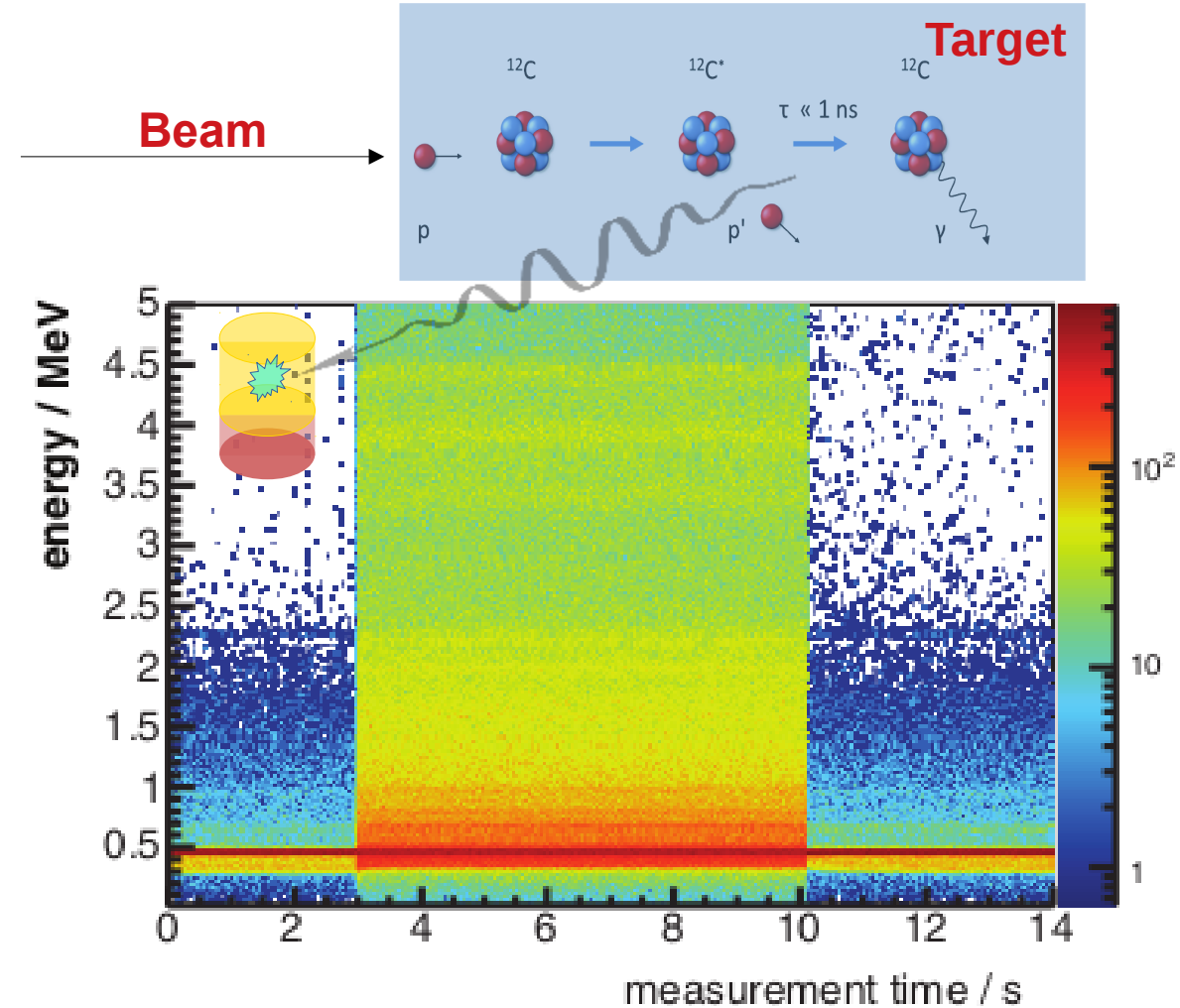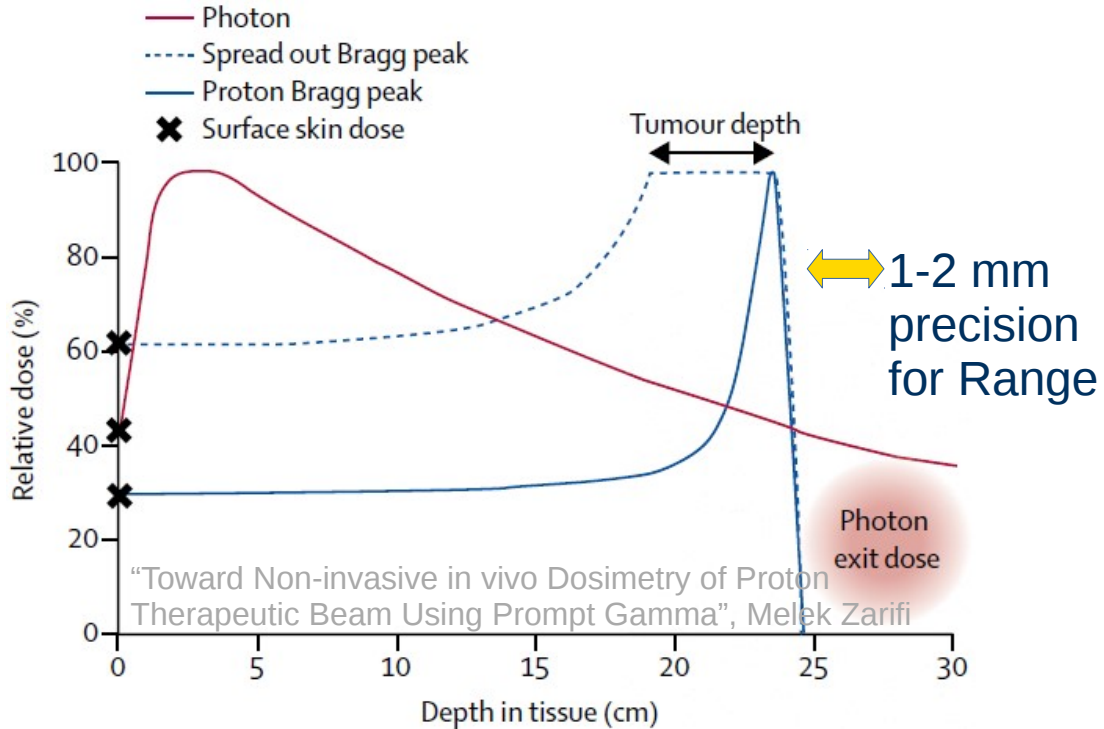Fakultät Physik
Institut für Kern- und Teilchenphysik

Optimization of PETsys TOFPET2 ASIC for Prompt Gamma Timing (PGT) Application

Olga Novgorodova
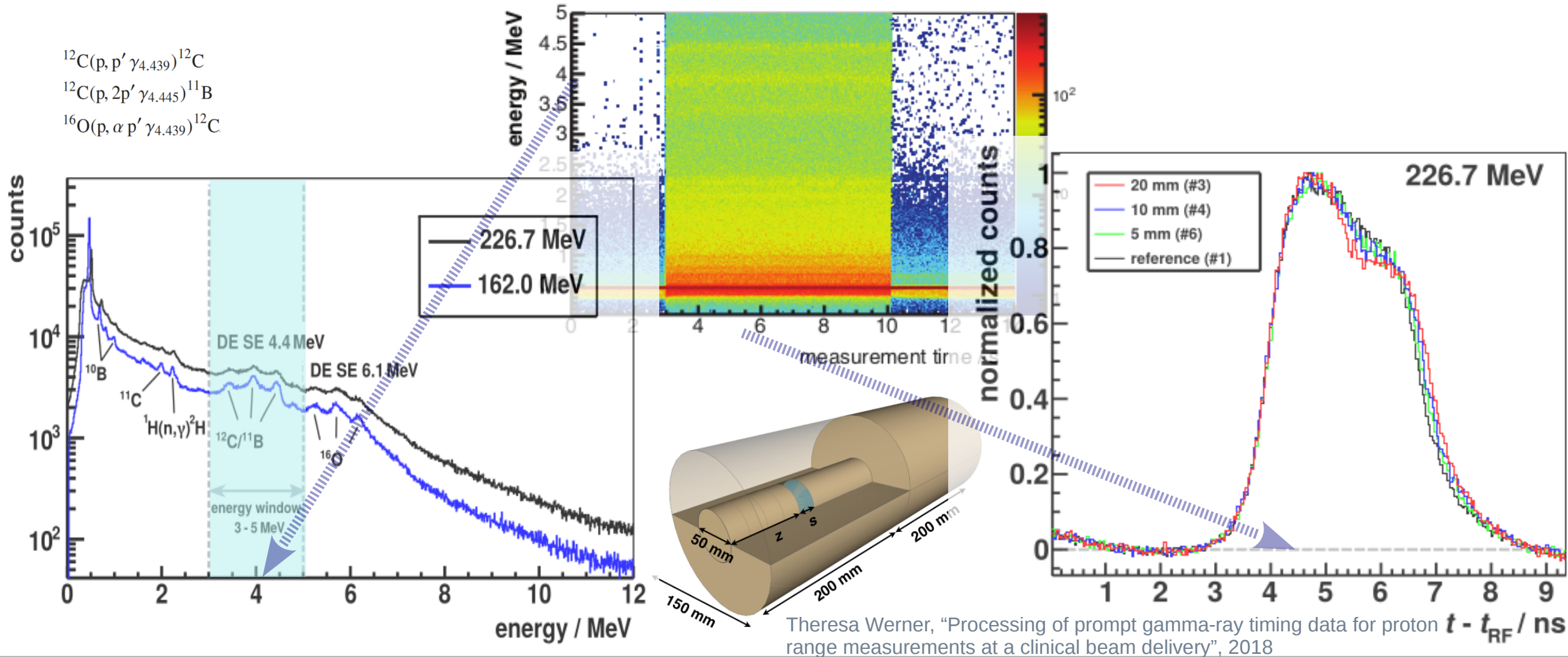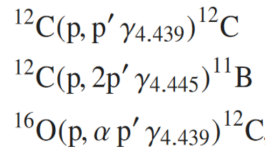
21st September 2022

Range problem in particle therapy

"Toward Non-invasive in vivo Dosimetry of Proton Therapeutic Beam Using Prompt Gamma", Melek Zarifi

1-2 mm precision for Range

Target

Beam

Range prediction and verification:
Dual-energy CT or Proton CT, PET, MRI
→ **Prompt Gamma-ray Timing (PGT)**

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Prompt Gamma Timing

$^{12}C(p, p' \gamma_{4.439})^{12}C$

$^{12}C(p, 2p' \gamma_{4.445})^{11}B$

$^{16}O(p, \alpha p' \gamma_{4.439})^{12}C$

Theresa Werner, "Processing of prompt gamma-ray timing data for proton range measurements at a clinical beam delivery", 2018

