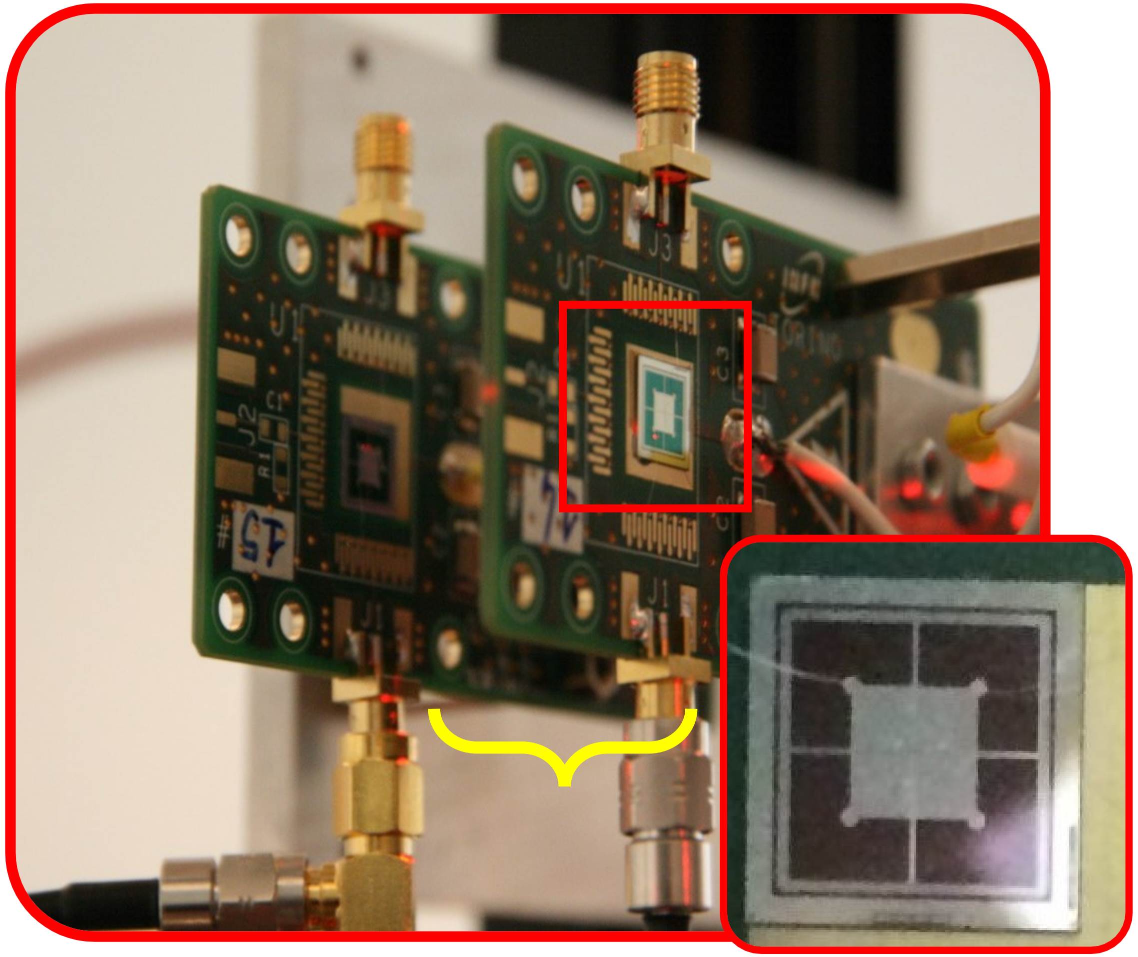




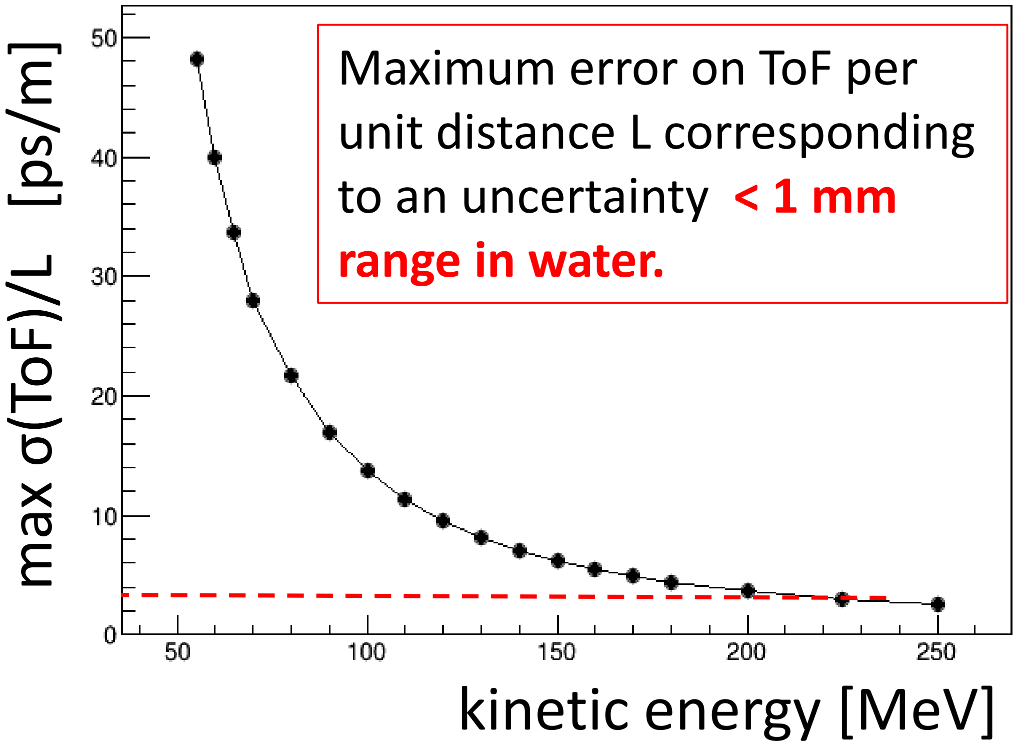


4 distances= 7, 37, 67, 97 cm

Hamamatsu 4* (3x3) mm^2 (80 µm)

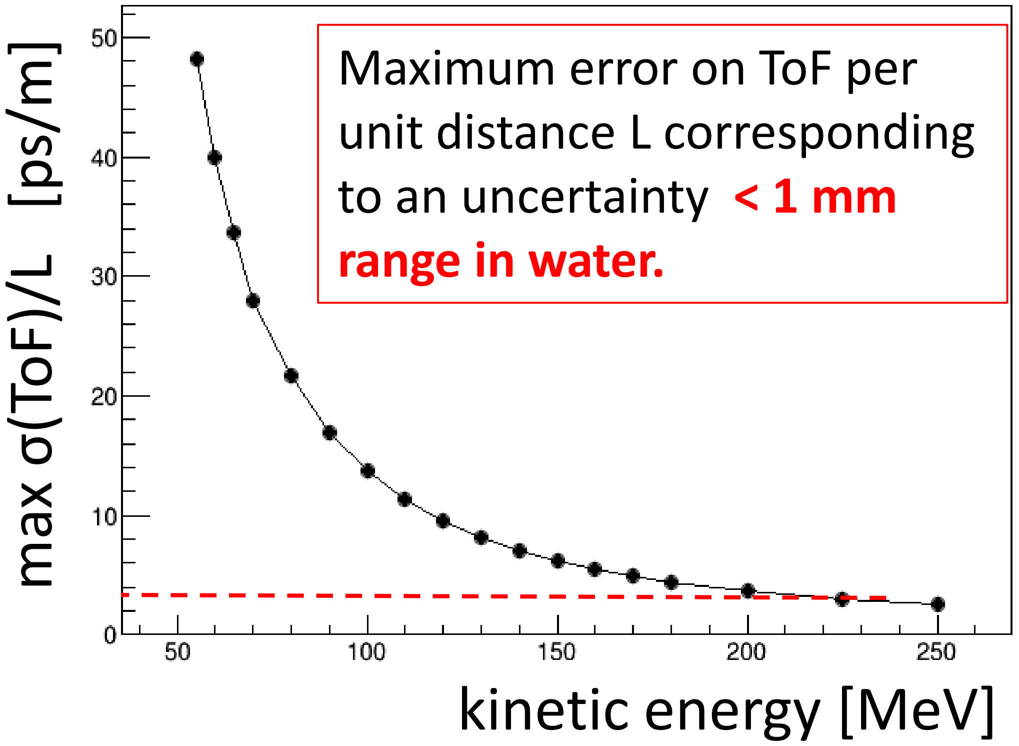
5 energies= 62.73, 80.70, 106.24, 150.99, 228.56 MeV

