Status of the HOLMES experiment

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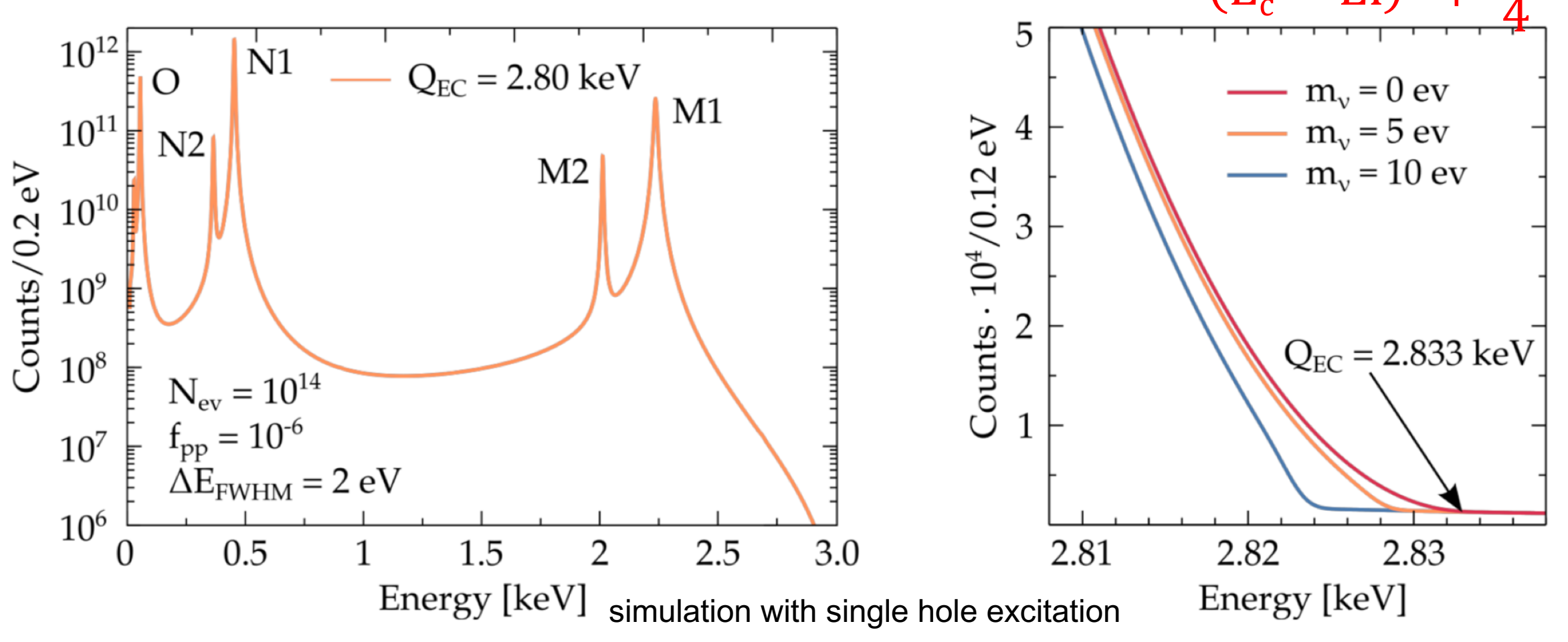
The assessment of the absolute ν mass scale is a crucial challenge in today particle physics and cosmology. The only experimental method which can provide a model independent measurement is the investigation of end-point distortion in beta/electron capture spectra. For such a kind of experiment it is mandatory to use an isotopic species with the lowest possible Q-value, because of statistical sensitivity scales as $1/Q^3$. For this reason, electron capture ^{163}Ho decay is a good choice, having a Q-value of 2.8 keV. The HOLMES experiment will exploit a calorimetric measurement of ^{163}Ho decay spectrum deploying a large set of cryogenic micro-calorimeters implanted with ^{163}Ho. In order to get the best experimental sensitivity, it is crucial to combine high activity with very small undetected pileup contribution. Therefore, the main tasks of the experiment are: the development of ~1000 fast (3 us time resolution) cryogenic micro-calorimeters with energy resolution down to few eV; the embedding inside the arrays of the highest ^{163}Ho compatible with detectors' thermodynamical properties and pile-up issues, avoiding contamination from other species, mainly ^{166m}Ho; the development of an efficient high bandwidth multiplexed readout. The commissioning of the first implanted array is currently on going; the first DAQ is expected to start in 2021. Here, the status of the experiment and the first results about detector commissioning will be discussed.

