VOXES: a millimetric effective source size HAPG crystals based Von Hamos spectrometer as a tool for extreme precision exotic atom spectroscopy

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High precision X-ray measurements 2021
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High resolution X-ray detectors overview

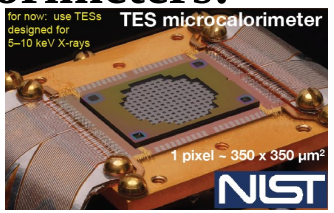
Solid state spectroscopic detectors: SDDs, CCDs operating in the energy range 2-20 KeV

- Intrinsic resolution (FWHM ~ 120 eV at 6 keV) $\sigma = \frac{FWHM}{2.35} = \omega\sqrt{W_N^2 + \frac{F \times E}{\omega}}$

electronic noise Fano Factor

See Miliucci's talk

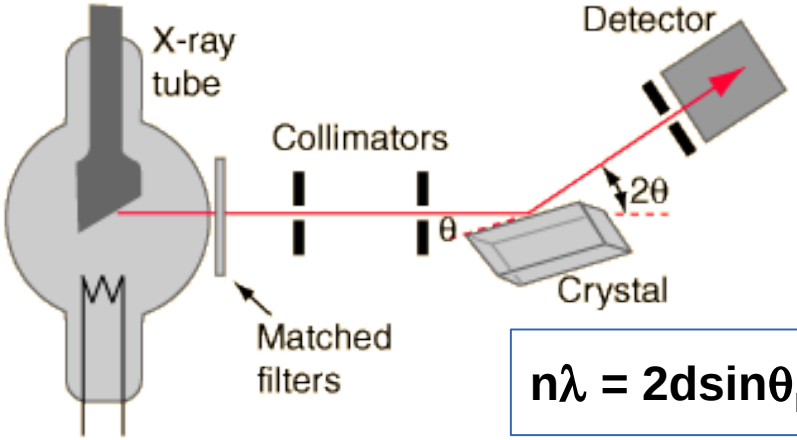
Superconducting Microcalorimeters: Transition Edge Sensors (TES):



- Excellent resolution (FWHM ~ few eV at 6 keV)
- very small active area
- working temperature ~50mK → high costs of complex cryogenic system

See Okada's and Hashimoto's talks

Crystal spectrometers:



$n\lambda = 2d\sin\theta_B$

FWHM ~ 1-10 eV
(related to the quality of the crystal and the detectors dimensions)

- Efficiencies range: 10^{-5} - 10^{-8}
- Typical d (Si) ≈ 5.5 Å (good for E < 6 keV)
- Source size ~ 10-100 μm

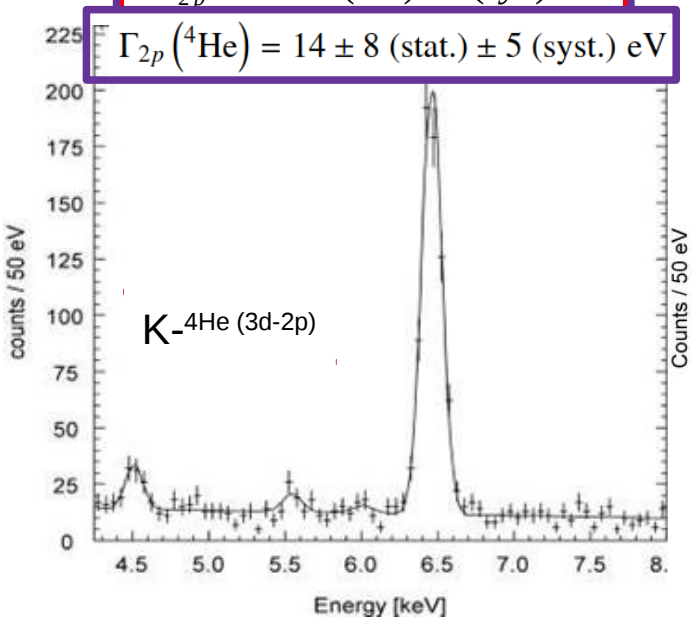
Motivation

- **Several goals already achieved in the field of physics with strangeness:**

the first measurements of gaseous kaonic helium-3 and kaonic helium-4 transitions to the 2p level and the most precise measurement of kaonic hydrogen transitions to the ground level

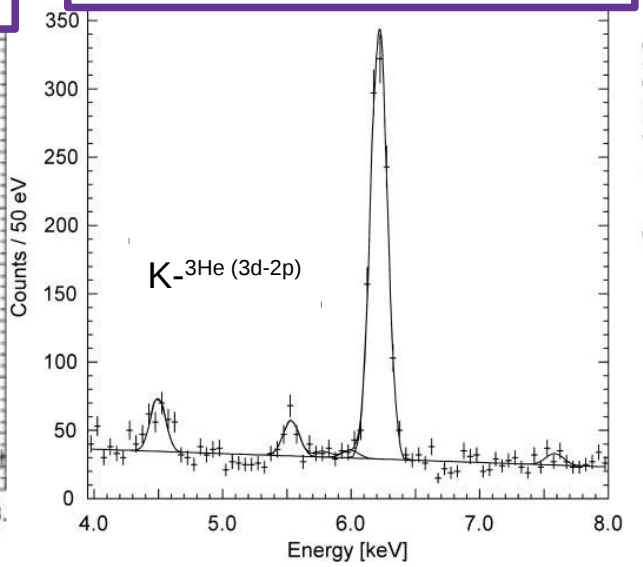
$\Delta E_{2p} = +5 \pm 3(sta) \pm 4(sys)$ eV

$\Gamma_{2p}\left({}^{4}\mathrm{He}\right) = 14 \pm 8$ (stat.) ± 5 (syst.) eV



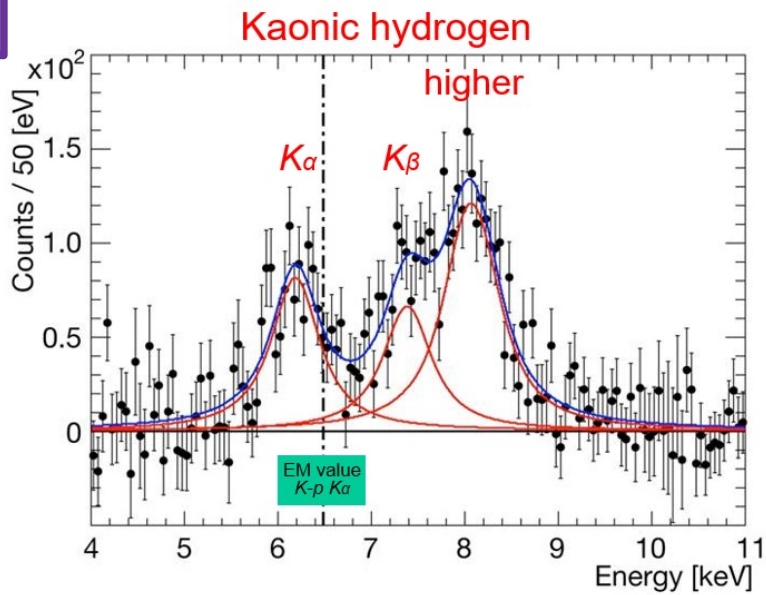
$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)$ eV

$\Gamma_{2p}\left({}^{3}\mathrm{He}\right) = 6 \pm 6$ (stat.) ± 7 (syst.) eV



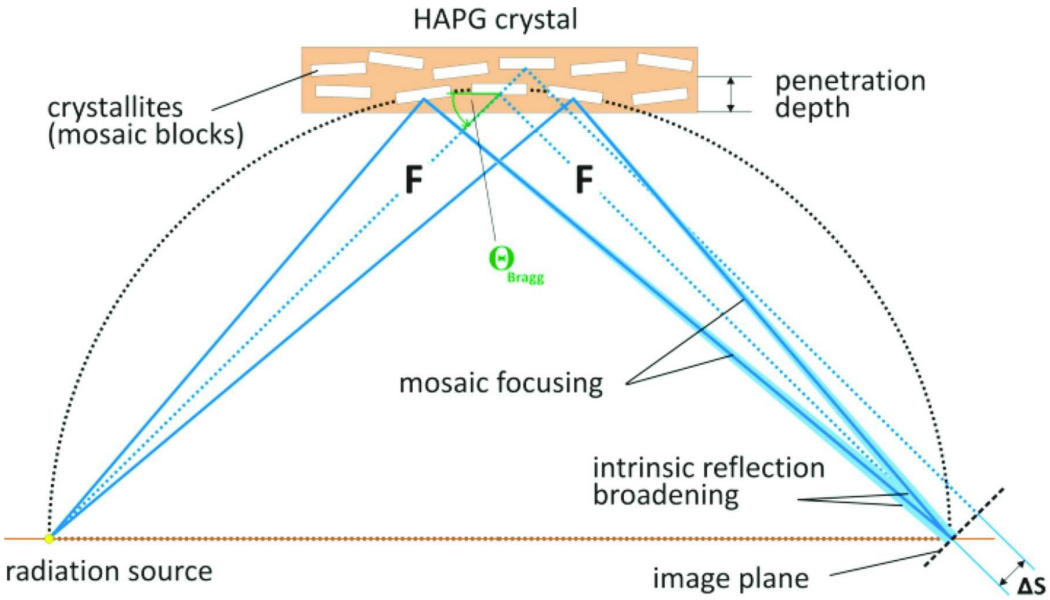
$\varepsilon_{1S} = -283 \pm 36$(stat) ± 6(syst) eV

$\Gamma_{1S} = 541 \pm 89$(stat) ± 22(syst) eV



→ **It is not the end of the history: the increasing of the measurements precision could help to solve, among the various item, the "kaon mass puzzle" or to investigate primary problems concerning global symmetry breaking or to perform extreme precision of kaonic atoms transitions that are of interest for BSM searches with exotic atoms**

Mosaic crystals



Mosaic crystals consist in a large number of nearly perfect small crystallites

Mosaicity makes it possible that even for a fixed incidence angle on the crystal surface, an energetic distribution of photons can be reflected → gain in efficiency (focusing) ~ 50

Pyrolitic Graphite mosaic crystals (d = 3.354 Å)

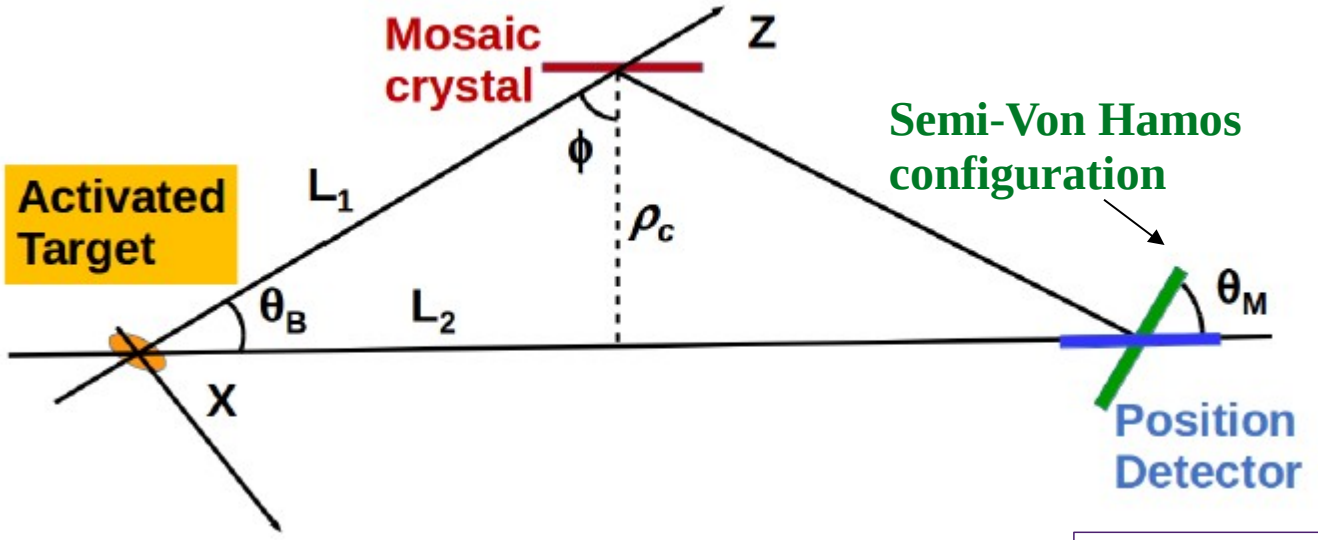
See Grigorieva's talk

Highly Oriented Pyrolitic Graphite (HOPG, Δθ≈1°)

Highly Annealed Pyrolitic Graphite (HAPG, Δθ≈0.01°)

Both types suitable to be used in the Von Hamos configuration (to further increase the efficiency)

Von Hamos Configuration



For each X-ray energy, the source-crystal (L1) and the source-detector (L2) distances are determined by the Bragg angle (θ_B) and the curvature radius of the crystal (ρ_c)

$$L_1 = \frac{\rho_c}{sin\theta_B},$$

$$L_2 = L_1 sin\phi.$$

Advantages:

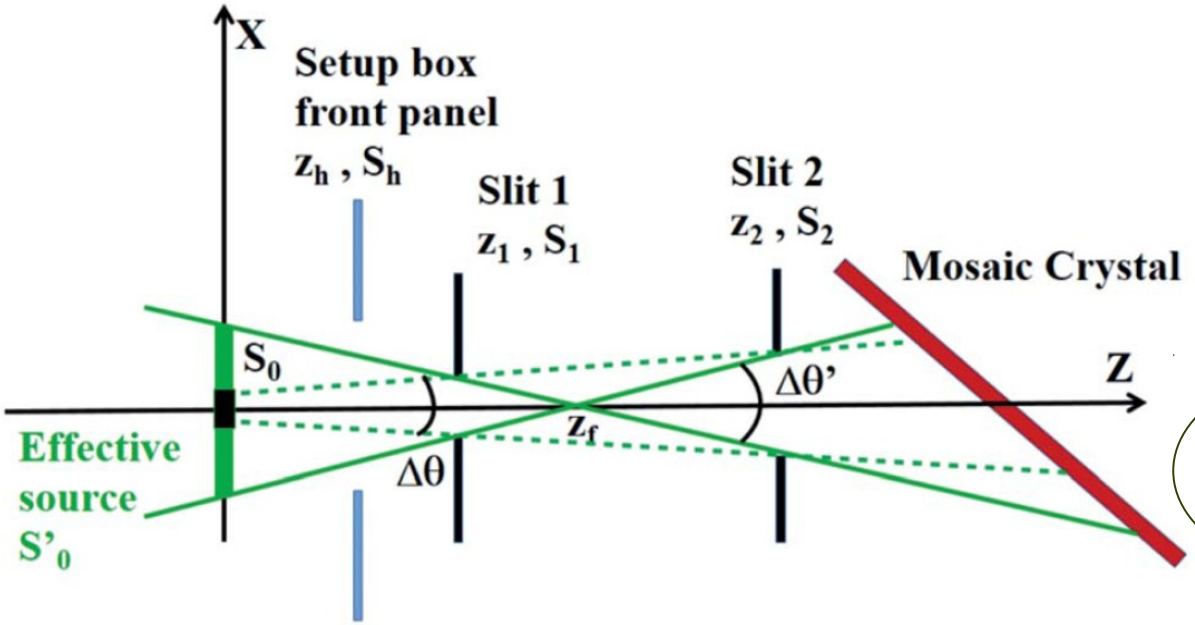
- **Focusing**
- **Distance from the source (background….)**
- **Perfect (linear) Bragg spectrum**

Disadvantages:

- **Absorption in air**
- **'Point-like' source needed (low geom. eff.)**

SVH Configuration – Horizontal plane

- To overcome the need of a point-like source *two slits-system* (S_1,S_2) has been developed



For a given Δθ', S0' pair :

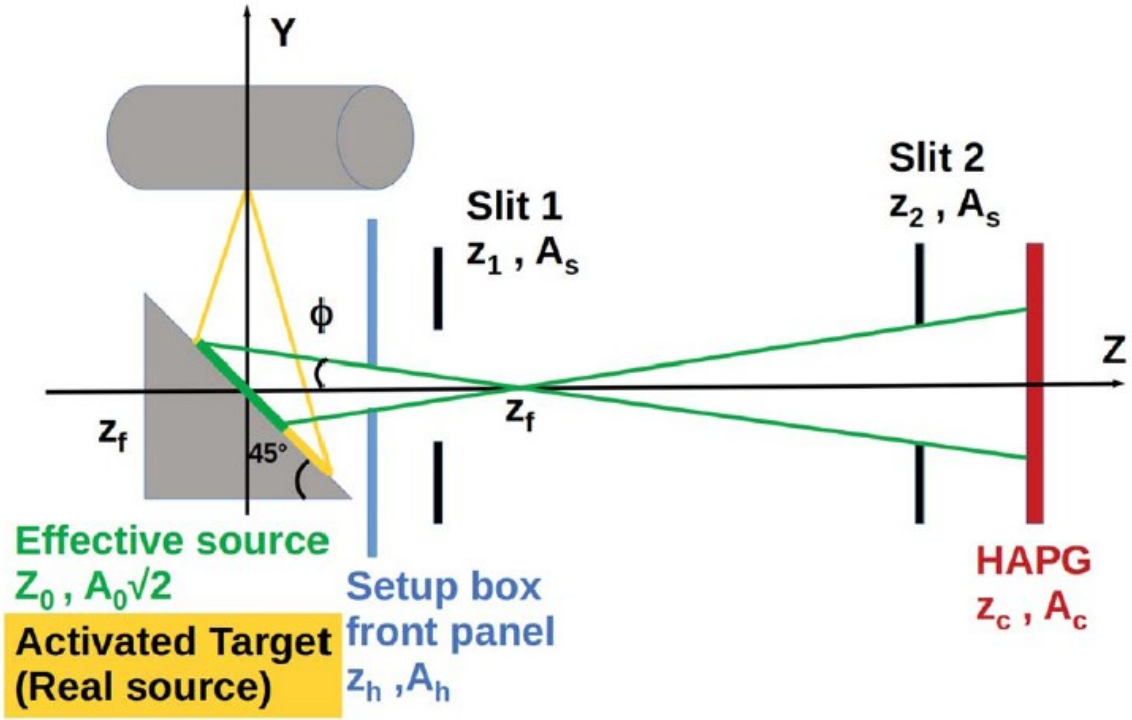
$$z_f = \frac{S'_0}{2}\cot g\left(\frac{\Delta\theta'}{2}\right)$$

$$S_1 = \frac{z_f - z_1}{z_f}S'_0 \qquad S_2 = \frac{z_2 - z_f}{z_f}S'_0$$

Production of an effective source with finite dimensions of the order of some millimeter

SVH Configuration – Vertical plane

- **The vertical spread of the X-ray beam is fixed by the slits positions (z1, z2) and their frame size (As) together with the exit circular hole in the front panel of the setup box (zh, Ah)**



$$tg\phi = \frac{A_s + A_h}{2(z_2 - z_h)}$$

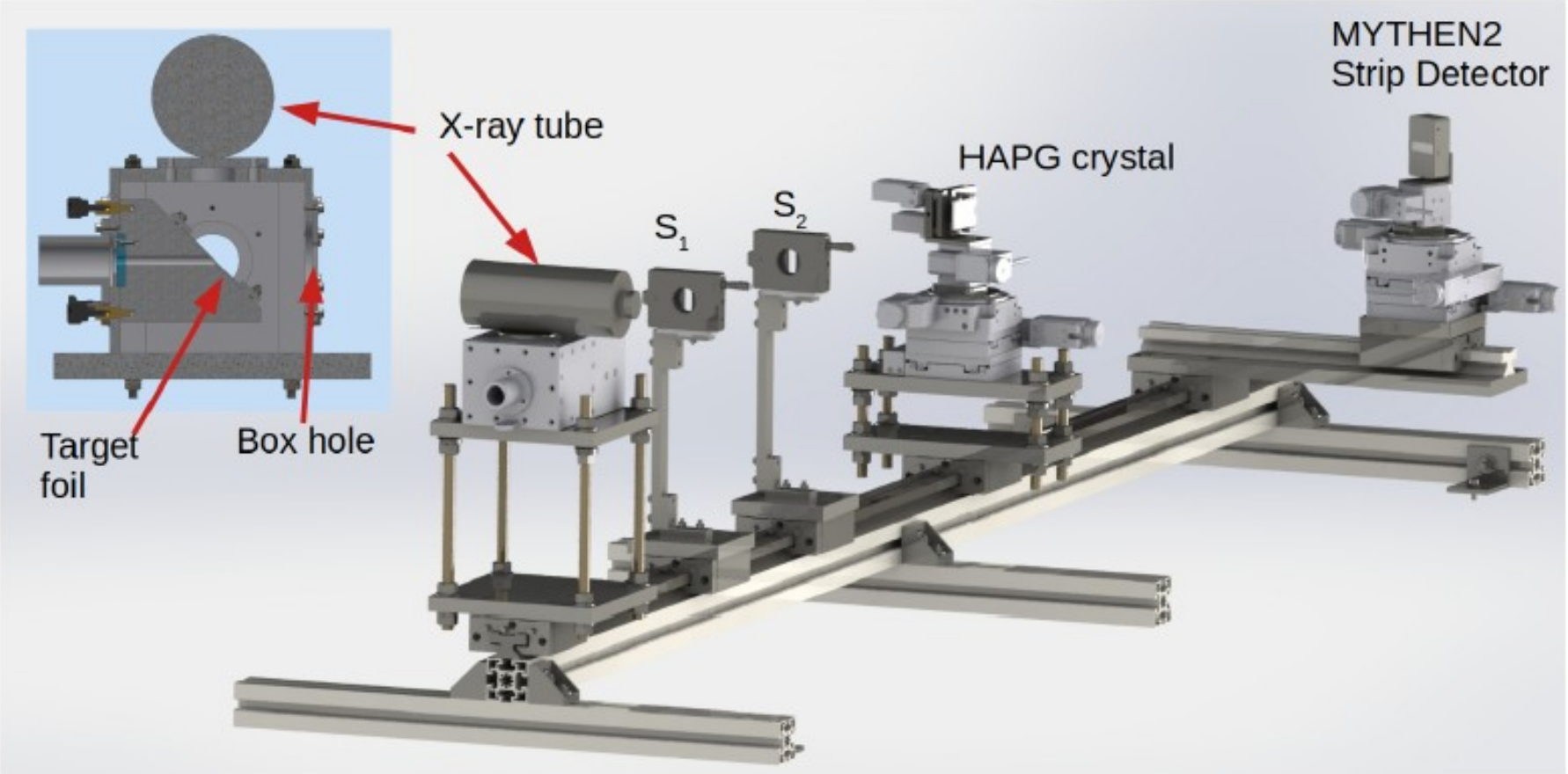
$$z_f = z_2 - \frac{A_s}{2tg\phi}$$

$$A_0 = 2z_f tg\phi$$

$$A_c = 2(z_c - z_f)tg\phi$$

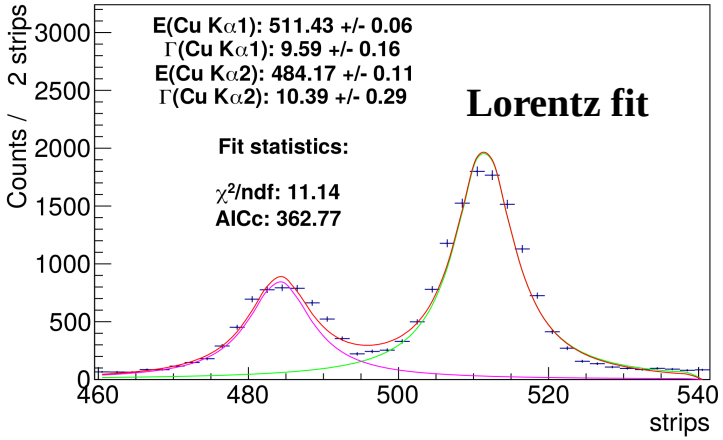
Vertical spread of the beam on the target (A0) and on the HAPG crystal (Ac)

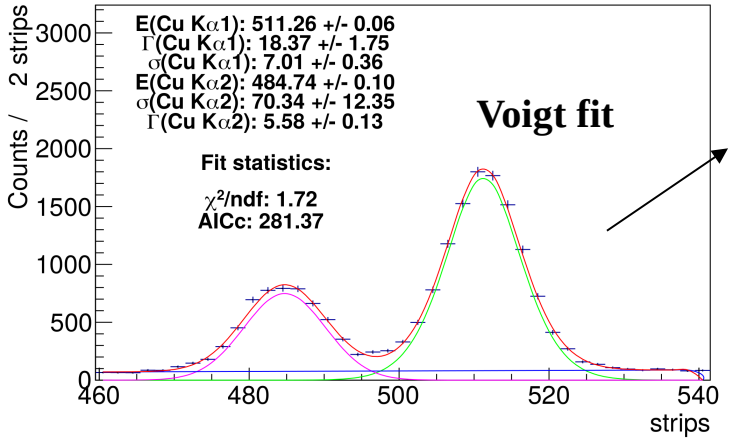
Experimental apparatus



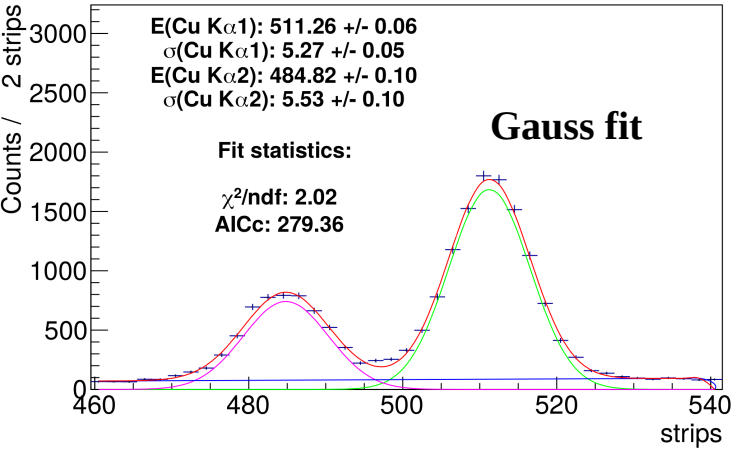
Spectrometer setup consisting of the X-ray tube, the source box, the slits, the HAPG crystal and the MYTHEN2 detector equipped to a positioning motorized system