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Challenges

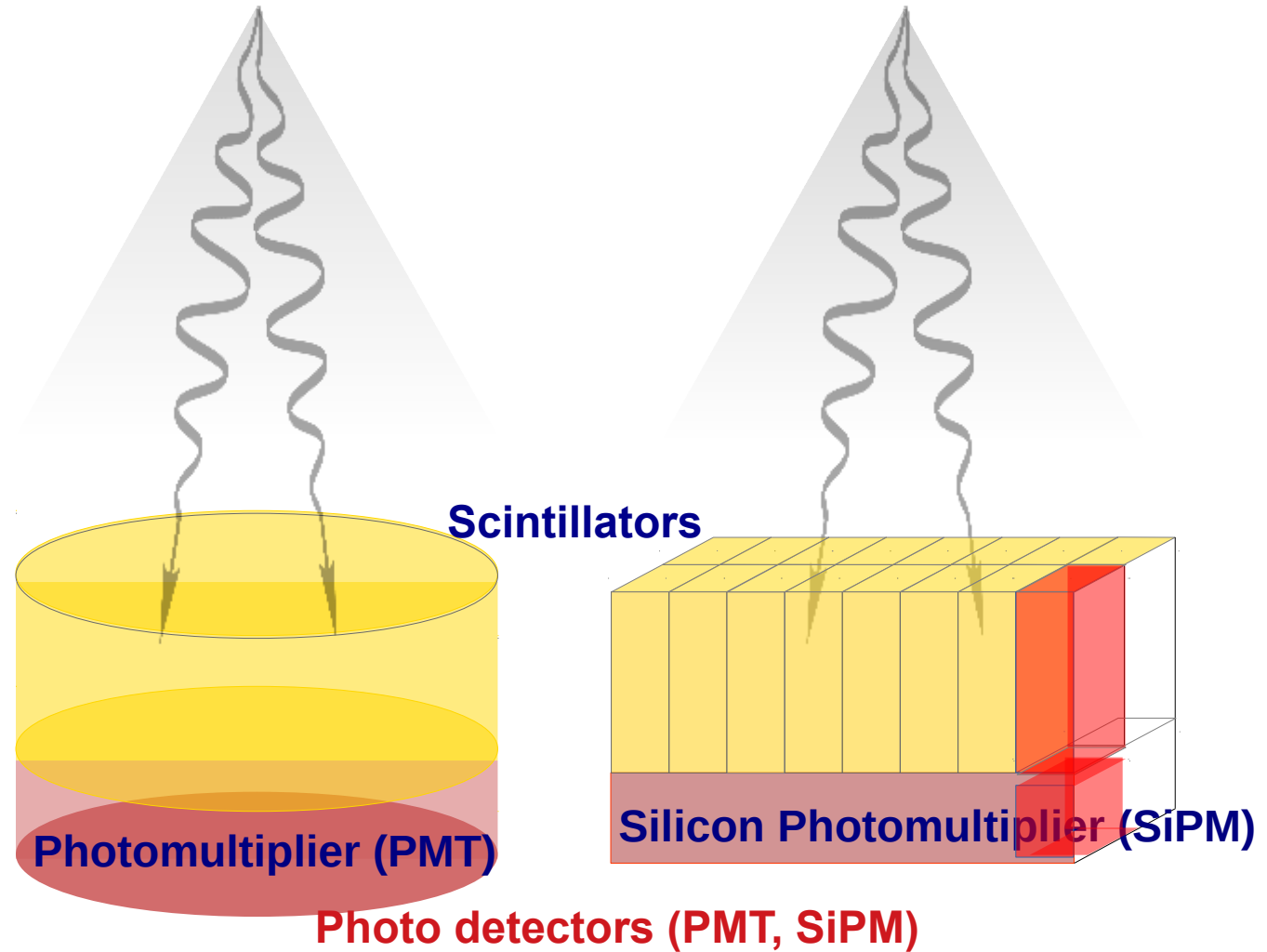**High statistics with full acceptance**
- $\sim 10^6 \ldots 10^8$ p$^+$/ Pencil Beam Spot (PBS)
- $\sim 2 \times 10^9$ Prompt Gamma's (PG) per second
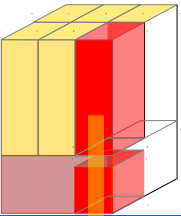- Extreme load tolerance

Reduce size of one channel:
- Reduce number of events
- Readout with Silicon Photomultipler (SiPM)
- Optimize PETsys for Prompt Gammas

Optimize the size of crystal:
- Energy spectrum & resolution
- Coincidence Time Resolution (CTR)
- High rates → Dead time → Pile-up

Scintillators

Photomultiplier (PMT)

Silicon Photomultiplier (SiPM)

Photo detectors (PMT, SiPM)

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PETsys Setup

Scintillators:

SiPM

SensL / OnSemi
35 µm microcell

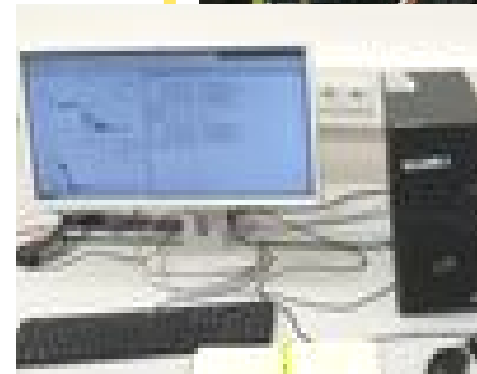Pin 5   Pin 8

CeBr$_3$

5×5×20 mm^3
10×10×30 mm^3

Hamamatsu
25 & 50 µm

Assembly

**PETsys Readout
for SiPM**

→ PETsys: application from PET to PG 3-8 MeV
→ Find fitting SiPM array
The PET Energy Resolution at 511 keV is 10.5 %
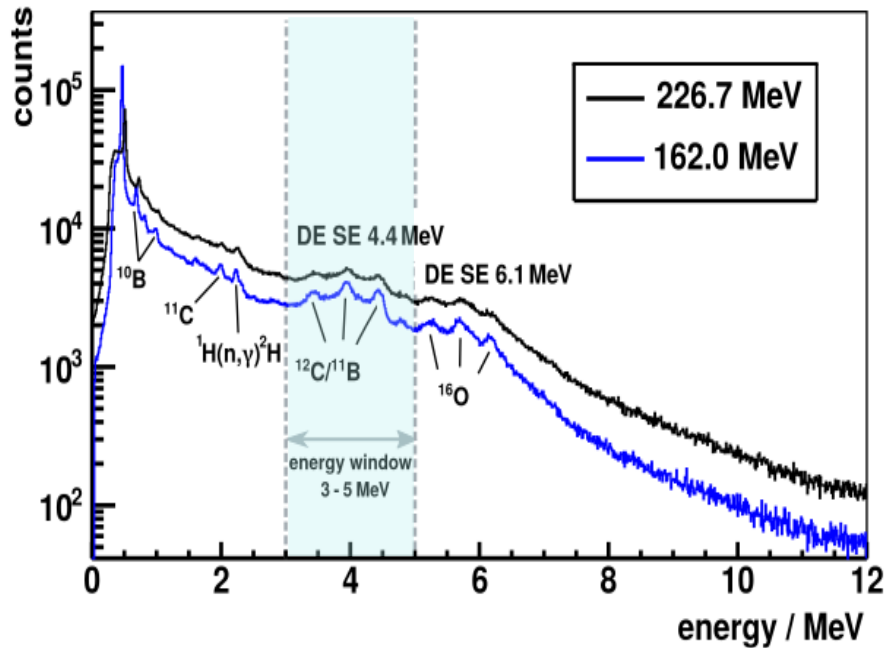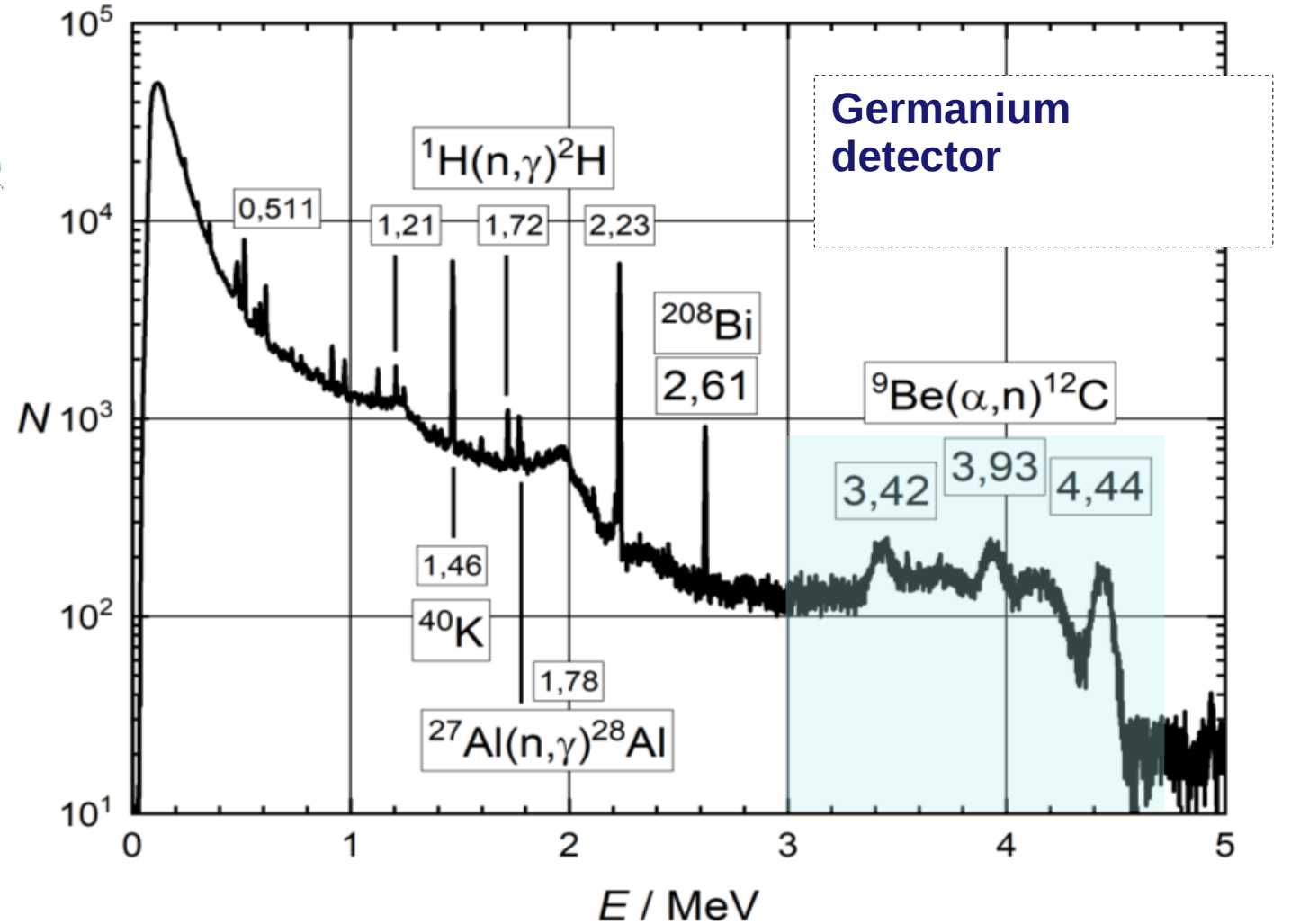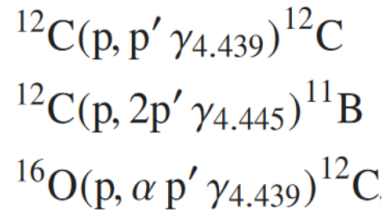→ $E_{resolution}$ ~ $1/\sqrt{E}$
Coincidence Time Resolution of 119 ps FWHM

→ **cost effective**
→ **fast**
→ **scalable**

https://www.petsyselectronics.com

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concept

Americium-Beryllium Source

$$^{12}C(p, p' \gamma_{4.439})^{12}C$$

$$^{12}C(p, 2p' \gamma_{4.445})^{11}B$$

$$^{16}O(p, \alpha p' \gamma_{4.439})^{12}C$$

Germanium detector

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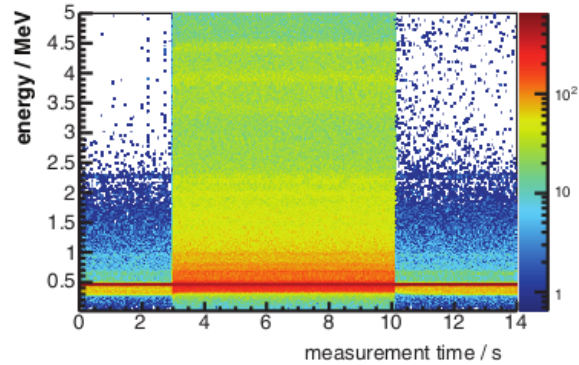
CAEN ADC Measurements with $CeBr_3$

