Precision X-Ray measurements with Silicon Drift Detectors in the SIDDHARTA-2 experiment

INFN
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Istituto Nazionale di Fisica Nucleare
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High Precision X-Ray Measurement 2025

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Physics of light kaonic atoms

- K^- slowed down and stopped inside a target
- Atomic capture followed by cascade process
- K^- captured in an highly excited state n
- Emission of radiation following the de-excitation

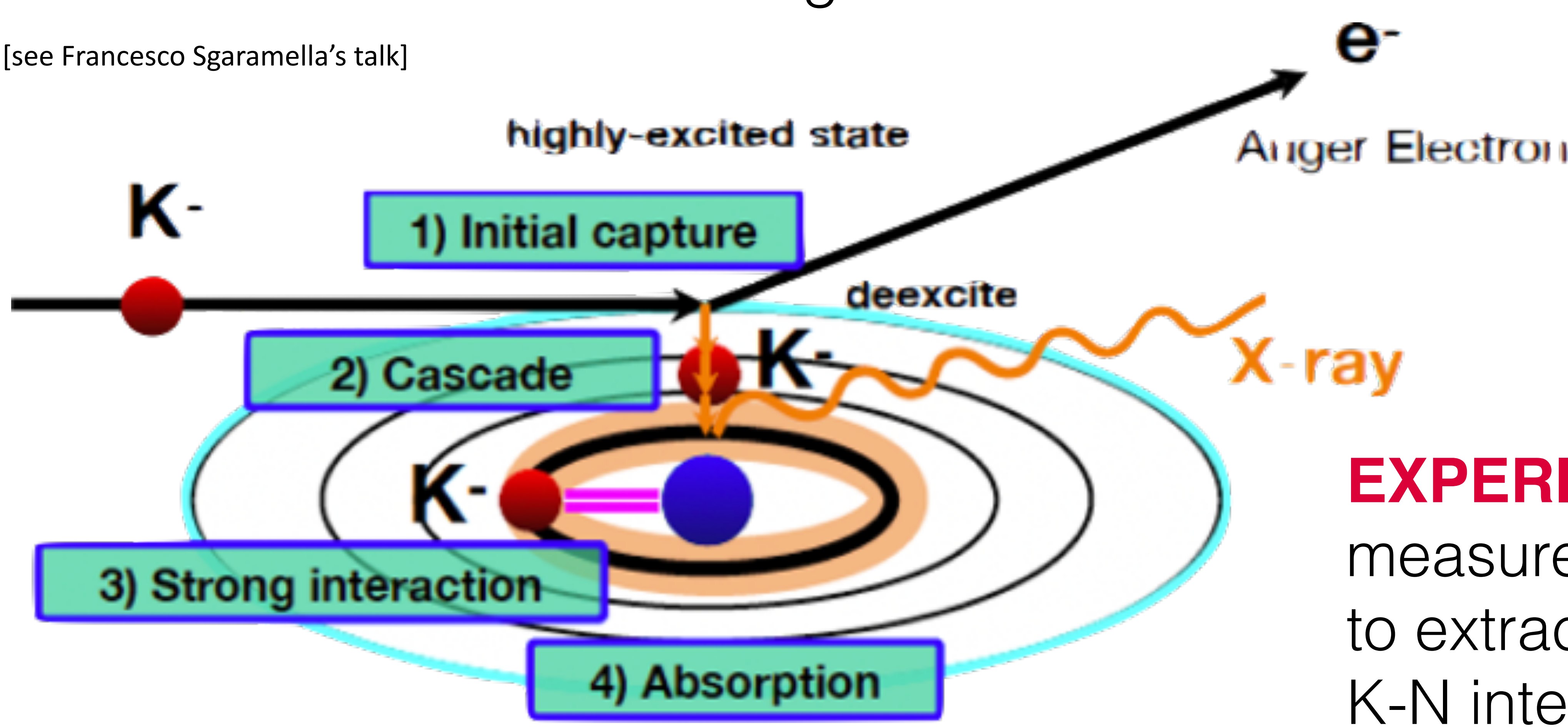
$$n \sim \sqrt{\frac{\mu}{m_e}} n_e$$

$n \sim 28$ K-^{4}He & K-D

$n \sim 25$ K-H

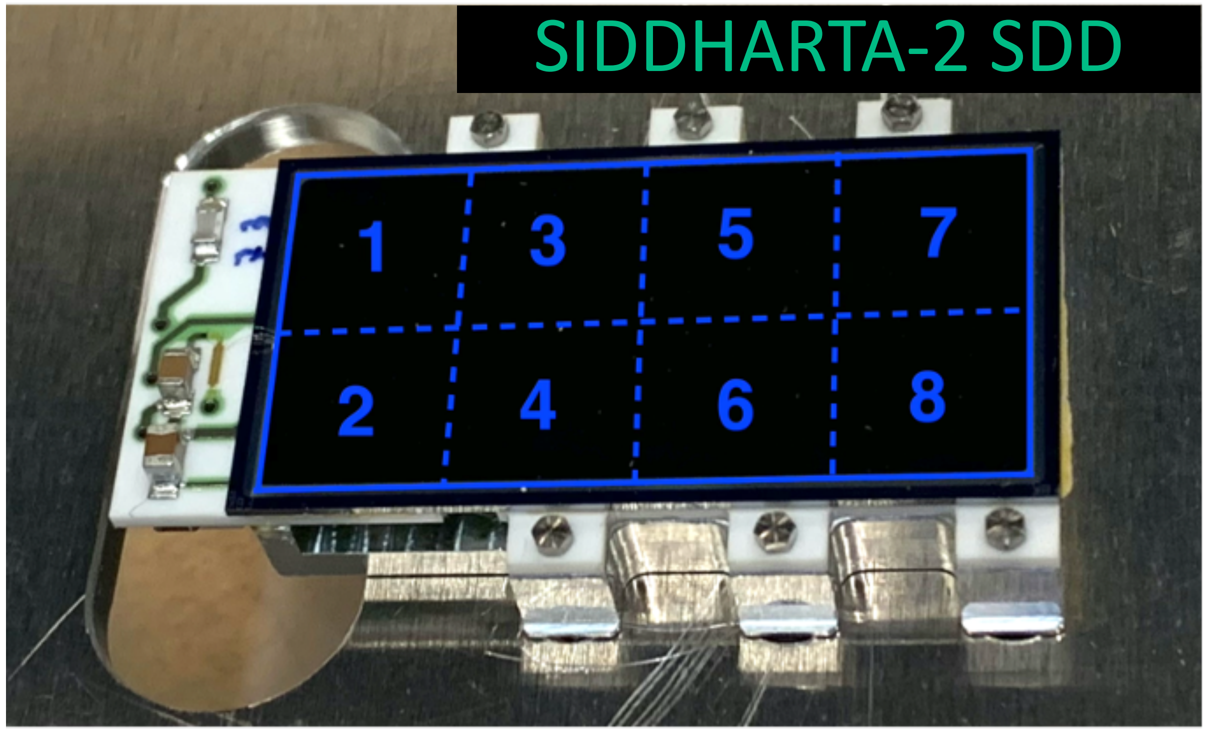
μ system's reduced mass

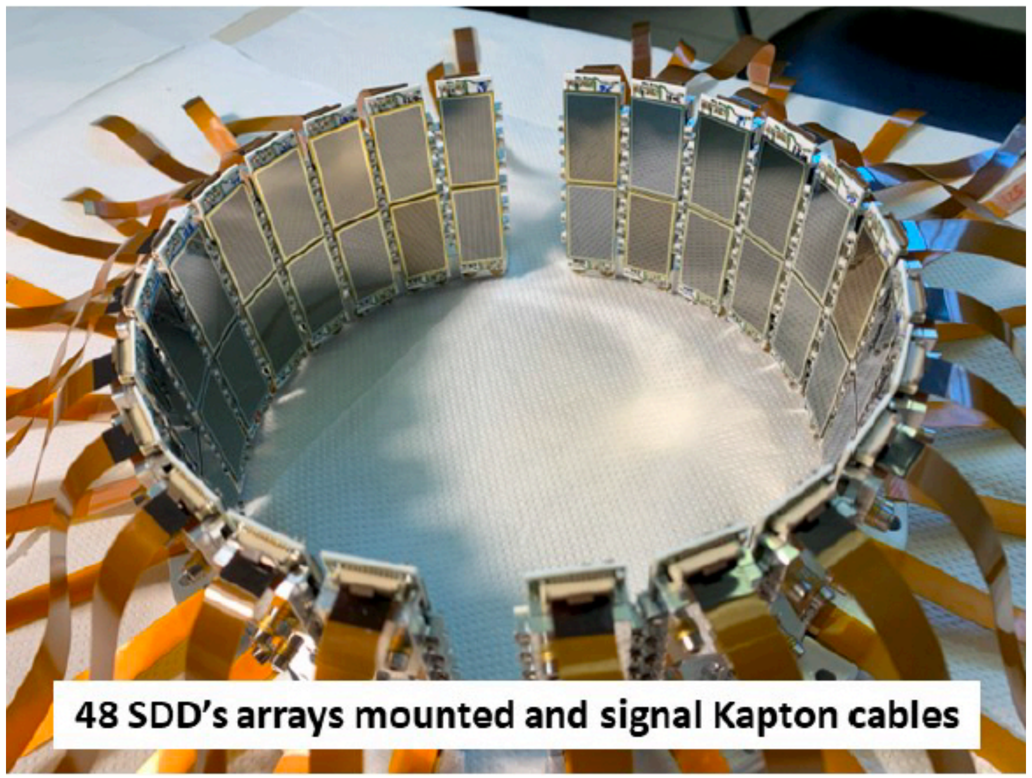
[see Francesco Sgaramella's talk]



EXPERIMENTAL GOAL:
measure the emitted X-Rays to extract information on the K-N interaction

The SIDDHARTA-2 Silicon Drift Detectors

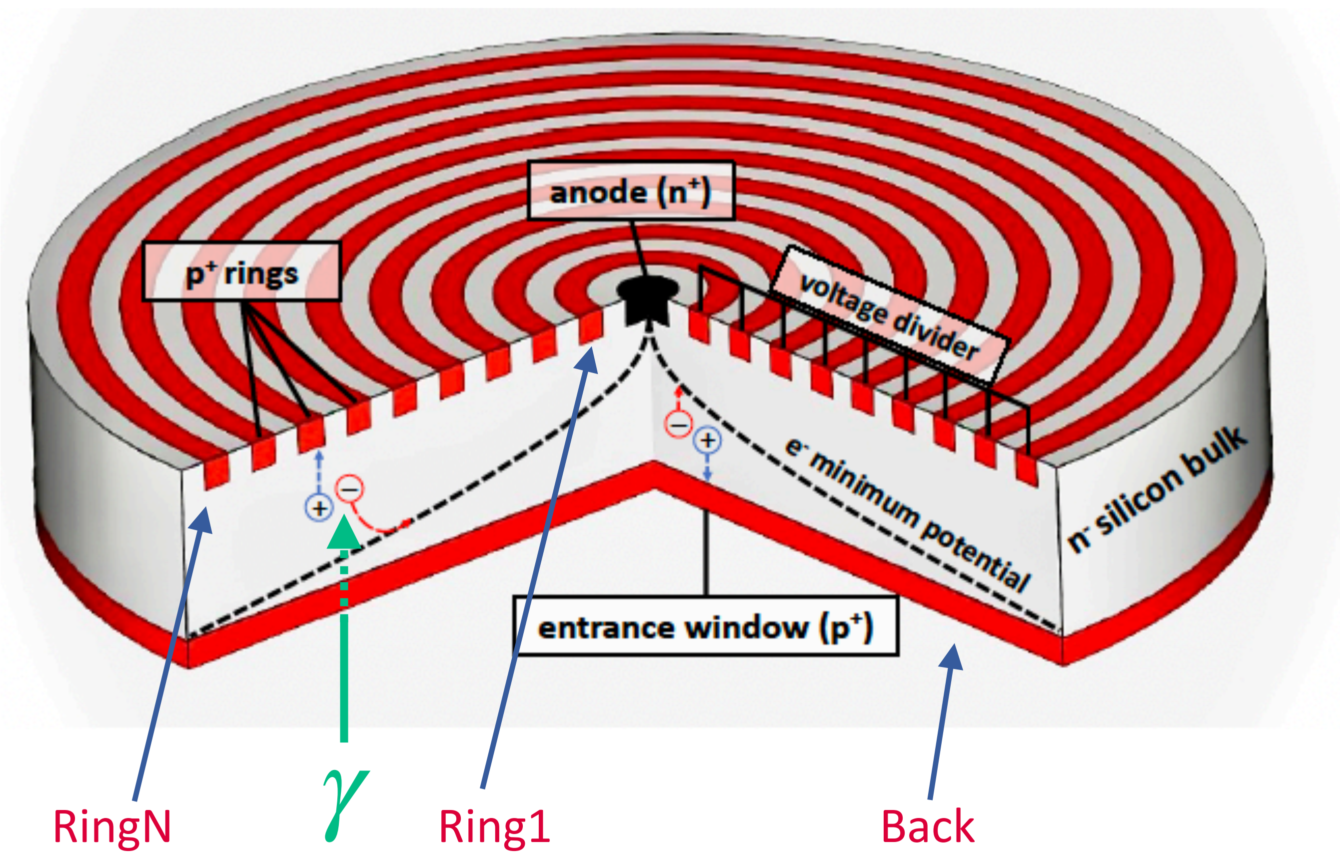


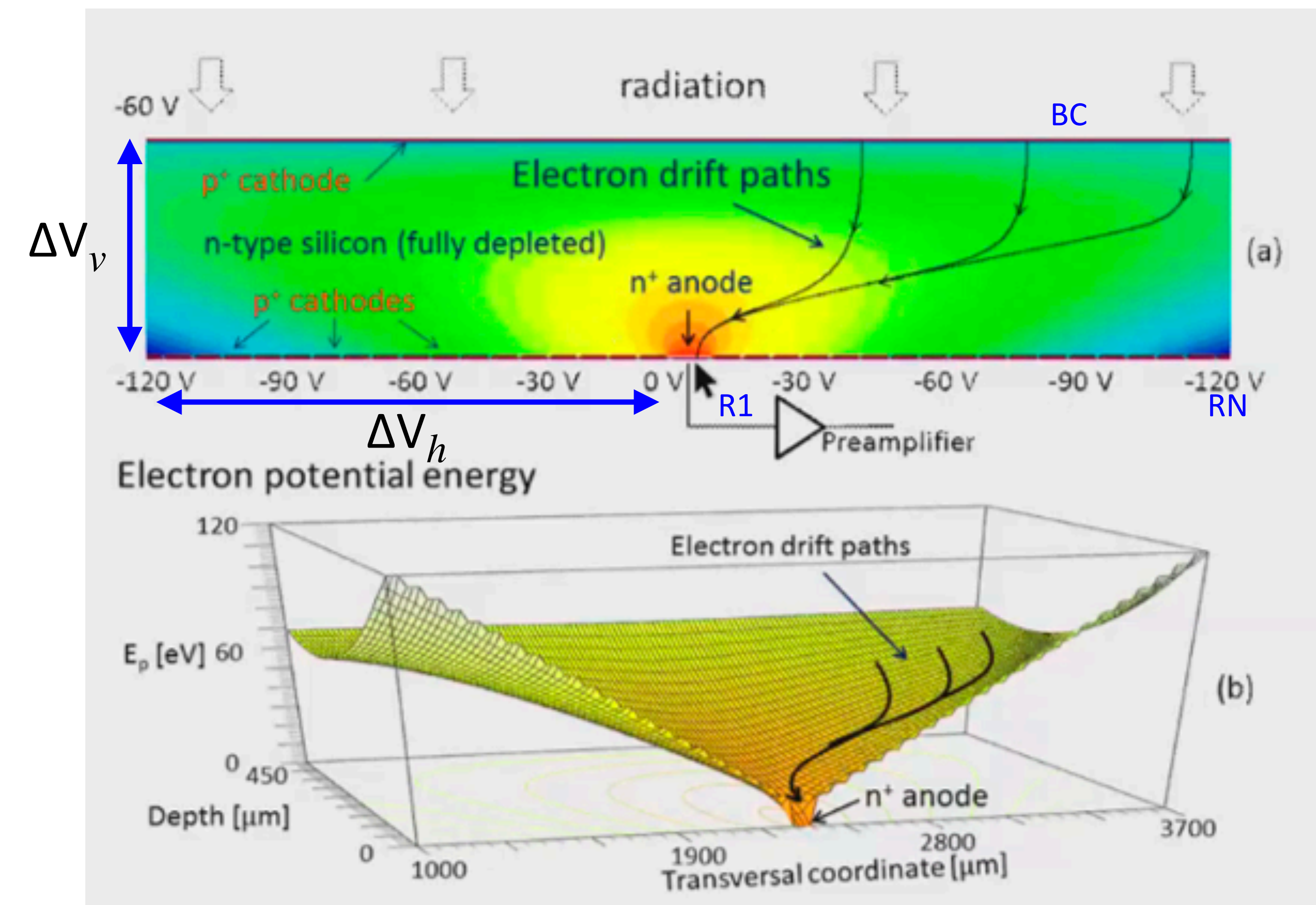


- SDD cells: 8x8mm^2 active area
- 450 μm thick silicon bulk: > 85% detection efficiency for 5-12 keV X-rays (region of interest for kaonic deuterium)
- SDD cells packed in 2x4 array (total active area of 5.12 cm^2)
- Extremely good linear behaviour and energy resolution in the range of interest
- $\Delta E/E < 10^{-3}$
- FWHM $\sim$ 170 eV @6.4 keV

The SIDDHARTA-2 Silicon Drift Detectors

- e-h pairs separated through a reverse polarisation field (“vertical drift”)
- Second electric field superposed to transport the charges towards a collection anode (“horizontal drift”)
- **“Gutter-like”** field configuration is achieved for the charge collection





Beyond SIDDHARTA-2: EXKALIBUR

1.1 - High precision kaonic neon measurement
To extract the charged kaon mass with a precision of about 5 keV

BSQED and Physics beyond Schwinger limit

1.2 - Light kaonic atoms (LHKA)
– solid target Li, Be, B
– integration of 1mm SDD

EXKALIBUR

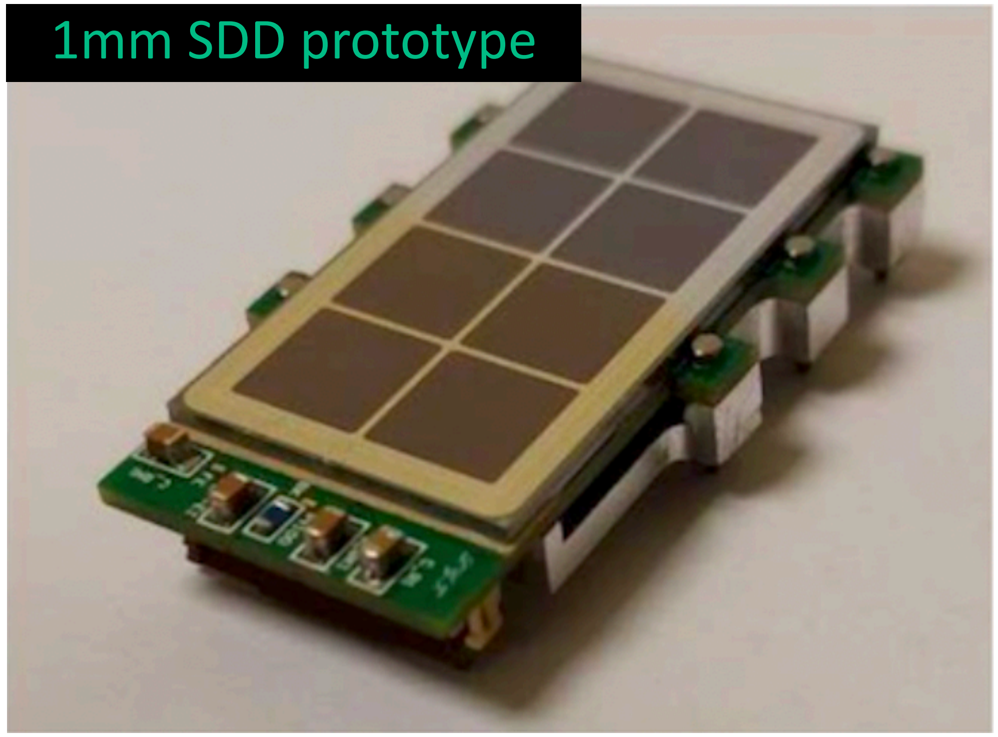
C. Curceanu et al., Front.in Phys. 11 (2023) 1240250

EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

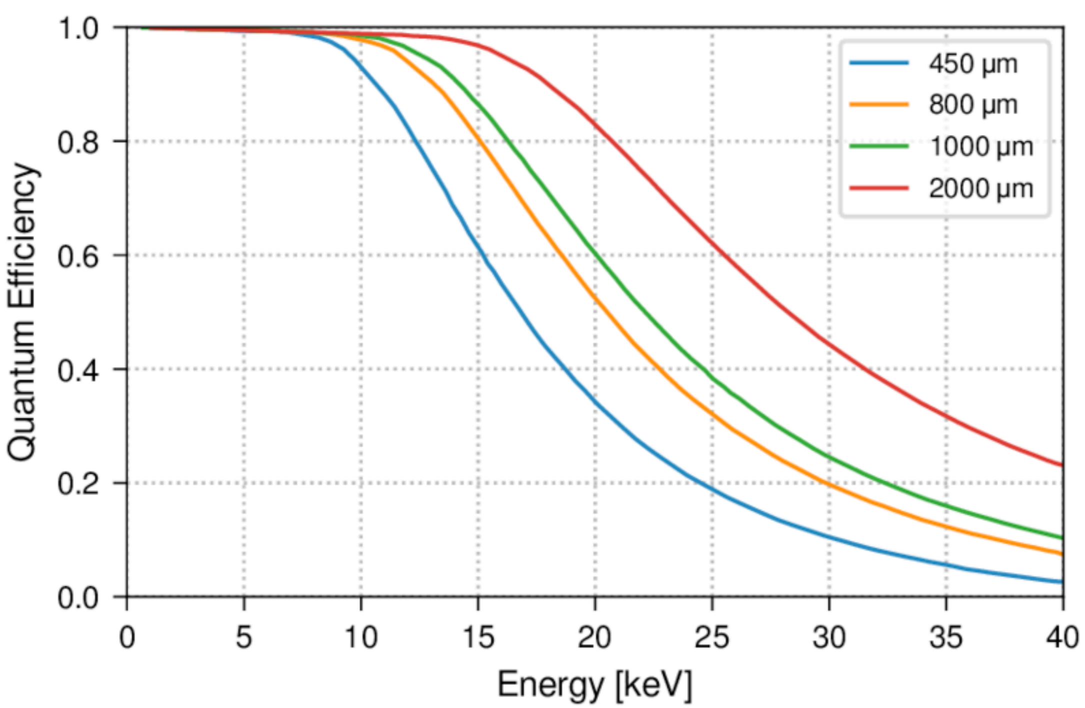
Intermediate kaonic atoms (IMKA)
In parallel we plan dedicated runs for kaonic atoms (*O, Al, S*) with CdZnTe detectors
- 200 -300 pb^{-1} of integrated luminosity/target

- Minimal modifications/adding to SIDDHARTA-2
- New calibration system (0.2 eV accuracy)
- **New 1mm thick SDDs**

New 1mm Silicon Drift Detectors

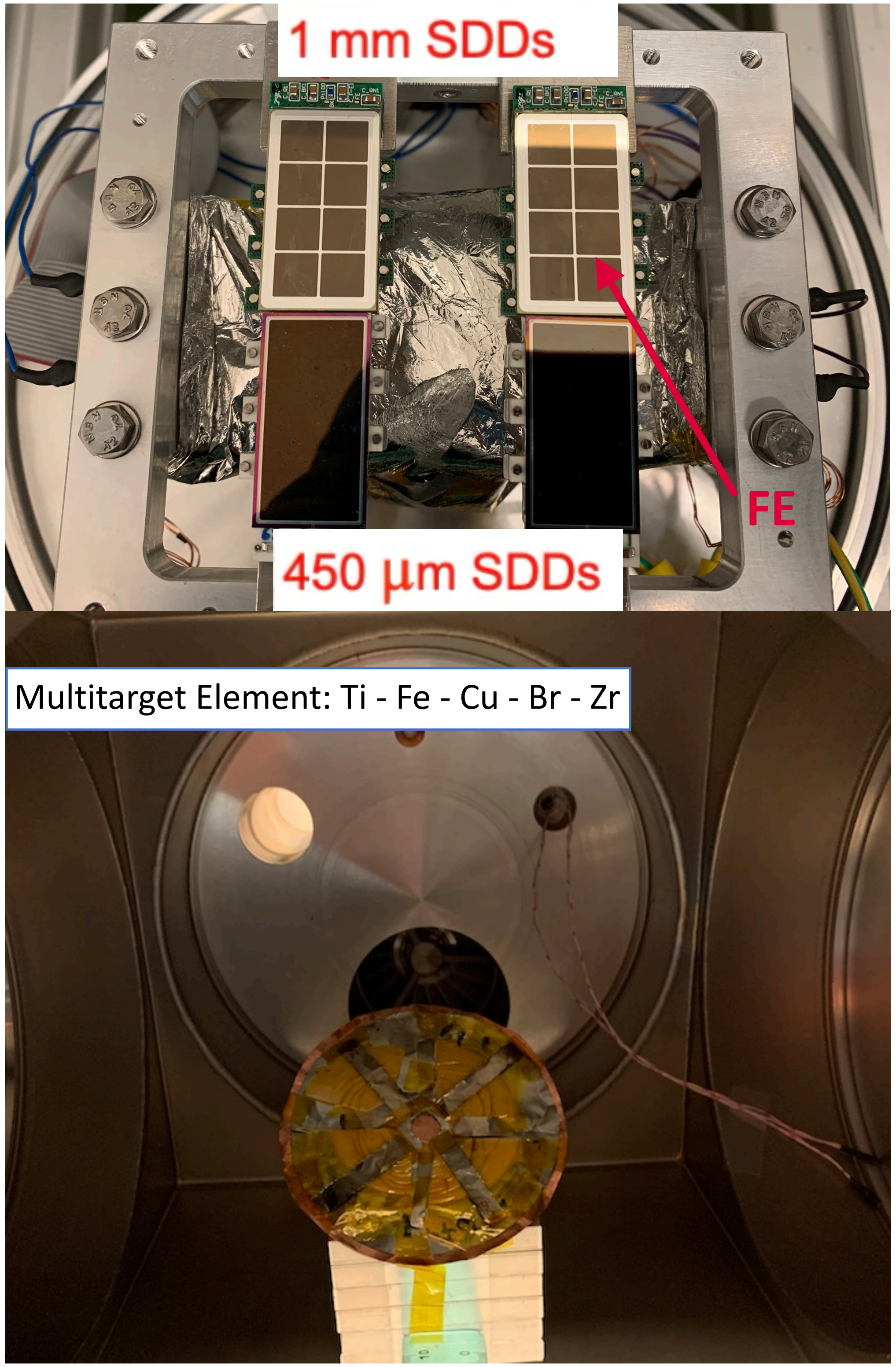


- Thicker silicon bulk will allow for a **much better efficiency at higher energy** (above 15 keV)
- Possibility to extend the range of kaonic atoms that we are able to measure
- Insight into the $K^- - NN$ strong interaction



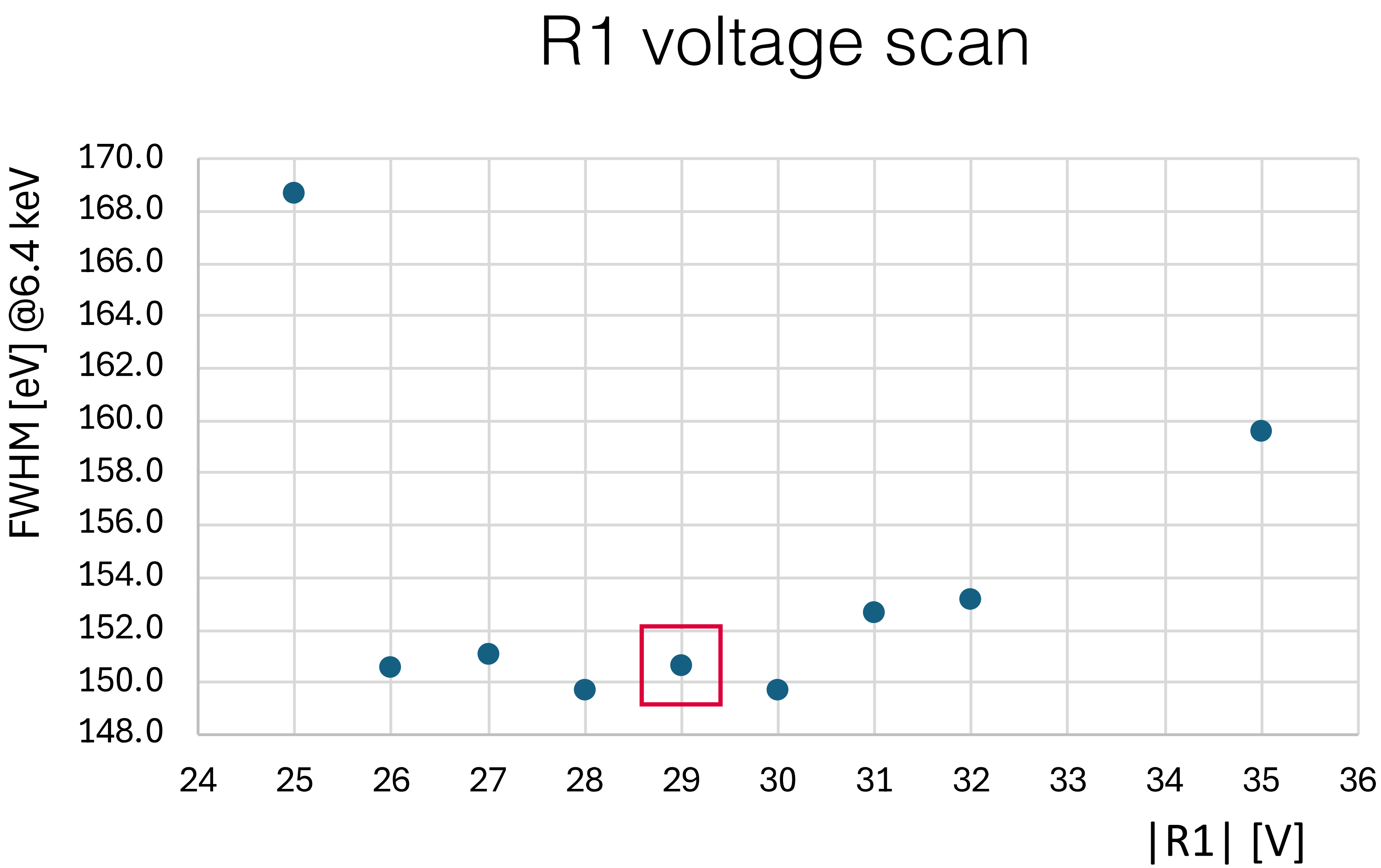
Lithium-6		Lithium-7		Beryllium-9	
Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)
$\mathbf{3 \to 2}$	**15.085**	$\mathbf{3 \to 2}$	**15.261**	$\mathbf{3 \to 2}$	**27.560**
$\mathbf{4 \to 2}$	**20.365**	$\mathbf{4 \to 2}$	**20.603**	$\mathbf{4 \to 3}$	**9.646**
$\mathbf{5 \to 2}$	**22.809**	$\mathbf{5 \to 2}$	**23.075**	$\mathbf{5 \to 3}$	**14.111**
$4 \to 3$	5.280	$4 \to 3$	5.341	$5 \to 4$	4.465
$5 \to 3$	7.724	$5 \to 3$	7.814	$6 \to 4$	6.890
$5 \to 4$	2.444	$5 \to 4$	2.472	$6 \to 5$	2.425
$6 \to 4$	3.771	$6 \to 4$	3.815		

New 1mm Silicon Drift Detectors



- Characterisation ongoing in the laboratory
- Energy resolution at different bias voltages
  - Ring1 (innermost ring)
  - RingN (outermost ring)
  - Back (depletion voltage)
  - Focusing Electrode
- FE characterisation to optimise the quality of charge collection
- In particular, it minimises charge sharing between adjacent SDDs

1mm SDDs characterization: energy resolution

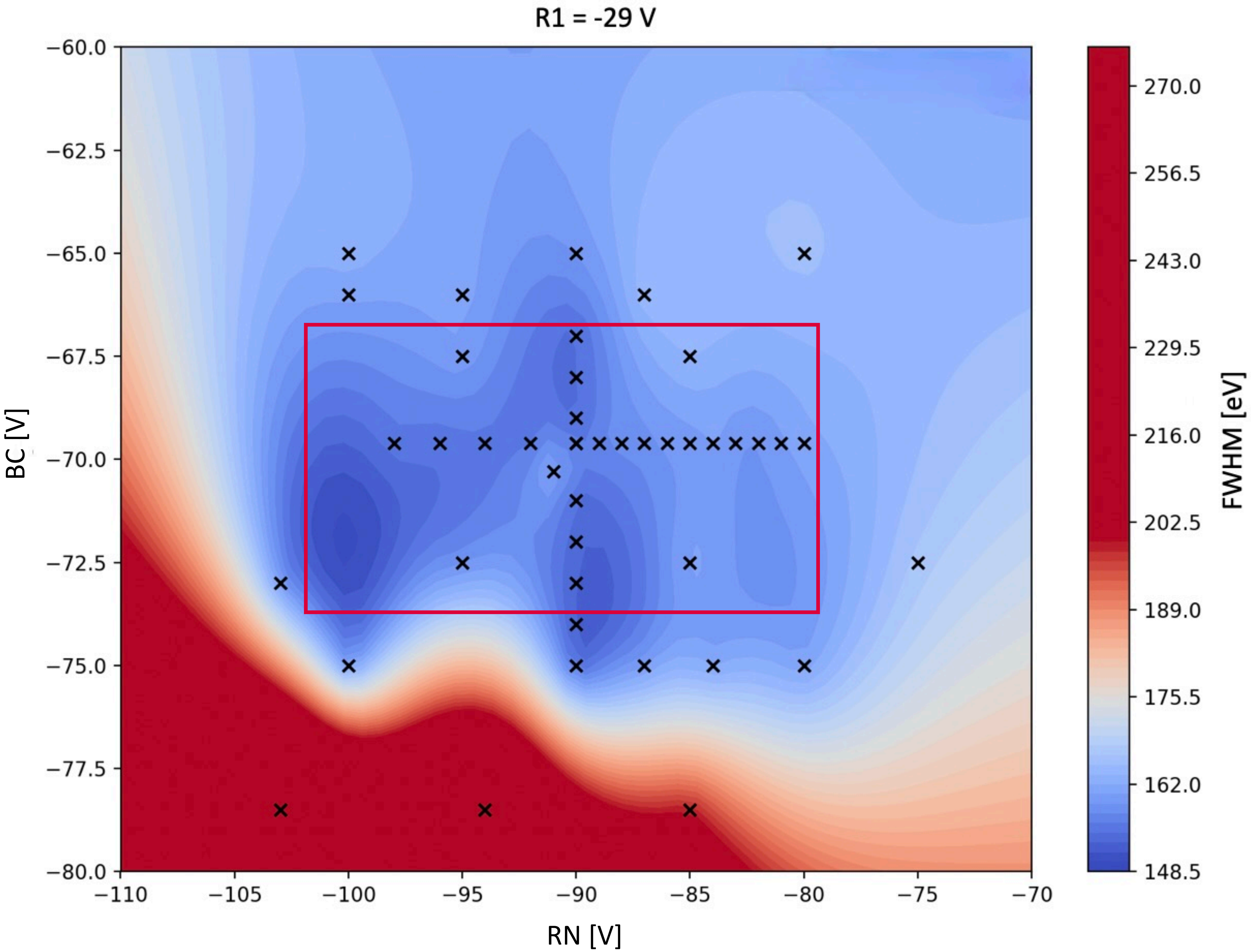


- Optimisation of the energy resolution at 6.4 keV (FeK$_\alpha$ line) as a function of the R1 bias voltage

- Energy resolution is stable within 1 eV when $26\ V \leq |R1| \leq 30\ V$

1mm SDDs characterization: energy resolution

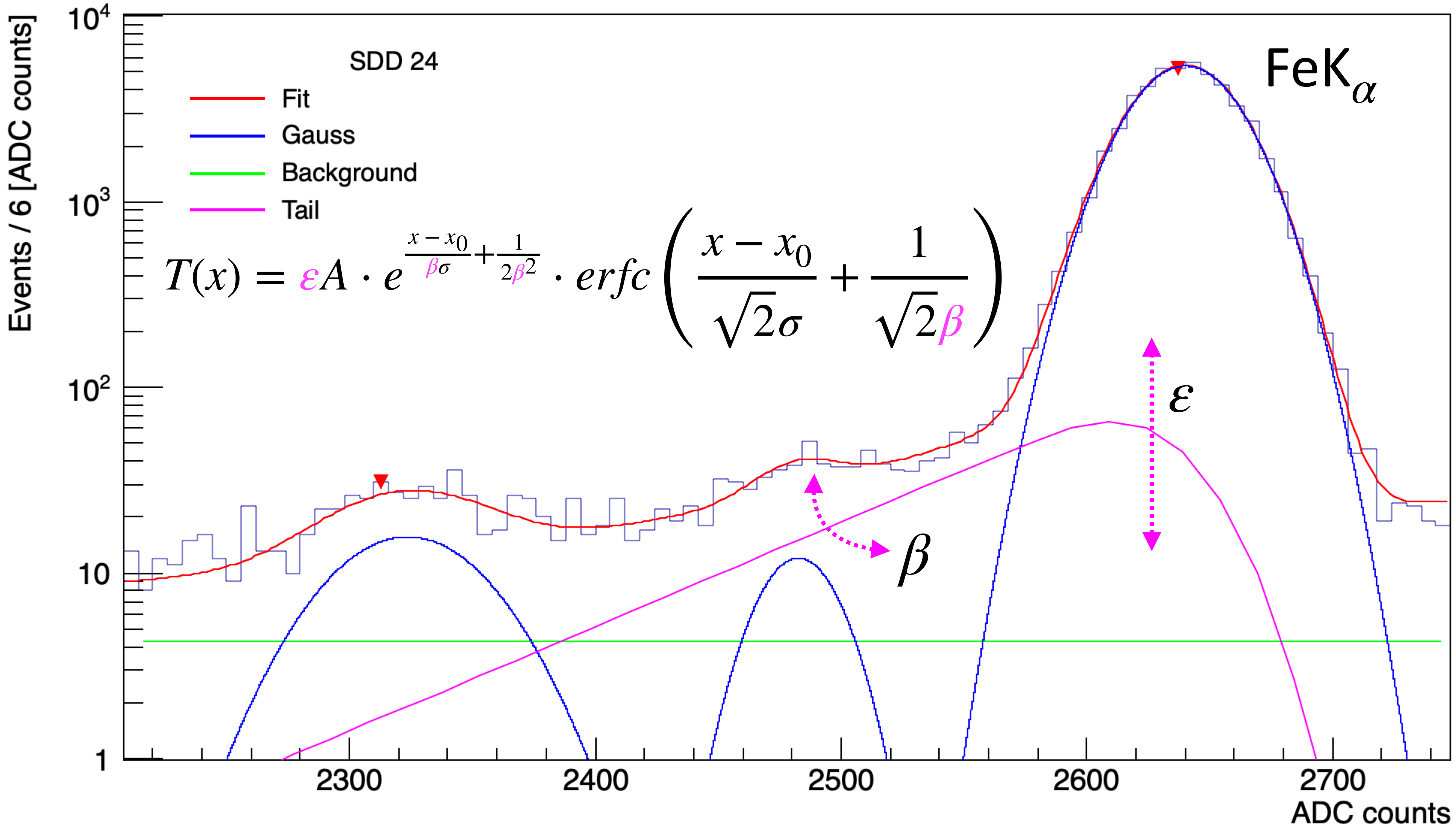
RN+BC voltage scan



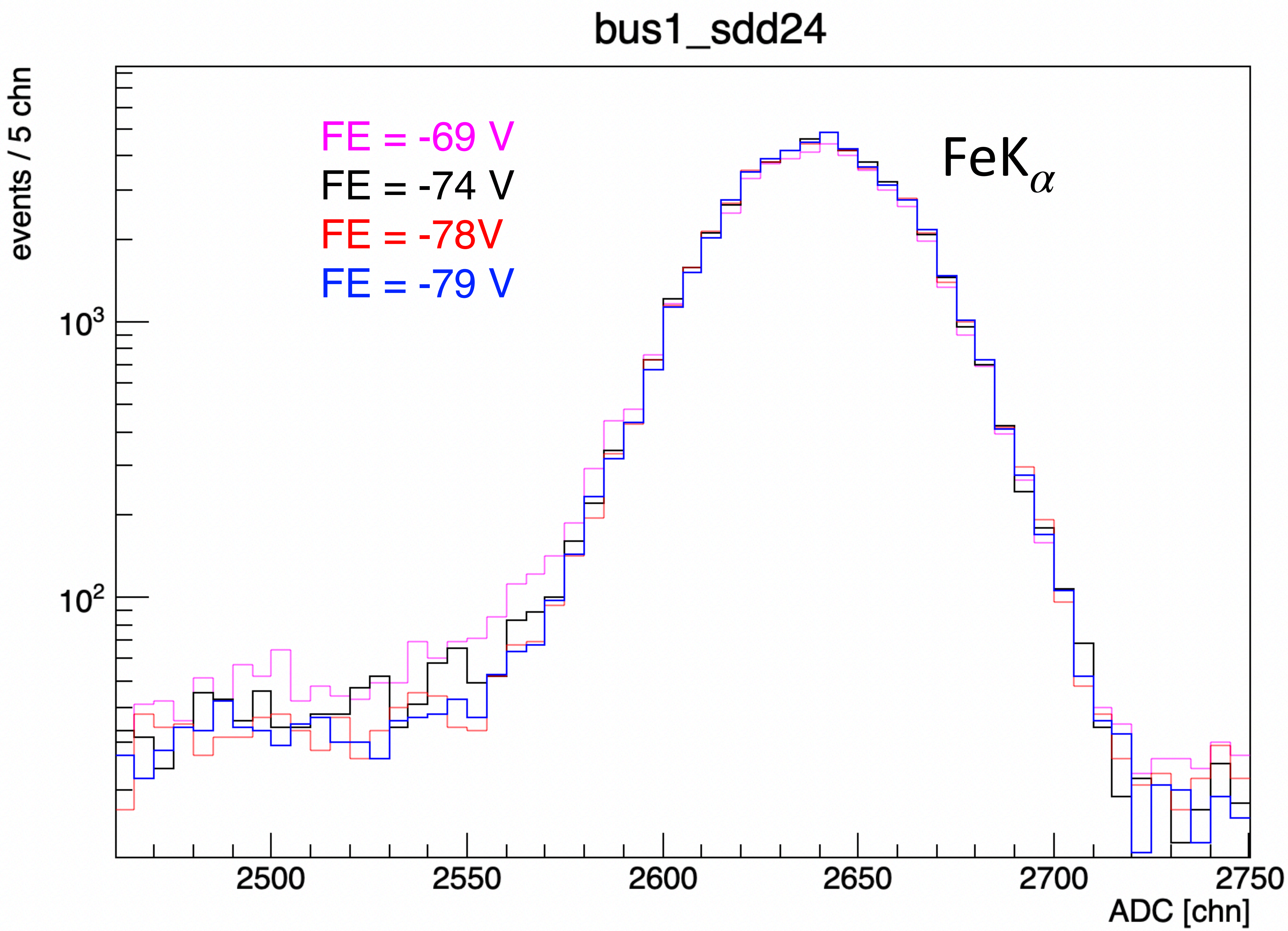
- Optimisation of the energy resolution at 6.4 keV as a function of the Back and RN bias voltages
- Optimal working point at RN=-90 V and BC=-69 V
- Fiducial region ~[-103V, -80V]x[-73.5V, -67V]
- Fluctuations of the bias voltages don't have a massive effect on the energy resolution

