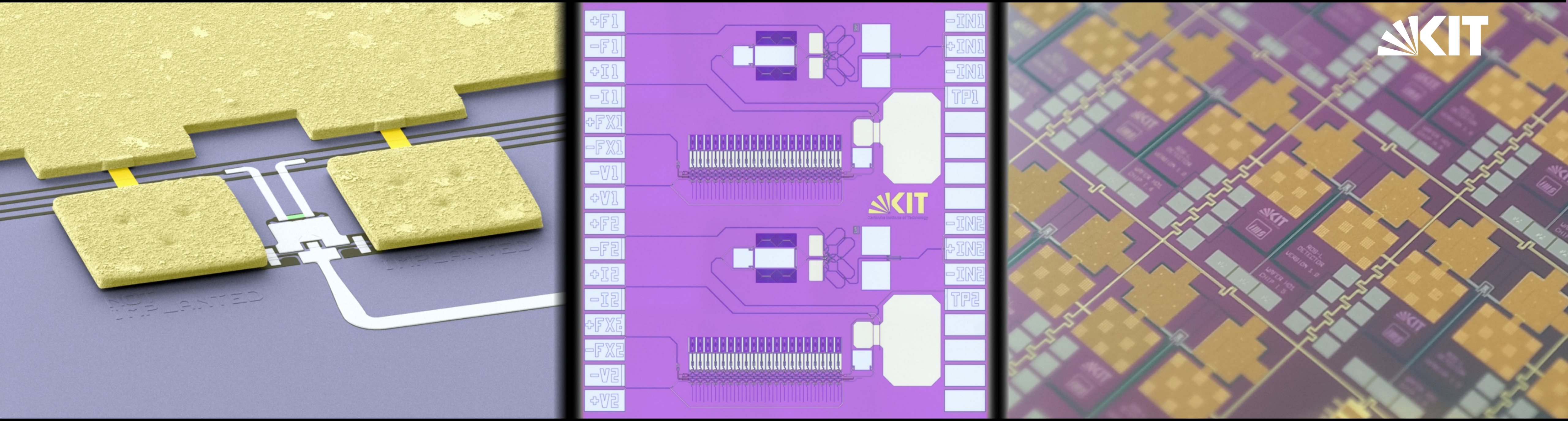


Quantum sensor arrays for KATRIN++
Concepts and challenges

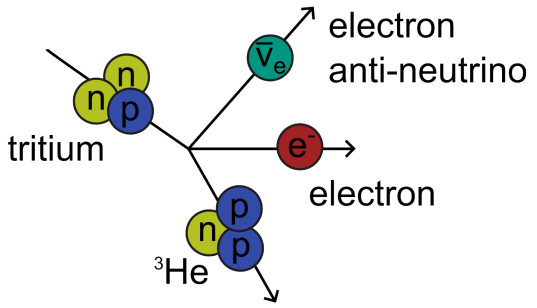
collaboration between
MT-DTS and MU-MRU

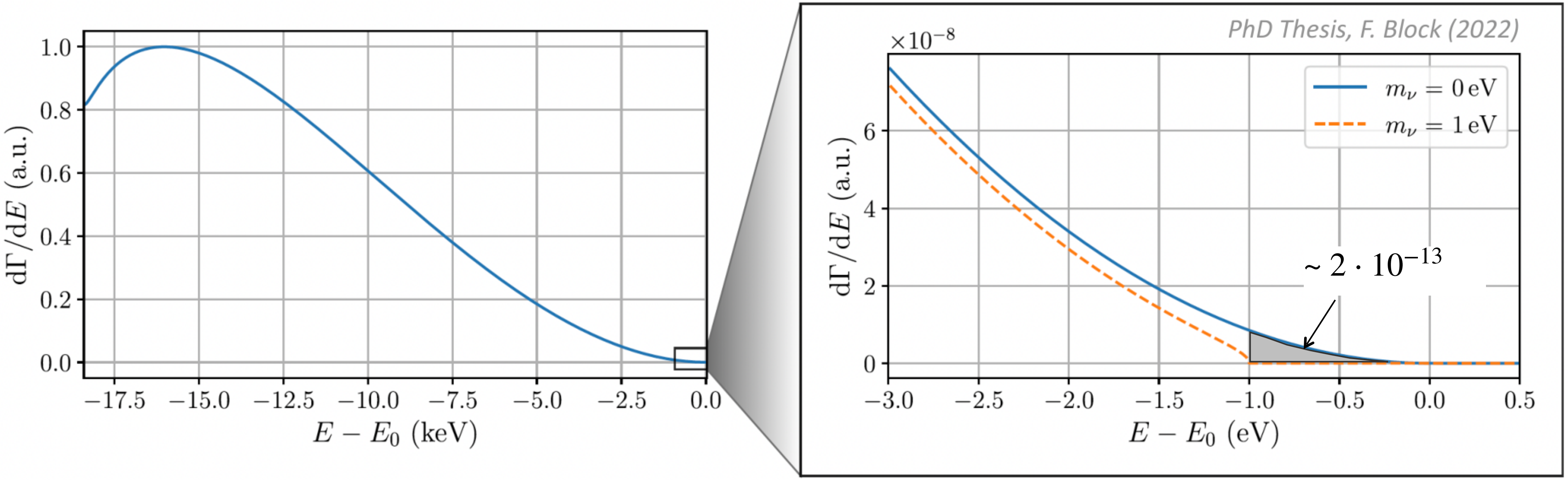
Sebastian Kempf
Institute of Micro- and Nanoelectronic Systems (IMS), Karlsruhe Institute of Technology (KIT)
11. Annual MT Meeting | GSI | Darmstadt | 2025-11-04

Karlsruhe Tritium Neutrino Experiment (KATRIN)

goal: measurement of tritium β^- decay spectrum to investigate (determine) the electron antineutrino mass

→ endpoint region of spectrum contains most information





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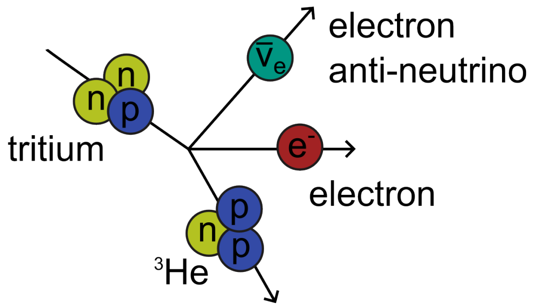

