Status of the HOLMES experiment to directly measure the electron neutrino mass

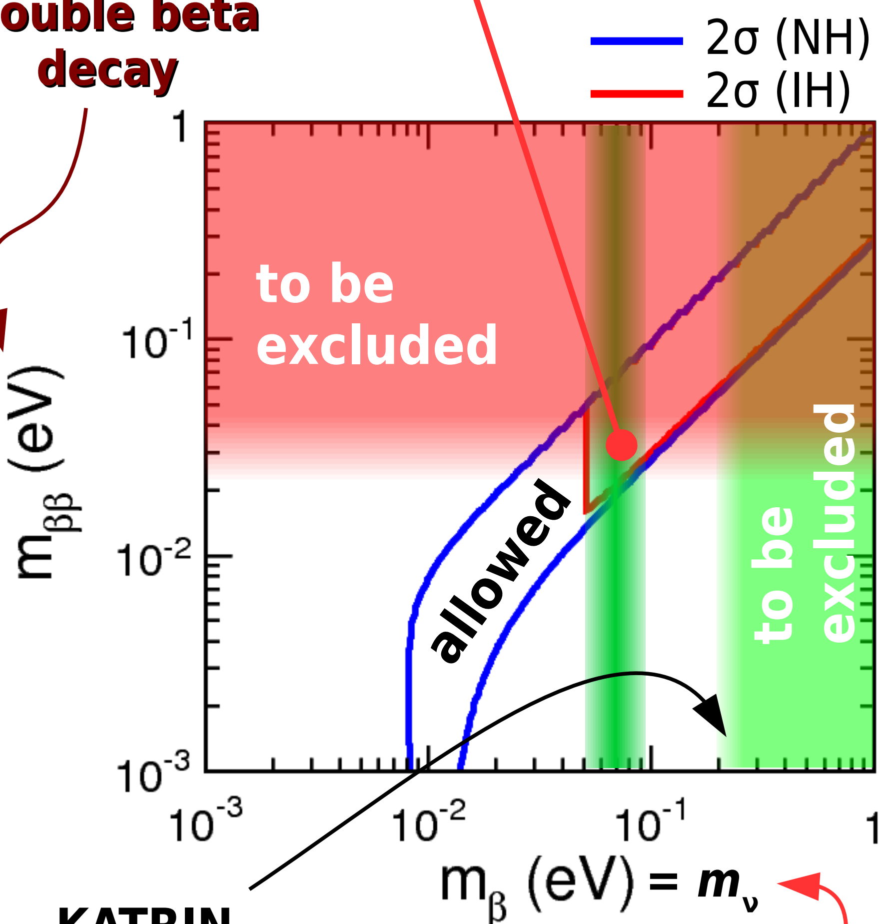
Angelo Nucciotti
on behalf of the HOLMES collaboration
Università di Milano-Bicocca e INFN - Sezione di Milano-Bicocca

LTD17
17th International Workshop on Low Temperature Detectors
July 17-21, 2017
Kurume, Fukuoka, Japan

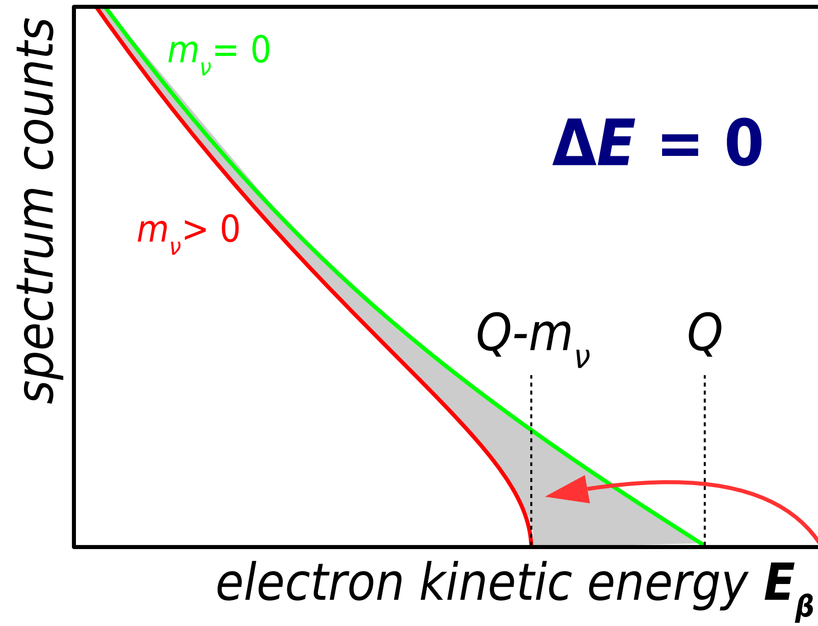
Assessing the neutrino mass

from **neutrinoless double beta decay**

how to get to here?



KATRIN spectrometer
m_ν<0.2 eV
in 2018



- **kinematics of weak decays with ν emission**
  - low *Q* nuclear beta decays (^3H, ^{187}Re...)
  - only energy and momentum conservation
  - no further assumptions

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$

$$N(E_\beta) \propto p_\beta E_\beta (Q-E_\beta)\sqrt{((Q-E_\beta)-m_\nu^2)}\,F(z,E_\beta)\,S(E_\beta)$$

- **2 approaches with different systematics:**
  - **spectrometry** with the β source outside
  - **calorimetry** with the β source inside

A. Nucciotti, Adv. High Energy Physics, 2016, 915304

Electron capture calorimetric experiments / 1

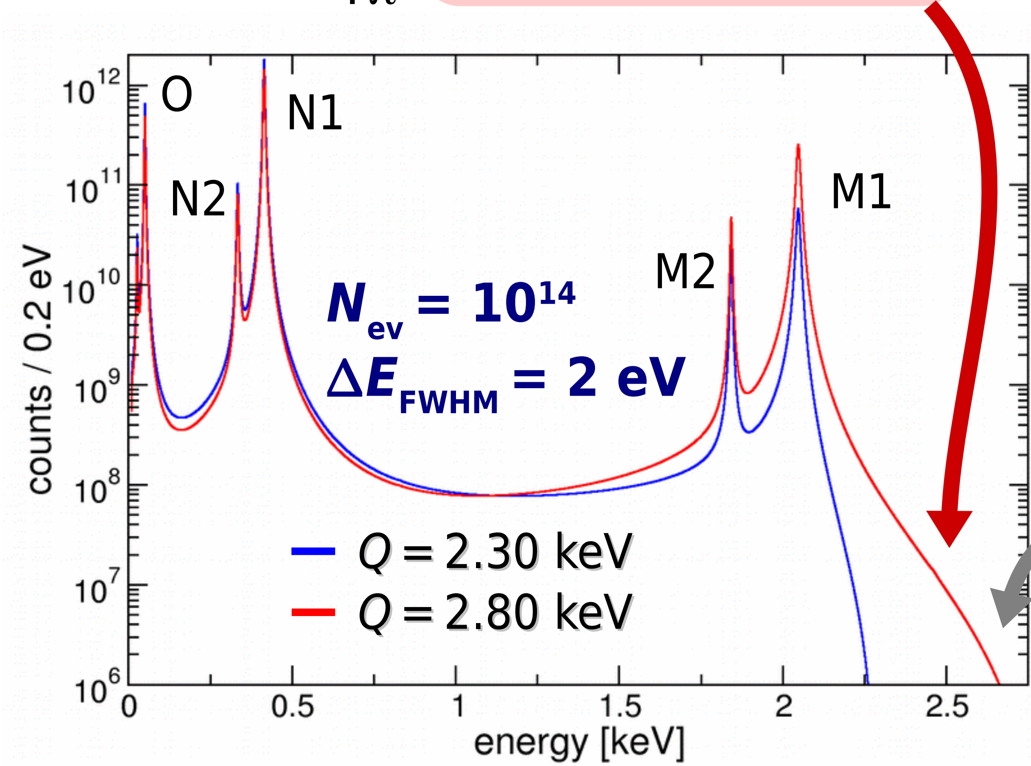
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

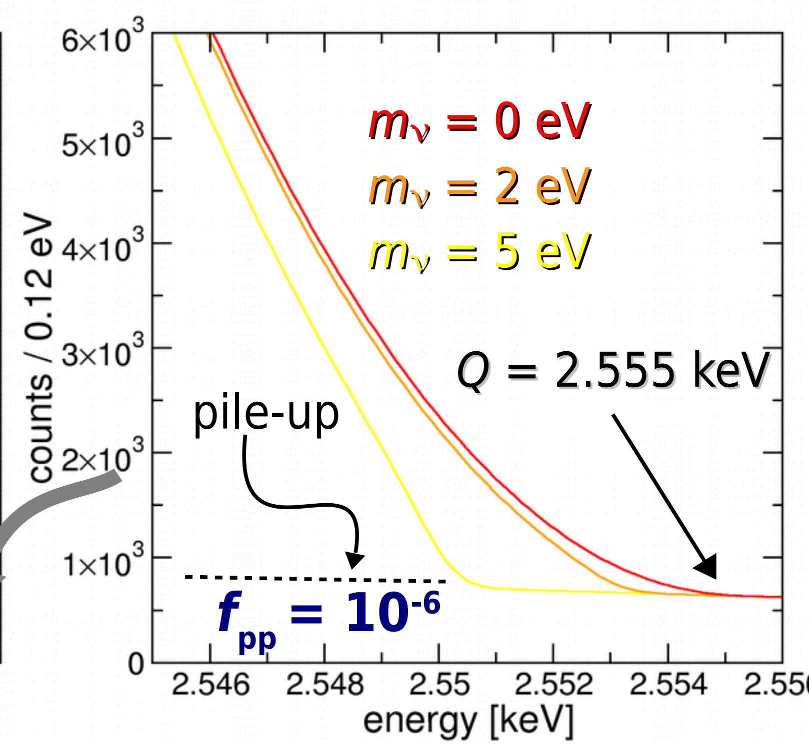
electron capture from shell ≥ M1

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

- **calorimetric measurement of Dy atomic de-excitations** (mostly non-radiative)
- ***Q* = 2.8 keV** (measured with Penning trap)
  - end-point rate and ν mass sensitivity depend on $Q - E_{M1}$
- **$\tau_{1/2}$ ≈ 4570 years** → 2×10^{11} ^{163}Ho nuclei ↔ 1Bq

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

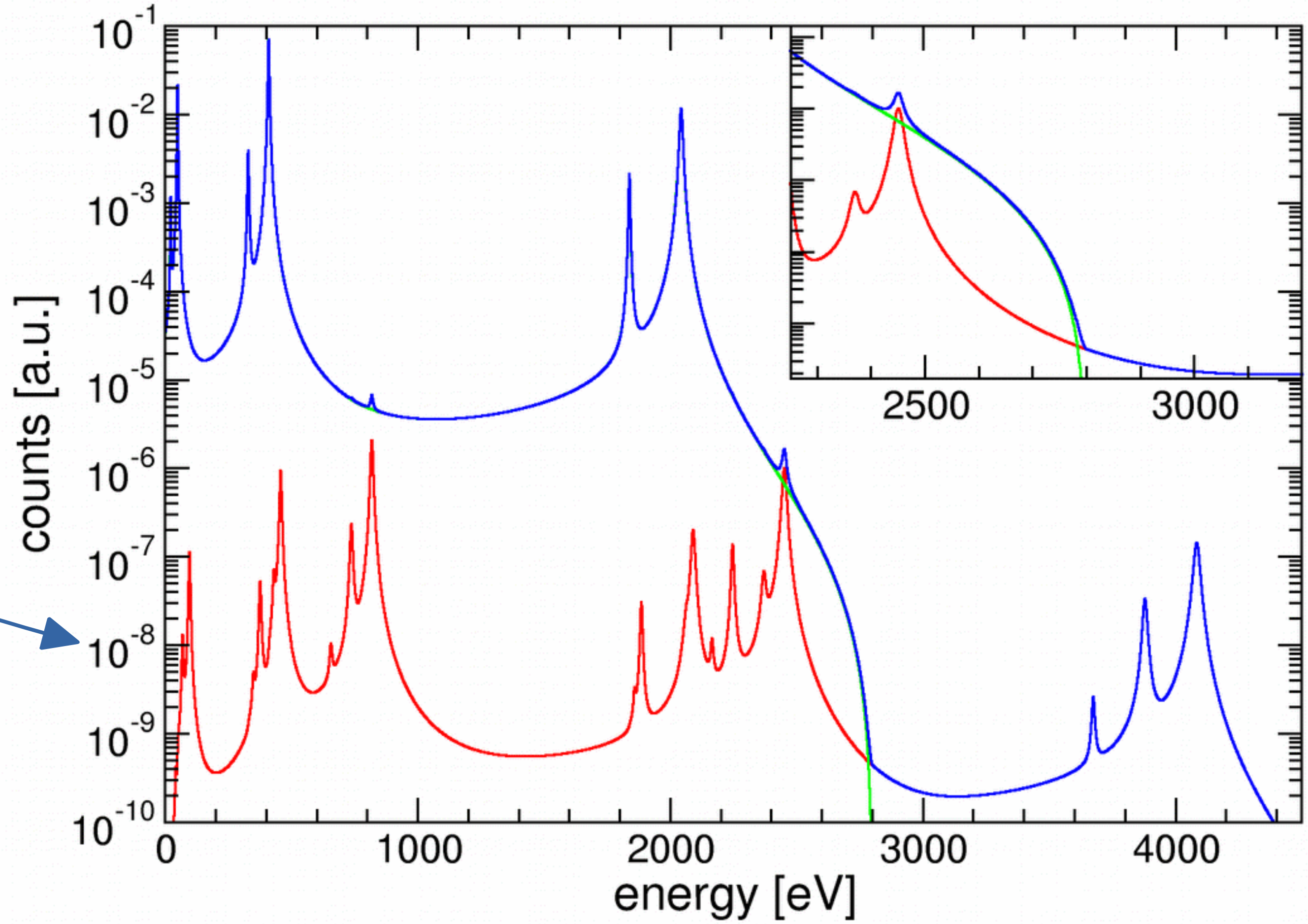




Electron capture calorimetric experiments / 2

- calorimetric measurement ↔ **detector speed is critical**
- complex pile-up spectrum
  - $N_{pp}(E) = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$ with $f_{pp} \approx A_{EC} \tau_R$

A_{EC} EC activity per detector
τ_R time resolution (≈rise time)



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

$N_{EC}(E)$ without higher order processes (shake up / shake off)