10x10x30 mm³

5x5x20 mm³

2.23   3.42
2.23   3.93
3.42   4.4
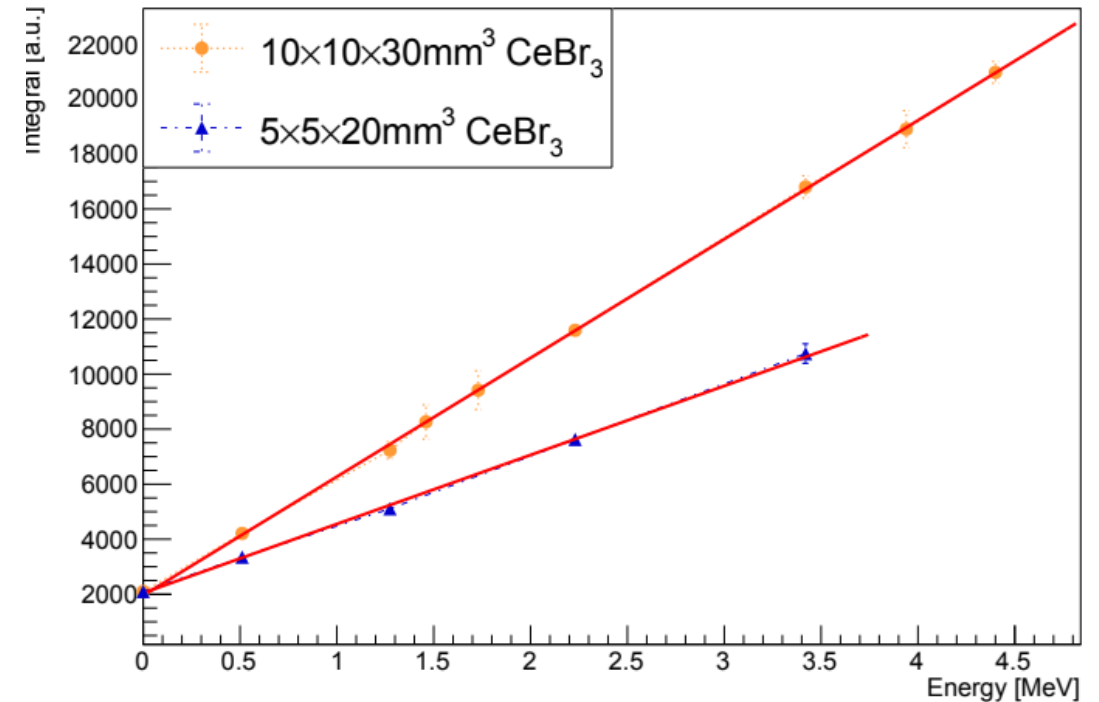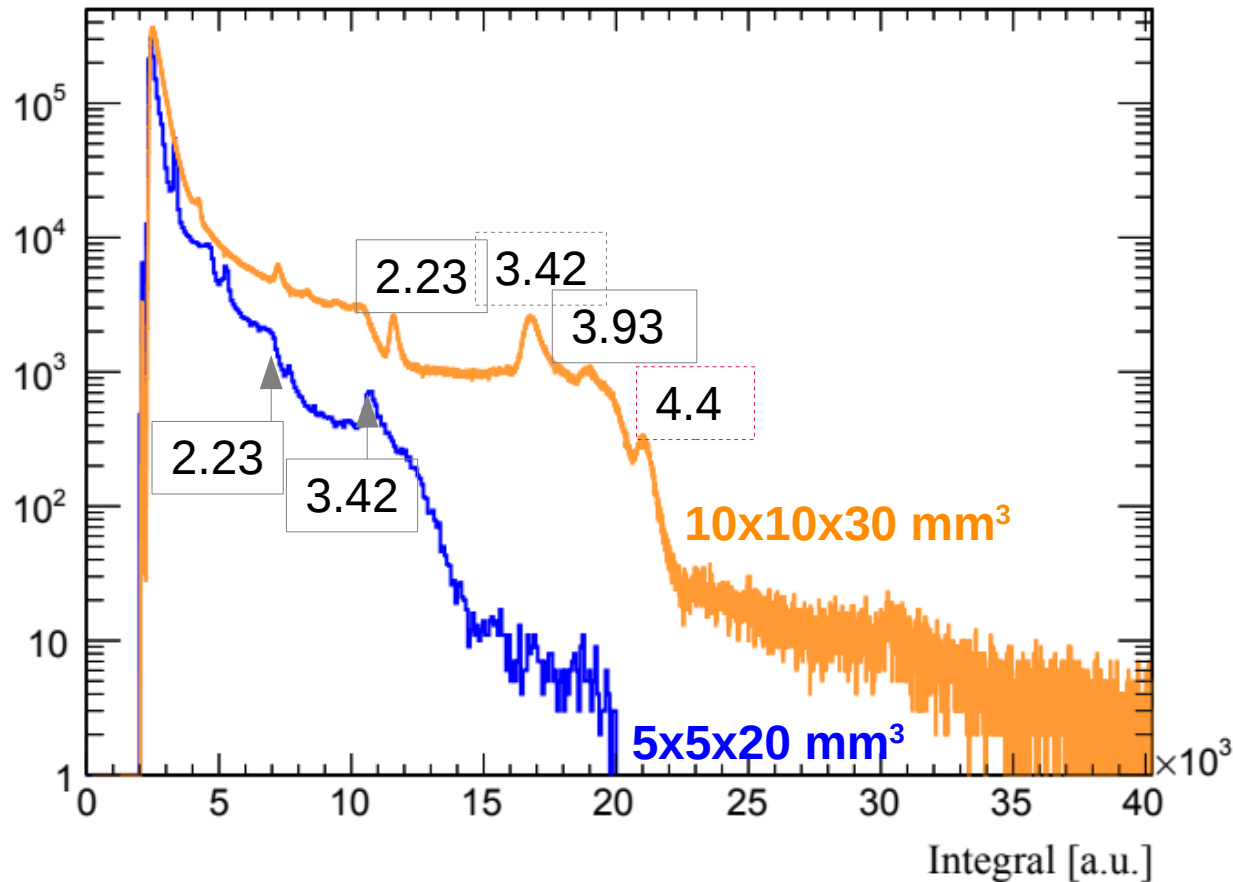
Calibration is linear

Smaller crystals – less signal → no 4.4 MeV and single escape peaks visible

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PETsys Measurements
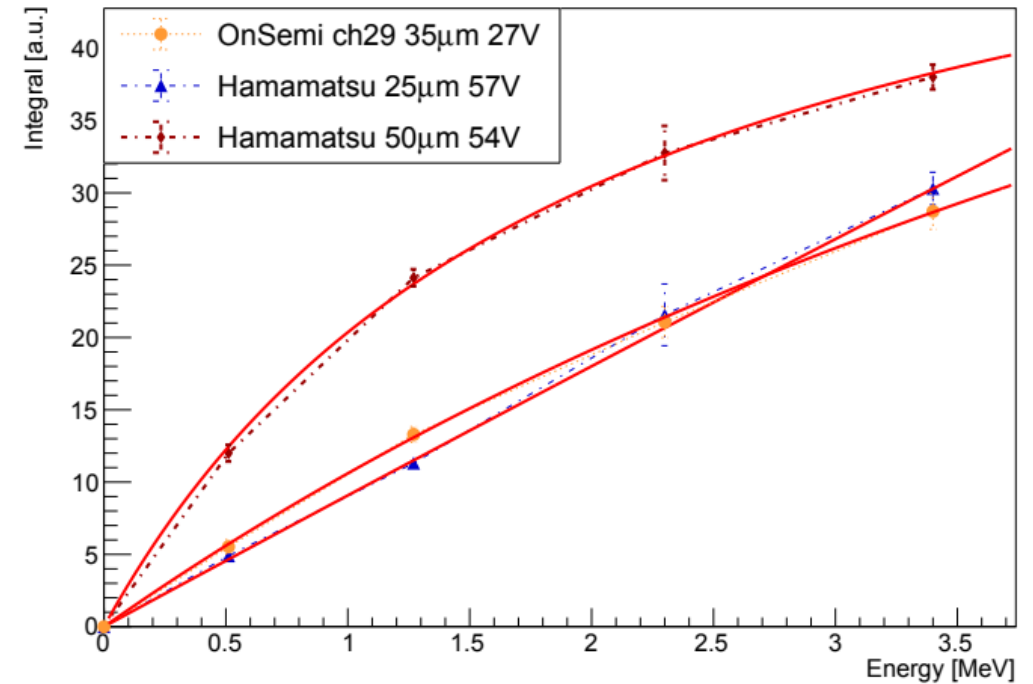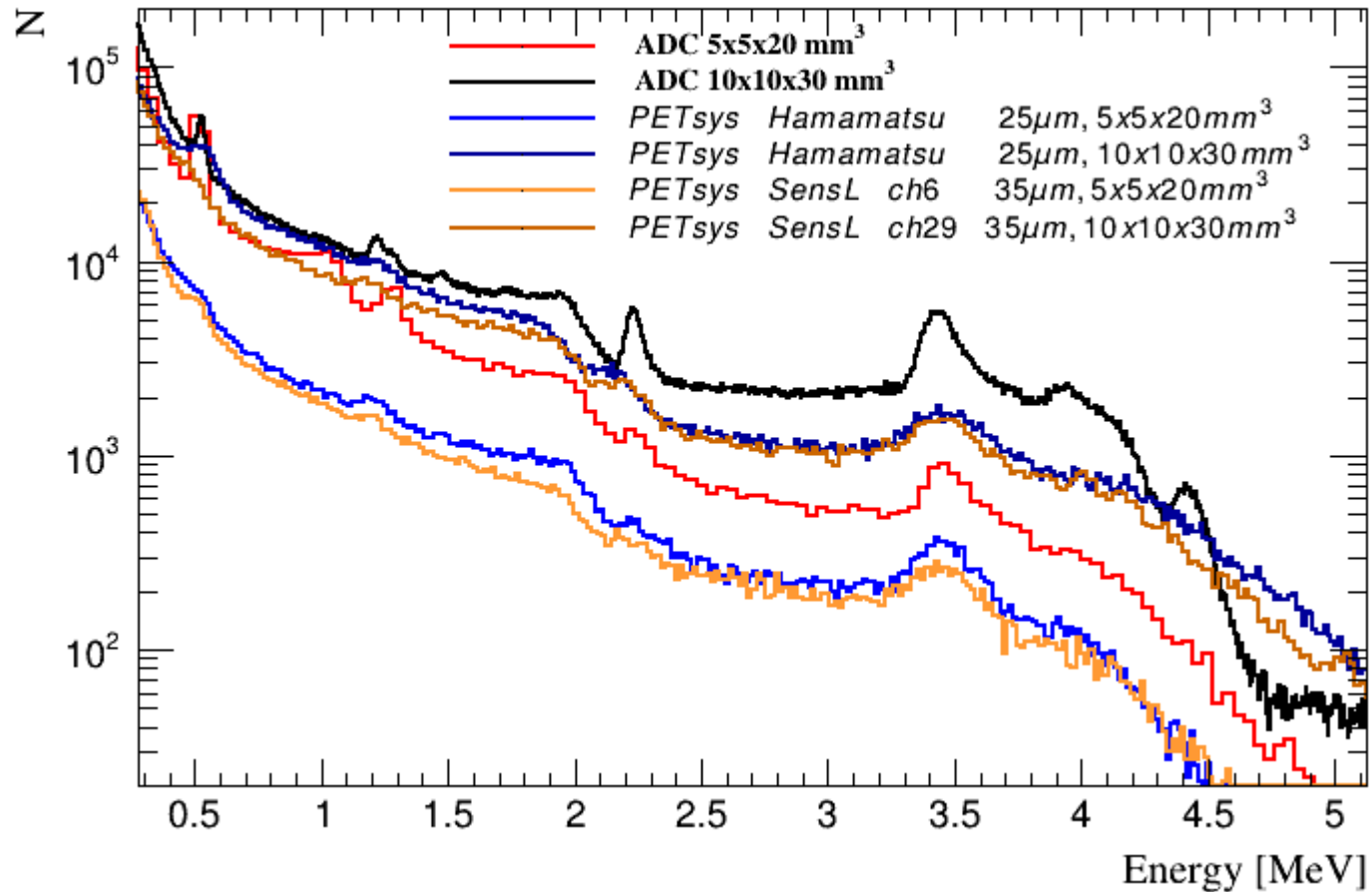
1. Compared 3 different SiPM's matrices
2. PETsys:
   → Hamamatsu 50µm - saturated
   → others – slightly saturated
   & can be corrected
3. 5x5x20 mm³ → double escape peak

