New detectors for kaonic nuclei/atoms measurements

Johann Zmeskal

WORKSHOP
Toward a new era of kaonic nuclei and atoms at DAFNE and J-PARC
RIKEN, Dec. 14, 2023

JRA8 - ASTRA

Advanced ultra-fast solid STate detectors for high precision RAdiation spectroscopy

Johann Zmeskal, SMI

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

JRA8 - project members

Beneficiary number	Organization legal name (in italics the Research Units)	Short name
2	Oesterreichische Akademie der Wissenschaften	OEAW
26	Sveuciliste u Zagrebu	UNIZG
28	Consiglio Nazionale delle Ricerche	CNR
30	Istituto Nazionale di Fisica Nucleare	INFN
31	Politecnico di Milano	POLIMI
38	Uniwersytet Jagiellonski	UJ

Why Cadmium Zinc Telluride (CZT)

Cadmium Zinc Telluride (CZT) is a very promising semiconductor materials for X-ray and gamma ray detection.

- The high atomic numbers of the materials ($Z_{Cd/Zn/Te}$=48, (30), 52) provide a high quantum efficiency in comparison with Si (Z=14).
- The larger band-gap energy Eg~1.5 eV allows the operation of the detector at room temperature (compared to Si Eg~1.1 eV, Ge Eg~0.7)

CZT energy range up to 50 keV resolution 500 eV (FWHM) @ 20 keV

CZT energy range 0.05 – 1 MeV resolution 1 keV (FWHM) @ 200 keV

➢ energy resolution is slight worse than achieved with HPGe, BUT better timing and high rate capability

CZT detectors - expected results

Compact modular room temperature detector systems optimized for two energy ranges with excellent energy resolution; FWHM about 3% at 60 keV and about 1% at 662 keV.

Strangeness precision frontier at DAΦNE (LNF-INFN):

- Determination of the charged kaon mass (K^-).
- Understanding the antikaon-nucleon interaction

Medical applications:

- Compton camera, PET (UY)
- Non-invasive input function measurement for positron emission tomography (SMI)
- Boron Neutron Capture Therapy (CNR-IMEM)

Physics motivation

LNF Workshop: Fundamental Physics at the Strangeness Frontier (Feb. 2021)

KAonic **HEL**ium 2p → 1s transition
The first measurement of the $K^{3,4}He(2p \rightarrow 1s)$ transitions will allow to extract the isospin dependent scattering length in a system with more than two nucleon, to put stronger constraints on the theoretical models describing the kaon nucleon interaction.

LIght **K**aomic **A**toms **M**easurements
Hints on the nature of the Λ(1405) can be obtained from the upper level transitions of light kaonic atoms like Li, Be and B

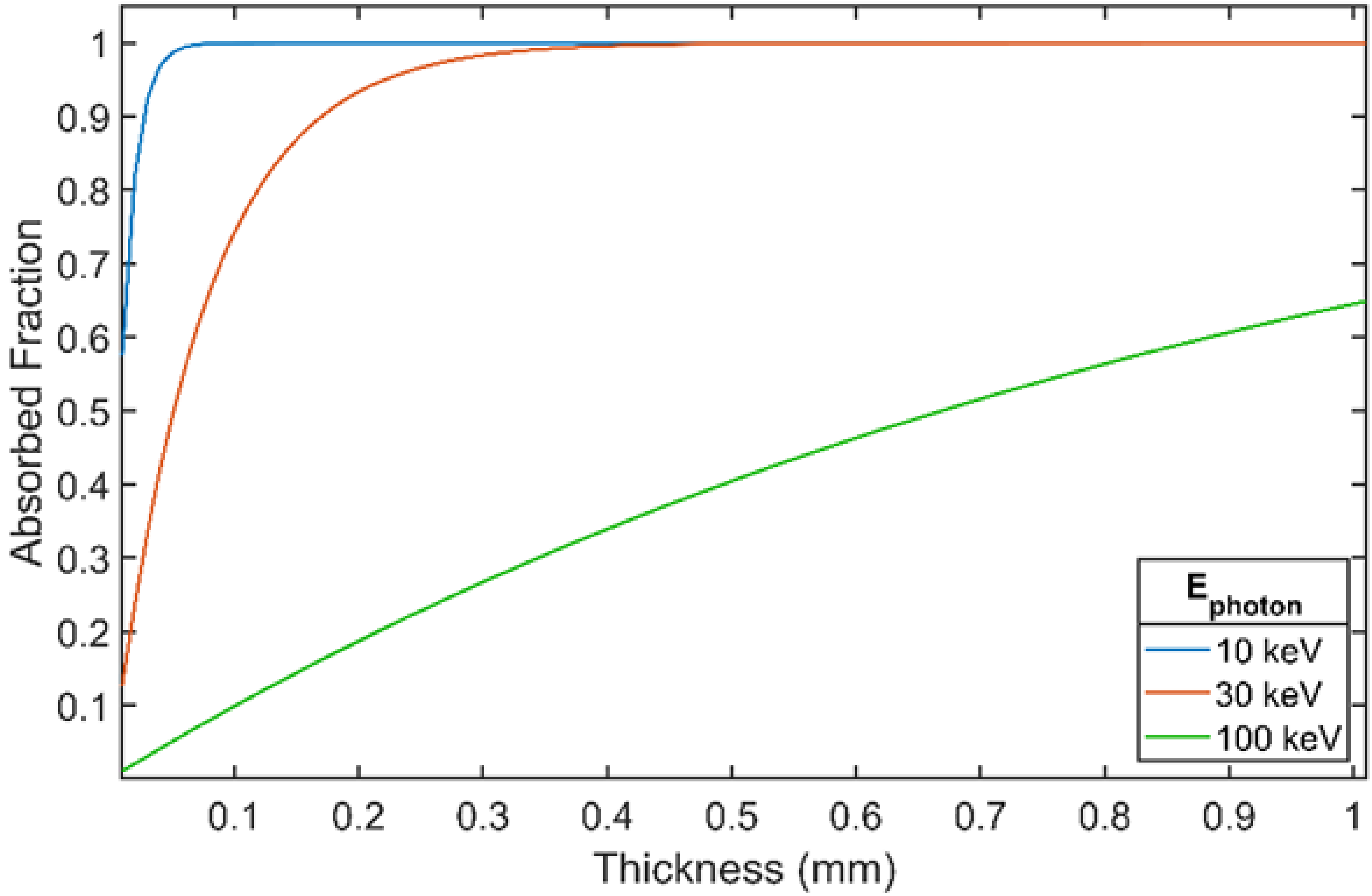
- with energies laying between 10 and 100 keV

ASTRA - project objectives

ASTRA will develop a versatile advanced detector system, from sensors and read-out electronics, to DAQ and controls, namely compact large-area CZT detectors to perform high precision photon energy measurements from 10-100 keV and up the MeV range, respectively.

- **Task 1:** Low energy detection region - energy range: 10 – 100 keV
- **Task 2:** High energy detection region - energy range: 50 – 1000 keV

Task1 – low energy detector



Low energy detection region

Fraction of absorbed radiation as a function of the CZT thickness for different photon energies.

- for 1 mm thick CZT
  efficiency at 30 keV ~100%;
  at 100 keV ~ 65%

Task1 – low energy detector

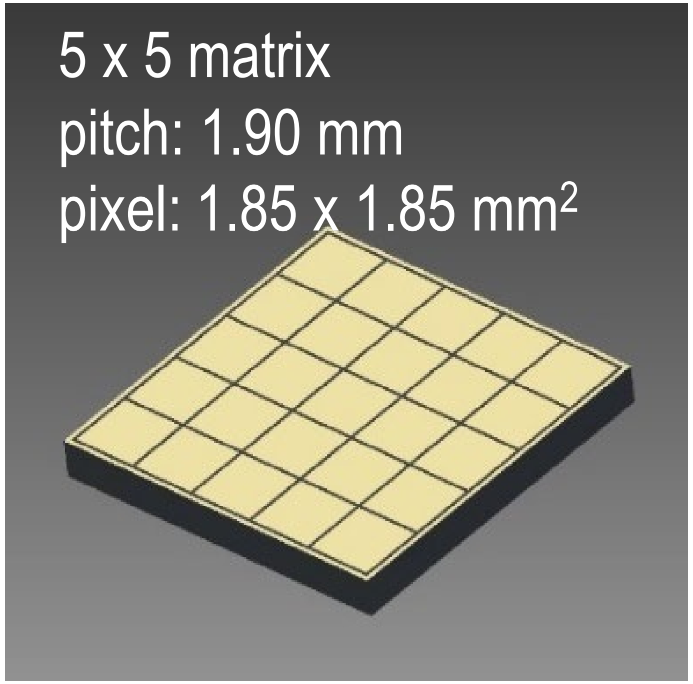
Pixel matrix design

Advantage

- The weighting potential is focused in a small region under the pixel.
- Possible effects due to crystal inhomogeneity can be corrected electronically.
- For a given flux, the number of events/channel is reduced (pileup effect is less probable).

Disadvantage

- A greater number of read-out channels is required.
- More events are shared among multiple pixels



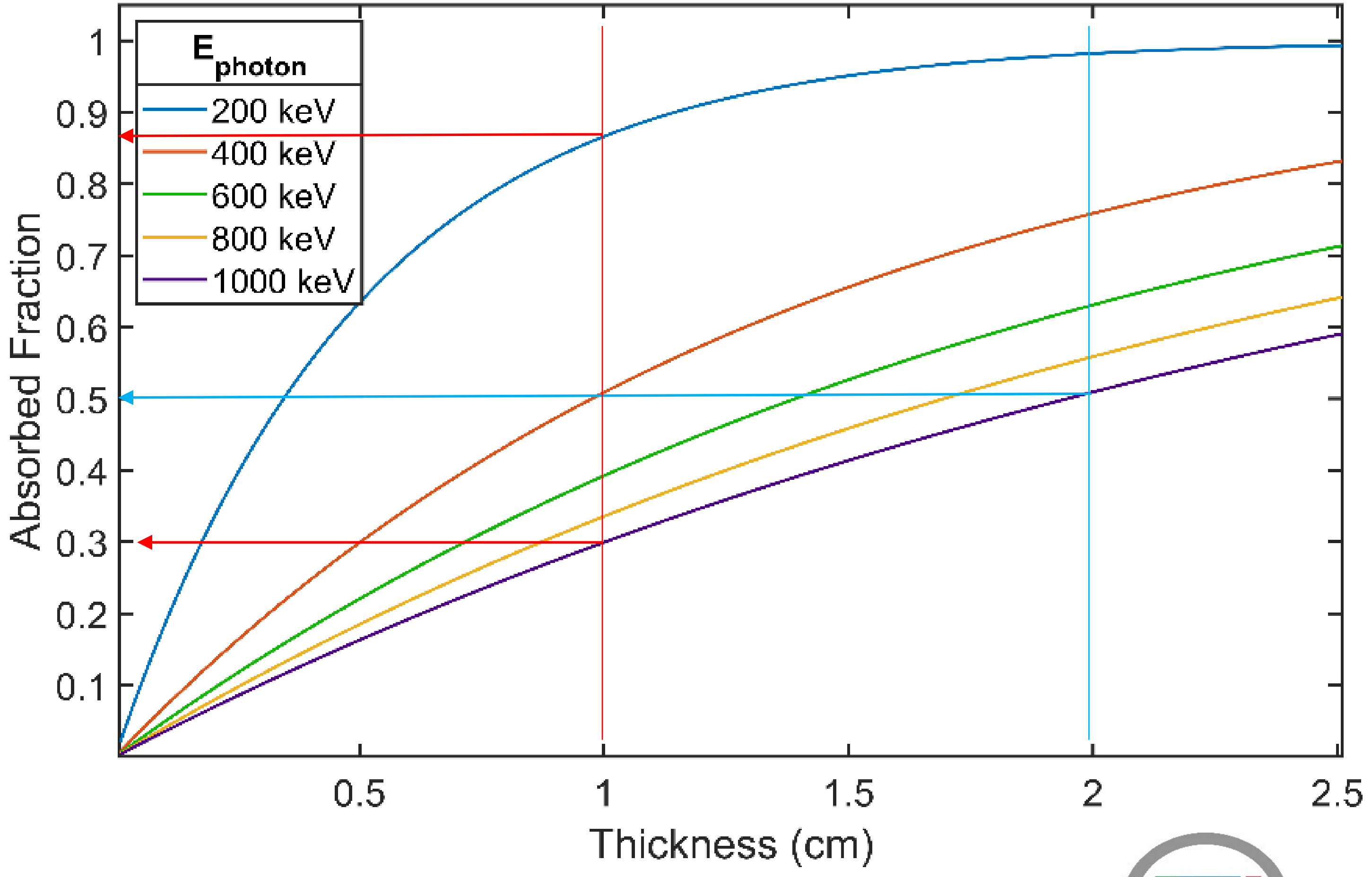
A possible detector design consists of a 5×5 matrix with a pitch of 1.9 mm (1850 μm pixel + 50 μm gap).

