Direct calorimetric measurement of the neutrino mass with HOLMES

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on behalf of the HOLMES collaboration

Electron capture calorimetric experiment

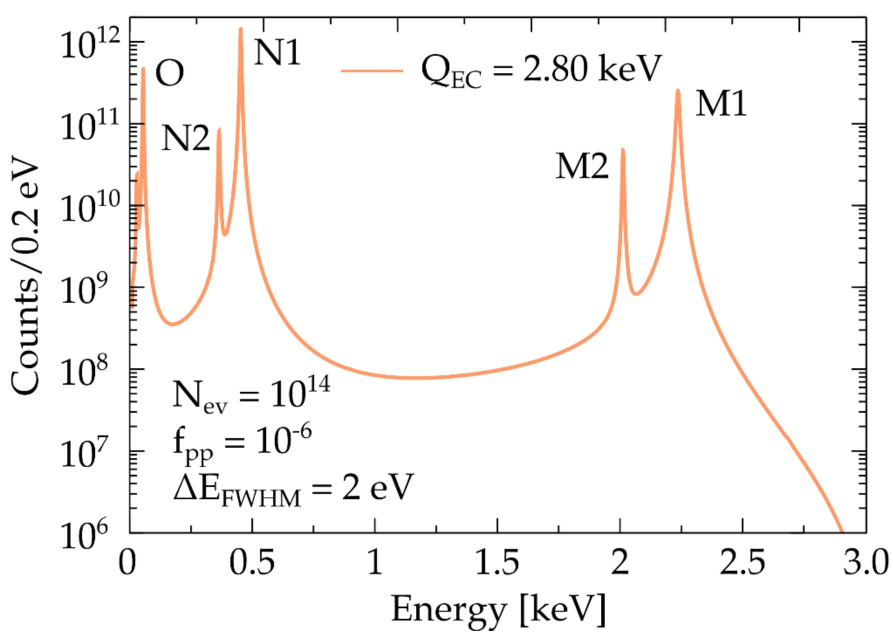
$$^{163}\mathrm{Ho} + e^- \longrightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$

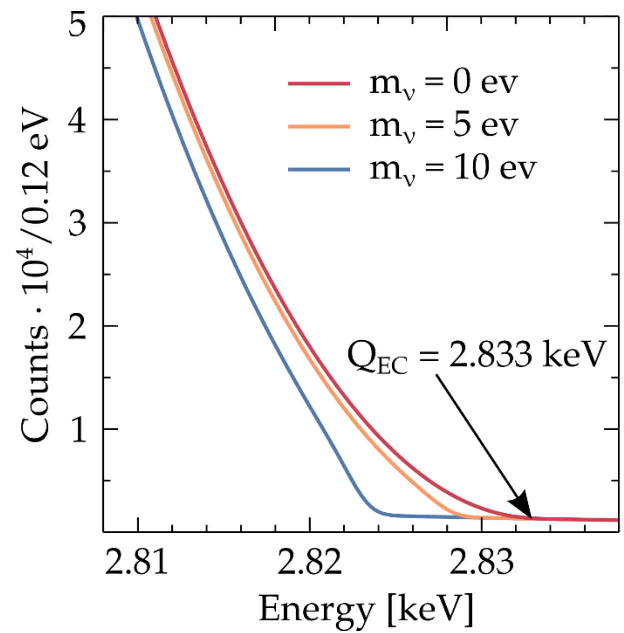
^{163}Ho decay via EC from shell ≥ M1, with $Q_{EC} \sim 2.8$keV

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

- calorimetric measurement of the Dy atomic de-excitation (mostly non-radiative)
- rate at the end point depends on **$(Q - E_{M_1})$**: the proximity to M1 resonance peak enhances the statistics at the end point (i.e. sensitivity on m_ν)
- $\tau_{1/2} \sim 4570$ years: few nuclei are needed