^{163}Ho decay via electron capture from shell ≥ M1, with Q_{EC} ~ 2.8 keV [1]:

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

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-Ec)\sqrt{(Q-Ec)^2 - m_\nu^2} \times \sum n_i c_i \beta_i^2 \frac{\Gamma_i}{2\pi}\frac{1}{(E_c - Ei)^2 + \frac{\Gamma_i^2}{4}}$$



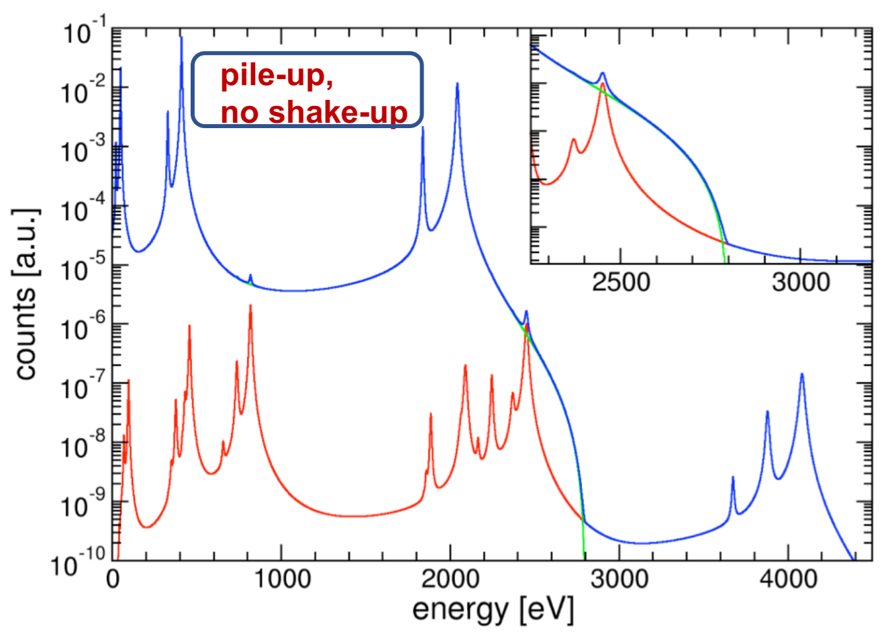
simulation with single hole excitation

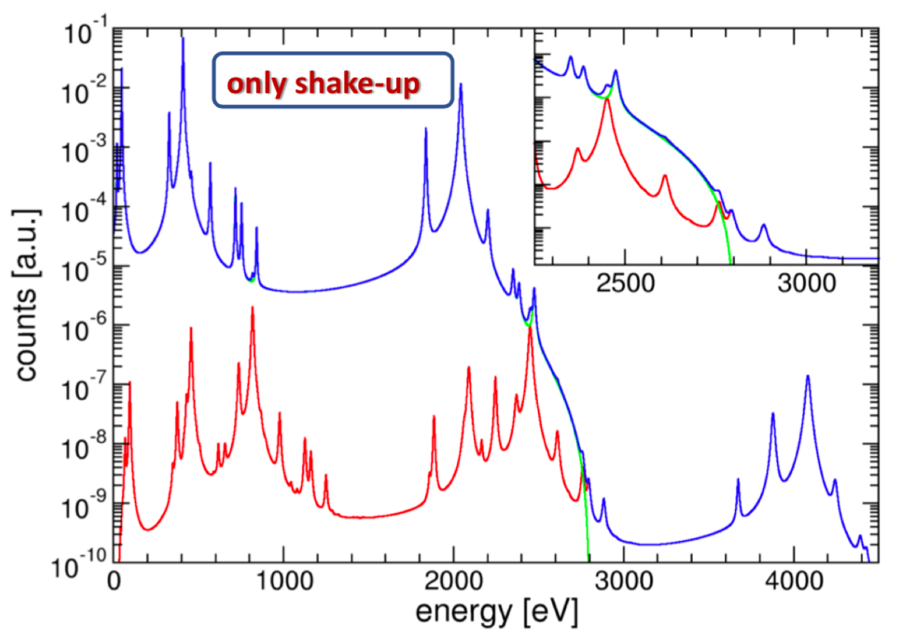
- **Calorimetric measurement** of Dy* de-excitation energy E_c
- **m_ν sensitivity depends on Q-value and capture peak position** (roughly ~$1/(Q-E_{M1})^3$)
- τ ~ 4570y: few active nuclei needed to obtain reasonable activity (1 Bq = 2 x 10^{11} nuclei)