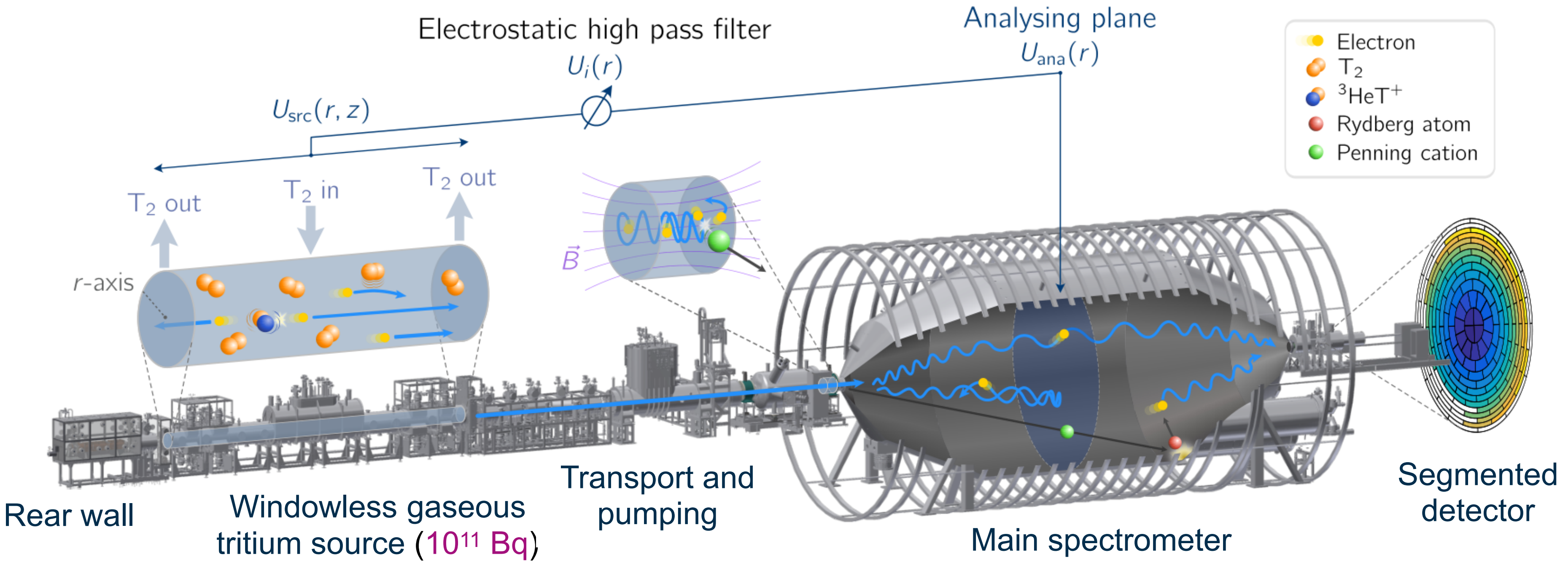

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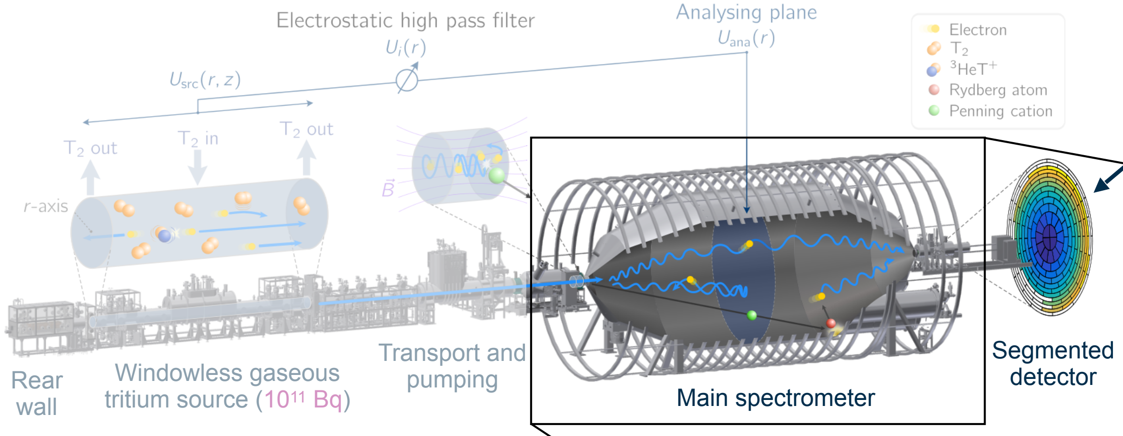
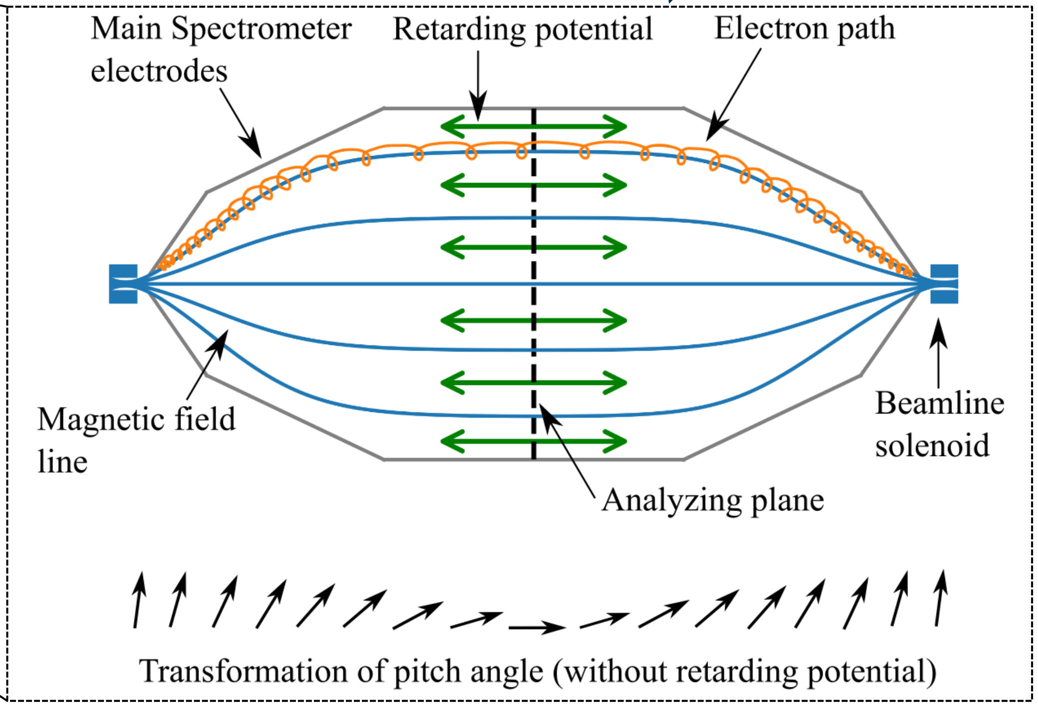


ΔE_{FWHM} = 1 - 2 keV

2 - 3 eV energy resolution (sigma)



B_{src} = 2.5 T $\quad$ $B_{ana} = 6.3 \cdot 10^{-4}$ T

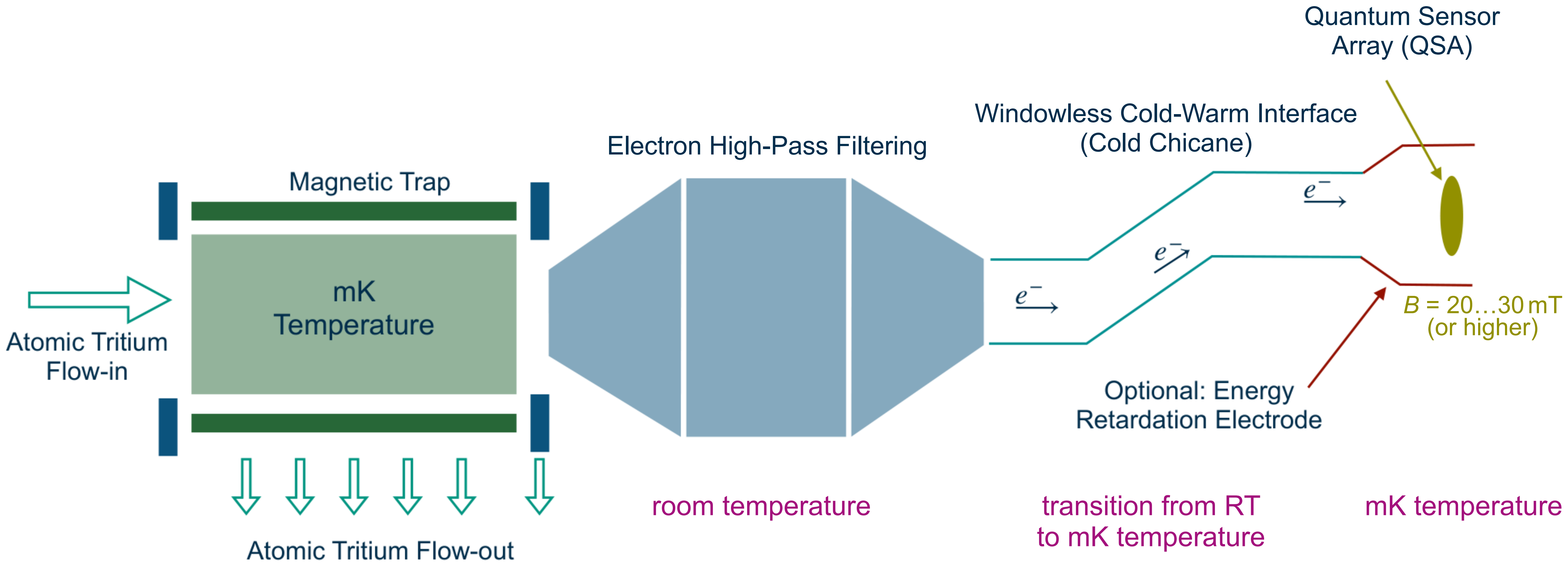
Magnetic Adiabatic Collimation with Electrostatic (MAC-E) filtering

Integral mode = scanning over retarding potential

→ measuring integral rate of electrons with kinetic energy above retarding potential

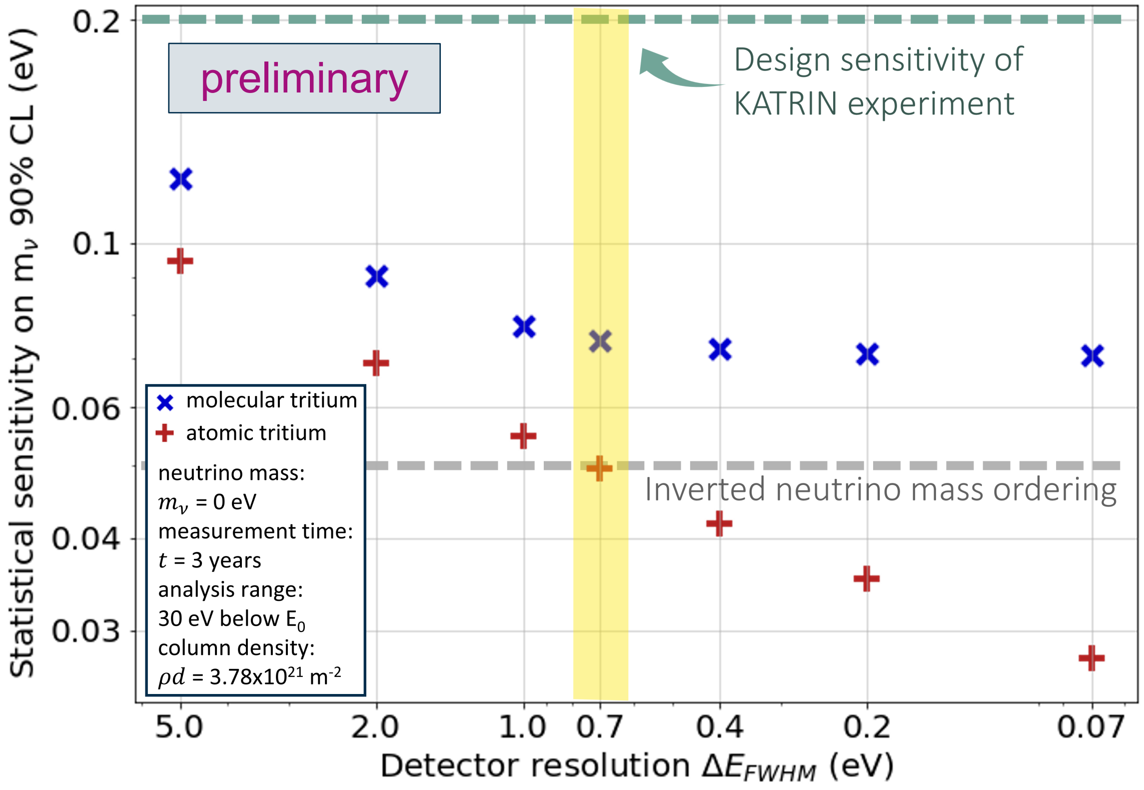
stat. sensitivity of 0.2 eV/c² (90% CL) on neutrino mass ⇨ not sufficient to resolve neutrino mass hierarchy

