

THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

Waveform Pattern Alignment for Precision Beam Diagnostics: Energy and Energy-Spread Calibration

W. Parol & A. Kozela & A. Kulessa & B. Sowicki

Division of Nuclear Physics and Strong Interactions

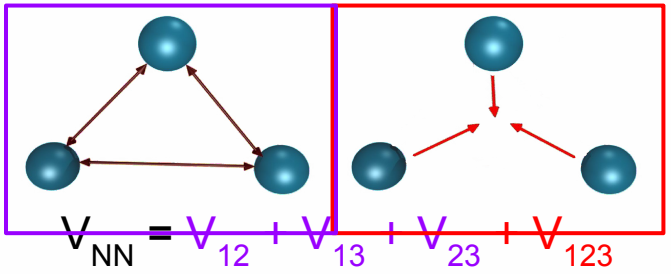
SPAS 2026

Kraków

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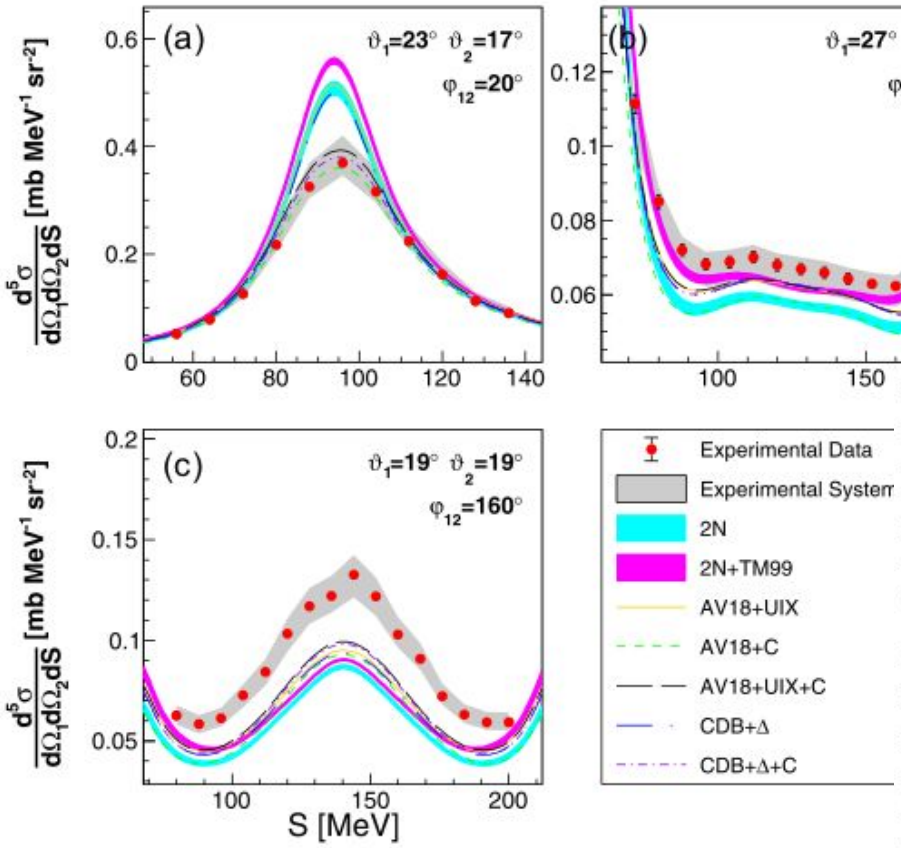
Motivation

p+d -> p + p + n
@ 70-200 MeV/A



+ Coulomb force
A. Deltuva Phys. Rev. C80 064002 (2009)

+ relativistic effects
H. Witała Phys. Rev. C83, 044001 (2011)



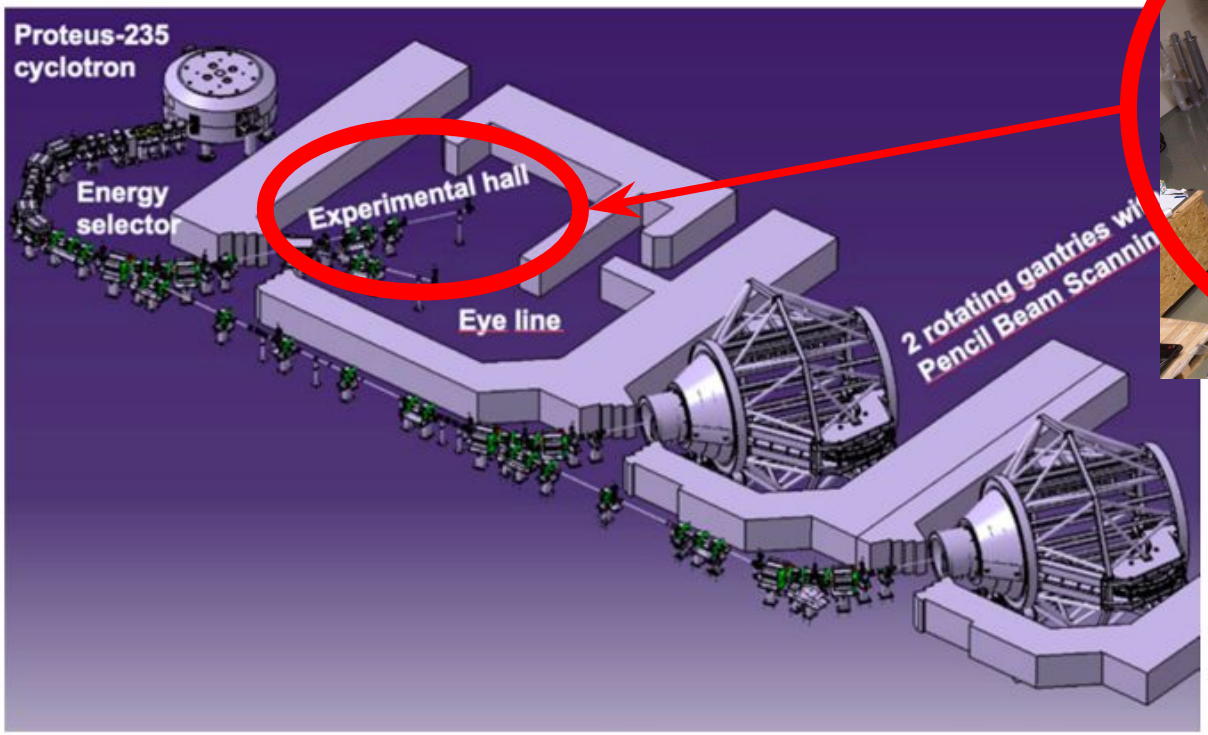
$\delta\sigma < 1\%$

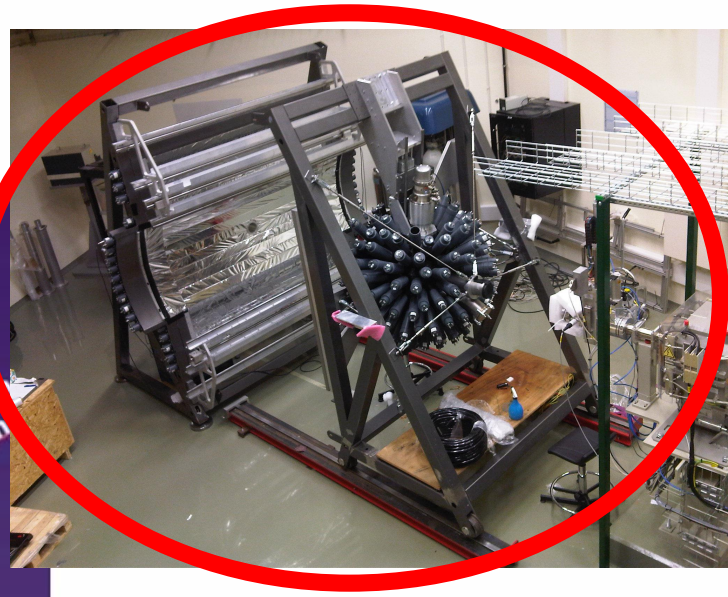
Normalization factor (luminosity):	
Reconstruction of angles	0.24%
Particle identification	0.7%
Cross section interpolation	4.1%
Breakup cross section:	
Reconstruction of angles	0.15%–0.24%
Particle identification	0.12%–7.6%
Hadronic reactions	3.8%
Configurational efficiency	0.1%–16.3%

