Transition-edge sensor arrays of microcalorimeters with Ho-163 for direct neutrino mass measurements with HOLMES

Angiola Orlando*

M. Biasotti*, V. Ceriale*, M. De Gerone*, F. Gatti, J. Hays-Wehle°, G. Pizzigoni*, D. Schmidt°, D. Swetz°, J. Ullom°

(*INFN Genova, °NIST)

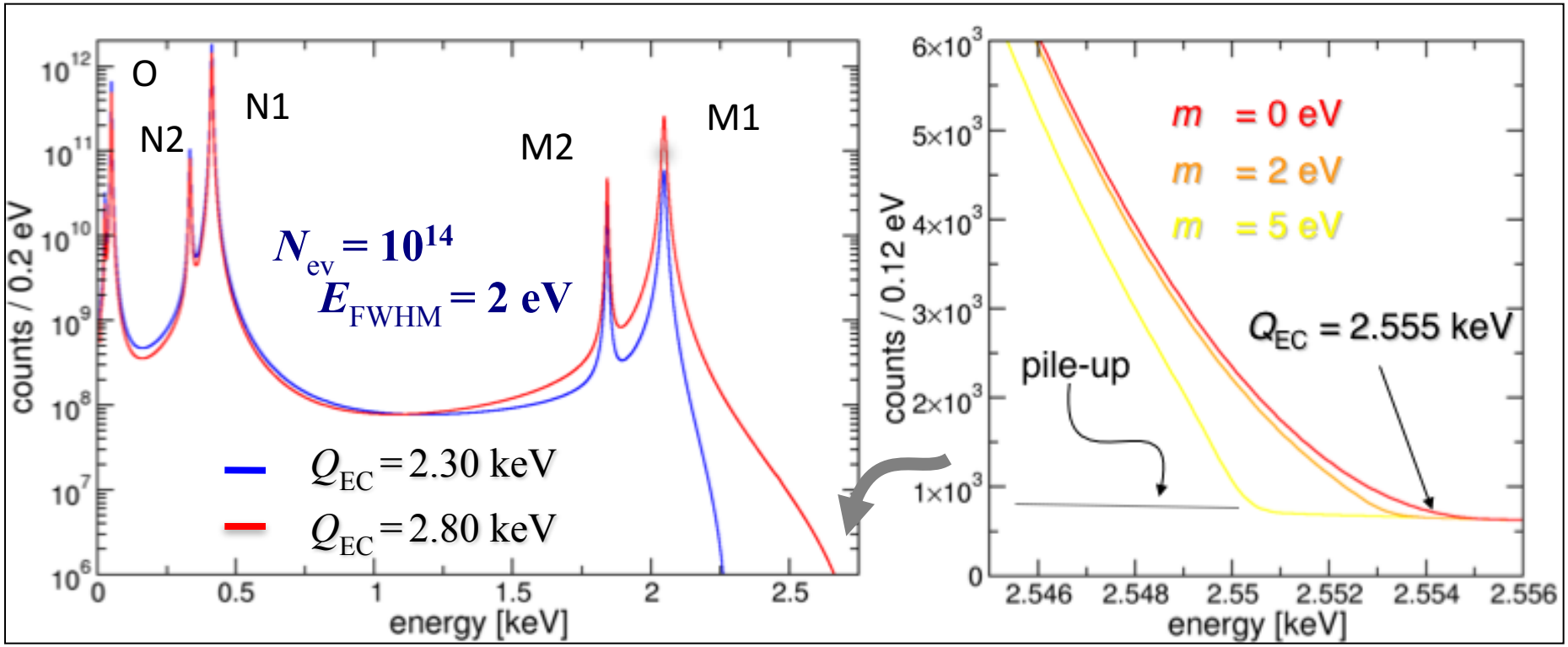
Electron capture end-point experiment

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

Electron capture from shell M1

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

- Calorimetric measurement of atomic de-excitations



HOLMES (ERC Advanced Grant)

Goals

•Neutrino mass measurement with statistical sensitivity as low as 0.4eV;
•prove technique and its scalability;
- assess EC Q value;
- assess systematic errors.