HOLMES *(ERC-Advanced Grant n. 340321)*

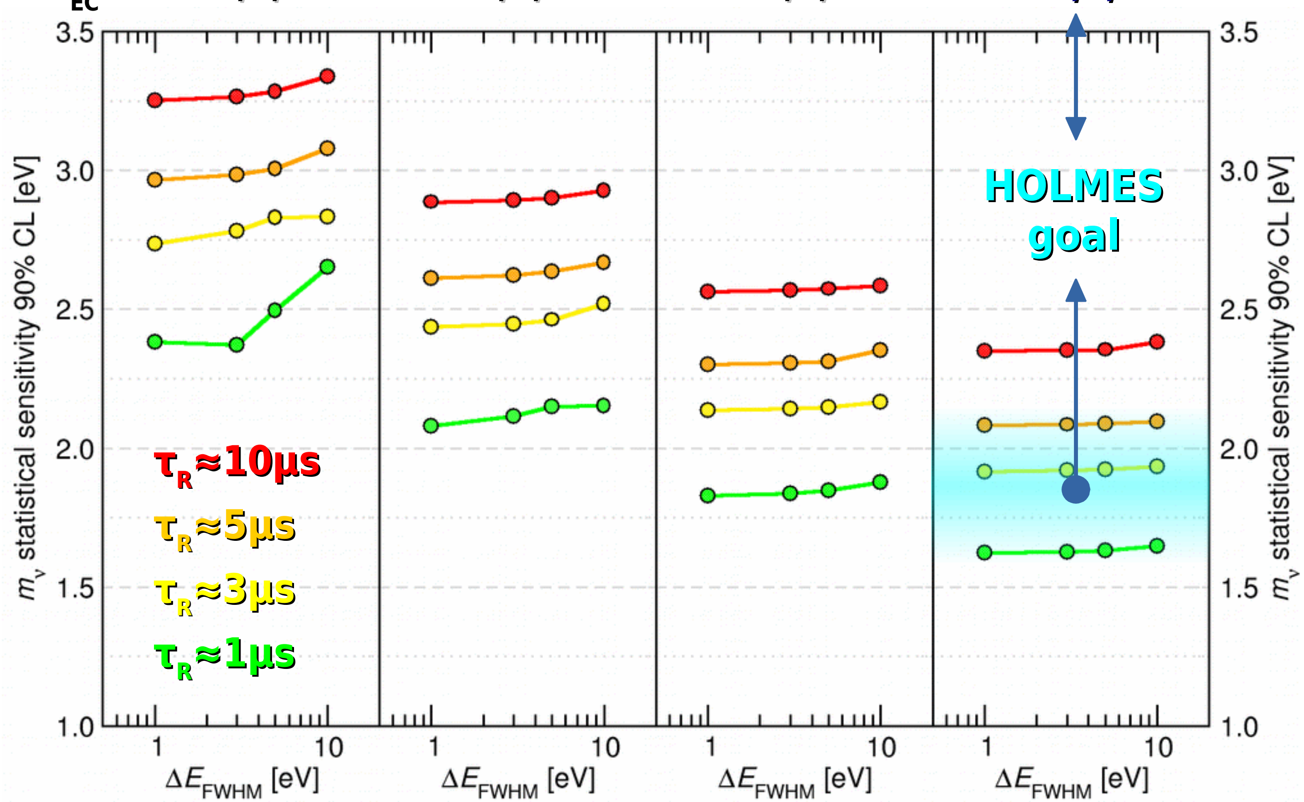
goal

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

baseline

- **TES microcalorimeters** with **implanted ^{163}Ho**
  - 6.5×10^{13} nuclei per pixel
    A_{EC} **= 300 c/s/det**
  - $\Delta E \approx 1$ **eV** and $\tau_R \approx 1$ **µs**
- **1000 channel** array
  - 6.5×10^{16} ^{163}Ho nuclei
    → ≈18 µg
  - 3×10^{13} events in **3 years**

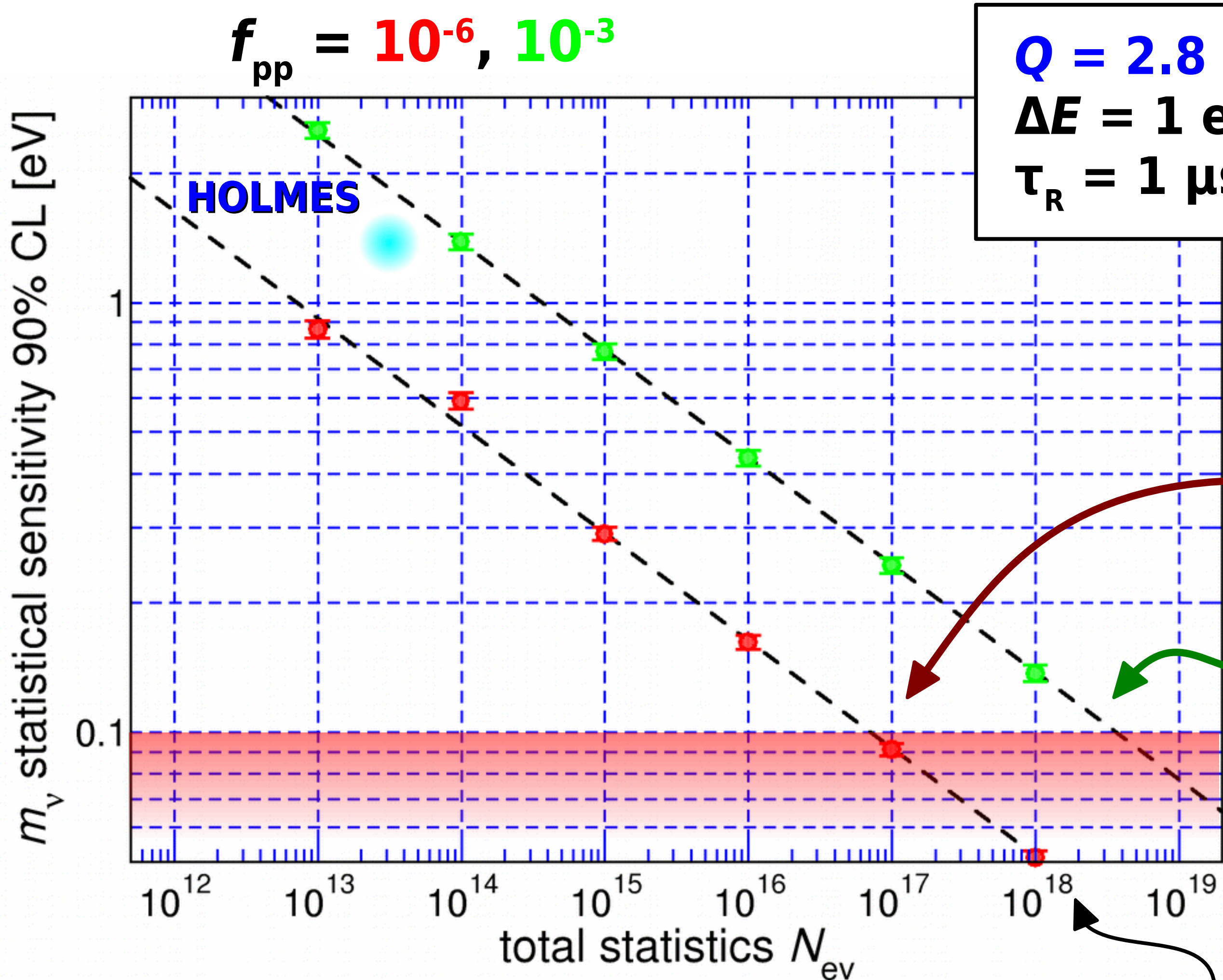
exposure = 1000 det × 3 y



5 years project started on February 1st 2014

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

Montecarlo simulations: ^{163}Ho sensitivity potential



$Q = 2.8$ keV
$\Delta E = 1$ eV
$\tau_R = 1$ µs

for $\Sigma(m_\nu) \leq 0.1$ eV

$A_{EC} = 1$ Bq
$N_{det} t_M \approx 2\times10^9$ det×y

$A_{EC} = 1000$ Bq
$N_{det} t_M \approx 10^8$ det×y

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

A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

Montecarlo simulations: low energy background

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

- **environmental γ radiation**
- **γ, X and β from close surroundings**
- **cosmic rays**
  - ▷ GEANT4 simulation for CR at sea level (only **muons**)
  - ▷ **Au pixel 200×200×2 μm^3 → *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$^-$, $\tau_{½}$ = 1200 y, produced along with ^{163}Ho)
  - ▷ **Au pixel 200×200×2 μm^3**
    GEANT4 simulation → ***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

^{163}Ho production by neutron activation

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

^{163}Er → ^{163}Ho + ν_e $\tau_{½}^{EC} \approx 75$min

- ^{162}Er irradiation at **ILL nuclear reactor** (Grenoble, France)
  - thermal neutron flux at **ILL**: 1.3×10^{15} n/cm^2/s
  - burn up ^{163}Ho(n,γ)^{164}Ho: $\sigma_{burn-up} \approx 200$b (preliminary result from **PSI** analysis)
  - ^{165}Ho(n,γ) (mostly from ^{164}Er(n,γ)) → **^{166m}Ho** (β, $\tau_{½}$=1200y) → $A(^{163}\text{Ho})/A(^{166m}\text{Ho})$=100~1000
- chemical pre-purification and post-separation at **PSI** (Villigen, CH)
- **HOLMES needs ≈ 200 MBq of ^{163}Ho**

  with reasonable assumptions on the (unknown) global embedding process efficiency...

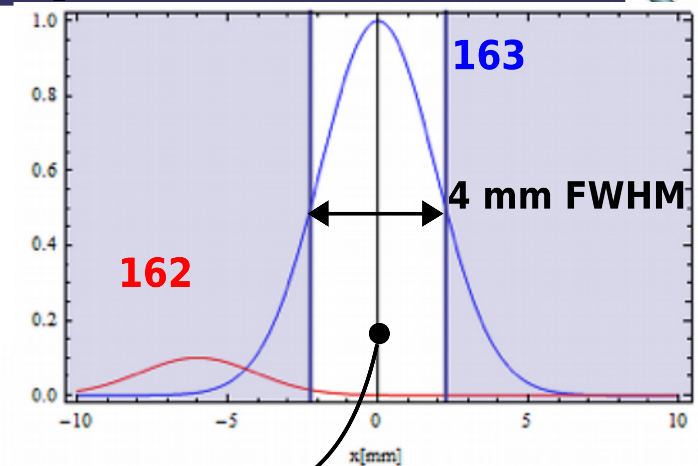
HOLMES source production

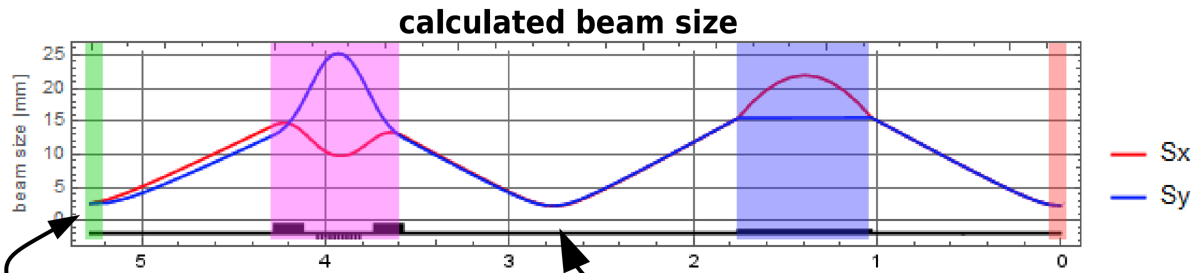
- **enriched Er_2O_3** samples* irradiated at **ILL** and pre-/post-processed at **PSI**
  - 25 mg irradiated for 55 days (2014) → ***A*(^{163}Ho) ≈ 5 MBq** (*A*(^{166m}Ho)≈10kBq)
  - 150 mg irradiated for 50 days (2015) → ***A*(^{163}Ho) ≈ 38 MBq** (*A*(^{166m}Ho)≈37kBq)
- **Ho radiochemical separation** with ion-exchange resins in hot-cell at **PSI**
  - **efficiency ≳79%** (preliminary)
- **540 mg of 25% enriched Er_2O_3** irradiated 50 days at **ILL** early in 2017
  - ***A*(^{163}Ho)$_{theo}$ ≈ 130 MBq** (enough for R&D and 500 pixels) (*A*(^{166m}Ho)≈180kBq)

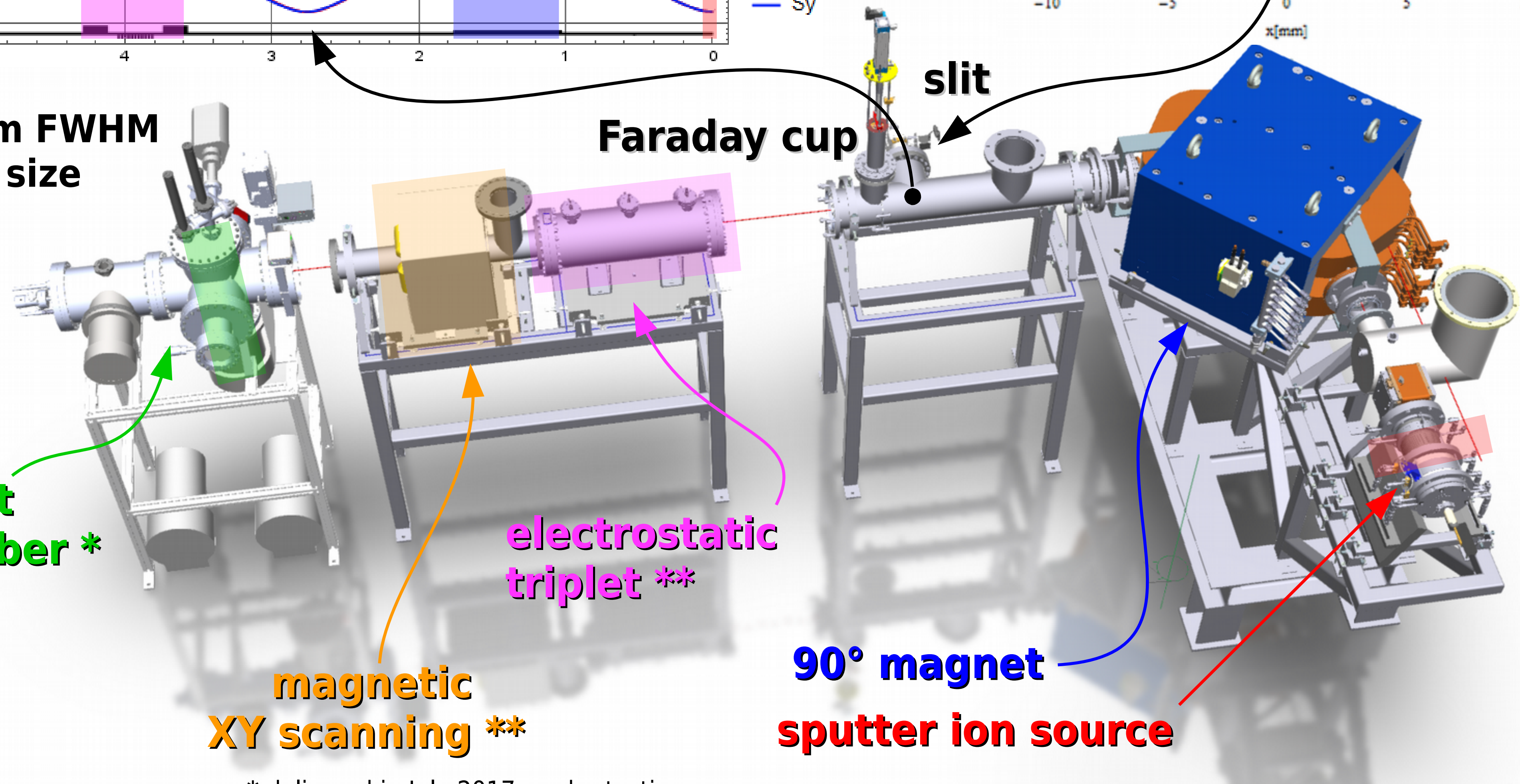
* from INFN and CENTRA (Lisbon)

