Silicon Drift Detectors for the new generation of Kaonic Atoms measurements

INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

FRANCESCO CLOZZA
Workshop on Fundamental Physics with Exotic Atoms 2025

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Physics of light kaonic atoms

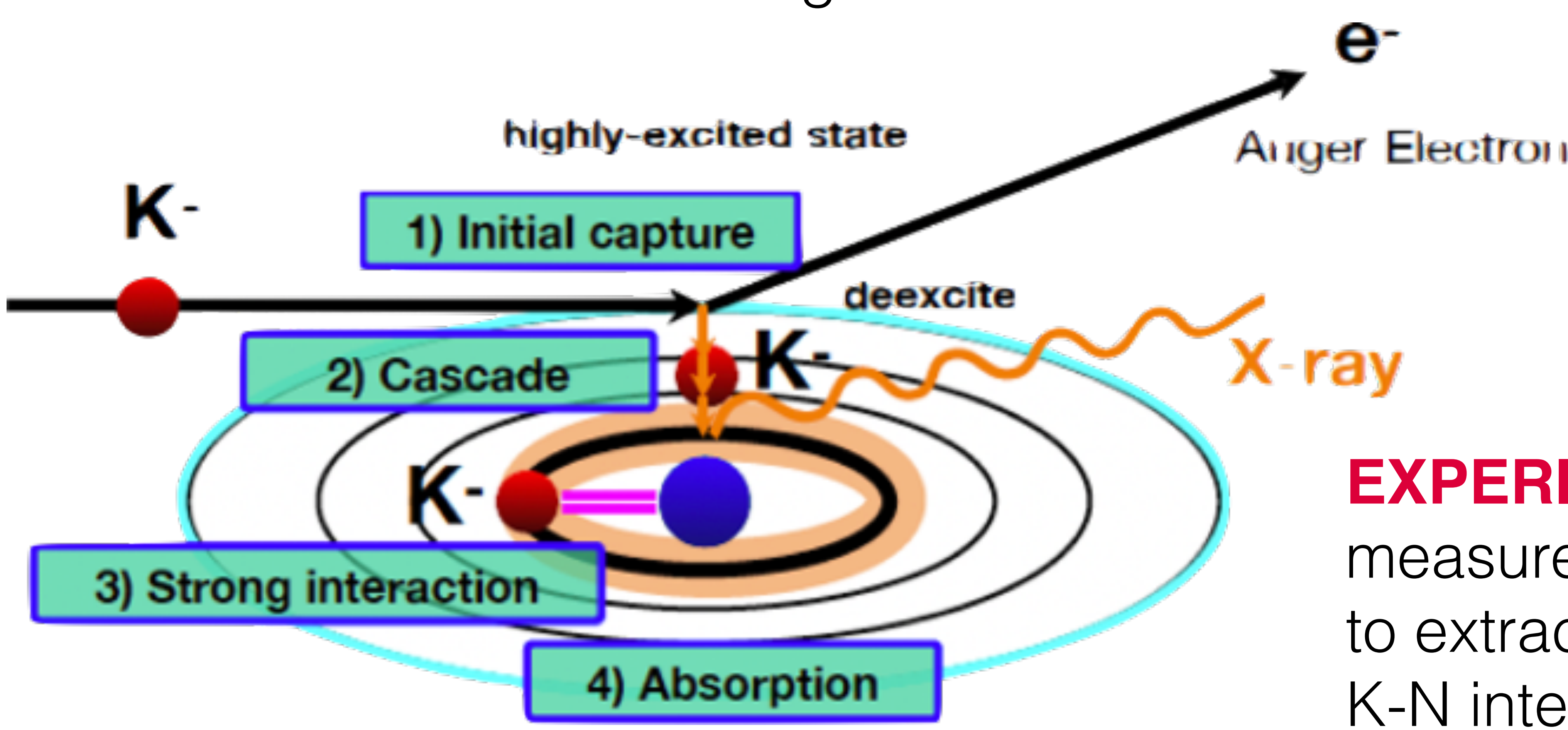
- K^- slowed down and stopped inside a target
- Atomic capture followed by cascade process
- K^- captured in an highly excited state n
- Emission of radiation following the de-excitation

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

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

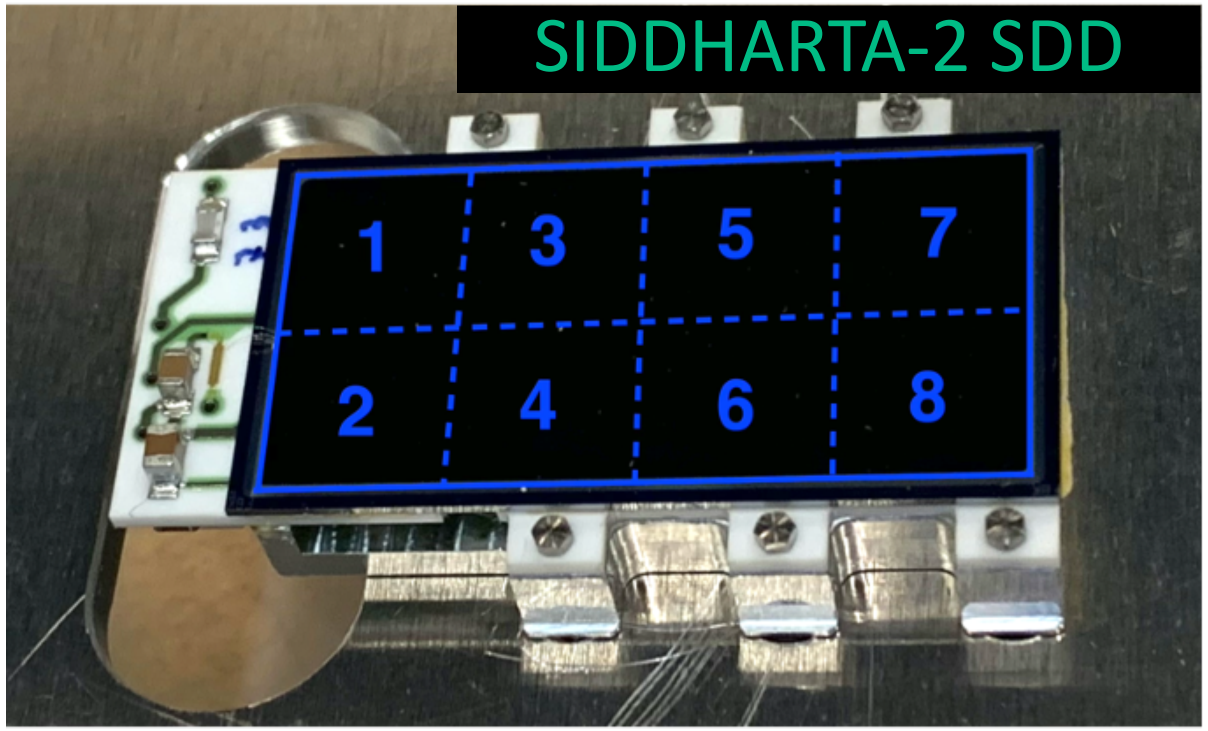
$n \sim 25$ K-H

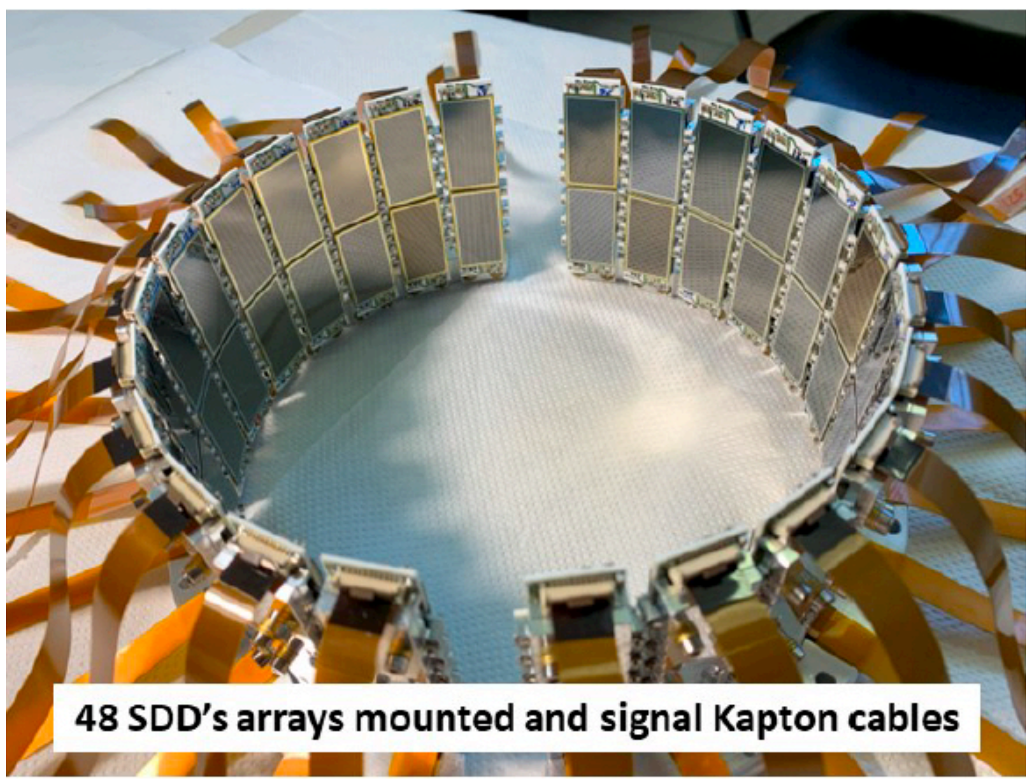
μ system's reduced mass



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

The SIDDHARTA-2 Silicon Drift Detectors

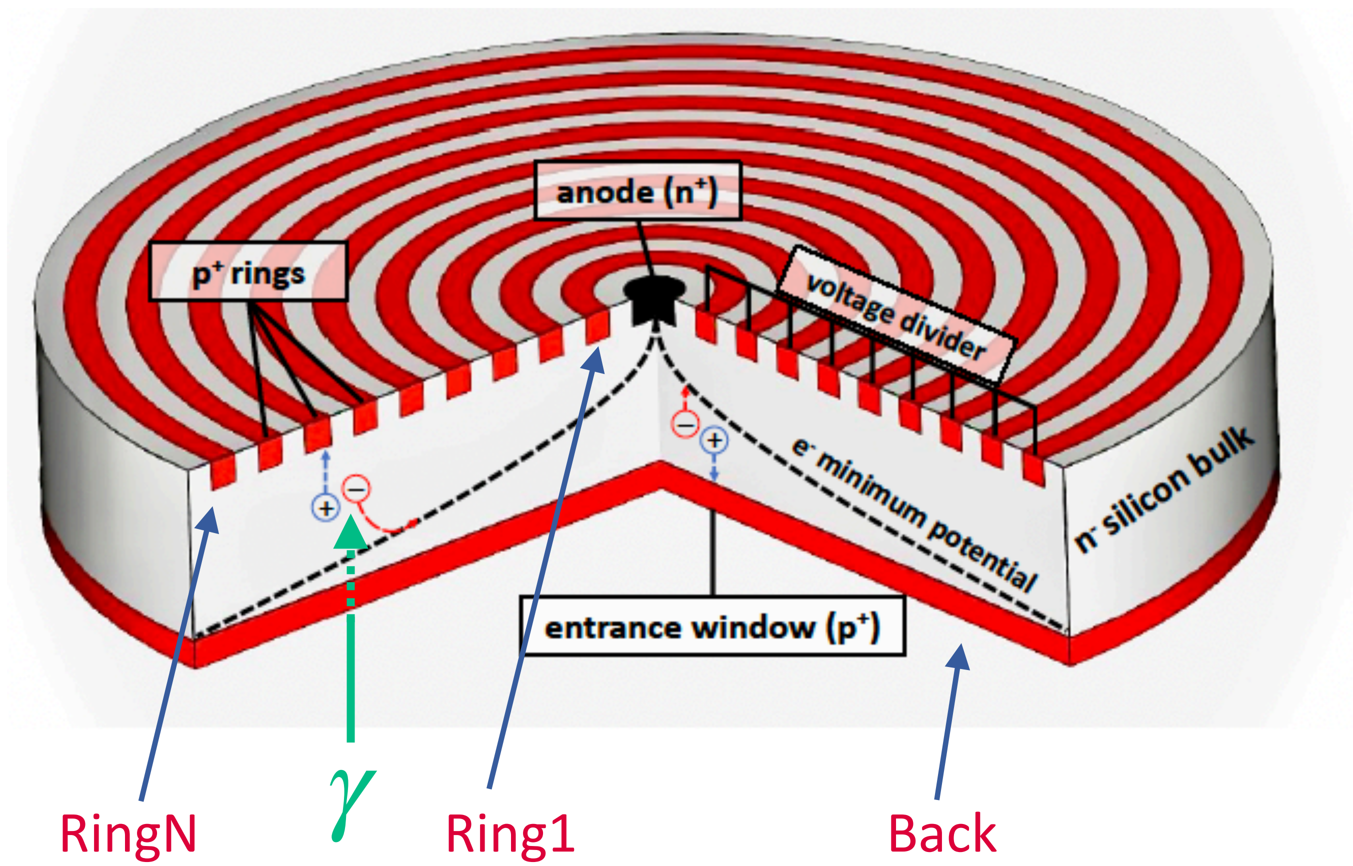


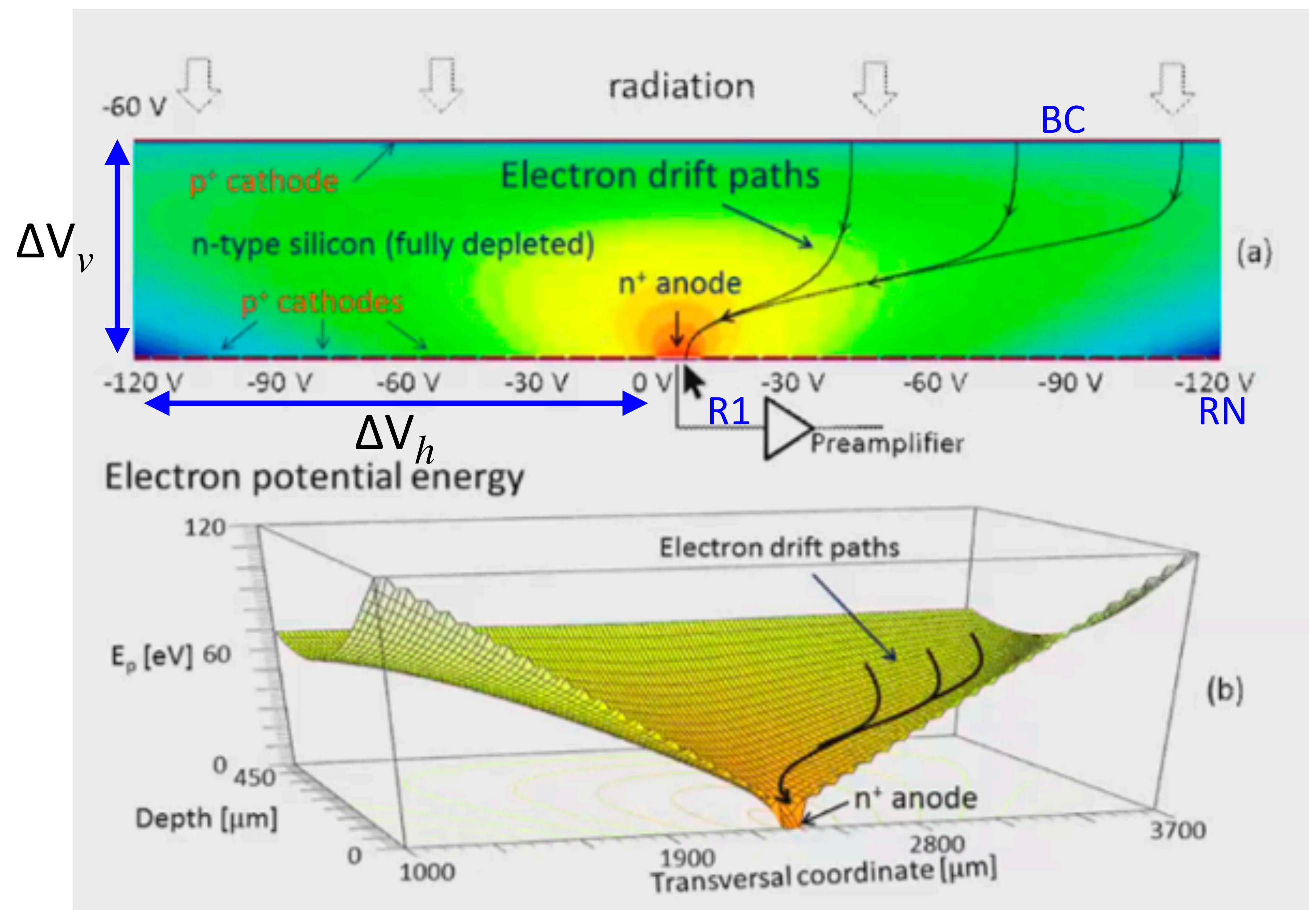


- SDD cells: 8x8mm^2 active area
- 450 μm thick silicon bulk: > 85% detection efficiency for 5-12 keV X-rays (region of interest for kaonic deuterium)
- SDD cells packed in 2x4 array (total active area of 5.12 cm^2)
- Extremely good linear behaviour and energy resolution in the range of interest
- $\Delta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

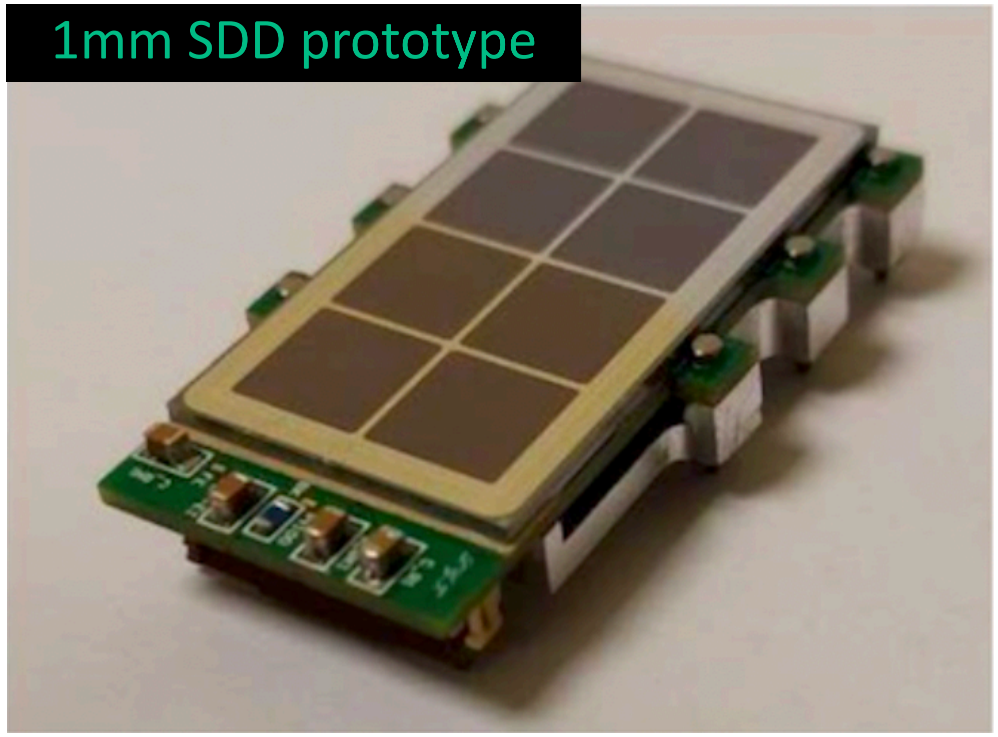
C. Curceanu et al., Front.in Phys. 11 (2023) 1240250

EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

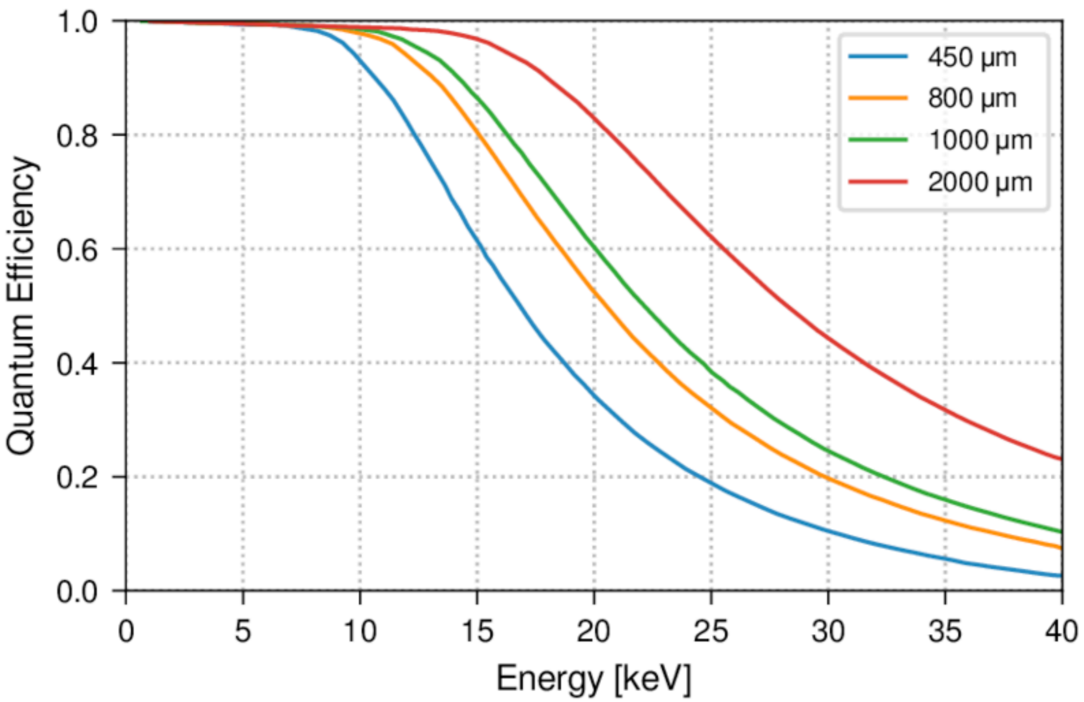
Intermediate kaonic atoms (IMKA)
In parallel we plan dedicated runs for kaonic atoms (*O, Al, S*) with CdZnTe detectors
- 200 -300 pb^{-1} of integrated luminosity/target