Baseline configuration

•TES with implanted ^{163}Ho
- 6.5×10^{13} nuclei per pixel
  → 300 dec/sec
- $\Delta E \approx 1$eV and $\tau_R \approx 1\mu$s

•1000 channels array
6.5×10^{16} ^{163}Ho nuclei
→ ≈18μg
3×10^{13} events in 3 years

Detector development for HOLMES

- Holmes will use large transition edge sensor arrays of microcalorimeters, readout by a microwave SQUID multiplexer.

- NIST has developed transition-edge x-ray microcalorimeters since 1990s, with best achieved energy resolutions = 2.1 eV at 5.9 keV and 1.5 eV at 1.5 keV (FWHM).

Challenging requirements

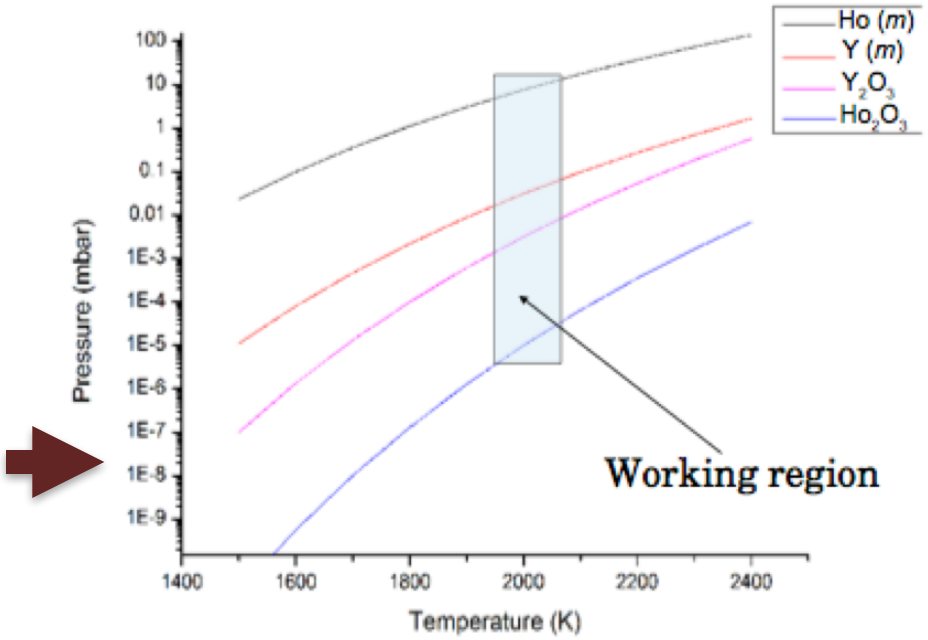
- Fast pulse response ($\lesssim$ 5μs rise time, ~ 10^{-4} s recovery time)
- Preserve resolution (~ 1eV @ 2.5keV)
- Need to be compatible with ^{163}Ho implantation

Holmium reduction and distillation/1

- ^{163}Ho is not present in nature. One of the methods for production is neutron irradiation of enriched ^{162}Er, which is typically in oxide form → the final product is composed mainly by both Ho and Er oxides.
- The presence of holmium oxide would modify the shape of the calorimetric spectrum → it is necessary to purify the holmium sample through a reduction and distillation process.

