

A young boy with glasses is sitting cross-legged on a tall stack of old, worn books. He is looking through a telescope held up to his eye. The background is a soft-focus sunset or sunrise over a city skyline.

Future kaonic atoms measurements at DAΦNE

“Fundamental Physics at the Strangeness frontier at DAΦNE”

A. Scordo, Frascati (LNF) - online, 25-26/02/2021

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 Universität 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

MAECl – Italy-Japan

Croatia IP-2018-01-8570

Poland No. 7150/E-338/M/2018

Interested industrial partners:

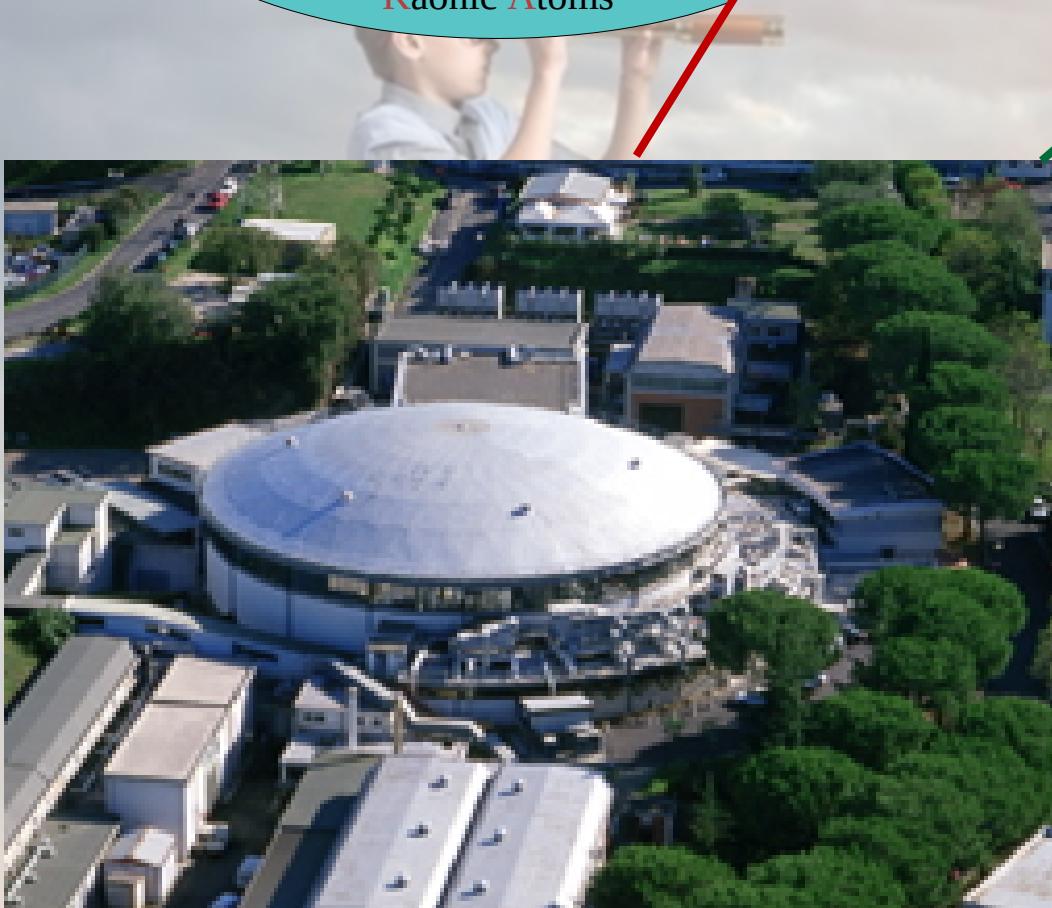
Fondazione Bruno Kessler: FBK, *Italy*

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 $2p \rightleftharpoons 1s$ 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($2 \rightarrow 1$) : 340 keV

KC($3 \rightarrow 1$): 402 keV

KSe($4 \rightarrow 3$): 733 keV

KSe($5 \rightarrow 4$): 339 keV

KSe($5 \rightarrow 3$): 1073 keV

KSe($6 \rightarrow 5$) : 184 keV

KSe($6 \rightarrow 4$): 524 keV

KZr($4 \rightarrow 3$): 1015 keV

KZr($5 \rightarrow 4$): 470 keV

KZr($5 \rightarrow 3$): 1485 keV

KZr($6 \rightarrow 5$) : 255 keV

KZr($6 \rightarrow 4$): 725 keV

KTa($6 \rightarrow 5$): 853 keV

KTa($7 \rightarrow 6$): 514 keV

KTa($7 \rightarrow 5$) : 1367 keV

KTa($8 \rightarrow 7$): 334 keV

KTa($8 \rightarrow 6$): 848 keV

KPb($6 \rightarrow 5$) : 1076 keV

KPb($7 \rightarrow 6$): 649 keV

KPb($8 \rightarrow 7$): 421 keV

KPb($8 \rightarrow 6$): 1070 keV

KPb($9 \rightarrow 8$): 289 keV

Expected Impact:

- Kaon Mass most precise measurement
 - (C. Amsler, S. Eidelmann)
 - 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

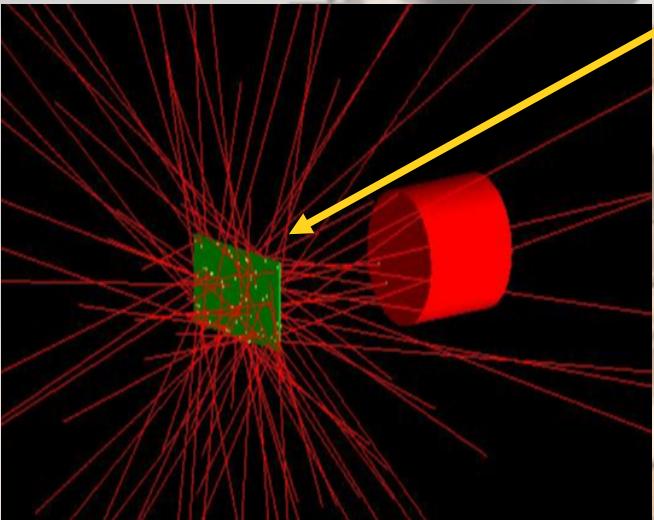
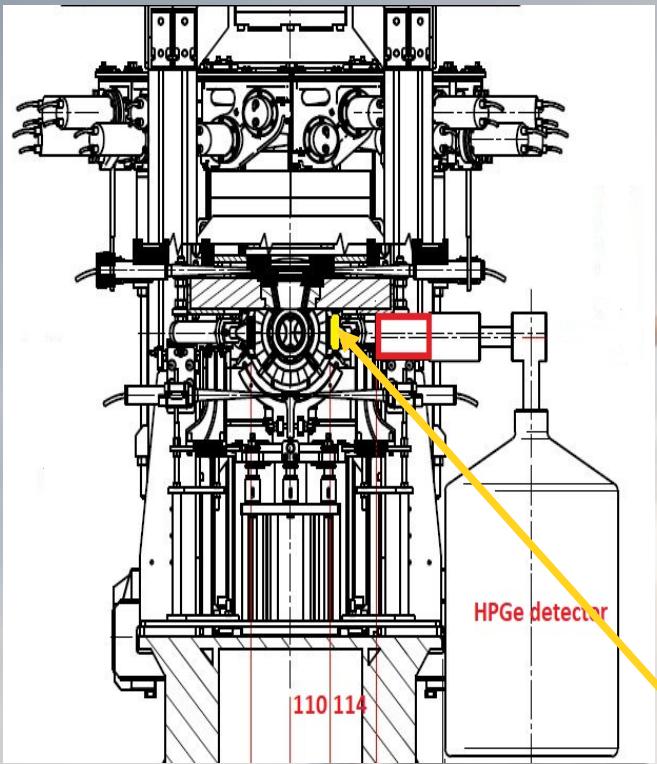


Detector system ready for measurements!