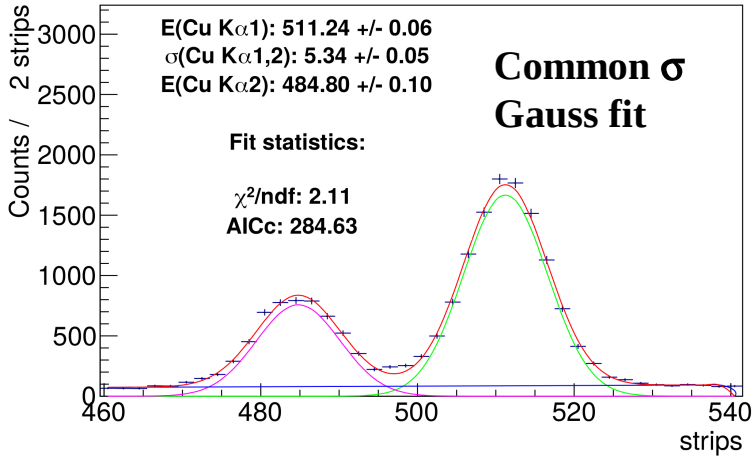
Data analysis: peak fitting function study





$$V(X) = \frac{A}{2\pi} \frac{\Gamma}{(x - x_0)^2 + \frac{\Gamma^2}{4}} \frac{e^{-\frac{(x-x_0)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}}$$





Akaike Information Criteria:

$$\mathrm{AIC} = 2p + N \ln\left(\frac{R}{N}\right)$$

N = num of fitted points

p = num of fit parameters

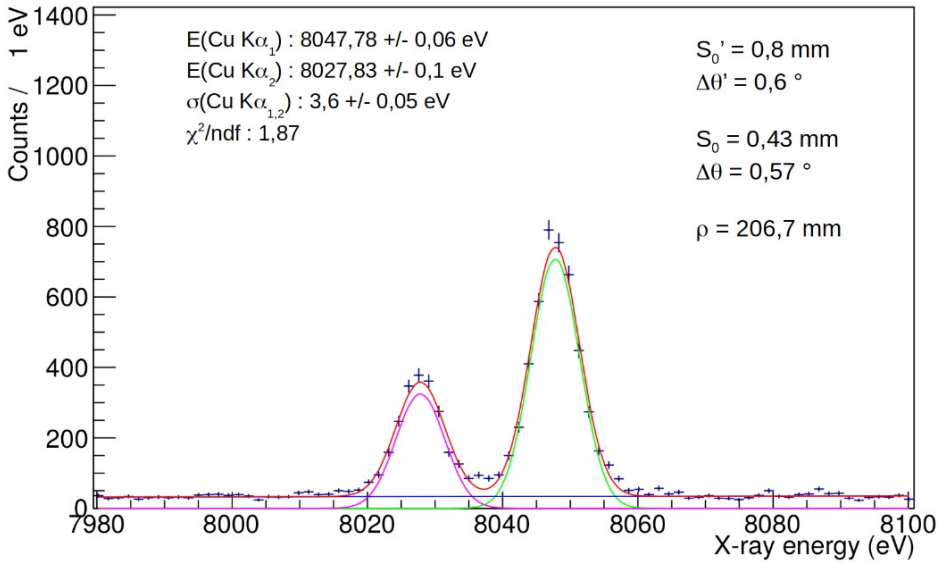
R= residuals $R = \sum_{i=1}^{I=N} (x_i - y_i)^2$

If N/p < 40:

$$\mathrm{AICc} = \mathrm{AIC} + \frac{2p(p+1)}{N - p - 1}$$

Gaussian fit chosen to describe the spectra since the small improvement in the χ^2 value of the voigtian with respect to the gaussian fit,is compensated by a small difference in the AICc values

Single element and multi-spectrum

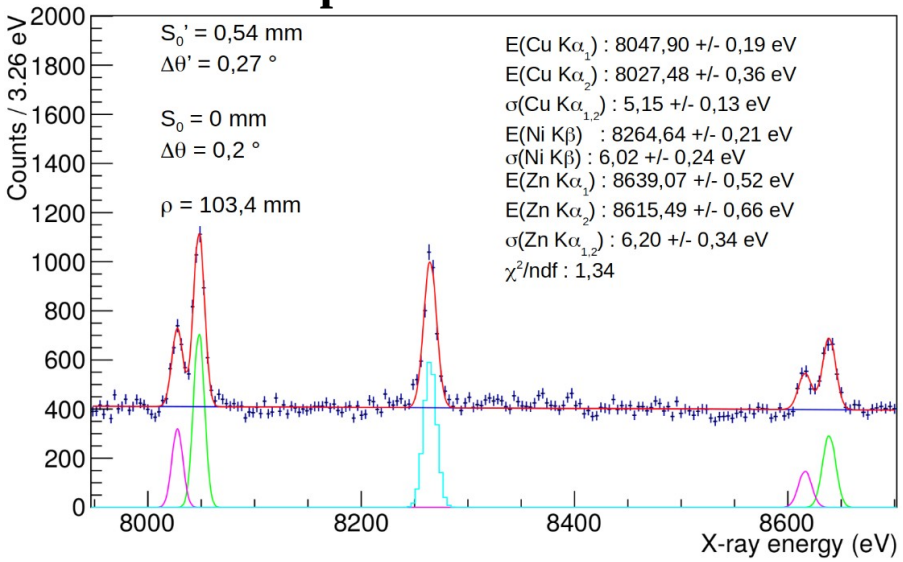


In the limit of a background free pure gaussian peak:

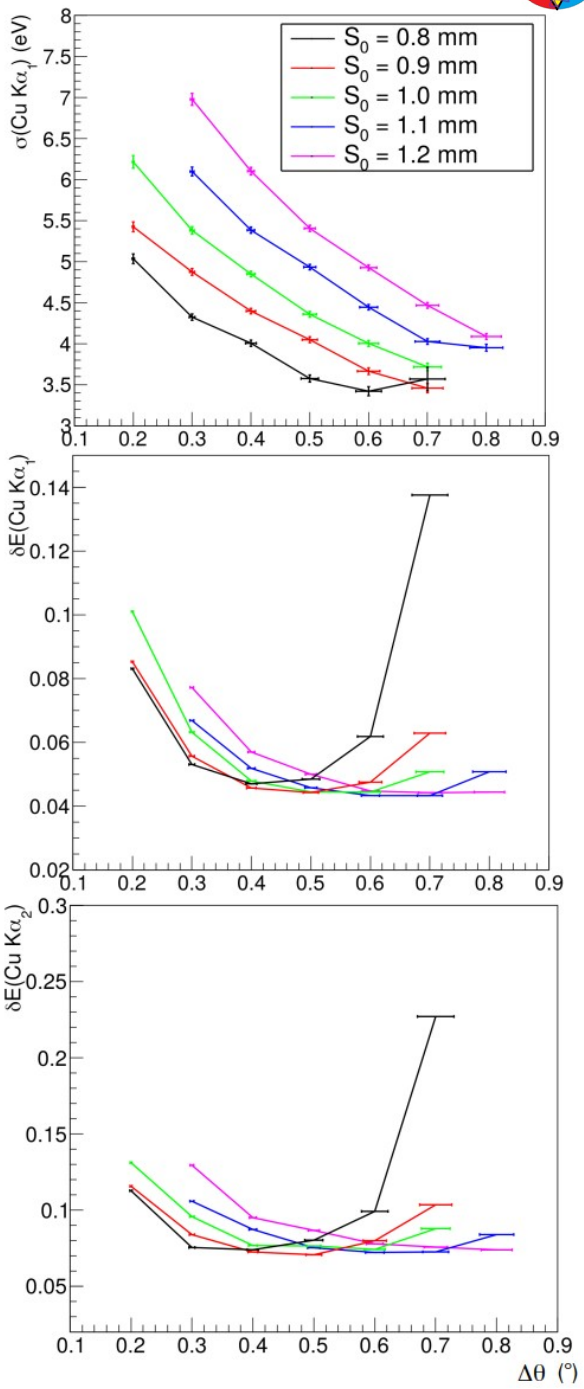
$$\delta E = \frac{\sigma E}{\sqrt{N}}$$

For a given crystal, we can find the best combination of S_0 and $\Delta\theta$ values which maximizes the peak precision