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

New 1mm Silicon Drift Detectors

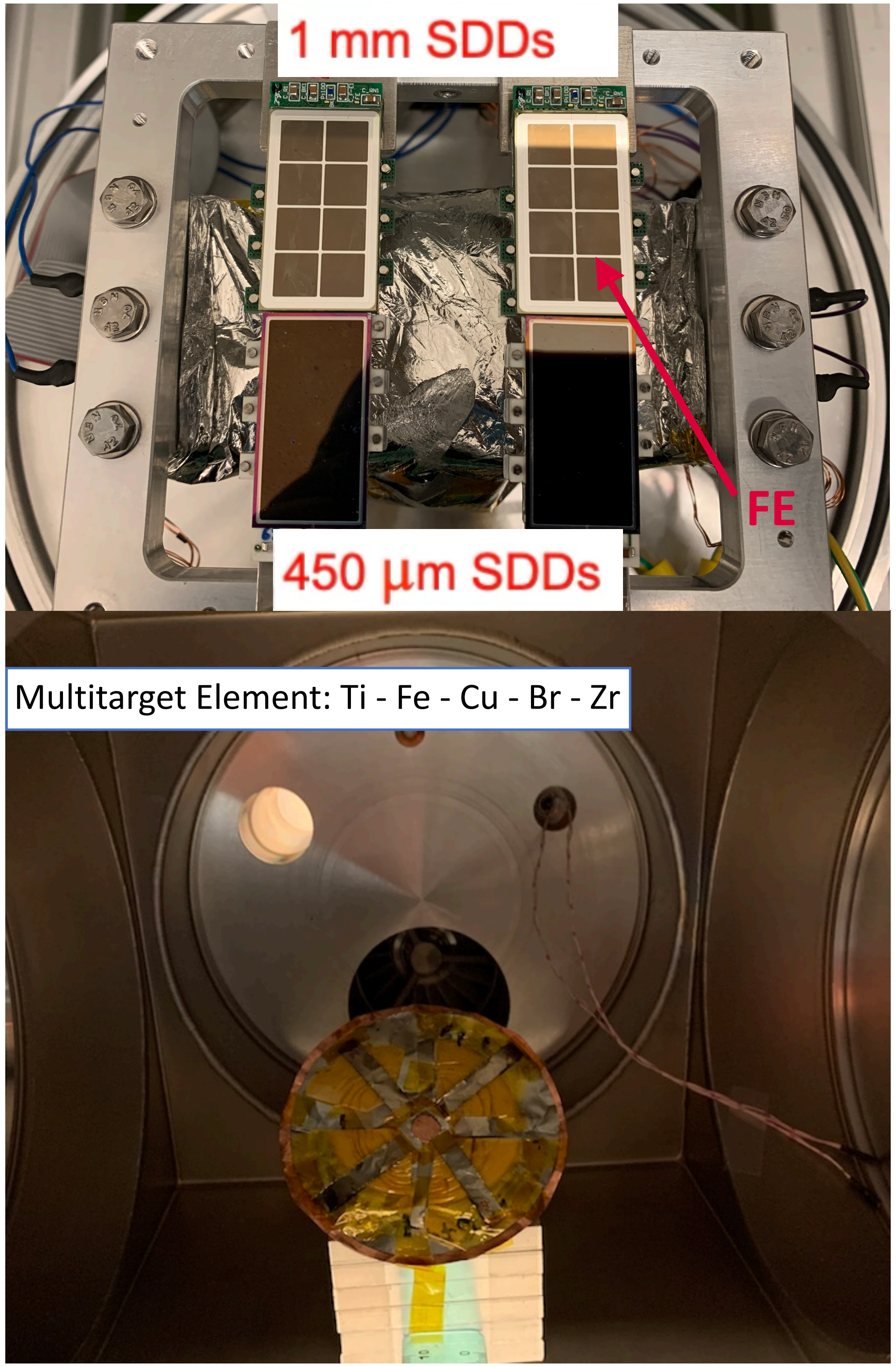


- Thicker silicon bulk will allow for a **much better efficiency at higher energy** (above 15 keV)
- Possibility to extend the range of kaonic atoms that we are able to measure
- Insight into the $K^{-} - NN$ strong interaction



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

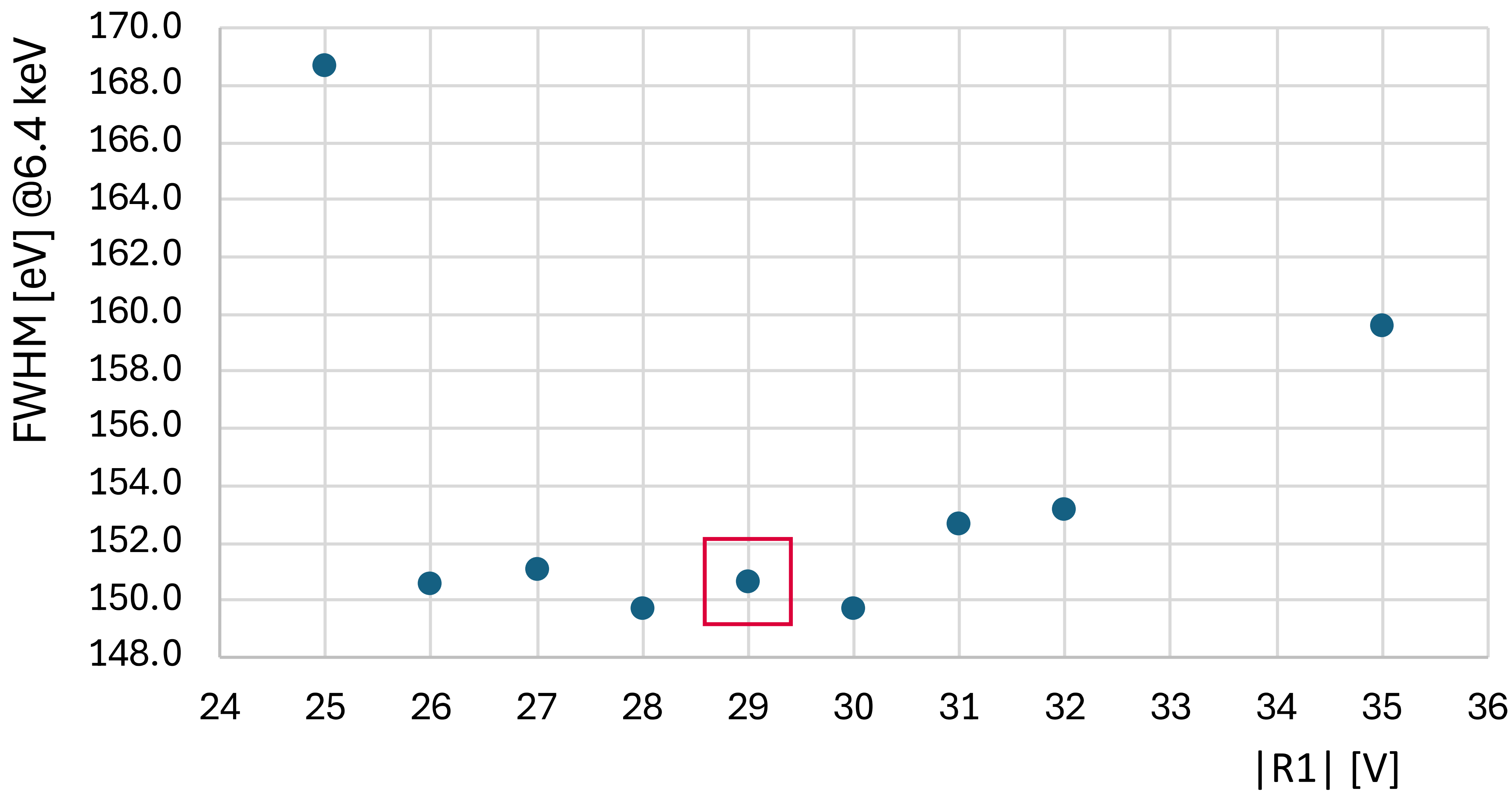
New 1mm Silicon Drift Detectors



- 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

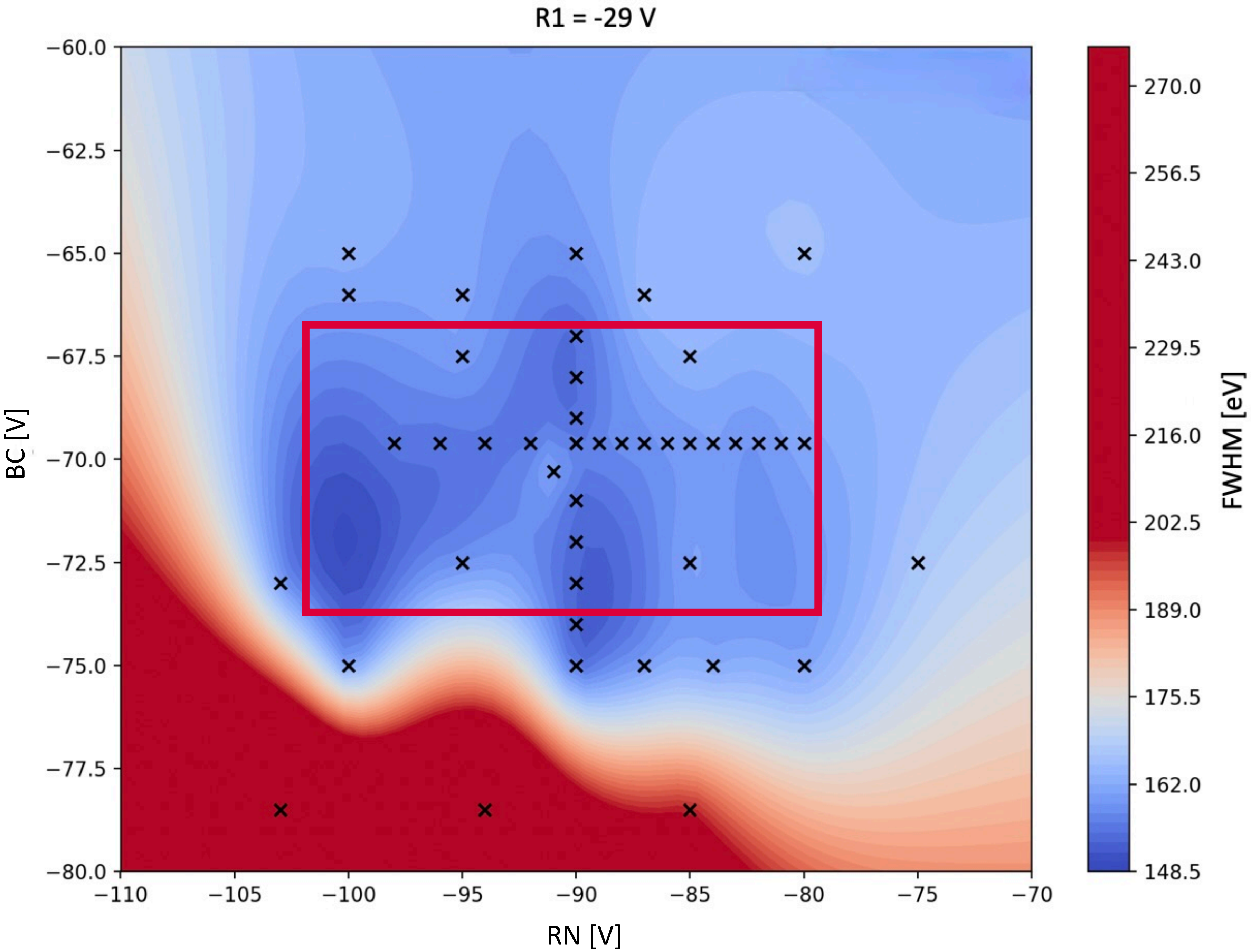
1mm SDDs characterization: energy resolution vs R1

- 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 ≤ |R1| ≤ 30 V



1mm SDDs characterization: energy resolution vs RNBC

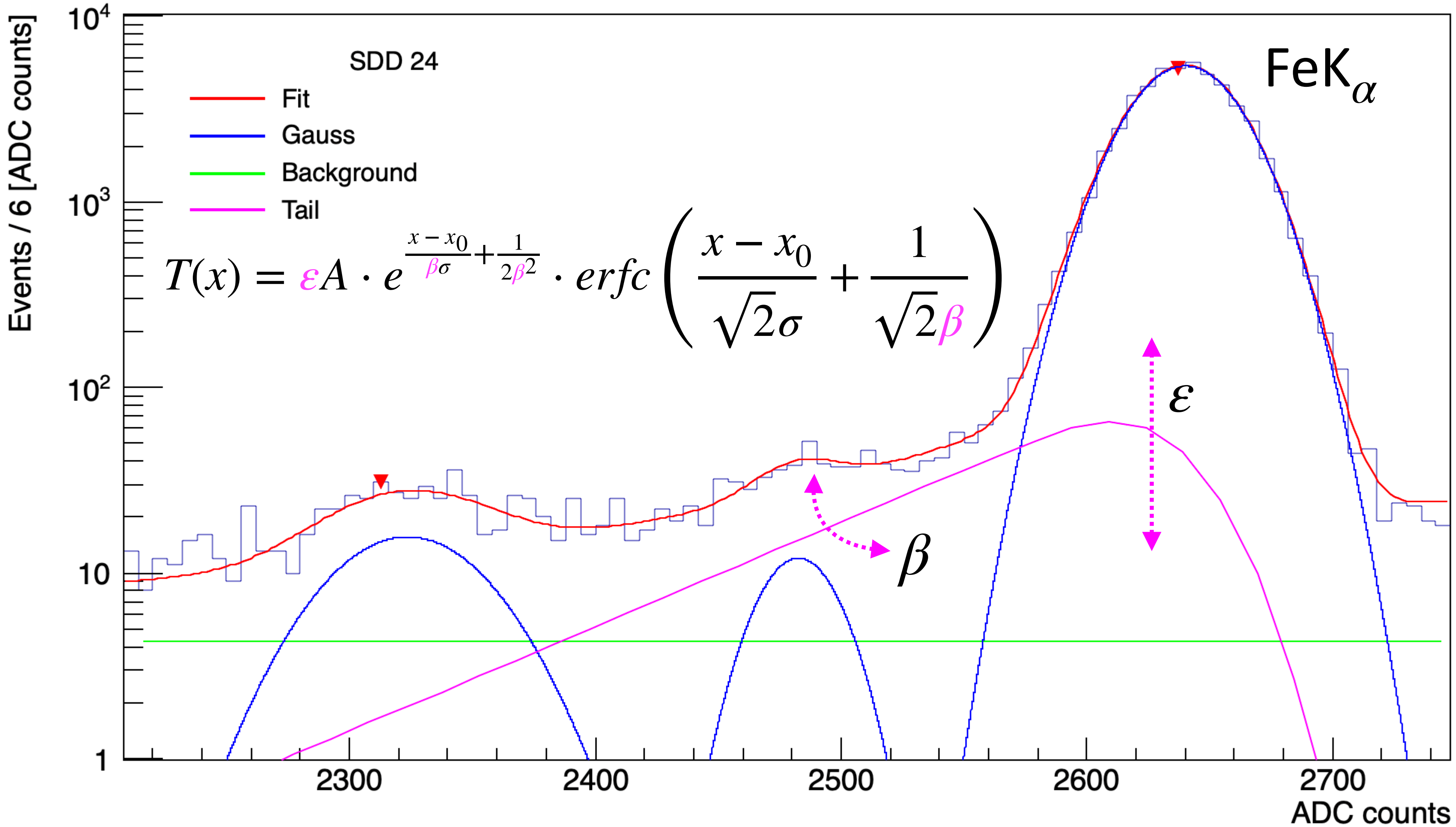
RN+BC voltage scan



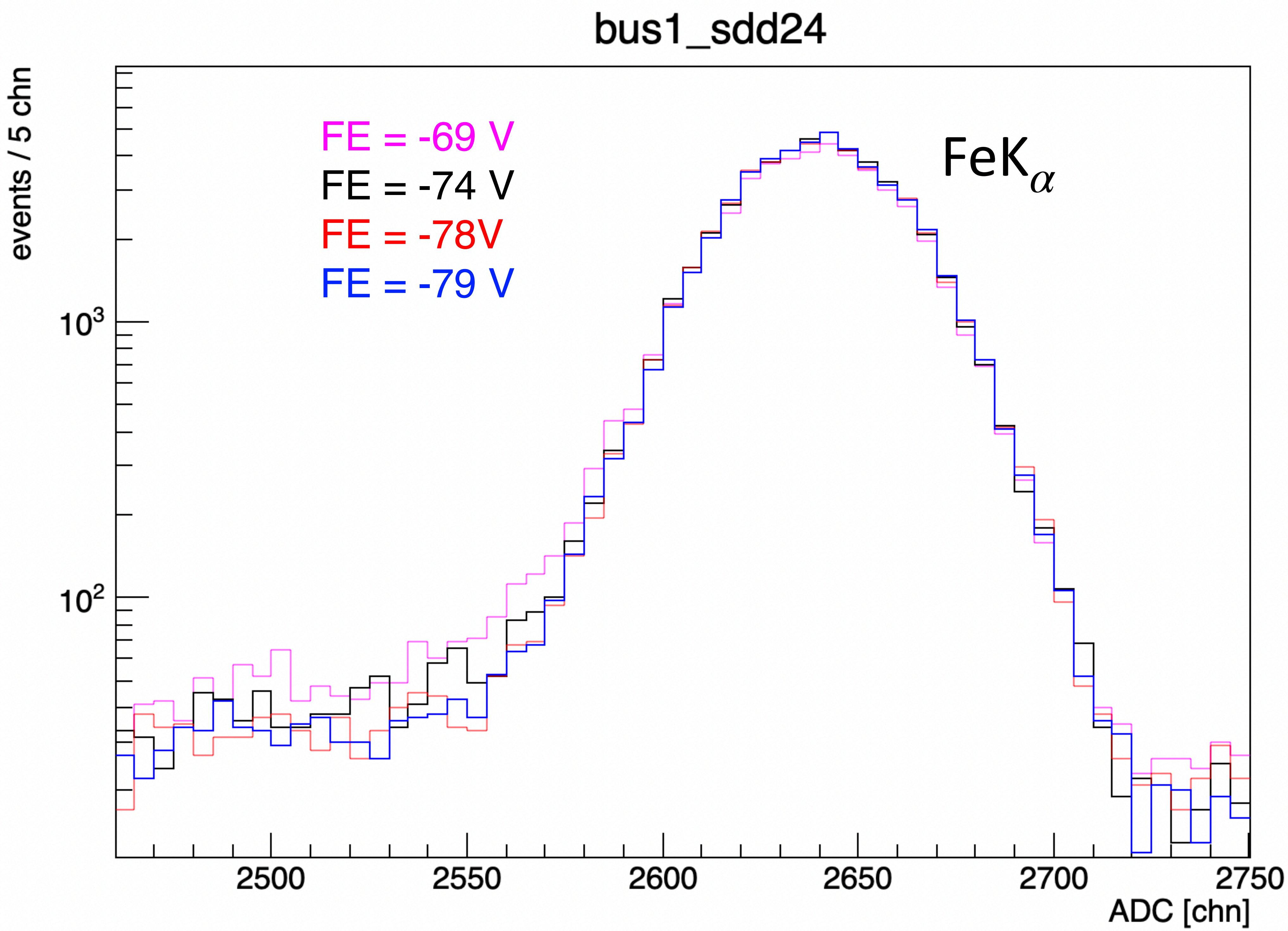
- Optimisation of the energy resolution at 6.4 keV as a function of the Back and RN bias voltages
- Optimal working point at RN=-90 V and BC=-69 V
- Fiducial region ~[-103V, -80V]x[-73.5V, -67V]
- Fluctuations of the bias voltages **don't have a massive effect** on the energy resolution