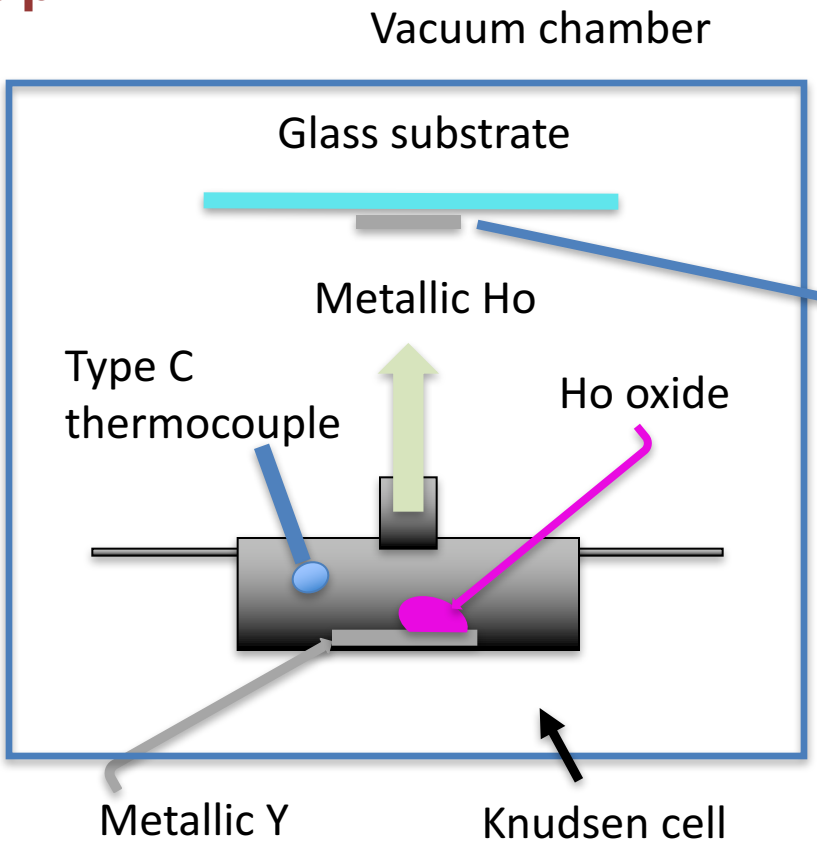
Methodology: heat a mixture of yttrium and holmium oxide above the melting point. Due to different std enthalpy of formation oxygen is captured by yttrium, leaving pure metallic holmium.

In order to separate the purified holmium from other species one can rely on the higher vapour pressure of the metallic holmium at a fixed temperature

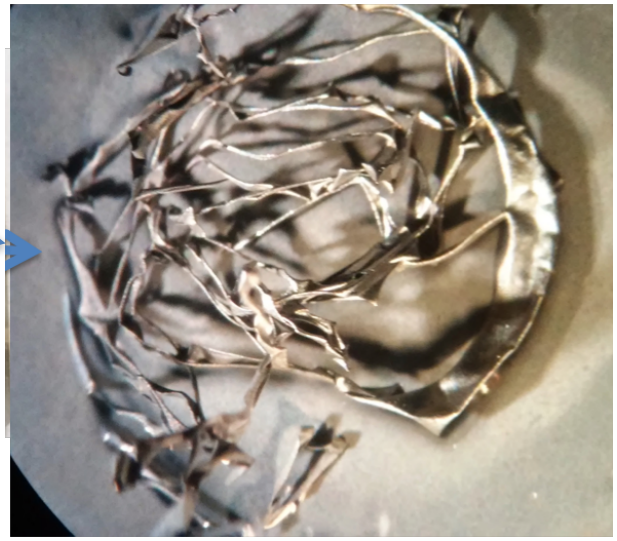


Holmium reduction and distillation/2

Setup



First metallic holmium



G. Pizzigoni

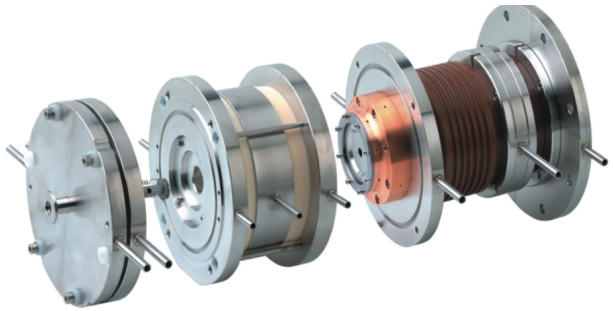
See Poster G 2.3 for more details

Distillation must be done in vacuum to avoid holmium vapour oxidation before condensing onto the target → the growth of the oxide on the metal surface is monitored in realtime using a XPS system.

