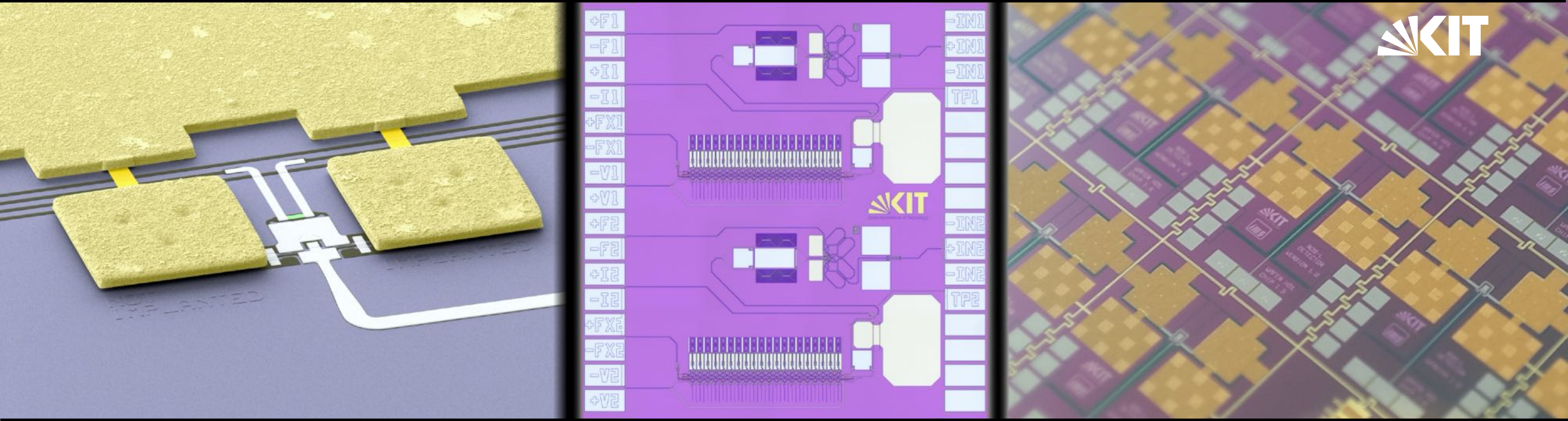
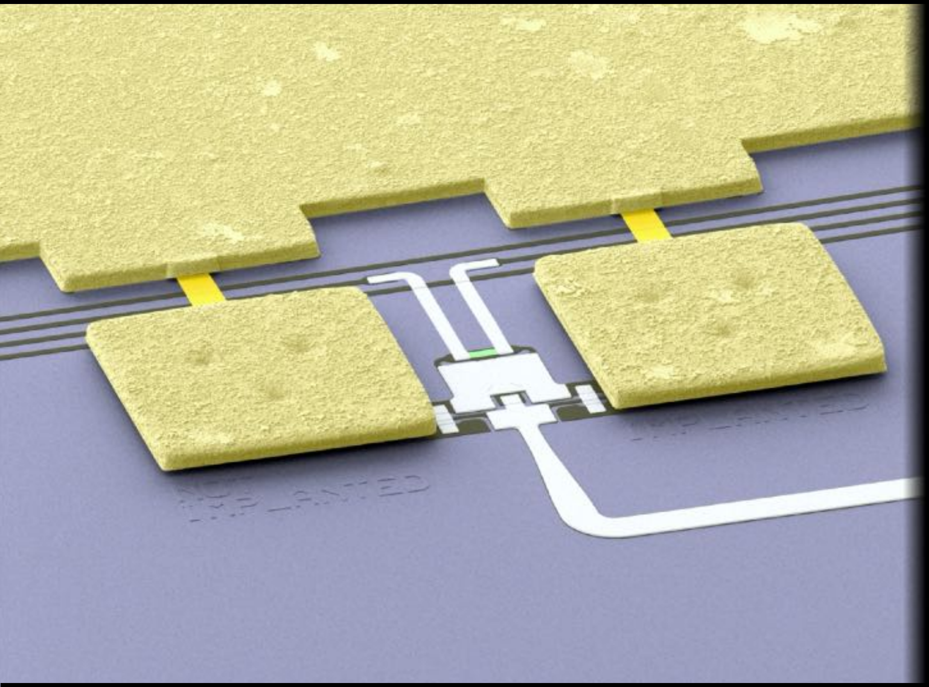
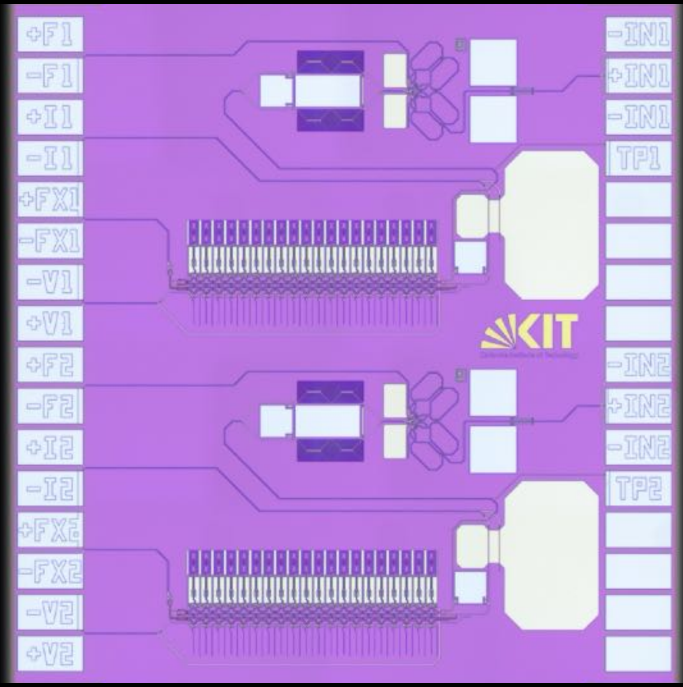
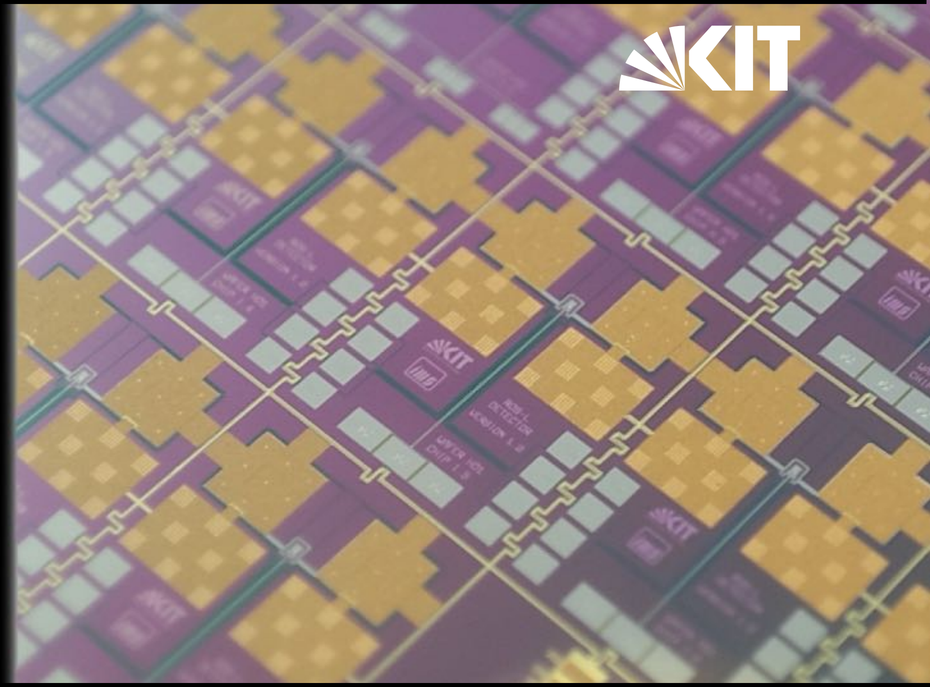


Investigation of MMC-based quantum sensors for electron detection

Sebastian Kempf on behalf of the KATRIN++ R&D group at KIT
Institute of Micro- and Nanoelectronic Systems (IMS), Karlsruhe Institute of Technology (KIT)
Kickoff-Meeting “QS4Physics“ | HI Mainz | Mainz | 2025-11-20







Towards a next-generation tritium-based neutrino mass measurement (KATRIN++)

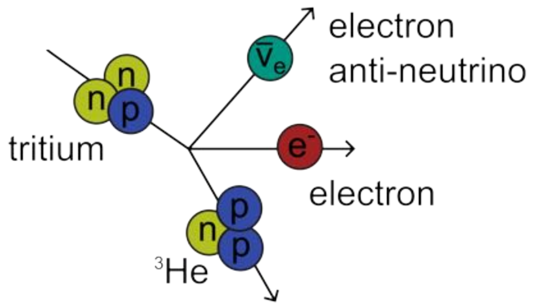
Sebastian Kempf on behalf of the KATRIN++ R&D group at KIT
Institute of Micro- and Nanoelectronic Systems (IMS), Karlsruhe Institute of Technology (KIT)

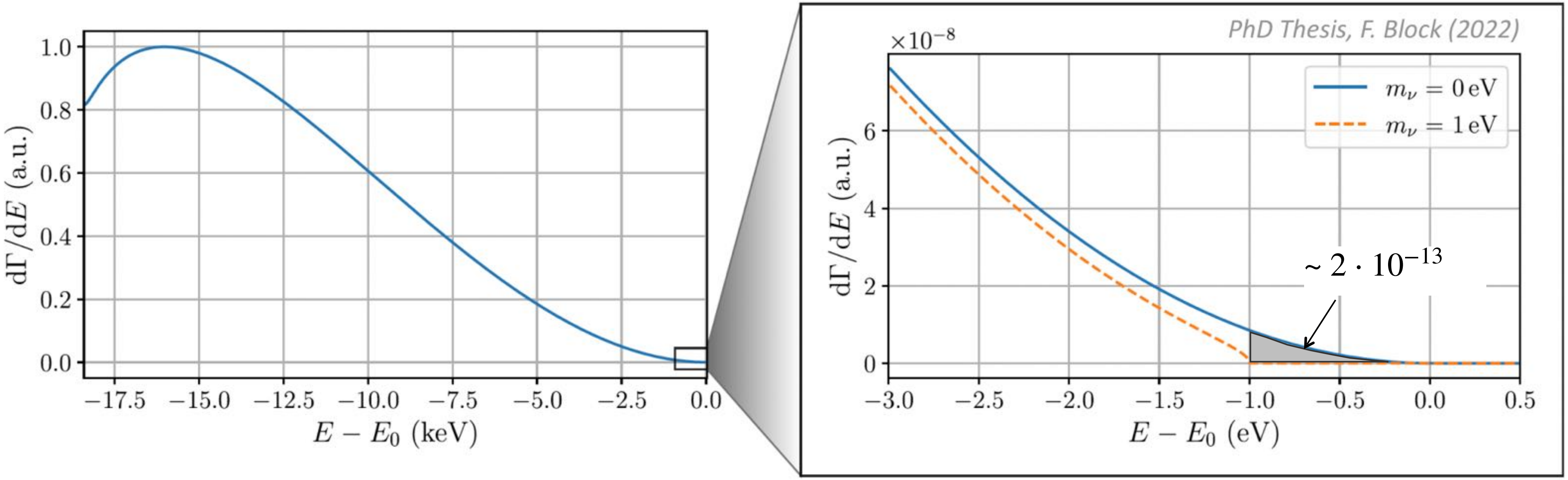
Kickoff-Meeting “QS4Physics“ | HI Mainz | Mainz | 2025-11-20

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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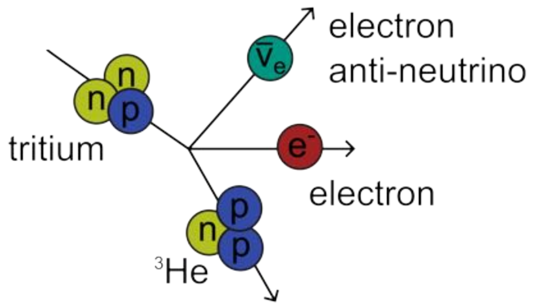