Task2 – high energy detector

For the high energy detector a complete absorption is not feasible.

The absorbed fraction as a function of the crystal thickness is shown in the figure for photons of different energies.

- ➢ 25 mm can be considered the maximum possible thickness since it represents the state-of-the-art for this class of detector.



Task2 – high energy detector

Material considerations

- For high energy detection CdTe cannot be an option since the polarization effect increases with the thickness and therefore we use CZT.
- From our experience, CZT from Redlen Technologies is one of the best materials to realize thick detector (>10 mm).
- The electron mobility and lifetime product ($\mu_e \tau_e$) allows a good CCE up to 25 mm.

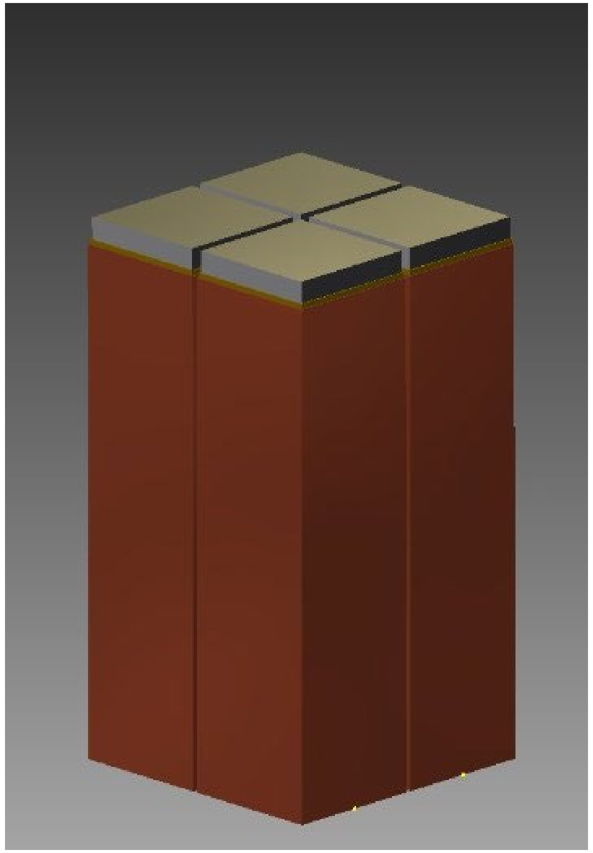
➢ The choice of the thickness has several consequences on the signal:
  - A strong electric field is required for collecting all electrons.
  - In case of multi-electrodes detector charge sharing effect will increase.
    ➢ Solution: Frisch grid detector has no charge sharing regardless the CZT thickness.

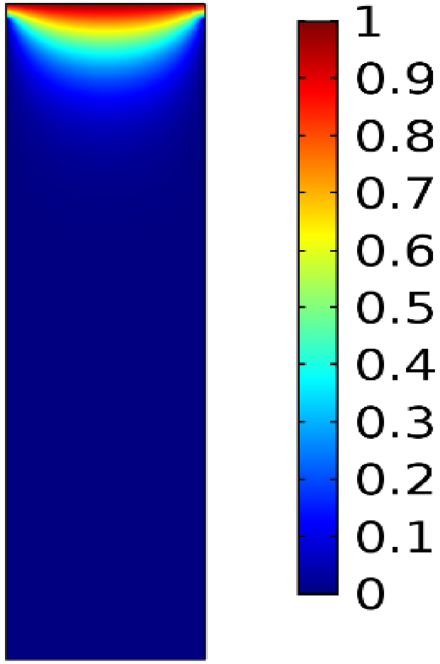
Task2 – high energy detector

Frisch-grid configuration

Due to the presence of non-collecting contacts on the lateral surfaces of the crystal, the weighting potential is focused in a small region under the collecting electrode.

The Frisch grid detector has only one collecting electrode, charge sharing is avoided in this type of geometry.

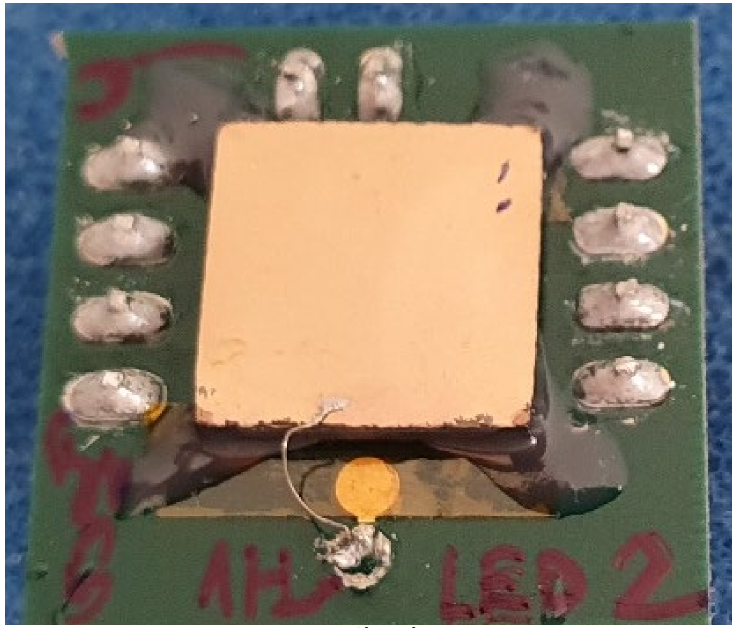




Low energy detector characterisation

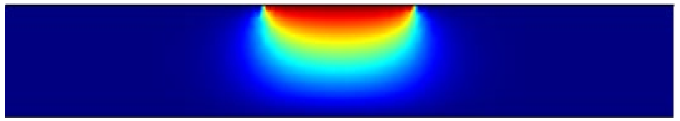
First low energy detector prototype

First low energy detector prototype
consisting of a 3×3 matrix with a pitch of 1.9 mm (1850 μm pixel + 50 μm gap), thickness 1.5 mm

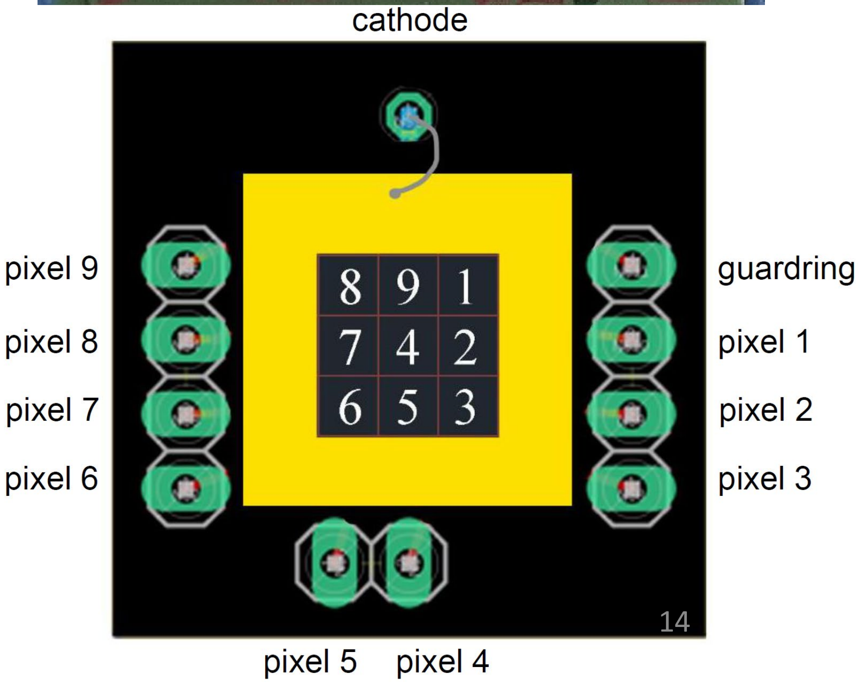


Advantage

- The weighting potential is focused in a small region under the pixel.



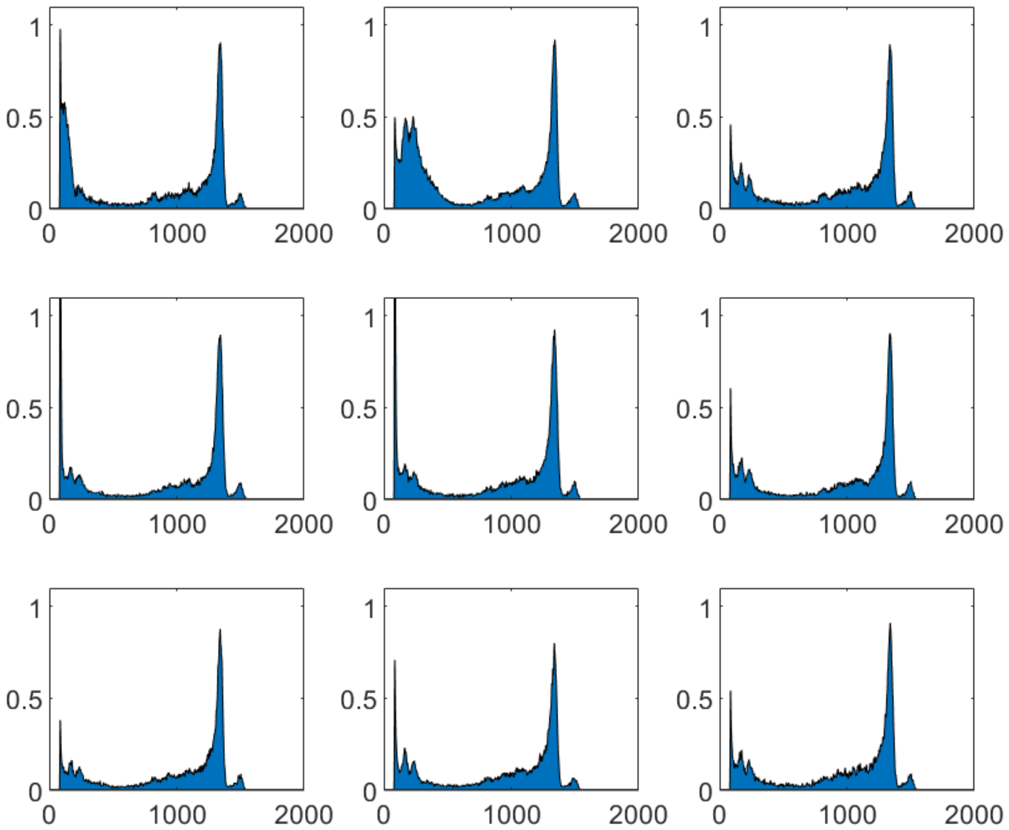
- Possible effects due to crystal inhomogeneity can be corrected with dedicated electronics.