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

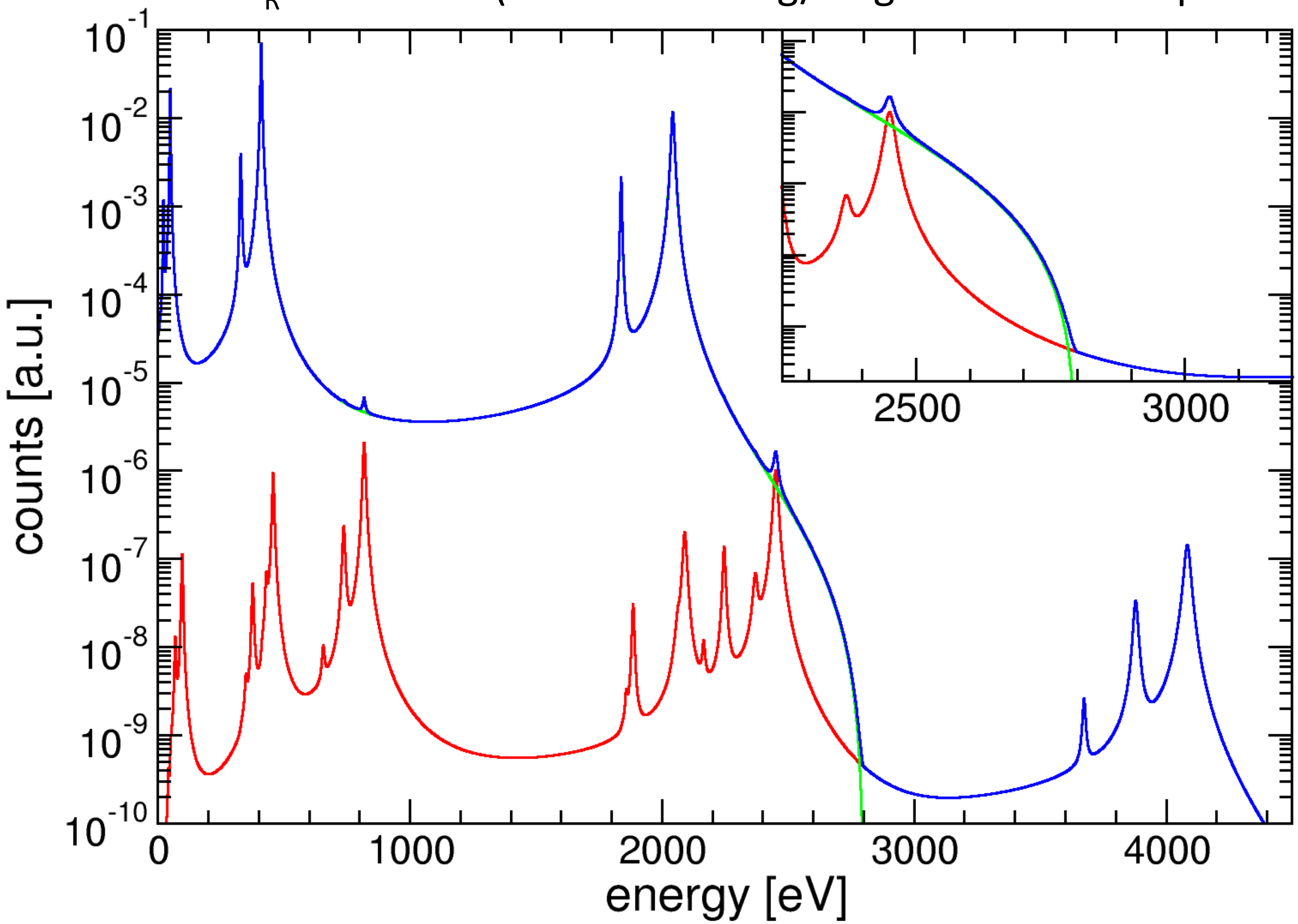




Electron capture calorimetric experiment (cont'd)

complex pile up spectrum: $N_{pp} = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$, $f_{pp} \approx A_{EC}\tau_R$

time resolution $\tau_R \leq$ rise time (Wiener filtering/Single value decomposition)



Q=2800 eV
$f_{pp}=10^{-4}$

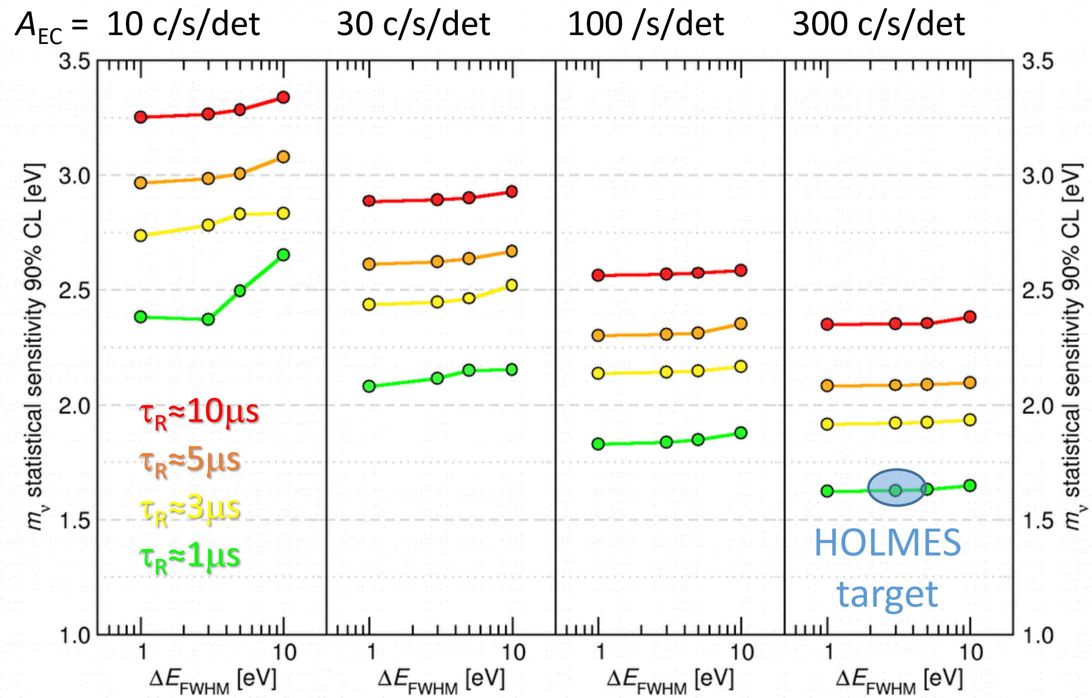
+ second order processes?

HOLMES (ERC-Advanced Grant n. 340321) PI: Stefano Ragazzi

- Neutrino mass determination with a sensitivity as low as ~ 1 eV
- calorimetric EC measurement
- assess of systematics

- Detectors: Mo/Cu Transition Edge Sensors (TES) with ^{163}**Ho implanted** absorbers
  - 6.5×10^{13} nuclei/pixel = 300 c/s/det
  - $\Delta E \approx 1$ eV, $\tau_R \approx 1$ μs
- two steps:
  - 16 channels mid-term prototype, t_M=1 month (m_ν < 10 eV)
  - full scale: **1000 channels**, 3×10^{13} events in 3 years
  - 6.5×10^{16} ^{163}Ho nuclei (≈18μg)

MonteCarlo with 1000 detectors x 3 years



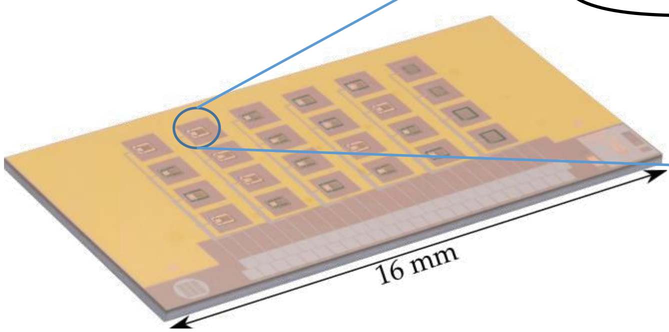
5 years project started on Feb. 1st 2014

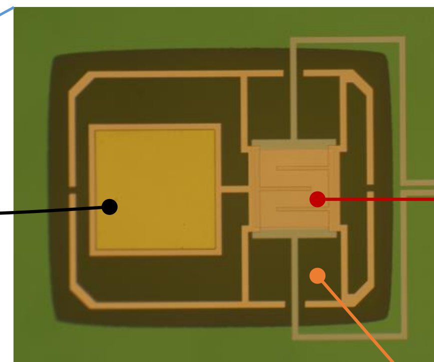
B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

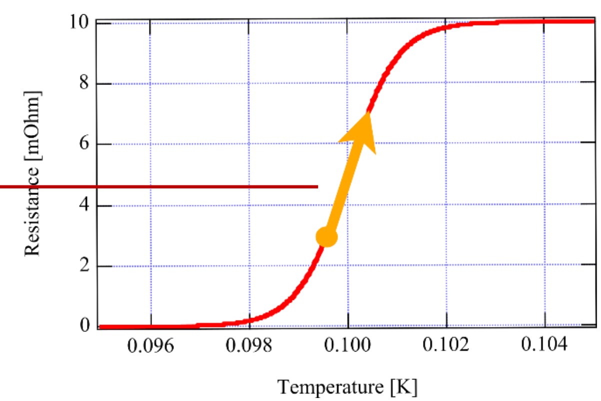
TESs for HOLMES (NIST @ Boulder, CO + INFN Genova)