Energy measurement – range requirements



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

Energy measurement – range requirements

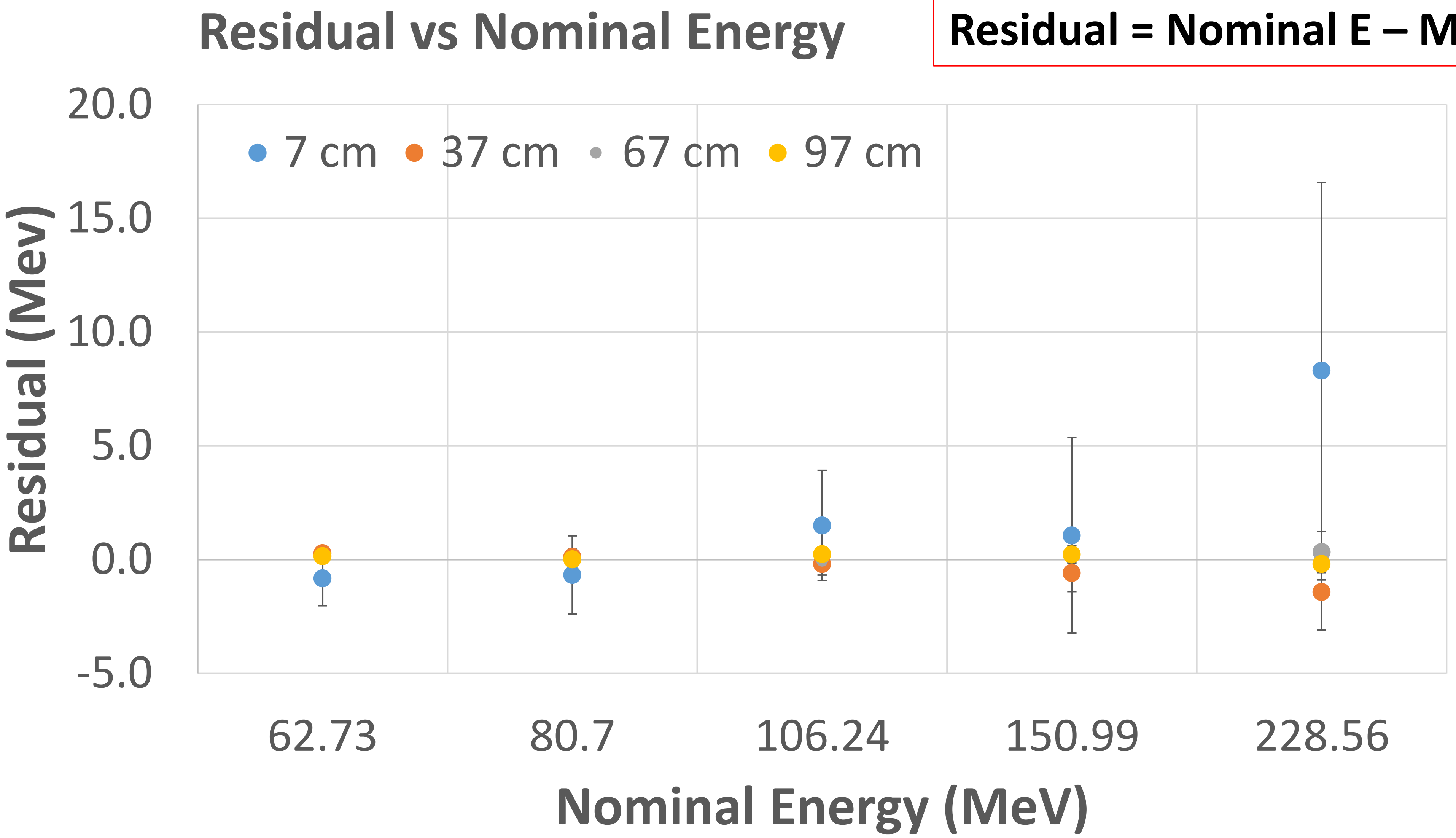


For 1m distance the **max error on TOF = 4 ps**

For 1m distance, 228 MeV, 10^{10} protons: **error on TOF = 4 ps**

Energy measurement – preliminary results

Residual = Nominal E – Measured E



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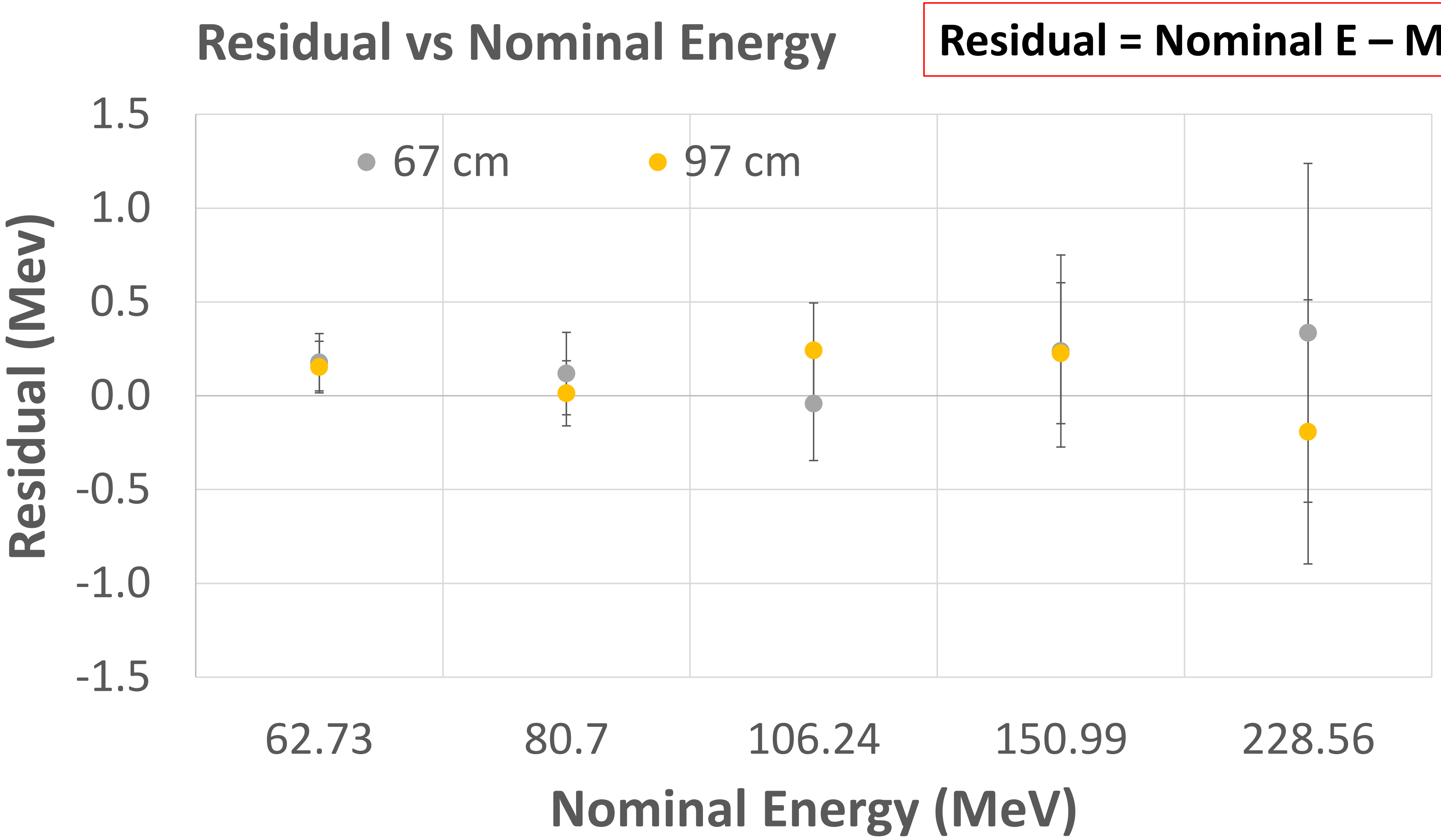
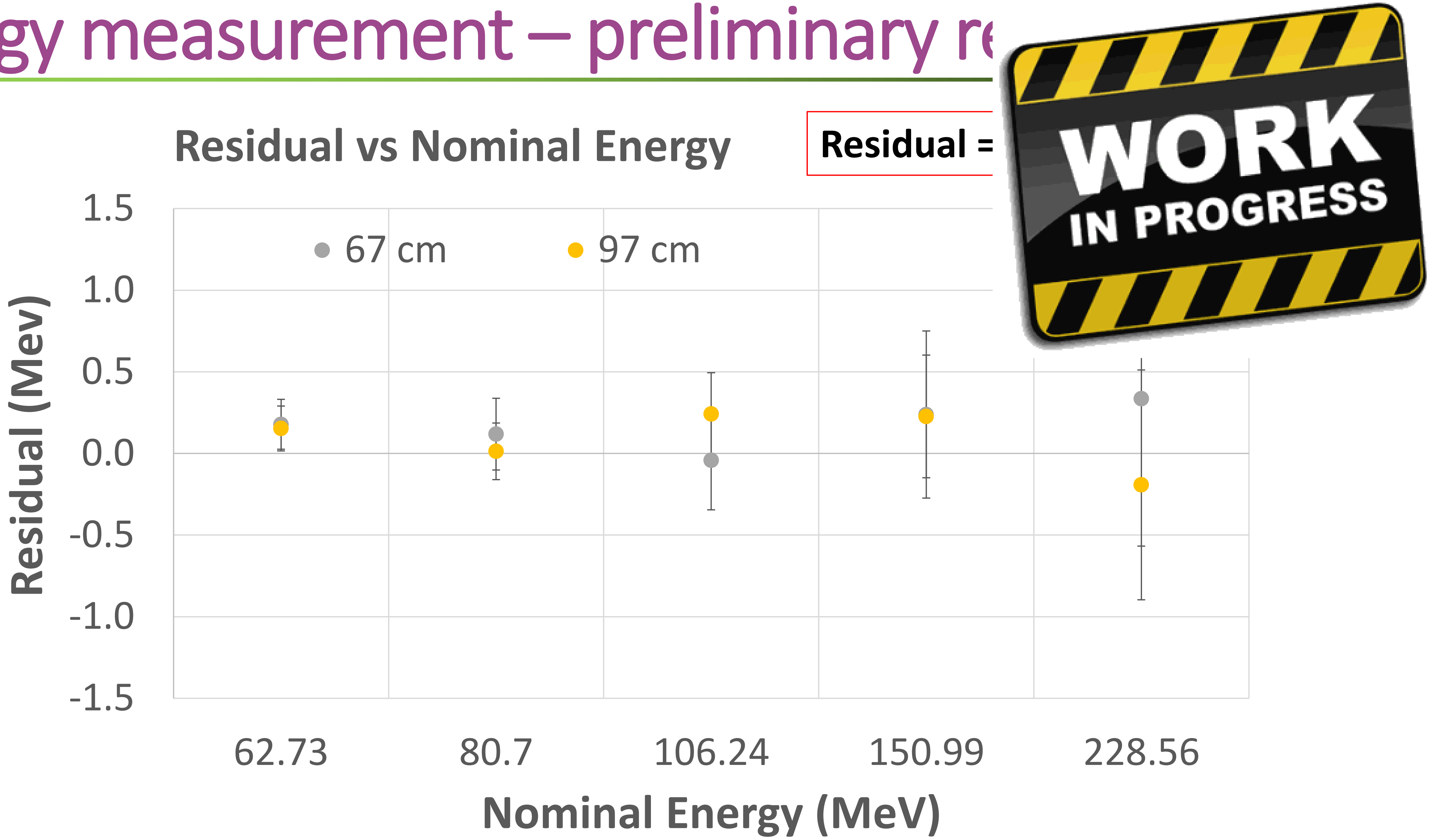