Motivation

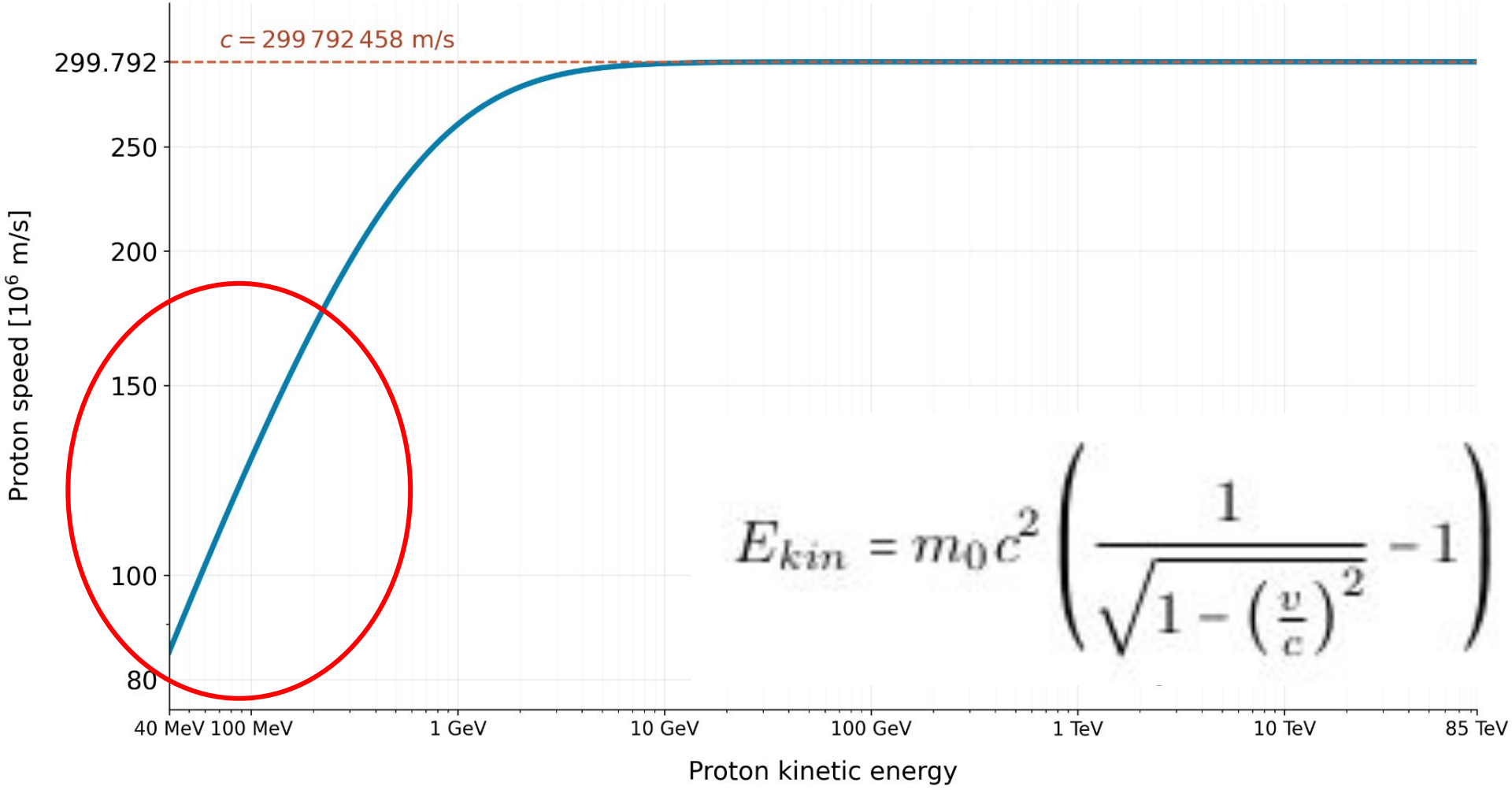
Direct energy and additionally its smearing monitoring is an asset

- Proteus-235 is calibrated in stopping range in water
- no measurement of beam profile on the target plane
- no precise measurement of beam current after the target





Time-of-flight for particles

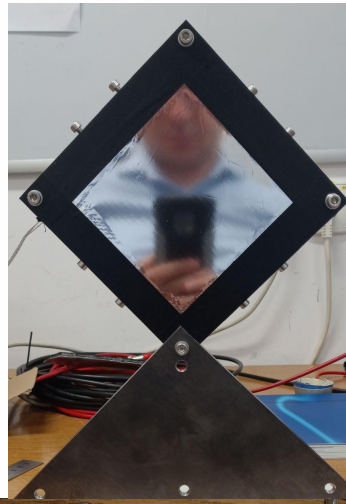


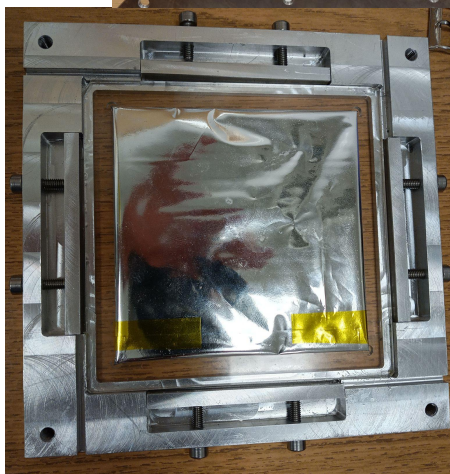
$$E_{kin} = m_0 c^2 \left(\frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} - 1 \right)$$

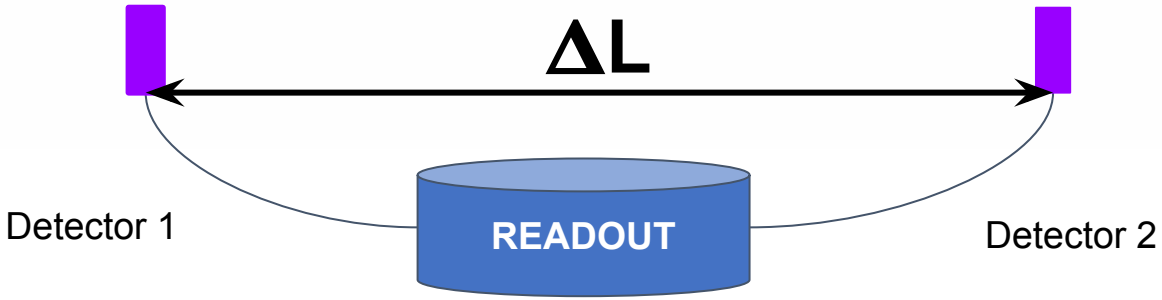
Time-of-flight method

$$E_{kin} = m_0 c^2 \left(\frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} - 1 \right)$$

- Development of applicable beam geometry analysing method:
  - **accurate and precise** -- energy measurement (70-230 MeV)
  - **fast** -- doable on spot “during” experiment or therapy
  - **cost efficient** -- relatively to actually adopted solutions
  - sufficient XY resolution for protons distribution on target plane
- Chosen hardware:
  - Thin plastic scintillators frame
  - Oscilloscope-like acquisition
  - Boards with Silicon PhotoMultipliers (SiMP)



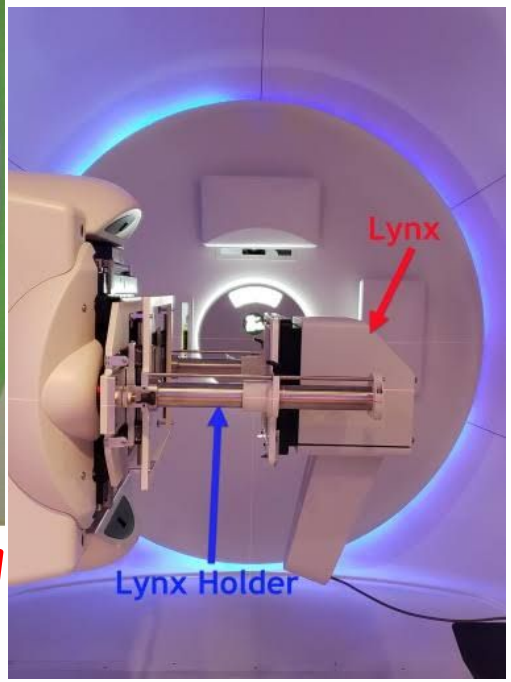




Motivation







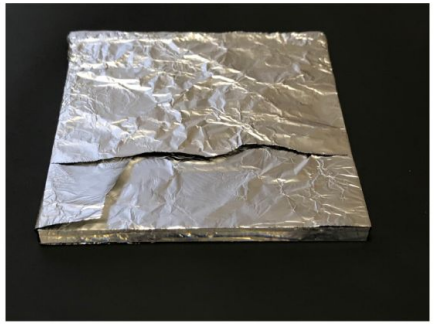
! DOSE NOT ENERGY !

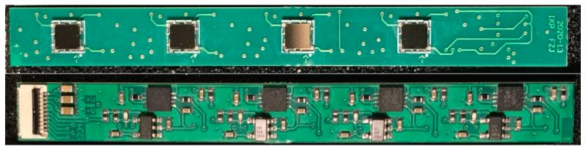
- Advantages for medical application:
  - auxiliary diagnostic support tool for medical beams
  - independent auxiliary diagnostic system
  - automatic mount

Prototypes

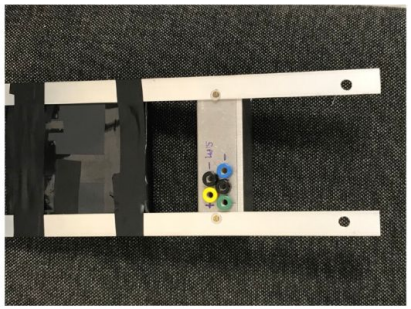
Active Area:

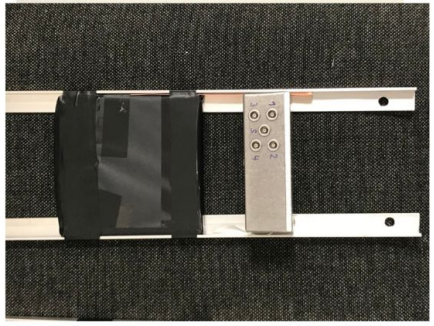
- plastic scintillator 90x90 [mm]
- aluminium foil light-reflecting wrapping
- pocalon optical cover wrapping









