Characterization of a High Resolution Von Hamos Spectrometer with HAPG Crystals for Extended Sources; a New Opportunity for High Precision Nuclear Physics Measurements

INFN-CSN5

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Scientific goal of VOXES

- High resolution (few eV) measurements of the X rays (2-20 keV) are strongly demanded and very difficult to be performed
- Semiconductor detectors: limited to 100 eV (FWHM)
- TES detectors : high cost, hard to handle, difficult lineshape calibration
- Standard Crystal Bragg spectrometers: low efficiency, limited in energy range (d)
- These X-rays not always are produced by a point-like source

VOXES's goal: to develop, test and qualify the first prototype of a high resolution X-ray Von Hamos spectrometer in the range of energies 2 - 20 keV using HAPG bent crystals able to work with 'extended' sources

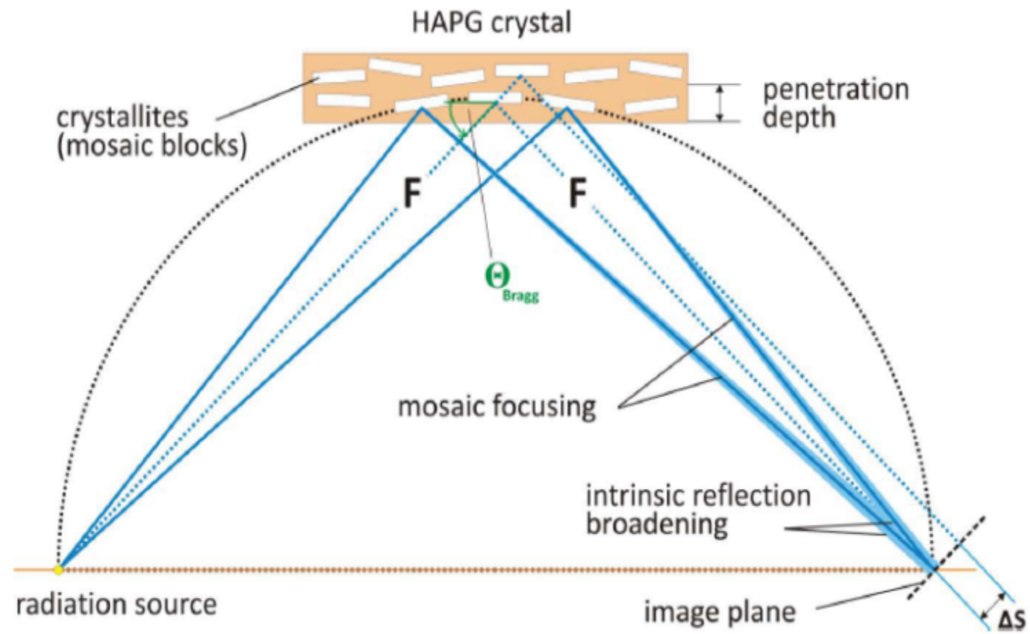
High resolution **vo**n-Hamos **X**-Ray spectrometer using HAPG for **E**xtended **S**ources in a broad energy range

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

VOXES: working principle and geometry - Mosaic crystals

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

Pyrolitic Graphite mosaic crystals (d = 3.354 Å):

$$nl = 2dsinq_B$$

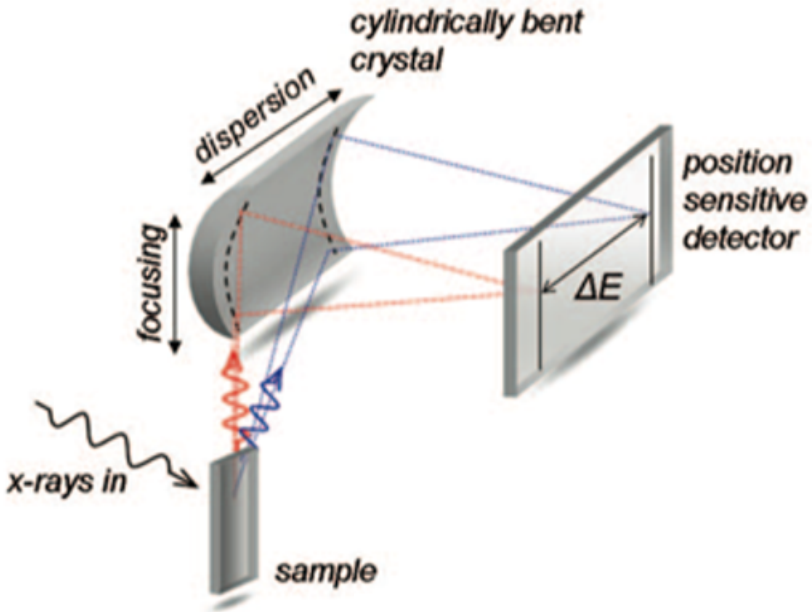
Highly Oriented Pyroliltic Graphite (HOPG, Dq≈1°)

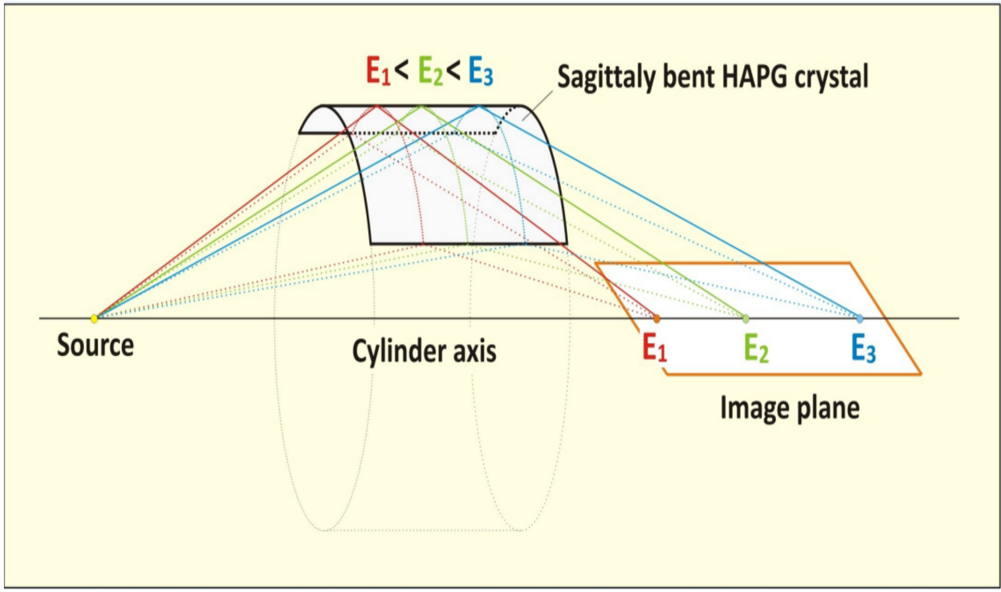
Highly Annealed Pyrolitic Graphite (HAPG, Dq≈0.07°)

flexible HAPG has twice higher spectral resolution, while flexible HOPG – approximately twice higher reflectivity

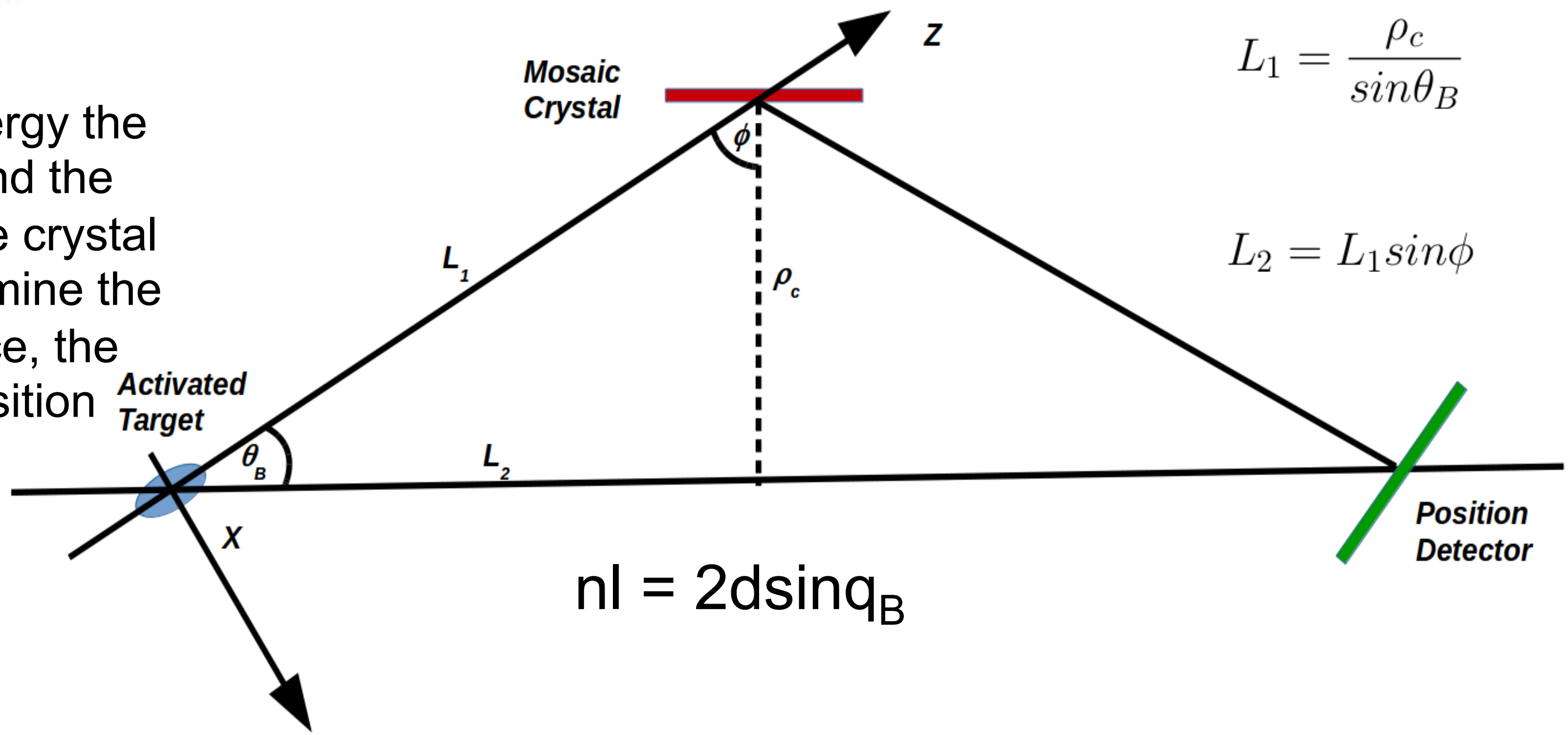
Tuneable based on the measurement requirements

VOXES: working principle and geometry - Von Hamos configuration





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



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

$$L_2 = L_1 sin\phi$$

$nl = 2dsinq_B$

Source size and VOXES geometry - Status of the art

Bragg spectroscopy is usually exploited by XAS, XES, synchrotron light users, etc…

- Point-like sources
- High yields (no need to increase them)
- 1 eV (Si, Mica, etc) or 2-3 eV (HAPG) resolution is very easily achievable

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

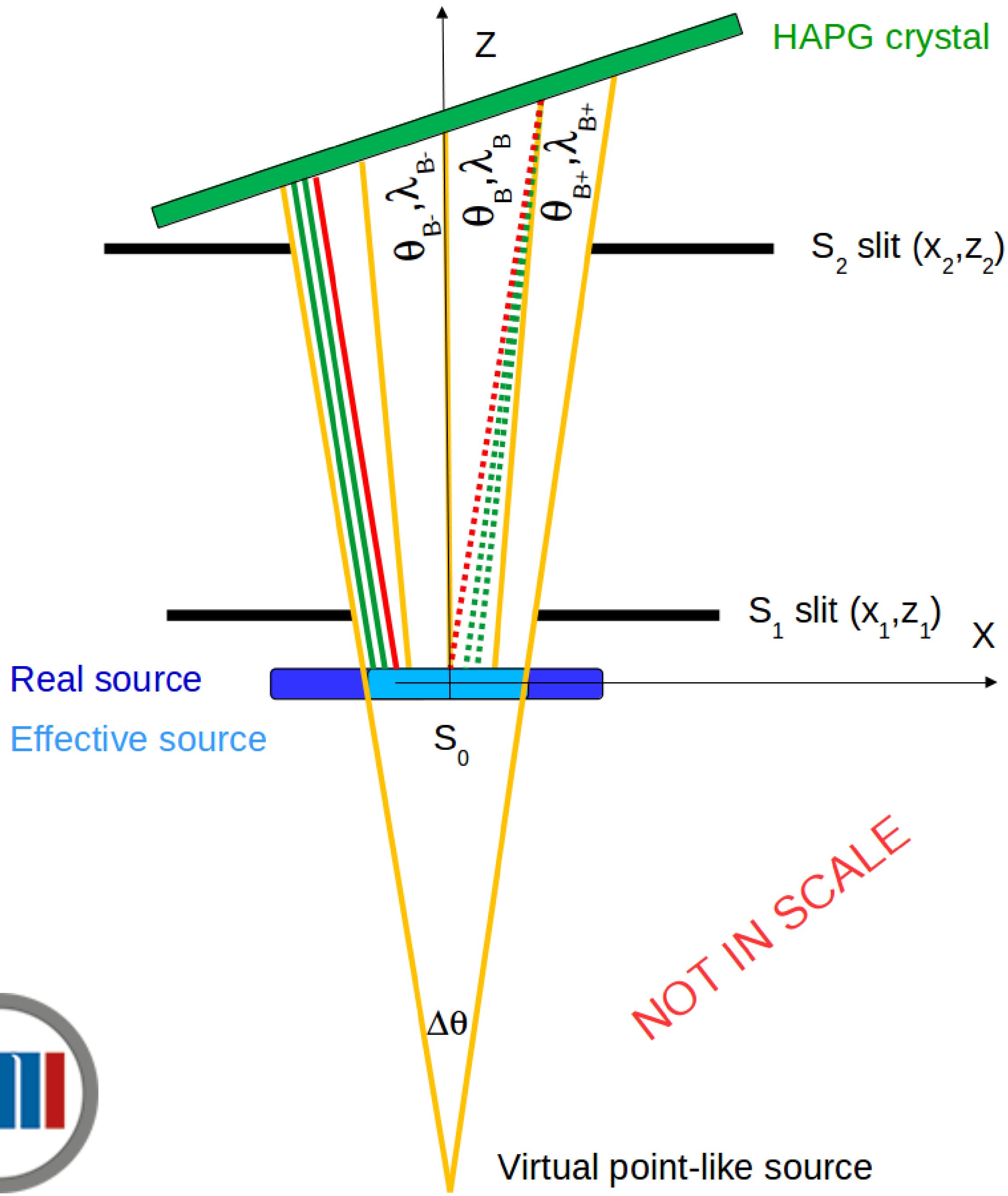
The spectrometer consists of three principal components the X-ray source, the HAPG optic, and the position sensitive detector. As source a watercooled 100 W micro focus X-ray tube with a tungsten anode and a focus size of 50 μm is used. The emitted radiation is focused onto the sample by a poly-capillary 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 $\sim$15 μm

But what if we really need wider sources for higher statistics?