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Energy Resolution CeBr$_3$
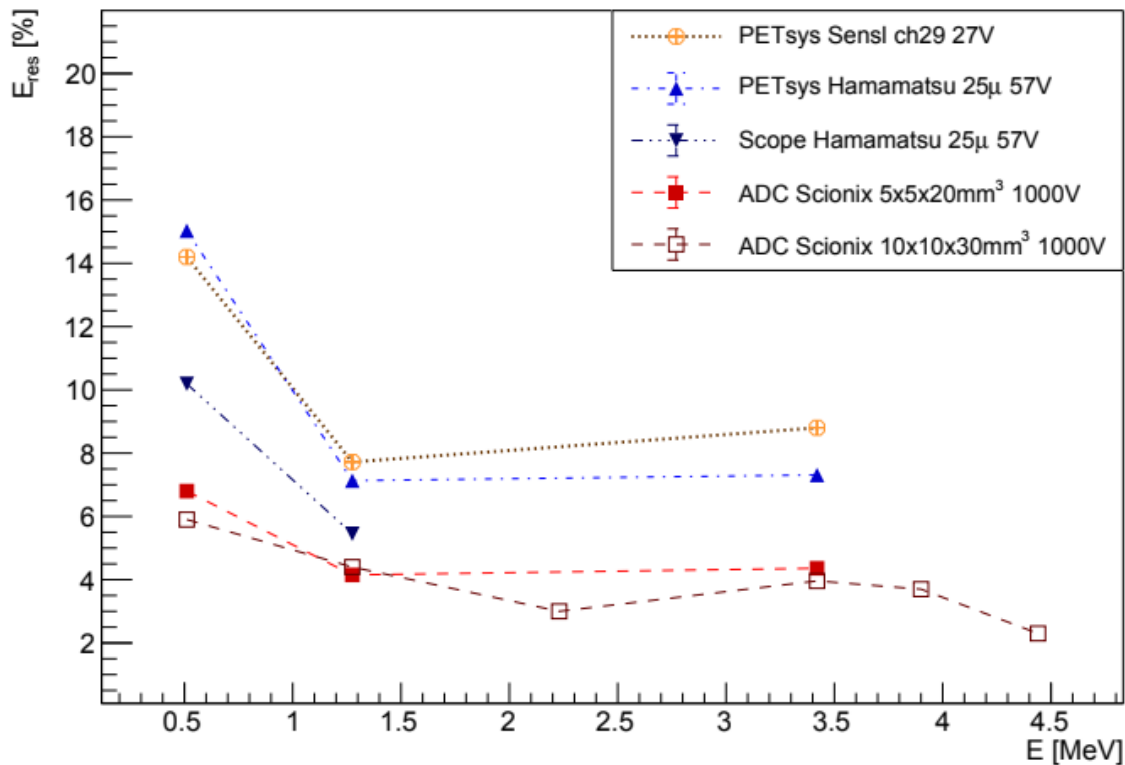
Comparison between 3 setups
- ADC   + PMT   + CeBr$_3$
- Scope   + SiPM + CeBr$_3$
- PETsys + SiPM + CeBr$_3$

Energy resolution with 2.355 conversion factor

We loose ~ 3% of energy resolution with PETsys

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Time Resolution

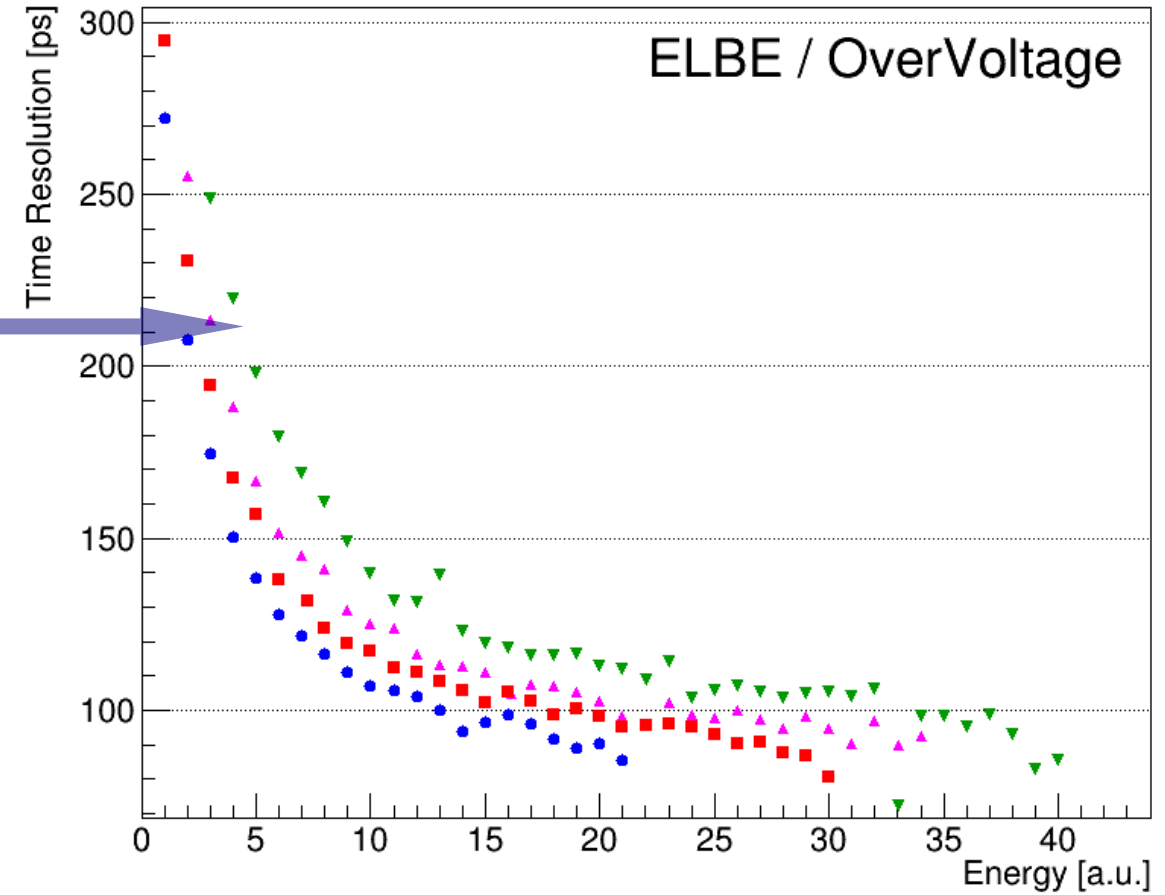ELBE at HZDR Rossendorf γ-source with ps time resolution [R. Schwengner et al., Nucl. Instr. Meth. A 555, 211 (2005)].

Sliced in energies → fit the distribution

→ take one sigma
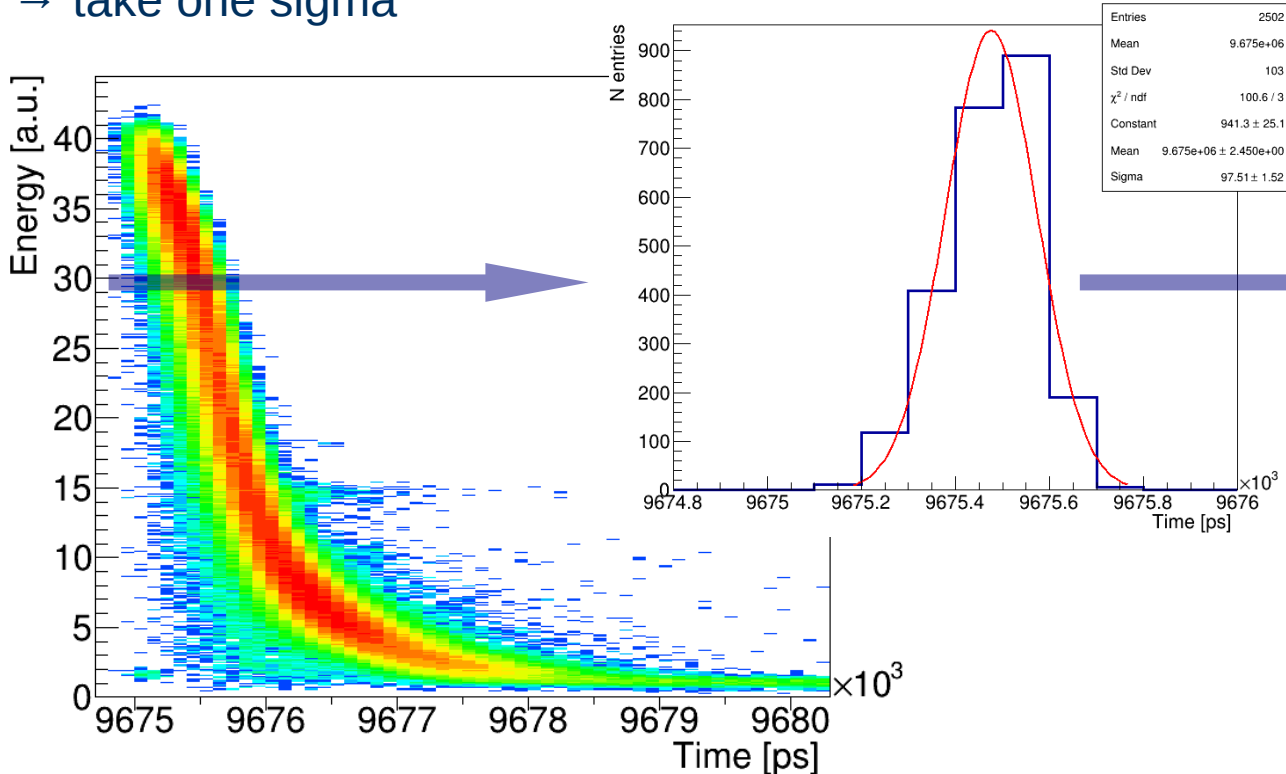
Reach time resolution below 100 ps