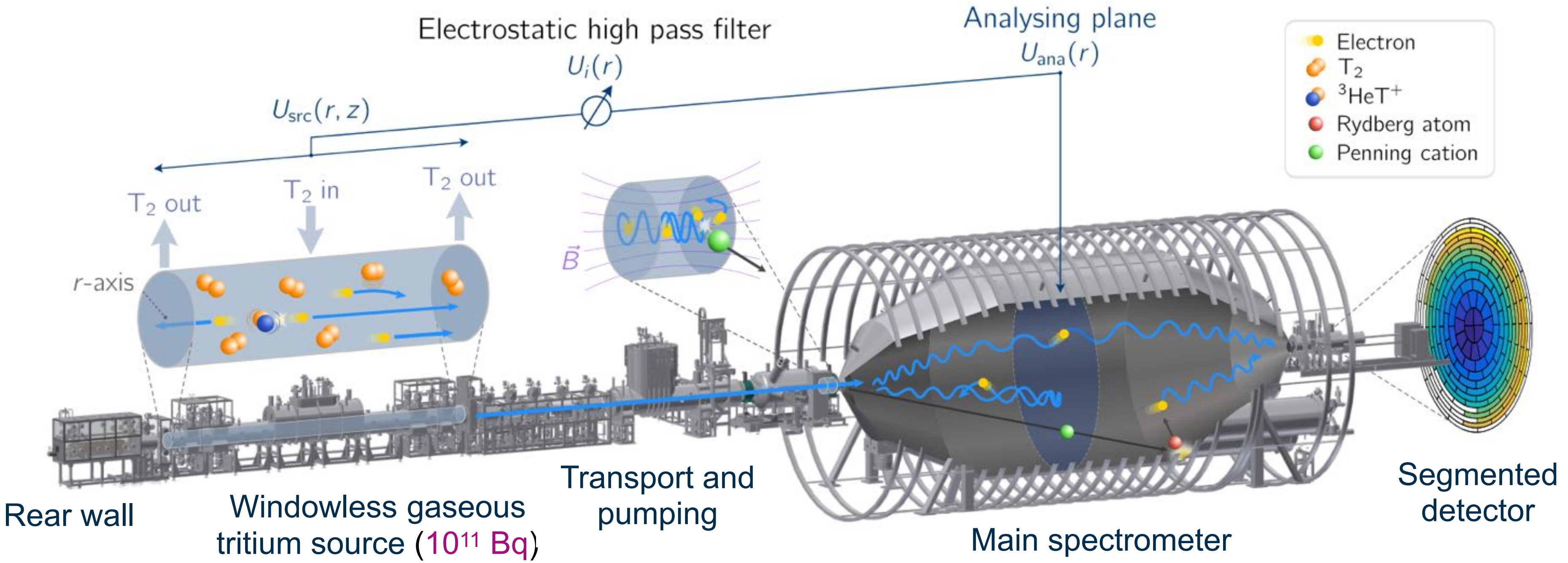

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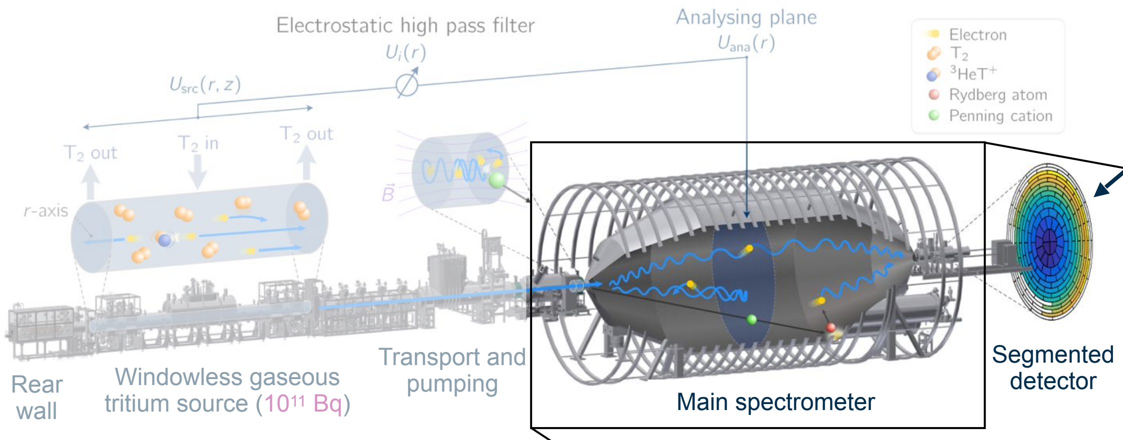
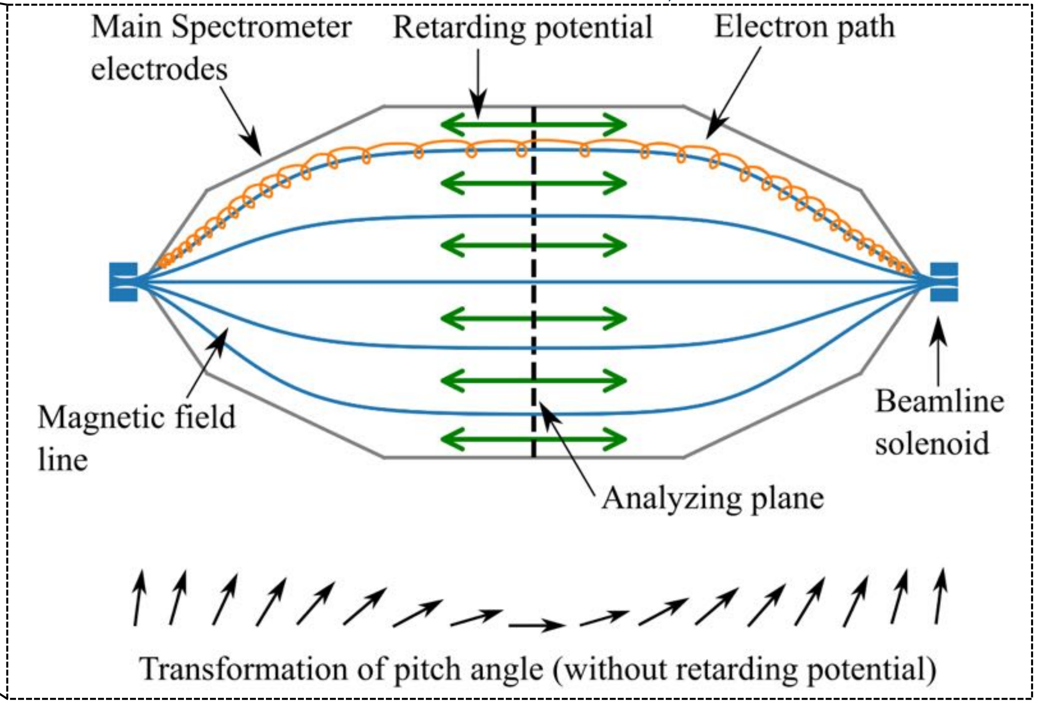


ΔE_{FWHM} = 1 - 2 keV

2 - 3 eV energy resolution



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

Magnetic Adiabatic Collimation with Electrostatic (MAC-E) filtering

Integral mode = scanning over retarding potential

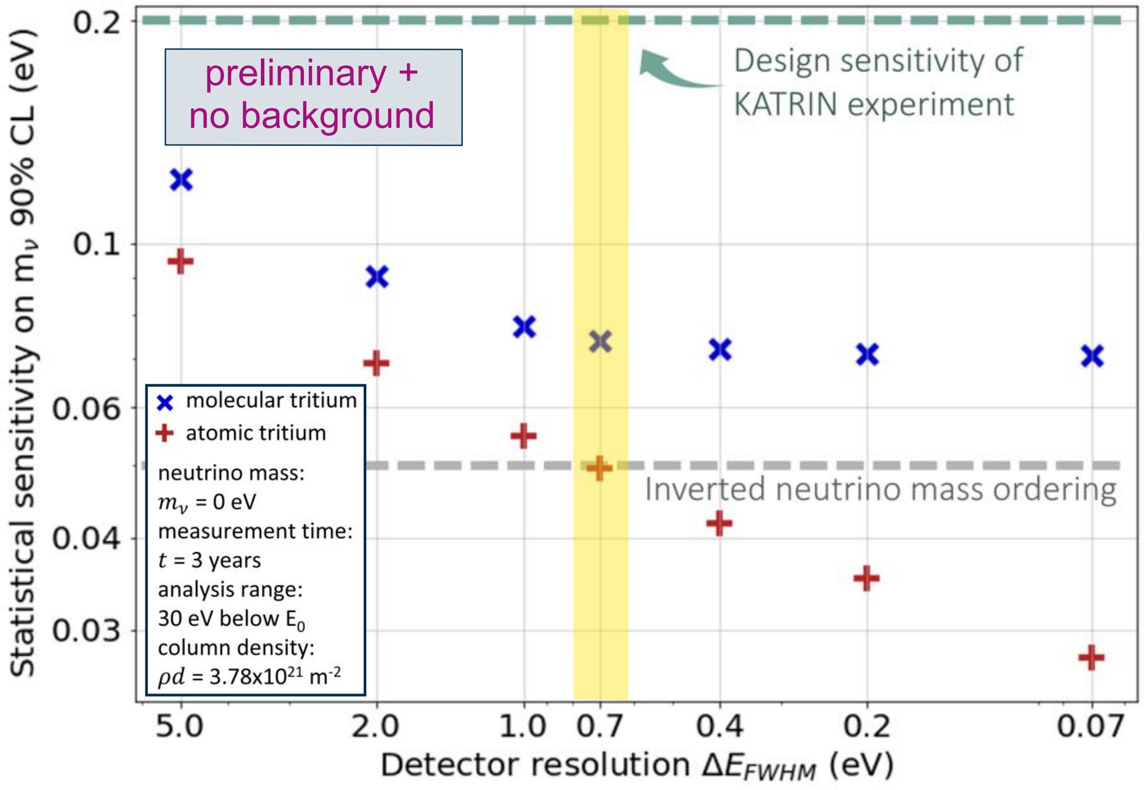
→ measuring integral rate of electrons with kinetic energy above retarding potential

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

Idea and sensitivity estimations of KATRIN++

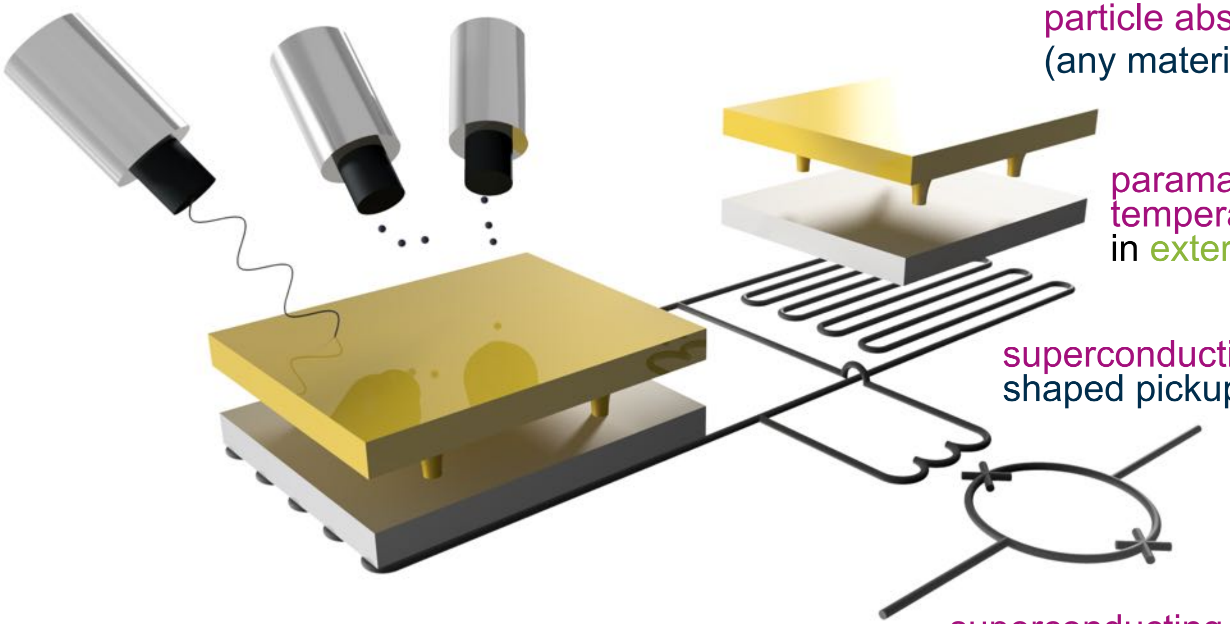
idea: keep main spectrometer at fixed voltage and measure electron energy by a differential (energy resolving) detector

study by S. Heyns and N. Kovac
(Institute for Astroparticle Physics @ KIT)

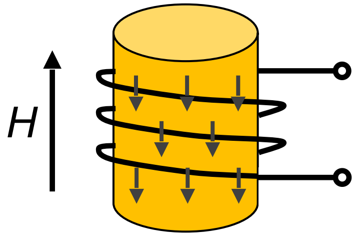


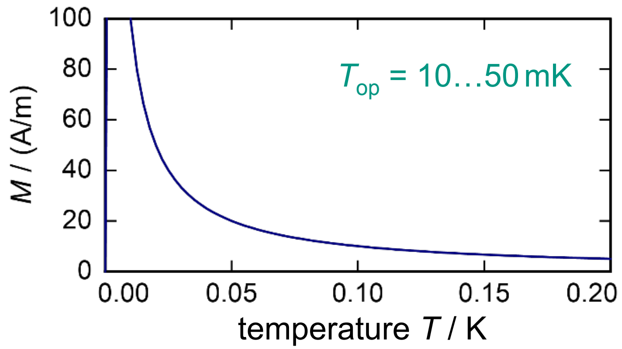
→ differential detector with sub-0.7eV (FWHM) energy resolution required to resolve inverted neutrino mass ordering