Or what if our photons come from a diffused isotropic source?

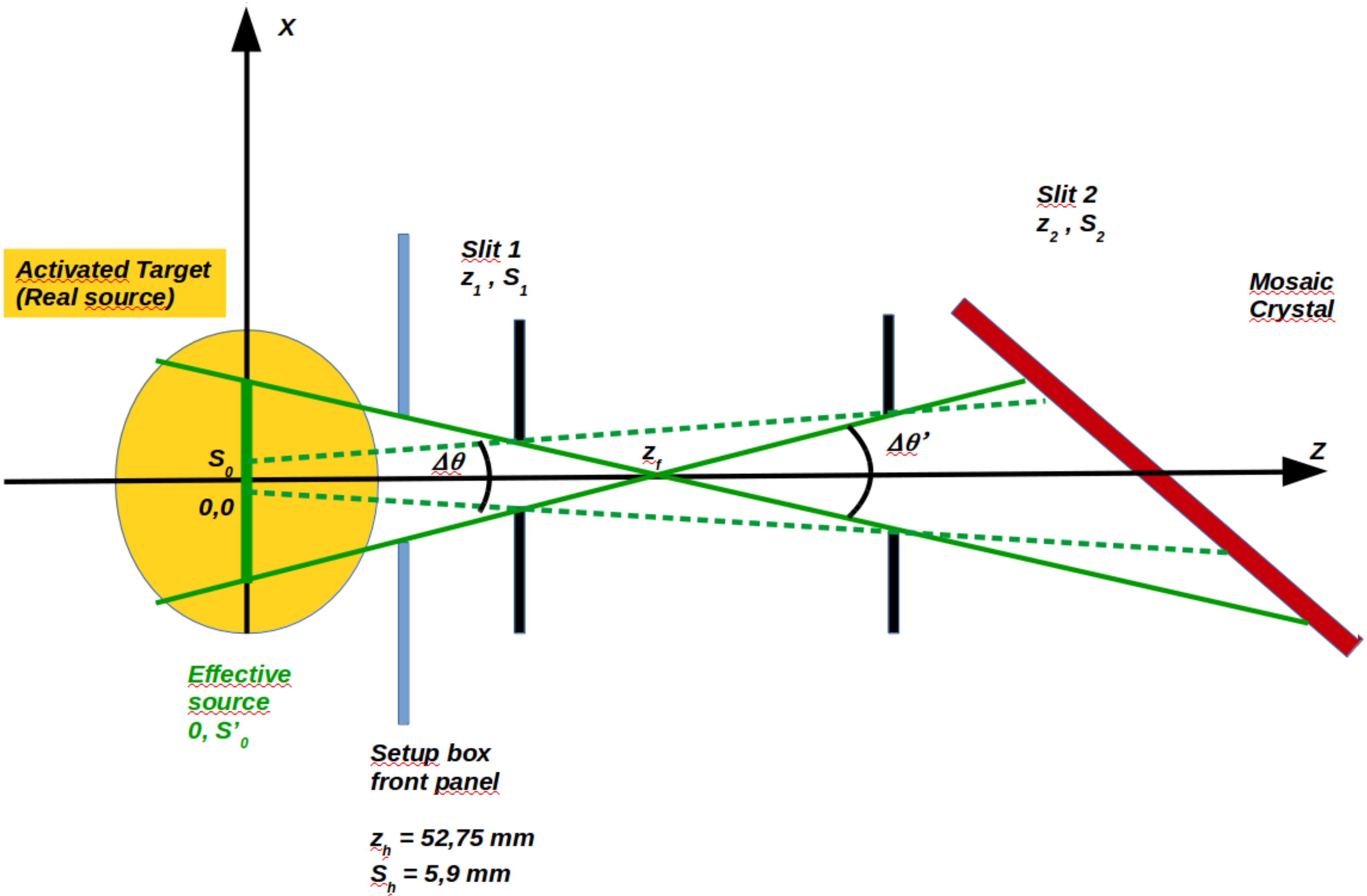
Source size and VOXES geometry - Virtual (point – like) source



X ray source
Slits
HAPG
Signal photons
Background (?)

With this configuration you are still limited to ~ mm sources and very compact spectrometers….

Source size and VOXES geometry - Dispersive plane source width



For each Δθ’ , S_0’ pair, the 2 values of the slits can be found; first, we define the position of the intersection point z_f :

$$z_f = \frac{S_0'}{2} ctg\left(\frac{\Delta\theta'}{2}\right)$$

Then, the 2 slits aperture are defined by:

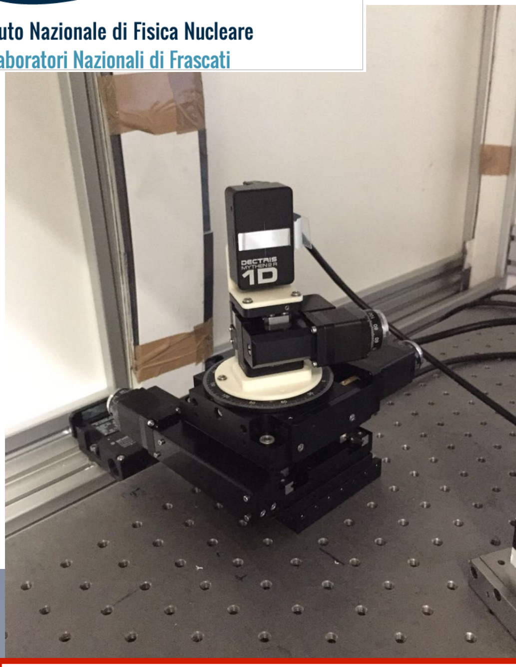
$$S_1 = \frac{z_f - z_1}{z_f} S_0'$$

$$S_2 = \frac{z_2 - z_f}{z_f} S_0'$$

and the vertical illuminated portion of the HAPG is

$$S_c = \frac{z_c - z_f}{z_f} S_0'$$

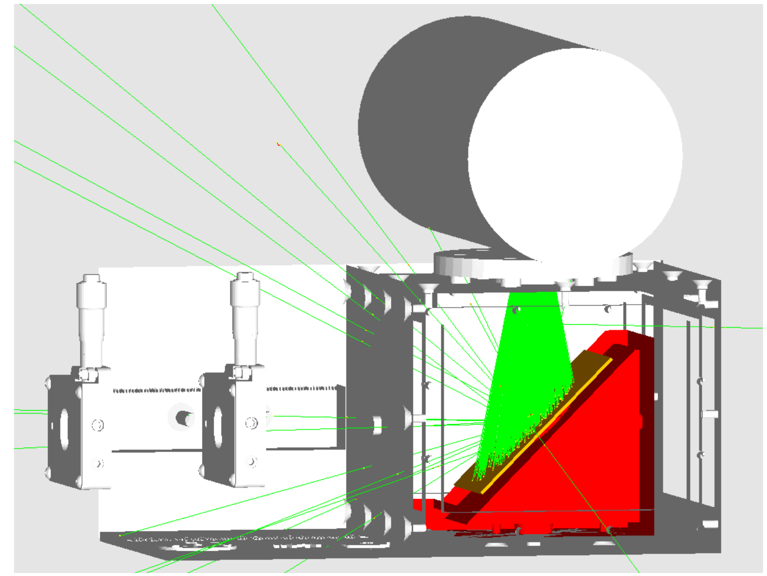
VOXES: Setup box and mechanics

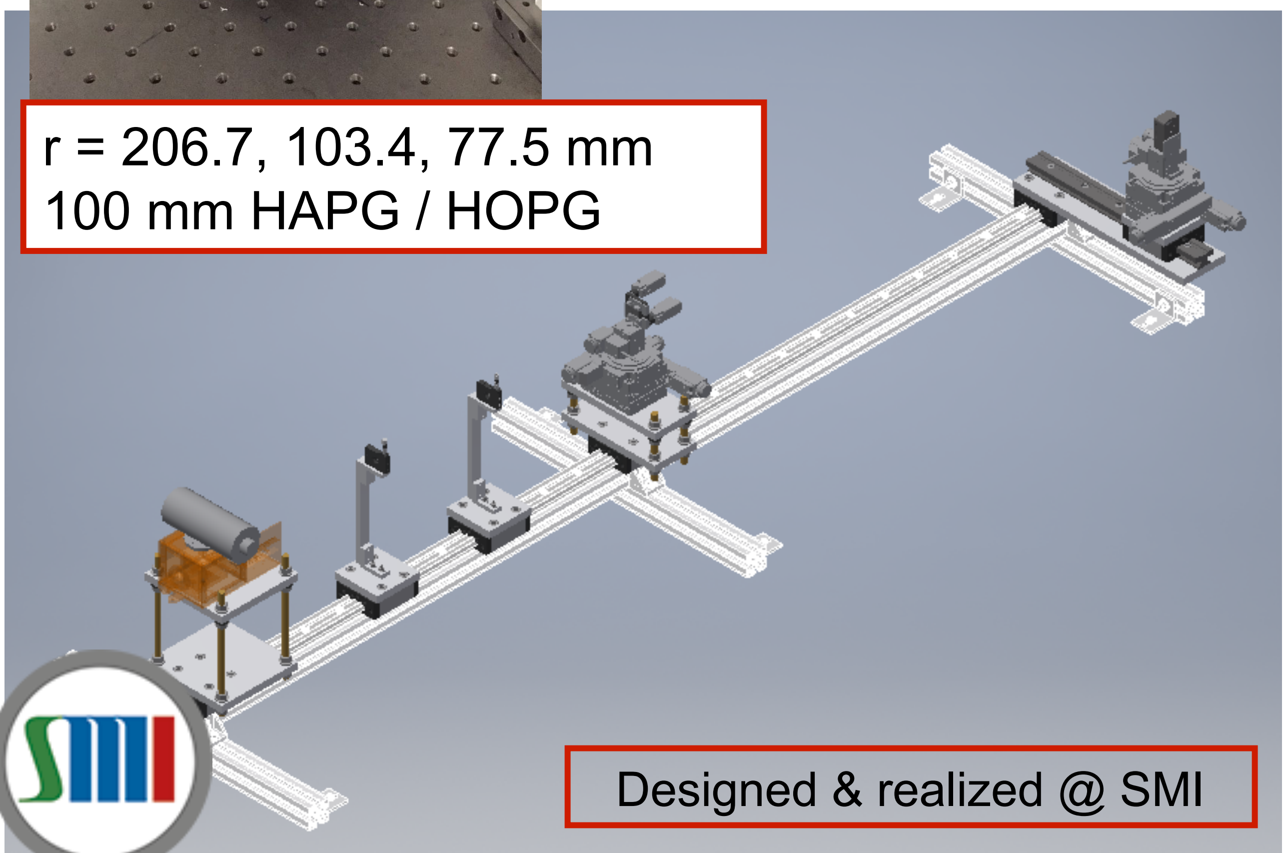


Dectris Ltd
MYTHEN2 detector:

32 x 8 mm surface
640 channels → 50 mm resolution
4-40 keV range
Working @ room temperature