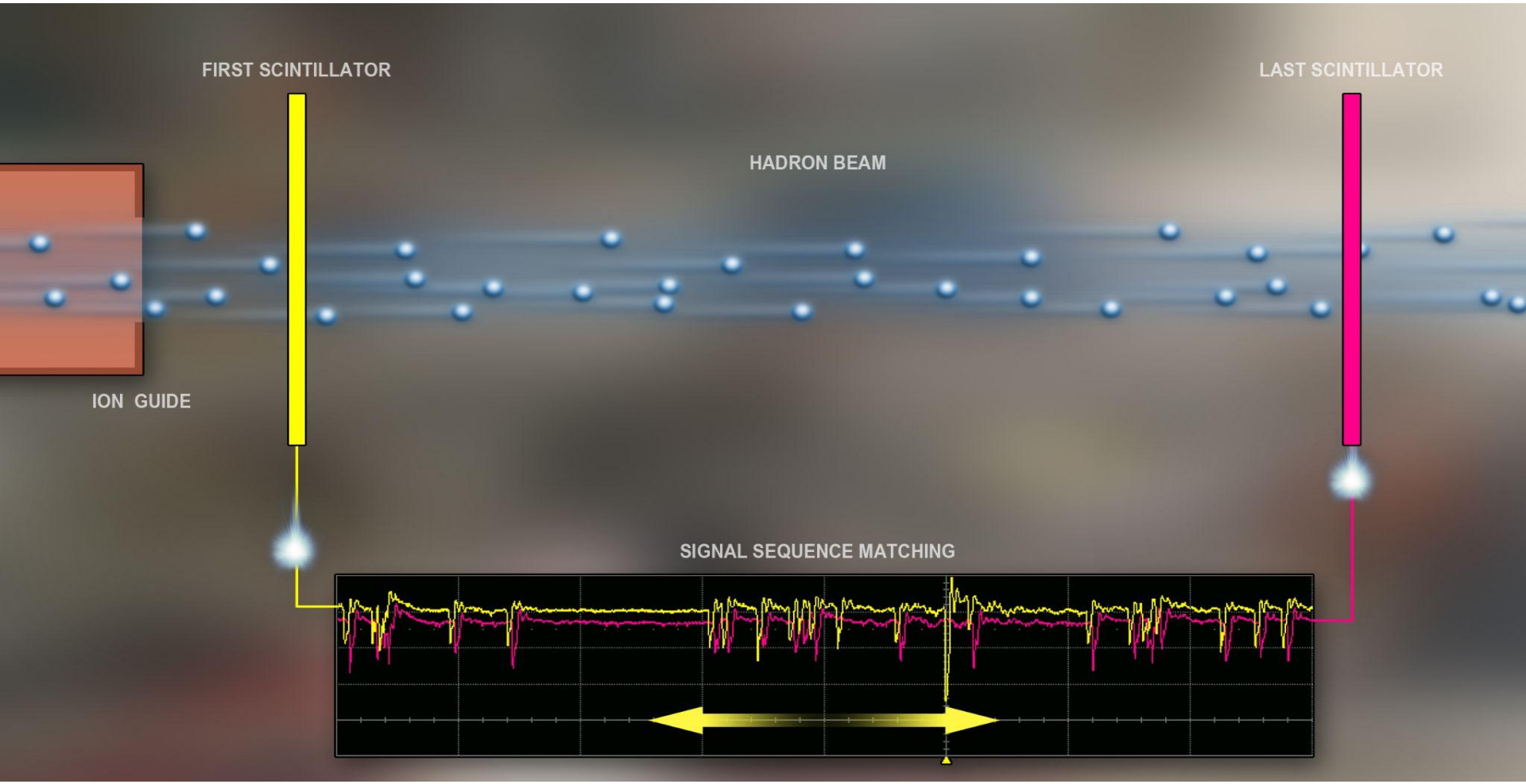


Signal readout:

- ➢ one-side
- ➢ 4x SiPM 3x3mm
- ➢ output signals:
  - individual for each SiPM
  - sum of all four
- ➢ signals time-distance due to cables different length under control (calibration)
- ➢ acquisition: 4-channel oscilloscope



Waveform Pattern Alignment (WPA)

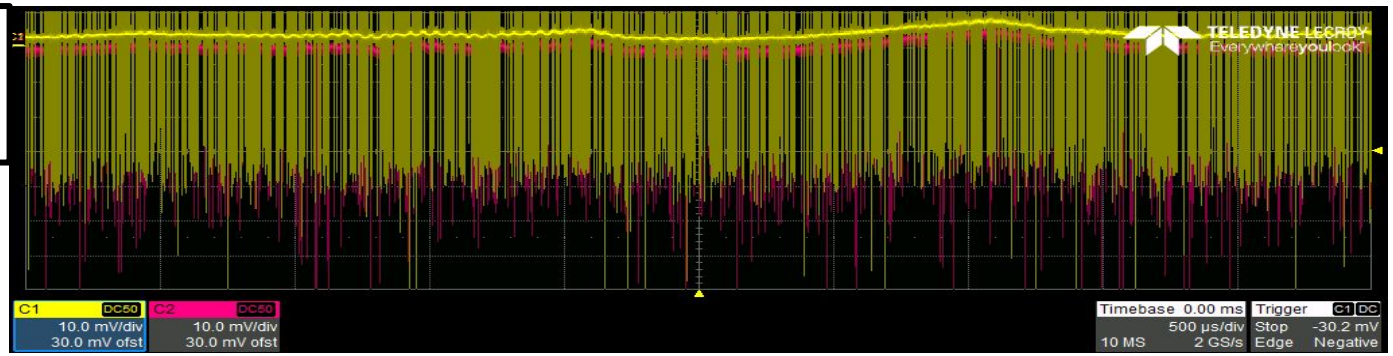


Signal pattern shift corresponds to time-of-flight

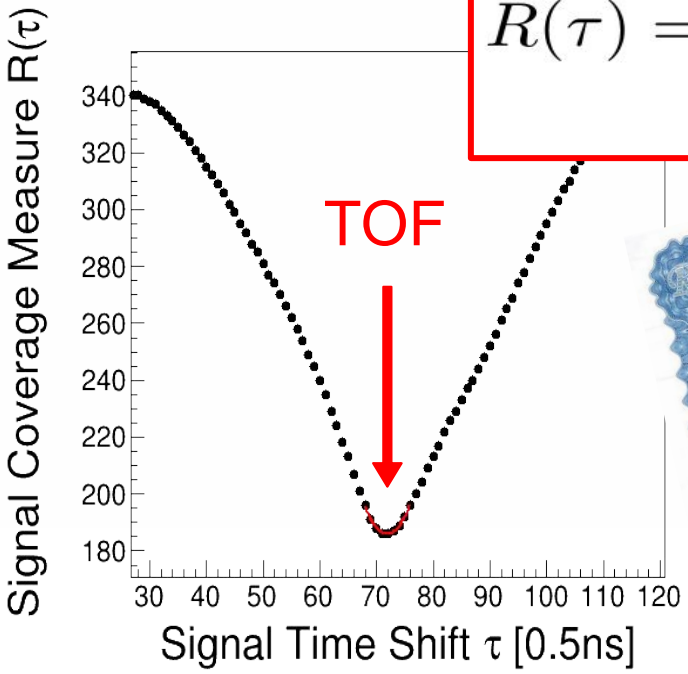
Signal overlap functional $R(\tau)$

τ - time-shift parameter

70 MeV
1 nA



$$R(\tau) = \frac{1}{N-\tau} \sum_{k=0}^{N-\tau} \left| S^A(k) - S^B(k+\tau) \right|$$



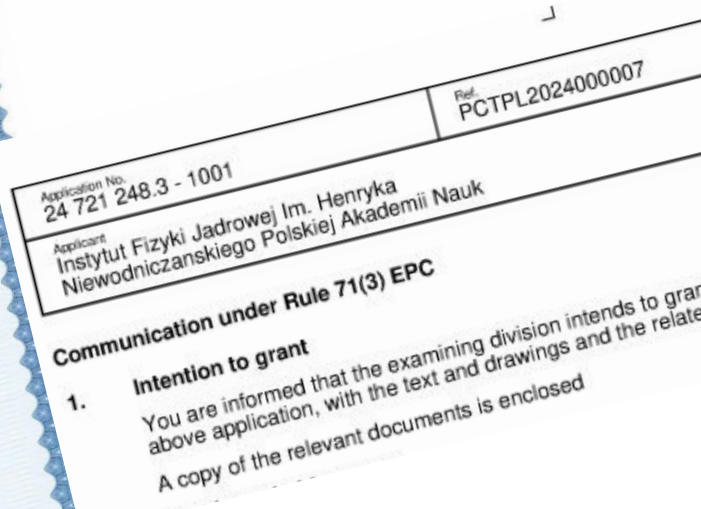

URZĄD PATENTOWY
RZECZYPOSPOLITEJ POLSKIEJ

DOKUMENT PATENTOWY

Na podstawie przepisów ustawy z dnia 30 czerwca 2000 r. Prawo własności przemysłowej (Dz. U. z 2023 r. poz. 1170) został udzielony na rzecz:

INSTYTUT FIZYKI JADROWEJ IM. HENRYKA NIEWODNICZAŃSKIEGO POLSKIEJ AKADEMII NAUK, Kraków, Polska

PATENT
NR 249360


Ref. PCTPL2024000007
Application No. 24 721 248.3 - 1001
Applicant Instytut Fizyki Jadrowej Im. Henryka Niewodniczanskiego Polskiej Akademii Nauk

