Strangeness@LNF:

Fundamental Physics with Kaonic Atoms

"Giornata di discussione sulle prospettive per la Fisica Fondamentale a Frascati (FFF) "

A. Scordo, Frascati (LNF), 13/01/2021

International & National partners and supports

Interested Institutes:

INFN (LNF, Parma, PoliMi, Pisa), *Italy*
CENTRO FERMI — Museo Storico della Fisicae Centro Studi e Ricerche “Enrico Fermi”, *Italy*
Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, *Italy*
IMEM-CNR (Istituto dei Materiali per l'Elettronica ed il Magnetismo), *Italy*
INFN Sezione di Roma I and Inst. Superiore di Sanità, *Italy*
Stefan Meyer Institut der österreichischen Akademie der Wissenschaften (SMI), *Austria*
Horia Hulubei National Institute of Physics and Nuclear Engineering, *Romania*
Department of Physics, Faculty of Science, University of Zagreb, *Croatia*
Excellence Cluster Universe, Technische Universiät MünchenGarching, *Germany*
University of Mainz, *Germany*
RIKEN, *Japan*
Sendai University, *Japan*
M. Smoluchowski Institute of Physics, Jagiellonian University, Kraków, *Poland*
HEPHY, Institute of High Energy Physics, *Austria*
Lund University, *Sweden*
Paul Scherrer Insitute (PSI), *Switzerland*

Financial Support:

STRONG-2020, EU
FWF Austria
MAECI – Ialy-Japan
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Poland No. 7150/E-338/M/2018

Interested industrial partners:

Fondazione Bruno Kessler: FBK, *Italy*
OptigraphGmbH, *Germany*
Dectris AG, *Switzerland*

Content

GEKA
High Purity Germanium detectors
precision measurements of X and γ-ray transitions in selected Kaonic Atoms

KAHEL & LIKAM-1
Kaonic Helium 2p→1s transition and other Light Kaonic Atoms Measurements

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

- What we can measure
- Impact & Detectors Key Points
- Feasibility
- Future implementations
- Timeline and Beam Requests

GEKA: Kaon Mass and High Z kaonic atoms

Possible kaonic transitions to be measured:

KC(2→1) : 340 keV
KC(3→1): 402 keV

KSe(4→3): 733 keV
KSe(5→4): 339 keV
KSe(5→3): 1073 keV
KSe(6→5) : 184 keV
KSe(6→4): 524 keV

KZr(4→3): 1015 keV
KZr(5→4): 470 keV
KZr(5→3): 1485 keV
KZr(6→5) : 255 keV
KZr(6→4): 725 keV

KTa(6→5): 853 keV
KTa(7→6): 514 keV
KTa(7→5) : 1367 keV
KTa(8→7): 334 keV
KTa(8→6): 848 keV

KPb(6→5) : 1076 keV
KPb(7→6): 649 keV
KPb(8→7): 421 keV
KPb(8→6): 1070 keV
KPb(9→8): 289 keV

Expected Impact:

- Kaon Mass most precise measurement
- High Z kaonic atoms physics

Detector Key Points:

- Very large dynamic range
- Possibility to test High Z targets
- High resolution for precision measurements
- Rate capability up to 150 kHz

Feasibility:

HPGe detector available,
Funded by University of Zagreb
Croatian Science Foundation project 8570

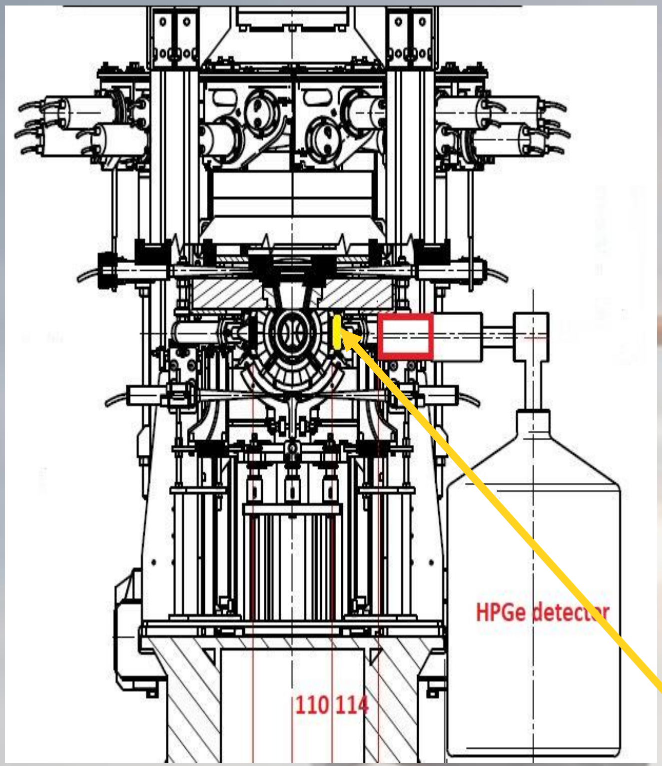
Resolutions (FWHM)
obtained with ^{60}Co, ^{133}Ba sources :

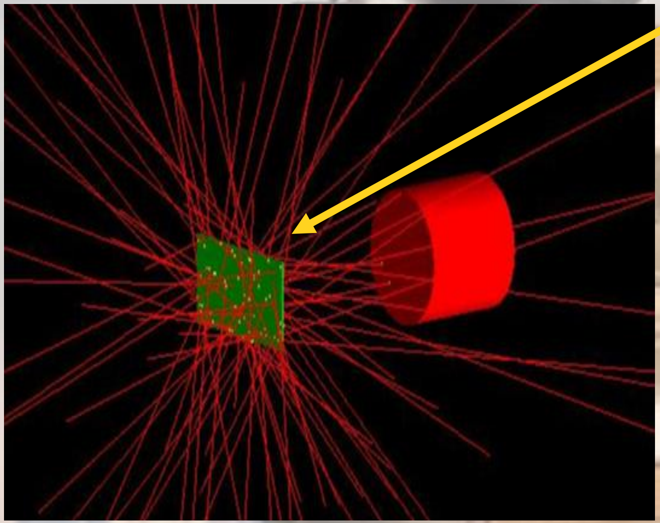
0.870 keV @ 81 keV
1.106 keV @ 302.9 keV
1.143 keV @ 356 keV
1.167 keV @ 1330 keV

Detector system ready for measurements!

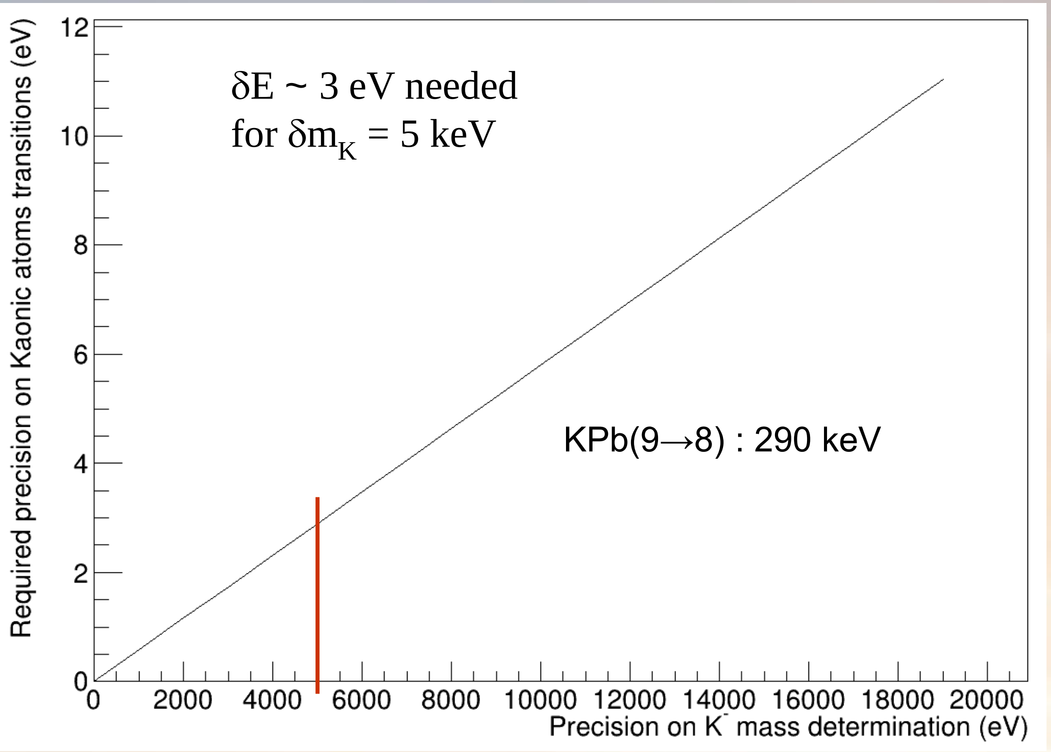
GEKA: Kaon Mass and High Z kaonic atoms

Feasibility test run during SIDDHARTA-2: KPb





Target just behind the luminometer, which is used as trigger



$$\sigma m_K = \frac{m_K^2}{\mu_{KN}^2} \frac{1}{Z^2} \frac{10^6}{26,6} \frac{\sigma E^K_{X \to Y}}{\left(\frac{1}{Y^2} - \frac{1}{X^2}\right)}$$

