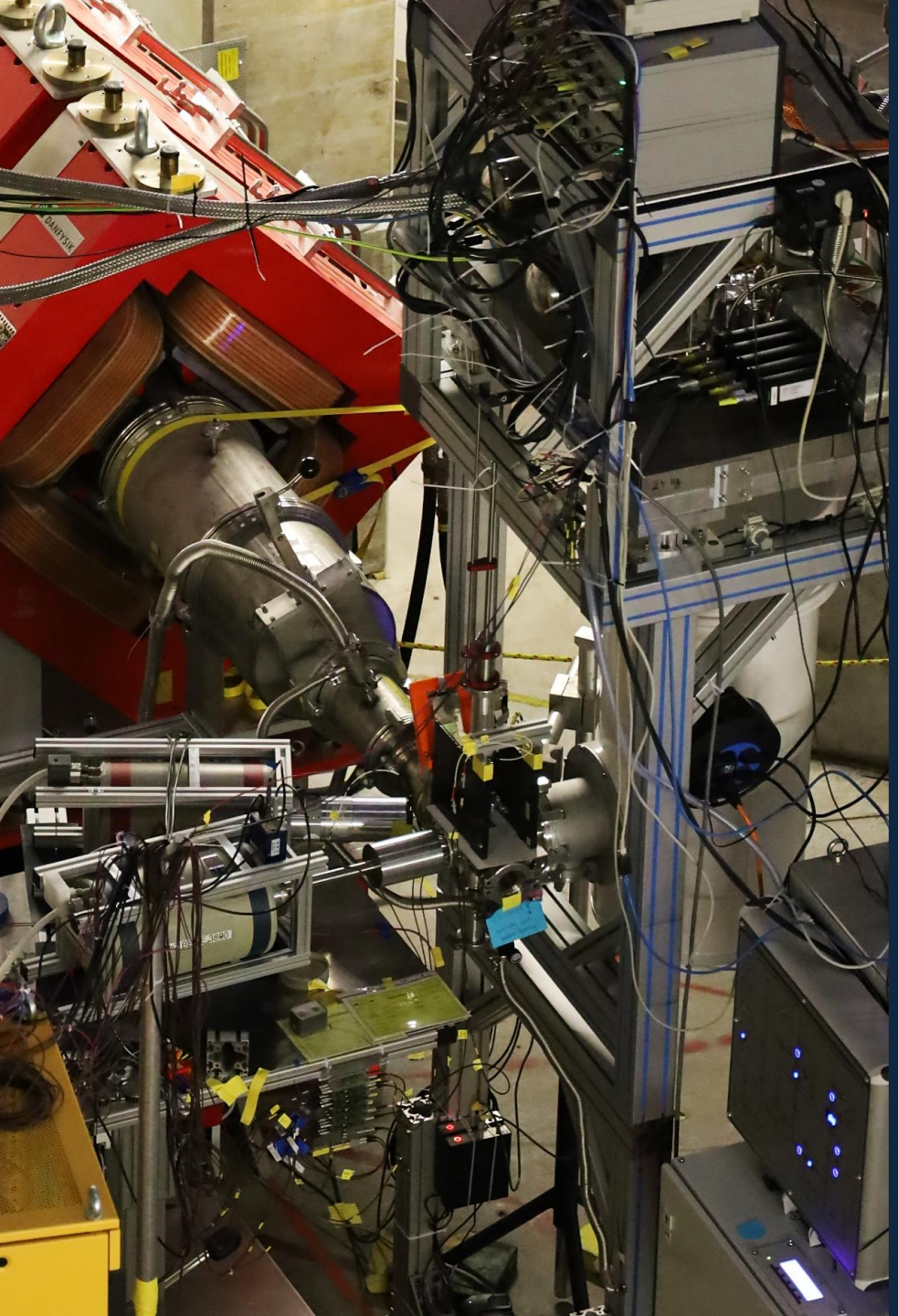


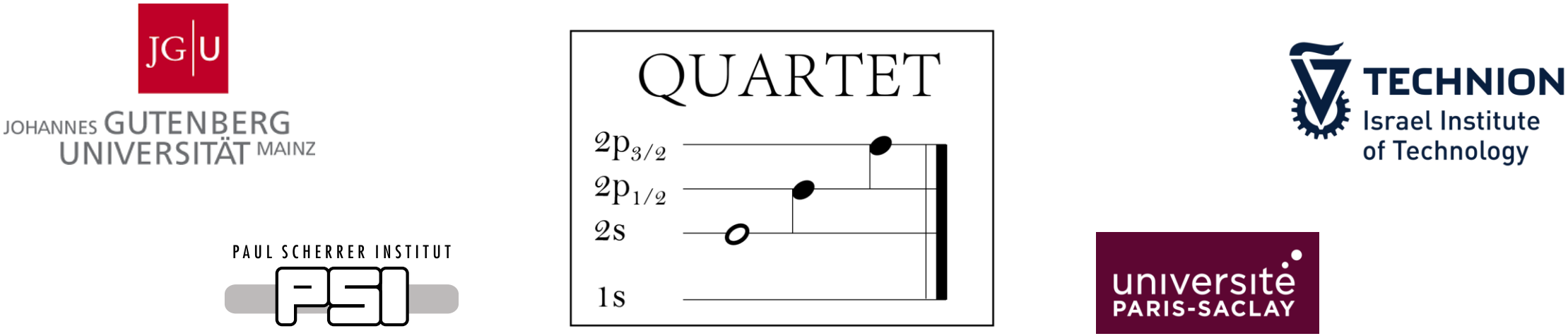
QUARTET: MMCs for Muonic X-ray Spectroscopy

HighRR BiWeekly-Seminar

D. Unger, A. Abeln, T. E. Cocolios, O. Eizenberg, C. Enss, A. Fleischmann, L. Gastaldo, C. Godinho, M. Heines, D. Hengstler, P. Indelicato, D. Kreuzberger, K. Kirch, A. Knecht, J. Machado, B. Ohayon, N. Paul, R. Pohl, K. von Schoeler, S. M. Vogiatzi, F. Wauters and A. Zendour

— for the QUARTET Collaboration

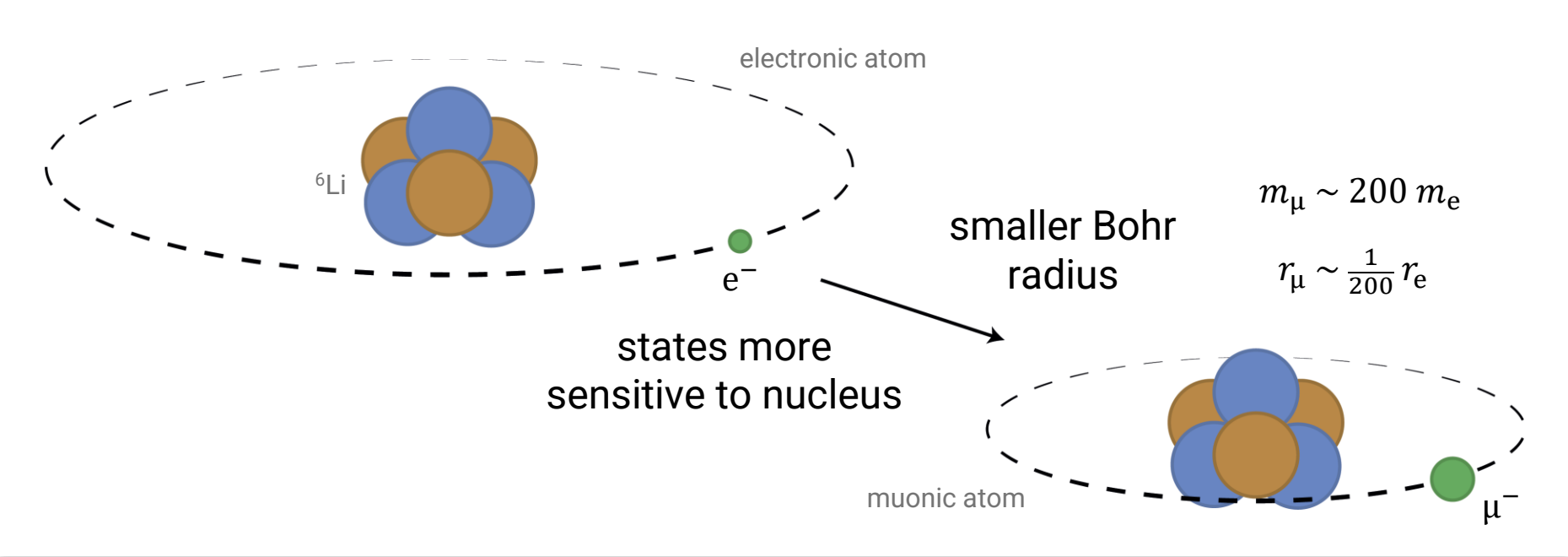
The QUARTET Collaboration



Quantum Interactions with Exotic Atoms

arXiv:2210.16929
Physics 2024, 6(1), 206-215
Unger et al, J Low Temp Phys (2024)

Transitions in Muonic Atoms



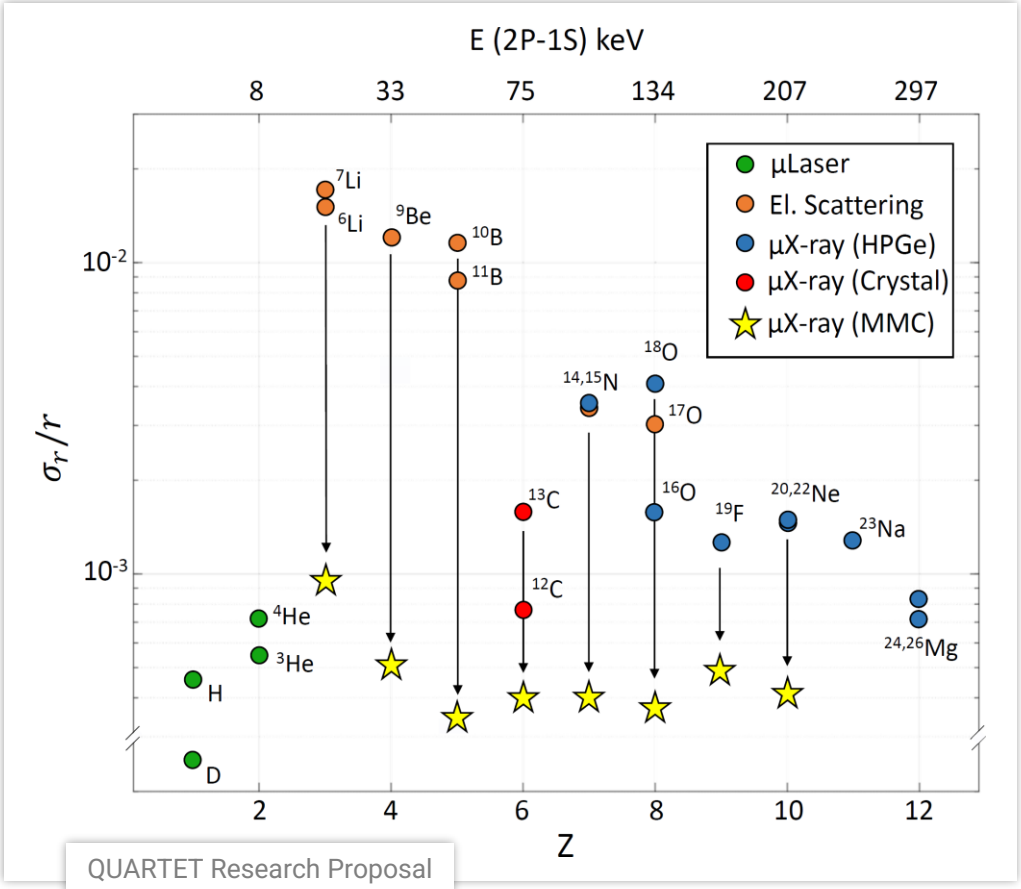
- Muonic atoms: low-lying states more sensitive to nuclear charge radius
- Precision measurements of transitions allow to test nuclear models