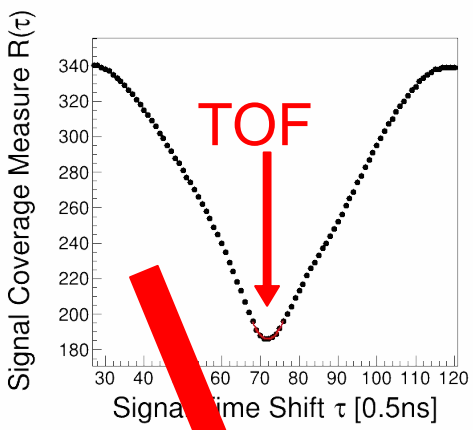
Communication under Rule 71(3) EPC

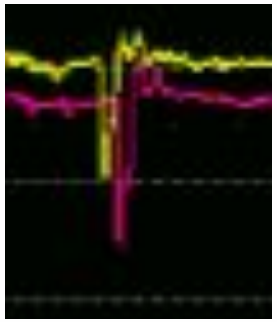
1. **Intention to grant**

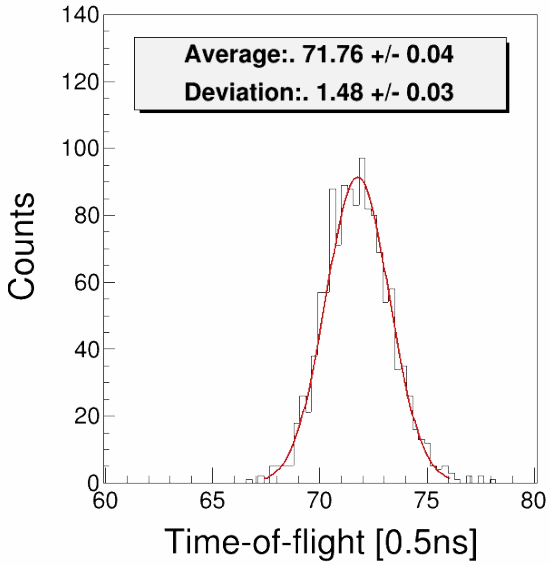
You are informed that the examining division intends to gran
above application, with the text and drawings and the relate

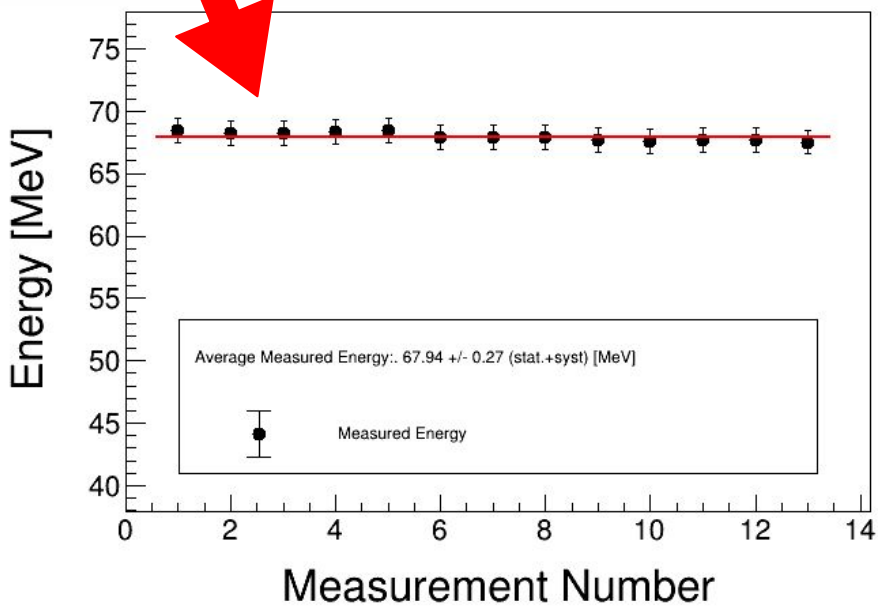
A copy of the relevant documents is enclosed

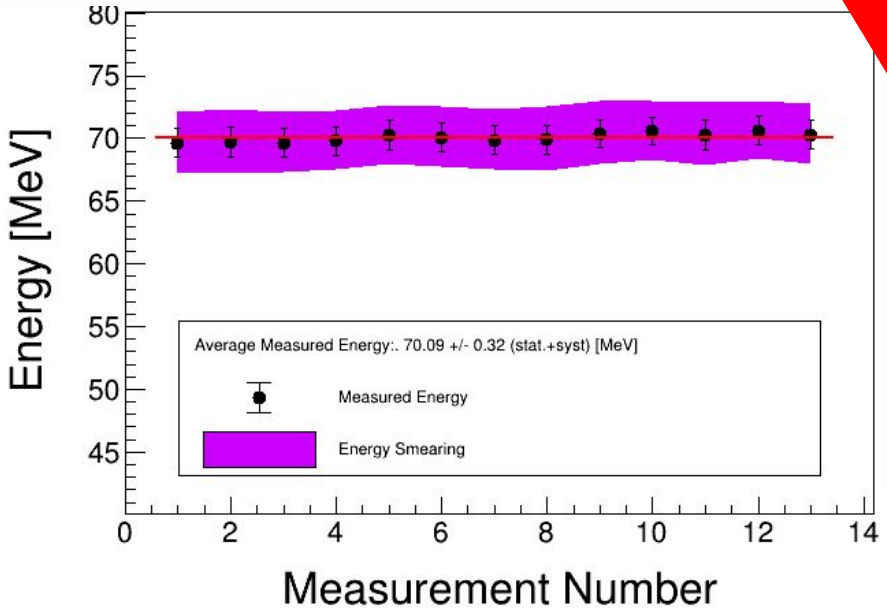
Waveform Pattern Alignment (WPA)











Wavefo… …gnment (WPA)



URZĄD PATENTOWY
RZECZYPOSPOLITEJ POLSKIEJ

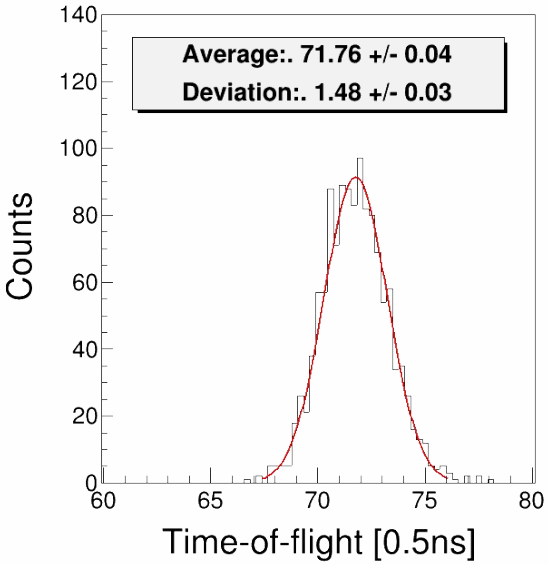
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INSTYTUT FIZYKI JADROWEJ IM. HENRYKA NIEWODNICZAŃSKIEGO POLSKIEJ AKADEMII NAUK,
Kraków, Polska

PATENT
NR 249361
NA WYNALAZEK PT.

wyznaczania rozmycia energii kinetycznej wiązki hadronowej




Application No.
24 721 786.2 - 1001
Applicant
Instytut Fizyki Jadrowej Im. Henryka Niewodniczanskiego PAN
Ref.
PCT/PL2024/000008
Date
17.09.2026

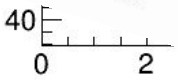
Communication under Rule 71(3) EPC

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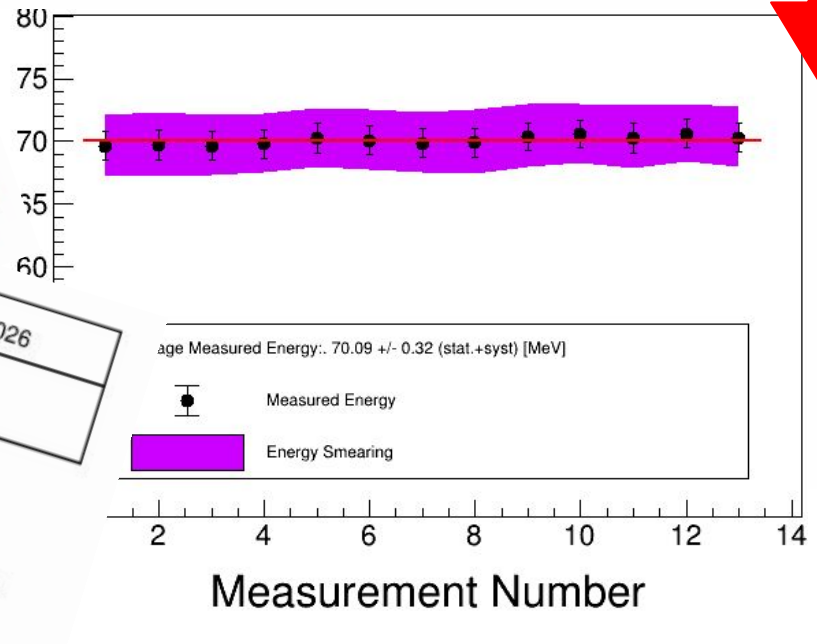
You are informed that the examining division intends to grant a European patent on the basis of the above application, with the text and drawings and the related bibliographic data as indicated below