Energy measurement – preliminary re

Residual =



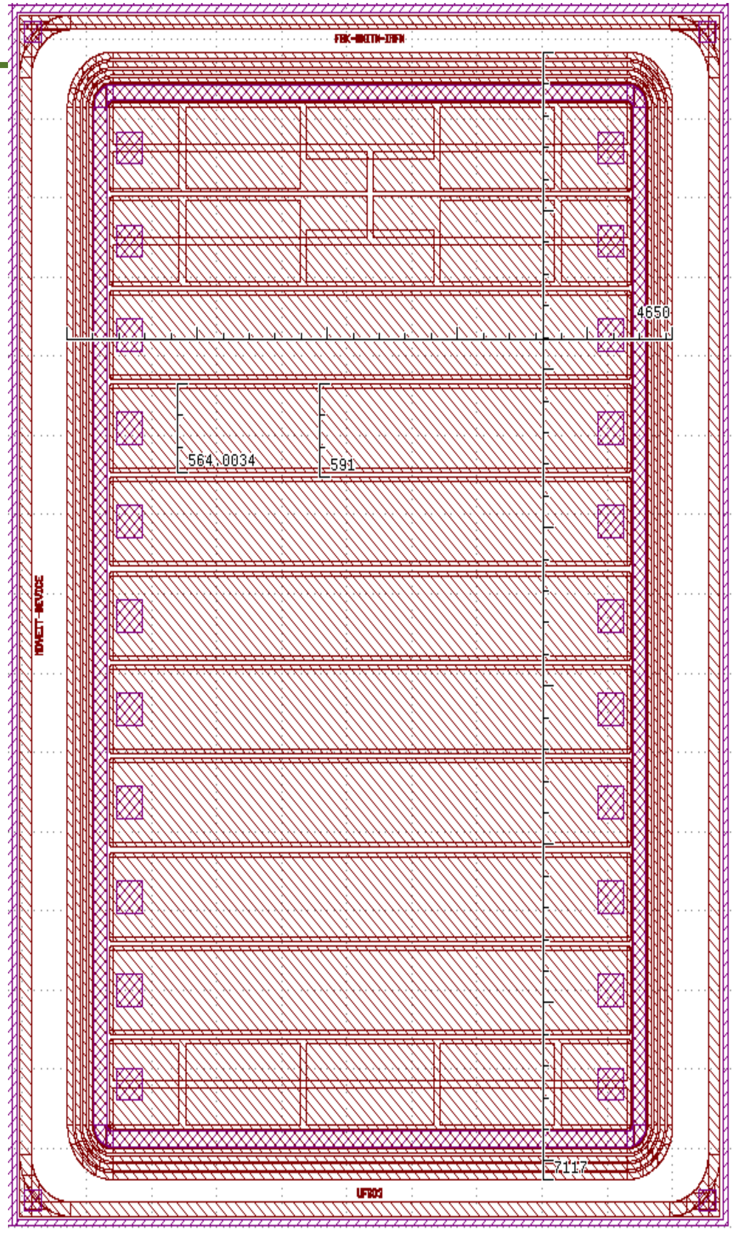
Energy measurement – outlook

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;

50 µm active thickness + 500 µm handling wafer.

Thinning of sensors;
Study and design of the read-out board;
Acquisition with DIGITIZER.



Conclusions & Outlook

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

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

2019

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

- ➢ Fast collection time + Large S/N ratio

➡ **directly count number of beam ions**

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- ✓ Prototype for real-time energy measurement ($4x4\ mm^2$ area).

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  ⇨ **directly count number of beam ions**

- Excellent time resolution
  ⇨ **real-time measurement of the beam energy**

Conclusions & Outlook

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⇩

Radiobiological experiments

- Fast collection time + Large S/N ratio
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⇓

Radiobiological experiments

- Fast collection time + Large S/N ratio
  - ⇒ **directly count number of beam ions**
  - ⇒ *OPEN ISSUE: pile-up inefficiency, radiation hardness*
- Excellent time resolution
  - ⇒ **real-time measurement of the beam energy**
  - ⇒ *OPEN ISSUE: sistematic errors, radiation hardness*

Conclusions & Outlook

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

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↓

Radiobiological experiments

↓

Clinics!

Acknowledgements

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) for the beam time accorded.

Thank you!

anna.vignati@to.infn.it

Spares

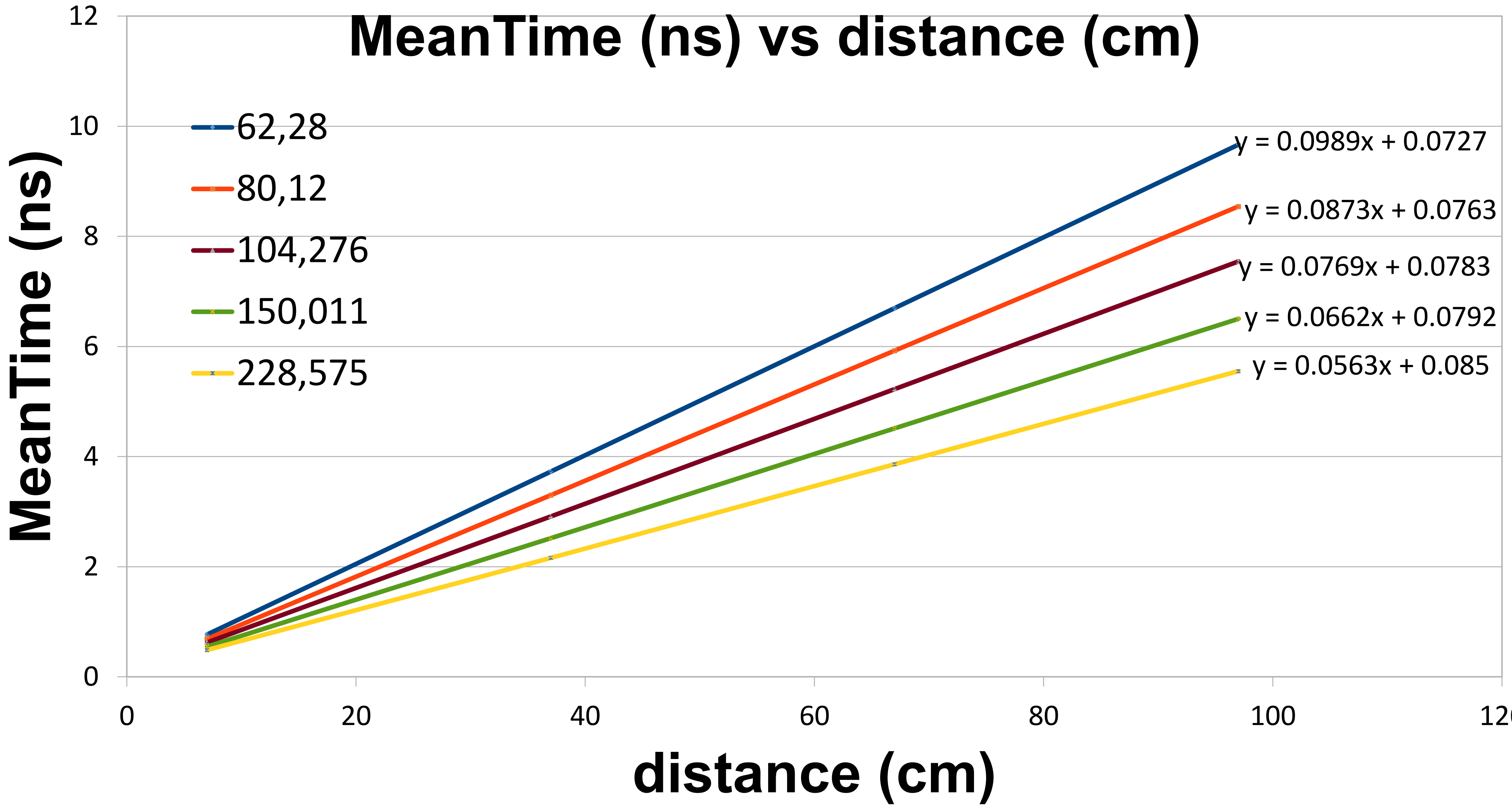
Energy measurement – Global Fit

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

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

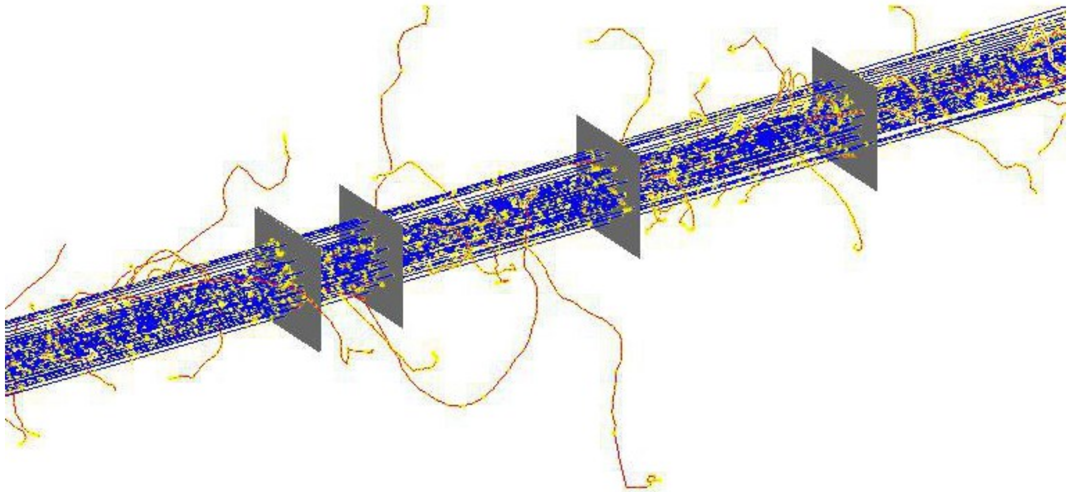
Where
i = 1 -> 5 (E_i = energies of the beams)
j = 1, 2, 3, 4 (d_j = distances between the two detectors).