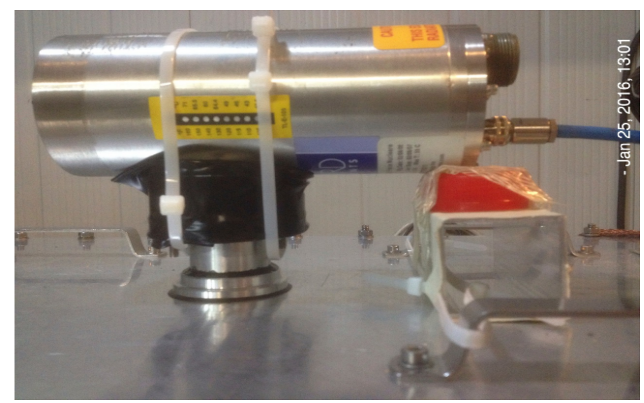
Designed & 3D-printed @ LNF





r = 206.7, 103.4, 77.5 mm
100 mm HAPG / HOPG

Designed & realized @ SMI



Oxford Instruments
XRF-5011
Tungsten (W) X-ray tube

Characterization and results in lab

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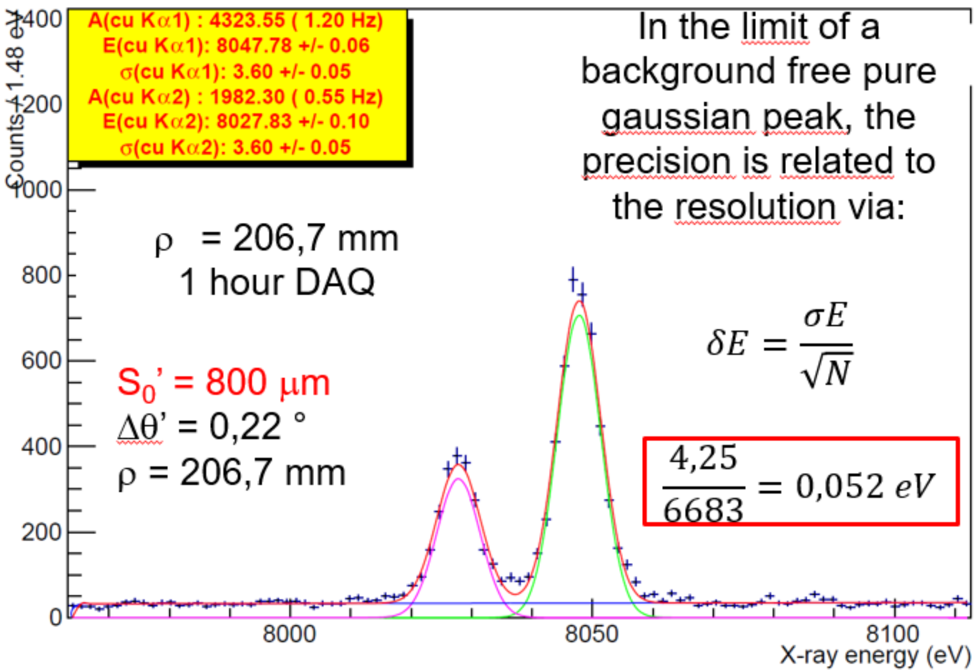
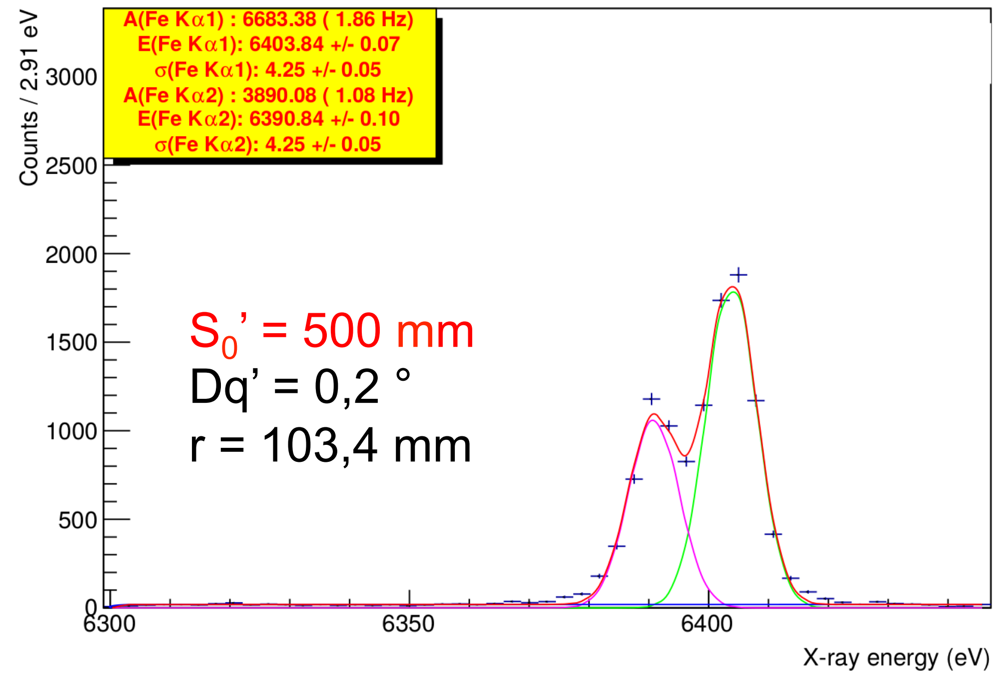
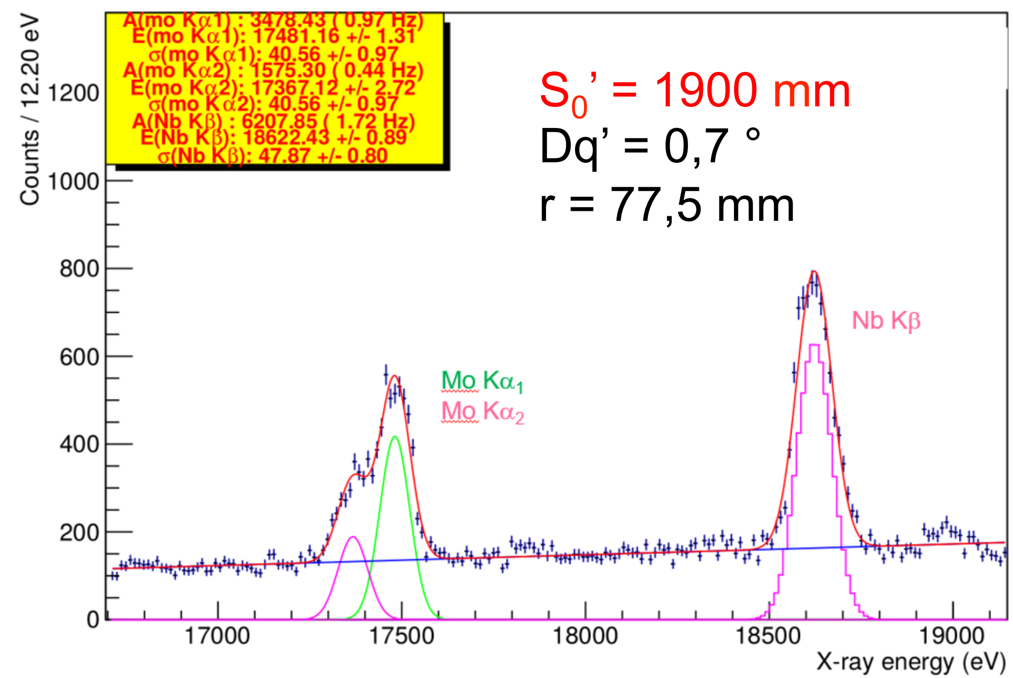


In the limit of a background free pure gaussian peak, the precision is related to the resolution via:

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

$$\frac{4,25}{6683} = 0,052\ eV$$



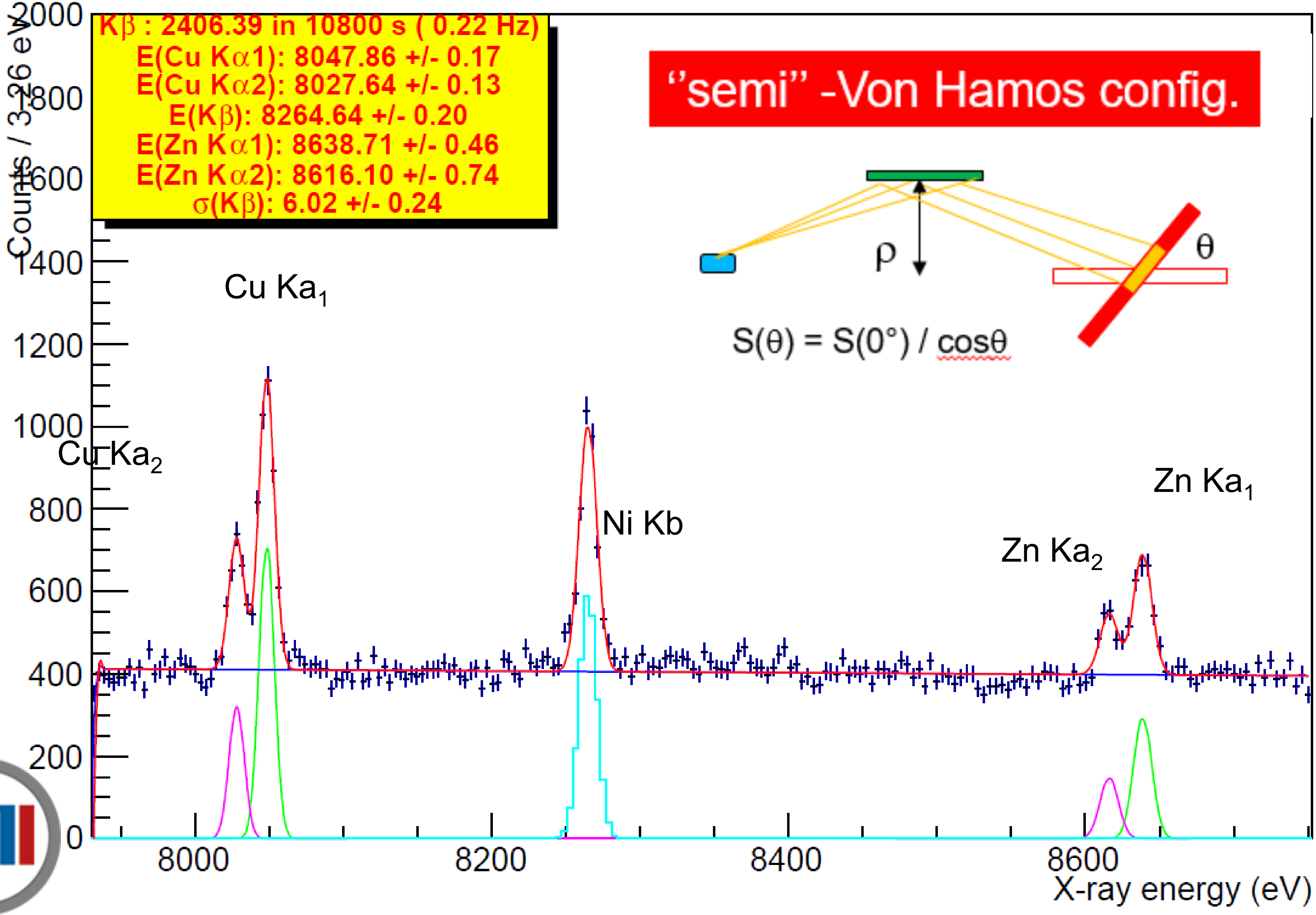


	Line (eV)	Line (A)	sinq	q	L1	L2
Fe Ka1	6403,84	1,94	0,29	16,77	716,58	686,09
Fe Ka2	6390,84	1,94	0,29	16,81	715,13	684,57
Fe Kb	7057,98	1,76	0,26	15,18	789,78	762,22

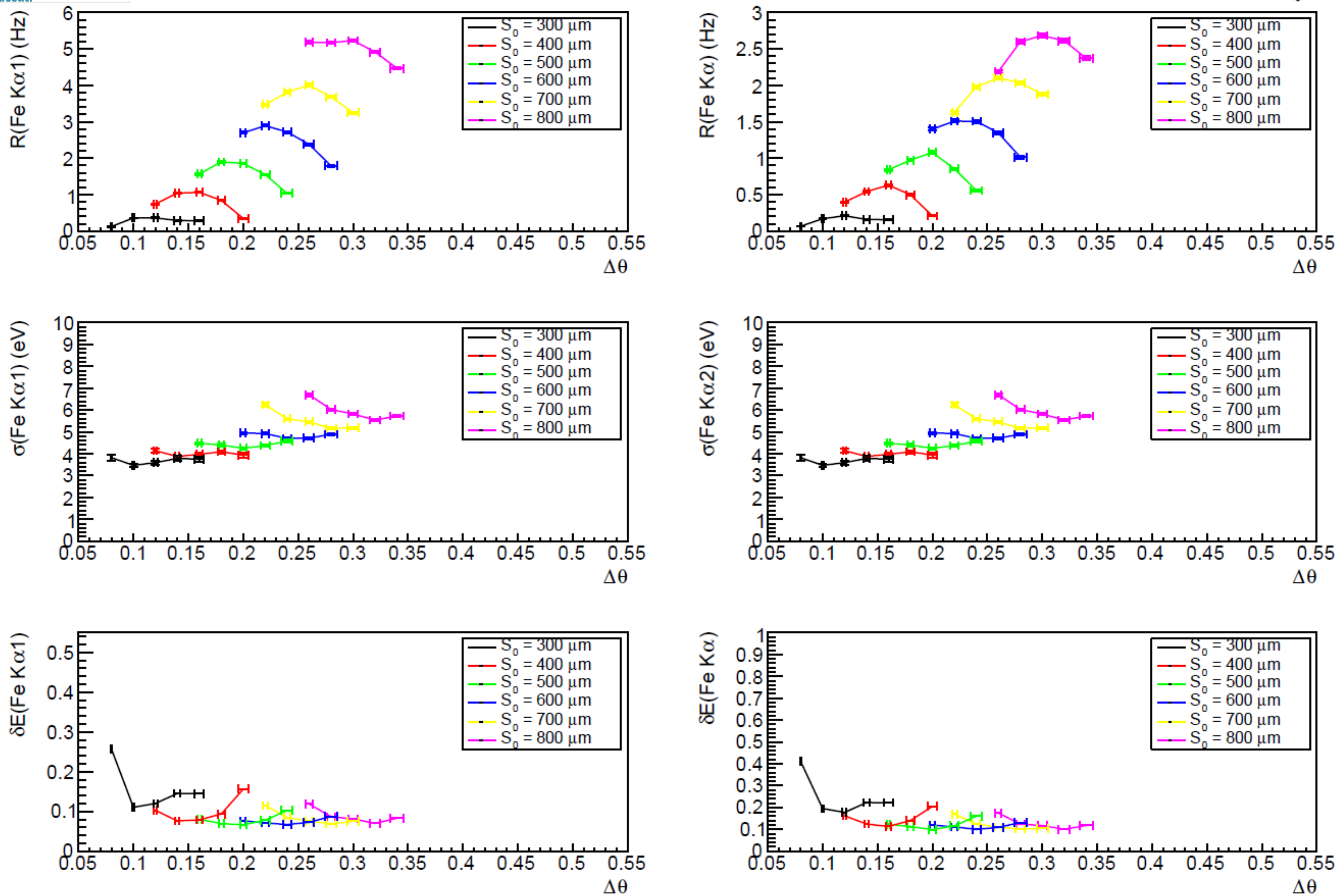
	Line (eV)	Line (A)	sinq	q	L1	L2
Cu Ka1	8047,78	1,54	0,23	13,28	900,54	876,47
Cu Ka2	8027,83	1,54	0,23	13,31	898,31	874,18
Cu Kb	8905,29	1,39	0,21	11,98	996,49	974,80

	Line (eV)	Line (A)	sinq	q	L1	L2
Mo Ka1	17479,34	0,71	0,11	6,07	733,35	729,24
Mo Ka2	17374,30	0,71	0,11	6,11	728,94	724,81
Nb Kb	18622,50	0,67	0,10	5,70	781,31	777,46