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

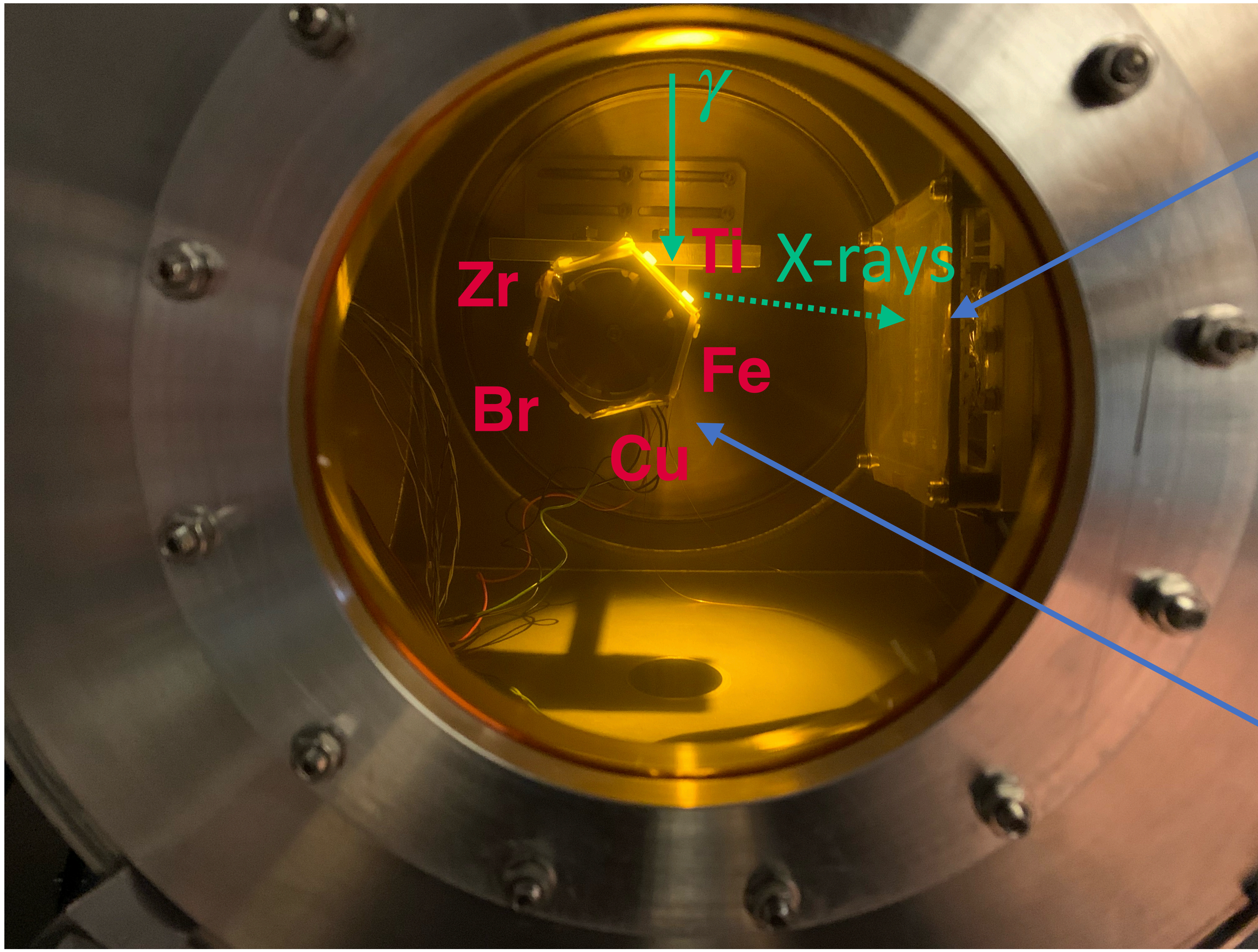


1mm SDDs characterization: tail contribution



1mm SDDs characterization: tail contribution

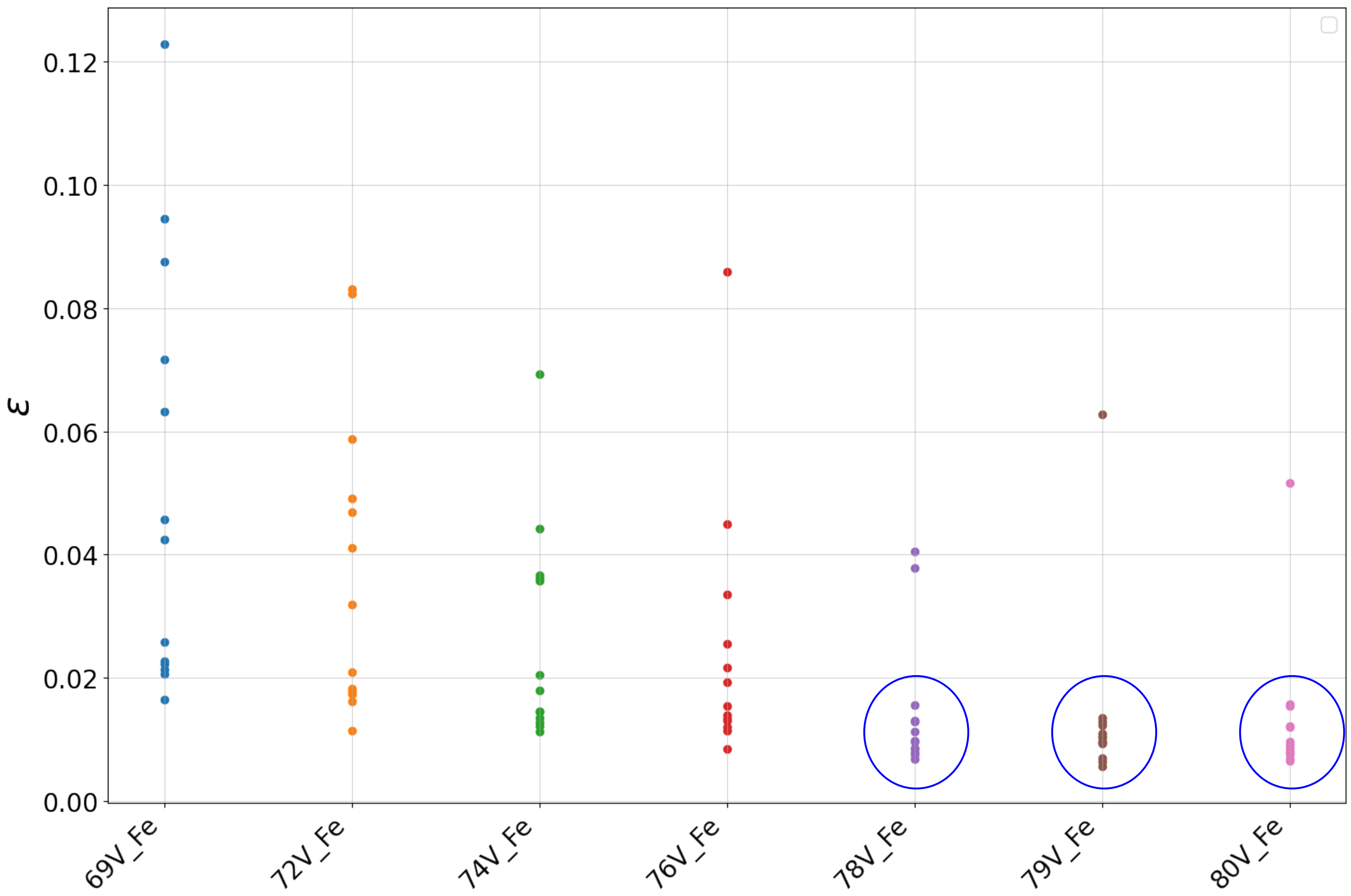
Response of the SDDs vs FE bias voltage scanned at different energies



Silicon Drift Detectors

Ti - Fe - Cu - Br - Zr
Rotating multitarget

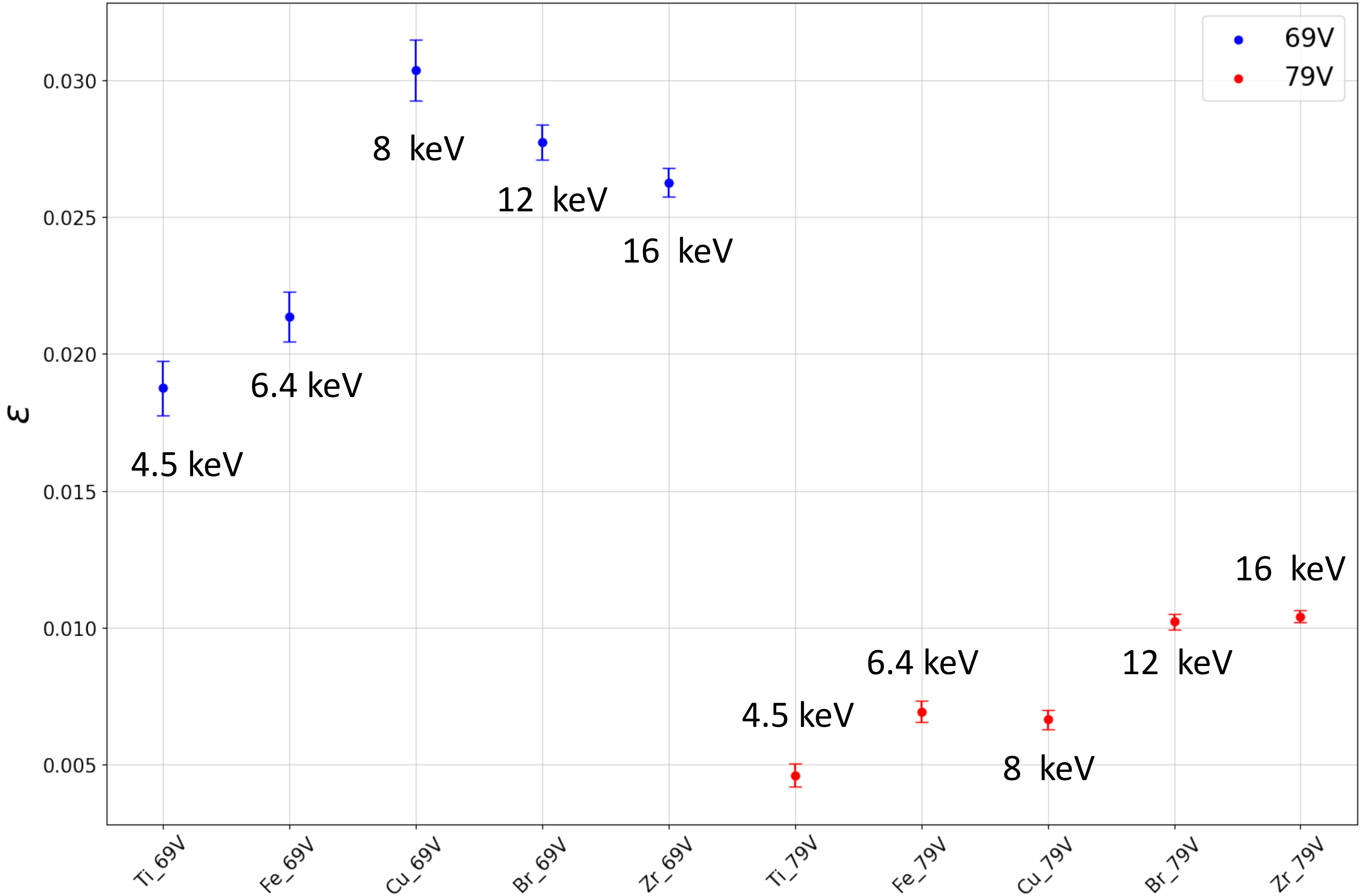
1mm SDDs characterization: tail contribution



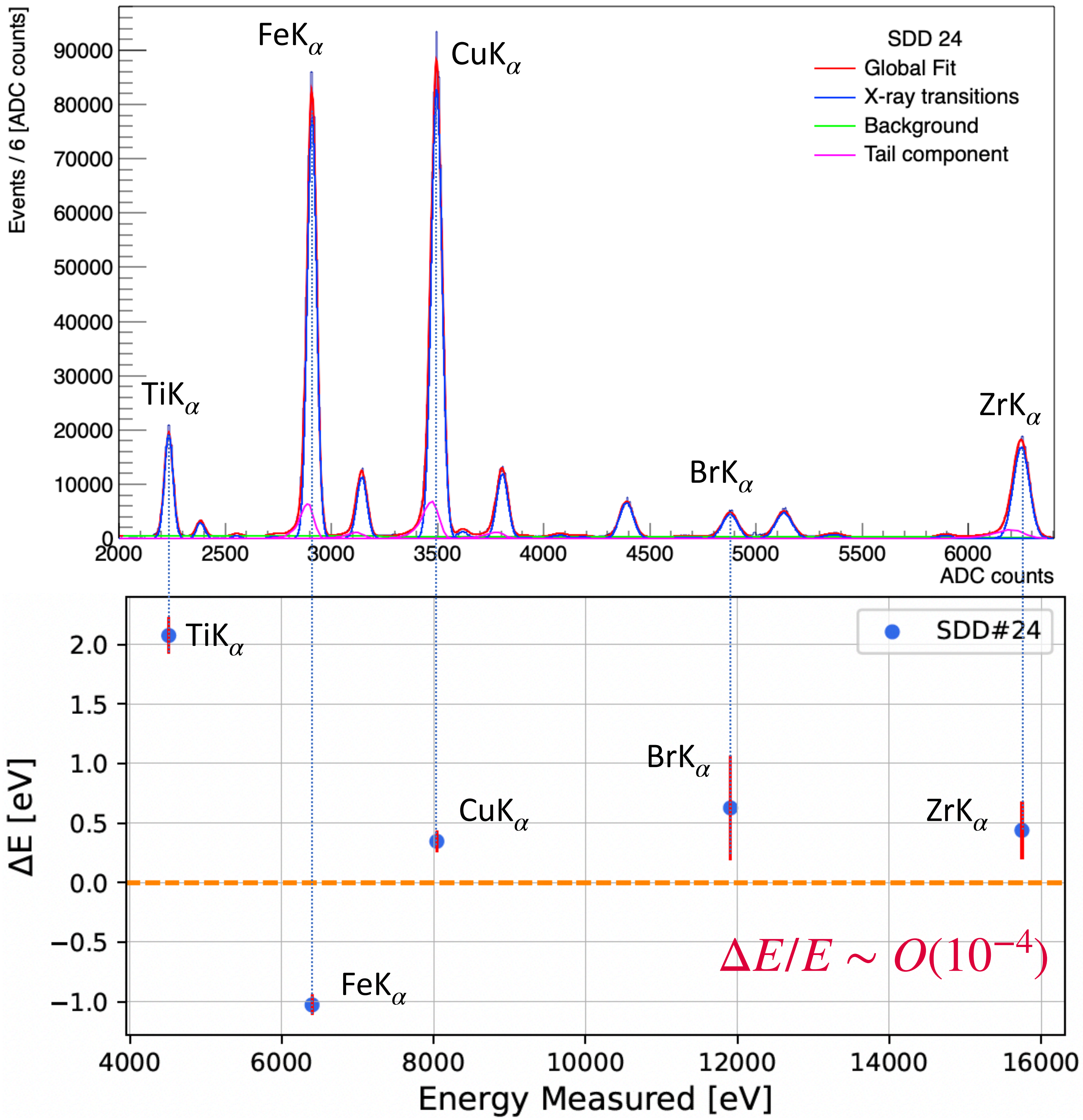
- Smaller tail contribution and more uniform response of the SDDs at higher FE bias voltages

- Optimal working point at FE=-79V

1mm SDDs characterization: tail contribution



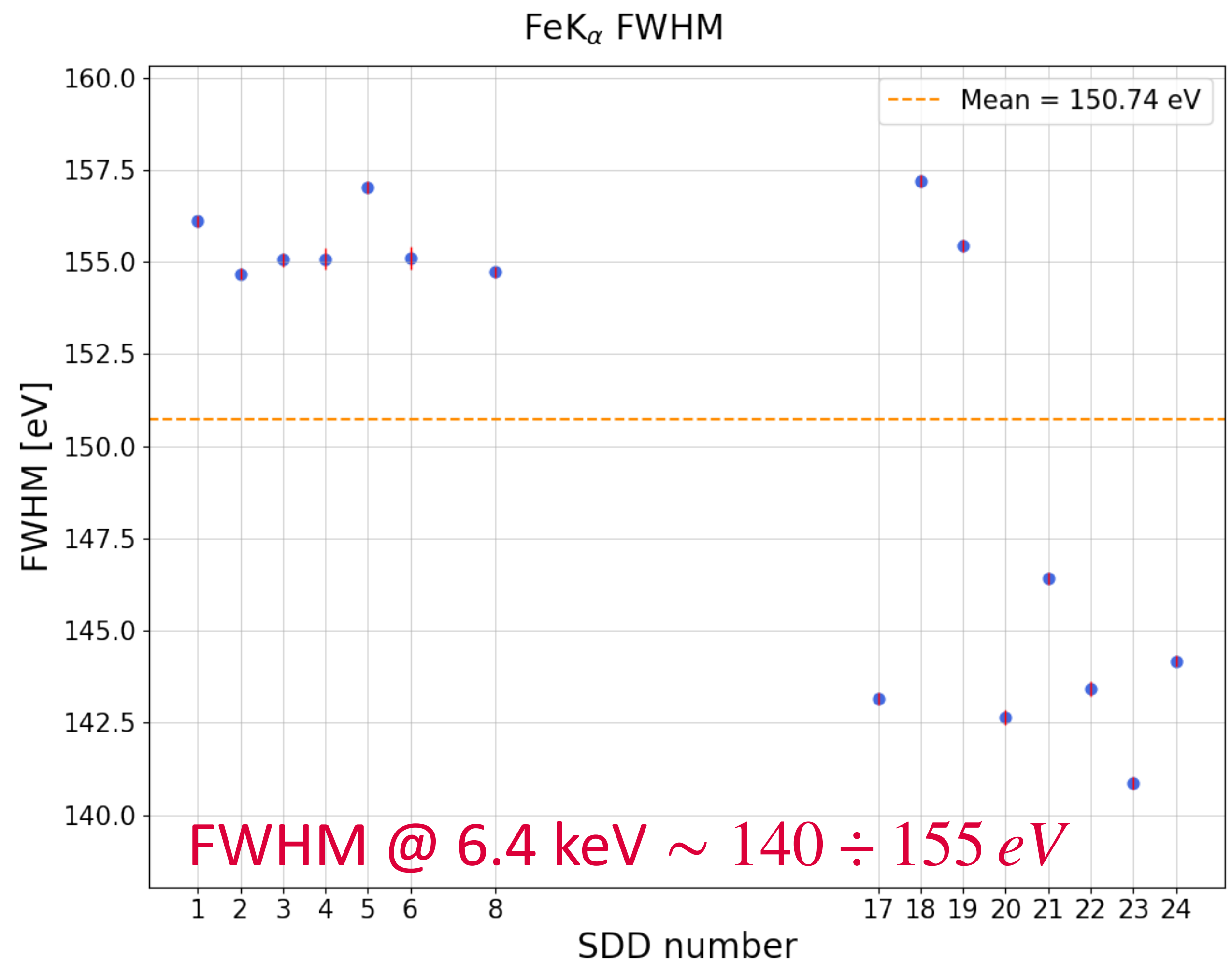
1mm SDDs characterization: optimal configuration



Voltages configuration:

R1 = -29V RN = -90V

BC = -69V FE = -79V



EXKALIBUR proof of concept: KB and KF

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BSQED and Physics beyond Schwinger limit

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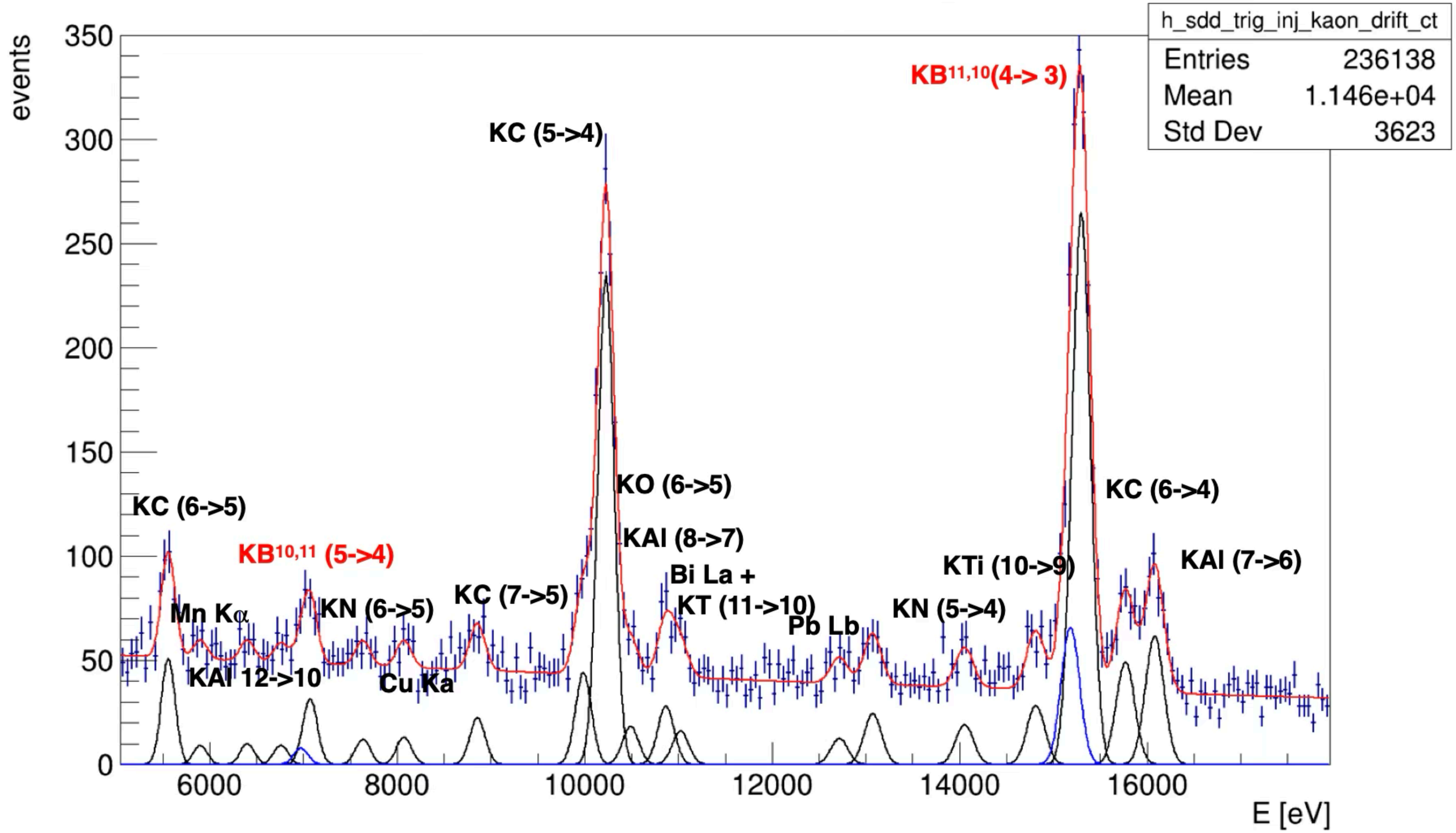
Intermediate kaonic atoms (IMKA)
In parallel we plan dedicated runs for kaonic atoms (*O*, *Al*, *S*) with CdZnTe detectors
- 200 -300 pb^{-1} of integrated luminosity/target