- **design compatible with ion implanting**
  - gold absorber thermally coupled to the sensor (several couplings tested)
- **fast detectors**
  - rise time determined by electrical cut-off (L/R) ⟶ small stray inductance
  - decay time set by C/G. Constrains on C (the absorber must contain all the energy: 2 μm of gold stop 99.99998% of the electrons) ⟶ large G

Ho-implanted absorber (Au)







sensor + absorber suspended on a Si_2N_3 membrane

Cu structures to expand the perimeter (i.e. increase G)

test @ NIST (with TDM mux) demonstrated

$\Delta E_{FWHM} \approx 4$ eV @ 5,9 keV, $\tau_{rise} \approx 6\ \mu s$ (L=38nH), $\tau_{decay} \approx 130 \mu s$

- **large number of detectors multiplexed**
  - microwave multiplexing

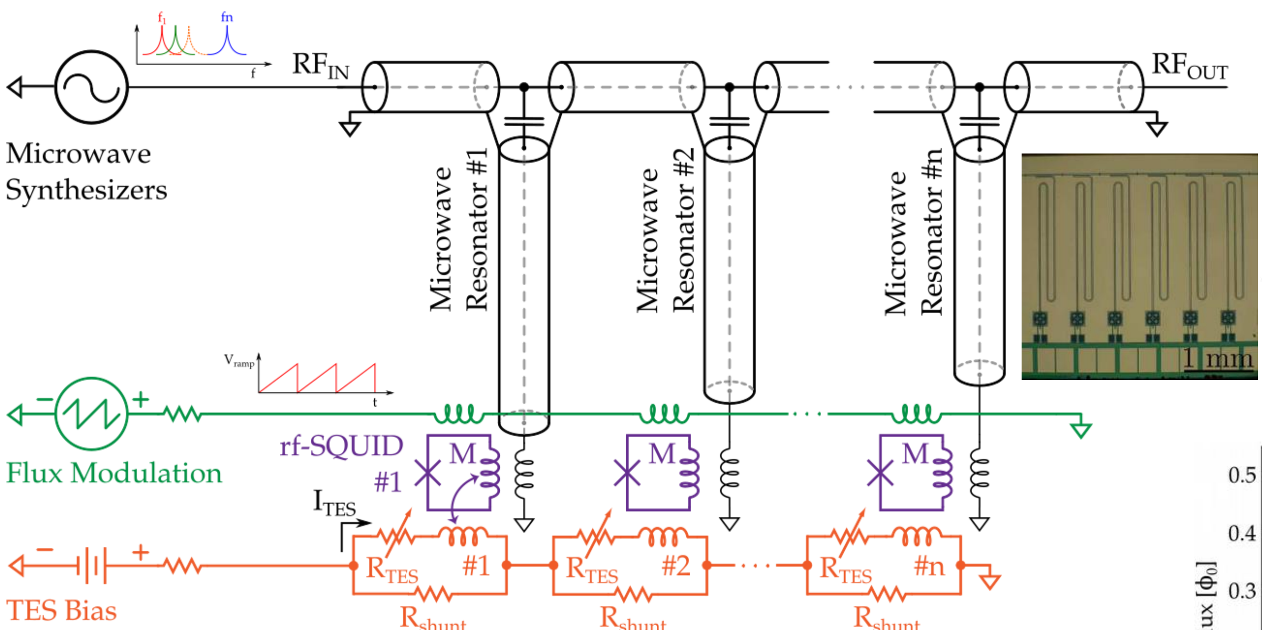
Microwave multiplexing

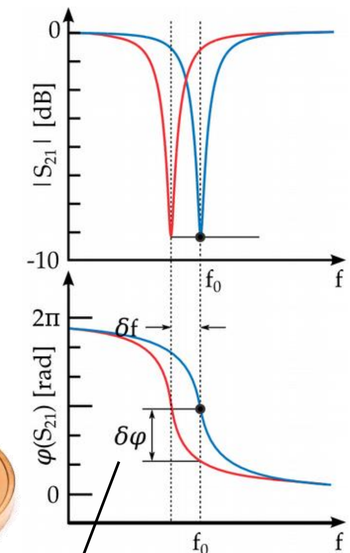
TESs read with microwave multiplexing technique

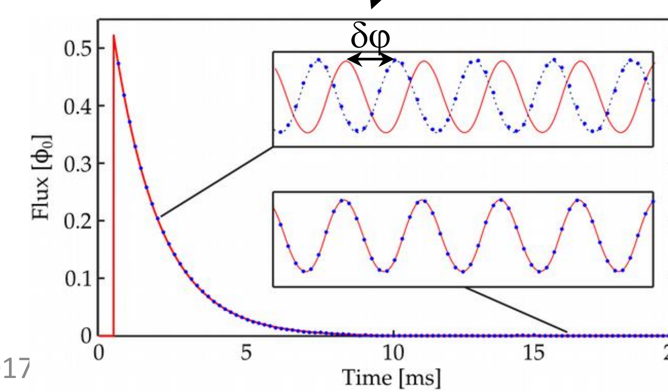
- each sensor inductively coupled to a RF-squid part of a $\lambda/4$ resonator
- a comb of signals probe the resonators at their characteristic resonant frequency

$$E \longrightarrow \delta T_{TES} \longrightarrow \delta I_{TES} \longrightarrow \delta\phi_{squid} \longrightarrow \delta f_{resonator}$$