1mm SDDs characterization: tail contribution

- Optimisation of the energy resolution and Tail component as function of the FE bias voltage
- Due to incomplete charge collection and e-h recombination

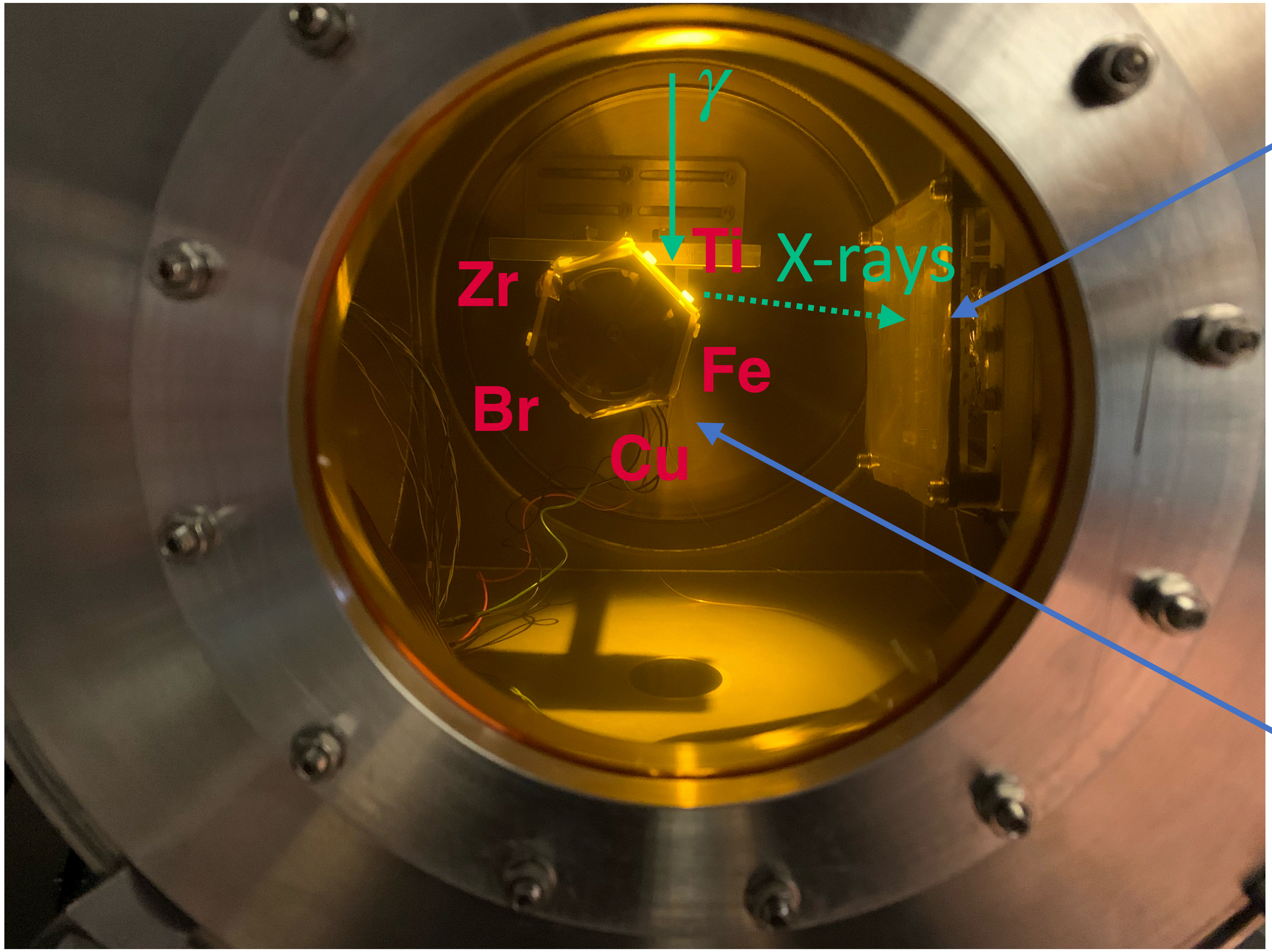


1mm SDDs characterization: tail contribution



1mm SDDs characterization: tail contribution

Response of the SDDs vs FE bias voltage scanned at different energies

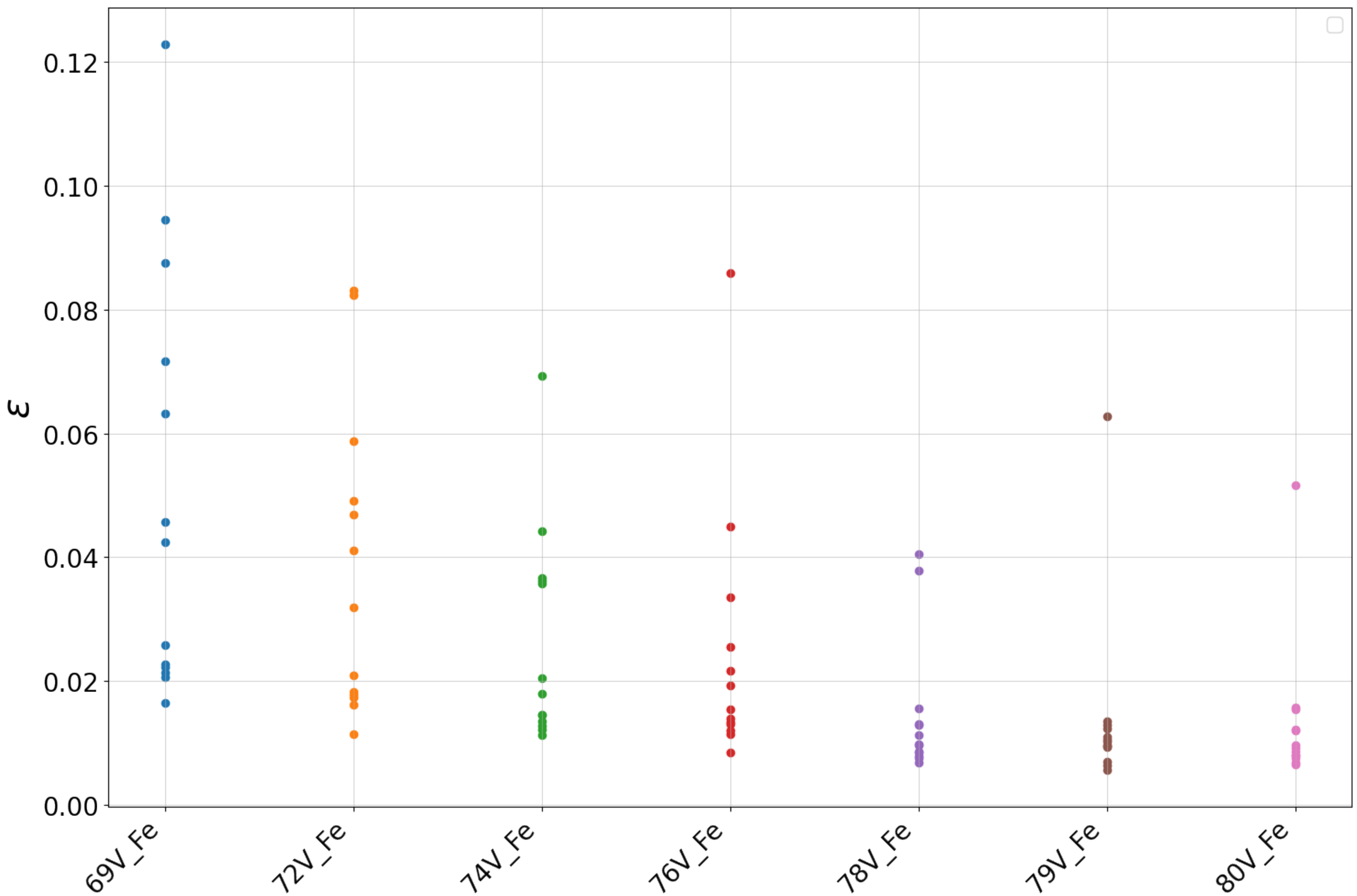


Silicon Drift Detectors

Ti - Fe - Cu - Br - Zr

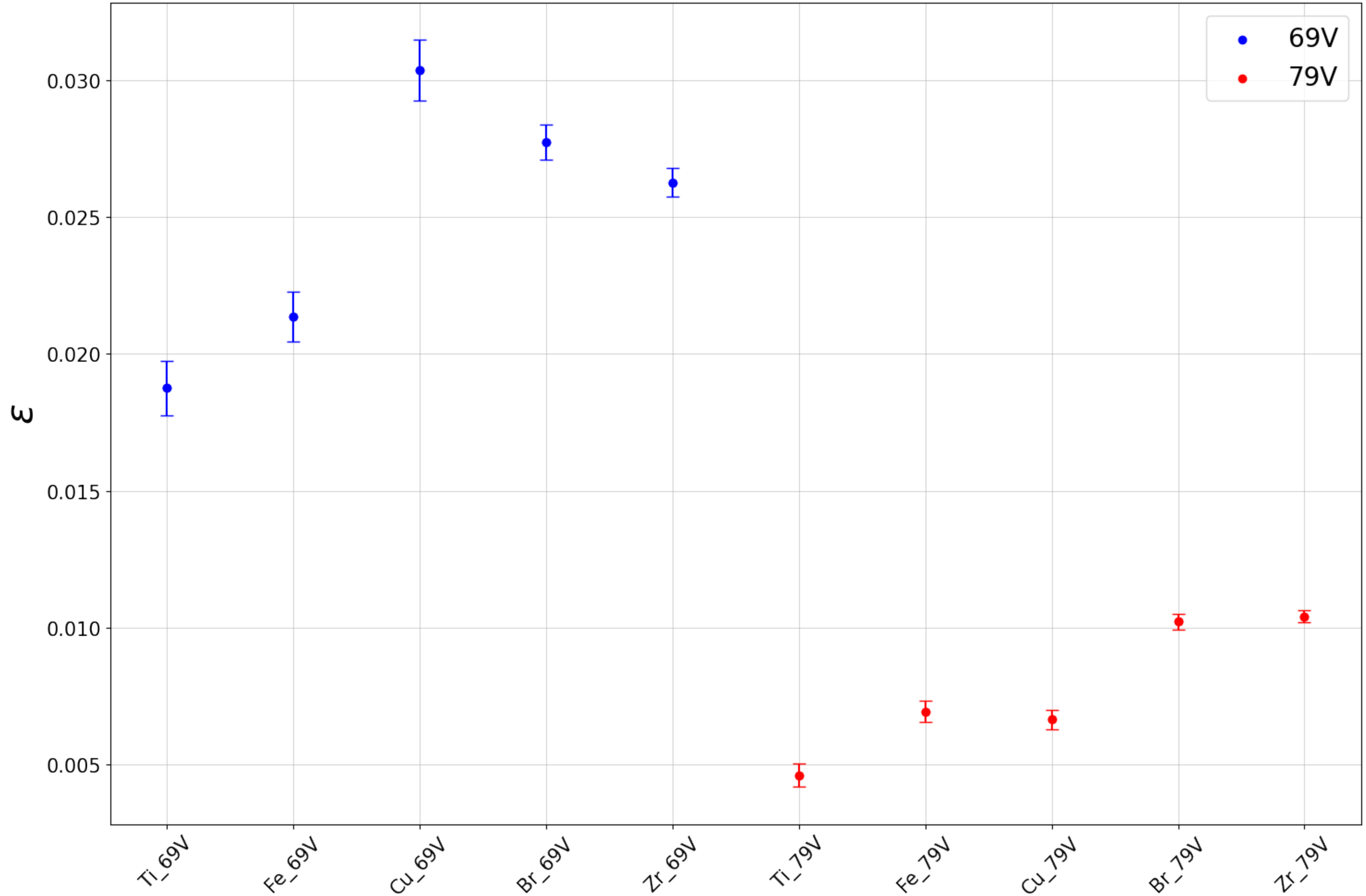
Rotating multitarget

1mm SDDs characterization: tail contribution

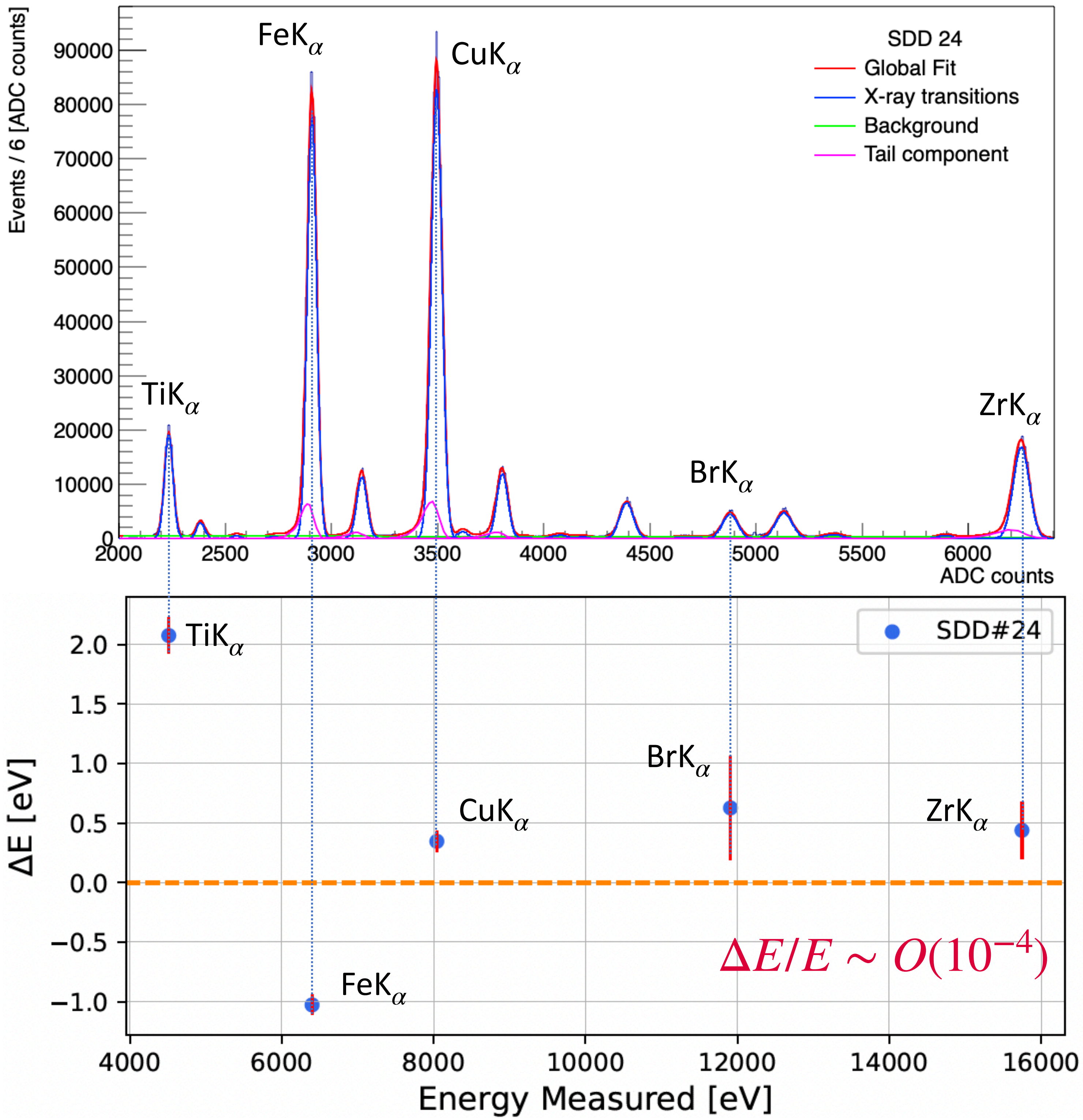


- Smaller tail contribution and more uniform response of the SDDs at higher FE bias voltages
- Optimal working point at FE=-79V

1mm SDDs characterization: tail contribution



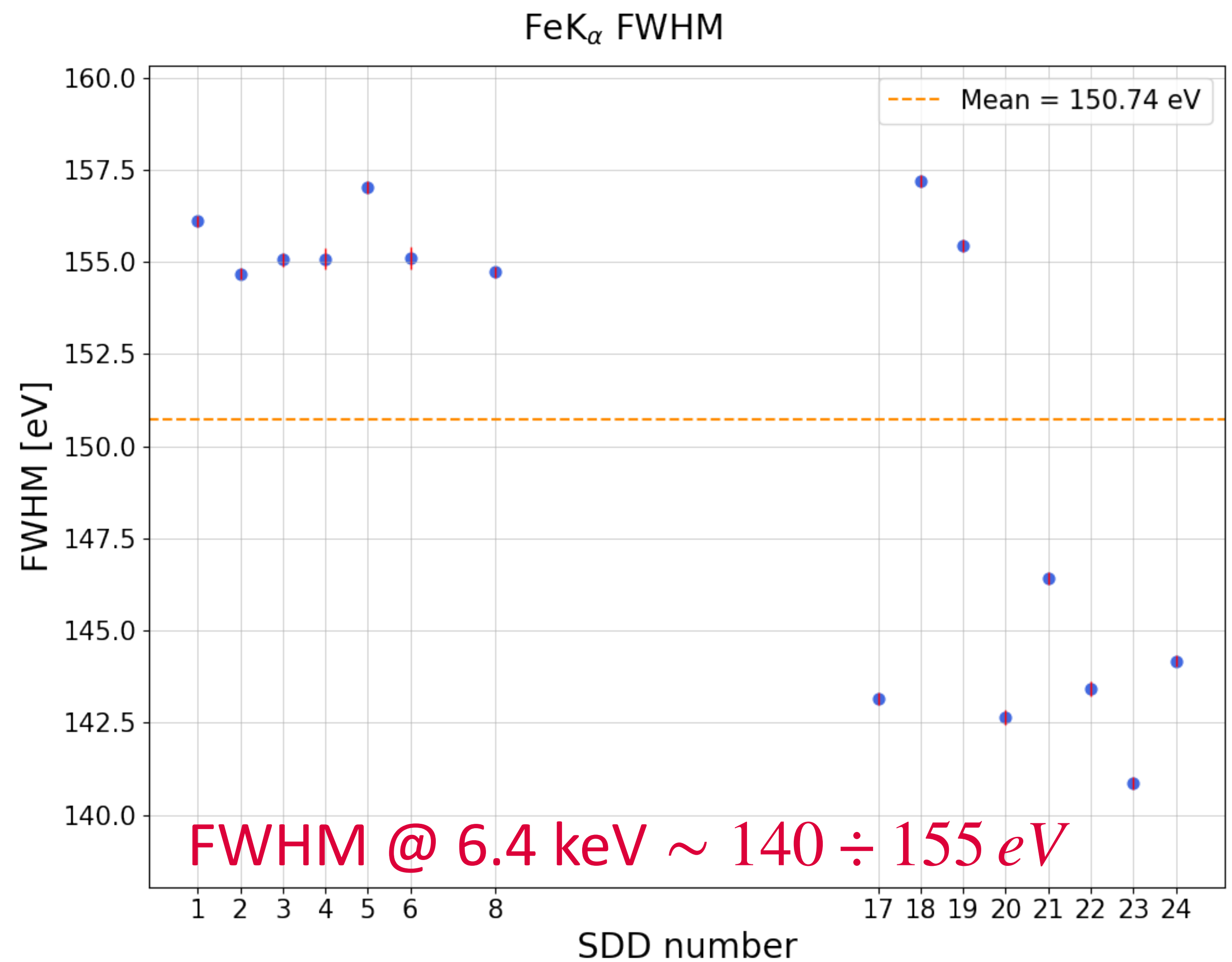
1mm SDDs characterization: optimal configuration