Wide dynamic range



Step-2: Multi line setup and and complete characterization

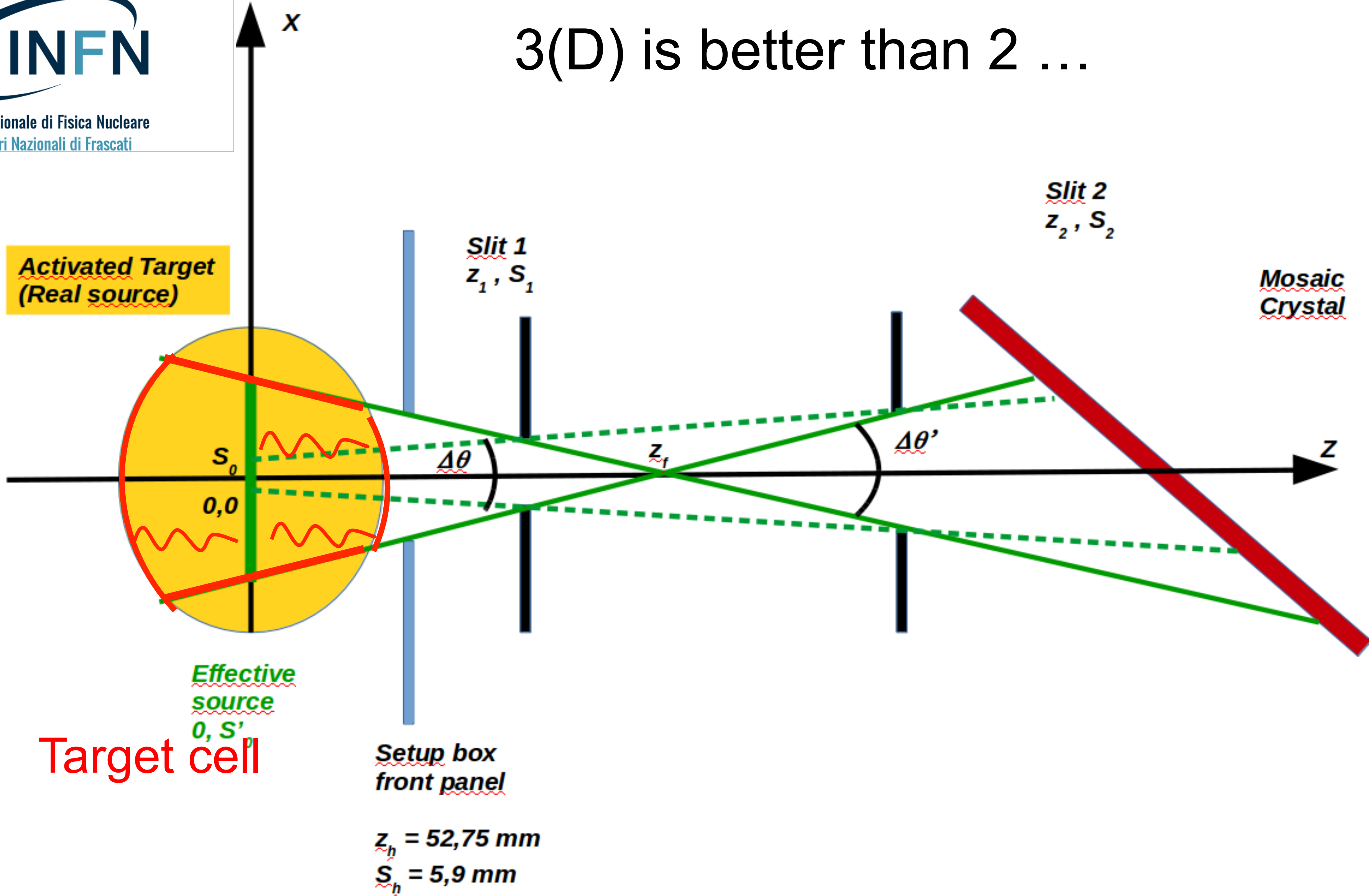


Example for Fe lines with r = 103,5 HAPG crystal, 60 m DAQ

Step-2: Multi line setup and and complete characterization

Crystal & Line	e (10^{-5})	s (eV)	dE (eV)
Cu (8 keV) r = 77,5 mm	2,7 (700 mm)	6,8 (700 mm)	0,07 (600 mm)
Cu (8 keV) r = 103,4 mm	2,8 (700 mm)	4,8 (300 mm)	0,04 (700 mm)
Cu (8 keV) r = 206,7 mm	1,1 (1100 mm)	3,6 (800 mm)	0,04 (1100 mm)
Fe (6 keV) r = 77,5 mm	4,5 (600 mm)	4,2 (300 mm)	0,1 (600 mm)
Fe (6 keV) r = 103,4 mm	1,6 (700 mm)	4 (300 mm)	0,09 (700 mm)
Fe (6 keV) r = 206,7 mm	0,8 (1300 mm)	3,6 (1100 mm)	0,1 (1200 mm)
Fe (6 keV) r = 103,4 mm NEW Al BOX	2,2 (800 mm)	3,5 (300 mm)	0,07 (500 mm)

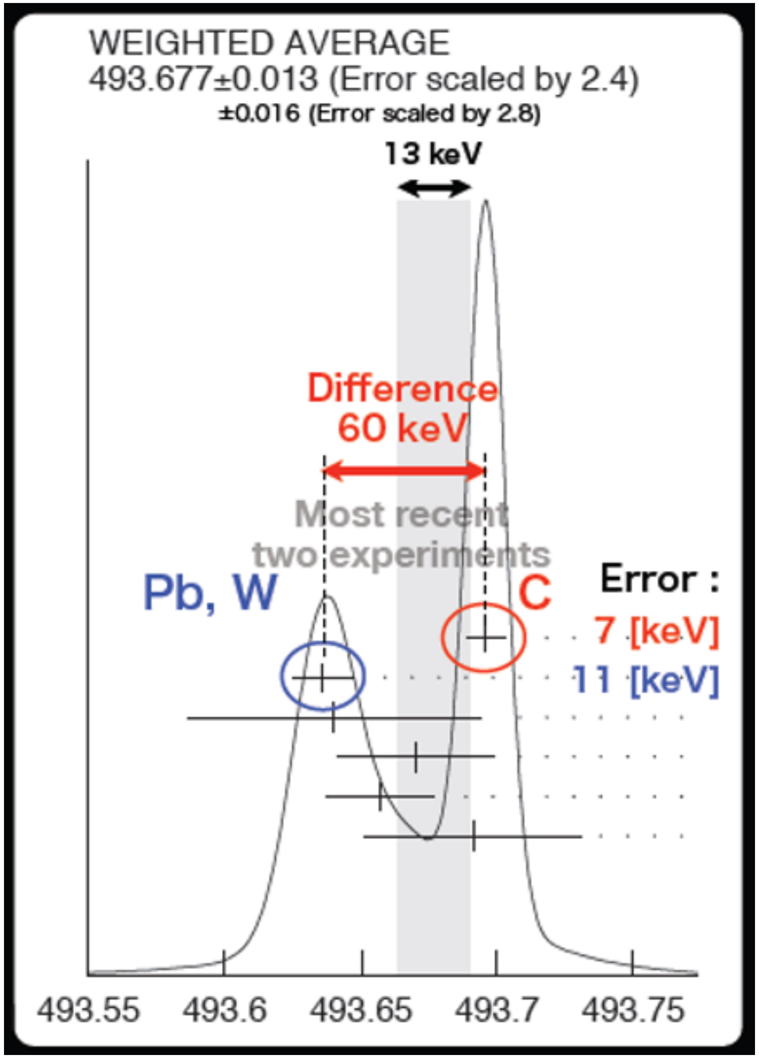
3(D) is better than 2 …

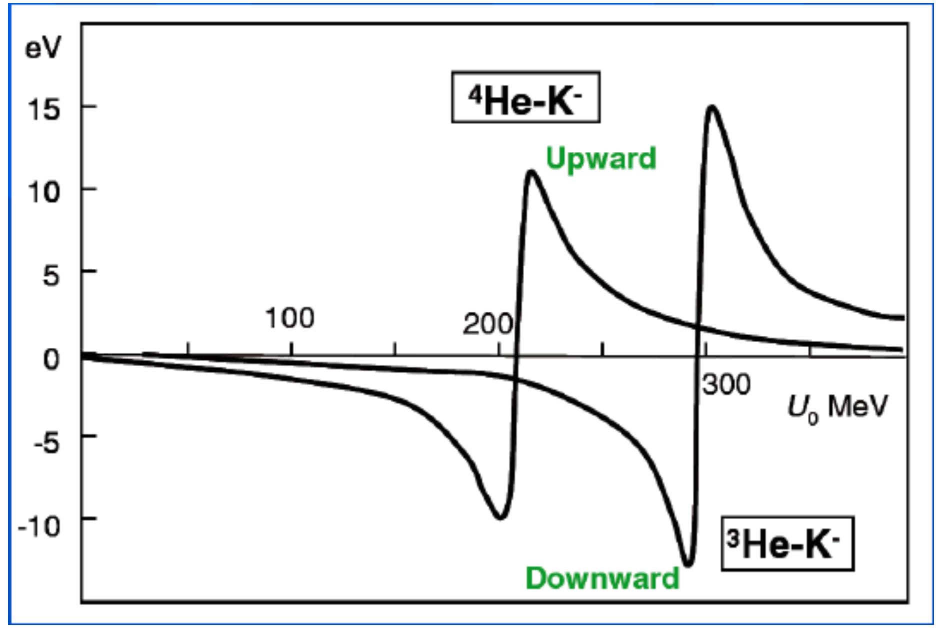


$A_T(r=103{,}4\ mm;\ S_0=0{,}7\ mm) = 100\ mm \times 8\ mm^2$

$A_T(r=103{,}4\ mm;\ S_0=0{,}7\ mm) = 100\ mm \times 8\ mm^2$

Possible applications in nuclear physics: kaonic atoms @ DAFNE





Best measurements:

Target	?	?
^{4}He	+5 ±3 (stat.) ±4 (syst.)	14 ±8 (stat.) ± 5 (syst.)
^{3}He	−2 ±2 (stat.) ±4 (syst.)	6 ±6 (stat.) ±7 (syst.)

Transition	Ryd. Energy (eV)	Exp. Energy (eV)	Prec. for 5 keV (eV)	Prec. for 10 keV (eV)
$KC(5 \to 4)$	10173.2	10216.5 ± 1.8	0.0906373	0.181275
$KC(6 \to 5)$	5526.17	5545.7 ± 4.2	0.0492351	0.0984702
$KN(5 \to 4)$	13931	13996	0.126397	0.252794
$KN(6 \to 5)$	7567.48	7560 ± 32	0.0686601	0.13732
$KN(7 \to 6)$	4562.95	4589 ± 32	0.0413998	0.0827997
$KO(6 \to 5)$	9929.12	9968.7	0.0913251	0.18265

In VOXES range

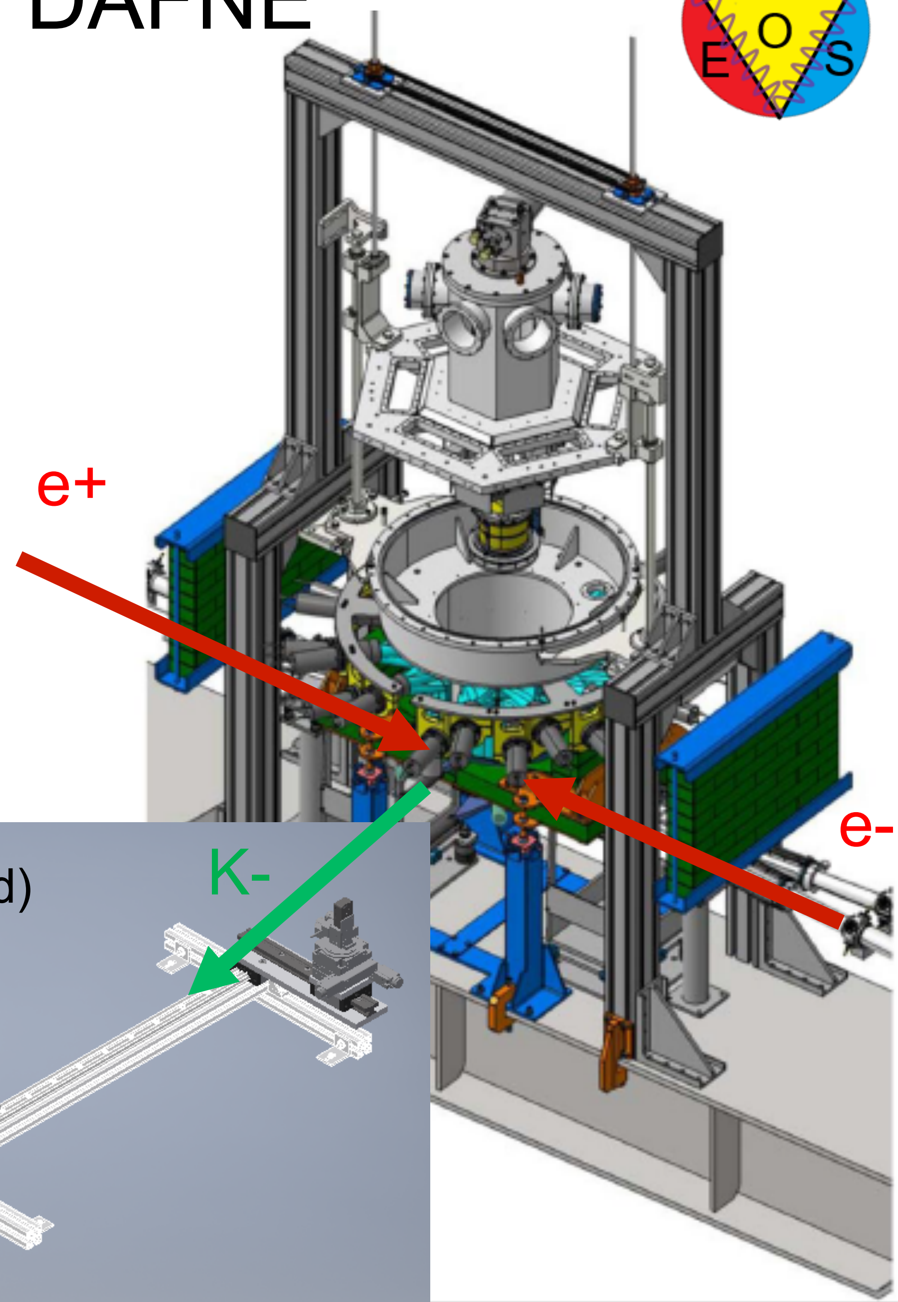
Test measurements @ DAFNE

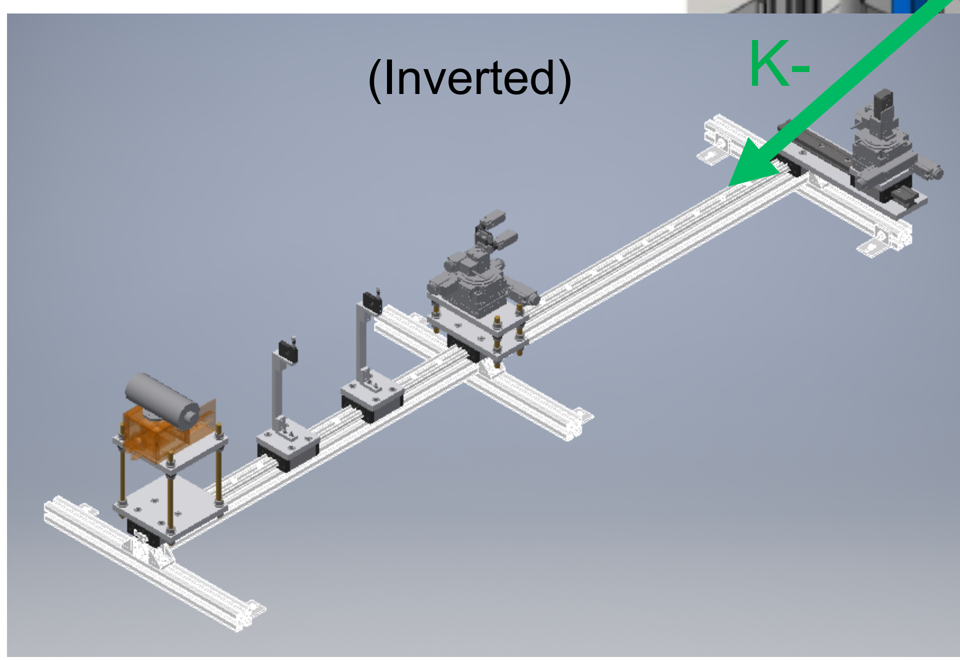
To be realized:

1) Shielding around Detector
2) Solid support structure (alignement)
3) Multi - Crystal support structure
4) Target (Solid or Liquid/Gas)

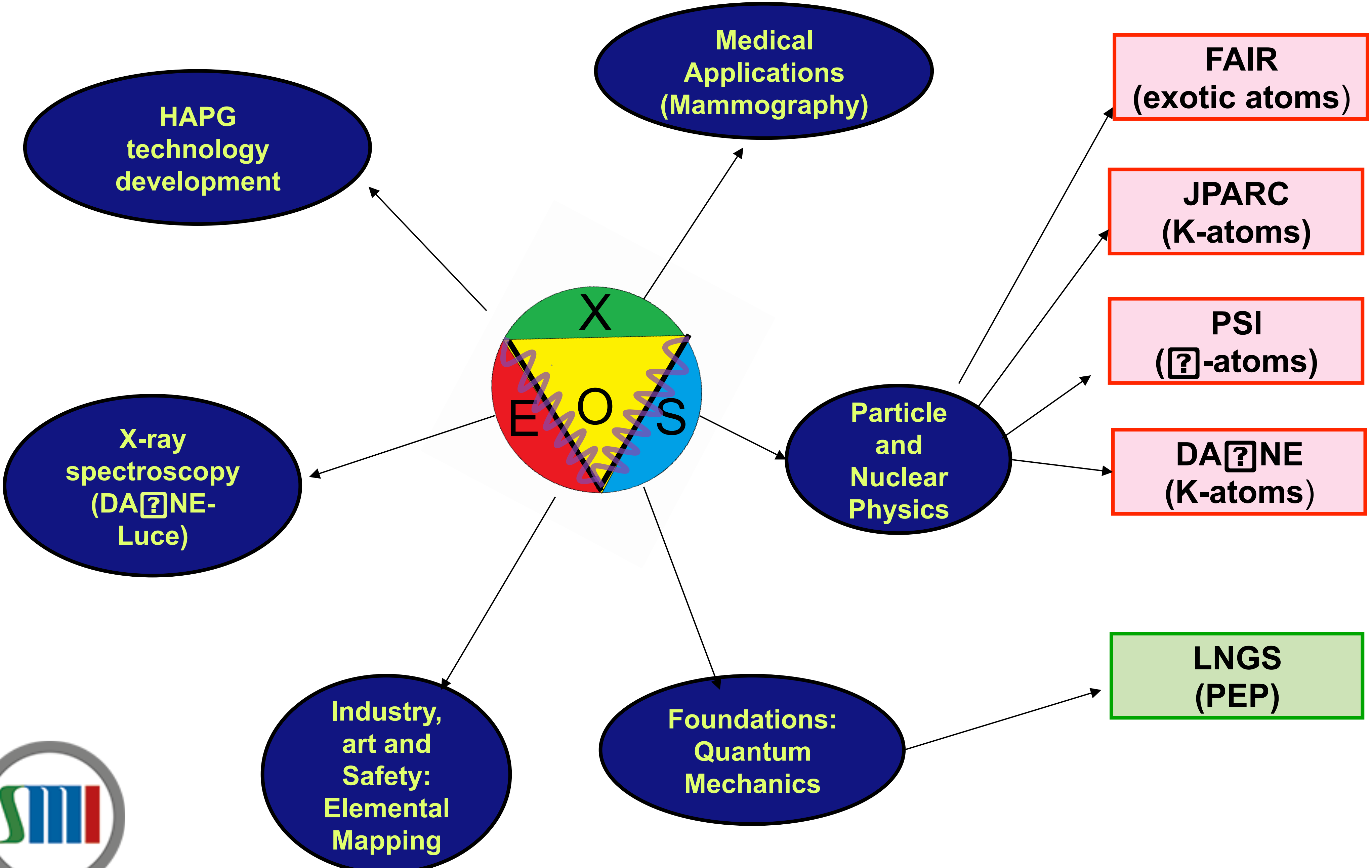
Available:

1) Optics
2) Alignement support
3) Target box
4) Detector
5) DAQ (integ. KM)



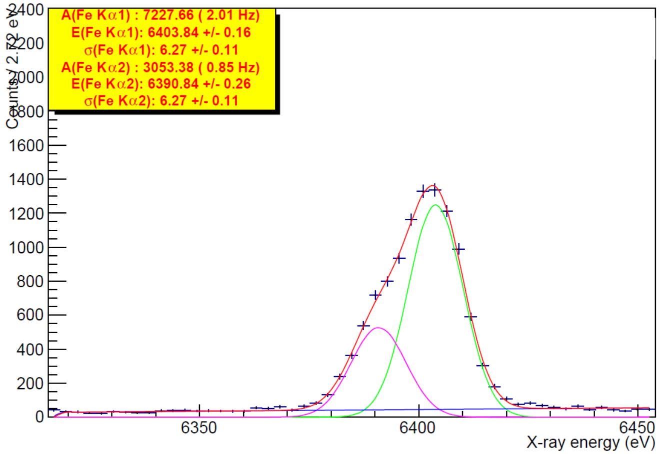


Impact (scientific, technological, socioeconomic)



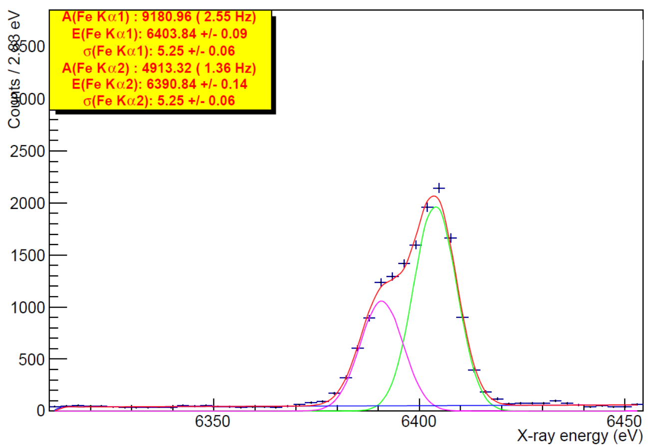
Thanks for your attention

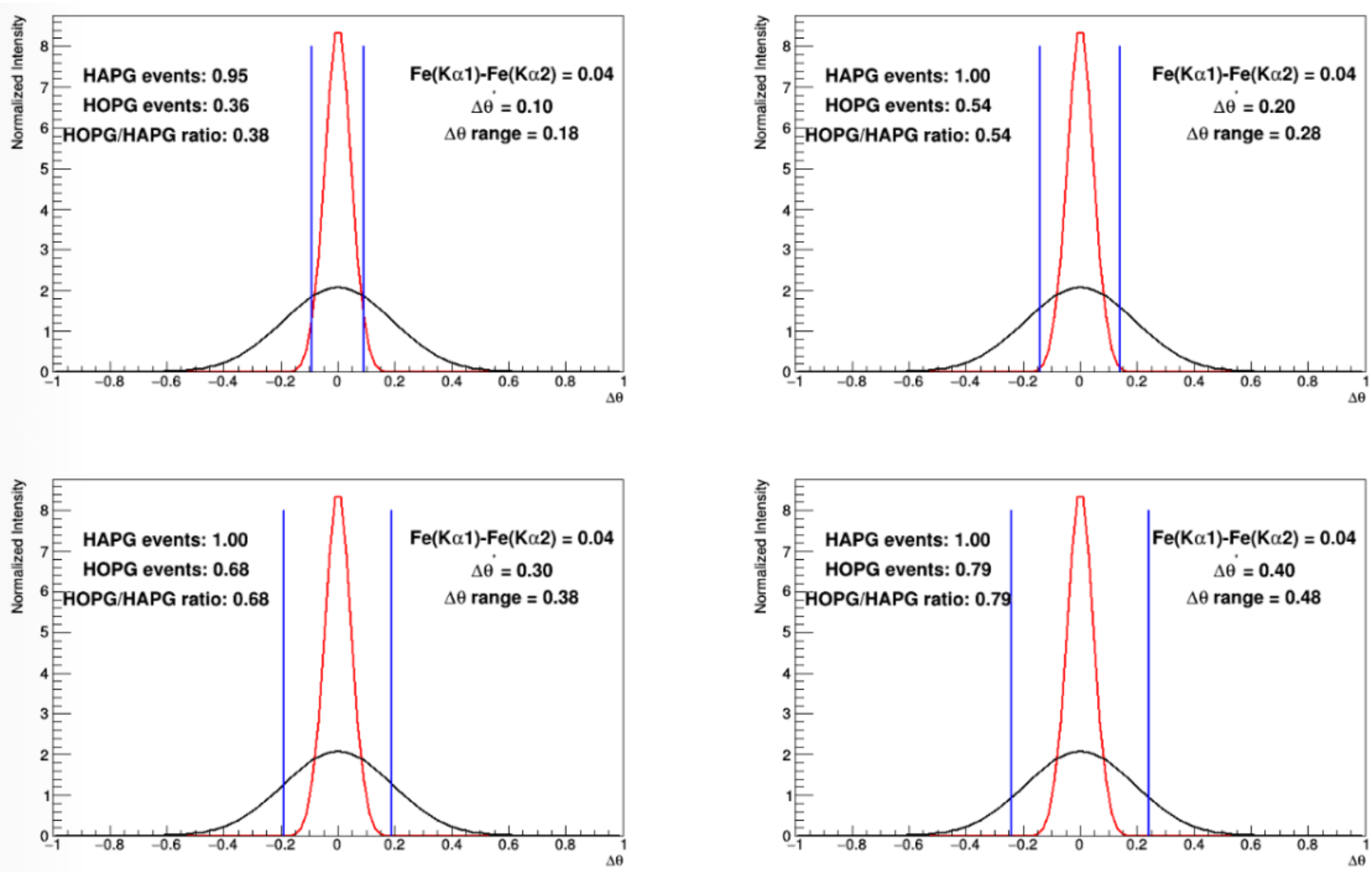
Fe Ka, 103,4 mm r



Best results for S_0' = 700 mm and
Dq' = 0,34°

dE (Fe Ka_1) = 0,09 eV
s (Fe Ka_1) = 5,44 eV





R(HOPG/HAPG) = 0,78

KC / KN @ DAFNE

Assuming SIDDHARTA like DAFNE conditions &

- Scaling for solid/gas target dimension
- 1->3 crystals
- Using K^-rate from KM (2009)
- Scaling efficiencies for KN/KC

Solid target	KC (5→4)	KC (7→5)
Yield	17,3 %	4 %
ev / 200 gg	95	16
dE (200 gg)	(≈) 0,7 eV	(≈) 1,6 eV

Liquid target	KN (6→5)	KN (5→4)
Yield	5,5 %	5,7 %
ev / 200 gg	22000	20000
dE (200 gg)	(≈) 0,04 eV	(≈) 0,05 eV

(Liquid/gas target allow different and more eff. Geometry)

Transition	Ryd. Energy (eV)	Exp. Energy (eV)	Prec. for 5 keV (eV)	Prec. for 10 keV (eV)
$KC(5 \to 4)$	10173.2	10216.5 ± 1.8	0.0906373	0.181275
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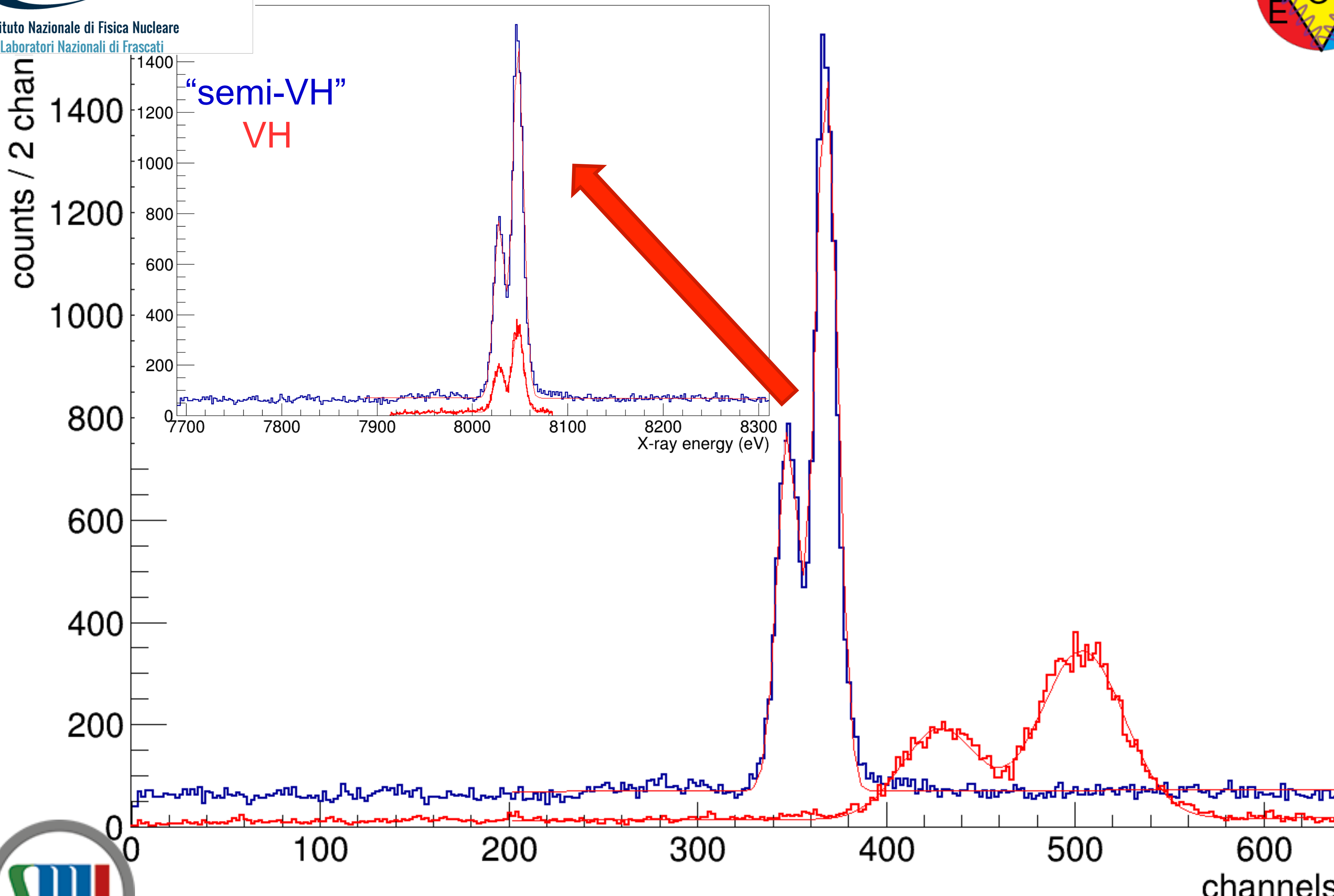
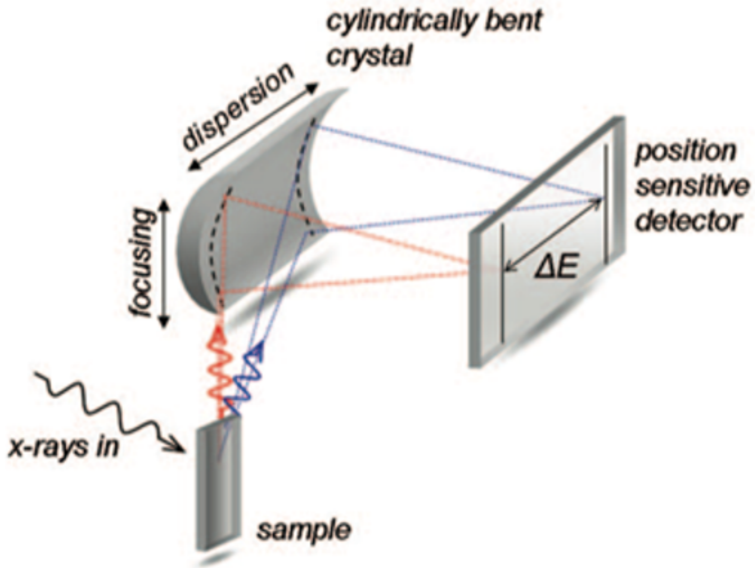
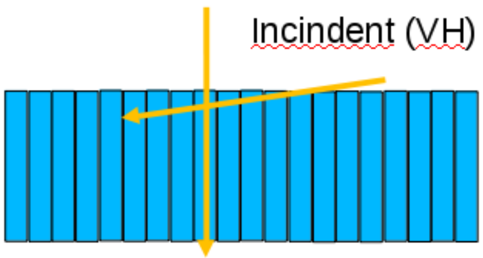
VH vs 'semi'-VH configuration