Our Goal

- High-resolution X-ray spectroscopy of low angular momentum states in light muonic atoms
- Determine absolute nuclear charge radii from muon transition energies
- Improve precision for stable nuclei from ^{6}Li to ^{22}Ne

$$E = E_{\mathrm{D}} + \delta E_{\mathrm{QED}} + \delta E_{\mathrm{FNS}} + \delta E_{\mathrm{TPE}} + \ldots$$

Physics 2024, 6(1), 206-215



QUARTET Research Proposal

Detector Requirements

Determining precisely the energy of X-ray lines requires:

1. Accurate energy calibration
2. Very good energy resolution
3. High rate
4. Low background

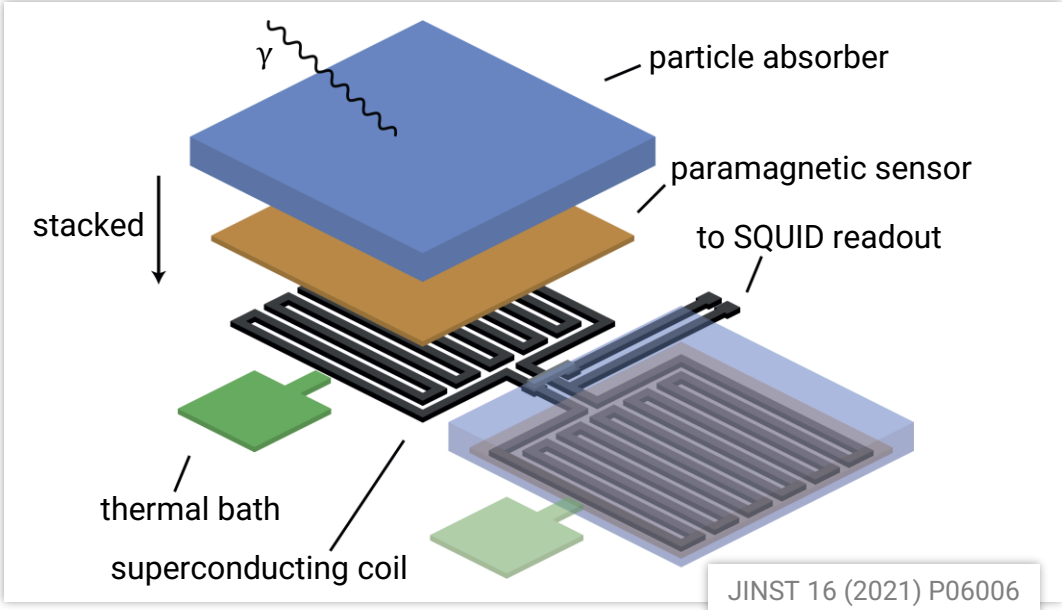
⇒ MMC-based detectors fulfil these requirement

Metallic Magnetic Calorimeter

- Cryogenic micro-calorimeter
- Operated at around 20 mK
- Based on paramagnetic temperature sensors

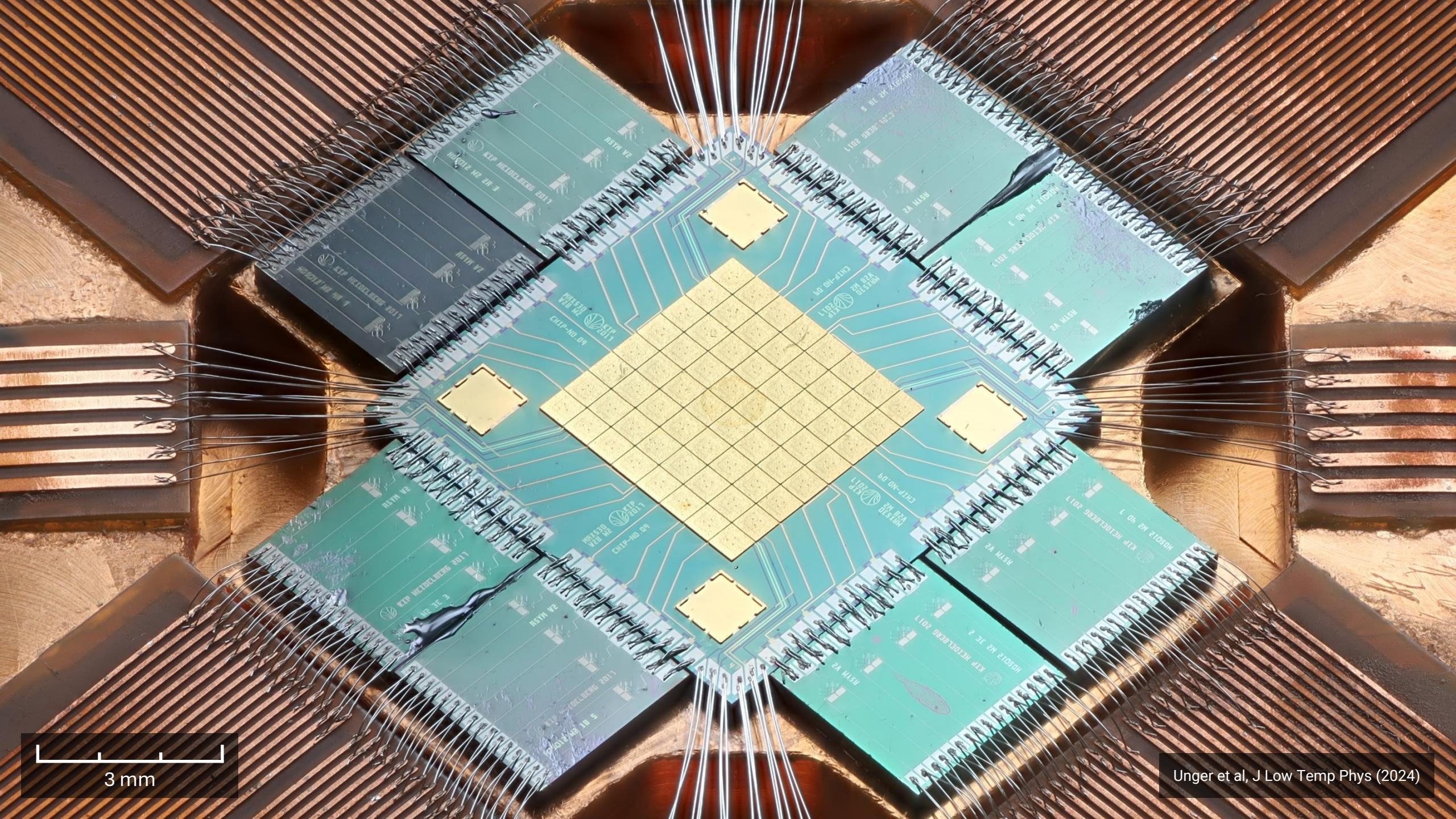
Ideal for broadband high-resolution X-ray spectroscopy:

- high quantum efficiency
- high resolving power
- large dynamic range
- reliable calibration with sub-eV resolution