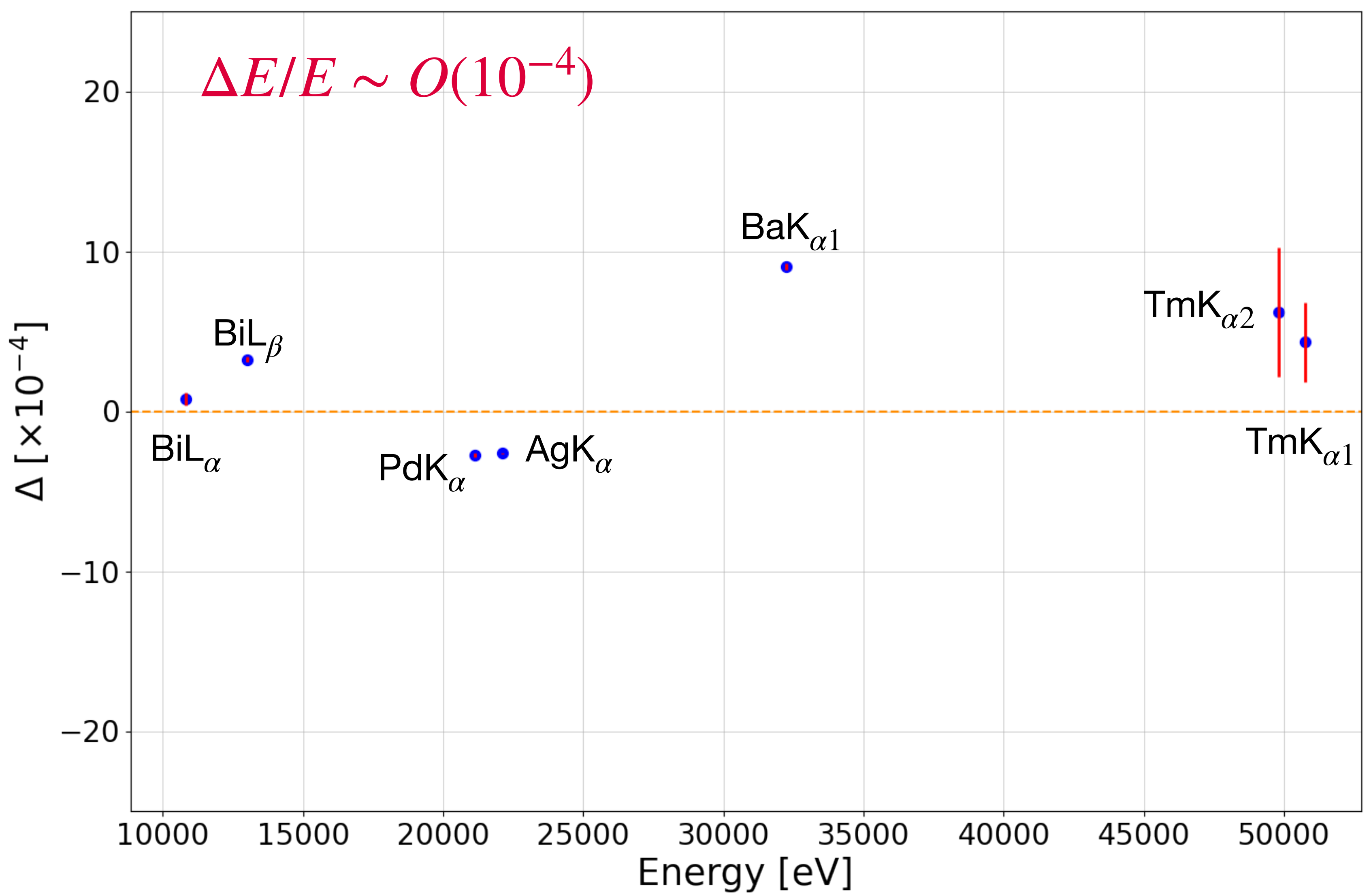
Voltages configuration:

R1 = -29V RN = -90V

BC = -69V FE = -79V

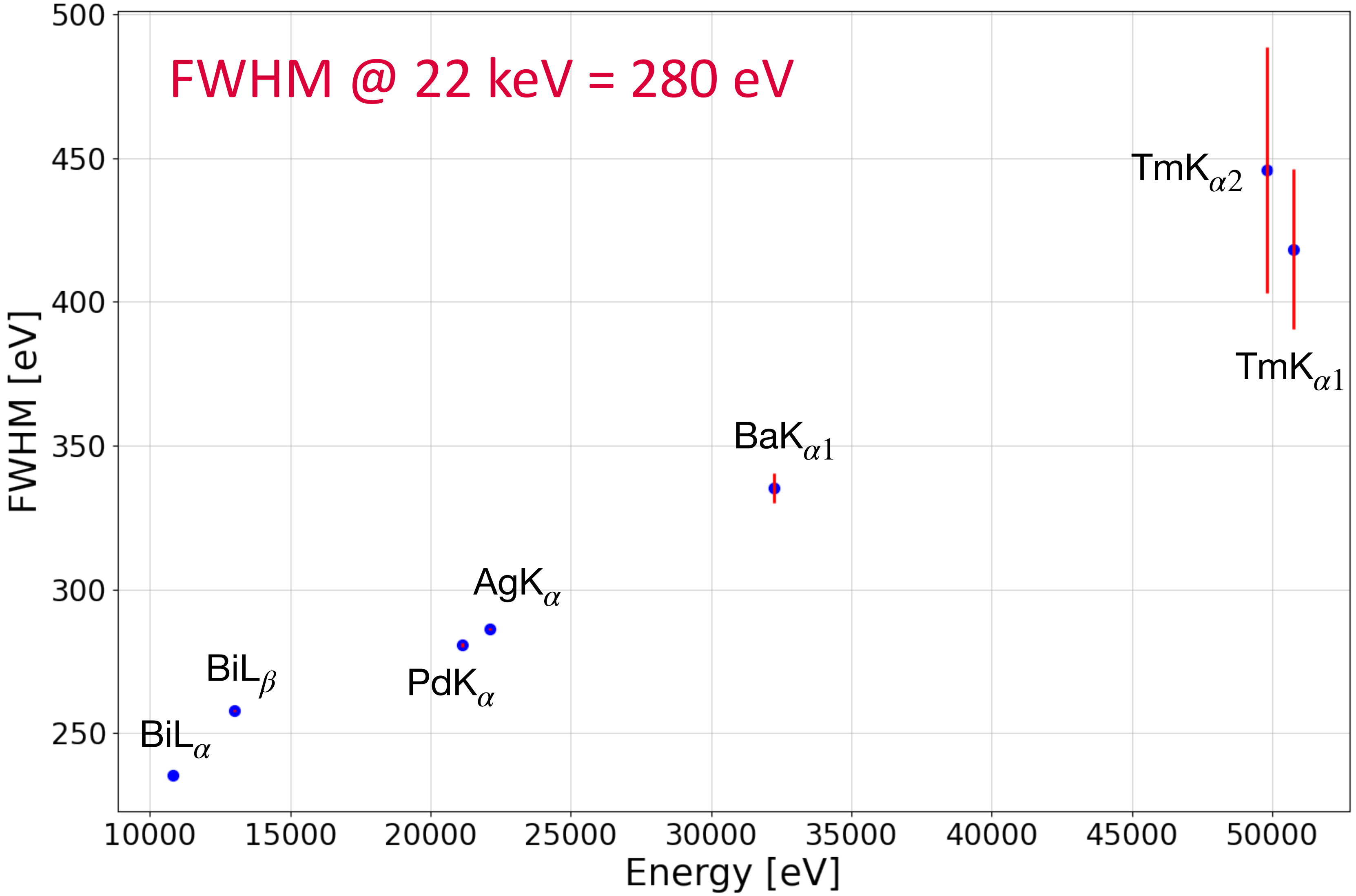


Feasibility test with SIDDHARTA-2: 450 μm SDDs



- First attempt to measure X-ray transitions at 50 keV with the 450 μm SDDs
- Characterisation performed to assess the performance of SDDs in the 10-50 keV energy range
- Linear calibration with known X-ray transition lines (BiL_α, PdK_α, AgK_α)
- Goodness of the calibration tested at 30 keV and 50 keV by measuring BaK_α and TmK_α X-ray transitions

Feasibility test with SIDDHARTA-2: 450 µm SDDs



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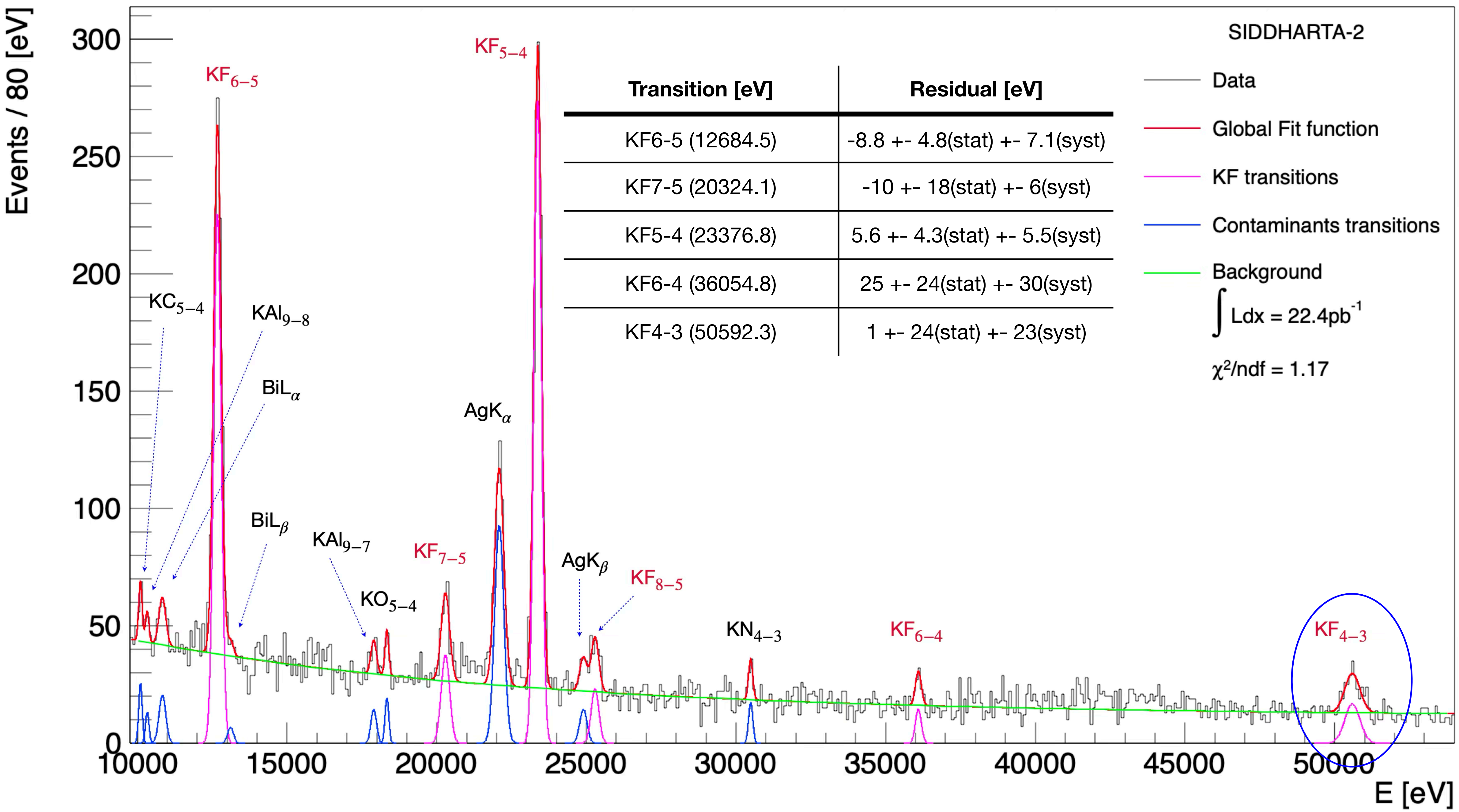
Feasibility test with SIDDHARTA-2: Kaonic Fluorine

- Once characterised, measurement of Kaonic Fluorine (Teflon C_2F_4 target) with the 450 μm SDDs



Transition [eV]	Residual [eV]
KF6-5 (12684.5)	-8.8 +- 4.8(stat) +- 7.1(syst)
KF7-5 (20324.1)	-10 +- 18(stat) +- 6(syst)
KF5-4 (23376.8)	5.6 +- 4.3(stat) +- 5.5(syst)
KF6-4 (36054.8)	25 +- 24(stat) +- 30(syst)
KF4-3 (50592.3)	1 +- 24(stat) +- 23(syst)

Conclusions

- SIDDHARTA-2 performs high precision X-ray measurement of light kaonic atoms
- EXKALIBUR will measure higher mass kaonic atoms
- To extend the range of measurable kaonic atoms, new 1mm thick SDDs are being developed and characterised
- Characterisation and optimisation of the SDDs' energy response as a function of the bias voltages (R1, RN, BC, FE)
- The first tests highlight an excellent linearity $(\Delta E/E \sim O(10^{-4}))$ and energy resolution (FWHM $\sim$ 150 eV @ 6.4 keV)
- The results of the feasibility test with 450 µm SDDs are **very promising**
- 50 keV transition line of Kaonic Fluorine $(4 \rightarrow 3)$ has been measured

Thank you for your attention

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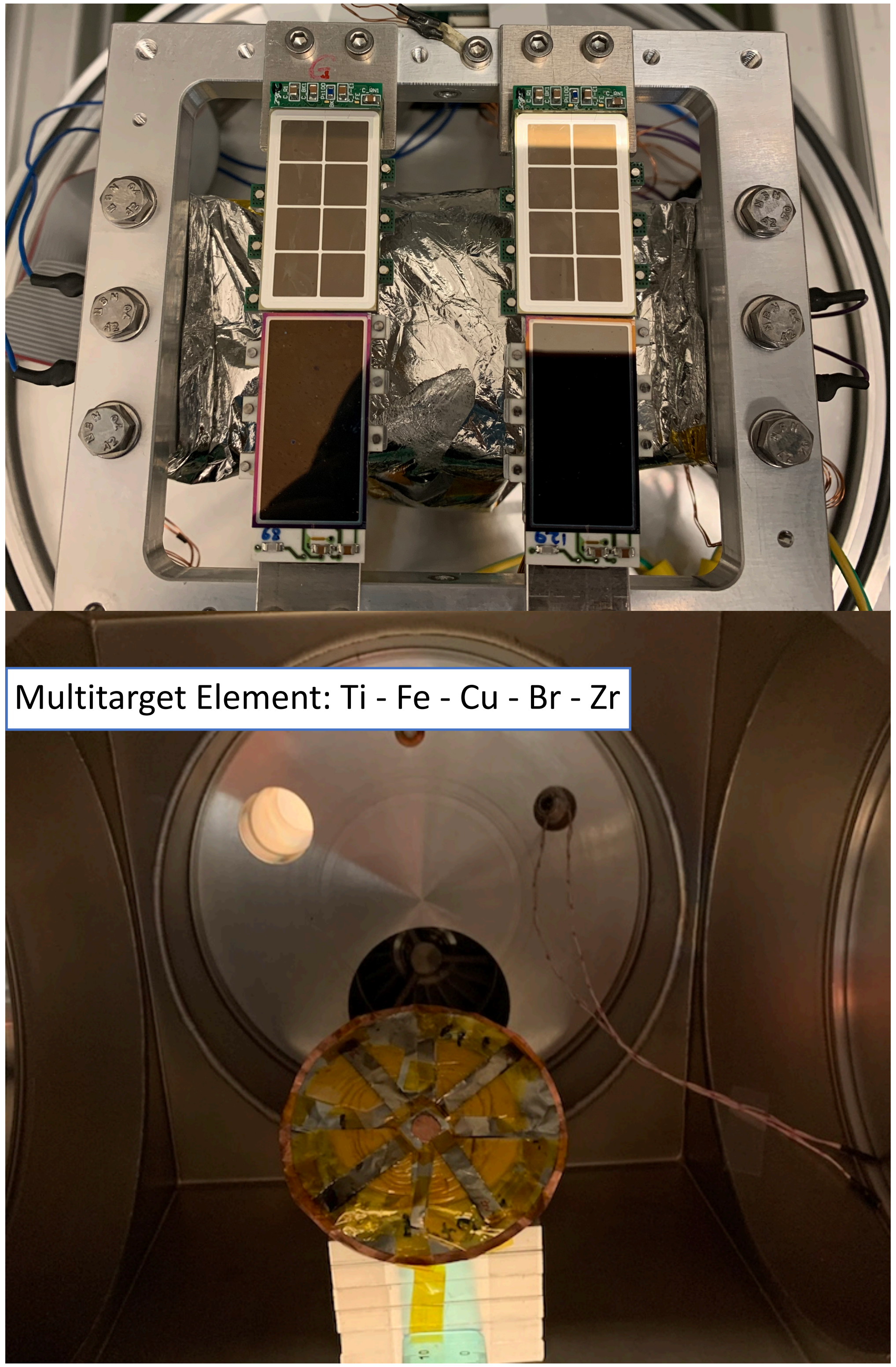
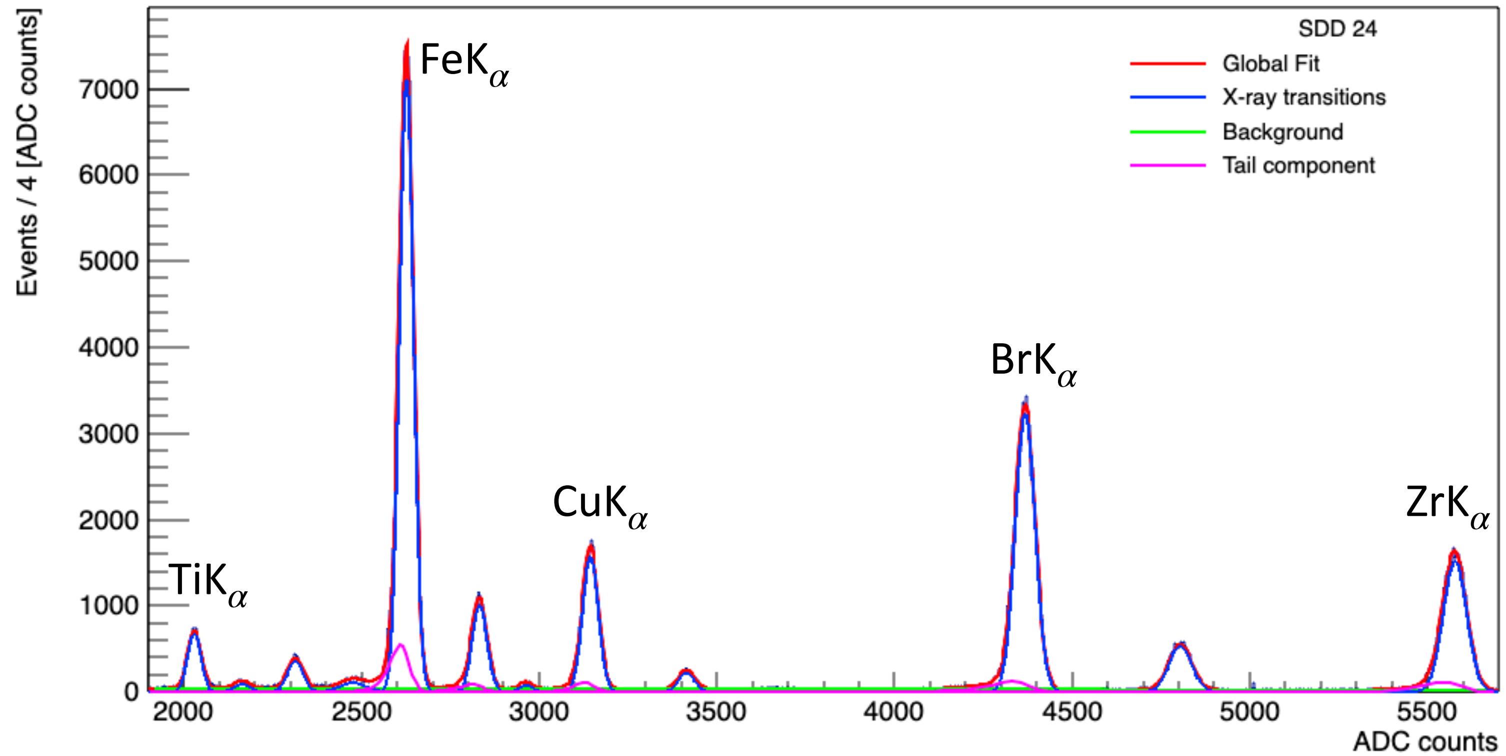
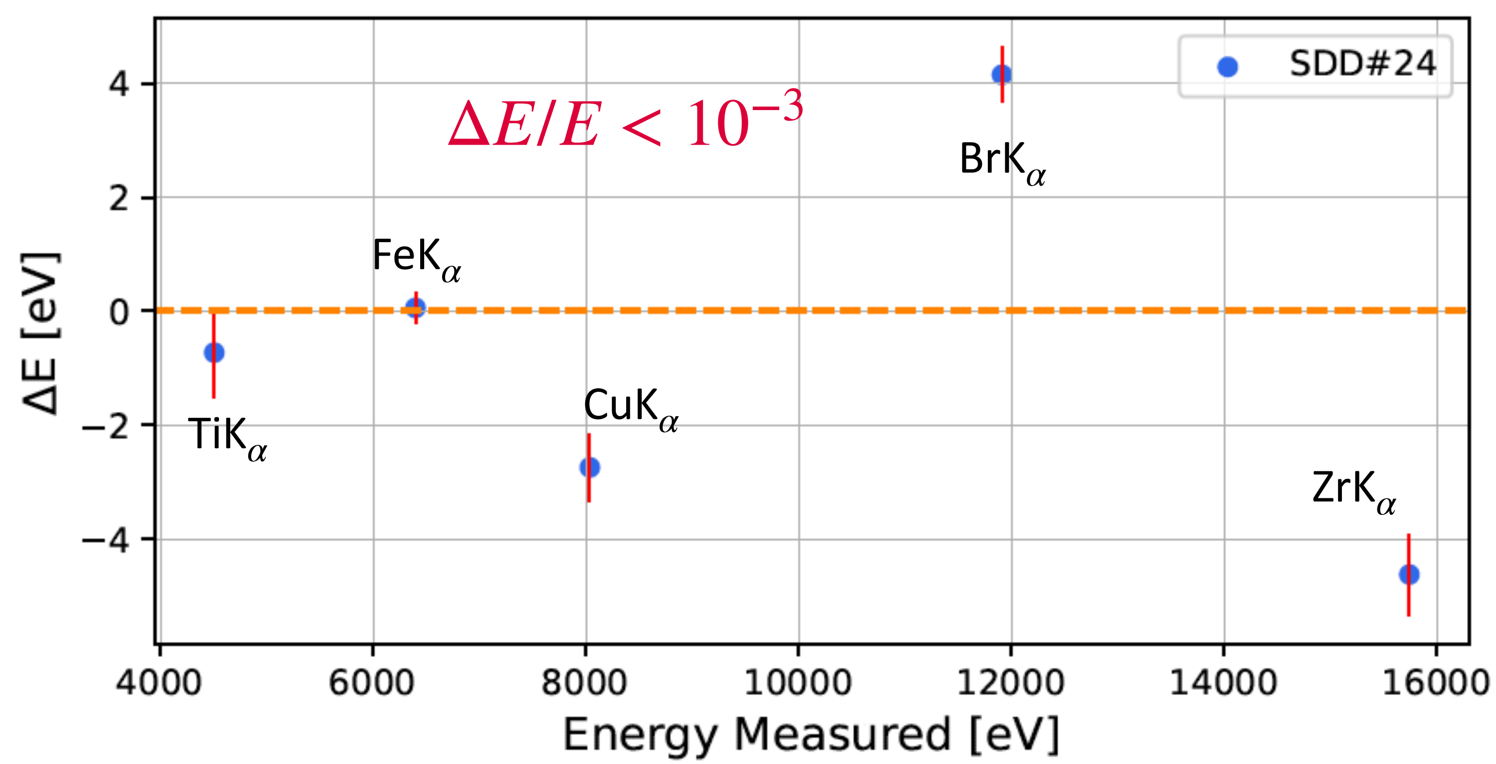
BACKUP