- a ramp signal added to the squids in order to linearize the response





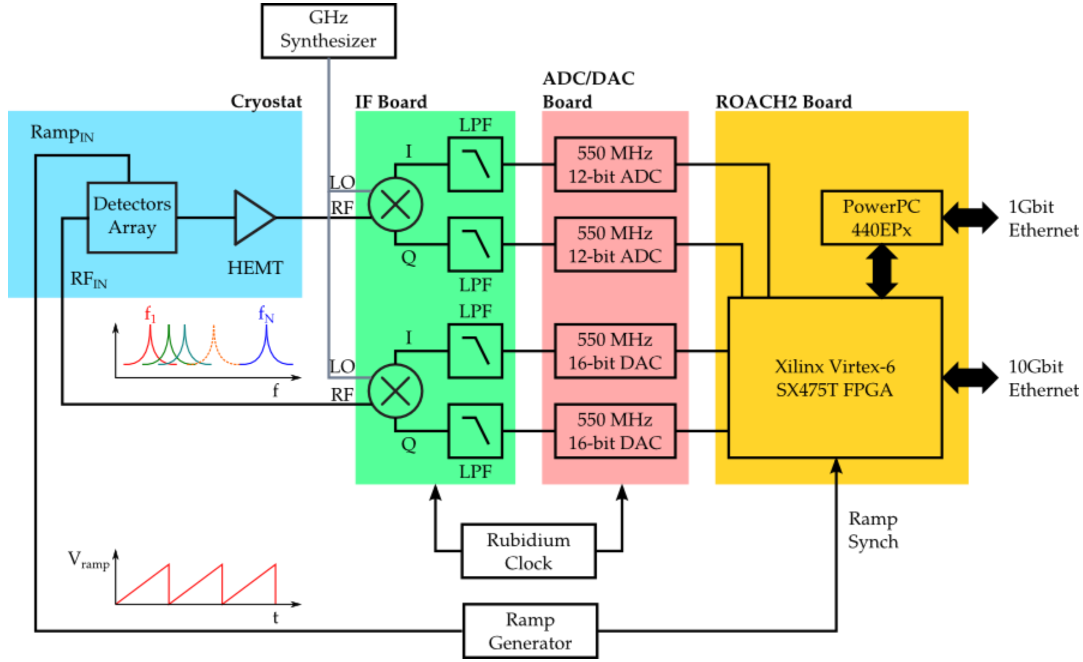


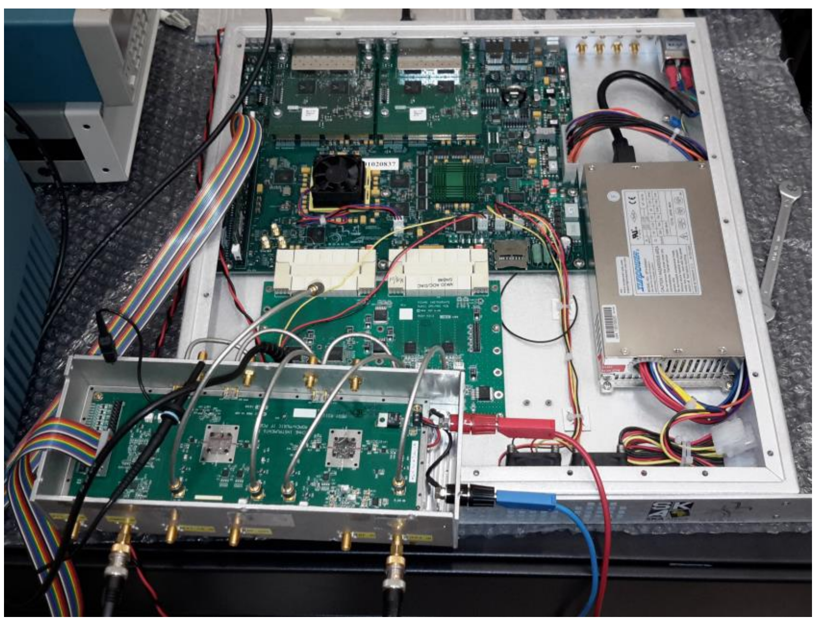
K. D. Irwin and K. W. Lehnert, Appl.Phys.Lett., 85:2107, 2004

DAQ: Readout with ROACH2 board (Software Defined Radio)

Readout made with the open system ROACH2 (by Casper collaboration)

- FPGA Virtex6 by Xilinx
- ADC bandwidth 550 MHz
- ~ 150 TB in 3 years (with threshold @ 2.02 keV; 20 TB/day with no threshold)
- Real time pulse reconstruction & threshold cut
- OF analysis and pileup detection made off-line





Bandwidth budget:

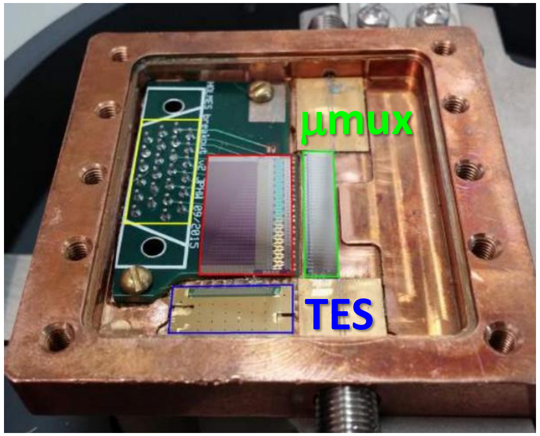
$$f_{samp} \geq \frac{R_d}{\tau_{rise}} \approx \frac{5}{\tau_{rise}}$$ signal sampling rate ≥ 500 kHz

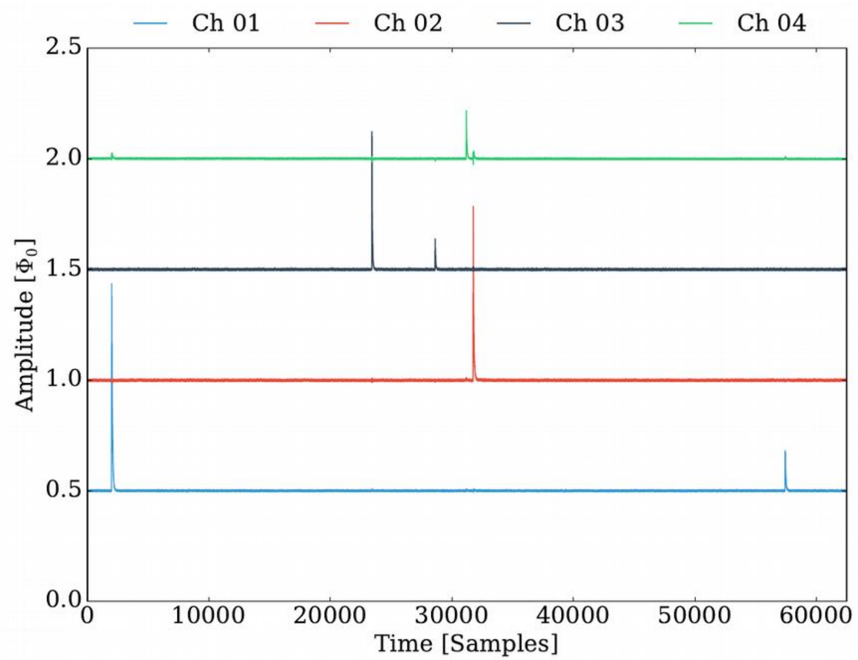
$$f_{res} \geq 2 n_{\phi_0} f_{samp}$$ resonator BW ≥ 2 MHz

