HAPG mosaic crystal Von Hamos spectrometer for high precision exotic atoms spectroscopy

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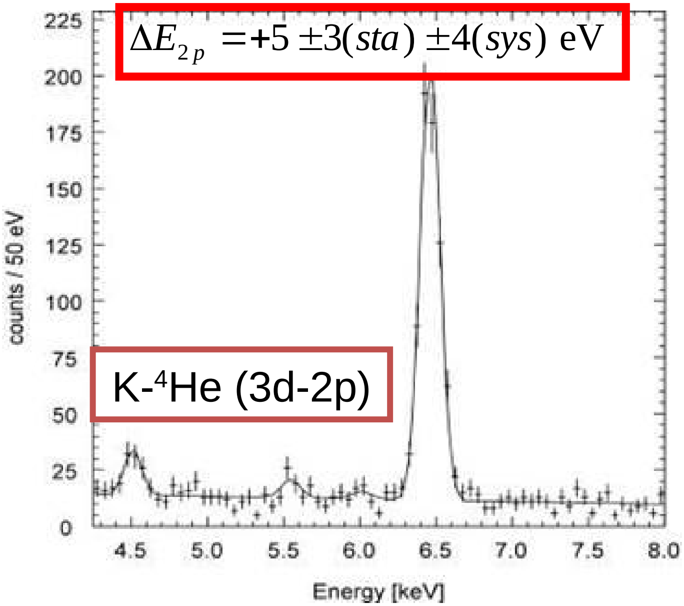
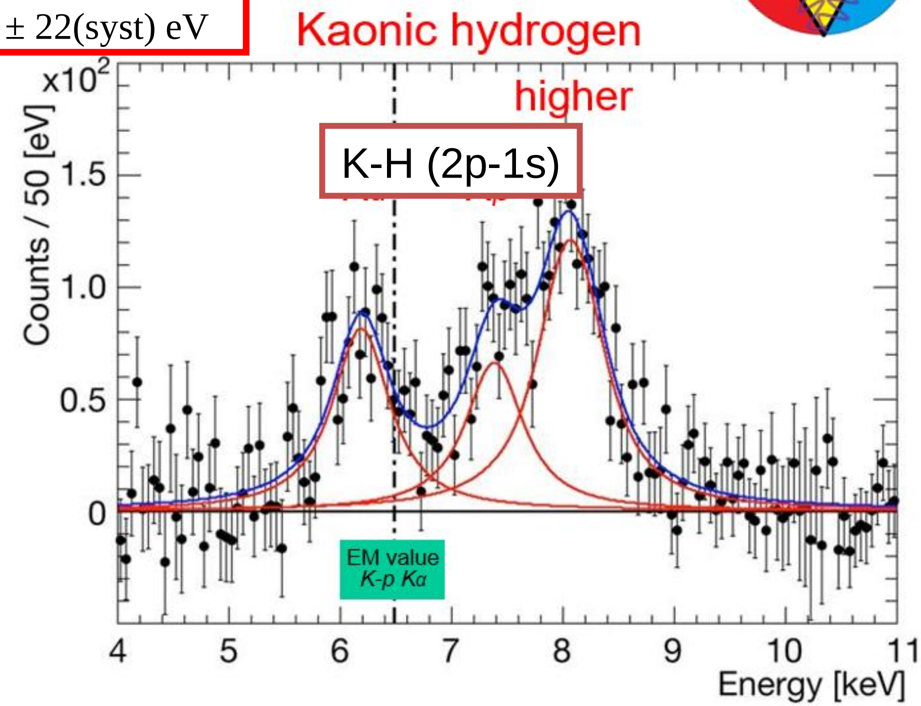
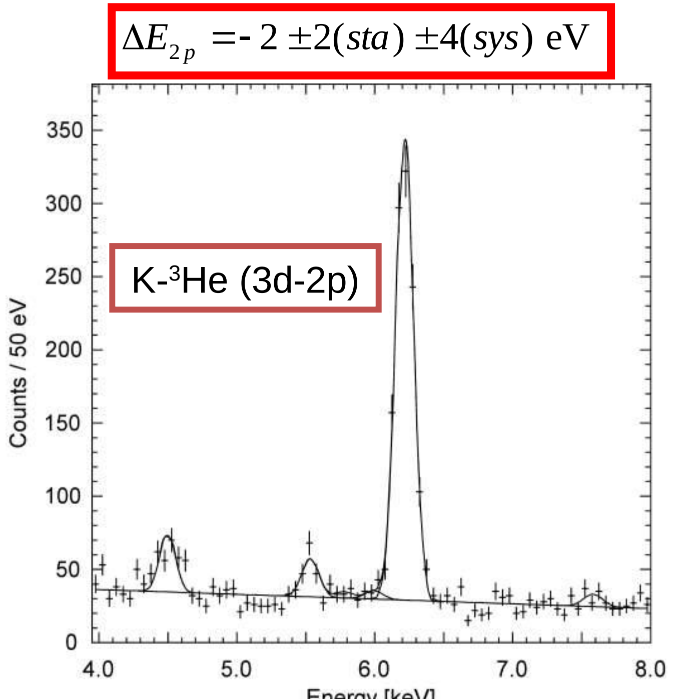
“Fundamental physics with exotic atoms and radiation detectors – LNF – 25-26/09/2021”

Latest results on kaonic atoms @ DAΦNE

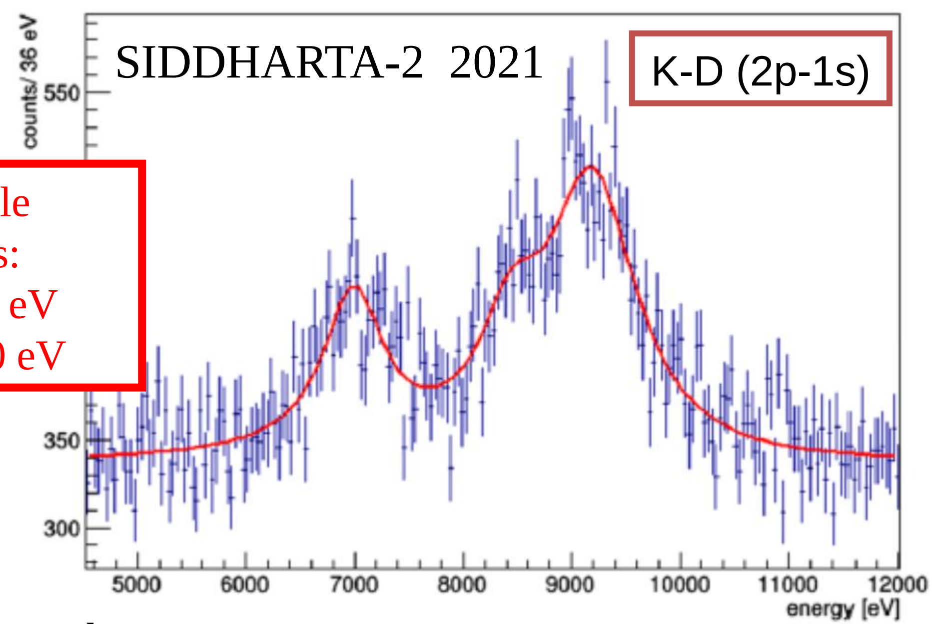
$\varepsilon_{1s} = -283 \pm 36(stat) \pm 6(syst)$ eV
$\Gamma_{1s} = 541 \pm 89(stat) \pm 22(syst)$ eV







Achievable precisions:
$\Delta\varepsilon(1s) = 30$ eV
$\Delta\Gamma(1s) = 70$ eV



"Fundamental physics with exotic atoms and radiation detectors – LNF – 25-26/09/2021"

Needs for higher precisions

FWHM obtained in these measurements are already at the Fano limit for solid state detectors

Precisions of 1 ~ 50 eV, depending on the statistics, can be reached with this FWHM

These values of FHWM and σE are not enough for many other measurements:

Example: KHe widhts measured by SIDDHARTA

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

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

Example: Upper level measurements with very small Γ

An advantage of "upper levels"*

SŁAWOMIR WYCECH

In analogy to antiprotons the scenario under the $\overline{K}N$ threshold is determined by a resonant state $\Lambda(1405)$ with a pole close to E_{cm} 1410 MeV that is in the ^{3}He region. On the other side one has $\Sigma(1385)$ state which exerts maximum repulsive effect in the ^{4}He region. Apparently these two main agents yield attractive shift in ^{3}He and repulsive in ^{4}He. Now, in order to go above the errors one has to magnify the shifts and enhance the atomic-nuclear overlaps. The proper targets would be ^{8}Be and ^{6,7}Li. These offer similar values of E_{cm} as ^{4}He and ^{3}He . A simple re-scaling of overlaps generates the level shifts of about 100 eV. One should perhaps consider also studies of $3D$ levels in these atoms. One interesting outcome might be the estimate where the isospin 0 Re $T(\overline{K}N \to \overline{K}N)$ amplitude crosses zero. That will help to settle the controversy as to where is the $\Lambda(1405)$ pole in the complex plane located.

Example: Kaon mass measurement

Charged Kaon Mass

Claude Amsler[1] and Simon Eidelman[2,3,4]

[1]Stefan Meyer Institute, Vienna, Austria
[2]Budker Institute of Nuclear Physics, Novosibirsk, Russia
[3]Novosibirsk State University, Novosibirsk, Russia
[4]Lebedev Physical Institute, Moscow, Russia

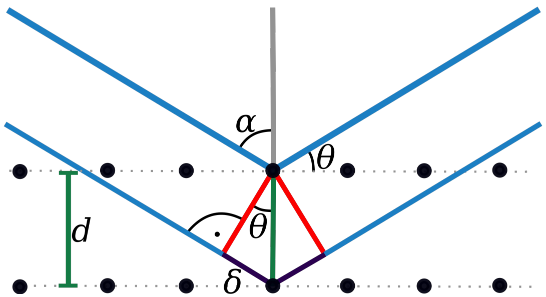
January 10, 2021

2003 [6]) was the first enigmatic state whose properties cannot be fully understood in the framework of the quark model. Despite very extensive efforts (the discovery paper with 1880 citations is one of the most cited experimental publications), there is no consensus today about its internal structure. The most popular explanation is that it is a mixture of a regular $q\bar{q}$ state and a $D^0\bar{D}^{*0}$ molecule. To test the validity of the molecular hypothesis it is of vital importance to know precisely how far the $\chi_{c1}(3872)$ state lies from the D^0D^{*0} threshold. Recently LHCb performed a study of $\chi_{c1}(3872)$ produced in decays of $B^{\pm}$ mesons and other b hadrons [7, 8]. Using the world-largest sample of almost 20k $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ decays, LHCb performed the most precise measurement of the $\chi_{c1}(3872)$ mass and of the energy difference $\delta E = m(D^0) + m(D^{*0}) - m(\chi_{c1}(3872)) = 0.07 \pm 0.12$ MeV. Again, the precision is limited by that of the charged kaon mass.

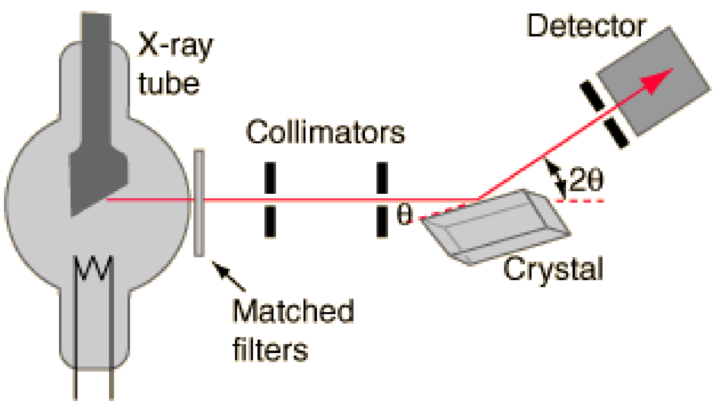
The precision on the D^0 mass also affects the mixing parameters in the D^0-$\bar{D}^0$ system [4], and in the long run, a more accurate kaon mass may become interesting for first-principle calculations on the lattice [9].

Example: Fine splitting of kaonic atoms levels for cascade processes

Bragg spectroscopy



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



FWHM ~ 1-10 eV can be achieved depending on the quality of the crystal and the dimensions of the detectors

Natural background reduction from geometry

But….

- Small solid angles can be covered
- Typical efficiencies : $10^{-5} – 10^{-8}$
- Typical d (Si) ≈ 5.5 Å (good for E < 6 keV)
- Typical source size 10-100 μm

The x-ray source, which was used for the measurements, is a low power microfocus x-ray tube (IfG) with a source diameter of about 50 μm. Measurements were performed with the Cu K_α emission of a Cu anode at 8 keV. The spec-

III. SPECTROMETER SETUP

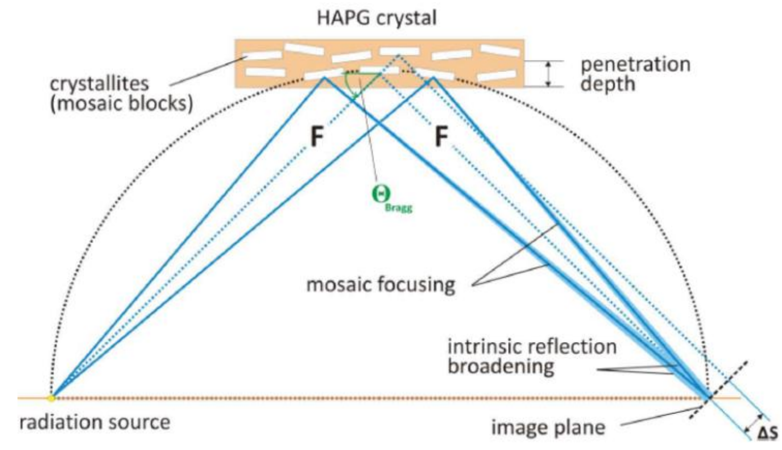
The spectrometer consists of three principal components: the X-ray source, the HAPG optic, and the position sensitive detector. As source a watercooled 100 W micro focus X-ray tube with a tungsten anode and a focus size of 50 μm is used. The emitted radiation is focused onto the sample by a poly-capillary full lense with a spot size of 35 μm. The HAPG

Laser-produced plasmas were created using the "Phoenix" Nd glass laser (the Lebedev Physical Institute) operated at a wavelength of 0.53 μm with pulse energy up to 10 J and 2 ns pulse duration. The laser beam was focused onto massive Mg, Al, Ti, or Fe targets (see Fig. 2). The focal spot diameter was about ~15 μm.