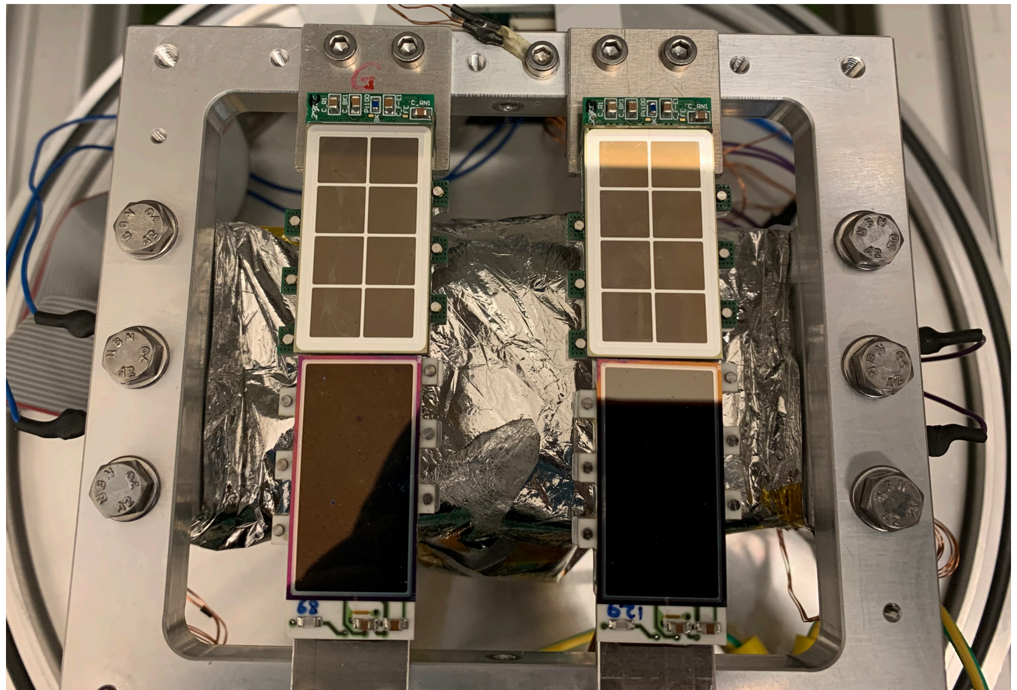
1mm SDDs characterization: linearity

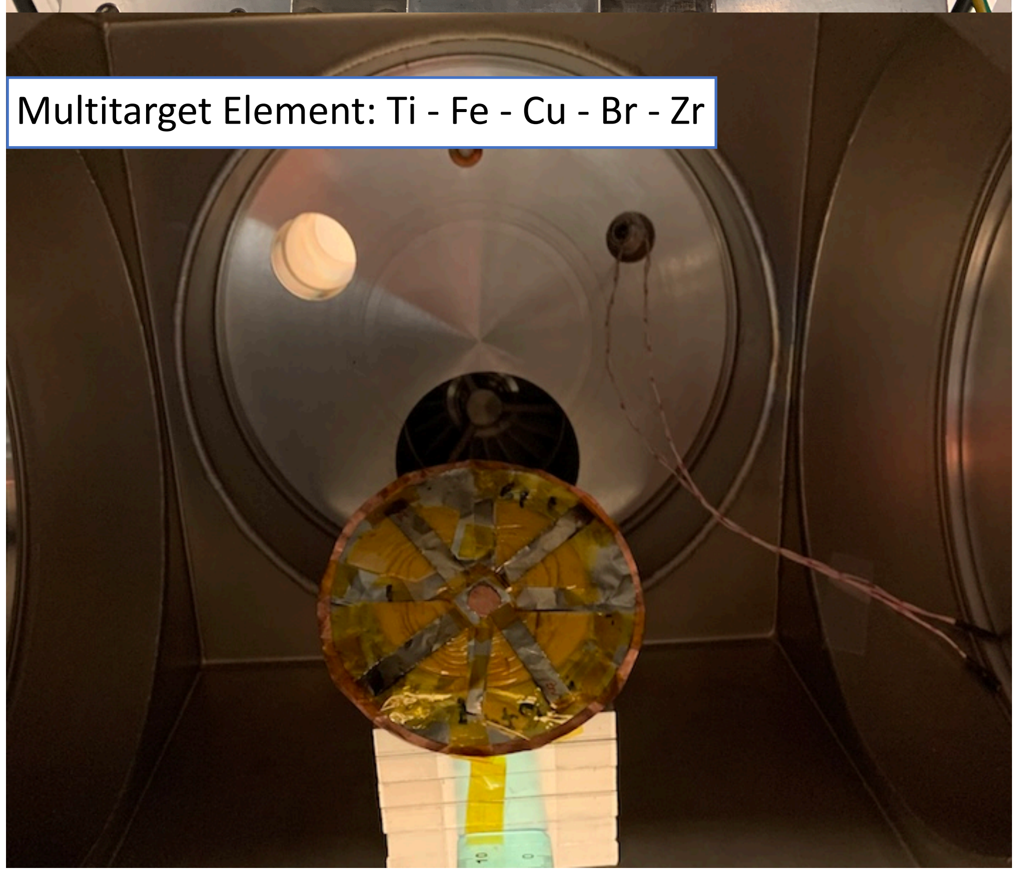


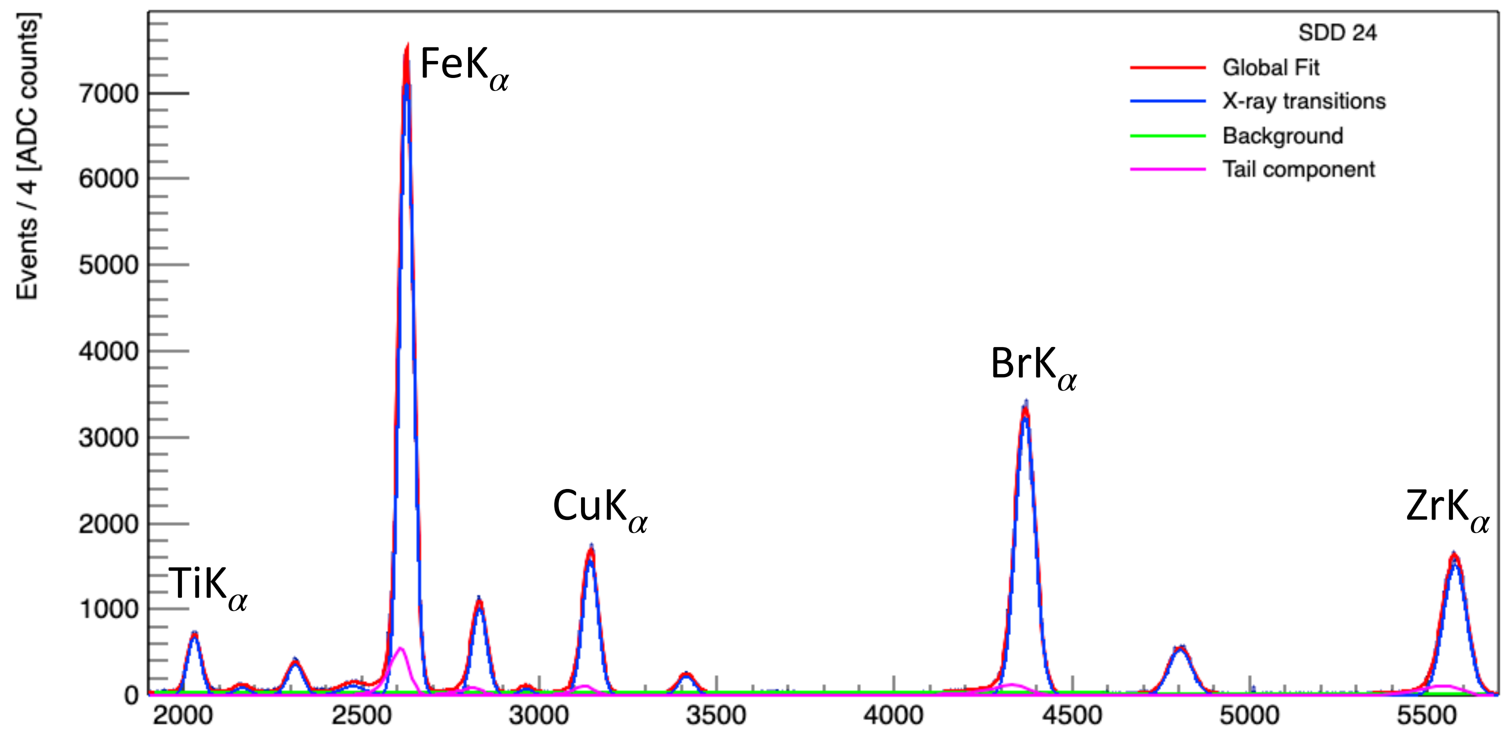




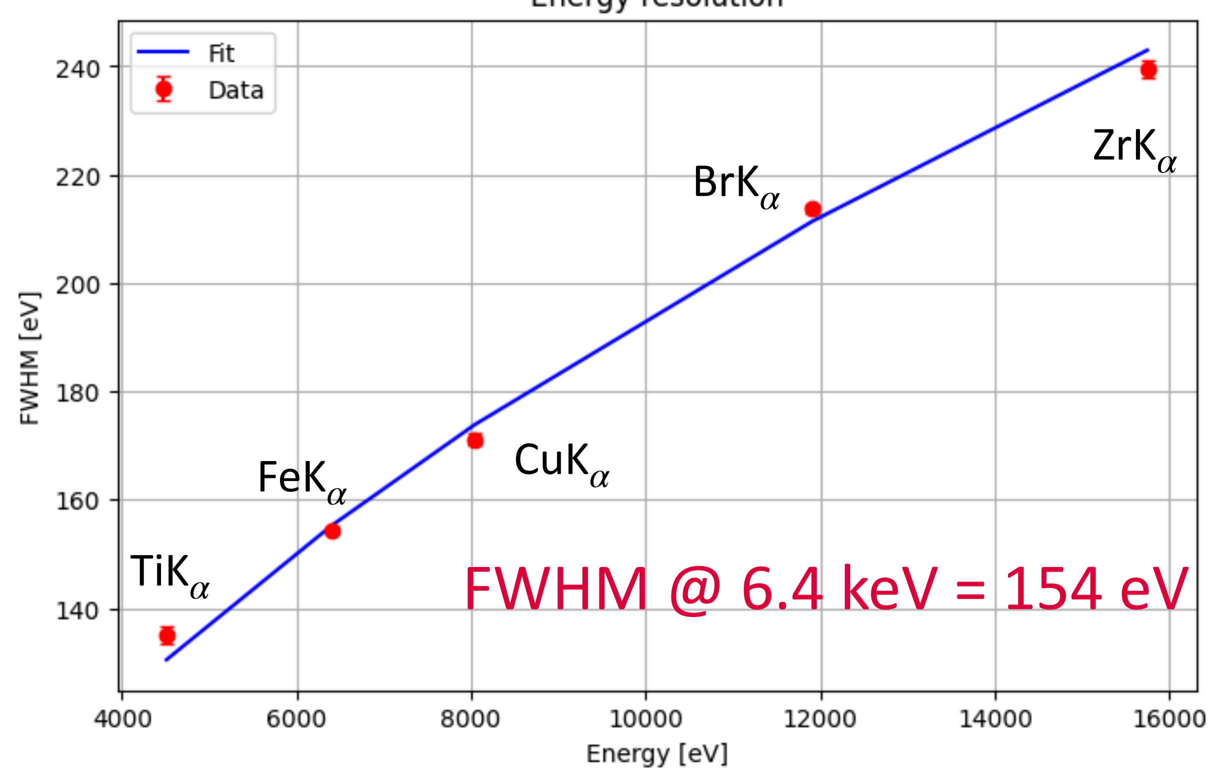
1mm SDDs characterization: energy resolution



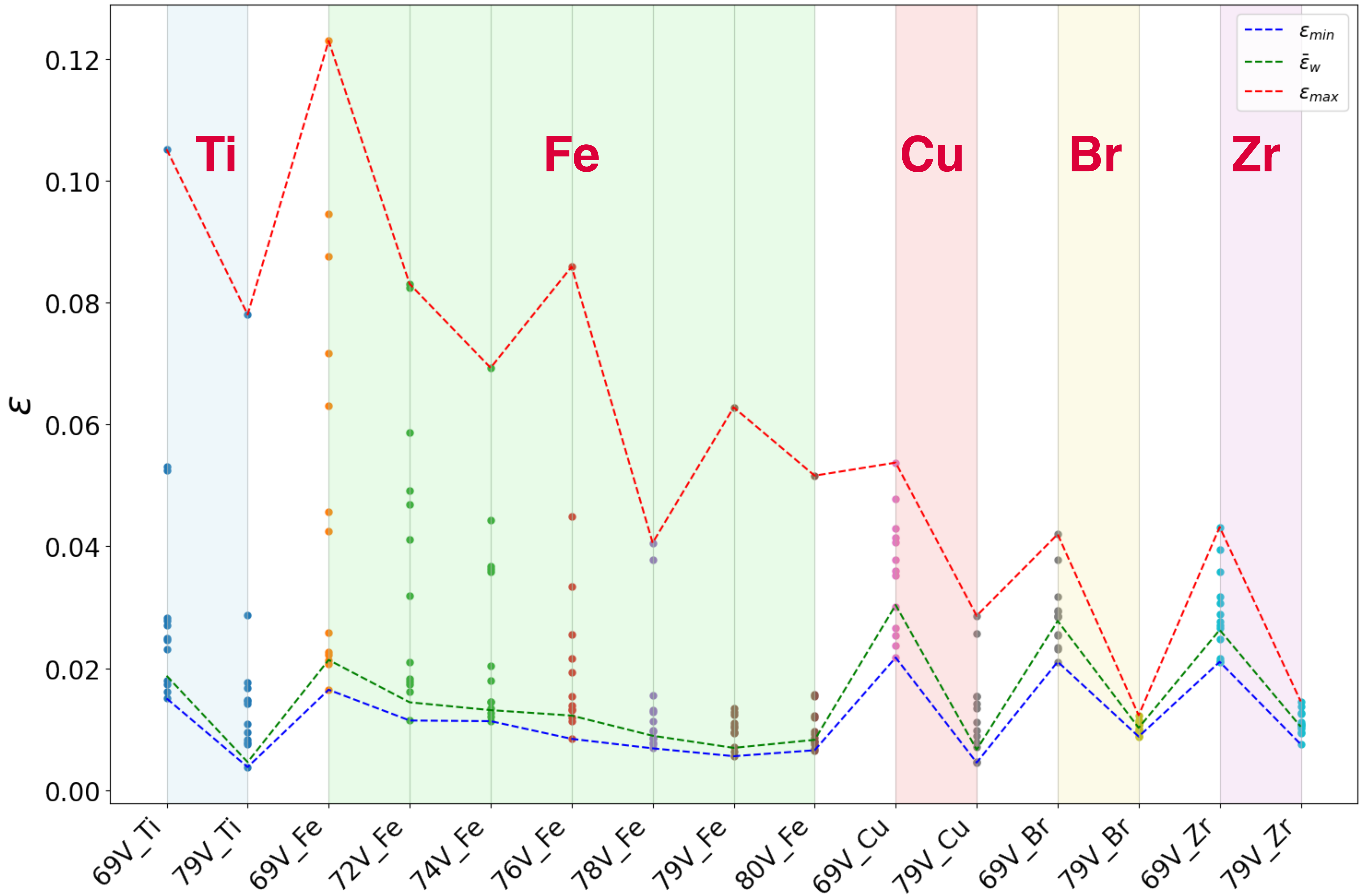




Energy resolution



1mm SDDs characterization: tail contribution



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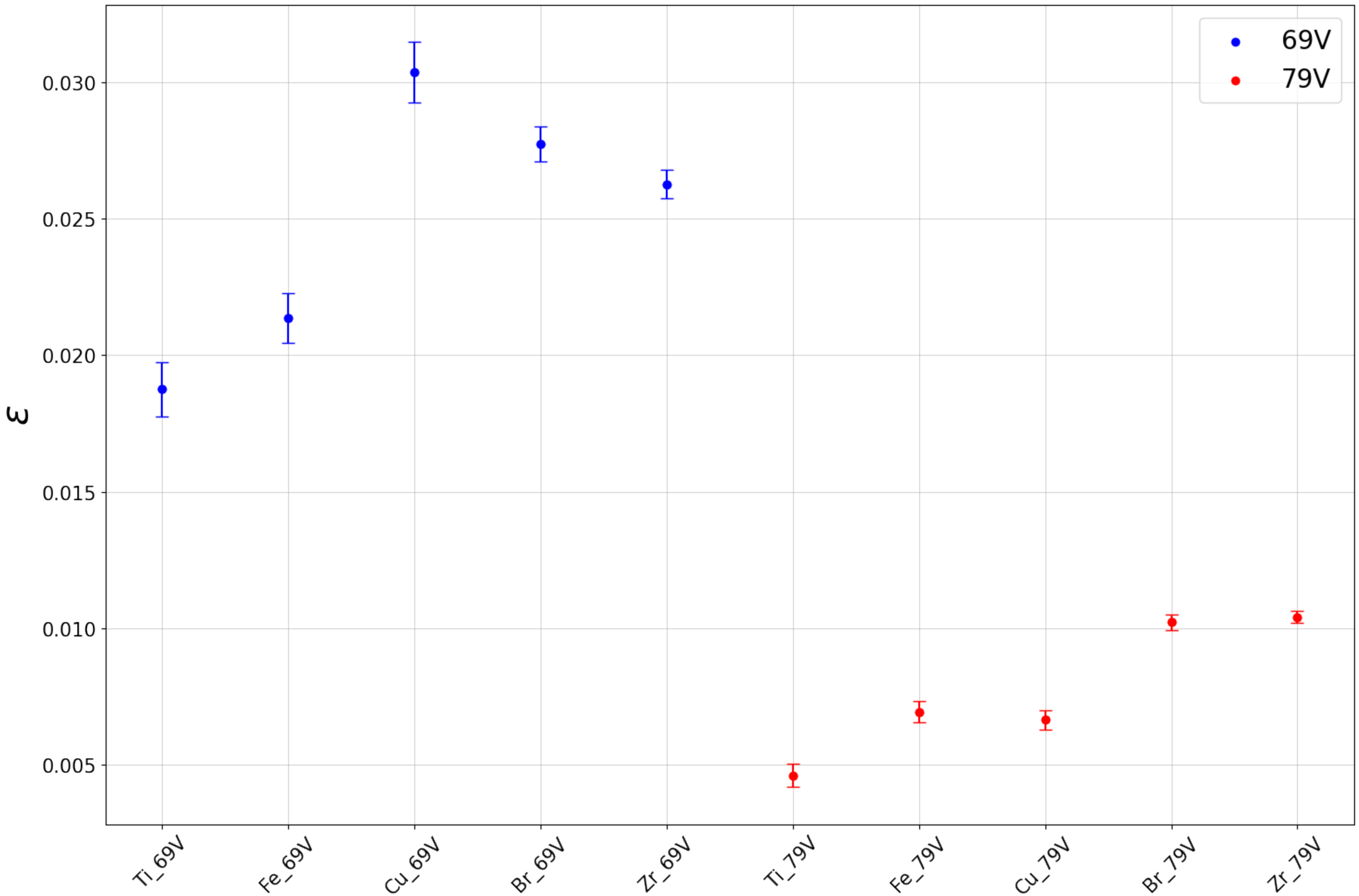