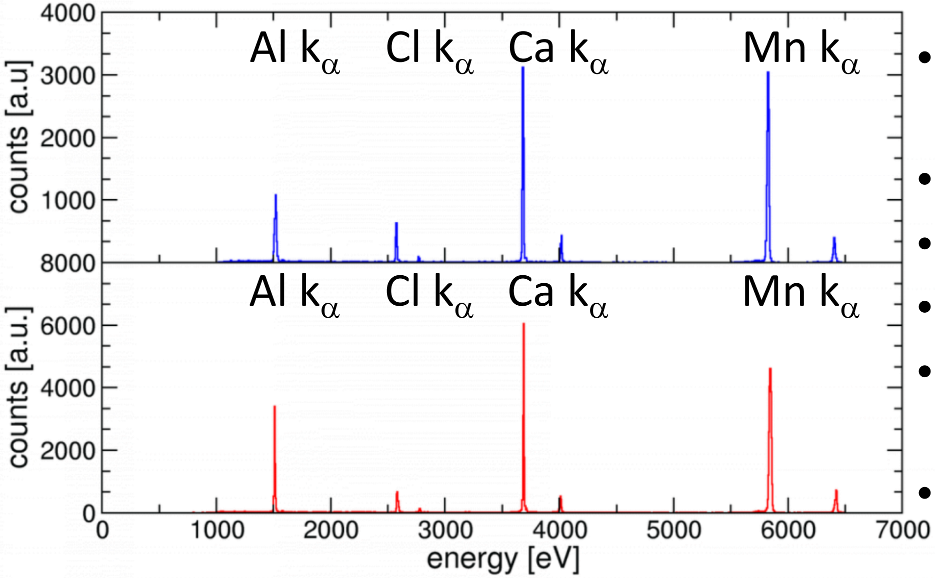
$$f_n \geq g_f f_{res} \geq \frac{2 R_d g_f n_{\phi_0}}{\tau_{rise}}$$ Δf amongst tones ($g_f \geq 8$)

$$\boxed{n_{TES} = \frac{f_{ADC}}{f_n} \leq \frac{f_{ADC}\tau_{rise}}{2 R_d g_f n_{\phi_0}}}$$ **MUX factor ≈ 34** (τ_R 10 μs)

TES pixel testing with HOLMES DAQ

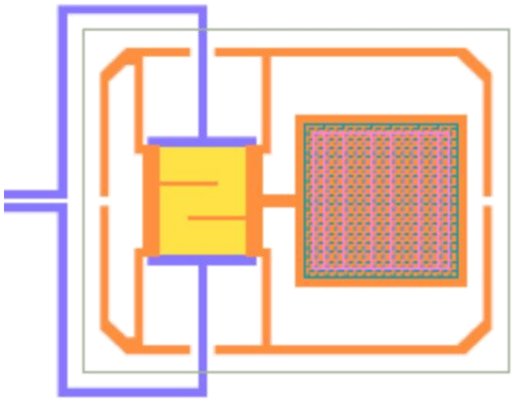






- Acquisition of 4 pixels limited by tone power (provisory discrete components IF)
- 16 ch firmware from NIST (only half of the BW)
- checks on algorithms, noise, ΔE, τ_R, slew rate, …
- fluorescence source: ^{55}Fe (primary) + Al, Cl, Ca
- $\Delta E_0 \approx 5$ eV, $\Delta E \approx 7.5$ eV @ 2.6 keV (with no collimation)
- slew rate ≈ 0,1 ϕ_0/S @ 2.6 keV

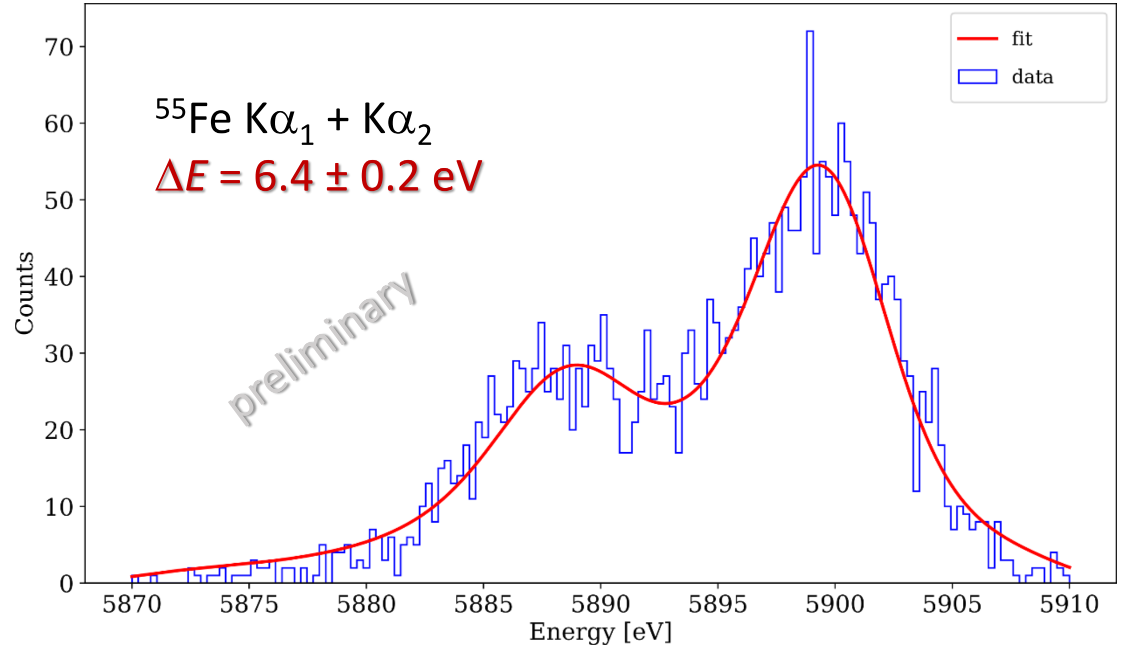
TES pixel testing with HOLMES DAQ (cont'd)



HOLMES pixel baseline

- f_{samp} = 500 kHz
- collimated source (i.e. lower activity per pixel)
- ΔE_0 = 4 eV
- low statistics on the Cl k_α line
- τ_{rise} 12 μs
- τ_{decay} 80 μs
- slew rate 0.4 ϕ_0/S @ 5.9 keV