Complex pile-up spectrum:
$N_{pp}(E) = f_{pp}N_{EC}(E) \otimes N_{EC}(E)$
with $f_{pp} = A_{EC} \times \tau_r$

Shake-up and shake-off process due to 2-holes excitation are possible:

- n holes excitations have much lower probability;
- energy and probabilities are still uncertain;
- Spectrum could be even more complicated.





Pile-up implies:

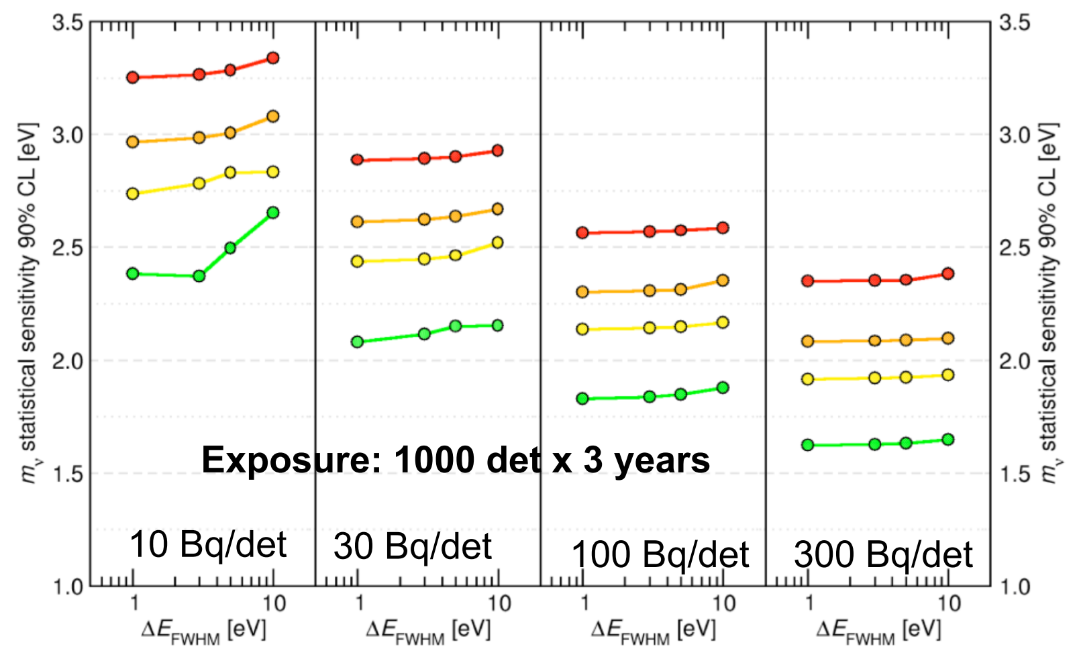
- tradeoff between detector activity and statistics;
- needs of detector with fast resolving time
- dedicated resolving algorithm.

Direct m_ν measurement with statistical sensitivity around 1 eV **using Transition Edge Sensors based microcalorimeters** with **^{163}Ho implanted Au absorber [2]**:

- 6.5 x 10^{13} nuclei/det, A_{EC} ~ 300 Bq/det
- Energy resolution O(eV), τ ~ 1μs
- 1000 channels array → 6.5 x 10^{16} total nuclei

Should prove the tecnique potential and scalability by: assessing EC spectral shape and systematic errors.
Two steps approach:

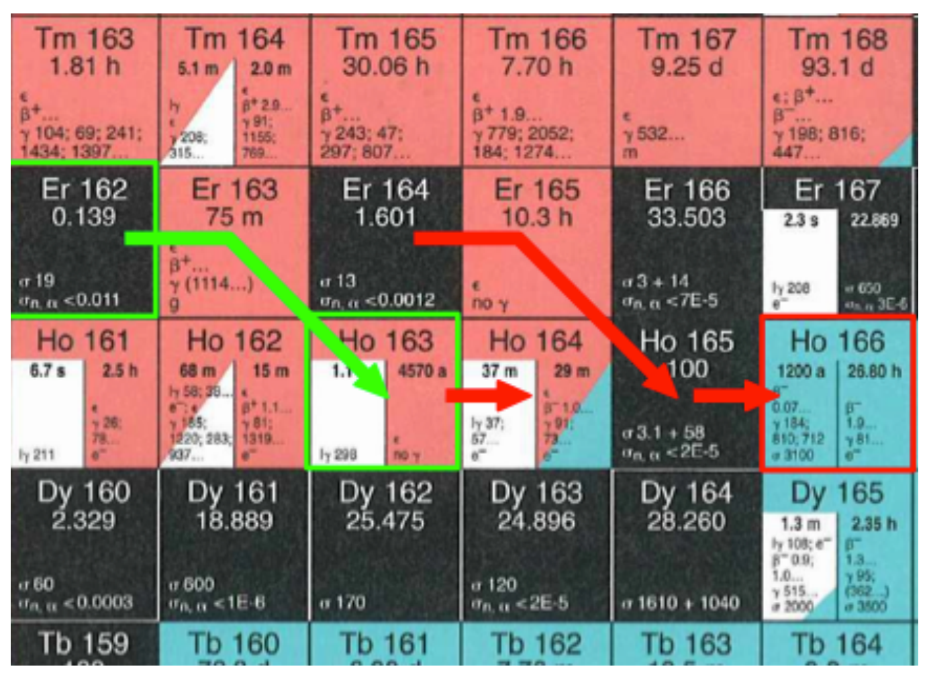
- 64 channels mid-term prototype, t_M = 1 month, m_ν sensitivity ~ 10 eV
- full scale: 512 channels, 1 x 10^{13} events collected in 3 years



Holmium production and embedding chain:

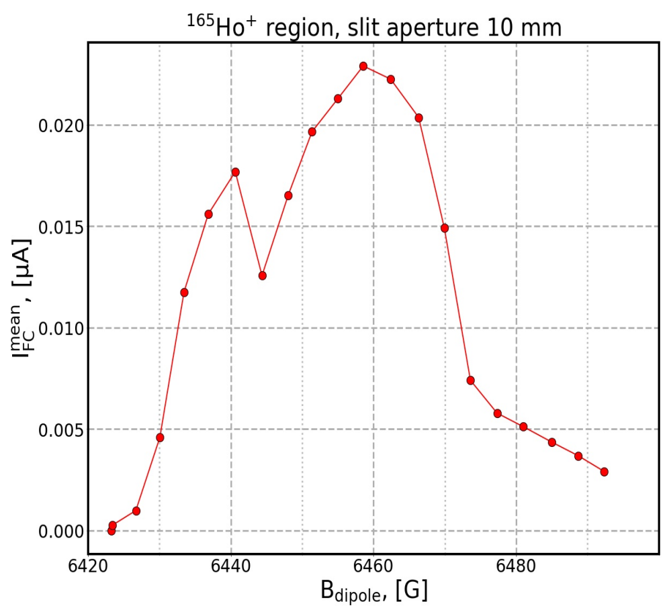
^{163}Ho is produced by n-activation of ^{162}Er sample:

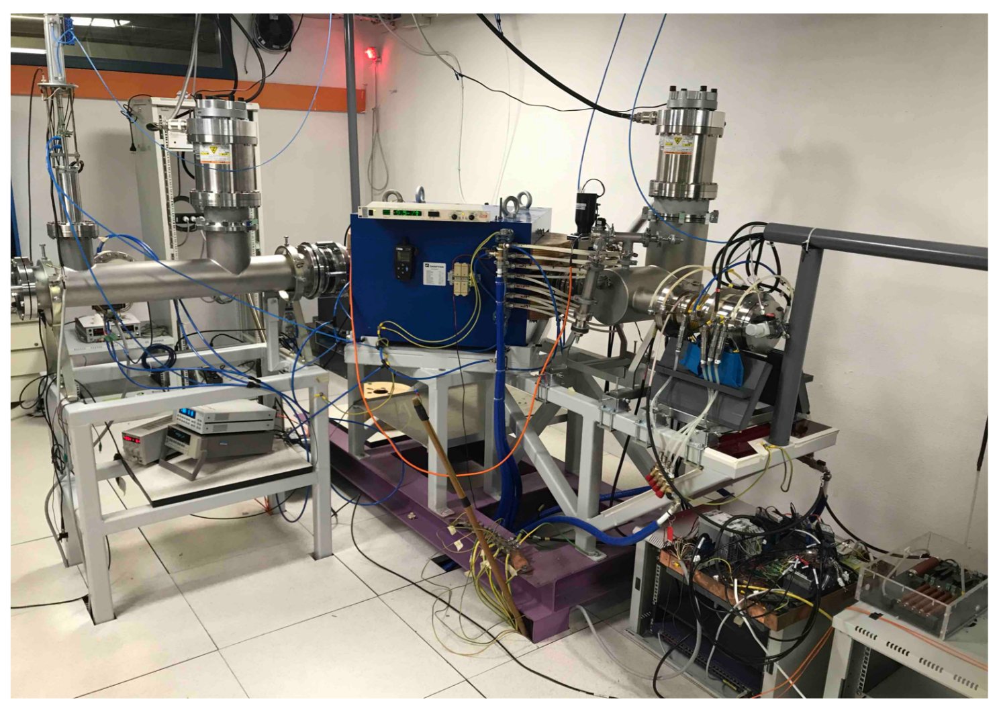
- $^{162}Er(n,\gamma)^{163}Er$, $^{163}Er + e^- \rightarrow {}^{163}Ho + \nu_e$ ($\tau_{1/2}$ ~ 75min)
- High yield (σ_{th}~ 20b), but contaminations from other species:
- $^{165}Ho(n,\gamma)^{166m}Ho$ (β, $\tau_{1/2}$ ~ 1200y)
- ^{166m}Ho is the main source of background.
- Could come from Ho contaminations or $^{164}Er(n,\gamma)$
- 2 steps purification procedure has been developed:



1) **Radiochemical purification pre and post irradiation**, based on ion exchange chromatography: eliminates all species other than Ho, leaves a 166:163 ratio better than 1:1000

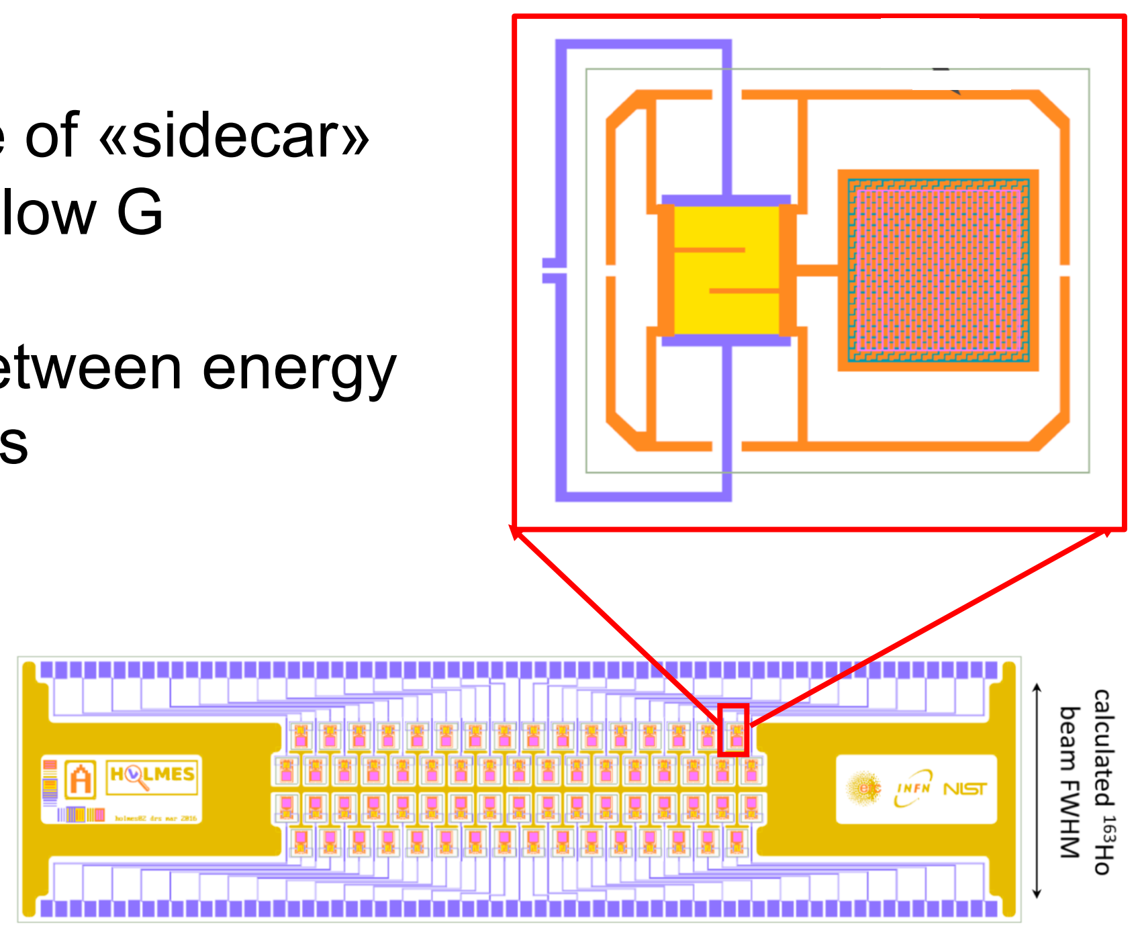
2) **Mass separation based on ion implanter** (E = 30 – 50 keV) **equipped with magnetic dipole + electrostatic quadrupole** produces a 163Ho beam with 4mm FWHM spot and mass separation 163/166 better than 5σ.