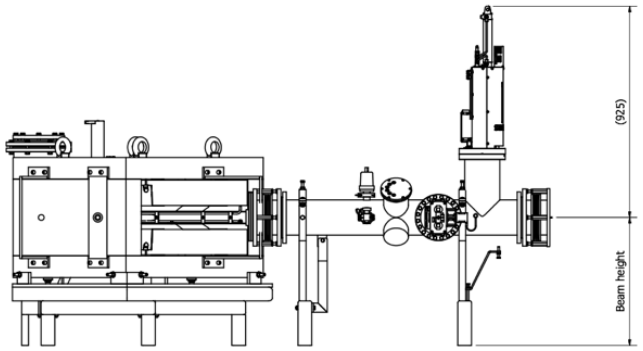
The XPS analysis of the condensed material doesn't show any yttrium contamination

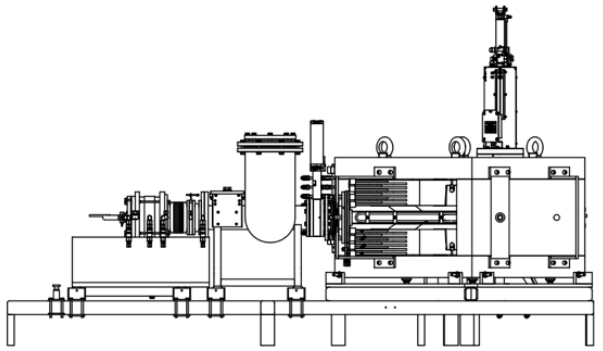
Need to measure system efficiency as function of temperature!

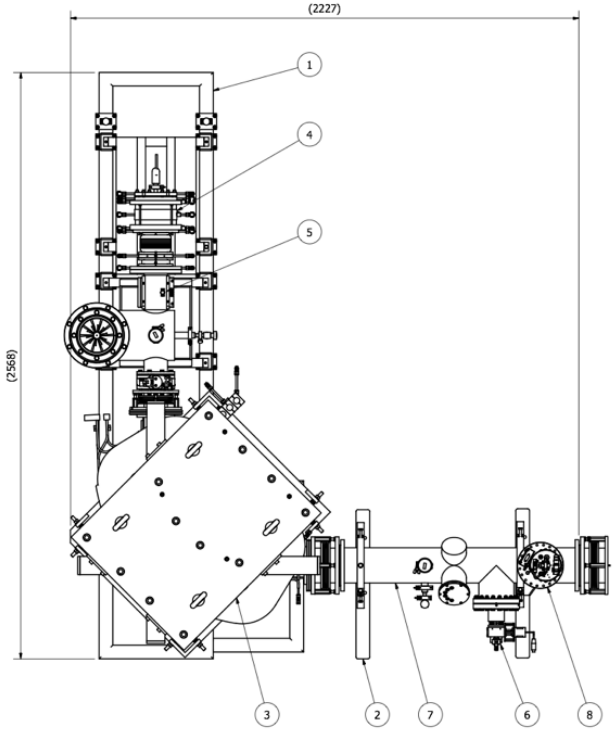
Custom ^{163}Ho source embedding system (preliminary layout)