- First attempt to measure X-ray transitions from solid targets with the 450 μm SDDs
- Data taking performed with a solid B and teflon (C_2F_4) target
- Explorative measurements of Kaonic Boron and Kaonic Fluorine X-ray transitions

EXKALIBUR proof of concept: Kaonic Boron

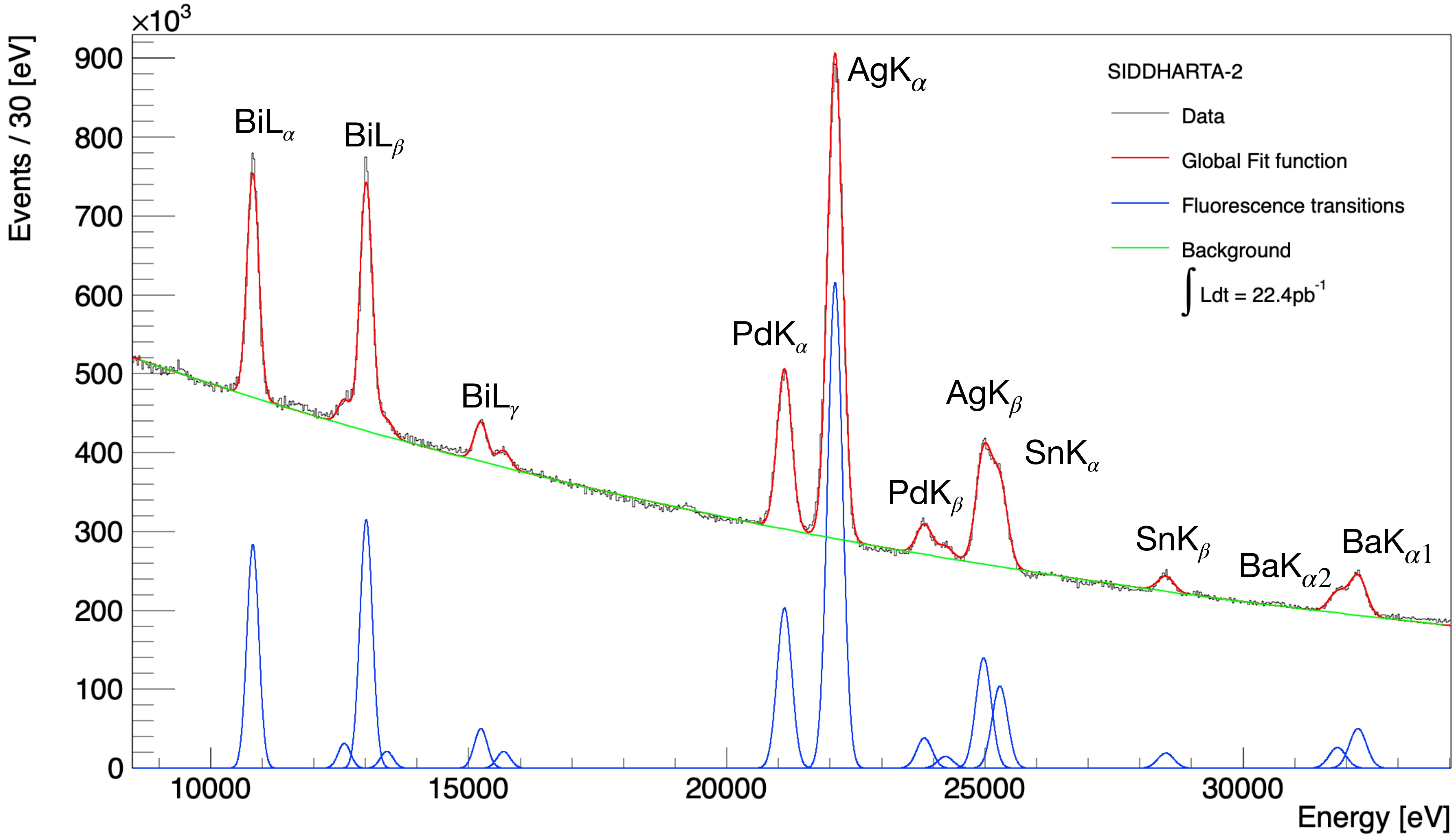


$K^{11}B(5 \rightarrow 4) = (7065 \pm 17)\, eV$ $K^{10}B(5 \rightarrow 4) = (6921 \pm 58)\, eV$

$K^{11}B(4 \rightarrow 3) = (15293.3 \pm 4.8)\, eV$ $K^{10}B(4 \rightarrow 3) = (15180 \pm 21)\, eV$

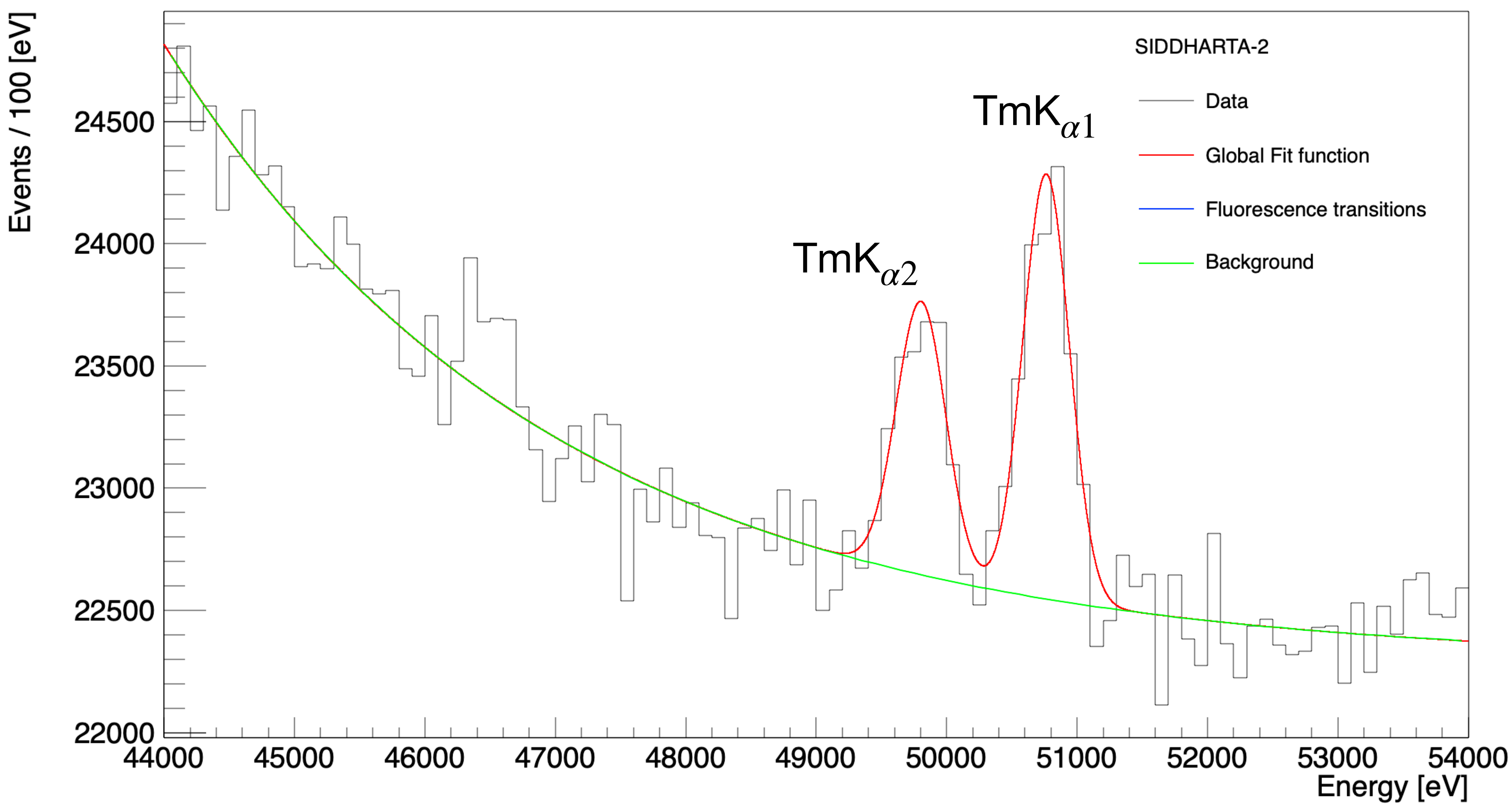
EXKALIBUR proof of concept: 50 keV X-rays

- 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

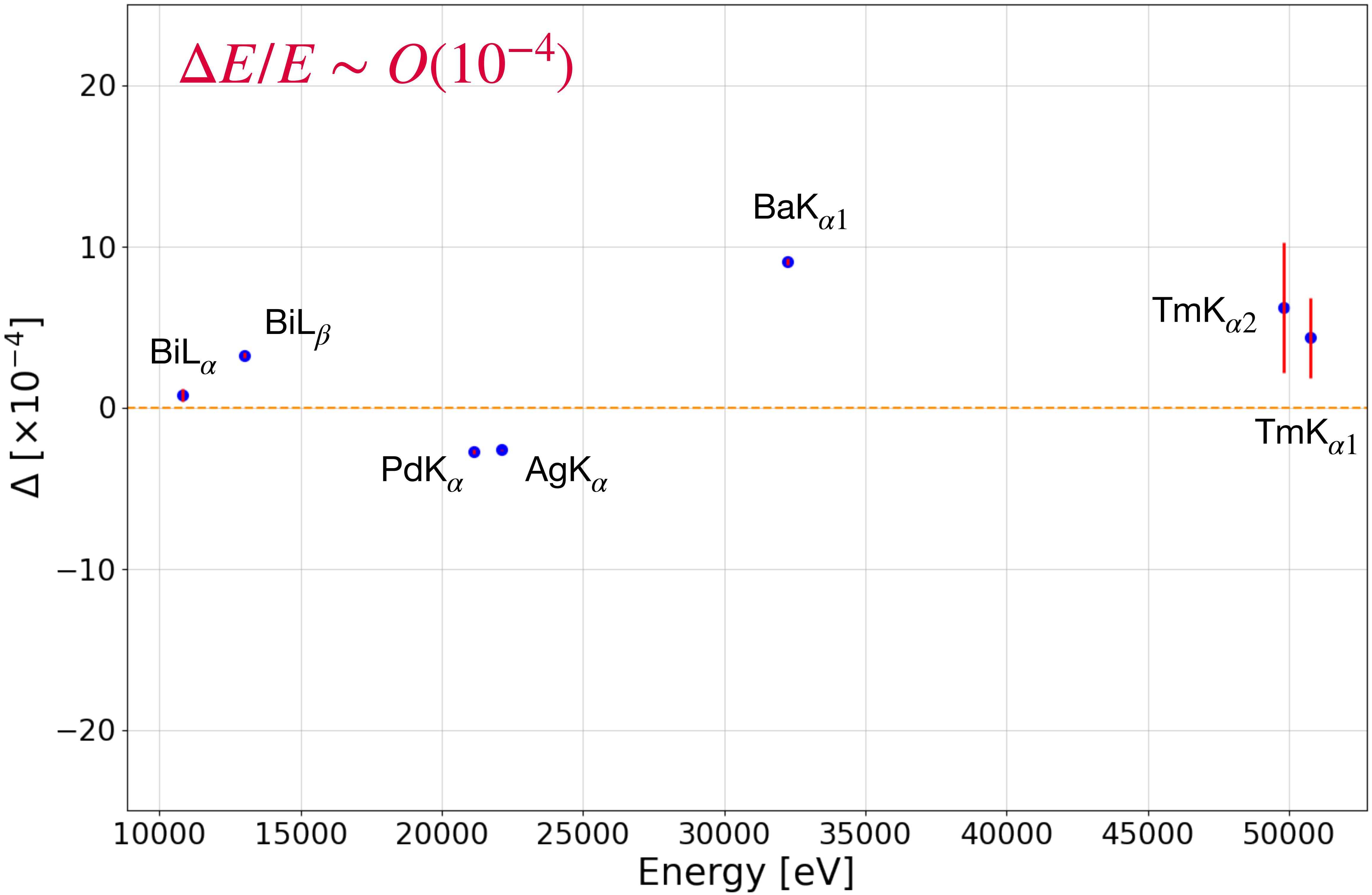


EXKALIBUR proof of concept: 50 keV X-rays

- Goodness of the calibration tested at 50 keV by measuringTmK_{α} X-ray transitions



EXKALIBUR proof of concept: 50 keV X-rays



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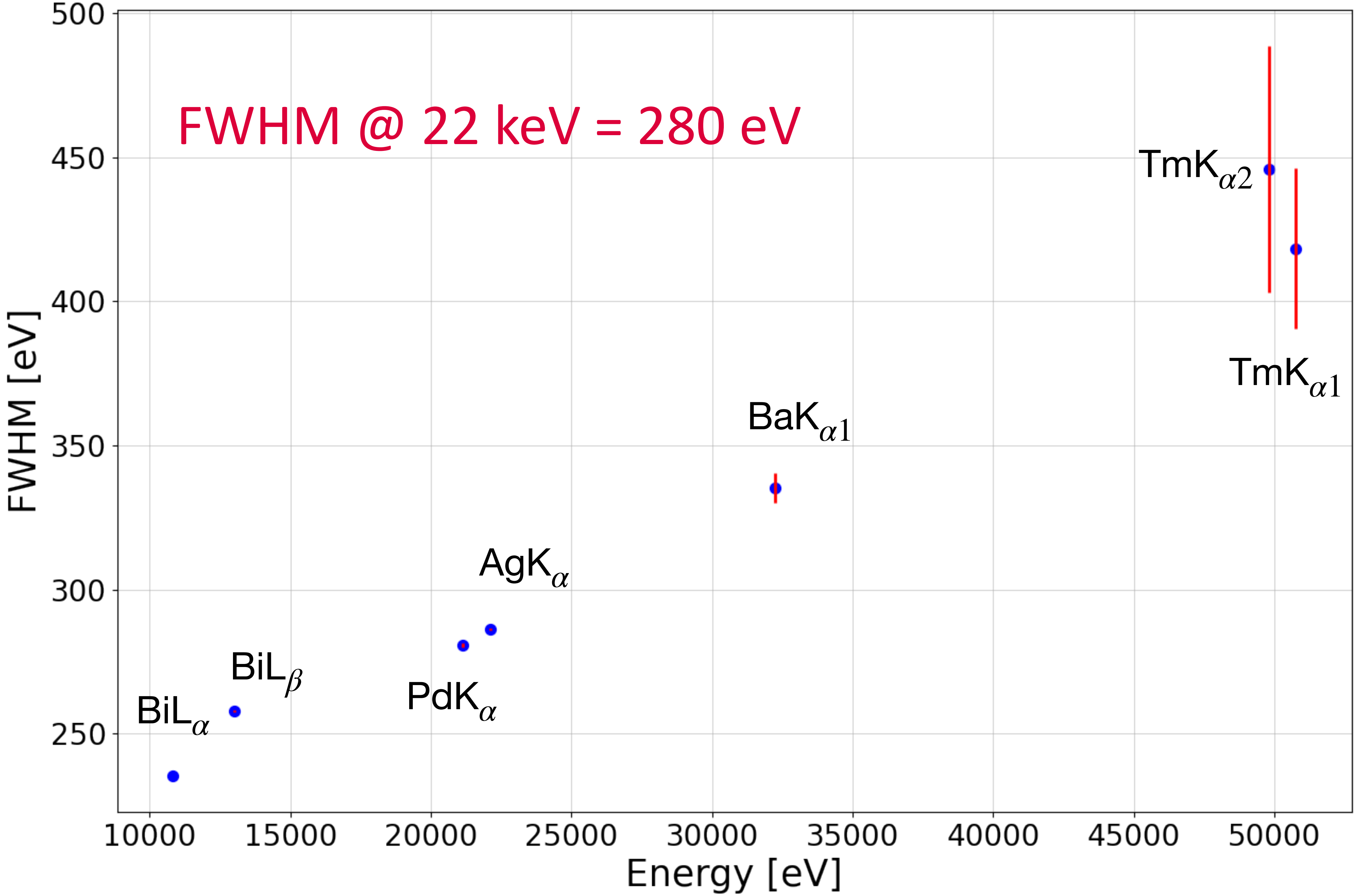
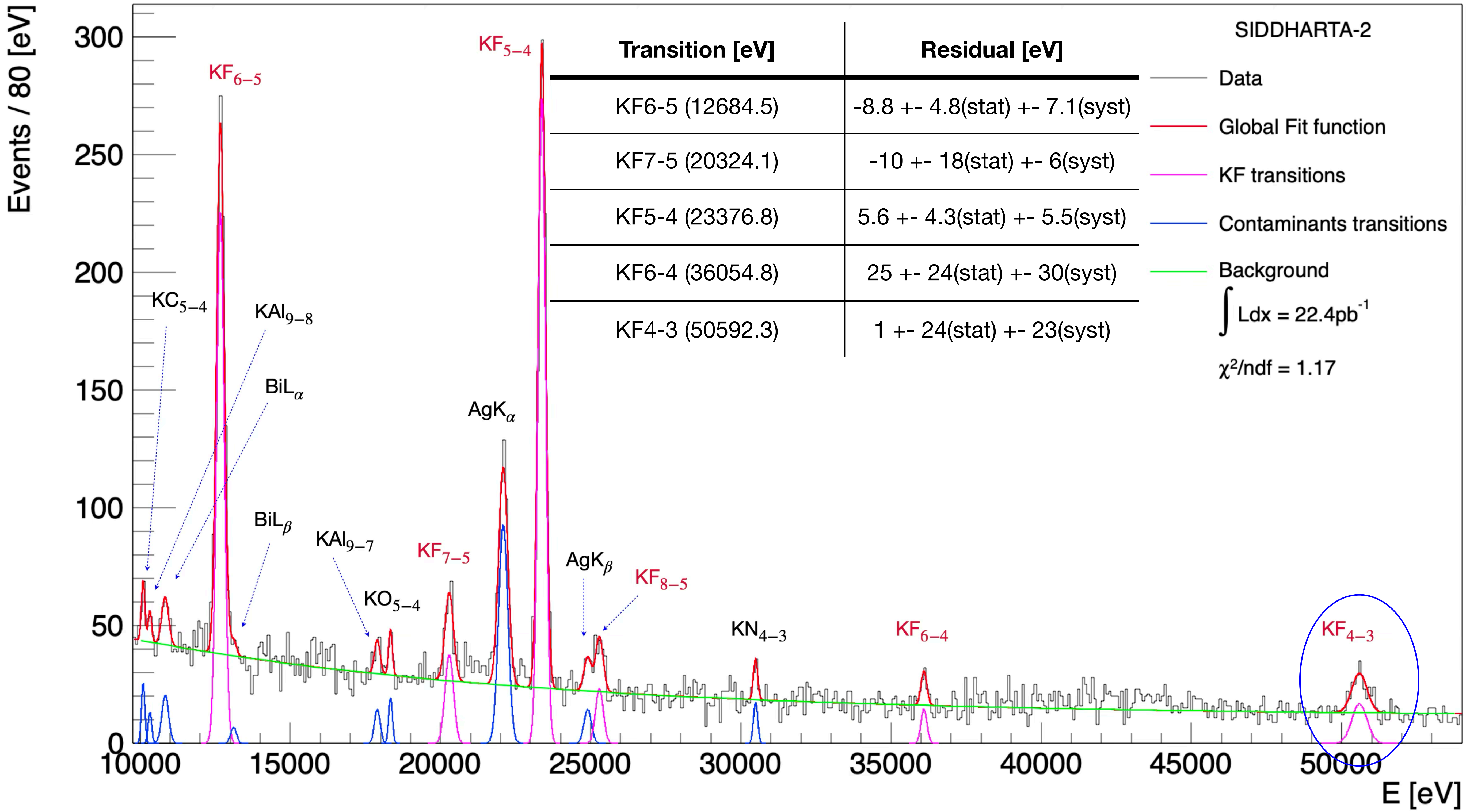