Multispectrum measurement

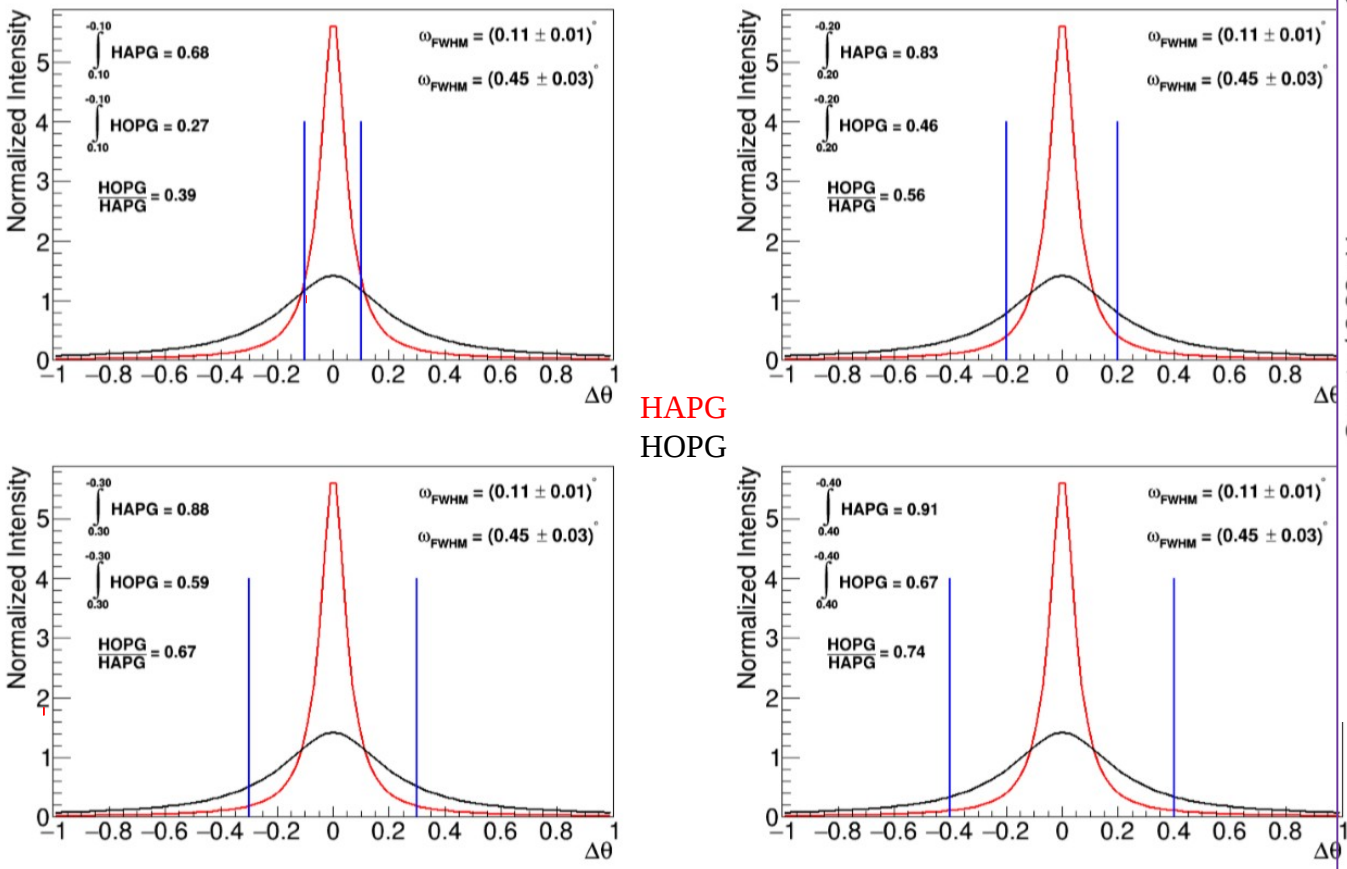


Study performed in the energy range 6-20 keV

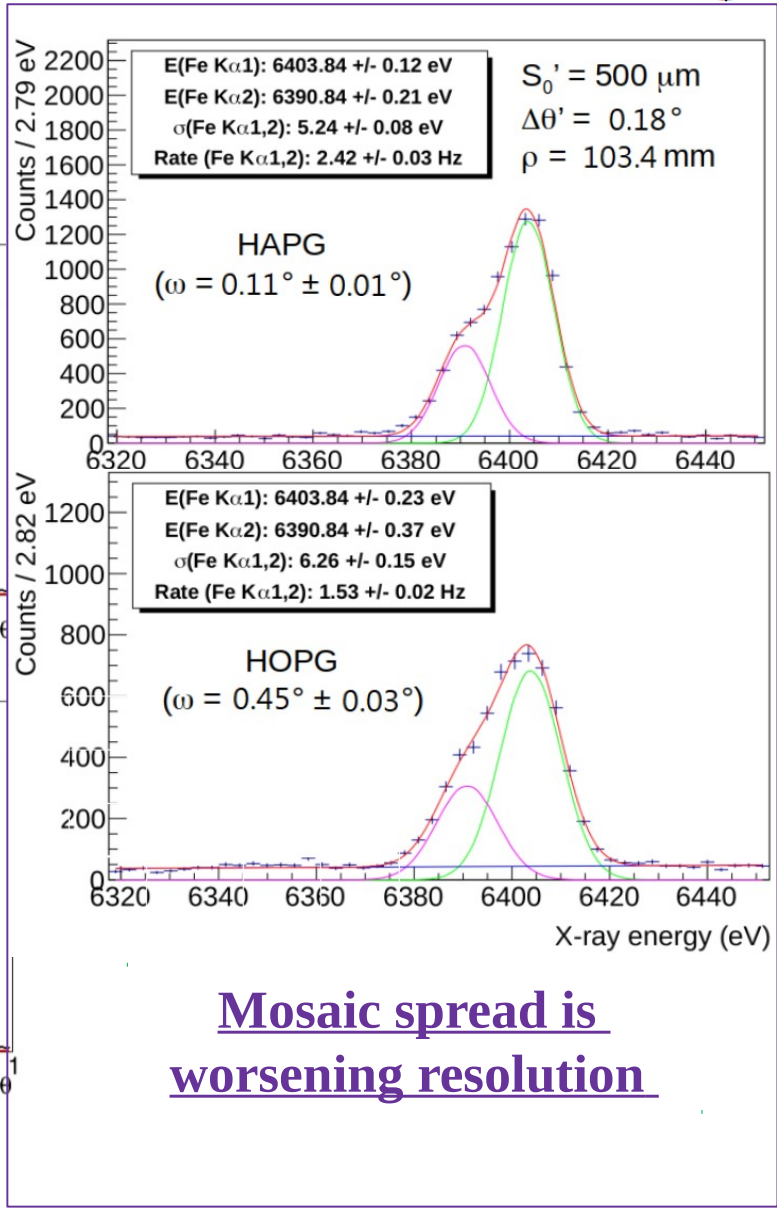


Crystal parameters: mosaic spread

Orientation distributions for the HAPG (red) and HOPG (black) crystals: the distributions are peaked around Δθ = 0, which represents the nominal Bragg angle



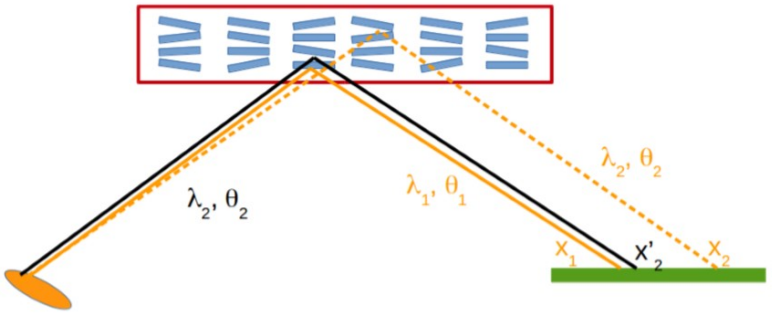
HAPG
HOPG



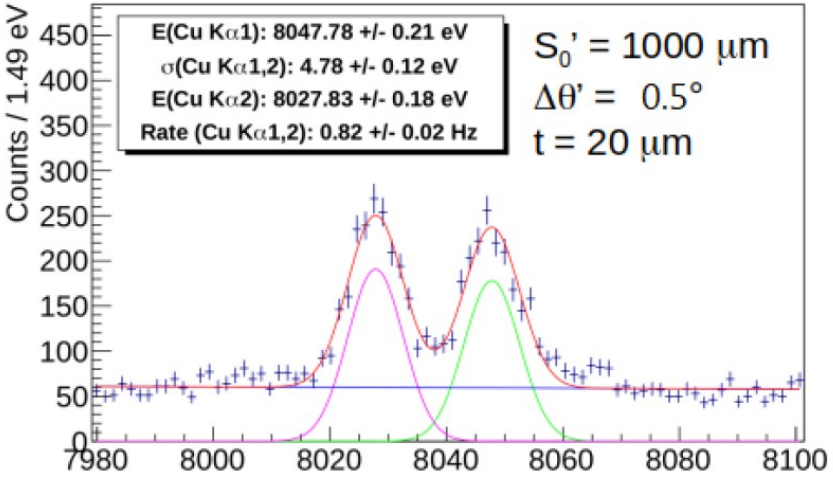
Mosaic spread is worsening resolution

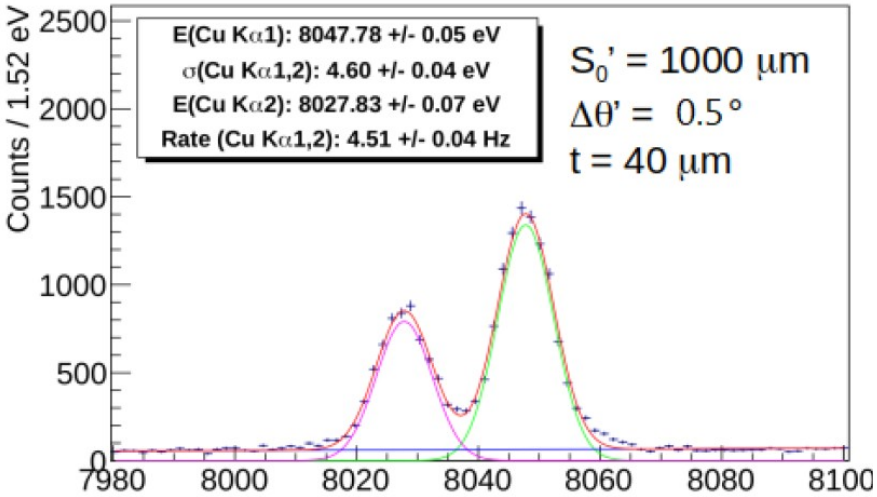
Higher number of reflected photons using the HAPG crystal with respect to using the HOPG one

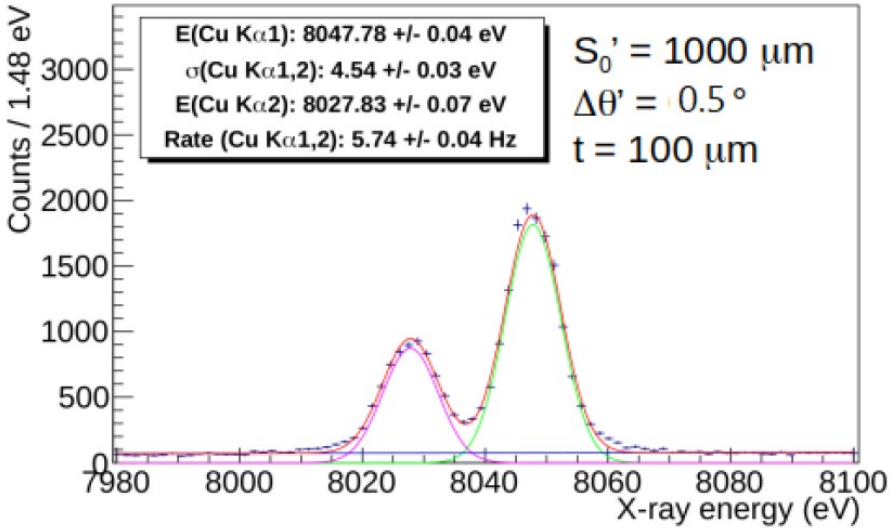
Crystal parameters: thickness



Photons emitted from different part of the source with the same λ_2, θ_2 can be reflected at different depths in the crystal by two distinct crystallites







The resolution worsening effect induced by the crystal thickness is not anymore predominant

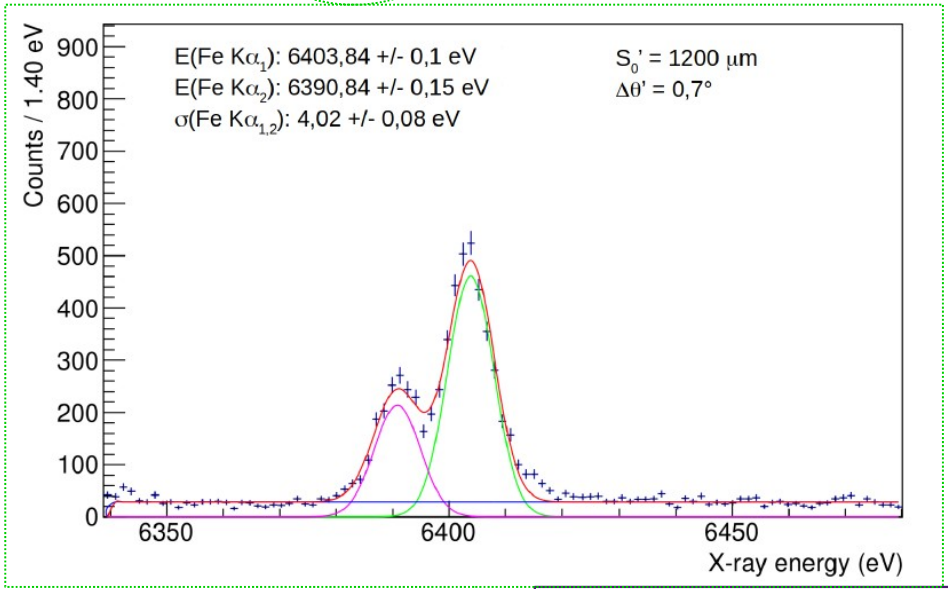
The resolution broadening induced by the source size is still the leading one

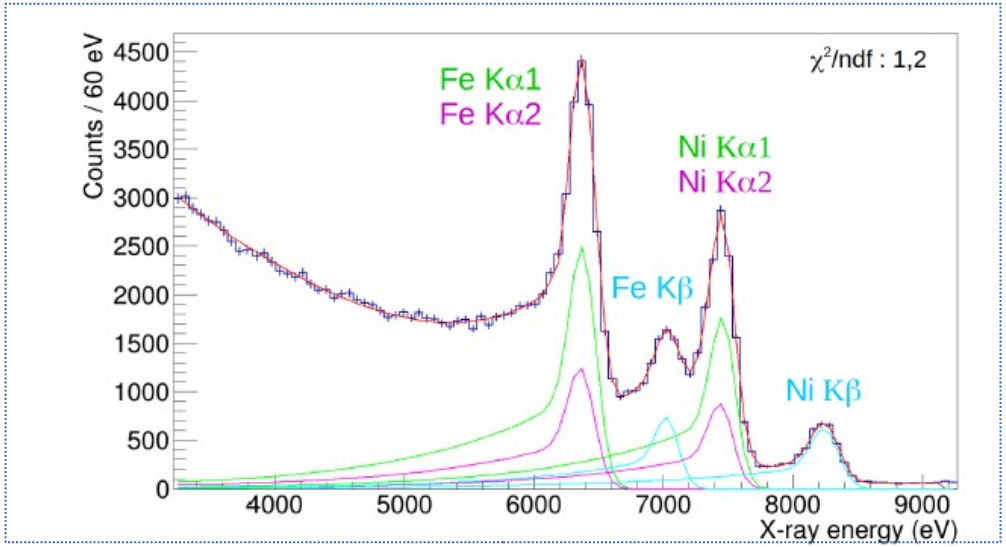
Reflection efficiency evaluation

$$\varepsilon^{R}_{\Delta\theta',S'_0} = \frac{R^{r}_{\Delta\theta',S'_0}}{R^{i}_{\Delta\theta',S'_0}}$$

$$R^{r}_{\Delta\theta',S'_0} = R^{B}_{\Delta\theta',S'_0}\frac{1}{T_{air}}\frac{1}{QE^{M}}$$

