HOLMES

The HOLMES experiment: status and perspectives

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Outline

^{163}Ho neutrino mass measurement

HOLMES experiment goal and design

HOLMES tasks status

- isotope production and chemical purification
- isotope mass separation and embedding
- HOLMES detectors and read-out

Conclusions and perspectives

The HOLMES collaboration

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HO Electron capture experiments

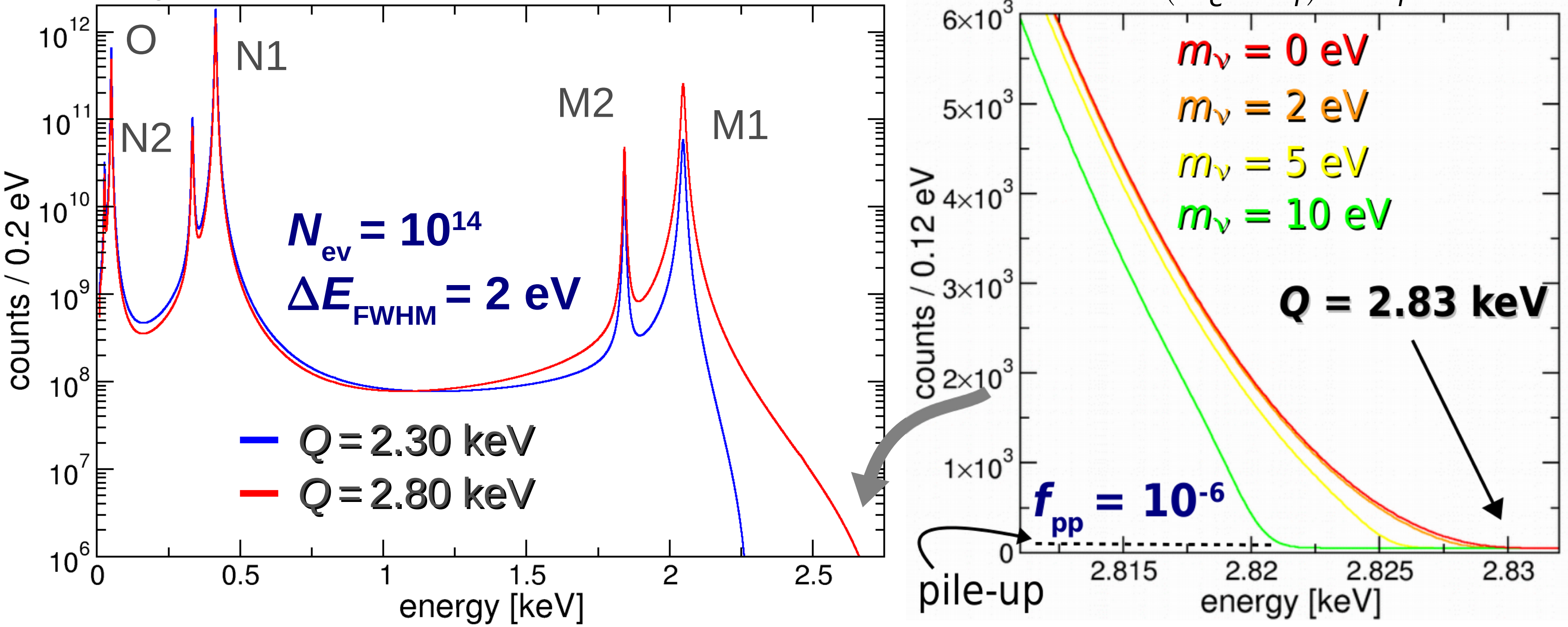
^{163}**Ho + e$^-$ → ^{163}Dy* + ν_e**

electron capture from shell ⩾ M1

A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429

- calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)
- rate at end-point and ν mass sensitivity depend on Q-E_{M1}
  - **Q = 2.83±0.04 keV** (determined with Penning trap in 2015)
- $\tau_{1/2} \approx$ 4570 years → few active nuclei are needed

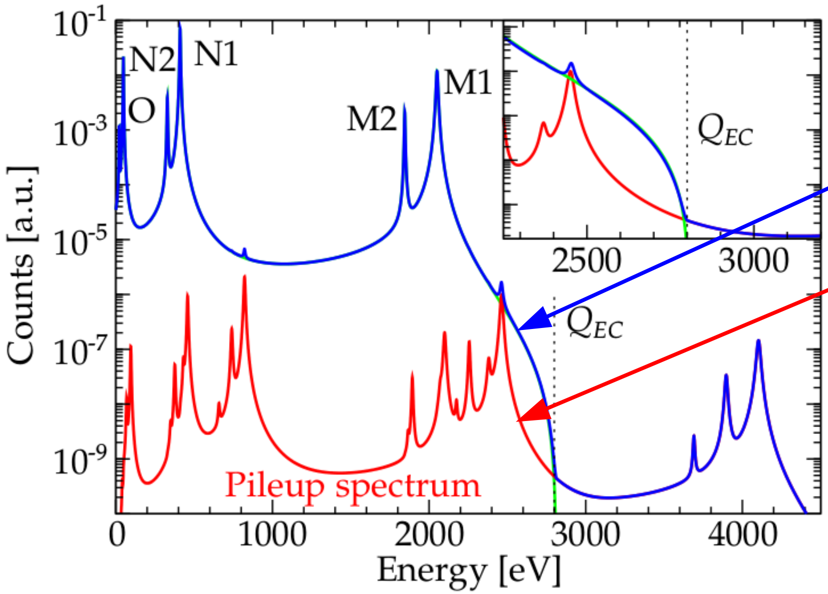
$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$



Ho Pile-up spectrum

calorimetric measurement ↔ **detector speed is critical**

accidental coincidences → **pile-up spectrum**



Q_{EC} = 2800 eV, ΔE = 2 eV, $N_{ev} = 10^{14}$, $f_{pp} = 10^{-4}$

$$S(E_c) = [N_{ev}(N_{EC}(E_c, m_\nu) + f_{pp} \times N_{EC}(E_c, 0) \otimes N_{EC}(E_c, 0)) + B(E_c)] \otimes R_{\Delta E}(E_c)$$

N_{ev} : total number of events

$N_{EC}(E_c, m_\nu)$: ^{163}Ho spectrum

$B(E)$: background energy spectrum

$R_{\Delta E}(E_c)$: detector energy response function

f_{pp} : fraction of pile-up events

$R_{\Delta E}(E_c)$: detector energy response function

ΔE intervall of energy

- Pile-up pulse occurs when multiple events arrive within the temporal resolving time of the detector;

- The 163Ho pile-up events spectrum is quite complex and presents a number of peaks right at the end-point of the decay spectrum;

- To resolve pile-up:
  - Detector with fast signal rise-time τ_{rise} ;
  - Pulse pile-up recovery algorithms → time resolution of ~ 1 μs with pulses with τ_{rise} ~ 10 μs

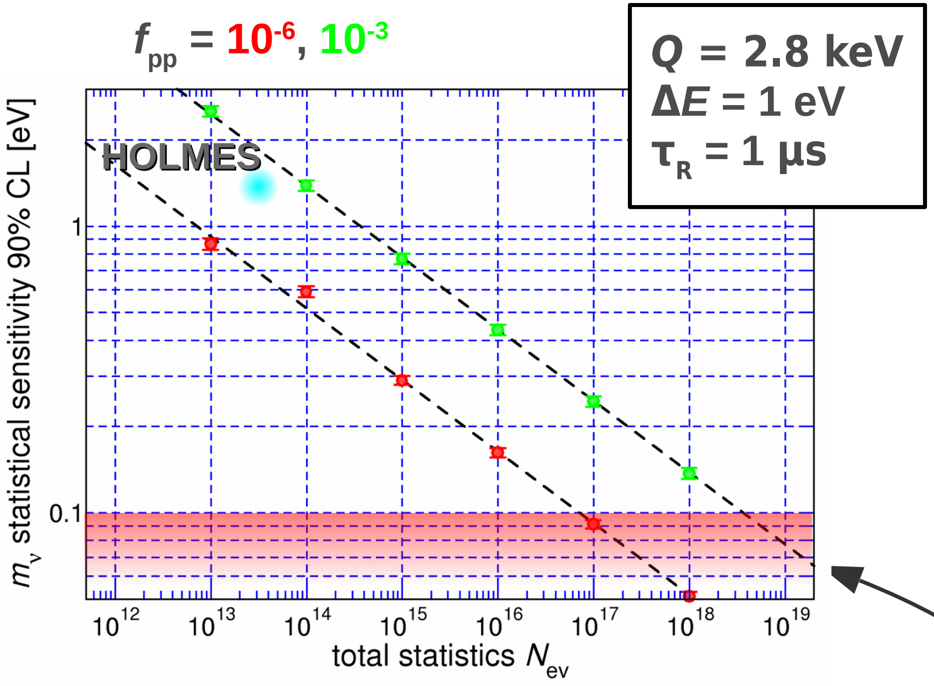
^{163}Ho statistical sensitivity - Montecarlo simulations

m_ν **sensitivity** mostly depends on

↑ total statistics

↓pile-up fraction

f_{pp} = 10^{-6}, 10^{-3}



Q = 2.8 keV
ΔE = 1 eV
τ_R = 1 μs

Requirements:

- ▸ high energy resolution ≈1eV
- ▸ fast response ≈1μs
- ▸ large multiplexable array ≈1000

$$\propto \sqrt[4]{1/N_{ev}}$$

M. Galeazzi et al., arXiv:1202.4763v2
A. Nucciotti, Eur. Phys. J. C, (2014) 74:3161

HOLMES (ERC-Advanced Grant n. 340321)

Goals

- neutrino mass measurement: m_ν statistical sensitivity around 1 eV
- prove technique potential and scalability:
  - assess EC Q-value
  - assess systematic errors

Detectors: Transition Edge Sensor
with ^{163}Ho implanted in Au absorbers

Activity: 6.5×10^{13} nuclei per detector
→ 300 dec/s

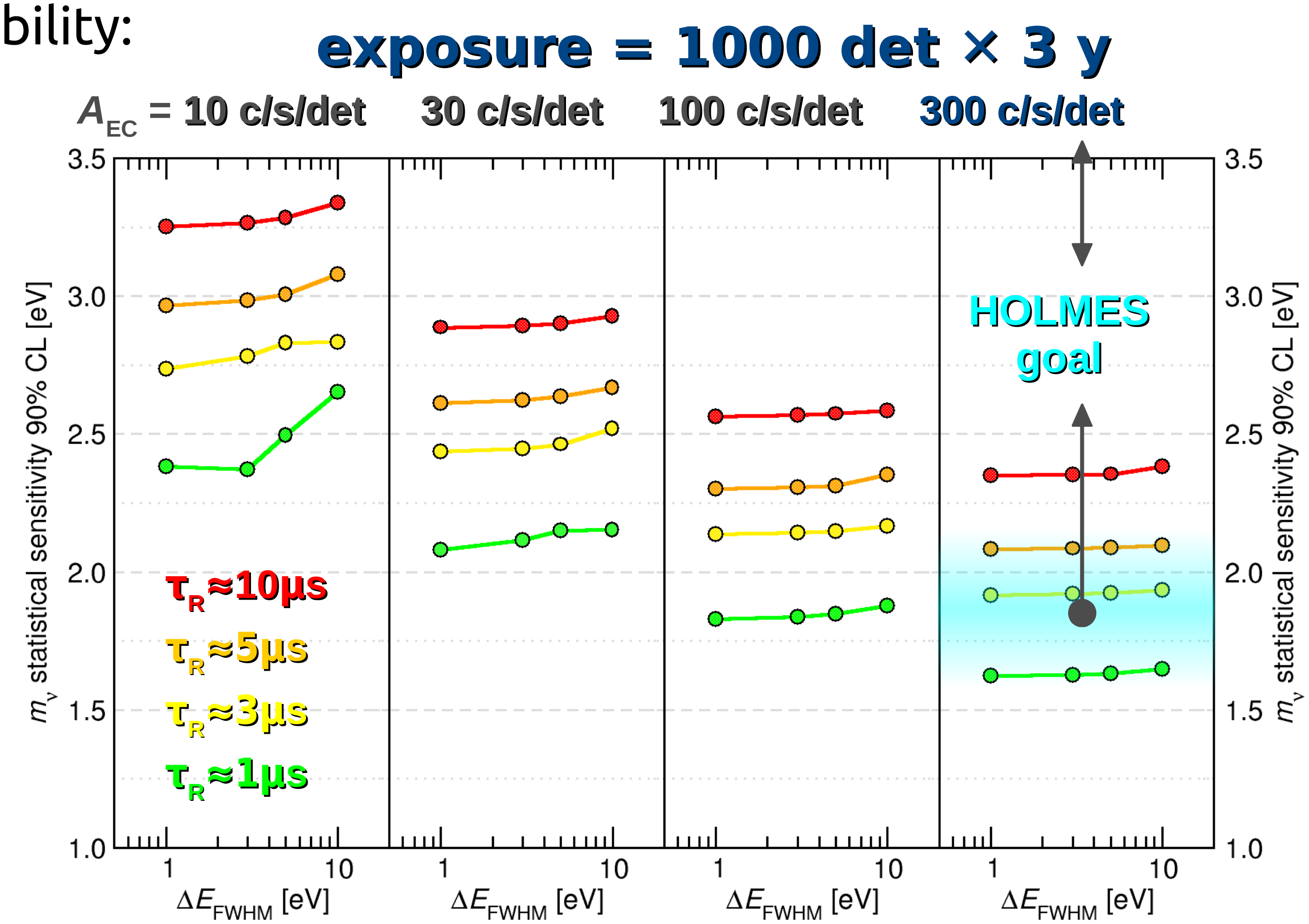
Performances: $\Delta E \approx 1$ eV, $\tau_R \approx 1$ μs