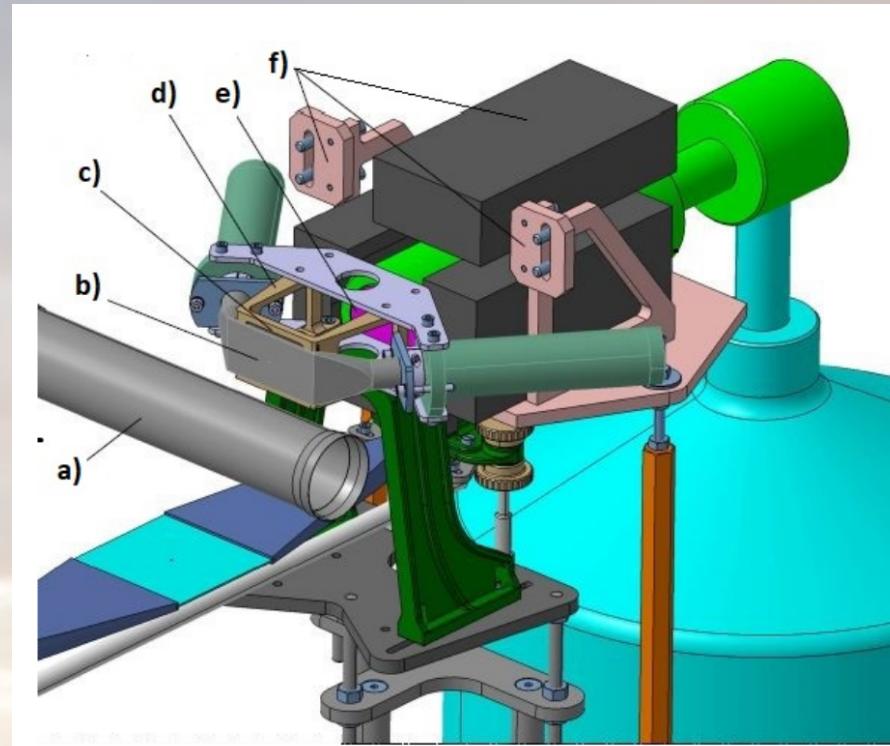


GEKA: Kaon Mass and High Z kaonic atoms

Feasibility test run during SIDDHARTA-2: K⁺Pb



Target just behind
the luminometer,
which is used as trigger



Future implementations:

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

See next talk by D. Bosnar

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

Months from start	Year	GEKA	
		Setup optim. from feasibility test	Run (5 targets x 1 month)
1	1st		
2			
3			
4			
5			
6			
7			
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 K⁻Pb (9->8) transition @ 291.6 keV, to be used for K⁻ mass measurement

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 $L = 1,4 \times 10^{32}$ ($\sim 10 \text{ pb}^{-1} / \text{day}$):

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



$\sim 360 \text{ pb}^{-1}$ (~ 1 month) of beamtime requested
to achieve $\delta E \sim 3 \text{ eV}$

!!! Similar estimations for each target !!!

KAHEL & LIKAM-1: Light Kaonic Atoms Measurements

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

$K^3He(2 \rightarrow 1)$: 33 keV
 $K^4He(2 \rightarrow 1)$: 35 keV

$K^{6,7}Li(3 \rightarrow 2)$: 15 keV
 $K^{6,7}Li(4 \rightarrow 2)$: 20 keV

$K^9Be(3 \rightarrow 2)$: 27 keV
 $K^9Be(4 \rightarrow 2)$: 37 keV
 $K^9Be(5 \rightarrow 3)$: 14 keV

$K^{10,11}B(4 \rightarrow 3)$: 15 keV
 $K^{10,11}B(5 \rightarrow 3)$: 22 keV
 $K^{10,11}B(6 \rightarrow 4)$: 11 keV

Feasibility:

1-2 mm SDDs already financed by INFN CSN3

Electronics is similar to SIDDHARTA-2 SDDs

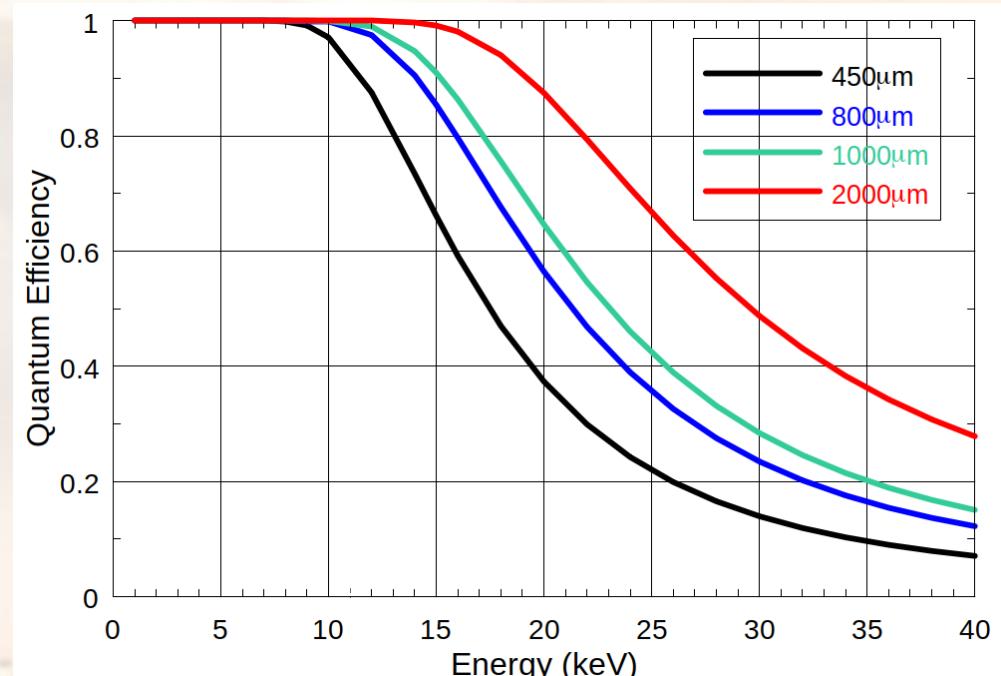
800 μ m and 1mm SDDs prototypes already produced
by FBK for ARDESIA (INFN)

Expected Impact:

- $K^{3,4}He (2p \rightarrow 1s)$ first measurements ever
- Features of KNN interactions in light kaonic atoms
 - (E. Friedman, A. Gal)
- Upper level measurements with tens eV Γ
 - (S. Wycech)

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)



KAHEL & LIKAM-1: Light Kaonic Atoms Measurements

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

$K^6Li(2 \rightarrow 1)$: 81 keV

$K^6Li(3 \rightarrow 1)$: 97 keV

$K^7Li(2 \rightarrow 1)$: 82 keV

$K^7Li(3 \rightarrow 1)$: 98 keV

$K^{10,11}B(4 \rightarrow 2)$: 58 keV

$K^{10,11}B(5 \rightarrow 2)$: 65 keV

$K^{10,11}B(6 \rightarrow 2)$: 69 keV

$K^{10,11}B(7 \rightarrow 2)$: 71 keV

$K^{11}B(4 \rightarrow 2)$: 59 keV

$K^{11}B(5 \rightarrow 2)$: 66 keV

$K^{11}B(6 \rightarrow 2)$: 70 keV

$K^{11}B(7 \rightarrow 2)$: 72 keV

Feasibility:

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

First prototypes will be available by mid 2022

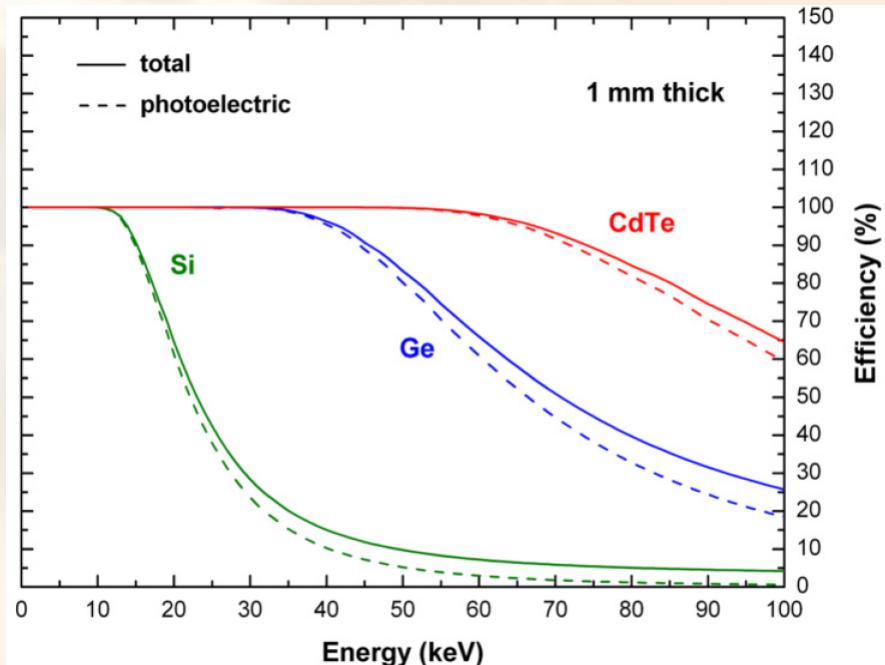
Electronics prototype will be also delivered

Expected Impact:

- Features of KNN interactions in light kaonic atoms (E. Friedman, A. Gal)
 - Upper level measurements with tens eV Γ
 - (S. Wycech)
 - Cascade processes

Detector Key Points:

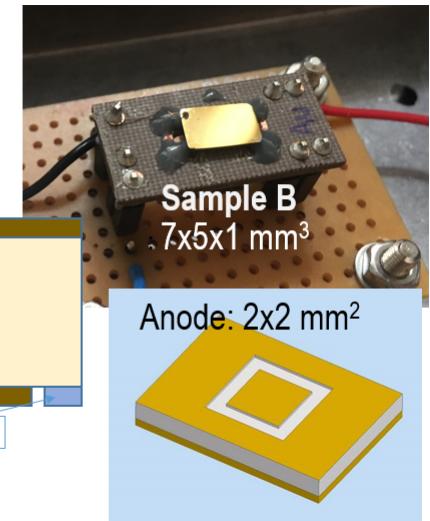
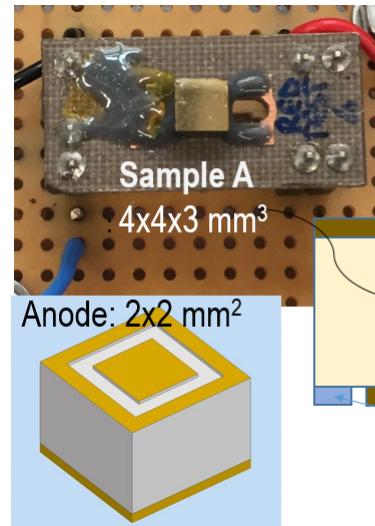
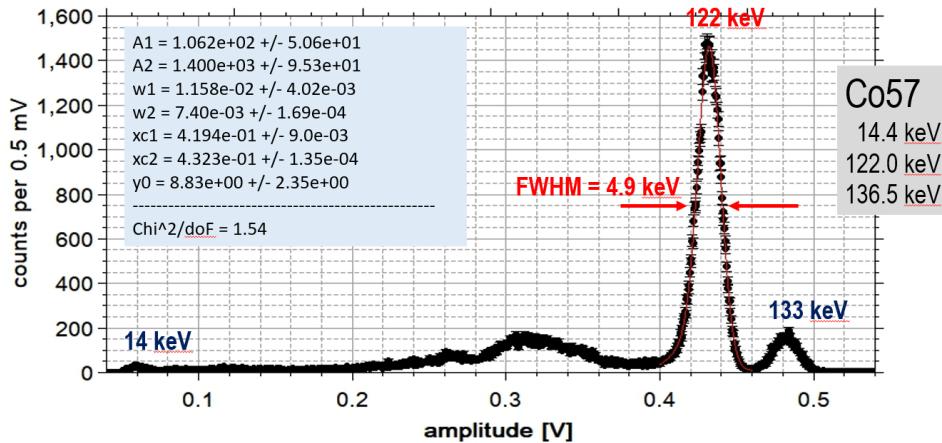
- High efficiency in the 50-100 keV region
- Good resolution (500 eV @ 20 keV / 1 keV @ 200 keV) to separate the lines of interest



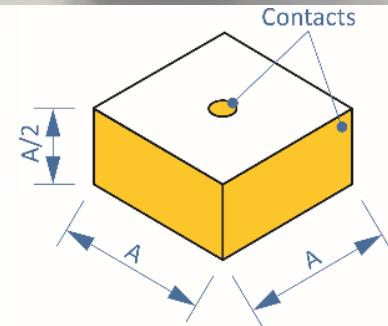
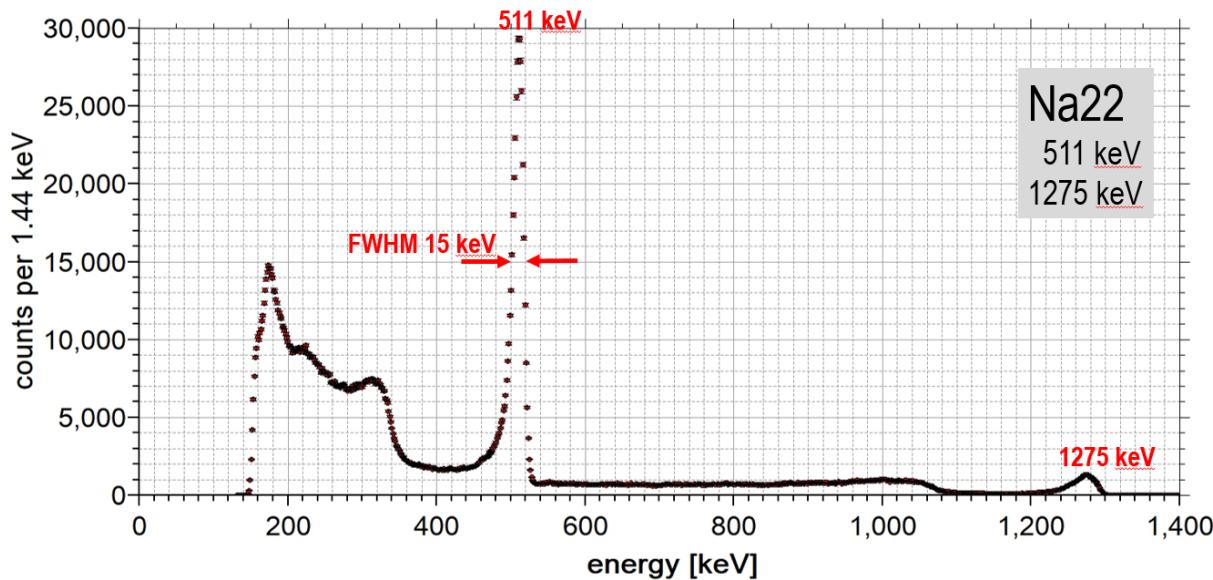
KAHEL & LIKAM-1: Light Kaonic Atoms Measurements