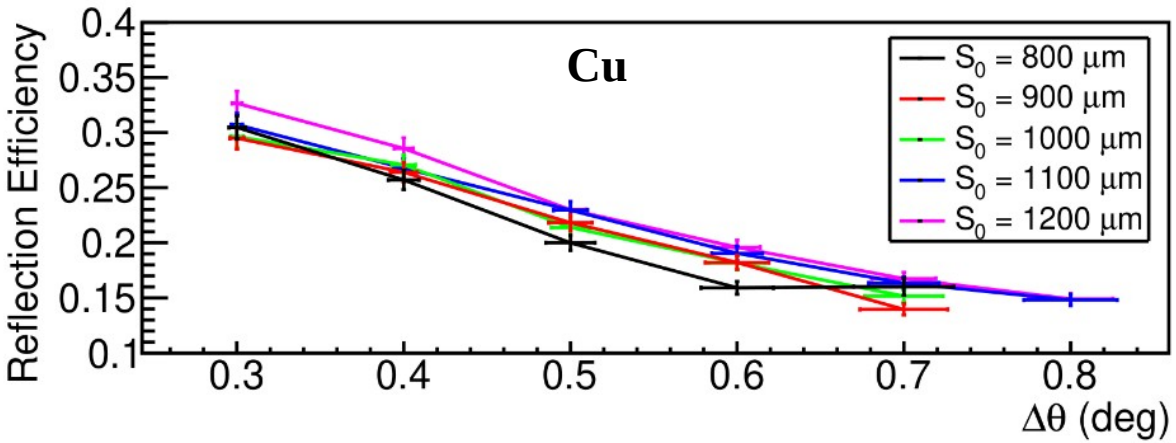
$$R^{i}_{\Delta\theta',S'_0} = R^{M}_{\Delta\theta',S'_0}\frac{1}{QE^{M}}R(S/B)\frac{A_c}{8\,mm}$$

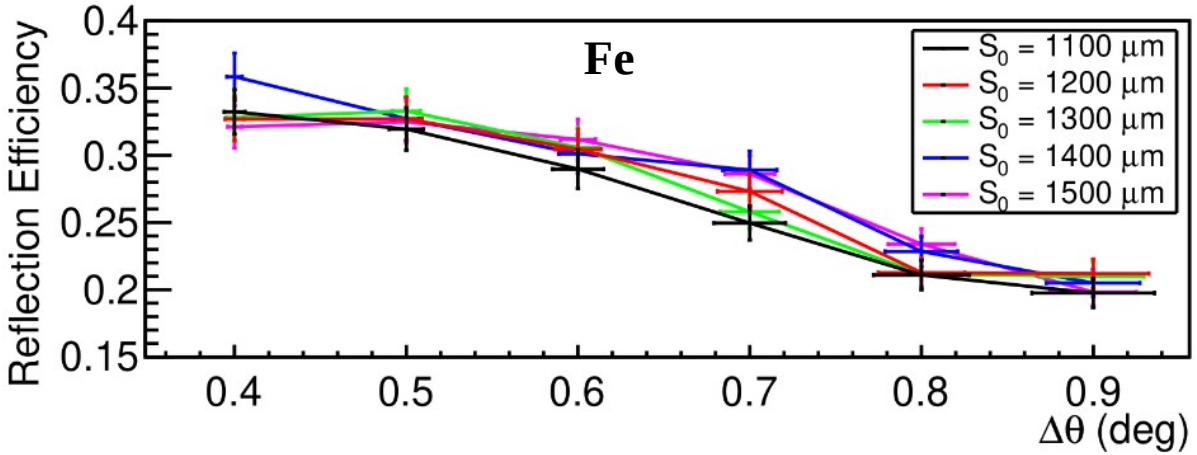




$$\varepsilon^{R}_{\Delta\theta',S'_0} = \frac{8R^{B}_{\Delta\theta',S'_0}}{T_{air}R^{M}_{\Delta\theta',S'_0}R(S/B)A_c}$$

Reflection Efficiency evaluation: exp results



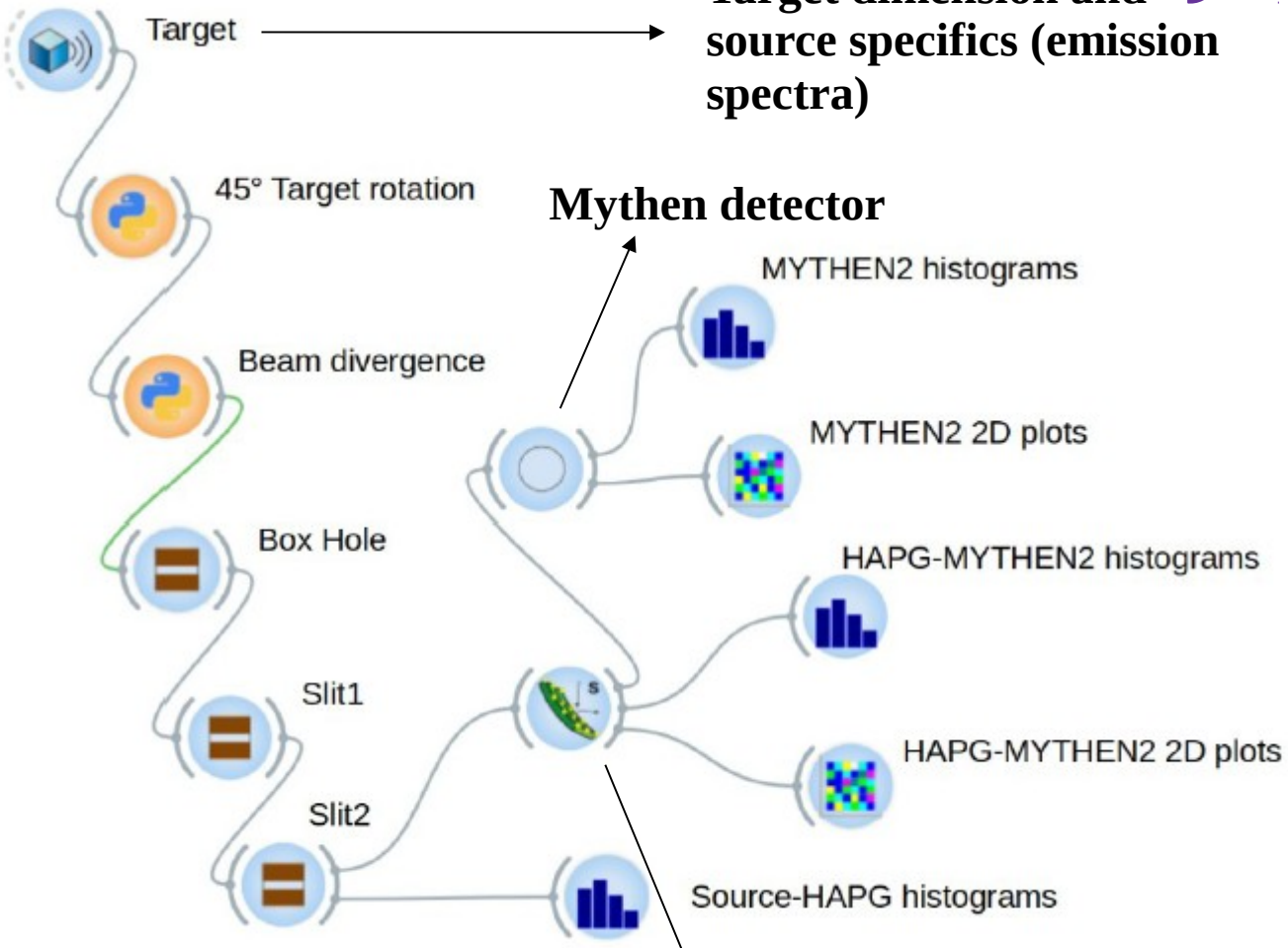


$$\varepsilon^{R}_{\Delta\theta',S_0'} = \frac{8R^{B}_{\Delta\theta',S_0'}}{T_{air}R^{M}_{\Delta\theta',S_0'}R(S/B)A_c}$$

Ray Tracing simulation

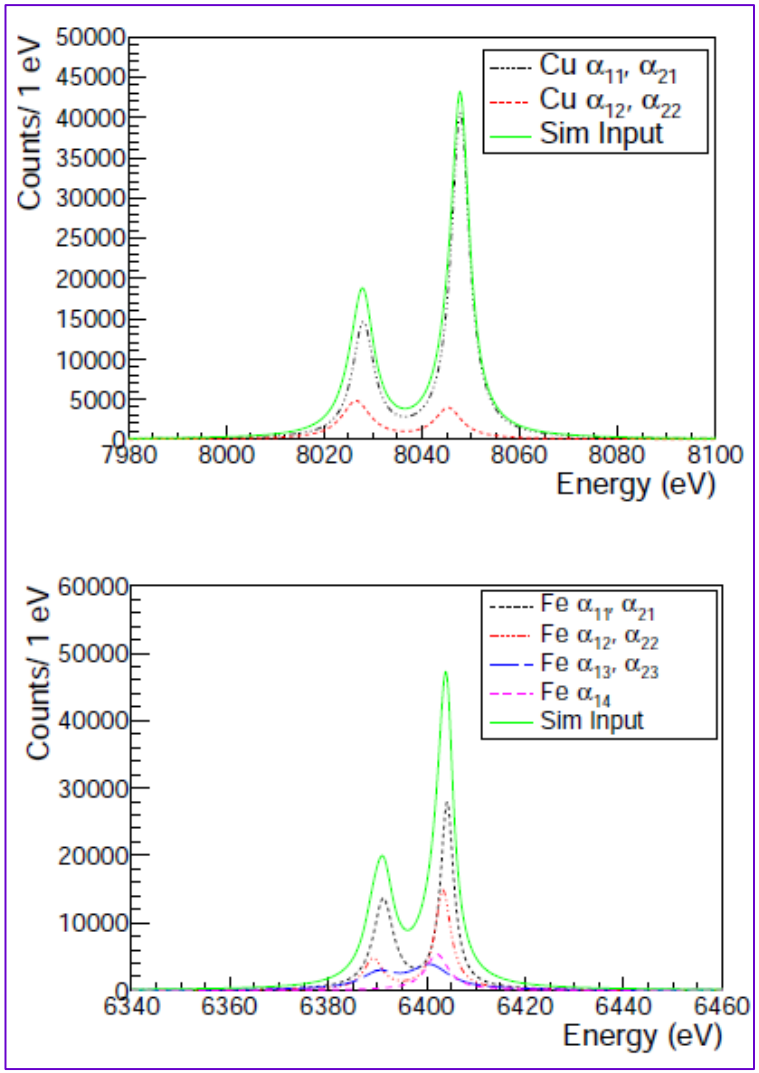
22 G. Hölzer *et al.*, *Phys. Rev. A*, 1997, **56**, 4554–4568.

SHADOW3 + XOPPY (Oasys framework)



Target dimension and source specifics (emission spectra)

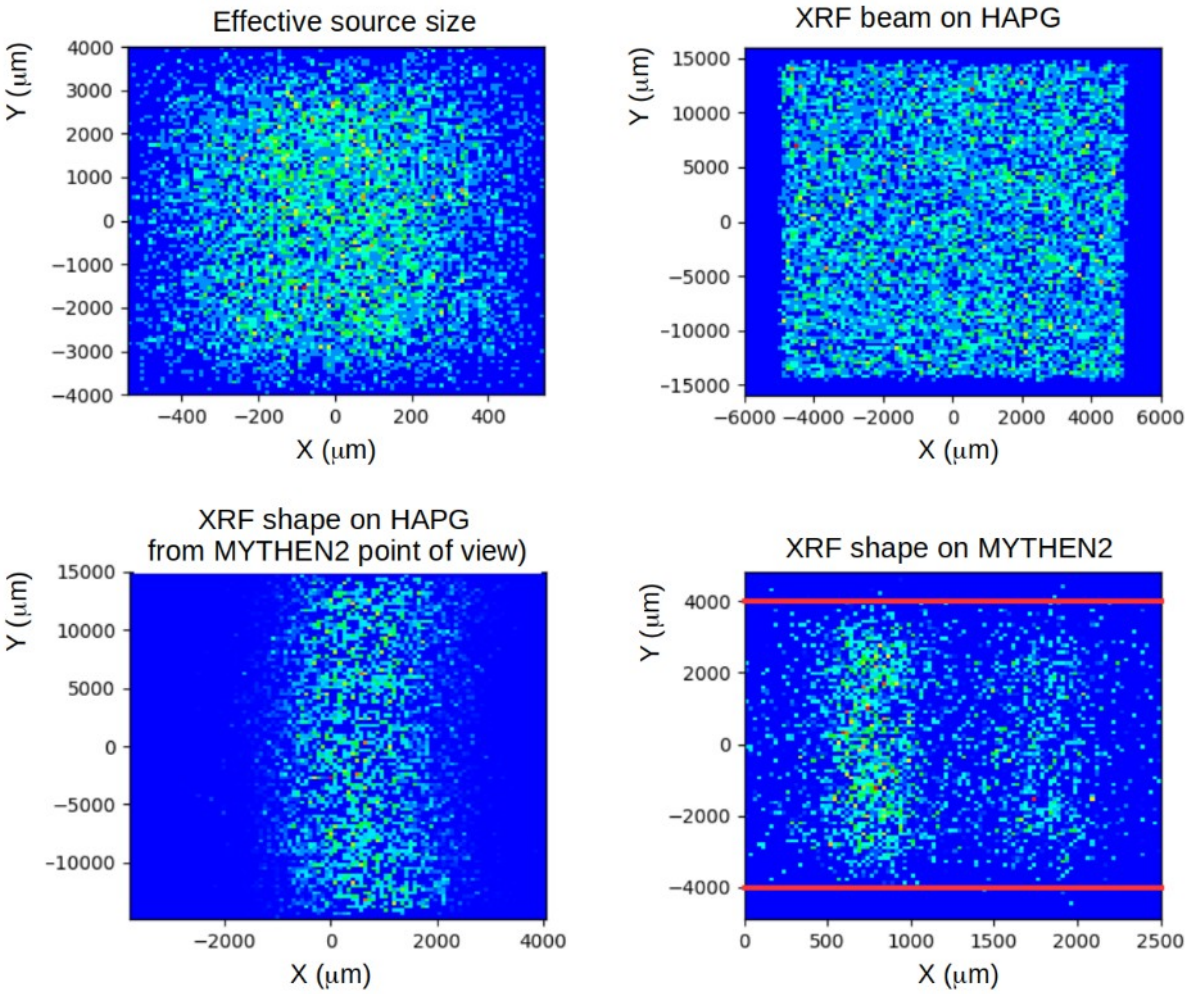
Crystal characteristics: thickness, mosaicity, θ_B ..