64 channel demonstrator

Final configuration: 1000 channel array

- 6.5×10^{16} ^{163}Ho nuclei
- 3×10^{13} events in 3 y

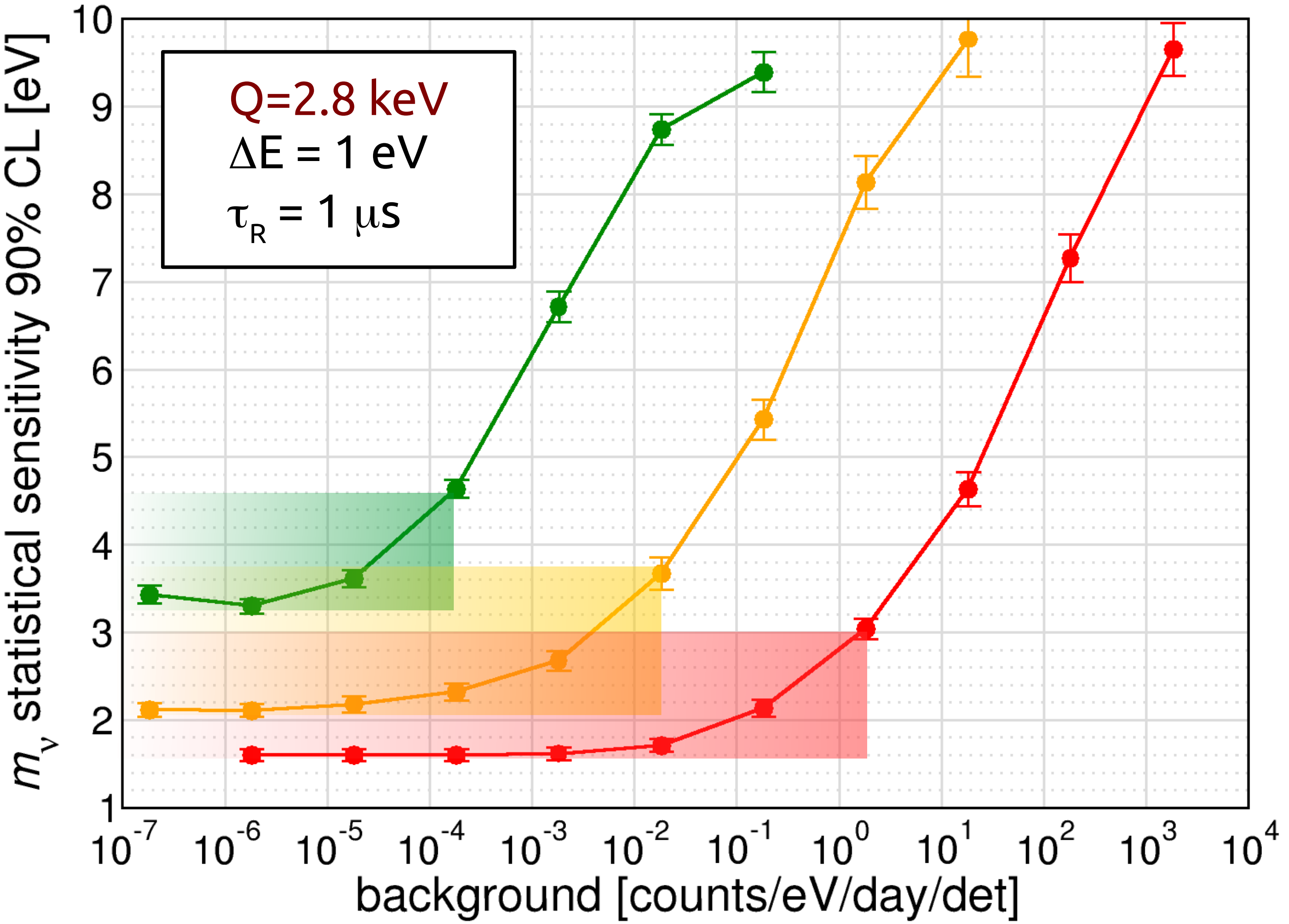
→ Project Started on February 1st 2014



B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

Effect of background on sensitivity

exposure $N_{det} t_M$ = 1000 det × 3 y



A_{EC}=3 Bq/det
f_{pp} = 3×10^{-6}

A_{EC}=30 Bq/det
f_{pp} = 3×10^{-5}

A_{EC}=300 Bq/det
f_{pp} = 3×10^{-4}

pile-up background ≈ average rate $\langle r_{pp} \rangle$

$\langle r_{pp} \rangle = A_{EC} f_{pp} / 2Q$ = **1.5×10^{-4}** **1.5×10^{-2}** **1.5** c/eV/day/det

Background

- environmental γ radiation
- γ, X and β from close surroundings

- cosmic rays

HOLMES target
for A_{EC} = 300 Bq
bkg < ≈0.1 c/eV/day/det

Au pixel 200×200×2 μm^3

▷ GEANT4 → **bkg ≈ 5×10^{-5} c/eV/day/det (0 - 4 keV)**

MIBETA experiment: 300×300×150 μm^3 $AgReO_4$ crystals at **sea level**

***bkg*(2-5keV)≈1.5×10^{-4} c/eV/day/det**

- internal radionuclides

→ ^{166m}Ho (β^-, Q = 1.8 MeV, $\tau_{1/2}$ = 1200 y, produced along with ^{163}Ho)

→ GEANT4 → bkg ≈ 0.5 c/eV/day/det/Bq(^{166m}Ho)

→ A(^{163}Ho) = 300Bq/det (↔ ≈6.5×10^{13} nuclei/det)

bkg(^{166m}Ho) < 0.1 c/eV/day/det → A(^{163}Ho)/A(^{166m}Ho) > 1500

→ N(^{163}Ho)/N(^{166m}Ho)>6000

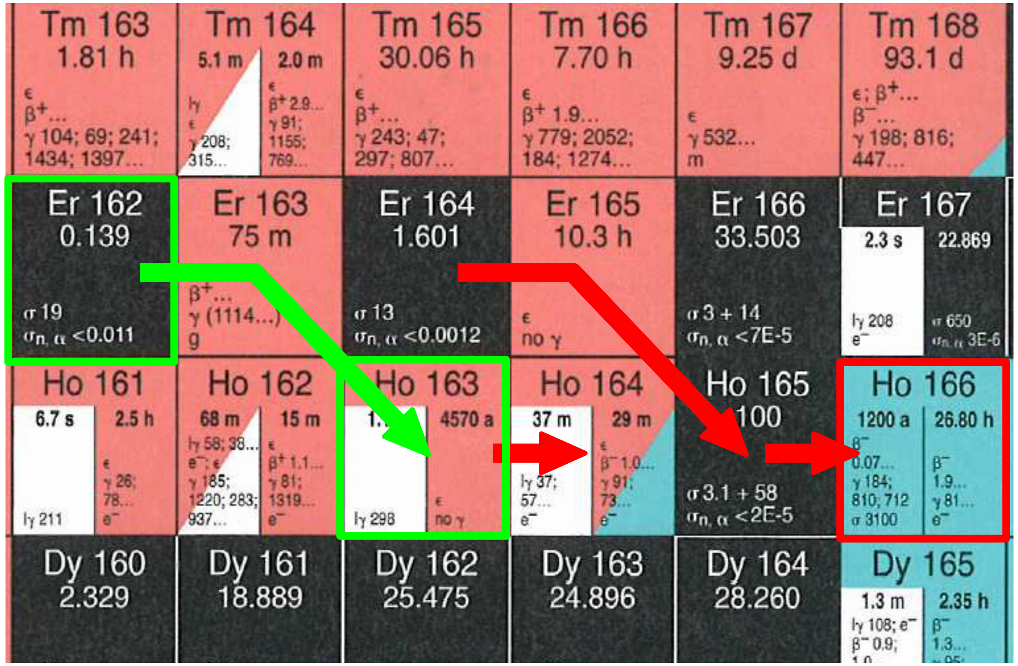
- a bkg measurement is under way with HOLMES detectors

^{163}Ho production

Production of ^{163}Ho:
neutron activation of enriched ^{162}Er

$$^{162}\mathrm{Er}\ (n,\gamma)\ ^{163}\mathrm{Er} \qquad \sigma_{\mathrm{thermal}} \approx 20\mathrm{b}$$

$$^{163}\mathrm{Er} \rightarrow {}^{163}\mathrm{Ho} + \nu_e \qquad \tau_{½}^{EC} \approx 75\mathrm{min}$$



- ^{162}Er irradiation at ILL nuclear reactor @ Grenoble: **high thermal n flux 1.3x10 15 n/cm ^{2} /s**
  - **cross section burn up** ^{163} Ho(n,γ) ^{164} Ho not negligible (~ 200 b)
  - ^{165} Ho(n,γ) (mostly from ^{164} Er(n,g)) → **^{166m} Ho, β^-, t $_{½}$ = 1200 y, Q = 1.8 MeV**

→ A(^{163} Ho)/A(^{166m} Ho) = 100 ~ 1000

- **chemical pre-purification and post-separation at PSI (Villigen, Switzerland)**
- **HOLMES needs ~ 200 MBq of 163 Ho ***