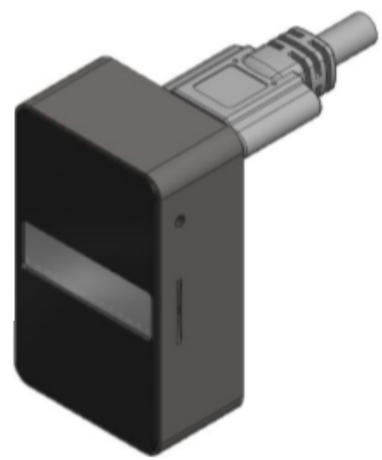
Semi – VH configuration



Incident (VH) angle θ ≈ 10°

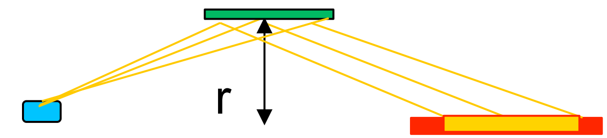


450 μm thickness
(optimized for 6-8 keV)

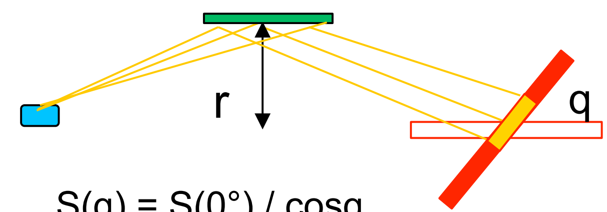


Protective layer
12 mm Mylar

Von Hamos configuration

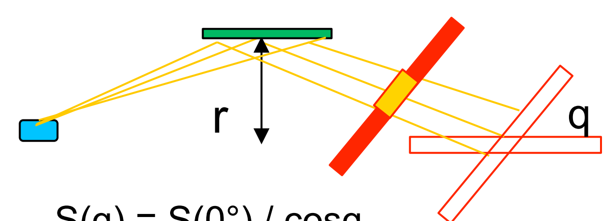


"semi" -Von Hamos config.



S(q) = S(0°) / cosq

OOF-"semi" -Von Hamos config.

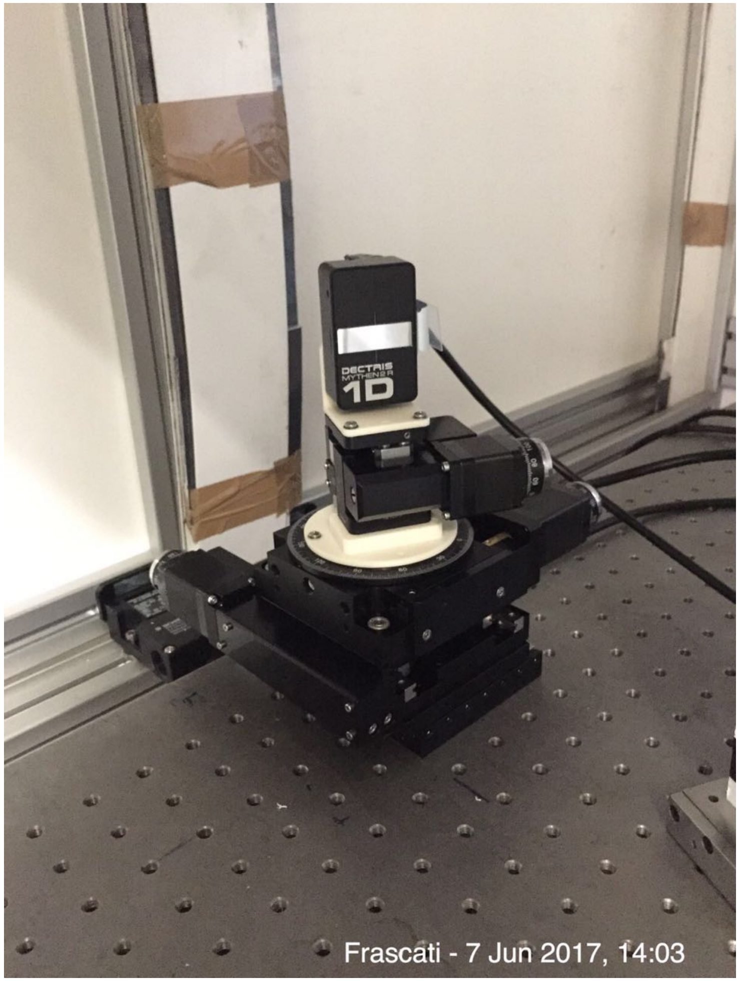


S(q) = S(0°) / cosq

Out Of Focusing configuration:

Exact focusing is not important within the detector strip length

VOXES: Mythen2 strip detector



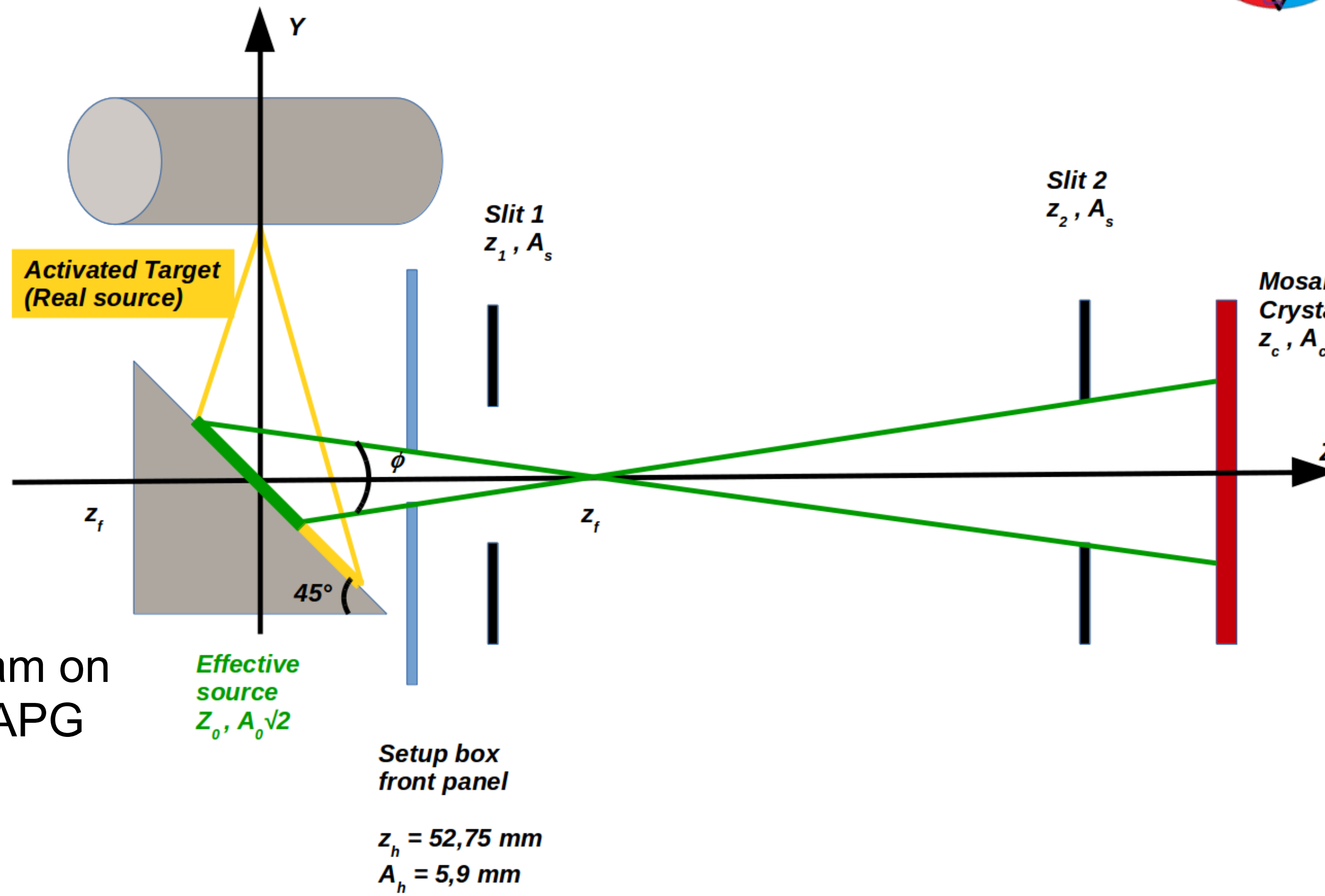
MYTHEN2 R	1K	1D
Sensor thickness [μm]	320, 450, 1000	
Strip width [μm]	50	
Strip length [mm]	8 and 4 (320 μm only)	
Dynamic range [bit]	24	
Energy range [keV]	4-40*	
Readout time [μs]	89	
Frame rate [Hz]	25	
Point-spread function [strip]	1	
Energy resolution[2] (rms) [eV]	687 ± 5	
Cooling	Air	
Module dimensions (WHD) [mm^3]	70x62x22	38x62x22
Module weight [g]	180	100
DCS4 dimensions (WHD) [mm^3]	110x30x160	
DCS4 weight [g]	400	

Peltier Cell to keep →

Condition	***Range***
Operating temperature	18°C to 28°C
Operating humidity	< 75% RH @ 23°C
Storage temperature	15°C to 40°C
Storage humidity	< 75% RH @ 20°C

Source size and VOXES geometry - Focusing plane source width

The vertical spread of the X-ray beam is fixed by the slits positions (z_1,z_2) and their frame size (A_s), together with the hole in the front panel of the setup box (z_h,A_h).



The vertical spread of the beam on the target (A_0) and on the HAPG crystal (A_c) are then:

$$A_0 = 2z_f tg\phi$$

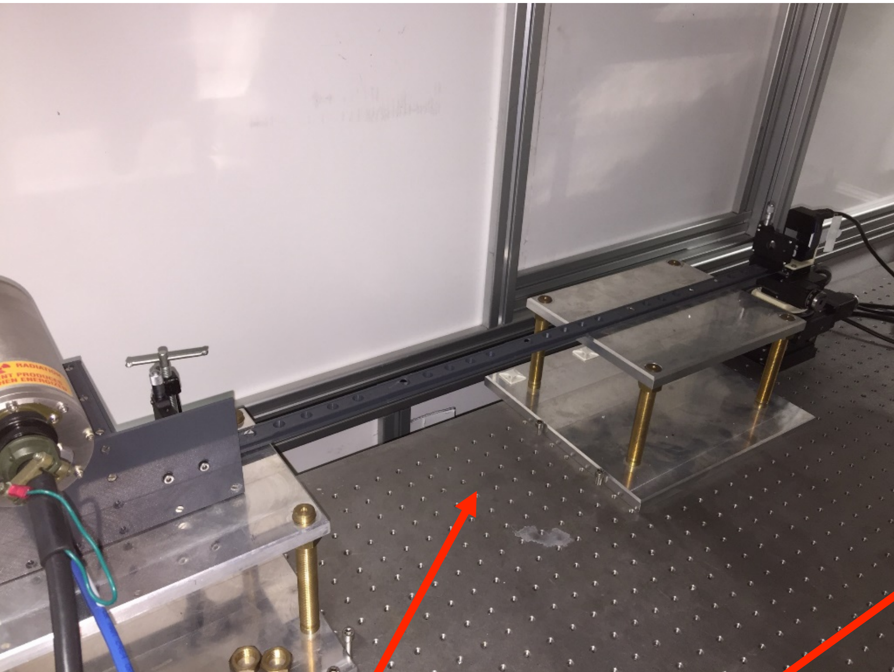
$$A_c = 2(z_c - z_f)tg\phi$$

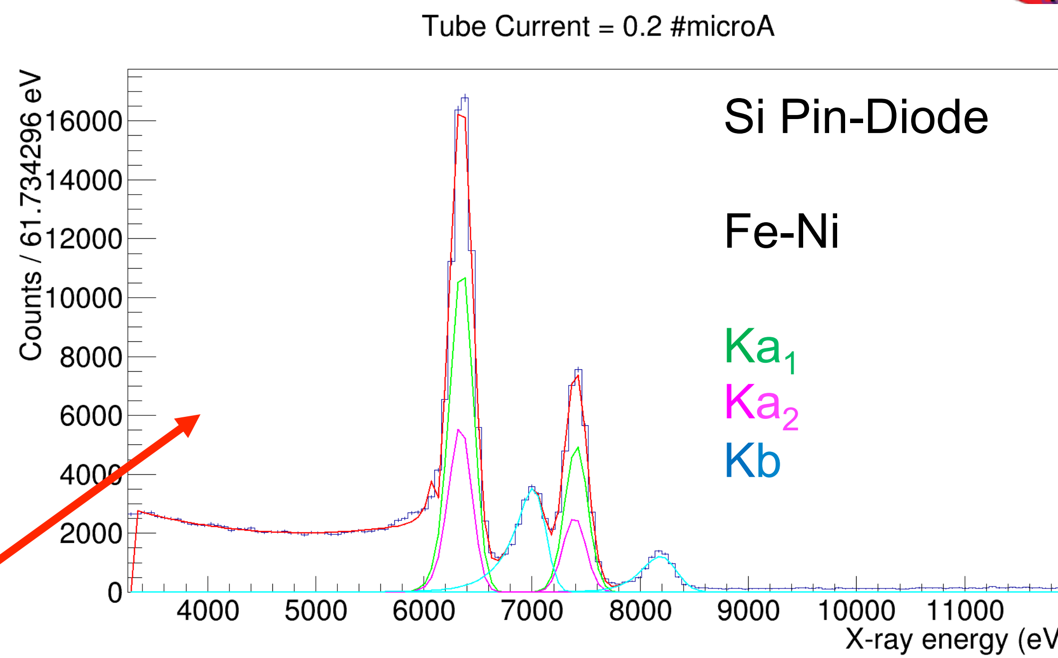
We first define the position of the intersection point z_f and the f angle :

