Kirchhoff-Institut for Physics

Calorimetric measurement of the ^{163}Ho electron capture spectrum

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for the ECHo collaboration

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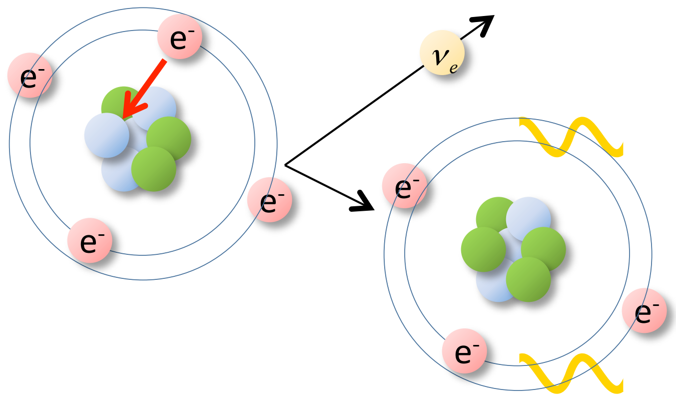
Contents

- Electron Capture and Direct Neutrino Mass Measurements
- Metallic Magnetic Calorimeter (MMCs)
- Experimental Results
- Conclusions

Electron Capture



A non- zero neutrino mass affects the de-excitation energy spectrum

Atomic de-excitation:

- X-ray emission
- Auger electrons
- Coster-Kronig transitions

} Calorimetric measurement

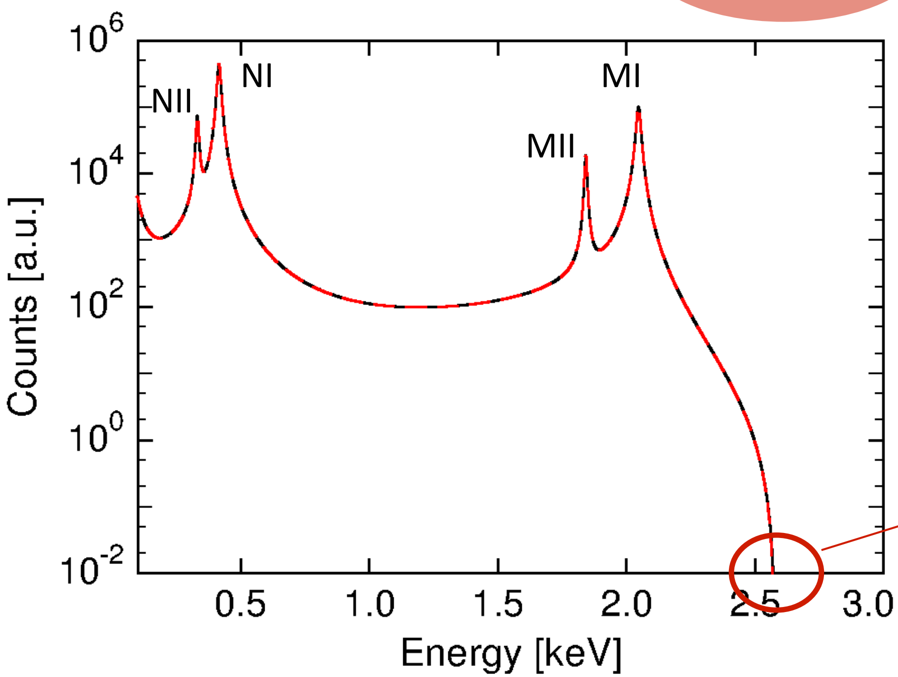
$$\frac{dW}{dE_C} = A\left(Q_{EC} - E_C\right)^2 \sqrt{1 - \frac{m_\nu^{\ 2}}{\left(Q_{EC} - E_C\right)^2}} \sum_H B_H \varphi_H^{\ 2}(0) \frac{\frac{\Gamma_H}{2\pi}}{\left(E_C - E_H\right)^2 + \frac{\Gamma_H^{\ 2}}{4}}$$

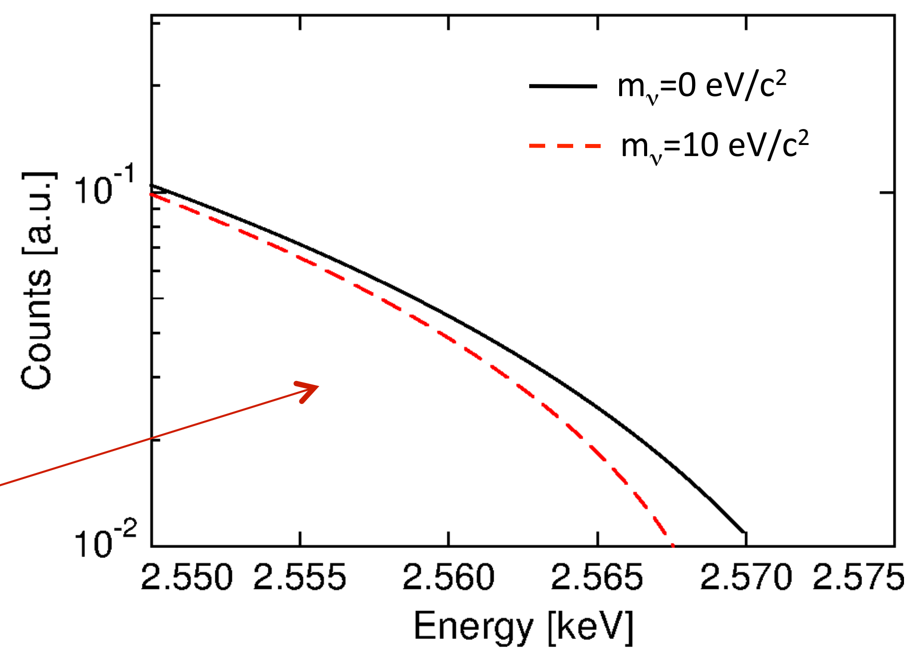
The Case of ^{163}Ho

$$ {}^{163}_{67}\mathrm{Ho} + e^- \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e $$

$$ {}^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{ph} + E_e $$

- $Q_{EC} \cong 2.5$ keV
- $\tau_{1/2} \cong 4570$ years

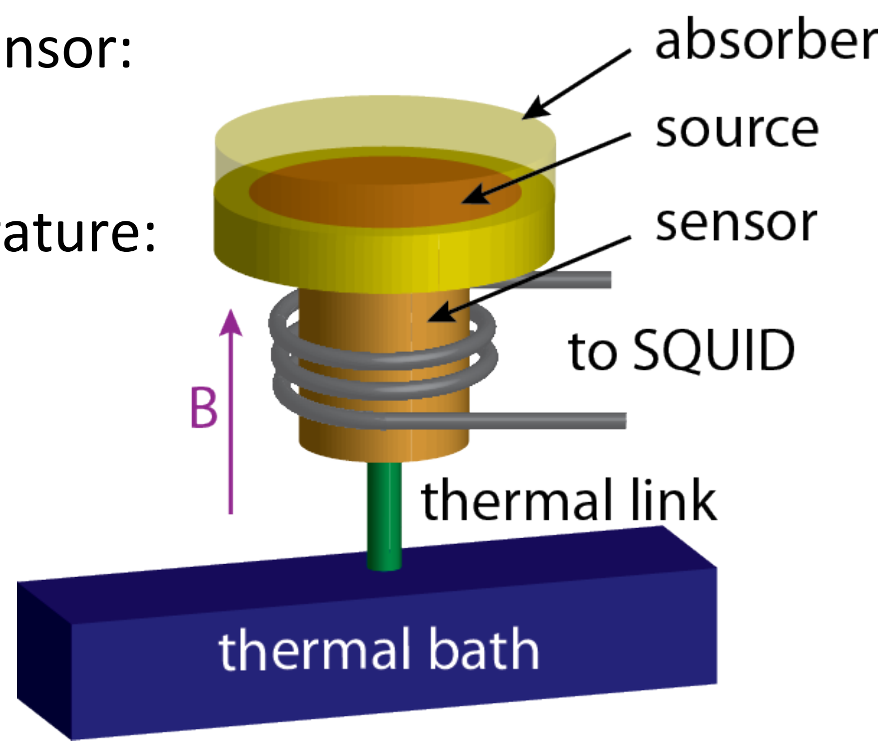


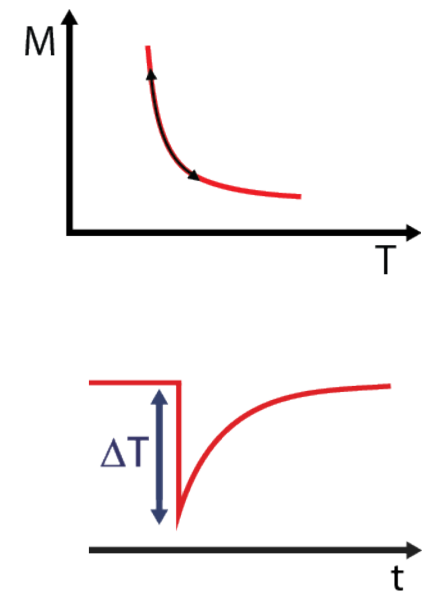


$$ \frac{dW}{dE_C} = A\left(Q_{EC} - E_C\right)^2 \sqrt{1 - \frac{m_\nu^2}{\left(Q_{EC} - E_C\right)^2}} \sum_H B_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{\left(E_C - E_H\right)^2 + \frac{\Gamma_H^2}{4}} $$