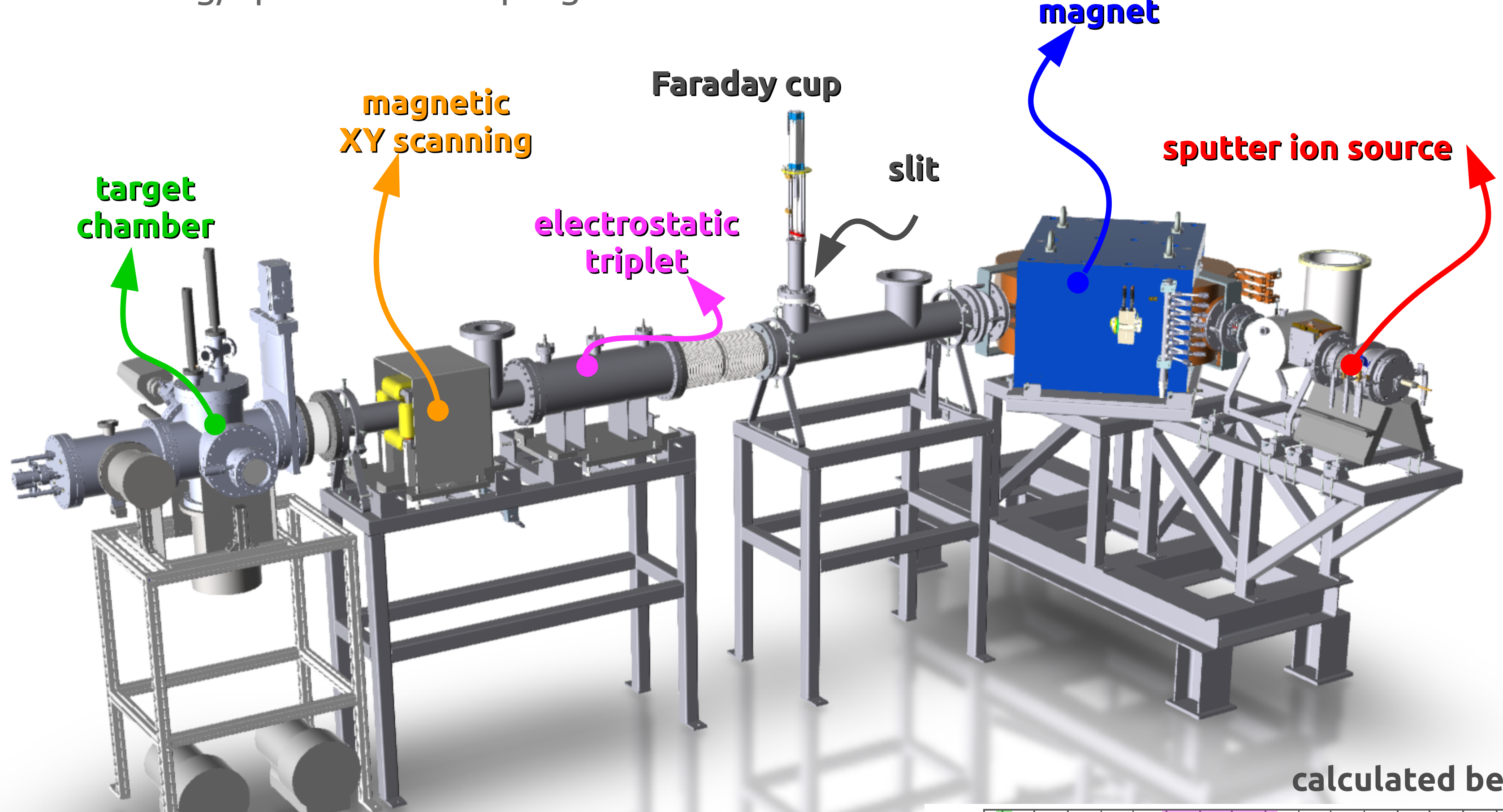
*depends on the actual global embedding process efficiency

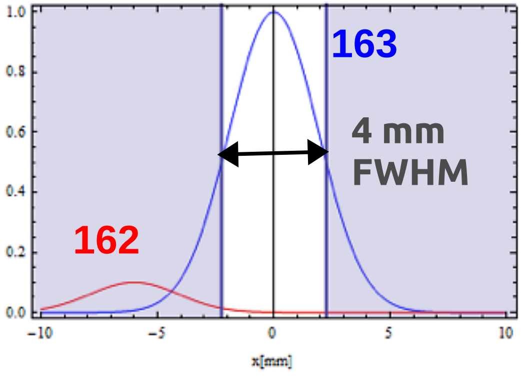
HOLMES source production

- Enriched Er_2O_3 samples irradiated @ **ILL**, pre/post processed @ **PSI** and :
    - 25 mg (enriched ~28%) irradiated for 55 days @ILL → 5 MBq (6 kBq) of ^{163}Ho (^{166m}Ho)
    - 150 mg (enriched ~26.5%) irradiated for 53 days @ILL → 23 MBq (37 kBq) of ^{163}Ho (^{166m} Ho)
    - 544 mg (enriched ~25%) irradiated for 50 days @ILL. Expected in 2018: 108 MBq (200 kBq) of ^{163}Ho (^{166m}Ho)
- total of ~100 MBq (243 kBq) of 163 Ho (^{166m}Ho): enough for R&D and 500 pixels
- Ho radiochemical separation with ion-exchange resins in hot-cells at PSI
- efficiency ≥ 79%

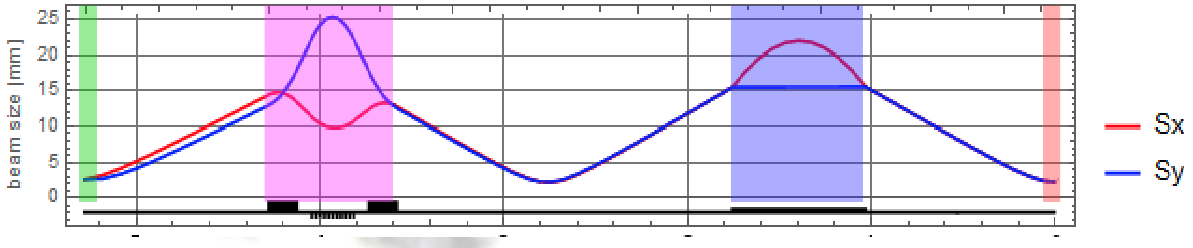
HOLMES mass separation and ion implanter

- extraction voltage 30-50 kV → 10-100 nm implant depth
- ^{163}**Ho / **^{166m}**Ho** separation better than 10^5
- testing/optimization in progress





calculated beam size



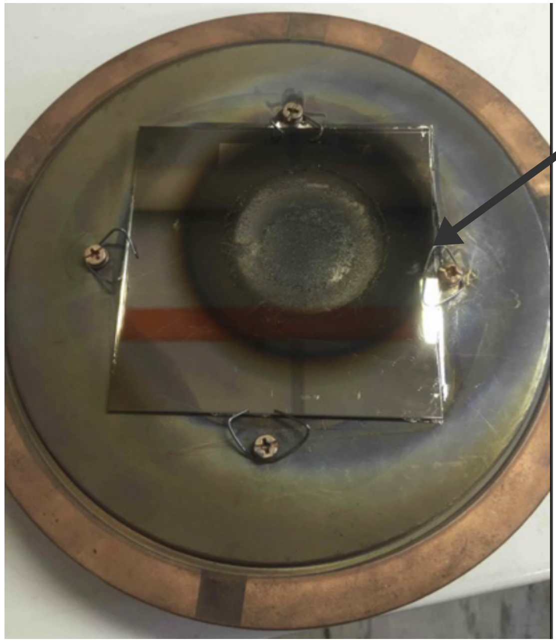
Ion source sputter target production 1

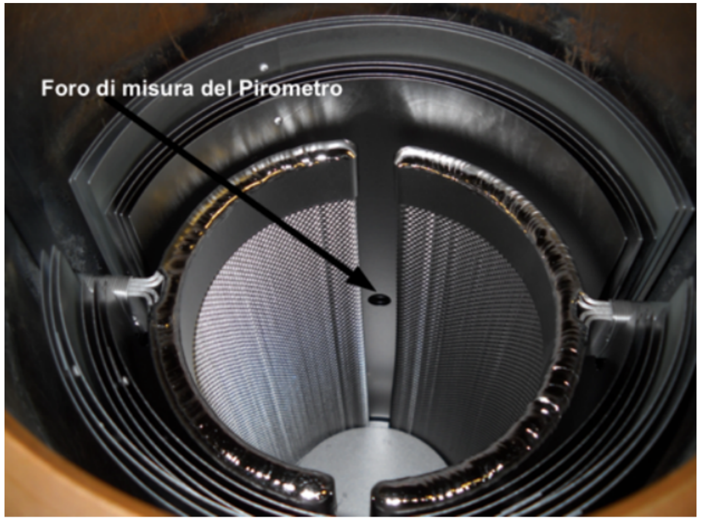
- Sputter target for ion-implanting has to be in metallic form for possible extraction efficiency loss
- Enriched $Er_2O_3 \rightarrow Ho_2O_3$
- Thermoreduction/distillation in furnace to obtain the metallic Ho target for implanta

$$Ho_2O_3 + 2Y(met) \rightarrow 2Ho(met) + Y_2O_3 \text{ @ } T > 1600\ ^\circ C$$

- distillation efficiency ≈ 70% (preliminary)

evaportated metallic holmium

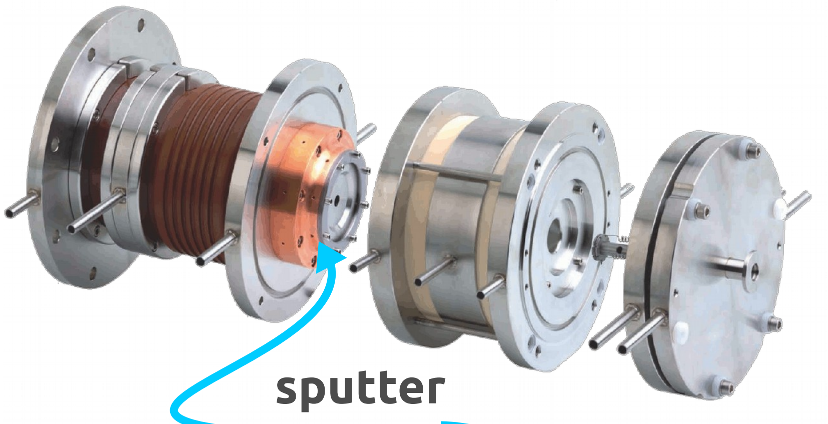




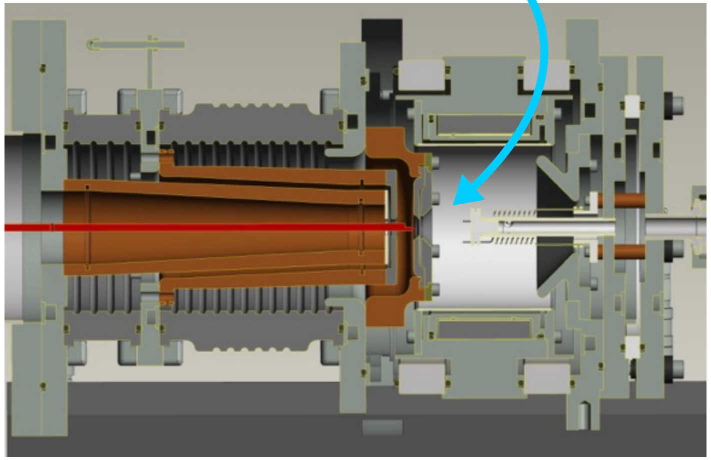
Ion source sputter target production 2

Sputter target for ion-implanting has to be in metallic form for possible extraction efficiency loss

- ➢ work in progress to produce the sputter target
- ➢ sintering of Ho with other metals
- ➢ production of targets with different metals to test the implanting efficiency



sputter target



high pressure
+
heat treatment

HOLMES detectors and read out

- **Transition edge sensors**
  - ➢ good energy resolution: few eVs @ Q-value
  - ➢ compatible with ion-implanting
  - ➢ detectors intrinsically fast O(100 ns) – slowed down to ~ 20 μs for bandwidth limitations
    - ➢ effective time resolution better than rise time → pile-up discrimination
  - ➢ 300 Hz/pixel: excess of heat capacity? Degradation of detector performances? To be investigated…

- **Microwave multiplexing**
  - ➢ rather simple readout scheme
  - ➢ compatible with fast sampling rate & intrinsic energy resolution

- **DAQ based on Software Defined Radio**
  - ➢ multiplexing factor limited by bandwidth of the ADC