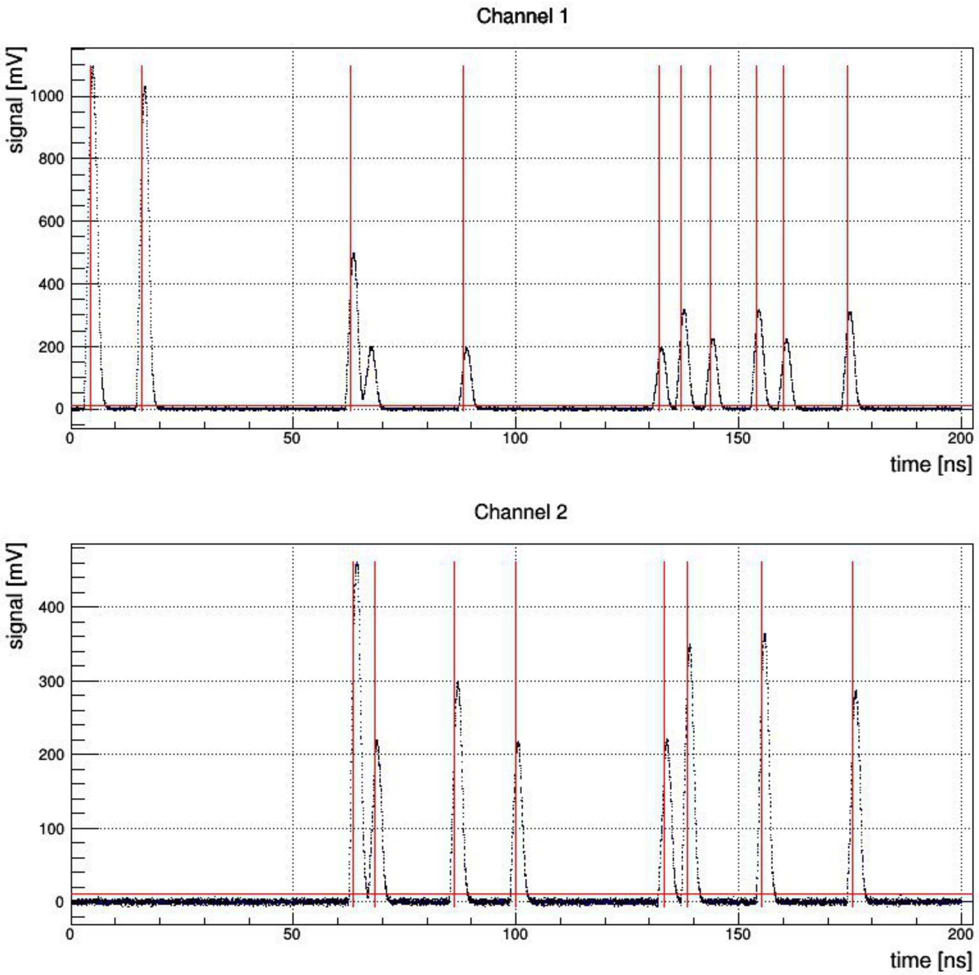
Preliminary results (80 µm) – Δt vs distance



Simulation

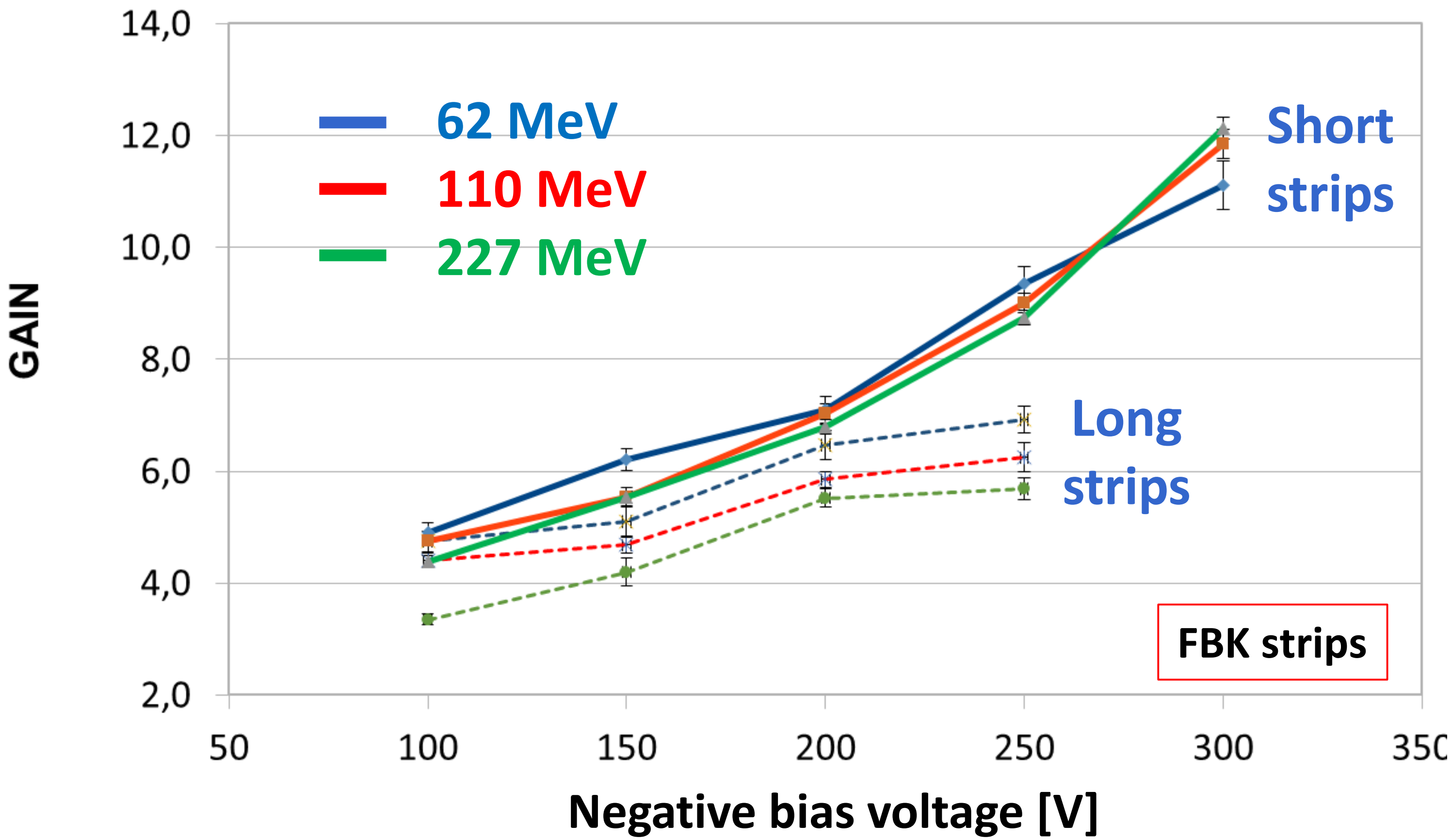
GEANT4 simulation of material effects (energy loss and multiple scattering)
WEIGHTFIELD2 simulation of the UFSD response.





Gain of strips detectors

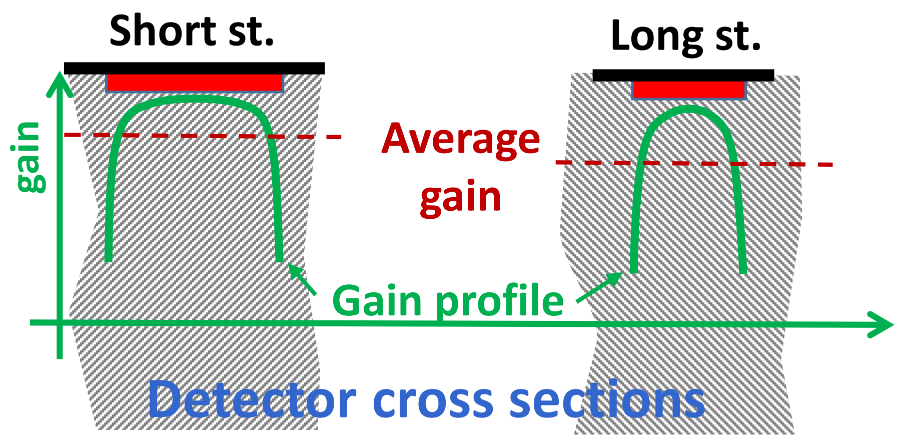
$$\text{Gain}(V) = \frac{\text{MPV}_{\text{gain}}(V)}{\text{MPV}_{\text{no gain}}(V)}$$



- 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)

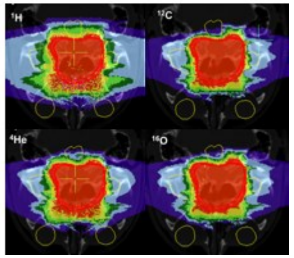
- RBE (eg. LEMx, MKM)
- OER
- DEF

Beamline specifics

Patient Imaging data

Including intratumor heterogeneity

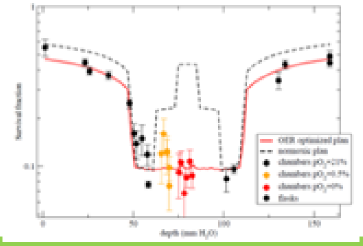
Effective Dose profile



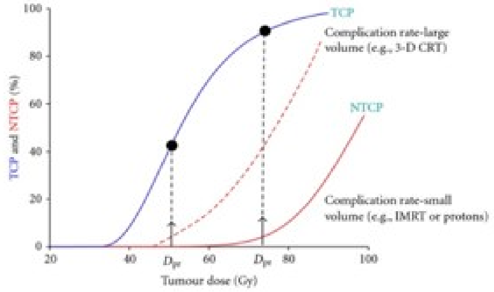
Verification

advanced beam monitoring

"Bio"-dosimetry



Clinical Impact



TCP/NTCP

Slide from E. Scifoni

Motivation for the doping strategy of UFSD2 production

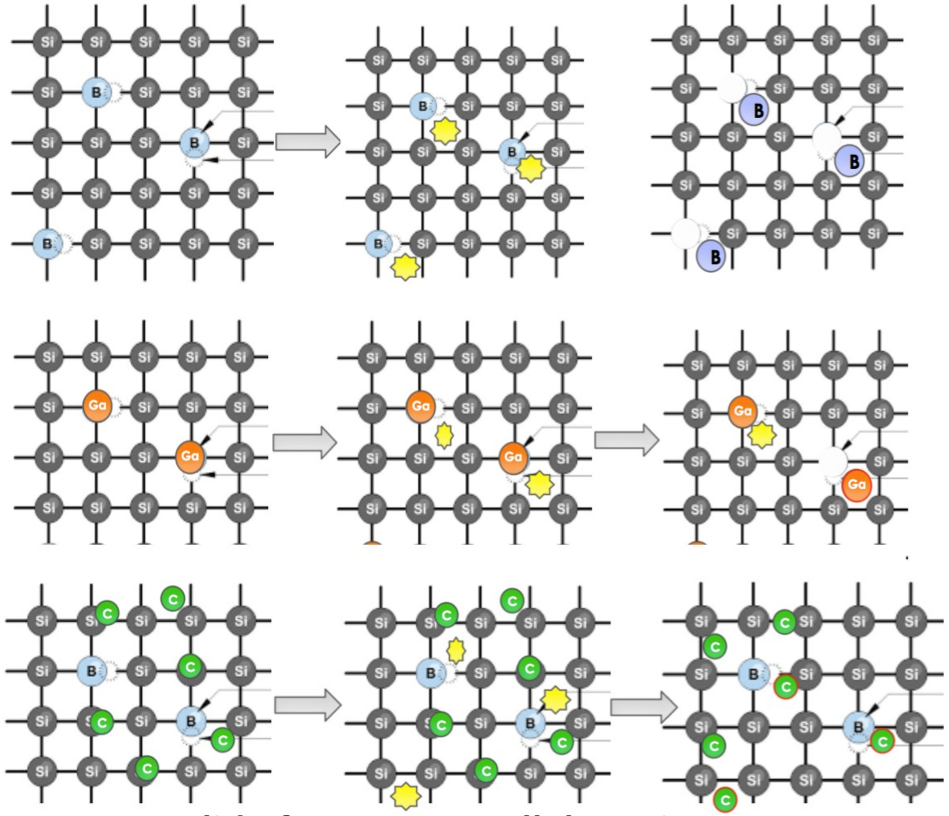
Main effect of the irradiation is the inactivation of the dopant in the gain layer