EXKALIBUR proof of concept: Kaonic Fluorine



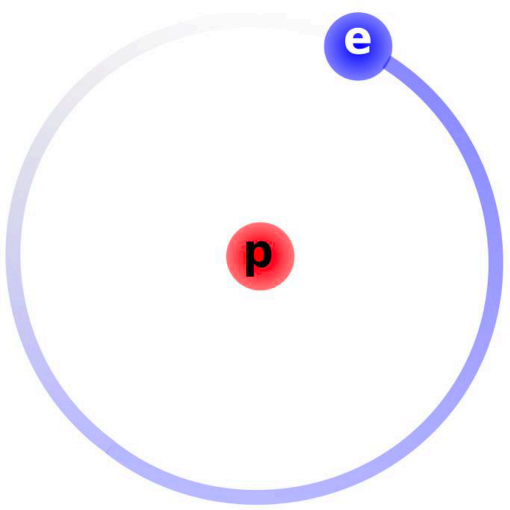
Transition [eV]	Residual [eV]
KF6-5 (12684.5)	-8.8 +- 4.8(stat) +- 7.1(syst)
KF7-5 (20324.1)	-10 +- 18(stat) +- 6(syst)
KF5-4 (23376.8)	5.6 +- 4.3(stat) +- 5.5(syst)
KF6-4 (36054.8)	25 +- 24(stat) +- 30(syst)
KF4-3 (50592.3)	1 +- 24(stat) +- 23(syst)

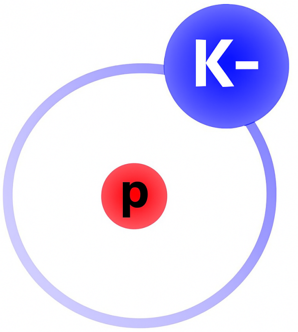
Strong Field QED with Kaonic Fluorine

- Bohr radius in exotic (kaonic) atoms is much smaller

$$a_0 = \frac{\hbar}{\mu c\alpha} \ll \frac{\hbar}{m_e c\alpha}$$

- The electric field between the kaon and the nucleus is $O(10^5)$ greater than that of "normal" atoms
- **Study of QED under strong field**
- Exotic atoms enable experimental access to Strong Electric Field [Paul *et al.*, PRL 126, 173001 (2021)]

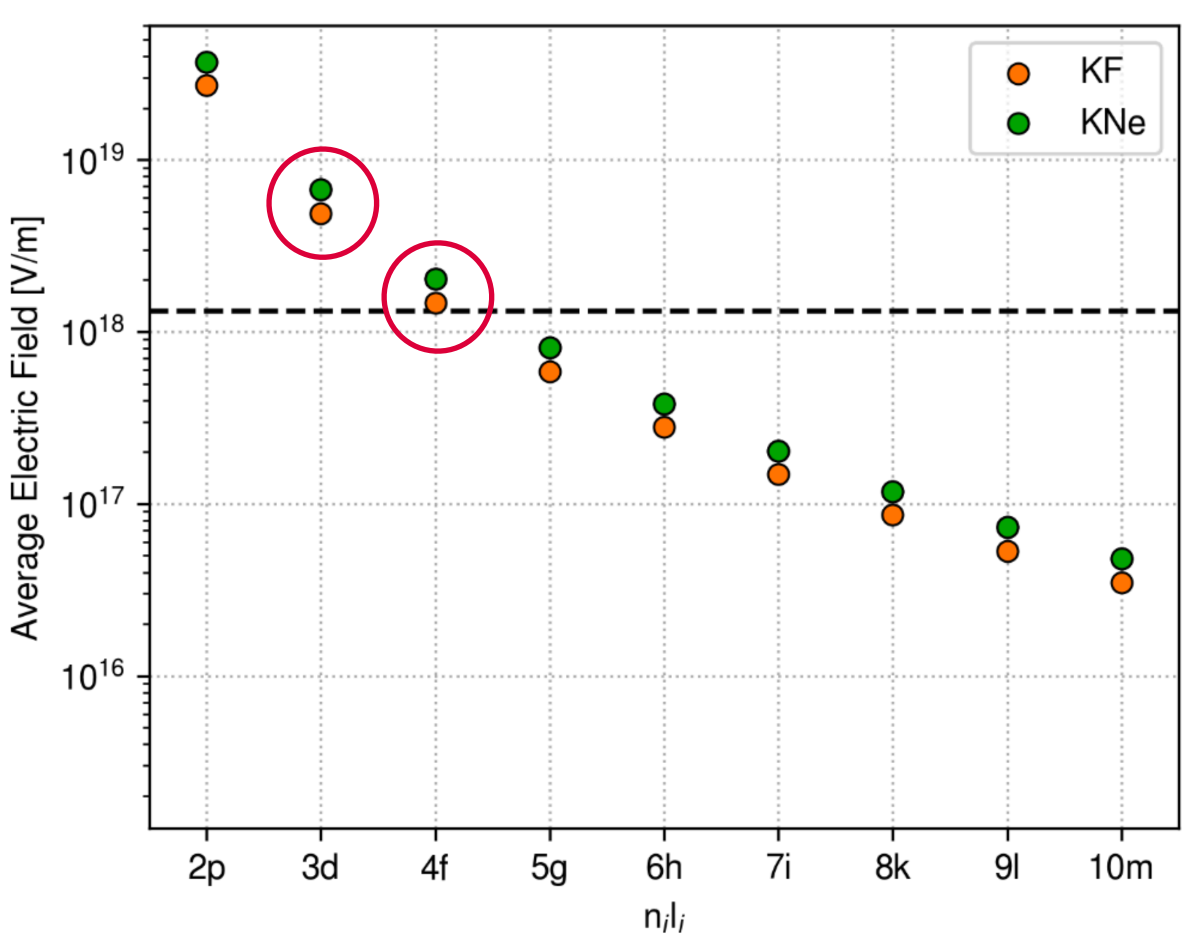


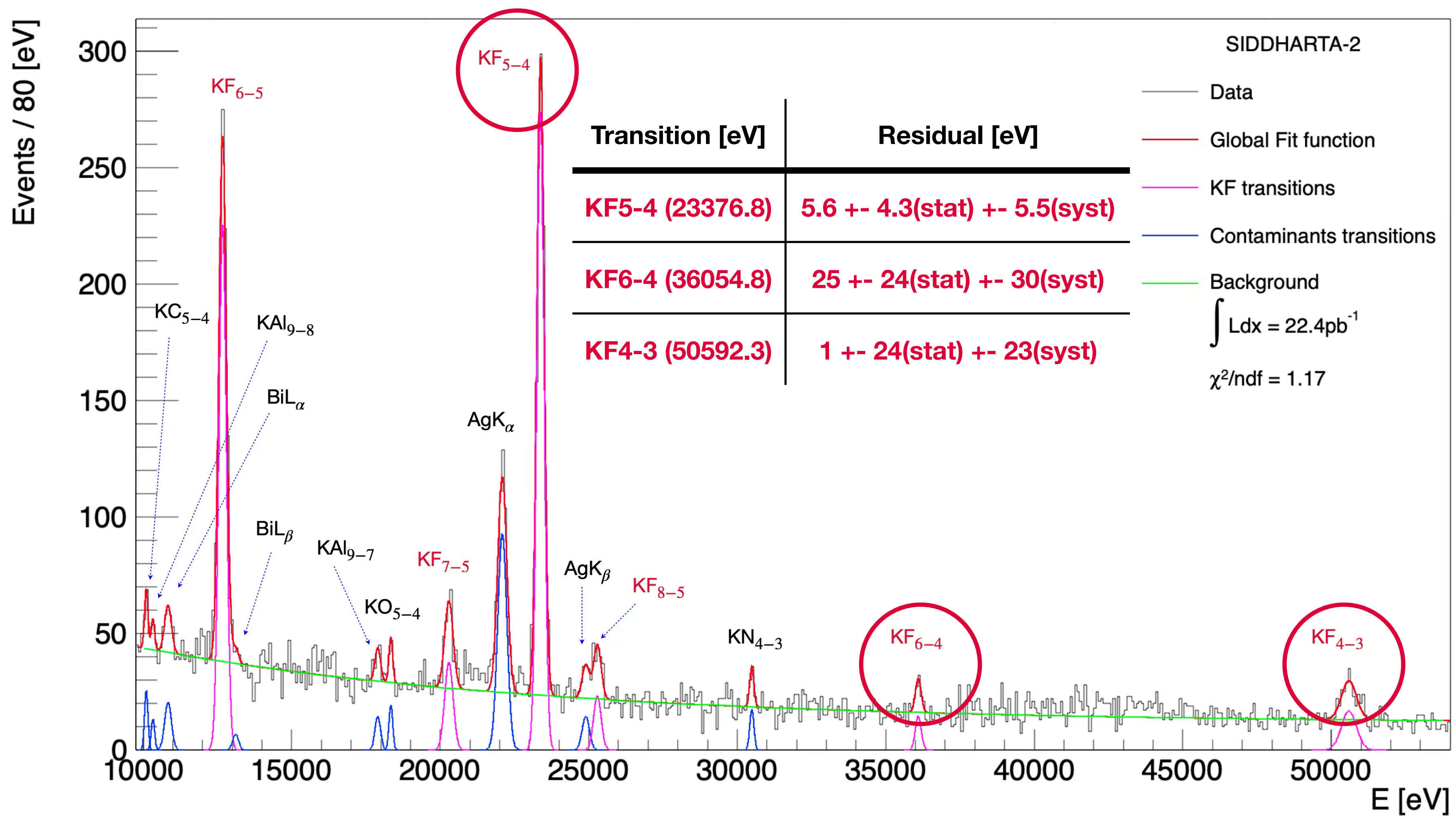


Strong Field QED with Kaonic Fluorine

- The **Schwinger Limit** for spontaneous e^-e^+ pair creation is:

$$E_c = \frac{m_e^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{18} V/m \qquad \langle E \rangle_{nl} = \int d^3r \, |\psi_{nl}(\mathbf{r})|^2 E(\mathbf{r})$$





Conclusions

- EXKALIBUR will measure higher mass kaonic atoms
- To extend the range of measurable kaonic atoms, new 1mm thick SDDs are being developed and characterised
- The first tests highlight an excellent linearity ($\Delta E/E \sim O(10^{-4})$) and energy resolution (FWHM ~ 150 eV @ 6.4 keV)
- The results of the feasibility tests with 450 μm SDDs are **very promising**
- 50 keV transition line of Kaonic Fluorine ($4 \rightarrow 3$) has been measured together with X-rays transitions of Kaonic Boron ($5 \rightarrow 4$ and $4 \rightarrow 3$)


Thank you for your attention
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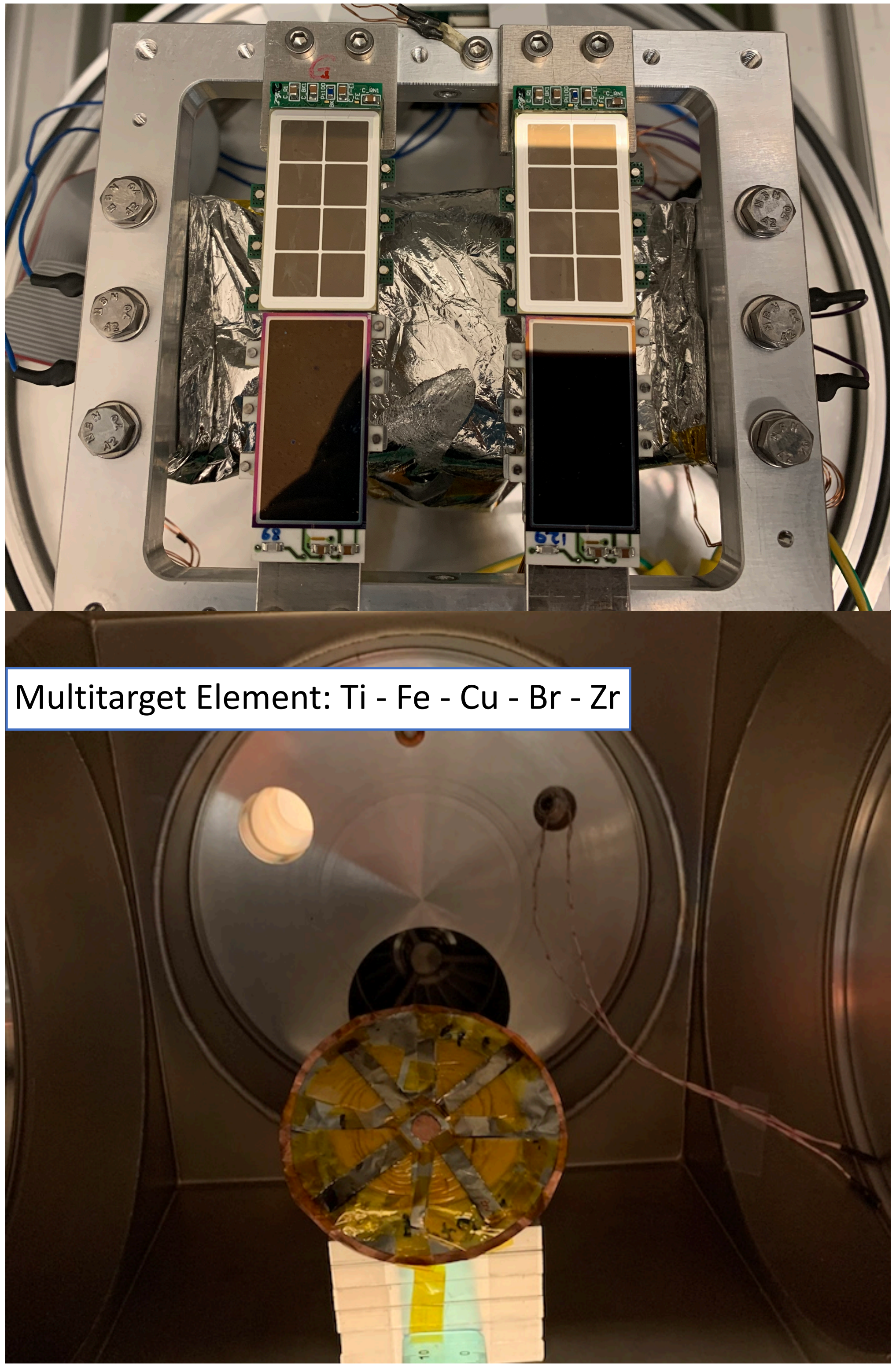
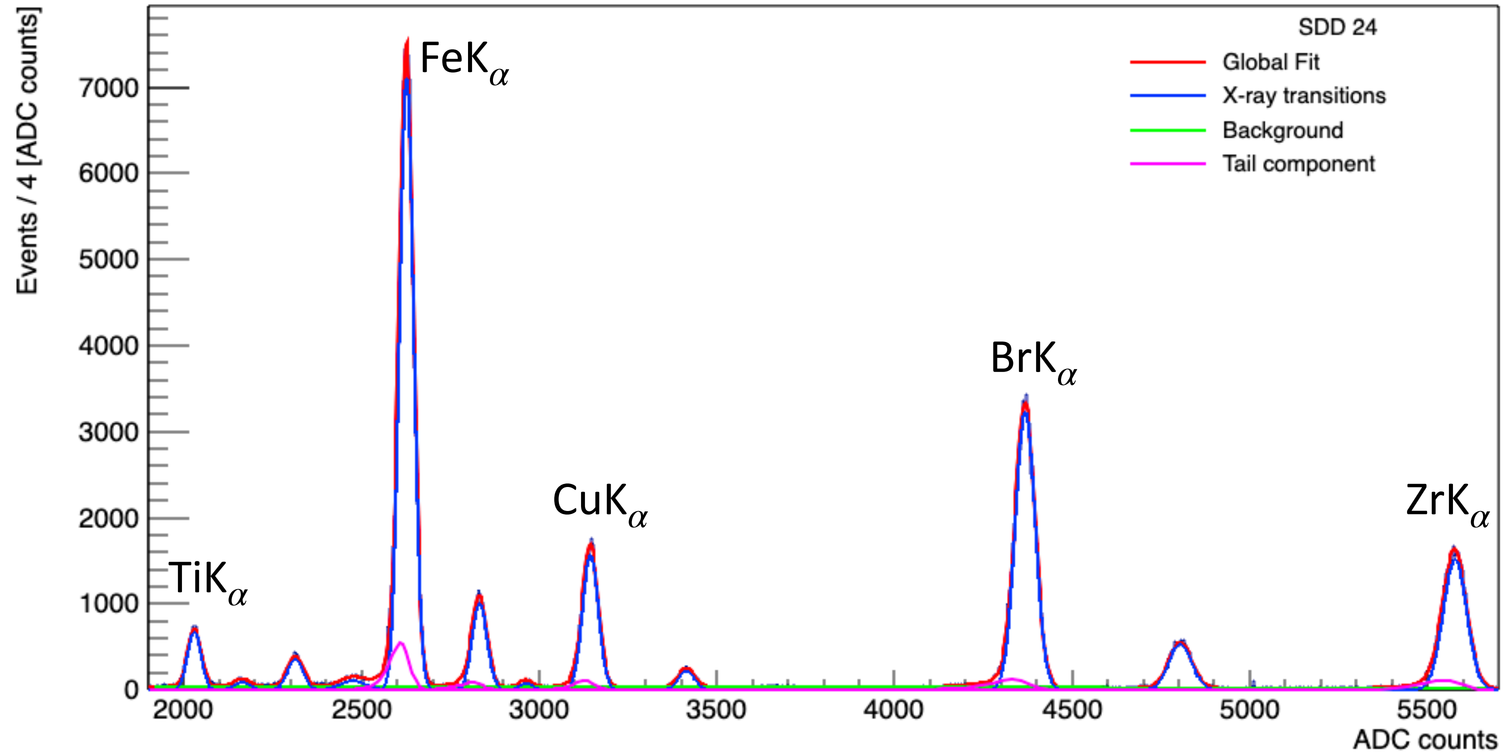
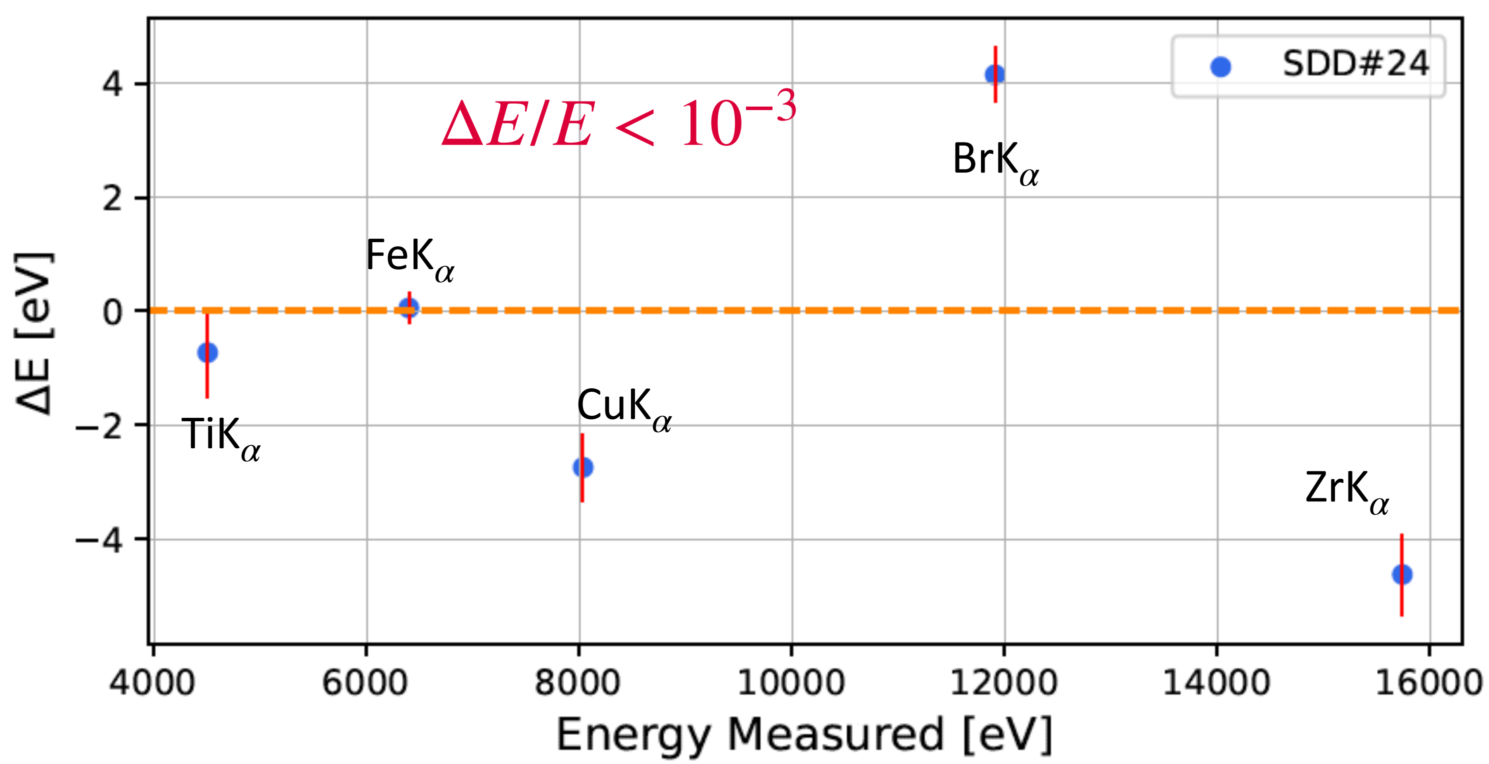
BACKUP