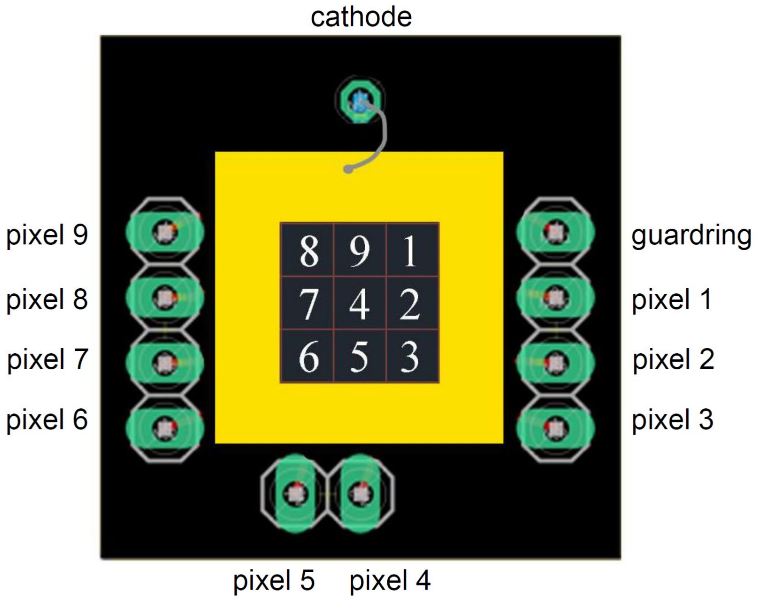


First low energy detector prototype

Spectroscopic performance, with Co57:

of a 3x3 matrix with pixel sizes of 1.85x1.85 mm^2 and a thickness of 1.25 mm

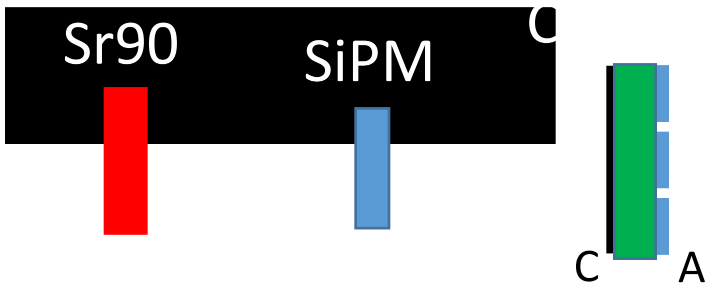


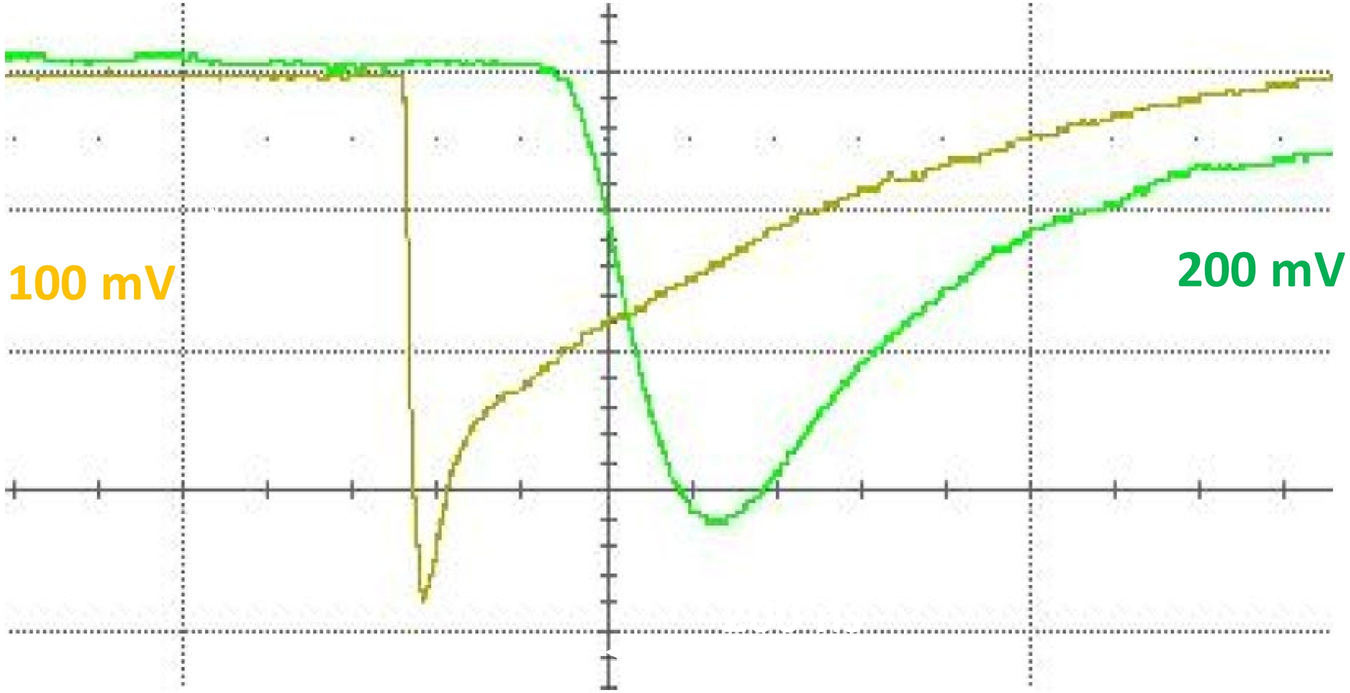


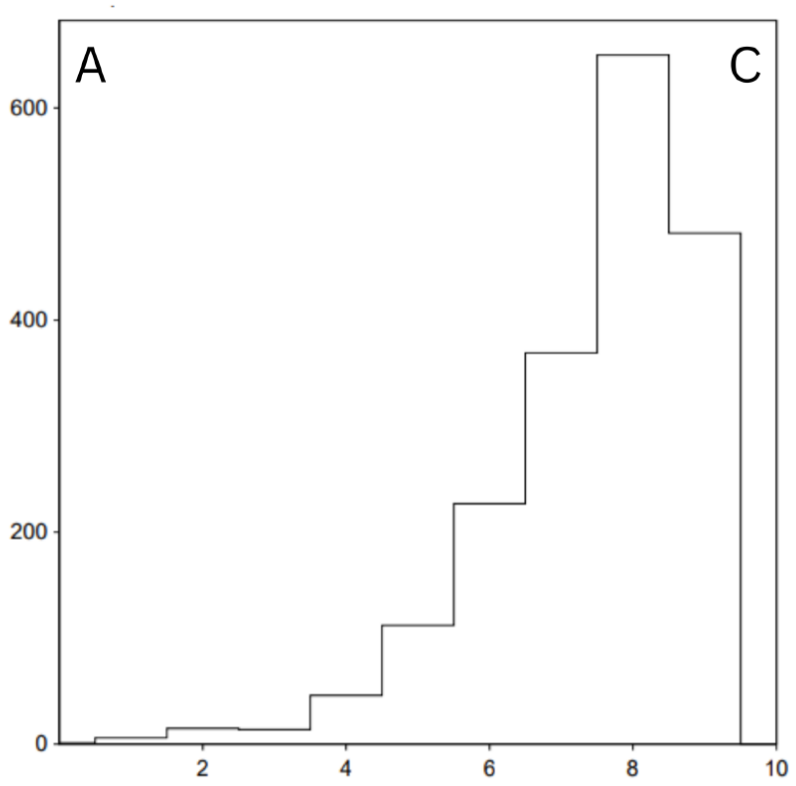
FWHM at 122 keV with Co57

3.6%	3.8%	4.3%
4.2%	4.4%	3.8%
3.6%	4.5%	3.6%

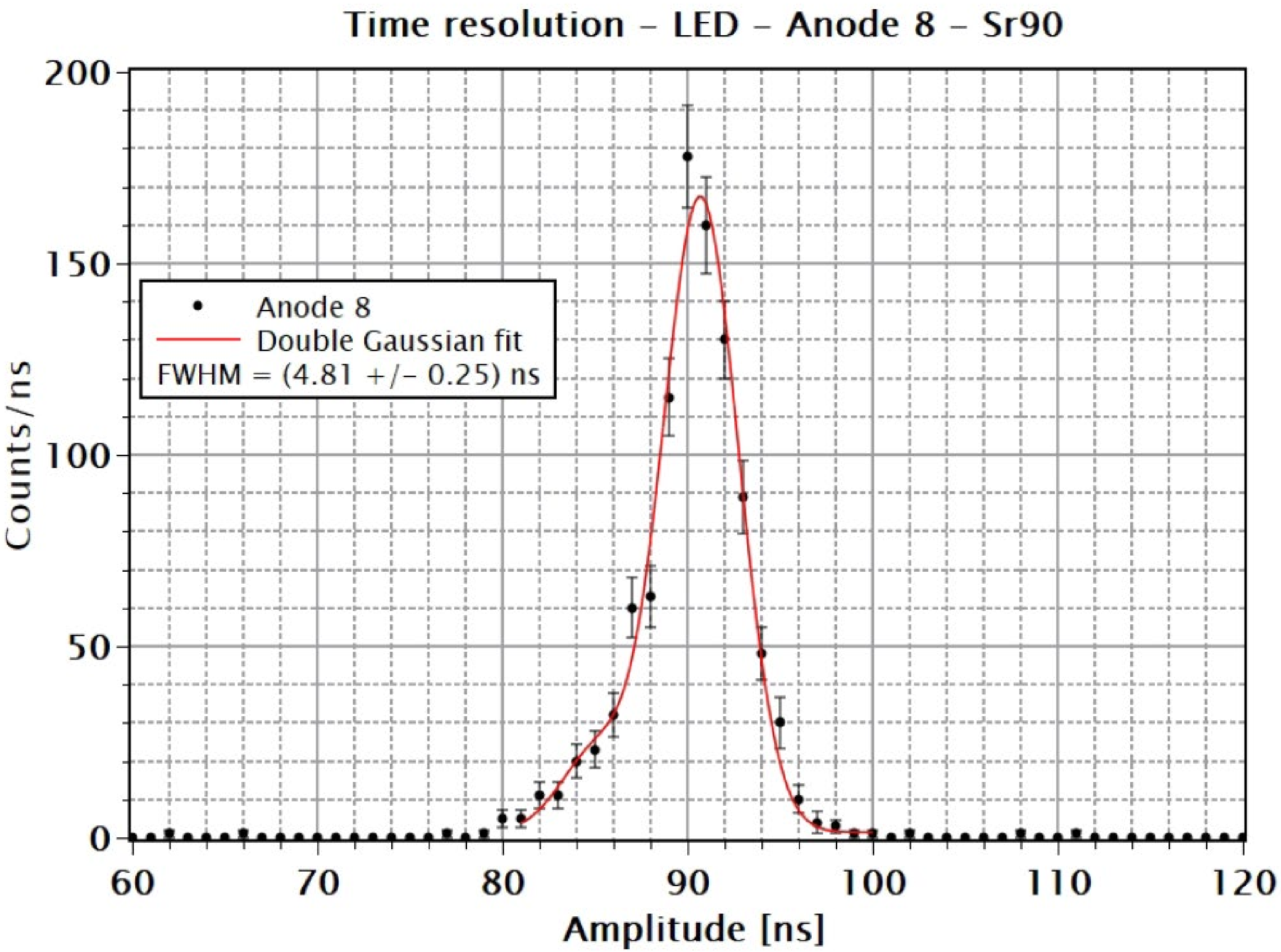
LED: timing with electron source Sr-90







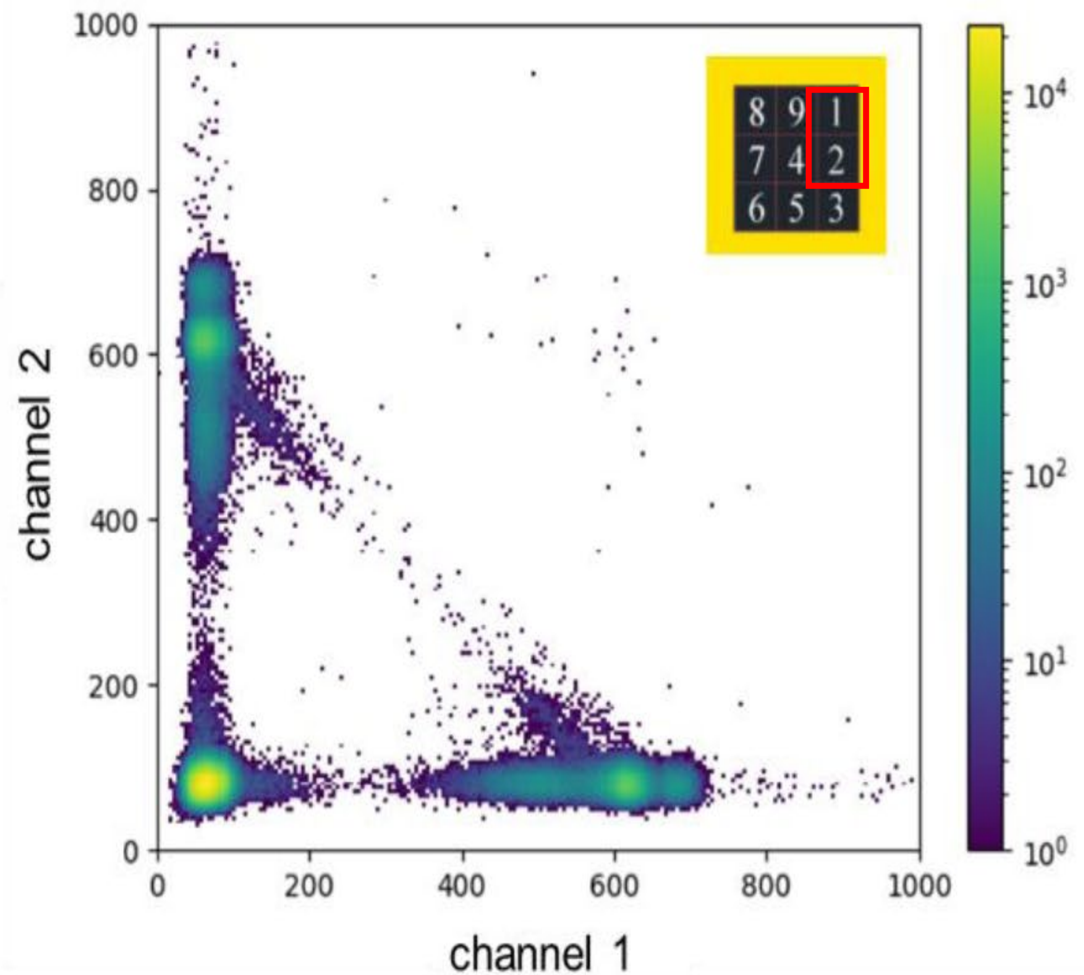
STRONG-2020

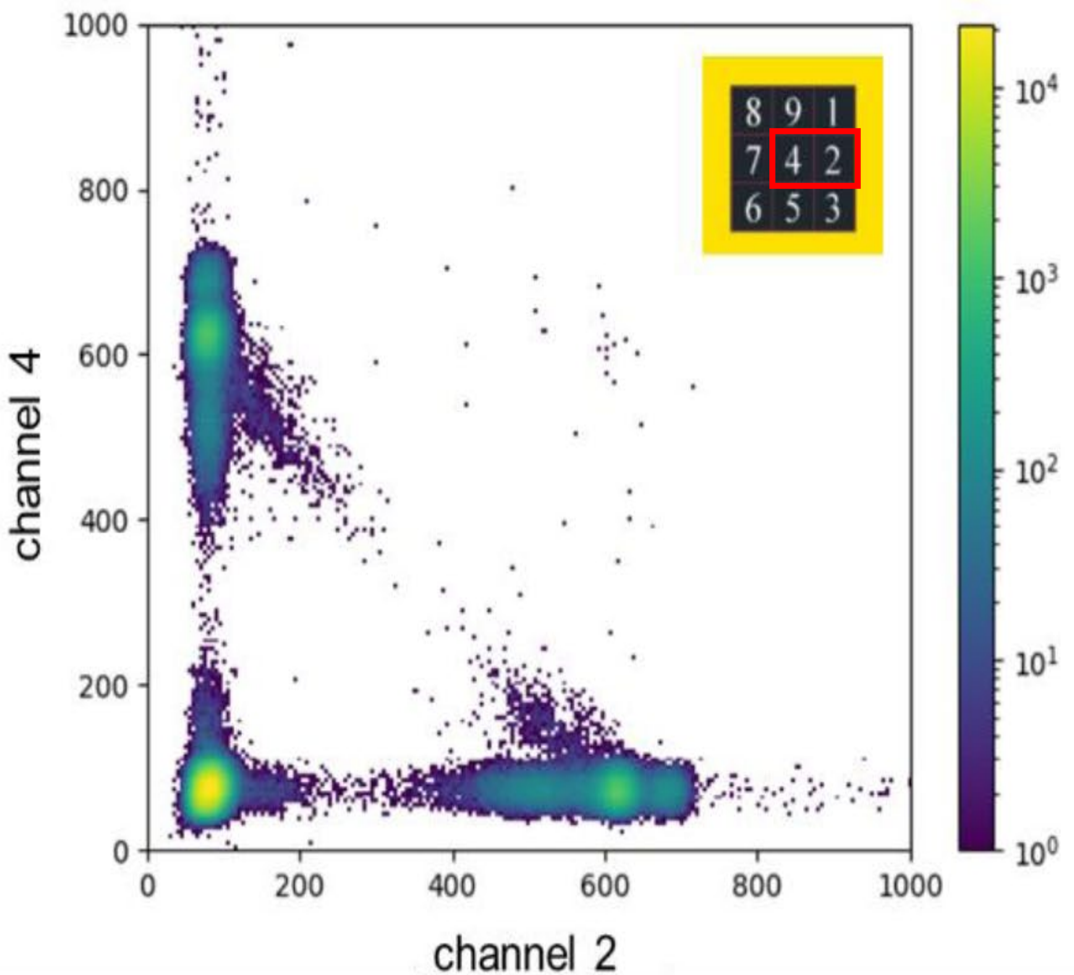


Time resolution [ns]			
	4.81	5.32	4.89
	4.66	5.75	5.16
	5.87	5.1	5.21

Anode			
	8	9	1
	7	4	2
	6	5	3

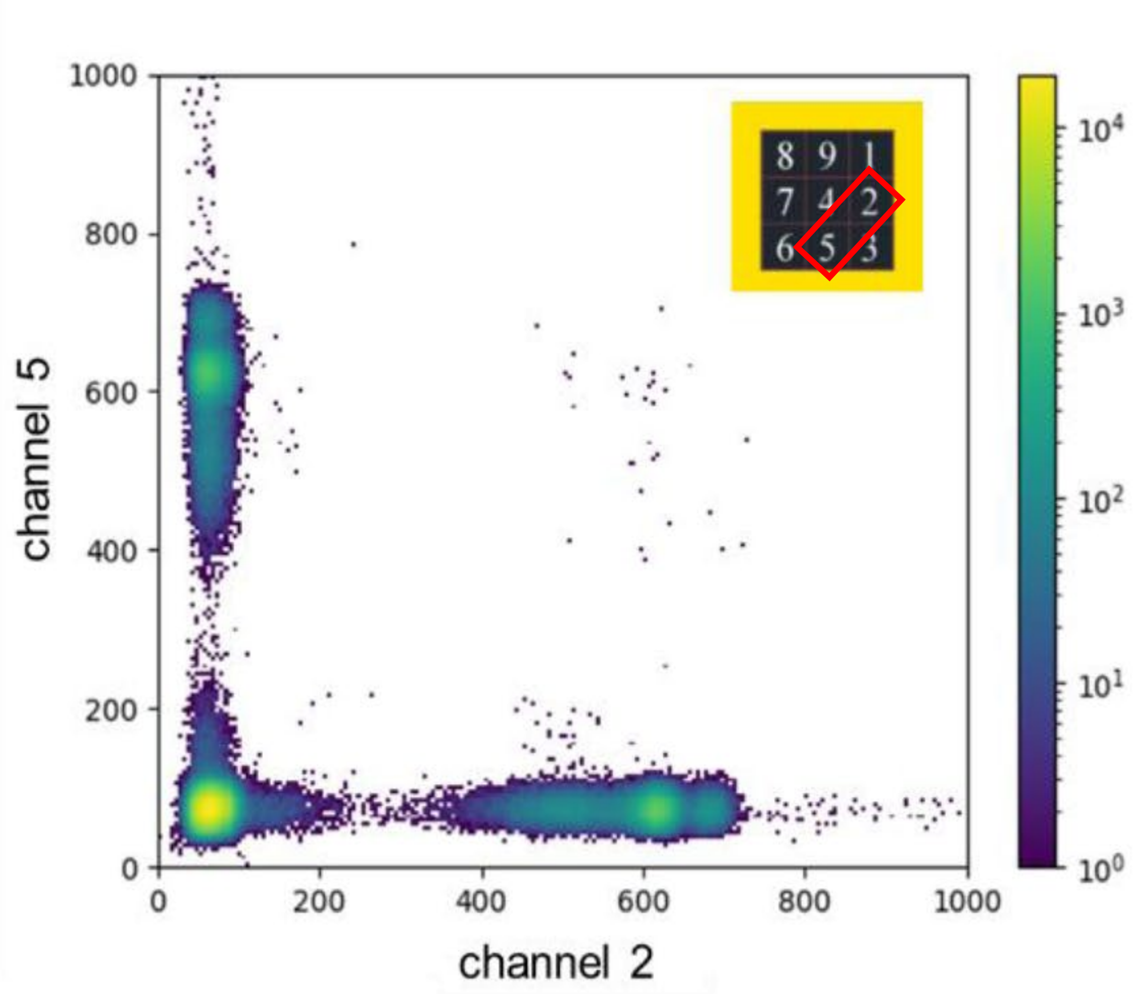
LED: cross-talk determination using Co-57