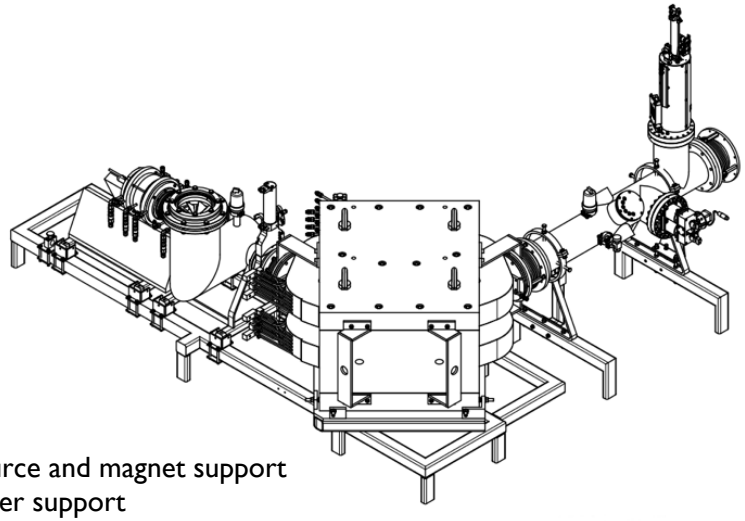


Preliminary layout



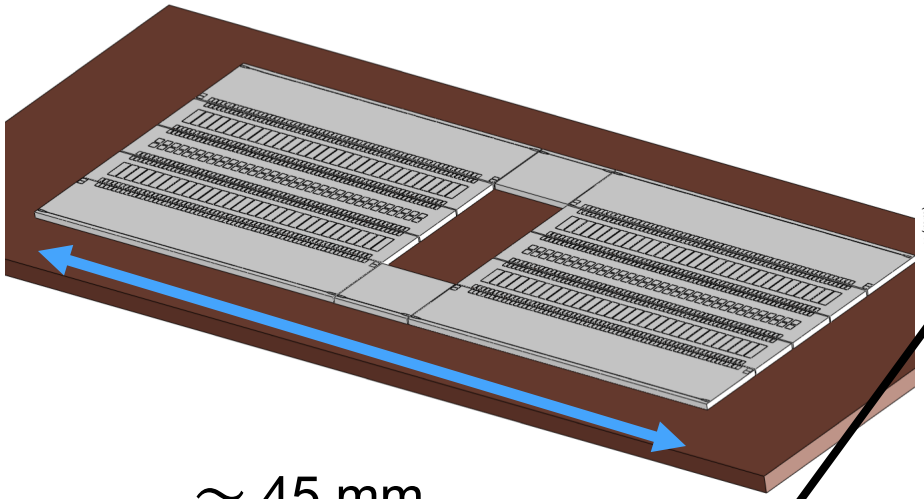


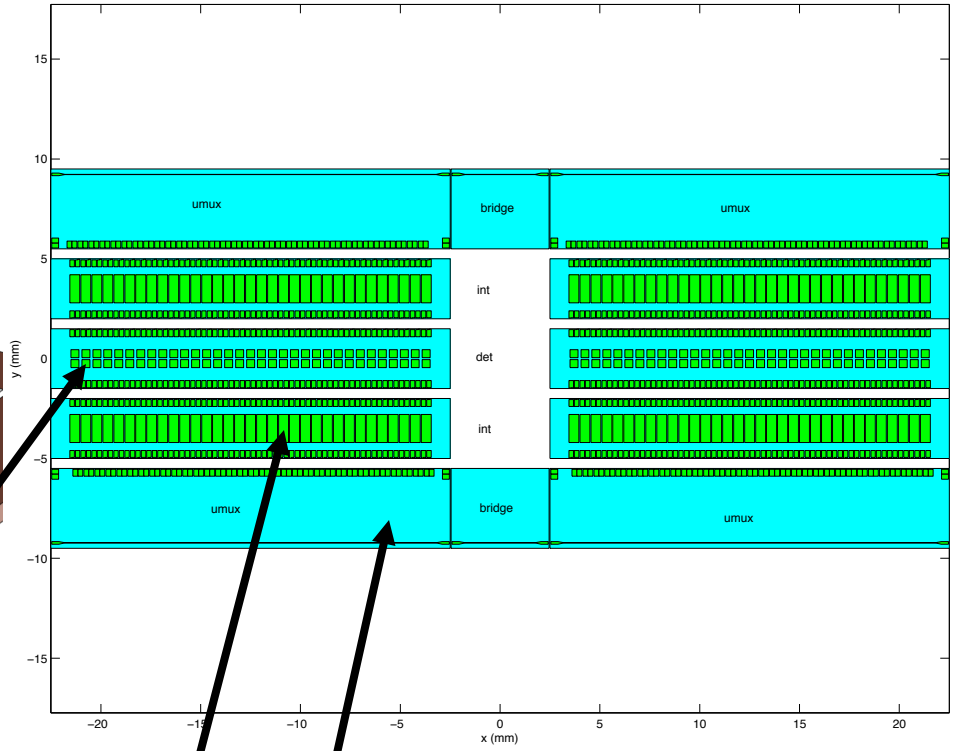




1) Ion source and magnet support
2) Chamber support
3) Analyzing dipole magnet
4) Ion source
5) Steering magnet
6) Water cooled slit
7) Vacuum chamber
8) Faraday cup