HAPG mosaic crystals: improving efficiency

Mosaic crystal 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

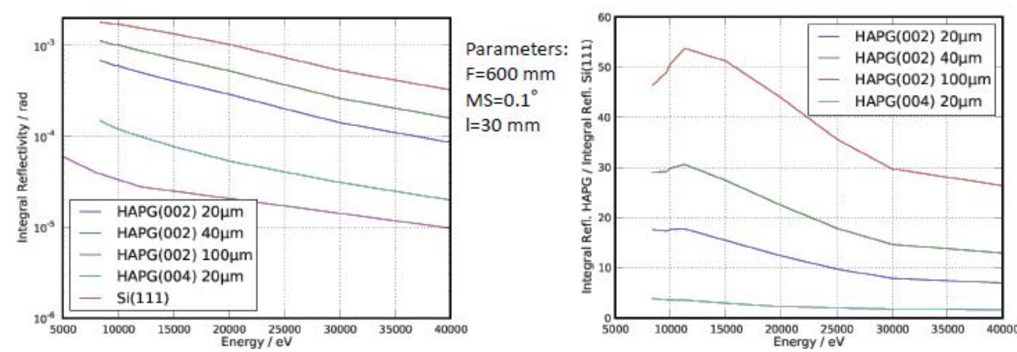


Increase of efficiency (focusing) ~ 50

Loss in resolution

Integral reflectivity

- Measured integral reflectivities (synchrotron measurements)



→ The integral reflectivity can be more than 50 times higher compared to Si(111) reflection.

→ The use of the von Hamos geometry can increase the overall efficiency even more.

Characterization of HAPG mosaic crystals using synchrotron radiation

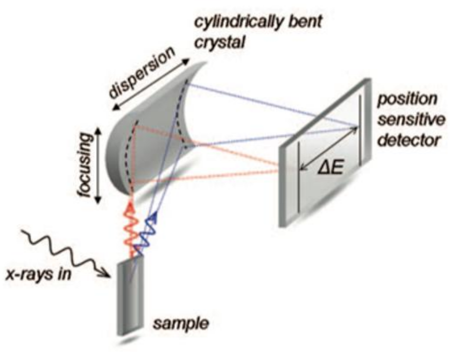
Martin Gerlach,[a] Lars Anklamm,[b] Alexander Antonov,[c] Inna Grigorieva,[c] Ina Holfelder,[a] Birgit Kanngießer,[b] Herbert Legall,[c] Wolfgang Malzer,[b] Christopher Schlesiger[b] and Burkhard Beckhoff[a]*

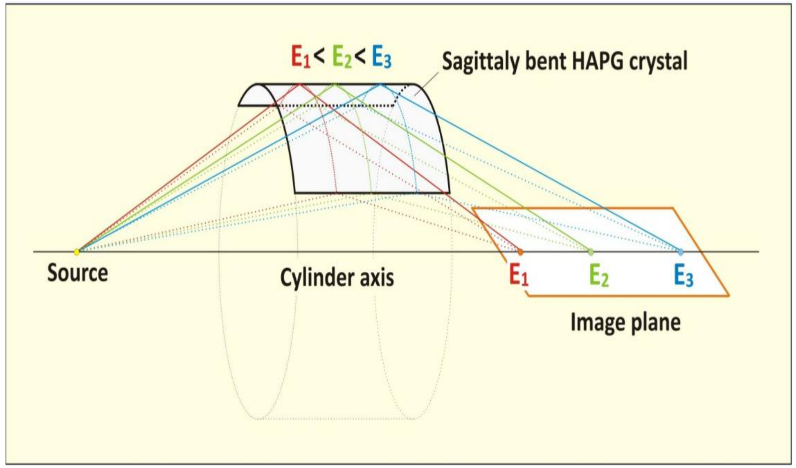
J. Appl. Cryst. (2015). **48**

Pyrolitic Graphite mosaic crystals (d = 3.354 Å):

- Bending does not influence resolution and intensity
- Mosaic spread down to 0.05 degree
- Integral reflectivity ~ 10^2 higher than for other crystals
- Variable thickness (efficiency)
- Excellent thermal and radiation stability

Von Hamos configuration: improving solid angle



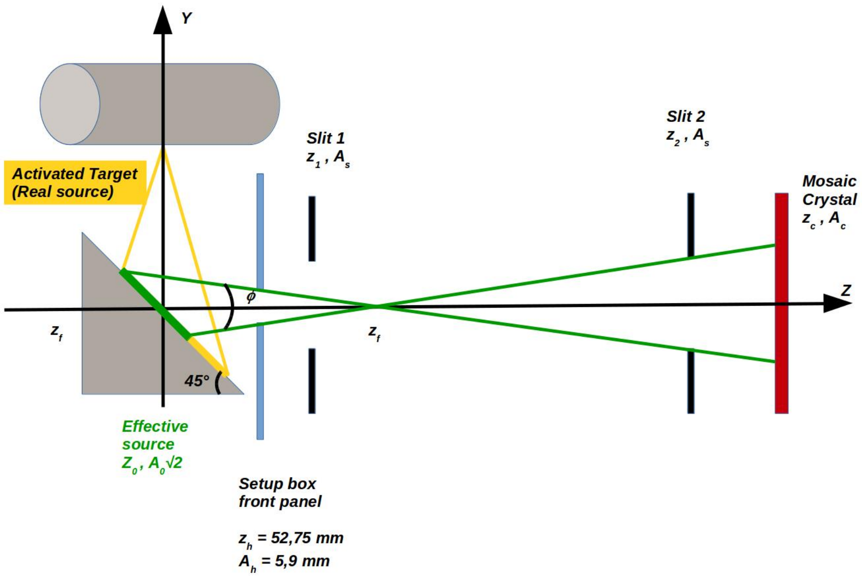


VH configuration can further improve the signal collection efficiency.

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

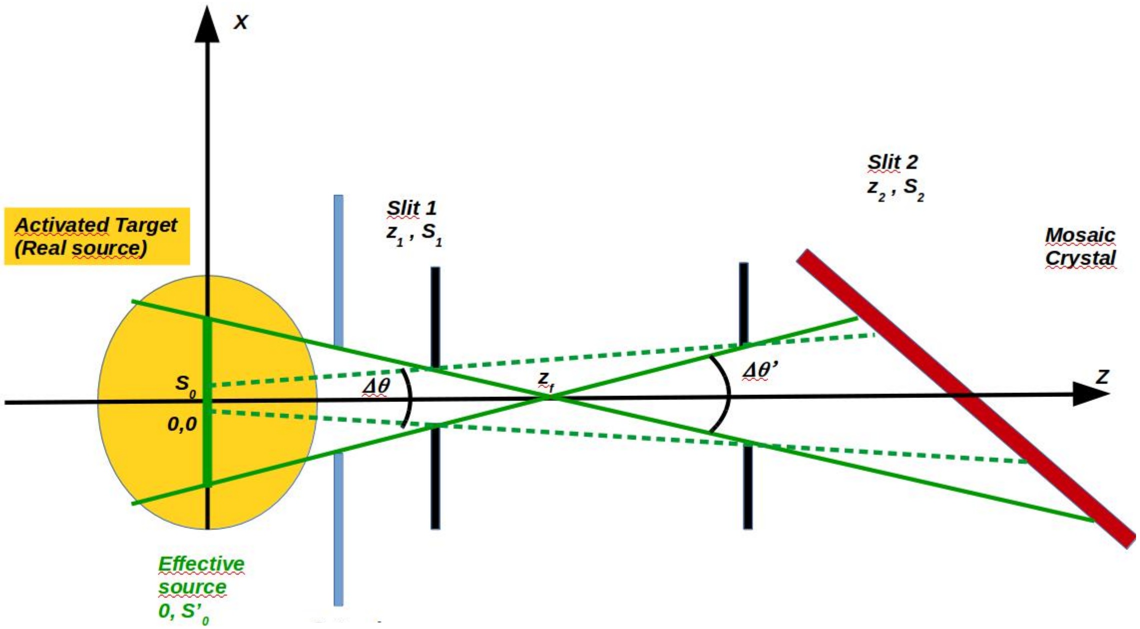
distance: F = 400 mm in (004)-reflexion @ 8 keV (Cu K_a)

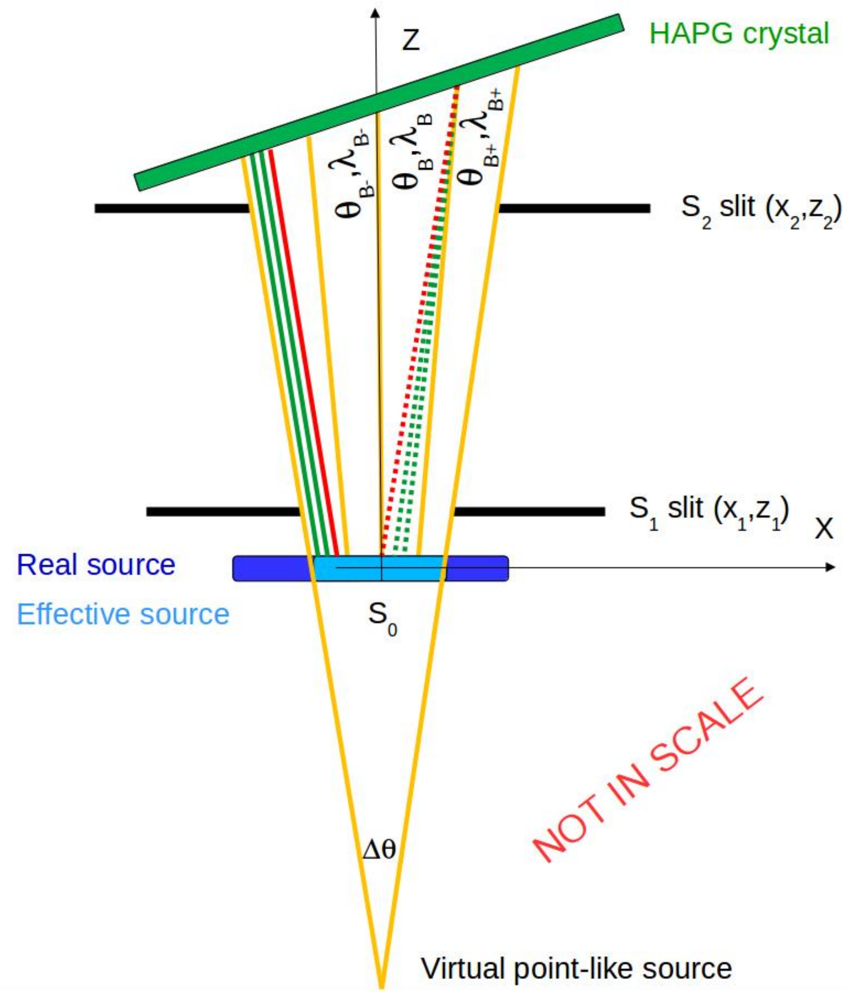
Spectral resolution of bent HAPG/HOPG crystal is comparable to the flat one !



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: setup

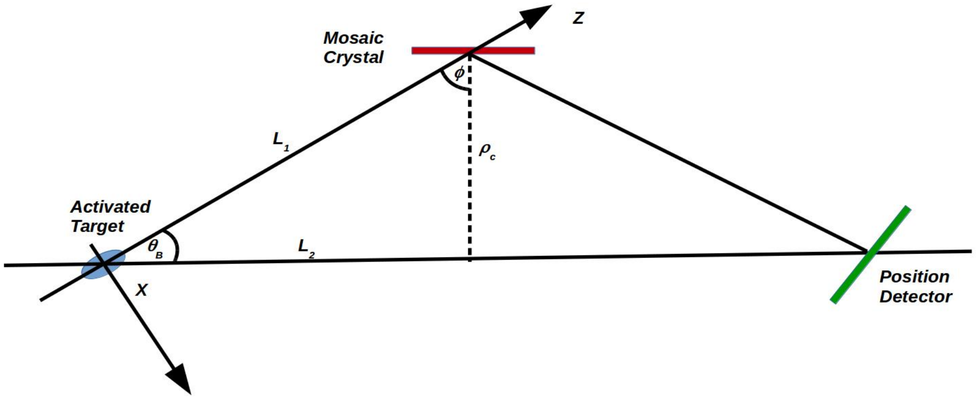


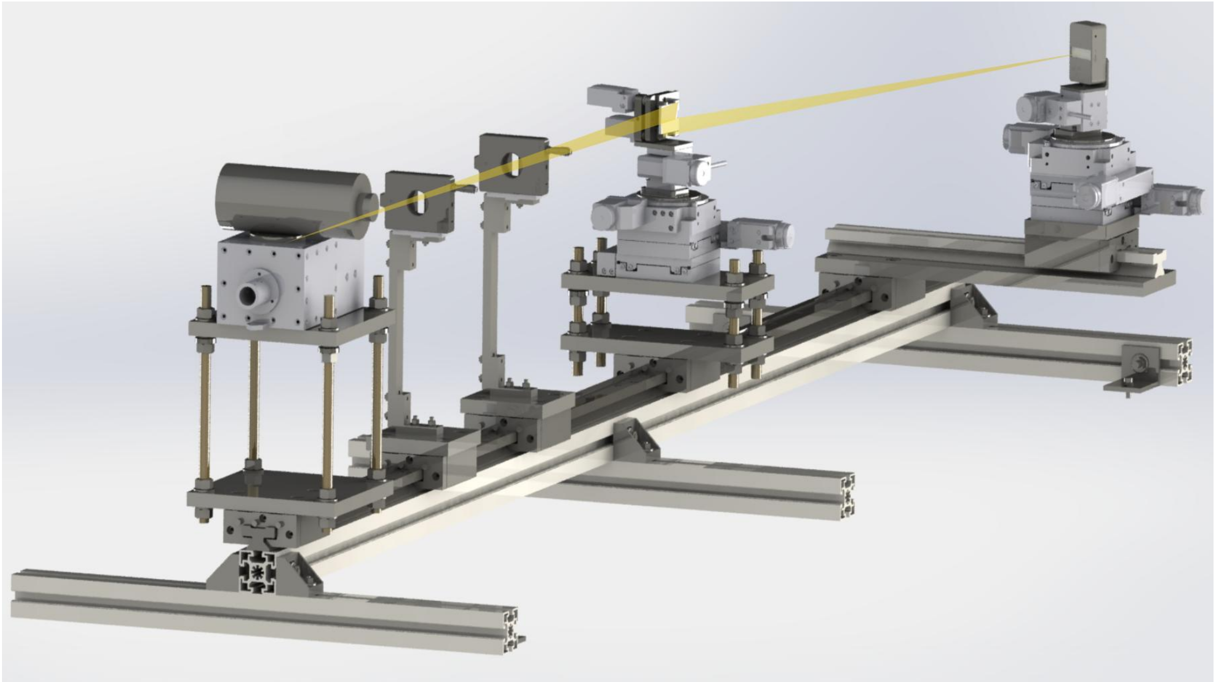
Table 1 List of the X-ray lines measured in this work and the corresponding Bragg angles θ_B