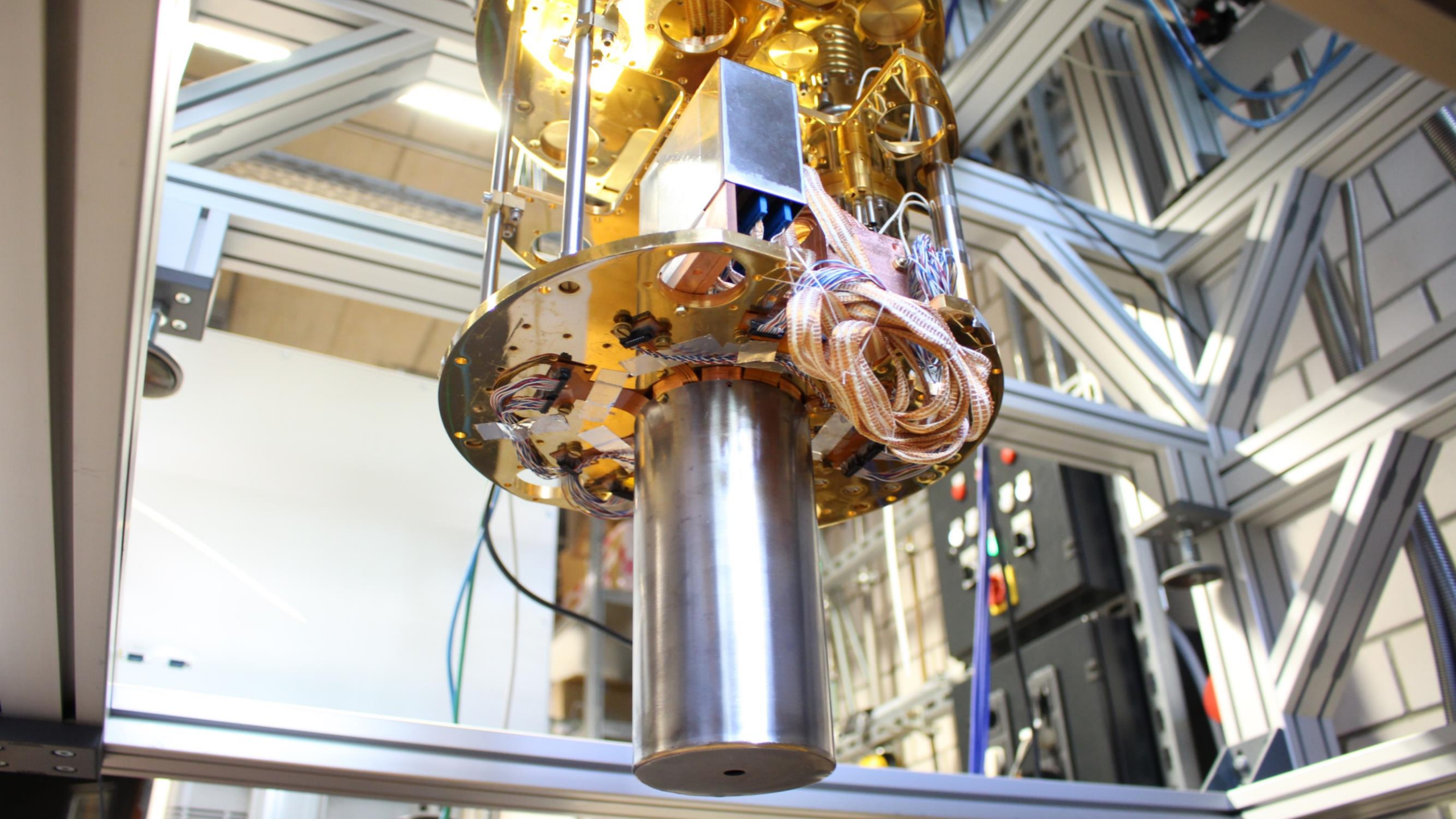


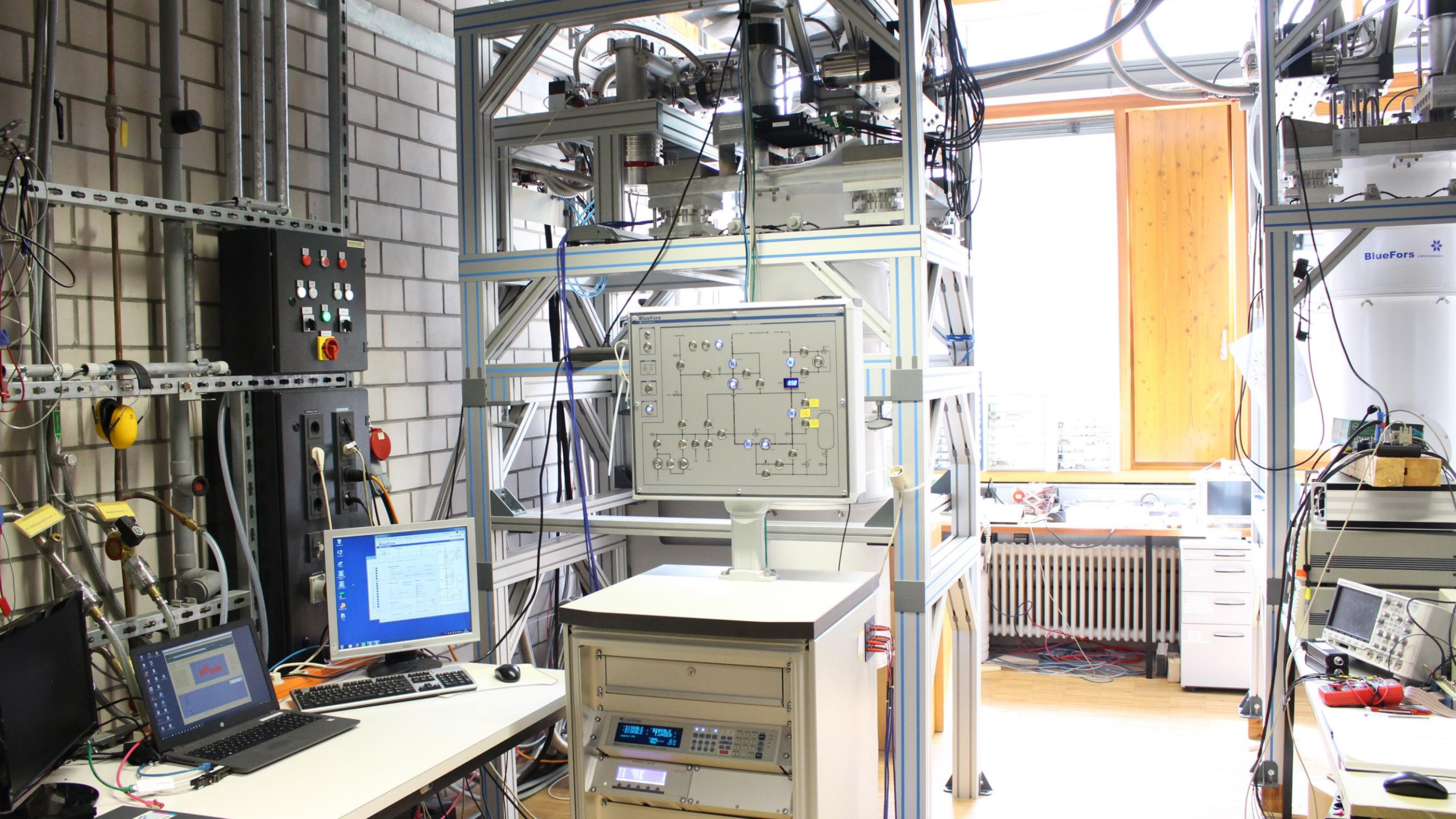
$$\delta E \longrightarrow \delta T = \frac{\delta E}{C} \longrightarrow \delta M = \frac{\partial M}{\partial T}\delta T \longrightarrow \delta\Phi \propto \delta M$$

energy deposition → temperature increase → magnetization decrease → change of magnetic flux

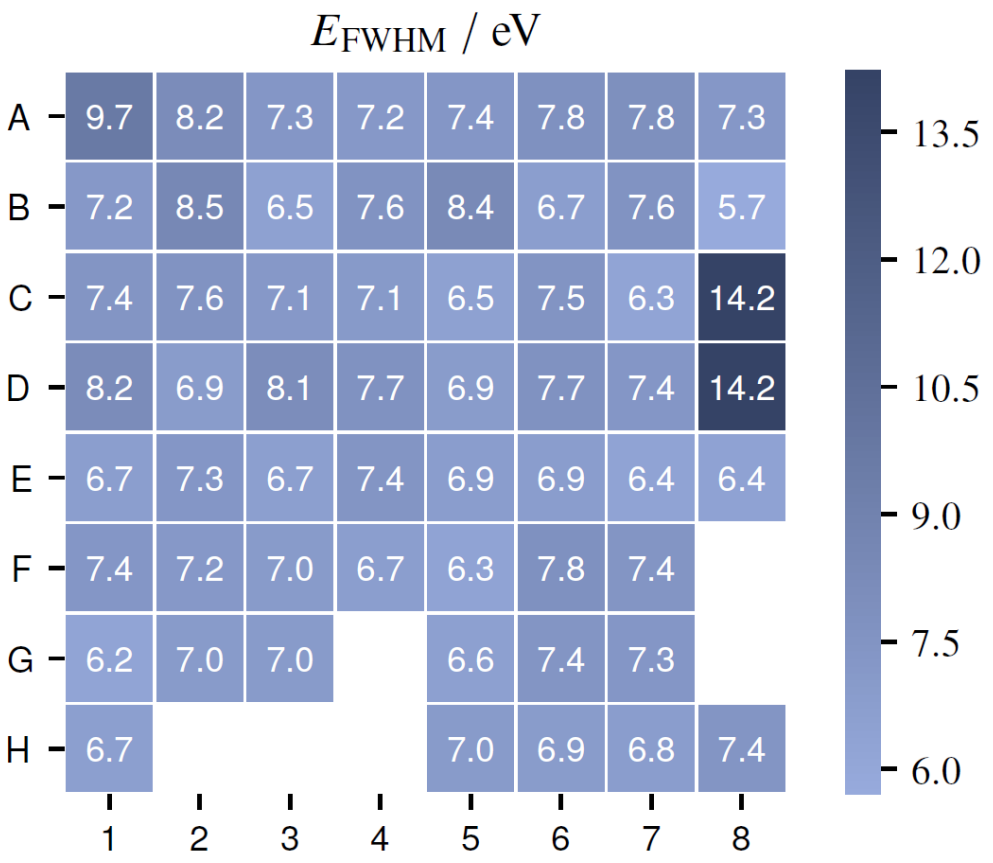


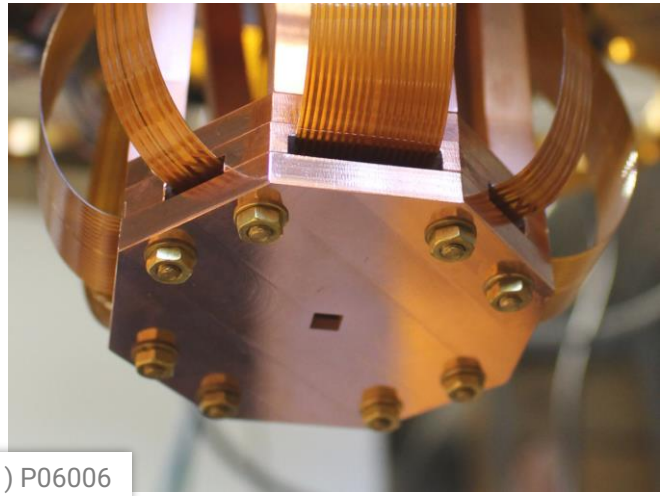
Unger et al, J Low Temp Phys (2024)



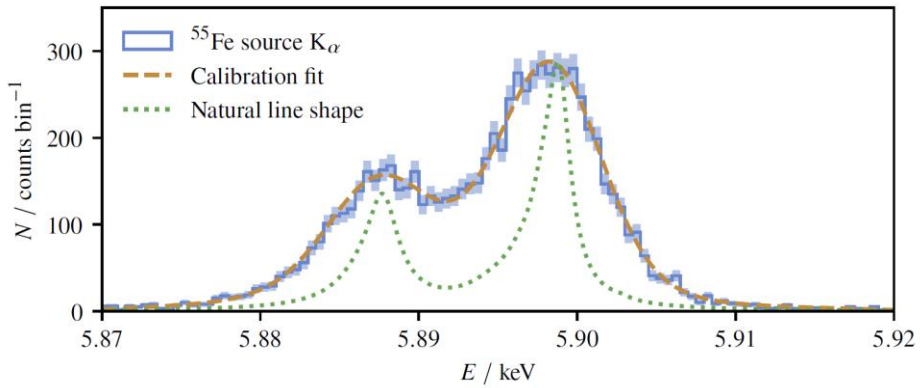

BlueFors
BlueFors

IAXO Detector Setup





JINST 16 (2021) P06006



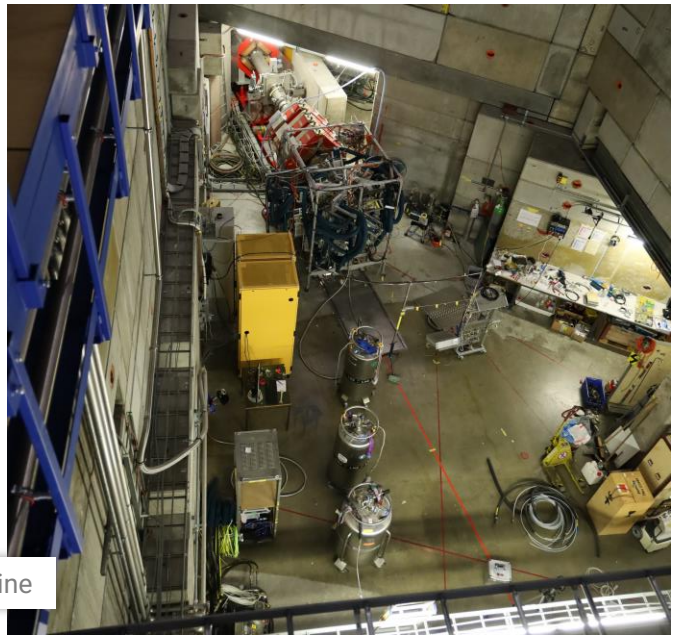
Test Beamtime

One week of test beamtime has been granted at PSI in October 2023

(piE1 beamline, continuous μ^- beam, ~10 kHz, ~28 MeV)