A modular experiment





∼ 45 mm

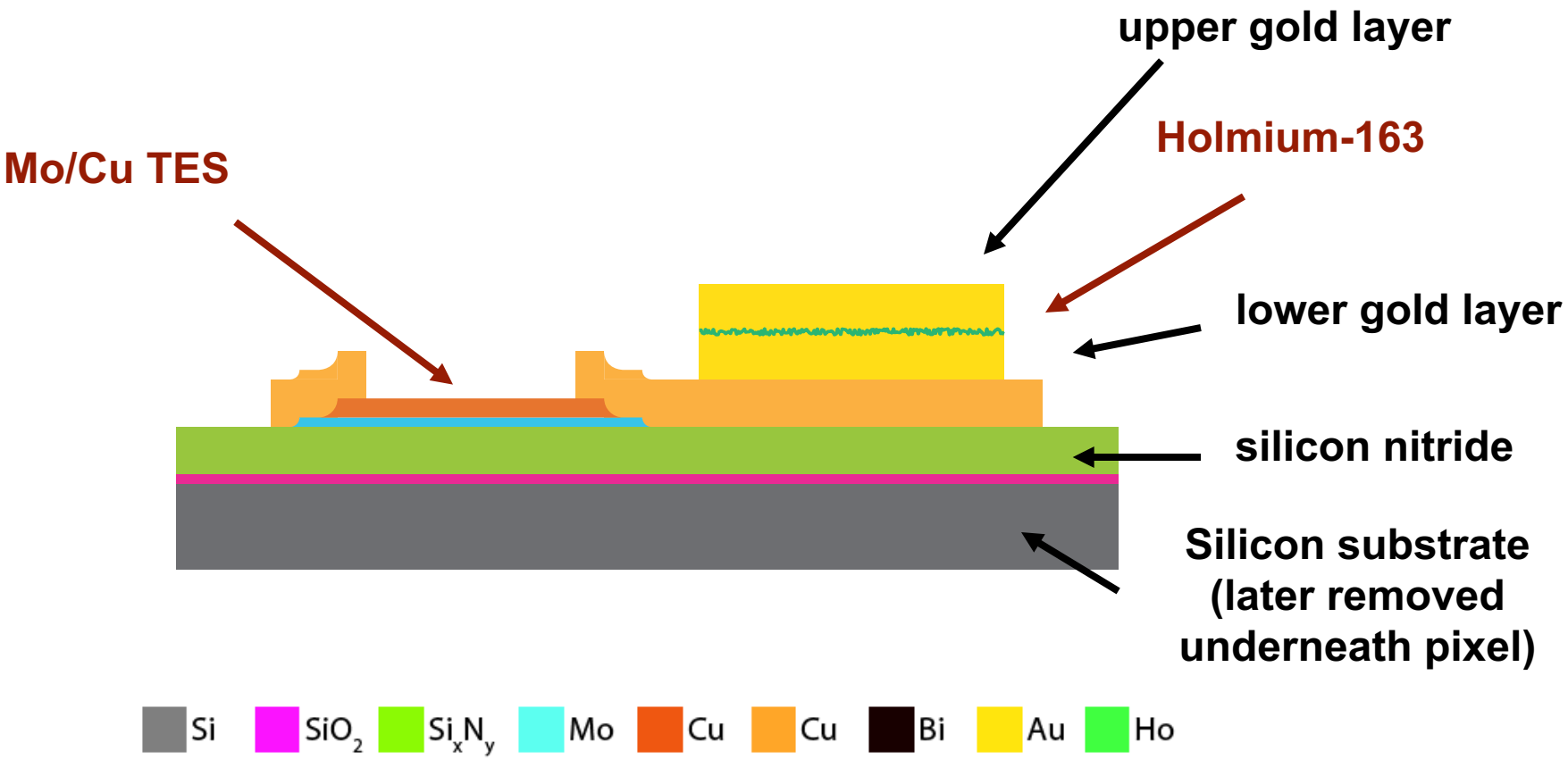
66 ^{163}Ho implanted sensors

interface chip with bias resistors

microwave SQUID readout chip

This package can be replicated or expanded to 1024 sensors

Cross section of current pixel design



TES parameters optimization

How to make detectors faster?