- ➢ 200 x 200 x 2 μm^3 gold absorber
- ➢ 99.99998% (99.927%) full stop of 2 keV electrons (photons)
- ➢ C = 0.9 pJ/K
- ➢ G = 570 pW/K

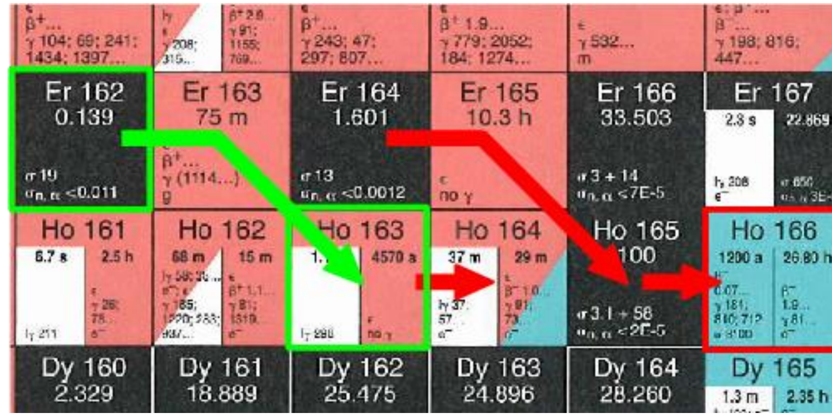


^{163}Ho production

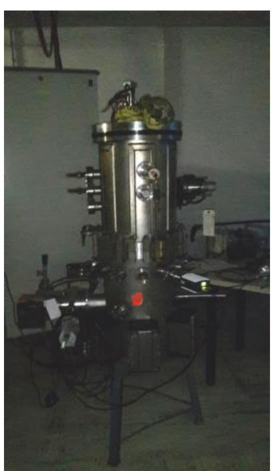
~ 200 MBq of ^{163}Ho required for HOLMES

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

^{163}Er $\longrightarrow$ ^{163}Ho + ν_e $\qquad$ $t_{½}^{EC} \approx 75$min

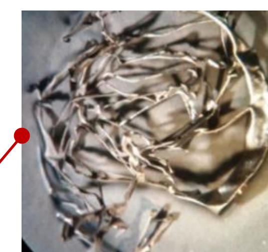


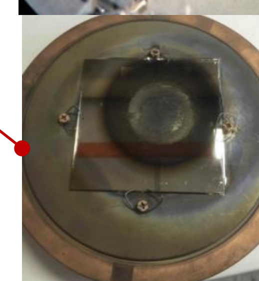
- ILL reactor @ Grenoble: thermal n flux 1.3x10^{15} n/cm^2/s
- cross section burn up ^{163}Ho(n,γ)^{164}Ho not negligible (~ 200 b)
- ^{165}Ho(n,γ) (mostly from ^{164}Er(n,^{g})) $\rightarrow$ ^{166mHo}, β $\tau_{½}$=1200y
- chemical pre-purification and post-separation at PSI (Villigen, Switzerland)



$$Ho_2O_3 + 2Y \longrightarrow 2Ho(met) + Y_2O_3 \qquad @\ T > 1600°C$$

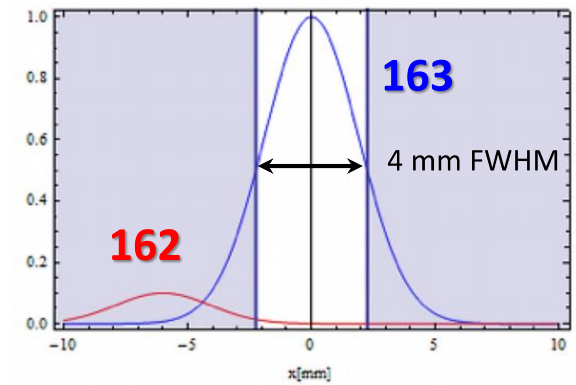
- ^{163}Ho reduced to metal (INFN-Genova)
- Ho target produced by pressing the metallic holmium
- measured efficiency ≈ 70% (preliminary)



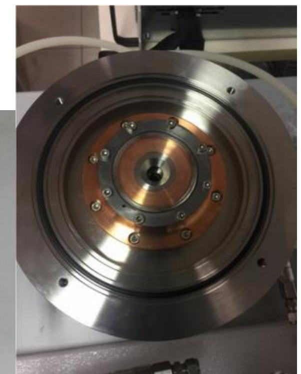


Mass separation and ion implantation

- 10-100 nm implantation depth
- $^{163}Ho/^{166m}Ho$ separation better than 10^5