Coincidence Time Resolution
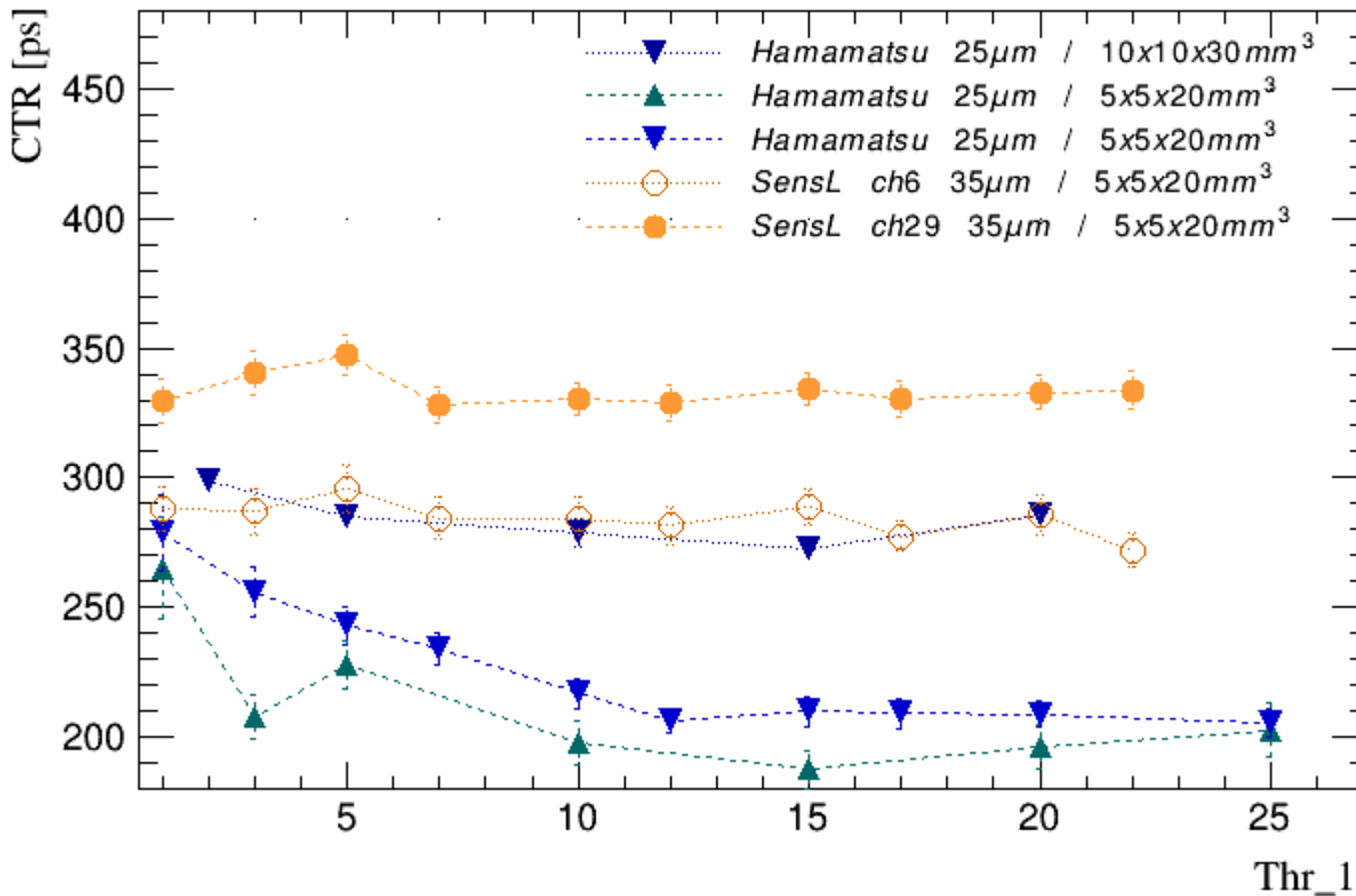
Measure in the Lab with ^{22}Na source

Increase of size of crystal – increase of the CTR

Hamamatsu 25µm and 50µm showed better coincidence time resolution

Rates

- Max channel hit rate: 600 kHz (test pulses).

- ^{60}Co and ^{137}Cs high rate sources tests – Loss of the events over 100 kcps.

- Pile-up effect → shift of the peak positions.
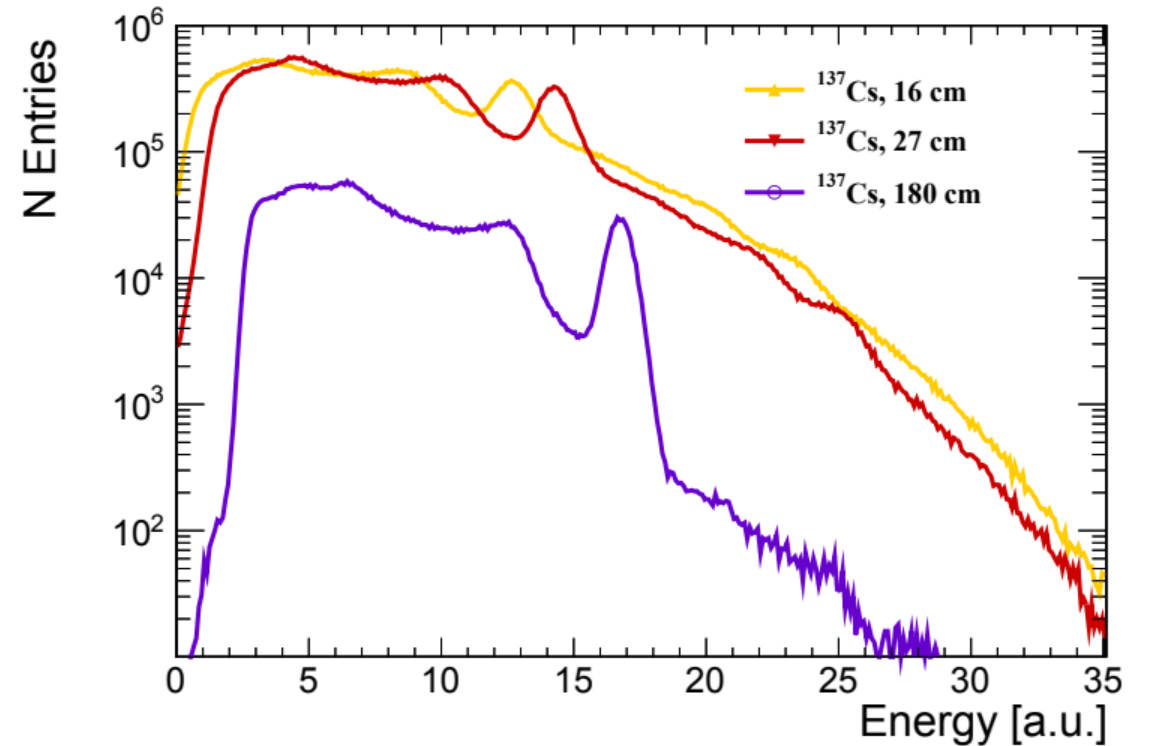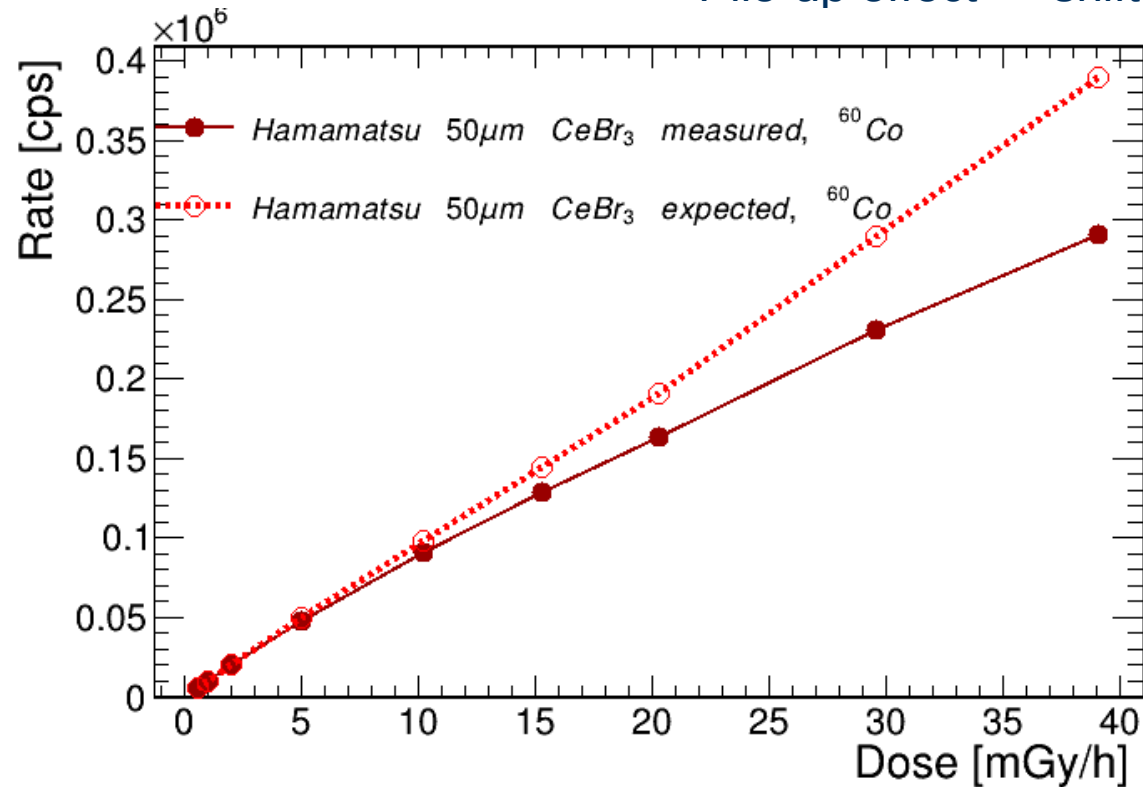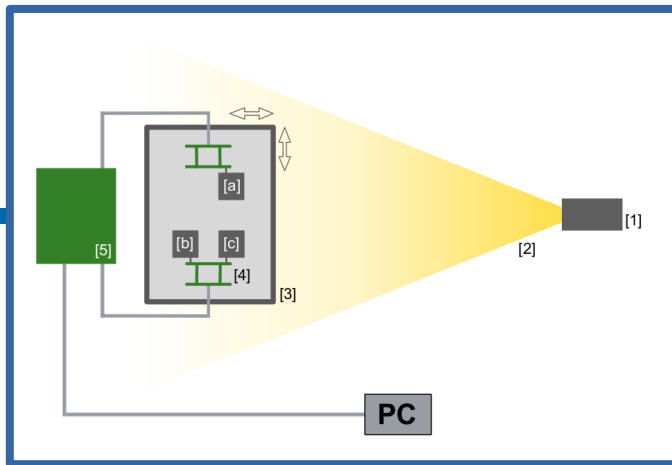
Conclusions

CeBr$_3$ Granularity:

5x5x20 mm³

+ Fit to SiPM

+ Best Energy & Time resolution

- Double escape peaks

10x10x30 mm³

- Loss of Energy and Time resolution

+ Single & double escape peaks

Silicon Photomultipliers (SiPM):

SensL 35 µm array   best available candidate

+ Good Energy resolution
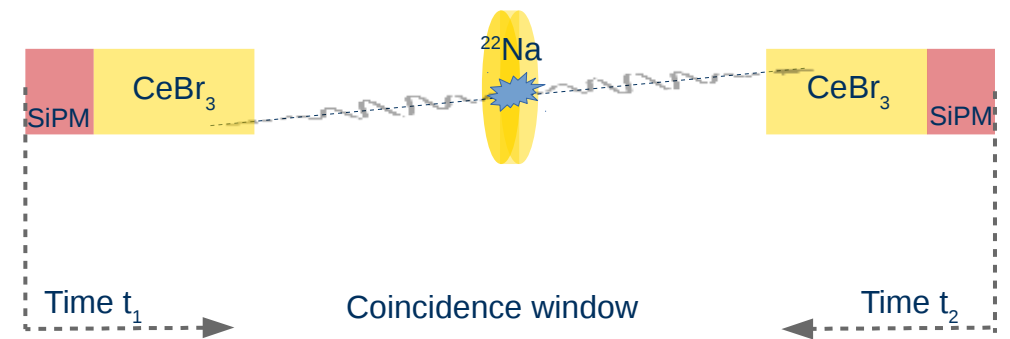
- Loss in Time resolution

Hamamatsu 25 µm

+ Best Energy and Time resolution

- Single SiPMs (build array)

+ Avoid crosstalk and alignment

PETsys Readout :   + easy scalable

+ ~100 ps time resolution

+ 3% loss in $E_{resolution}$

- Time walk correction

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Takeaway

CeBr₃ Granularity:

5x5x20 mm³

    + Fit to SiPM

    + Best Energy & Time resolution

    - Double escape peaks

10x10x30 mm³

    - Loss of Energy and Time resolution

    + Single & double escape peaks

Performance looks promising

Silicon Photomultipliers (SiPM):

SensL 35 μm **It appeared to be sufficient for Prompt Gamma Timing measurements**

    + Good Energy resolution   + Best Energy and Time resolution

    - Loss in Time **Realistic measurements at proton beam to confirm the performance**

    + Single SiPMs (solid array)

    + Avoid crosstalk and alignment

PETsys Readout :   + easy scalable

                    + ~100 ps time resolution

                    + 3% loss in $E_{resolution}$

                    - Time walk correction

Thank you for your attention...