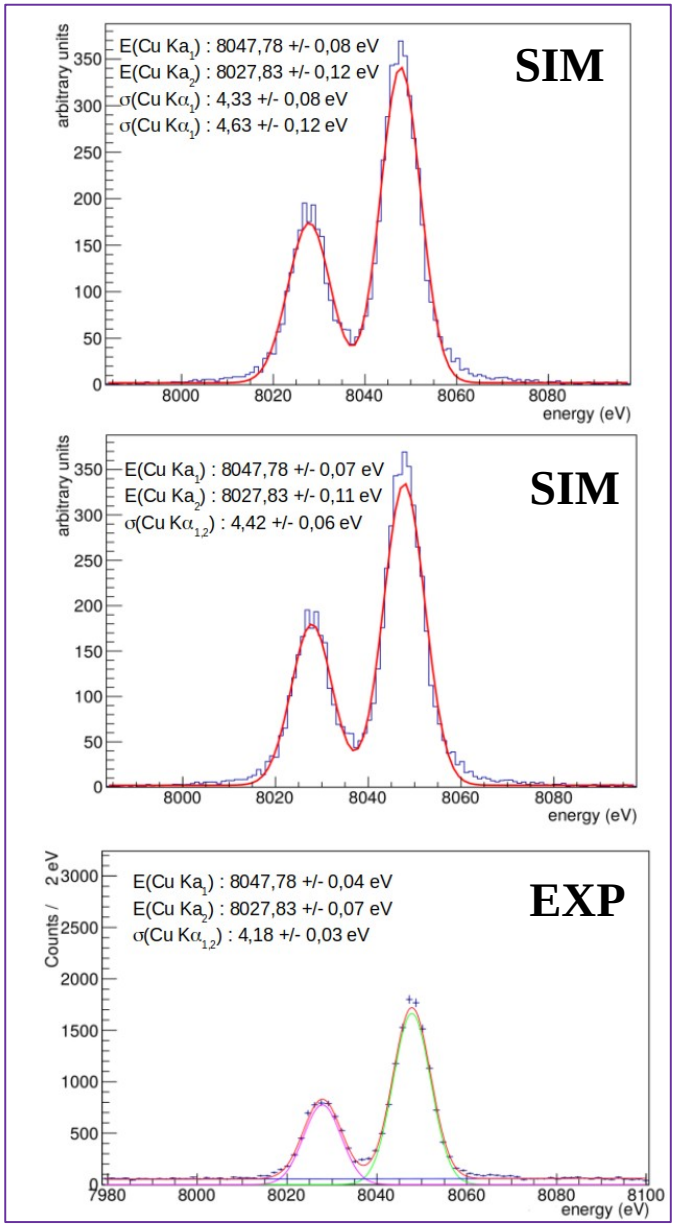


Ray Tracing simulation

- **Check on the XRF beam dimensions obtained with ray tracing simulations**

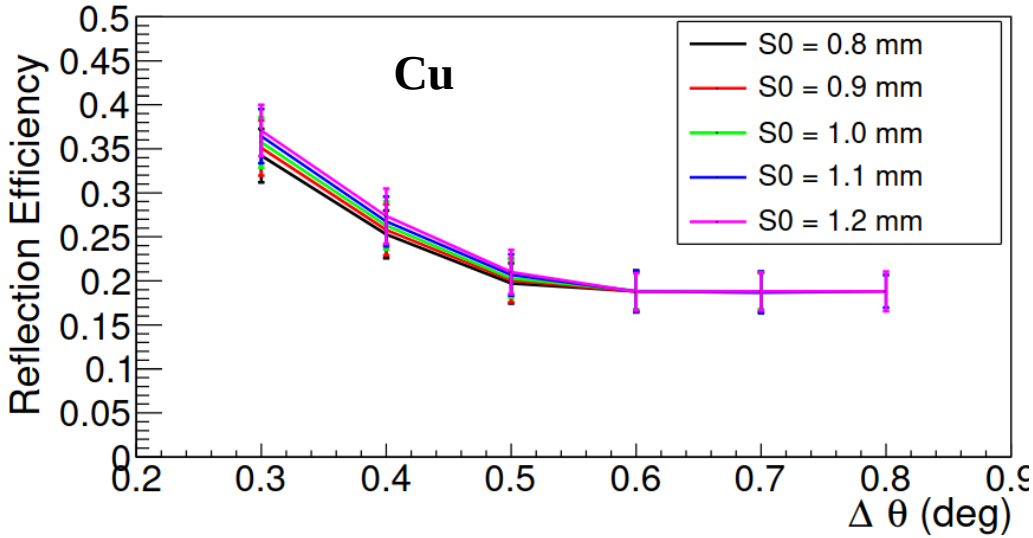
Physical source size 2.5x2.5 cm

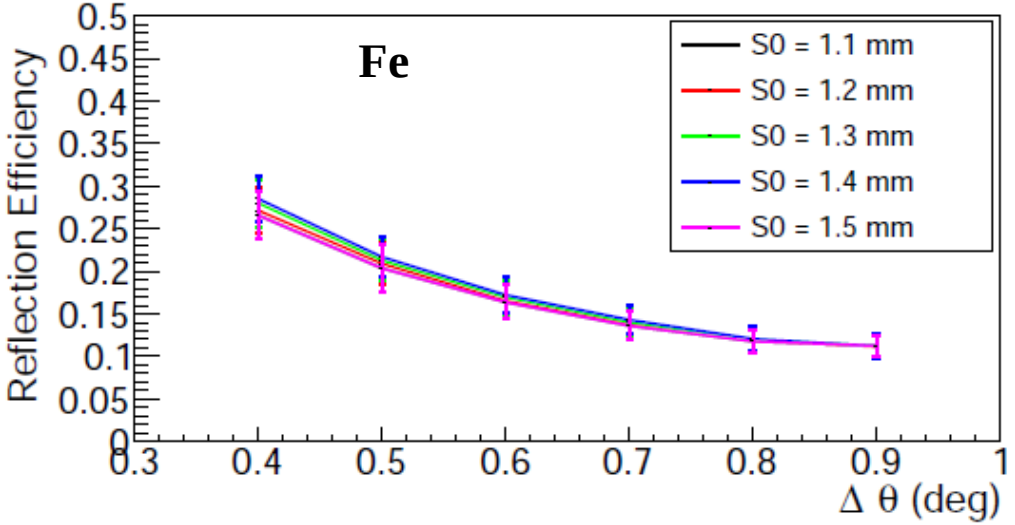


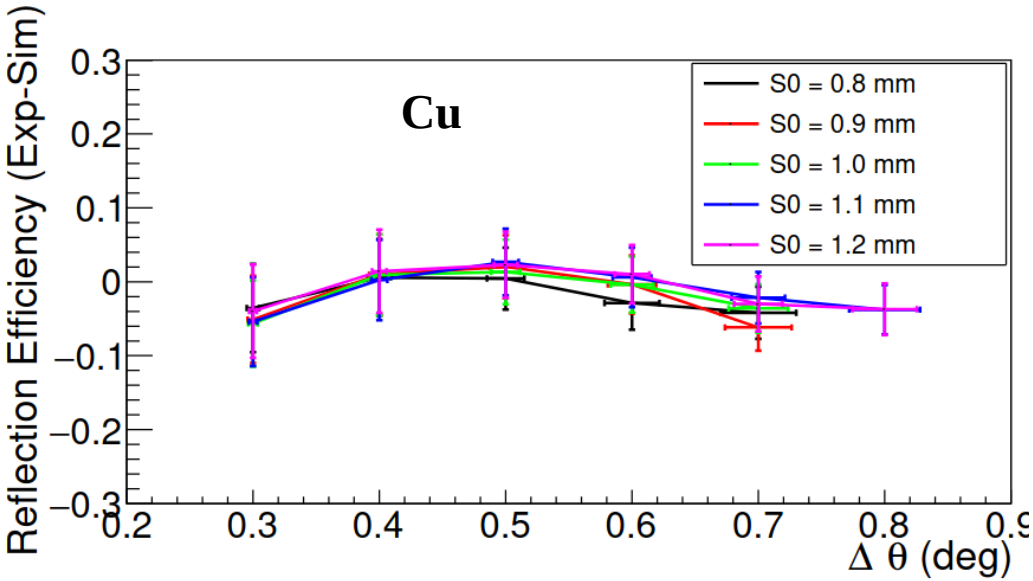


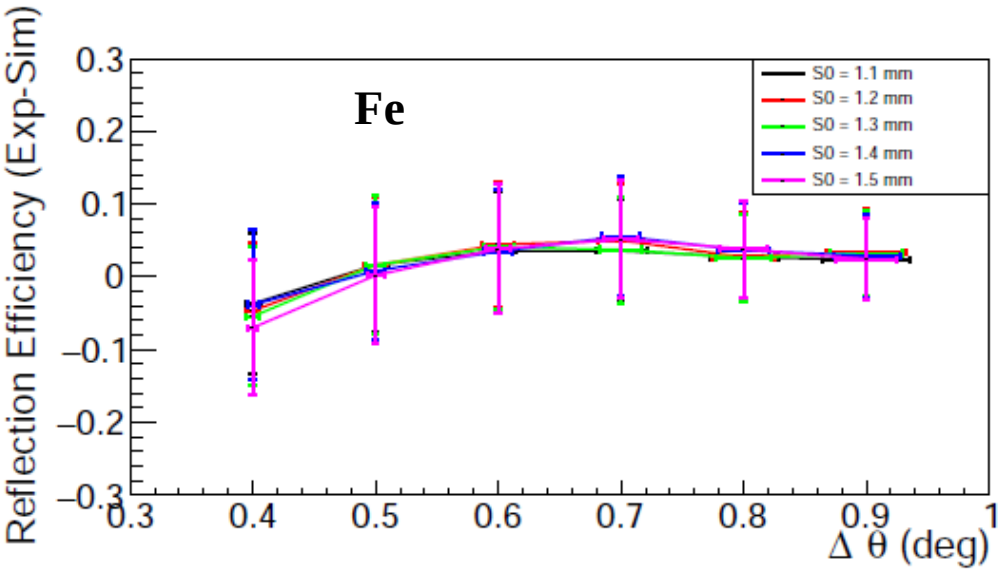
<u>Peak position and σ well reproduced</u>

Reflection efficiency: exp & sim data comparison









Good description of the simulated reflection efficiency wrt the experimental one

Conclusions & Future perspectives

- **The performance of the VOXES Von Hamos spectrometer based on mosaic crystals of pyrolytic graphite (HAPG) has been analyzed. Reported results demonstrated its capability to obtain precisions and resolutions below 1 eV and 10 eV, respectively, when used with extended and diffused isotropic sources (mm/cm).**

- **The response of this spectrometer has been compared also with the MC ray tracing simulations showing consistent results between experimental and simulated data.**

- **This scenario opens to a promising via for future applications like the measurement of the isotopic shift or the kaon mass precise determination by means of the simultaneous measurements of $K^{3,4}He(7,6,5,4,3 \rightarrow 2)$ and $KN(12,11,10,9,8,7,6 \rightarrow 7,6,5)$ transitions respectively**