Detectors

Transition Edge sensors: exploit the strong dependence of R vs T of a superconductor kept in its transition

fast detector response for high counting rate

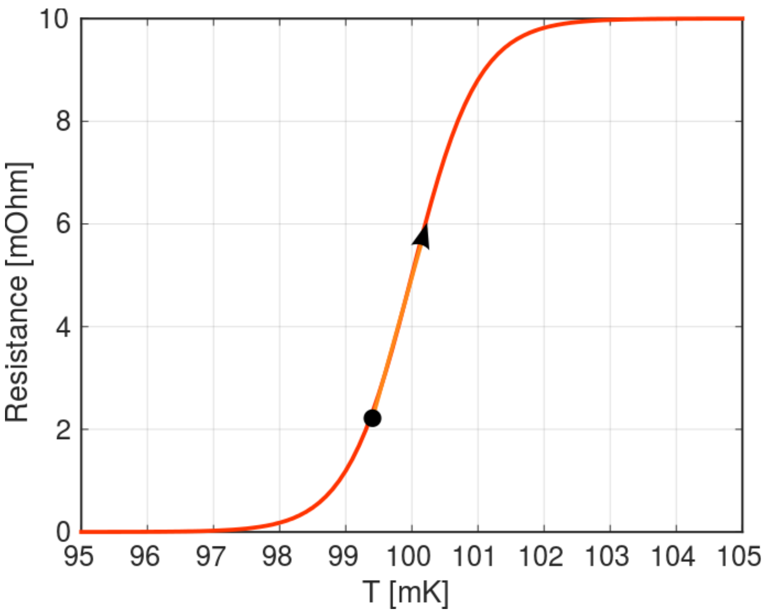
➢ signal rise time determined by electrical cut-off (L/R)

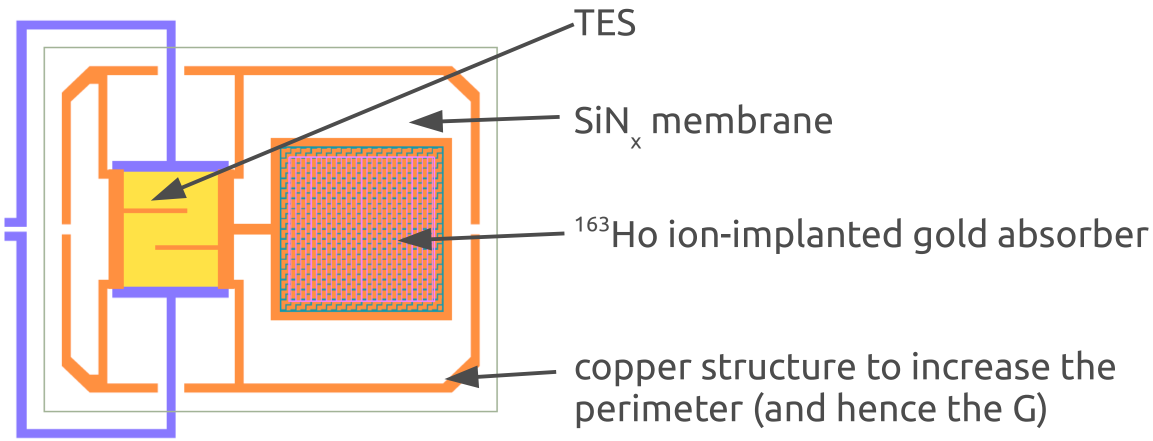
➢ signal decay time (at the first order) set by C/G: large G to reduce dead time

^{163}Ho ion-implanted gold absorber thermally coupled to the sensor

“side-car” geometry to prevent proximity effect

absorber thickness determined by stopping power of electrons and photons



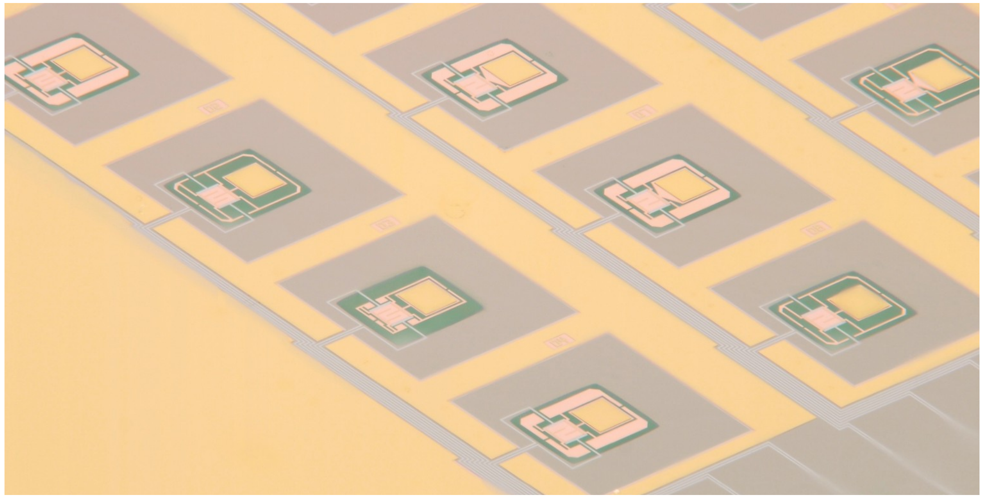


TES

SiN_x membrane

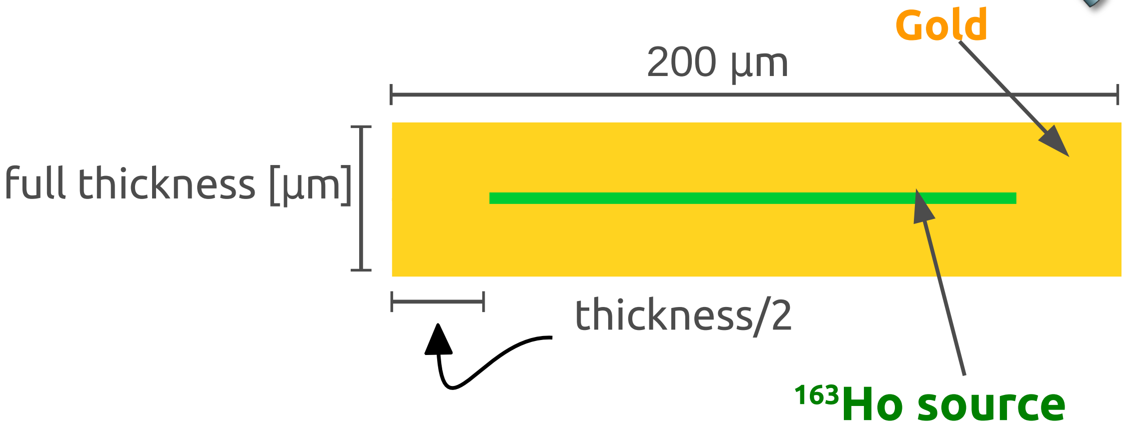
^{163}Ho ion-implanted gold absorber

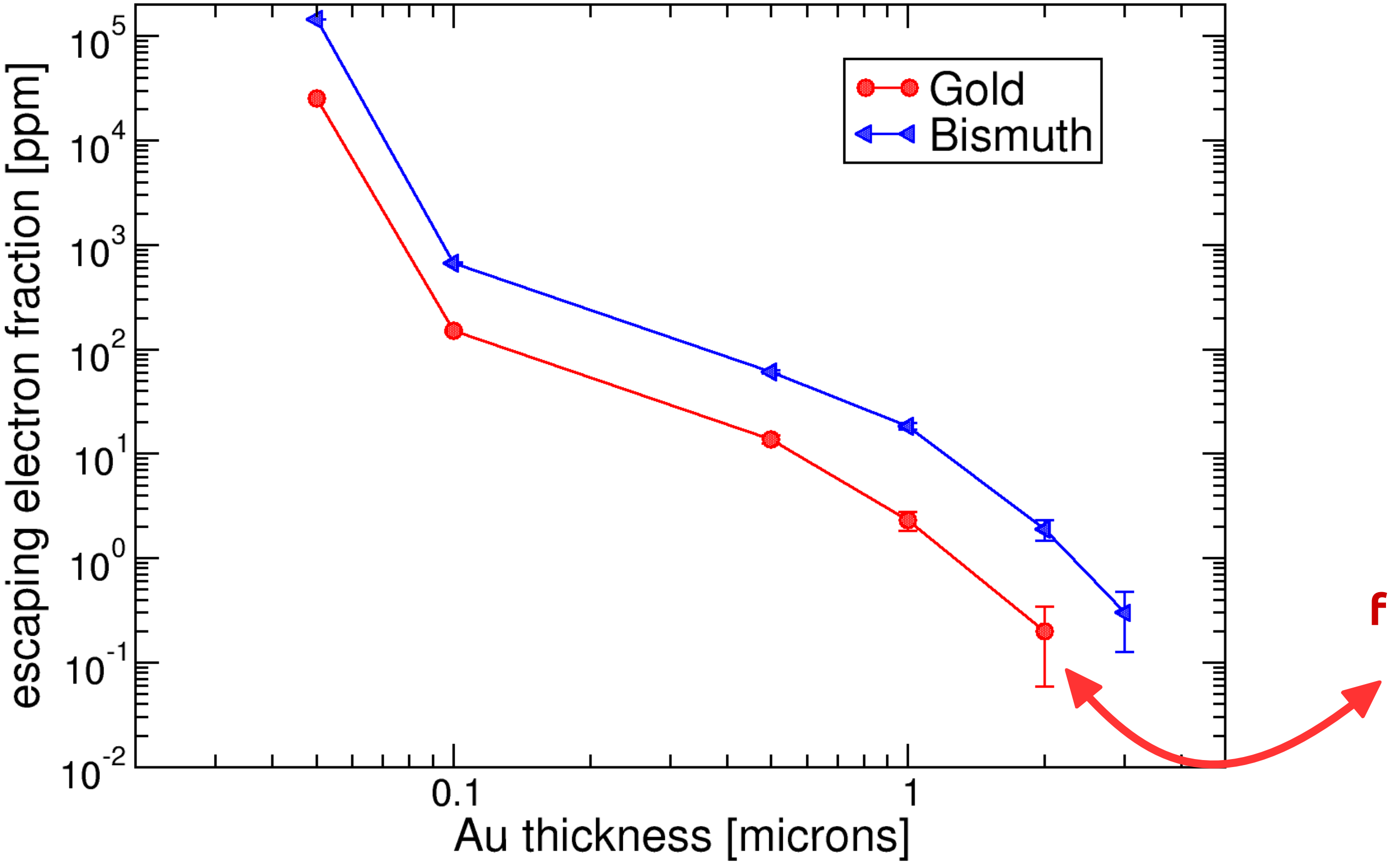
copper structure to increase the perimeter (and hence the G)