Future implementations:

- Targets : C, Se, Zr, Ta, Pb
- New mechanics to reduce the distance from IP
- Optimised shielding according to MC and feasibility test

GEKA: A possible timeline

Possibility to start immediately after SIDDHARTA-2 run

First 2 months dedicated to the setup optimisation, based on the results of the feasibility tests performed during SIDDHARTA-2 run

			GEKA	
Months from start	Year		Setup optim. from feasibility test	Run (5 targets x 1 month)
1				
2				
3				
4				
5				
6				
7	1st			
8				
9				
10				
11				
12				

6 monts of run:
5 targets x 1 month
+
DAΦNE beam optimisation and dismounting

Estimation of the requested beam time for KPb (9->8) transition @ 291.6 keV, to be used for K^- mass measurement

$\delta E \sim 3$ eV needed
for $\delta m_K = 5$ keV

For a FWHM (@302.9 keV) of 1.106 keV
$N \approx 30000$ events / peak are needed for 3 eV precision

From MC simulations,
assuming $L = 1{,}4 \times 10^{32}$ (~ deliv. int. 12 pb^{-1} / day):

- ~ 4000 recorded signals / day
- S/B ~ 1/3
- ~ 120000 total events needed

↓

~ 360 pb-1 (~ 30 days) of beamtime requested

!!! Similar estimations for each target !!!

KAHEL & LIKAM-1: Light Kaonic Atoms Measurements

Possible kaonic transitions to be measured with 1-2 mm SDDs:

$K^3He(2\rightarrow1)$: 33 keV
$K^4He(2\rightarrow1)$: 35 keV

$K^{6,7}Li(3\rightarrow2)$: 15 keV
$K^{6,7}Li(4\rightarrow2)$: 20 keV

$K^{8,9}Be(3\rightarrow2)$: 27 keV
$K^{8,9}Be(4\rightarrow2)$: 37 keV
$K^{8,9}Be(5\rightarrow3)$: 14 keV

$K^{9,10,11}B(4\rightarrow3)$: 15 keV
$K^{9,10,11}B(5\rightarrow3)$: 22 keV
$K^{9,10,11}B(6\rightarrow4)$: 11 keV

Expected Impact:

- $K^{3,4}He$ (2p→1s) first measurements ever
- Test chiral vs phenomenological models
- Isospin dependent KN scattering length (like KH+KD)
- Upper level measurements (hints on Λ(1405) nature)

Detector Key Points:

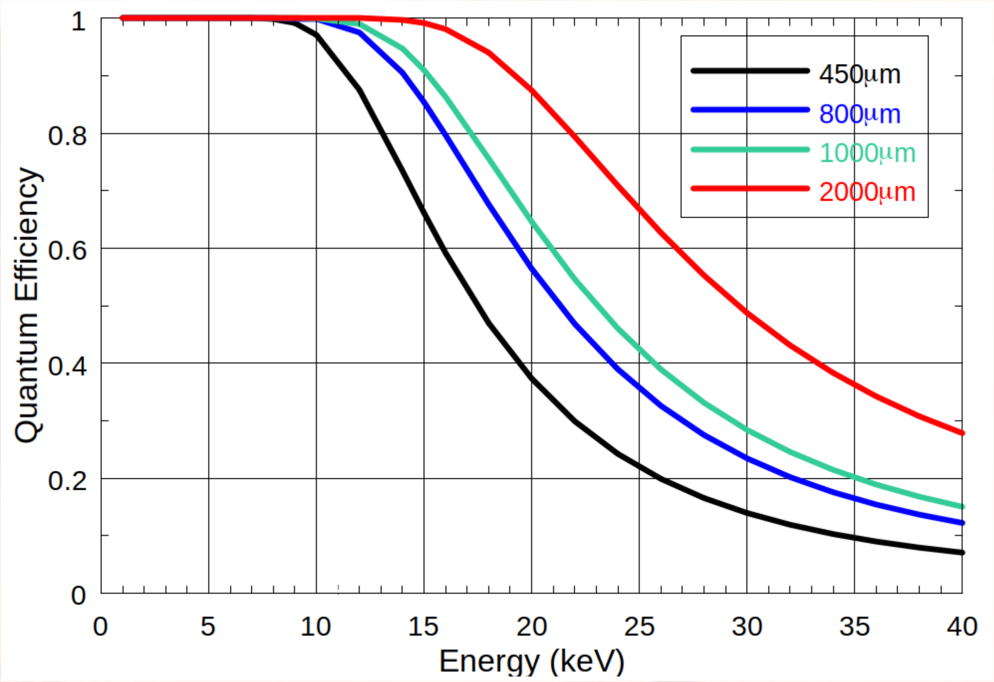
- Higher efficiency in the 10-40 keV region
- Well known behaviour and calibration procedure
- High resolution for precision measurements of Z>2 elements (~100 eV shifts)

Feasibility:

1-2 mm SDDs already financed by INFN CSN3

Electronics is similar to SIDDHARTA-2 SDDs

800µm and 1mm SDDs prototypes already produced by FBK for ARDESIA (INFN)



KAHEL & LIKAM-1: Light Kaonic Atoms Measurements

Possible kaonic transitions to be measured with Cd(Zn)Te detectors:

$K^6Li(2\rightarrow1)$: 81 keV
$K^6Li(3\rightarrow1)$: 97 keV
$K^7Li(2\rightarrow1)$: 82 keV
$K^7Li(3\rightarrow1)$: 98 keV

$K^{9,10}B(4\rightarrow2)$: 58 keV
$K^{9,10}B(5\rightarrow2)$: 65 keV
$K^{9,10}B(6\rightarrow2)$: 69 keV
$K^{9,10}B(7\rightarrow2)$: 71 keV
$K^{11}B(4\rightarrow2)$: 59 keV
$K^{11}B(5\rightarrow2)$: 66 keV
$K^{11}B(6\rightarrow2)$: 70 keV
$K^{11}B(7\rightarrow2)$: 72 keV

Expected Impact:

- Test chiral vs phenomenological models
- Isospin dependent KN scattering length (like KH+KD)
- Upper level measurements (hints on $\Lambda(1405)$ nature)
- Cascade processes

Detector Key Points:

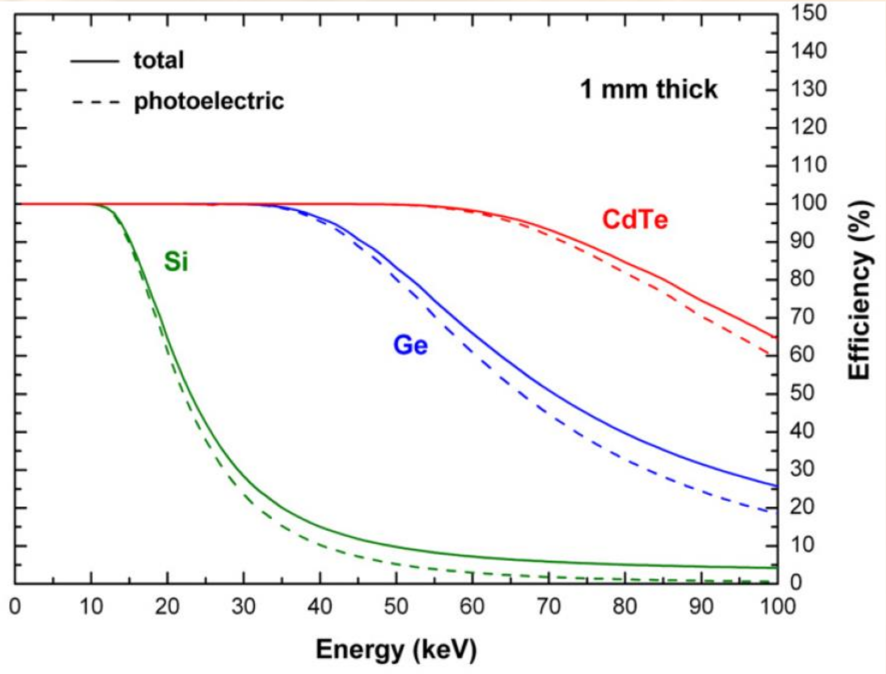
- High efficiency in the 50-100 keV region
- Good resolution (500 eV @ 20 keV / 1 keV @ 200 keV) to separate the lines of interest