Line	E (eV)	θ_B (°)
Fe($K_{\alpha 1}$)	6403,84	16,77
Fe($K_{\alpha 2}$)	6390,84	16,81
Cu($K_{\alpha 1}$)	8047,78	13,28
Cu($K_{\alpha 2}$)	8027,83	13,31
Ni(K_{β})	8264,66	12,92
Zn($K_{\alpha 1}$)	8638,86	12,35
Zn($K_{\alpha 2}$)	8615,78	12,39
Mo($K_{\alpha 1}$)	17479,34	6,07
Mo($K_{\alpha 2}$)	17374,30	6,11
Nb(K_{β})	18622,50	5,70

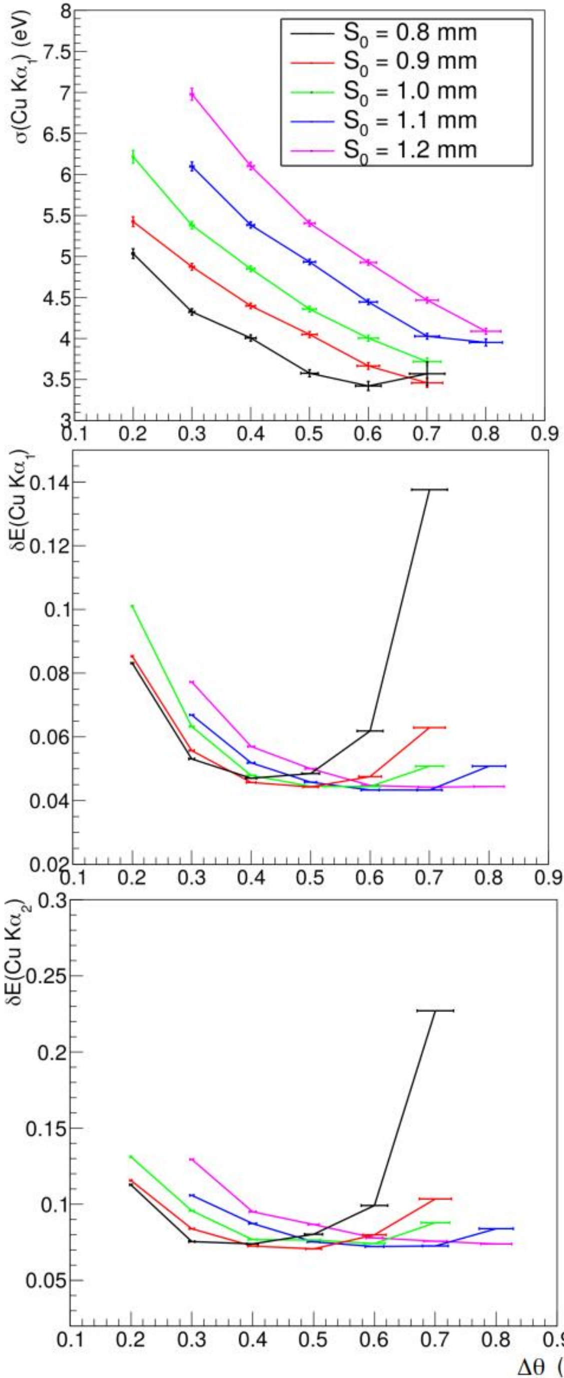
For a given X-ray energy the Bragg angle (θ_B) and the curvature radius of the crystal (ρ_c) completely determine the position of the source, the crystal and the position detector

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

$$L_2 = L_1 sin\phi$$



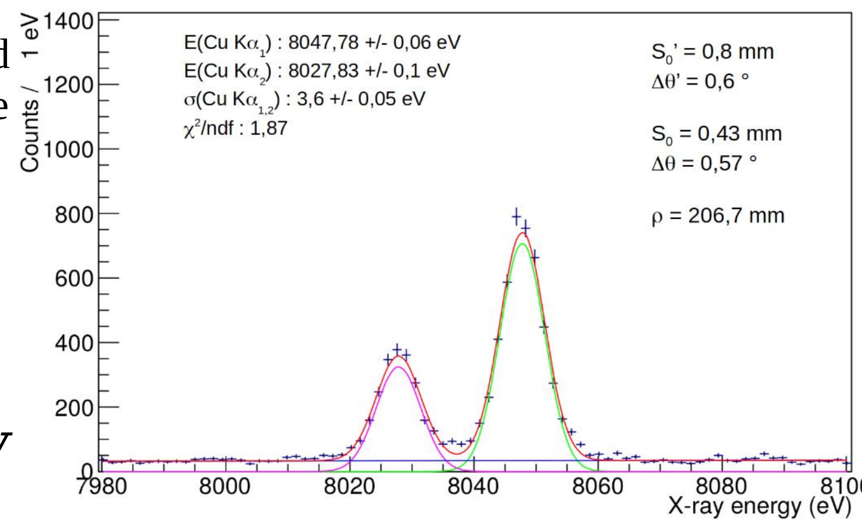
VOXES: results



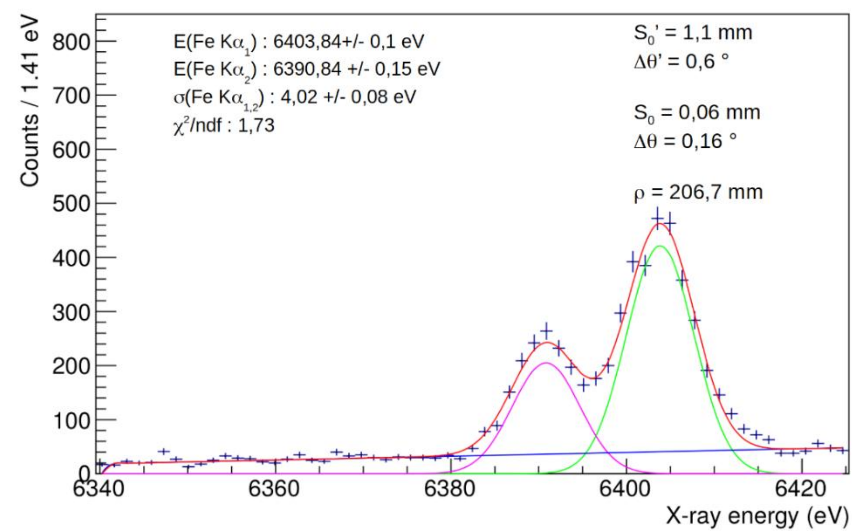
In the limit of a background free pure gaussian peak, the precision is related to the resolution via:

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

$$\frac{3,6}{\sqrt{4323}} = 0,0547\, eV$$

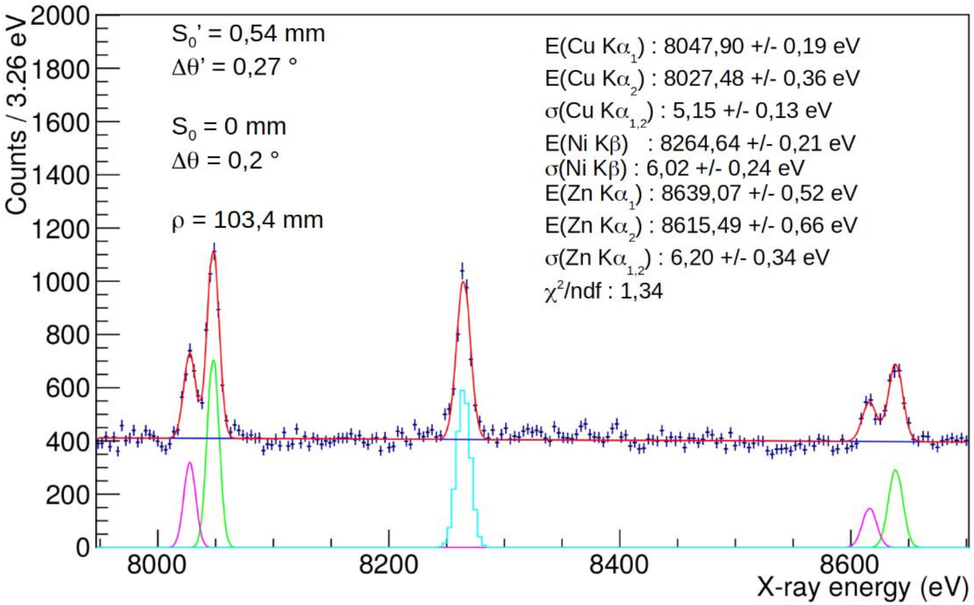


Given the energy and ρ_c it is alwasy possible to find the optimal configuration to obtain the best peak position precision



Valid for all energies (tested for 6-20 keV)

VOXES: results



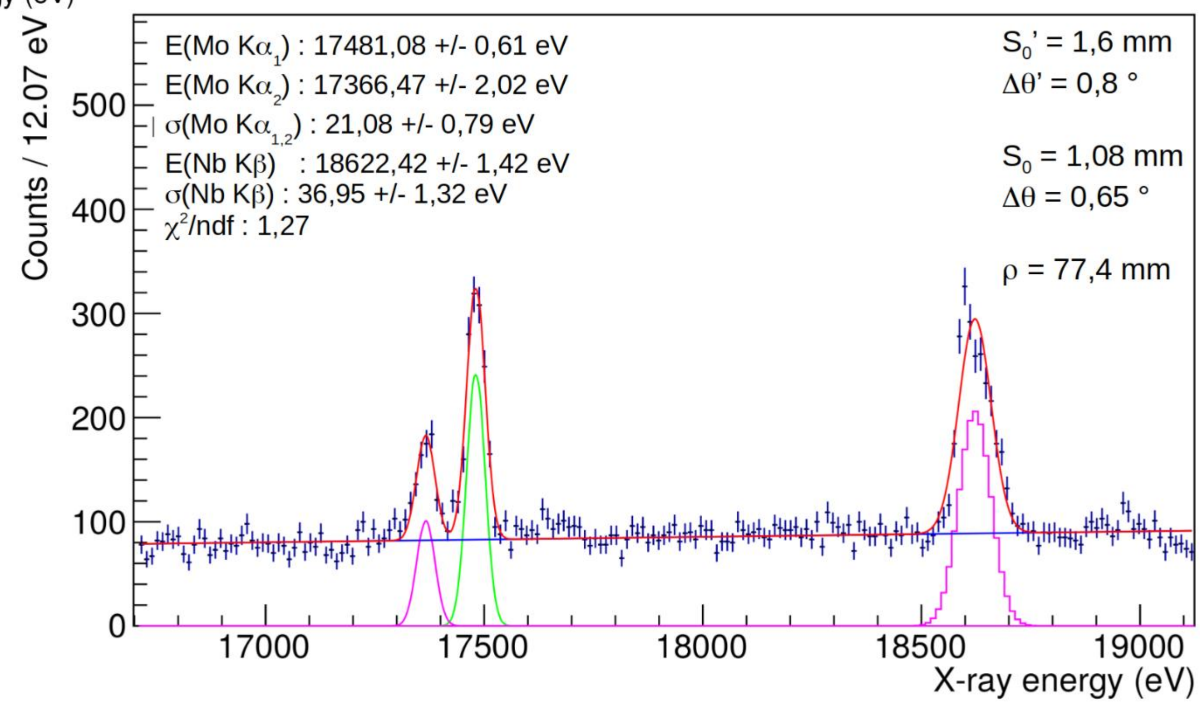
700 eV dynamic range (one shot)

Resolution still at 6 eV level (σ)