TES absorber design: stopping EC radiation

Geant4 + LowEnergyEM MC simulation

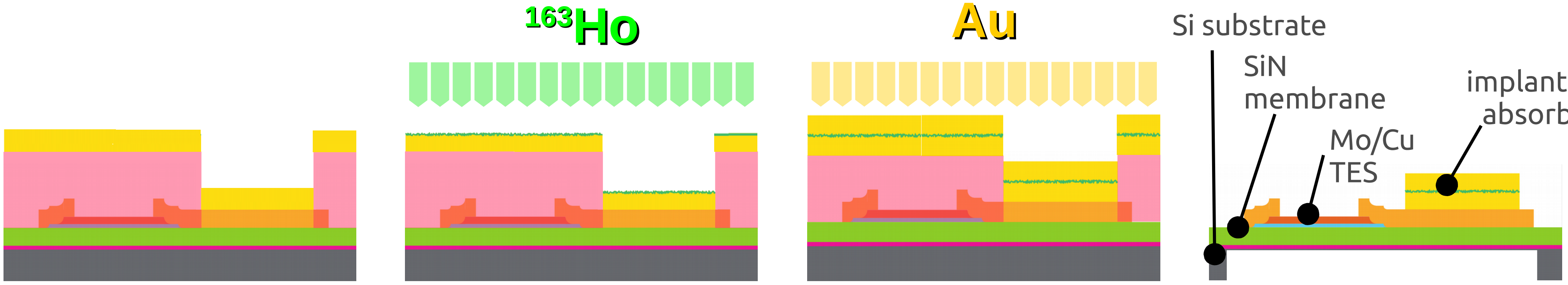




$I_x \approx 10^{-5}\, I_e$

99.99998%
full stopping
for 2keV electrons

Detector fabrication



Ion implantation

Full incapsulation by sputtering

SiN membrane release

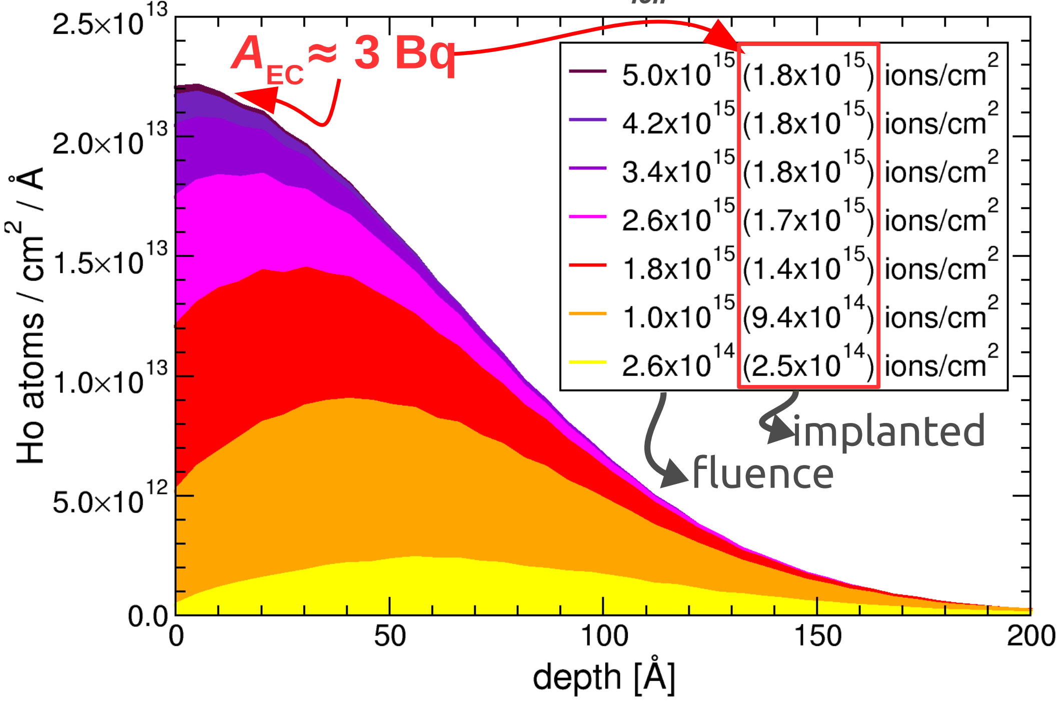
NIST → INFN

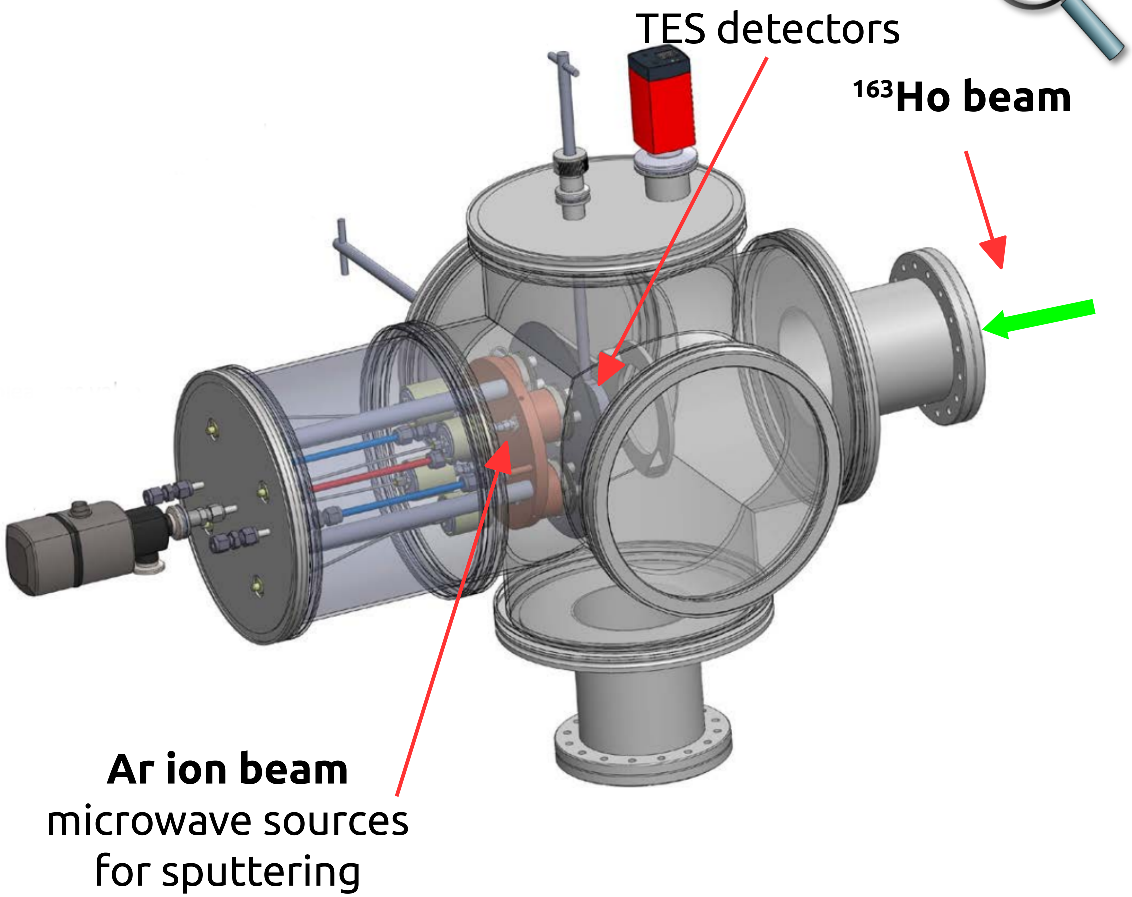
- TES originally fabricated at NIST, Boulder, CO, USA
- ^{163}Ho implantation and final 1 μm Au layer deposition at INFN, Genova, Italy
- final micromaching step definition in progress (SiN membrane release)
- HOLMES 4 x 16 linear sub-array for low parasitic L and high implant efficiency

Target chamber 1

ion implant simulation with SRIM2013

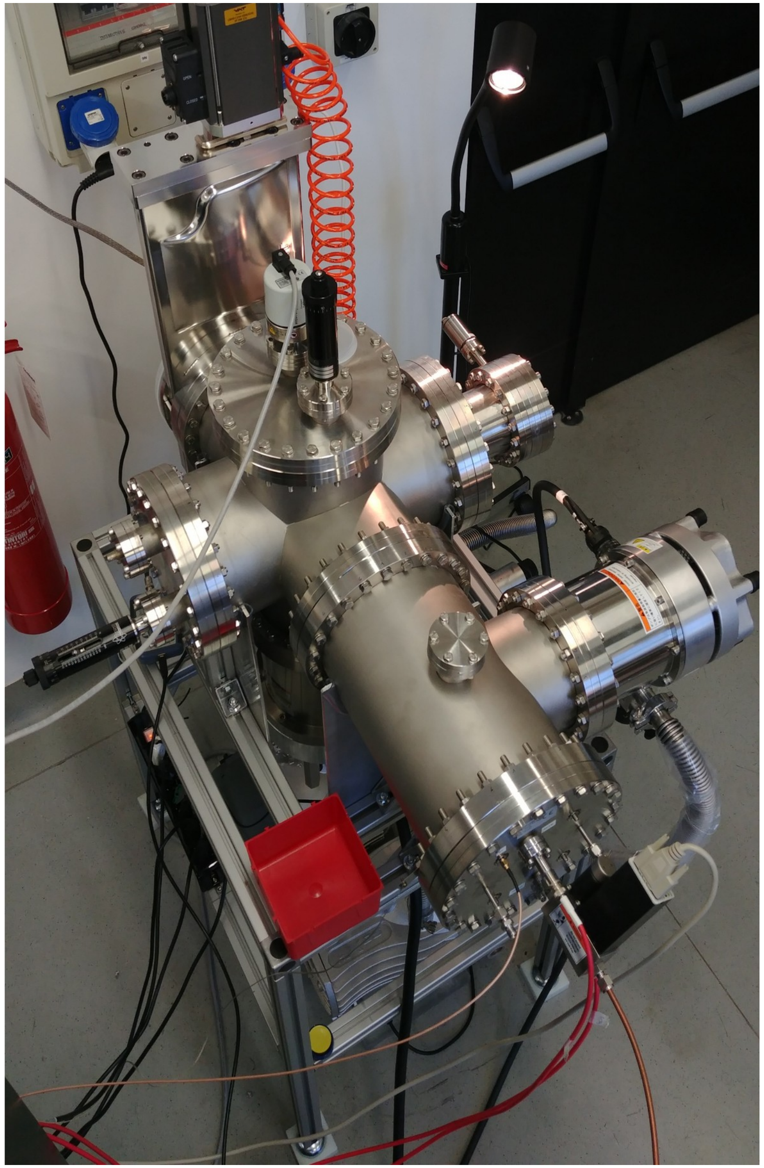
^{163}Ho ions on Au (E_{ion} = 50 keV)





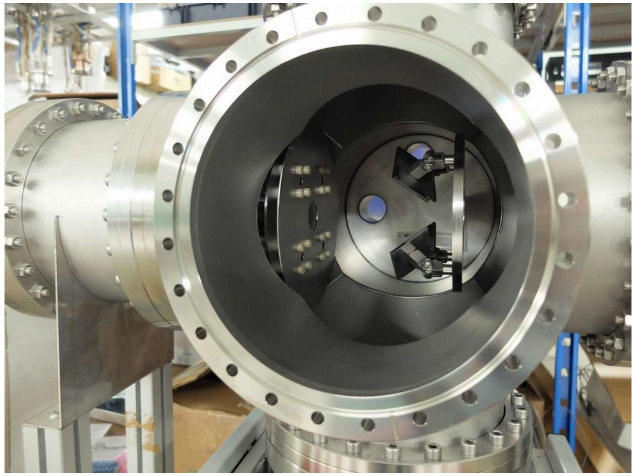
- ^{163}Ho concentration in absorbers saturate because ^{163}Ho sputters off Au from absorber
- effect compensated by Au co-evaporation (also for heat capacity reasons)
- final 1 μm Au layer deposited in situ to avoid oxidation

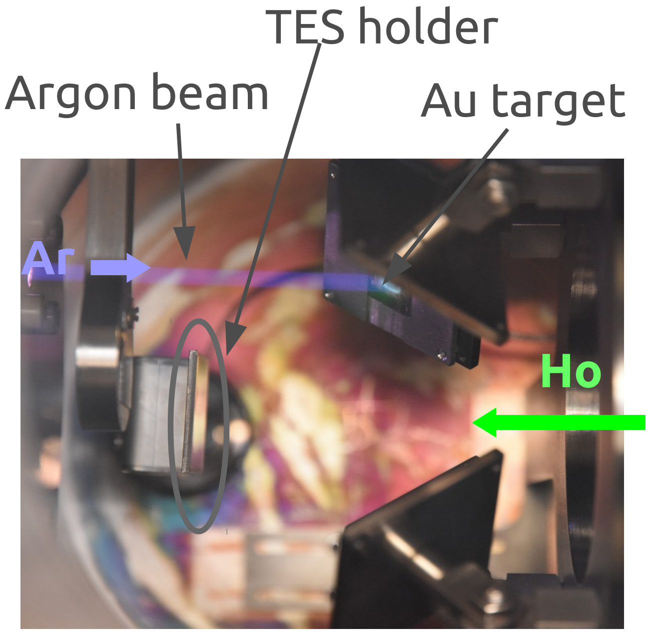
Target Chamber 2



Ion Beam sputter system for on-line deposition

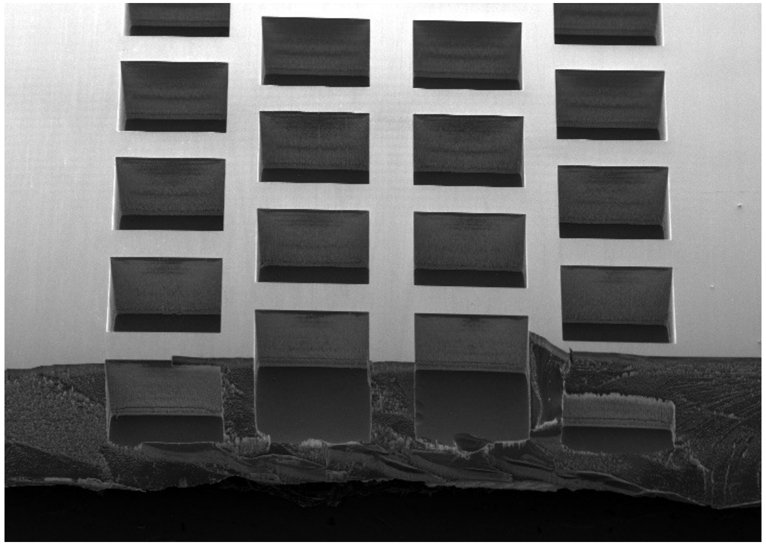
- Up to 4 ECR ion beam sources
- Testing/optimization in progress with 1 ECR source
    - → Au deposition rate control and maximization
    - → Au film quality and uniformity characterization