Feasibility:

CdTe (and also CdZnTe) detectors will be developed in the JRA8-ASTRA (STRONG-2020) project

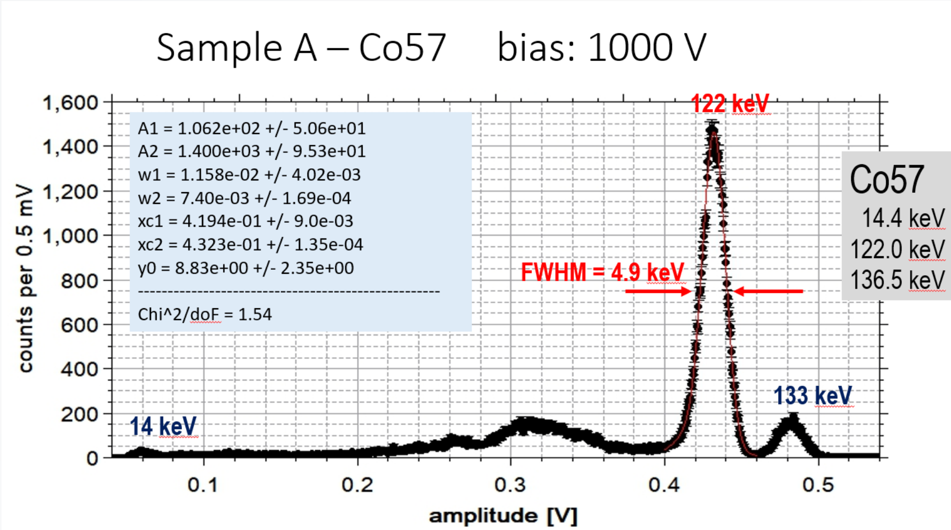
First prototypes will be available by mid 2022

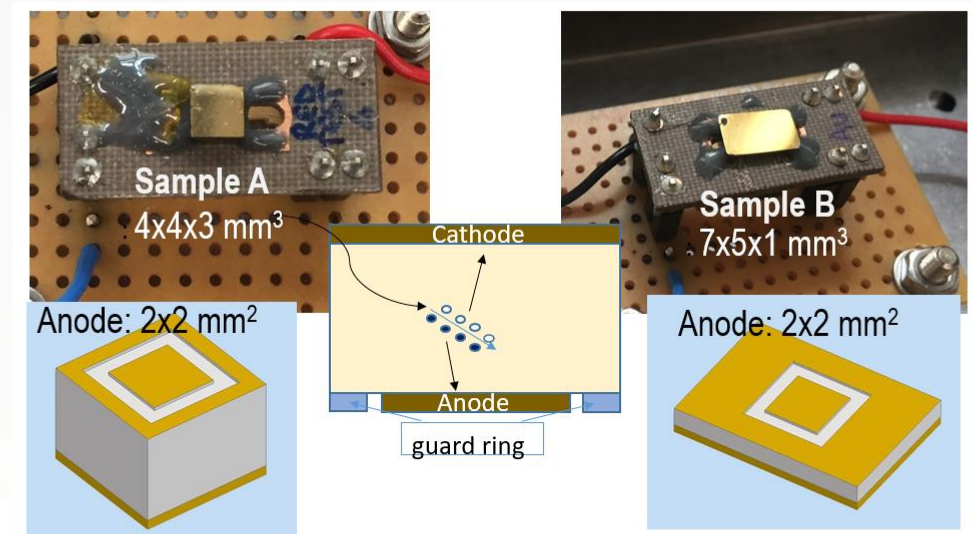
Electronics prototype will be also delivered

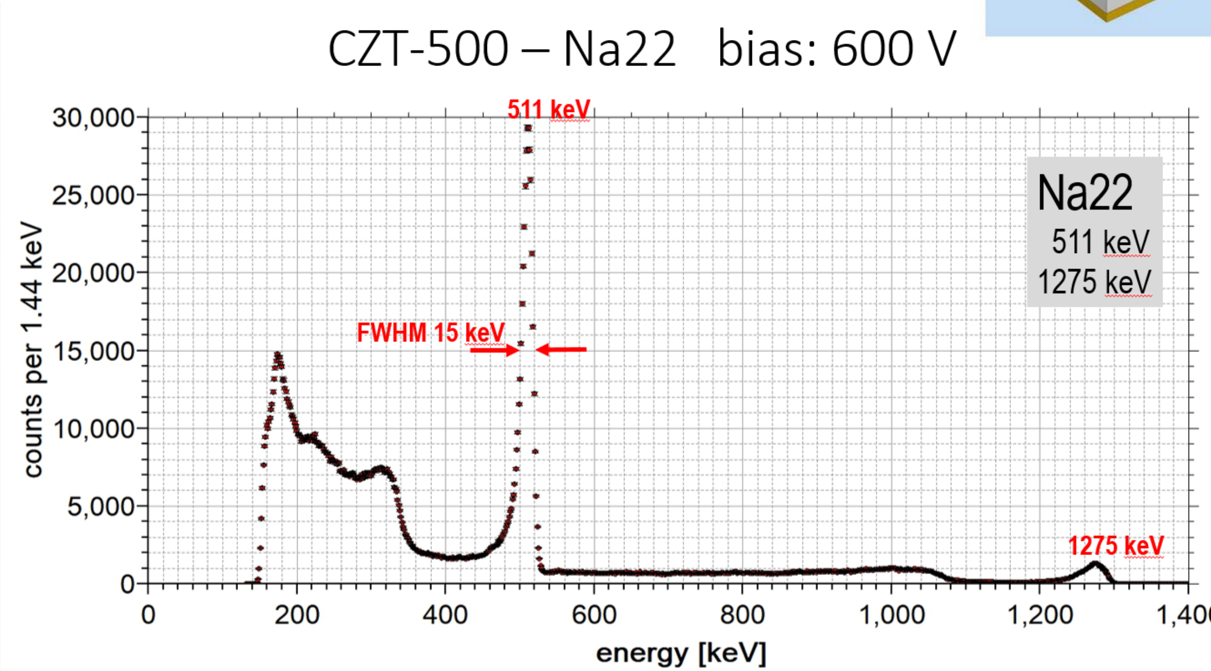


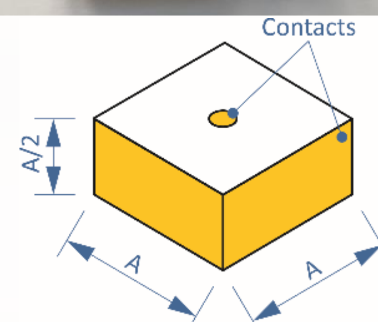
KAHEL & LIKAM-1: Light Kaonic Atoms Measurements