Metallic Magnetic Calorimeters: Concept

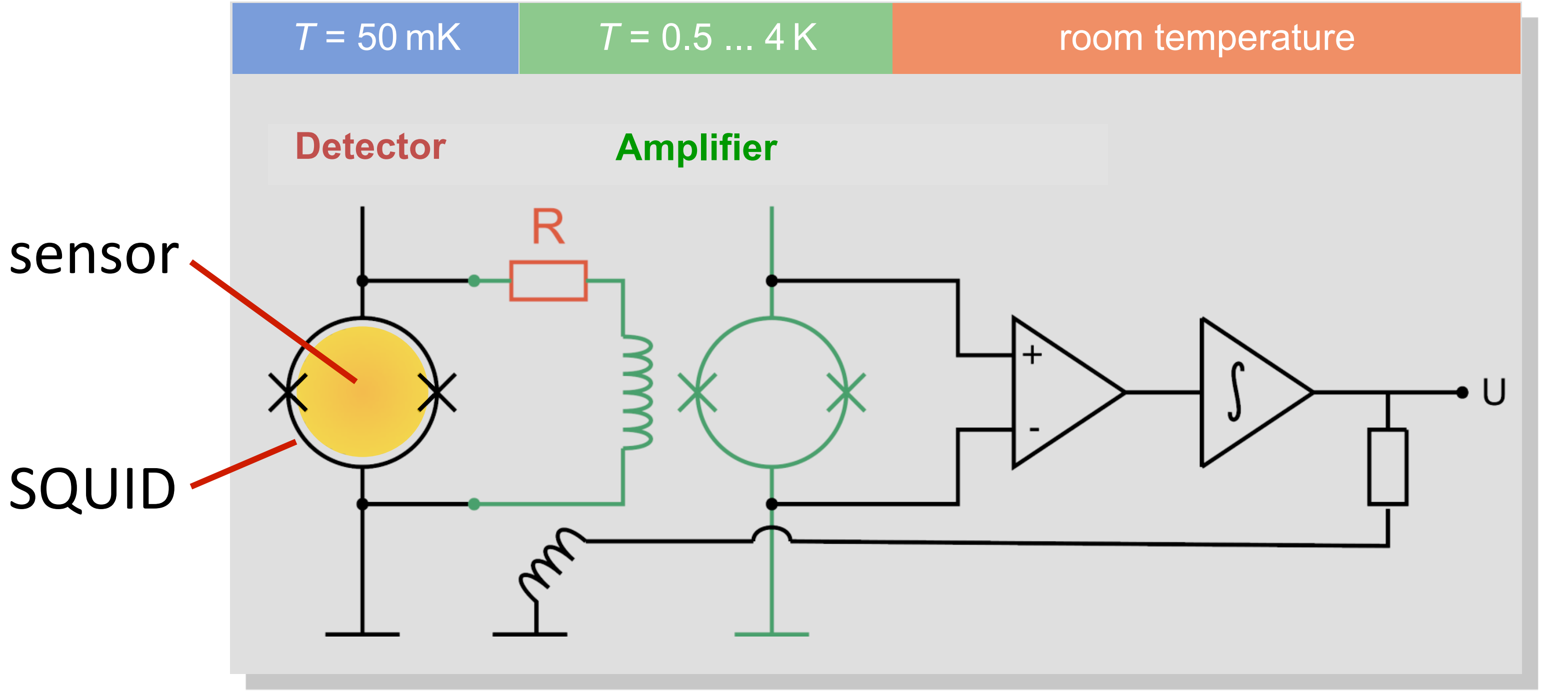
- Paramagnetic sensor:
  Au:Er
- Working temperature:
  ~30 mK





$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \quad \rightarrow \quad \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$

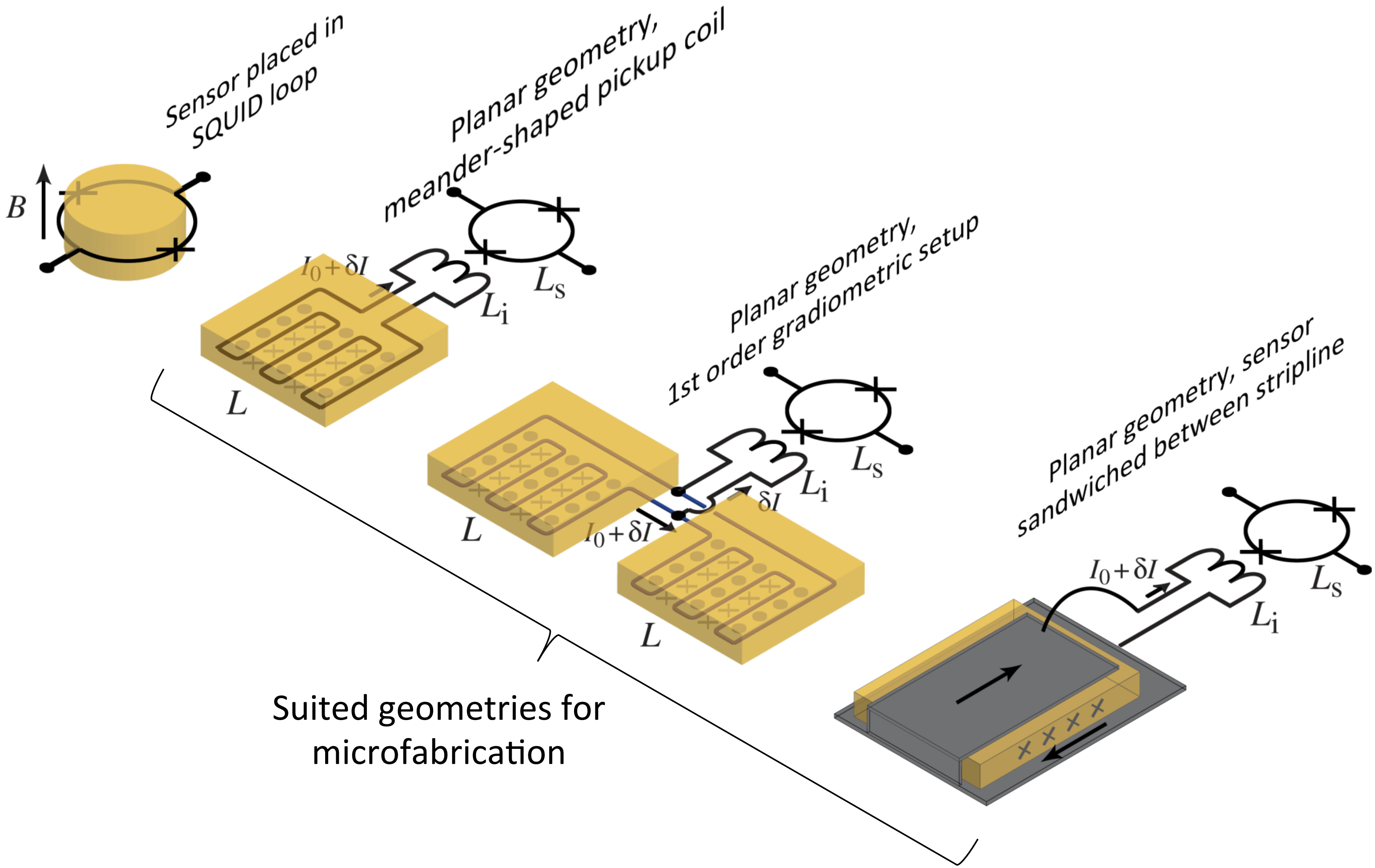
MMCs: Readout



Two-stage SQUID setup with flux locked loop to linearize the first stage SQUID:

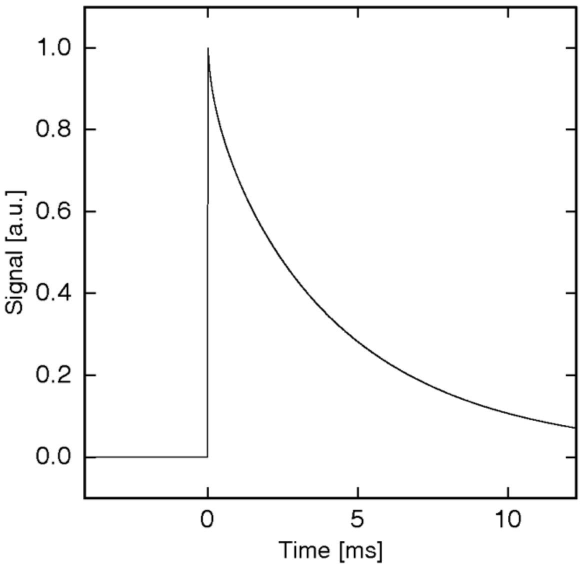
- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)

Metallic Magnetic Calorimeters: Geometry

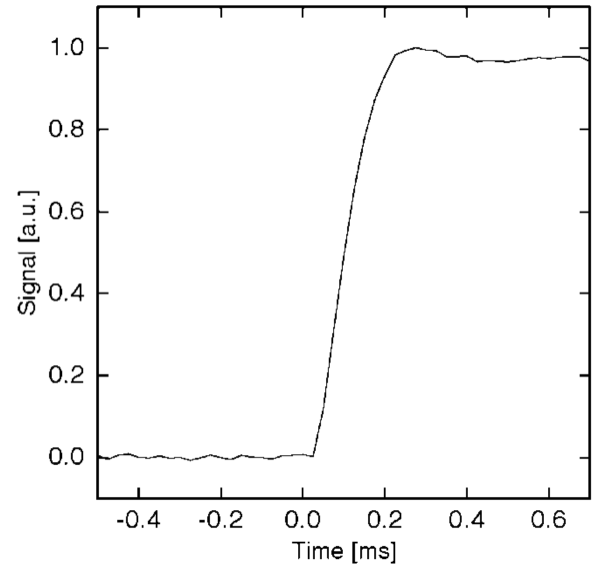


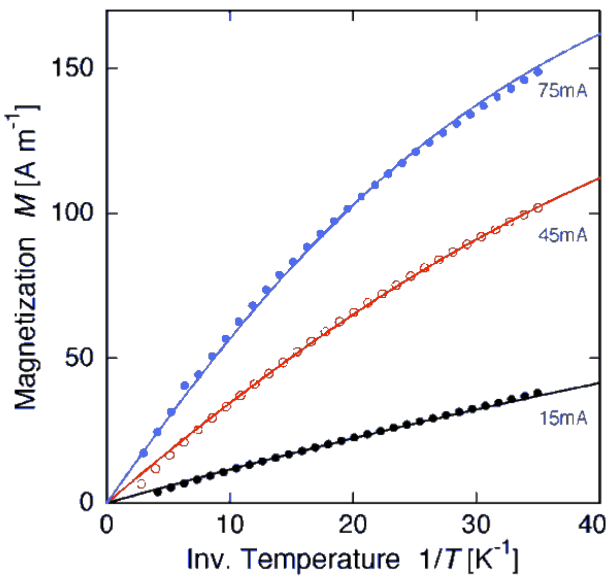
Suited geometries for microfabrication

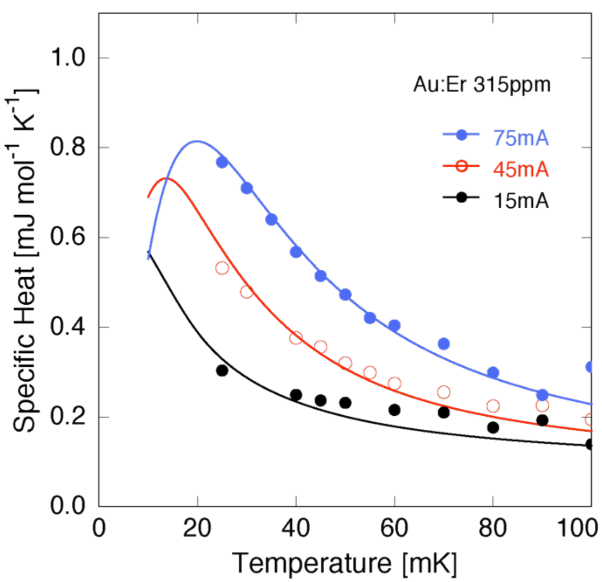
MMCs: Signal Properties



$$\delta\Phi(t) = \kappa \frac{\partial M}{\partial T} \frac{\delta E}{C_A + C_S} p(t)$$