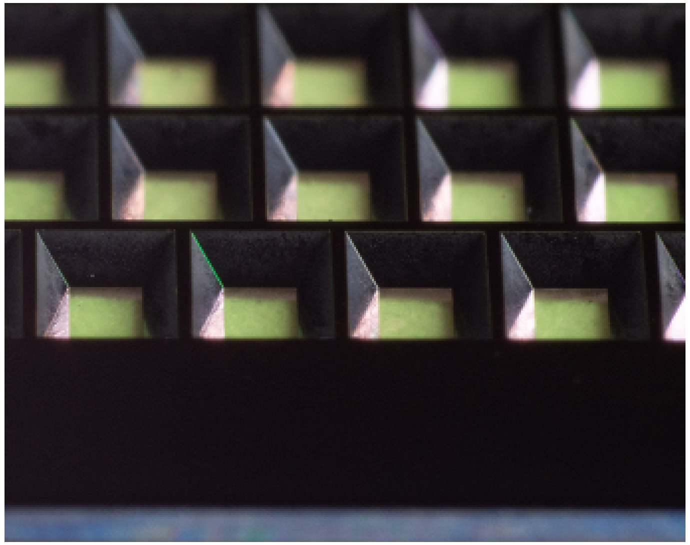




Detector array fabrication

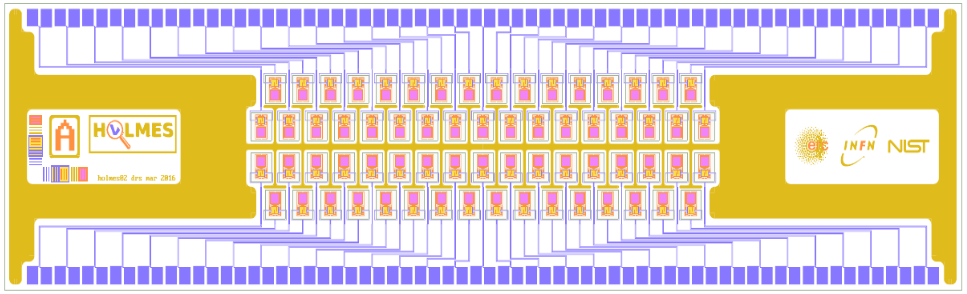
two options for membrane release (i.e. final array fabrication step)



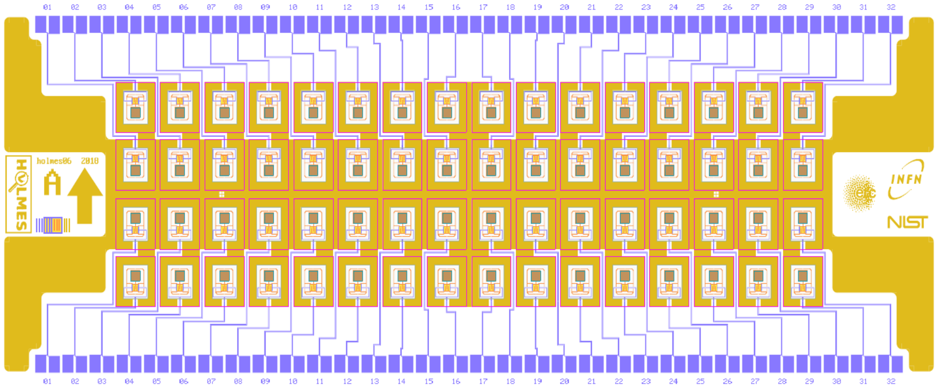


- Silicon Deep Reactive Ion Etching (DRIE)
- best for close packing and high implant efficiency
- not yet properly tuned → work in progress

- Silicon KOH anisotropic wet etching
- requires more spacing between pixels
- succesfully tuned → **HOLMES baseline**



calculated ^{163}Ho beam FWHM width



RF-Squid read out with multiplexing microwave

- RF- SQUID coupled with DC biased TES and a λ/4-wave resonant circuit

- RF-SQUID read out with flux ramp demodulation (common flux line inductively coupled to all SQUIDs)

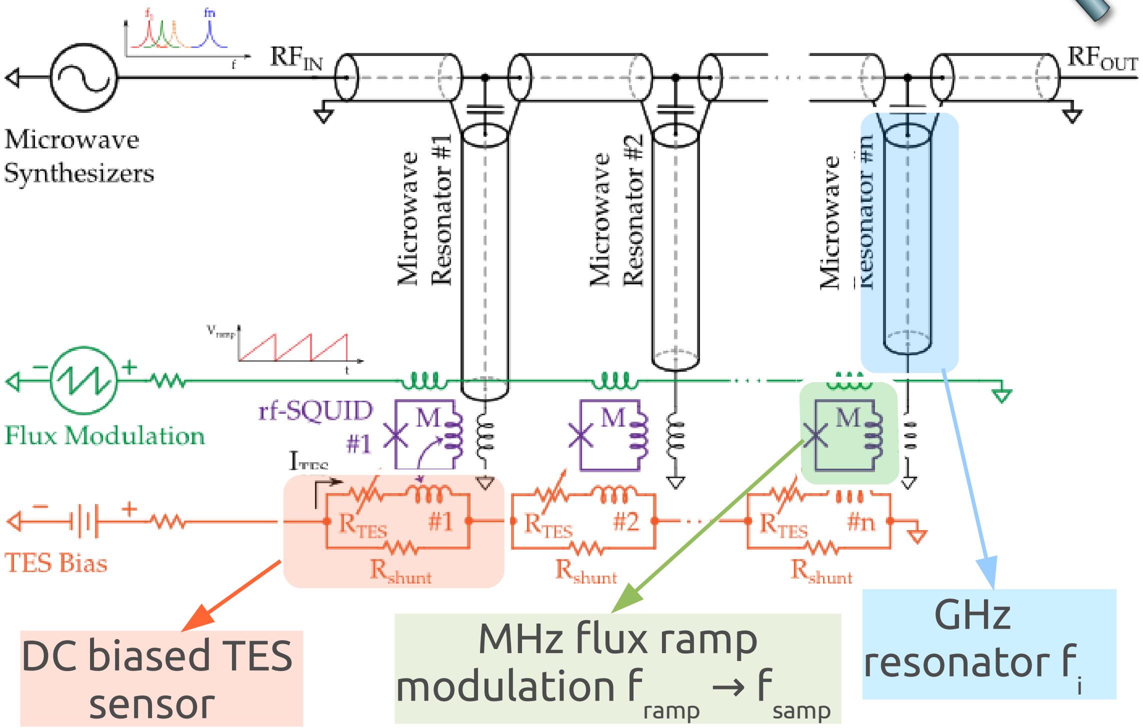
- Signal reconstructed by Software Defined Radio Technique (ROACH 2, ADC bandwidth 550 MHz)

1. An event in the absorber increases the temperature and therefore the resistance of the TES;

2. Change in TES current ⇒ change in the input flux to the SQUID;

3. The RF-SQUID transduces a change in input flux into a variation of resonant frequency;

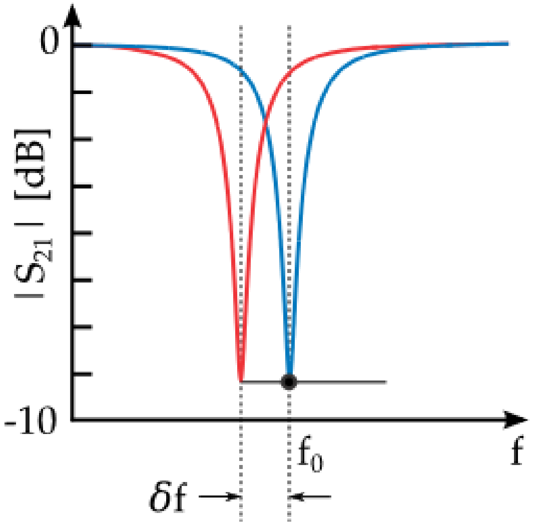
4. The ramp induces a controlled flux variation in the rf-SQUID, which is crucial for linearizing the response.