- 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



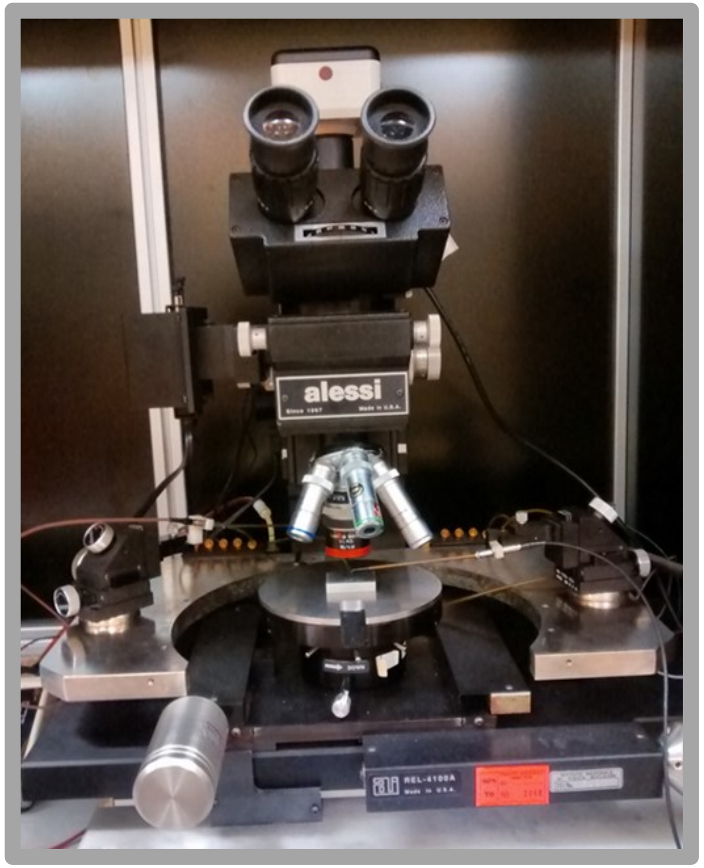
Slide from RD50 Collaboration

UFSD2 production @ FBK:

- 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

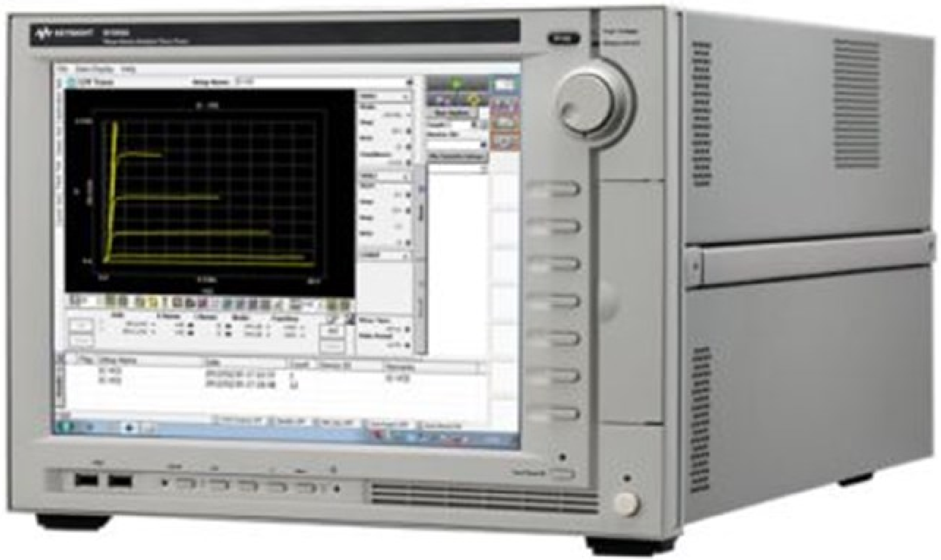
MANUAL PROBE STATION ALESSI



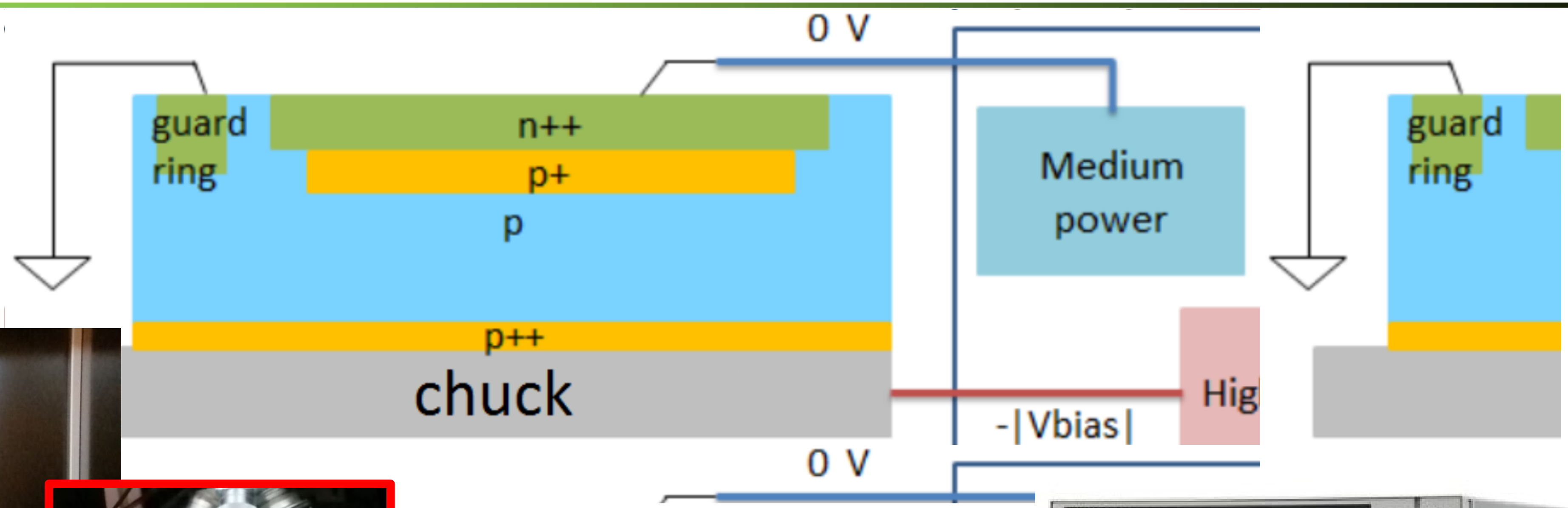
CUSTOM PROBE CARD FOR SIMULATANEOUS CONTACT TO ALLSTRIPS + GUARD RING

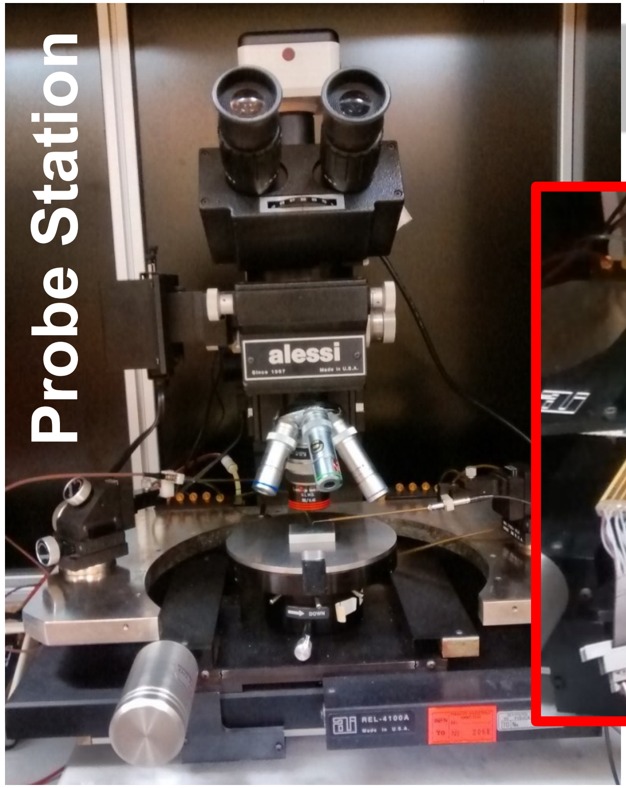
POWER DEVICE ANALYZER/CURVE TRACKER

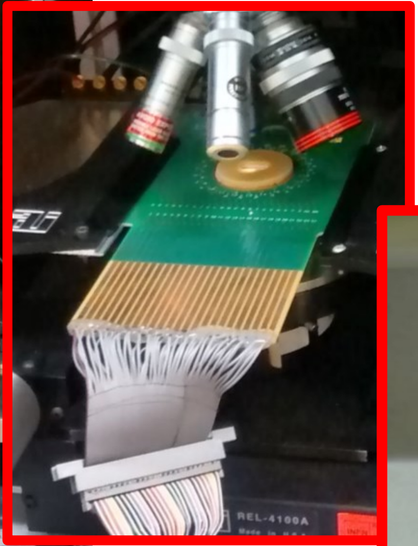
MODEL : KEYSIGHT B1505A



Strip Characterization

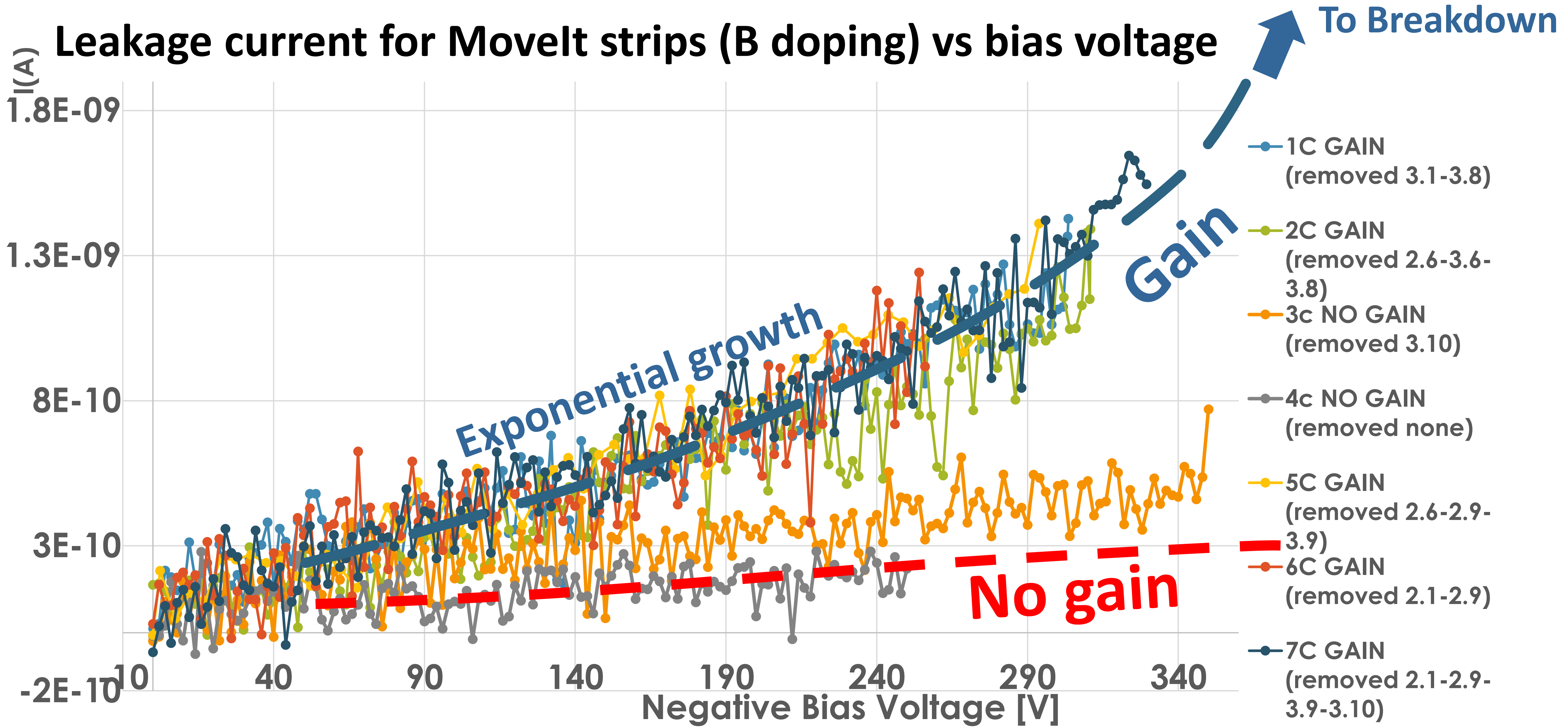






Probe Card

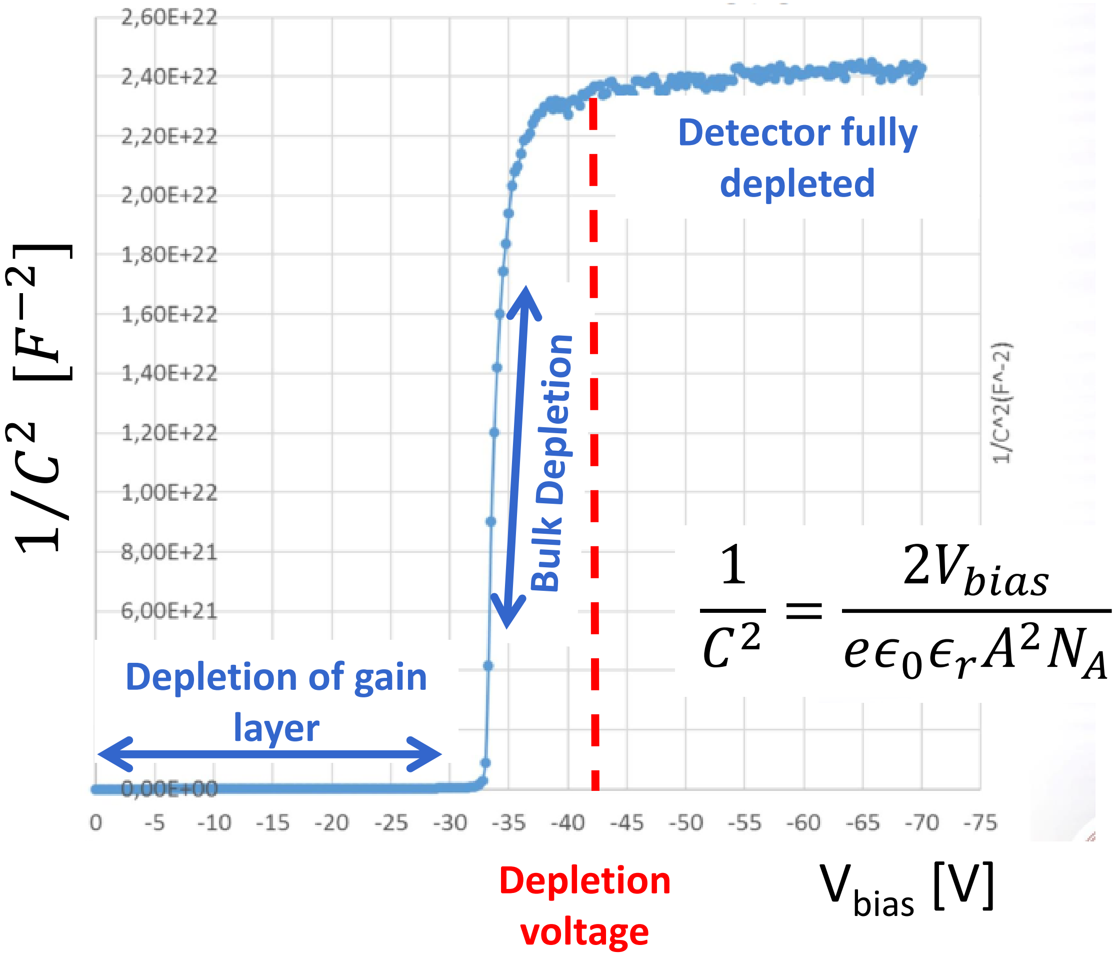
IV curves



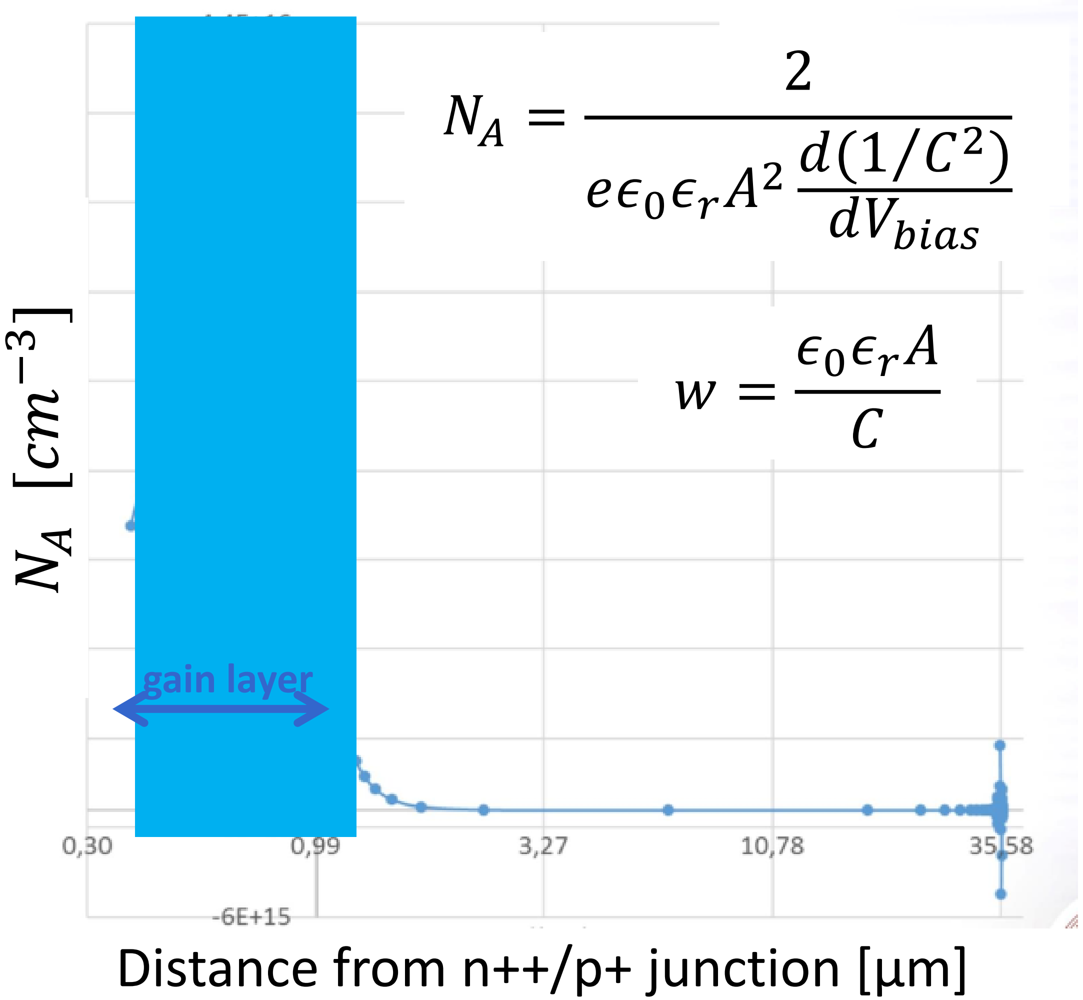
Leakage current for MoveIt strips (B doping) vs bias voltage
To Breakdown
I(A)
1.8E-09
1.3E-09
8E-10
3E-10
-2E-10
10
40
90
140
190
240
290
340
Negative Bias Voltage [V]
Exponential growth
Gain
No gain
1C GAIN (removed 3.1-3.8)
2C GAIN (removed 2.6-3.6-3.8)
3c NO GAIN (removed 3.10)
4c NO GAIN (removed none)
5C GAIN (removed 2.6-2.9-3.9)
6C GAIN (removed 2.1-2.9)
7C GAIN (removed 2.1-2.9-3.9-3.10)