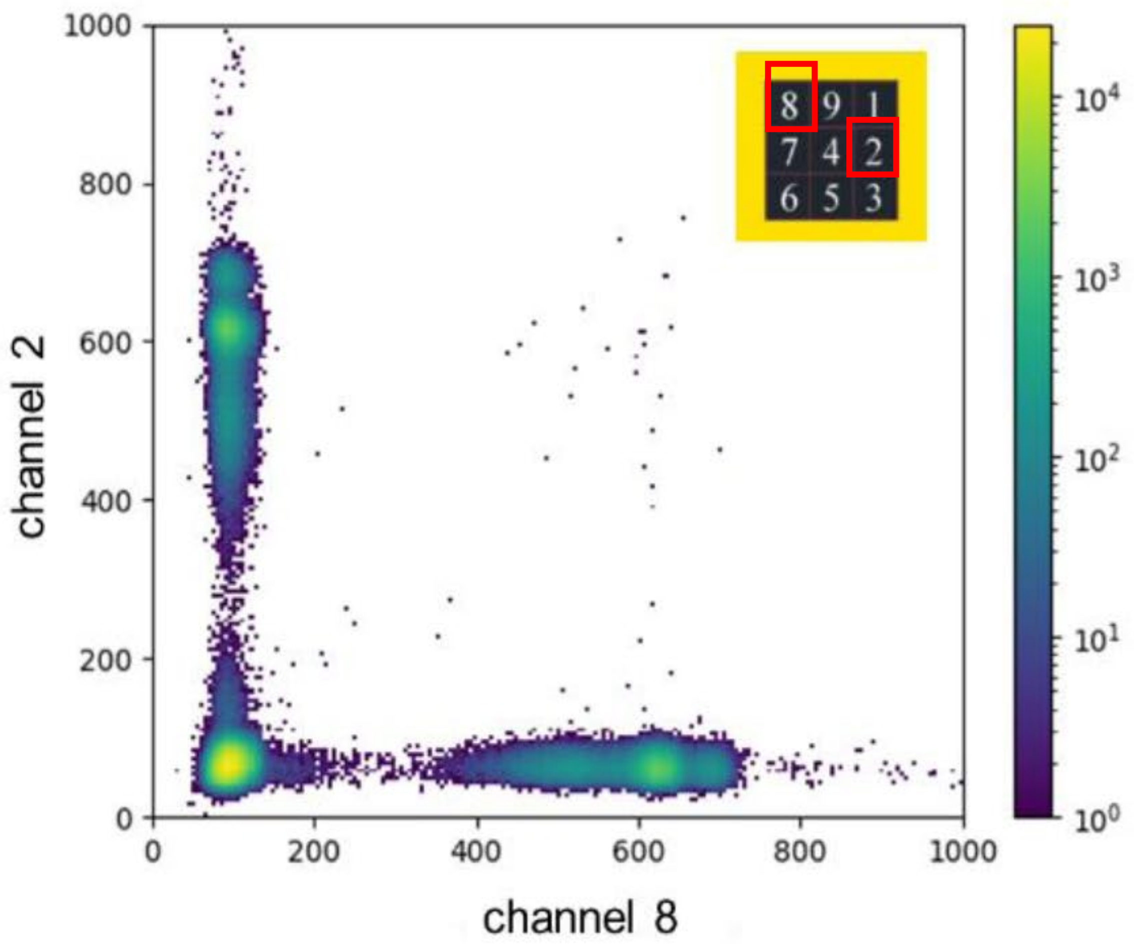




STRONG-2020

LED: cross-talk determination using Co-57



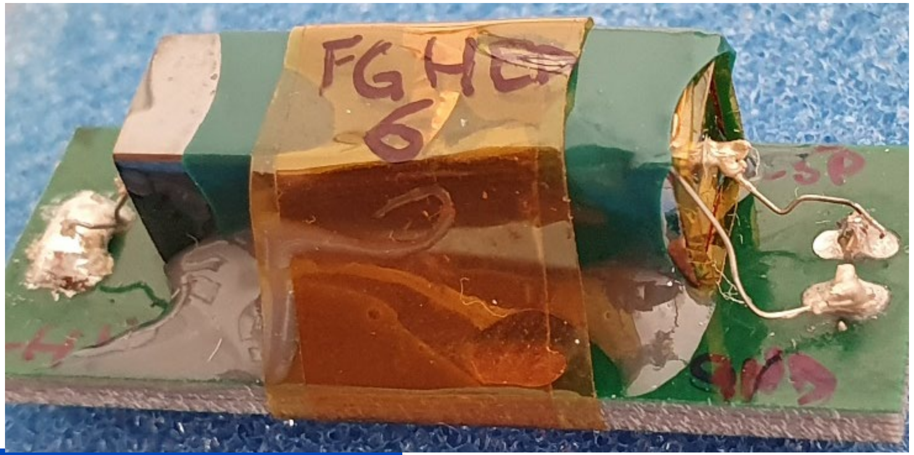


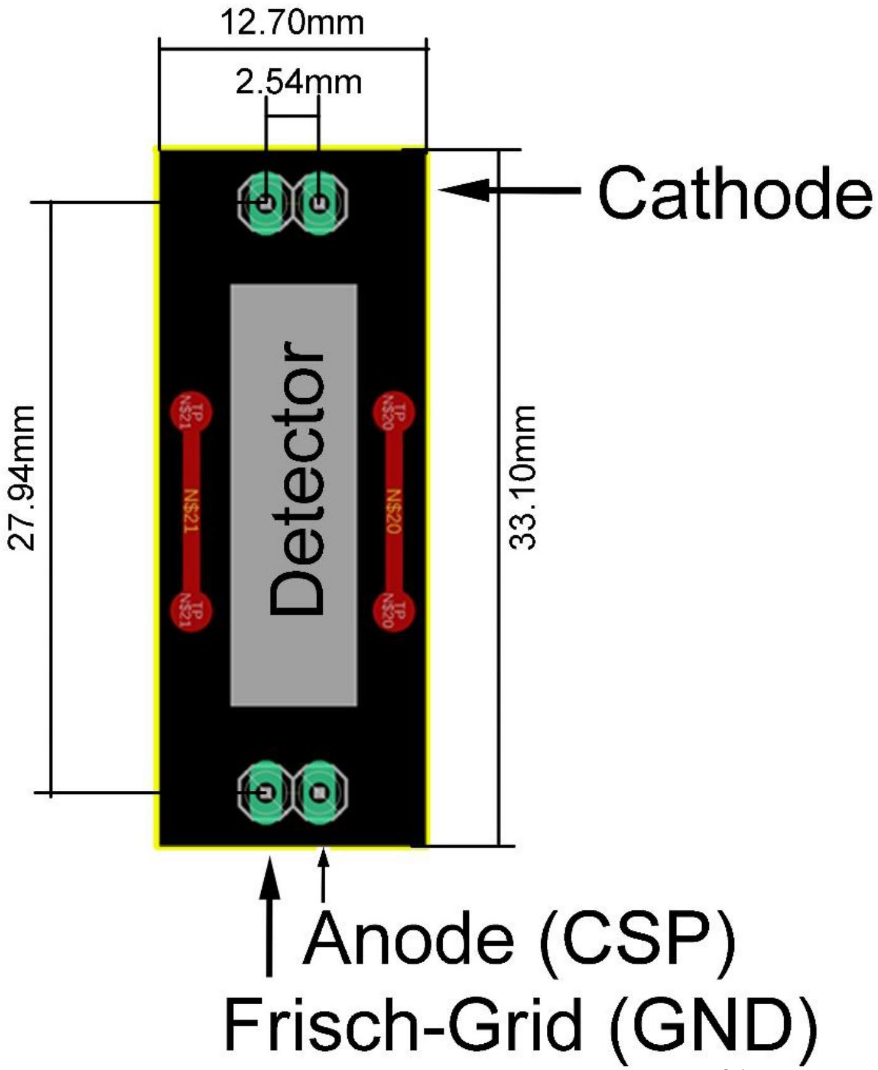
Low energy detector characterisation

First high energy detector prototype

Fabrication:

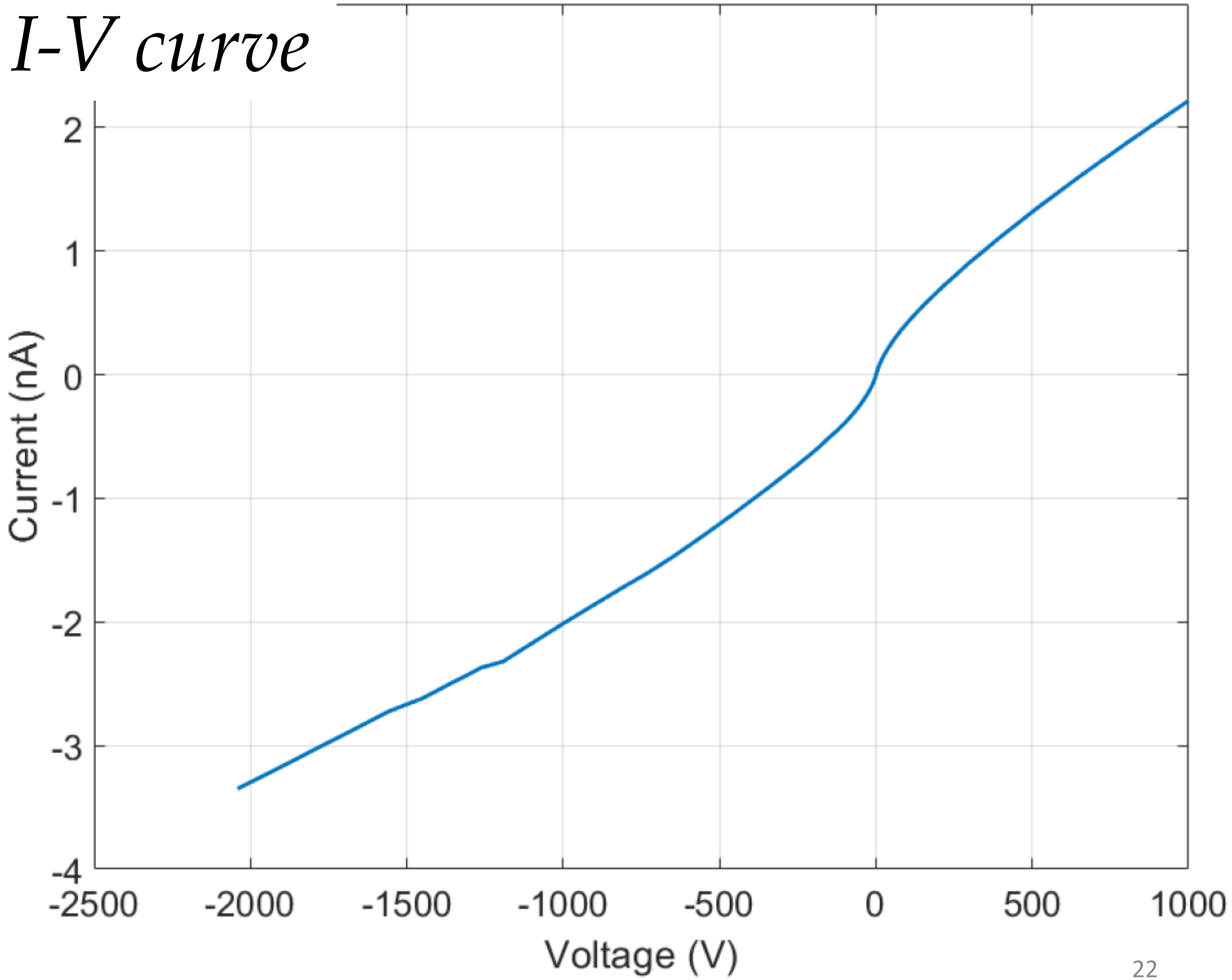
- A 19.4x19.4x6 mm^3 Redlen crystal was cut in dimensions of **6x6x19.4 mm^3**
- Lateral surfaces of sample were covered with Kapton foils and, at the anode side, a 5mm Cu tape was coiled around the samples (Frisch-grid).
- The CZT was bonded on a dedicated Diclad PCB