First prototypes of Cd(Zn)Te delivered by JRA8-ASTRA (STRONG-2020) and tested



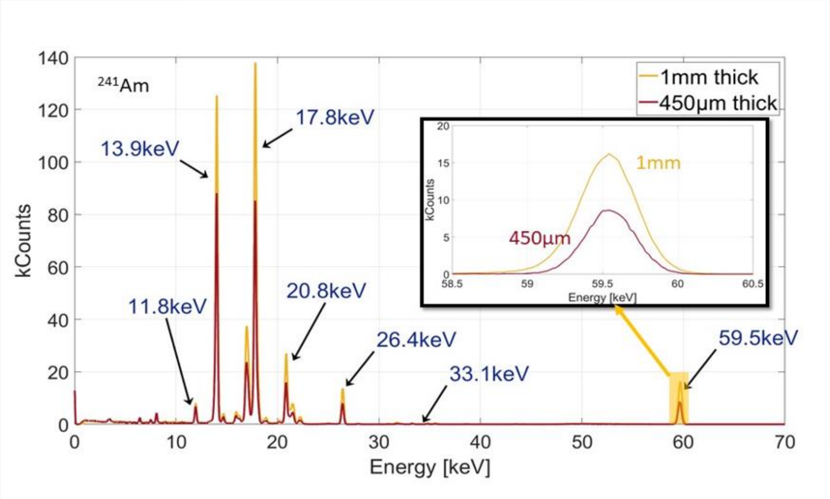






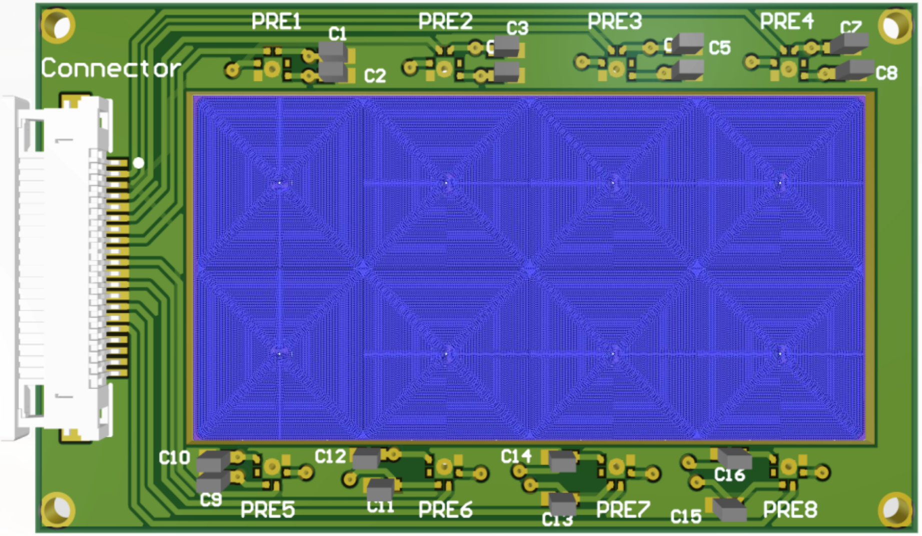
KAHEL & LIKAM-1: Light Kaonic Atoms Measurements

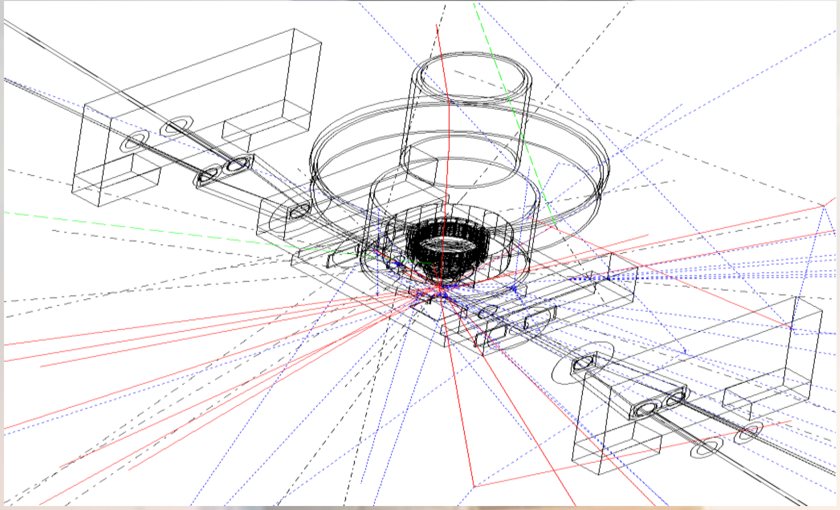
800μm and 1mm SDDs prototypes already produced by FBK for ARDESIA (INFN)



First XRF tests with known targets show very promising results

Prototypes of electronics boards are already available





Future implementations:

- Targets : ^{3,4}He, ^{6,7}Li, ^{8,9}Be, ^{9,10,11}B
- Second SIDDHARTA-2 like setup
- Optimised shielding according to feasibility test
- MC implementation (already started) with real DAΦNE conditions

KAHEL & LIKAM-1: A possible timeline

KAHEL & LIKAM-1 can run in parallel in a SIDDHARTA-2 like configuration with two separate targets above and below IP

			KAHEL + LIKAM-1							
Months from start	Year		Electronics proj.	Electronics prod.	Mechanics proj.	Mechanics prod.	DAQ preparation	Calib & Tests	Installation	Run (6 targets x 1 month)
1										
2										
3										
4										
5										
6										
7	1st									
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
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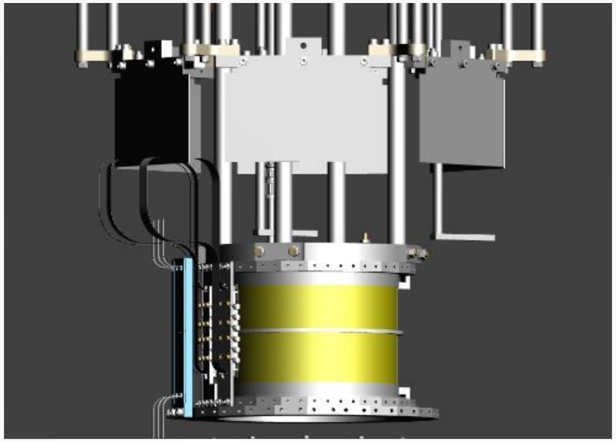
23										
24										
25										



x2

From MC simulations:

- Assuming $\mathcal{L}$ = 1,4x10^{32}

(~ del. int. 12 pb^{-1} / day → ~ int. 8 pb^{-1} / day)

- Assuming reasonable yields in the order of 20 %
- Integrating 800 pb^{-1} for Kaonic Helium
- Integrating 300 pb^{-1} for each of the other targets

↓

we can do precision measurements of a series of kaonic atoms strongly impacting in the QCD studies (including chiral symmetry) within 6-7 months

NUMES: sub-eV precision Kaonic Atoms measurements

Kaon-Nucleon interaction:
Chiral or Phenomenological models?

There is only ONE possible solving measurment:
The $K^{3,4}He$ isotopic shift measurement

Calculated quantity [1]	Phenomenologica [2]	Chiral [3]
ε (K^4He)	-0,41 eV	-0,09 eV
ε (K^3He)	0,23 eV	-0,1 eV
ε (K^4He) - ε (K^3He)	-0,64 eV	0,01 eV

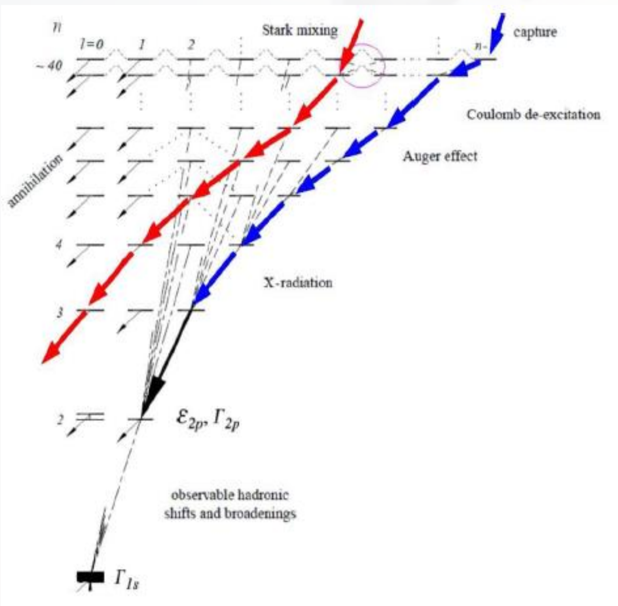
Solve the kaonic helium isotopic shift problem

Precise determination of the K^- mass

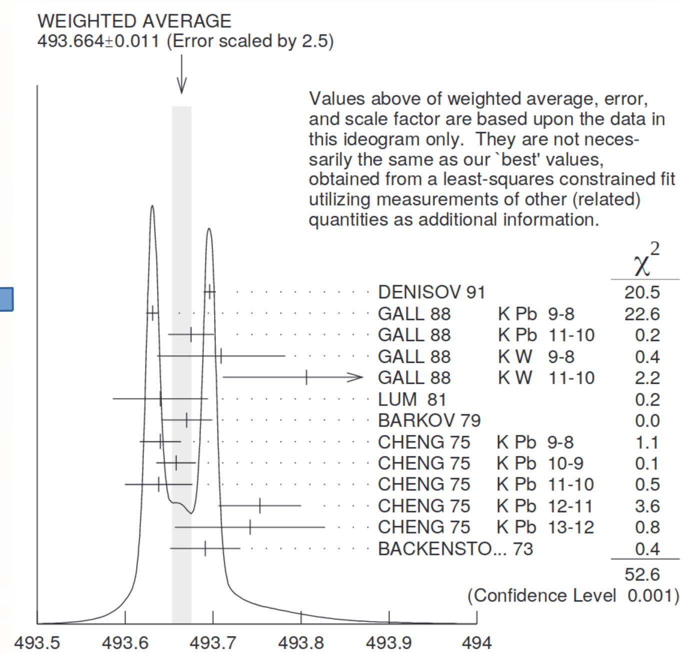
Stronger constraints for the EM cascade models for kaonic atoms

… ALL IN PARALLEL

But...levels and calculated shifts depend on the K^- mass value...