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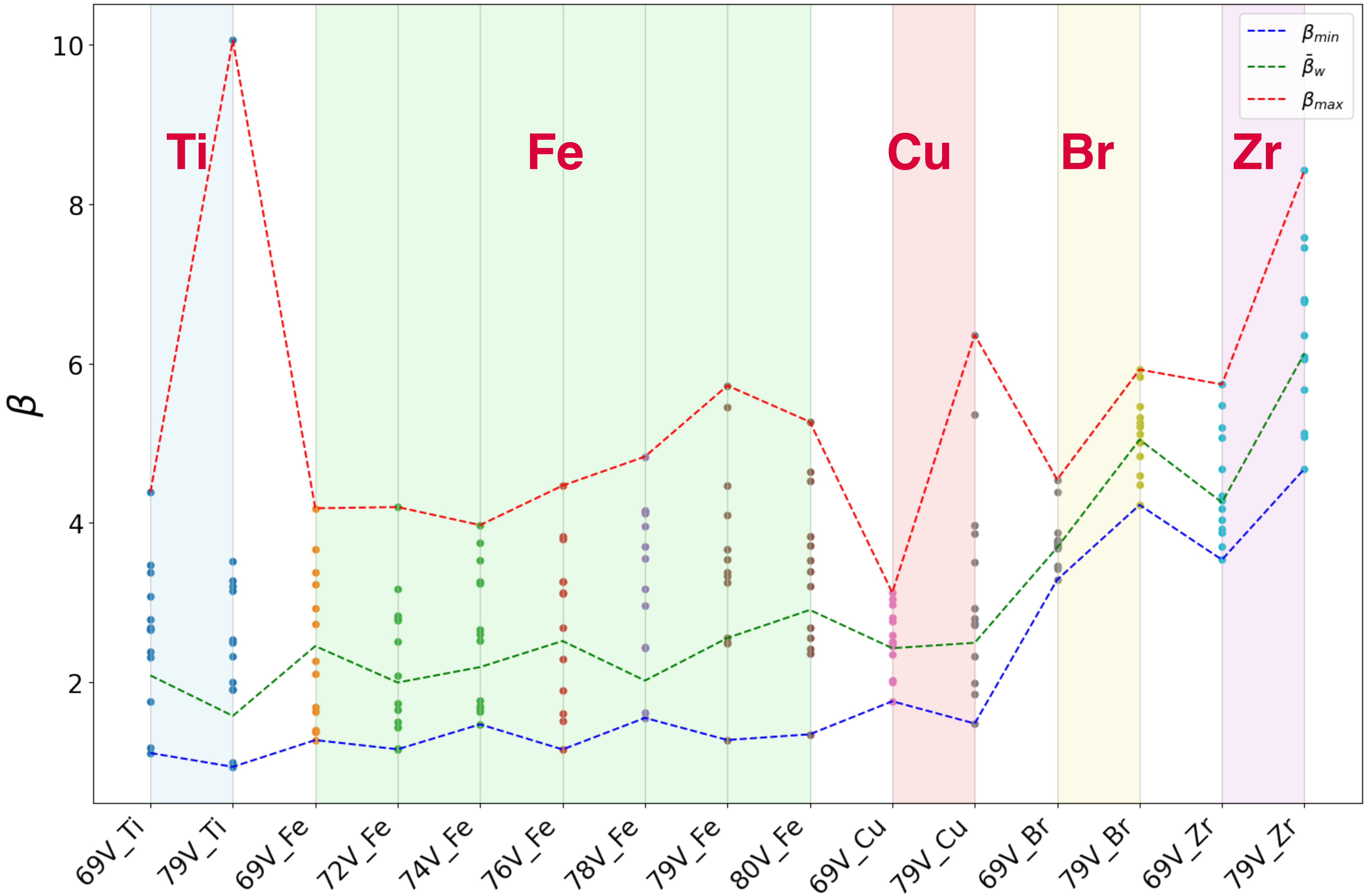

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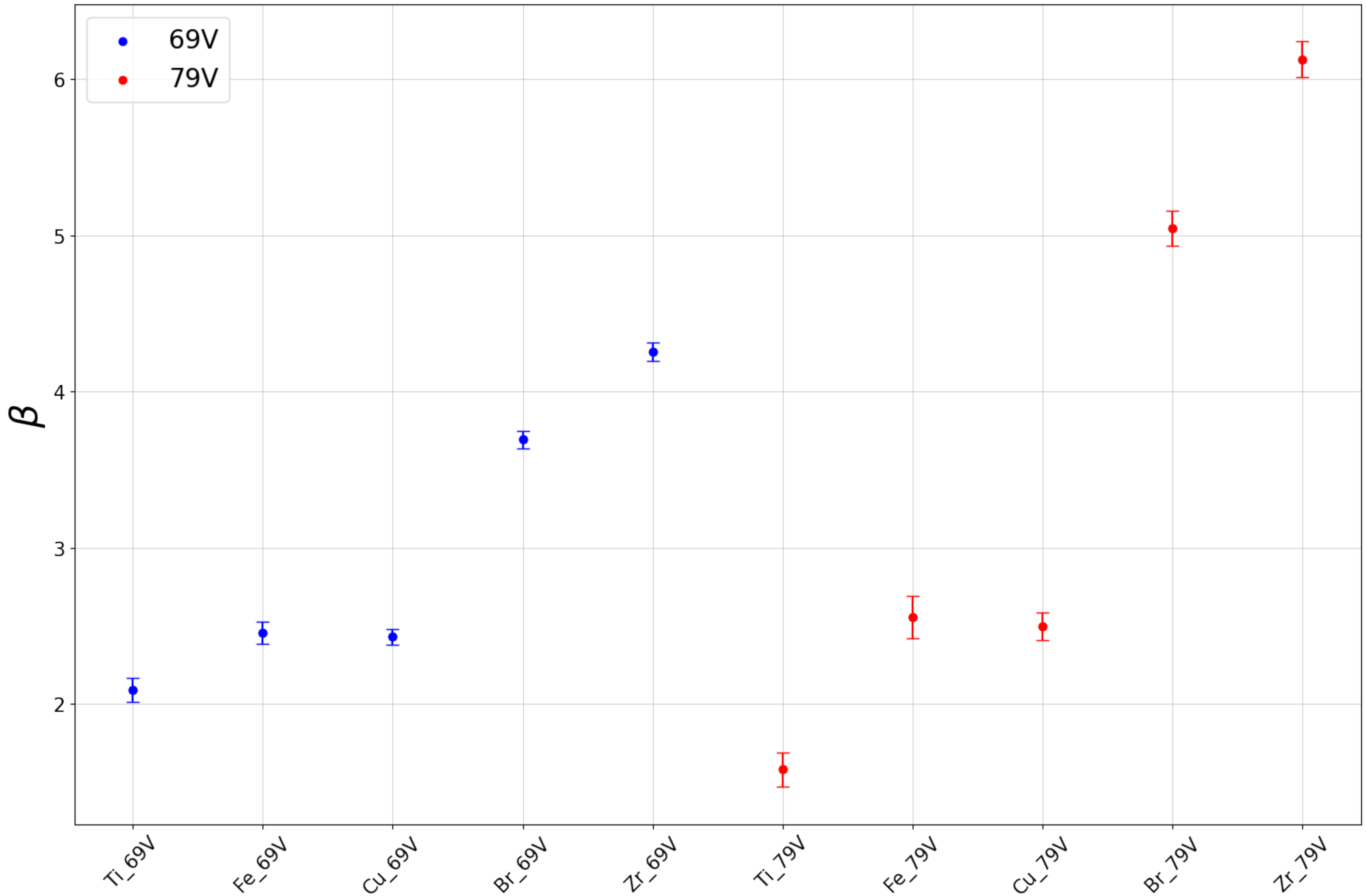

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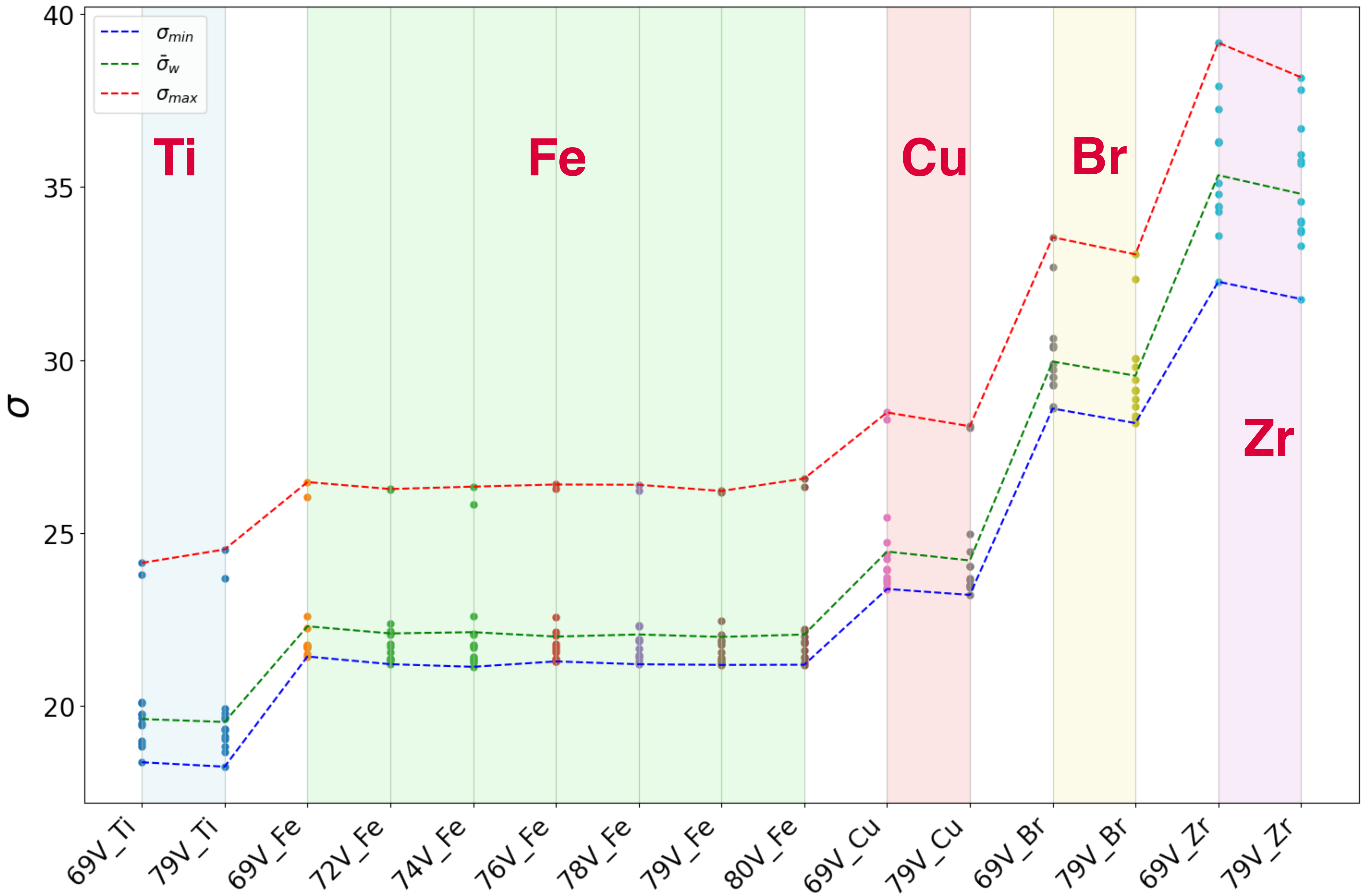

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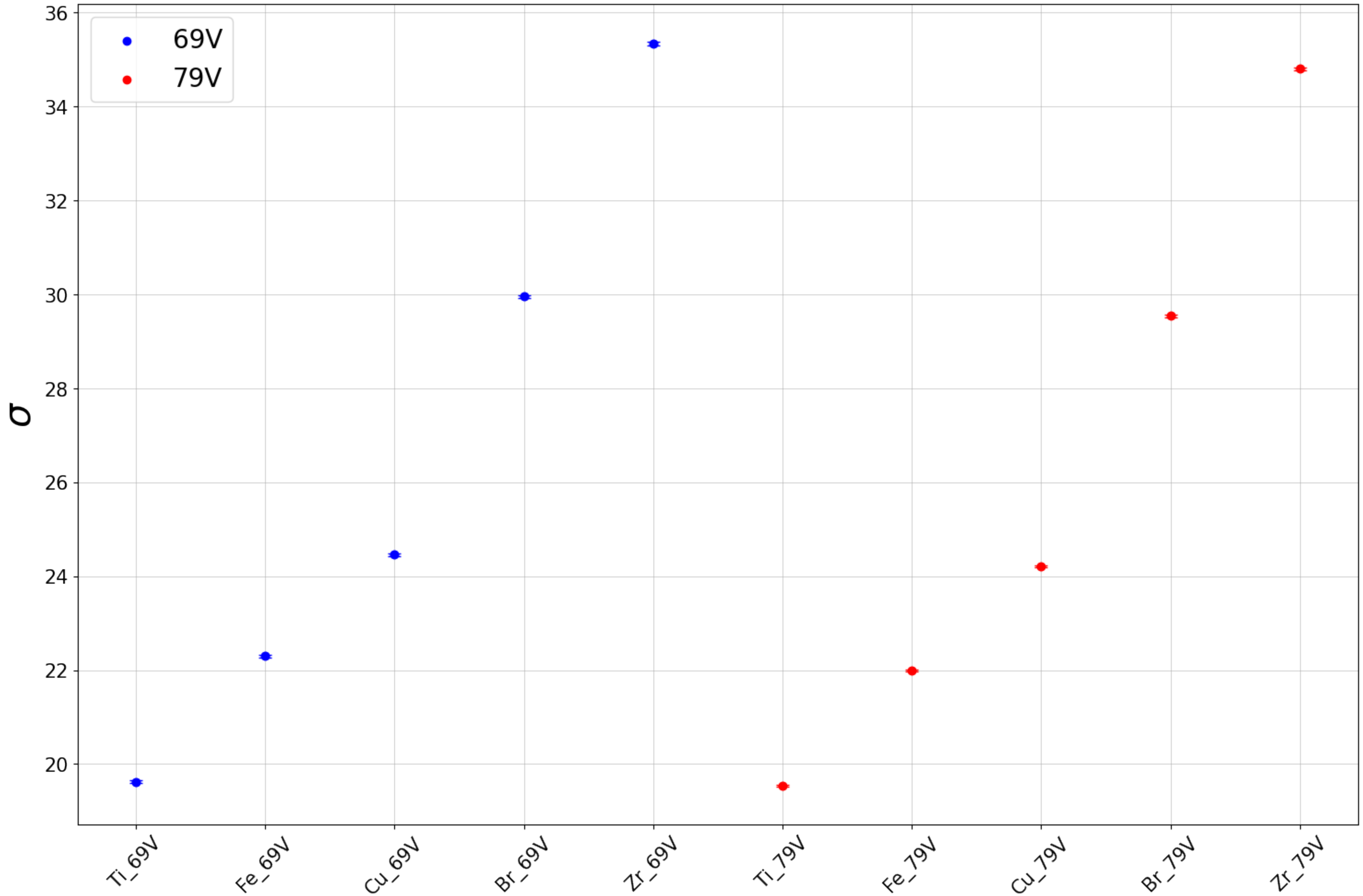

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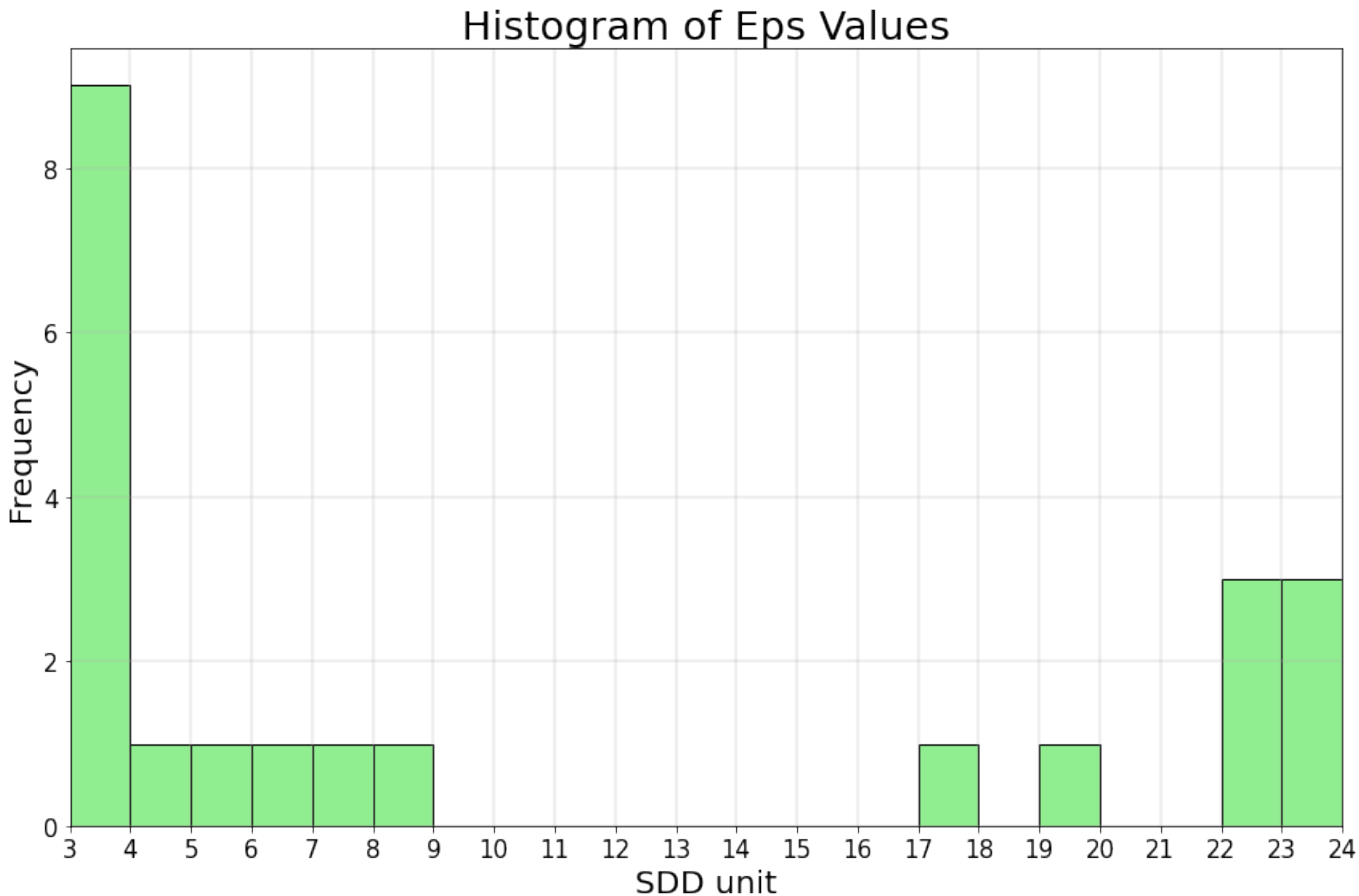
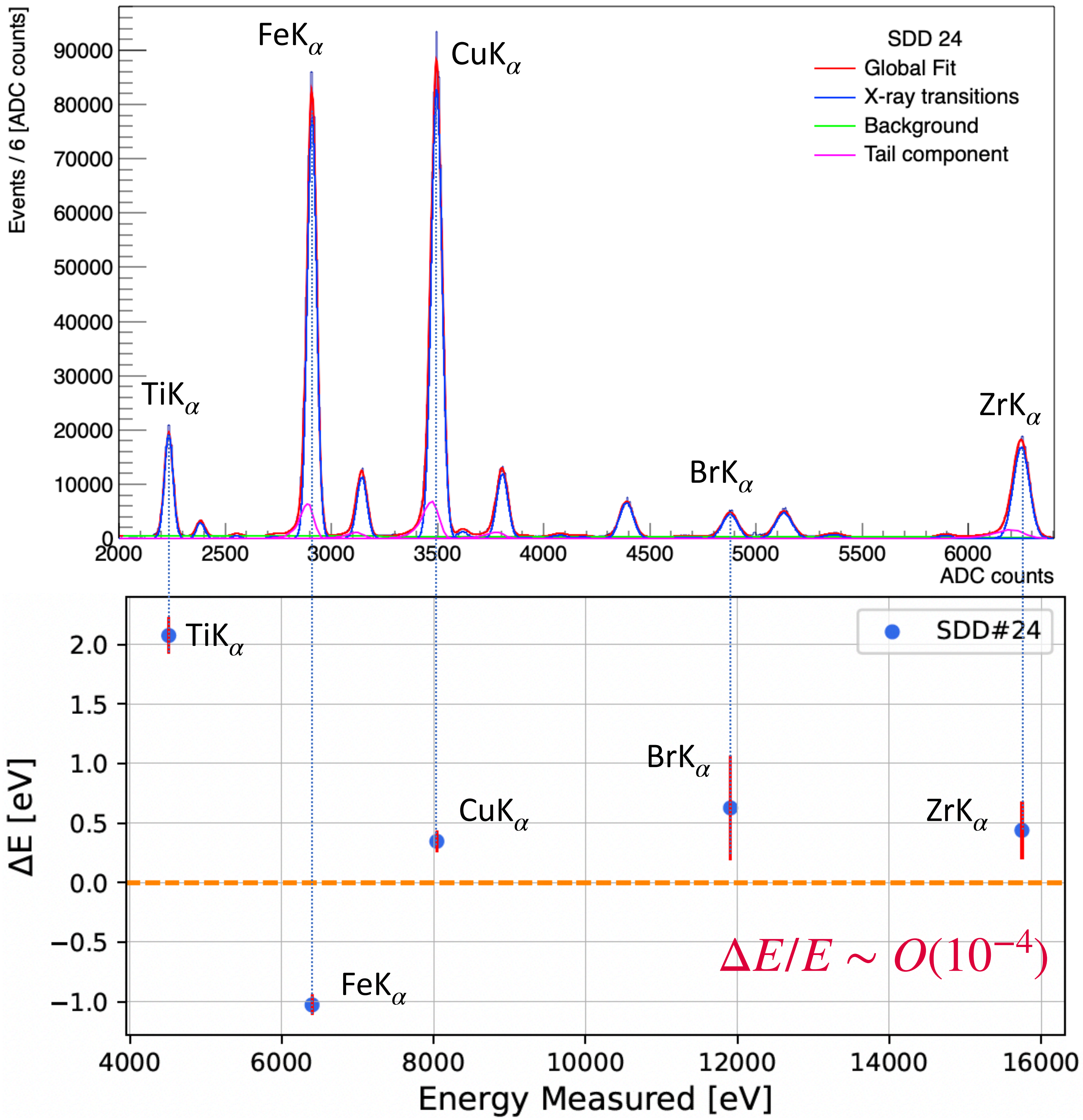