⇒ First application of MMCs with exotic atoms

⇒ Proof-of-principle measurement with Li, Be and B



piE1 beamline

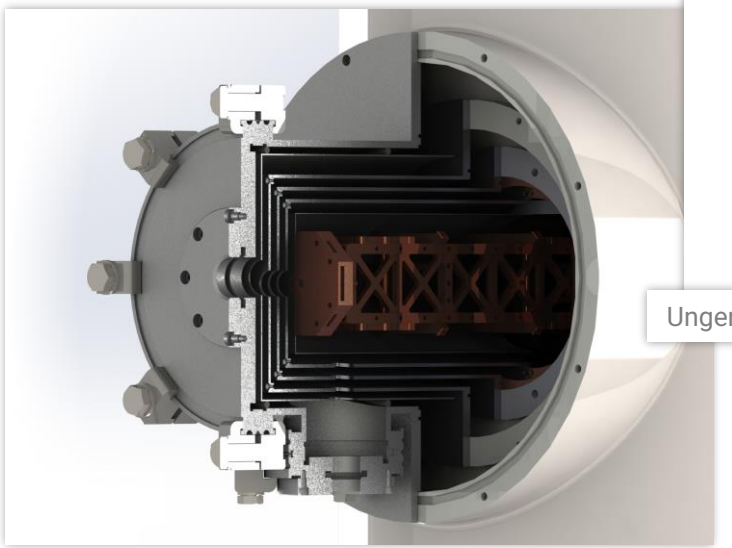
Preparation @ KIP

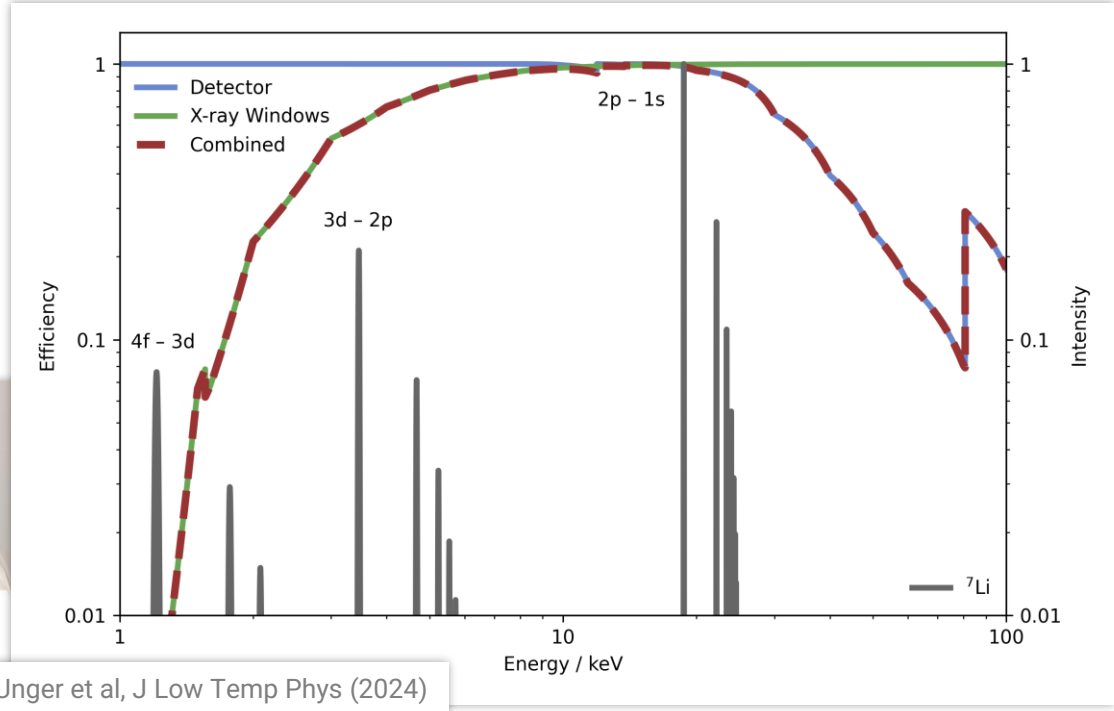
Preparation of a test beamtime setup at KIP:

1. Development of a cryostat sidearm for QUARTET
2. Assembly and test of a SQUID amplifier module
3. Verification of setup functionality at KIP
4. Arrange transport to PSI

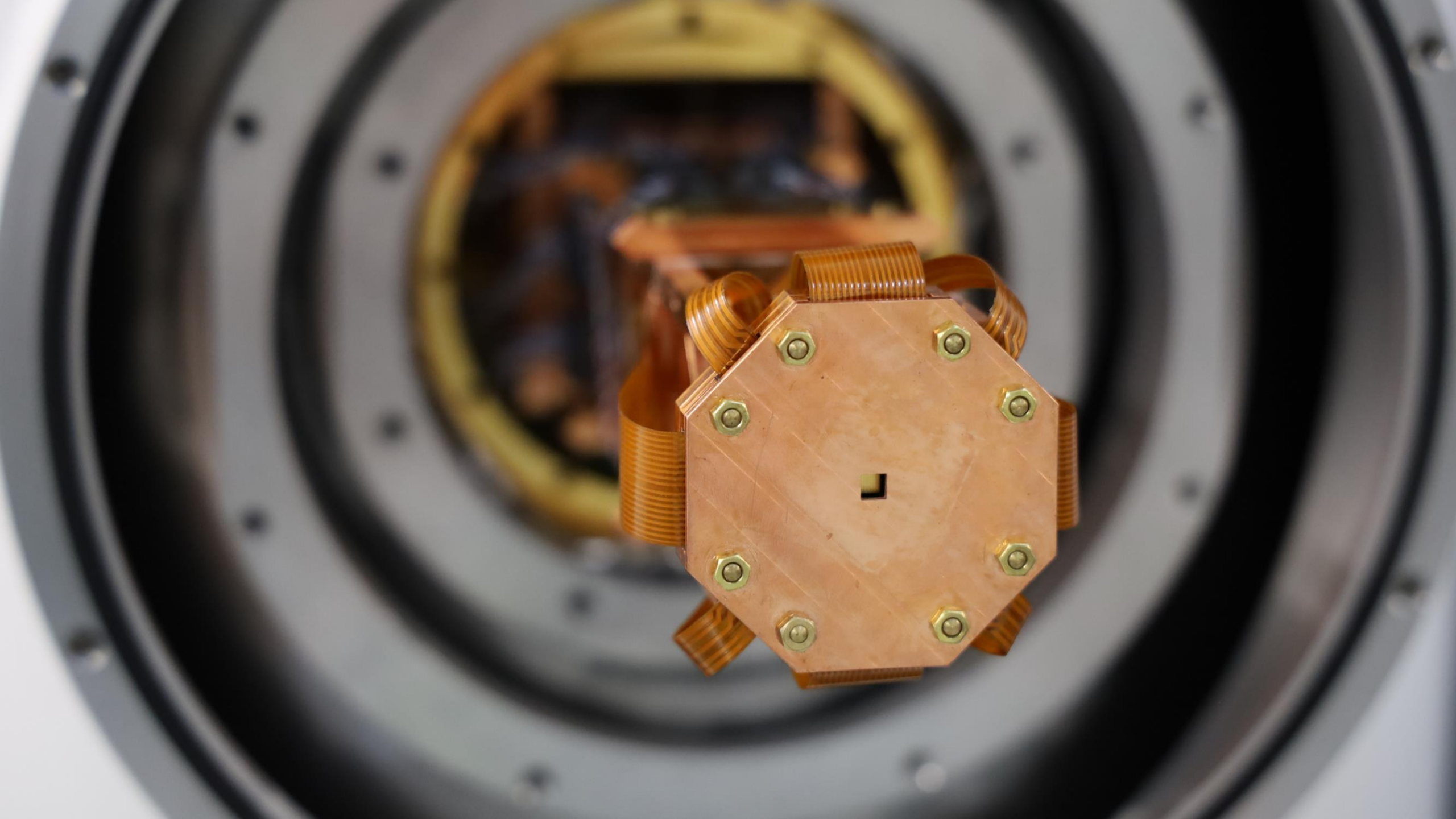
Cryostat Sidearm

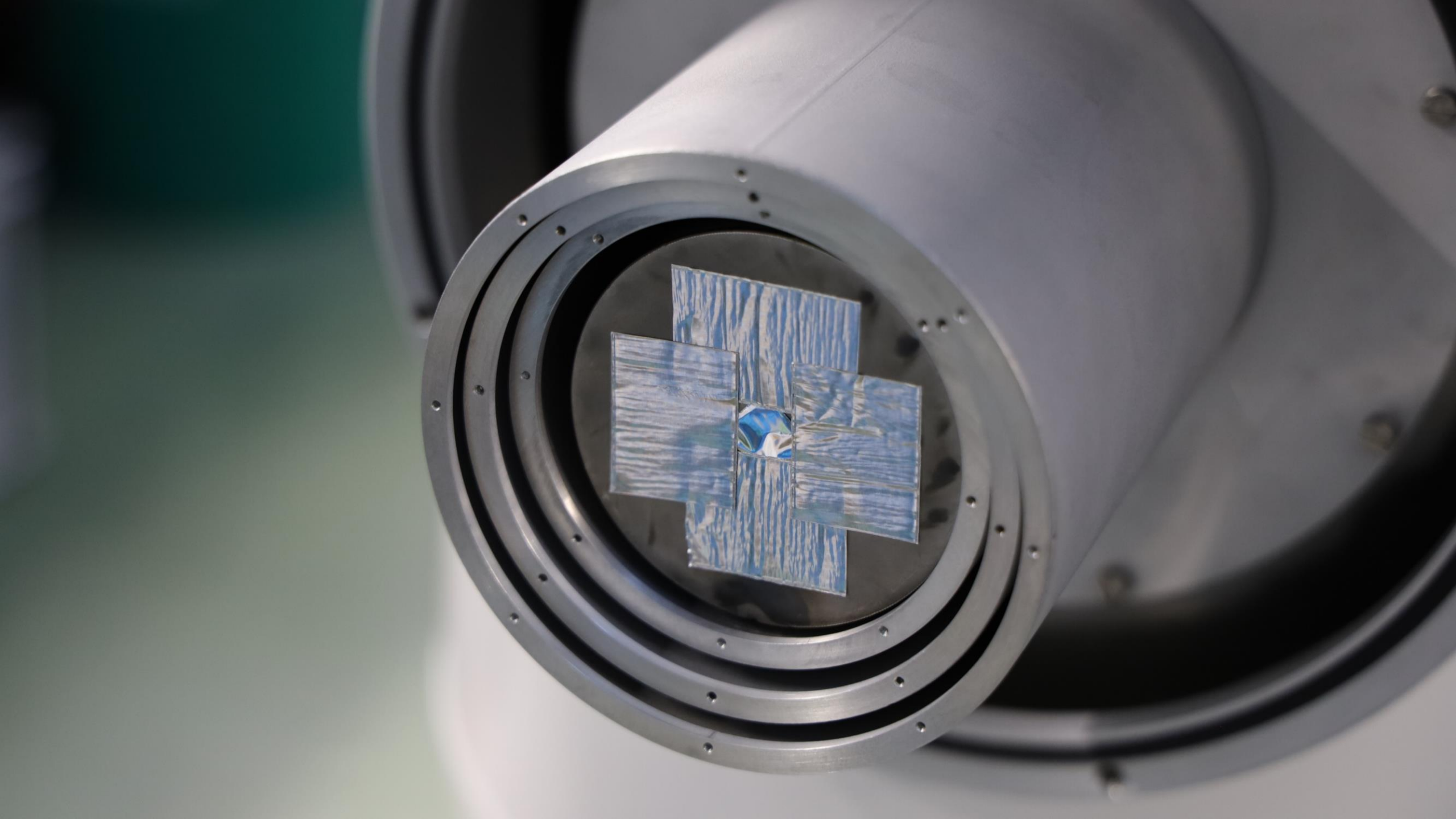
- New dilution refrigerator sidearm with X-ray windows for QUARTET
- Well suited to measure 2p-1s transitions of light muonic atoms