HOLMES mass separation and ion implantation

- extraction voltage 30-50 kV → 10-100 nm implant depth
- **^{163}Ho / ^{166m}Ho** separation better than 10^5
- **ion source**, **magnet** and **slit** delivered end **2016**







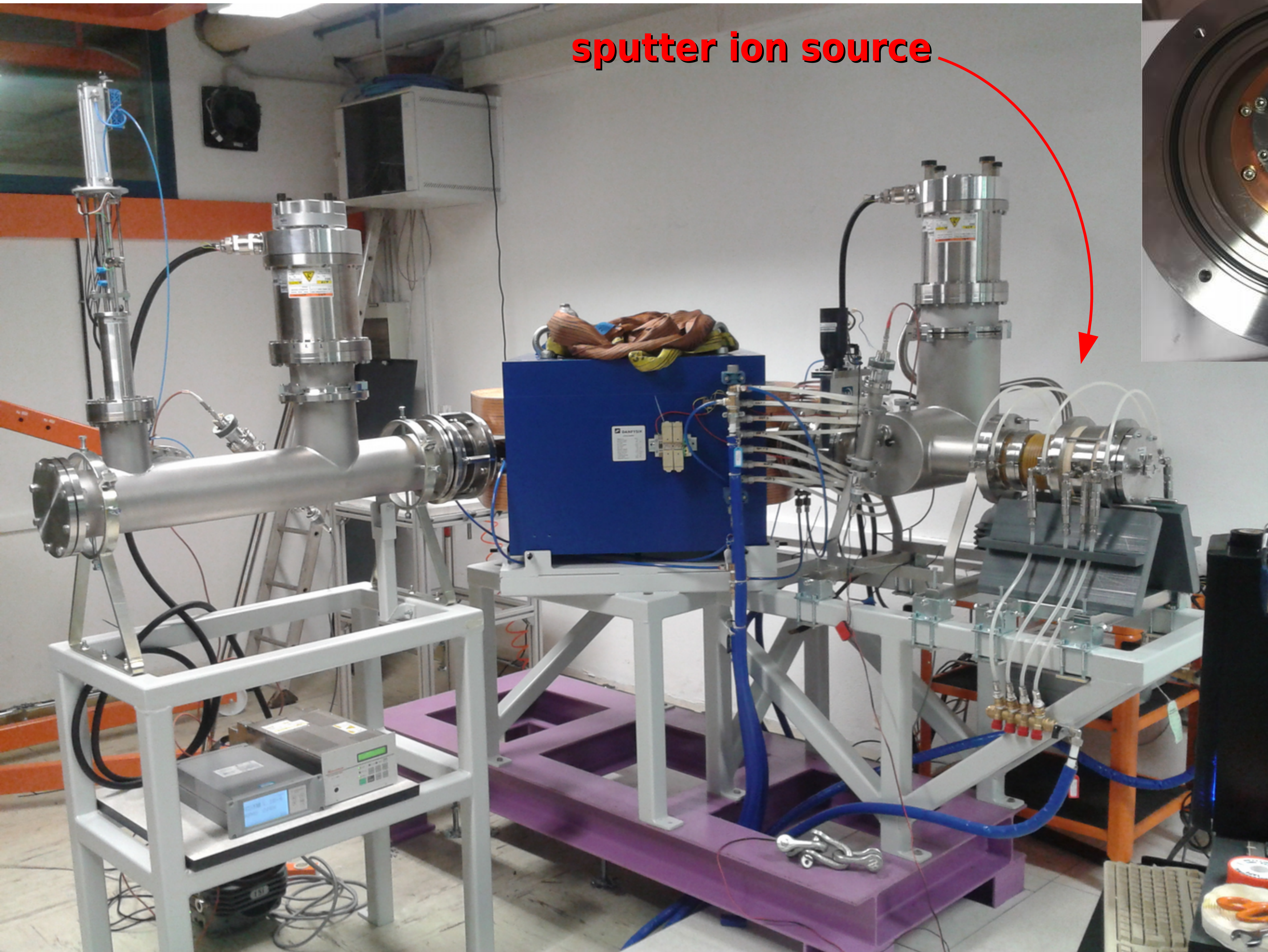
* delivered in July 2017: under testing
** delivery planned for end of 2017

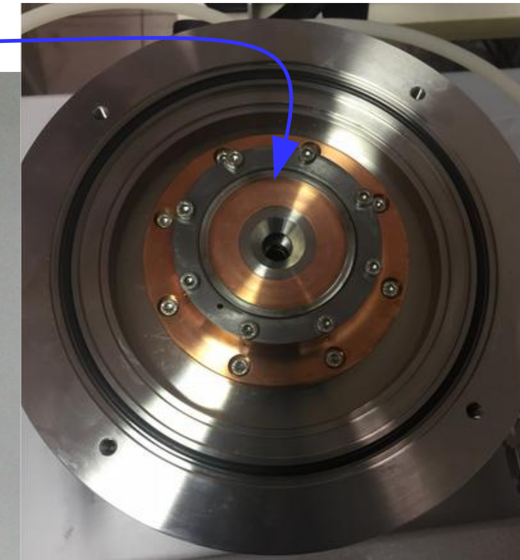
see G. Gallucci PE-28

HOLMES ion implantation system testing

sputter target

sputter ion source

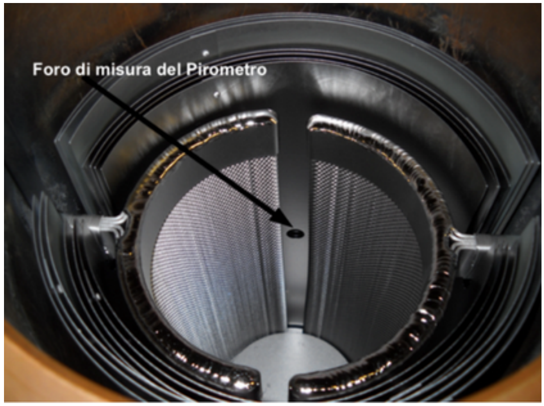


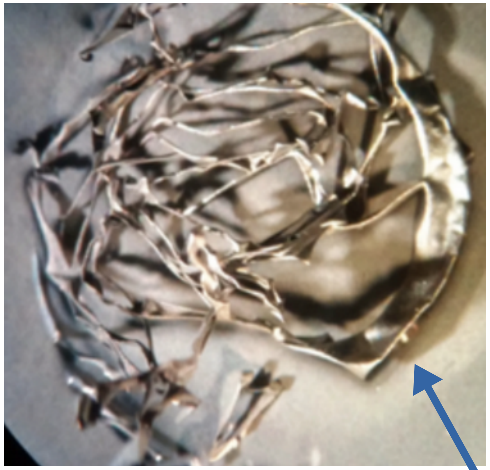


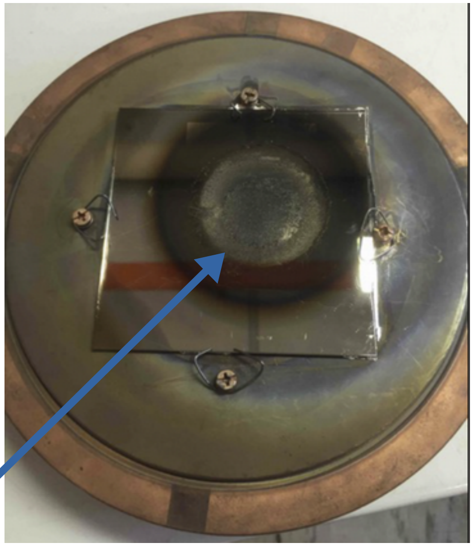
Ion source sputter target production / 1

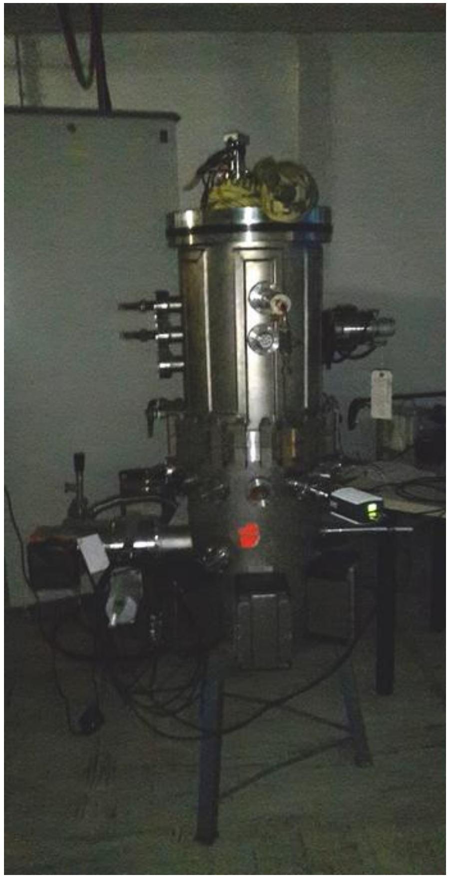
- **metallic holmium sputter target** for implanter ion source
- enriched $Er_2O_3 \rightarrow Ho_2O_3$
- thermoreduction/distillation in furnace
  - **$Ho_2O_3 + 2Y(met) \rightarrow 2Ho(met) + Y_2O_3$ at $T > 1600°C$**
- new furnace set-up in 2016
- work in progress to
  - optimize the process
  - measure efficiency (**≈70%**, preliminary)