TES design and production:

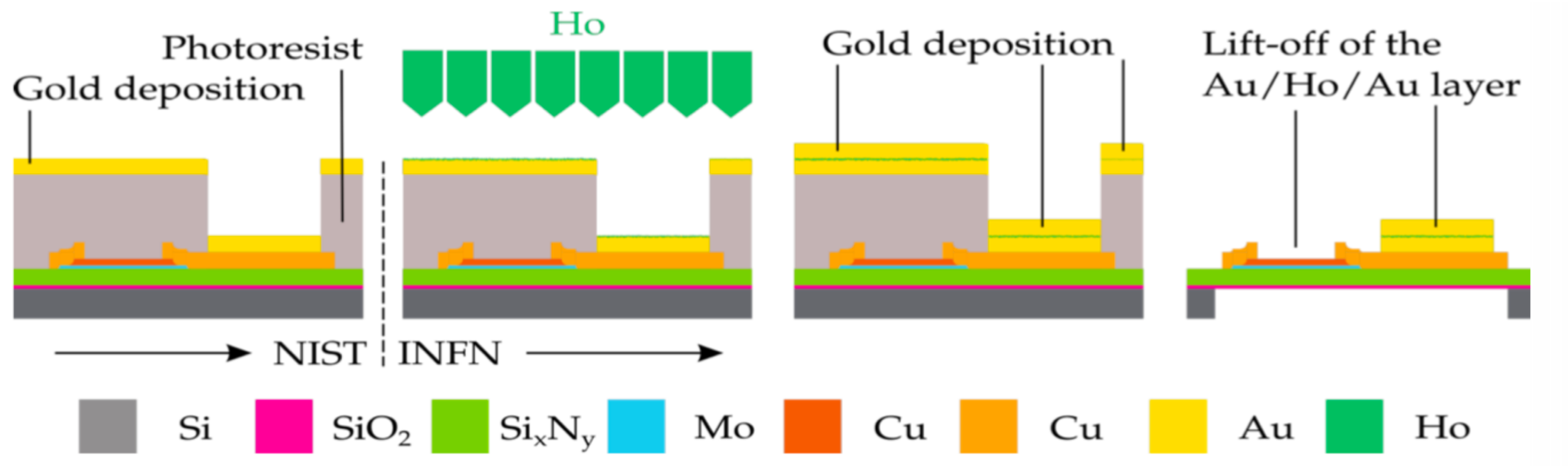
2 μm Au absorber for full e^-/γ absorption, usage of «sidecar» configuration to avoid TES proximization and allow G engineering for τ control.
Desing optimized to obtain best compromise between energy resolution and time response: ΔE O(eV), τ ~ 1μs