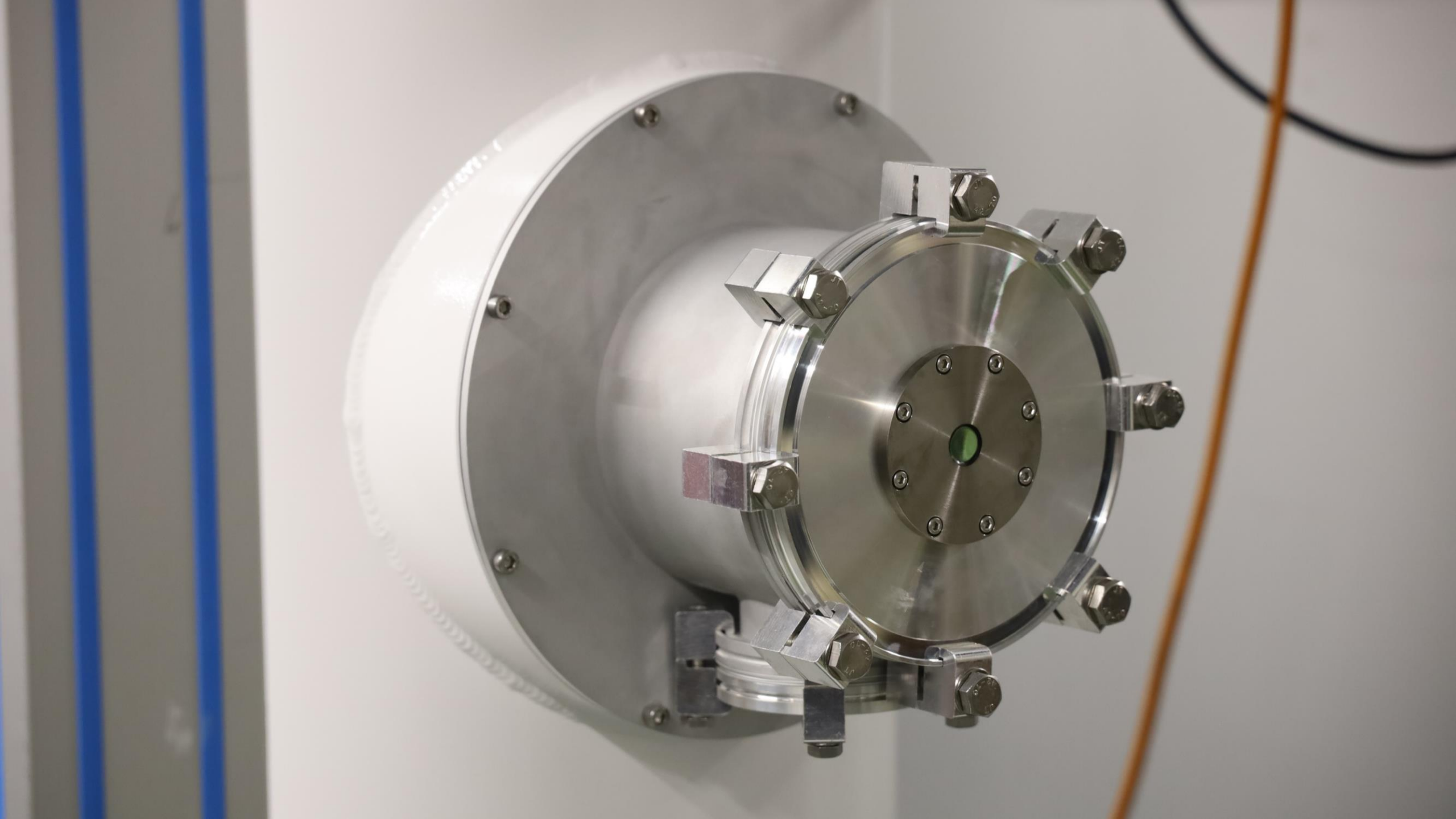




Unger et al, J Low Temp Phys (2024)







Tanzboden @ PSI

- Preparation for beamtime at a staging area near the beamline one month prior to beamtime
- Test detector setup in beamline environment after transport
- Optimize settings for best performance at beamtime

Staging area at PSI, September 2023

Countdown to Beamtime

Date	21.9	22-23	24-27	28.9 - 4.10	5-9	10-11	12	13-15	16-17	18	19	20-25
MMC Det.	Transport & Crane	Set up, Cooling, Prepare electronics	< 10 mK tuning	Tests complete det.	Long calibration test	Rate test	Source test (high-E photon)	Warm up & Prepare for craning	Crane Cool down	Tunning First pulses		**Beamtime!**
DAQ		Cryo data in MIDAS	←		Data-Syncing	←	←	←	←	←	Pixel fit	**…**
Source			55Fe	55Fe	Fe Cd Ba Y	Ba	137Cs			Rate tests 241Am	55Fe, 241Am	…
Target Chamber	Design mounts			Gluing windows		Assembly & leak test	Final Assembly	Cover with Copper	Assemble target Ladder I		Assemble target Ladder II	…
SDD & HPGe	Test (MuX exp.)	←	←	←						Set up	Opt. Calib.	…

⇒ No damage during transport observed

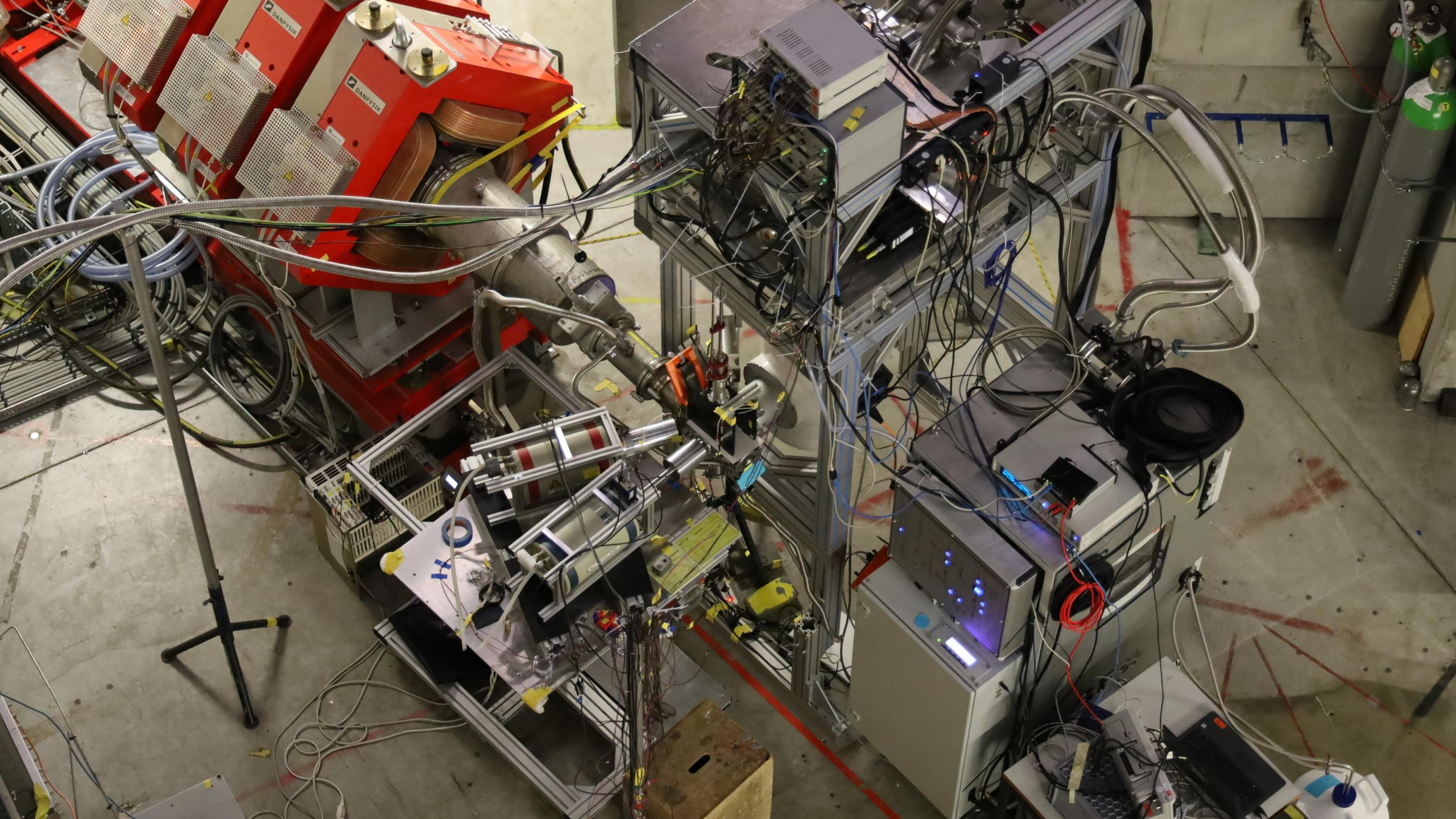
⇒ Optimized detector, SQUID and cryostat settings for the beamtime

Beamtime @ piE1

- Craning the setup in parts with premounted detector
- Assembly of the cryostat, removing craning protection of the sidearm
- Fast manual cooldown and automatic SQUID tuning
- Operate detector with optimized settings from Tanzboden