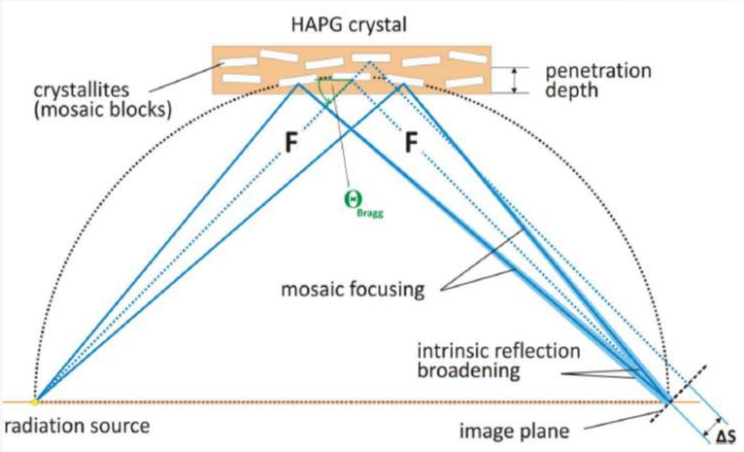


But...EM calculated levels depend on the cascade processes...



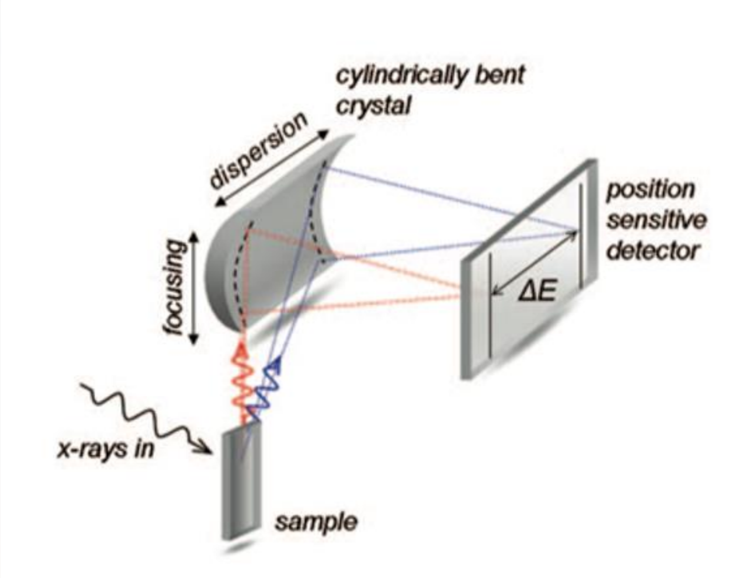
NUMES: sub-eV precision Kaonic Atoms measurements

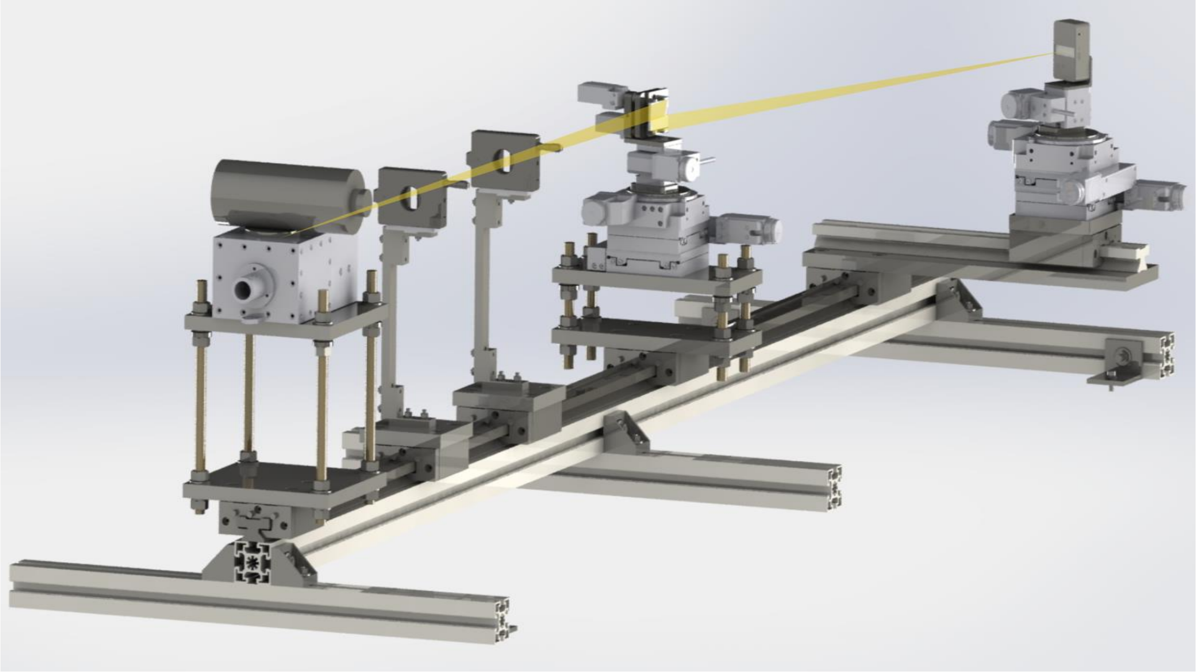
Spectrometer developed under CSN5 Young Researcher Grant (2016-2018)



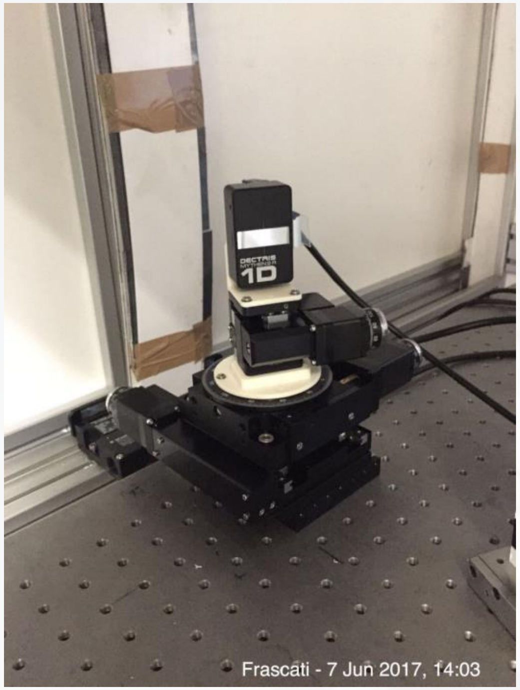
HAPG mosaic crystals in Von Hamos configuration:

- Higher intrinsic reflectivity wrt standard crystals
- VH configuration to exploit sagittal focusing
- Optical optimisation to work with millimetric/centimetric sources





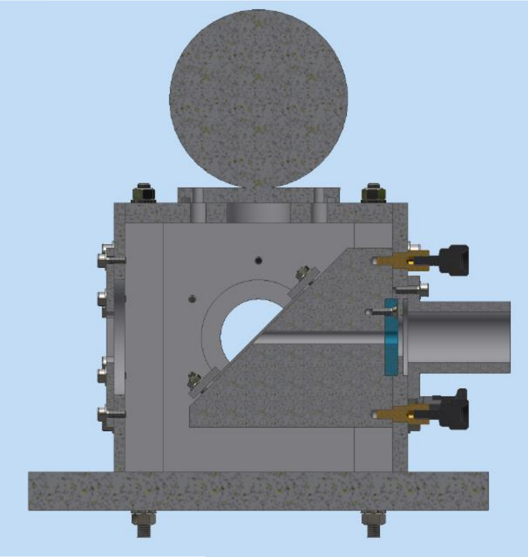
NUMES: sub-eV precision Kaonic Atoms measurements

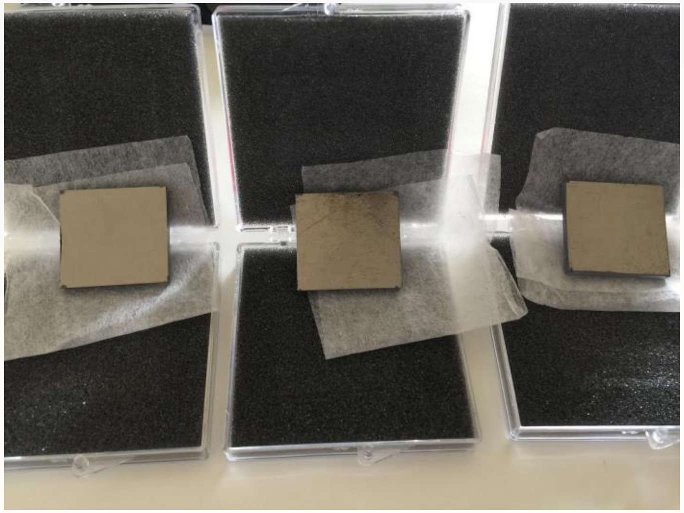


Dectris Ltd
MYTHEN2 detector:

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

Designed at SMI





Set of different parameters HAPG crystals (mosaicity, radius, thickness,..)