see G. Gallucci PE-28





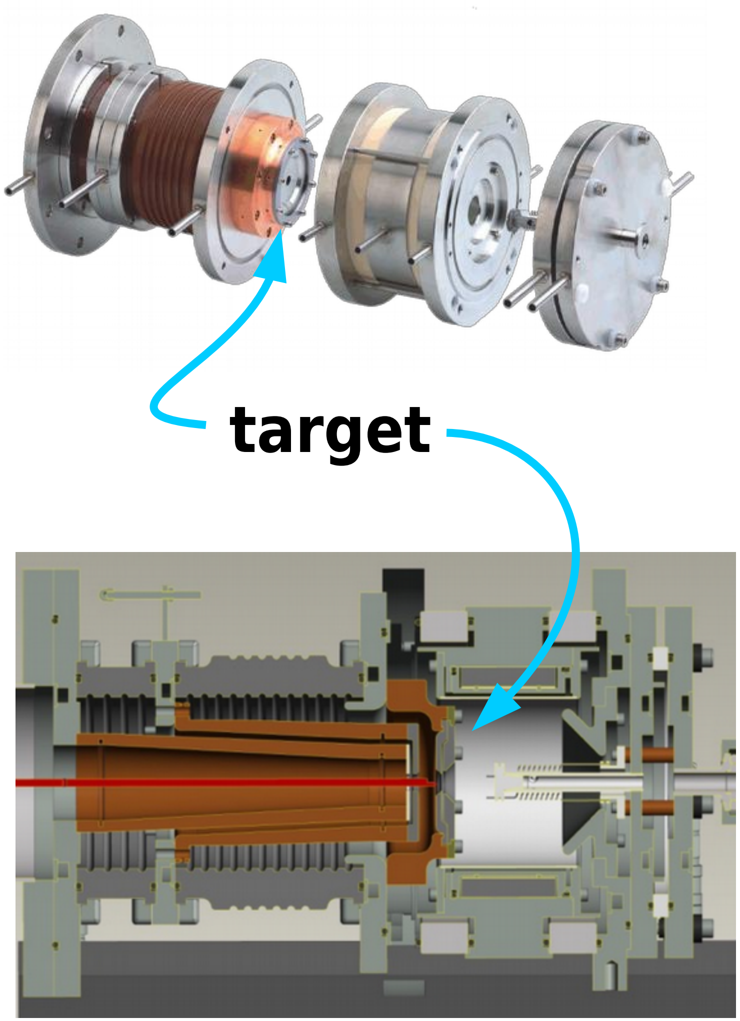


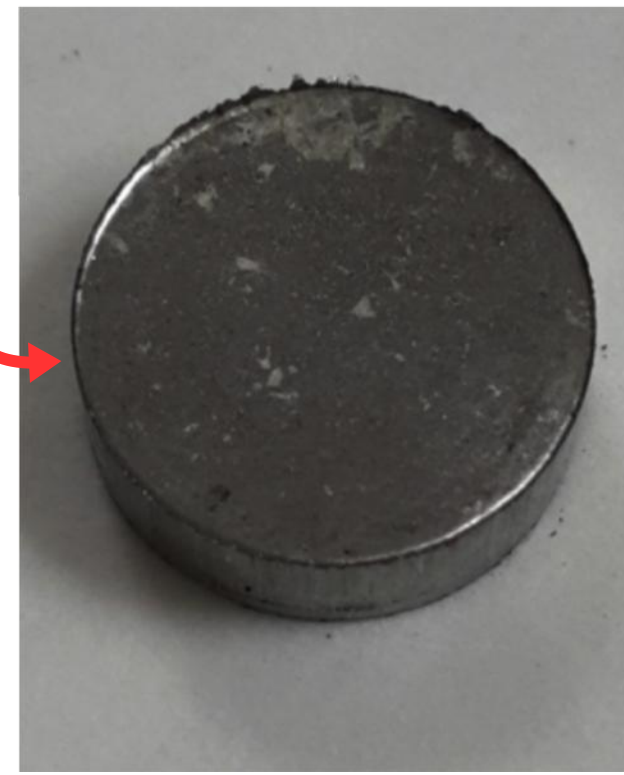


evaportated metallic holmium

Ion source sputter target production / 2

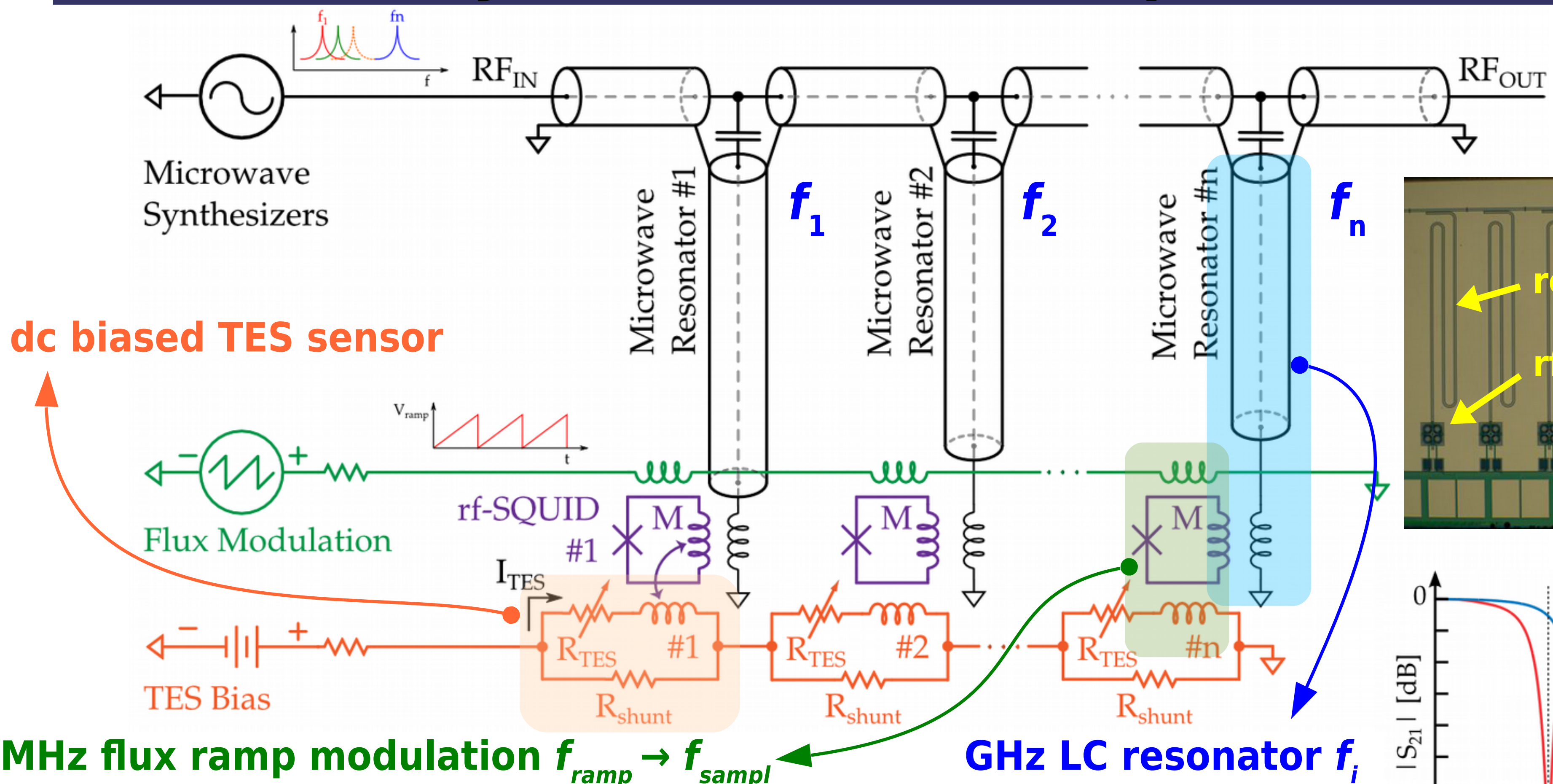
- **metallic holmium sputter target** for implanter ion source
  - work is in progress to produce the sputter target
  - sintering Ho with other metals

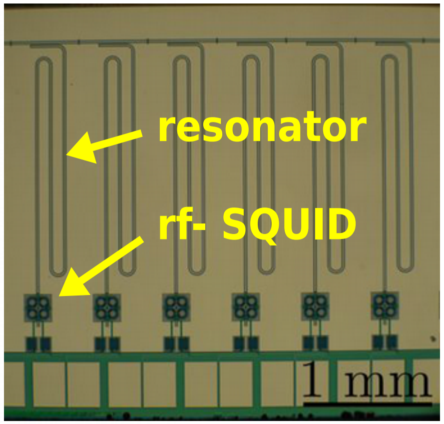


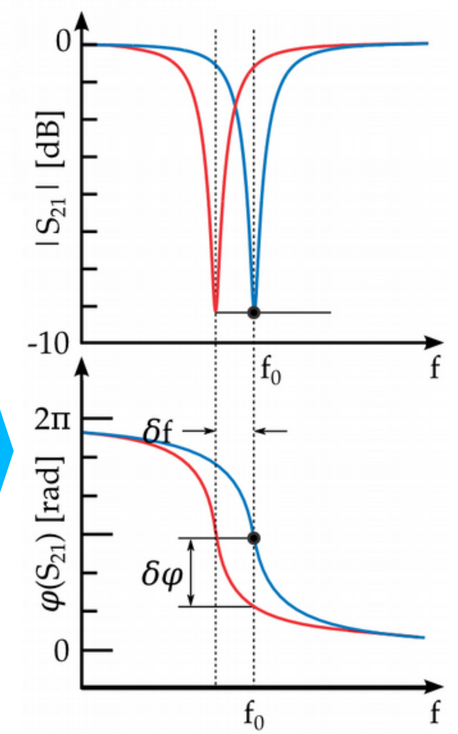


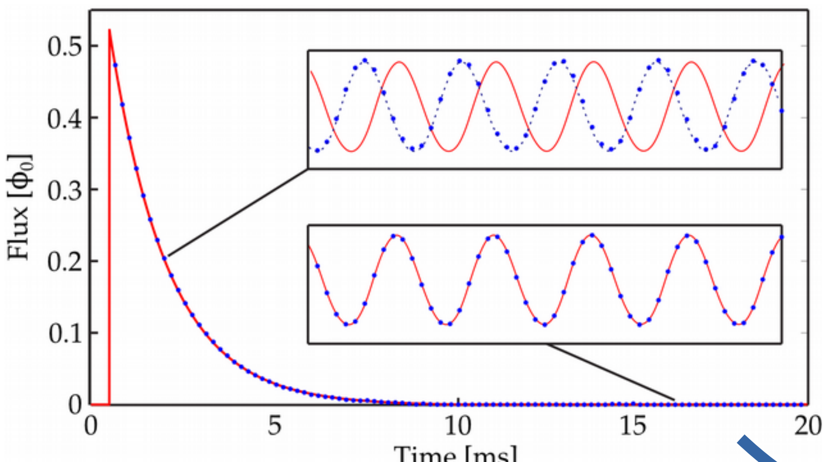
see G. Gallucci PE-28

HOLMES array read-out: rf-SQUID μwave mux

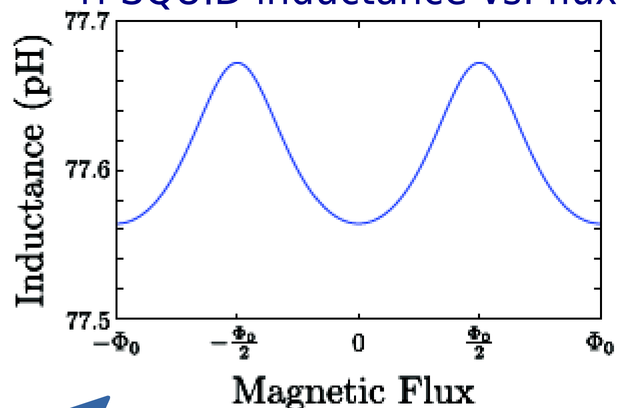






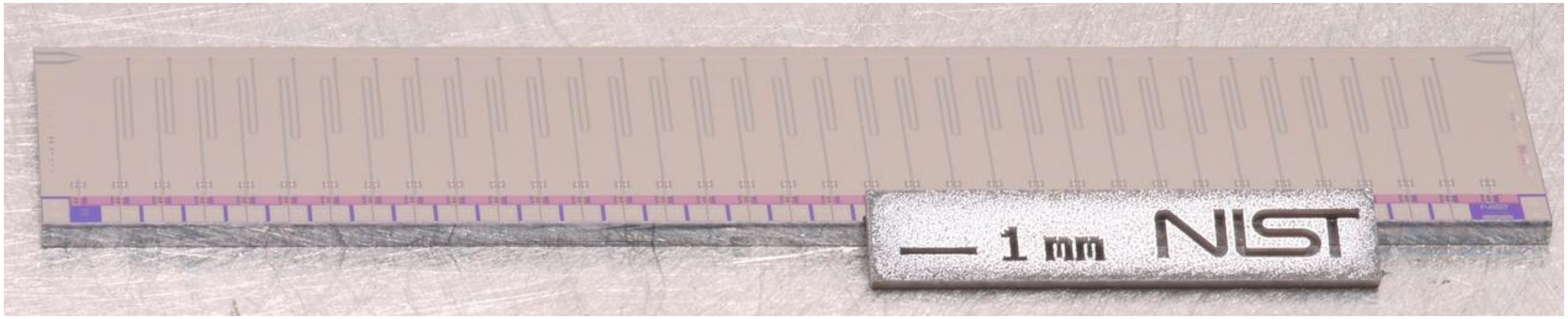


rf-SQUID inductance vs. flux

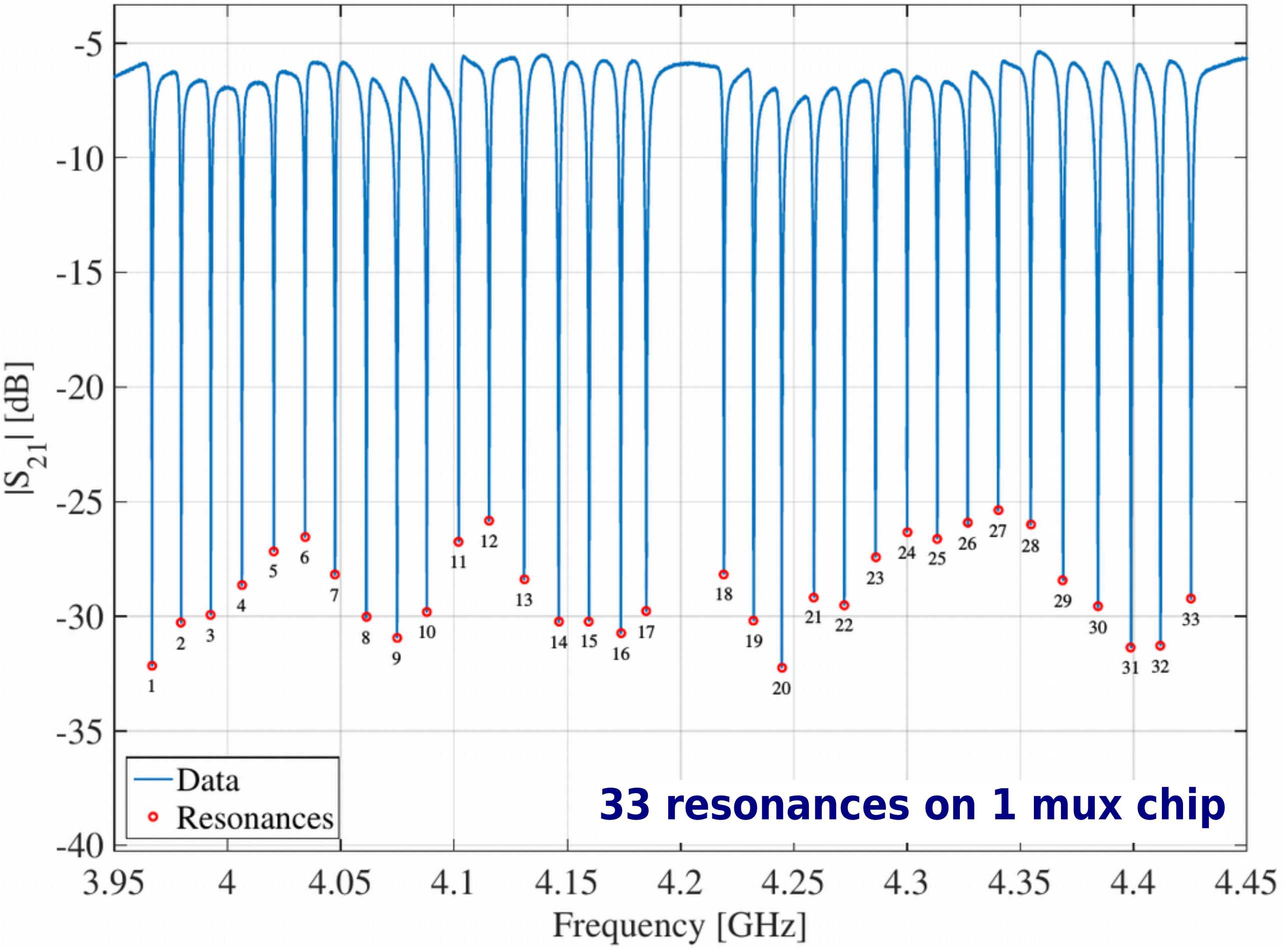


see O-53 O-54 O-55

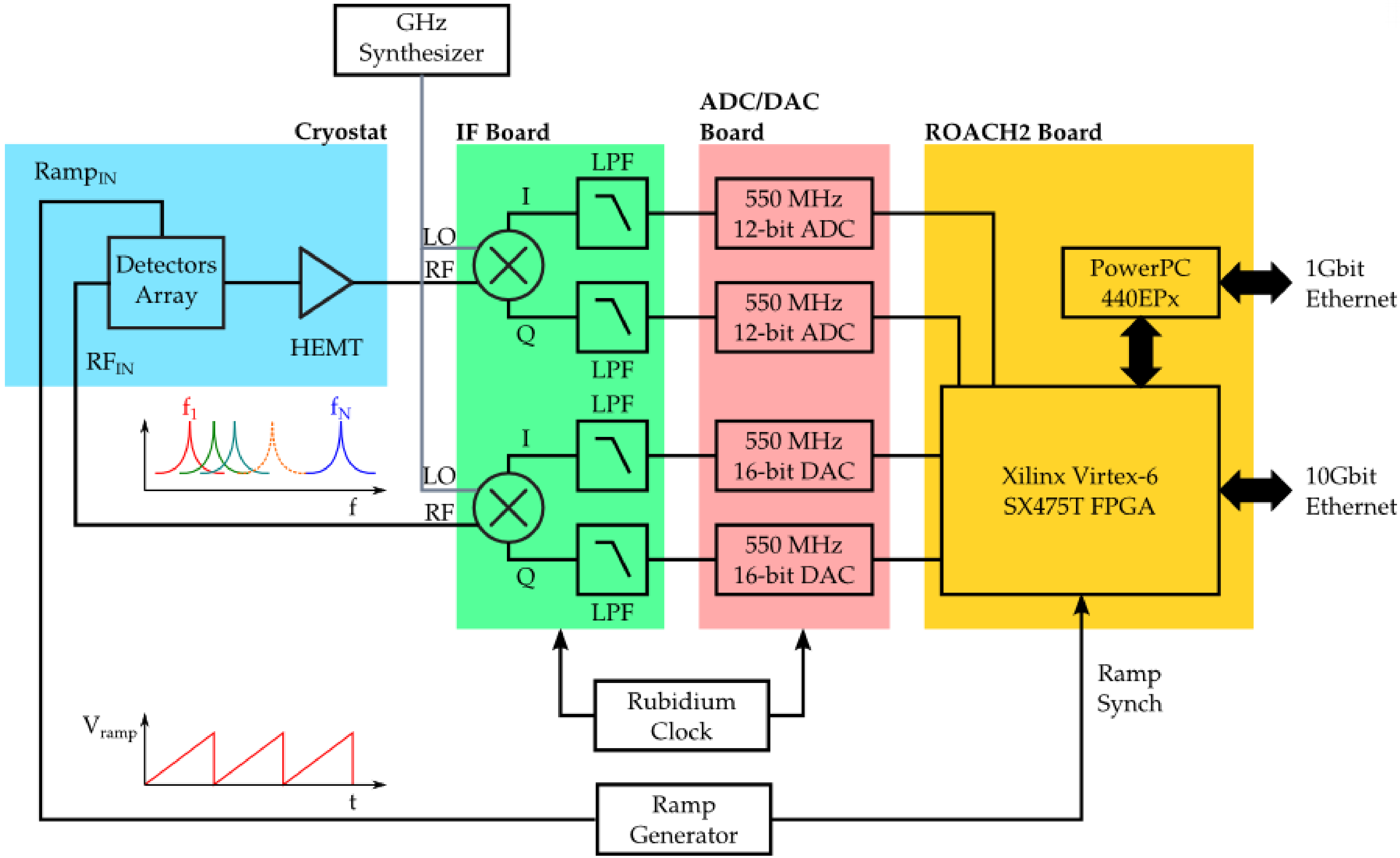
HOLMES µwave multiplexed TES read-out



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



HOLMES DAQ: Software Defined Radio



multiplexing factor n_{TES}

f_{BW} required bandwidth per channel ($f_{BW} \propto 1/\tau_{rise}$) → $n_{TES} \approx \frac{f_{ADC}}{10\, f_{BW}}$