⇒ First signals within 48 hours

⇒ 24/7 monitoring during beamtime


DANFYSIK
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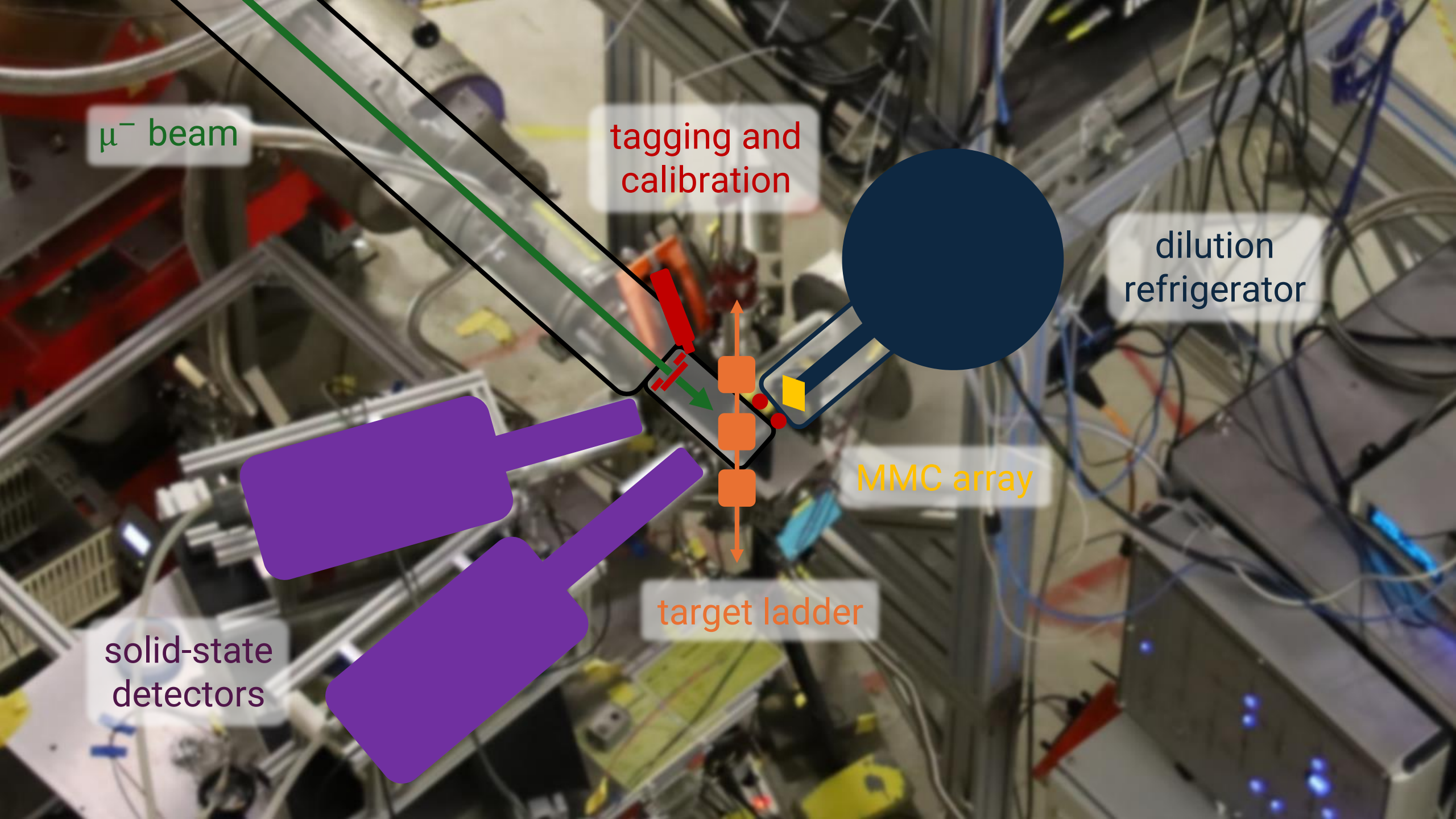
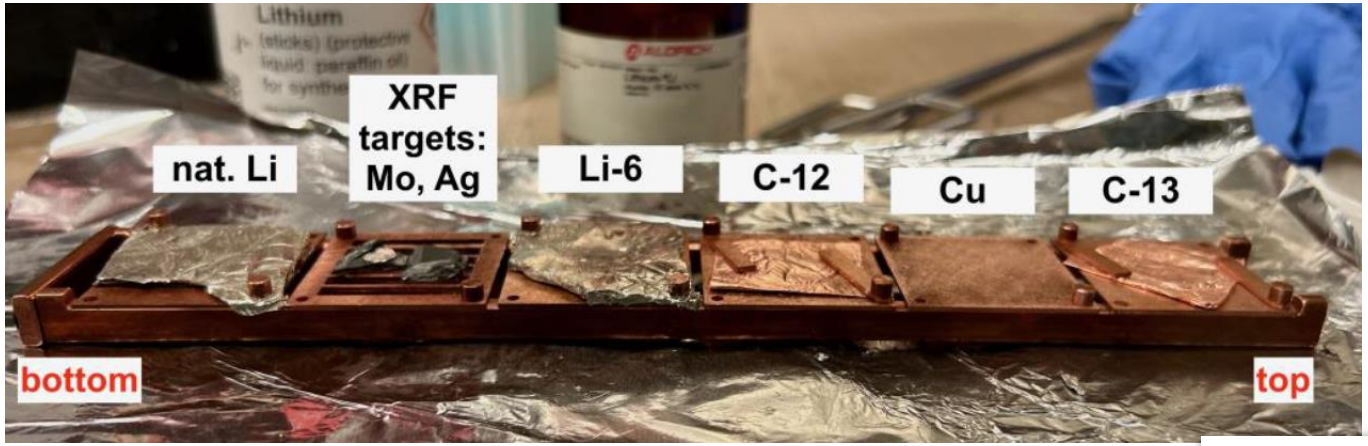
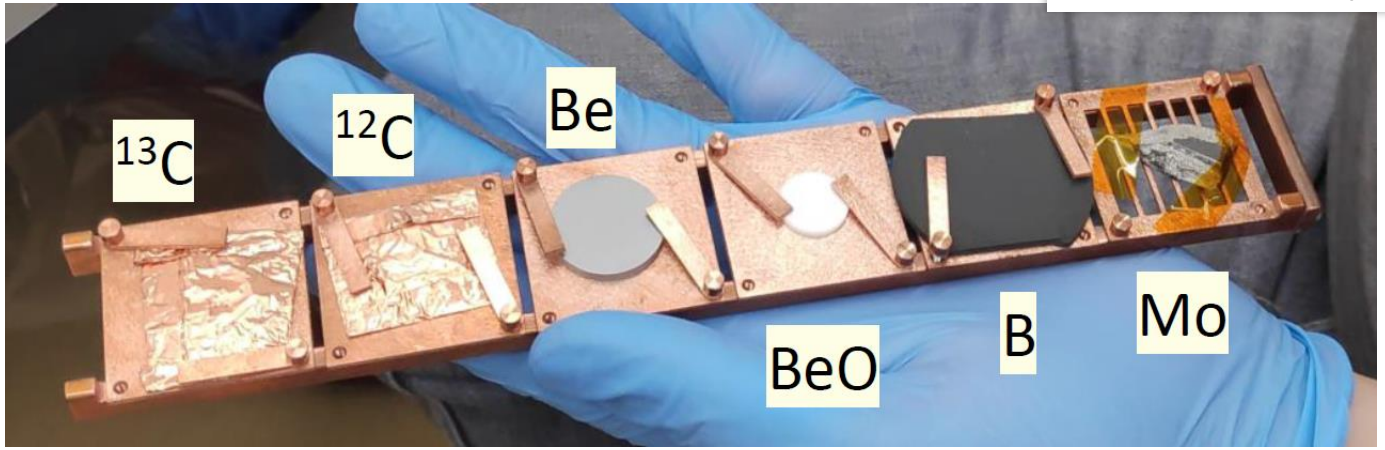
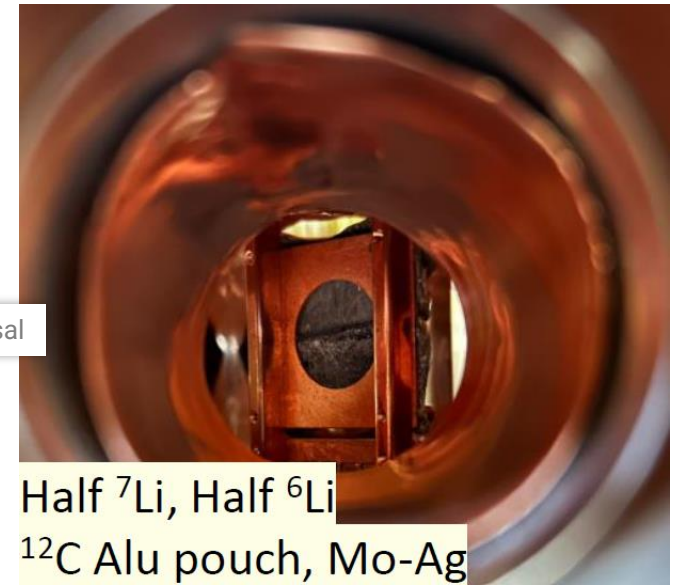

μ⁻ beam
tagging and calibration
dilution refrigerator
MMC array
target ladder
solid-state detectors

Targets



QUARTET Research Proposal

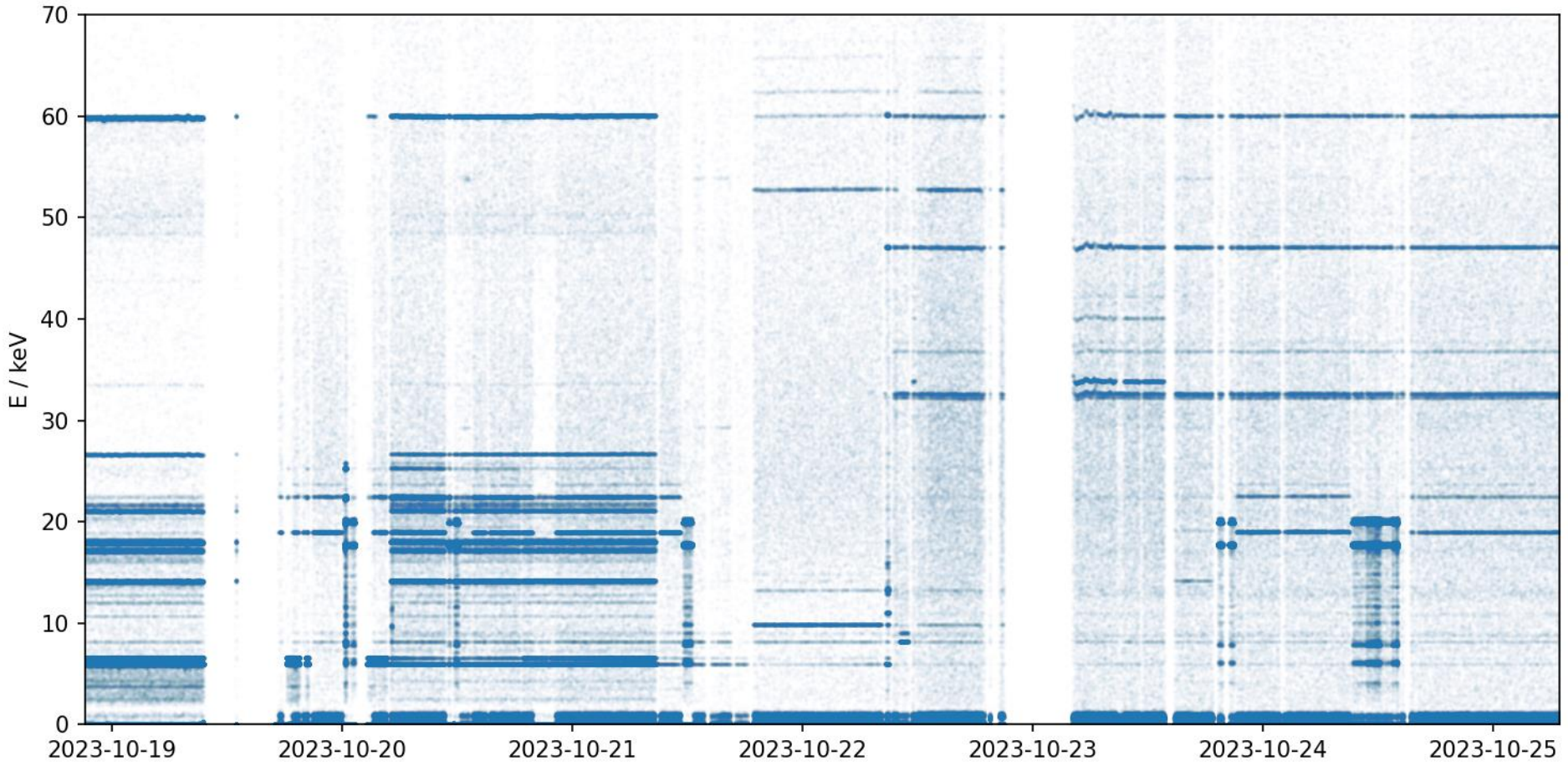




Beamtime Schedule

Day	I				II				III					IV					V		(VI)
Time	00:00 - 1:00	**2:00 - 11:00**	11:00 - 12:00	12:00 -13:30	**13:30 - 11:30**	11:30 - 12:30	12:30 -16:30	17:00 - 18:30	**19:00 – 10:00**	10:00 – 11:00	11:00 – 12:00	**12:00 – 19:00**	21:30 - 23:00	23:30 - 1:30	**1:30 - 13:30**	14:00 - 15:00	**15:00 – 19:00**	19:00 – 21:00	**21:00 – 9:30**	9:30 – 14:00	**14:30- 7:00**
Goal	Calib.	**Production**	Calib.	Bgnd	**Production**	Calib.	Implant. test	Bgnd	**Production**	Calib.	Rate test	**Production** + beam tuning	Beam tuning while reset	Beam tuning while reset	**Production**	Pile-up test	**Production**	Calib.	**Production**	Calib. + rate study	**Production**
Target	Mo-Ag	^{7}Li	Mo-Ag	Cu	^{6}Li	Mo-Ag	^{12}C	Empty	^{10,11}B	Mo	Be	^{10,11}B	^{13}C	^{12}C	^{9}Be	^{12}C	^{12}C	Mo-Ag	^{6}Li / (^{7}Li)	Mo-Ag	^{6}Li / ^{7}Li
Source		^{55}Fe, ^{109}Cd, ^{241}Am	←	←	←	←	^{55}Fe	←	^{55}Fe, ^{210}*Pb*, ^{241}Am, ^{137}*Cs*	^{55}Fe, ^{210}Pb, ^{241}Am, ^{137}Cs	←	←	←	←	←	←	←	←	←	←	←
Ladder	I	I	I	I	I	I	I		II	II	II	II	II	II	II	III	III	III	III	III	III
MMC Det.	V	V	V	V	V	V	V	V	V	V	V	V	Soft reset	Soft reset	V	V	V	V	V	V	V
DAQ					sync				MMC CSV output												