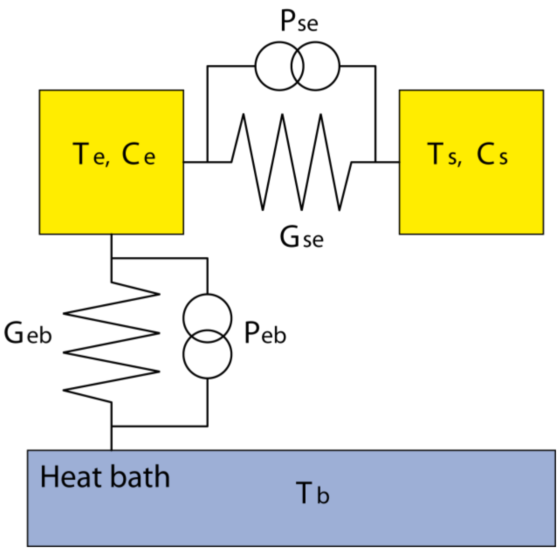


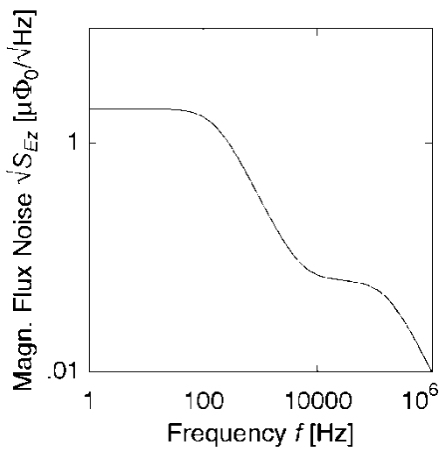




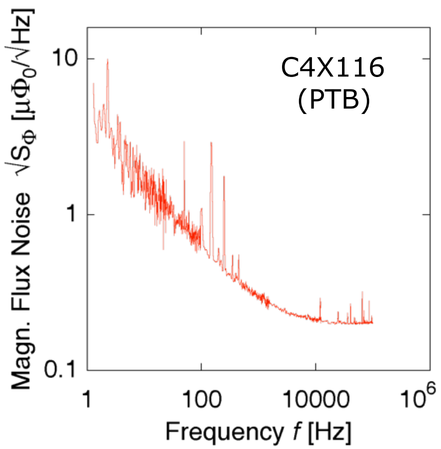
MMCs: Noise Contributions

- Thermodynamic fluctuations

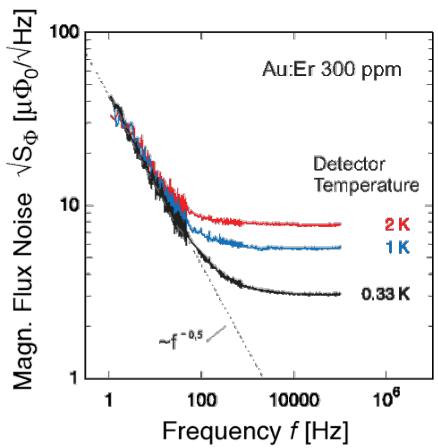




- SQUID & readout noise

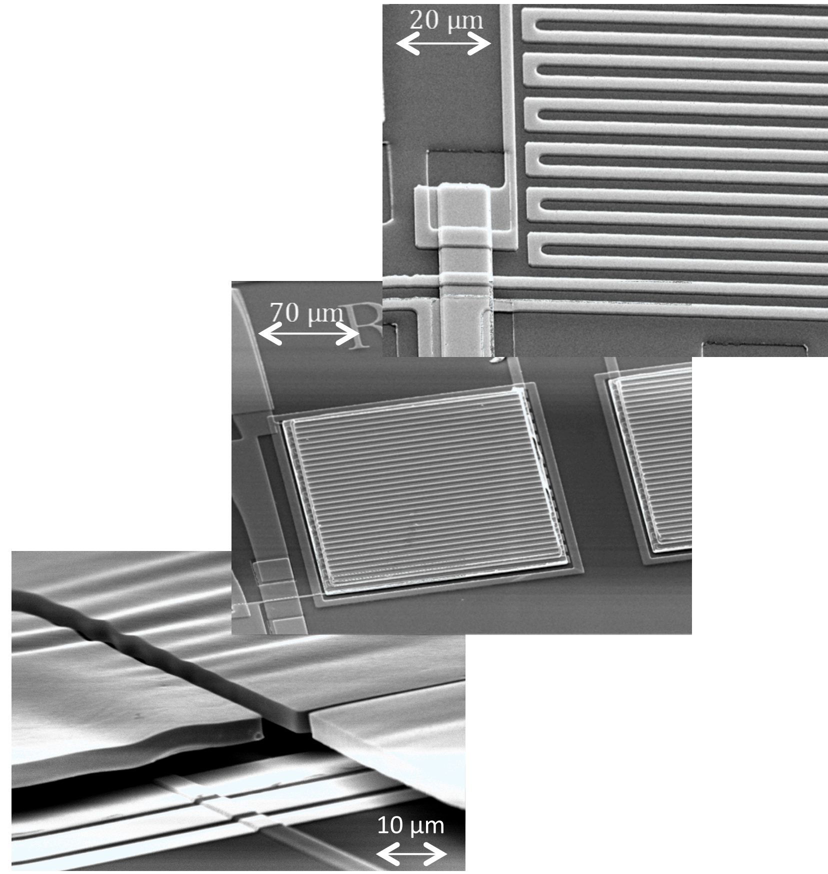


- 1/f noise due to Er ions



MMCs: Optimization

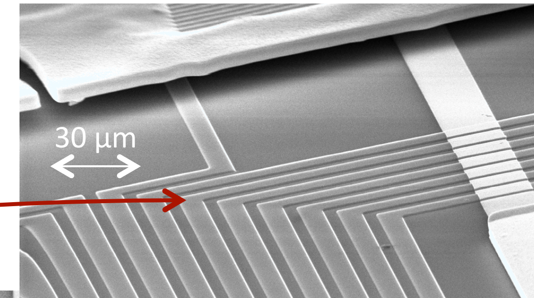
- Signal and noise can be predicted with good confidence
- $SNR^2(f) = \left|\tilde{p}(f)\right| / S_{\Phi,tot}(f)$
- $\Delta E_{FWHM} \propto \left(\int SNR^2(f)\,df\right)^{-1/2}$
- ΔE_{FWHM} depends on:
  - Absorber: C_a, τ_0
  - Sensor: h_S, A_S, x_{Er}, τ_1
  - Pick-up coil: A_C, p, w/p, I_0
  - SQUID: L_i, L_S, $S_{\Phi,SQ}$
  - Temperature: T

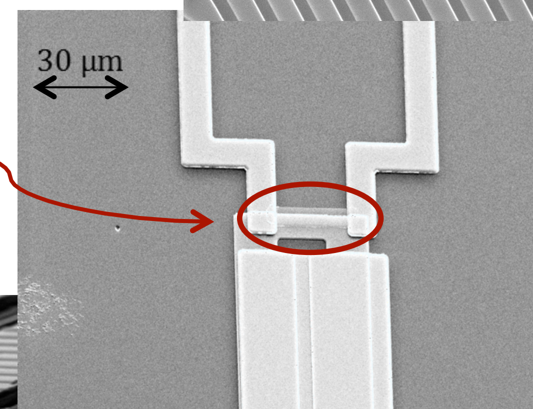


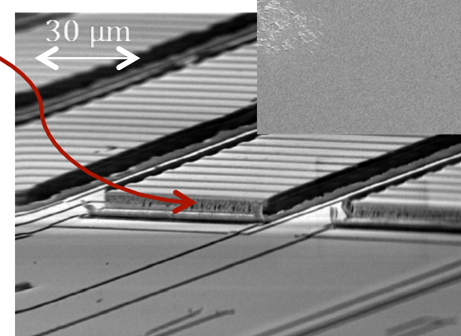
- Detectors can be optimized for best energy resolution

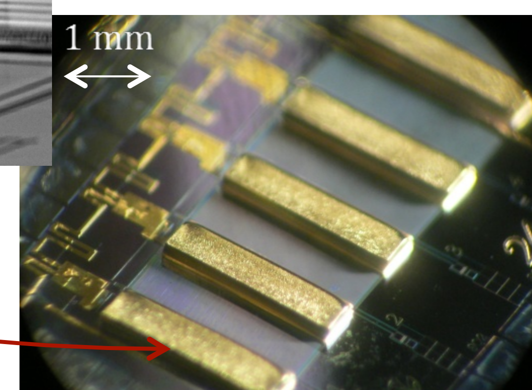
MMCs: Microfabrication

- 6 to 20 layer process
- Sputterdeposition of
  - Nb (pickup coils & wiring)
  - SiO_2 (insulation)
  - Au:Pd (persistent current switch heater)
  - Au:Er (sensors)
- Electrodeposition of Au (absorbers & thermal links)
  - overhanging
  - positioned on stems
  - up to 200 μm thick