HOLMES detector design

design mostly driven by **read-out bandwith** requirements

- TES microwave multiplexing with rf-SQUID ramp modulation + Software Defined Radio (SDR)

read-out specs	→		→	
SDR ADC f_{ADC} multiplexing factor n_{TES}		signal sampling f_{samp} signal rise time τ_{rise}		HOLMES targets τ_R ΔE N_{det}

$$f_{samp} \geq \frac{R_d}{\tau_{rise}} \approx \frac{5}{\tau_{rise}}$$ detector signal sampling (signal BW)

$$f_{res} \geq 2 n_{\Phi_0} f_{samp}$$ flux ramp modulated signal BW (resonator BW)

$$f_n \geq g_f f_{res} = \frac{2 R_d g_f n_{\Phi_0}}{\tau_{rise}}$$ microwave tones separation ($g_f \gtrsim 10$)

multiplexing factor

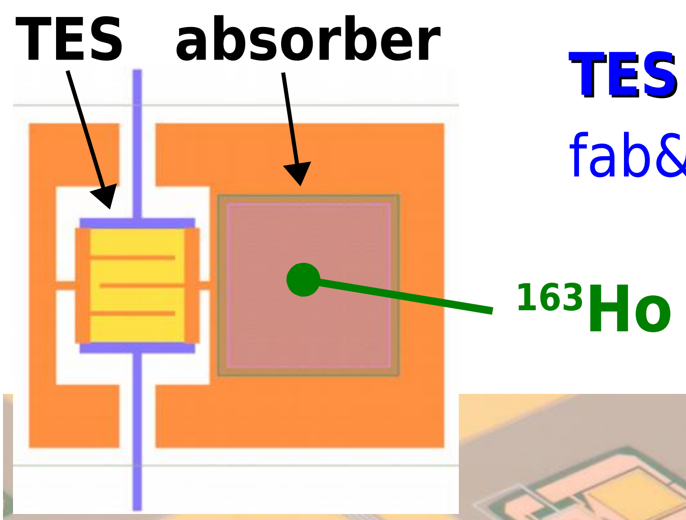
$$n_{TES} = \frac{f_{ADC}}{f_n} \leq \frac{f_{ADC} \tau_{rise}}{2 R_d g_f n_{\Phi_0}} \approx \frac{f_{ADC} \tau_{rise}}{200}$$

for fixed f_{ADC}**=550MHz** and n_{TES}**≈30** ↔ τ_{rise}**≈10µs** with f_{samp}**=0.5MHz**

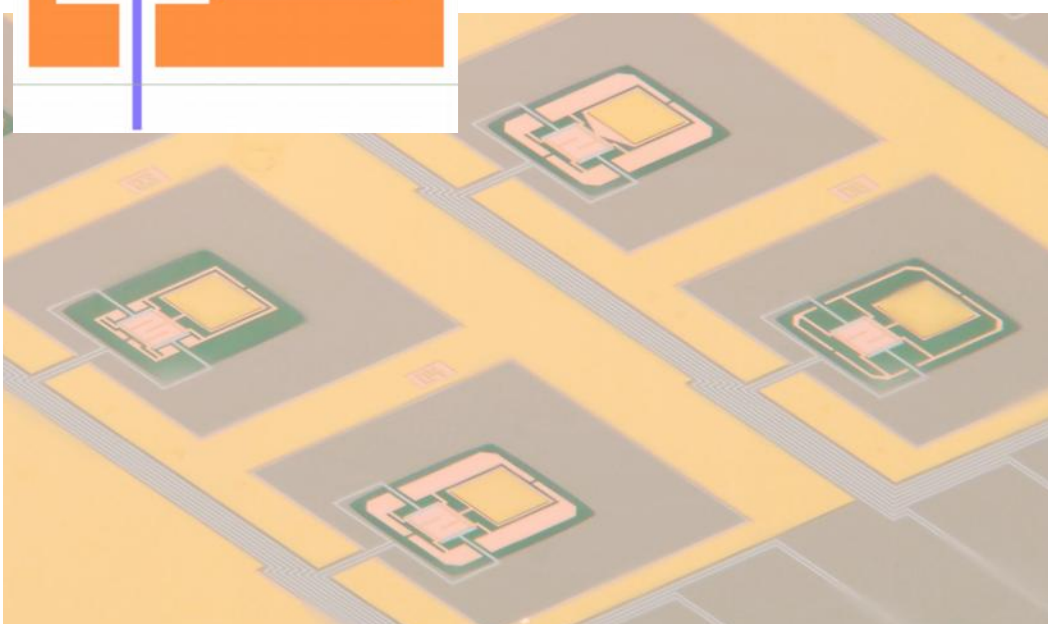
→ **check for slew rate, τ_R and ΔE...**

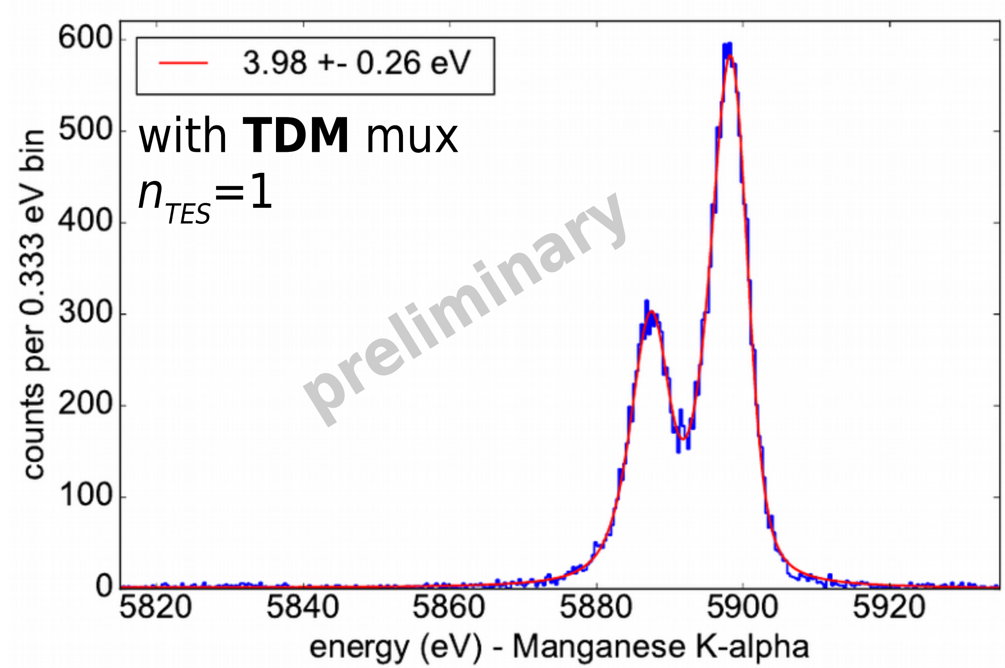
HOLMES pixel design and test

- optimize design for speed and resolution
  - ▷ **specs @3keV : ΔE_{FWHM} ≈ 1eV, τ_{rise} ≈ 10μs, τ_{decay} ≈ 100μs**
- **2 μm Au** thickness for *full* electron and photon absorption
  - ▷ GEANT4 simulation: 99.99998% / 99.927% full stopping for 2 keV electrons / photons
- ***side-car*** design to avoid TES proximitation and *G* engineering for τ_{decay} control



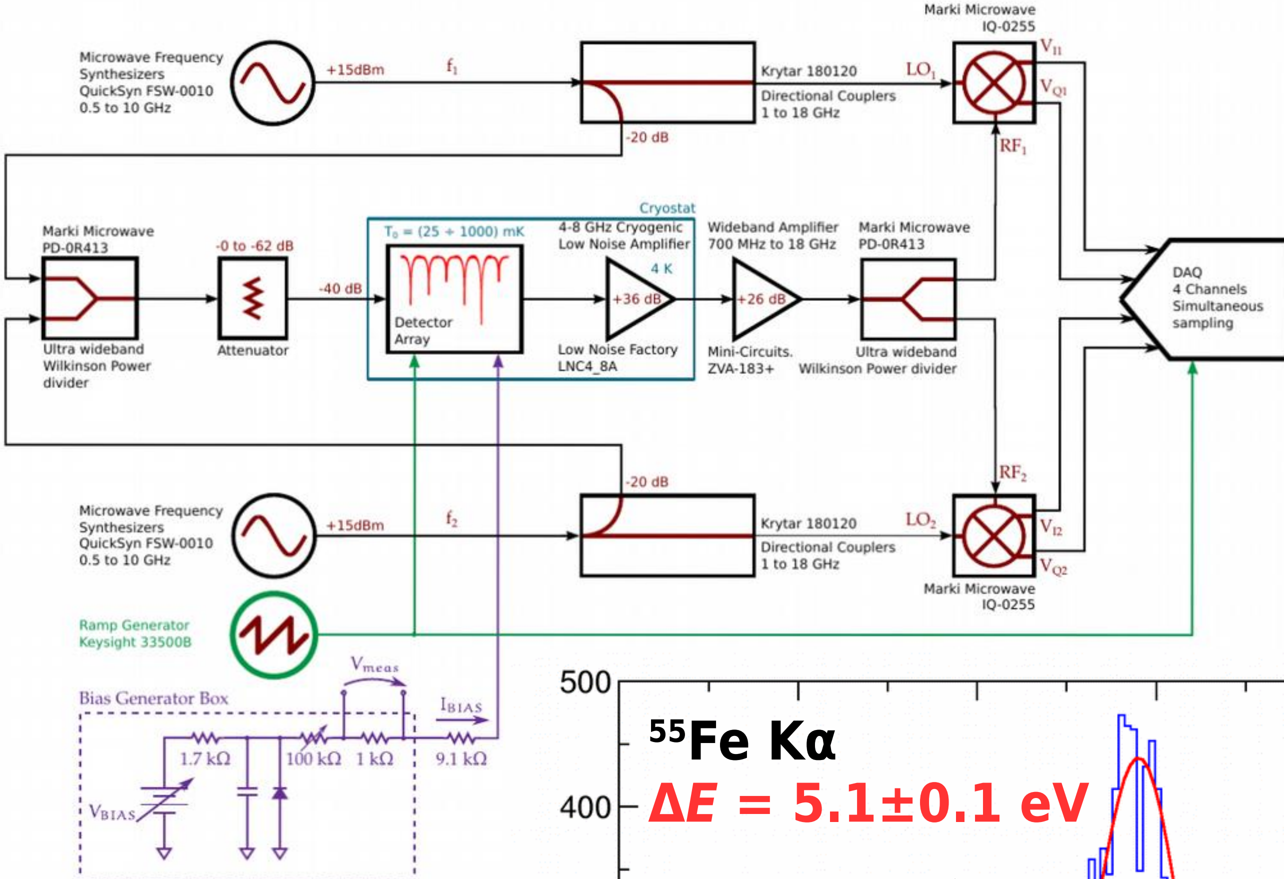
TES prototypes
fab&test @ **NIST**

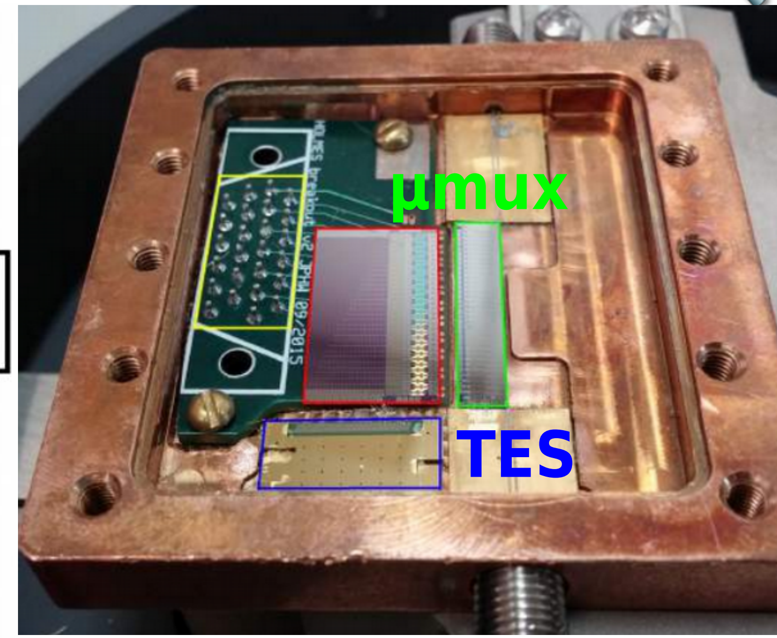


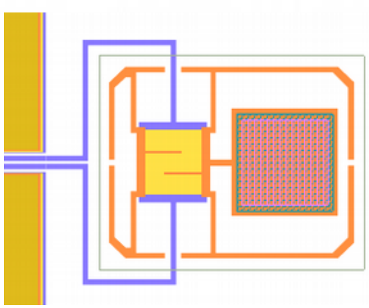


- ▷ ΔE_{FWHM} ≲ **4 eV** @ 6 keV (→ **≈3 eV** @ Q_{EC})
- ▷ τ_{rise} ≈ **6 μs** (with *L*=38nH → to be slowed)
- ▷ τ_{decay} ≈ **130 μs** (still tunable)