Aknowledgements:
OncoRay TU Dresden
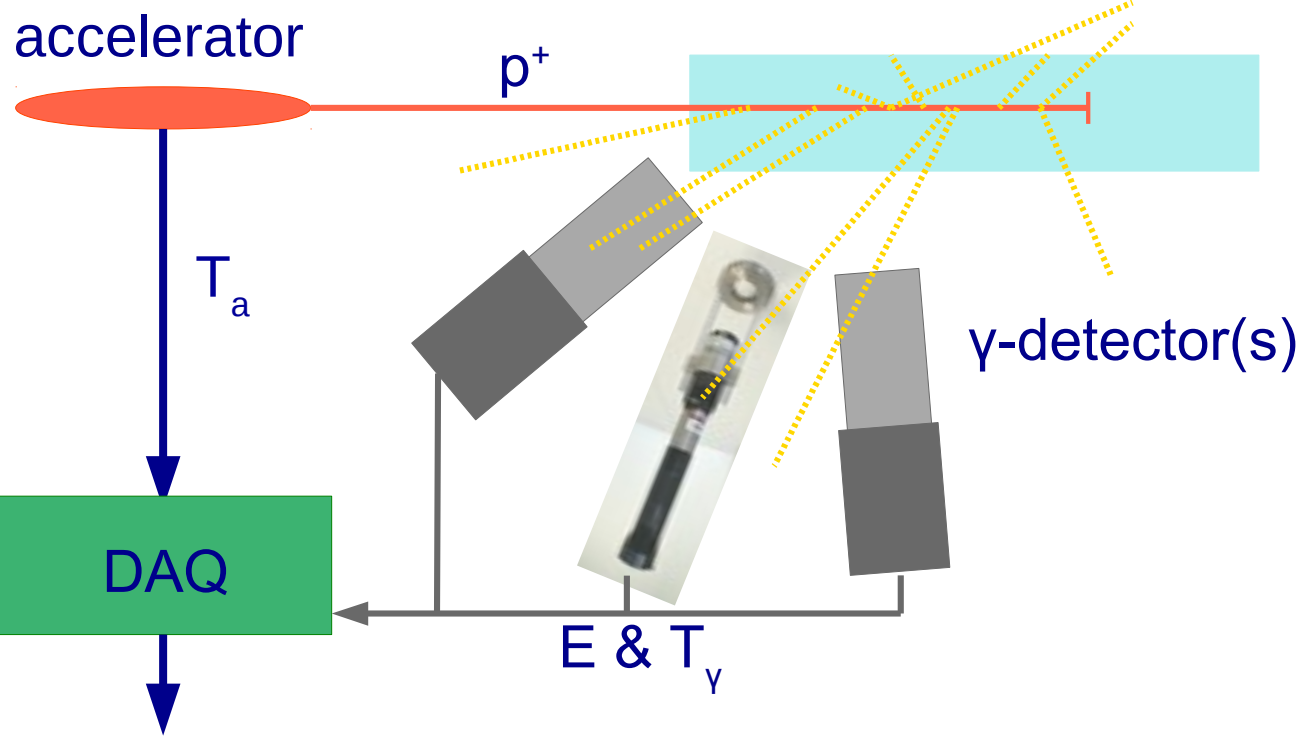ELBE HZDR Rsesondorf – gamma source
G. Pausch, T. Kögler, B. Lutz & K. Römer
PETsys electronics for support & Scionix for $CeBr_3$ production

Continue to backup slides....

References:

- Melek Zarifi, "Toward Non-invasive in vivo Dosimetry of Proton Therapeutic Beam Using Prompt Gamma"

- Theresa Werner, "Processing of prompt gamma-ray timing data for proton range measurements at a clinical beam delivery", 2018

- PETsys readout electronics https://www.petsyselectronics.com

- R. Schwengner et al., Nucl. Instr. Meth. A 555, 211 (2005). ELBE at HZDR Rossendorf γ-source with ps time resolution.

- CAEN,V1730 / V1730S 16/8 Channel 14 bit 500 MS/s Digitizer,www.caen.it/products/v1730/

- Hamamatsu,HAMAMATSU MPPC s13360 Series, www.hamamatsu.com/resources/pdf/ssd/s13360_series_kapd1052e.pdf

- OnSemi,Silicon Photomultiplier (SiPM) High Fill-Factor Arrays,www.onsemi.com/pdf/datasheet/arrayj-series-d.pdf

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Measurements

accelerator

p^+

T_a

DAQ

E & T_γ

Energy & Time

γ-detector(s)

Source

HV

Scintillator

PMT, SiPM

Fast ADC or Scope

Measurements: Accelerator or Sources in the LAB

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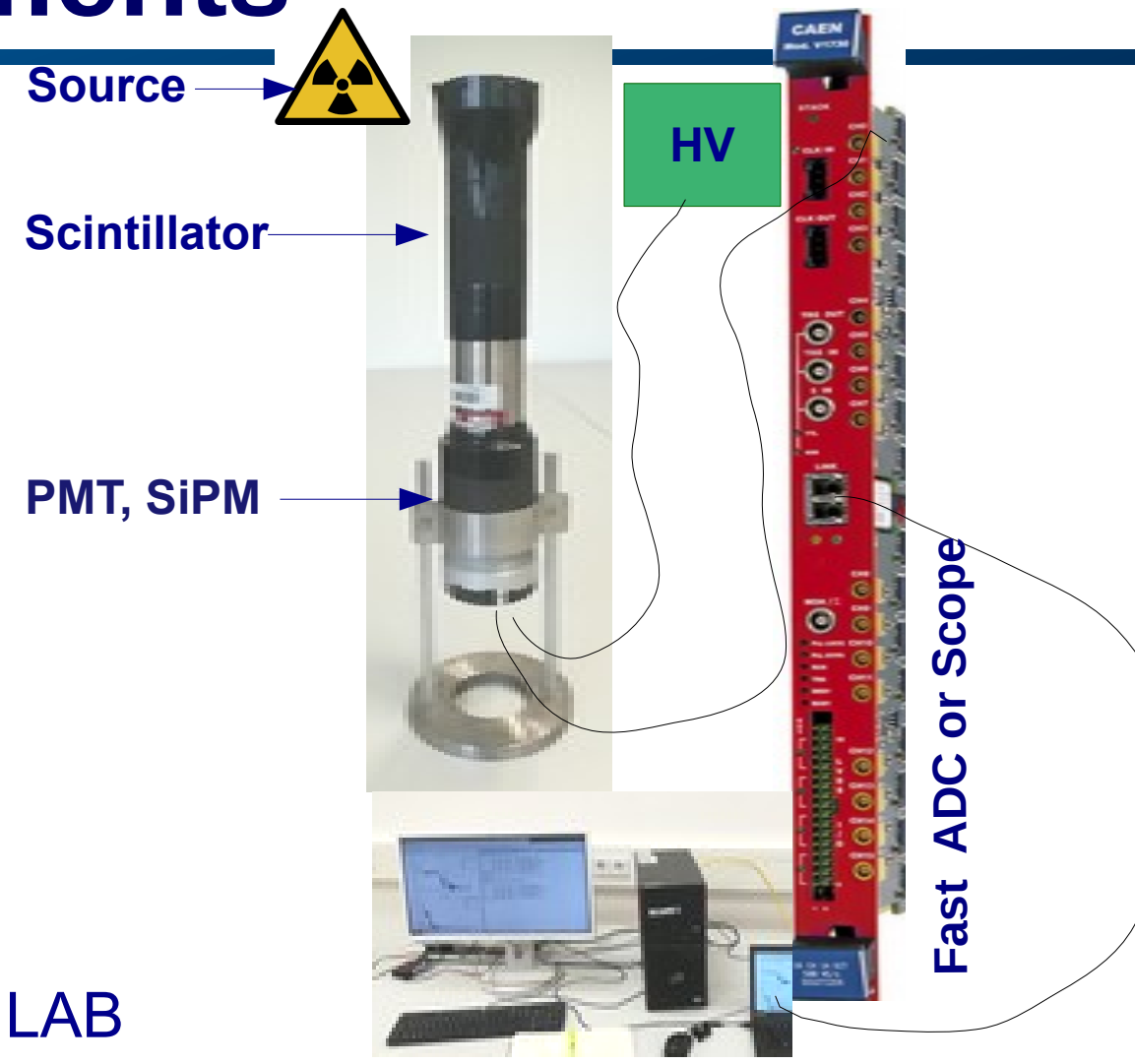
Scintillator Characteristics

Characteristics	BGO	LYSO	CeBr3	GAGG(Ce)
τ (ns)	300	41	19	88
Time resolution 4.4 MeV (ps)	980	385	189	600
Energy resolution 662 keV %	9.78	10.3	4.0	6.5
Energy resolution 4.4 MeV %	4.5	4.12	2.2	3.8
Max. Emission (nm)	480	422	358	528
Photons per MeV	8200	32000	60000	32400-57000
Z_{eff}	75	54	45.9	54.4
Density / g cm^3	7.13	5.37	5.1	6.63
Hygroscopic	No	No	Yes	No
Internal activity	No	Yes	No	No

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SiPM Characteristics

Name	Pixel Pitch / mm	Pixel Size / μm	N Pixels	Opt. λ / nm
KETEK PA3325-WB-0808	3.36	25	13920	430
Hamamatsu S13360-6025CS	6.0	25	57600	450
Hamamatsu S13360-6050CS	6.0	50	14400	450
Hamamatsu S13361-3050NE-08	3.0	50	3584	450
Sensl ARRAYJ-60035-4P-PCB	6.33	35	22292	420