A copy of the relevant documents is enclosed

Text intended for grant

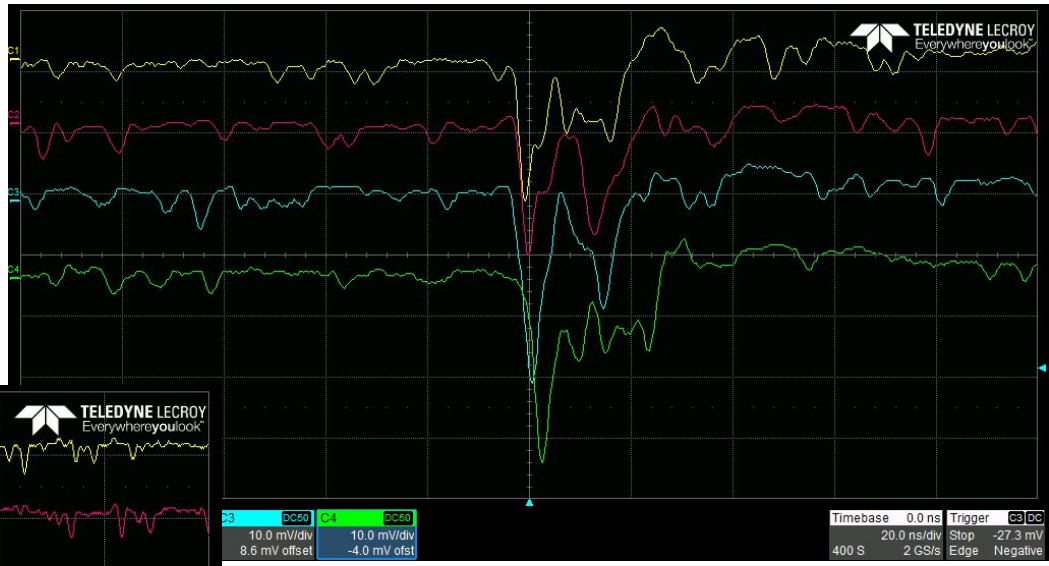


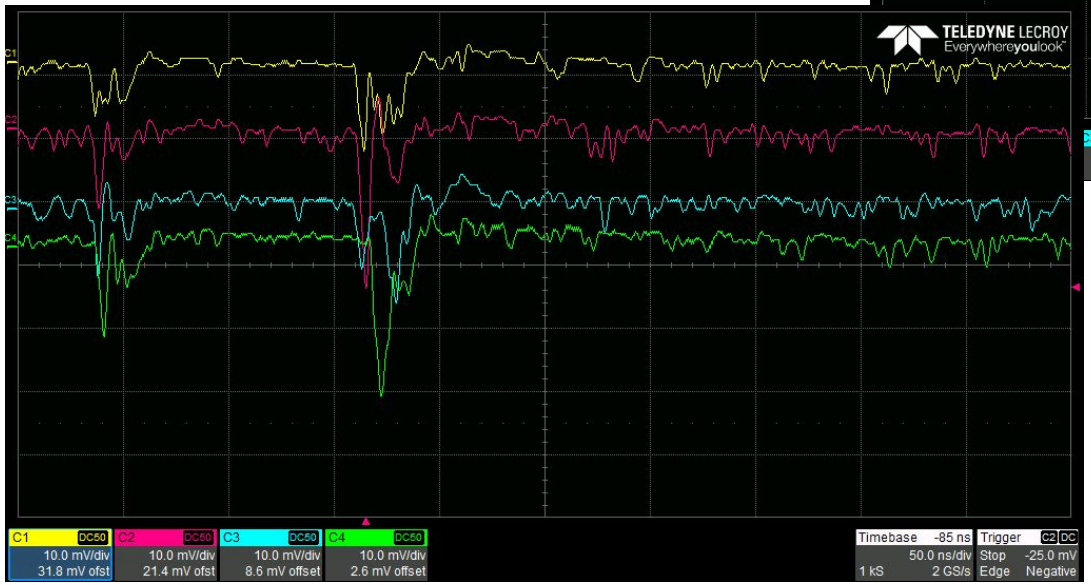
Measuremen…



1. Pairing signals from the same particle detection
2. Different signal amplification in both detectors
3. Registration some particles only in one detector
4. Overlapping pulses generated by different particles or accidental coincidences
5. Time Synchronisation
6. Smearing Calibration

3 SiMP individual channels compare

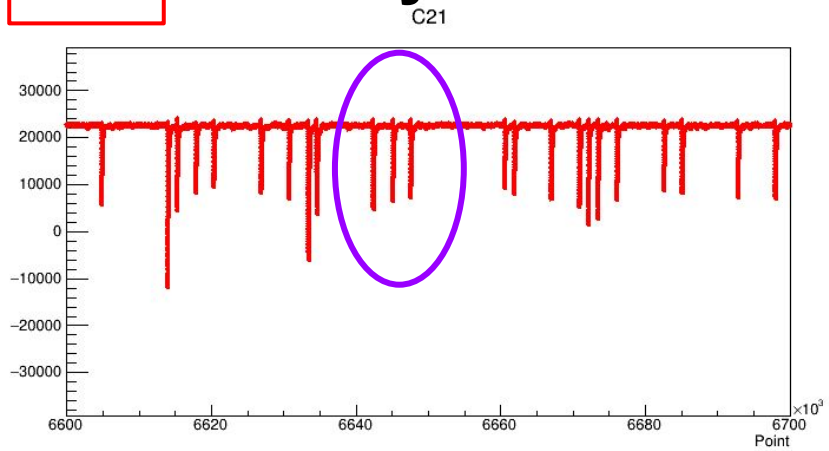


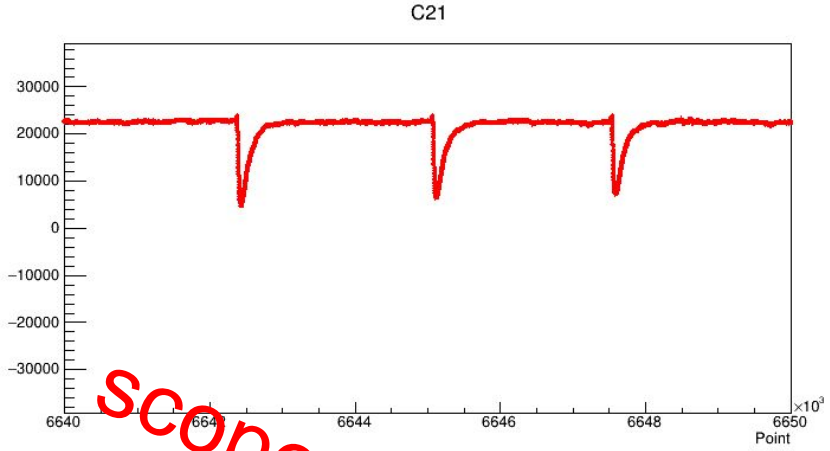


Efficiency > 99%

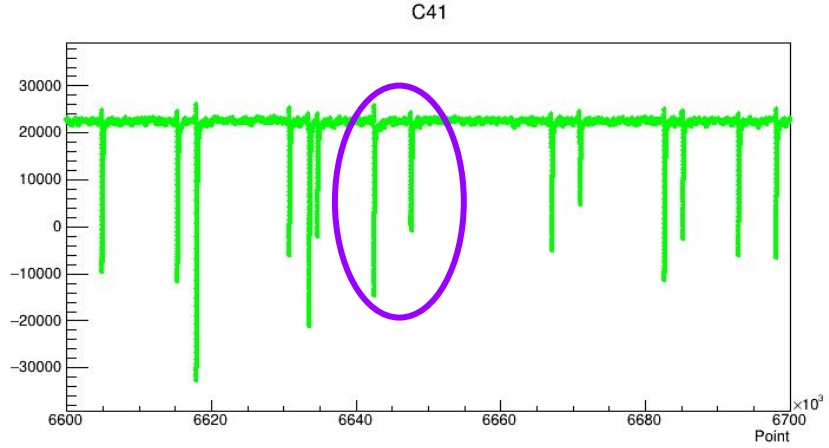
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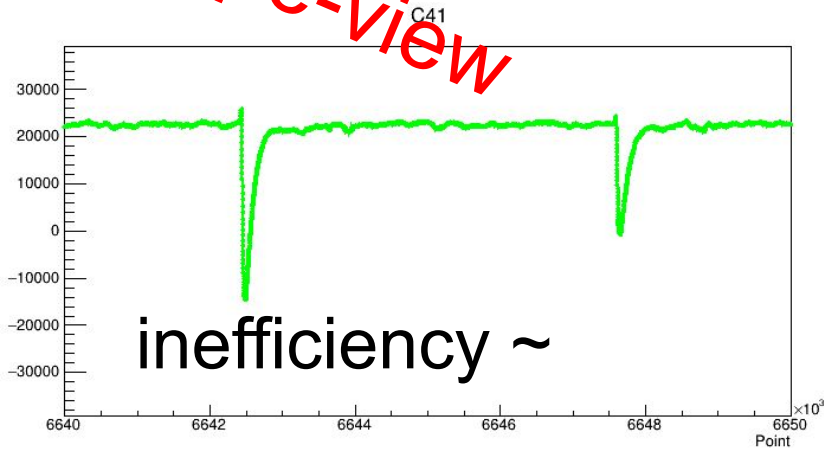
Inefficiencies - Registration some particles only in one detector