Magnetic microcalorimeters (MMCs)



magnetization of a paramagnetic material



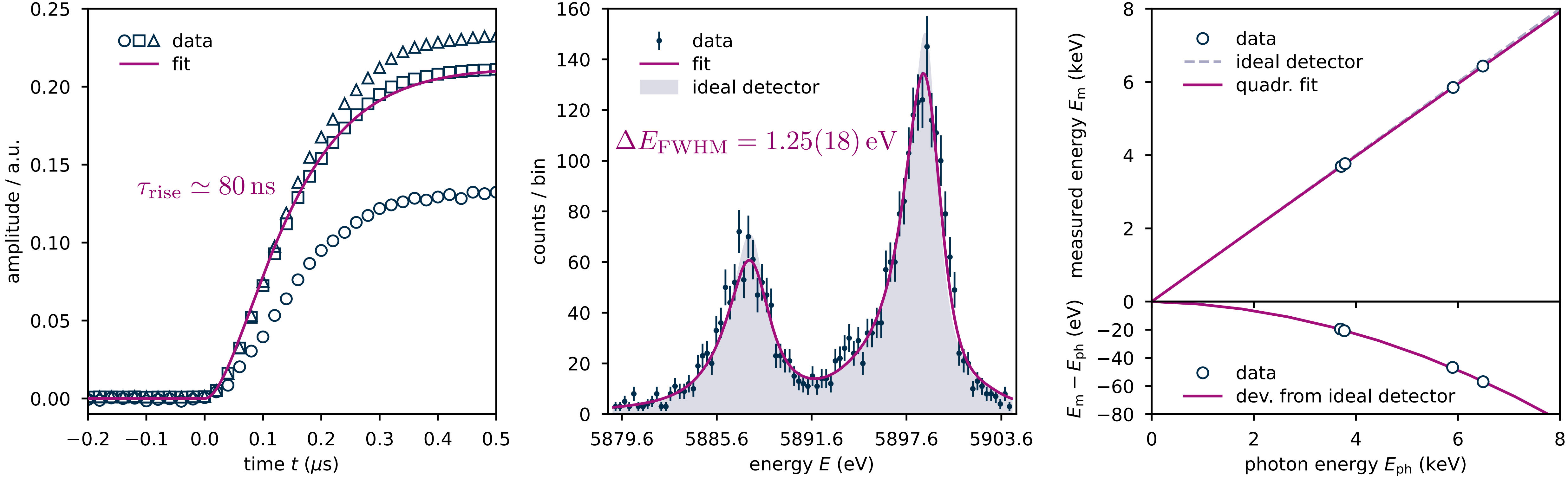


large variation of magnetization at mK temperature

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

Performance of state-of-the-art MMCs

example: magnetic microcalorimeter for soft and tender X-ray spectroscopy



M. Krantz *et al*, Appl. Phys. Lett. **124** (2024) 032601
F. Toschi *et al*, Phys. Rev. D **109** (2024) 043035
S. Kempf *et al,* J. Low Temp. Phys. **193** (2018) 365

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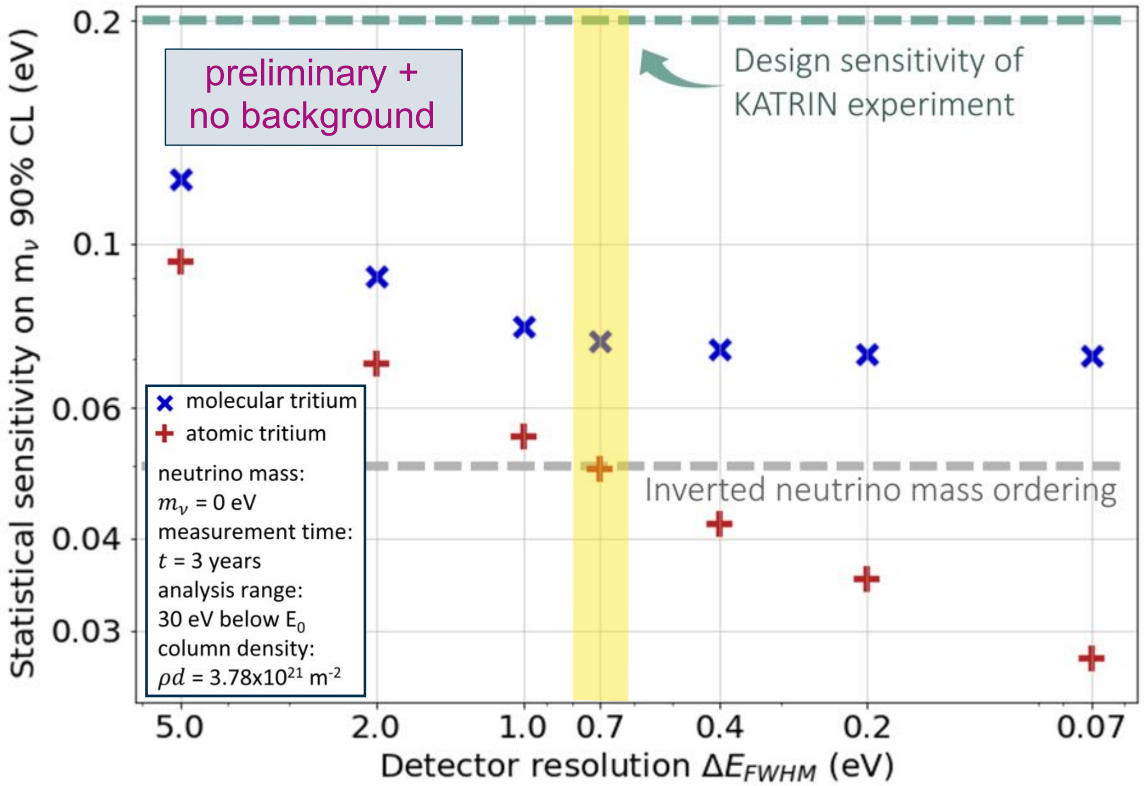
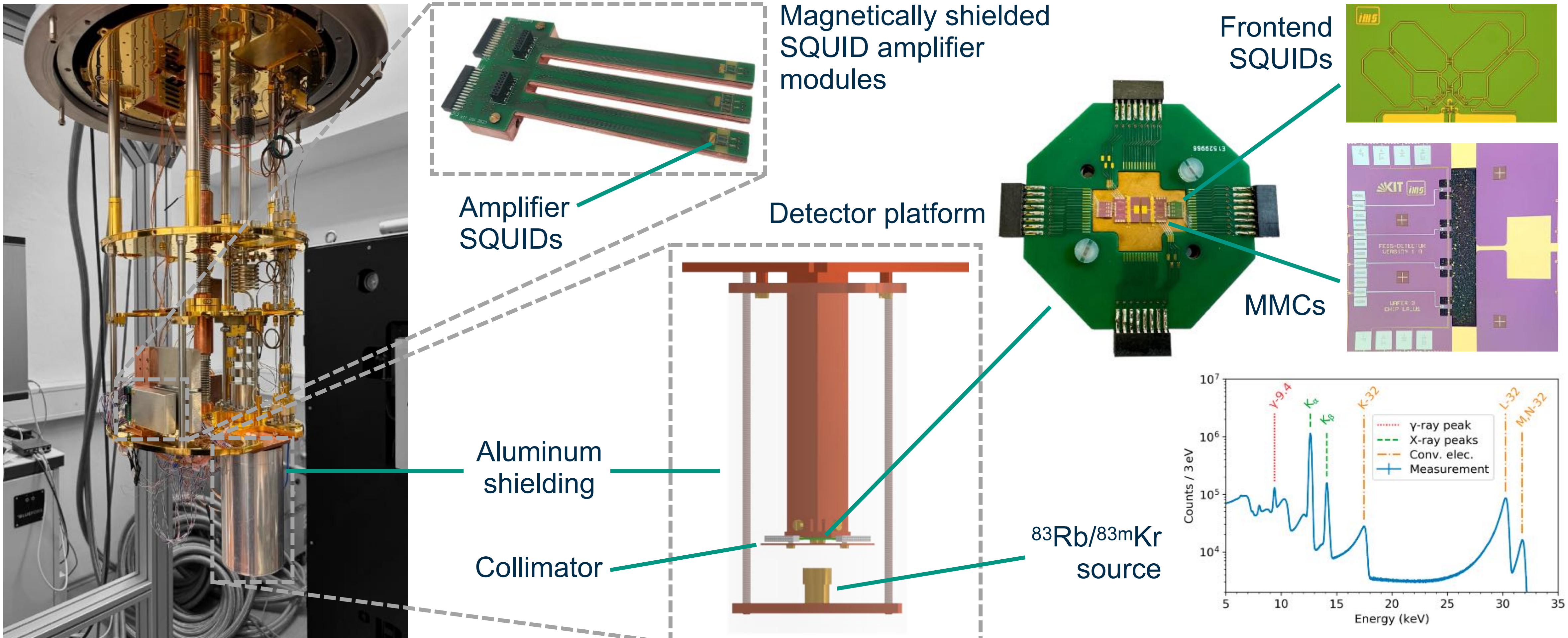


→ differential detector with sub-0.7eV (FWHM) energy resolution required to resolve inverted neutrino mass ordering

\+

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

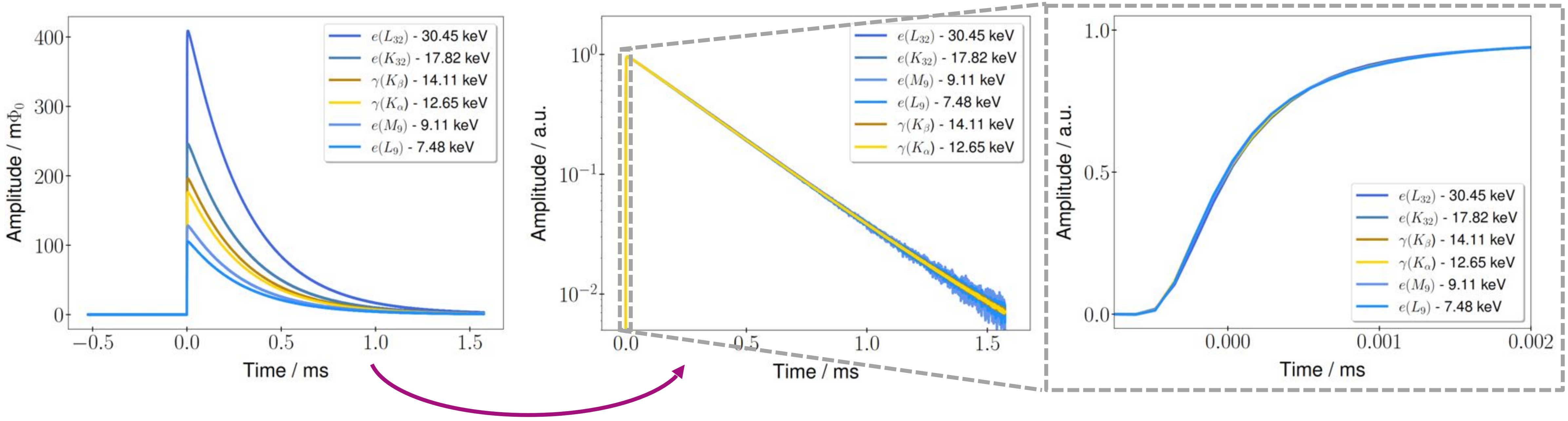
ELECTRON project: Comparison of MMC response for photons and external electrons