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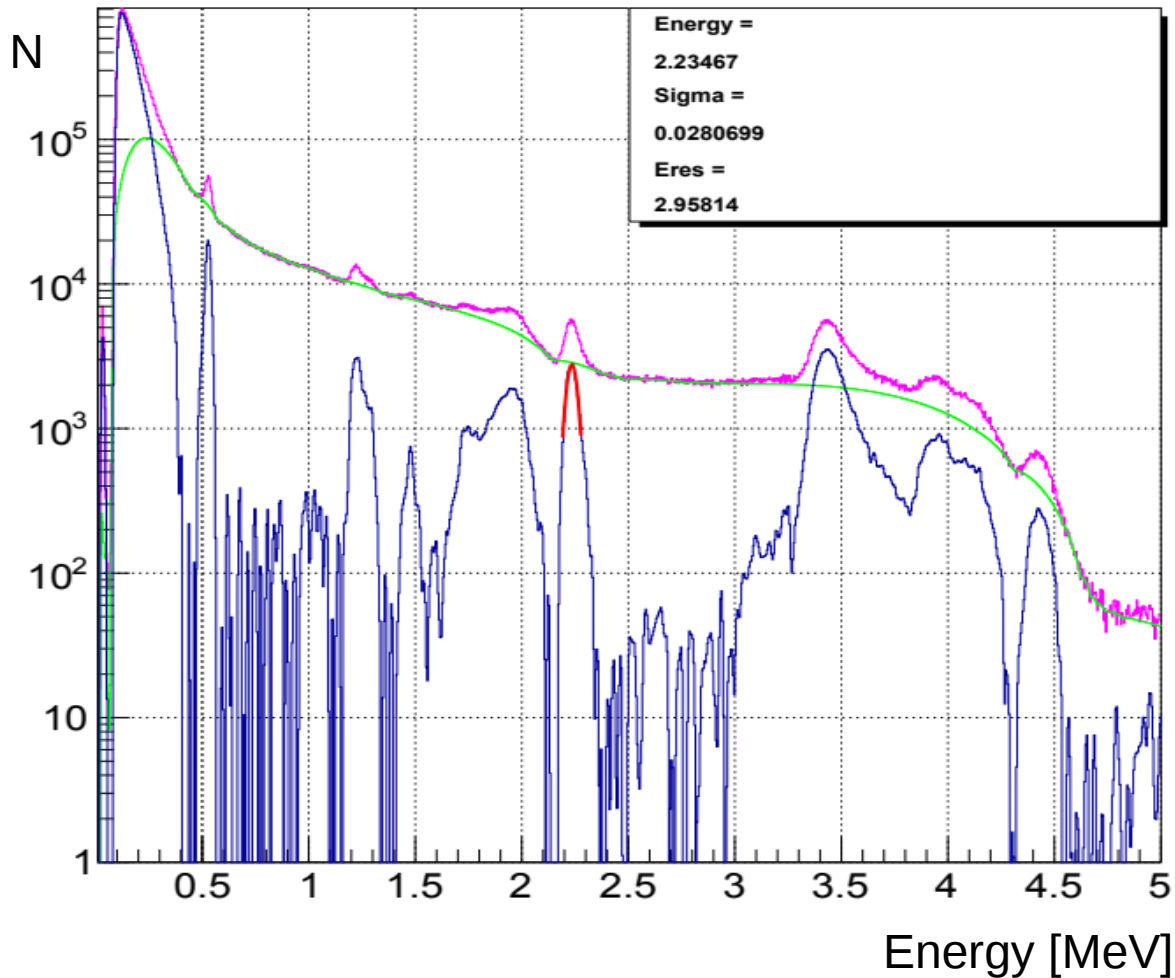
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Time Walk

Required time resolution few 100 ps
– PETsys ~100 ps
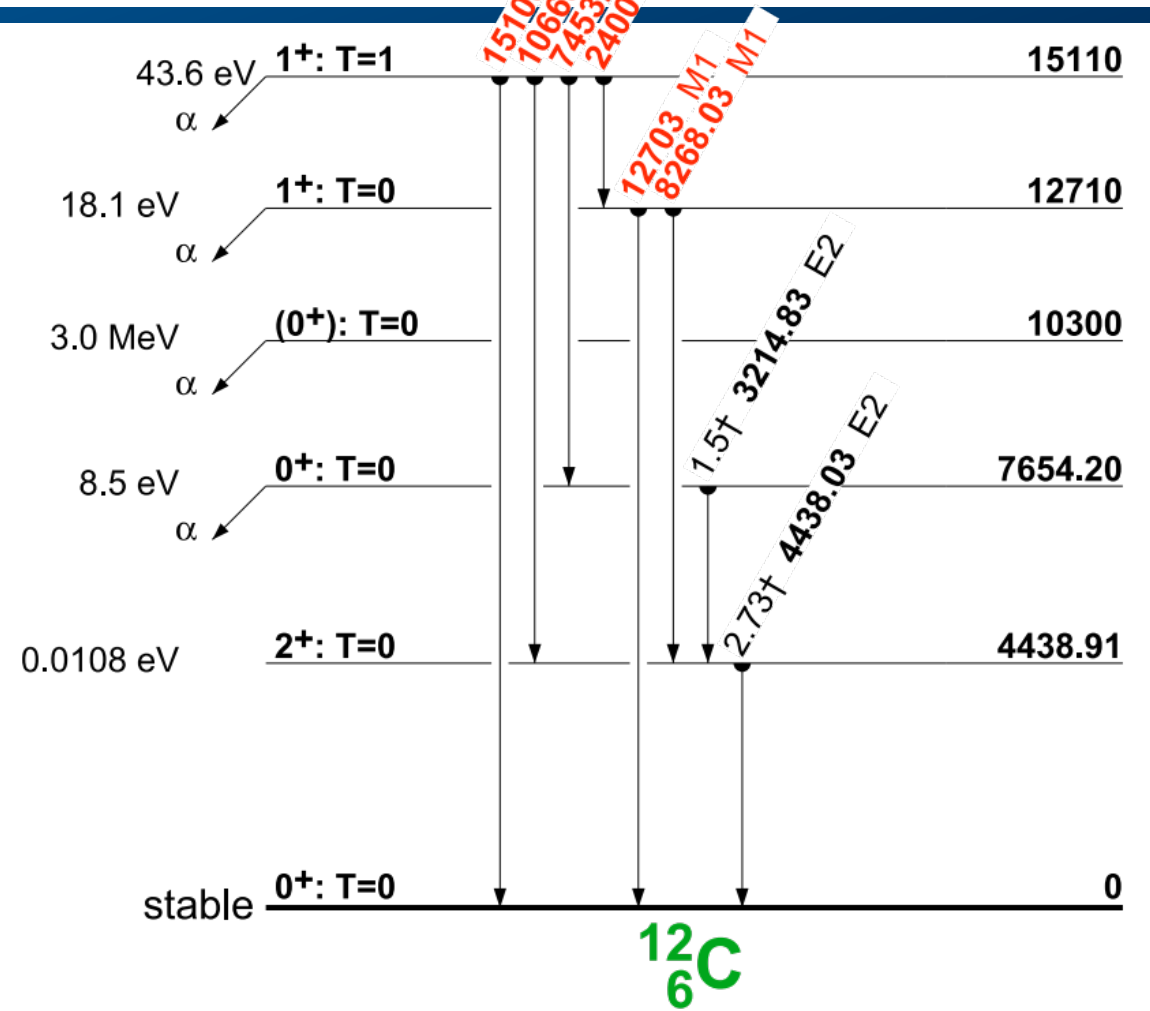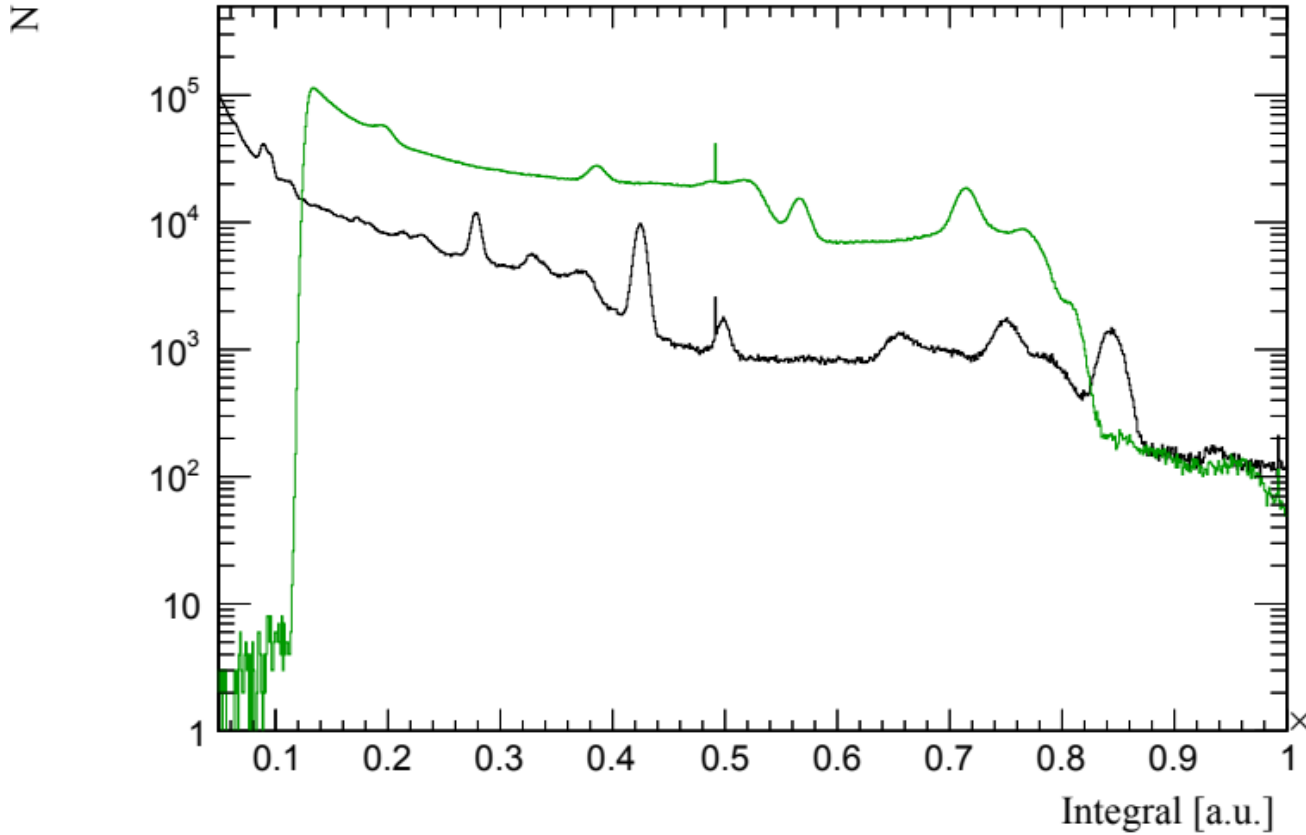Fixed thresholds instead of CFD is a
disadvantage:

Time walk up to 500 ps

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Energy Resolution CeBr$_3$

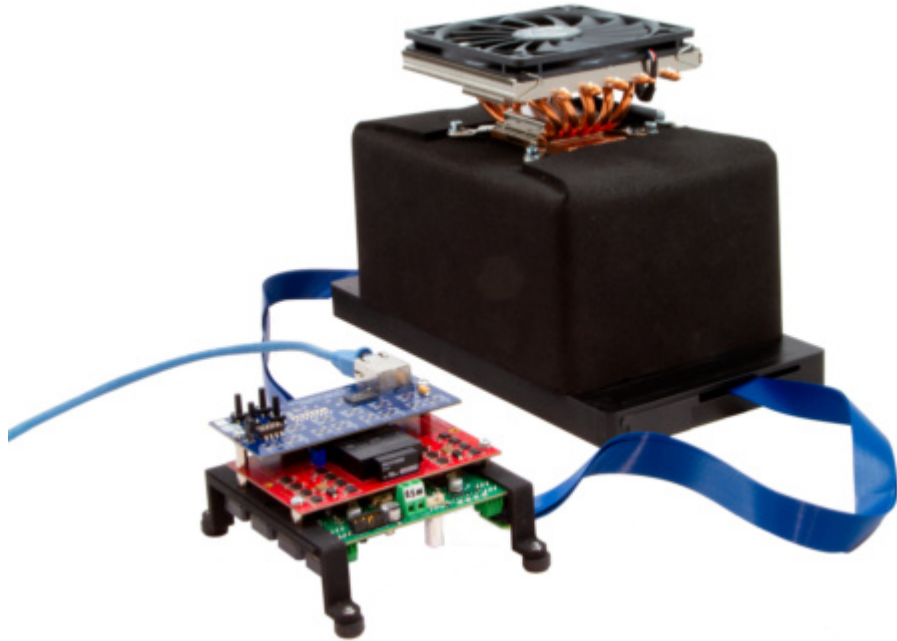Energy =
2.23467
Sigma =
0.0280699
Eres =
2.95814