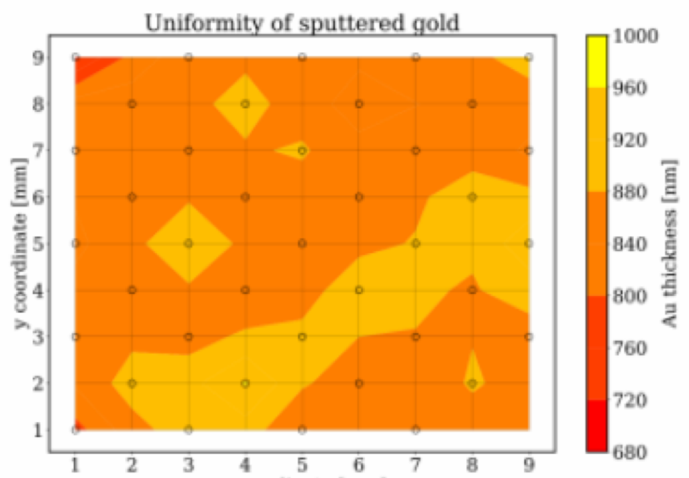


Multistep production:

1. TES array is produced up to first 1μm Au layer;
2. ^{163}Ho implantation and Au co-evaporation;
3. 1μm Au final layer deposition;
4. membrane release with KOH or DRIE process.