scope-view

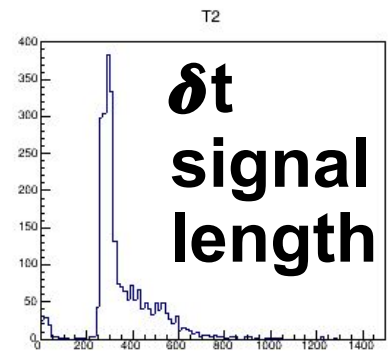


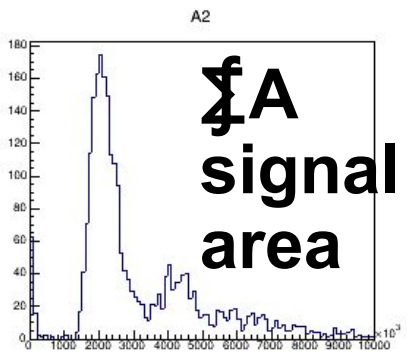


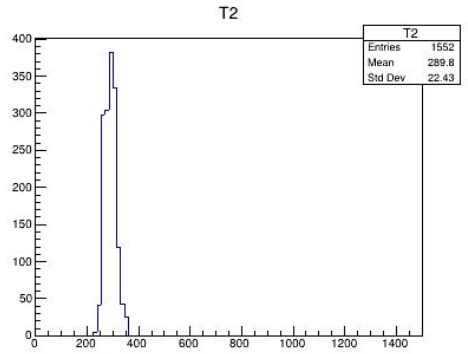
inefficiency ~

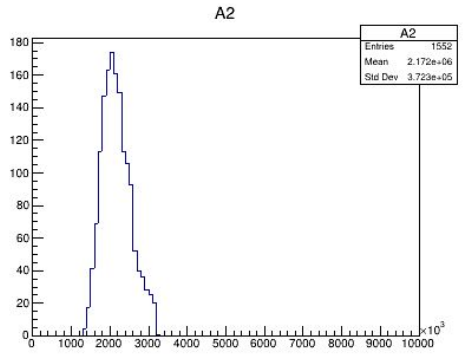
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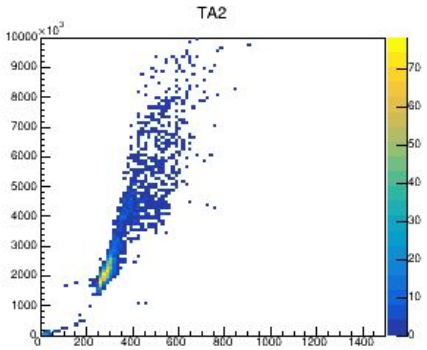
Overlapping pulses generated by different particles or accidental coincidences - PID

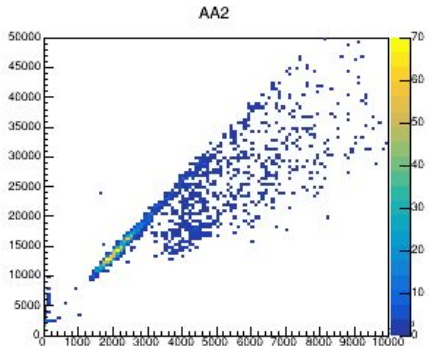


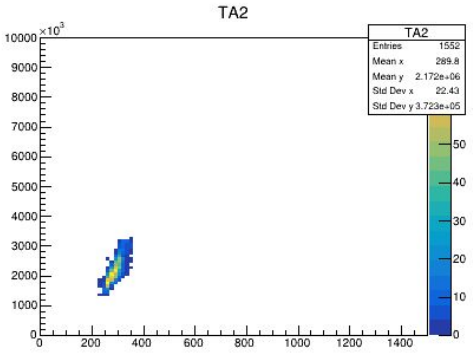


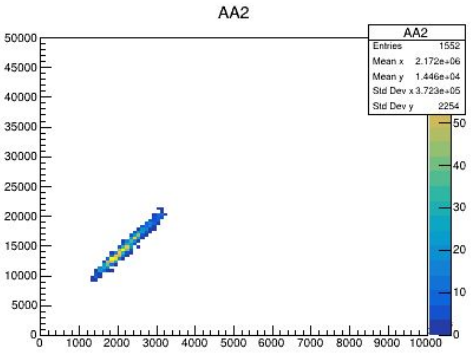












δt vs. ∑A **A vs. ∑A**

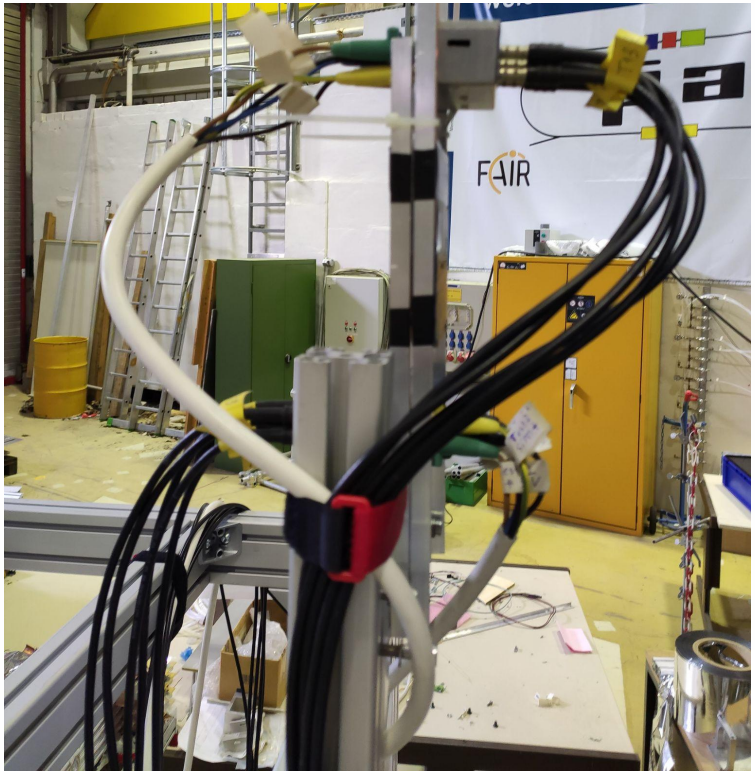
After Cuts

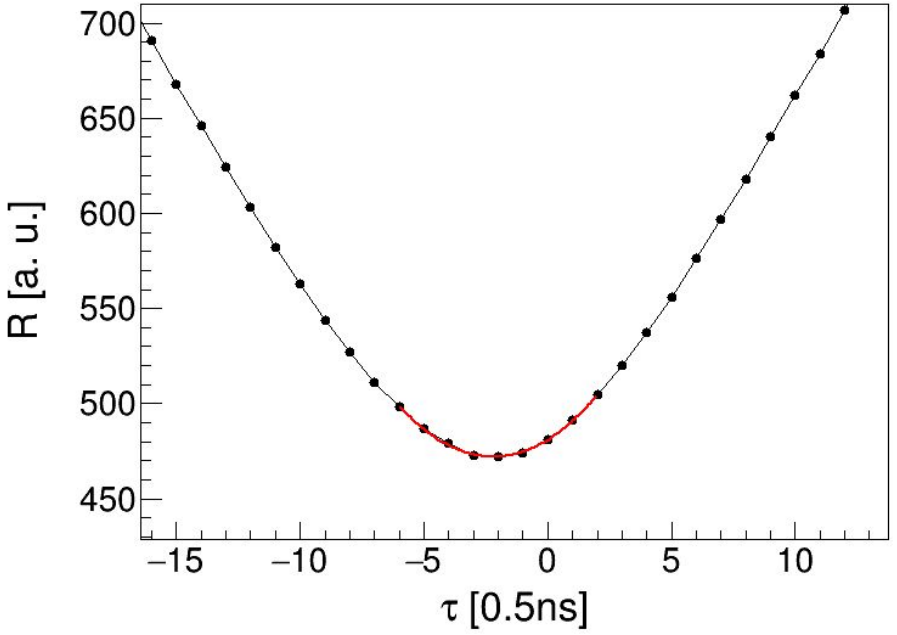
1. Pairing signals from the same particle detection
2. Different signal amplification in both detectors
3. Registration some particles only in one detector
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5. Time Synchronisation
6. Smearing Calibration

5 Time synchronisation

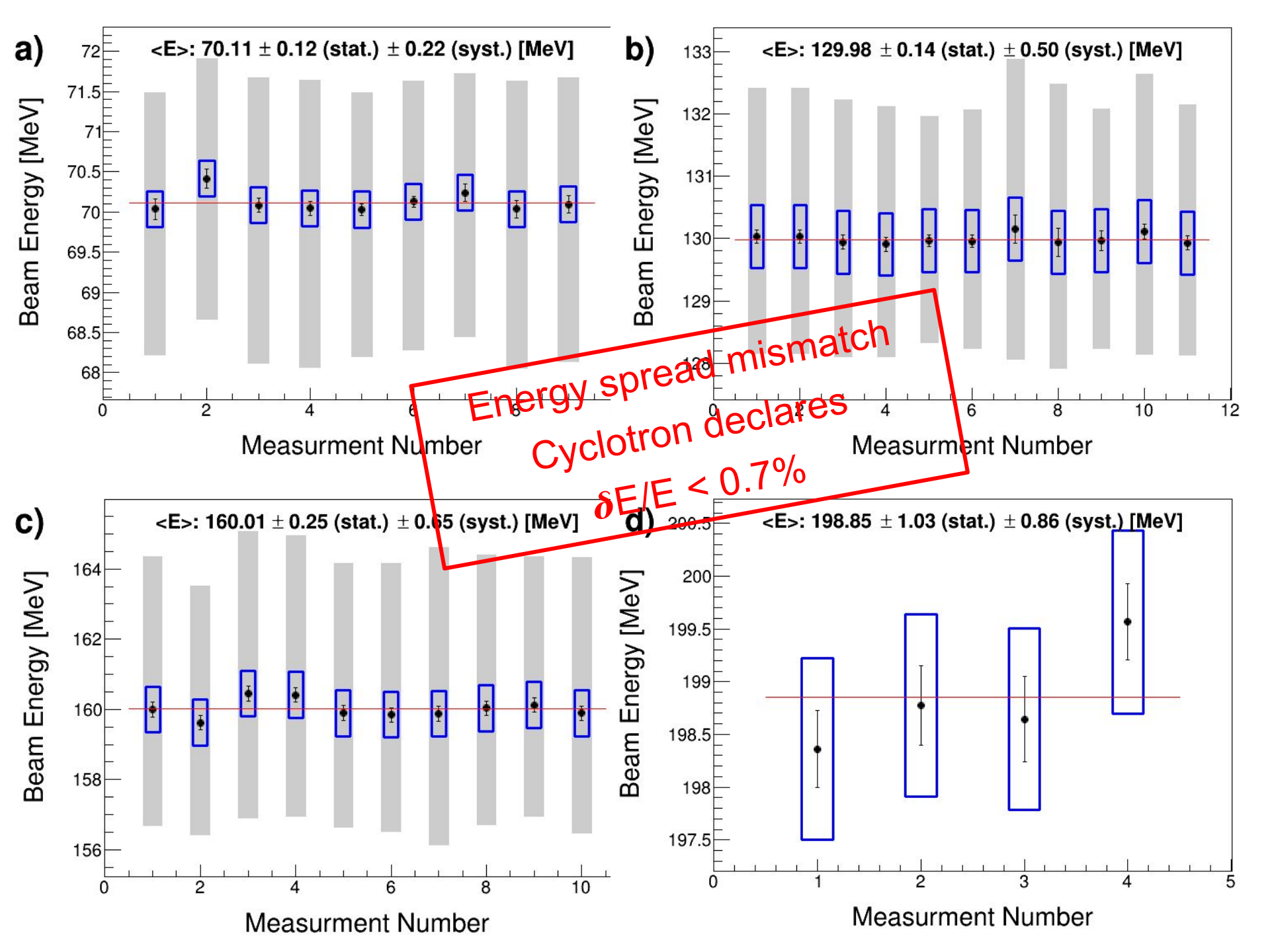
$$R(\tau) = \frac{1}{N-\tau} \sum_{k=0}^{N-\tau} \left| S^A(k) - S^B(k+\tau) \right|$$