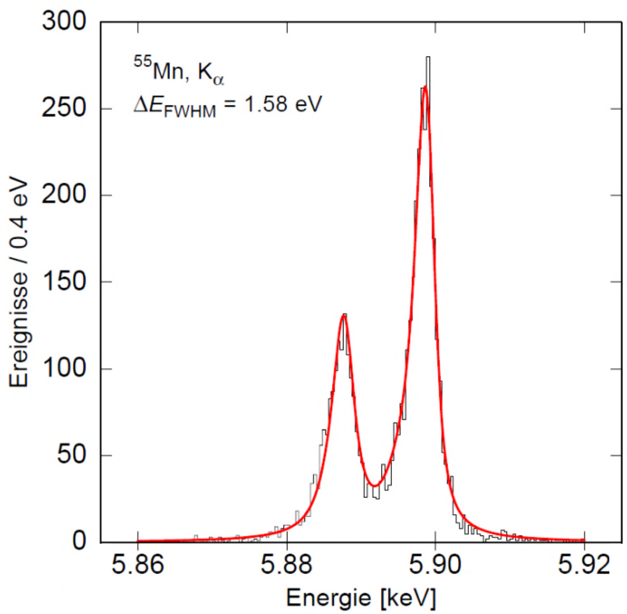


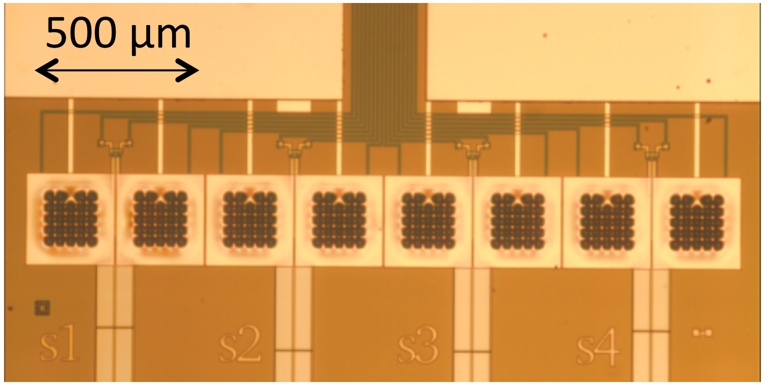






Metallic Magnetic Calorimeters: Performance



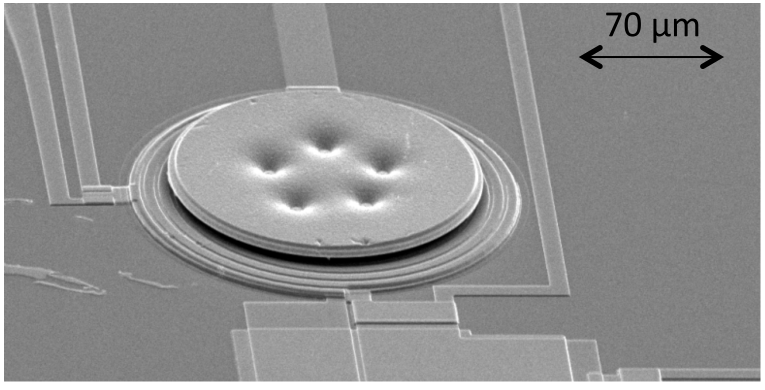


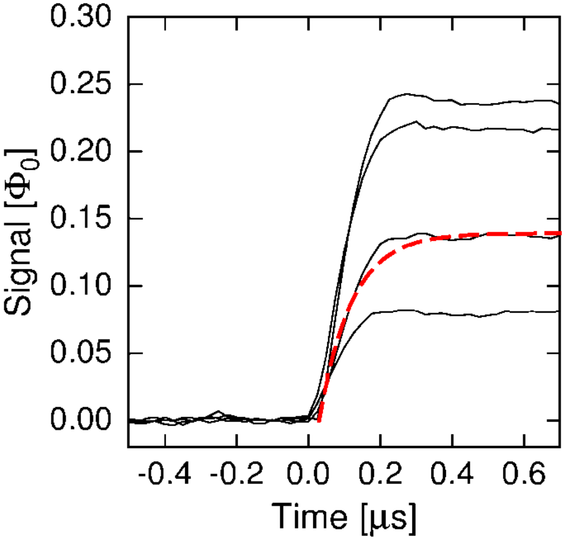
Very fast rise-time

τ_r = 90 ns

Very good energy resolution

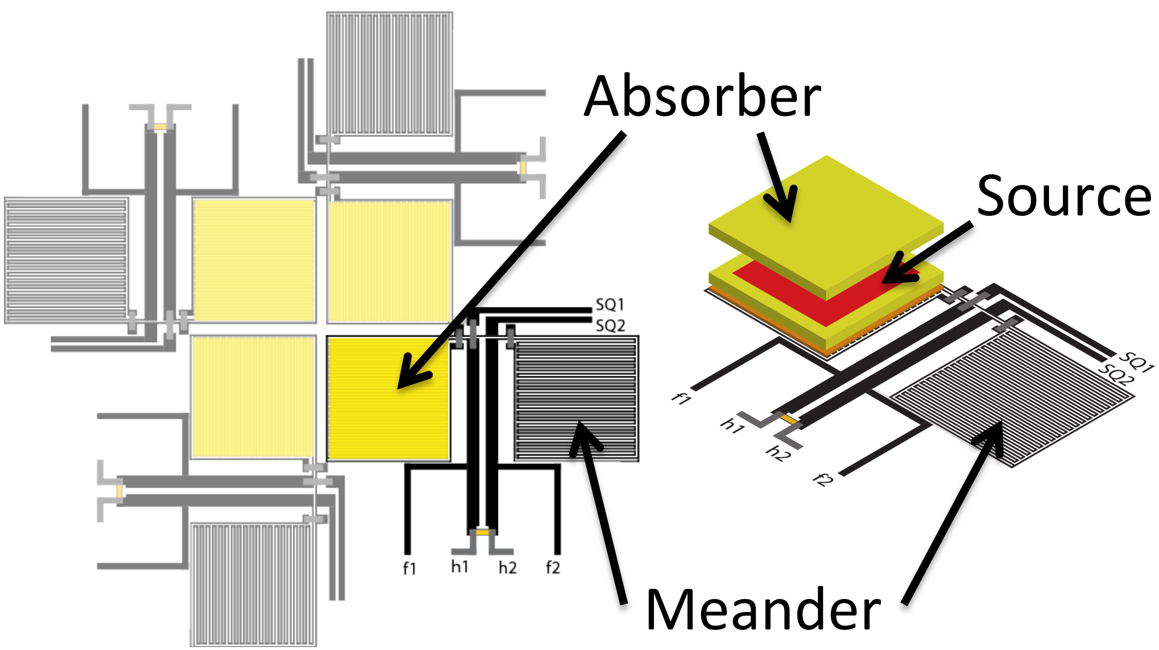
ΔE_{FWHM} = 1.6 eV @ 6 keV

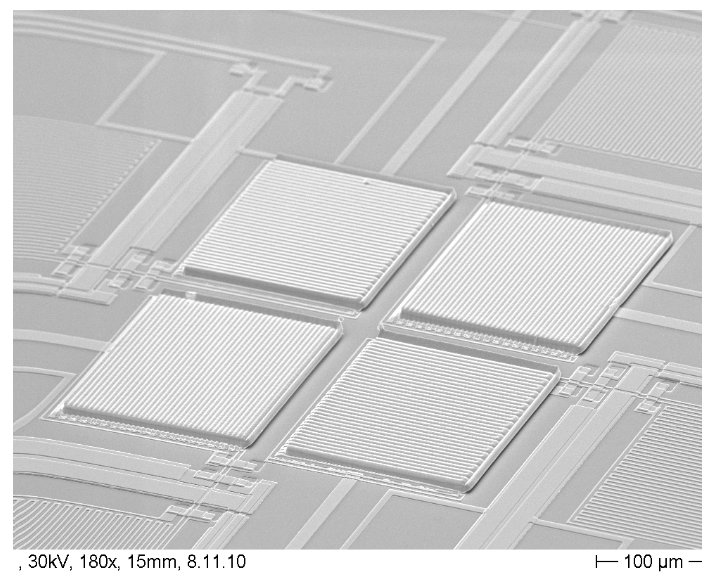




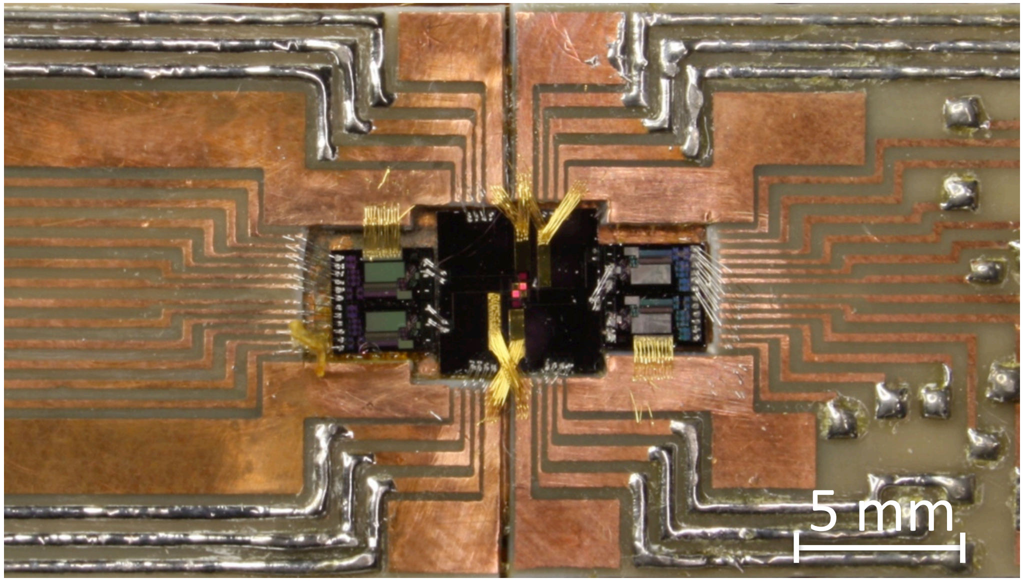
^{163}Ho Detector Prototype

- Planar meander shaped pick-up coil
- 4 detectors on 5 mm x 5 mm silicon substrate
- Centered 190 µm x 190 µm absorbers for ion implantation at ISOLDE/CERN
- 4π geometry with close to 100 % quantum efficiency