0.00125° step rotator (θ_B) (STANDA 8MR191-28)

1.25 μm step positioners (XZ) (STANDA 8MT167S-25LS)

8MUP21-2 - Motorized Optical Mount (STANDA)

< 1 arcsec resolution

0.01 μm step positioners (Y) (STANDA 8MVT40-13)

0-10 mm opening
26 mm circular frame
< 1 μm sensitivity
Slits
(STANDA 10MAOS10-1)

NUMES: sub-eV precision Kaonic Atoms measurements

Possible kaonic transitions to be measured with HAPG crystal spectrometer:

$K^3He(3\rightarrow2)$: 6.2 keV
$K^3He(4\rightarrow2)$: 8.4 keV
$K^3He(5\rightarrow2)$: 9.4 keV
$K^3He(6\rightarrow2)$: 9.9 keV
$K^3He(7\rightarrow2)$: 10.2 keV

$K^4He(3\rightarrow2)$: 6.4 keV
$K^4He(4\rightarrow2)$: 8.7 keV
$K^4He(5\rightarrow2)$: 9.7 keV
$K^4He(6\rightarrow2)$: 10.3 keV
$K^4He(7\rightarrow2)$: 10.7 keV

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

Expected Impact:

- Test chiral vs phenomenological models (Isotopic shift puzzle)
- 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)

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:

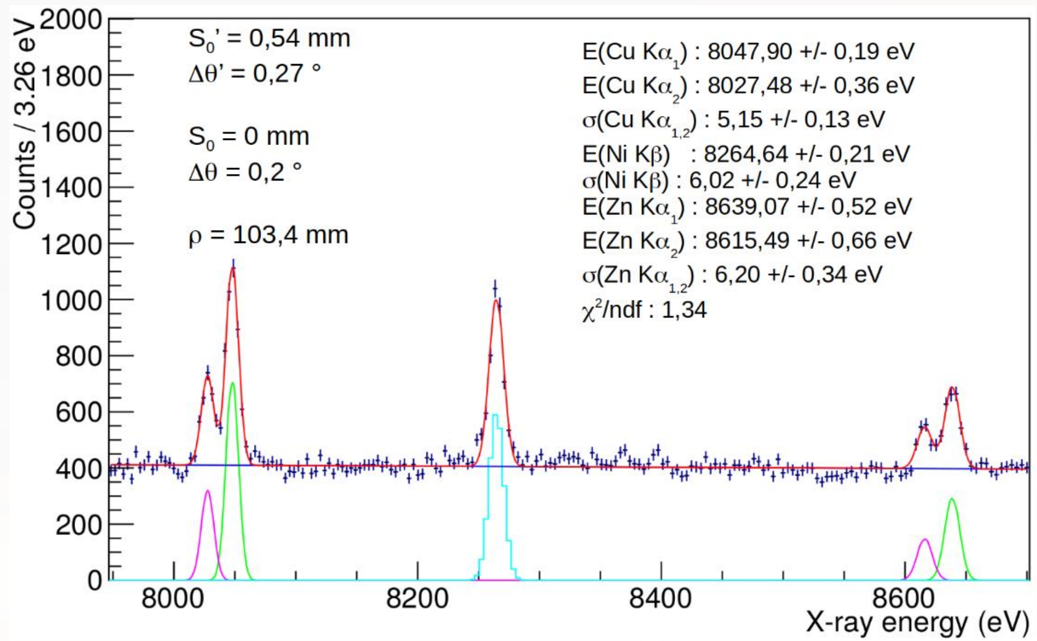
- Working principle tested in laboratory
- Dependence from HAPG parameters well investigated and published (thickness, mosaicity, …)
- Consistent Ray Tracing simulations available
- Few eV resolutions confirmed for solid sources with millimetric dimensions

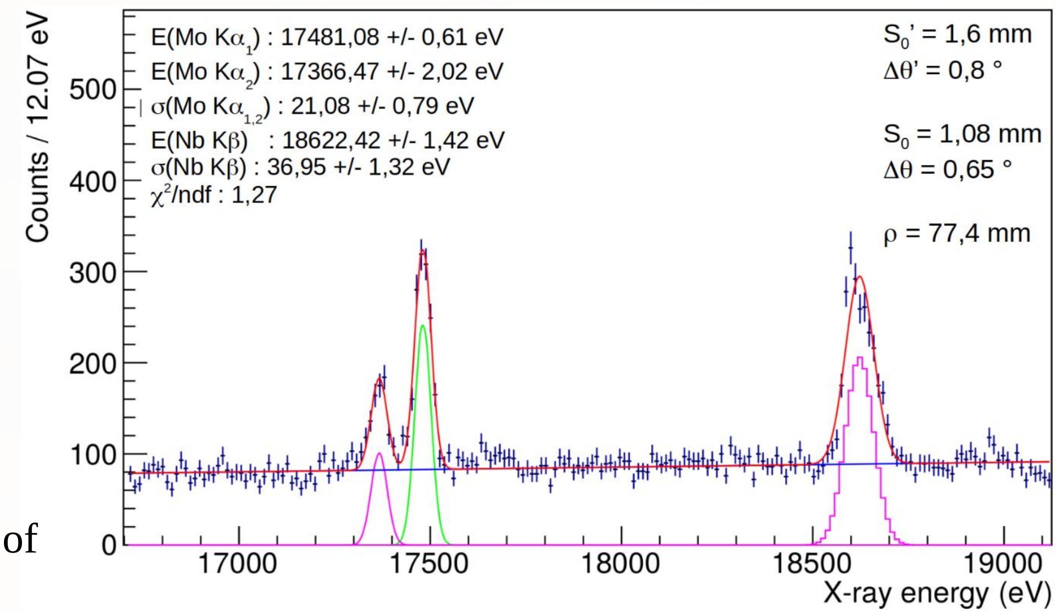
NUMES: sub-eV precision Kaonic Atoms measurements

Table 3 Best achieved resolutions and precisions summary.

Element	ρ_c (mm)	Parameter	value (eV)	$S_0'/\Delta\theta'$ (mm,°)
		$\sigma(K\alpha_{1,2})$	$4,17 \pm 0,16$	0,3/0,24
	77,5	$\delta(K\alpha_1)$	0,11	0,6/0,44
		$\delta(K\alpha_2)$	0,18	0,6/0,44
		$\sigma(K\alpha_{1,2})$	$4,05 \pm 0,13$	0,3/0,18
Fe	103,4	$\delta(K\alpha_1)$	0,09	0,7/0,34
		$\delta(K\alpha_2)$	0,13	0,7/0,34
		$\sigma(K\alpha_{1,2})$	$4,02 \pm 0,08$	1,1/0,60
	206,7	$\delta(K\alpha_1)$	0,1	1,2/0,70
		$\delta(K\alpha_2)$	0,15	1,2/0,70
		$\sigma(K\alpha_{1,2})$	$6,8 \pm 0,07$	0,3/0,16
	77,5	$\delta(K\alpha_1)$	0,07	0,6/0,32
		$\delta(K\alpha_2)$	0,1	0,6/0,32
		$\sigma(K\alpha_{1,2})$	$4,77 \pm 0,05$	0,3/0,16
Cu	103,4	$\delta(K\alpha_1)$	0,04	0,7/0,32
		$\delta(K\alpha_2)$	0,07	0,7/0,32
		$\sigma(K\alpha_{1,2})$	$3,60 \pm 0,05$	0,8/0,60
	206,7	$\delta(K\alpha_1)$	0,04	1,1/0,70
		$\delta(K\alpha_2)$	0,07	1,1/0,70
		$\sigma(K\alpha_{1,2})$	$5,15 \pm 0,13$	0,5/0,27
Cu	103,4	$\delta(K\alpha_1)$	0,10	0,6/0,22
		$\delta(K\alpha_2)$	0,21	0,6/0,22
		$\sigma(K\beta)$	$6,02 \pm 0,24$	0,5/0,27
Ni	103,4	$\delta(K\beta)$	0,13	0,6/0,22
		$\sigma(K\alpha_{1,2})$	$6,20 \pm 0,34$	0,5/0,27
Zn	103,4	$\delta(K\alpha_1)$	0,26	0,6/0,22
		$\delta(K\alpha_2)$	0,42	0,6/0,22
		$\sigma(K\alpha_{1,2})$	$21,1 \pm 0,8$	1,6/0,80
Mo	77,5	$\delta(K\alpha_1)$	0,6	1,6/0,80
		$\delta(K\alpha_2)$	2,0	1,6/0,80
		$\sigma(K\beta)$	$36,9 \pm 1,3$	1,6/0,80
Nb	77,5	$\delta(K\beta)$	1,3	1,6/0,80