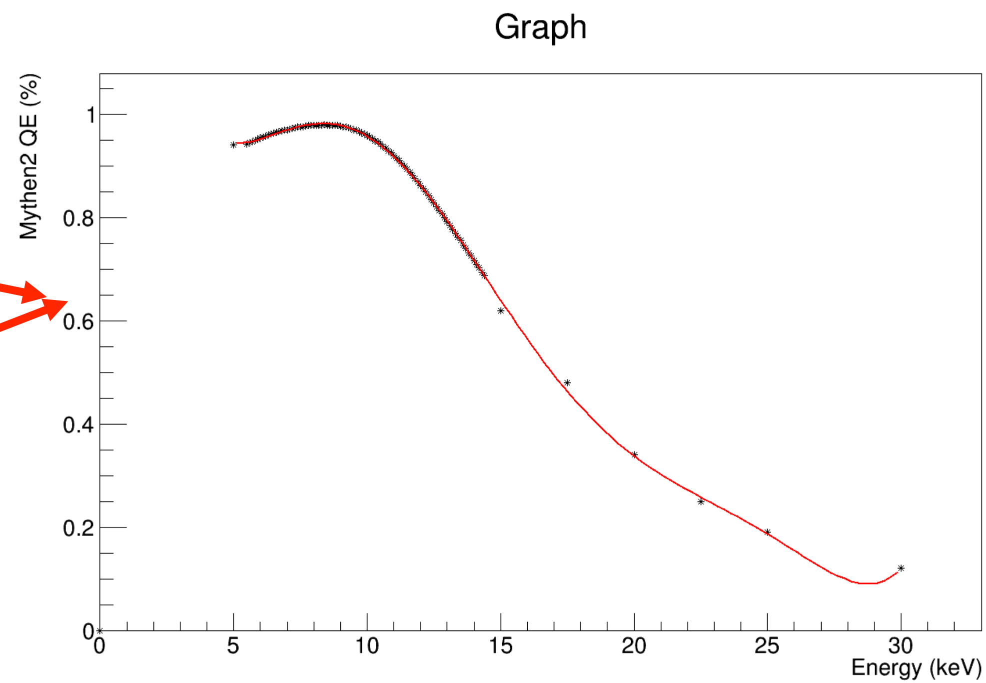
$$tg\phi = \frac{A_s + A_h}{2(z_2 - z_h)}$$

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

Crystal reflection efficiency







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

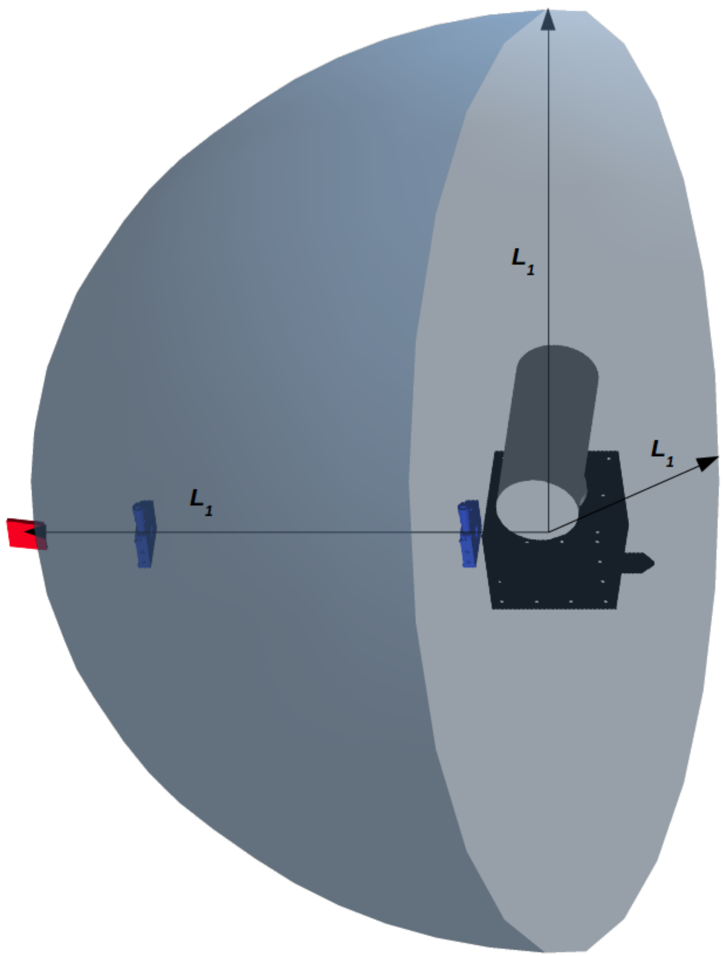
$$R^B = R^B_{\Delta\theta', S'_0} \frac{1}{T_{air}} \frac{1}{QE^M}$$

$$\epsilon_R = \frac{R^B}{R^D} = \frac{R^B_{\Delta\theta', S'_0} \times 8\,mm}{R^M_{\Delta\theta', S'_0} \times T_{air} \times R(S/B) \times A}$$

Spectrometer efficiency

$$R^M_{\Omega_{4\pi}} = \frac{R^M_{\Delta\theta',S'_0}}{QE^M}\frac{L1^2}{A^M_{\Delta\theta',S'_0}}R(S/B)$$

$$\epsilon_{\Omega 4\pi} = \frac{R^B_{\Delta\theta',S'_0}QE^M A^M_{\Delta\theta',S'_0}}{R^M_{\Delta\theta',S'_0}R(S/B)L_1^2}$$

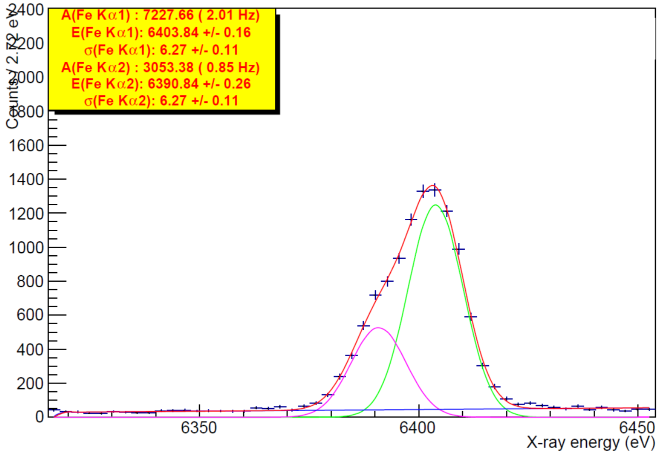


With respect to a 23,4 mm^2 TES placed at L_1 from the source:

$$R^{TES} = R^M_{\Delta\theta',S'_0}\frac{QE^{TES}}{QE^M}\frac{A^{TES}}{A^M_{\Delta\theta',S'_0}}R(S/B)$$

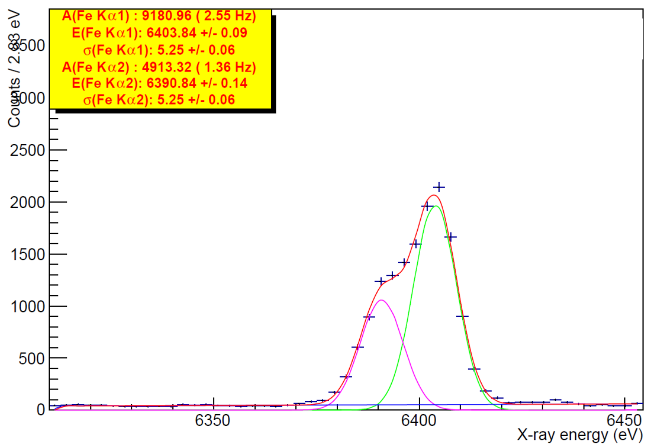
$$\epsilon_{TES} = \frac{R^B_{\Delta\theta',S'_0}}{R^M_{\Delta\theta',S'_0}R(S/B)}\frac{QE^M}{QE^{TES}}\frac{A^M_{\Delta\theta',S'_0}}{A^{TES}}$$

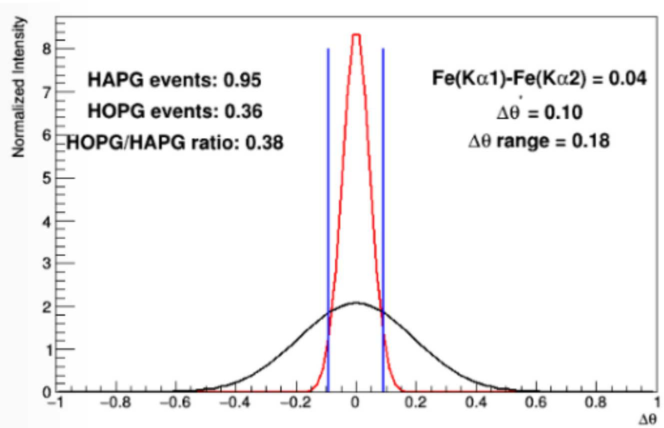
Fe Ka, 103,4 mm r

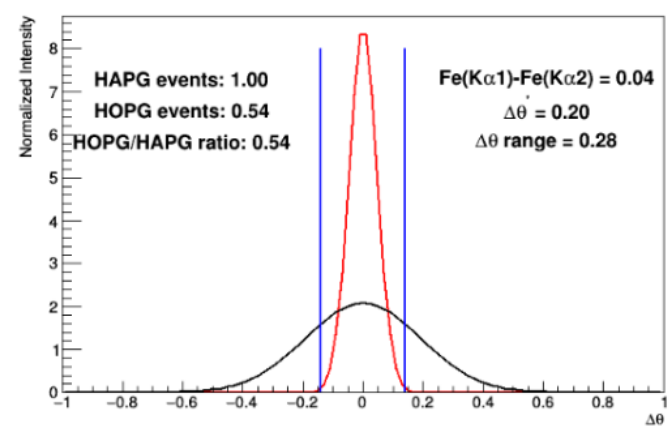


Best results for S_0' = 700 mm and
Dq' = 0,34°

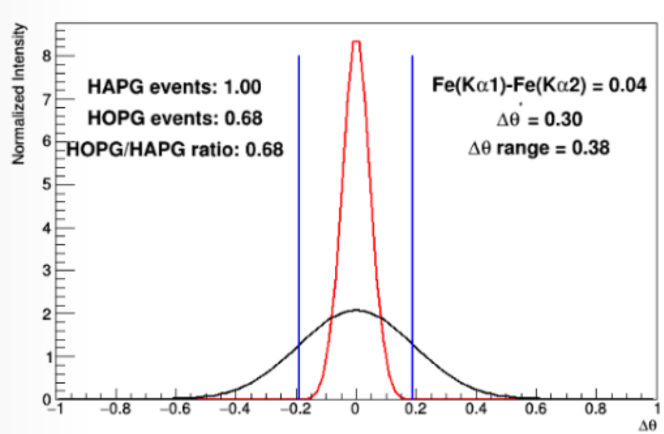
dE (Fe Ka_1) = 0,09 eV
s (Fe Ka_1) = 5,44 eV