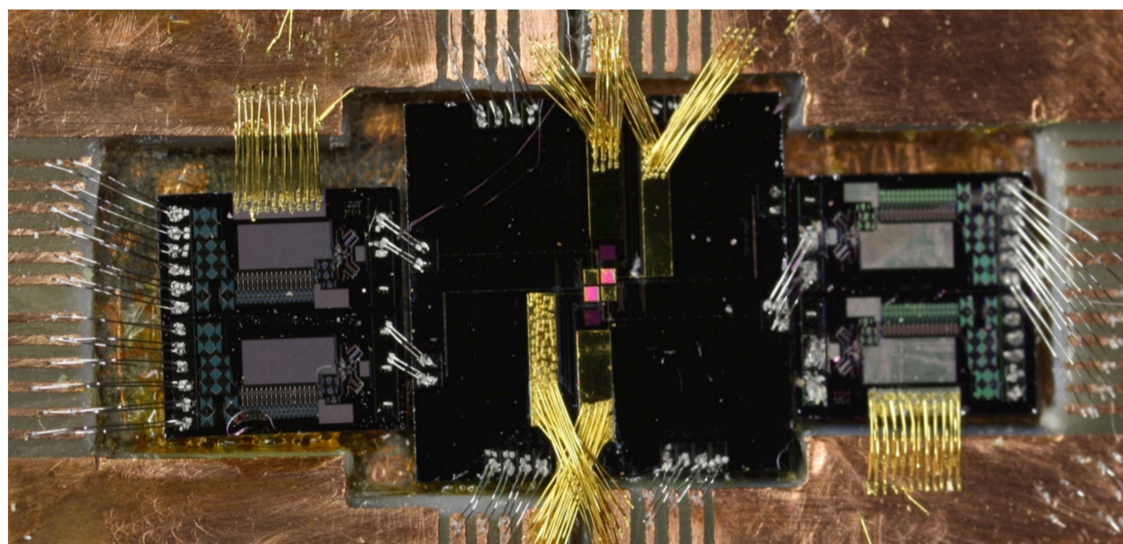
^{163}Ho Detector Prototype



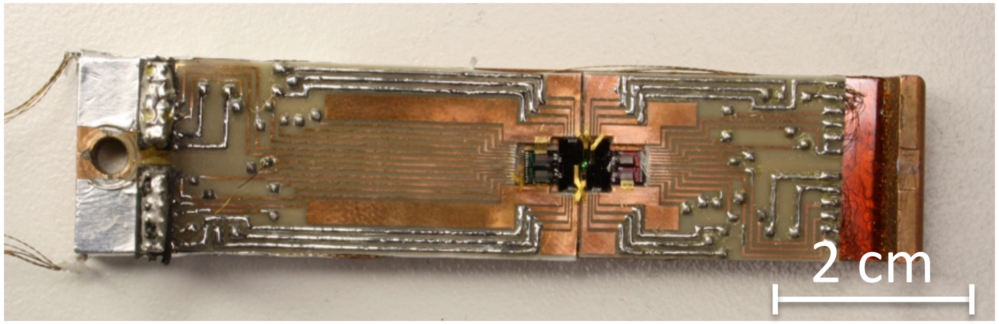
- 4 channel read-out (2 channels measured)
- Newest generation C6X114W SQUIDs
  ➔ best noise performance

- Oct. '12 to Dec. '12
- Jun. '13 to Sep. '13

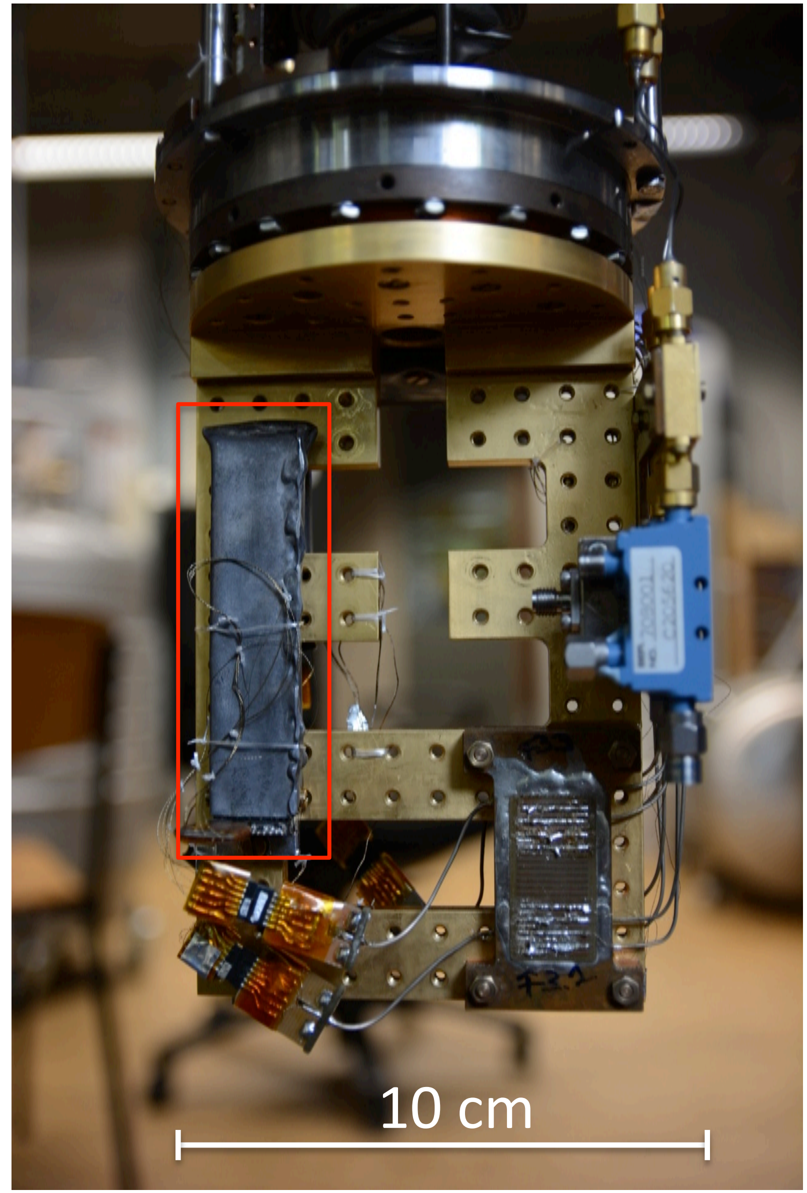
- Cu holder
- CuFlon circuit board
- Pb shielding



^{163}Ho Detector: Experimental Environment



- Cu holder
- CuFlon circuit board
- Pb shielding

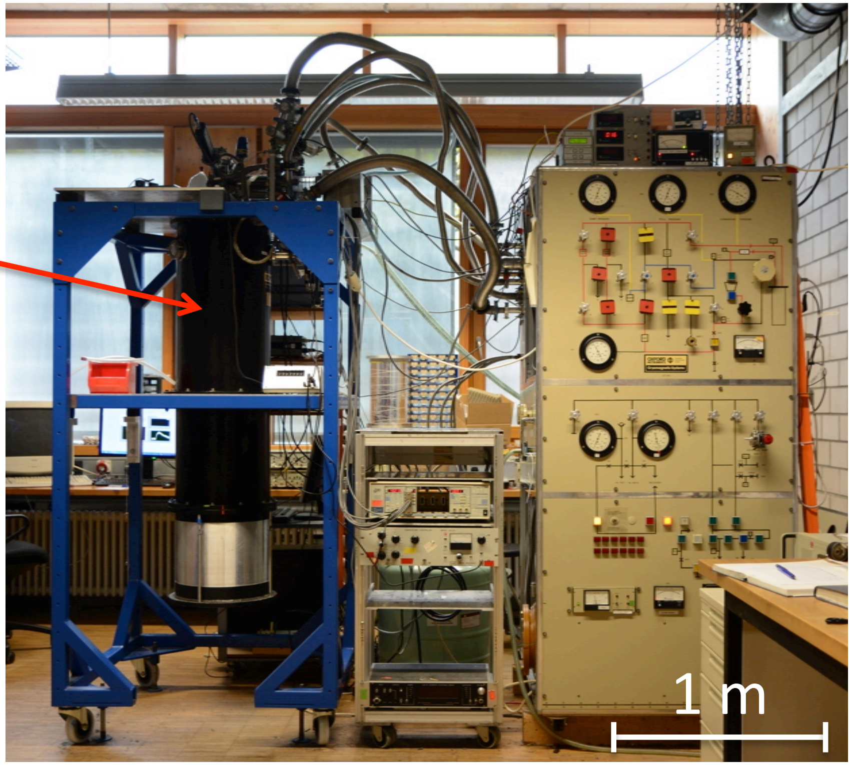


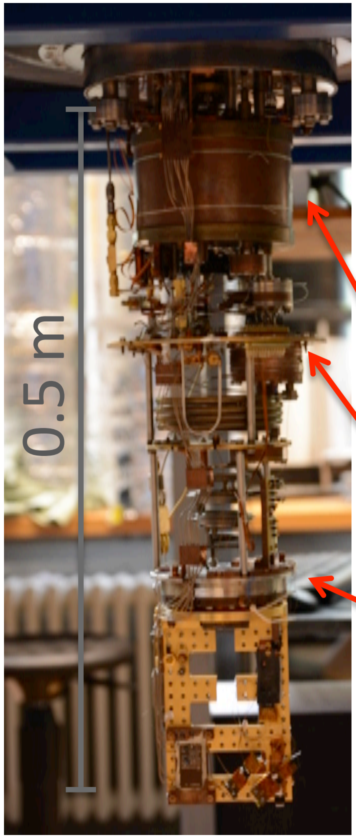
- ^{3}He/^{4}He dilution refrigerator (Oxford instruments)
- Cu experimental platform (Au plated)
- T ≈ 20 mK

^{163}Ho Detector: Experimental Environment

Layered precooling:

- Liquid N_2 ~ 77 K
- Liquid ^{4}He ~ 4.2 K
- Recycle time ~ 24 h





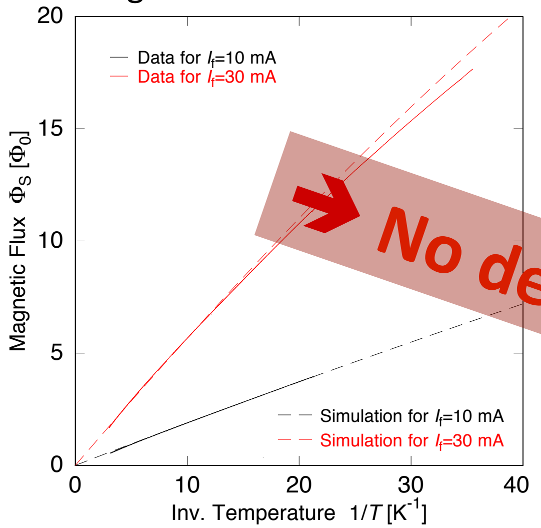
Dilution unit

- 1st stage ~ 1.5 K
- 2nd stage ~ 0.6 K
- Experimental platform ~ 20 mK

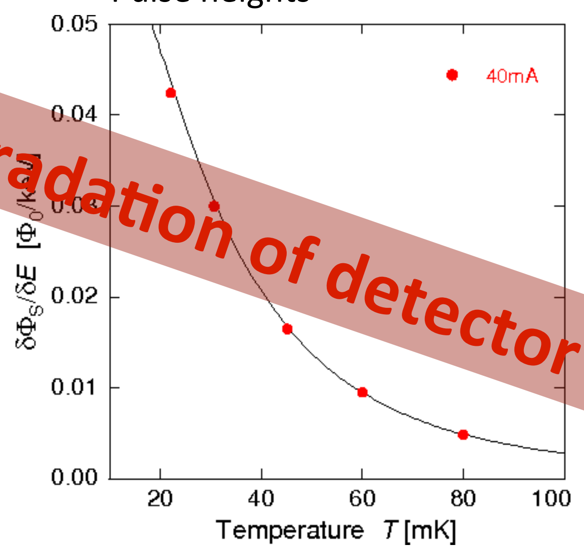
^{163}Ho experiment: Detector performance

- Magnetization (➔ temperature calibration) agrees with simulation
- Pulse heights (➔ heat capacity) as expected
- Decay time: 5.5 ms@30mK ➔ consistent with designed thermal link

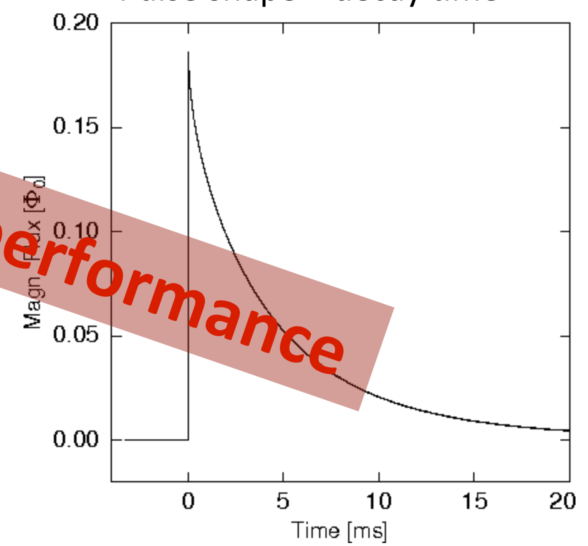
Magnetization



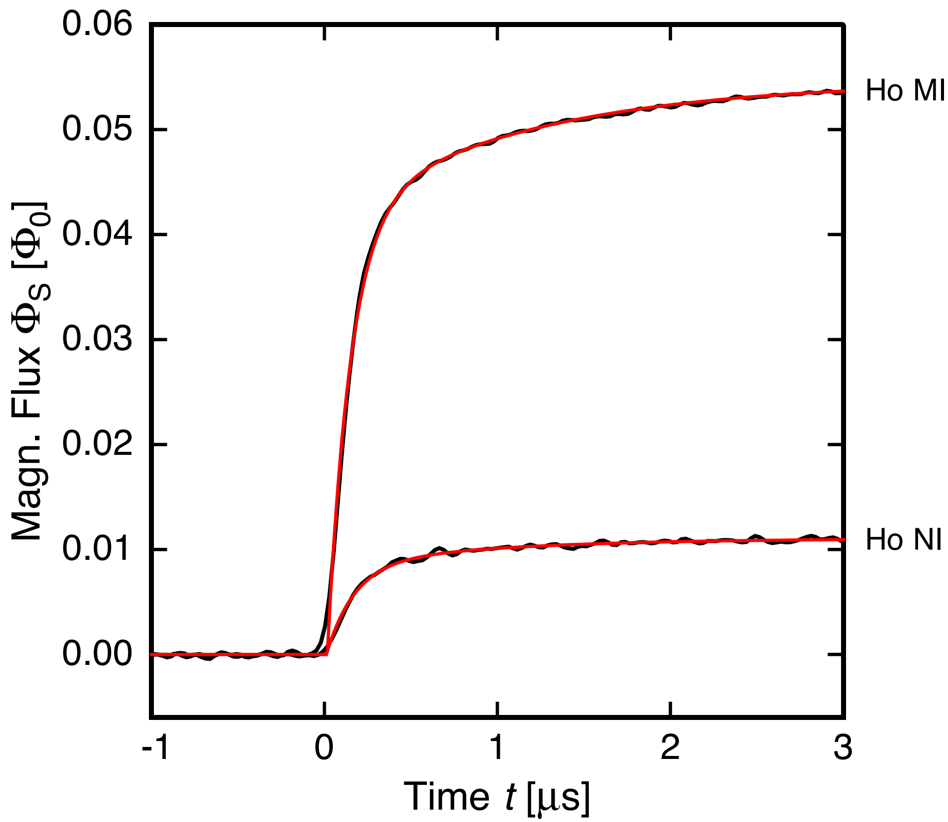
Pulse heights

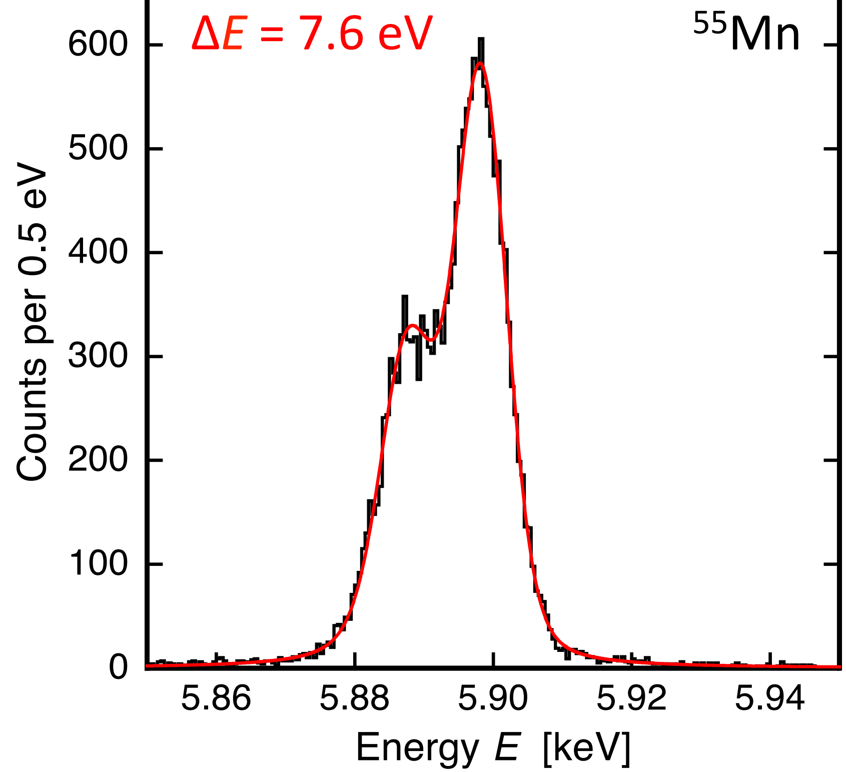


Pulse shape – decay time



^{163}Ho experiment: Detector performance

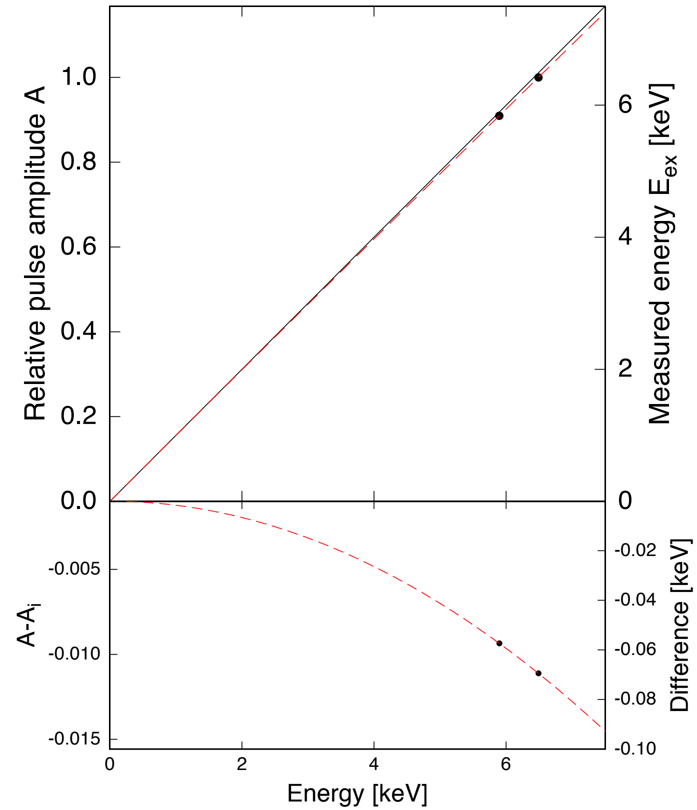




- Rise time: ~130 ns ➔ limited by e⁻-spin interaction
- 1 pixel irradiated with ^{55}Fe calibration source
  ➔ Precise energy calibration