N

Energy [MeV]
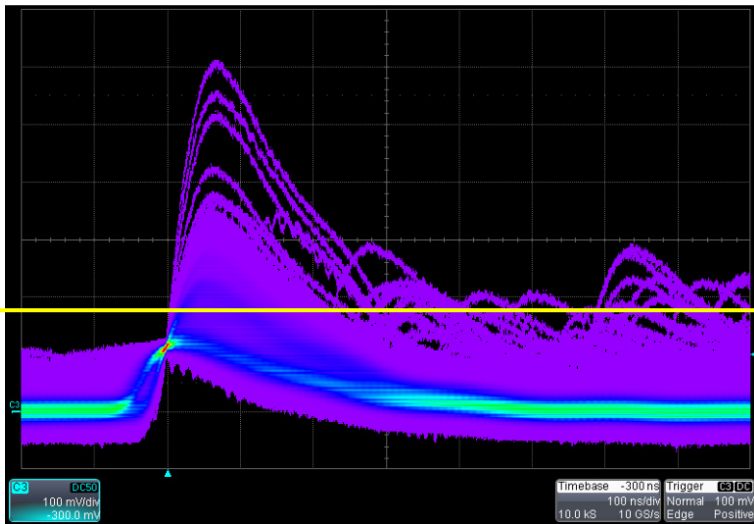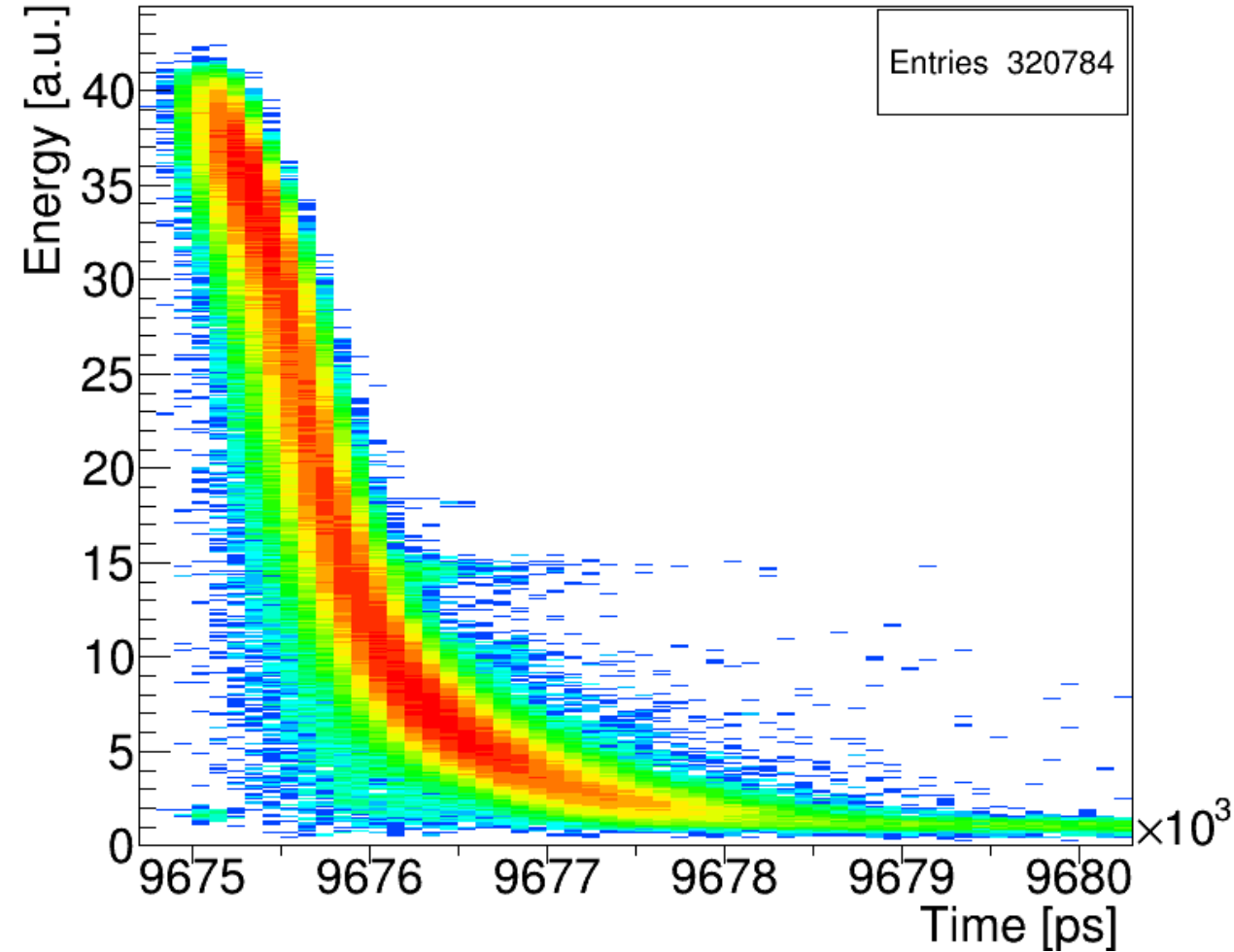
1. ROOT TSpectrum to estimate background (green)
2. After background subtraction (blue)
3. Gaussian fit (red)
4. $E_{res} = \sigma/\mu * 2.355$
5. 2.355 - conversion factor to calculate full width at half maximum (FWHM)

– due to difficulties to estimate background for the full energy range and low statistics at higher energies.

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PETsys Evaluation Kit

→ cost effective
→ fast
→ scalable

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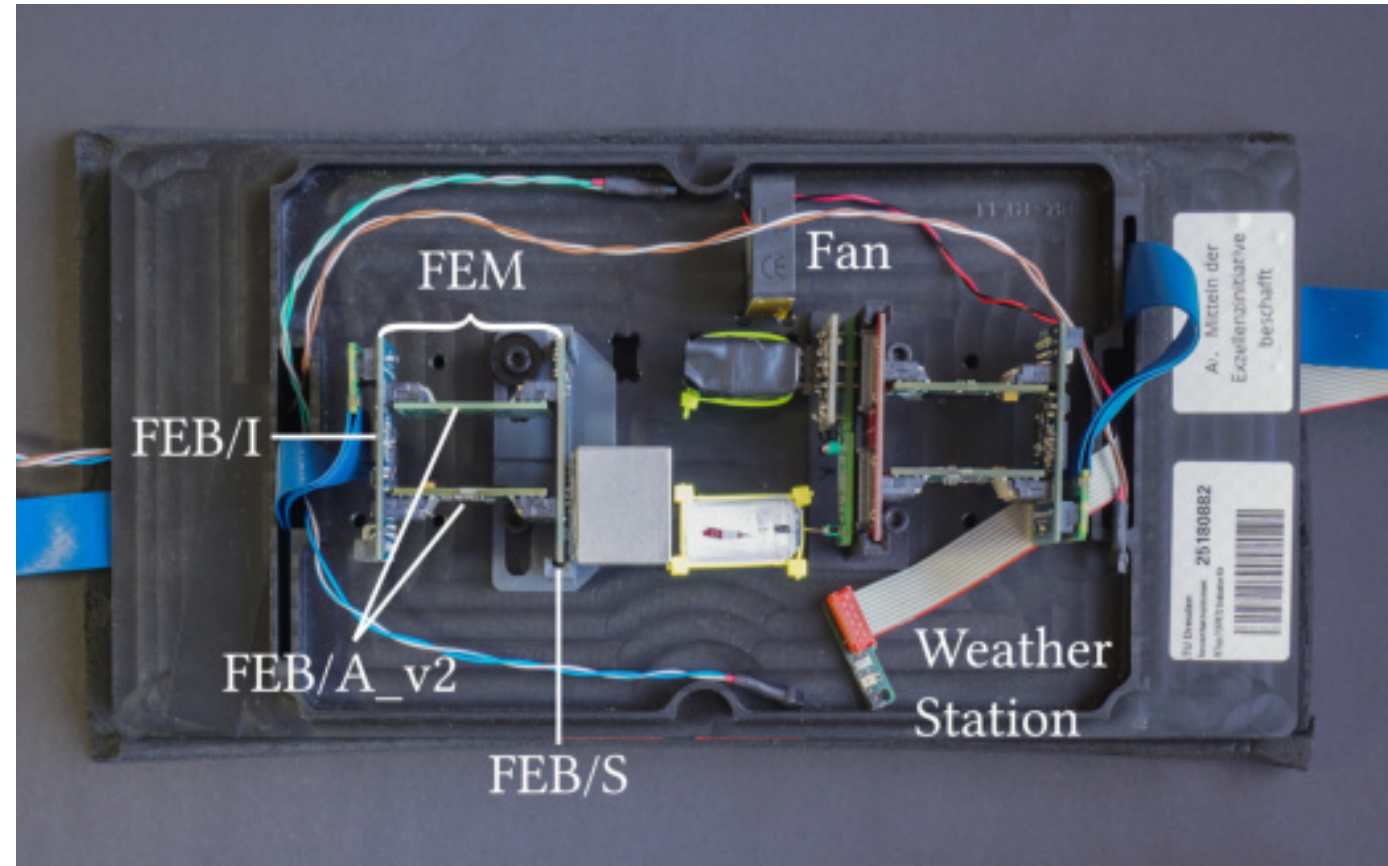
PETsys TOFPET2 ASIC

- Designed in standard CMOS 110 nm technology.
- Version 2.d accepts positive or negative input signals;
- Signal amplification and discrimination for each of 64 independent channels.
- Separately configurable t1, t2 and energy thresholds for each channel.
- Rejects dark counts without triggering, allowing to handle large dark counts rates.
- Configurable charge integration time up to two microsecond.
- Quad-buffered TDCs and charge integrators for each channel. The first branch is used for timing measurement. The second branch can either be used for time-overthreshold (ToT) or charge measurement with a Wilkinson ADC.
- Dynamic range: 1500 pC.
- TDC time binning: 30 ps.
- Gain adjustment per channel in the charge branch: 1, 1/2, 1/4, 1/8.
- On-chip charge calibration pulse generator with 6-bit programmable amplitude.
- Main clock frequency: 160-200 MHz.
- Configurable digital data output over 1, 2, or 4 LVDS data links at 2x the main clock frequency and single data rate (SDR) or double data rate (DDR).
- Max output data rate per ASIC: 3.2 Gb/s.
- Max event rate per channel: 500 kevent/s, 80 bits per event.
- Power dissipation per channel: 5 to 8.2 mW, depending on settings.

The Energy Resolution at 511 keV is 10.5 % (LYSO 3x3x5 mm^3 crystal with a KETEK-PM3325-WB SiPM at 4 V.)
Coincidence Time Resolution of 119 ps FWHM (LYSO 2x2x3 mm^3 crystals with two Hamamatsu S13361-30361-3050AE SiPM arrays.)