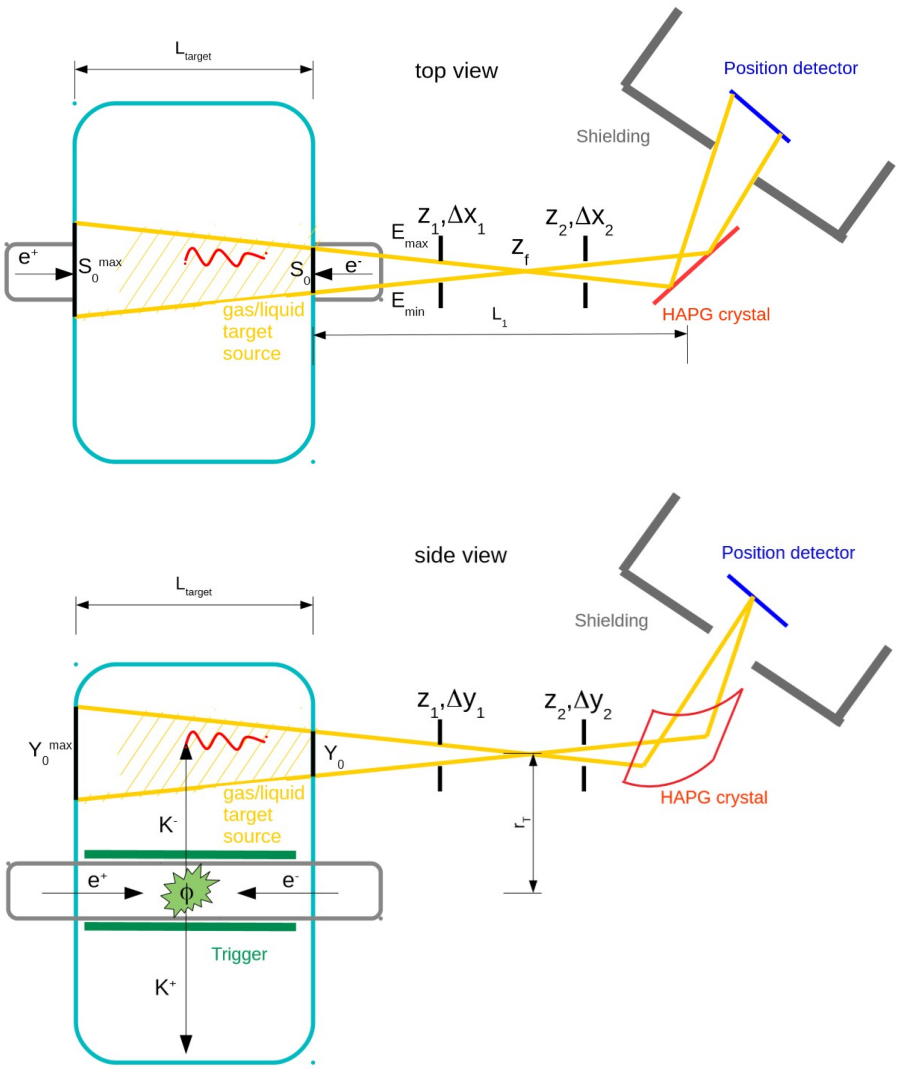
(*"Fundamental physics at the strangeness frontier at DAΦNE. Outline of a proposal for future measurements"*, arXiv:2104.06076v2 [nucl-ex]**).**

VOXES spectrometer has been included in that proposal for future experiments to be carried on at DAΦNE after SIDDHARTA-2.

THANK YOU!!!

SPARE

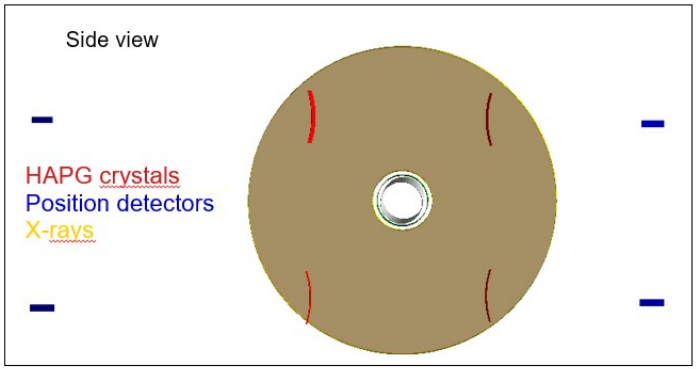
VOXES: future plans at DAΦNE

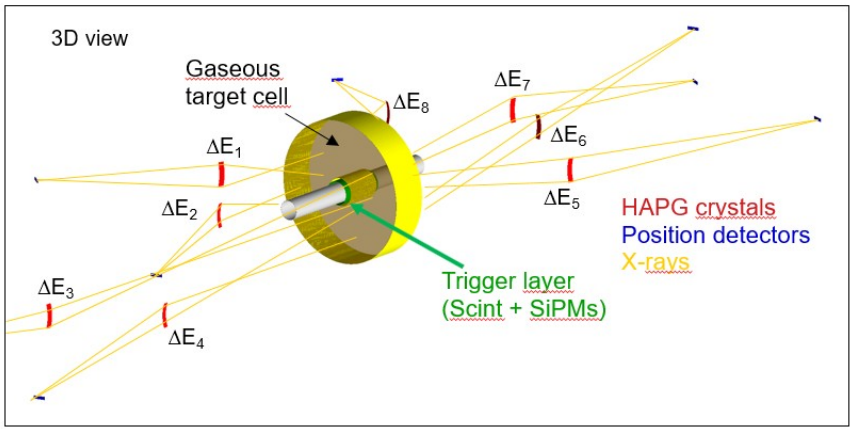


Example:

30 cm cylindrical target around the beampipe with inner trigger (5cm and 40 cm inner and outern radii)

50 cm² HAPG crystals and 10 cm2 Position Detectors (total)



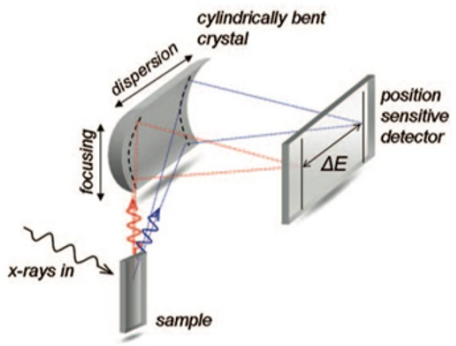


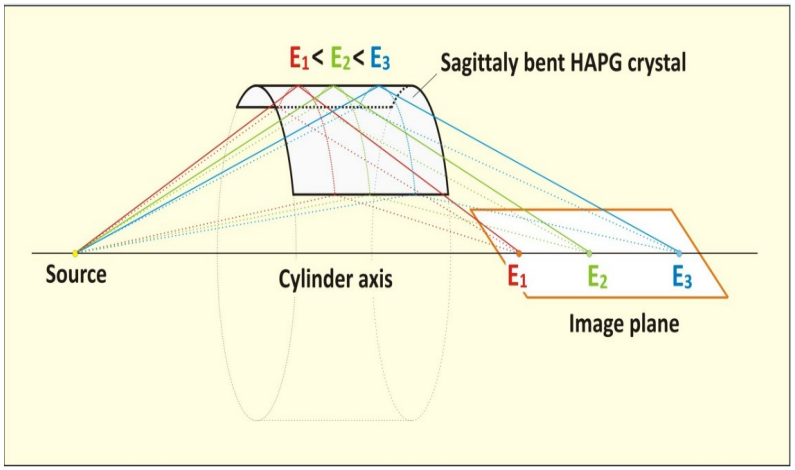
Completely new experiment / setup consisting of 8 spectrometer arms devoted to a specific energy range each

Real opportunity to apply for external fundings

Possibility to attract new interested institutes

Von Hamos configuration: improving solid angle

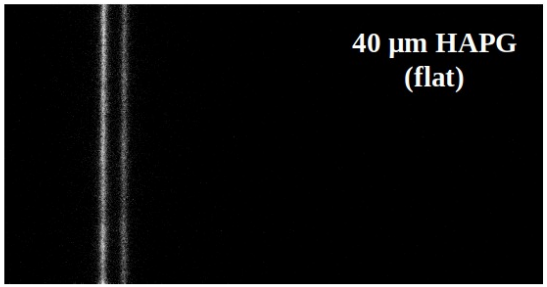


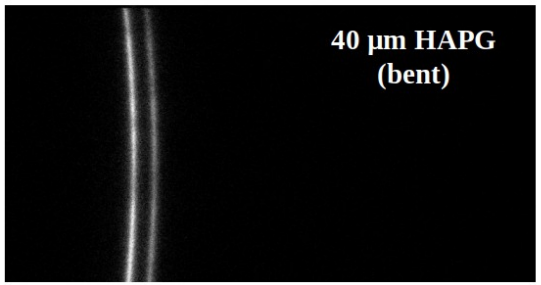


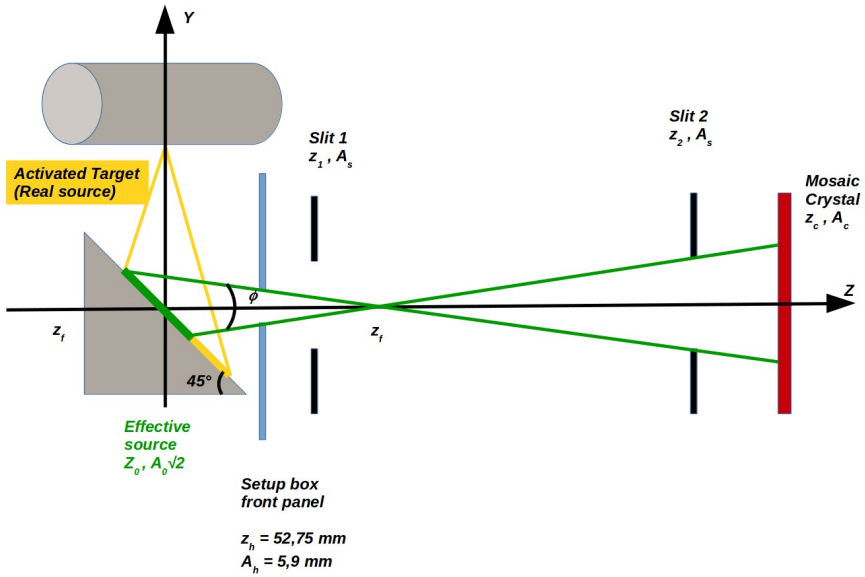
VH configuration can further improve the signal collection efficiency.

In this configuration, also the vertical dimension of the X-ray source can be exploited

distance: F = 400 mm in (004)-reflexion @ 8 keV (Cu K_a)