Distance ~ 0

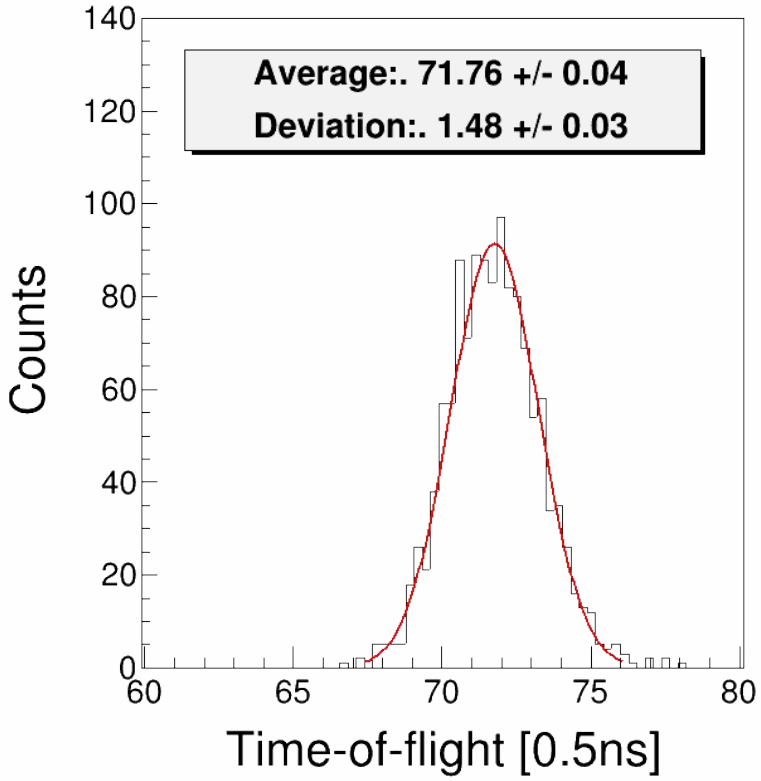


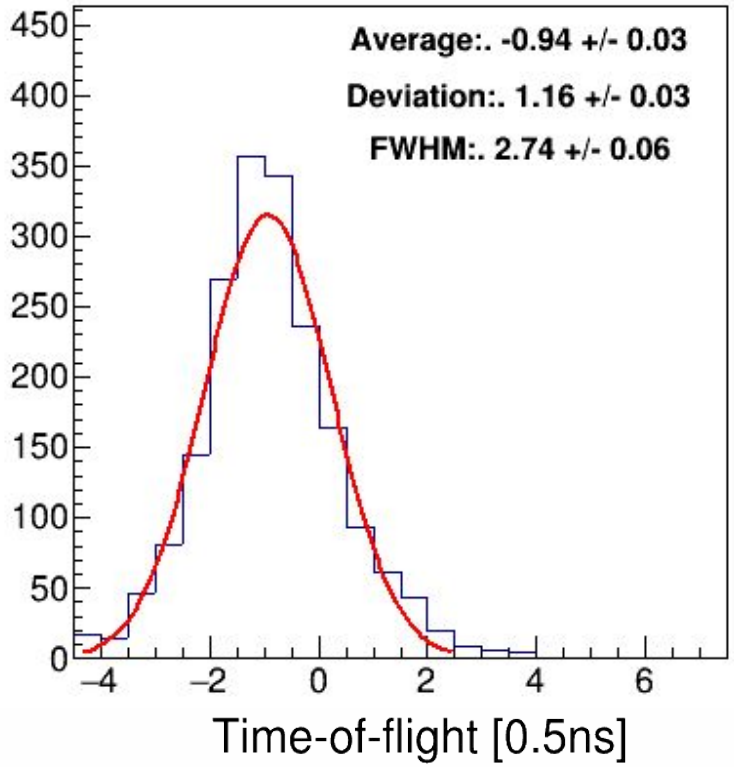




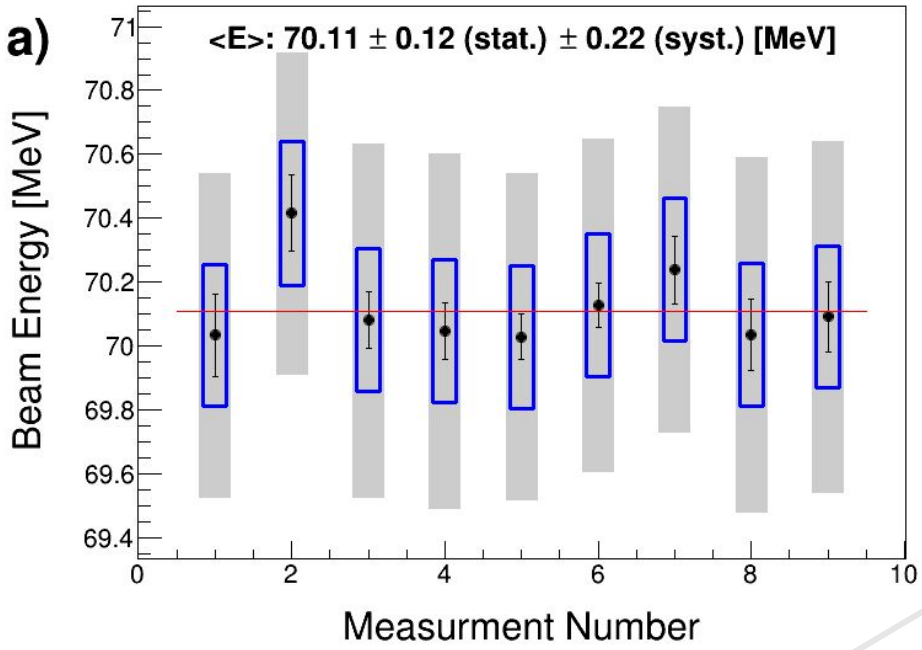

a)
<E>: 70.11 ± 0.12 (stat.) ± 0.22 (syst.) [MeV]
Beam Energy [MeV]
Measurment Number
b)
<E>: 129.98 ± 0.14 (stat.) ± 0.50 (syst.) [MeV]
Beam Energy [MeV]
Measurment Number
Energy spread mismatch
Cyclotron declares
δE/E < 0.7%
c)
<E>: 160.01 ± 0.25 (stat.) ± 0.65 (syst.) [MeV]
Beam Energy [MeV]
Measurment Number
d)
<E>: 198.85 ± 1.03 (stat.) ± 0.86 (syst.) [MeV]
Beam Energy [MeV]
Measurment Number