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

Sample A – Co57 bias: 1000 V

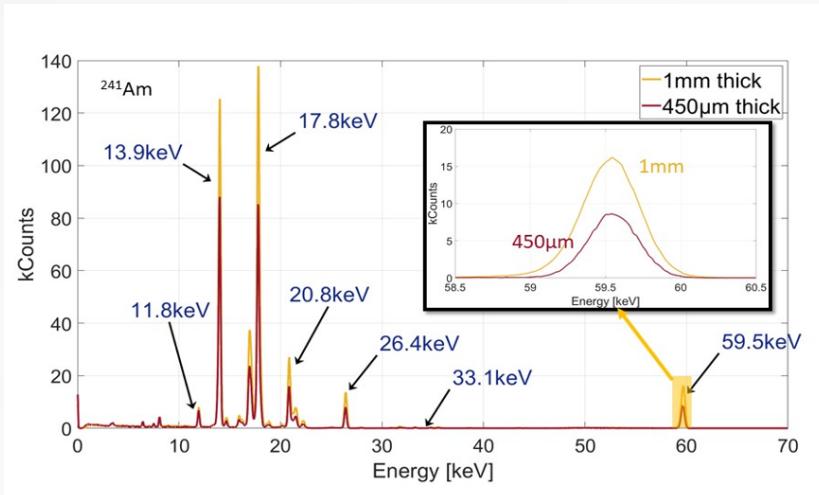


CZT-500 – Na22 bias: 600 V

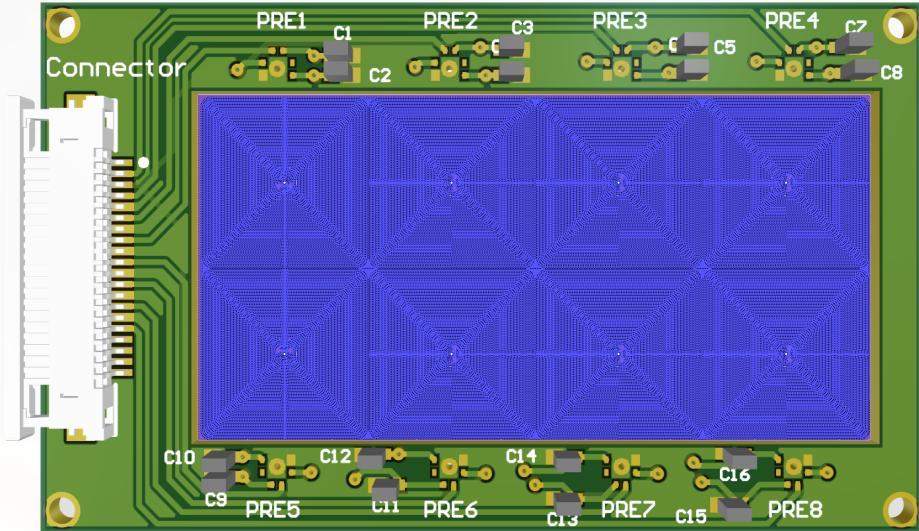


KAHEL & LIKAM-1: Light Kaonic Atoms Measurements

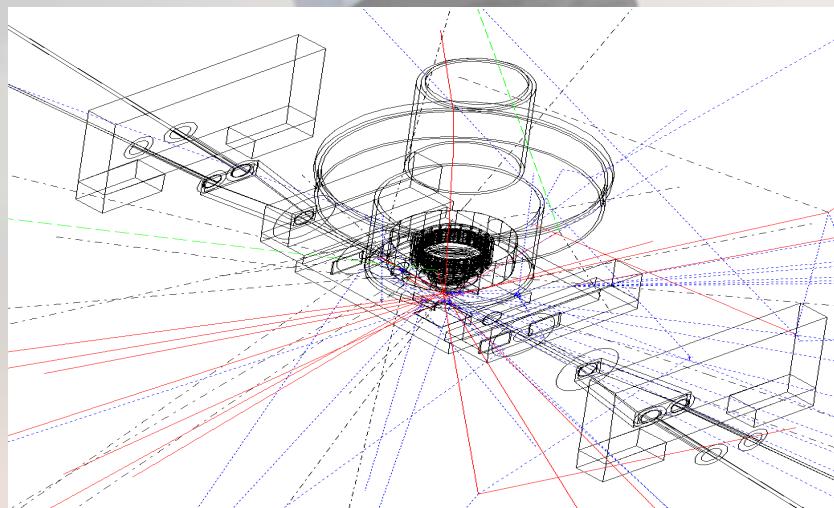
800 μ m and 1mm SDDs prototypes already produced by FBK for ARDESIA (INFN)



Prototypes of electronics boards are already available



First XRF tests with known targets show very promising results



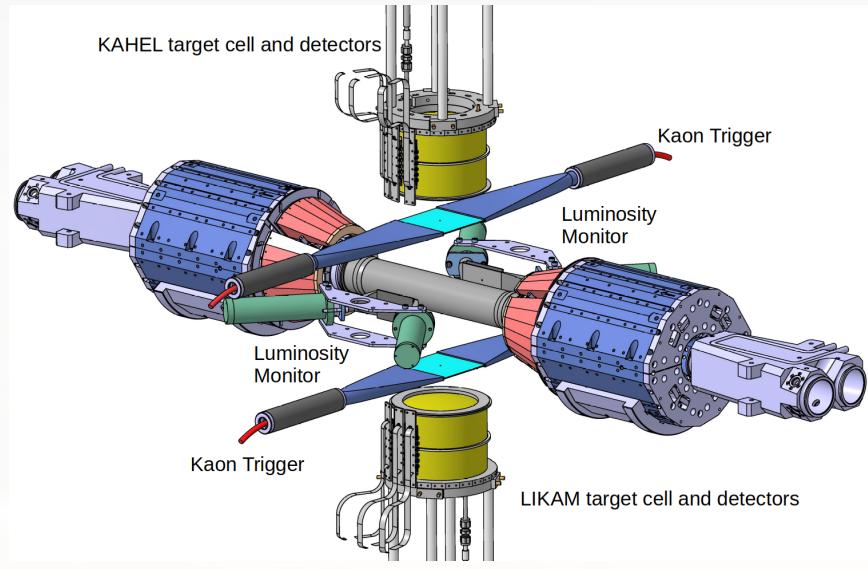
Future implementations:

- Targets : $^{3,4}\text{He}$, $^{6,7}\text{Li}$, $^{8,9}\text{Be}$, $^{9,10,11}\text{B}$
- 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

Months from start	Year	KAHEL + LIKAM-1							
		Electronics proj.	Electronics prod.	Mechanics proj.	Mechanics prod.	DAQ preparation	Calib & Tests	Installation	Run (6 targets x 1 month)
1	1st								
2									
3									
4									
5									
6									
7									
8									
9									
10									
11	2nd								
12									
13									
14									
15									
16									
17									
18									
19									
20									
21									
22									
23									
24									
25									



From MC simulations:

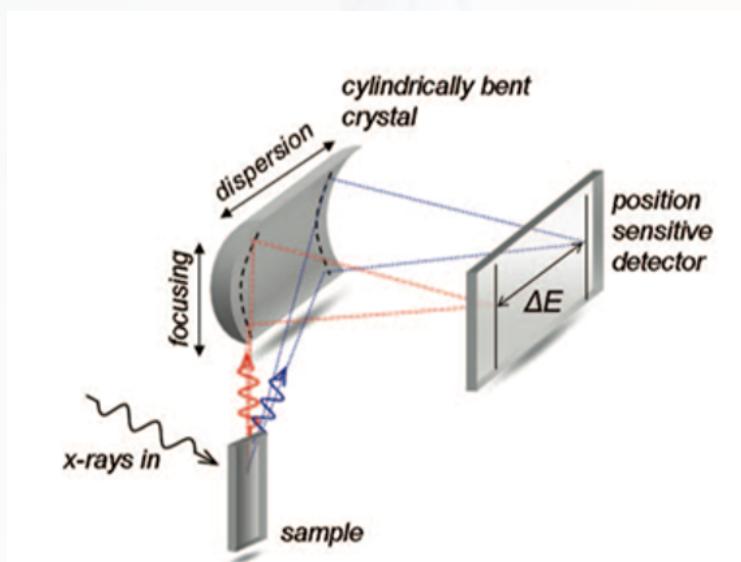
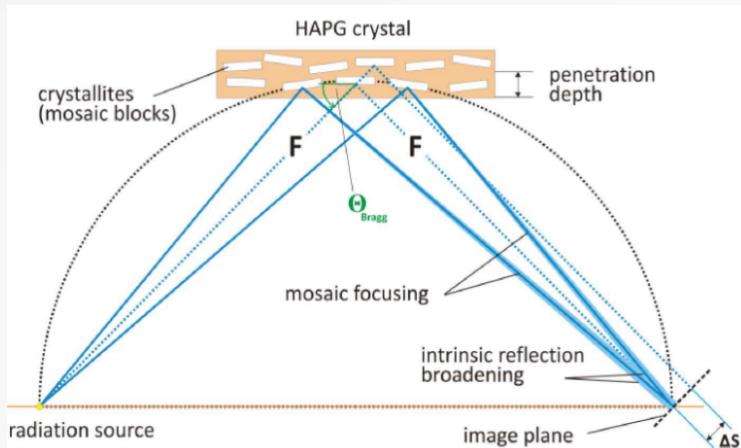
- Assuming $L = 1,4 \times 10^{32}$ ($\sim 10 \text{ pb}^{-1} / \text{day}$)
- Assuming reasonable yields in the order of 20 %
- Integrating 800 pb^{-1} for Kaonic Helium
- Integrating 400 pb^{-1} for each of the other targets



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

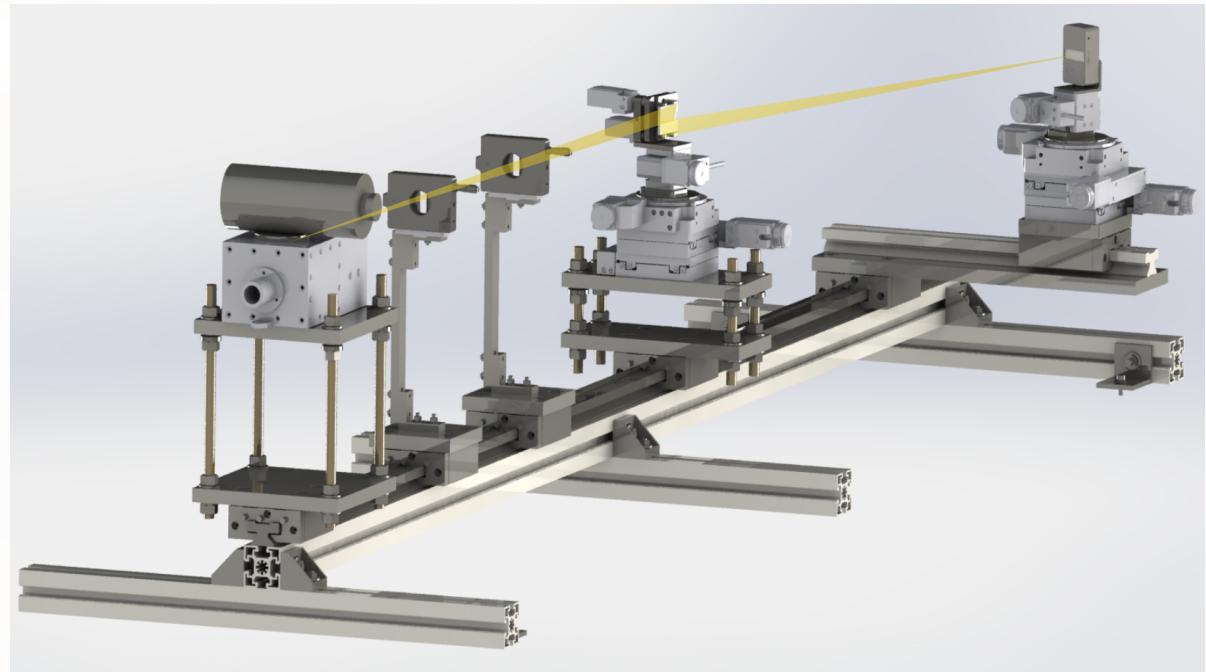
NUMES: sub-eV precision Kaonic Atoms measurements

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

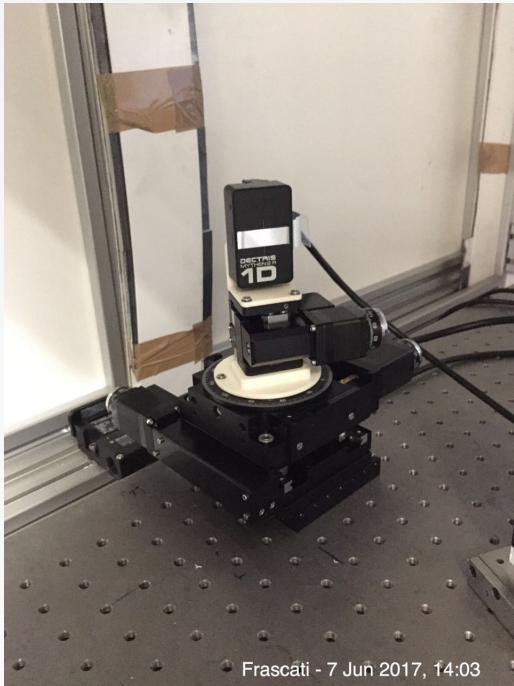


HAPG mosaic crystals in Von Hamos configuration:

- 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



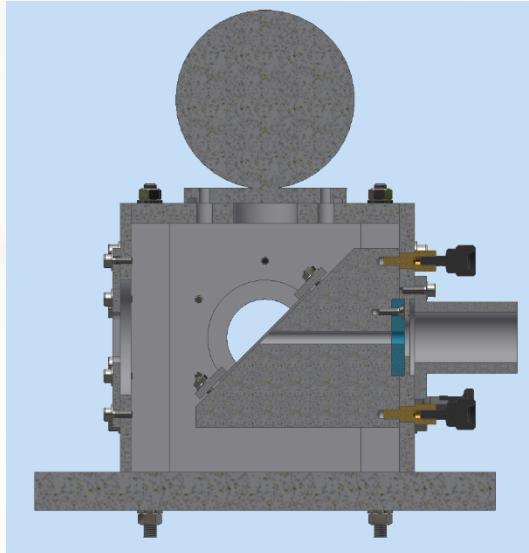
Dectris Ltd
MYTHEN2 detector:

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

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



Designed at SMI



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



8MUP21-2 - Motorized Optical
Mount (STANDA)

< 1 arcsec resolution



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



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

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:

$K^3He(3 \rightarrow 2)$: 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 measurements with very small Γ
- Proton radius puzzle (???)