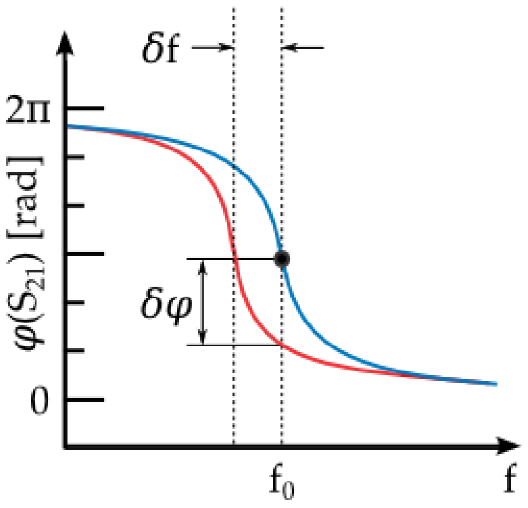


DC biased TES sensor

MHz flux ramp modulation $f_{ramp} \rightarrow f_{samp}$

GHz resonator f_i

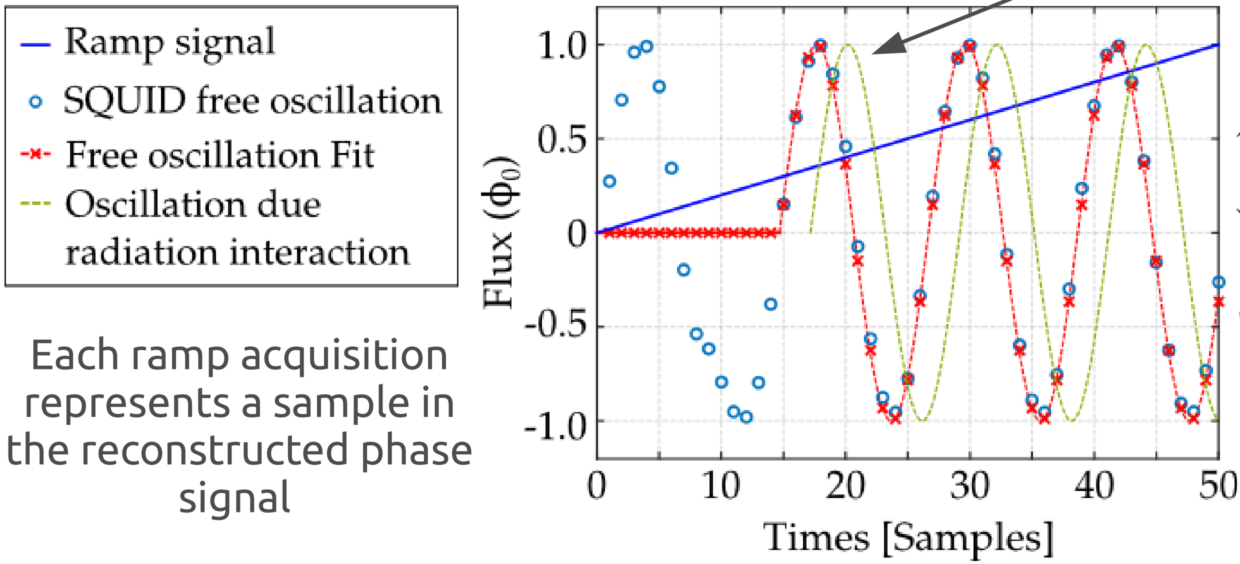




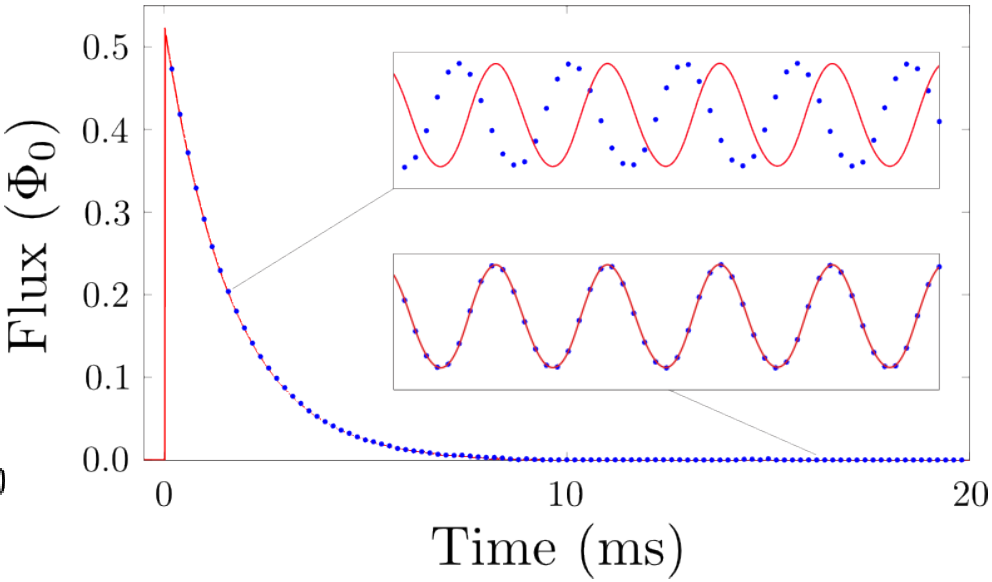
Signal reconstruction

$n_{\Phi_0}=3$ ($n_{\Phi_0}\geq 2$)

$f_{mod}=n_{\Phi_0}f_{ramp}$



Each ramp acquisition represents a sample in the reconstructed phase signal



The signal is reconstructed by comparing the phase shift caused by the interaction of the radiation in the absorber, with the free oscillation of the SQUID, when the TES is not biased.

TES microwave multiplexing with RF-SQUID ramp modulation + ROACH2-based Software Defined Radio (SDR)

DAQ Bandwidth budget

The detector design is mostly driven by the read-out bandwidth requirements.

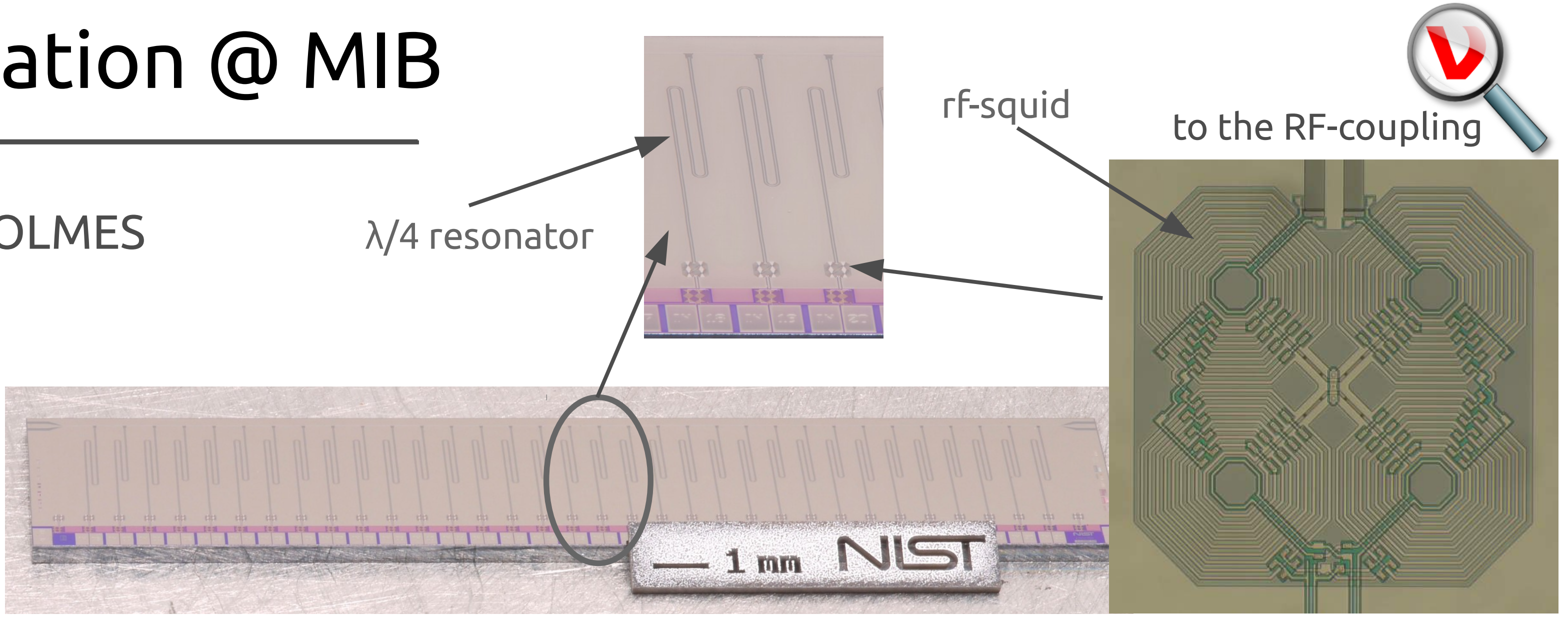
- Effective sampling rate is set by the ramp: $f_{ramp} = f_{samp}$
- Necessary resonator bandwidth per flux ramp: $f_{res} \geq 2 n_{\Phi_0} f_{samp}$
- To avoid cross talk spacing between resonances: $f_n \geq g_f f_{res} \quad [g_f = 7]$
- To avoid distortions (signal BW): $f_{samp} \geq \frac{R_d}{\tau_{rise}} \approx \frac{5}{\tau_{rise}}$ [τ_{rise} exponential]
- Available ADC bandwidth f_{ADC} with ROACH2 system 550 MHz
- Multiplexing factor:

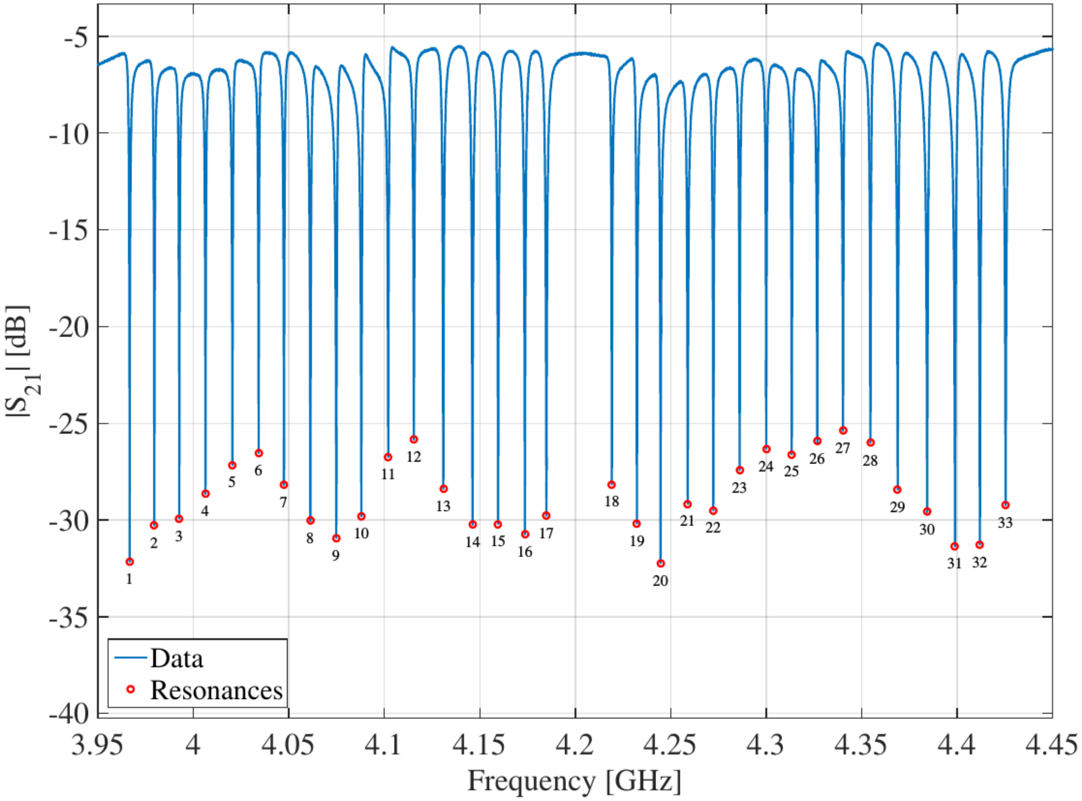
$$\boxed{n_{TES} = \frac{f_{ADC}}{f_n} \leq \frac{f_{ADC}\,\tau_{rise}}{2 R_d g_f n_{\Phi_0}} \approx \frac{f_{ADC}\,\tau_{rise}}{140}}$$

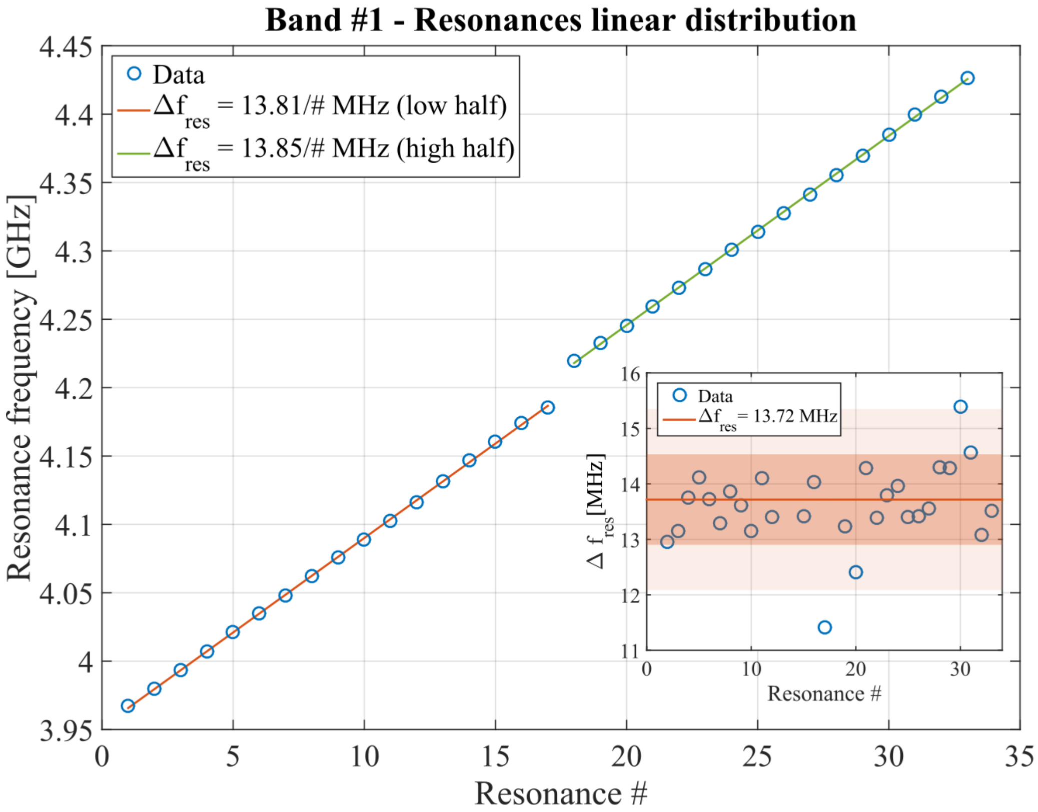
for fixed **f_{ADC}=500MHz** and **n_{TES}≈35 ↔** τ**$_{rise}$≈10μs** with **f_{samp}=0.5MHz**