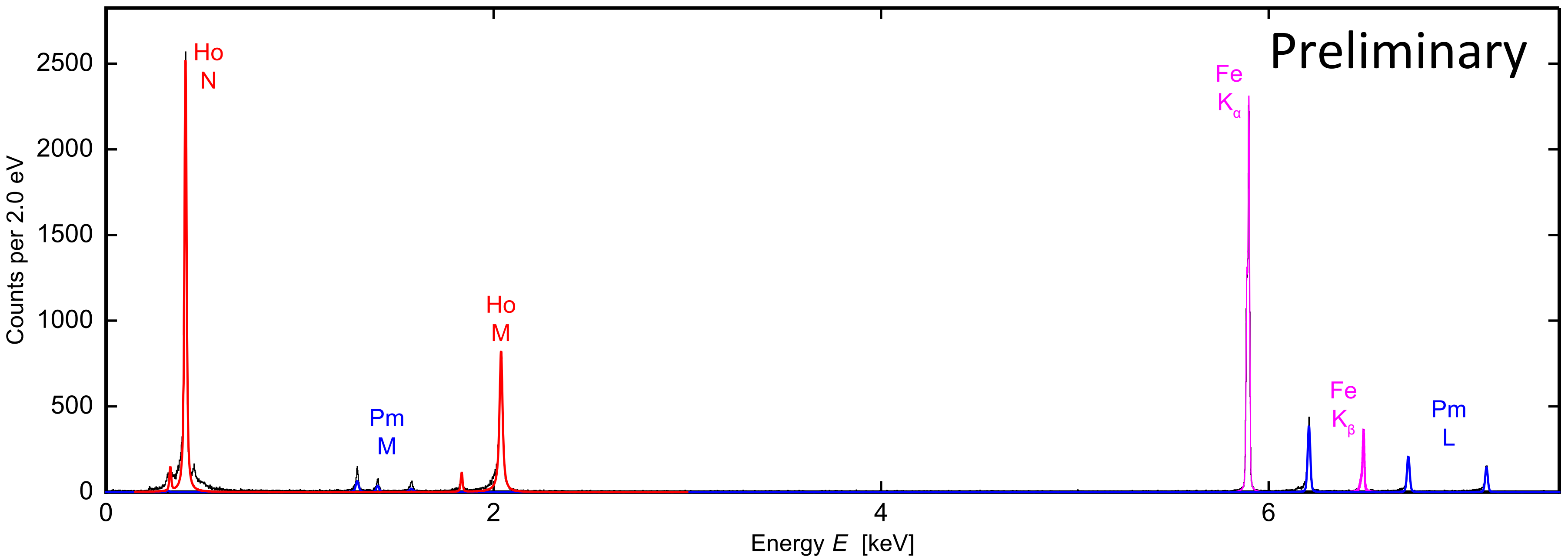
➢ Further detector optimization (goal: ~2 eV)

^{163}Ho experiment: Total Spectrum



- External calibration with ^{55}Fe source on one pixel
  - Non-Linearity < 1 % @ 6 keV

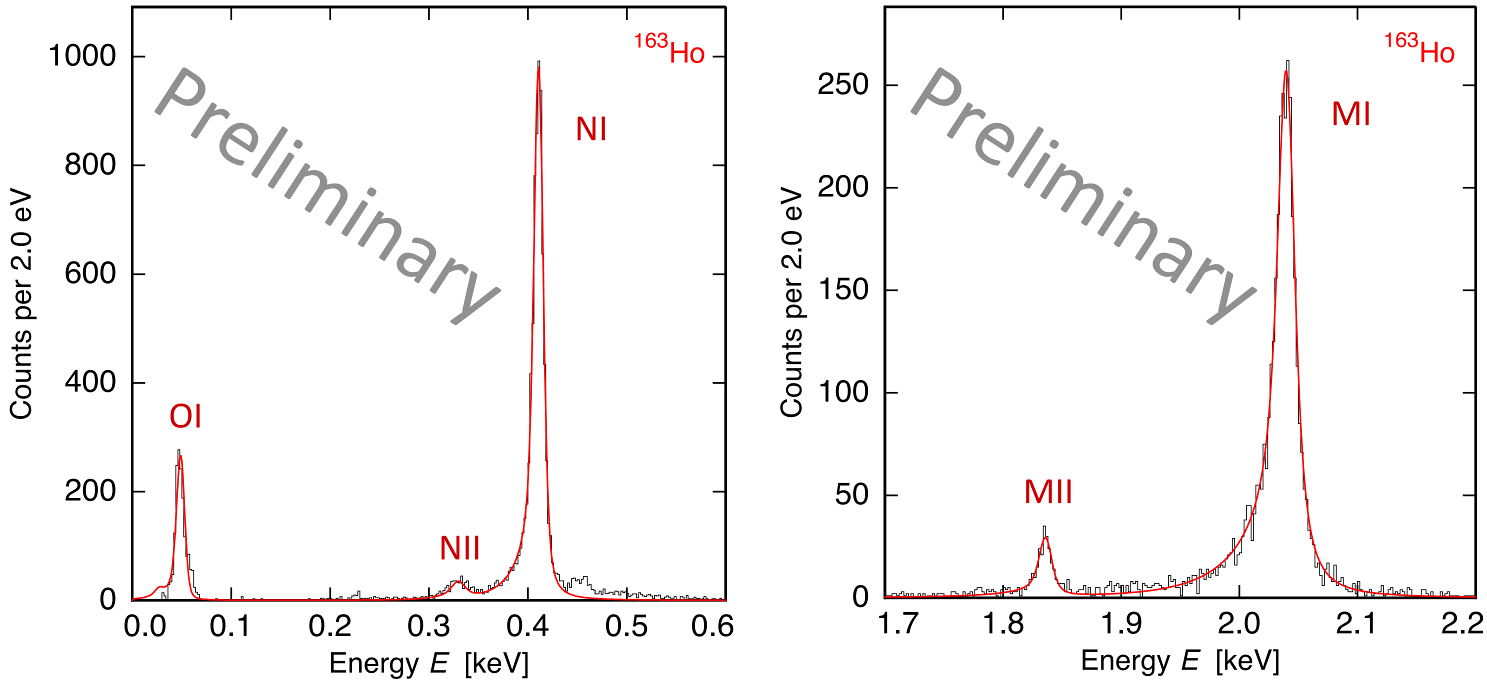
^{163}Ho experiment: Total Spectrum



- External calibration with ^{55}Fe source on one pixel
  - Non-Linearity < 1 % @ 6 keV
- "High statistics" spectrum (~40000 ^{163}Ho events)
- Beam contamination: ^{144}Pm decays