Test Beamtime

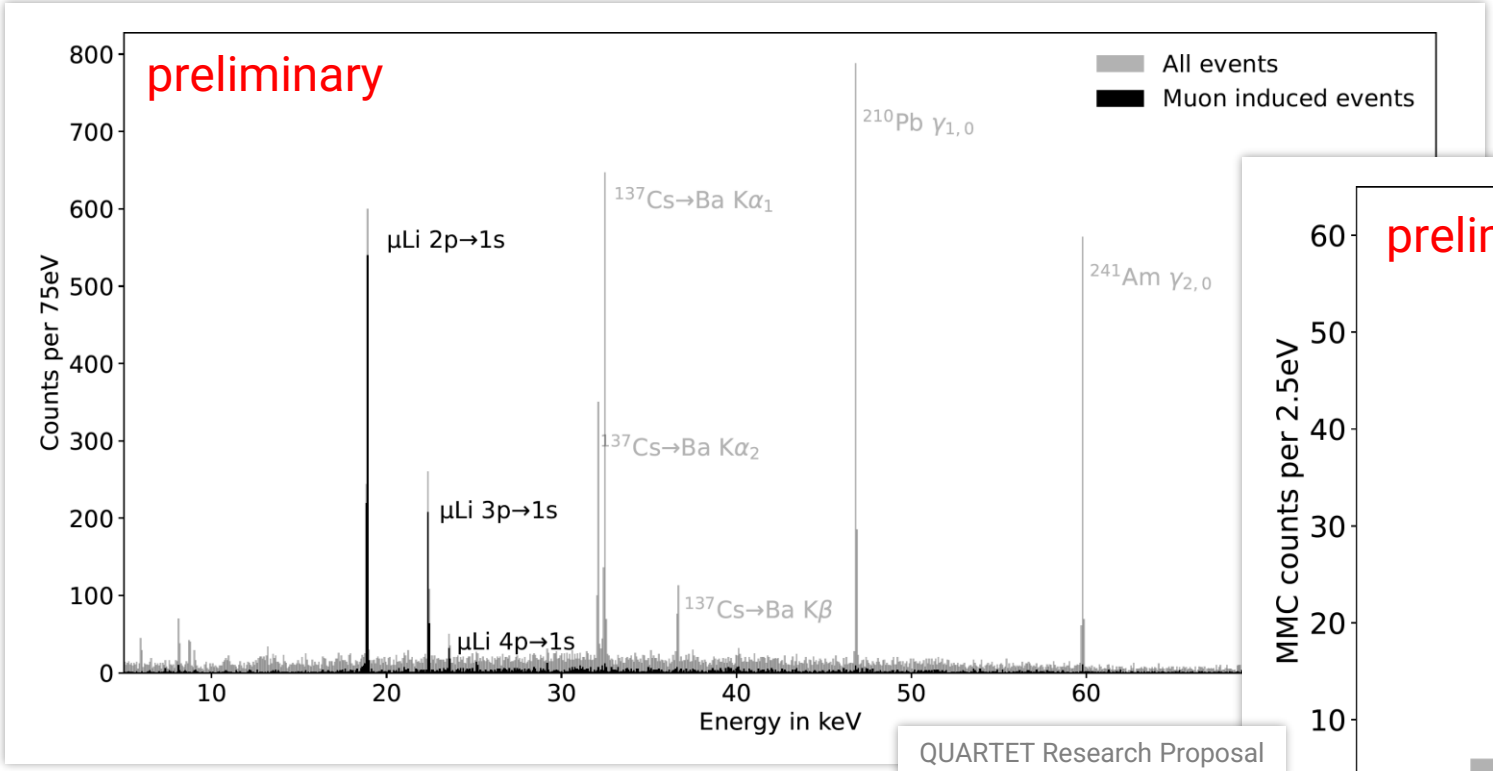


42 000 @ 60 keV

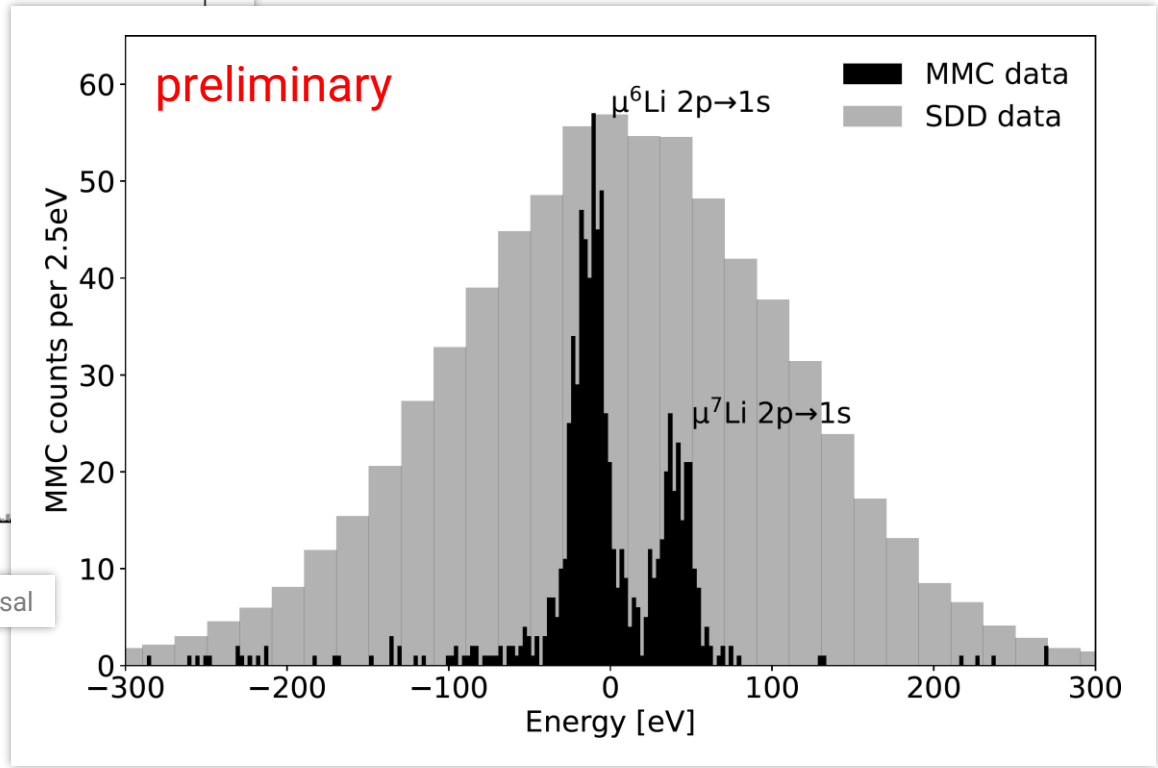
12 000 @ 26 keV

480 000 @ 6 keV

Preliminary Results



QUARTET Research Proposal



Test Beamtime Result

- Successful proof-of-principle measurement with Li, Be and B at PSI in October 2023
- Identification of present limitations and their improvements

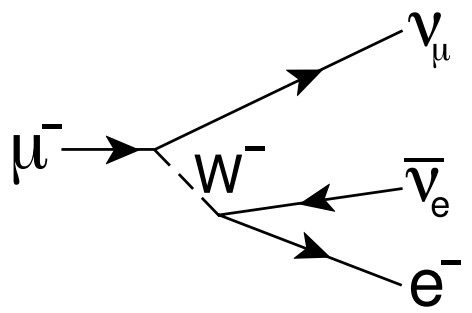
⇒ Two weeks beamtime granted at PSI in October 2024

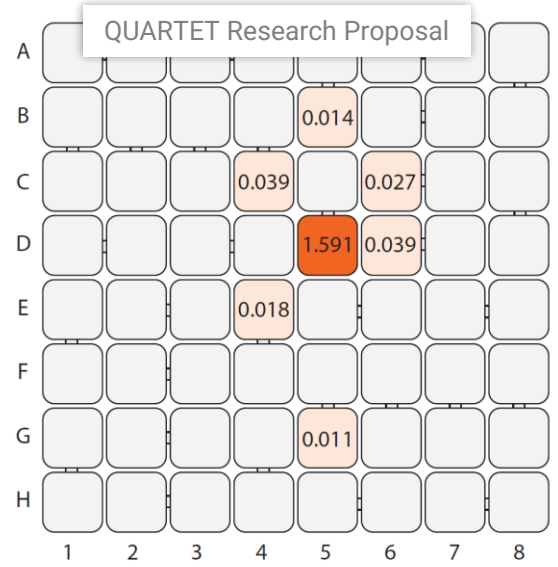
Beamtime at PSI, October 2023

Michel Electrons

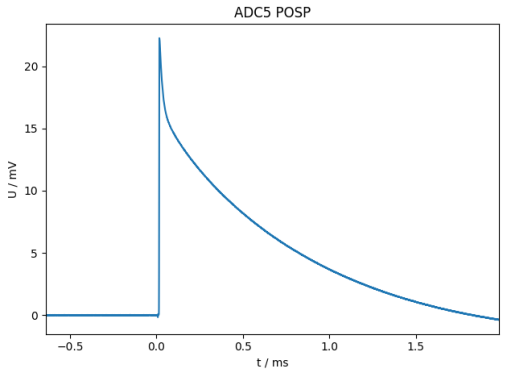
- Muons decay to electrons (and neutrinos)
- Electrons (~40 MeV) deposit energy as MIPs in the detector substrate
- Detector-wide temporary temperature increase due to athermal phonons from the substrate

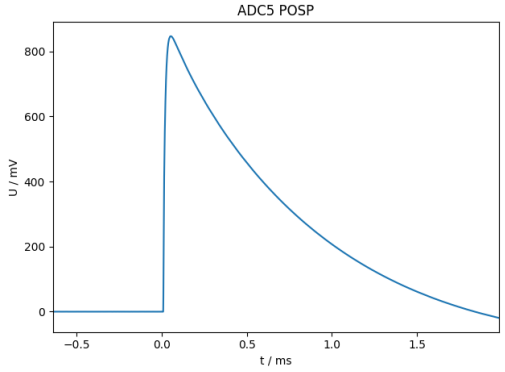
⇒ Electron related events need to be identified