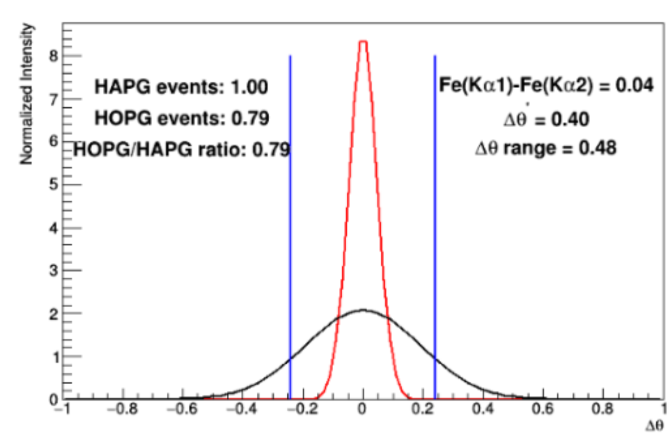






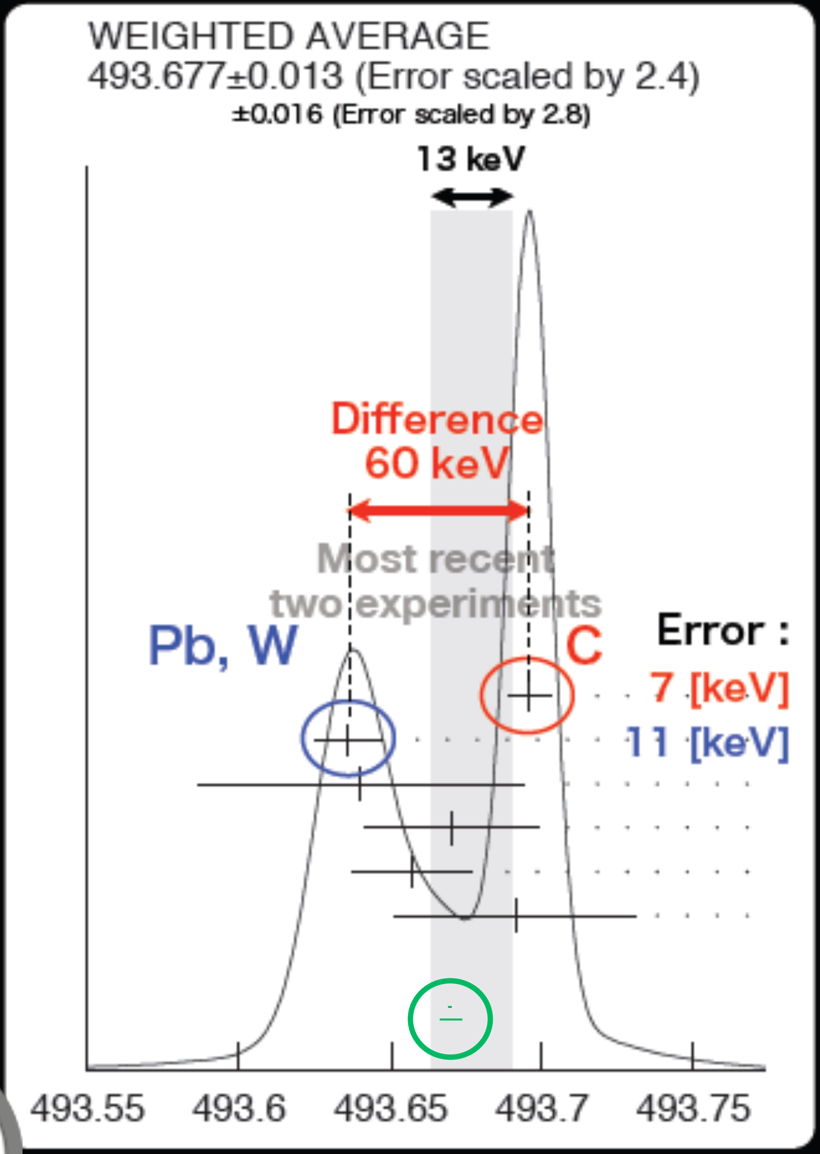
R(HOPG/HAPG) = 0,78





A possible application: the K⁻ mass puzzle

K- mass puzzle



K^- mass is a fundamental quantity in physics

Call for new measurement !!

Requirements :

1. **high-resolution** detector
2. K-atom with low-Z **gas** target

to reduce the electron screening effect

Needs precision below 0.1 eV!

Kaon mass precise measurement

The main disagreement is between the two most recent and precise results,

$$m_{K^\pm} = 493.696 \pm 0.007 \text{ MeV} \quad \text{DENISOV 91}$$

$$m_{K^\pm} = 493.636 \pm 0.011 \text{ MeV (S = 1.5)} \quad \text{GALL 88}$$

$$\text{Average} = 493.679 \pm 0.006 \text{ MeV}$$

$$\chi^2 = 21.2 \text{ for 1 D.F., Prob.} = 0.0004\% , \quad (3)$$

both of which are measurements of x-ray energies from kaonic atoms. Comparing the average in Eq. (3) with the overall

http://pdg.lbl.gov/2015/reviews/rpp2014-rev-charged-kaon-mass.pdf

New measurements of the mass of the K^- meson

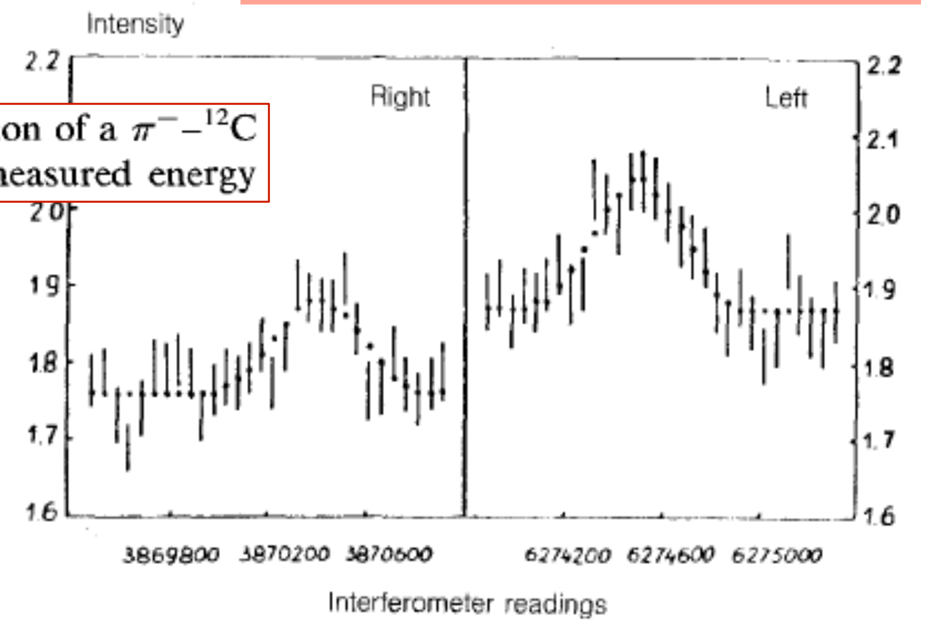
A. S. Denisov, A. V. Zhelamkov, Yu. M. Ivanov, L. P. Lapina, P. M. Levchenko, V. D. Malakhov, A. A. Petrunin, A. G. Sergeev, A. I. Smirnov, V. M. Suvorov, and O. L. Fedin
B. P. Konstantinov Leningrad Institute of Nuclear Physics, Academy of Sciences of the USSR, 188350, Gatchina, Leningrad Oblast'

(Submitted 30 September 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **54**, No. 10, 557–561 (25 November)

The energy of the $4f$-$3d$ transition in the K^-–^{12}C atom has been measured with the help of a Cauchois crystal diffraction spectrometer at the proton synchrotron of the Institute of High-Energy Physics. A new value has been found for the mass of K^- meson: 493.6960 ± 0.0059 MeV. This figure is significantly different from the previously accepted value.

6.3 eV resolution
$E_{4f->3d}$ = 22105.61 ± 0.26 eV

As a control, we carried out measurements on the $4d$–$2p$ transition of a π^-–^{12}C atom in parallel with the K^--atom measurements (Fig. 2.). The measured energy



pC will be measured @ PSI
Could we do better with KC?

Kaon mass precise measurement

PHYSICS LETTERS B

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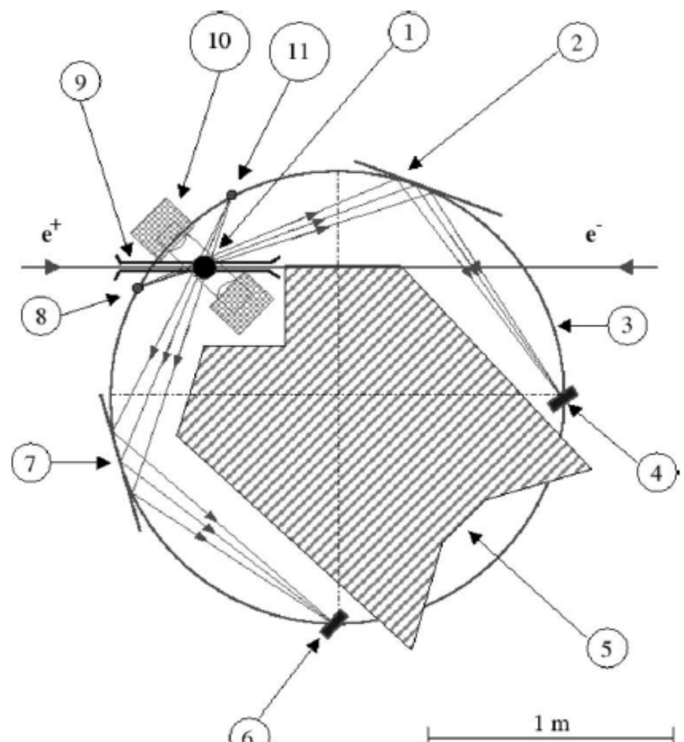
Physics Letters B 535 (2002) 52–58

www.elsevier.com/locate/npe

A new method to obtain a precise value of the mass of the charged kaon

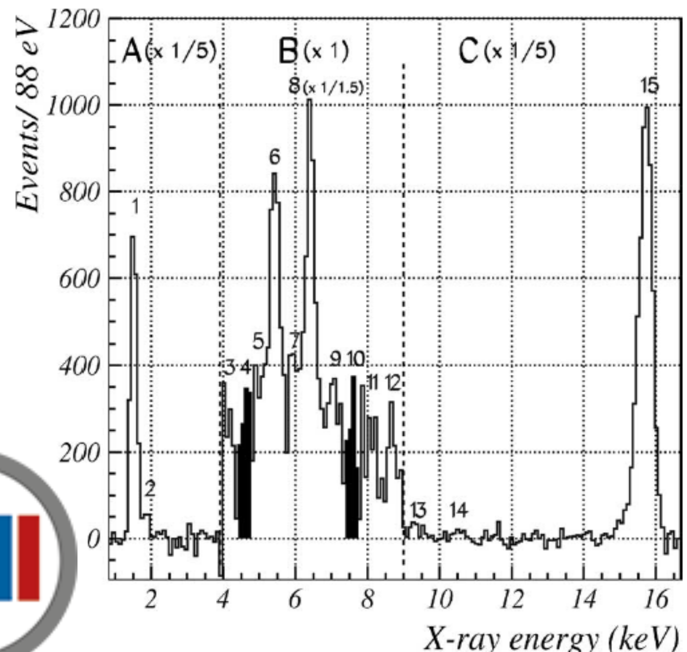
G. Beer[b], A.M. Bragadireanu[c,e], W. Breunlich[a], M. Cargnelli[a], C. Curceanu (Petrascu)[c,e], J.-P. Egger[g], H. Fuhrmann[a], C. Guaraldo[c,*], M. Giersch[a], M. Iliescu[c,e], T. Ishiwatari[d], K. Itahashi[d], B. Lauss[h], V. Lucherini[c], L. Ludhova[f], J. Marton[a], F. Mulhauser[f], T. Ponta[e], A.C. Sanderson[b], L.A. Schaller[f], D.L. Sirghi[c,e], F. Sirghi[c], J. Zmeskal[a]



Johann spectrometer

(6→5) kaonic nitrogen transition: 7560± 32 eV,
(7→6) kaonic nitrogen transition: 4589± 37 eV.

Exploratory test with DEAR @ DA?NE



Efficiency ≈ 5 x 10^{-5}

Not yet performed

Calculated efficiency ~ 400 times less than @ DAFNE

K^- mass @ DAFNE

Assuming SIDDHARTA like DAFNE conditions

A_T(r=103,4 mm; S_0=0,7 mm) = 100 mm x 8 mm^2 → R(target) = 14,55 x 10^{-3} Hz @ 20 cm from IP

10 cm from IP, new slits, in vacuum, X 3 HAPG

	KC (5→4) 10216,4 eV	KC (7→5) 8885,8 eV
Yield	17,3 %	4 %
ev / 200 gg	95	16
dE (200 gg)	(<=) 0,7 eV	(≈) 1,6 eV

	KN (6→5) 7595,7 eV	KN (5→4) 13999,6 eV
Yield	55 % (Yield) X 10 % (K^-_s)	57 % (Yield) X 10 % (K^-_s)
ev / 200 gg	22	20
dE (200 gg)	(≈) 1,4 eV	(<=) 1,5 eV

Kaonic Carbon @ DAFNE

R_{K^-} (L=1,5x10^{32}cm^{-2}s^{-1}) → 1,8 x 10^{-3} Hz/mm^2

DEAR KM: V. Lucherini et al. / NIM A 496 (2003) 315–324

A_T(r=103,4 mm; S_0=0,7 mm) = 100 mm x 8 mm^2 → R(target) = 14,55 x 10^{-3} Hz @ 20 cm from IP

	KC (5→4) 10216,4 eV	KC (7→5) 8885,8 eV
Yield	17,3 %	4 %
	2,5 x 10^{-3} Hz	0,6 x 10^{-3} Hz
e	2,4 x 10^{-5}	1,9 x 10^{-5}
	6 x 10^{-8} Hz	1,1 x 10^{-8} Hz
10 cm from IP	3,2 x 10^{-7} Hz	4,5 x 10^{-8} Hz
Slits	9,7 x 10^{-7} Hz	1,3 x 10^{-7} Hz
In vacuum	1,8 x 10^{-6} Hz	3 x 10^{-7} Hz
X 3 HAPG	5,5 x 10^{-6} Hz	9 x 10^{-7} Hz
ev / 200 gg	95	16
dE (200 gg)	(<=) 0,7 eV	(≈) 1,6 eV

bration procedure, is proposed. A two-arm symmetric curved crystals assembly of 20 × 10 cm^2 with a Rowland circle radius of 95 cm on the CCD detectors side will be used. However, the extended target

ings [21]. The reflectivity amounts to 4% at 3 keV and the overall efficiency of each arm of the graphite spectrometer (including CCD efficiency) at this energy is about 5.4 × 10^{-5}, which is about 400 times lower than the efficiency of the test setup [13].

A_{HAPG}^{MAX} = 3 x 3,2 cm^2

Kaonic Nitrogen @ DAFNE

R_{K^-} (L=1,5x10^{32}cm^{-2}s^{-1}) → 1,8 x 10^{-3} Hz/mm^2

DEAR KM: V. Lucherini et al. / NIM A 496 (2003) 315–324

A_T(r=103,4 mm; S_0=0,7 mm) = 100 mm x 8 mm^2 → R(target) = 14,55 x 10^{-3} Hz @ 20 cm from IP

	KN (6→5) 7595,7 eV	KN (5→4) 13999,6 eV
Yield	55 % (Yield) X 10 % (K^-_s)	57 % (Yield) X 10 % (K^-_s)
	0,8 x 10^{-3} Hz	0,8 x 10^{-3} Hz
e	1,5 x 10^{-5}	2,9 x 10^{-5}
	1,2 x 10^{-8} Hz	2,3 x 10^{-8} Hz
10 cm from IP	4,8 x 10^{-8} Hz	9,2 x 10^{-8} Hz
Slits	1,4 x 10^{-7} Hz	2,8 x 10^{-7} Hz
In vacuum	4,5 x 10^{-7} Hz	3,9 x 10^{-7} Hz
X 3 HAPG	1,3 x 10^{-6} Hz	1,2 x 10^{-6} Hz
ev / 200 gg	22	20
dE (200 gg)	(≈) 1,4 eV	(<=) 1,5 eV

But…