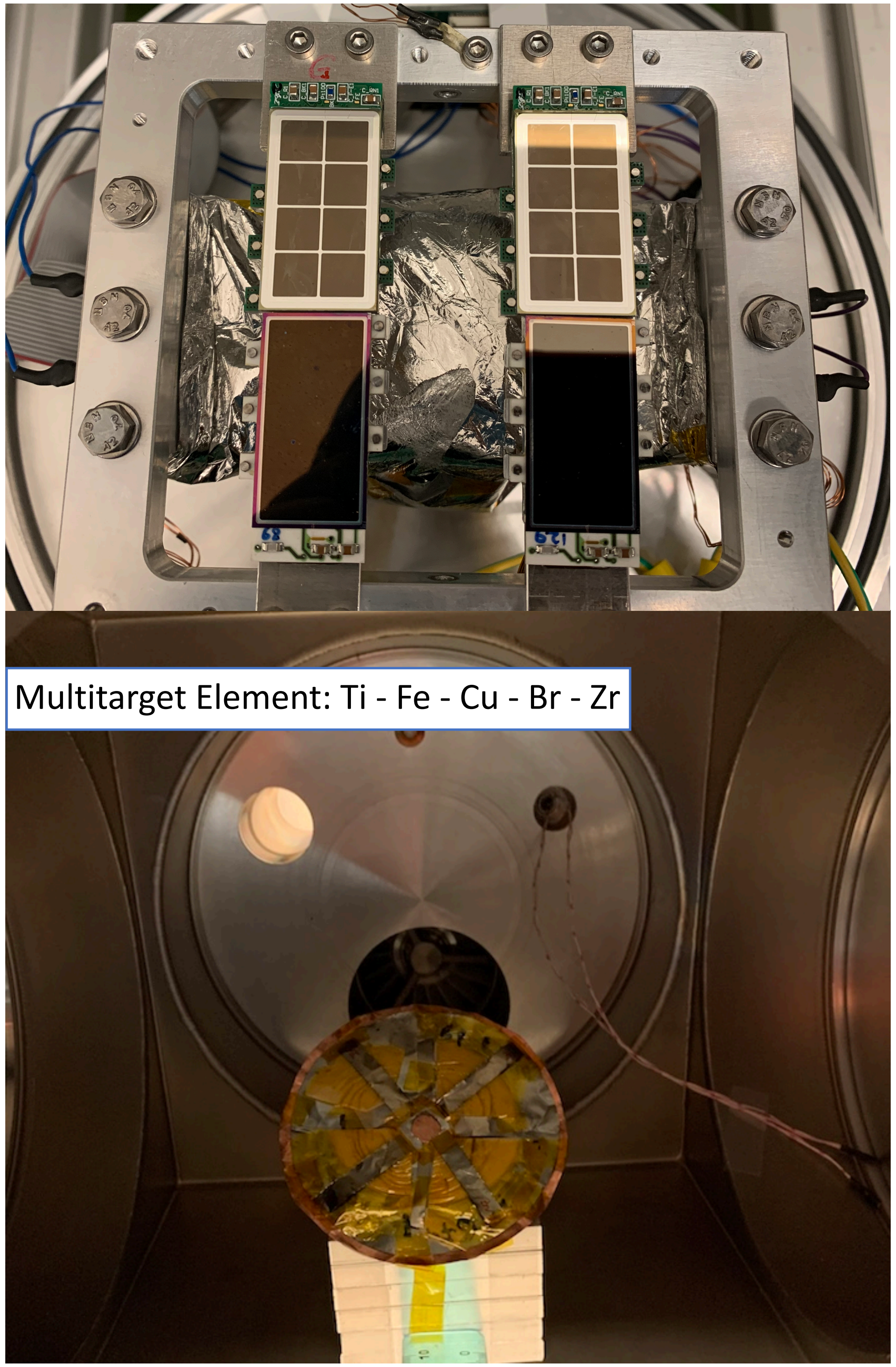
1mm SDDs characterization: linearity

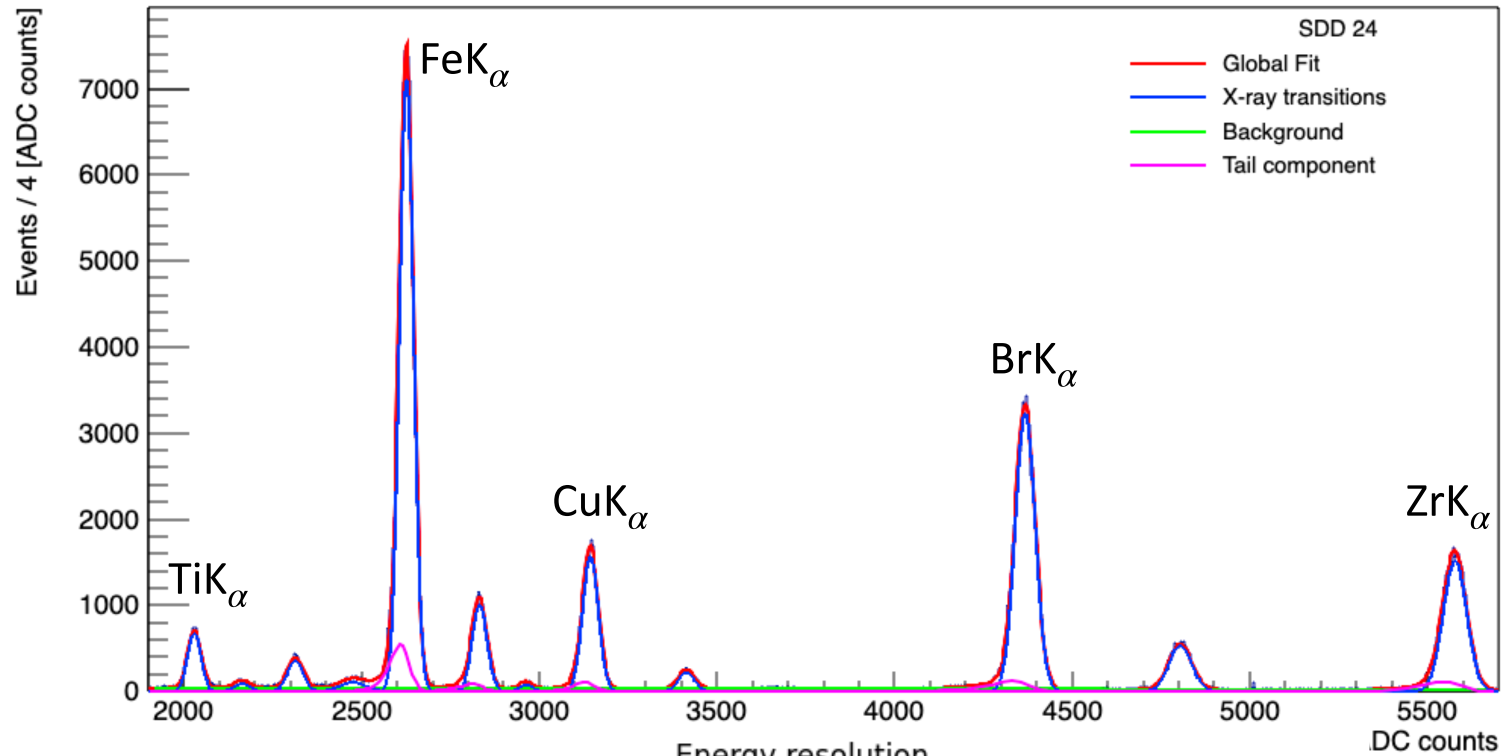




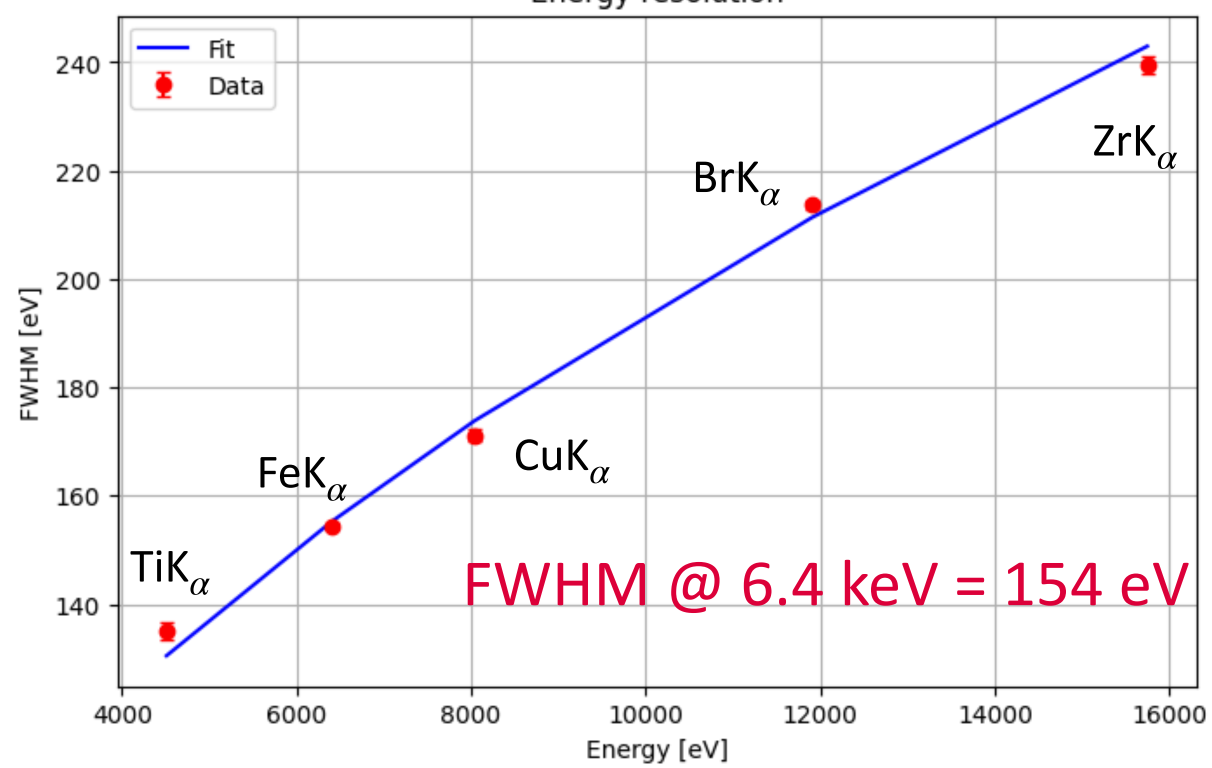


1mm SDDs characterization: energy resolution

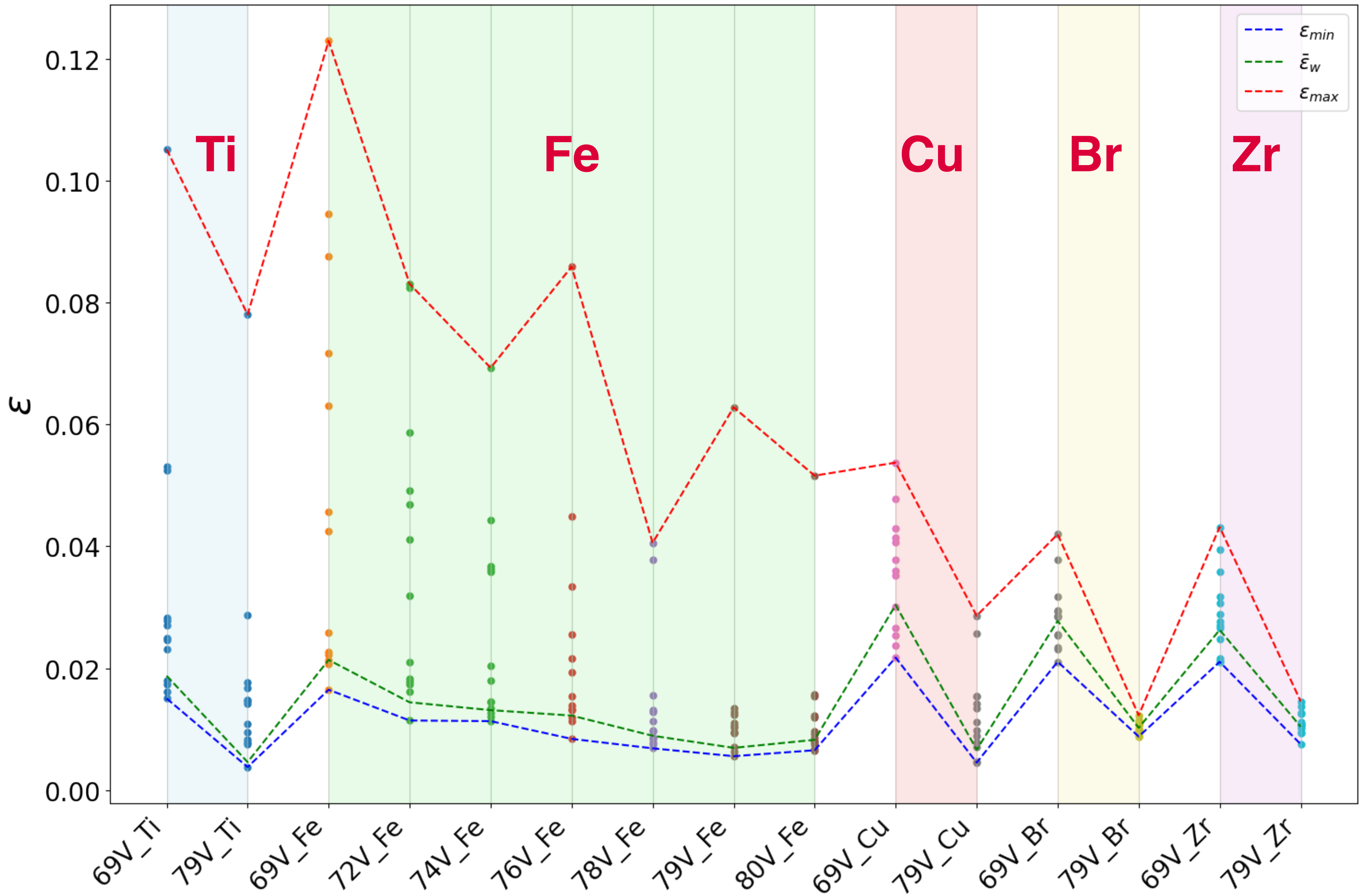




Energy resolution



1mm SDDs characterization: tail contribution



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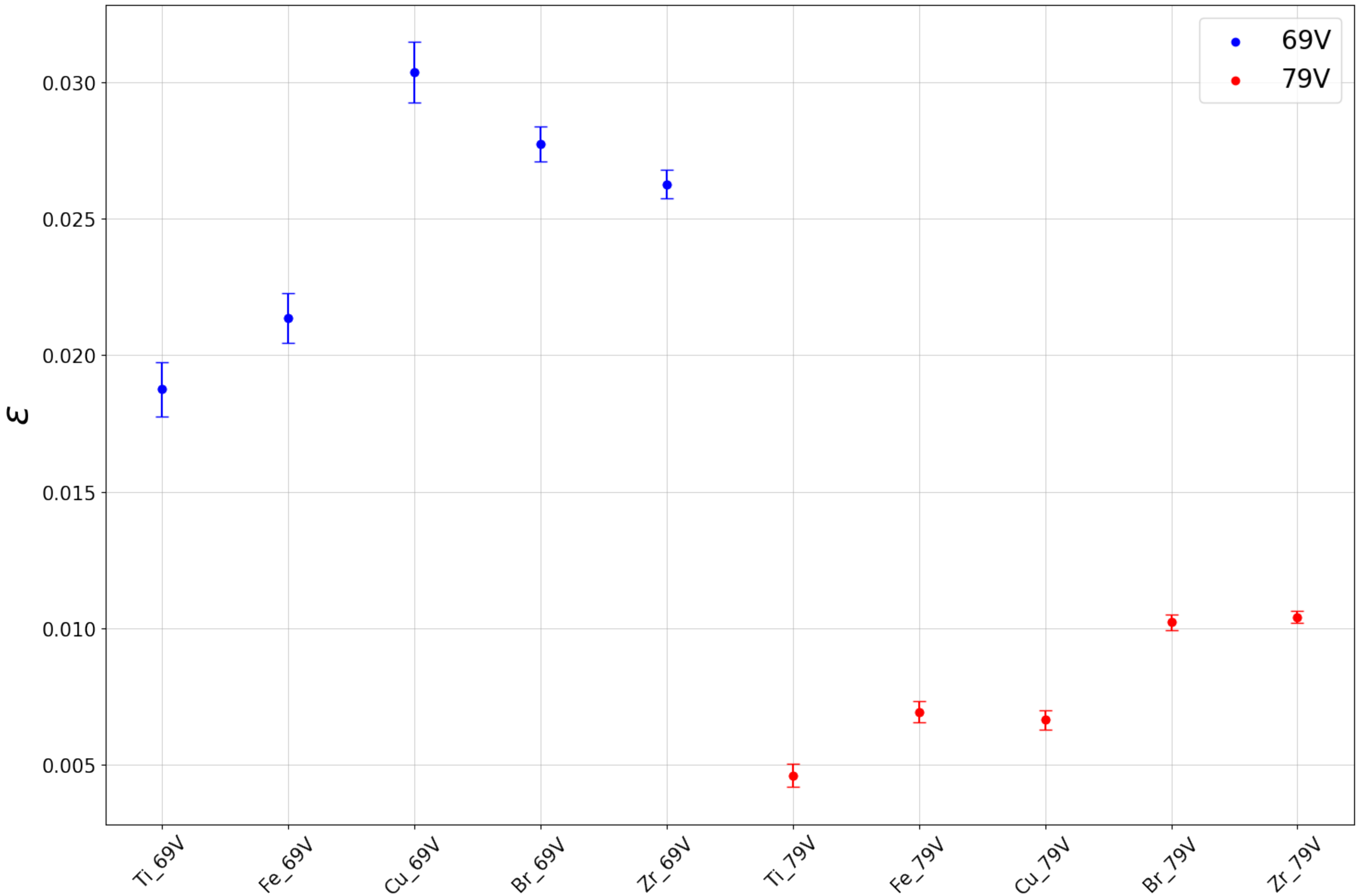

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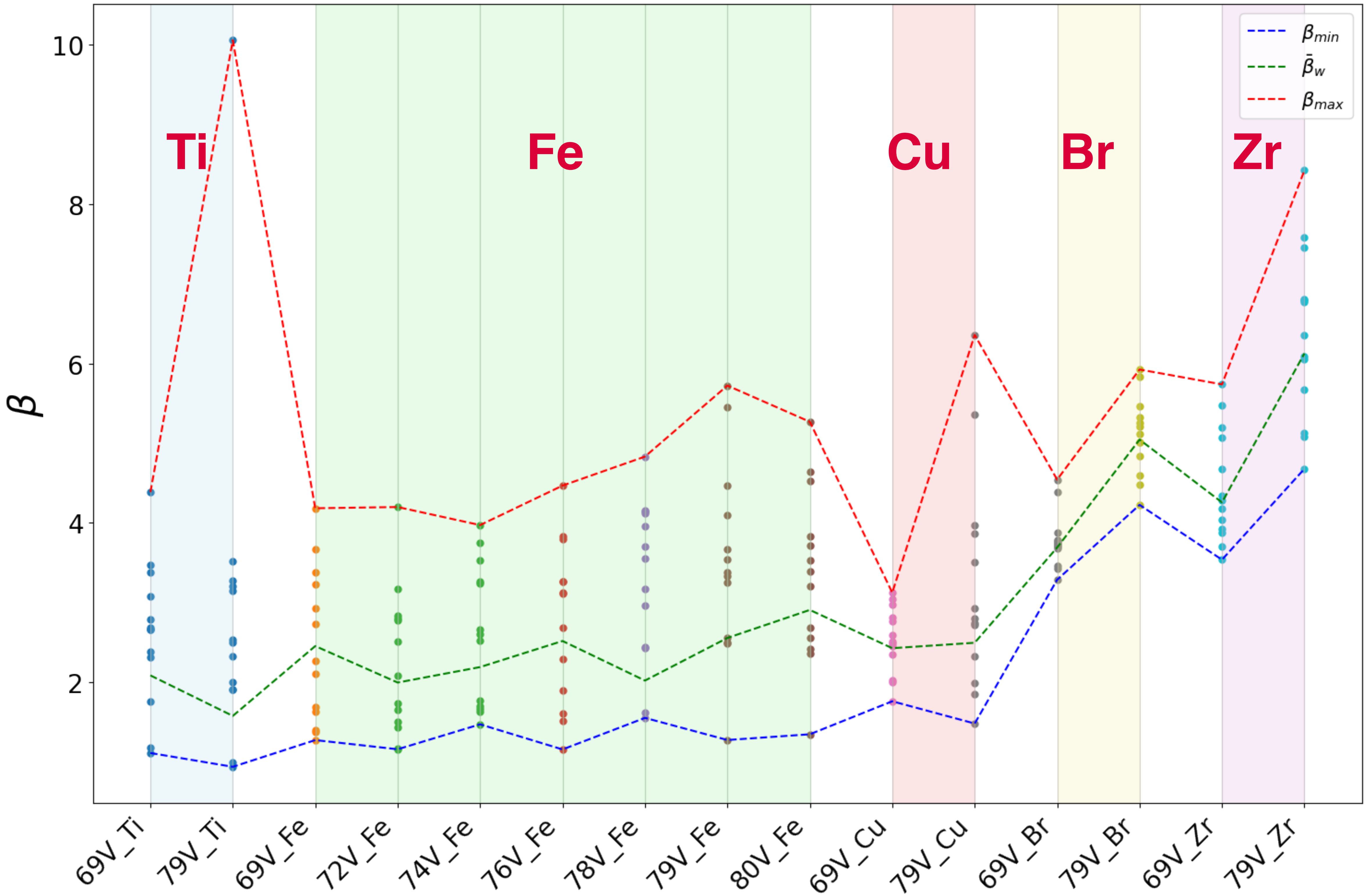