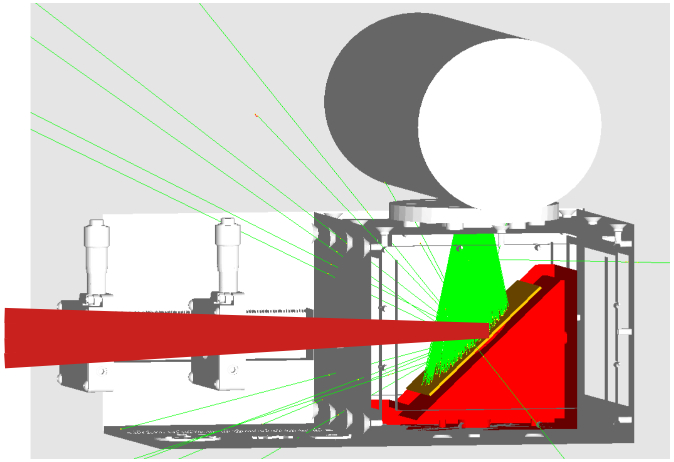
>1 keV dynamic range

Resolution still at 1,2 ‰

Almost 2 mm source size



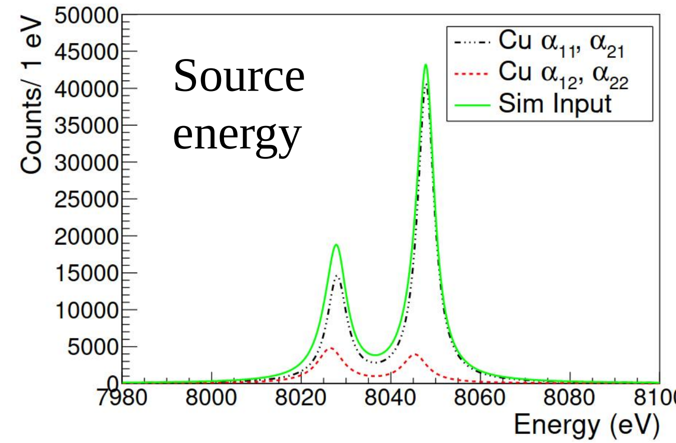
VOXES: ray tracing simulations

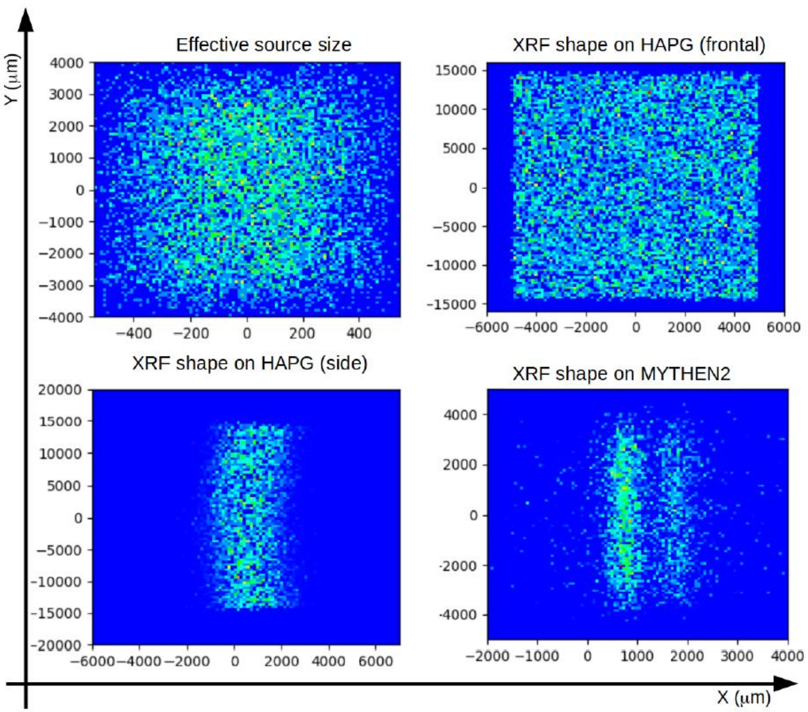


Software:
XOP → HAPG and ray tracing
SHADOW → Visualization

Integrated in OASYS tool

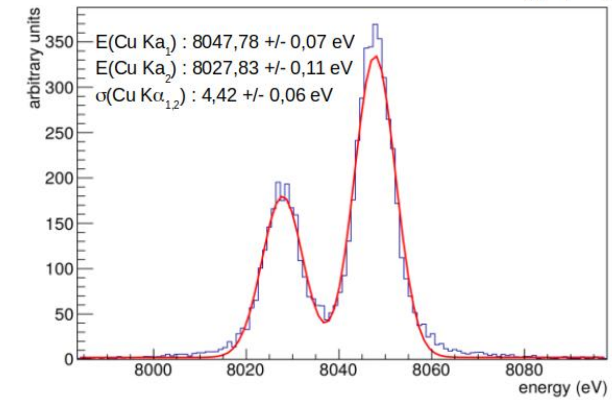
22 G. Hölzer *et al.*, *Phys. Rev. A*, 1997, **56**, 4554–4568.

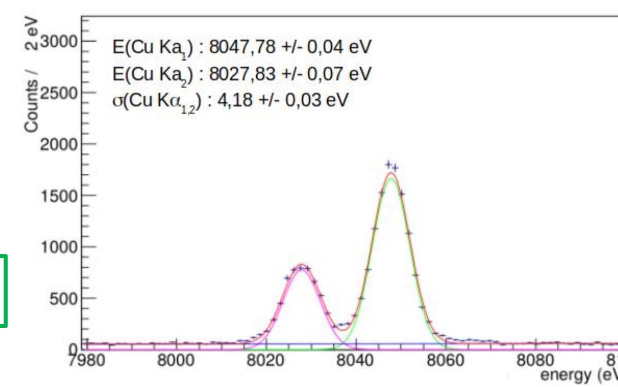




The physical source size is large (2,5x 2,5 cm)

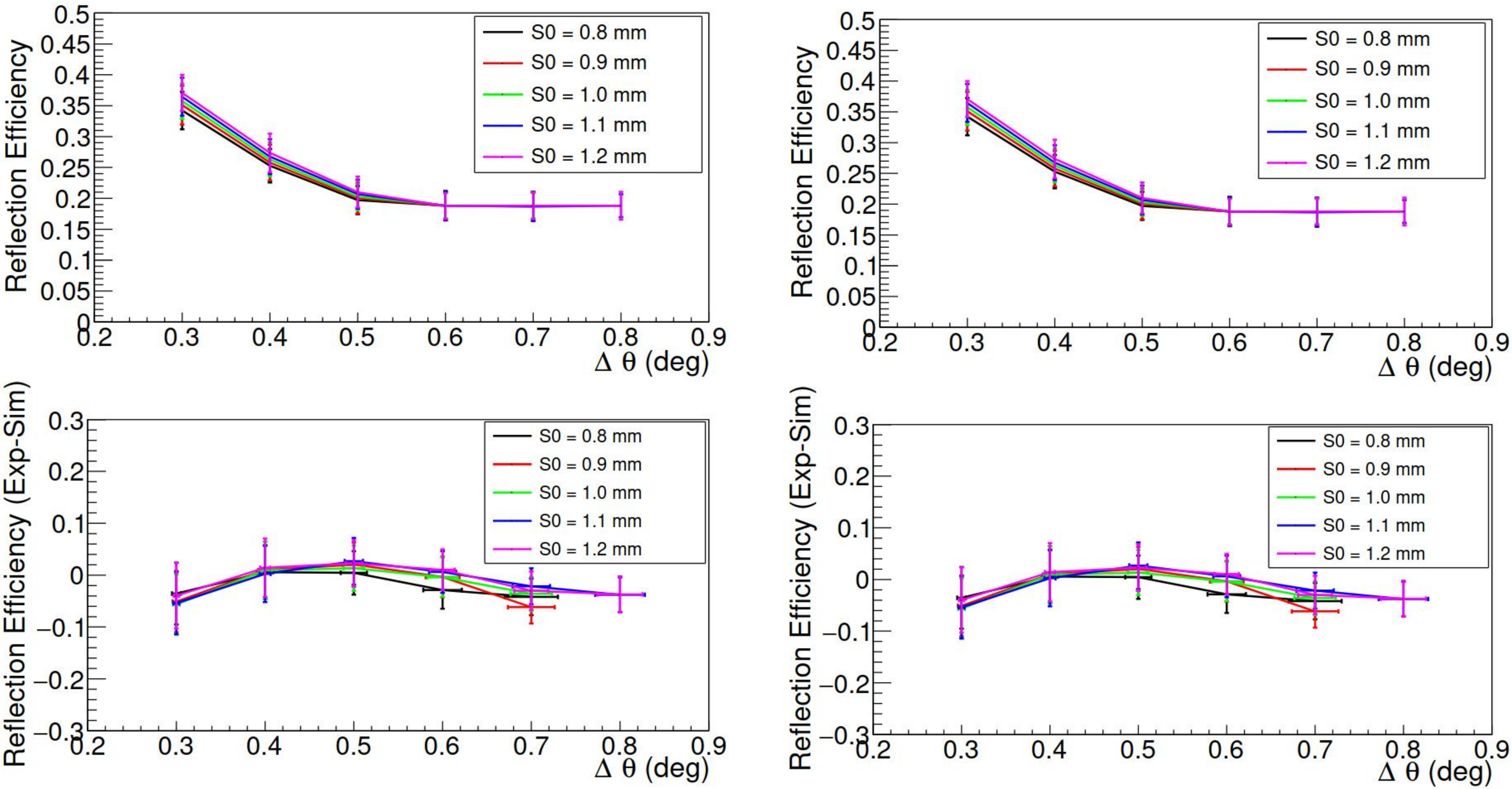
We want to check the effective source size dimensions as coming from ray tracing simulations





Peak position and σ well reproduced

VOXES: ray tracing simulations



Reflection efficiencies are also well reproduced and under control

VOXES: ray tracing simulations

Possible kaonic transitions to be measured with HAPG crystal spectrometer:

$K^3He(3 \rightarrow 2)$: 6.2 keV
$K^3He(4 \rightarrow 2)$: 8.4 keV
$K^3He(5 \rightarrow 2)$: 9.4 keV
$K^3He(6 \rightarrow 2)$: 9.9 keV
$K^3He(7 \rightarrow 2)$: 10.2 keV

$K^4He(3 \rightarrow 2)$: 6.4 keV
$K^4He(4 \rightarrow 2)$: 8.7 keV
$K^4He(5 \rightarrow 2)$: 9.7 keV
$K^4He(6 \rightarrow 2)$: 10.3 keV
$K^4He(7 \rightarrow 2)$: 10.7 keV

$KN(6 \rightarrow 5)$: 7.6 keV
$KN(7 \rightarrow 5)$: 12.1 keV
$KN(8 \rightarrow 5)$: 15.1 keV
$KN(7 \rightarrow 6)$: 4.6 keV
$KN(8 \rightarrow 6)$: 7.5 keV
$KN(9 \rightarrow 6)$: 9.6 keV
$KN(10 \rightarrow 6)$: 11 keV
$KN(11 \rightarrow 6)$: 12.1 keV
$KN(10 \rightarrow 7)$: 6.5 keV
$KN(11 \rightarrow 7)$: 7.5 keV
$KN(12 \rightarrow 7)$: 8.3 keV

Expected Impact:

- - Kaon mass measurements from different lines in parallel
- Cascade processes
- Impact on dark matter search driven experiments using exotic atoms in space (accurate cascade models calculations)
- Upper level measurments with very small Γ
- Proton radius puzzle (???)

Manifestatation of interest from international institution and research centers (PSI, …)

Detector Key Points:

- Tunable energy range from 2-20 keV
- Extremely high resolutions of few eV
- Very low background after shielding

Feasibility:

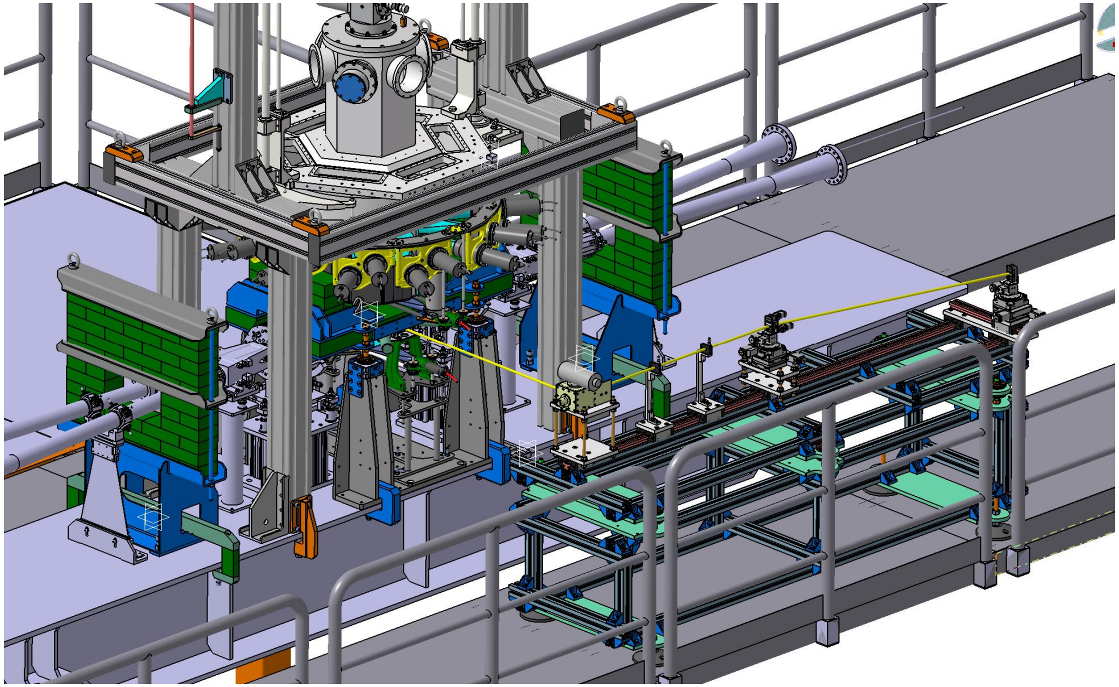
- Working principle tested in laboratory
- Dependence from HAPG parameters well investigated and published (thickness, mosaicity, …)
- Consistent Ray Tracing simulations available
- Few eV resolutions confirmed for solid sources with millimetric dimensions

VOXES: a possible preliminary run

First run with KC for a feasibility test and background evaluation

Available:

1) Multi - Crystal support structure
2) Target (Solid or Liquid/Gas)
3) Optics
4) Alignement support
5) Target box
6) Detector
7) DAQ (integ. KM)