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

ELECTRON project: Detector response

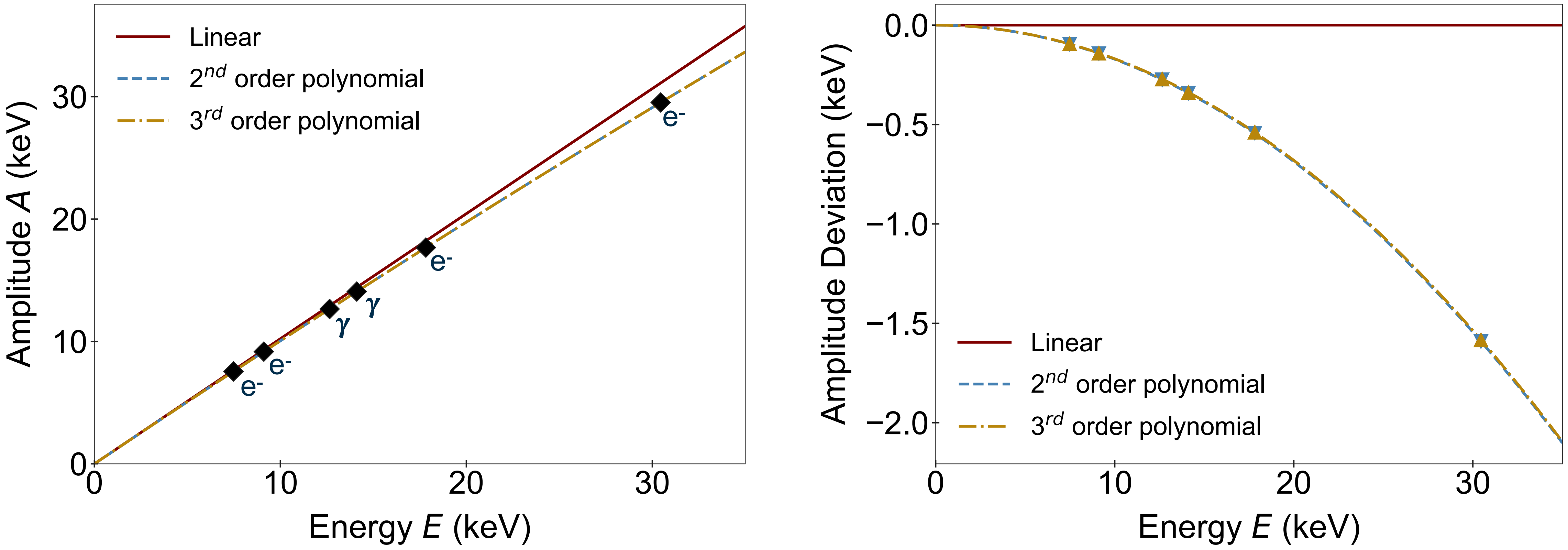
N. Kovač et al., *Nuclear Inst. and Methods in Physics Research A* **1080** (2025)



MMCs show detector response for electrons and photons

ELECTRON project: Energy calibration

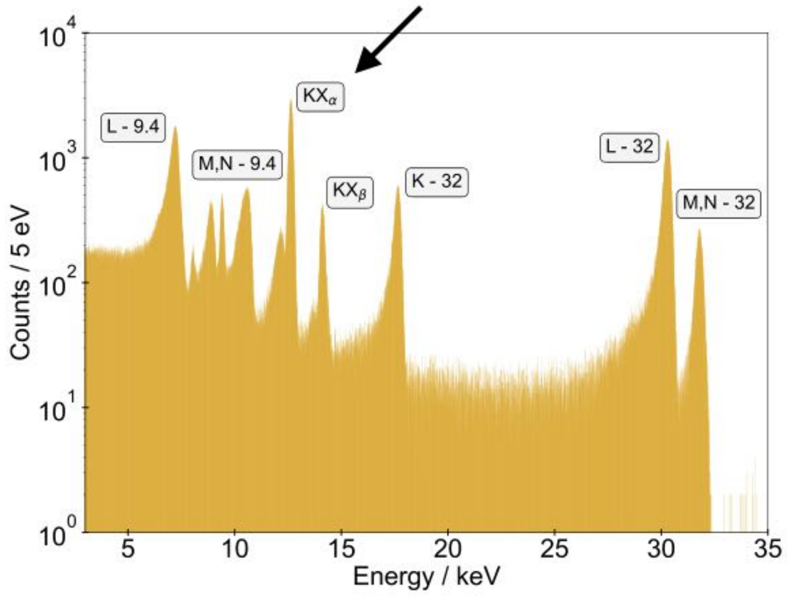
N. Kovač et al., *Nuclear Inst. and Methods in Physics Research A* **1080** (2025)

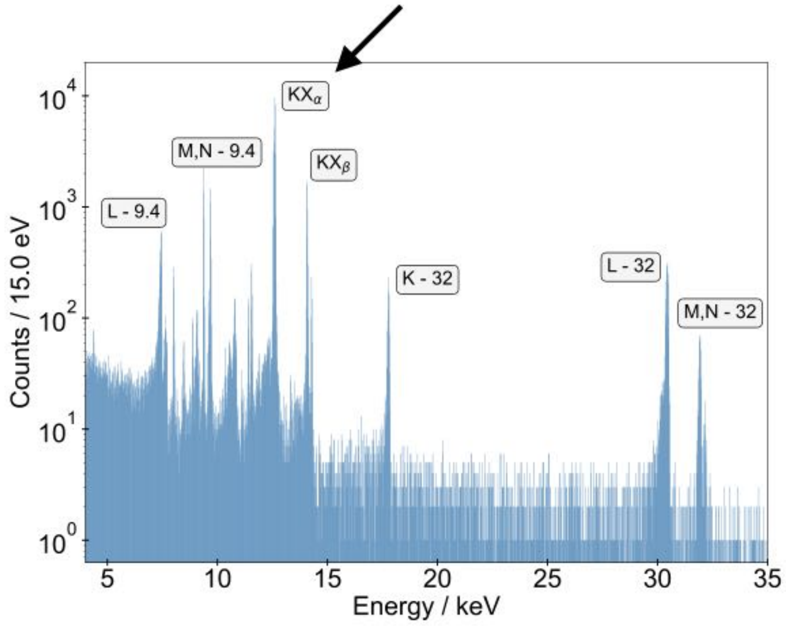


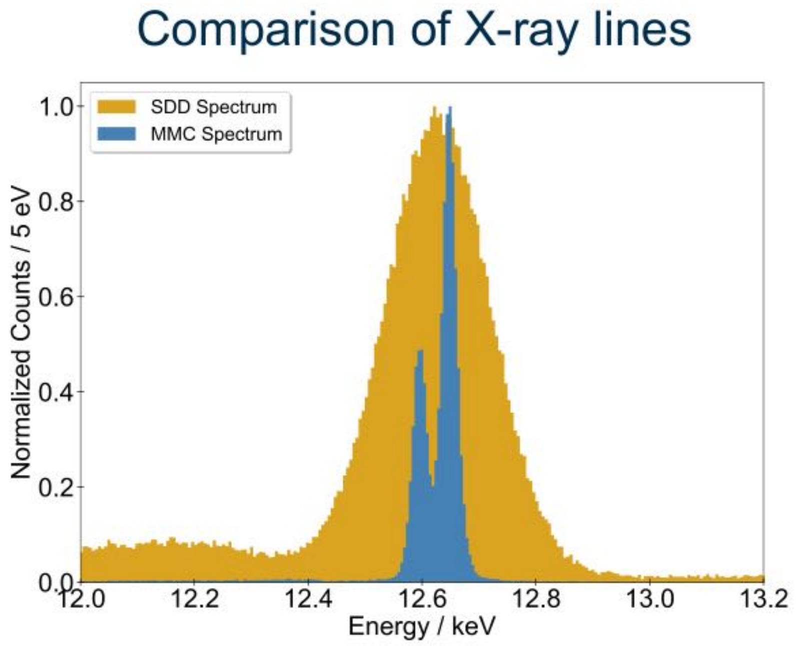
MMCs show same calibration function for electrons and photons

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

„SDD detector vs. MMC“



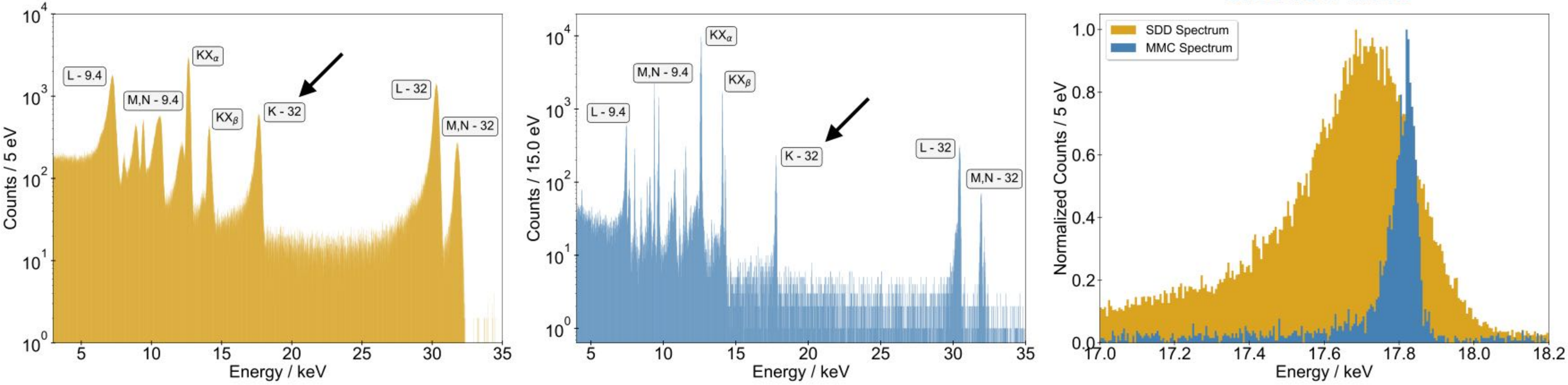




ELECTRON project: ^{83}Rb/^{83m}Kr spectrum

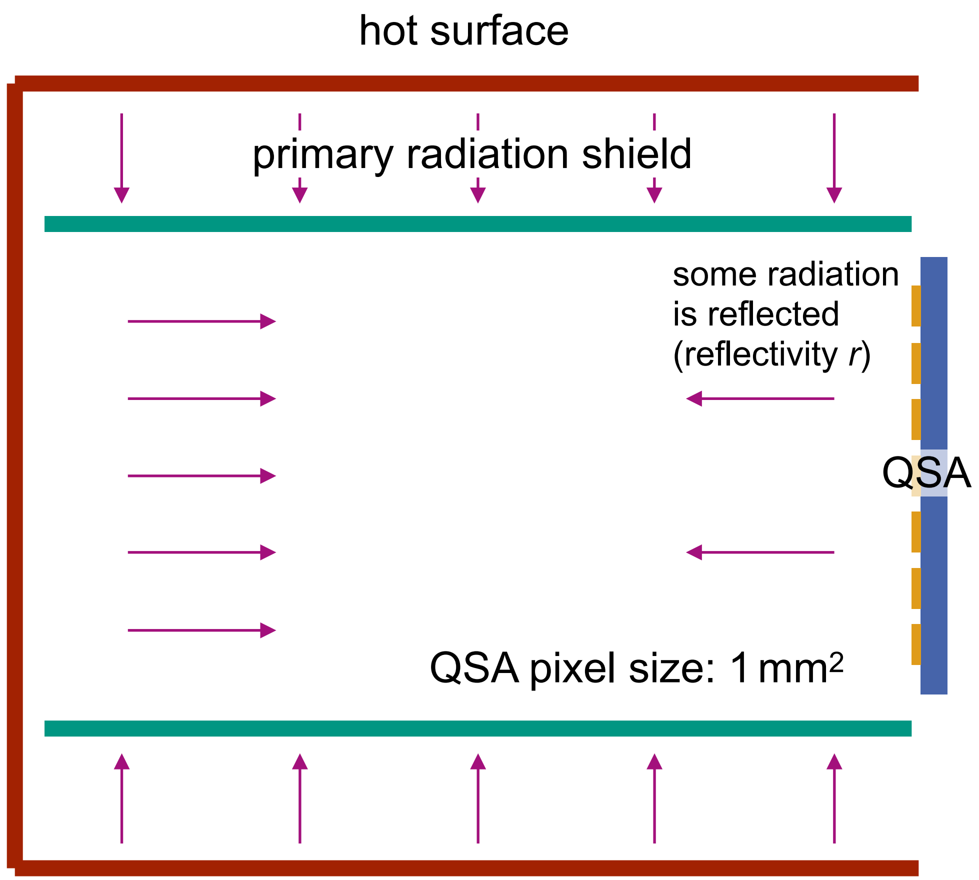
„SDD detector vs. MMC“

Comparison of conversion electron lines



Heat radiation / photon noise I setting

assumption: most simple geometry (not to scale):