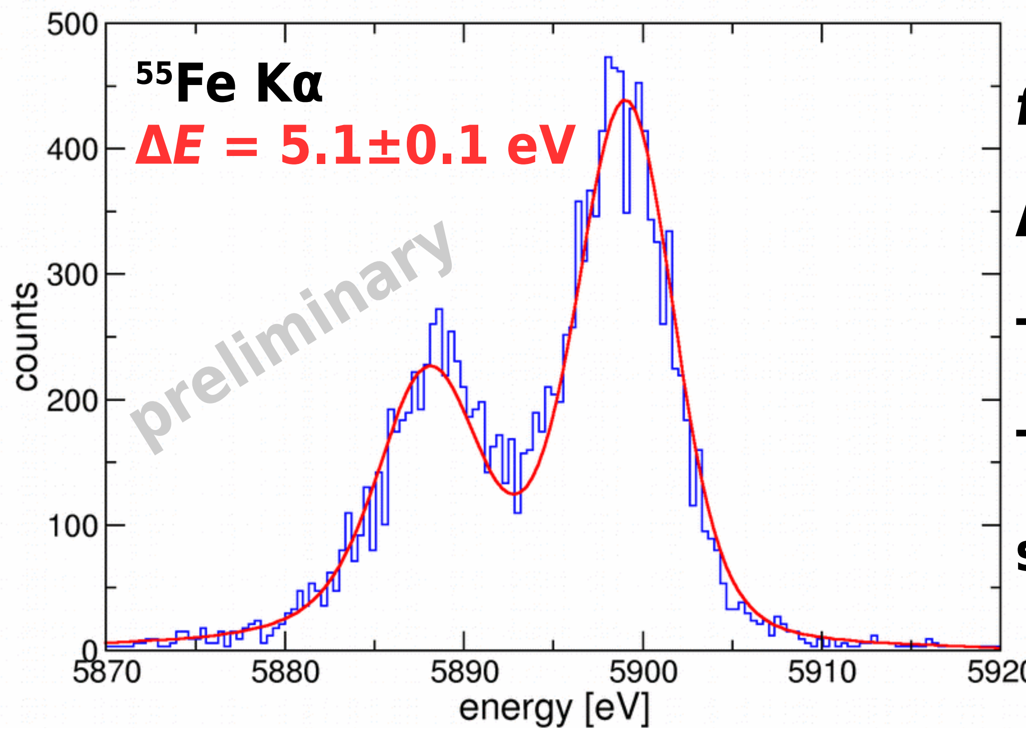
TES pixel testing with homodyne read-out







200×200 μm² absorber
C = 0.9 pJ/K
G = 570 pW/K



f_{samp} = 400 kS/s

ΔE_0 = 4.0 eV

τ_{rise} = 35 μs

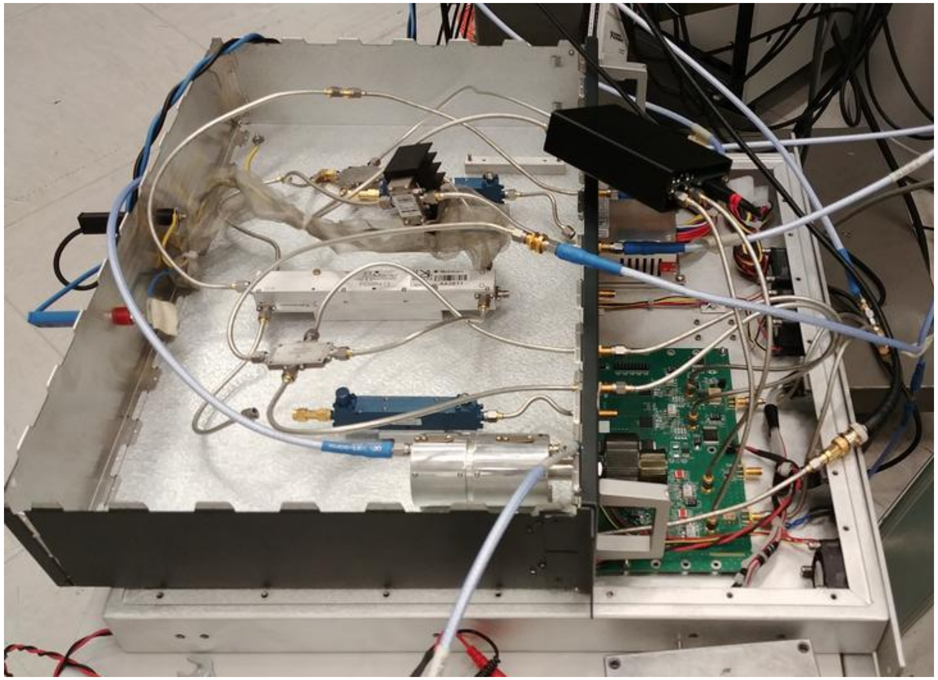
τ_{decay} = 141 μs

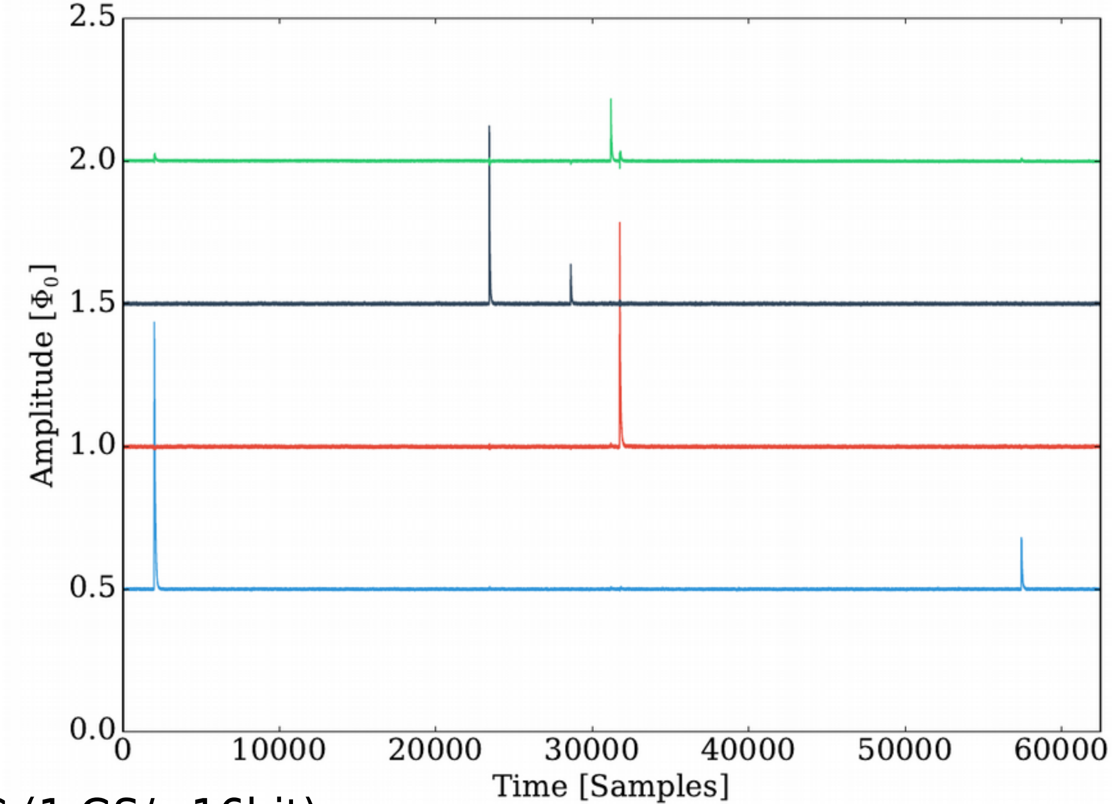
slew rate ≈ 0.2 Φ_0/S

see A. Puiu PE-20

TES pixel testing with HOLMES DAQ / 1

ROACH-2 based Software Defined Radio

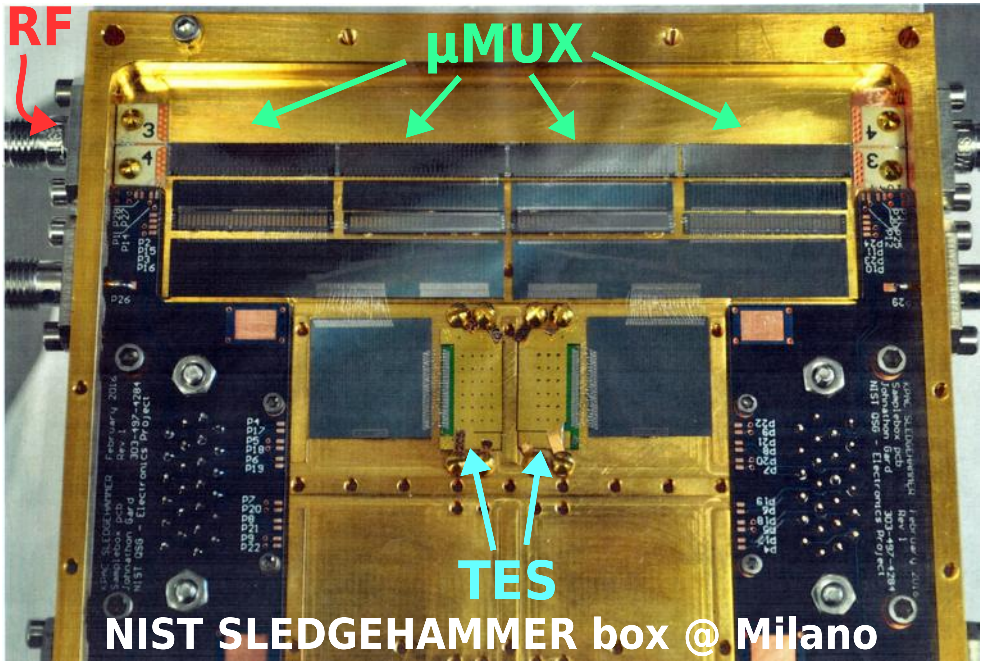


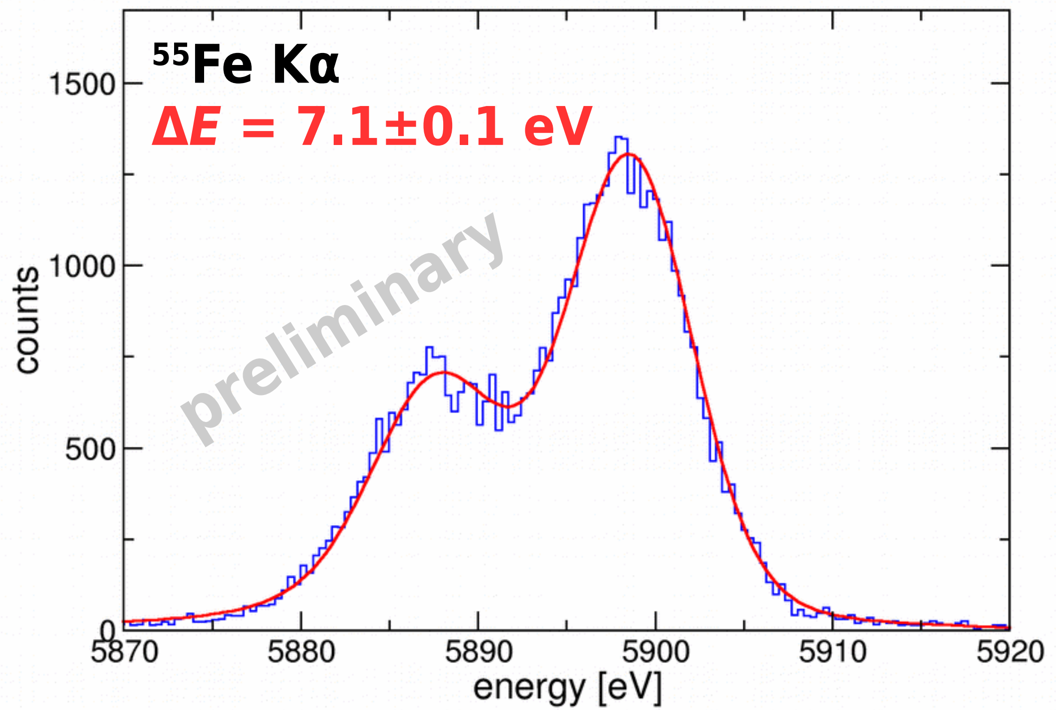


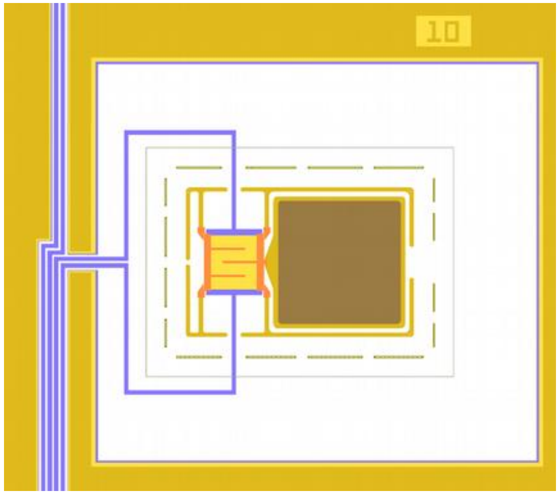
- ADC (550 MS/s 12bit) / DAC (1 GS/s 16bit)
- discrete components IF
- $n_{\Phi 0} = 2$, $f_{samp} = 500$ kS/s
- 16 ch firmware from NIST (uses only half of available ADC bandwidth)
- 4 pixel measurements → limited by available tone power
- tests on pixels similar to HOLMES ones (but not quite the same)
- checking algorithms, noise, ΔE, τ_R and slew rate