- Simplified recovery time:

$$\tau = C/(G + \frac{\alpha P}{Tc}) \approx C/(G\left(1 + \frac{\alpha}{n}\right))$$

- G = dP/dT[W/K]
- C = heat capacity
- $\alpha = \frac{T}{R}\frac{dR}{dT}$, temperature sensitivity
- $\beta \equiv \frac{I}{R}\frac{dR}{dI}$, current sensitivity

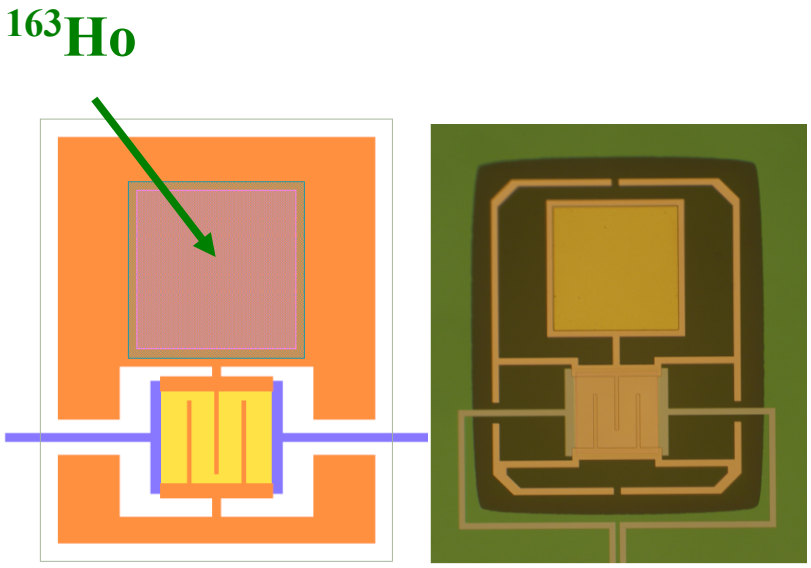
- $E_{max} = C\ T_c/\ \alpha$ → decreasing C and increasing α is not ideal

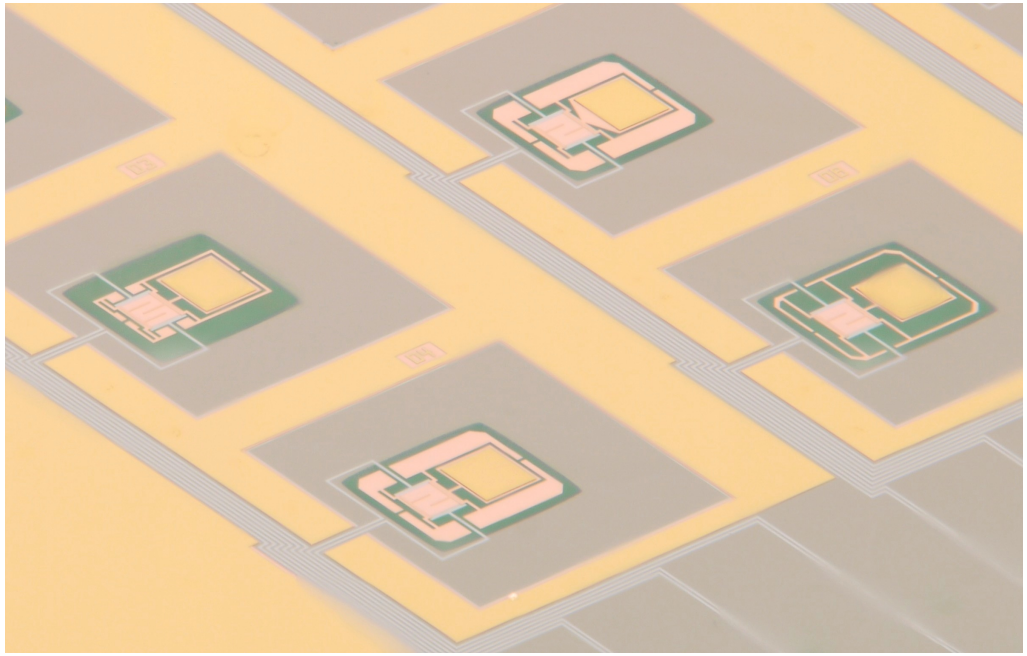
- Energy resolution : $\Delta E \approx \sqrt{4kbT^2C(1+\beta)/\alpha}$

best way to speed up pixels is to increase G

HOLMES pixel design

- optimize design for speed and resolution
- **specs @2.5keV : $\Delta E_{FWHM} \approx 1$eV, $\tau_{rise} \lesssim 5\mu$s, $\tau_{decay} \approx 100\mu$s** (* exponential time constants)
- *G* engineering for speed → any G from 40pW/K up to 1nW/K is achievable (**see P1.1**)
- 2 μm Au thickness for *full* electron and photon absorption
  - GEANT4 simulation: 99.99998% / 99.927% full stopping for 2 keV electrons / photons
- define process for ^{163}Ho implantation