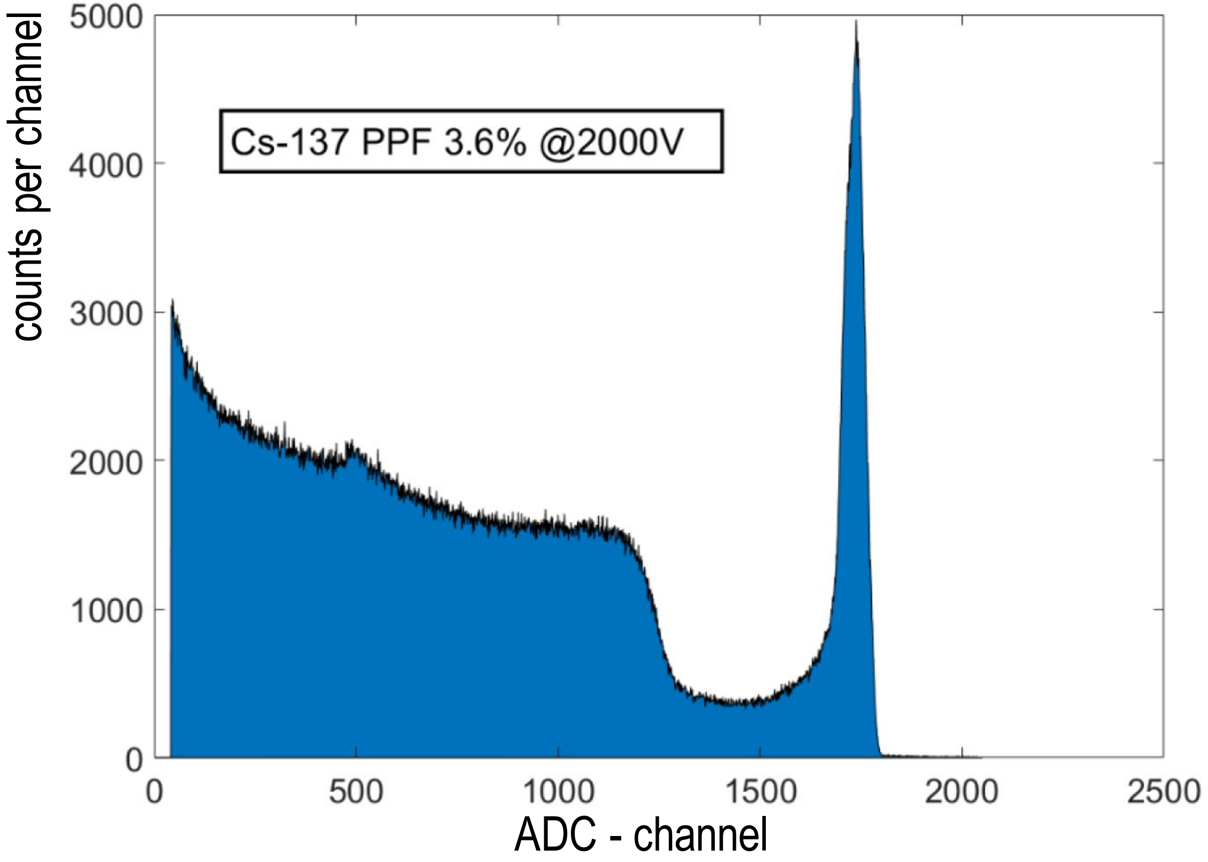


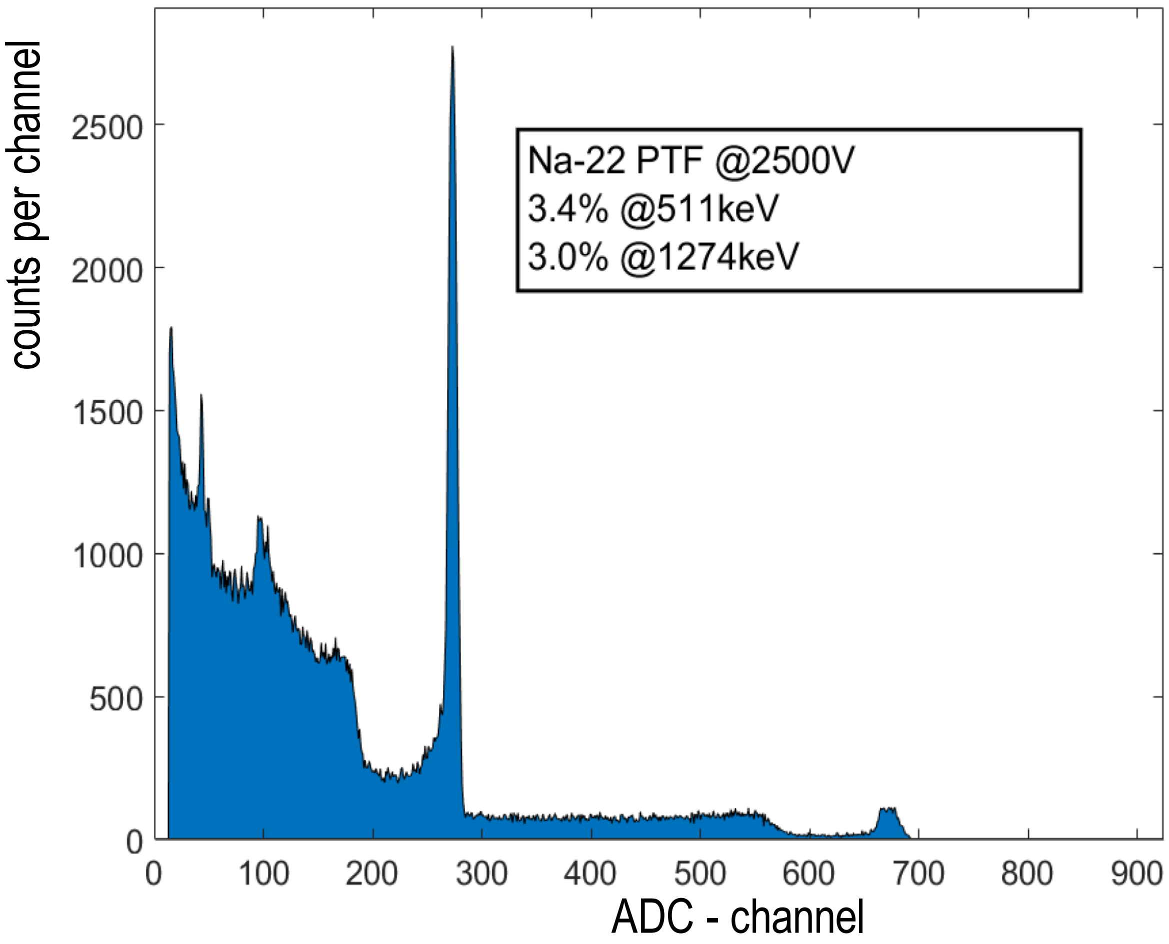
High energy detector I-V curve

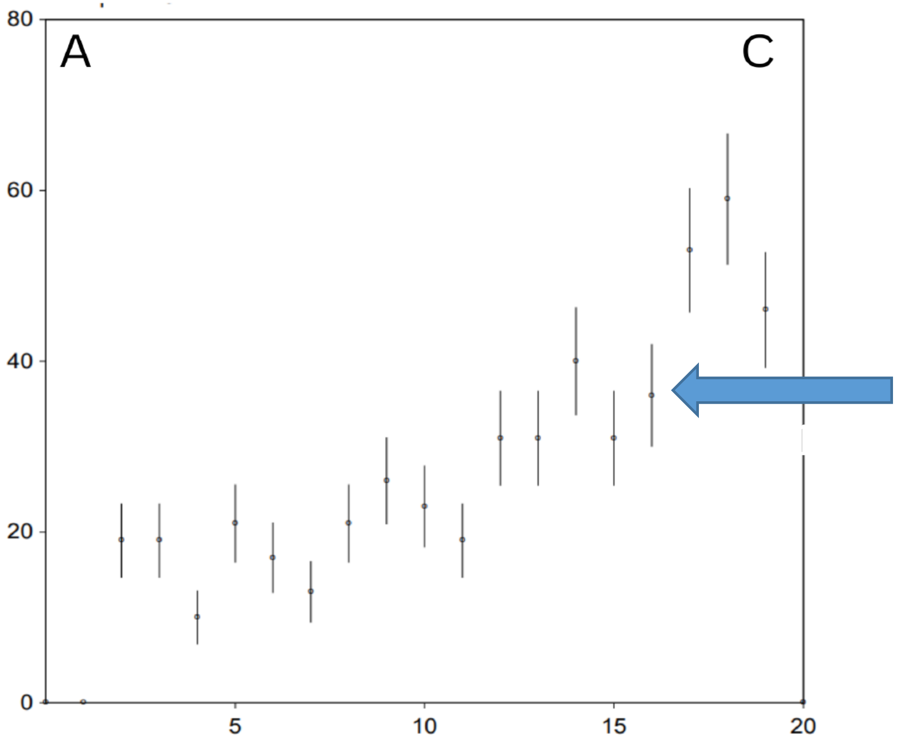
The very low leakage current is remarkable: about 3.2nA at - 2000V