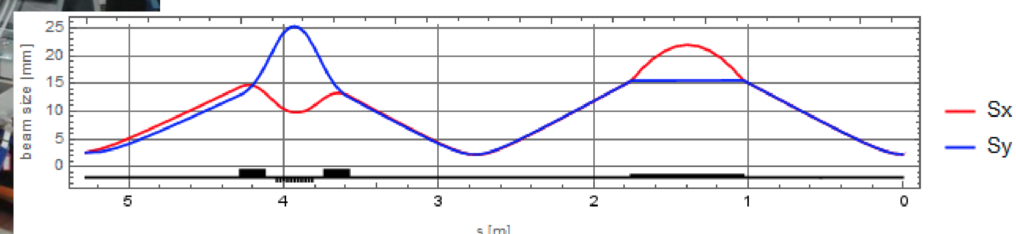


sputter target

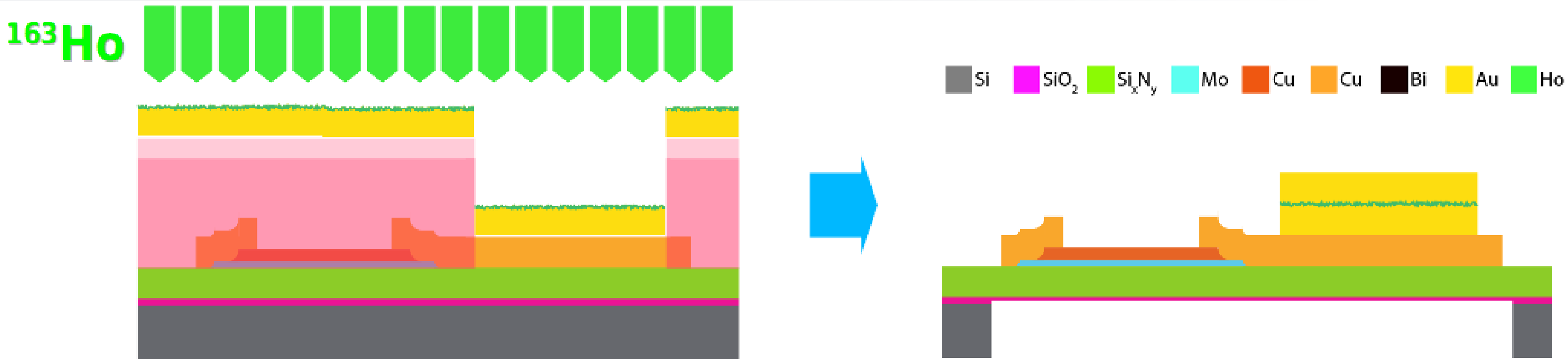


sputter ion source

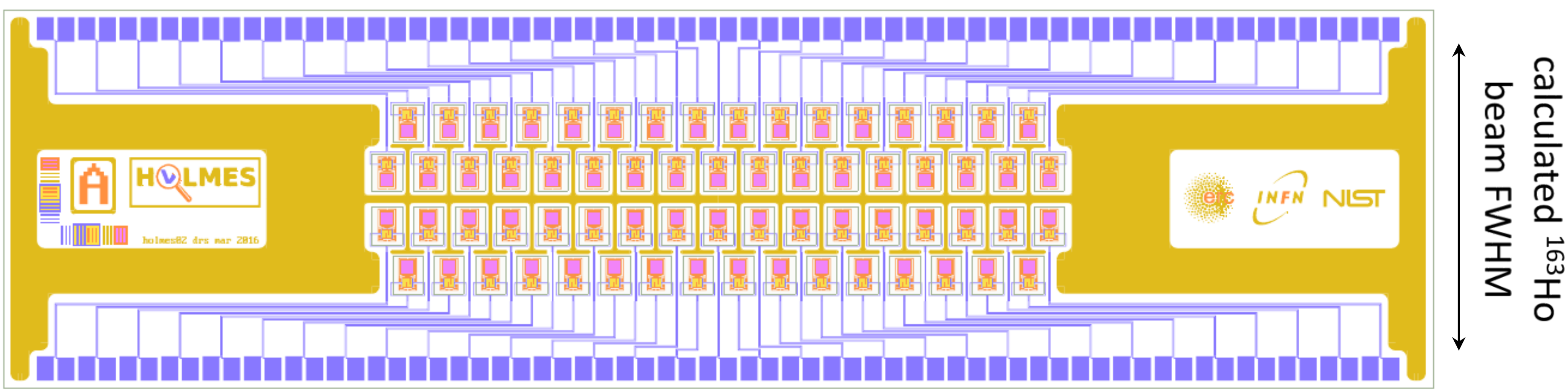
calculated beam size



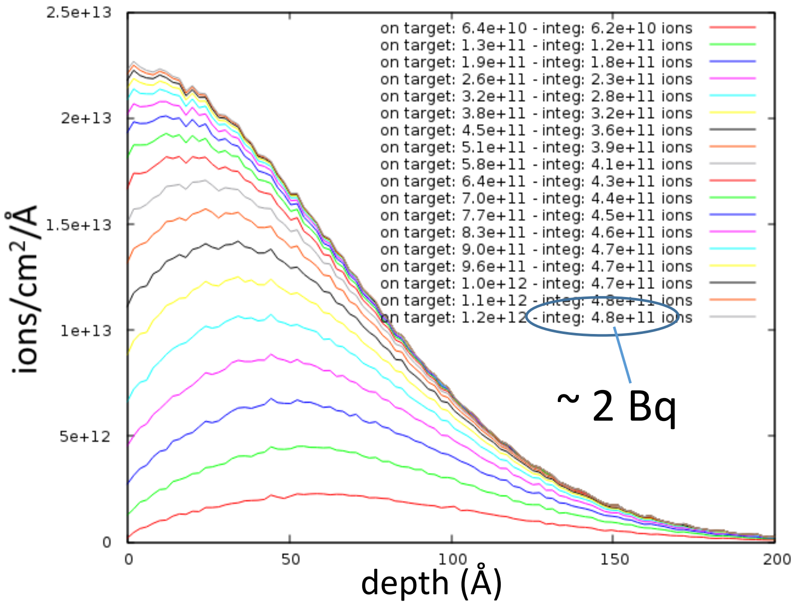
Detectors fabrication

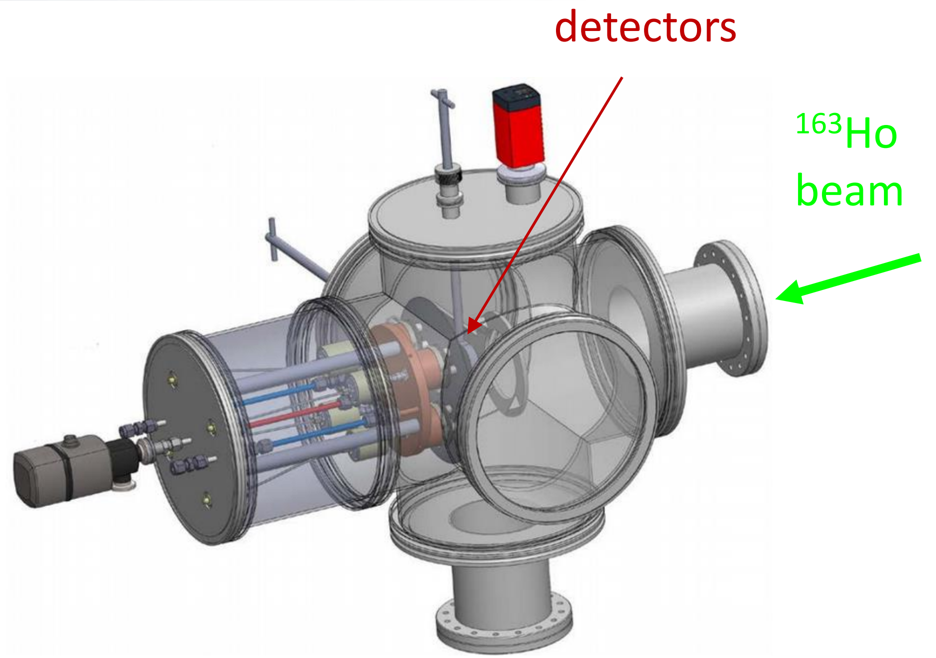


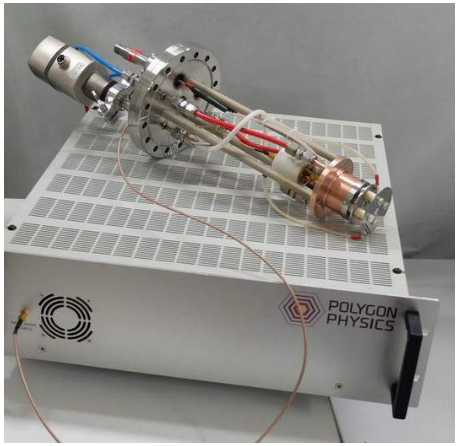
- TES fabricated at NIST, Boulder, CO, USA
- ^{163}Ho implantation at INFN, Genova, Italy
- 1 μm Au final layer deposited at INFN, Genova, Italy
- final fabrication process definition in progress
- HOLMES 4 x 16 linear sub-array for low parasitic *L* and high implant efficiency