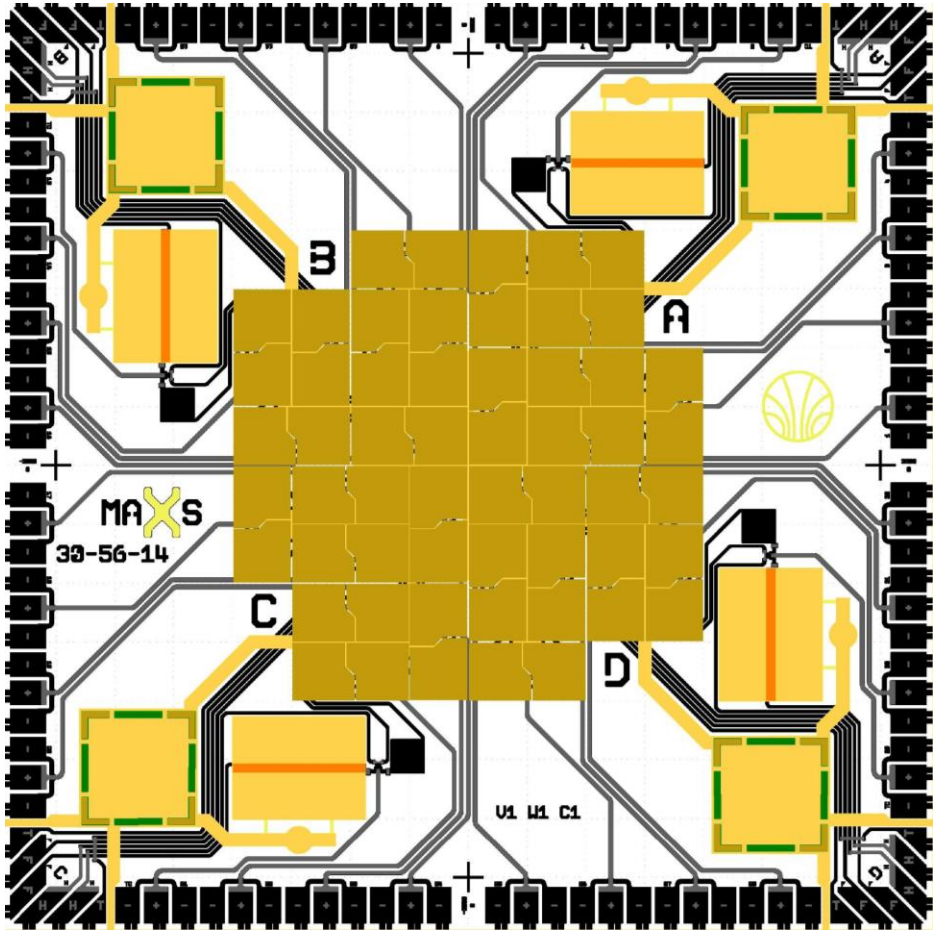
Signal Families

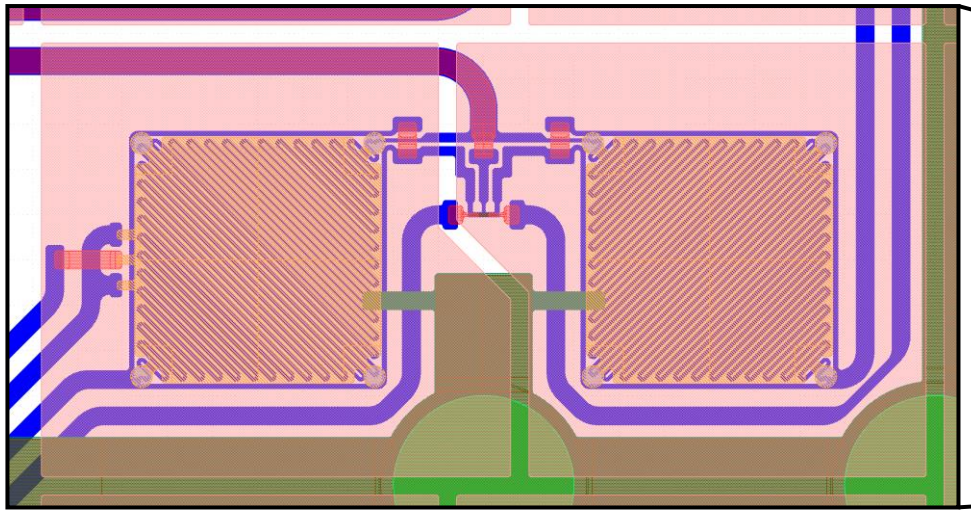


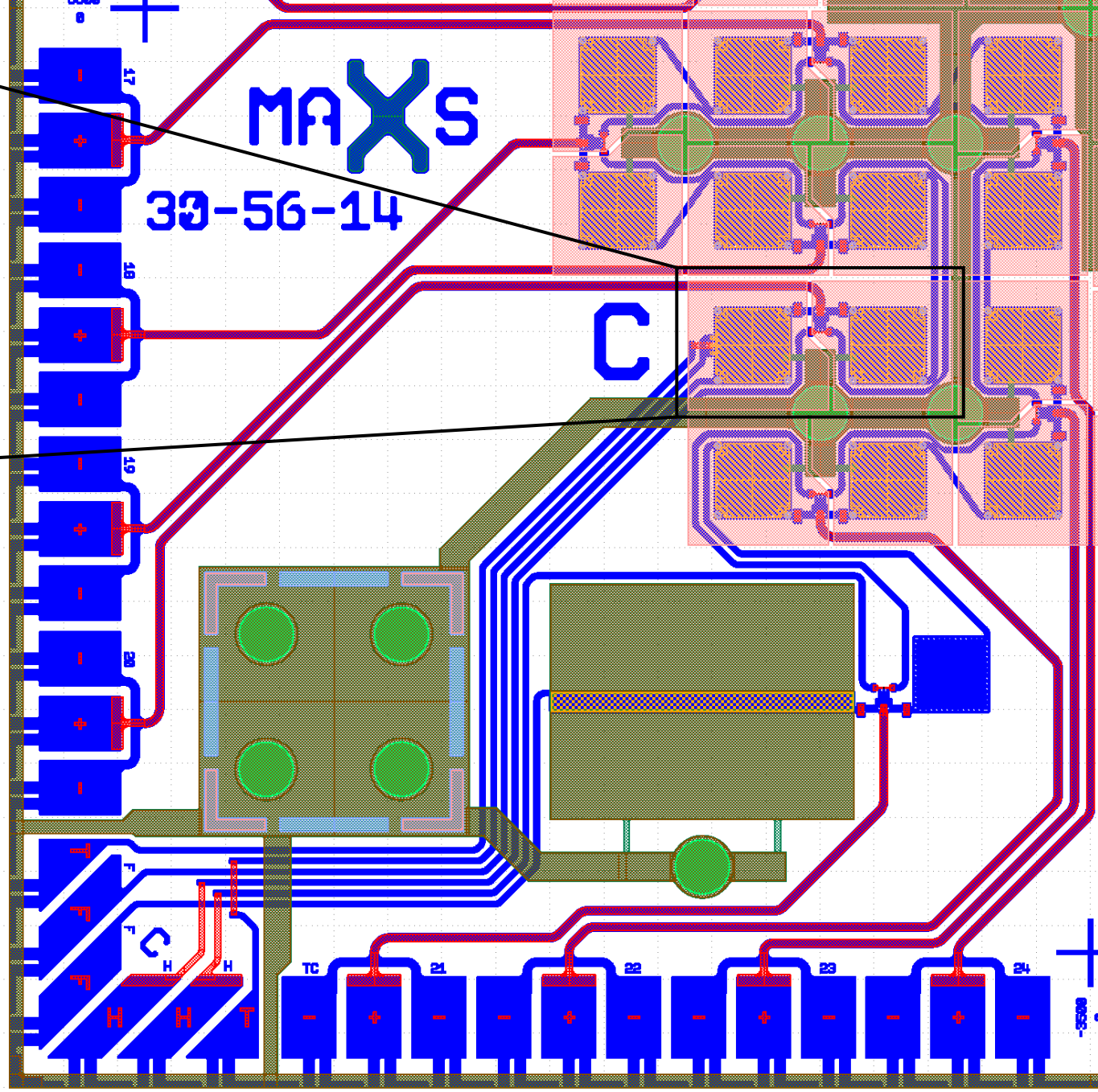


Detector for QUARTET

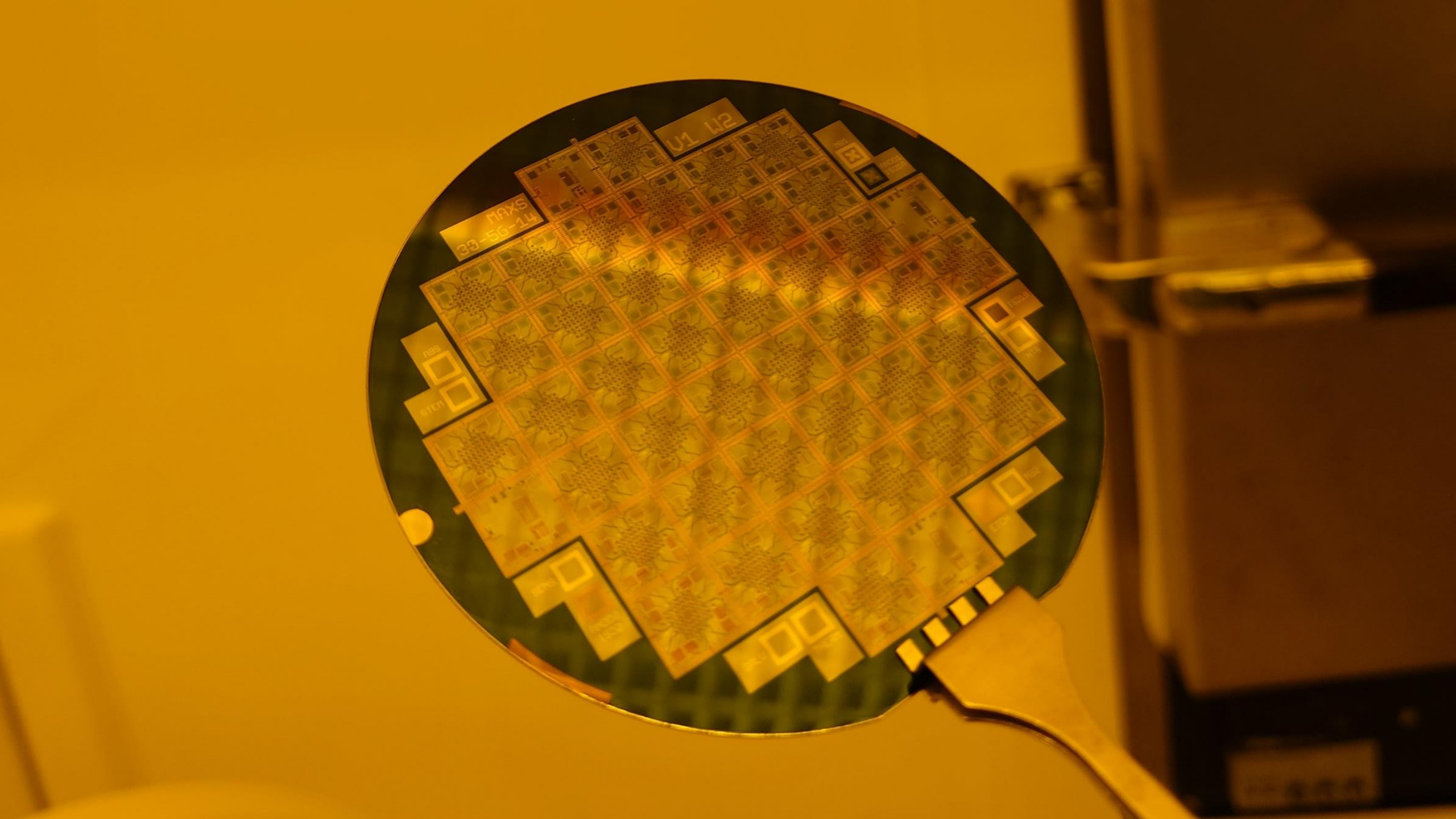
- maXs 30-56-14: new detector design
- Optimized for the upcoming QUARTET beamtime
- Improvements:
  - Optimized MMC design
  - Michel electron identification
  - Sensitive substrate thermometer
  - Faster thermalization







Layer	Process	Material	Tickness / nm
1	Nb1	Nb	250
2	Anod1	Nb2O5	(20)
3	Iso1a	SiO2	130
4	Iso1b	SiO2	170
5	Heater	AuPd	160
6	Nb2	Nb	400
7	Nb & SiO2 Etch	-	(-250)
8	Therm	Au	500
9	ThermGalv	Au	2000
10	Anod2	Nb2O5	(20)
11	Iso2	SiO2	180
12	TSV	-	-
13	TSV-Fill	Cu	3800
14	Backside	Cu	1000
15	Sensor	AgEr + Au	1000 + 100
16	Stems	Au	10000
17	Absorber	Au	20000
18	Dicing	-	-


U1 U2
MAX5
38-56-14

Beamtime Goal

- Physics run with long Li, Be, B measurements
- New detector with faster thermalization and Michel electron identification
- Most accurate high-resolution X-ray spectroscopy of muonic Li

⇒ More than one order of magnitude improvement for the absolute nuclear charge radii of Li

⇒ Significant improvement for Be and B

Conclusion & Outlook

- QUARTET: high-precision absolute nuclear charge radii from ^{6}Li to ^{22}Ne
- Very successful proof-of-principle measurement with Li, Be and B at PSI in October 2023
- Ongoing data analysis and evaluation of present physics case
- Two weeks beamtime granted at PSI in October 2024
- Fabrication of a new detector for the first physics run, designed and optimized for QUARTET