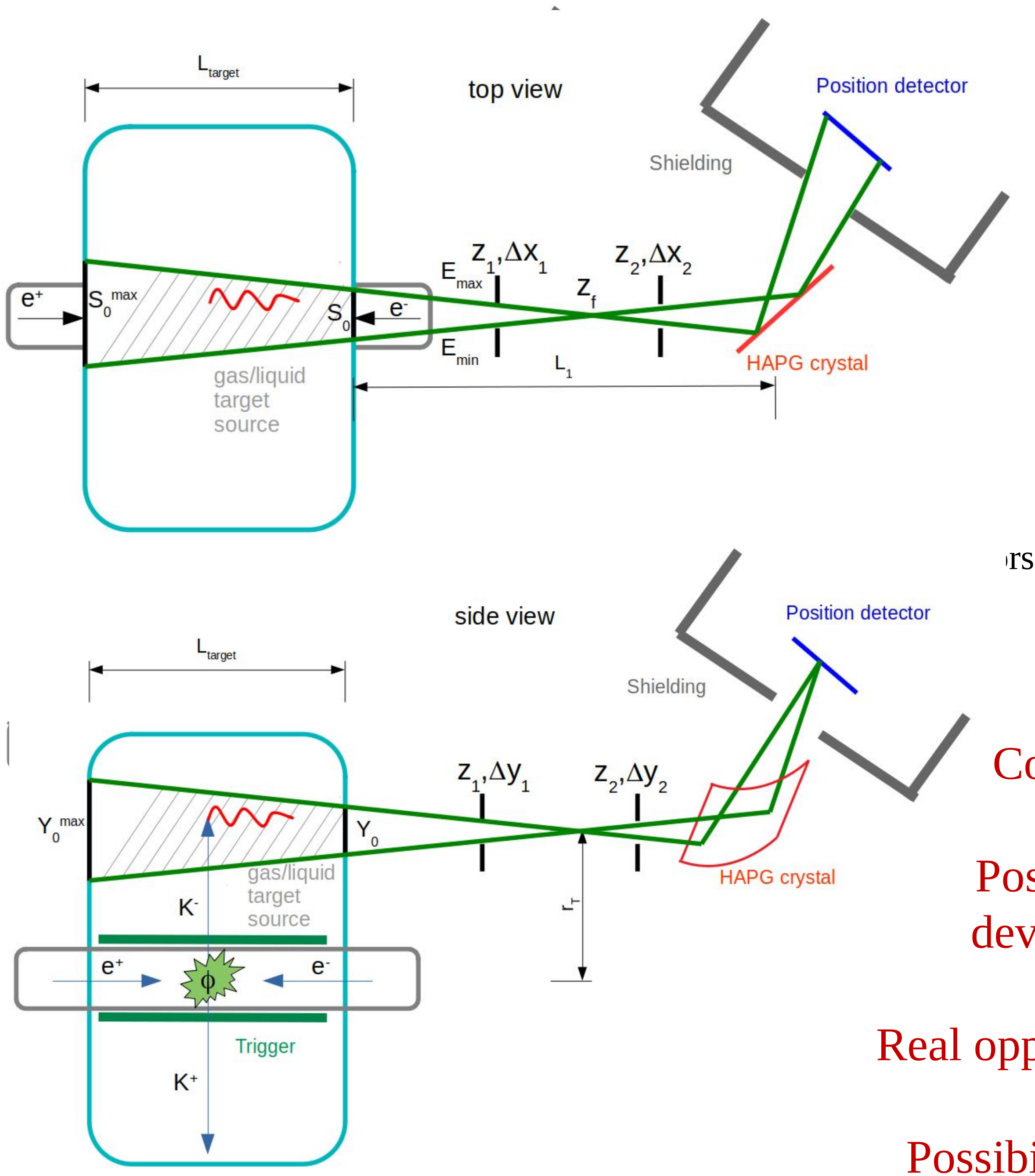


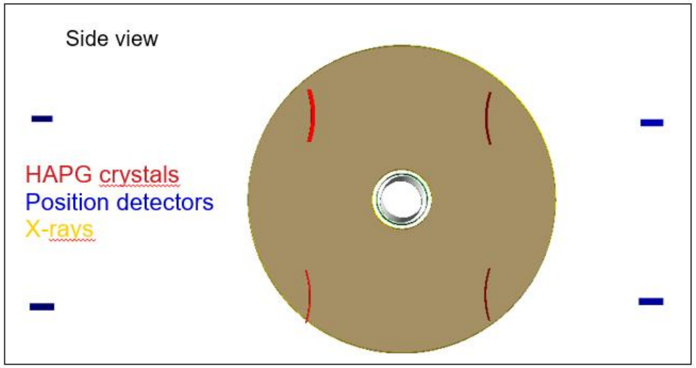
Future implementations:

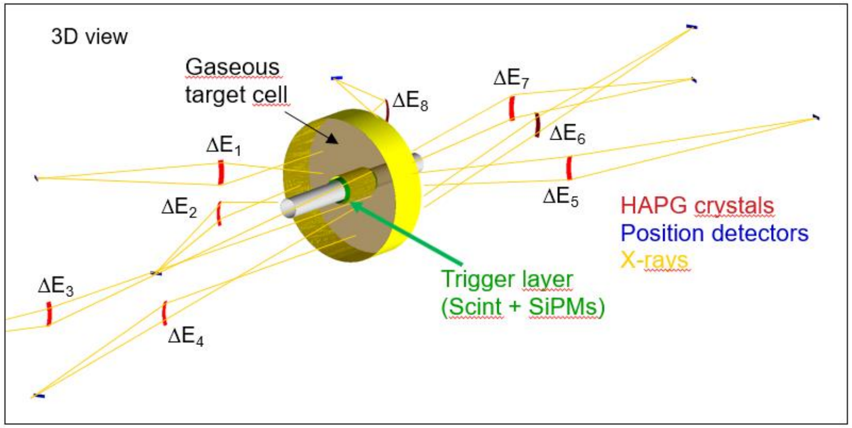
- Shielding around Detector
- Solid support structure

Possible run in parallel with SIDDHARTA-2 @ LNF in spring 2022

VOXES: future scenarios on DAΦNE







Completely new experiment / setup

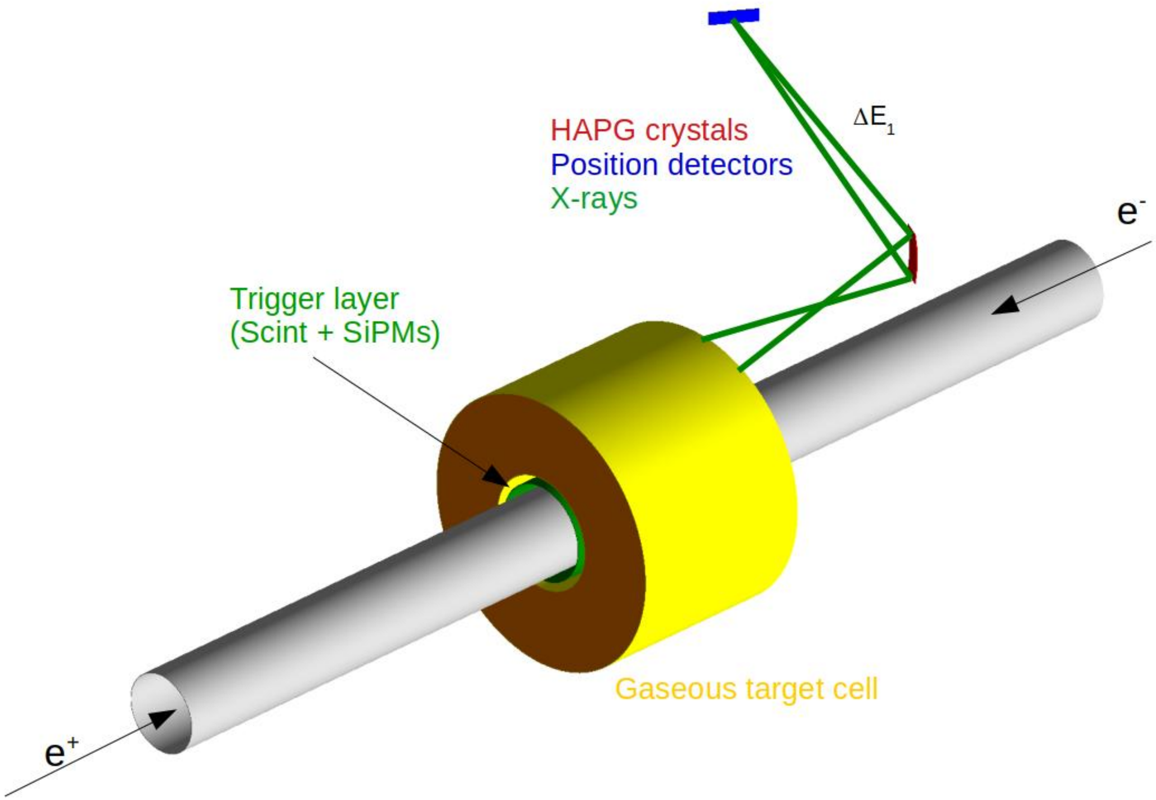
Position Detector and HAPG crystals development with R&D opportunities

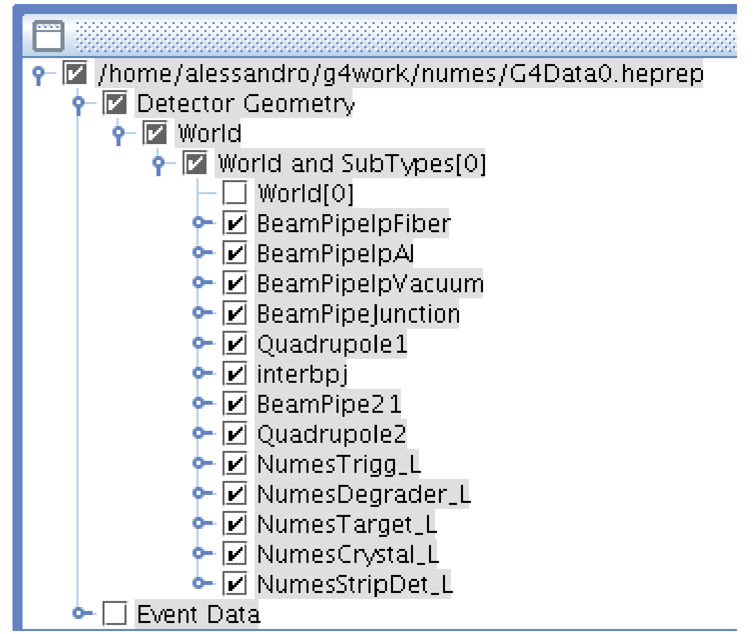
Real opportunity to apply for external fundings

Possibility to attract new interested institutes

VOXES → NUMES: future scenarios on DAΦNE

NUMES : Novel X-ray detector system for Ultra-high precision Measurements of Exotic atoms from macroscopic Sources





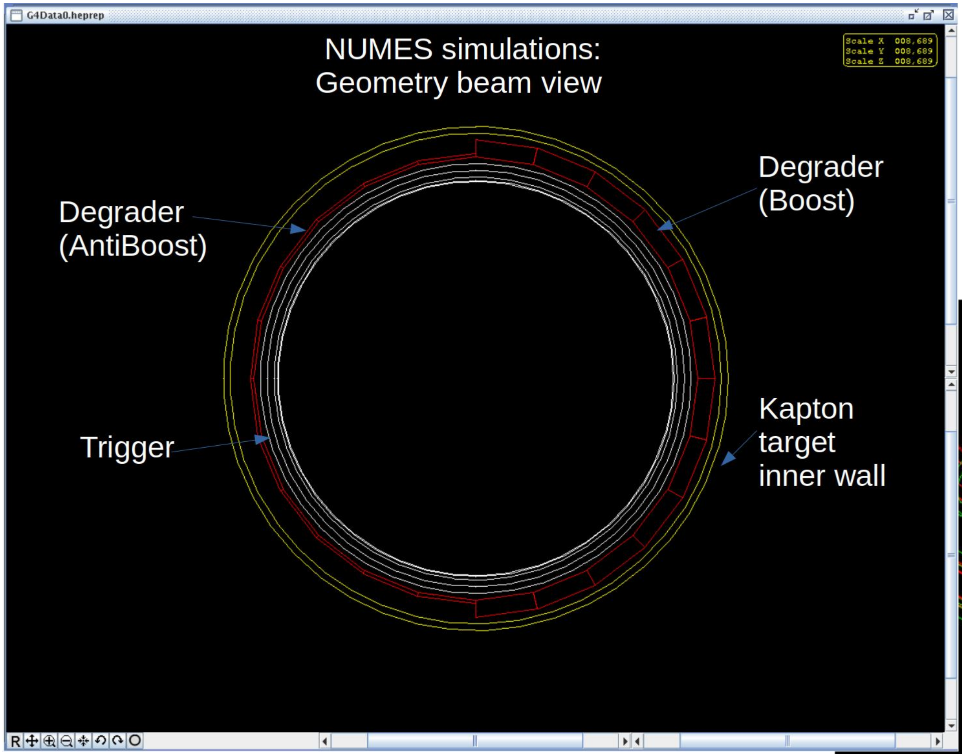
Ray tracing simulations:

Starting point are VOXES simulations

Geant4:
Starting point is SIDDHARTA-2 MC

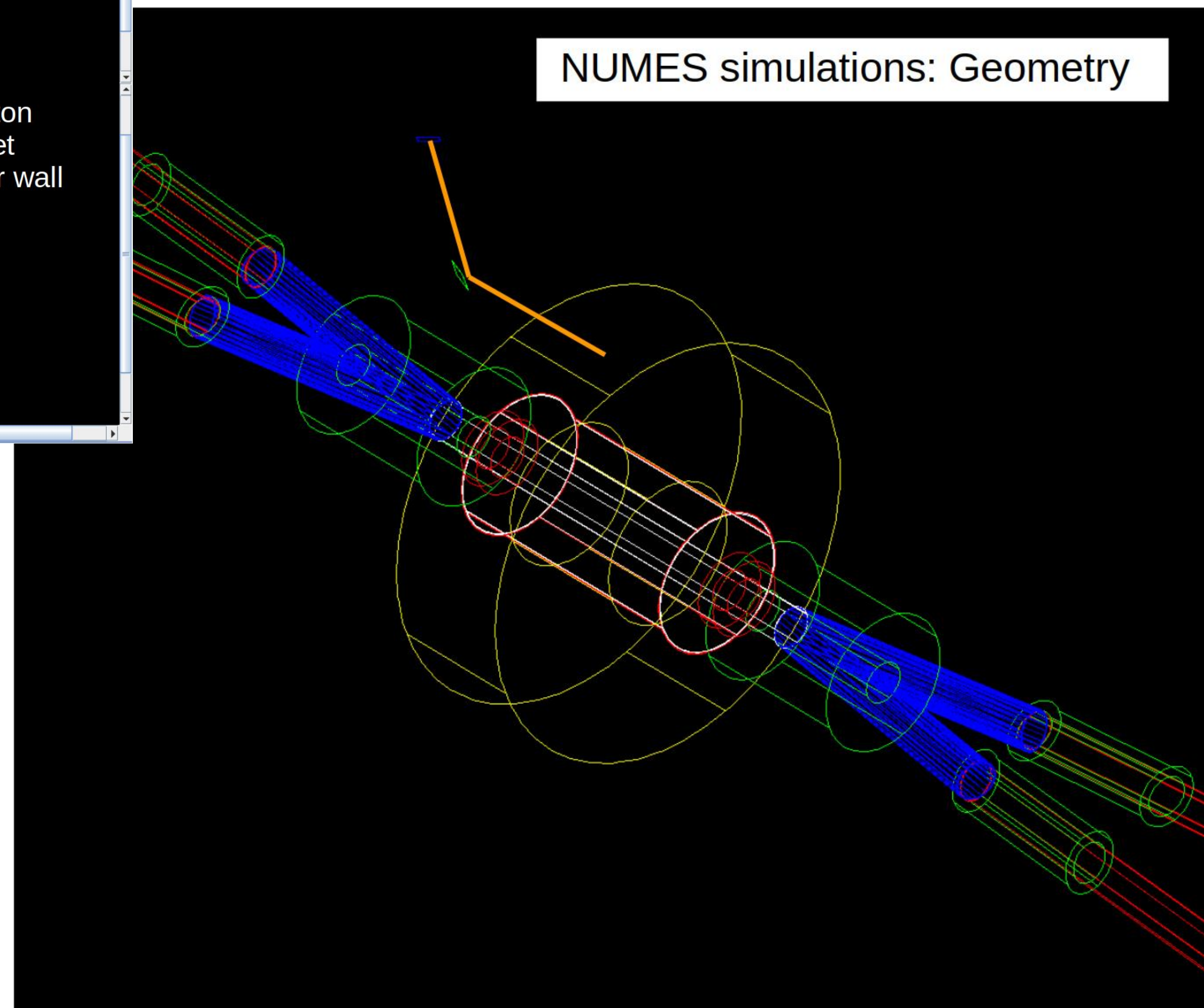
Geometry:
- BeamPipe & Quadrupoles from SIDDHARTA-2
- Other parts are removed
- Trigger: 1mm BC420 cylinder
- Degrader: variable thickness Mylar cylinder
- Cylindrical Target: ΔR>=10 cm, L=40 cm

VOXES → NUMES: future scenarios on DAΦNE



Kaons stopping number and position is strongly dependent on the geometry and on the degrader / trigger materials and thicknesses

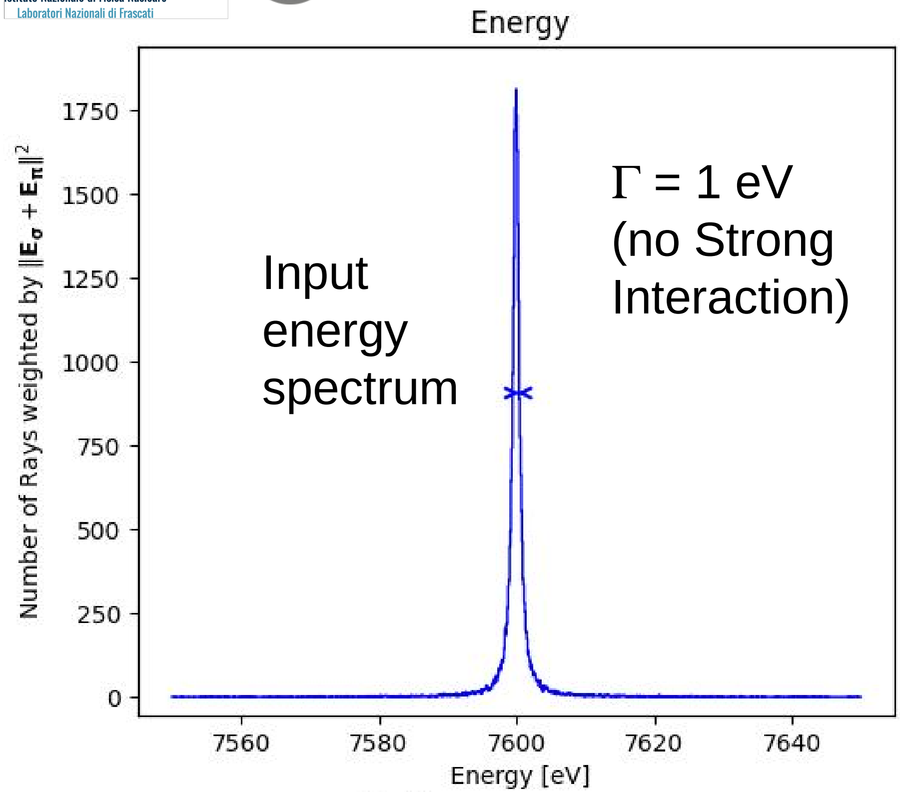
→ A proper optimization requires a big effort

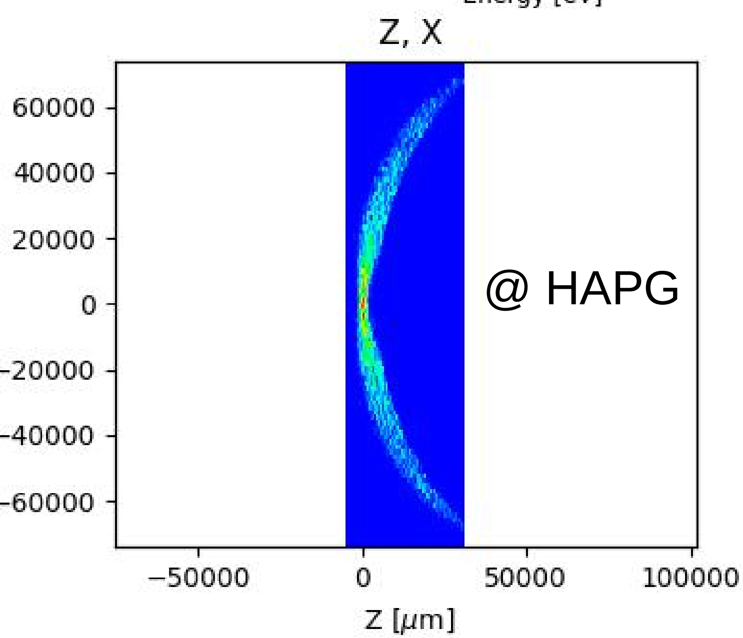


2-steps simulation:

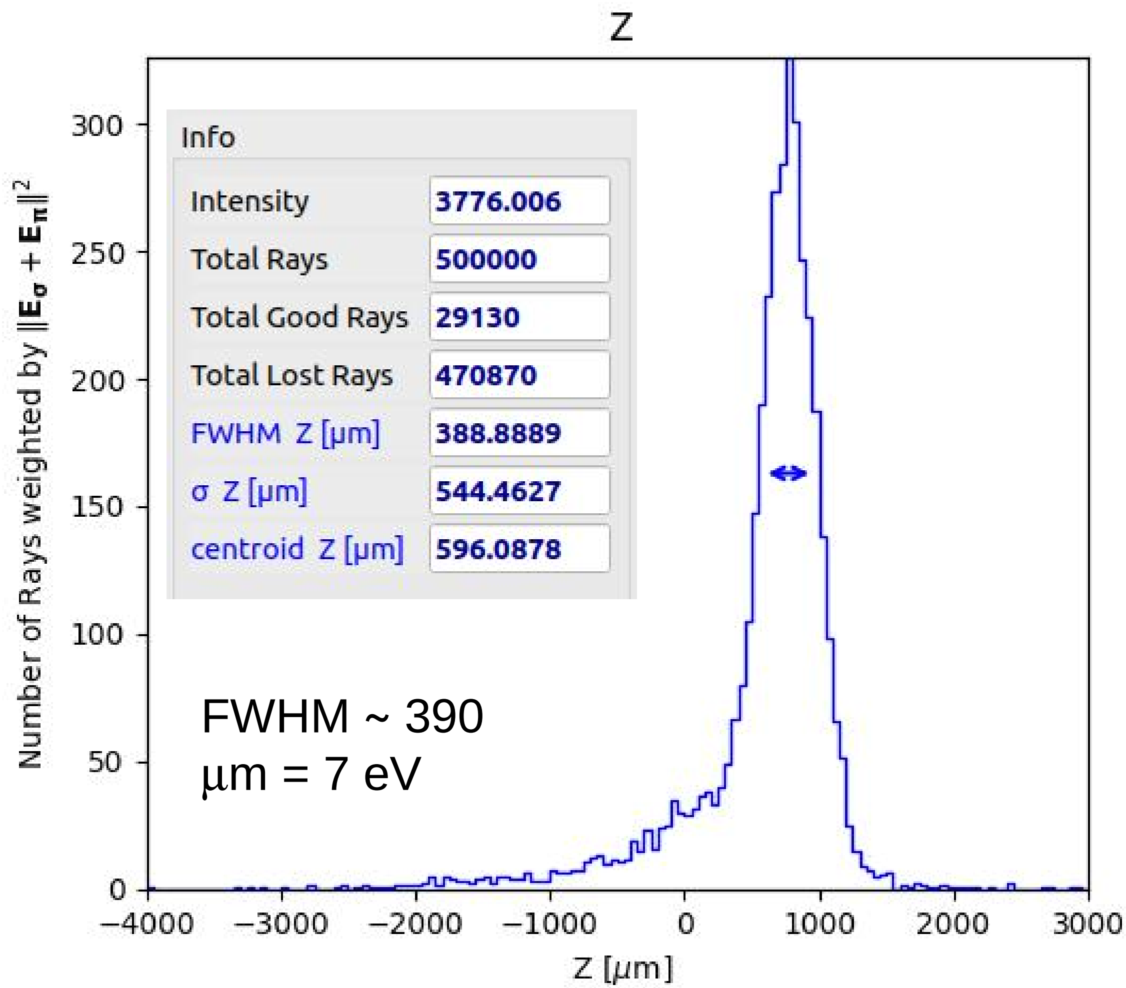
The geometrical distribution of the K- stopped is used as input source for ray tracing simulations

KN 6→5 @ 7.6 keV



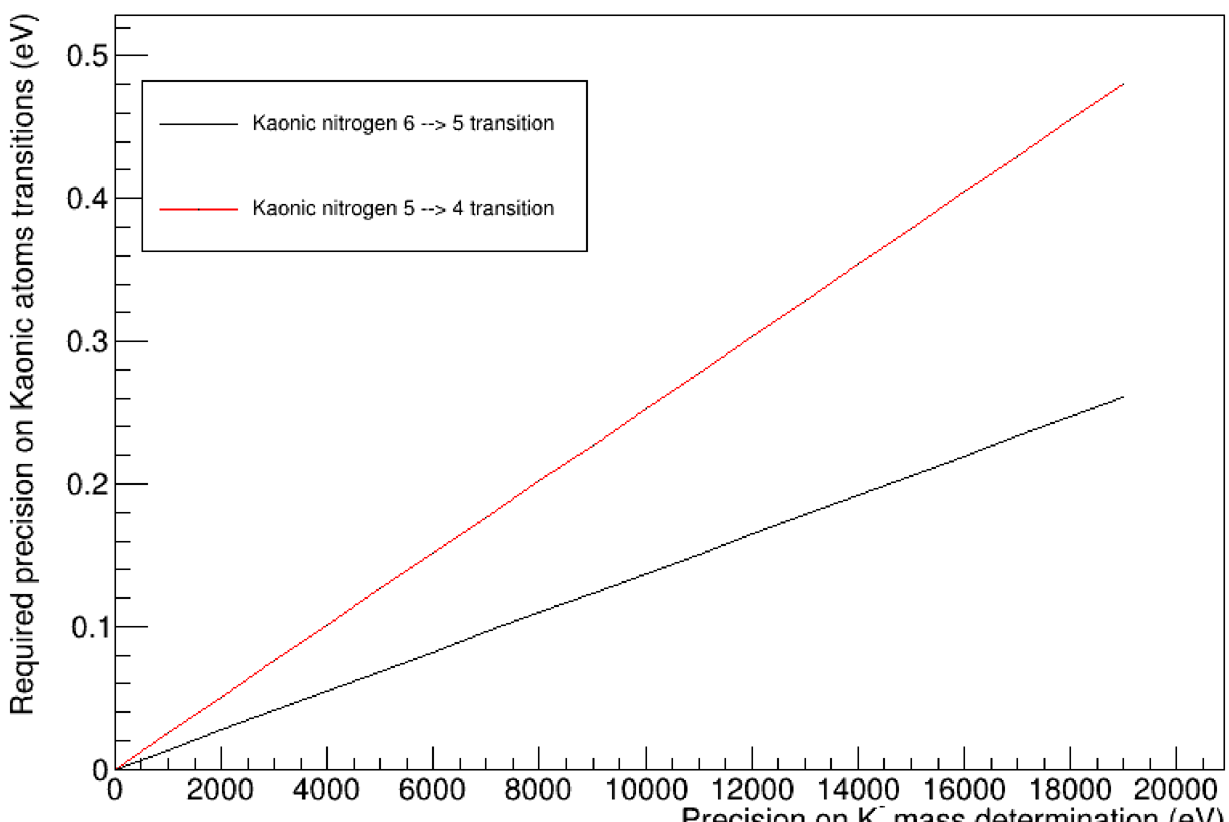


Simulated Bragg spectrum
(1 bin = 1 50 μm strip)



KN 6→5 @ 7.6 keV

N to have 0,15 eV precisions	Lumi (pb-1) / 8 arm needed	N to have 0,2 eV precisions	Lumi (pb-1) / 8 arm needed	N to have 0,25 eV precisions	Lumi (pb-1) / 8 arm needed
394,35	878,66	221,82	494,25	141,96	316,32