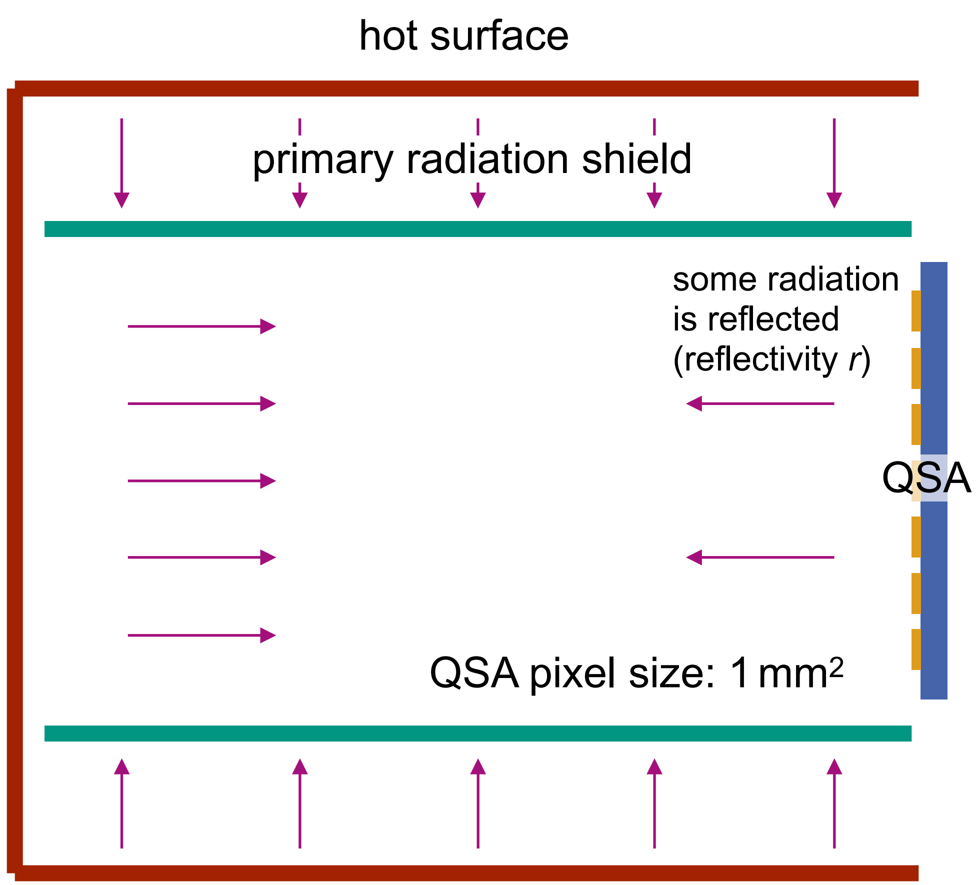


two reasony why to worry about heat radiation:

- heat flux causes thermal load of cryostat and all components (must be cooled by the cryostat)
- photons cause random events in the detector pixels. (photon noise)

Heat radiation / photon noise I setting

assumption: most simple geometry (not to scale):

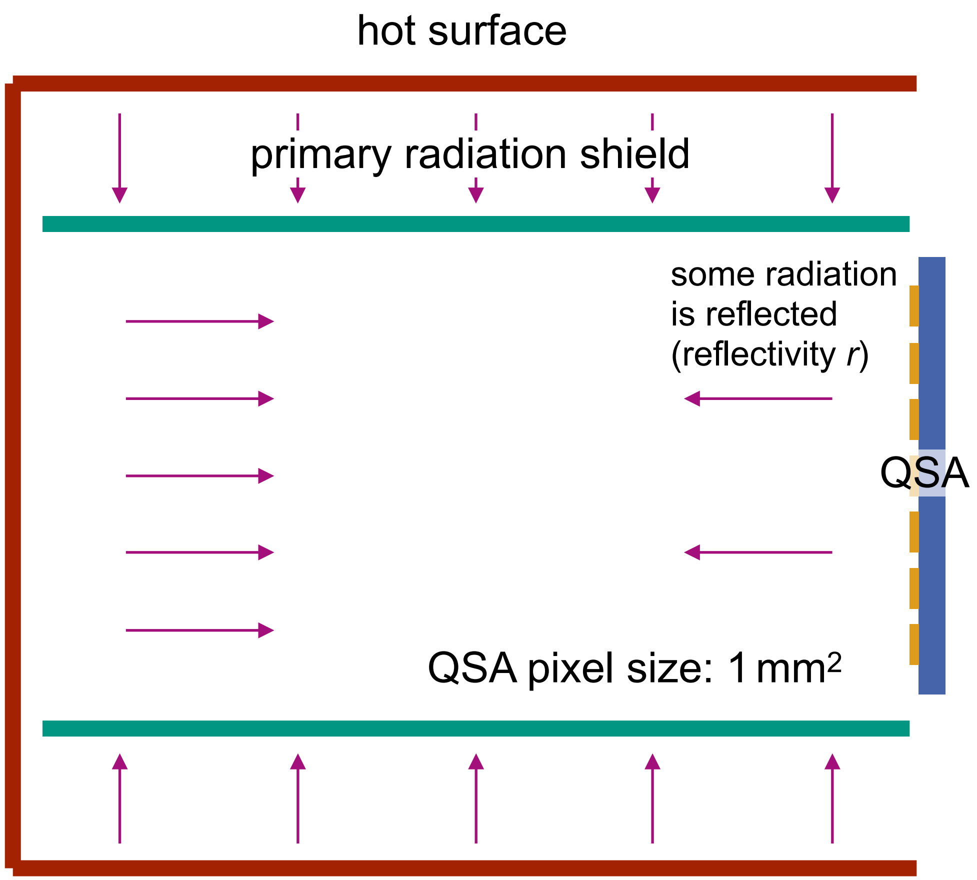


assumptions for back-on-the-envelope estimation:

- neglect radiation from front surface to primary radiation shield
- neglect radiation from radiation shield (if warm) to QSA
- diffusive heat radiation (blackbody radiation)
- neglect emission from cold surfaces
- consider only energy resolution, not radiative heat load

Heat radiation / photon noise I results

assumption: most simple geometry (not to scale):



condition (arbitrary): $\Delta E_{\mathrm{FWHM,photon}} < 0.1\,\mathrm{eV}$

QSA diameter = 30 cm, reflectance = 0, shield length = 50 cm → $T_{\mathrm{hot}} < 74\,\mathrm{mK}$

QSA diameter = 30 cm, reflectance = 0.99, shield length = 50 cm → $T_{\mathrm{hot}} < 230\,\mathrm{mK}$

QSA diameter = 10 cm, reflectance = 0.99, shield length = 50 cm → $T_{\mathrm{hot}} < 390\,\mathrm{mK}$

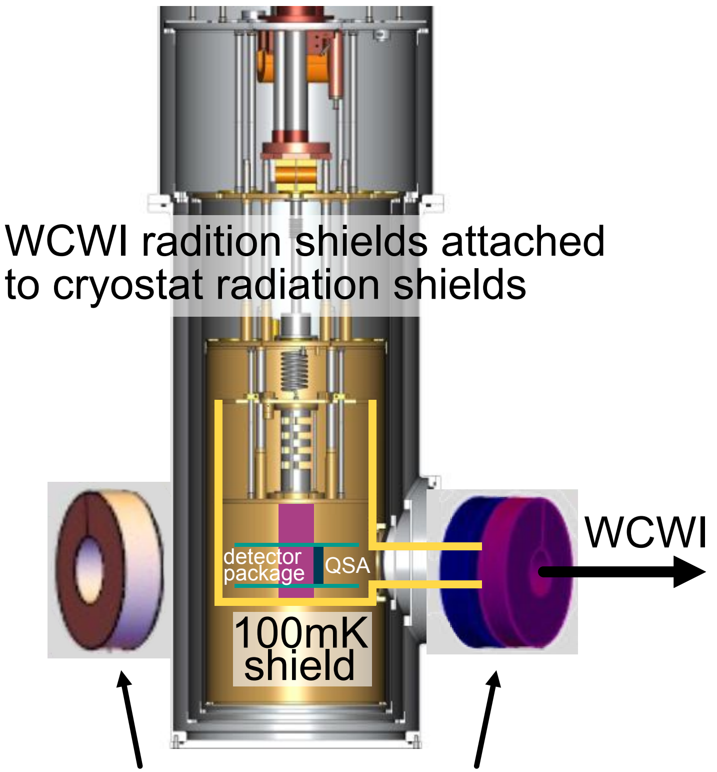
QSA diameter = 10 cm, reflectance = 0.99, shield length = 1000 cm → $T_{\mathrm{hot}} < 560\,\mathrm{mK}$

→ QSA not allow to „view“ surfaces hotter than $O(100\,\mathrm{mK})$

+ infrared filters (thin foils) are not allowed

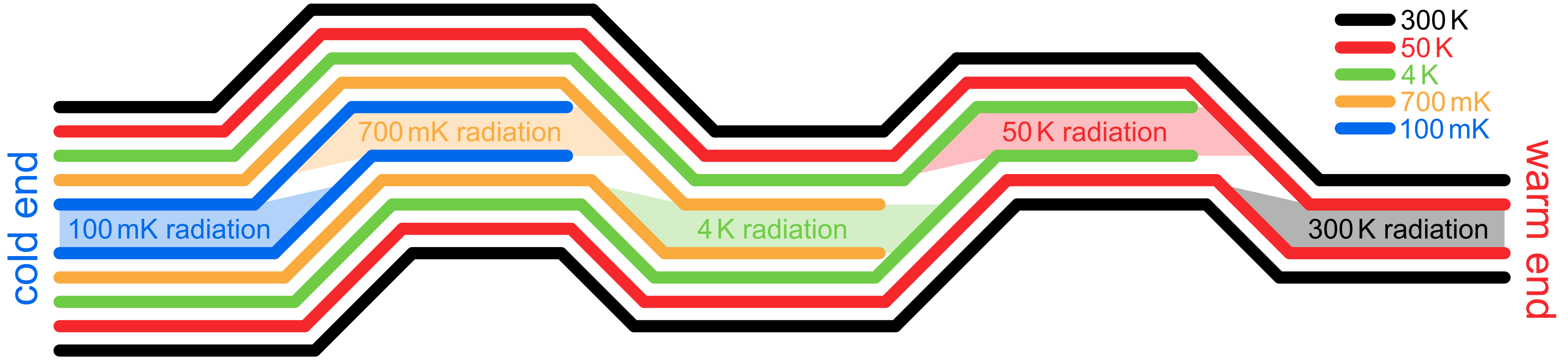
Windowless warm-cold interface (WCWI)

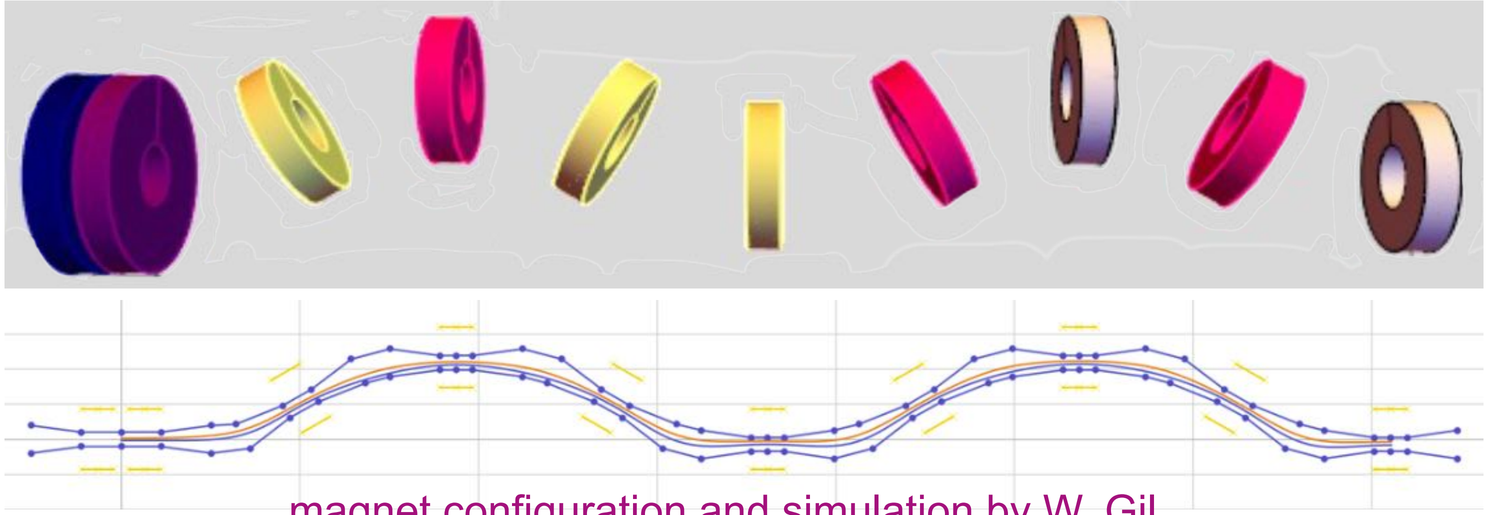
MAC-E filter like configuration



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

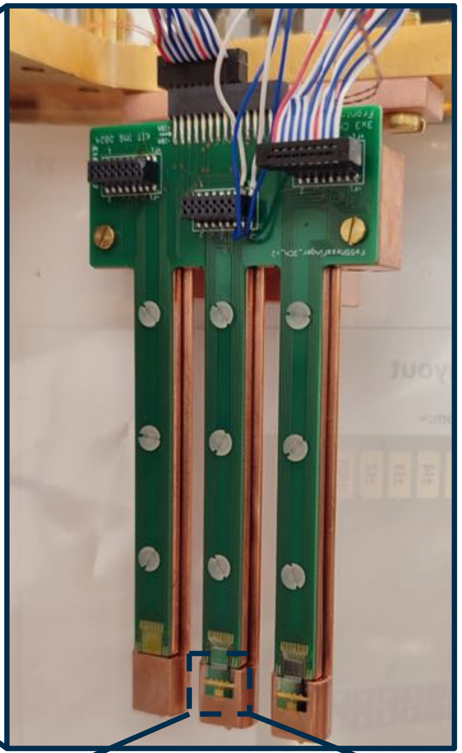




magnet configuration and simulation by W. Gil

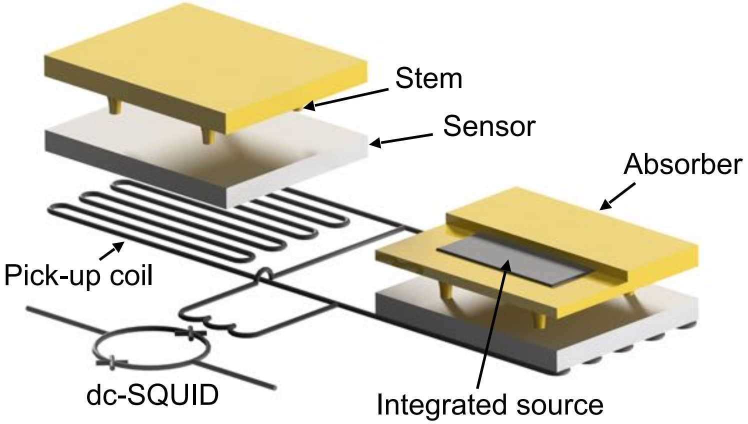
MMC operation in external magnetic field