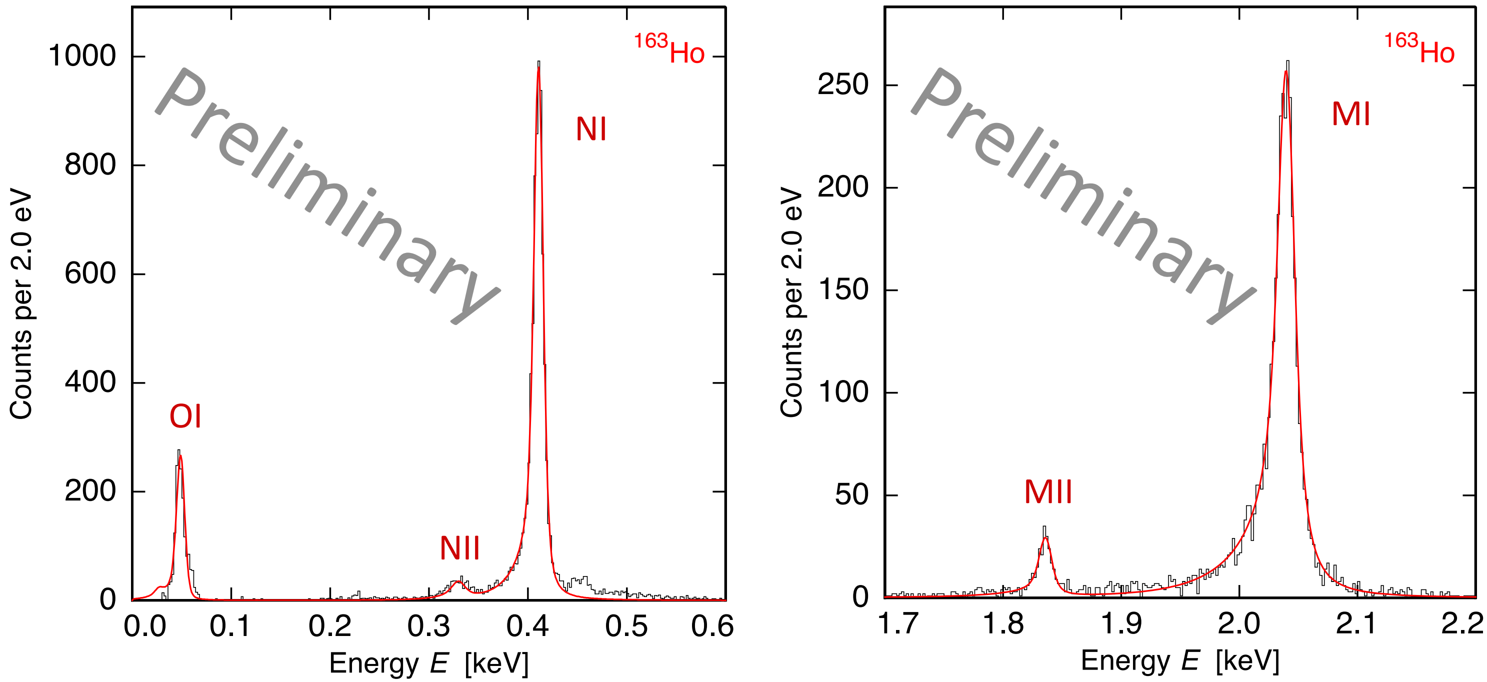
  ➔ Need of high purity ^{163}Ho source

^{163}Ho experiment: Spectrum analysis



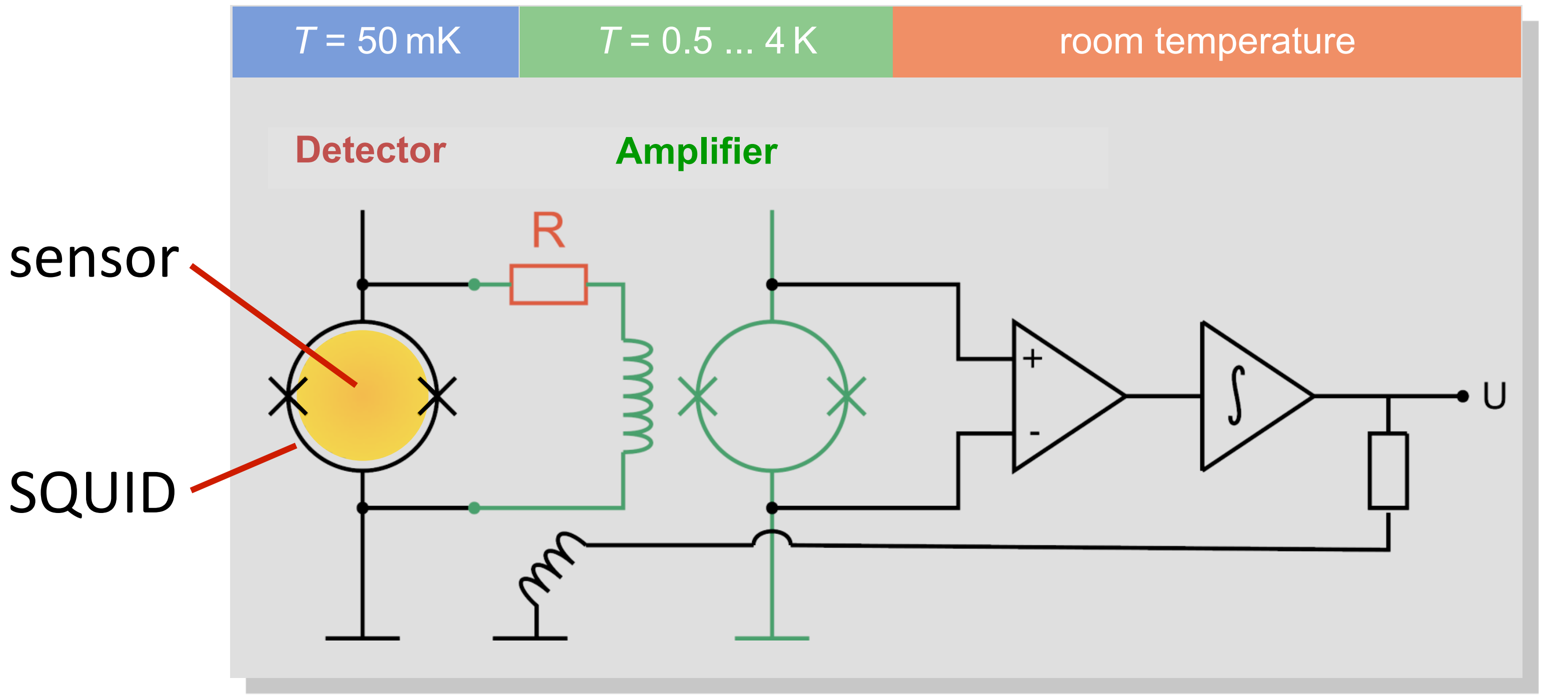
- No external sources
- 2nd “High statistics“ spectrum (~20000 ^{163}Ho events)
- Improved triggers and cuts
  → First observation of OI line (at ~ 50 eV)
- Modeling athermal phonon loss (low energetic tails) with exponentially modified Gaussian

^{163}Ho experiment: Spectrum analysis



^{163}Ho-Line	$E_{lit,Dy}$ [keV]	E_{exp} [keV]	$\Gamma_{lit,Dy}$ [eV]	Γ_{exp} [eV]
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3

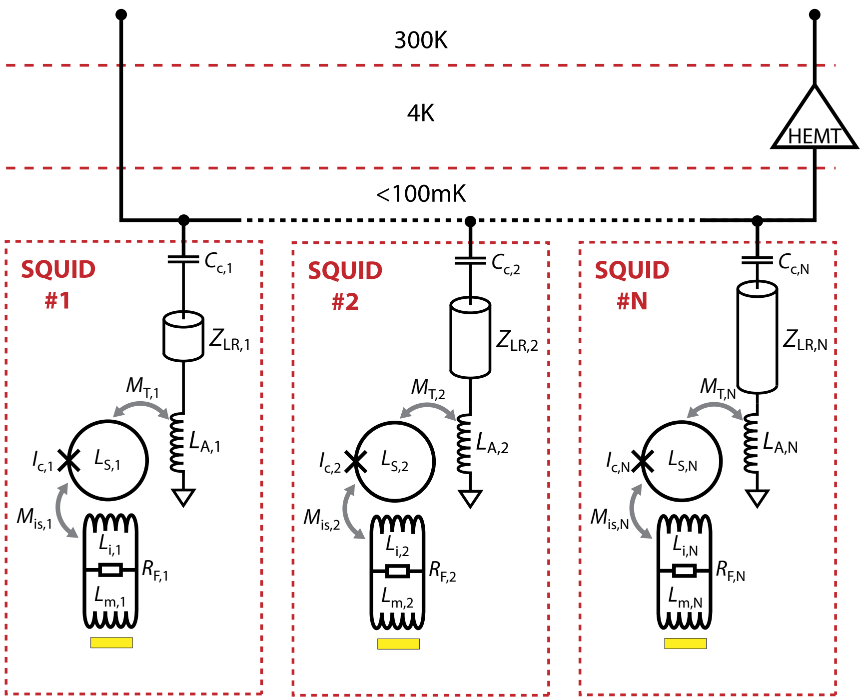
MMCs: Readout



Two-stage SQUID setup with flux locked loop to linearize the first stage SQUID:

- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)
- Not scalable to large detector numbers (max. ~ 100)

MMCs: Multiplexed Readout[1]



Detector coupled to rf-SQUID

⬇

Flux change in rf-SQUID

⬇

Frequency shift in resonator

⬇

Monitoring frequency shift in amplitude/phase as signal

Advantages:

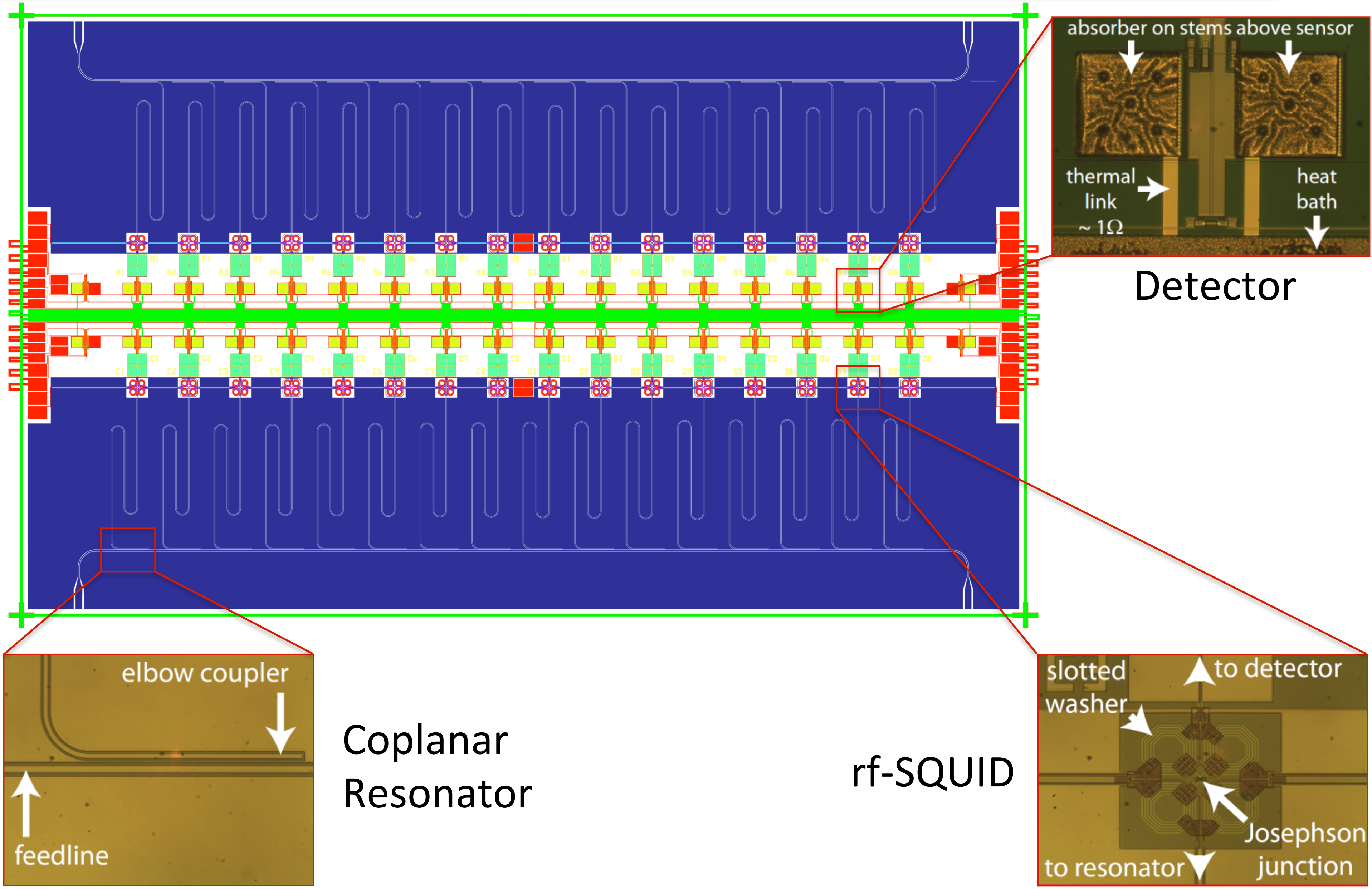
- Two Coaxes and one HEMT for readout of ~1000 detectors
- Dissipated power inside the cryostat very low
- Large bandwidth per detector

Challenges:

- Complex room temperature readout electronics

[1] J.A.B. Mates, G.C. Hilton, K.D. Irwin, L.R. Vale, and K.W. Lehnert, Appl. Phys. Lett. 92(2) (2008)

64 Pixels Array with integrated rf-SQUID Readout



Conclusions & Outlook

- Metallic magnetic calorimeters
  - Well understood
  - Versatile detectors suitable for ECHo
- First Detector with implanted ^{163}Ho shows promising results
  - Ongoing detector R&D
  - ^{163}Ho production
- From single pixel to arrays
  - Microwave multiplexing

Thank you!

ECHo