KATRIN++ I a next-generation T-based neutrino mass measurement
…based on quantum sensor array (QSA)



Sensitivity estimations for KATRIN++

study by S. Heyns and N. Kovac
(IAP @ KIT)

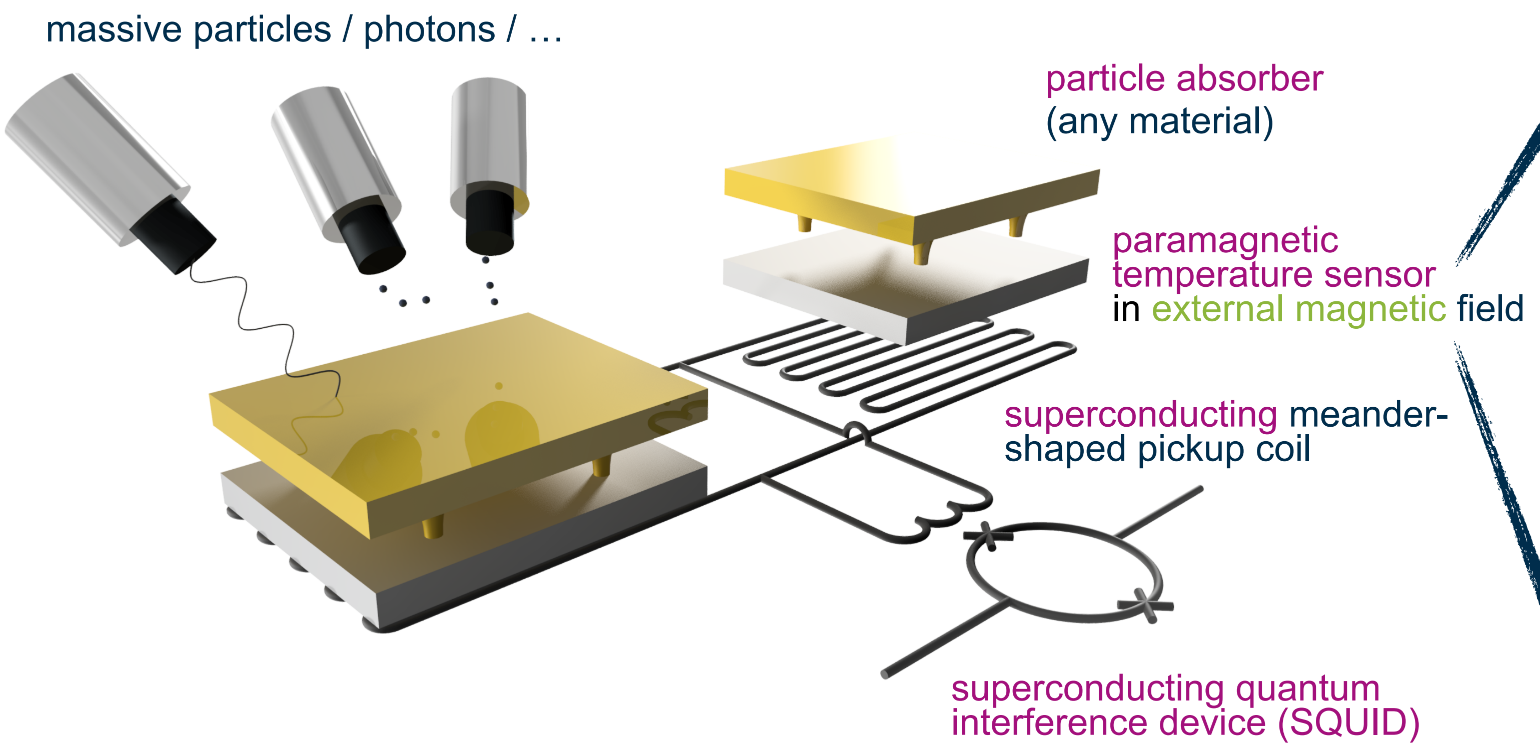


⇒ differential detector with sub-0.7eV (FWHM) energy resolution required to resolve inverted neutrino mass ordering

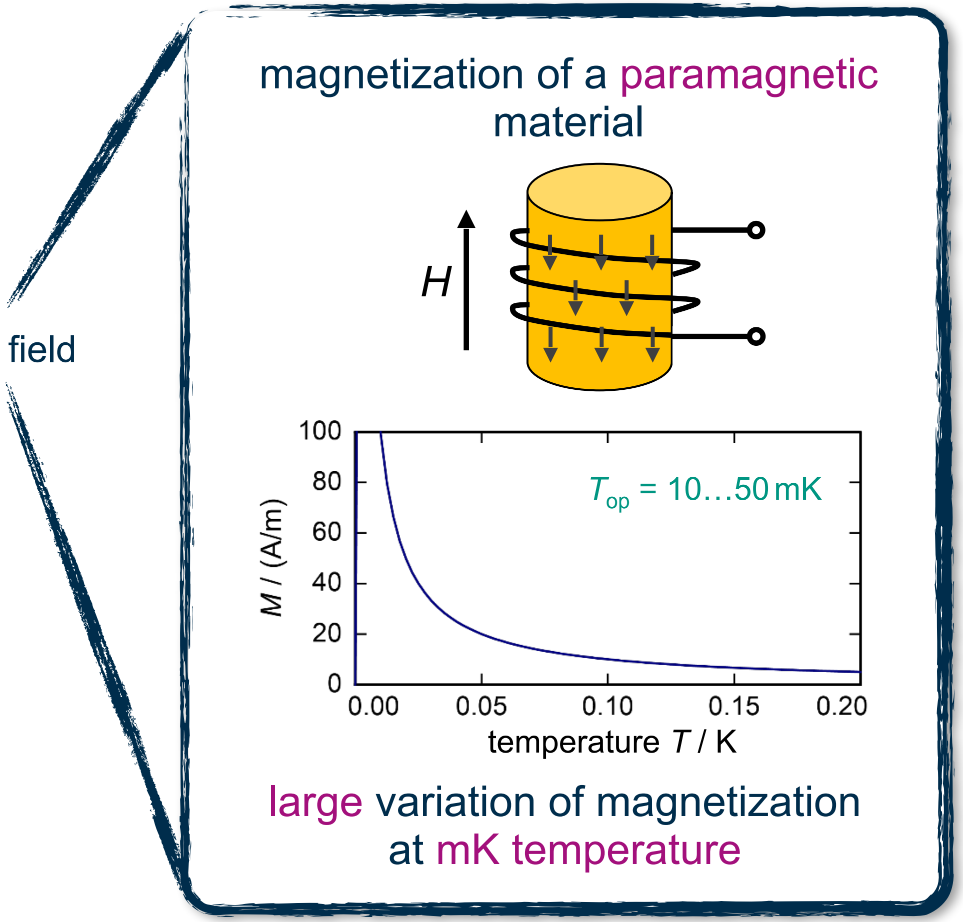
+

- detection of external electrons: backscattering, detector response, …
- QSA operation in ambient magnetic field
- flux tube conservation: area vs. *B*-field strength
- room-temperature electron ‚source' (prefilter): windowless warm-cold interface (cryo-chicane)
- energy resolution must be known to a level better than 1% (for all pixels): calibration challenge

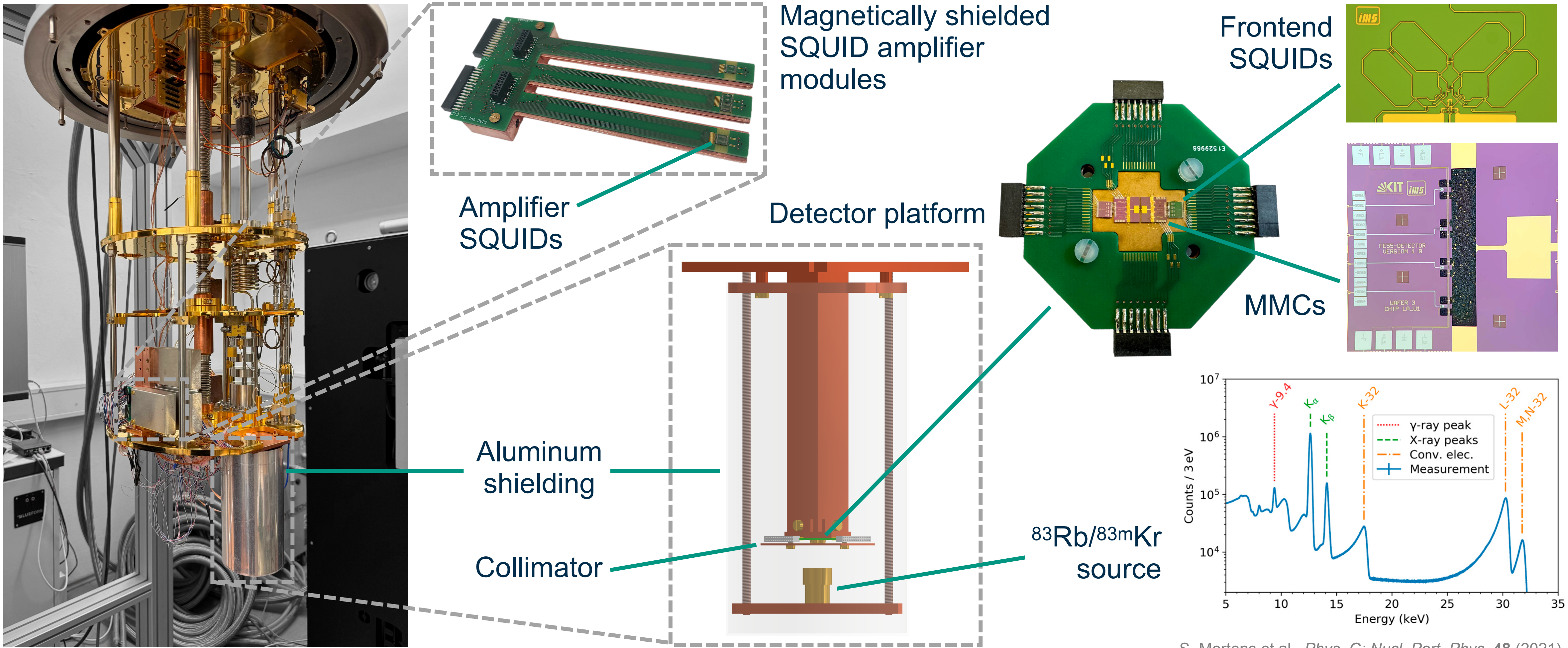
Magnetic microcalorimeters (MMCs)



energy resolution: $\Delta E_{\mathrm{FWHM}} \simeq 2.36\sqrt{4k_{\mathrm{B}}C_{\mathrm{abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{\frac{1}{4}}$