Manifestation 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

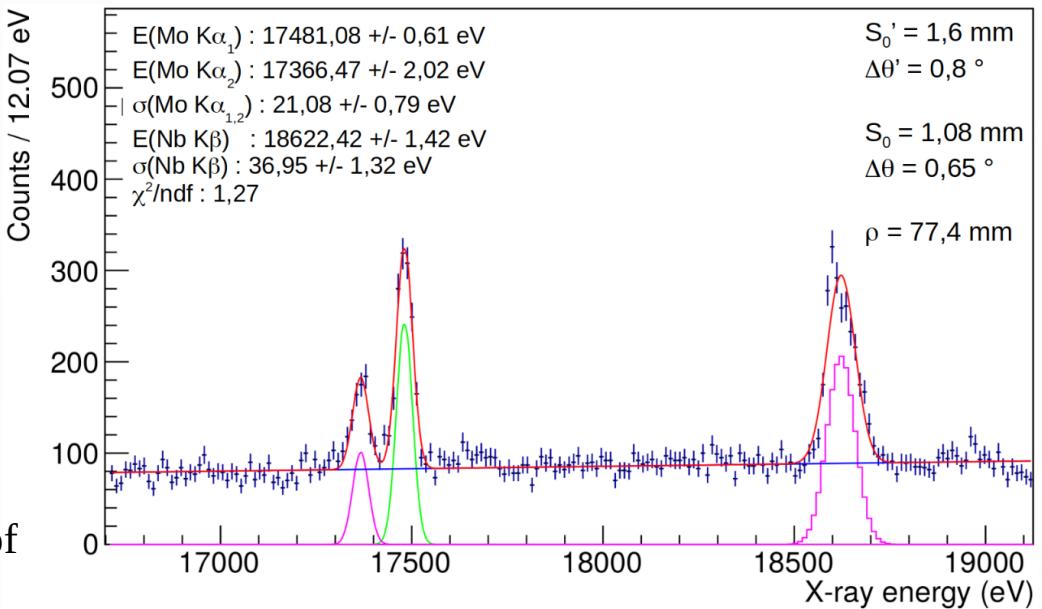
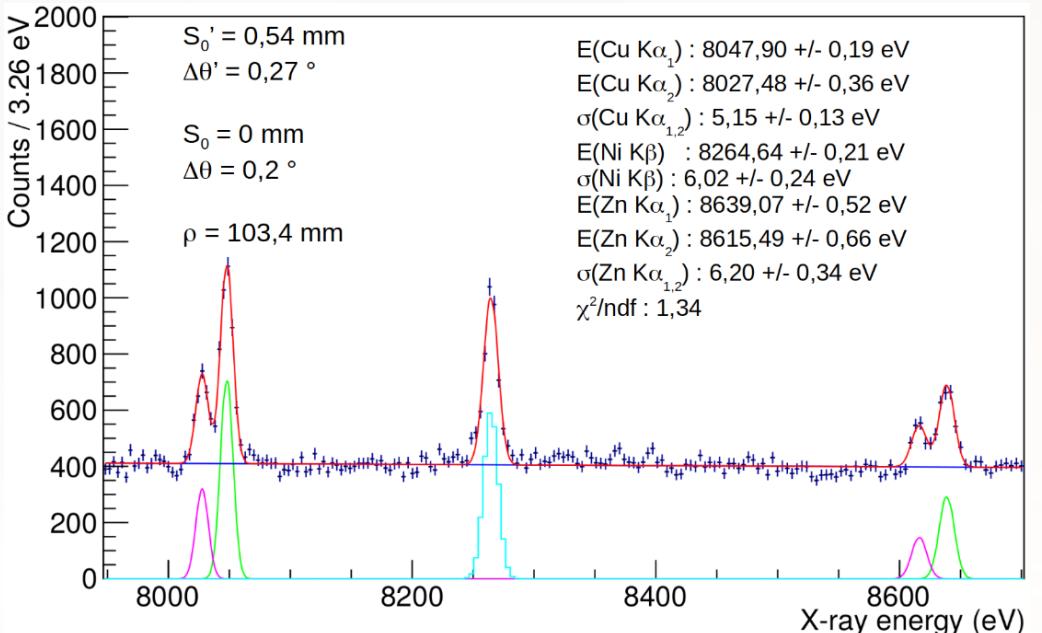
Table 3 Best achieved resolutions and precisions summary.

Element	ρ_c (mm)	Parameter	value (eV)	$S'_0/\Delta\theta'$ (mm,°)
77,5	77,5	$\sigma(K\alpha_{1,2})$	$4,17 \pm 0,16$	$0,3 / 0,24$
		$\delta(K\alpha_1)$	0,11	$0,6 / 0,44$
		$\delta(K\alpha_2)$	0,18	$0,6 / 0,44$
Fe	103,4	$\sigma(K\alpha_{1,2})$	$4,05 \pm 0,13$	$0,3 / 0,18$
		$\delta(K\alpha_1)$	0,09	$0,7 / 0,34$
		$\delta(K\alpha_2)$	0,13	$0,7 / 0,34$
Cu	206,7	$\sigma(K\alpha_{1,2})$	$4,02 \pm 0,08$	$1,1 / 0,60$
		$\delta(K\alpha_1)$	0,1	$1,2 / 0,70$
		$\delta(K\alpha_2)$	0,15	$1,2 / 0,70$
Cu	77,5	$\sigma(K\alpha_{1,2})$	$6,8 \pm 0,07$	$0,3 / 0,16$
		$\delta(K\alpha_1)$	0,07	$0,6 / 0,32$
		$\delta(K\alpha_2)$	0,1	$0,6 / 0,32$
Cu	103,4	$\sigma(K\alpha_{1,2})$	$4,77 \pm 0,05$	$0,3 / 0,16$
		$\delta(K\alpha_1)$	0,04	$0,7 / 0,32$
		$\delta(K\alpha_2)$	0,07	$0,7 / 0,32$
Zn	206,7	$\sigma(K\alpha_{1,2})$	$3,60 \pm 0,05$	$0,8 / 0,60$
		$\delta(K\alpha_1)$	0,04	$1,1 / 0,70$
		$\delta(K\alpha_2)$	0,07	$1,1 / 0,70$
Cu	103,4	$\sigma(K\alpha_{1,2})$	$5,15 \pm 0,13$	$0,5 / 0,27$
		$\delta(K\alpha_1)$	0,10	$0,6 / 0,22$
		$\delta(K\alpha_2)$	0,21	$0,6 / 0,22$
Ni	103,4	$\sigma(K\beta)$	$6,02 \pm 0,24$	$0,5 / 0,27$
		$\delta(K\beta)$	0,13	$0,6 / 0,22$
Zn	103,4	$\sigma(K\alpha_{1,2})$	$6,20 \pm 0,34$	$0,5 / 0,27$
		$\delta(K\alpha_1)$	0,26	$0,6 / 0,22$
		$\delta(K\alpha_2)$	0,42	$0,6 / 0,22$
Mo	77,5	$\sigma(K\alpha_{1,2})$	$21,1 \pm 0,8$	$1,6 / 0,80$
		$\delta(K\alpha_1)$	0,6	$1,6 / 0,80$
		$\delta(K\alpha_2)$	2,0	$1,6 / 0,80$
Nb	77,5	$\sigma(K\beta)$	$36,9 \pm 1,3$	$1,6 / 0,80$
		$\delta(K\beta)$	1,3	$1,6 / 0,80$