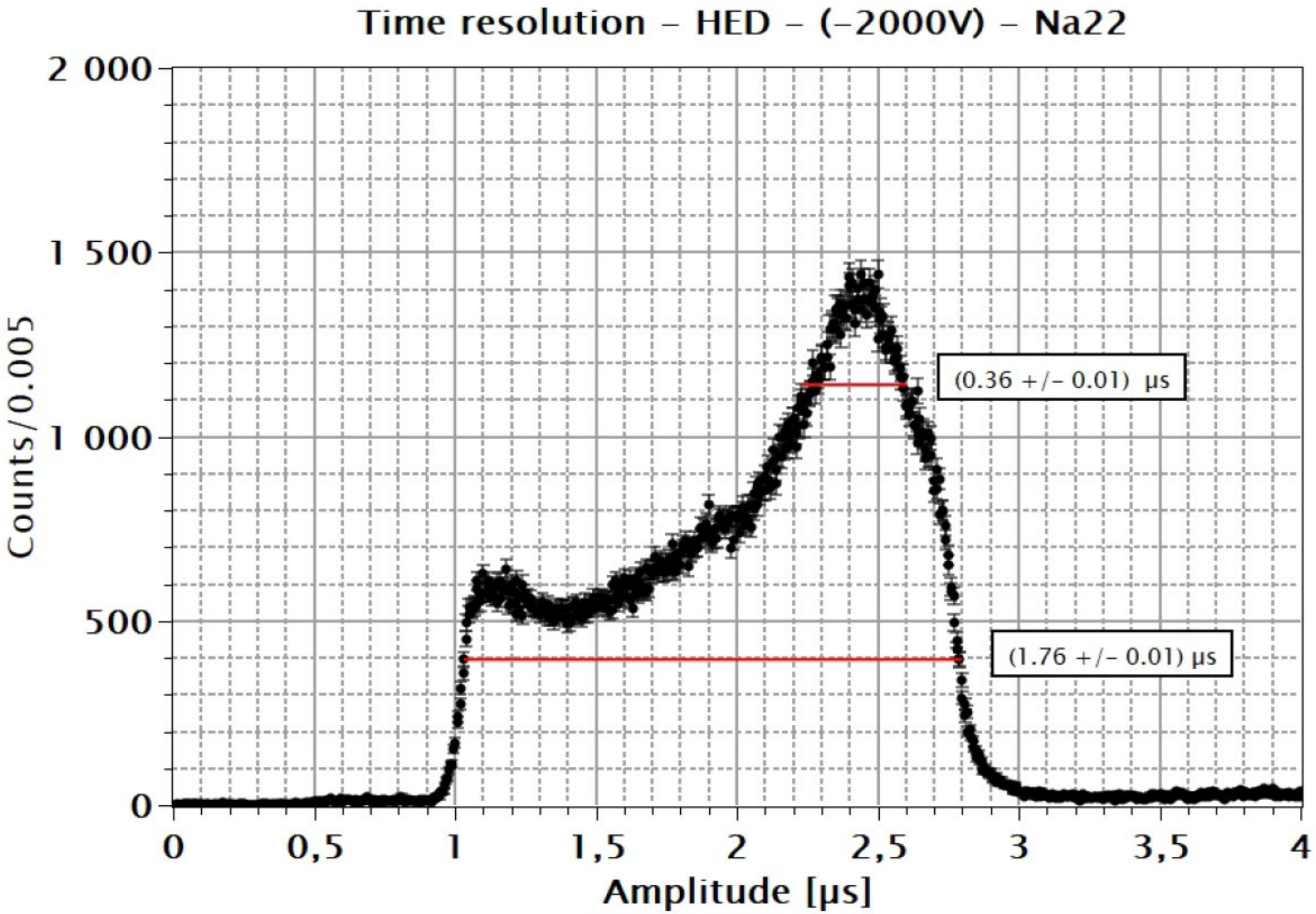


High energy detector spectroscopy



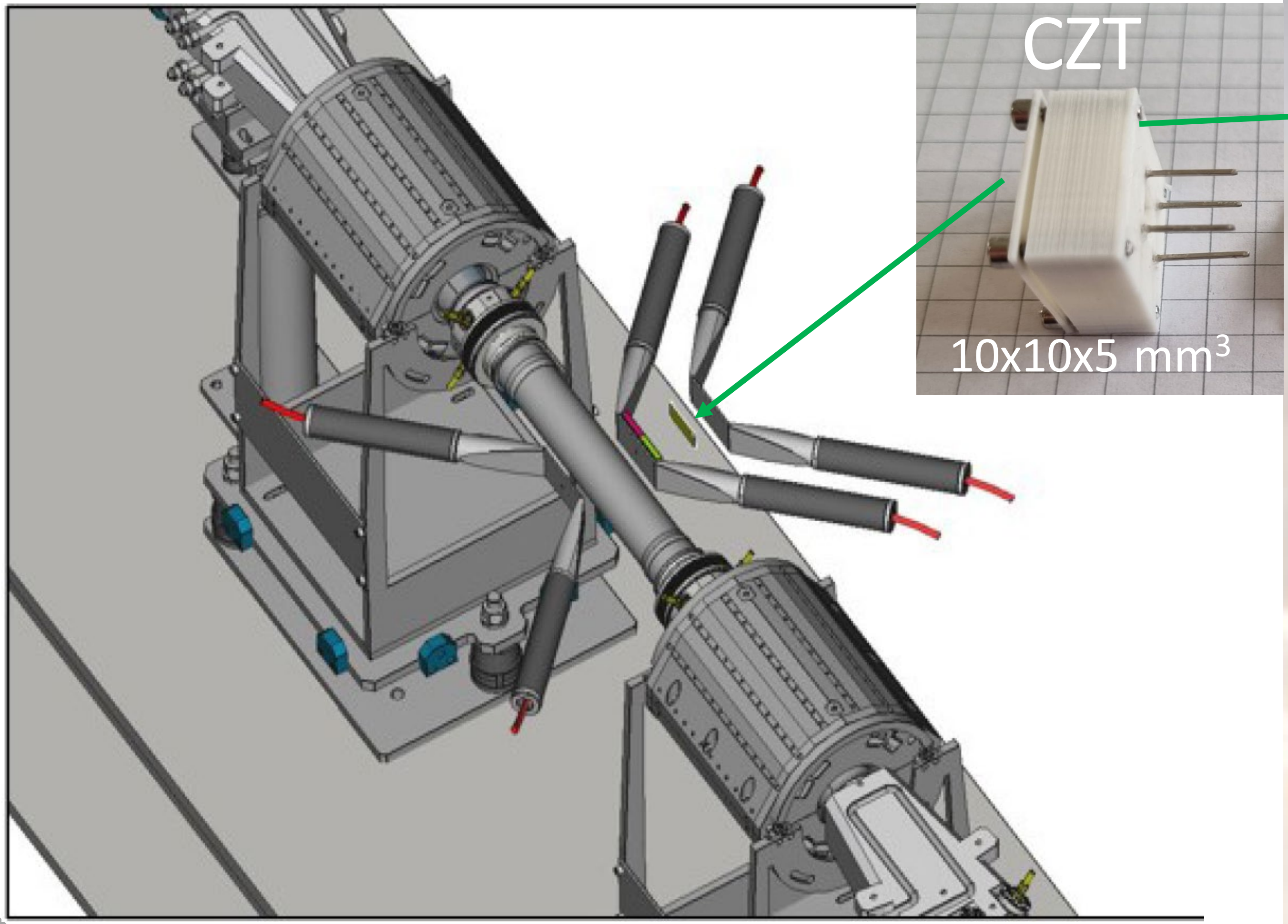


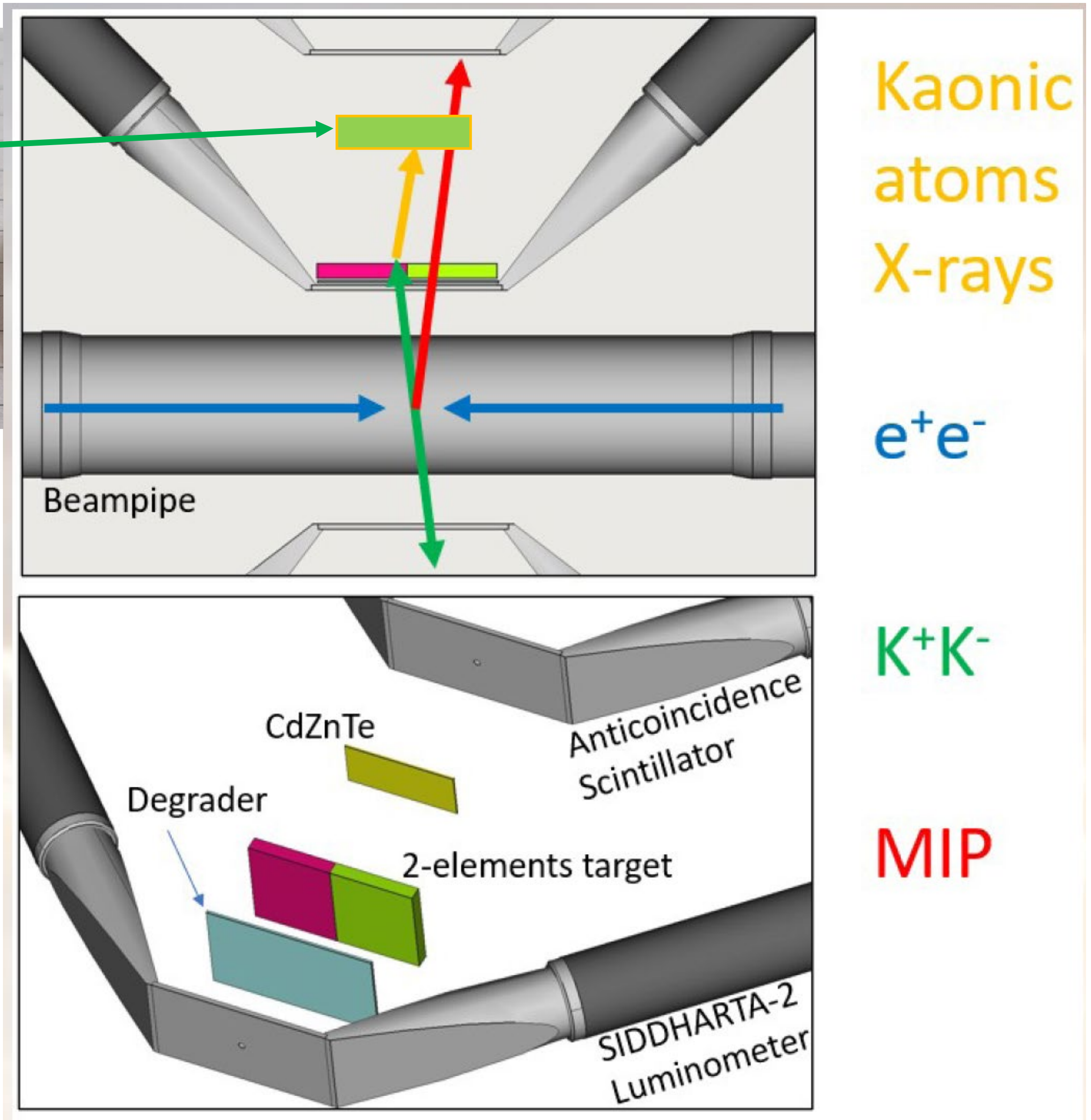

A
C
80
60
40
20
0
5
10
15
20


Time resolution – HED – (-2000V) – Na22
Counts/0.005
Amplitude [µs]
(0.36 +/- 0.01) µs
(1.76 +/- 0.01) µs
2 000
1 500
1 000
500
0
0,5
1
1,5
2
2,5
3
3,5
4