1mm SDDs characterization: optimal configuration



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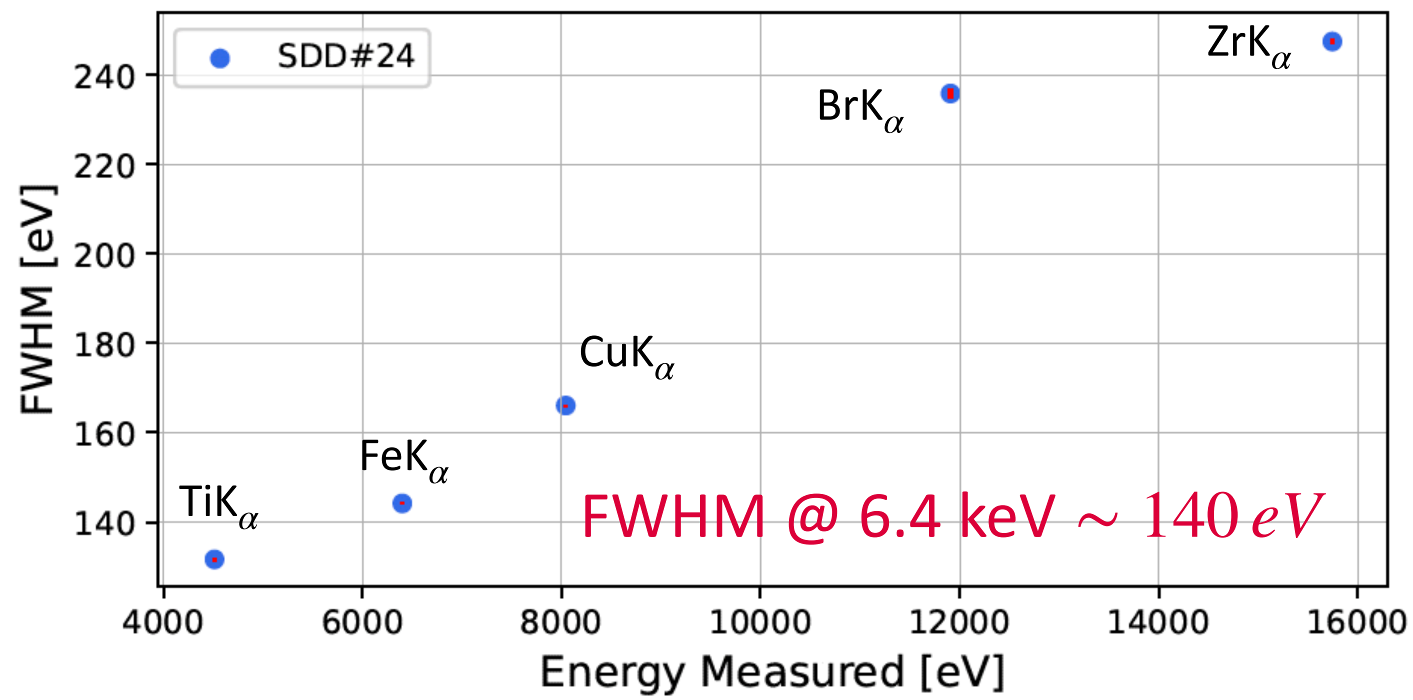
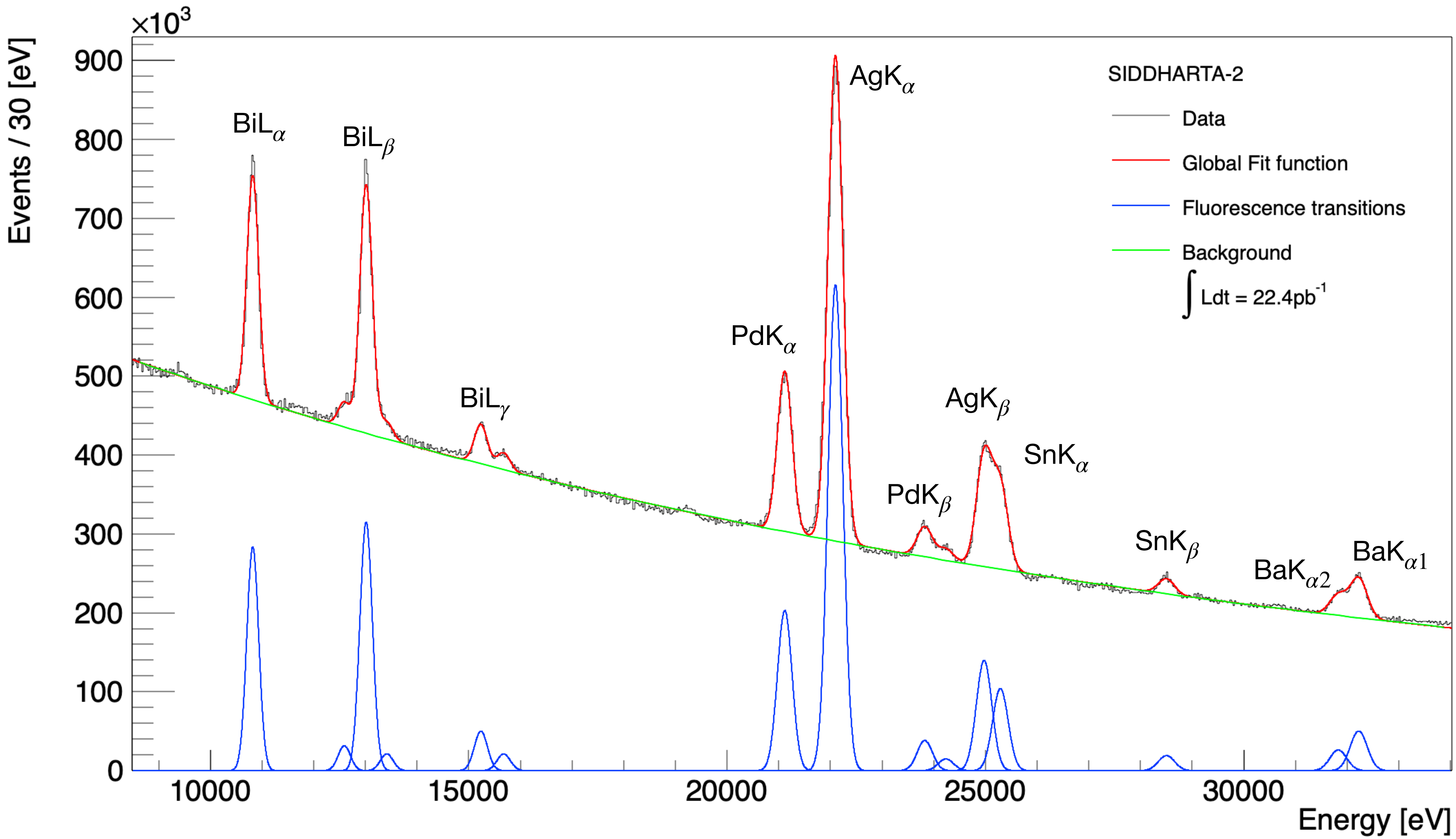


Feasibility test with SIDDHARTA-2: 450 μm SDDs



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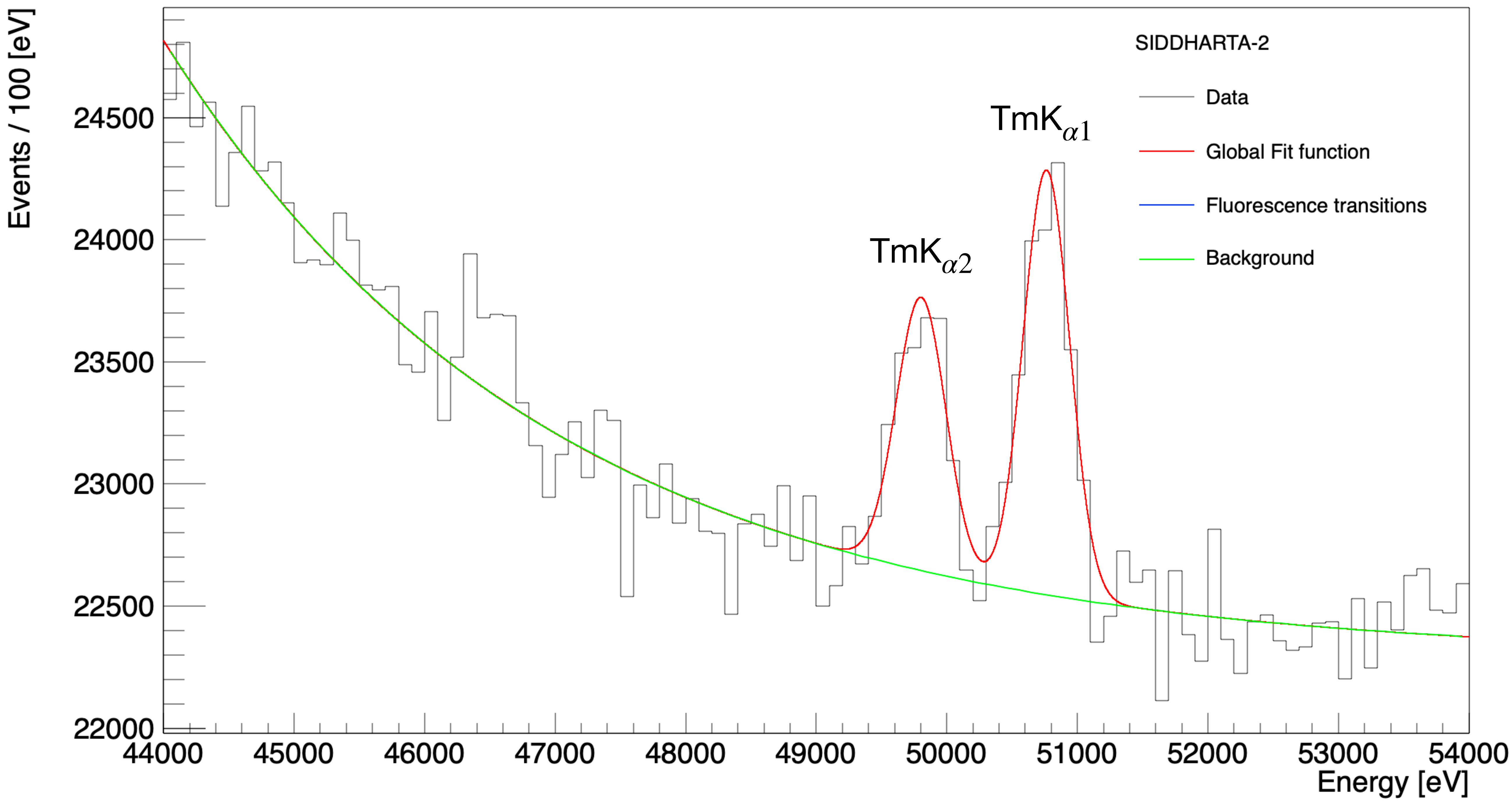

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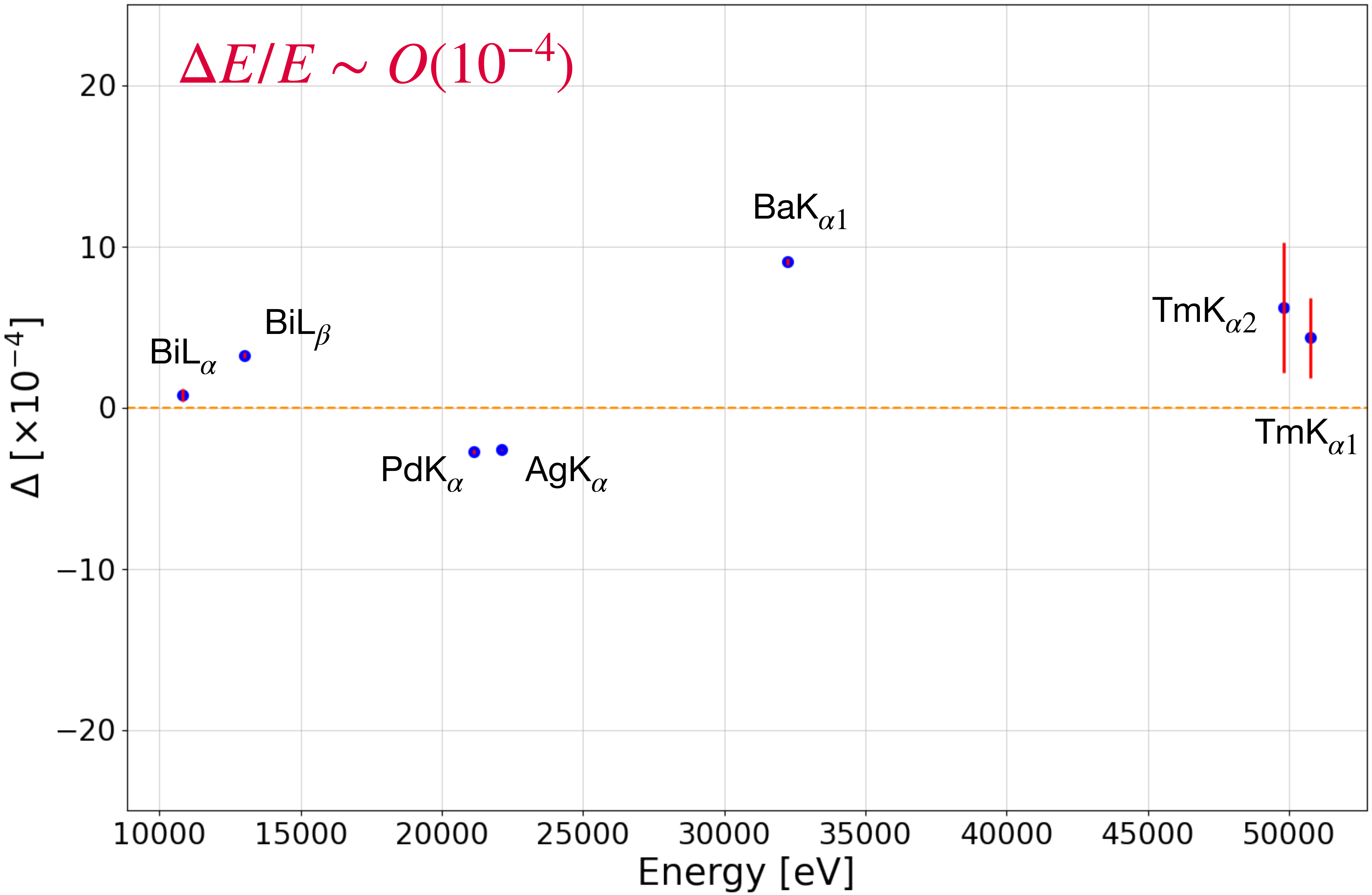

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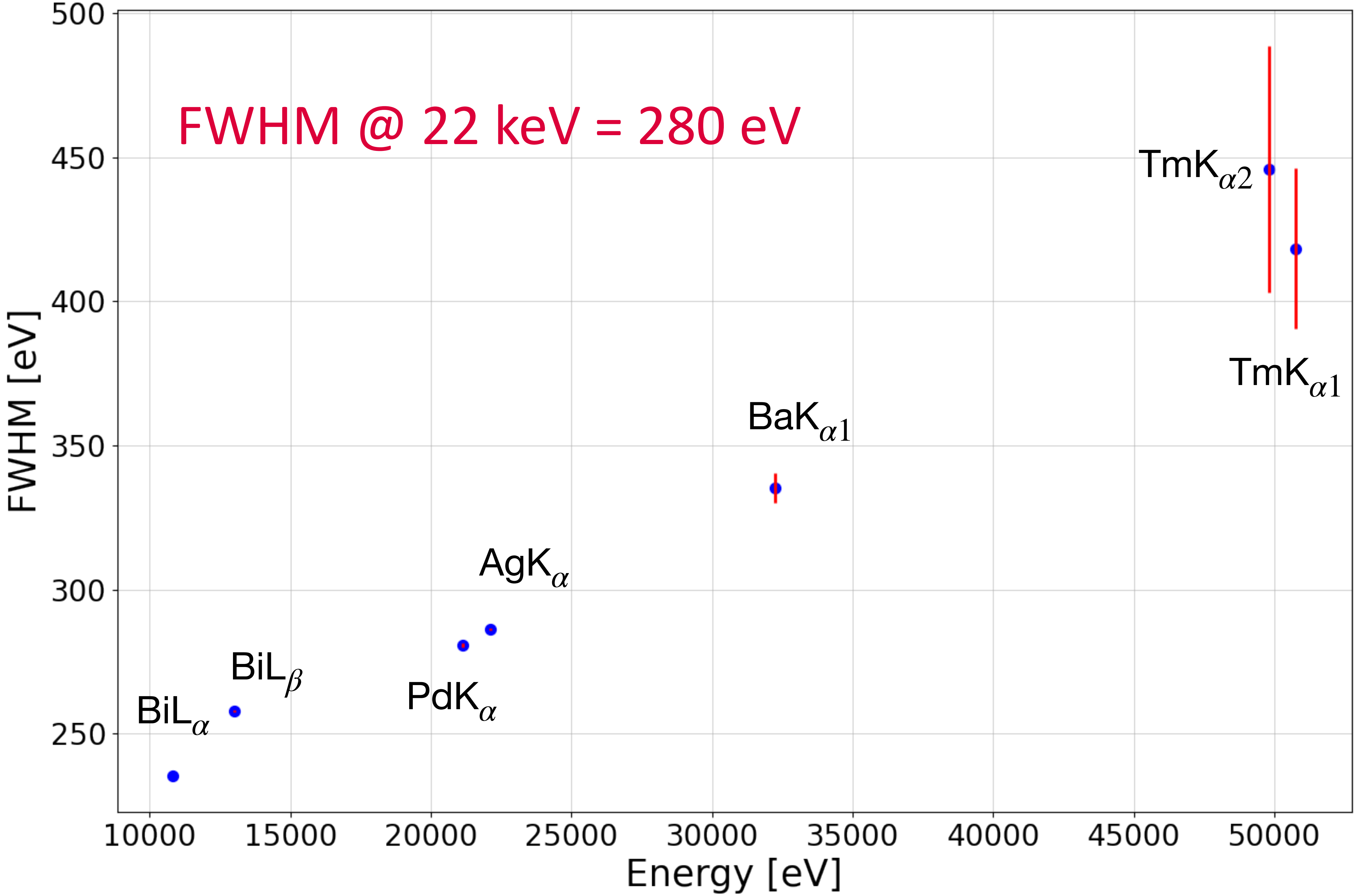
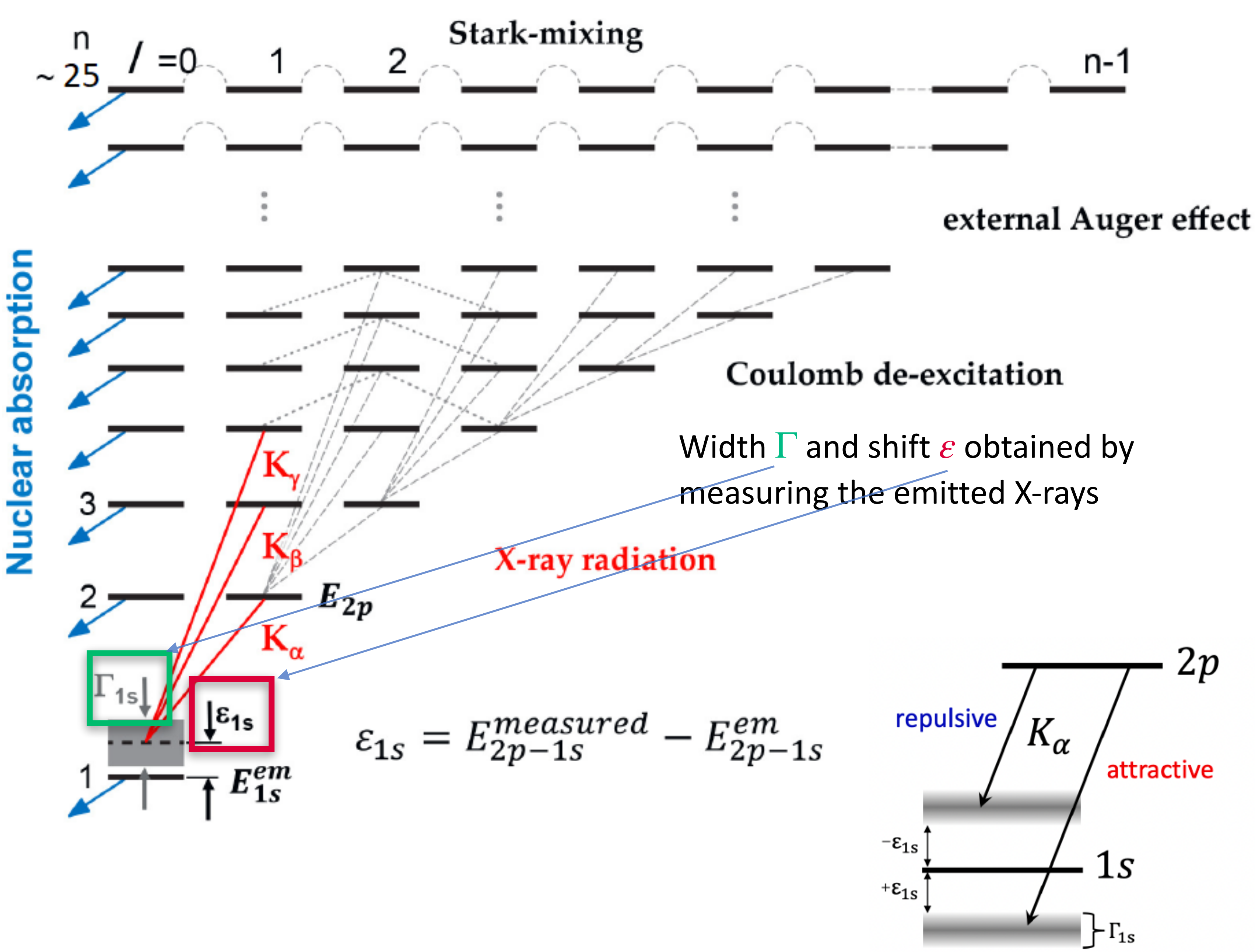