detector module

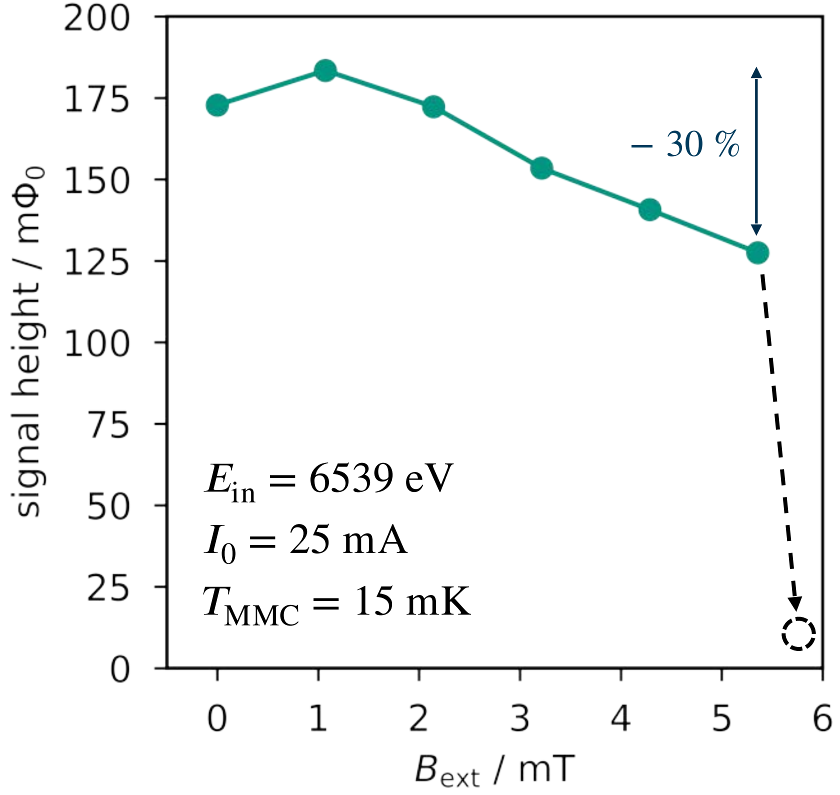


particle absorber of MMC
ion-implanted with ^{55}Fe source

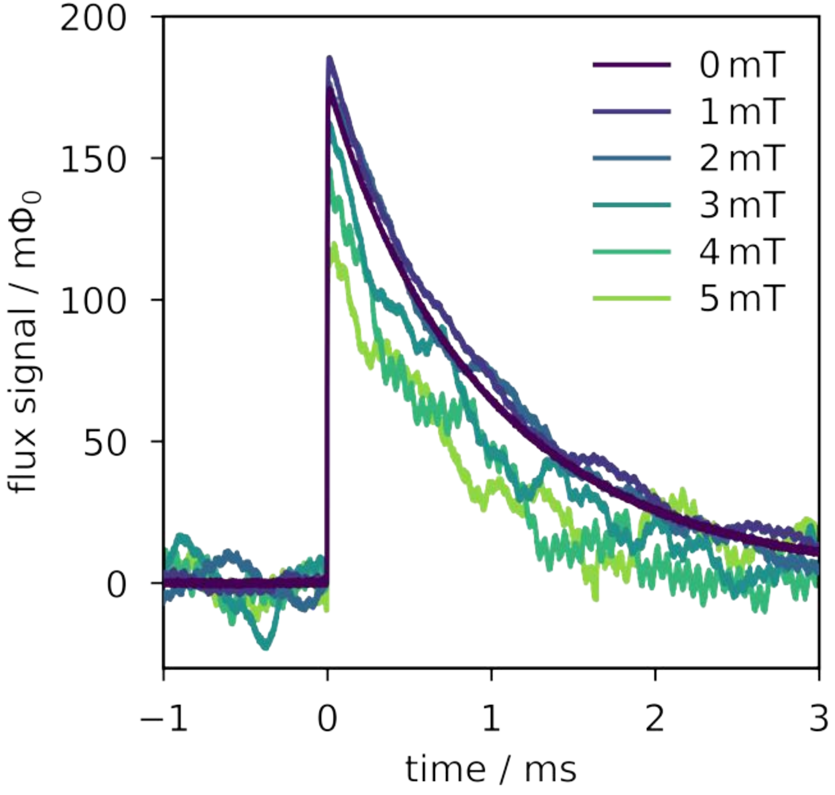
- *B*-field generated by external Helmholtz coil
- capable of generating up to B = 30 mT
- no magnetic shielding of detector module



Pulse height measurements

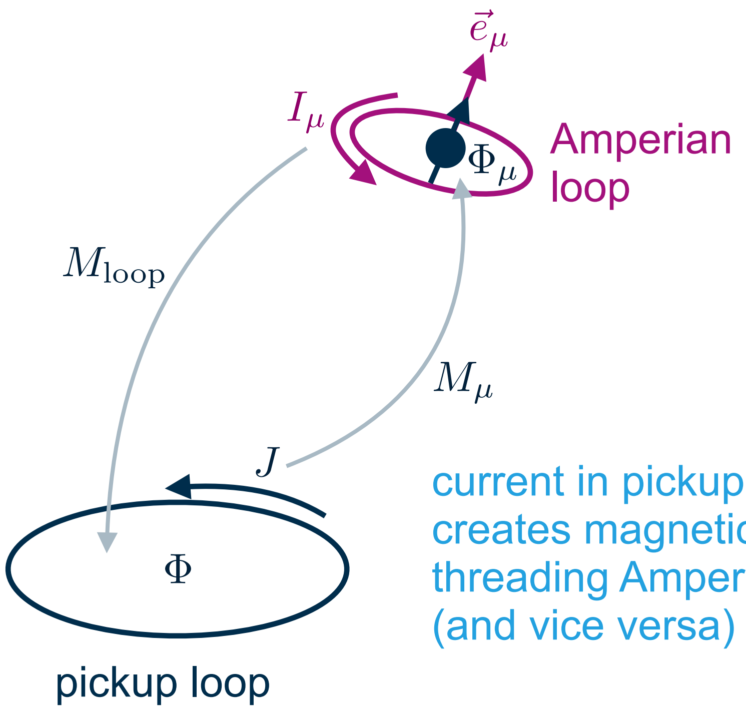


raw detector signals



- 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}

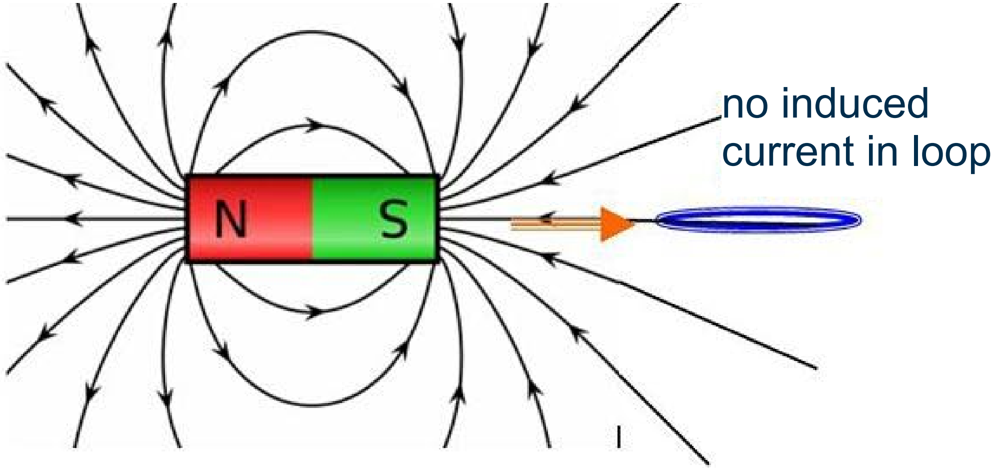
Spin flip detection



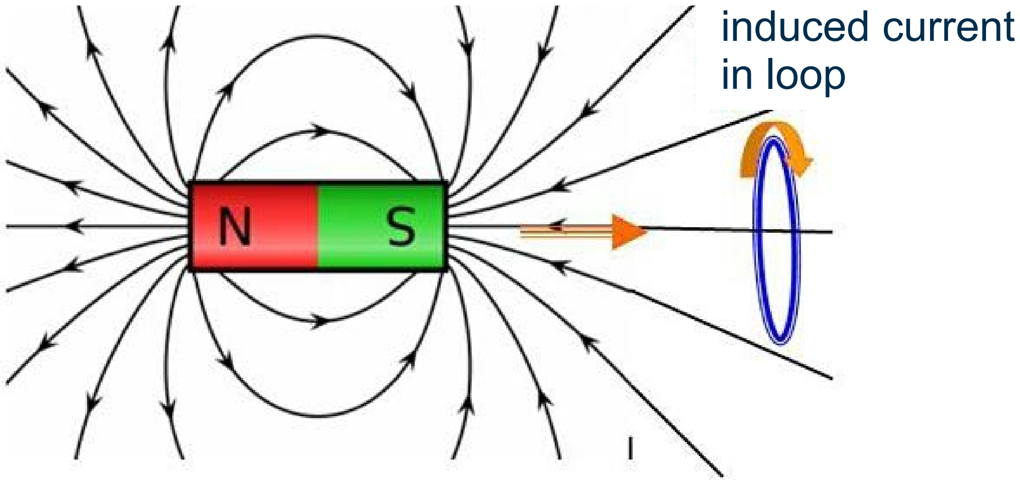
current in pickup coil creates magnetic field threading Amperian loop (and vice versa)

coupling factor: $\phi_\mu(\vec{r}, \vec{e}_\mu) = \dfrac{\vec{e}_\mu \cdot \vec{B}_J(\vec{r})}{J}$

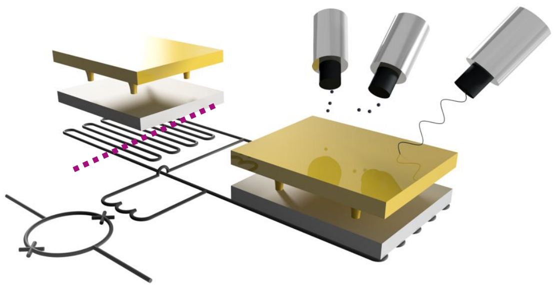
field lines of magnetic moment and pickup loop are parallel