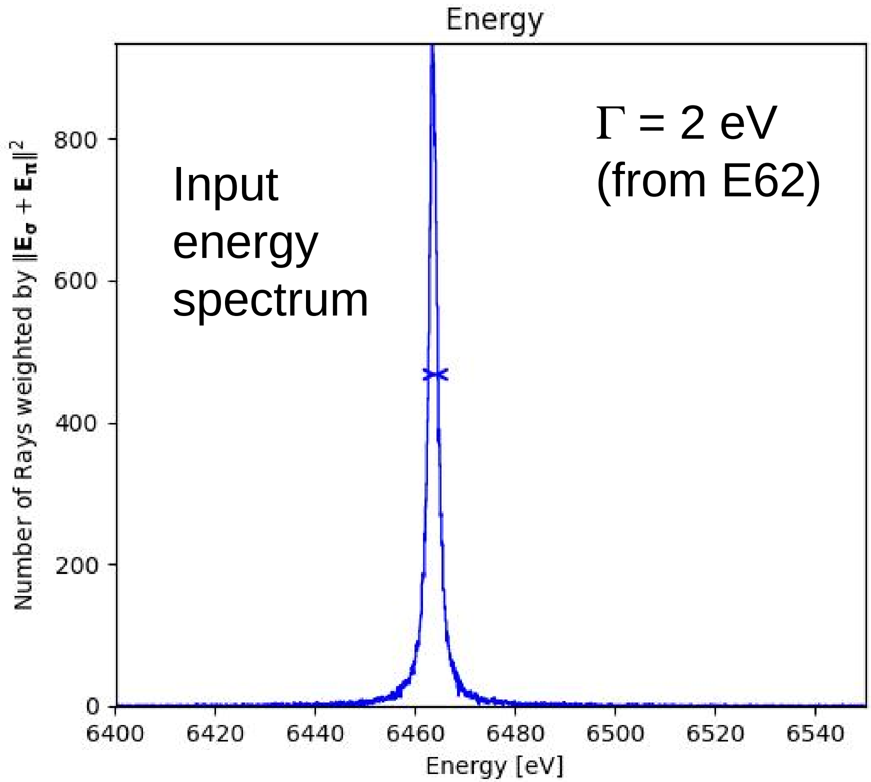


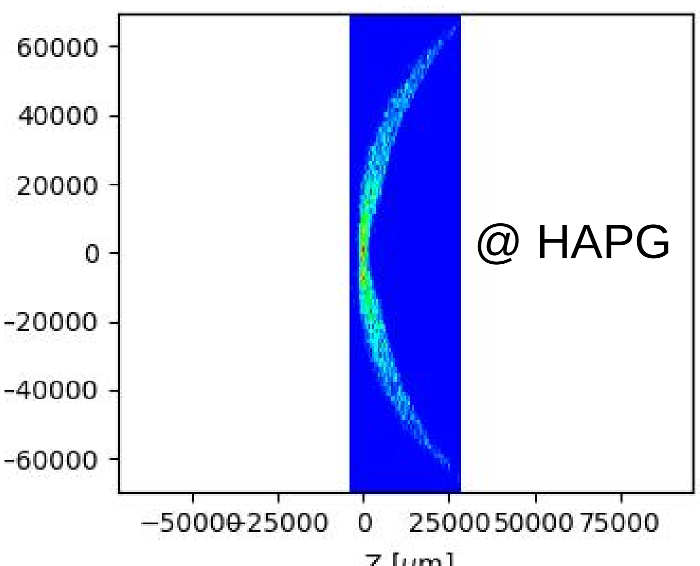
Depending on true DAFNE luminosity (in Siddharta it was in average 2-3x10^{32} ~ 20 pb^{-1} / day) we have the possibility to perform a measurement of the K- mass well below 7 keV

Using 2 crystals for each arm, there is the possibility to focus also KN(5-->4) line @ 14 keV on the same position detector.

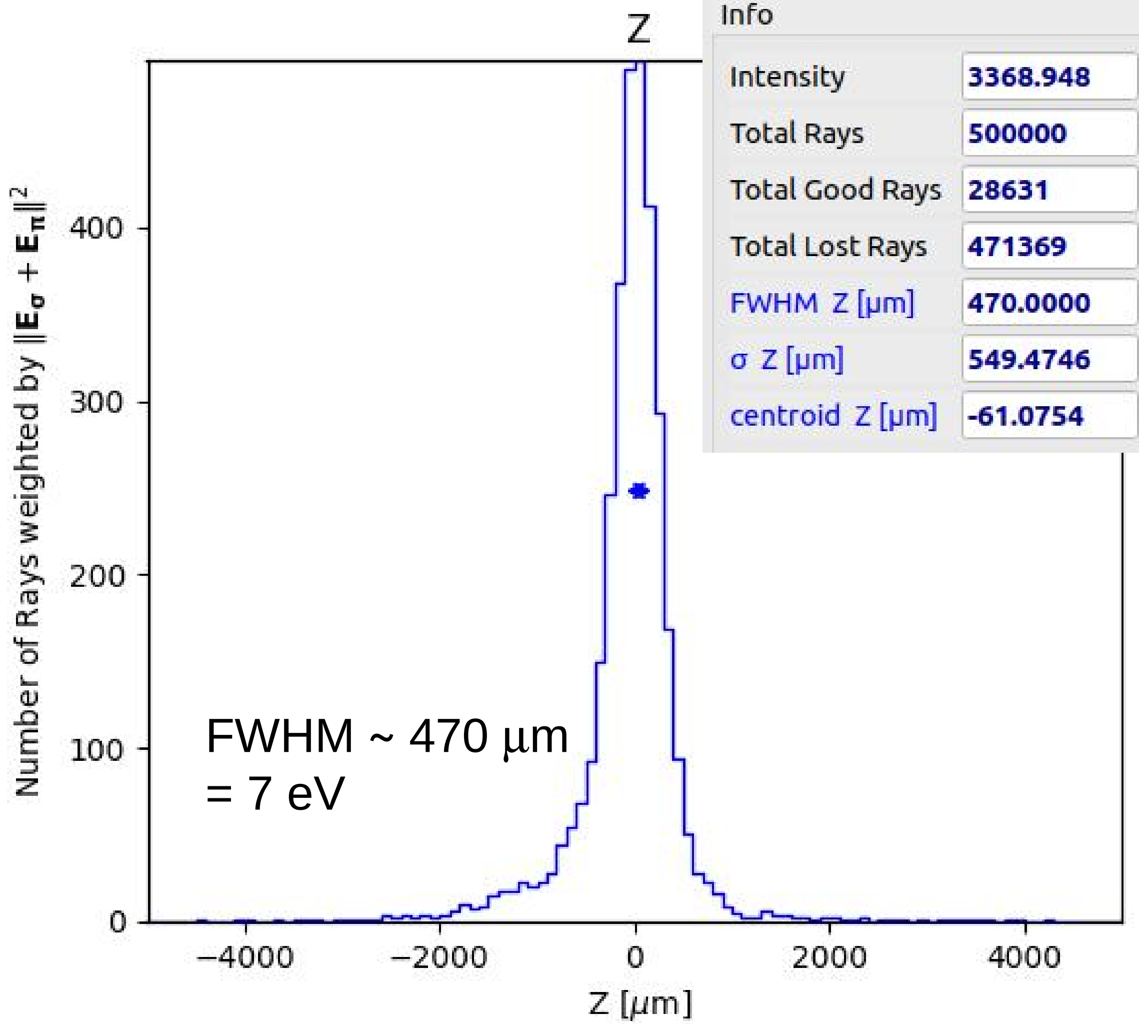
In this way, more statistics could be achieved with low costs

KHe @ 6.4 keV



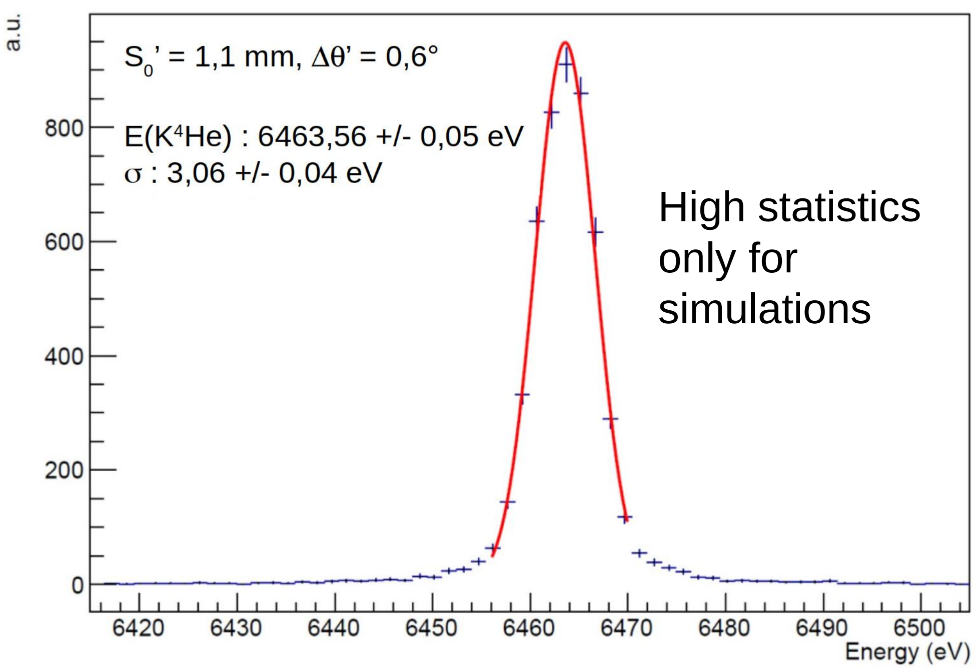


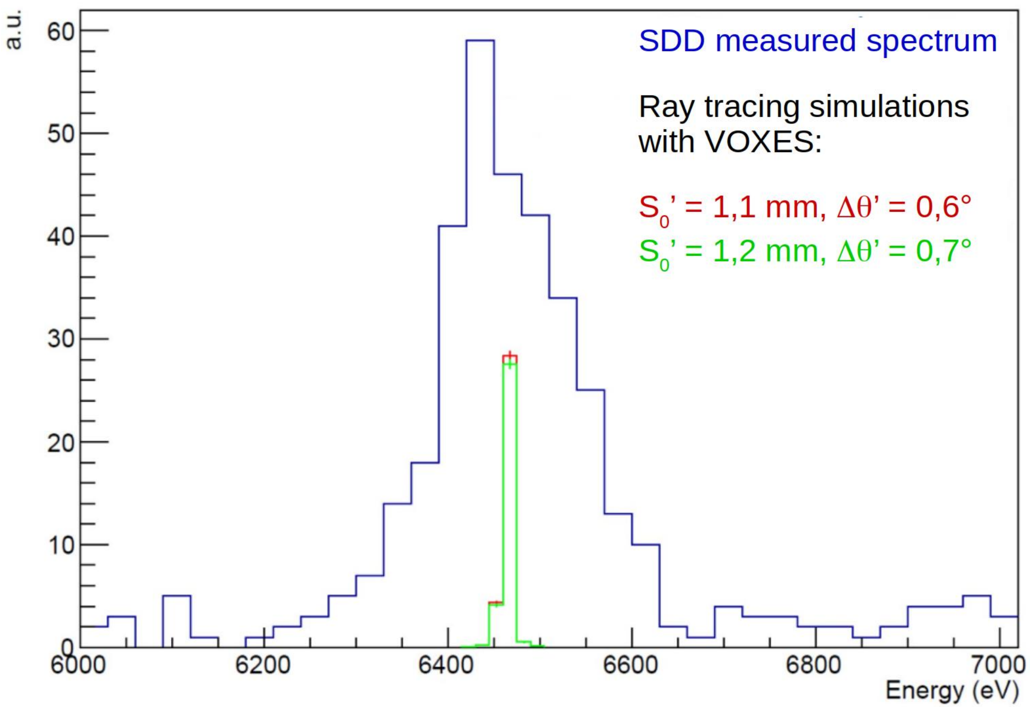
Simulated Bragg spectrum
(1 bin = 1 50 µm strip)



KHe @ 6.4 keV

N to have 0,1 eV precisions	Lumi (pb-1) / 8 arm needed	N to have 0,15 eV precisions	Lumi (pb-1) / 8 arm needed	N to have 0,2 eV precisions	Lumi (pb-1) / 8 arm needed
862,11	1558,92	383,16	692,85	215,53	389,73