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

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

High precision measurements with VOXES in LNF Lab



NUMES v1: KC run with existing setup

NUMES v1

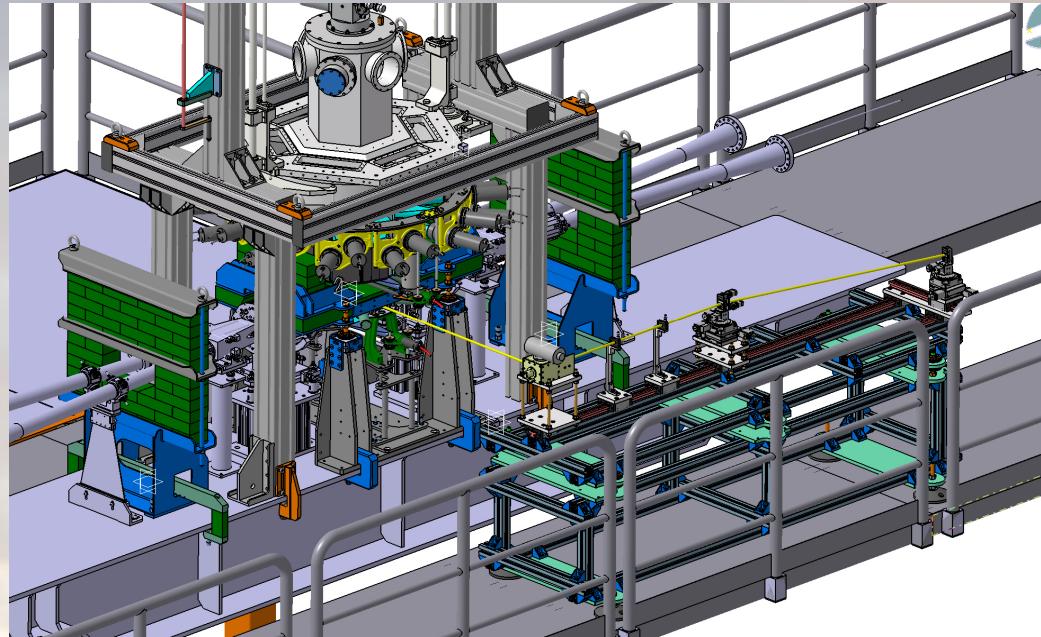
First run with KC for a K- mass measurement

Available:

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

Future implementations:

- Shielding around Detector
- Solid support structure



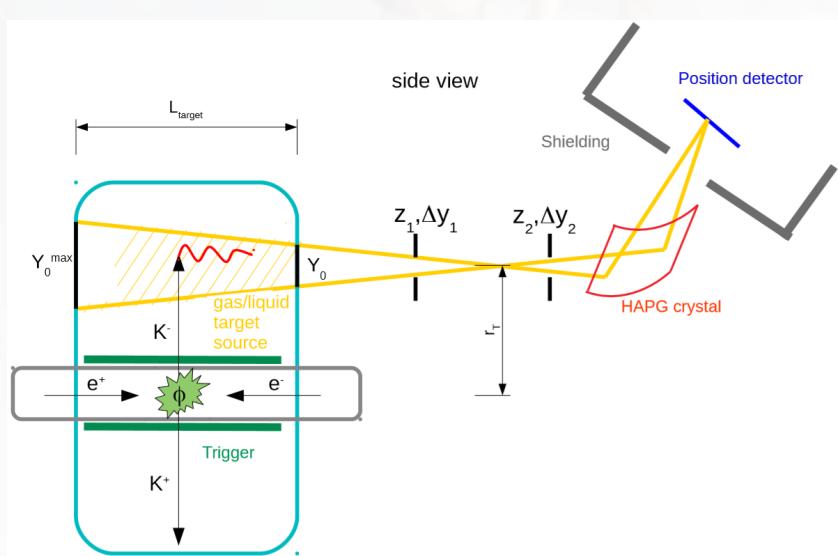
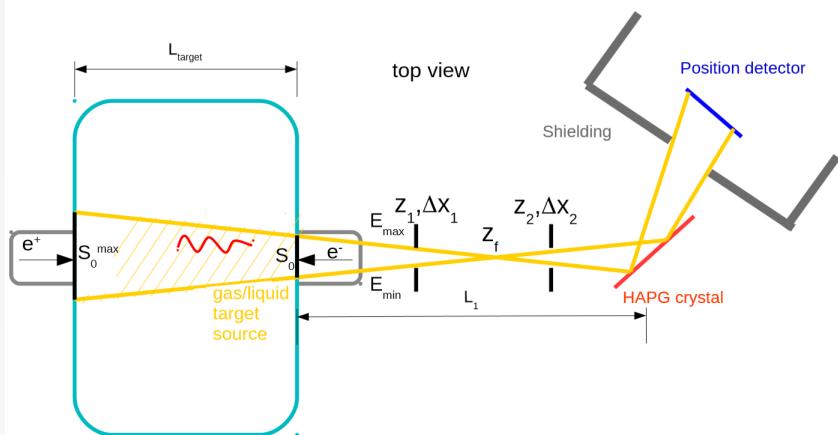
From MC simulations,
assuming $L = 1,4 \times 10^{32}$ ($\sim 10 \text{ pb}^{-1} / \text{day}$):

- $\sim 1,4$ recorded signals / day
- ~ 250 total events goal ($\delta E \sim 0,2 - 0,3 \text{ eV}$)
- $\sigma = 3,6 \text{ eV}$ @ 8 keV (from Cu lab measurements)



$\sim 2000 \text{ pb}^{-1}$ (~ 200 days) of beamtime requested

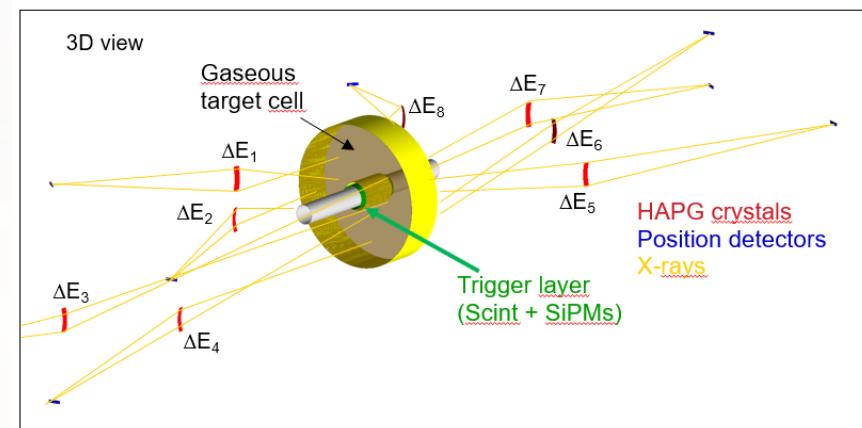
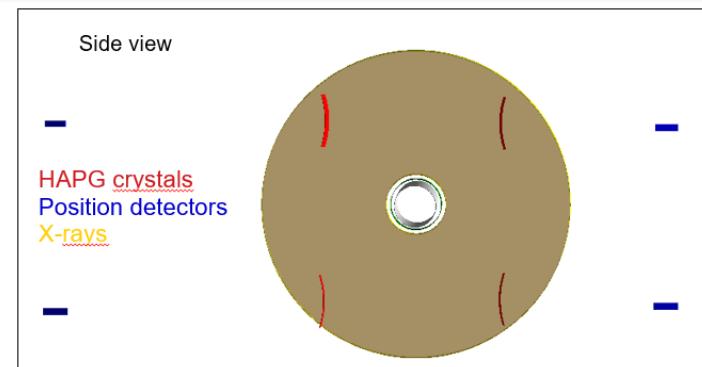
NUMES v2: K^{3,4}He and KN measurements



Example:

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

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



Completely new experiment / setup

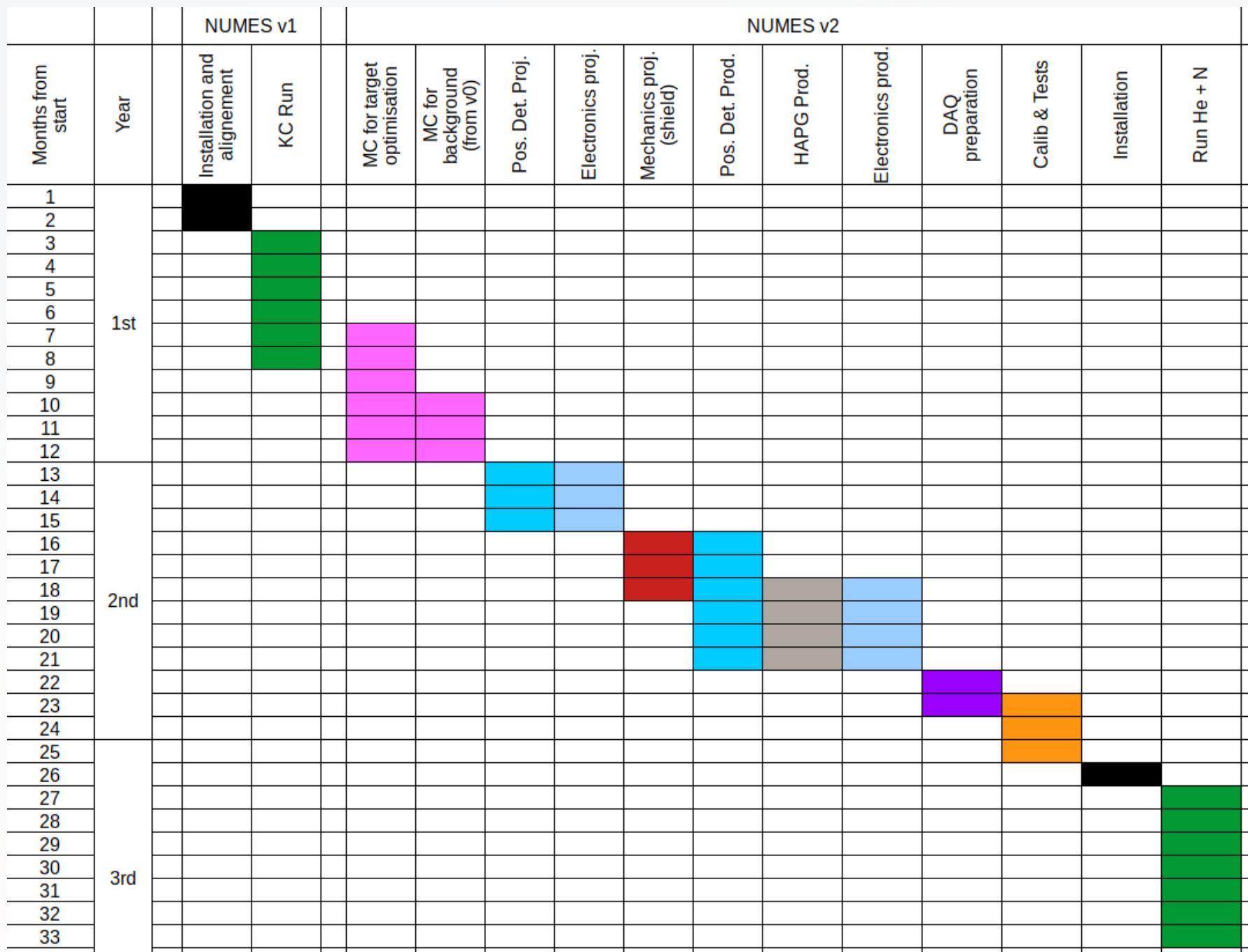
Position Detector and HAPG crystals development with R&D opportunities

Real opportunity to apply for external fundings

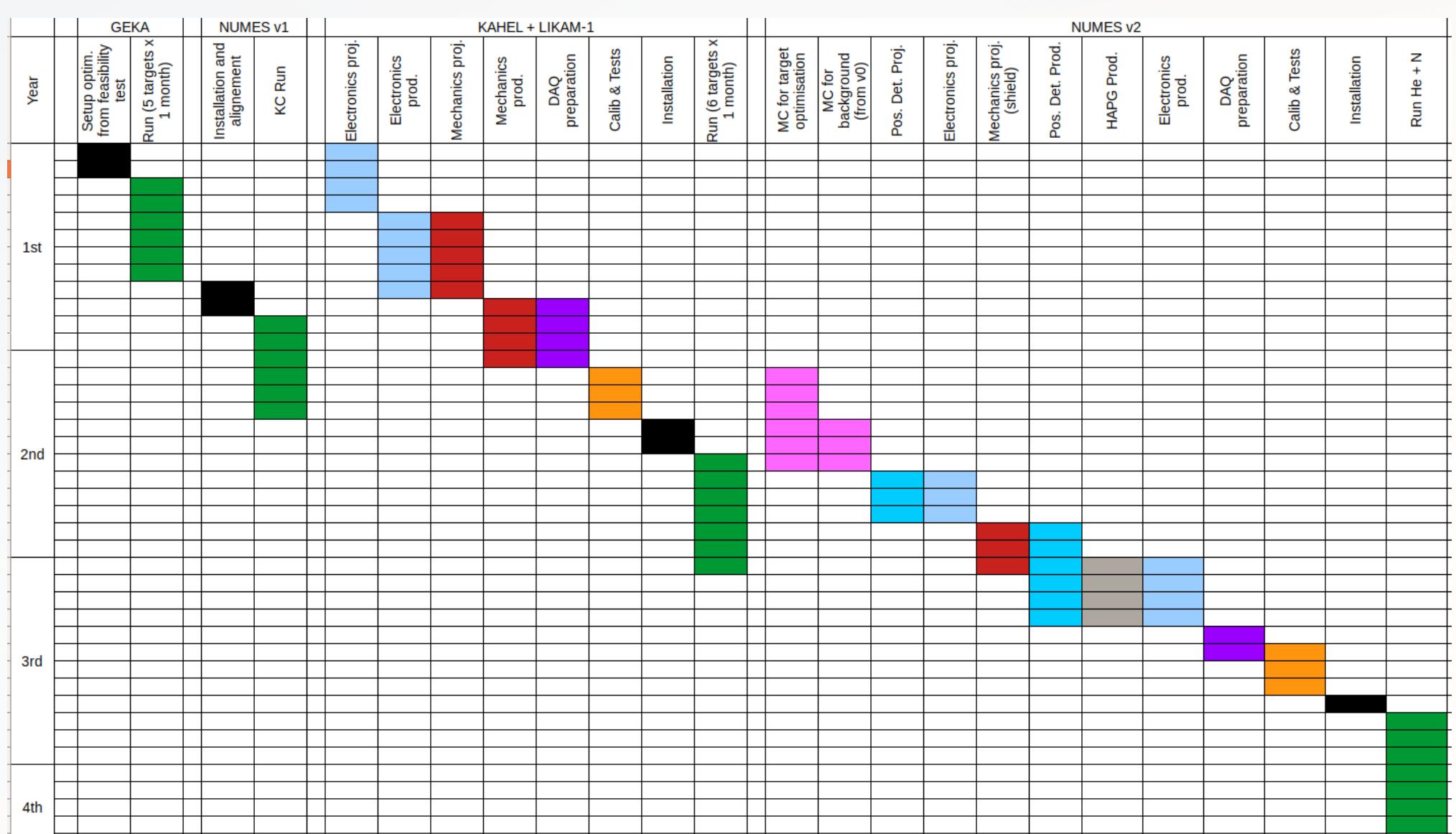
Possibility to attract new interested institutes

To achieve the ~ 0,1 eV precision, ~ 2000 pb⁻¹ (~ 200 days) of beamtime are requested

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, ...)