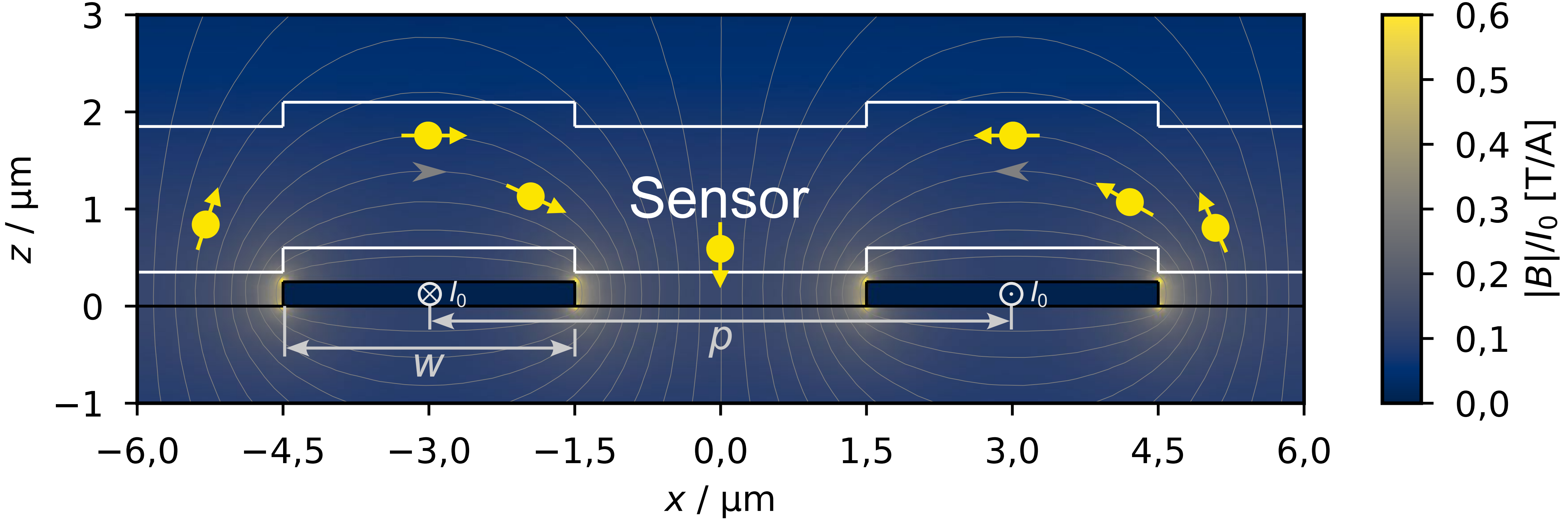
field lines of magnetic moment and pickup loop are perpendictular



MMCs with meander-shaped pickup coils
(w/o magnetic background field)

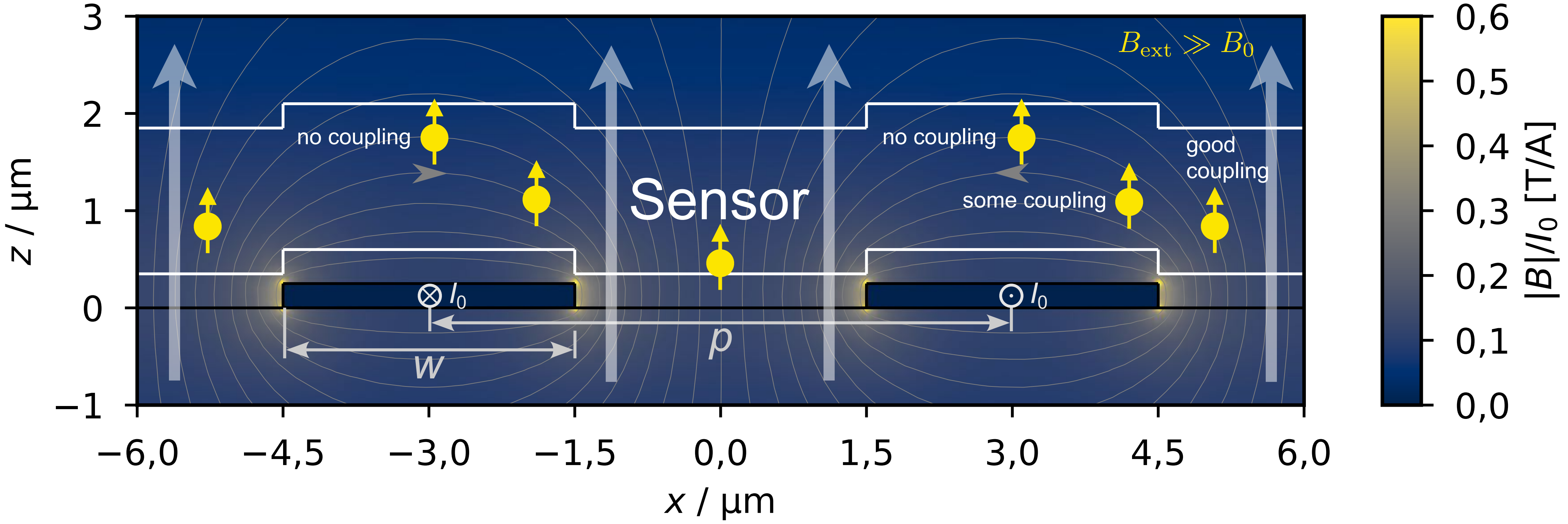


spin alignment determined by persistent current in meander-shaped pickup coil
→ spin direction and magnetic field of bias coil always parallel



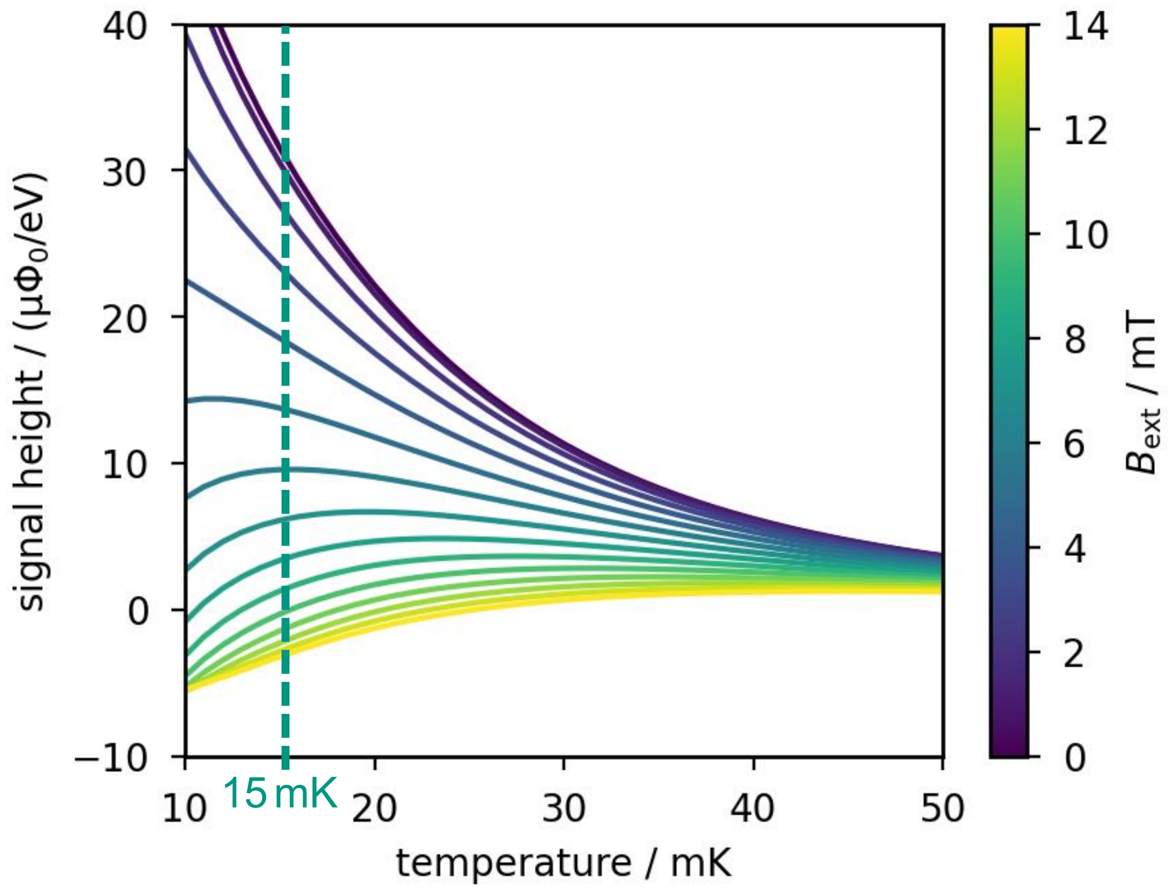
MMCs with meander-shaped pickup coils
(w/ magnetic background field)

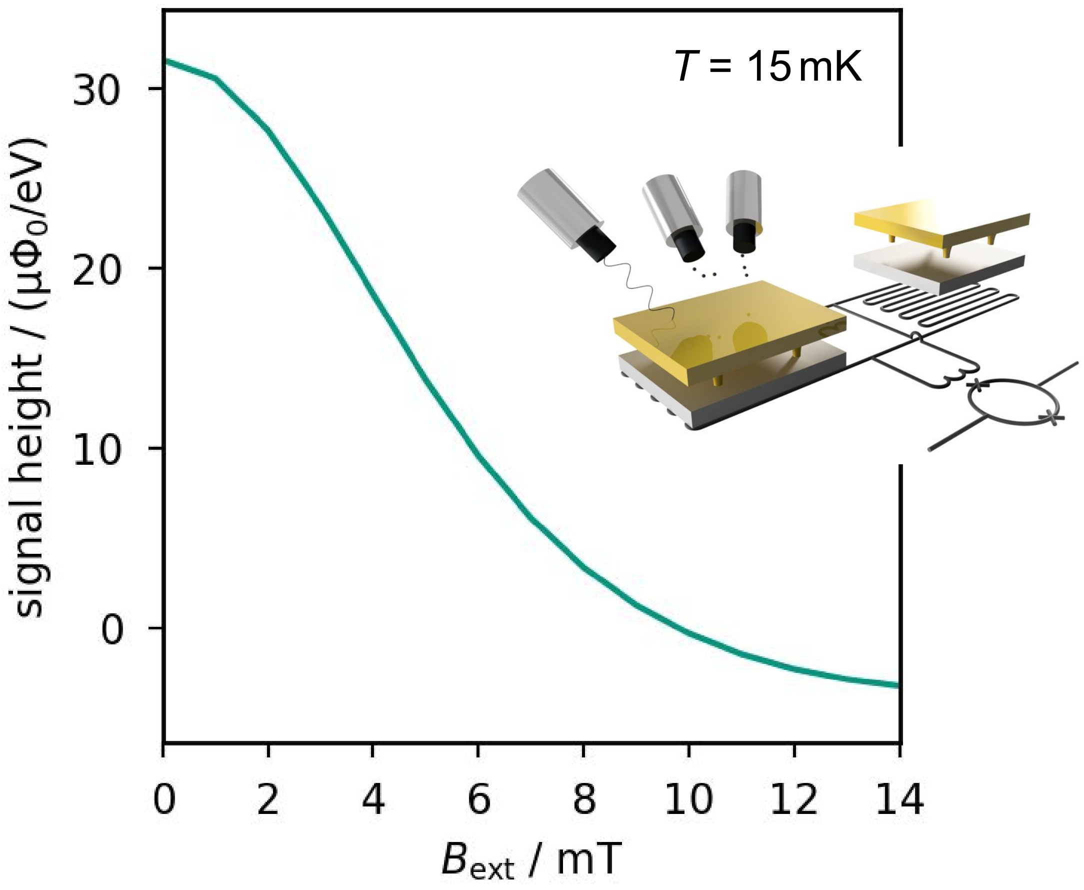
spin alignment determined by persistent current in meander-shaped pickup coil and magnetic background field
→ some spins effective couple, others not