High precision measurements with VOXES in LNF Lab





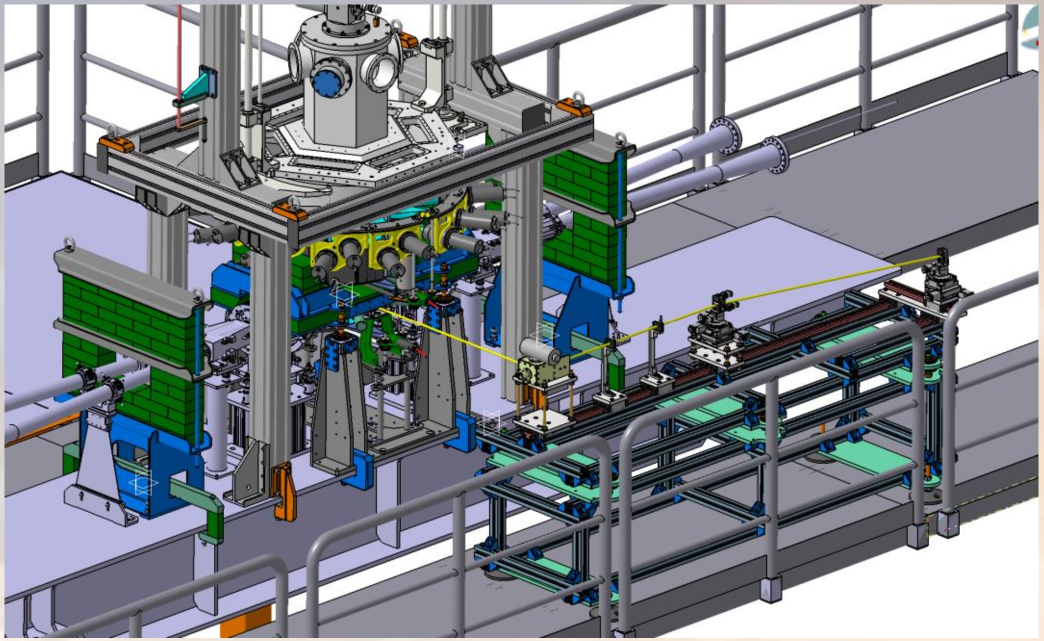
Possible feasibility test to be done in parallel with SIDDHARTA-2

Main goal: assess background and on beam behaviour of crystals and strip detector

NUMES v1: KC run with existing setup

NUMES v1

First run with KC for a K- mass measurement



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)

From MC simulations,
assuming $L = 1{,}4 \times 10^{32}$ (~ 12 pb^{-1} / day):

- ~ 1,4 recorded signals / day
- ~ 250 total events goal (δE ~ 0,2 – 0,3 eV)
- σ = 3,6 eV @ 8 keV (from Cu lab measurements)

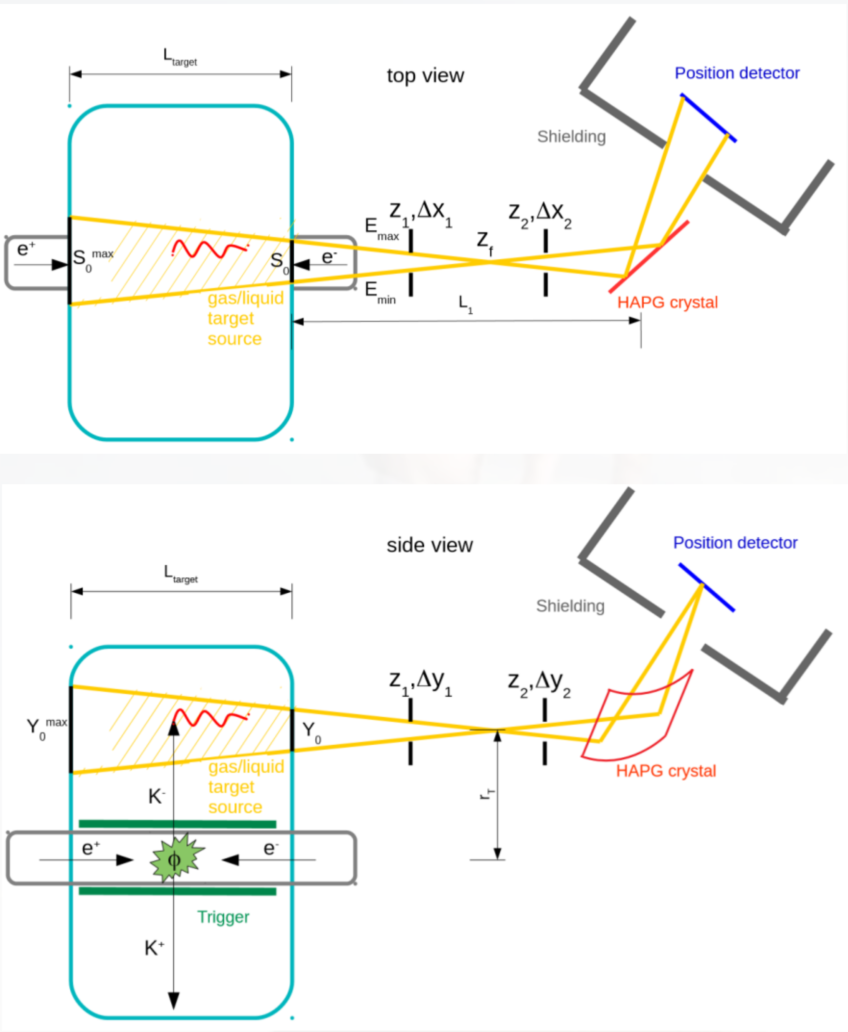
↓

~ 2000 pb^{-1} (~ 180 days) of beamtime requested

Future implementations:

- Shielding around Detector
- Solid support structure

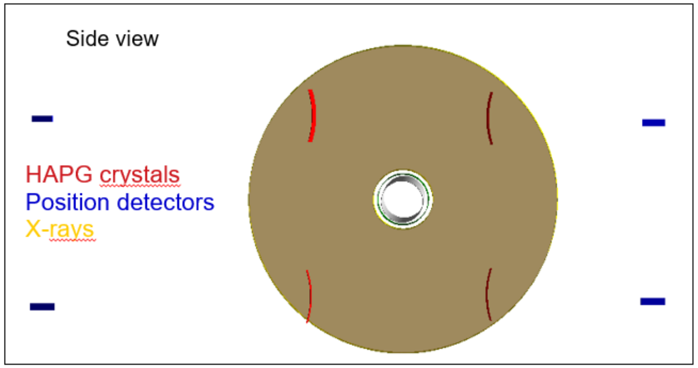
NUMES v2: $K^{3,4}He$ and KN measurements

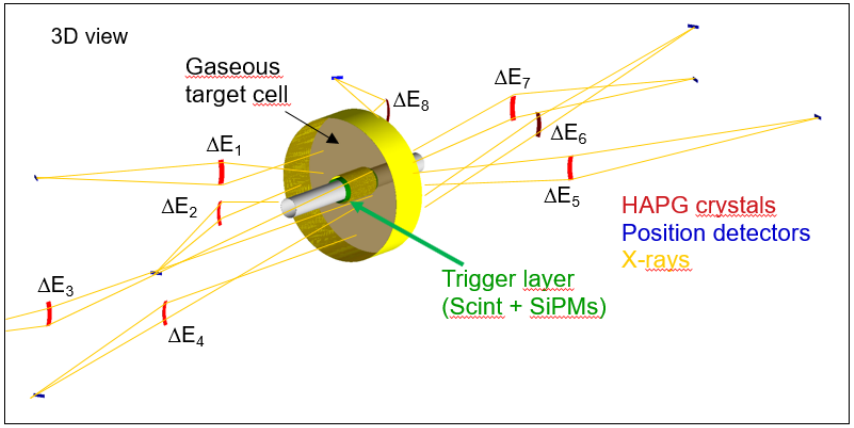


Example:

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

50 cm^2 HAPG crystals and 10 cm^2 Position Detectors (total)





To achieve the required precision to address the isotopic shift problem (~ 0,1 eV), ~ 2000 pb^{-1} (~ 180 days) of beamtime are requested