μmux characterization @ MIB

- → **μMUX17A** optimized for HOLMES
- → 33 resonances in 500 MHz
  - ➢ width 2 MHz
  - ➢ separation 14 MHz
- → squid noise <≈2 $\mu\Phi_0/\sqrt{Hz}$

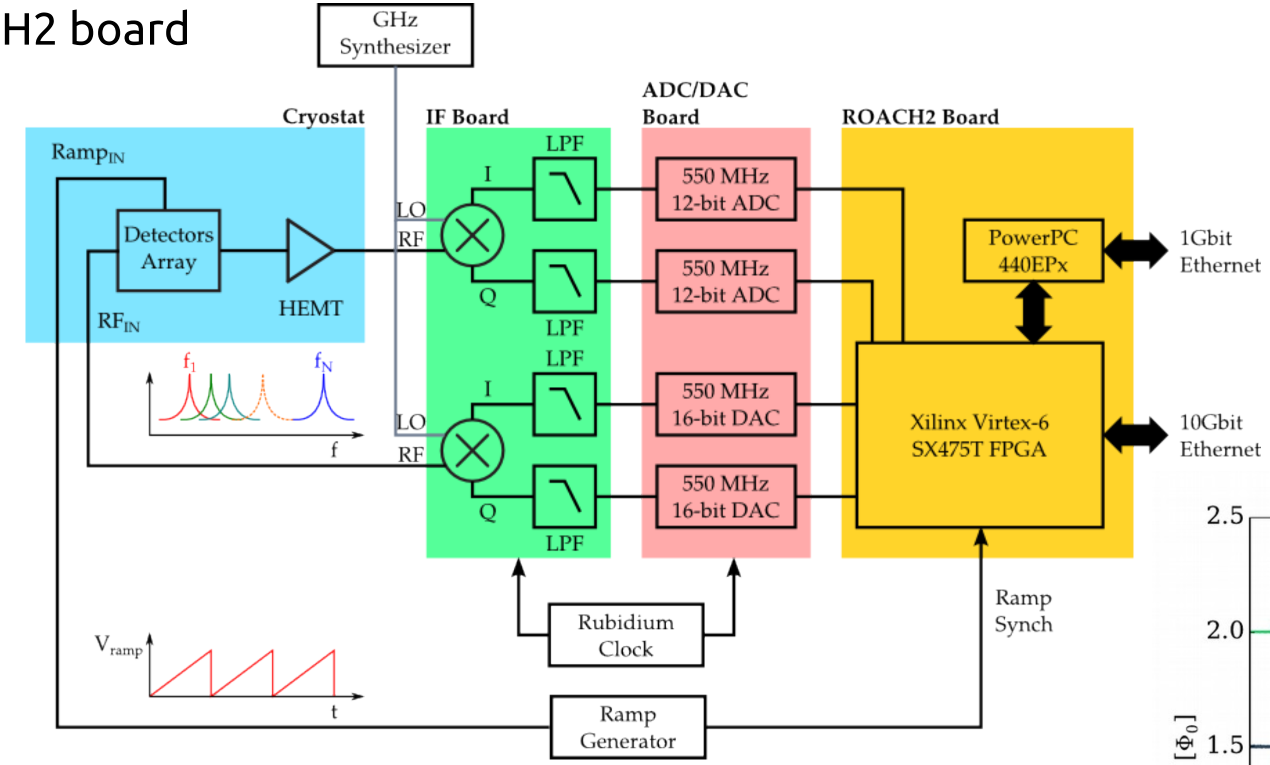


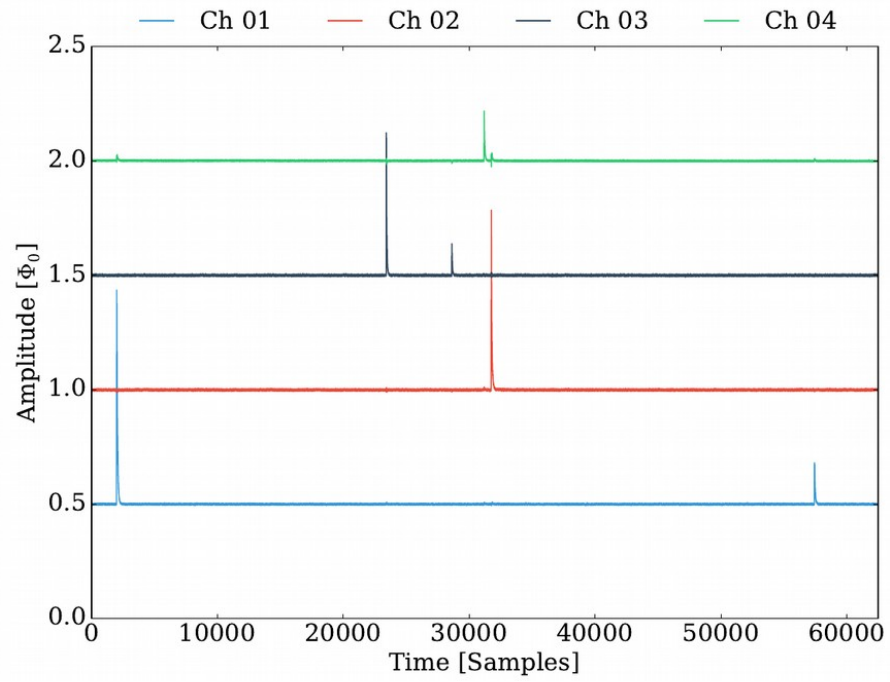




TES read out with ROACH2

With the 550 MHz ADC BW of the ROACH2, 500 kHz effective pulse sampling, 14 MHz resonance spacing, 2 MHz resonance width and $2\Phi_0$ SQUID oscillation/ramp → 33 multiplexable channels per ROACH2 board





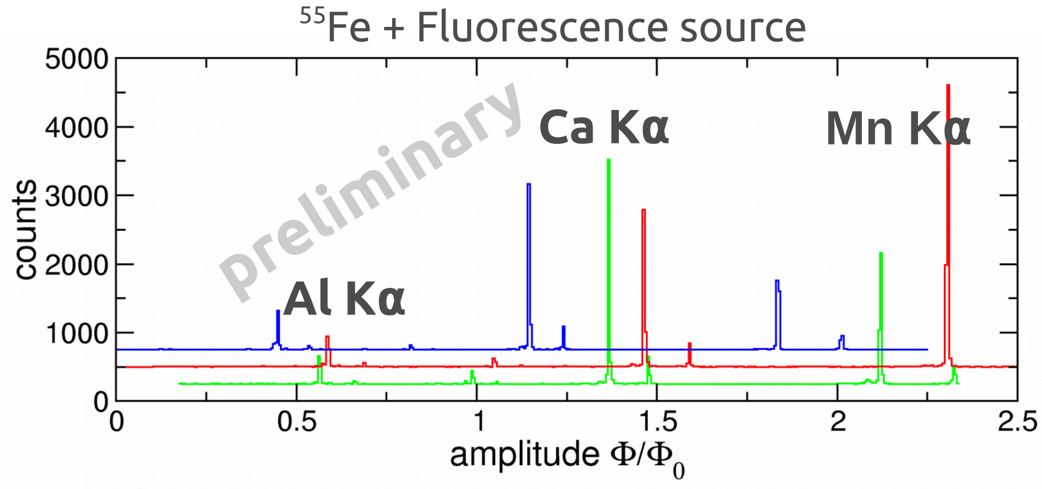
- Acquisition with ROACH2 board of 4 pixels limited by tone power (temporary discrete IF components)
- 16 ch firmware from NIST (only half of the BW)
- checks on algorithms, noise, ΔE, τ_R, slew rate
- fluorescence source: ^{55}Fe (primary) + Al,Cl,Ca

Detector testing with HOLMES DAQ

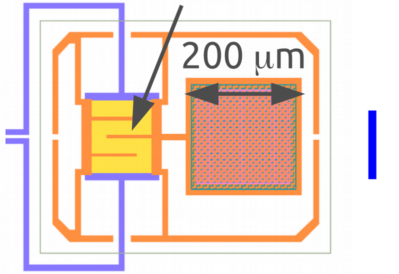
Different geometries understudy:
- different absorber/TES coupling
- different sensors
- different heat capacities

Selected stray L to obtain $\tau_R \approx 10\ \mu s$

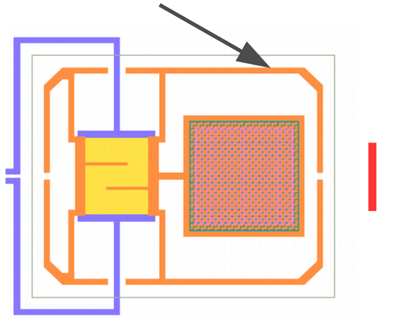
Not implanted with Holmium!



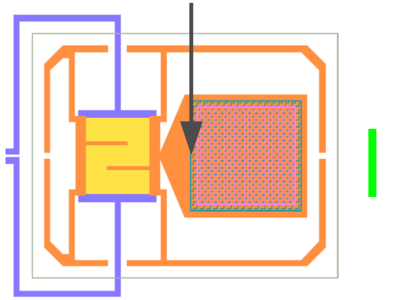
3 Cu bars for steering the current in a meandering pattern

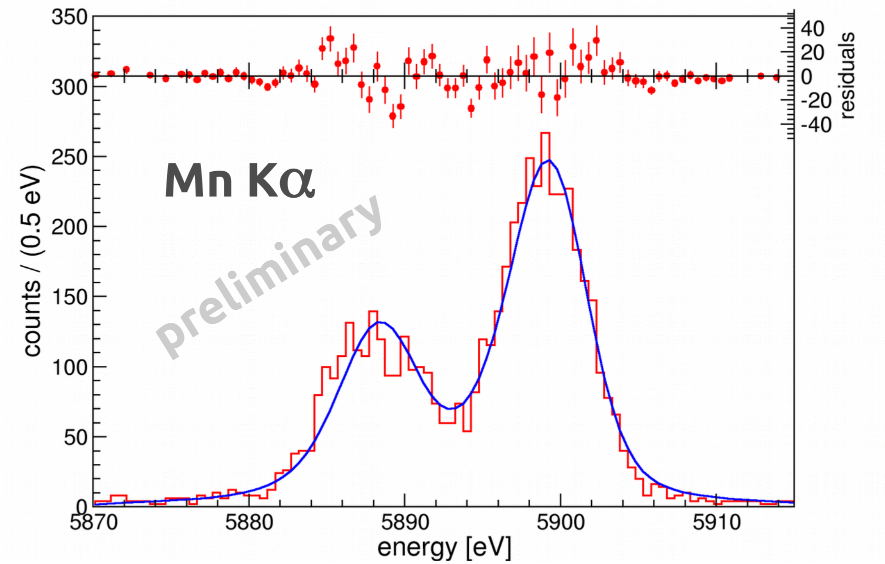


The perimeter increases G without raising the heat capacity C



Stronger coupling between absorber and TES





$\Delta E_0 \approx 3.3$ eV

$\Delta E_{FWHM} = 4.5\pm0.1$ eV @ 6 keV

$\tau_{Rise} \approx 15\ \mu s$

$\tau_{decay} \approx 54\ \mu s$

Conclusion

The HOLMES experiment will performe a direct measurement of the neutrino mass by using microcalorimenter with 163 Ho-implanted absorber:

- first detector arrays are being fabricated at NIST
- first ion implantation tests with ^{163}Ho before the end of 2018
  - ► first not-optimized ion implanted detectors late in 2018
- ^{163}Ho implanted activity optimized during 2019
  - ► first high ^{163}Ho activity array running in 2019
  - ► **1 month data taking can provide a m_ν statistical sensitivity ≈10 eV**
  - ► full array deployment will follow