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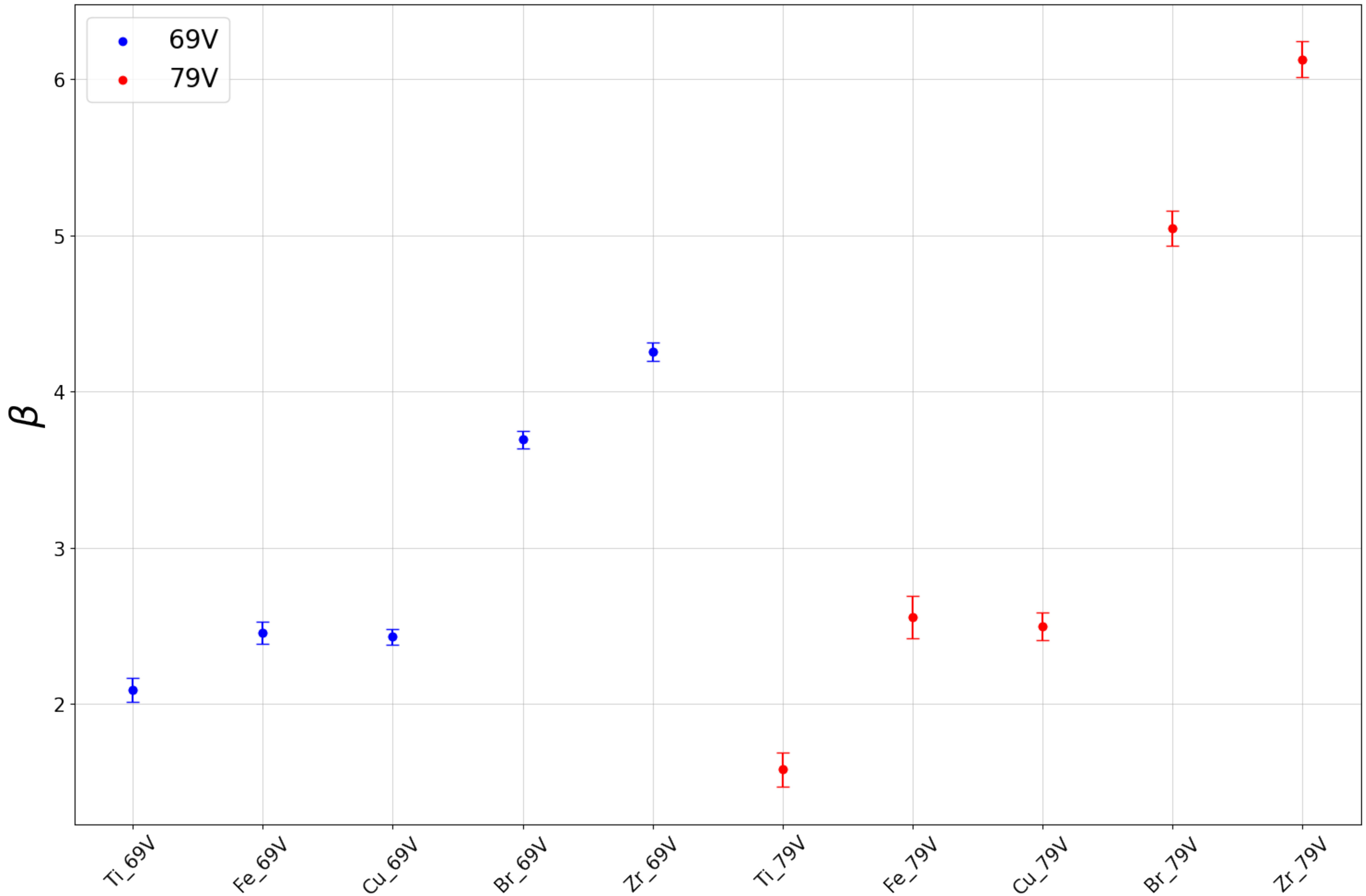

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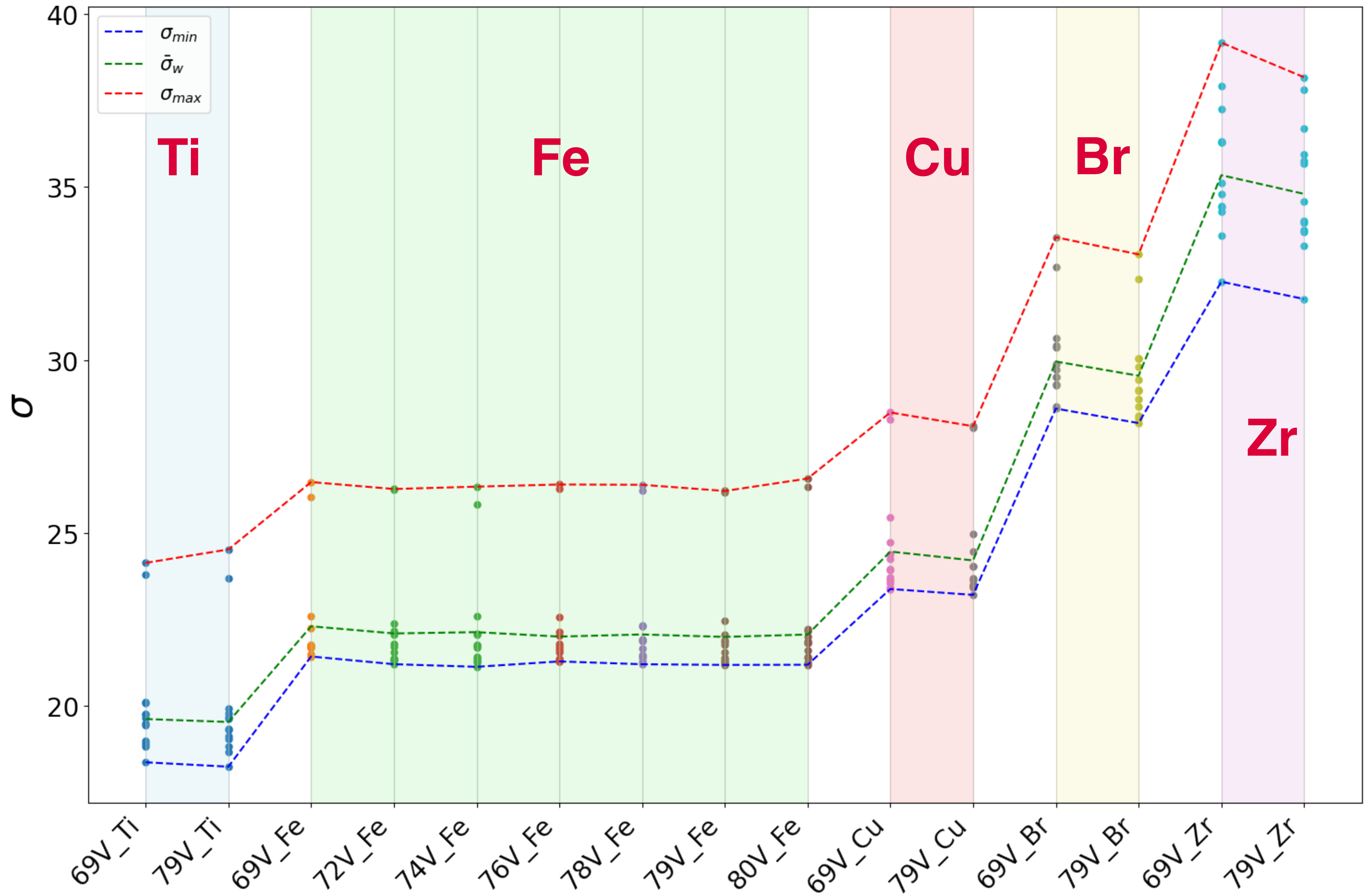

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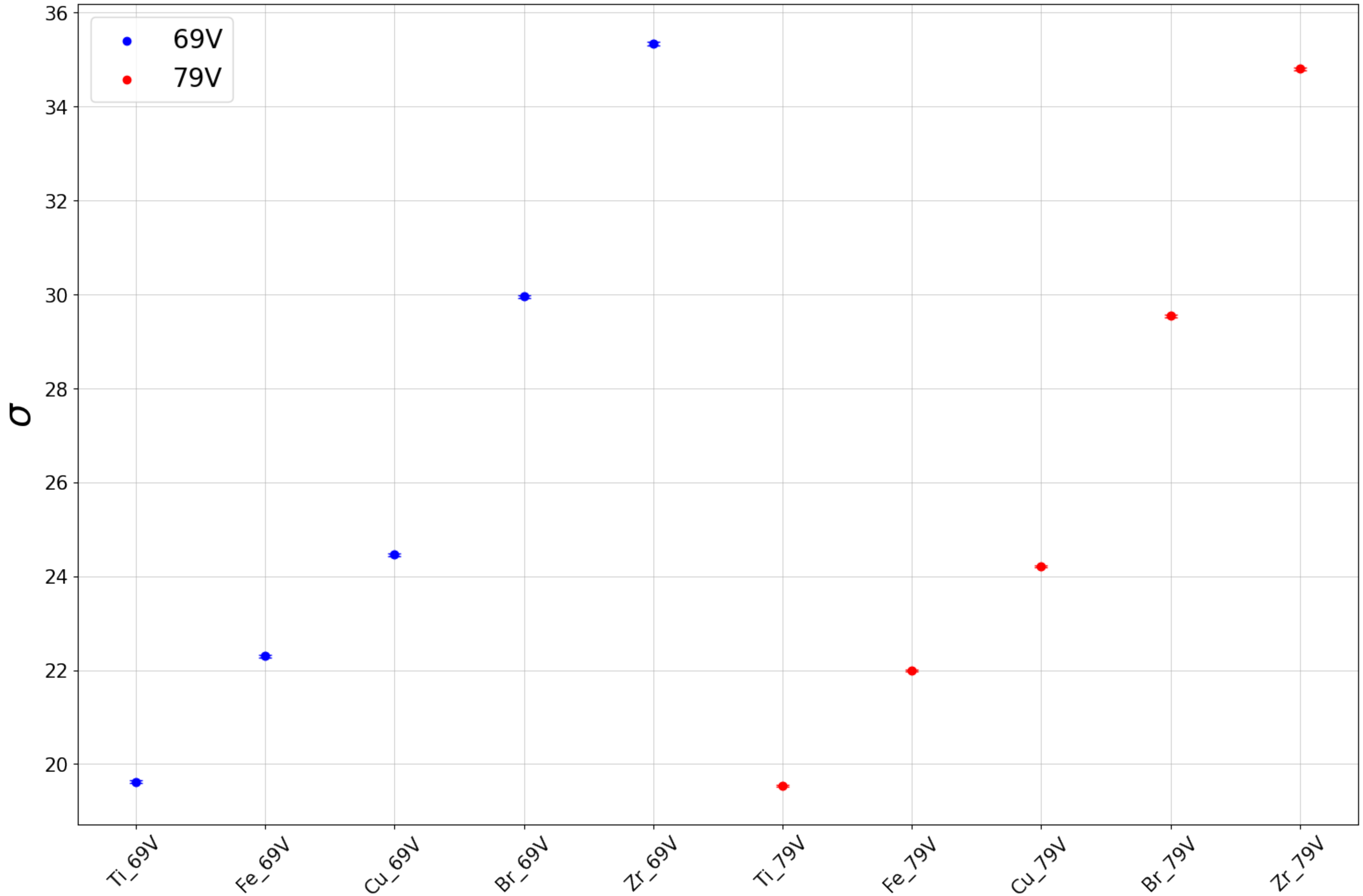

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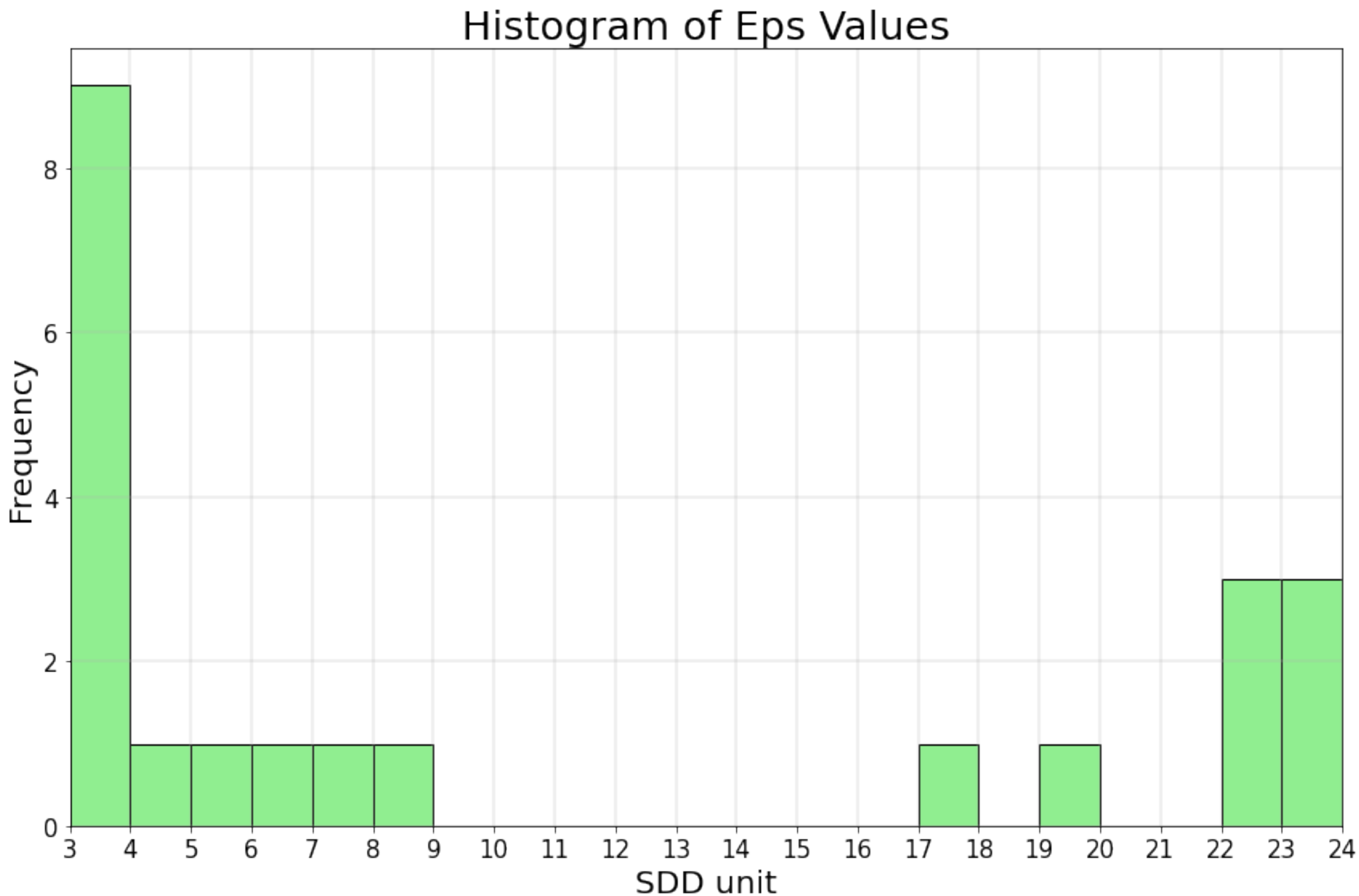
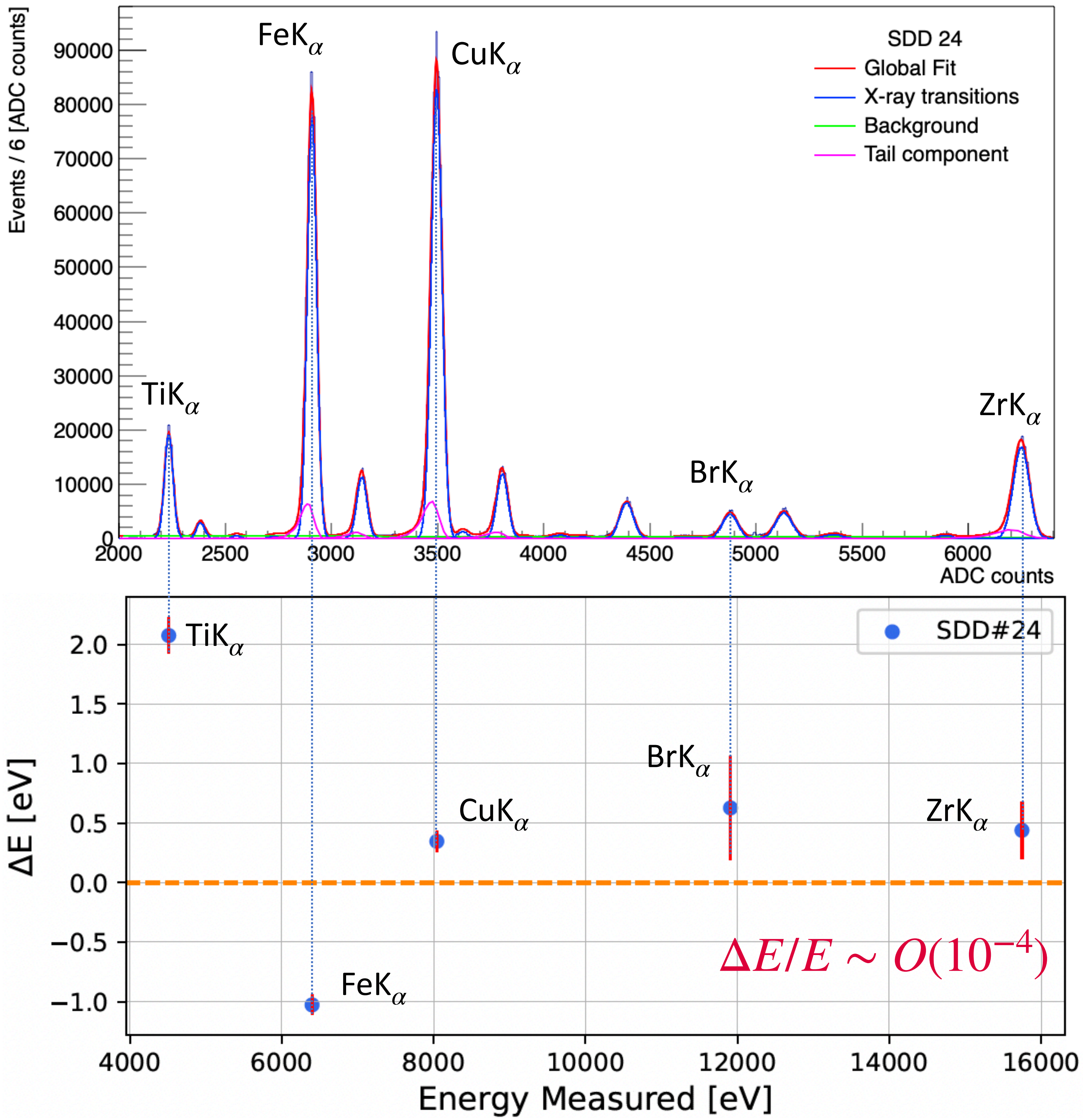


1mm SDDs characterization: optimal configuration



Voltages configuration:

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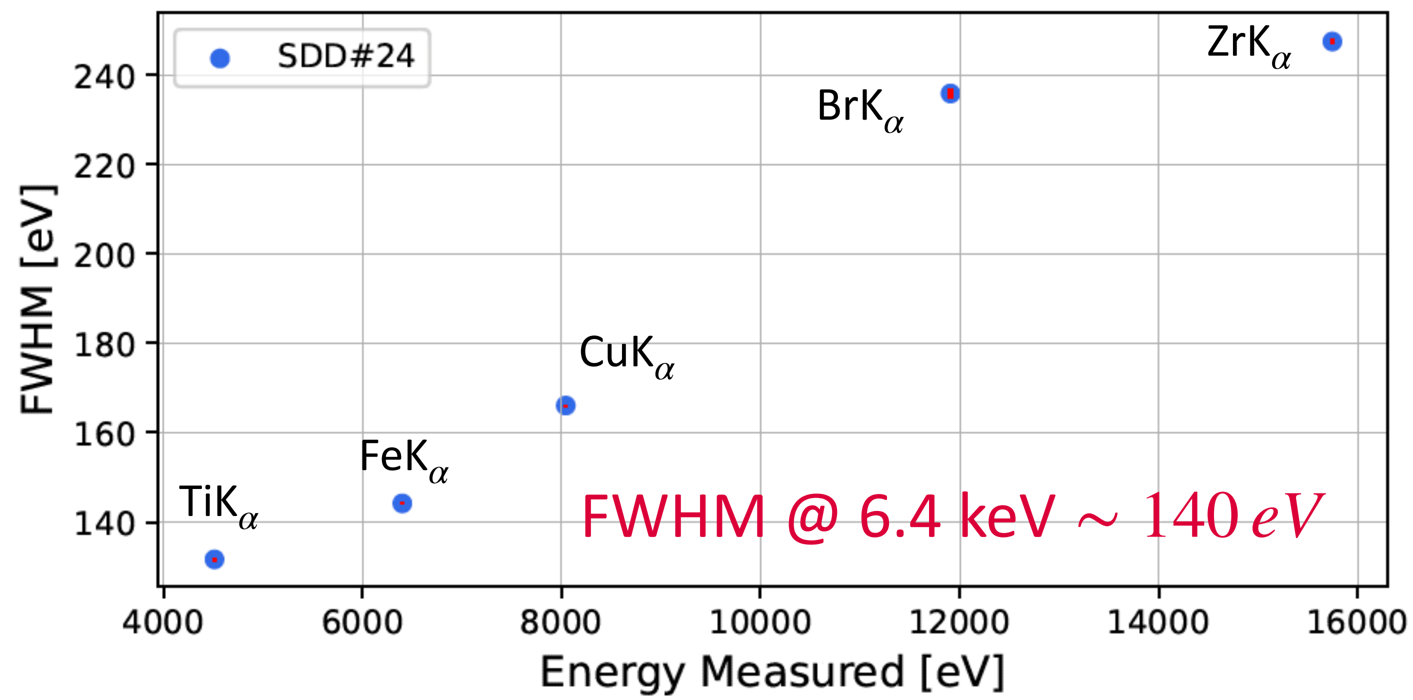
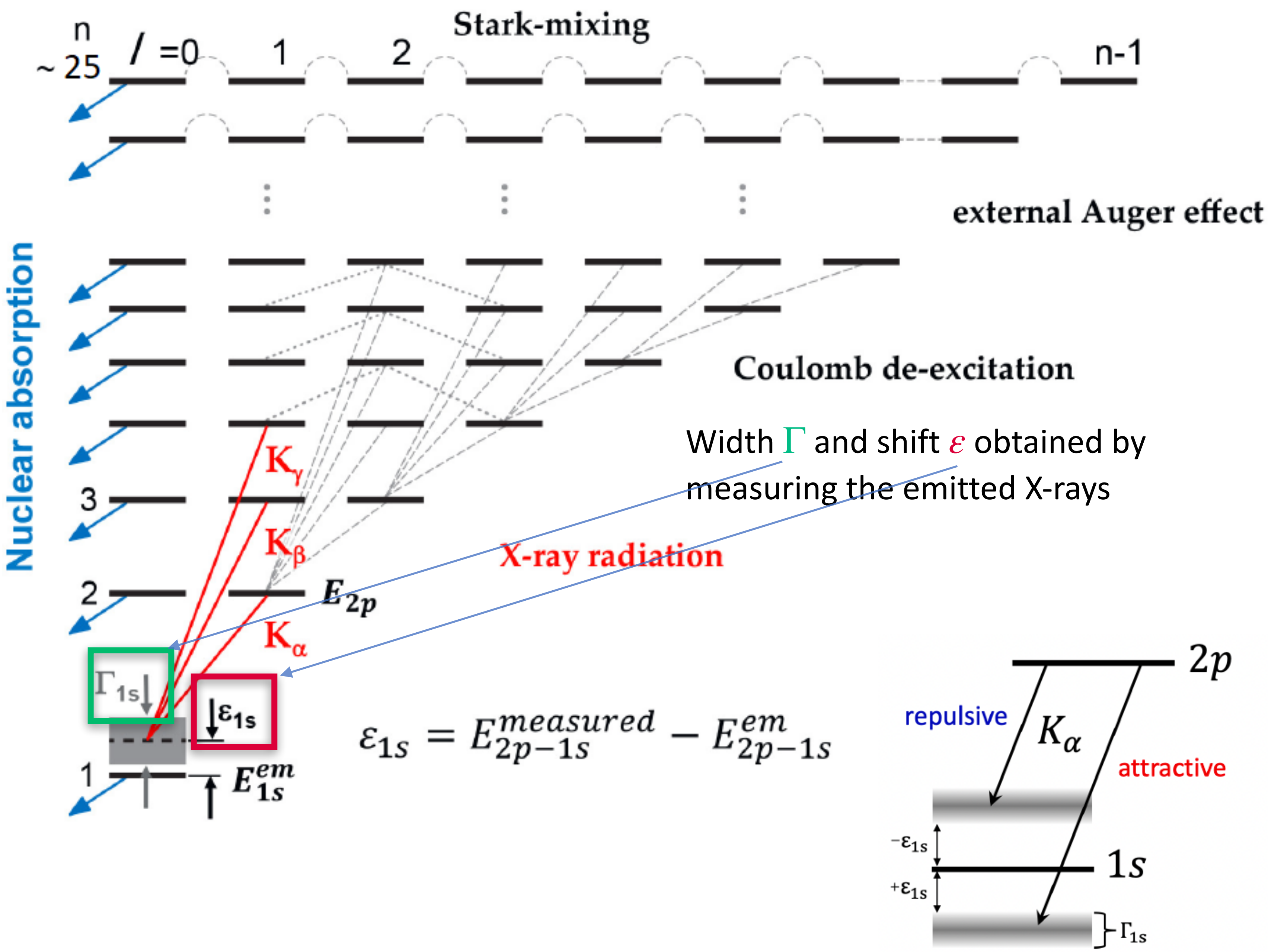


Physics of light kaonic atoms



$$\varepsilon_{1s} = E^{measured}_{2p-1s} - E^{em}_{2p-1s}$$

- 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

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

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).

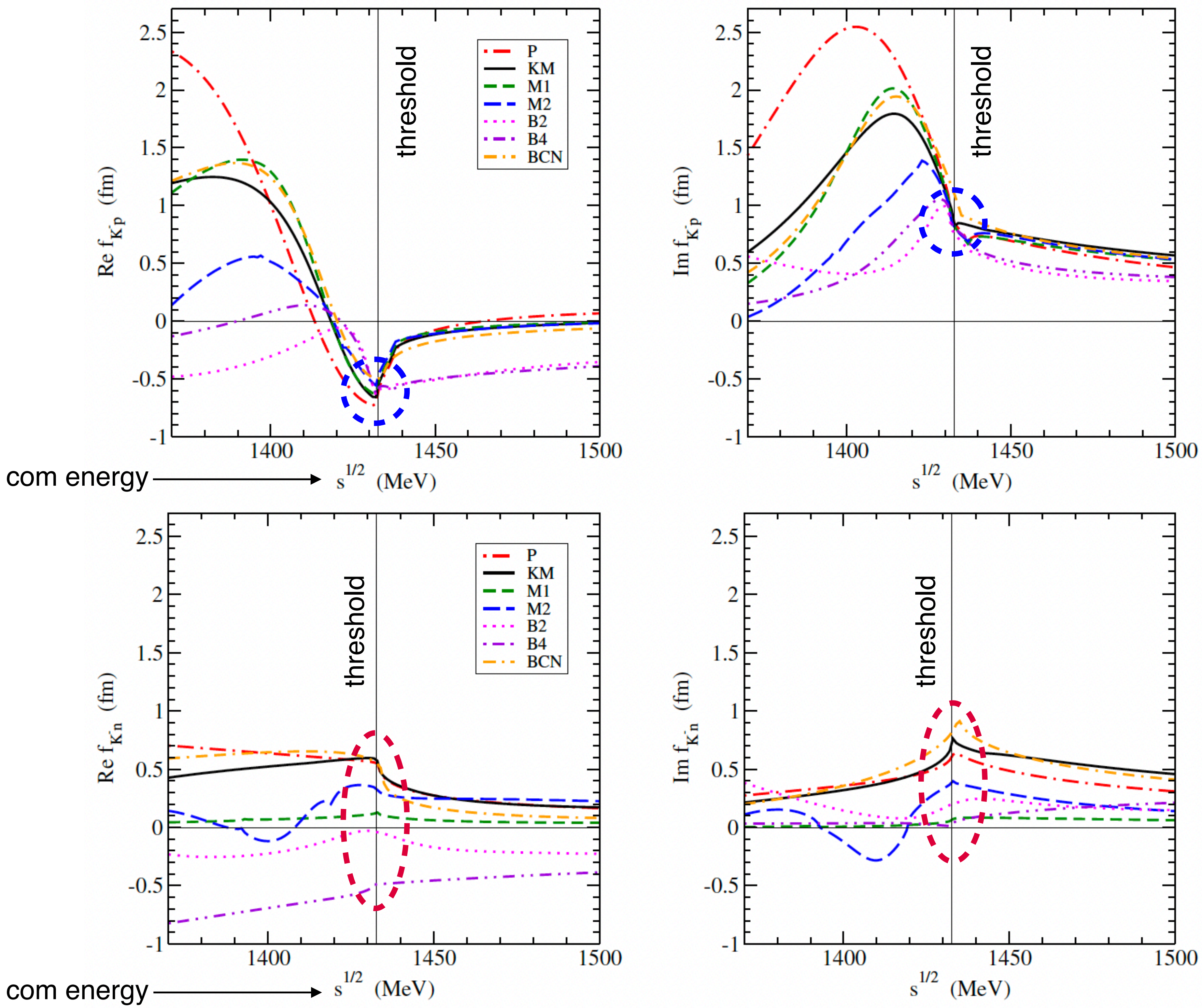
$$\lim_{k\to 0} \sigma_e = 4\pi a^2$$

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

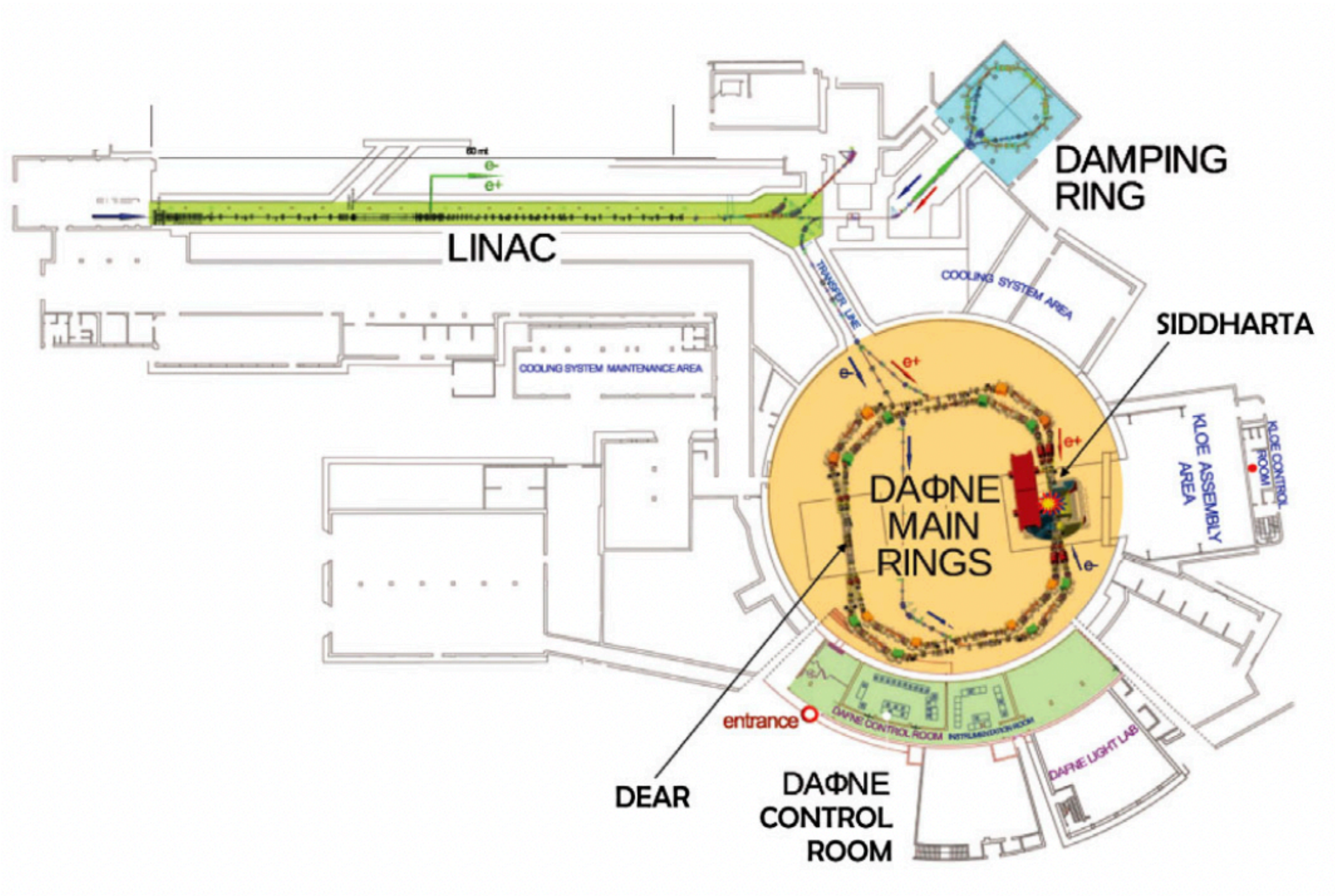


- Theoretical models in good agreement K^-p low momentum scattering amplitude

- Theoretical models for the K^-n low momentum scattering amplitude highly spread

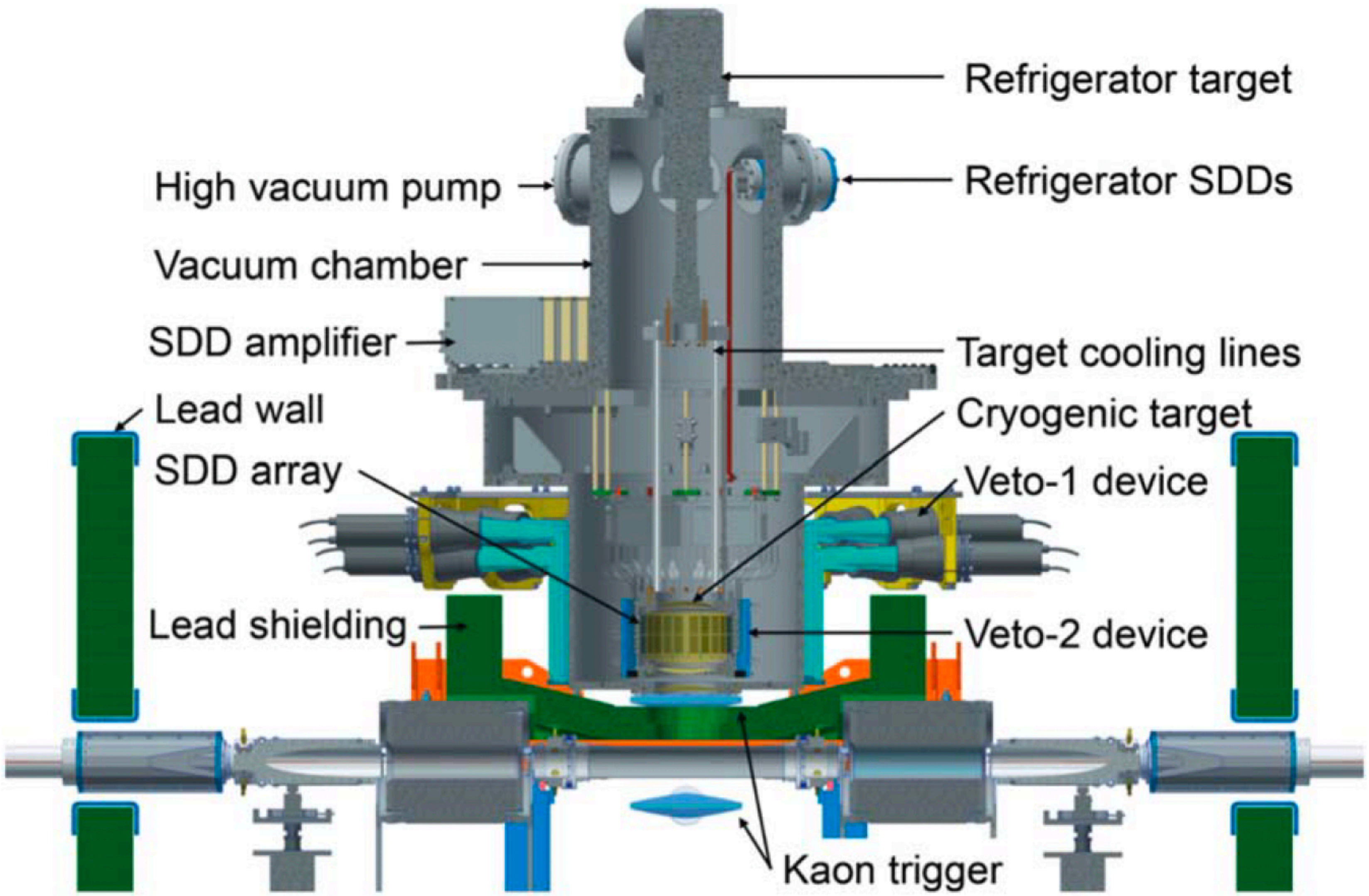
Óbertová, J., Friedman, E., Mareš, J. & Ramos, À. On K–nuclear interaction, K–nuclear quasibound states and K-atoms. In EPJ Web of Conferences, vol. 271, 07003 (EDP Sciences, 2022).

The DAΦNE Collider of INFN-LNF



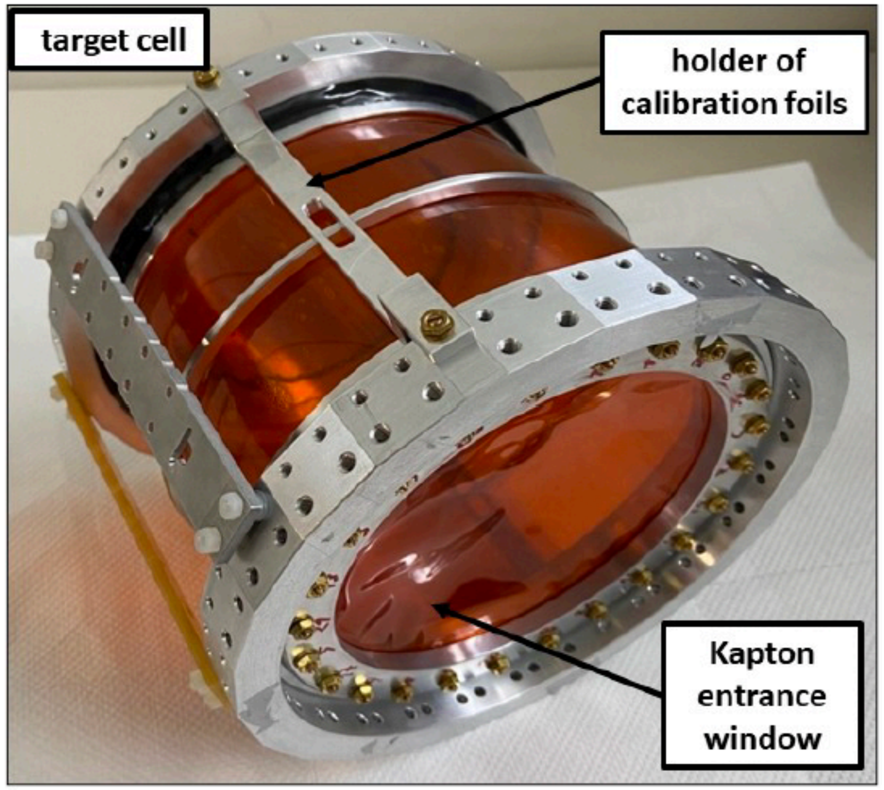
- SIDDHARTA-2 experiment installed on the Interaction Point (IP) of DAΦNE
- e^+e^- collider working at a center of mass energy of the ϕ meson mass (1.02 GeV/c^2)
- Decay to K^+K^- pairs with a BR of 48.9%
- **Kaon momentum 127MeV/c**
- Not (much) relativistic $\beta \sim 0.25$, $\beta\gamma \sim 0.26$

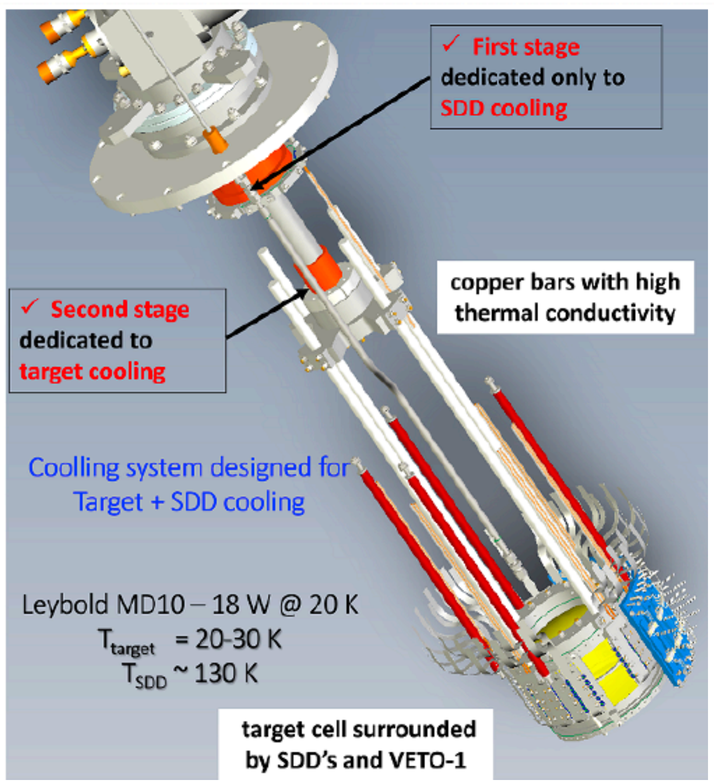
The SIDDHARTA-2 apparatus



- 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