Physics of light kaonic atoms



- Detected X-Rays carry information about the (strong) interaction
- Broadening (Γ) and shift (ε) of the energy level induced by the strong interaction
- **Scientific goal:** performing the first measurement of kaonic deuterium X-ray transition to the fundamental level to extract ε_{1s} and Γ_{1s}

Physics of light kaonic atoms

- Antikaon-nucleon scattering lengths $(a_{\bar{K}N})$ related to these observables

$$\epsilon_{1s}^{H} + \frac{i}{2}\Gamma_{1s}^{H} = 2\alpha^3\mu^2 a_{\bar{K}p}\left[1 - 2\alpha\mu(ln\alpha - 1)a_{\bar{K}p} + \ldots\right]$$

fine structure constant

reduced mass

Meißner, U.-G., Raha, U. & Rusetsky, A. Spectrum and decays of kaonic hydrogen. The European Physical Journal C-Particles and Fields 35, 349–357 (2004).

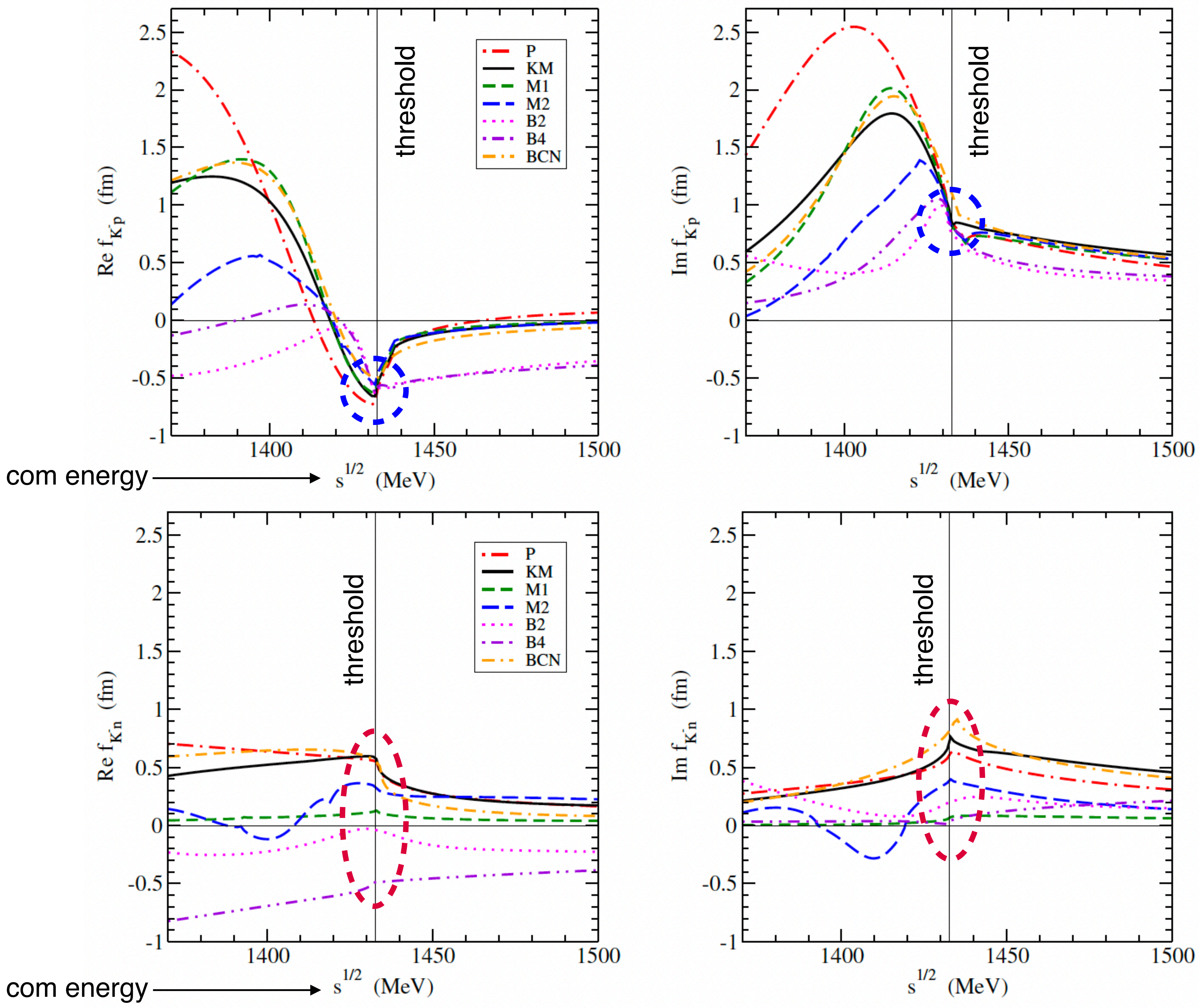
$$\lim_{k\to 0} \sigma_e = 4\pi a^2$$

elastic cross section

Landau, L. D. & Lifshitz, E. M. Quantum Mechanics: non-relativistic theory, vol. 3 (Elsevier, 2013).

- Combined analysis of kaonic hydrogen and kaonic deuterium to extract the isospin-dependent antikaon-nucleon scattering lengths
- Kaonic hydrogen measured by the SIDDHARTA experiment in 2009
- Lack of a kaonic deuterium measurement

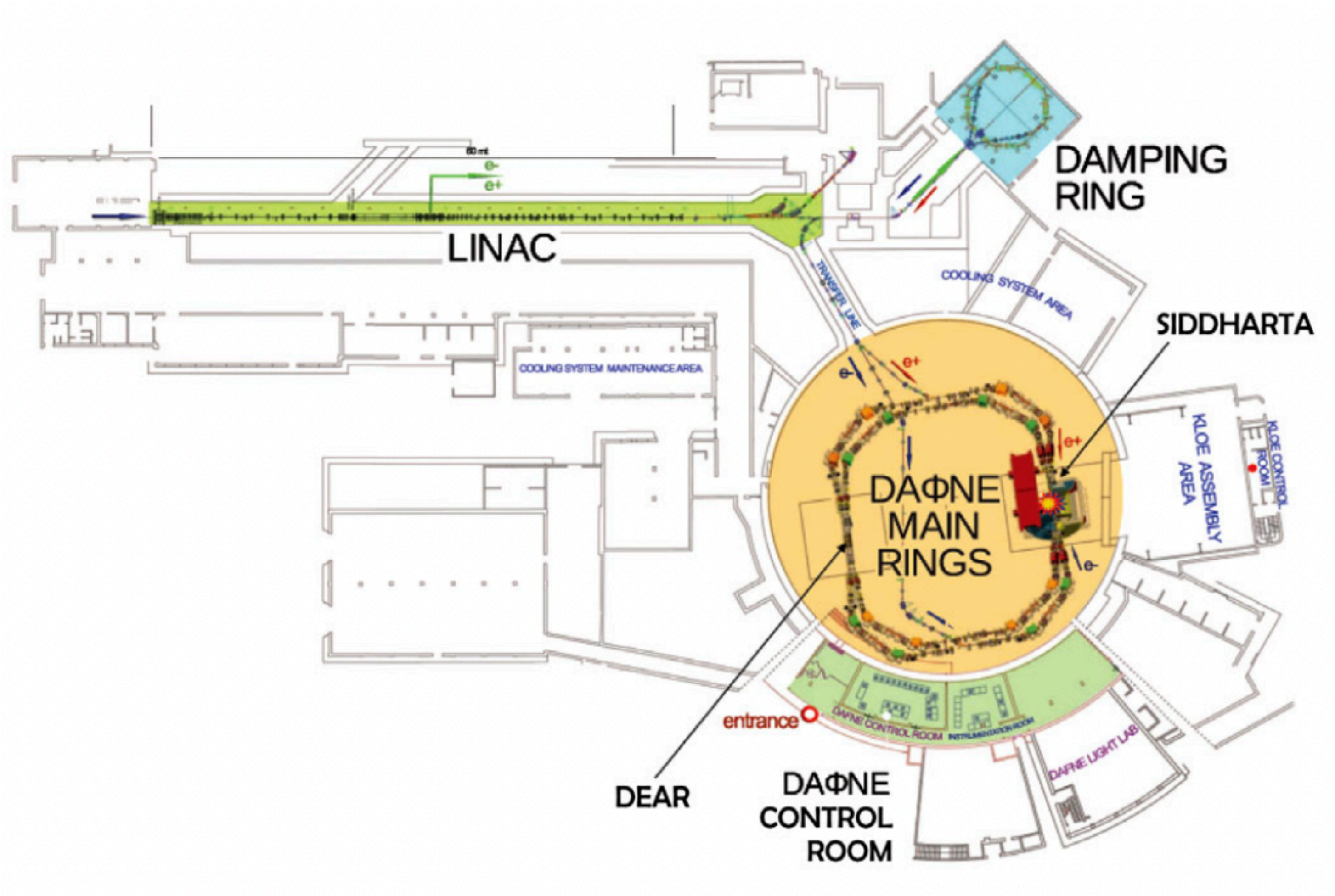
Physics of light kaonic atoms



- Theoretical models in good agreement K^-p low momentum scattering amplitude
- Theoretical models for the K^-n low momentum scattering amplitude highly spread

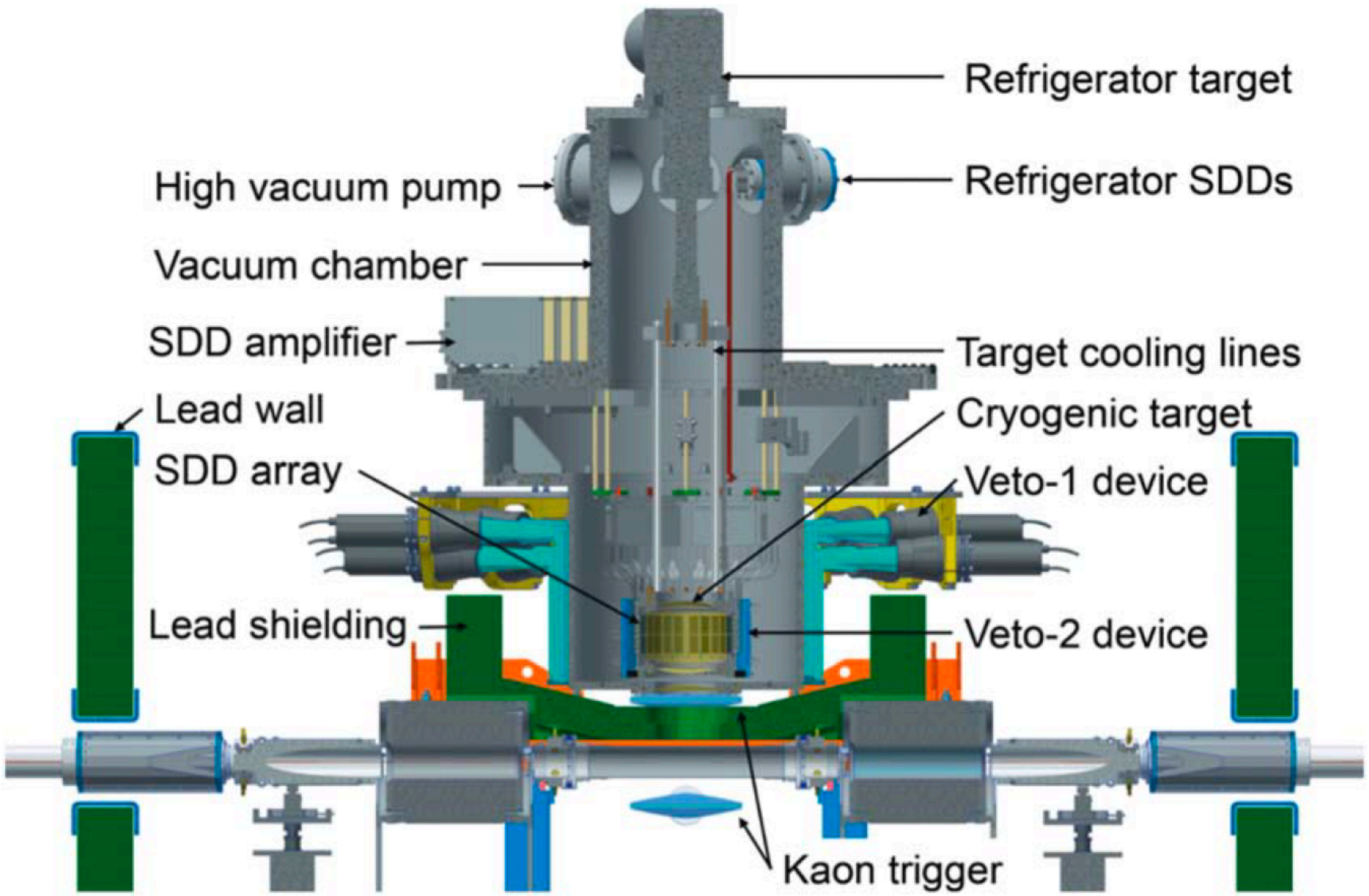
Óbertová, J., Friedman, E., Mareš, J. & Ramos, À. On K–nuclear interaction, K–nuclear quasibound states and K-atoms. In EPJ Web of Conferences, vol. 271, 07003 (EDP Sciences, 2022).

The DAΦNE Collider of INFN-LNF



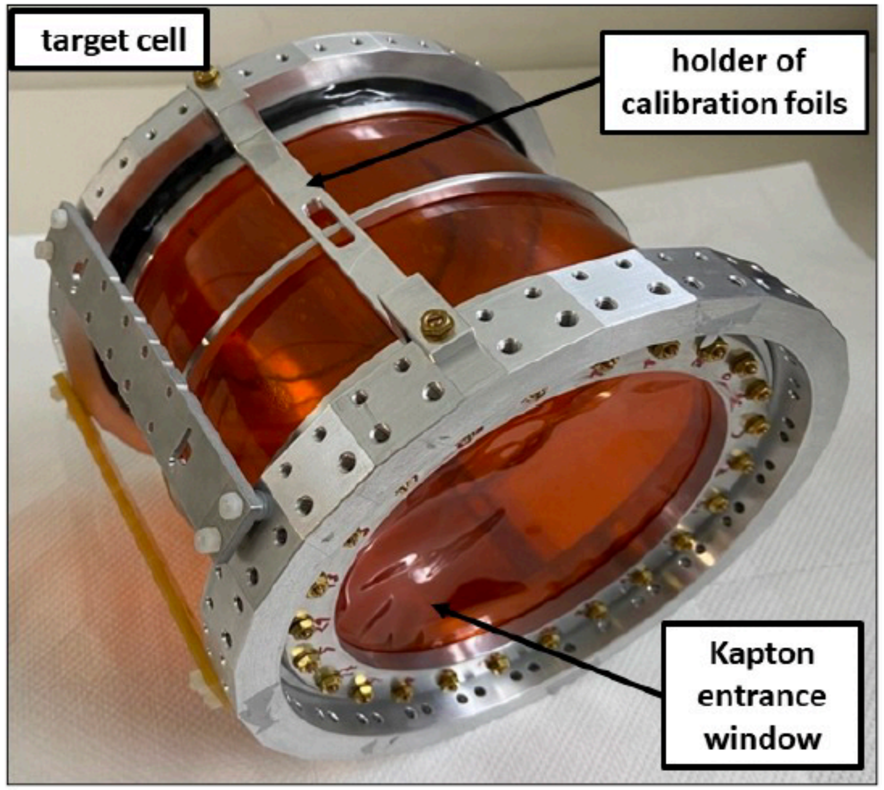
- SIDDHARTA-2 experiment installed on the Interaction Point (IP) of DAΦNE
- e^+e^- collider working at a center of mass energy of the ϕ meson mass (1.02 GeV/c^2)
- Decay to K^+K^- pairs with a BR of 48.9%
- **Kaon momentum 127MeV/c**
- Not (much) relativistic $\beta \sim 0.25$, $\beta\gamma \sim 0.26$

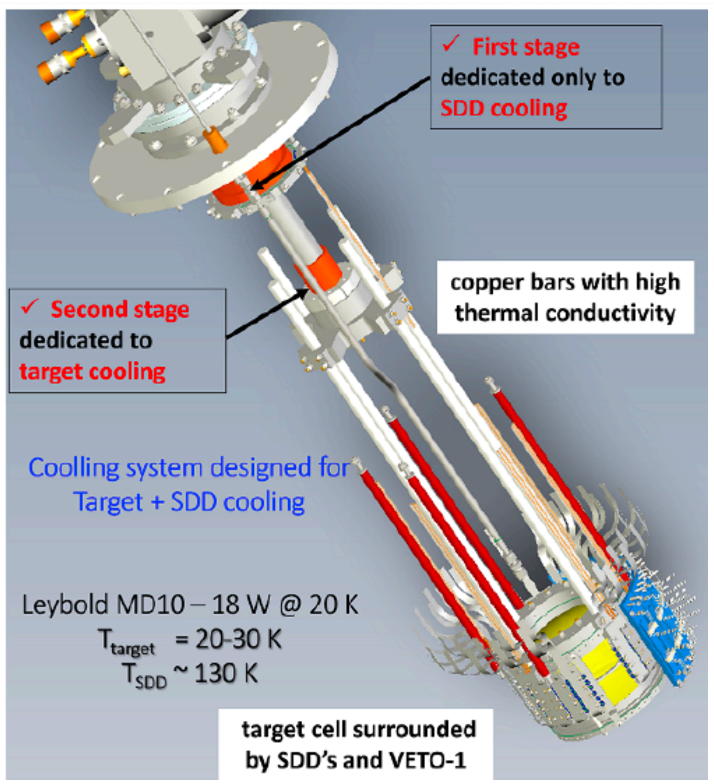
The SIDDHARTA-2 apparatus



- Cylindrical vacuum chamber
- Cryogenic target cell
- Kaon trigger
- 384 X-Ray detectors (SDDs)
- Mylar degrader
- Luminosity monitor
- Veto Systems

The SIDDHARTA-2 apparatus: cryogenic target





- Cylindrical volume (144mm diameter x 125mm height)
- Side walls made of two layers of 75μm kapton ($C_{22}H_{10}N_2O_5$)
- Thermal and Mechanical properties of kapton are suitable for cryogenic operations
- Reinforcement structure of high purity aluminum
- 125μm thick kapton entrance window
- Dedicated holder for calibration target
- **Gaseous target**
- Target cell kept between 20-30K with a closed-cycle helium refrigeration system