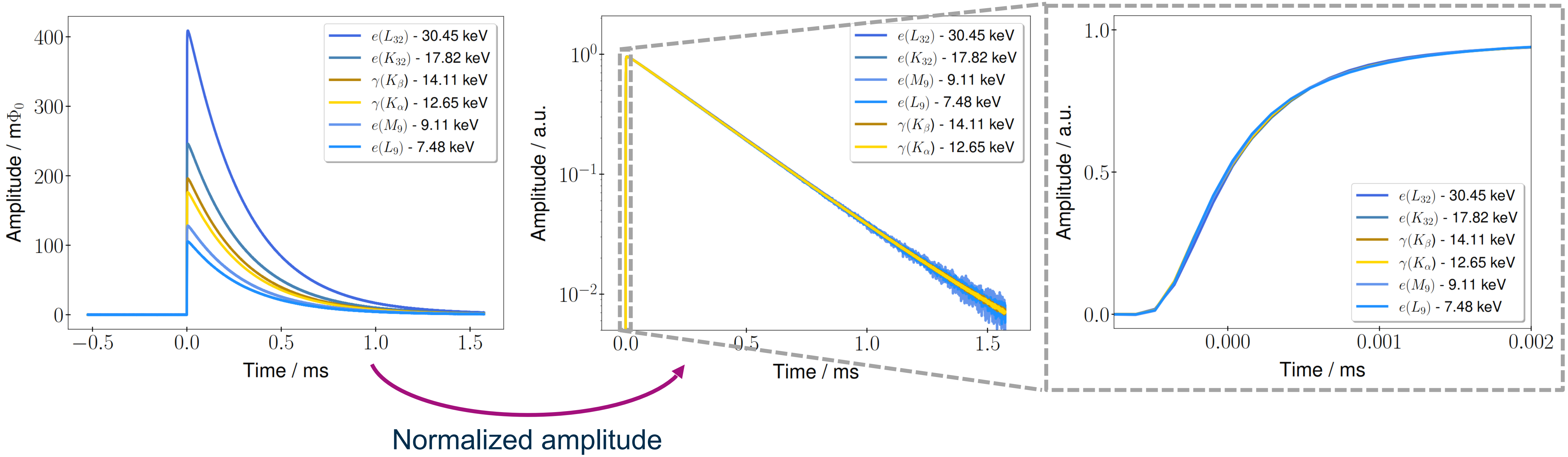
ELECTRON project: Comparison of MMC response for photons and external electrons



S. Mertens et al., *Phys. G: Nucl. Part. Phys.* **48** (2021)

ELECTRON project: Detector response

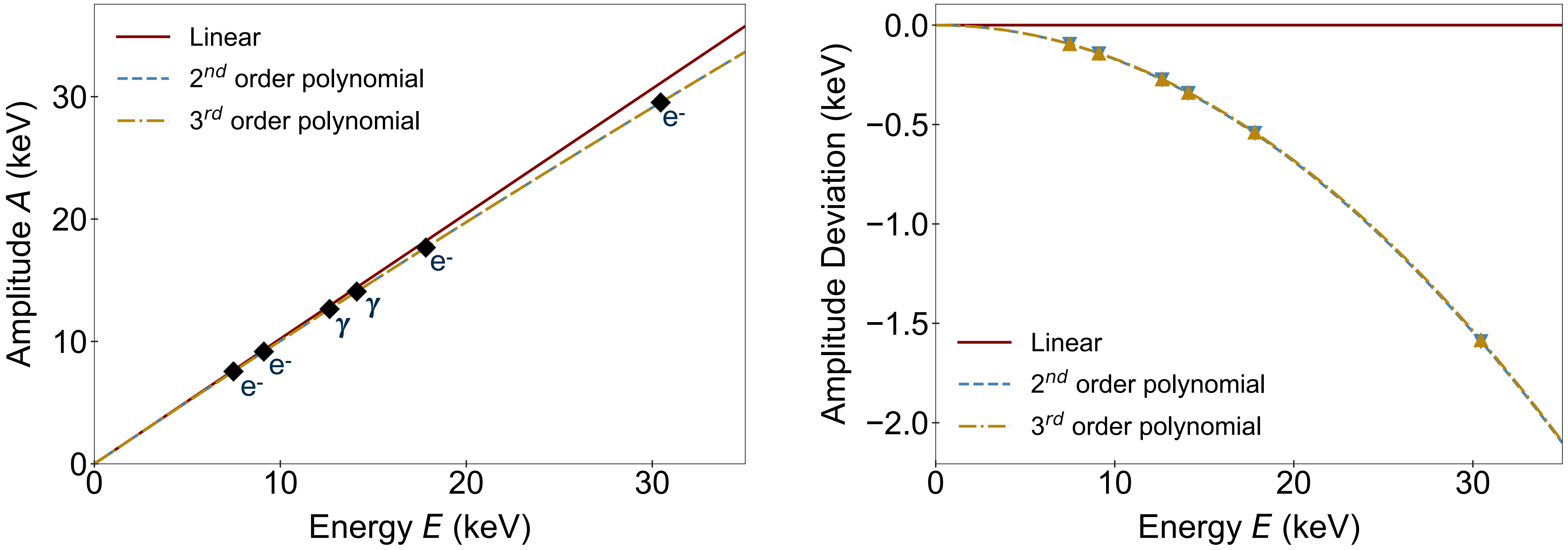
N. Kovač et al., *Nuclear Inst. and Methods in Physics Research A* **1080** (2025)



MMCs show detector response for electrons and photons

ELECTRON project: Energy calibration

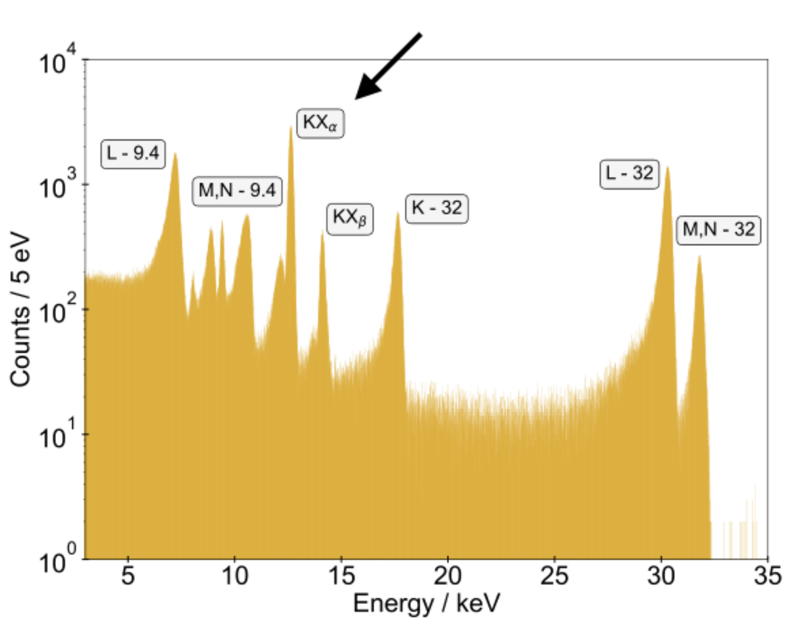
N. Kovač et al., *Nuclear Inst. and Methods in Physics Research A* **1080** (2025)