but: all spins contribute to heat capacity

Pulse height simulations



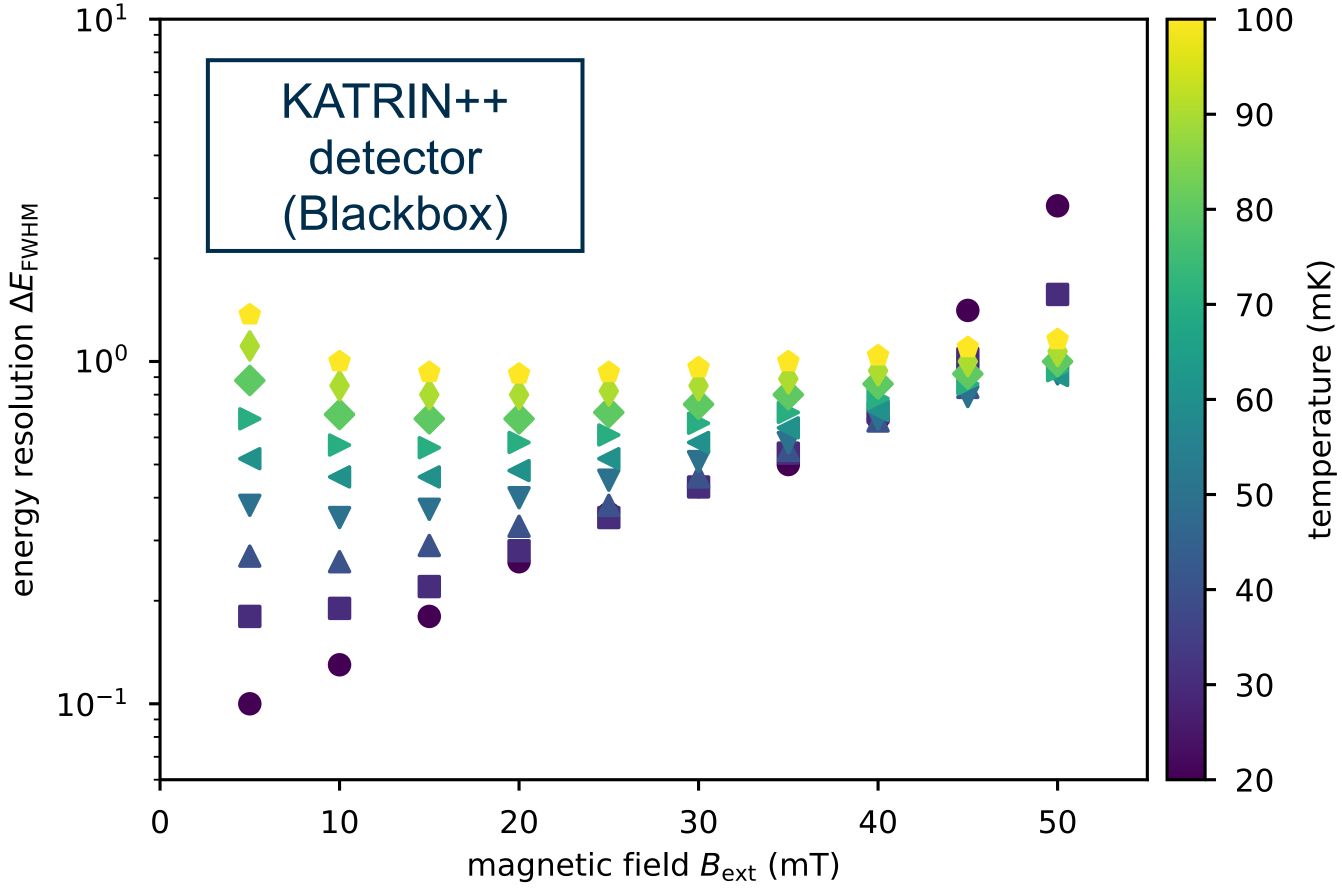


- drastic decrease in signal height with higher B_{ext}
- optimal operation temperature (in terms of signal height)

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

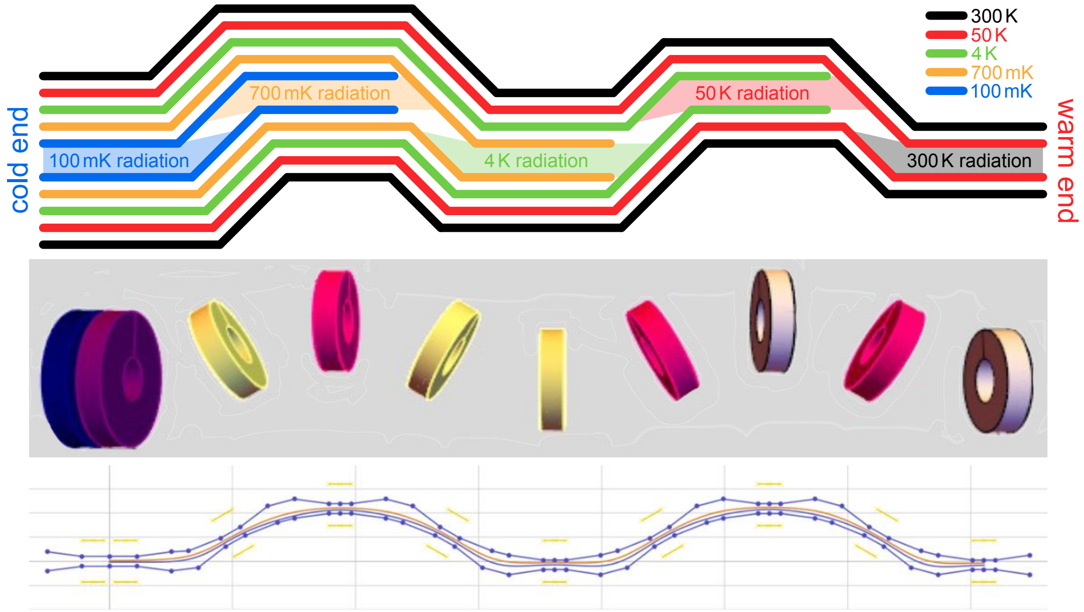
MMC detector for operation on ambient fields

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

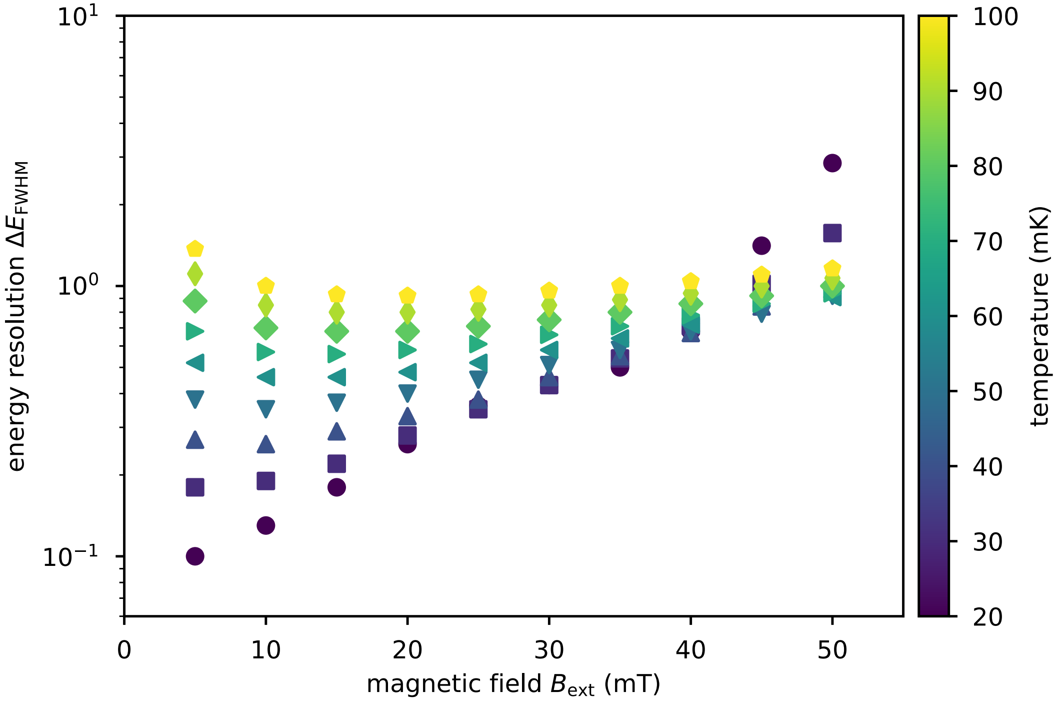


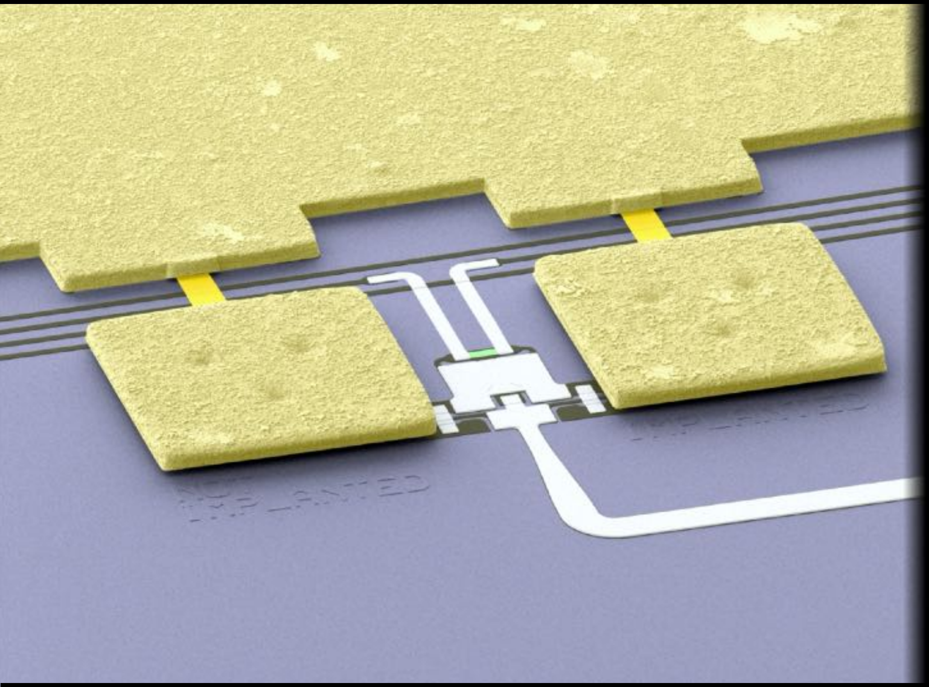
Conclusion and outlook

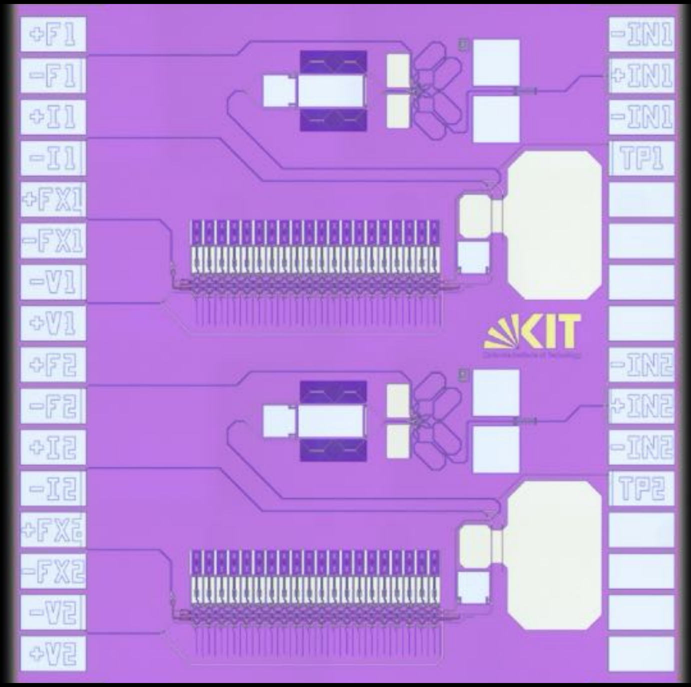
windowless cold-warm interface

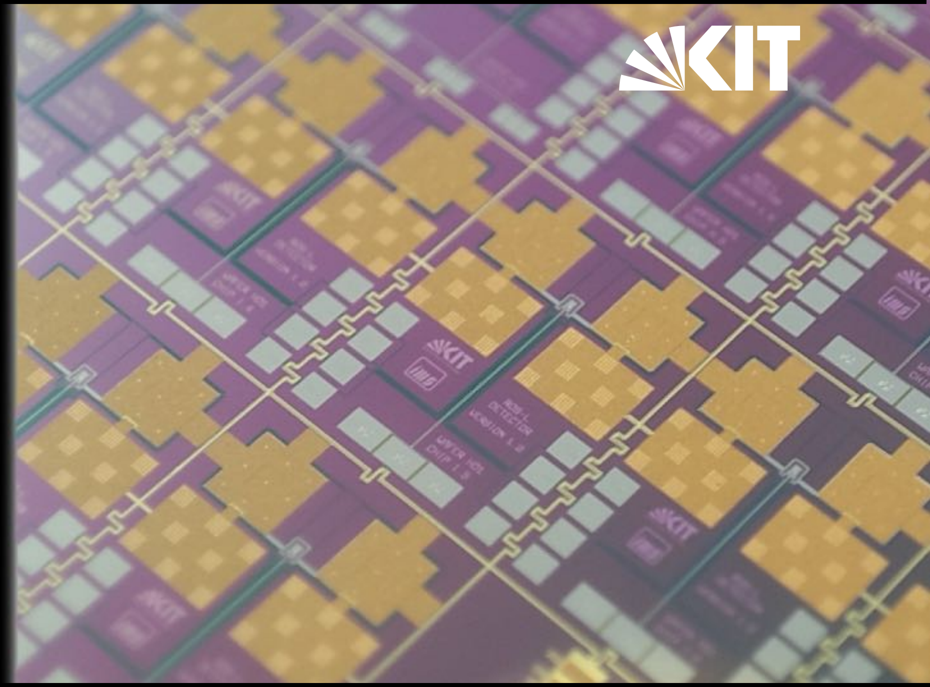


MMC operation in ambient fields









Investigation of MMC-based quantum sensors for electron detection

Thank you for your attention

Sebastian Kempf on behalf of the KATRIN++ R&D group at KIT
Institute of Micro- and Nanoelectronic Systems (IMS), Karlsruhe Institute of Technology (KIT)
Kickoff-Meeting “QS4Physics“ | HI Mainz | Mainz | 2025-11-20