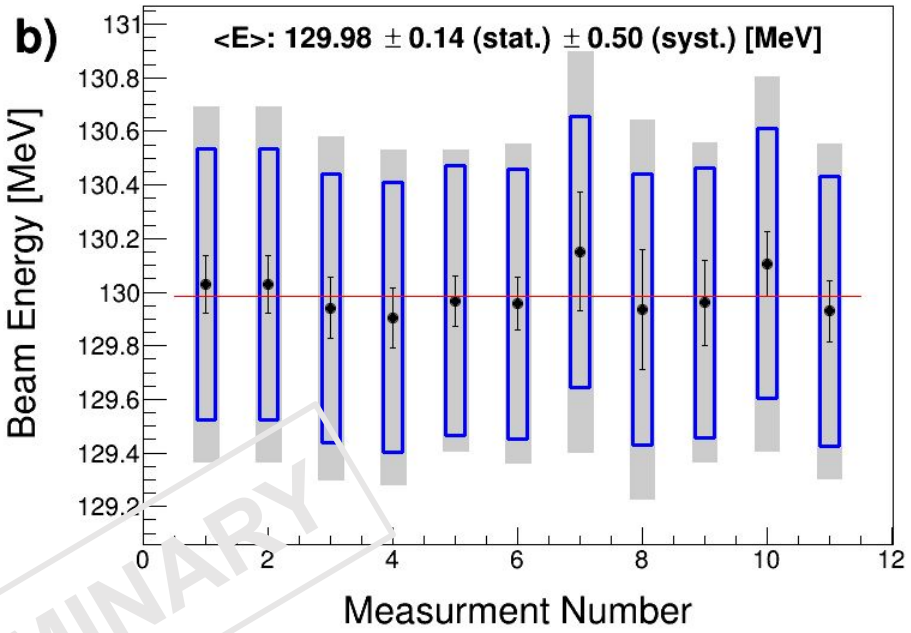
6 Smearing calibration

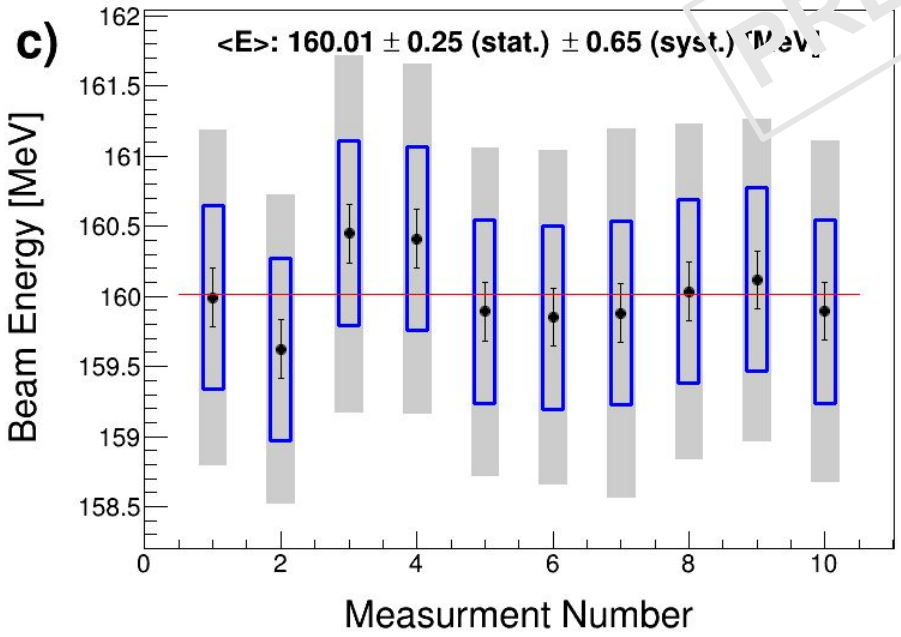




$$\sigma = \sqrt{\sigma_{tof}^2 - \sigma_{smear}^2}$$

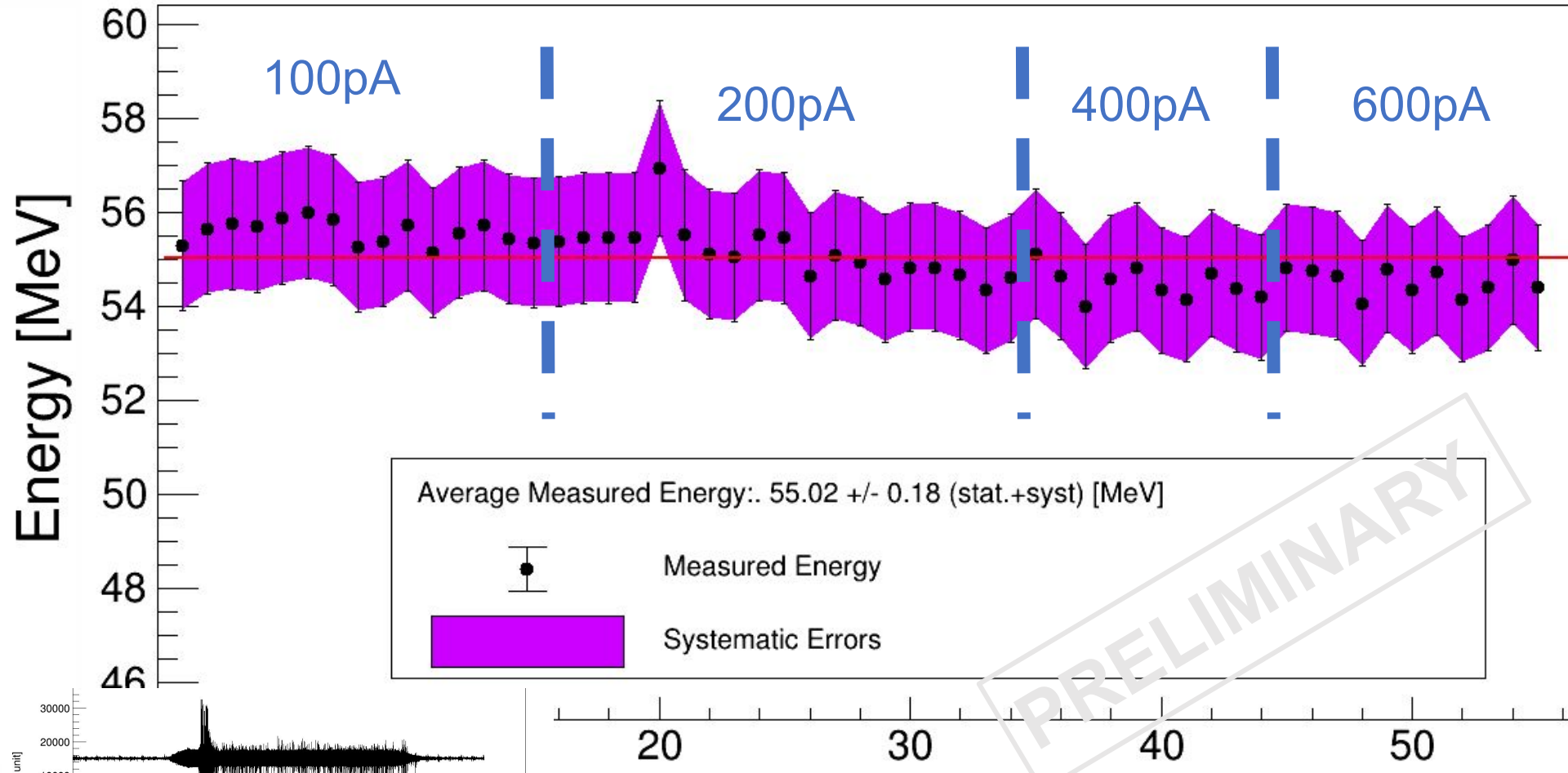


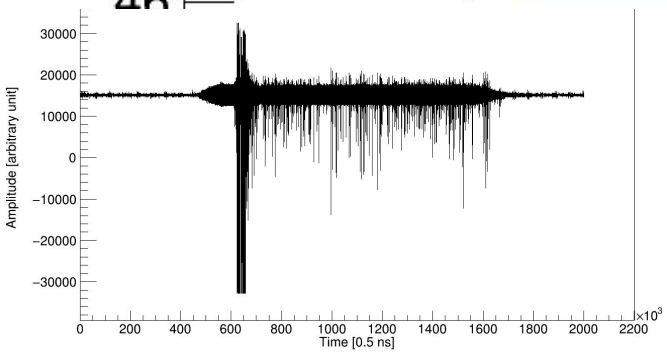




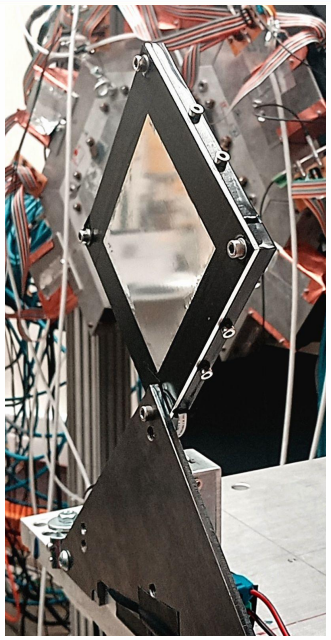
PRELIMINARY

$$\sigma = \sqrt{\sigma_{tof}^2 - \sigma_{smear}^2}$$


100pA
200pA
400pA
600pA
Energy [MeV]
60
58
56
54
52
50
48
46
Average Measured Energy:. 55.02 +/- 0.18 (stat.+syst) [MeV]
Measured Energy
Systematic Errors
PRELIMINARY
20
30
40
50


Amplitude [arbitrary unit]
30000
20000
10000
0
−10000
−20000
−30000
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
×10³
Time [0.5 ns]

Summary



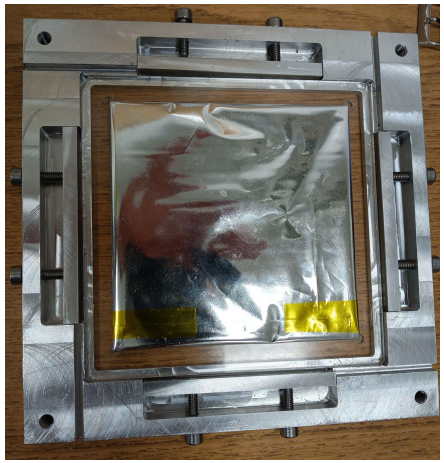
Offline device readiness:

- ➢ set-up on demand to operate during the experiments
- ➢ diagnostic checkouts and “offline” monitoring

Near future:

- ➢ vacuum test and scan of CCB energy range
- ➢ struggle to build dedicated electronics






THANK YOU