CV curves

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



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



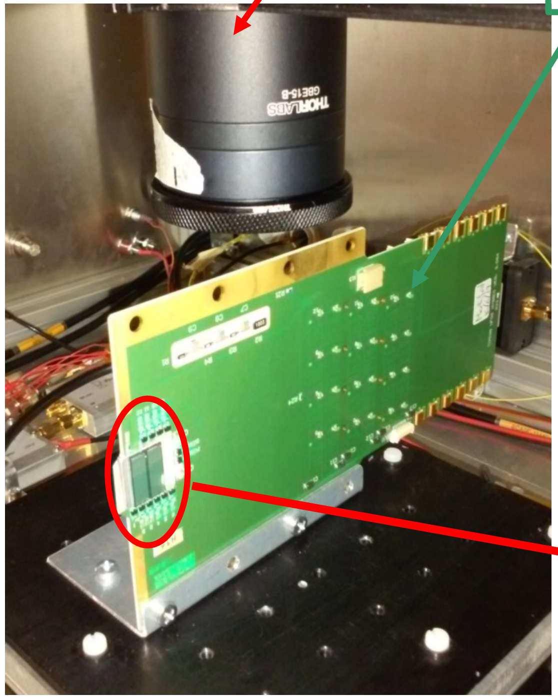
$$N_A = \frac{2}{e\epsilon_0\epsilon_r A^2 \frac{d(1/C^2)}{dV_{bias}}}$$

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

Strip characterization with laser scan

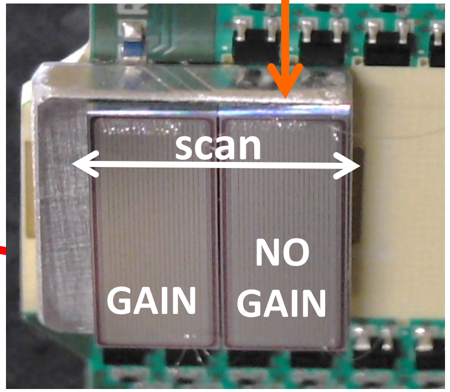
Picosecond Pulsed IR laser:
λ = 1060 nm, Spot size ~ 20 µm

Multichannel Amplifier/Shaper board (CMS CT-PPS)



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

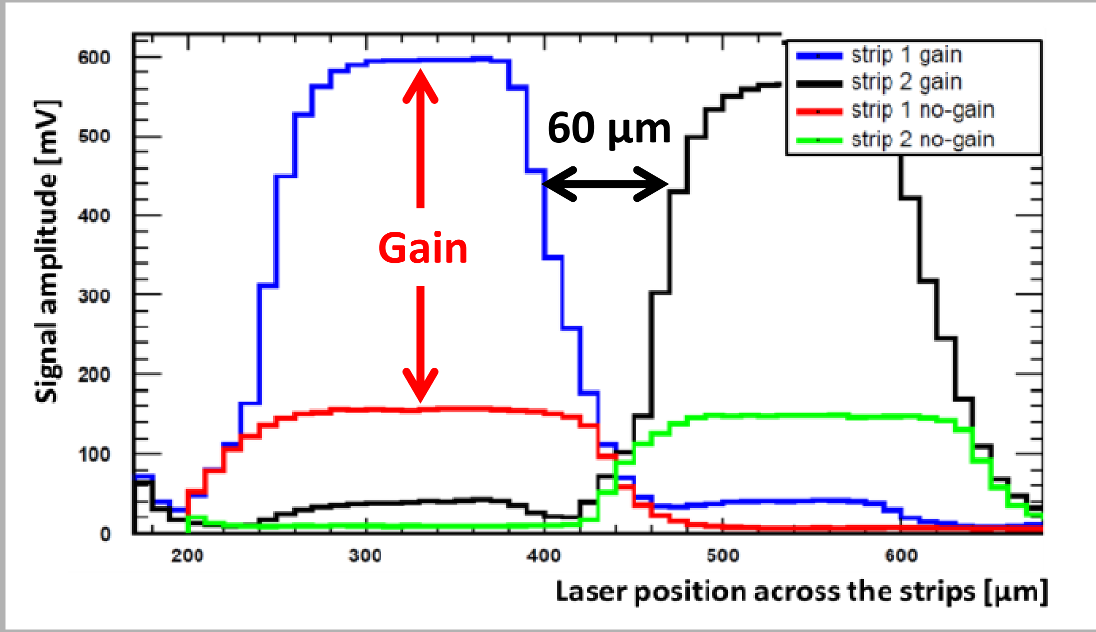
Laser beam



Short strips of (B doped)

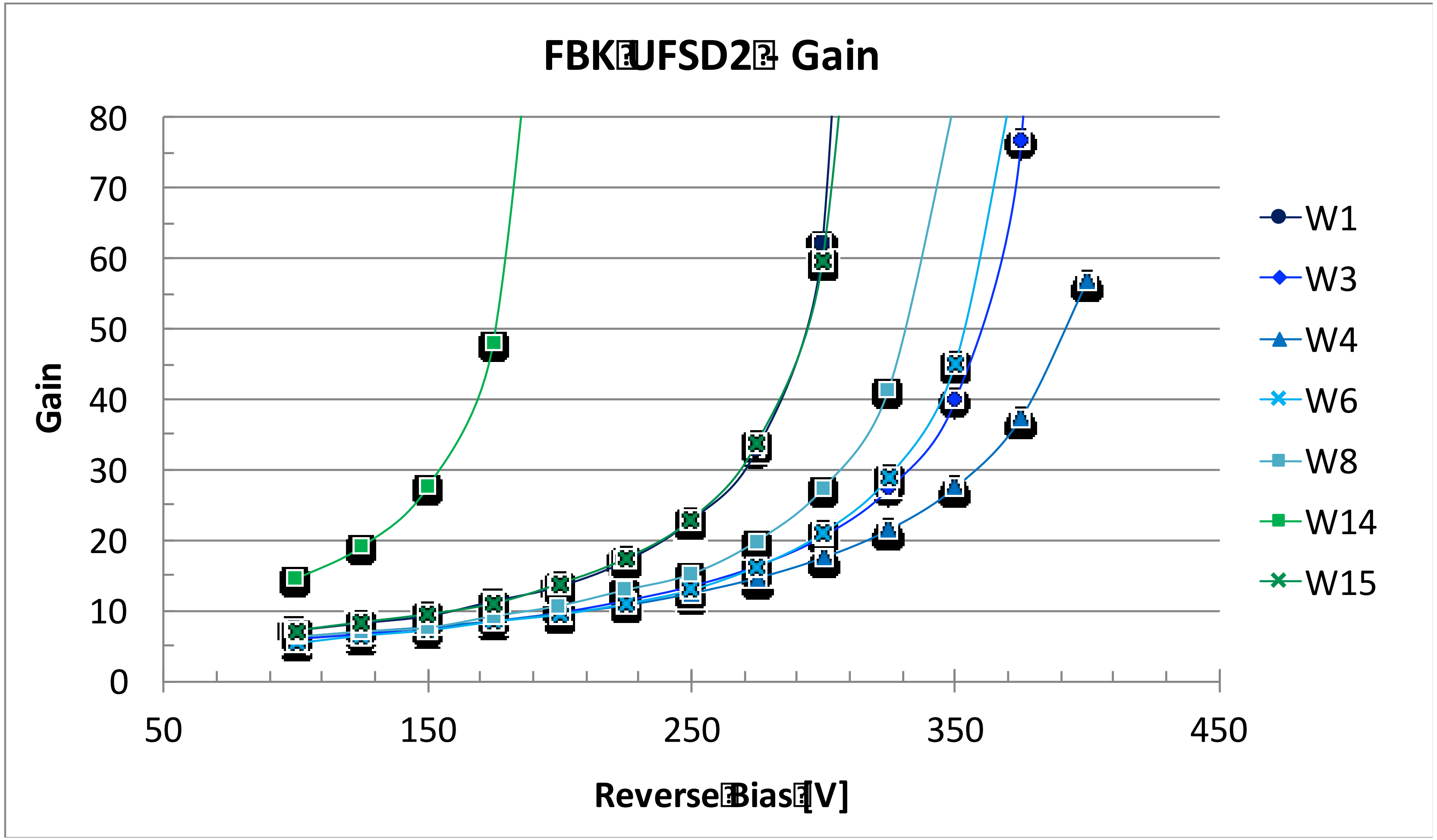
Results

Signal amplitude scan between adjacent strips

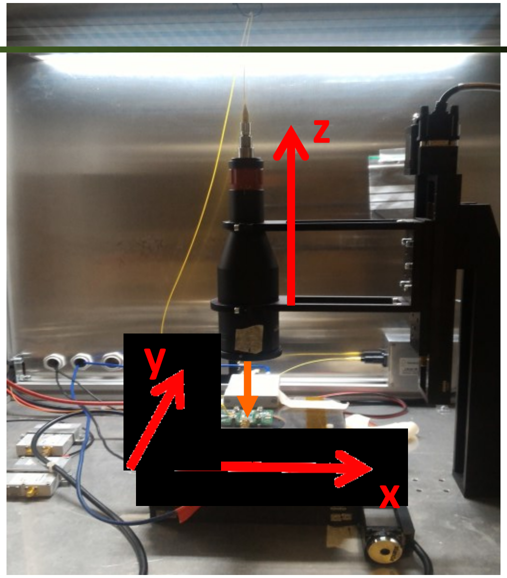


- **Gain** ≈ 4 at V_{bias}= -230 V
- **Dead area** ~ 60 µm
  - expected by sensor layout and by the production technology, in agreement with TCAD simulations
  - **possibly reduced in next UFSD production**