see J. Gard PB-10

TES pixel testing with HOLMES DAQ / 2







280×280 µm² absorber
C = 0.75 pJ/K
G = 330 pW/K

f_{samp} = 500 kS/s

ΔE_0 = 5.6 eV

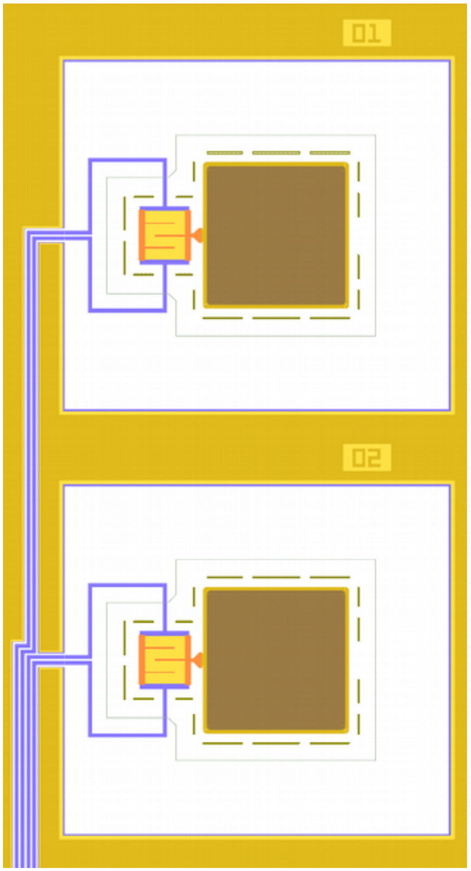
τ_{rise} = 6.5 µs

τ_{decay} = 67 µs

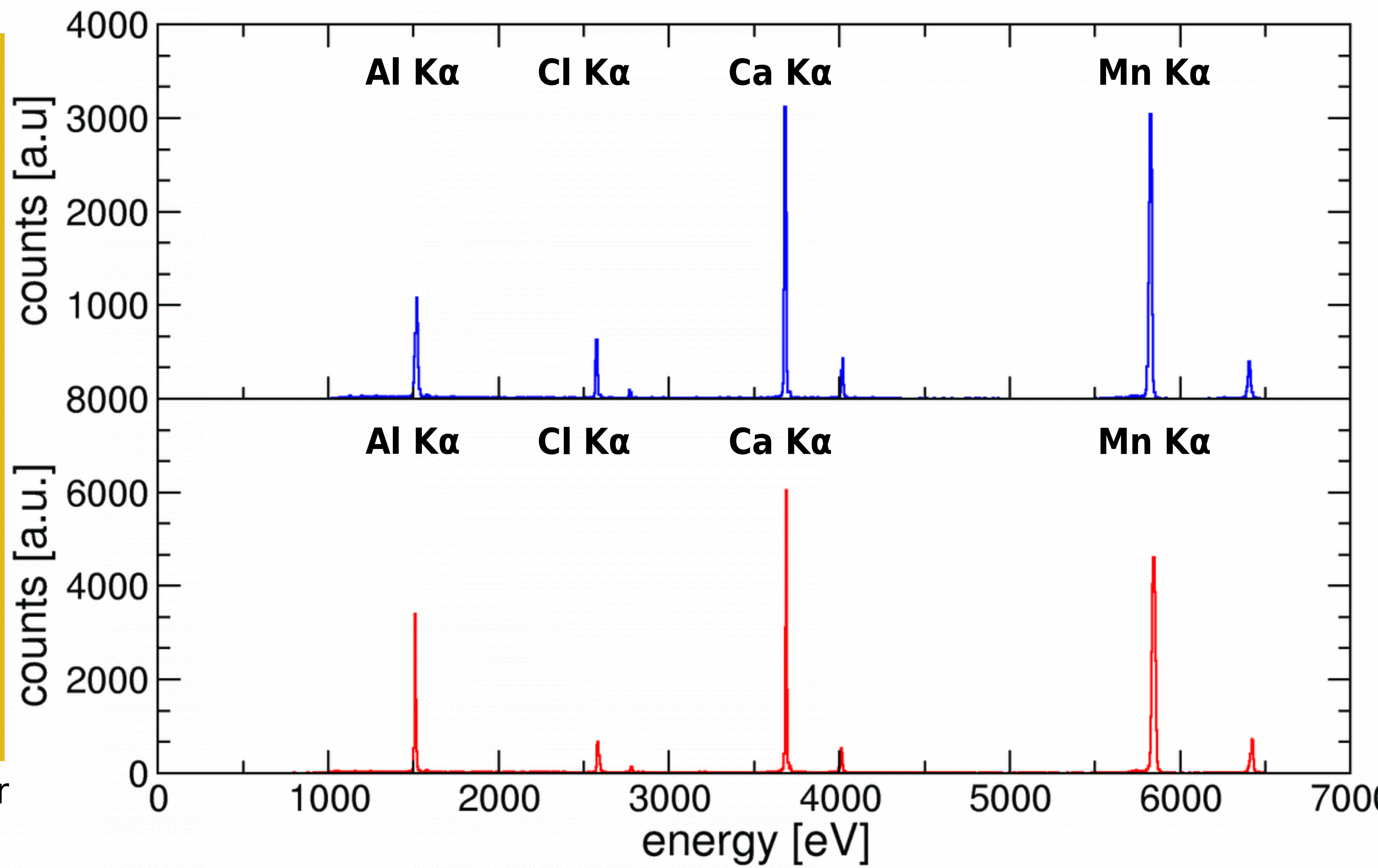
slew rate ≈ 0.4 Φ_0/S

see A. Puiu PE-20

TES pixel testing with HOLMES DAQ / 3



380×380 μm² absorber
C = 0.9 pJ/K
G = 480 pW/K



HOLMES-like pixels
without collimator

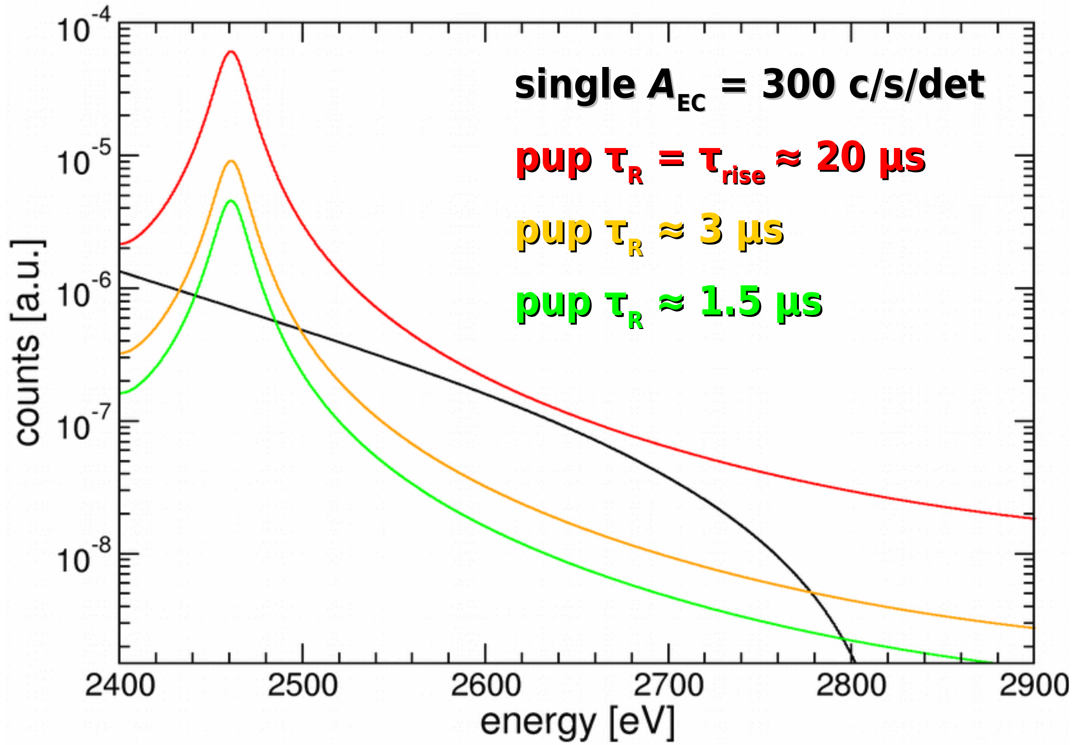
- **$\Delta E_0 \approx$ 5 eV** **$\Delta E \approx$ 7.5 eV @ 2.6 keV**
- **$\tau_{rise} \approx$ 20 μs** **$\tau_{decay} \approx$ 140 μs**
- **slew rate ≈ 0.1 Φ_0/S @ 2.6 keV**

Detector time resolution

- for subsequent (Δt) events with energy E_1 and E_2: time resolution $\boldsymbol{\tau_R = \tau_R(E_1, E_2)}$

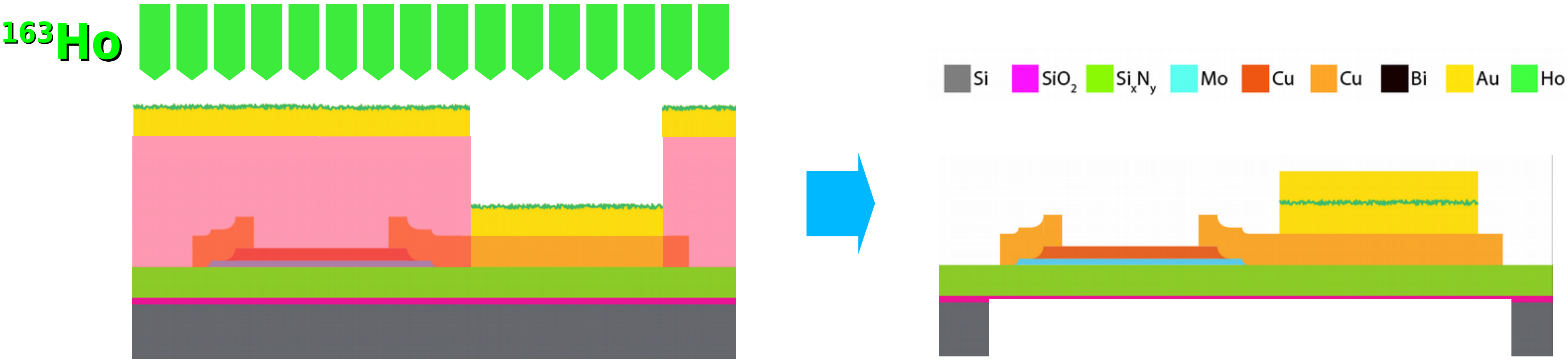
$$N_{pp}(E) = A_{EC}\int_0^\infty \tau_R(E,\epsilon)N_{EC}(\epsilon)N_{EC}(E-\epsilon)\,d\epsilon$$

- **Montecarlo pile-up spectrum simulations**
  - ▷ event pairs with $E_1+E_2 \in [2.4\ \text{keV}, 2.9\ \text{keV}]$ (drawn from ^{163}Ho spectrum), $\Delta t \in [0, 10\mu s]$
  - ▷ pulse shape and noise from NIST TES model, sampled with f_{samp}, record length, and n bit
- **process with pile-up detection algorithms:**
  - ▷ **Wiener Filter WF** or **Singular Value Decomposition SVD**
  - ▷ for $\boldsymbol{f_{samp} = 0.5\text{MHz}, \tau_{rise} \approx 20\mu s}$
    - **WF → $\boldsymbol{\tau_R \approx 3\ \mu s}$**
    - **SVD → $\boldsymbol{\tau_R \approx 1.5\ \mu s}$**

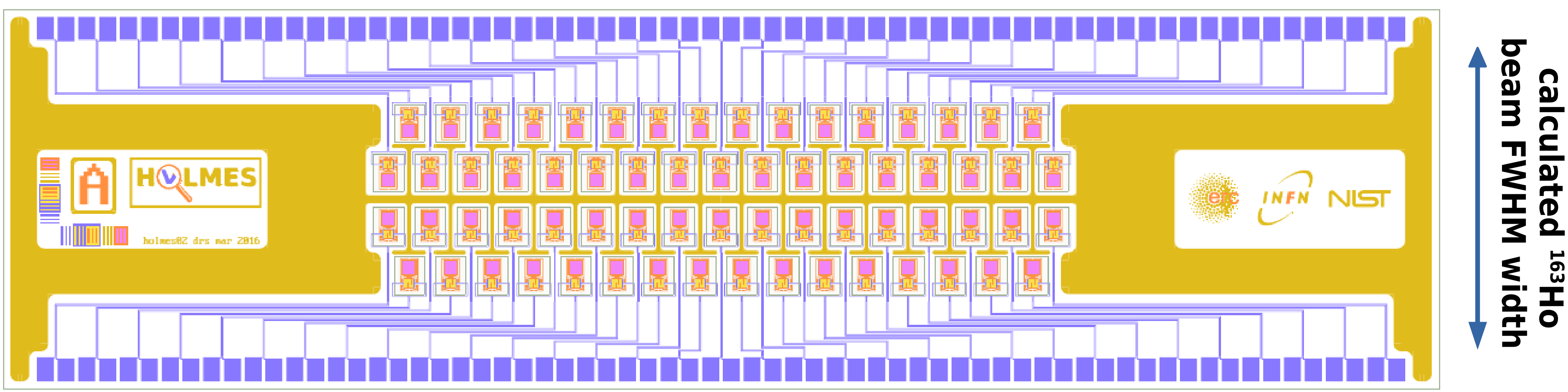


see B. Alpert PB-25

HOLMES detector design and fabrication



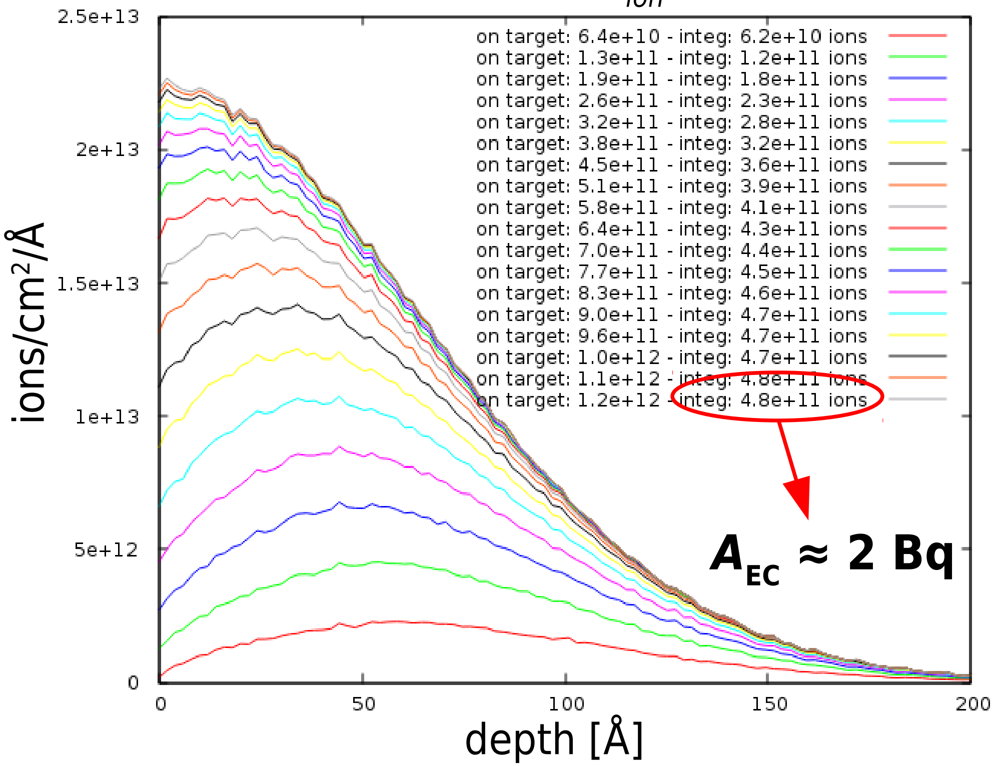
- TES array fabricated at **NIST**, Boulder, CO, USA
- ^{163}**Ho** implantation at **INFN**, Genova, Italy
- 1 µm **Au** final layer deposited at INFN Genova
- final fabrication process definition in progress
- HOLMES **4×16 linear sub-array** for low parasitic *L* and high implant efficiency