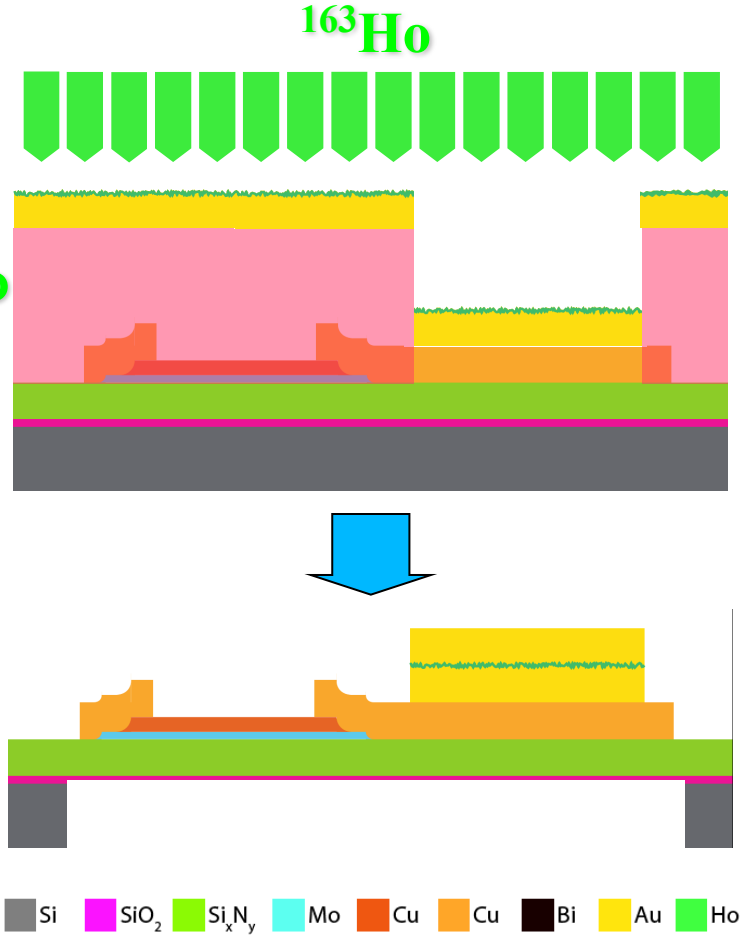


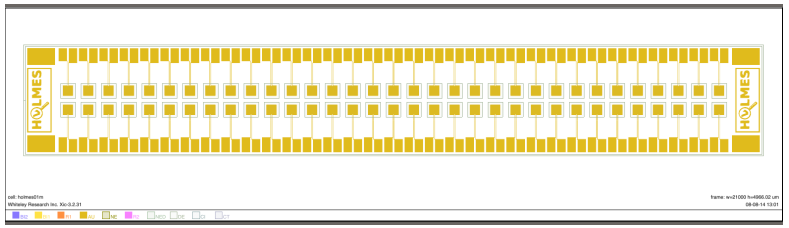


- **tests at NIST are in progress**
  - from preliminary measurements model predicts:
  - **$\Delta E_{FWHM} \approx 3$ eV, $\tau_{rise} \approx 6$ μs, $\tau_{decay} \approx 130$ μs** (L = 35 nH)

HOLMES detector array fabrication

- 2 μm thick Au encapsulating implanted ^{163}Ho
- TES and first layer of Au absorber (~ 1 μm) fabricated at NIST
- ^{163}Ho implantation, second layer Au deposition and Si_3N_4 membrane release at INFN Genova





Conclusions

- HOLMES technology development is really challenging, but it is well underway;
- Distillation of metallic holmium, starting from holmium oxide, has been demonstrated in Genoa→ needs optimization;
- Custom ion implanter has been defined and purchase is almo st finalized – it should be delivered to Genoa by end of year.
- TES pixel design optimization is ongoing and it is showing promising results.