Gain Measurement with PS laser



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



TCT Setup from Particulars

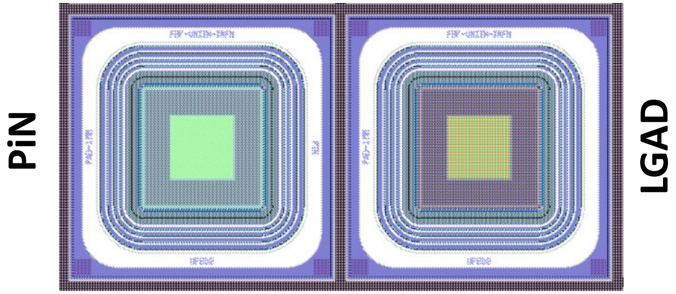
Pico-second IR laser at 1064 nm

Laser spot diameter ~ 50 µm

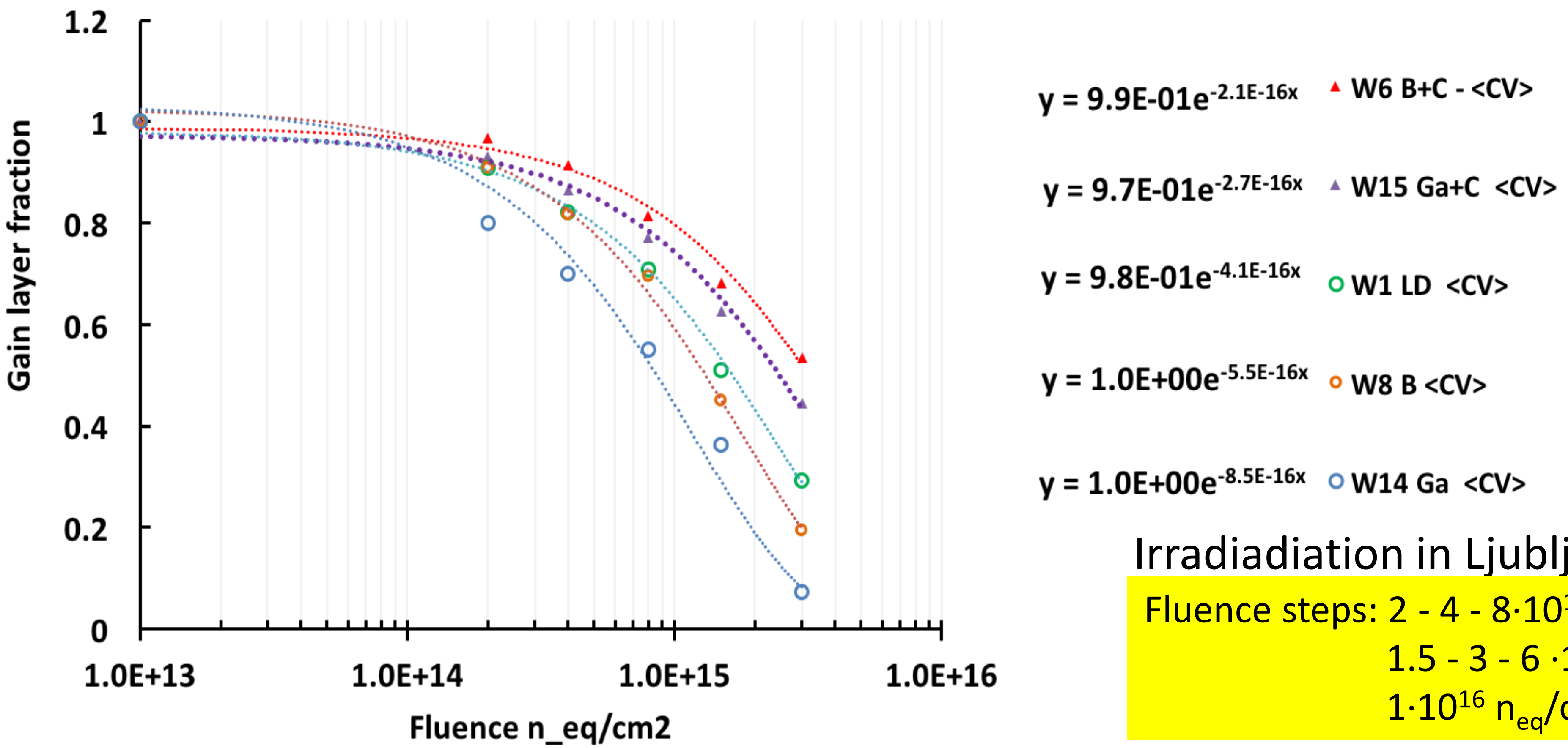
Cividec Broadband Amplifier (40dB)

Oscilloscope Lecroy 640Zi

Room temperature



Irradiation with neutrons

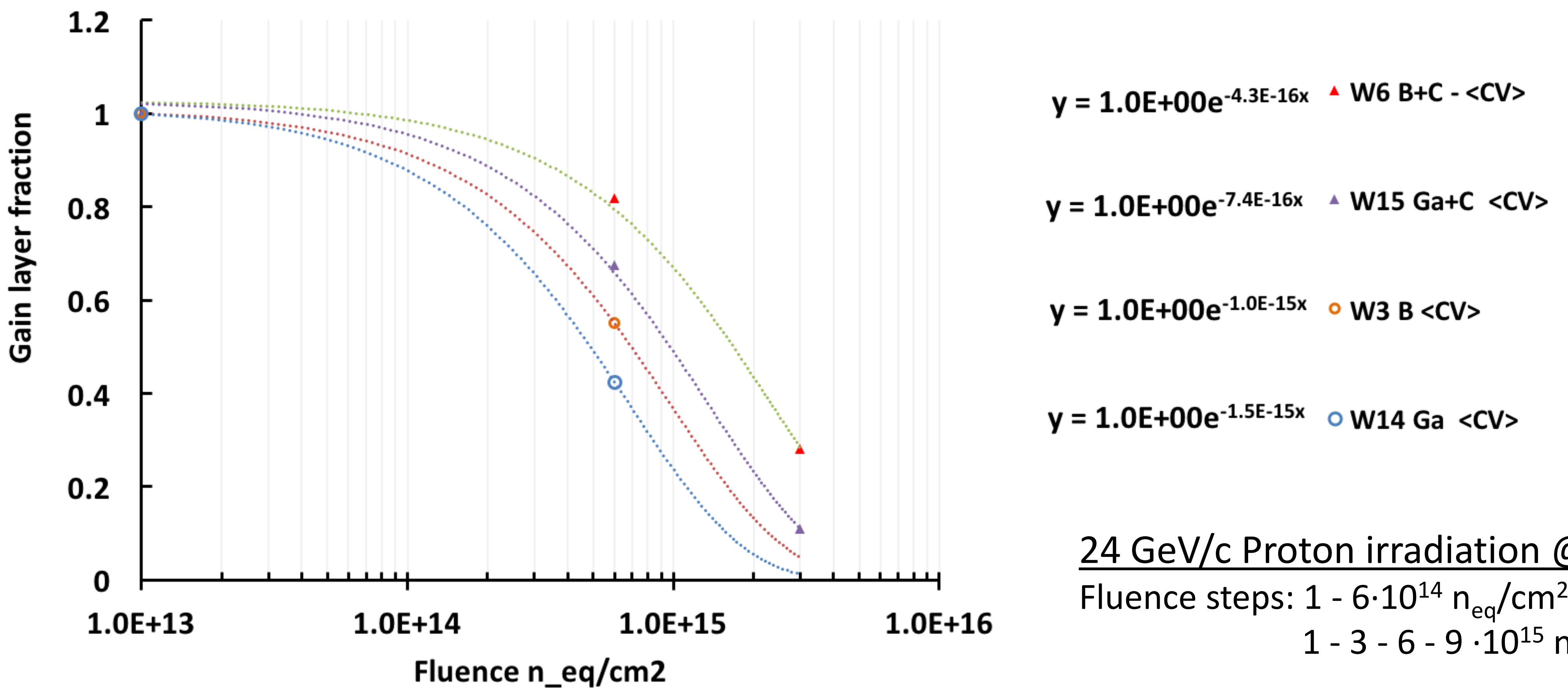


Irradiadiation in Ljubljana

Fluence steps: 2 - 4 - 8·10^{14} n_{eq}/cm^2
1.5 - 3 - 6 ·10^{15} n_{eq}/cm^2
1·10^{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



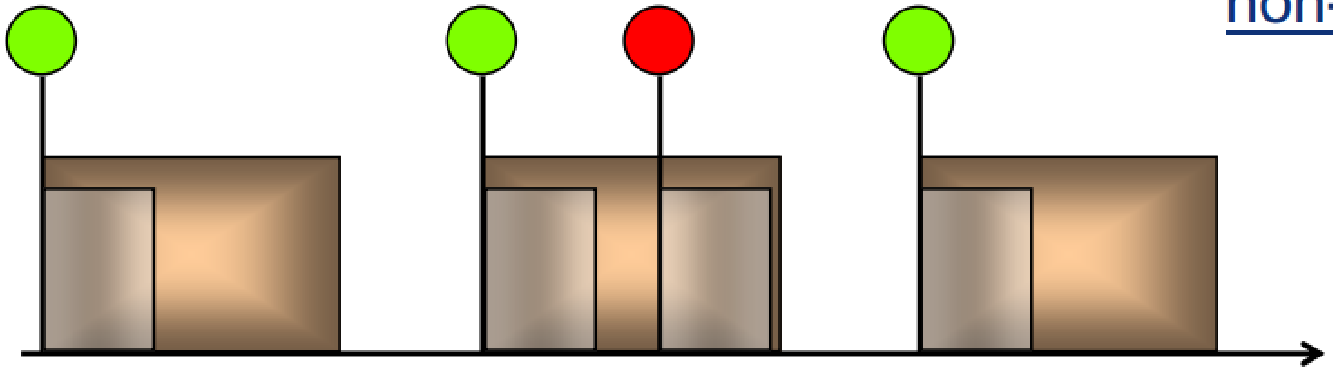
24 GeV/c Proton irradiation @ CERN PS

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

1 - 3 - 6 - 9 ·10^{15} n/cm^2

Pileup models

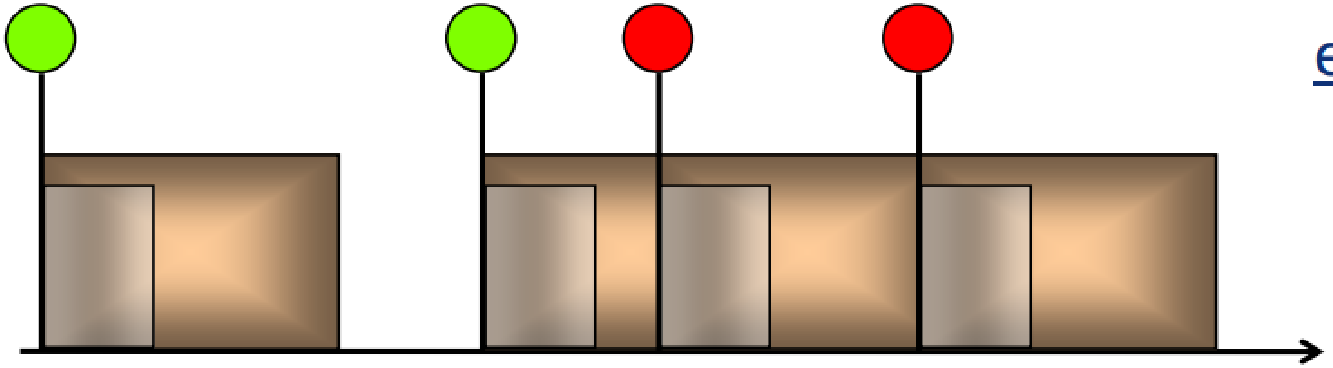
Non- paralyzable model



non-extending dead time

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

Paralyzable model



extending dead time

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