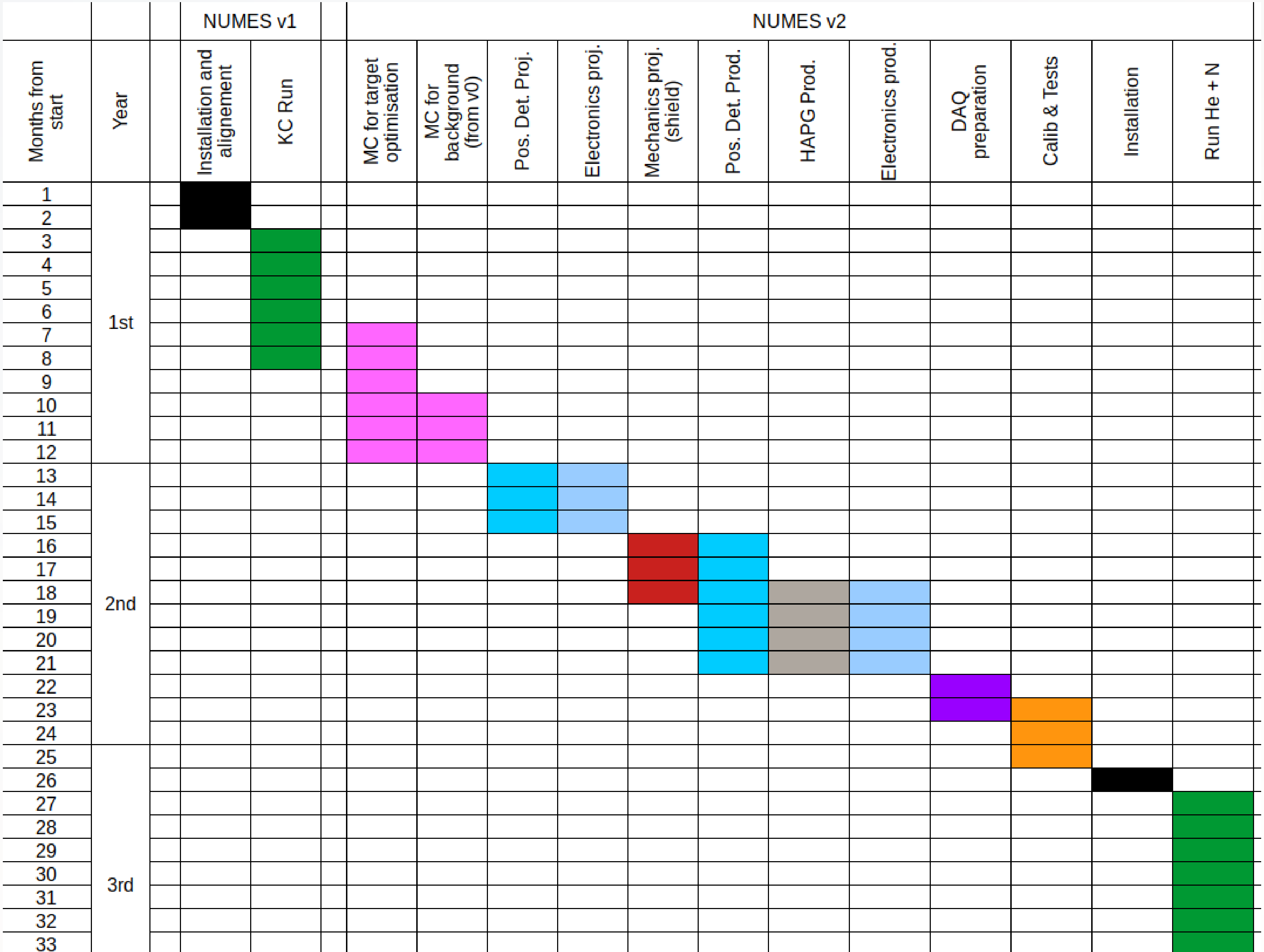
Completely new experiment / setup

Position Detector and HAPG crystals development with R&D opportunities

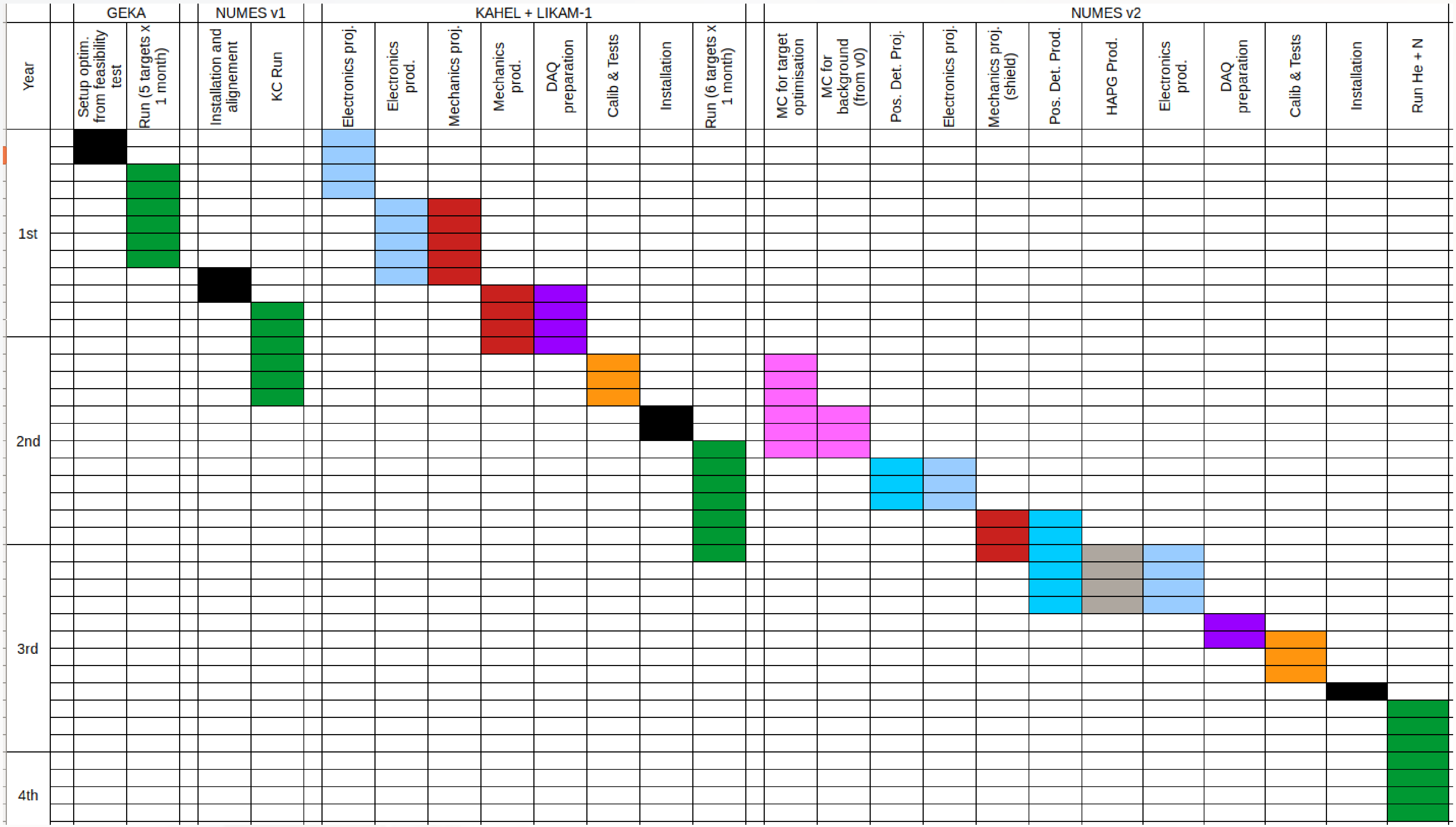
Real opportunity to apply for external fundings

Possibility to attract new interested institutes

NUMES: a possible timeline



SUMMARY:
Kaonic Atoms measurements timeline



CONCLUSIONS

- Kaonic atoms measurements are still strongly demanded in the nuclear physics (and not only) community
- DAFNE is a unique facility in the world to perform such kind of measurements
- There is a plethora of fundamental kaonic atoms transition lines to be measured, with different detectors and techniques, able to cover almost 4 years after the end of the SIDDHARTA-2 run.
- To perform the still missing fundamental kaonic atoms measurements a challenging and inspiring detector development needs to be carried on
- LNF team, together with all the partner institutes and companies, can contribute with a longstanding know-how in physics, technology, data taking and analysis, mandatory for a successful measurements campaign
- The proposed experiments will be able to attract new fundings, researchers and institutes and will represent a unique opportunity for young scientists of several fields (physics, electronics, informatics, ...)