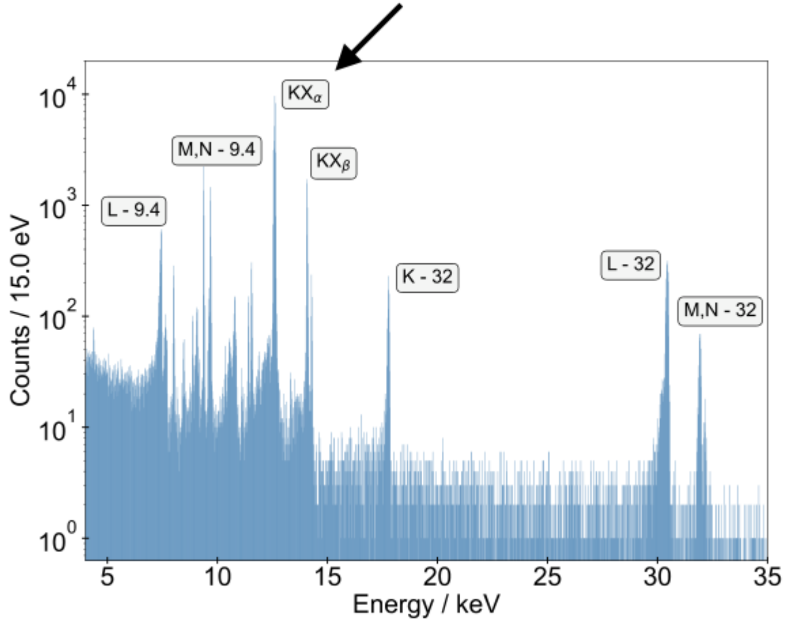


MMCs show same calibration function for electrons and photons

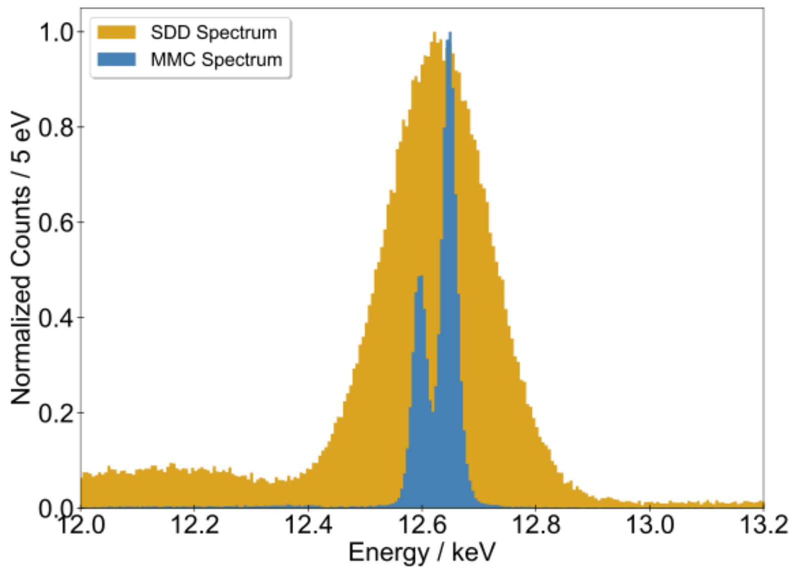
ELECTRON project: $^{83}Rb/^{83m}Kr$ spectrum

„Silicon SDD detector vs. MMC“





Comparison of X-ray lines



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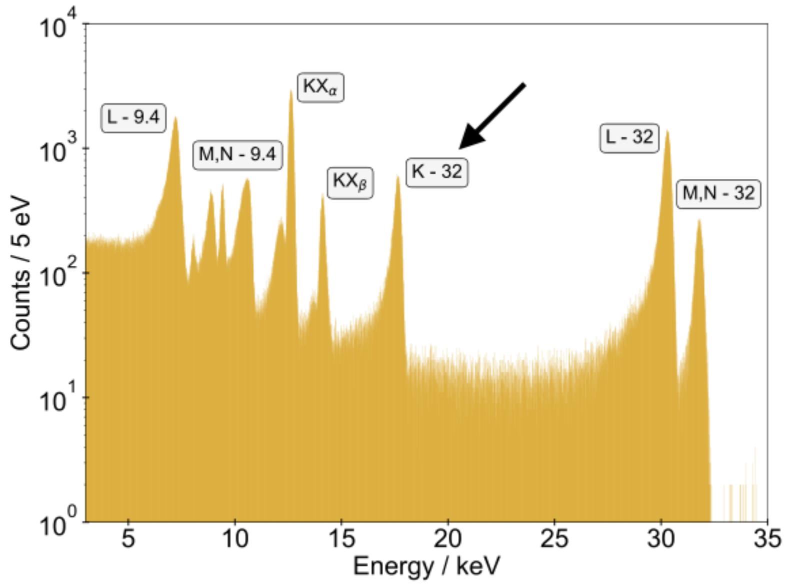
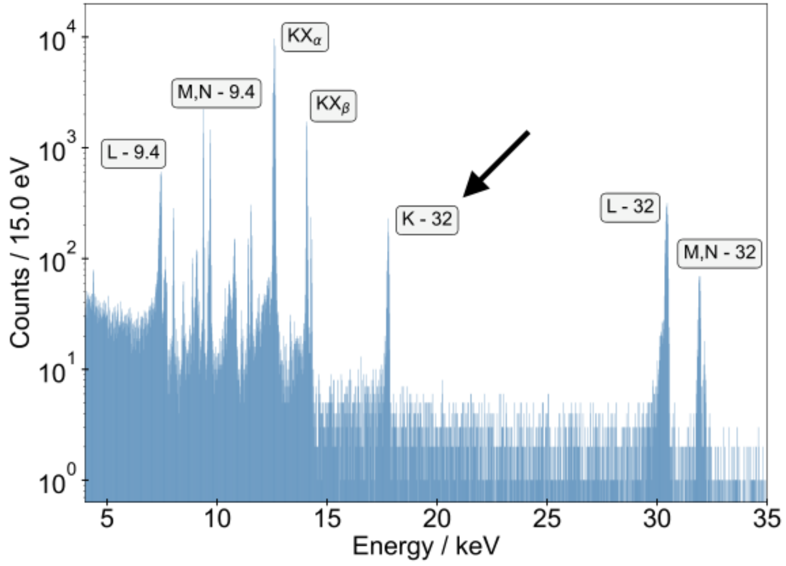
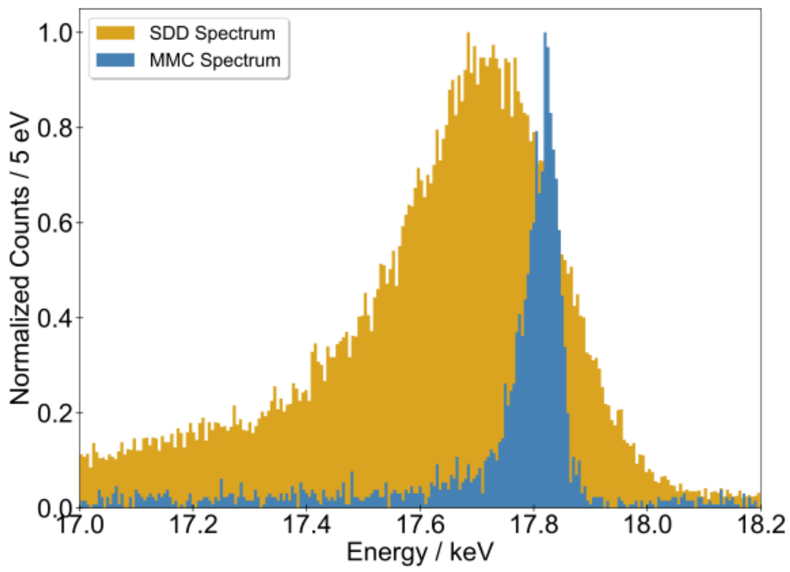