Target chamber for absorber fabrication



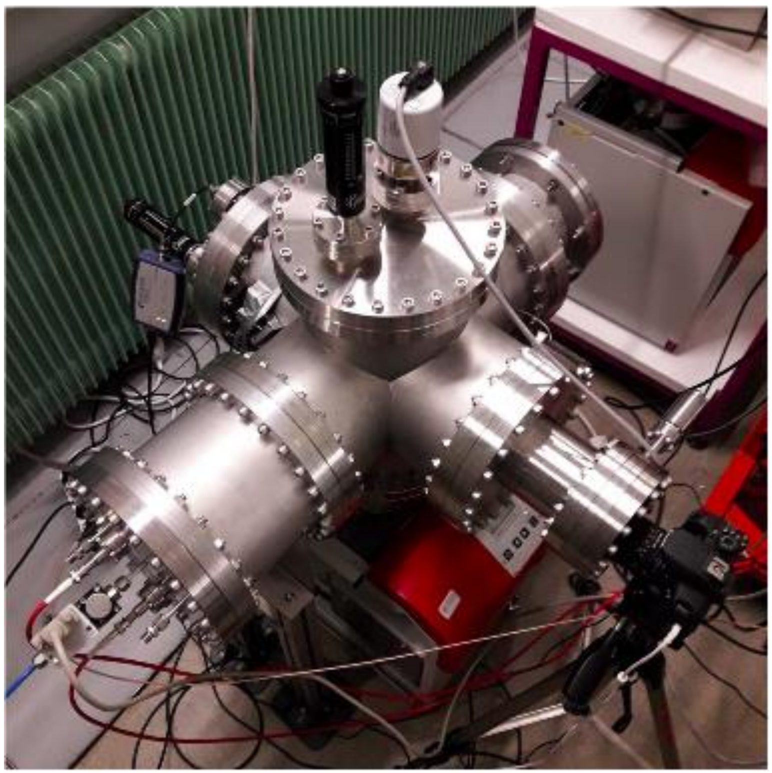


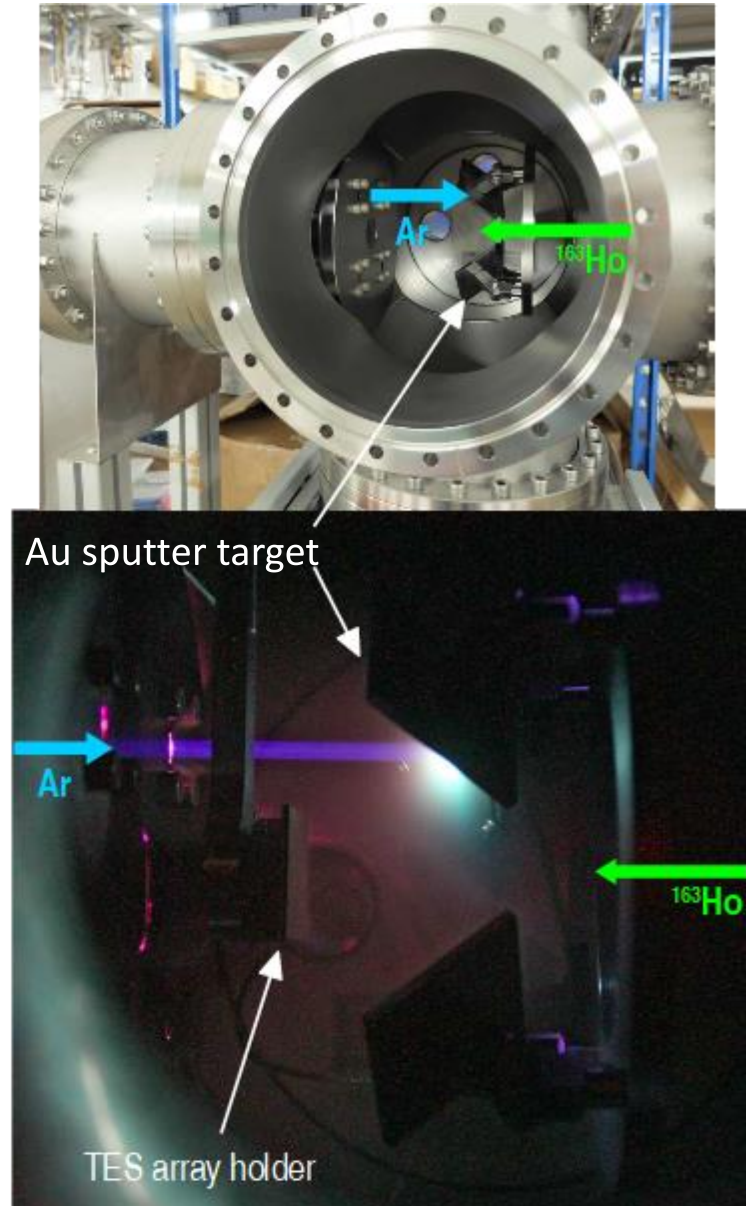


- ^{163}Ho concentration in absorbers saturate beacuse ^{163}Ho sputters off Au from absorber
- effect compensated by Au co-evaporation (also for heat capacity reasons)
- final 1 μm Au layer deposited in situ to avoid oxidation

Target chamber for absorber fabrication (cont'd)

system in testing phase





Conclusions - schedule

HOLMES is a challenging experiment aimed at the direct neutrino mass measurement

- ✓ Good performances of single pixel achieved with HOLMES DAQ (still room for improvements)
- ✓ Simultaneous readout of 4 pixels has been proved
- ✓ Firsts components of the implanter has been delivered and testing is in process