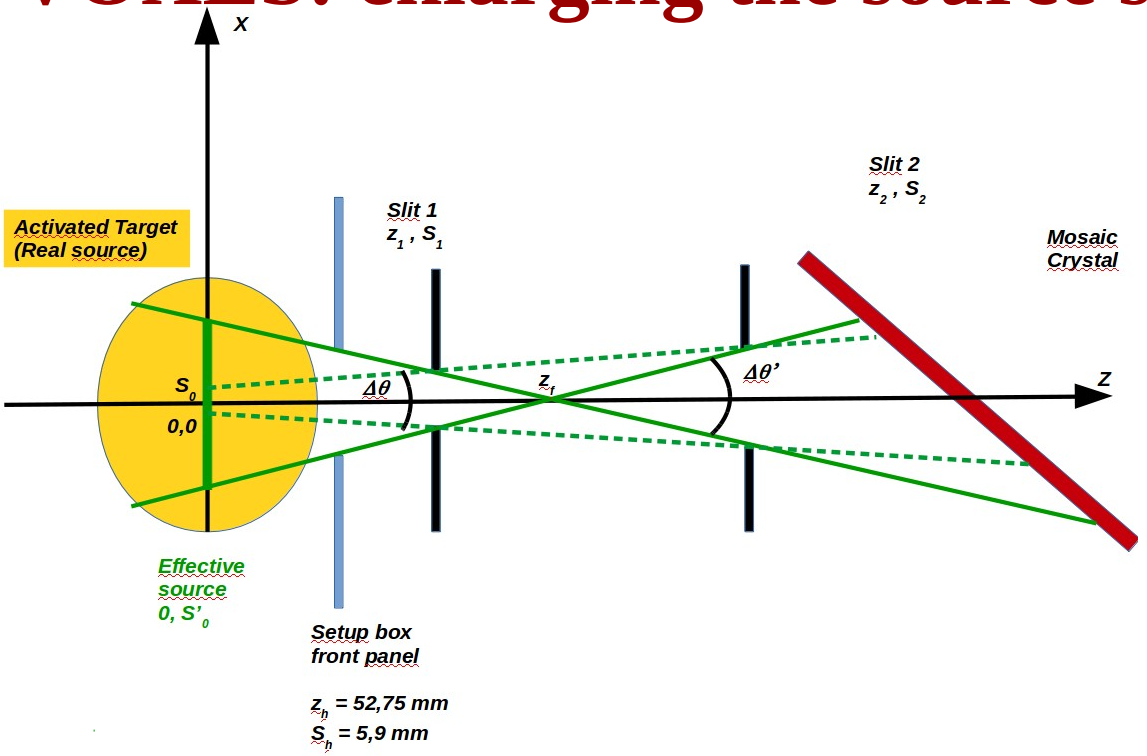


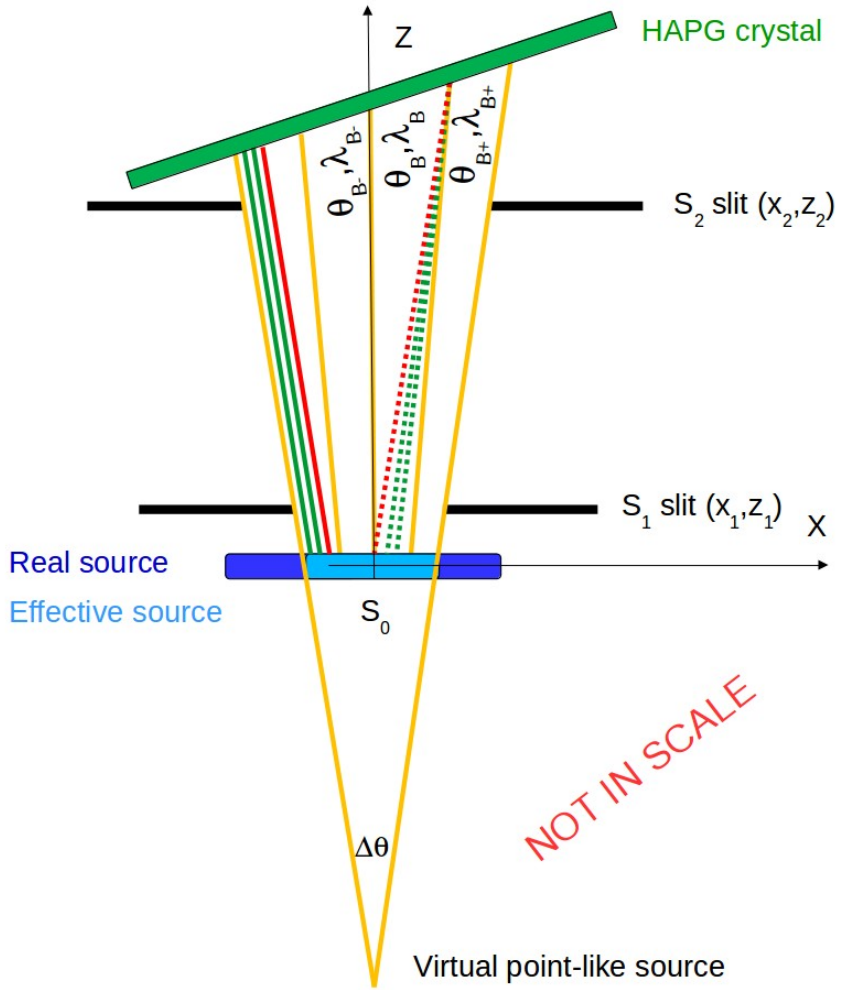


Spectral resolution of bent HAPG/HOPG crystal is comparable to the flat one !

H. Legall, H. Stiel, I. Grigorieva, A. Antonov et al., FEL Proc. 2006

VOXES: enlarging the source size



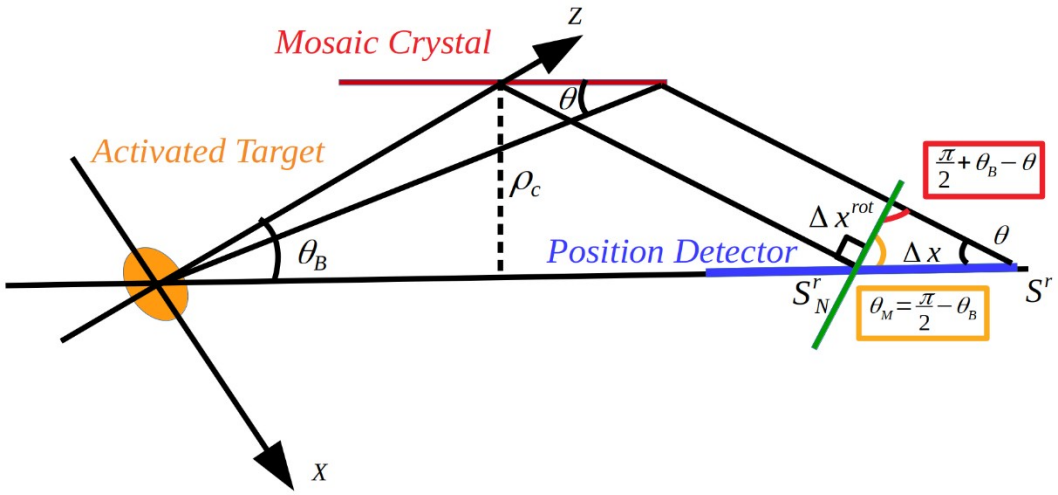


The shape of the "signal" beam can be optimized to increase the effective source size

On the other hand, this may lead to a worsening of the resolution

How big can a source be keeping FWHM < 10 eV?

VOXES: energy calibration



Standard VH calibration: $\Delta x = 2\rho_c \cdot (cotg\theta_B - cotg\theta)$

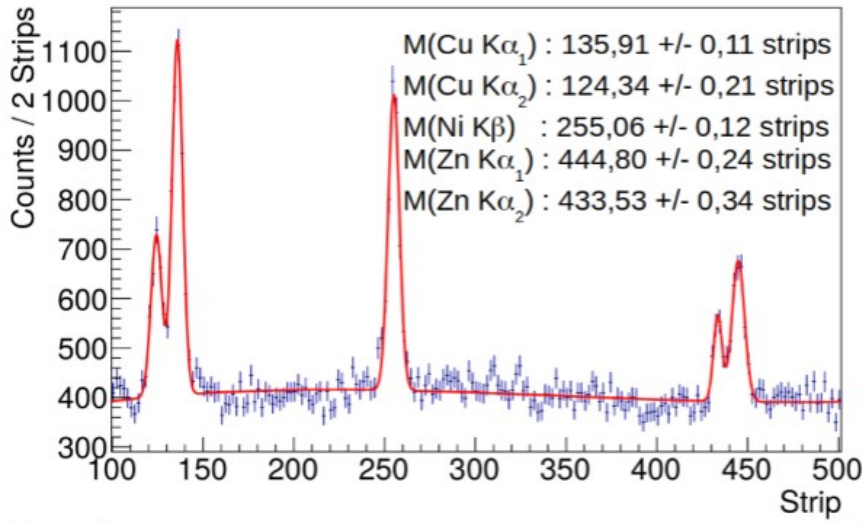
Semi VH calibration: $\Delta x^{rot} = \dfrac{2\rho_c \cdot (cotg\theta_B - cotg\theta) \cdot sin\theta}{sin(\frac{\pi}{2} - \theta_M - \theta)}$

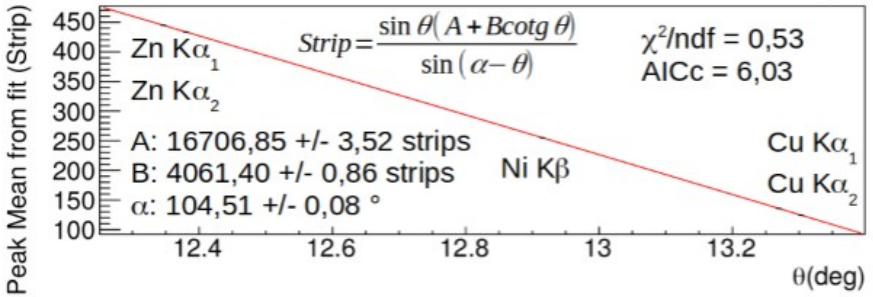
Parametric form: $\Delta x^{rot} = \dfrac{(A + B \cdot cotg\theta) \cdot sin\theta}{sin(\alpha - \theta)}$

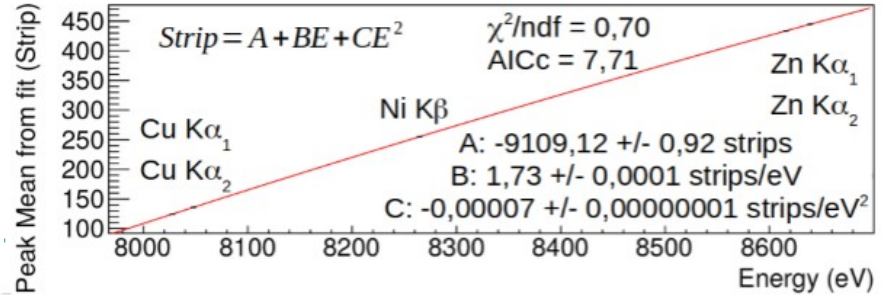
Given the small θ values (sinθ ≈ θ),
is it also possible to calibrate with a polynomial?

Information loss???

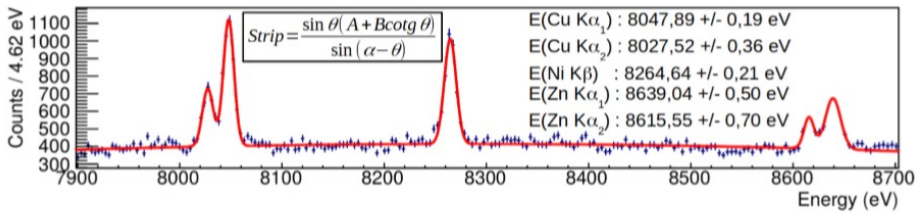
$S'_0 = 540\,\mu m$ and $\Delta\theta' = 0,27°$

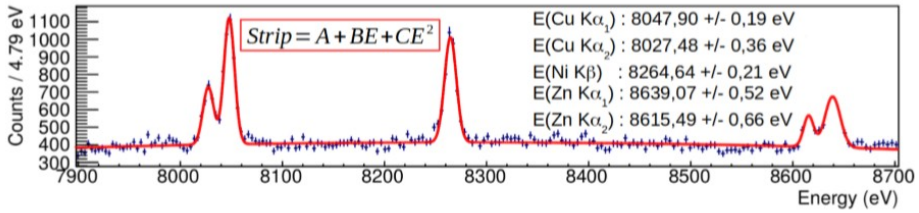


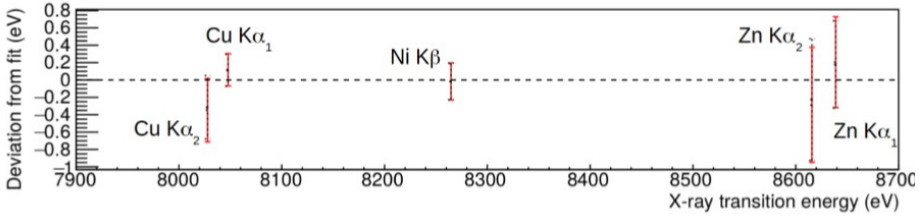




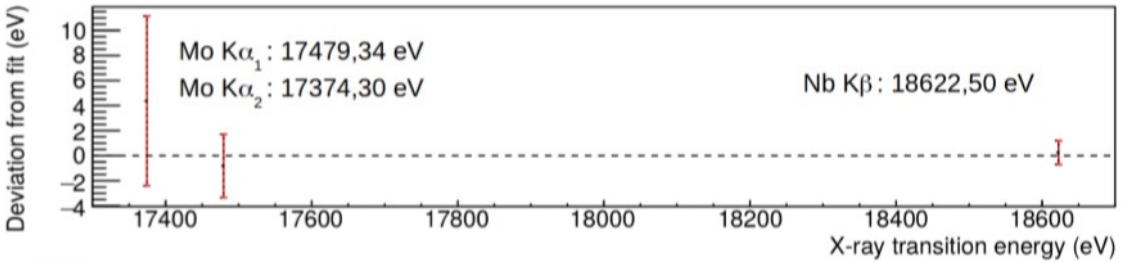
VOXES: energy calibration

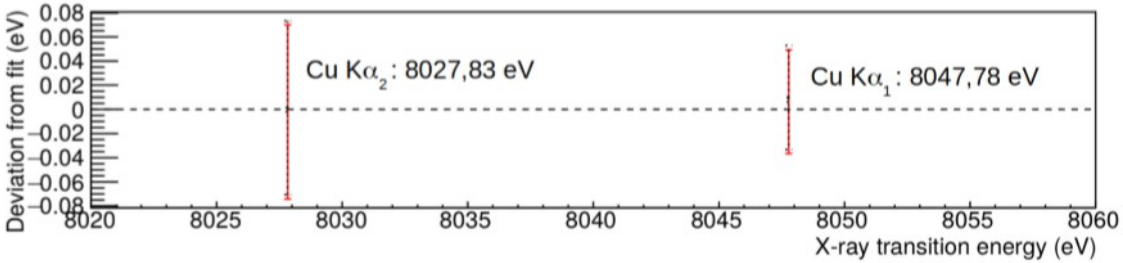


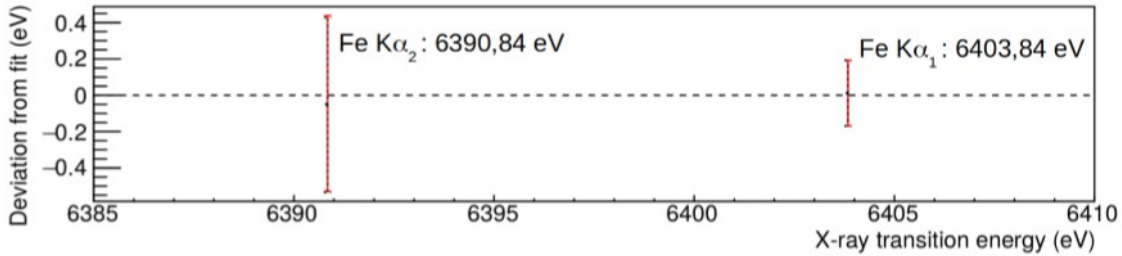




The (small) information loss is not influencing the peak positions







Also valid for higher and wider energy ranges (and higher θ, Δθ values)