Conclusions

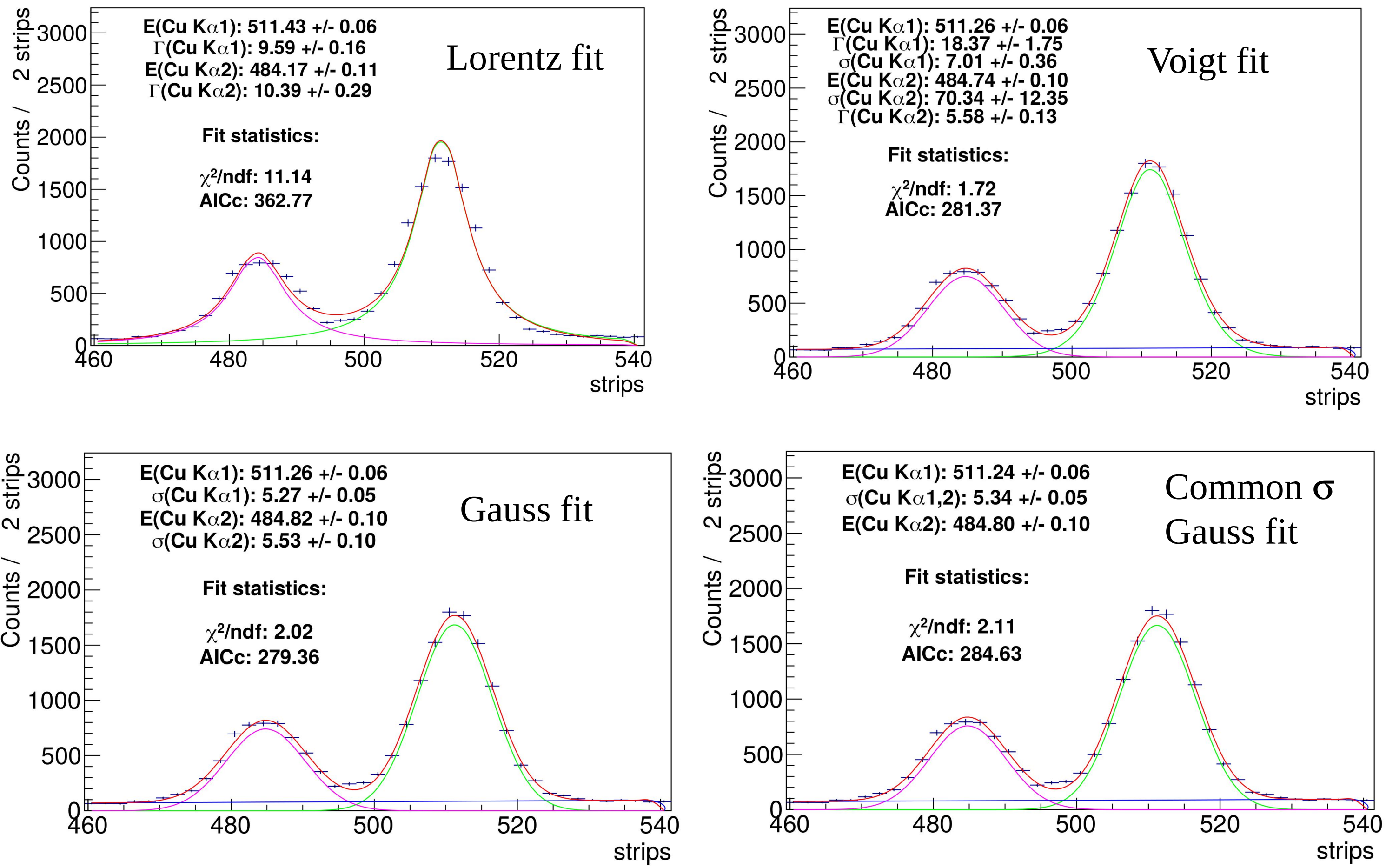
- HAPG based Bragg spectrometers represents a concrete possibility for future sub-eV precision kaonic atoms measurements
- VOXES collaboration developed in Frascati a version of such a spectrometer, to be used also with sources up to mm/cm dimensions
- Detailed investigation and optimization of crystal parameters, calibration procedure and peak shape description has been carried on
- The obtained results are very promising, showing precisions and resolution (well) below 1 eV and 10 eV, respectively
- MC ray tracing simulations have been also performed, which proved to be solid and to perfectly match the data. All these ingredients represent a fundamental starting point for future application
- With a first preliminary test and an expanded ad-hoc setup, VOXES spectrometer has been included in the proposal for future experiments to be carried on at DAΦNE after SIDDHARTA-2:
- *"Fundamental physics at the strangeness frontier at DAΦNE. Outline of a proposal for future measurements"*, arXiv:2104.06076v2 [nucl-ex]

References:
A. Scordo et al., J. Anal. At. Spectrom., 2020, 35, 155–168.
A. Scordo et al., Condensed Matter, 2019, 4, 59.
A. Scordo et al., JINST, 2018, 13, C04002.
A. Scordo et al., Acta Phys. Polon., 2017, B48, 1715.

Spares

VOXES: peak shape analysis

Which is the correct shape to be used for peak fitting?
(Natural linewidths are Lorentzian but….)



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

Is Voigt really better?

Akaike Information Criteria:

$$AIC = 2p + N \cdot ln(\frac{R}{N})$$

N = num of fitted points
p = num of fit parameters

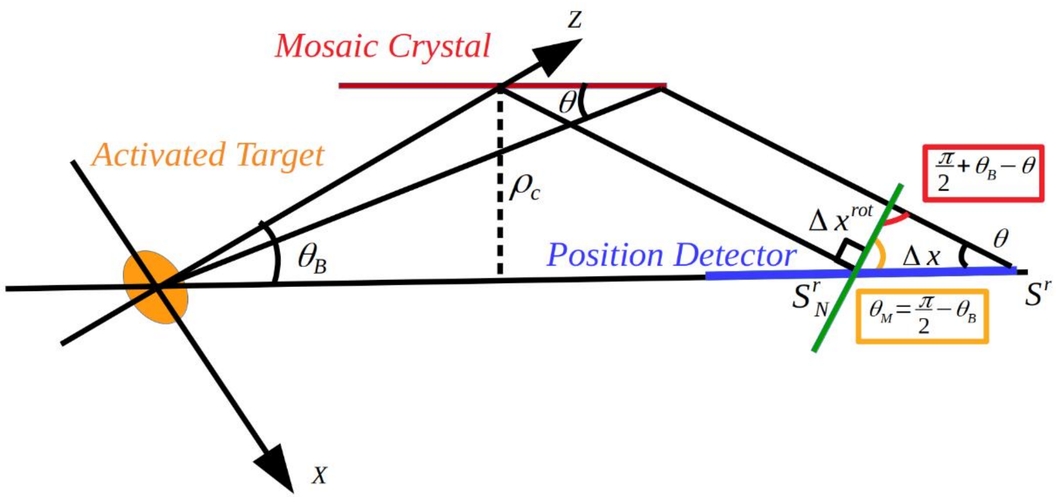
$$AICc = AIC + \frac{2 \cdot p \cdot (p+1)}{N-p-1}$$

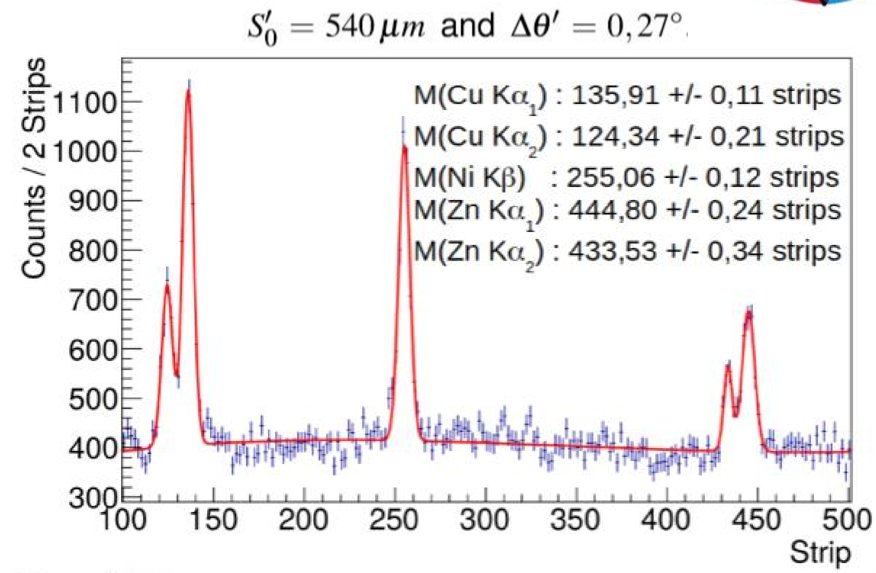
(for N/p < 40)

Not much information loss using gaussian shape

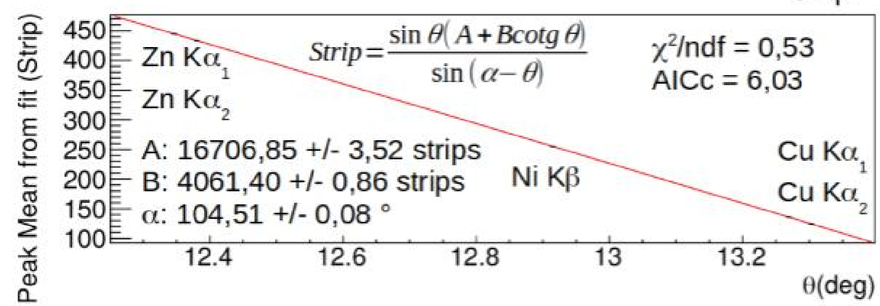
For each model i the quantity $e^{-0,5(AICcmin-AICi)}$ is proportional to the probability of the i-th model to minimize the (estimated) information loss as good as the minimum AICc one.

VOXES: energy calibration



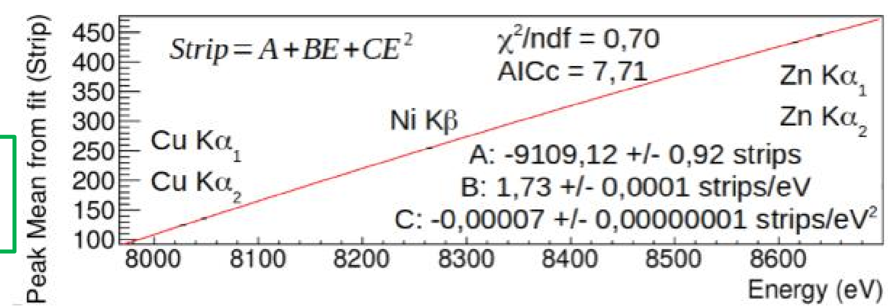


Standard VH calibration: $\Delta x = 2\rho_c \cdot (cotg\theta_B - cotg\theta)$



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

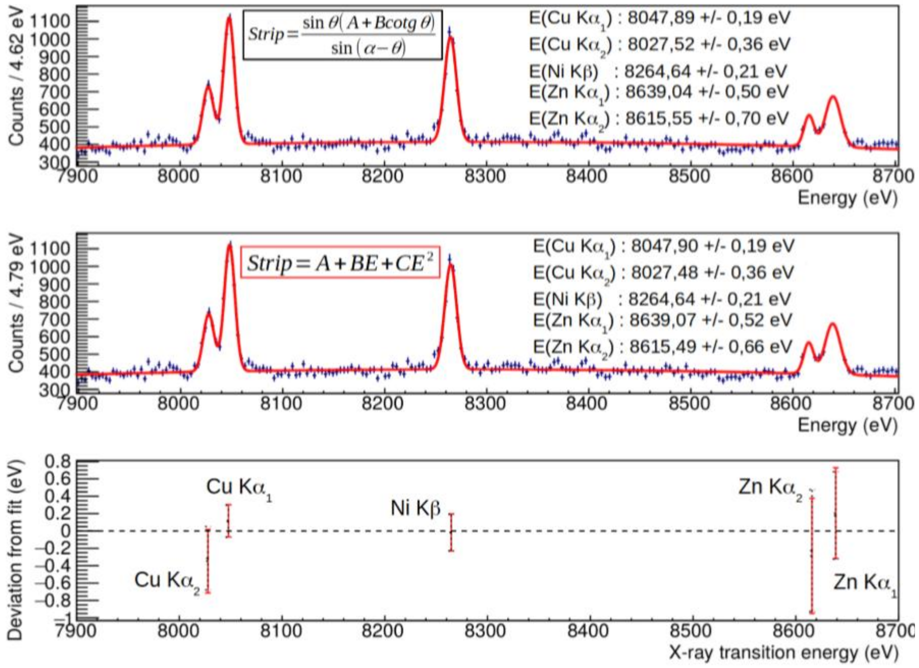
Parametric form: $$\Delta x^{rot} = \frac{(A + B \cdot cotg\theta) \cdot sin\theta}{sin(\alpha - \theta)}$$



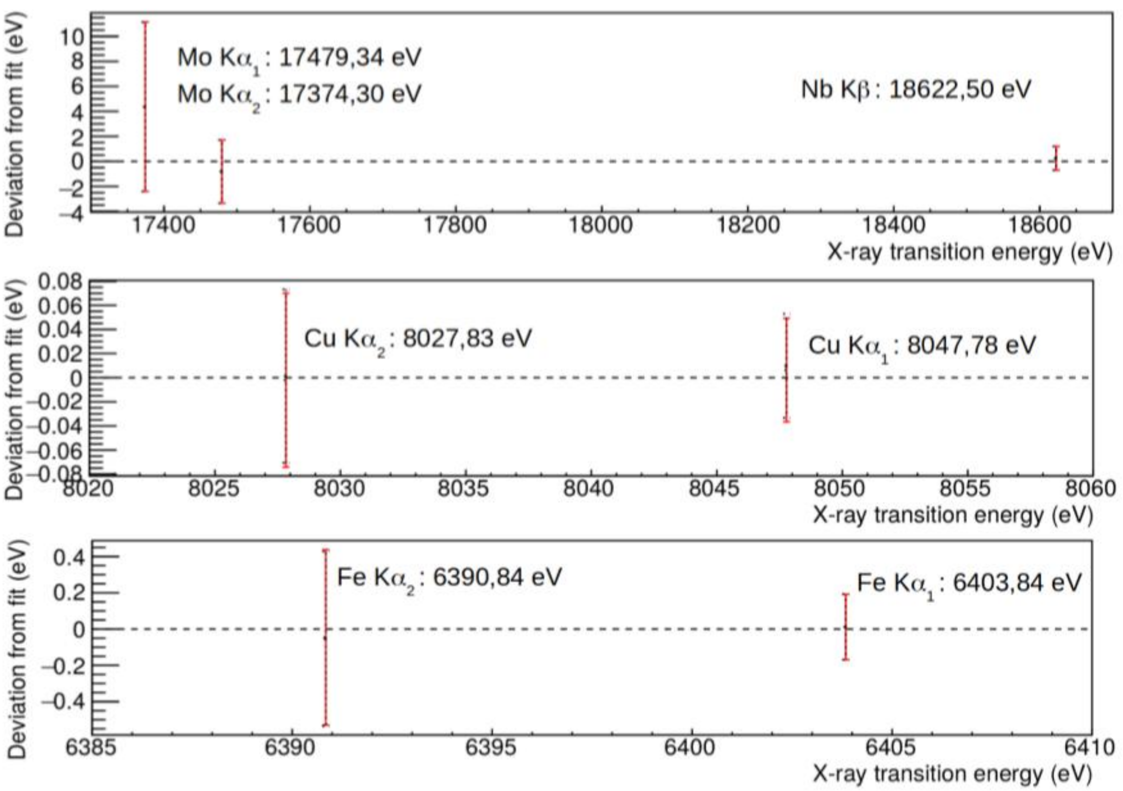
Given the small θ values (sinθ ≈ θ),
is it also possible to calibrate with a polynomial?

Information loss???

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)