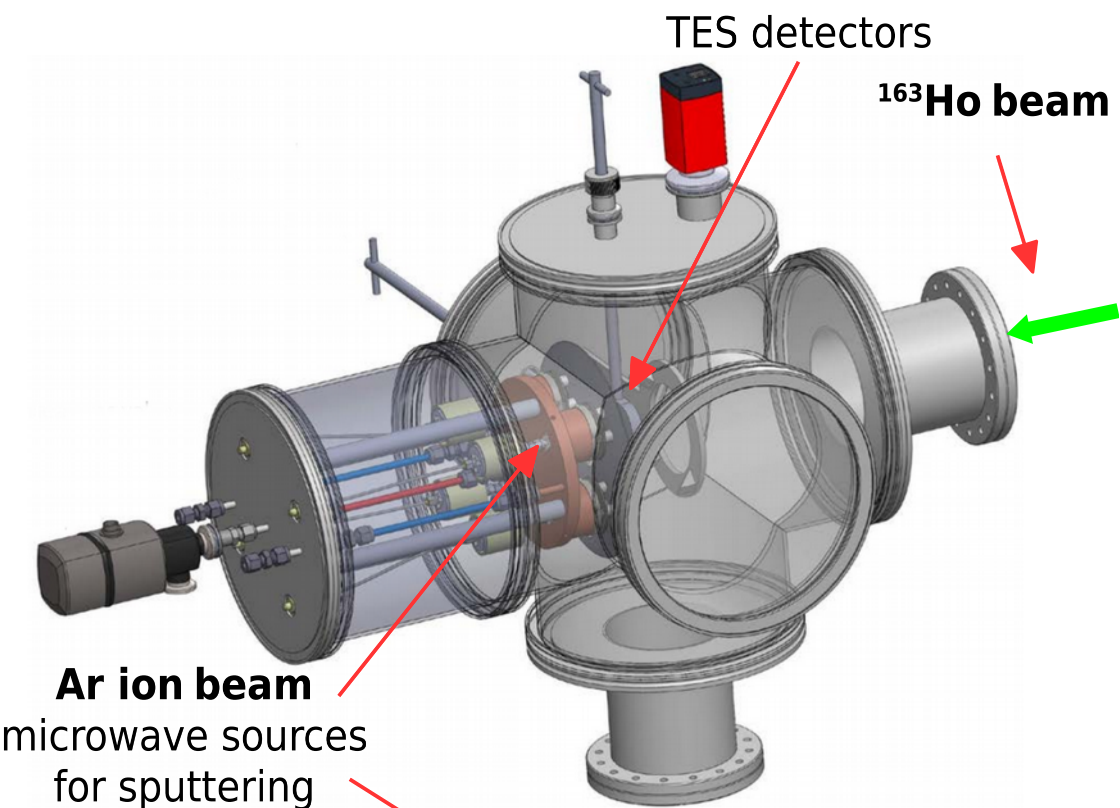


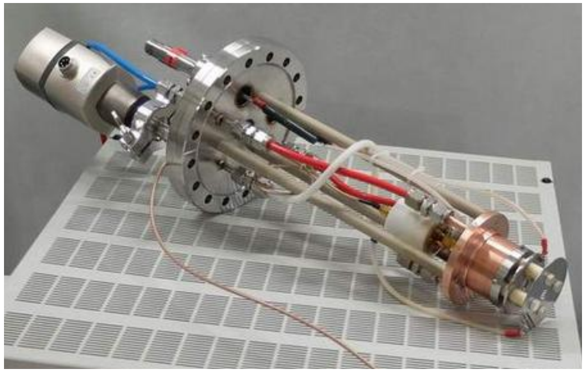
see A. Orlando PC-25

Target chamber for absorber fabrication / 1

ion implant simulation with SRIM2013
^{163}Ho ions on Au (E_{ion} = 50 keV)





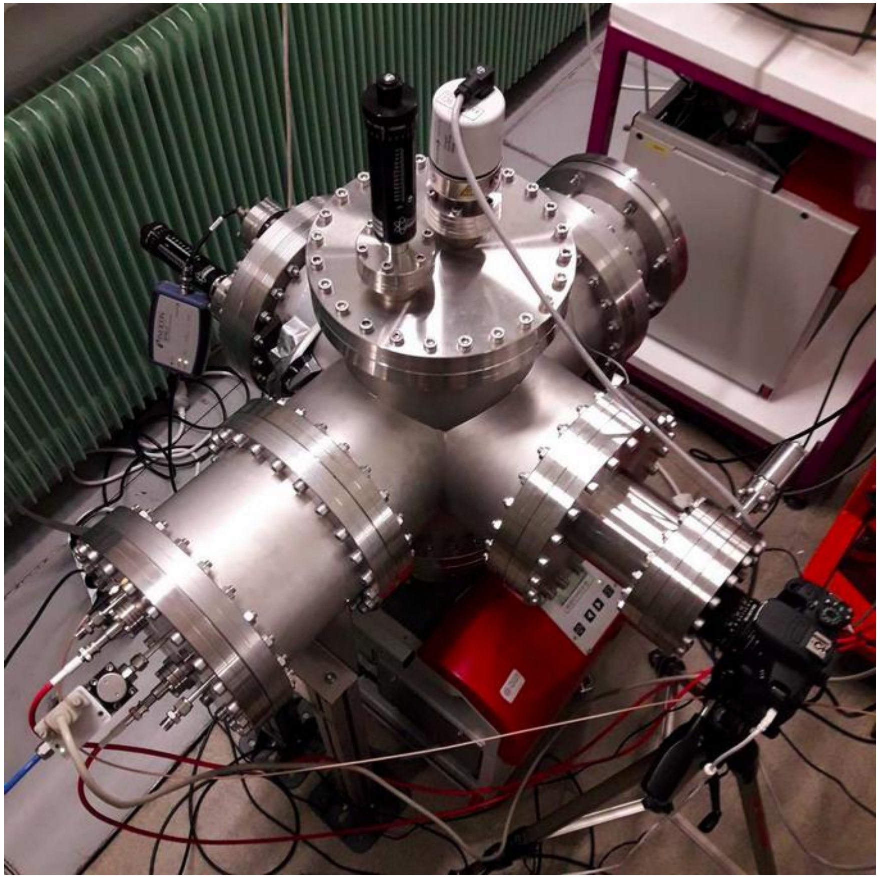


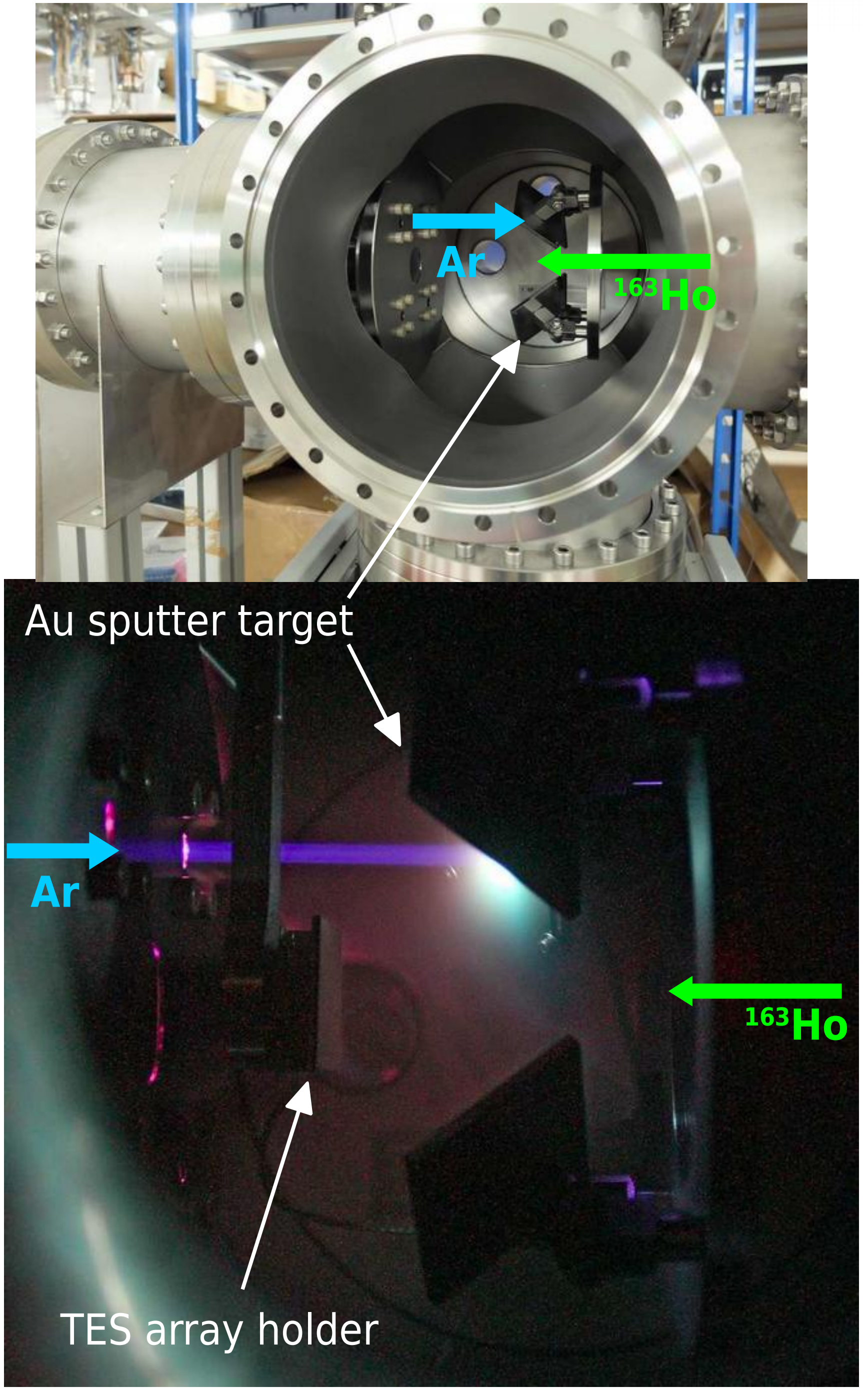
- ^{163}Ho ion beam sputters off Au from absorber
  - ^{163}Ho concentration in absorber saturates
  - compensate by Au co-evaporation
- final 1 µm Au layer in situ deposition

see A. Orlando PC-25

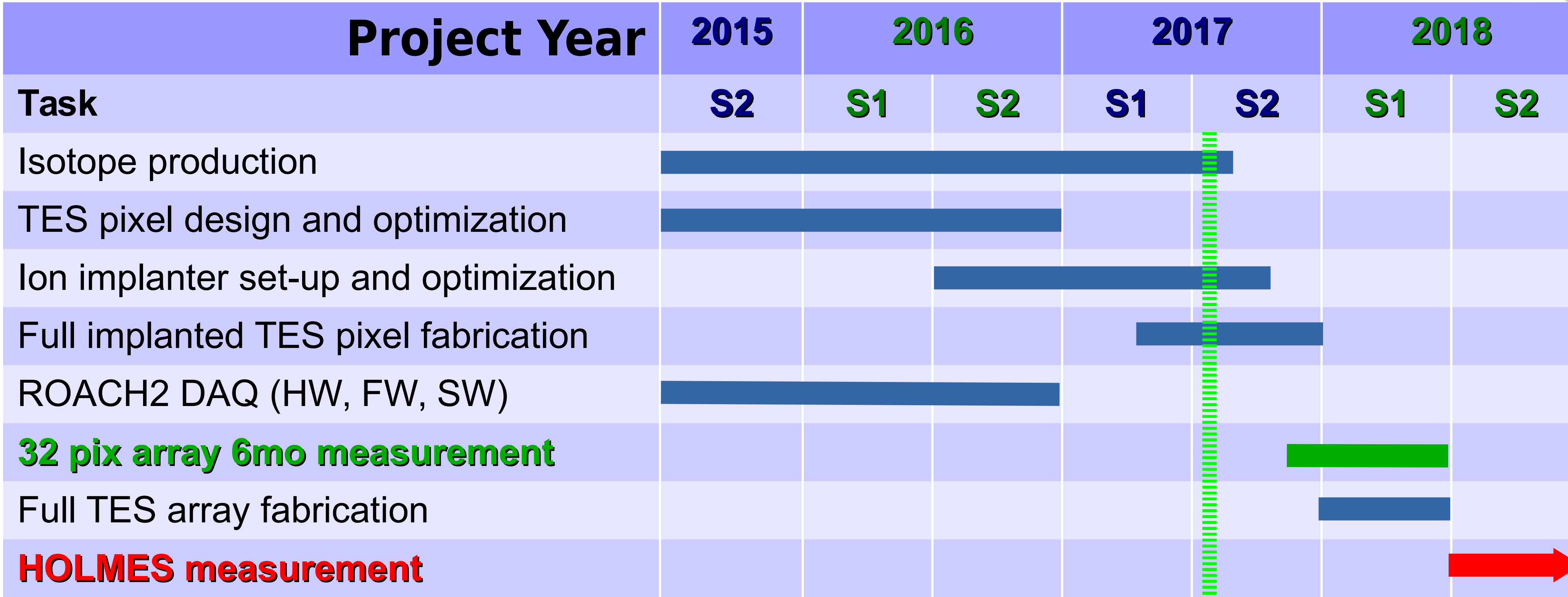
Target chamber for absorber fabrication / 2

- system just delivered
- **test are in progress**





HOLMES schedule and conclusions



- **HOLMES project status**
  - TES array and DAQ ready
  - ion implanter setting up is in progress
  - first ^{163}Ho implantation coming shortly
  - spectrum measurements will begin late in 2017
    - **32 pixels for 1 month → m_ν sensitivity ≈10 eV**

HOLMES collaboration

Univ. Milano-Bicocca
INFN Milano-Bicocca
G.Ceruti
M.Faverzani
E.Ferri
A.Giachero
A.Nucciotti
A.Orlando
G.Pessina
A.Puiu
S.Ragazzi

INFN Genova
M.Biasotti
V.Ceriale
G.Gallucci
M.De Gerone
F.Gatti
L.Parodi
F.Siccardi

INFN Roma
M.Lusignoli

INFN LNGS
S.Nisi

NIST
B.Alpert
D.Becker
D.Bennett
J.Fowler
J.Gard
J.Hays-Wehle
G.Hilton
J.Mates
C.Reintsema
D.Schmidt
D.Swetz
J.Ullom
L.Vale

PSI
R.Dressler
S.Heinitz
D.Schumann

CENTRA-IST
M.Ribeiro-Gomes

ILL
U.Koester