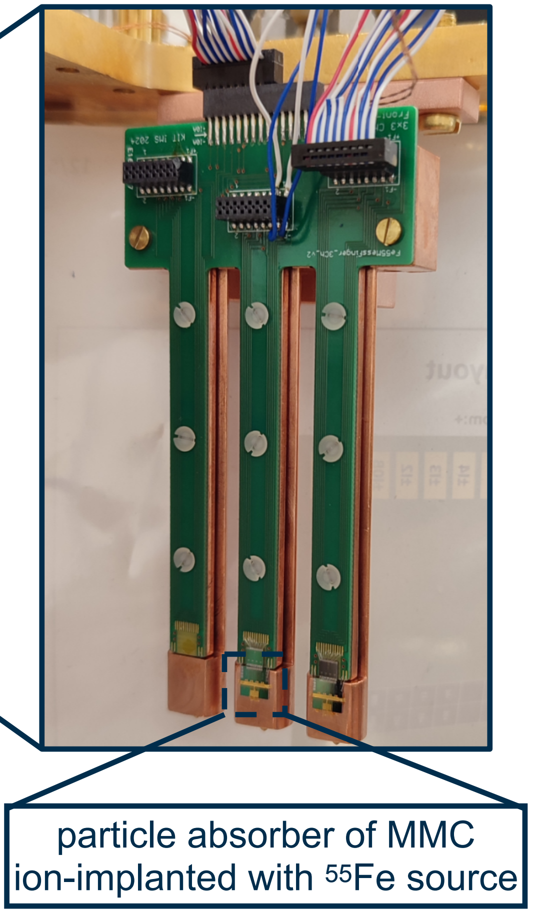


Comparison of conversion electron lines

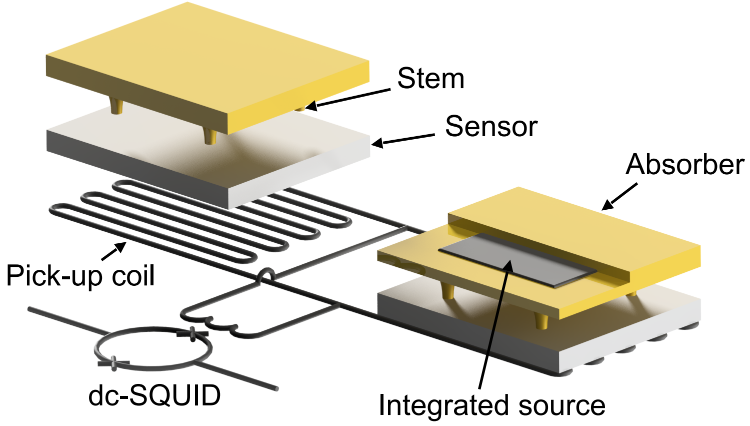


MMC operation in external magnetic field

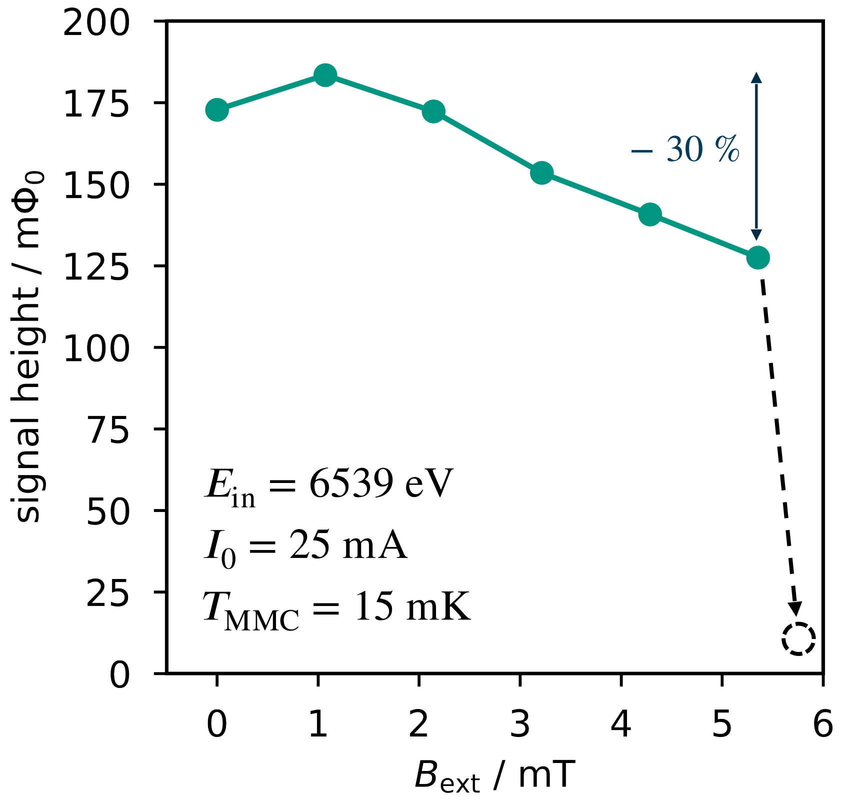
detector module

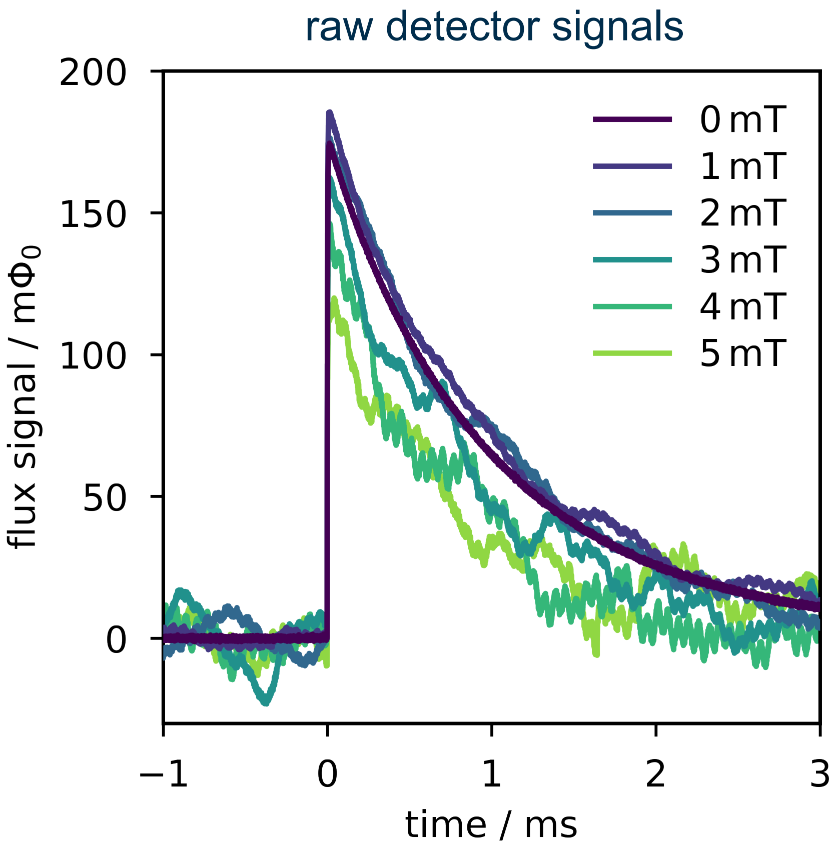


- *B*-field generated by external Helmholtz coil
- capable of generating up to B = 30 mT
- no magnetic shielding of detector module



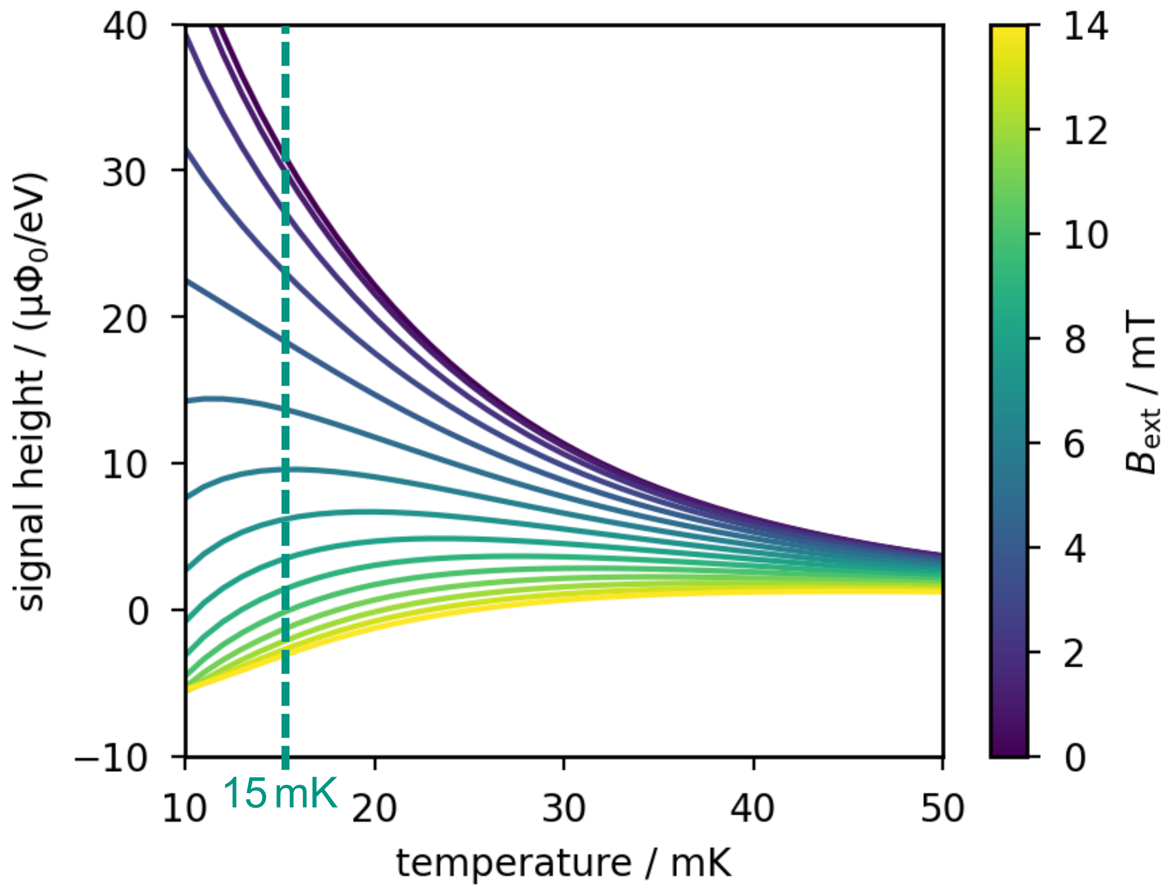
Pulse height measurements

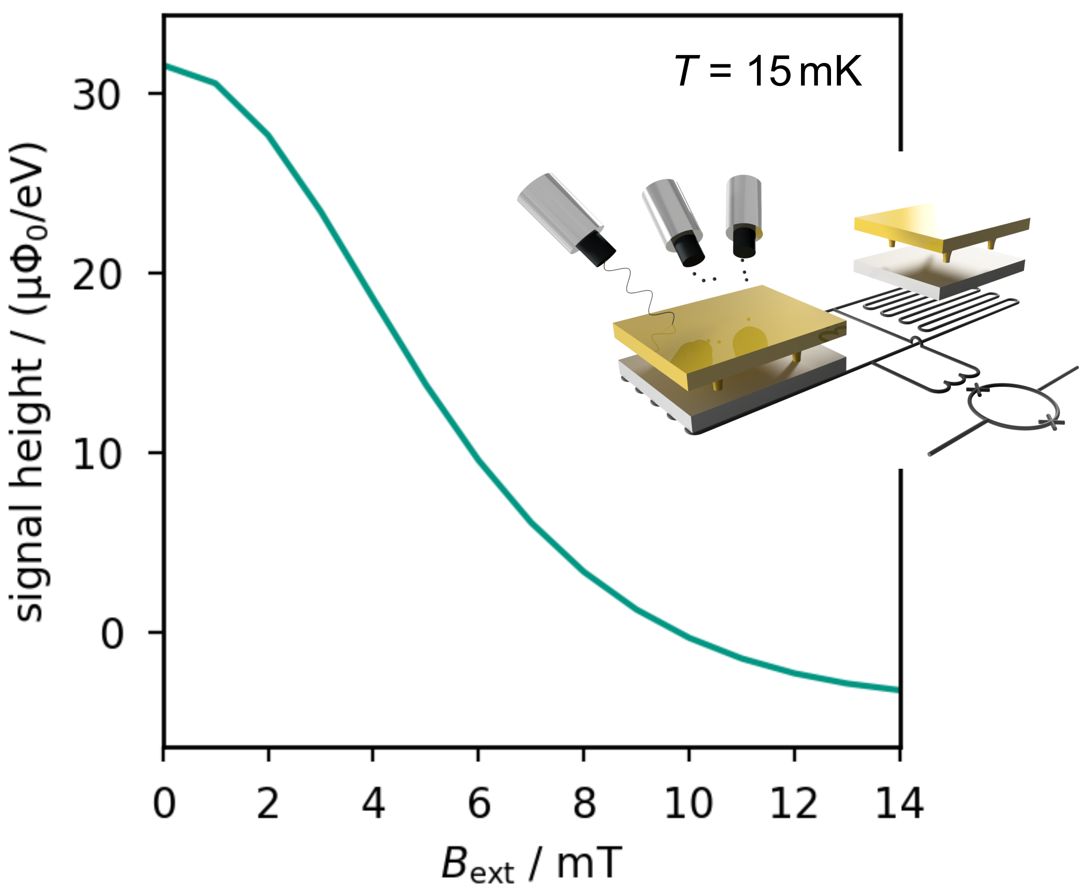




- drastic decrease in signal height
- @ B_{ext} > 5.5 mT: Sudden disappearance of detector signal → quench of Al wire bonds?
- strong noise with increasing B_{ext}