- 4 x 16 linear array for low parasitic L and high implant efficiency

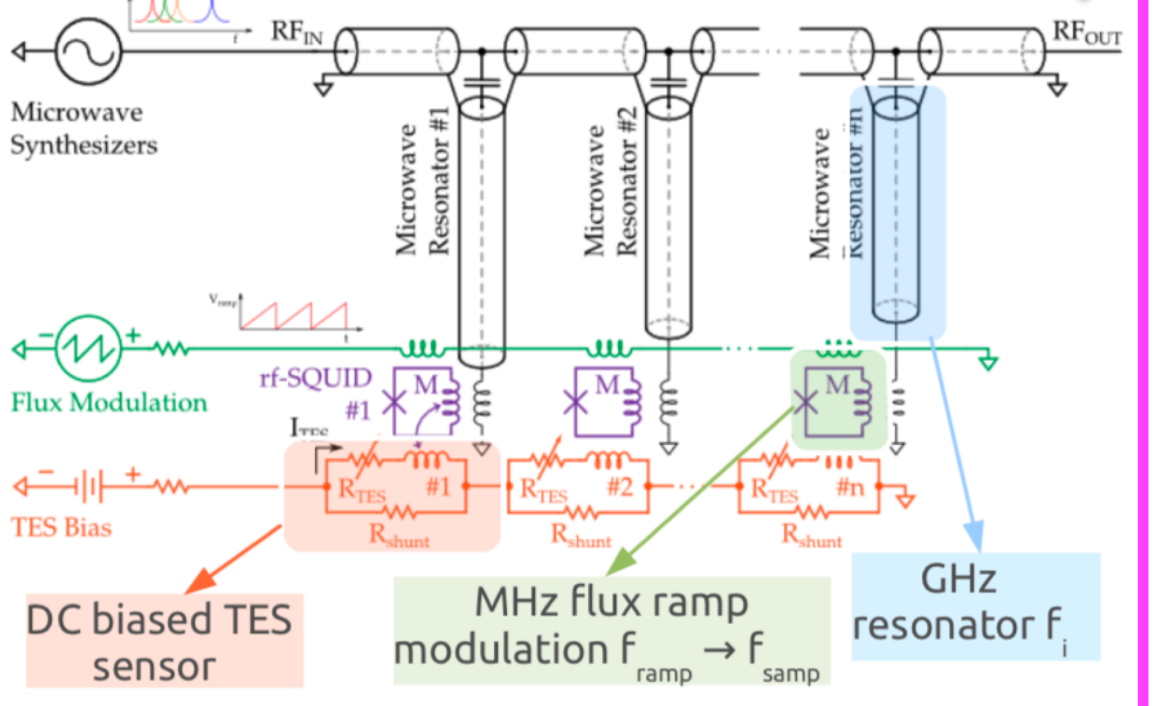


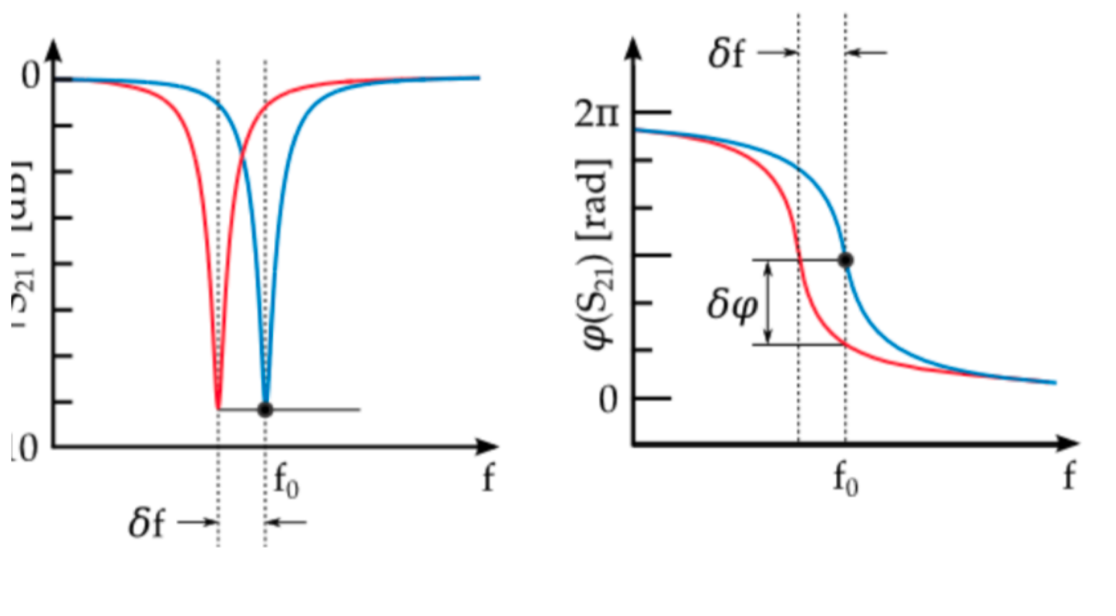


RF SQUID readout with microwave multiplexing: SQUID coupled with DC biased TES and a λ/4-wave resonant circuit:

- readout with flux ramp demodulation (common flux line inductively coupled to all SQUIDs);
- signal reconstructed by Software defined Radio Technique (ROACH2, ADC bandwidth 550MHz).

1. Energy deposit in the absorber increases the temperature and therefore the TES resistance.
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.



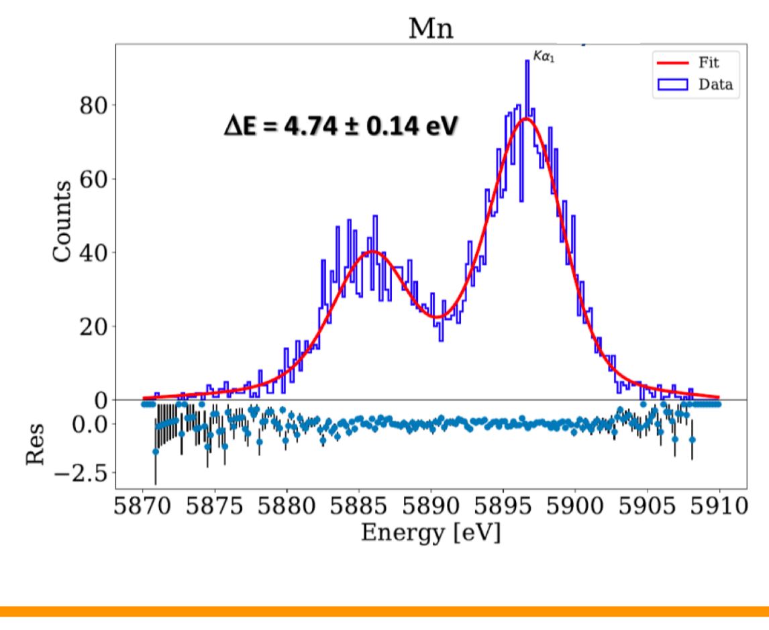


Status and perspectives:

Source production: 3 batches have been already irradiated at ILL (Grenoble, FR), for a total of 140MBq of ^{163}Ho. The radiochemical separation process has been proved to work with an efficiency ≥ 79%

Ion implanter: the comissioning of the machine is almost finished in Genova's INFN laboratory. Test with different targets containing 165Ho are on going.

Microcalorimeter test: several geometries were tested using ^{55}Fe (5.9 keV) and fluorescence source (Mn - 5.9 keV, Ca - 3.7 keV, Cl – 2.6 keV, Al – 1.7 keV). A 3.5 to 5 eV energy resolution have been evaluated on those lines.



[1] A. De Rujula, M. Lusignoli Phys. Lett. B 118 (1982) 429
[2] B. Alpert et al., Eur. Phys. J. C (2015) 75:112