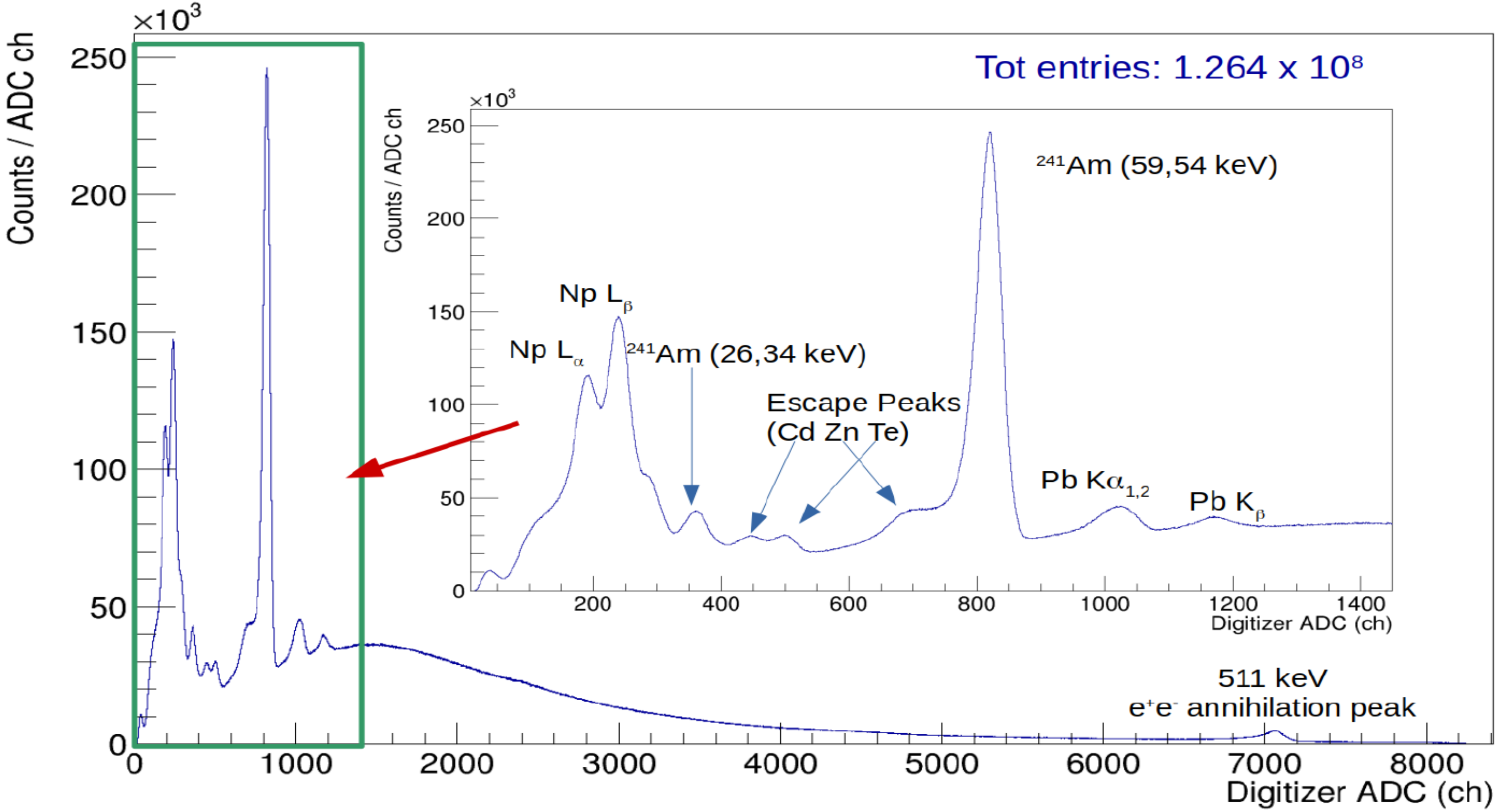
]

First test measurements at DAΦNE

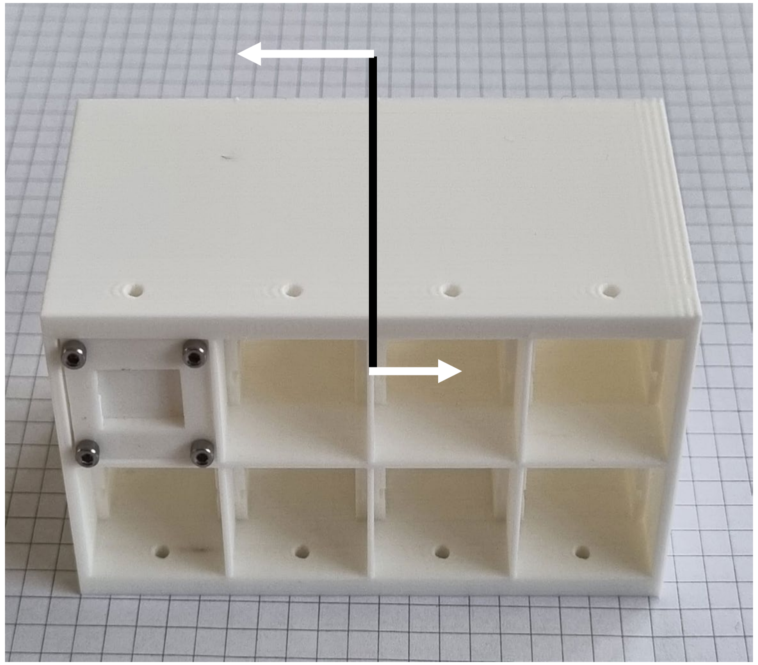

CZT
10x10x5 mm³


Kaonic atoms X-rays
e+e-
K+K-
MIP
Beampipe
CdZnTe
Anticoincidence Scintillator
Degrader
2-elements target
SIDDHARTA-2 Luminometer

STRONG-2020


Tot entries: 1.264 x 10⁸
Counts / ADC ch
×10³
Digitizer ADC (ch)
511 keV
e⁺e⁻ annihilation peak
²⁴¹Am (59,54 keV)
Np Lβ
Np Lα
²⁴¹Am (26,34 keV)
Escape Peaks
(Cd Zn Te)
Pb Kα1,2
Pb Kβ

Kaonic atom spectroscopy with CZT at DAΦNE



We plan to measure kaonic atom transitions of Al and C

Improvements:

Detector surface area: 1 cm^2 → ~16 cm^2

8 pieces of 1,3x1,5 cm^2

thickness of 5 mm

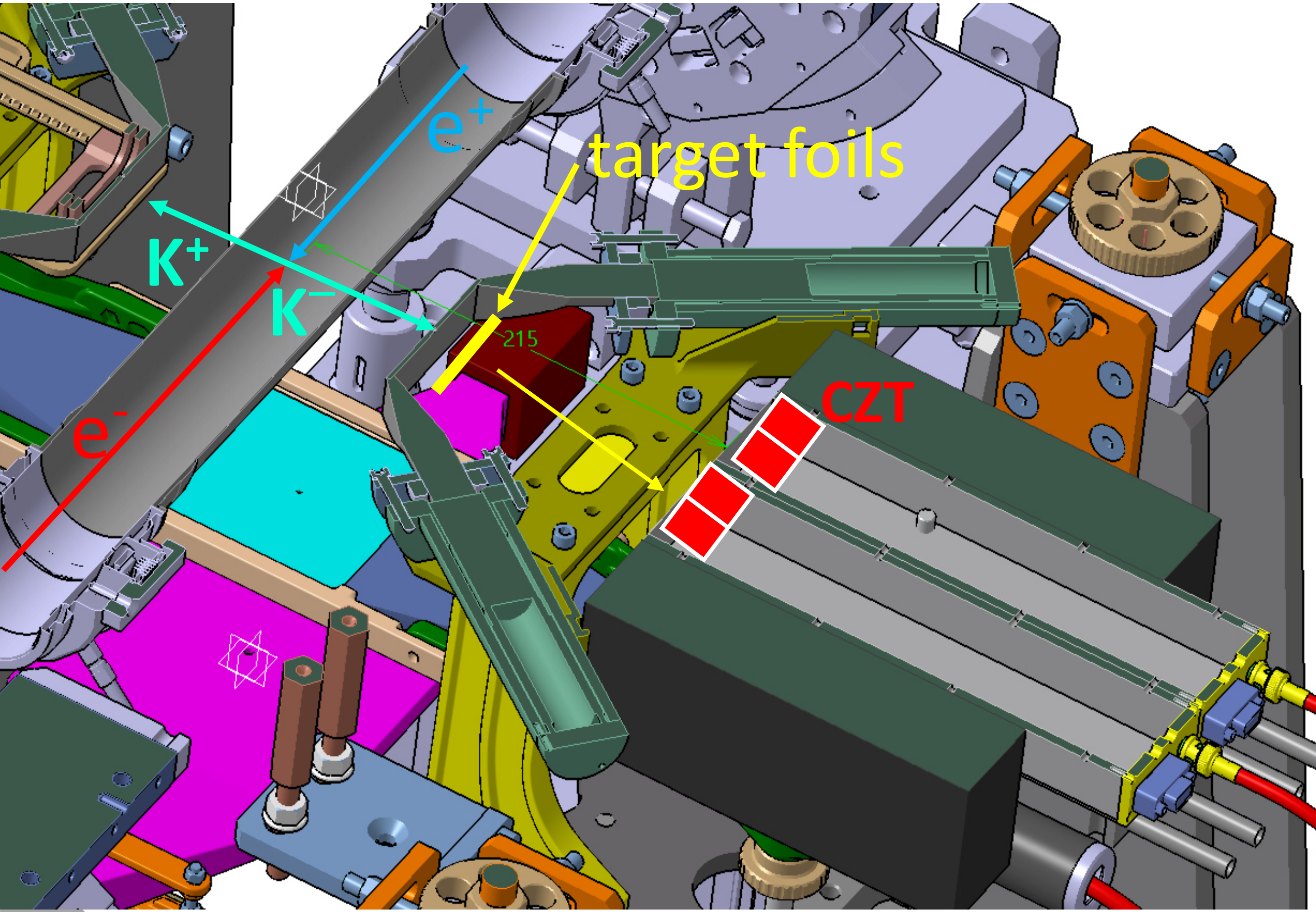
- Lateral 5 cm lead shielding

Degrader and target geometry tuned with GEANT4 MC

New mechanical setup to maintain alignment with the LM

- Installation completed end of Oct. 2023

Kaonic atom spectroscopy with CZT



Element	Transition	E (keV)
$K^{12}C$	3-->2	63
$K^{12}C$	4-->2	85
$K^{12}C$	5-->2	95
$K^{12}C$	6-->2	101
$K^{12}C$	7-->2	104
$K^{12}C$	4-->3	22
$K^{12}C$	5-->3	32
$K^{12}C$	6-->3	38

Element	Transition	E (keV)
$K^{27}Al$	3-->2	302
$K^{27}Al$	4-->3	106
$K^{27}Al$	5-->3	155
$K^{27}Al$	6-->3	181
$K^{27}Al$	7-->3	197
$K^{27}Al$	8-->3	208
$K^{27}Al$	5-->4	49
$K^{27}Al$	6-->4	76
$K^{27}Al$	7-->4	91
$K^{27}Al$	8-->4	102
$K^{27}Al$	9-->4	109
$K^{27}Al$	10-->4	114

Summary

First low and high energy **CZT** prototypes were successful tested at SMI, CNR and LNF

- Master thesis at SMI ("Characterization of CdZnTe Detectors") finished
- new Master thesis started at Sept. 2021

Readout electronic and DAQ

- further optimisation on preamplifier and DAQ are ongoing, by POLIMI and UZ
  - PhD thesis at POLIMI

First tests with beam (parasitic to SIDDHARTA-2) for low and high energy prototypes are ongoing!

Thanks