Pulse height simulations

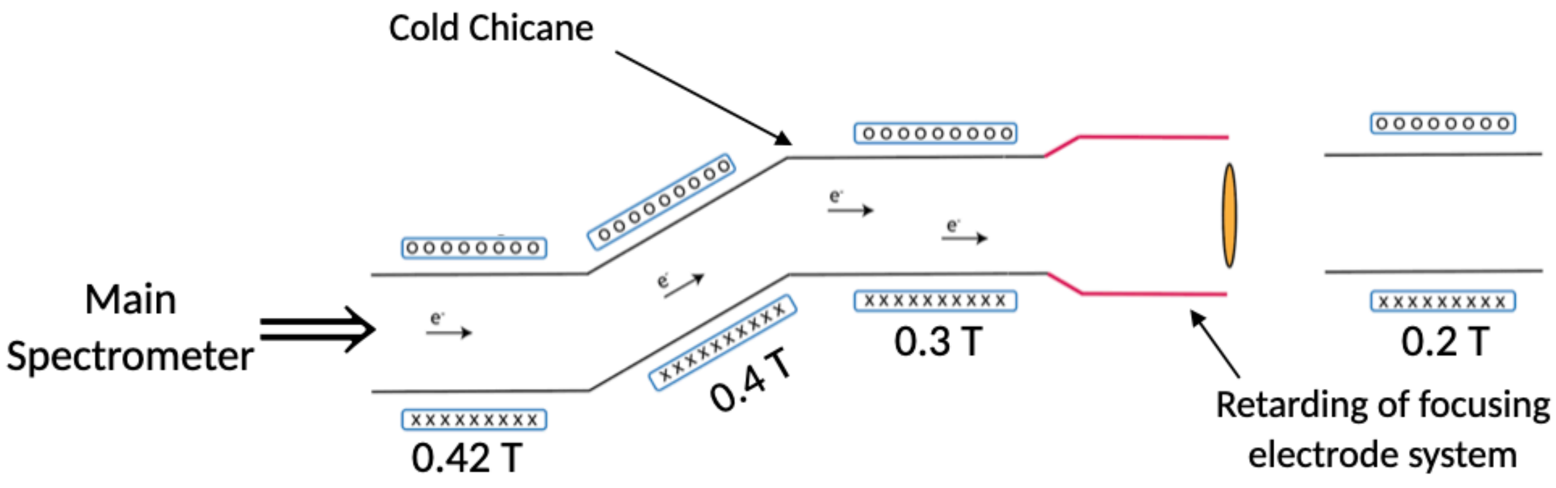




- drastic decrease in signal height with higher B_{ext}
- optimal operation temperature (in terms of signal height)

Conventional MMC with meander-shaped pickup coil not feasible for KATRIN++

Outlook: QSA scenarios



	d (cm)	B (mT)	A (cm²)	(Tcm²)
WGTS	9	500	63	32
QSA	37	30	1060	32

→ ~2.7 Mio pixels (200 µm x 200 µm)

the straightforward way to go
(further improvements hard to impossible)
(fallback option)

entrance window-free silicon quantum sensor

	d (cm)	B (mT)	A (cm²)	(Tcm²)
WGTS	9	500	63	32
QSA	≤ 28	≥ 50	≤ 636	32

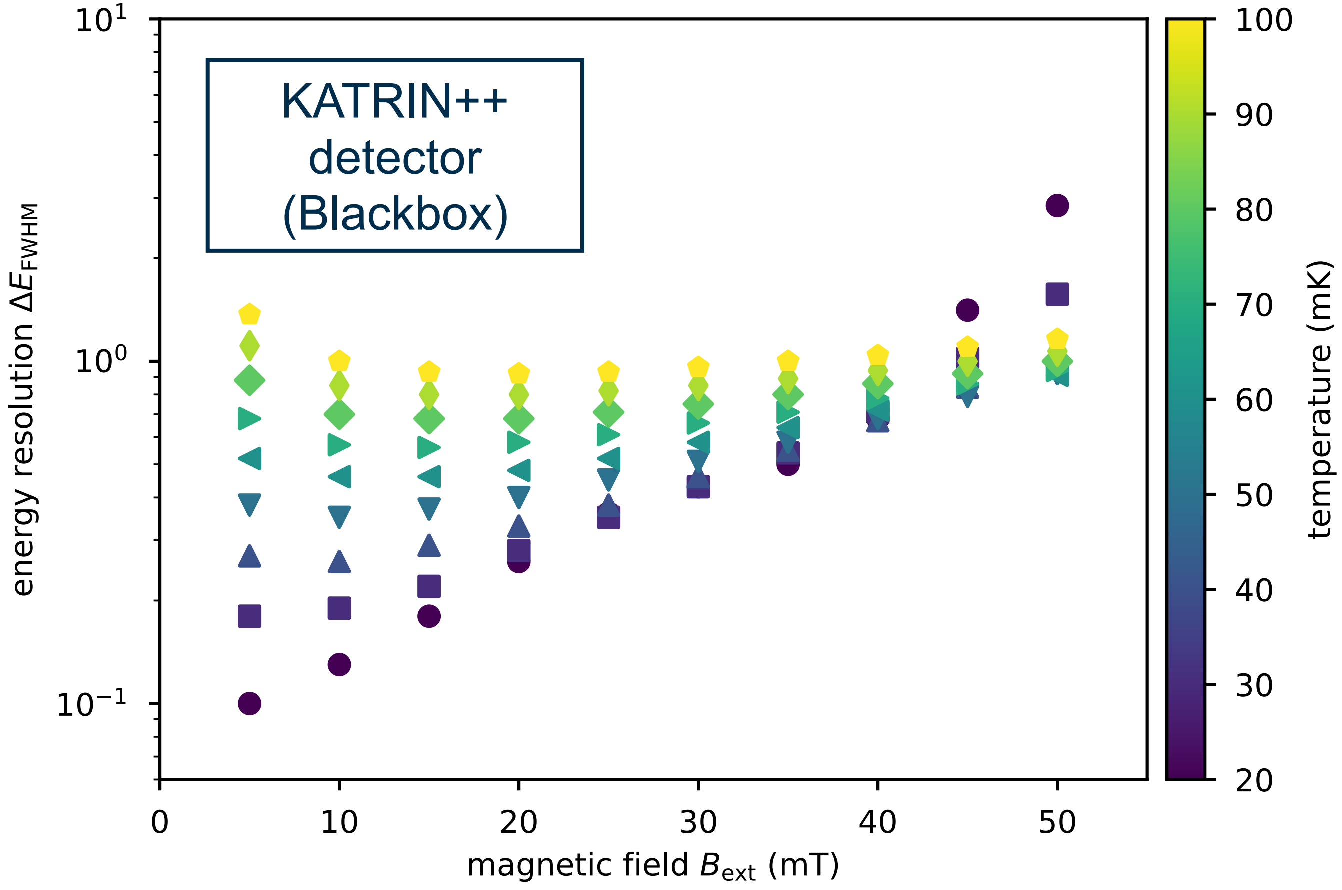
→ ~7.000 pixels (3 mm x 3 mm)

we take up this challenge!!!!

the „challenging way“ to go
(further improvements ‚easily‘ possible)

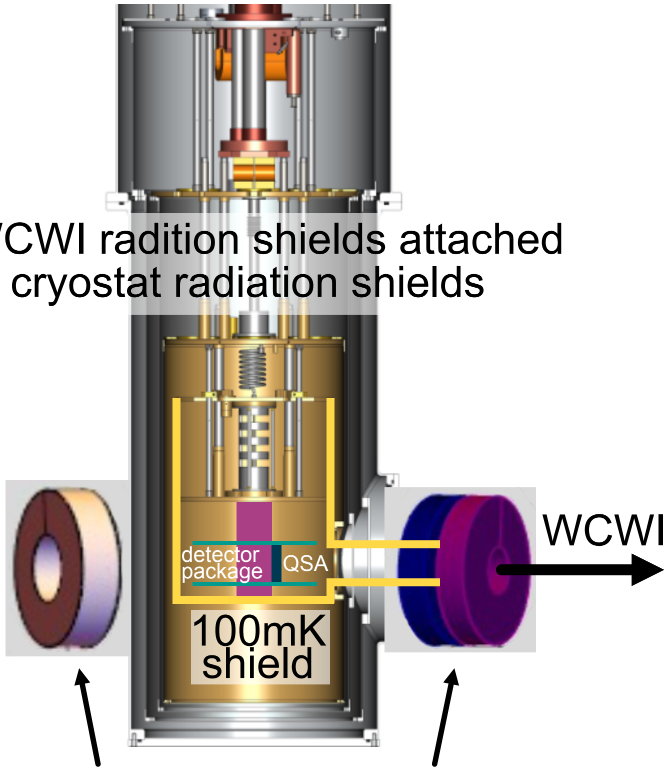
Outlook: QSA scenarios

top secret: we have already a very sophisticated detector concept in mind
which we are currently pushing forward



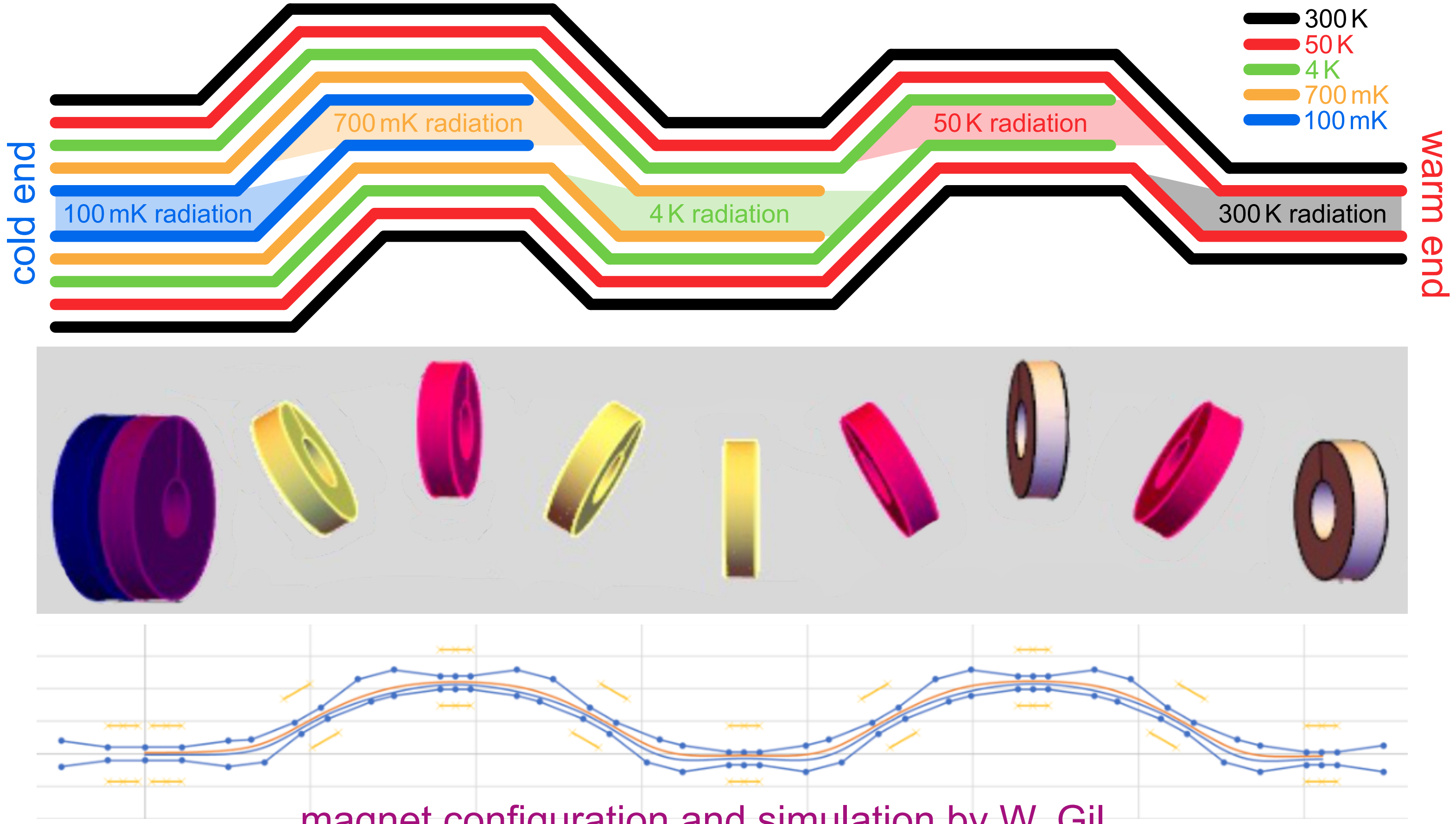
Outlook: Windowless warm-cold interface (WCWI)

MAC-E filter like configuration

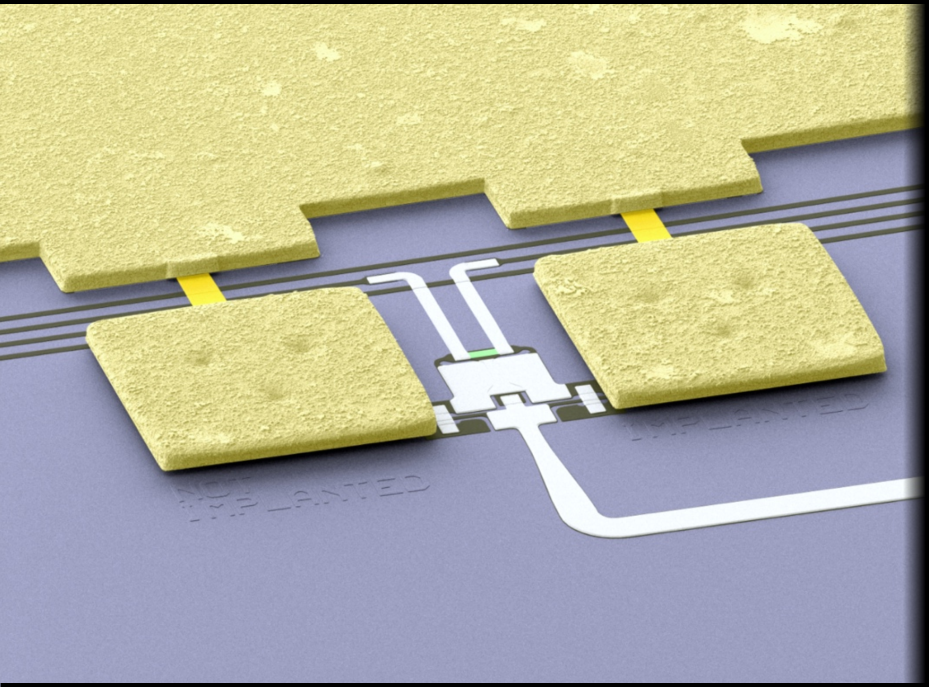


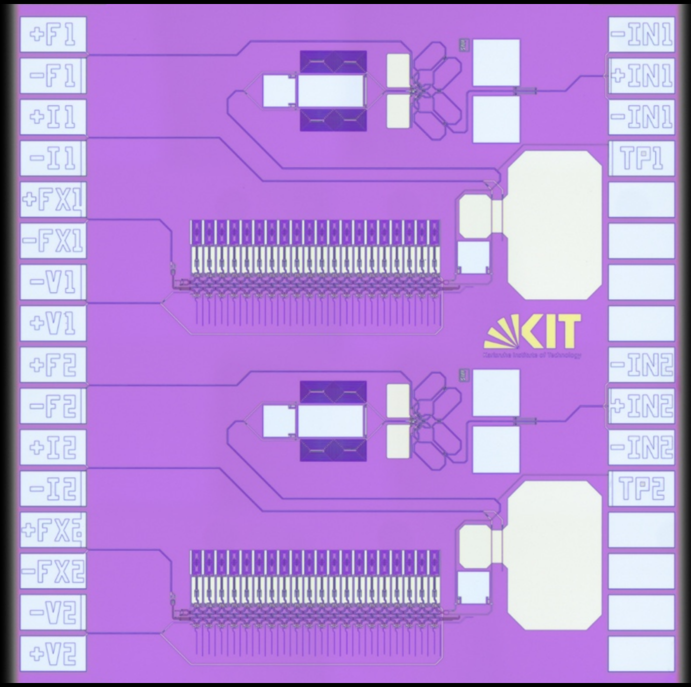
magnets' strength and distance define ambient field at QSA position

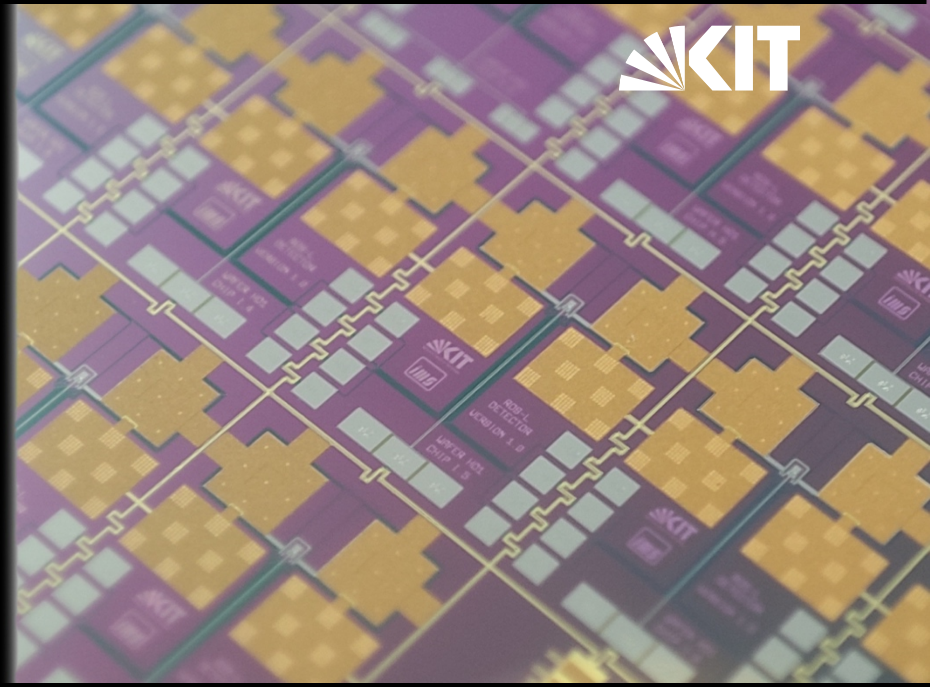
a temperature stage should ideally have a direct line-of-sight to the next higher temperature stage



magnet configuration and simulation by W. Gil







Quantum sensor arrays for KATRIN++ Concepts and challenges

Thank you for your attention

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