^{163}Ho implantation on TES-based micro-calorimeters for the HOLMES experiment

Matteo De Gerone - INFN Genova

^{163}Ho electron capture and ν mass

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

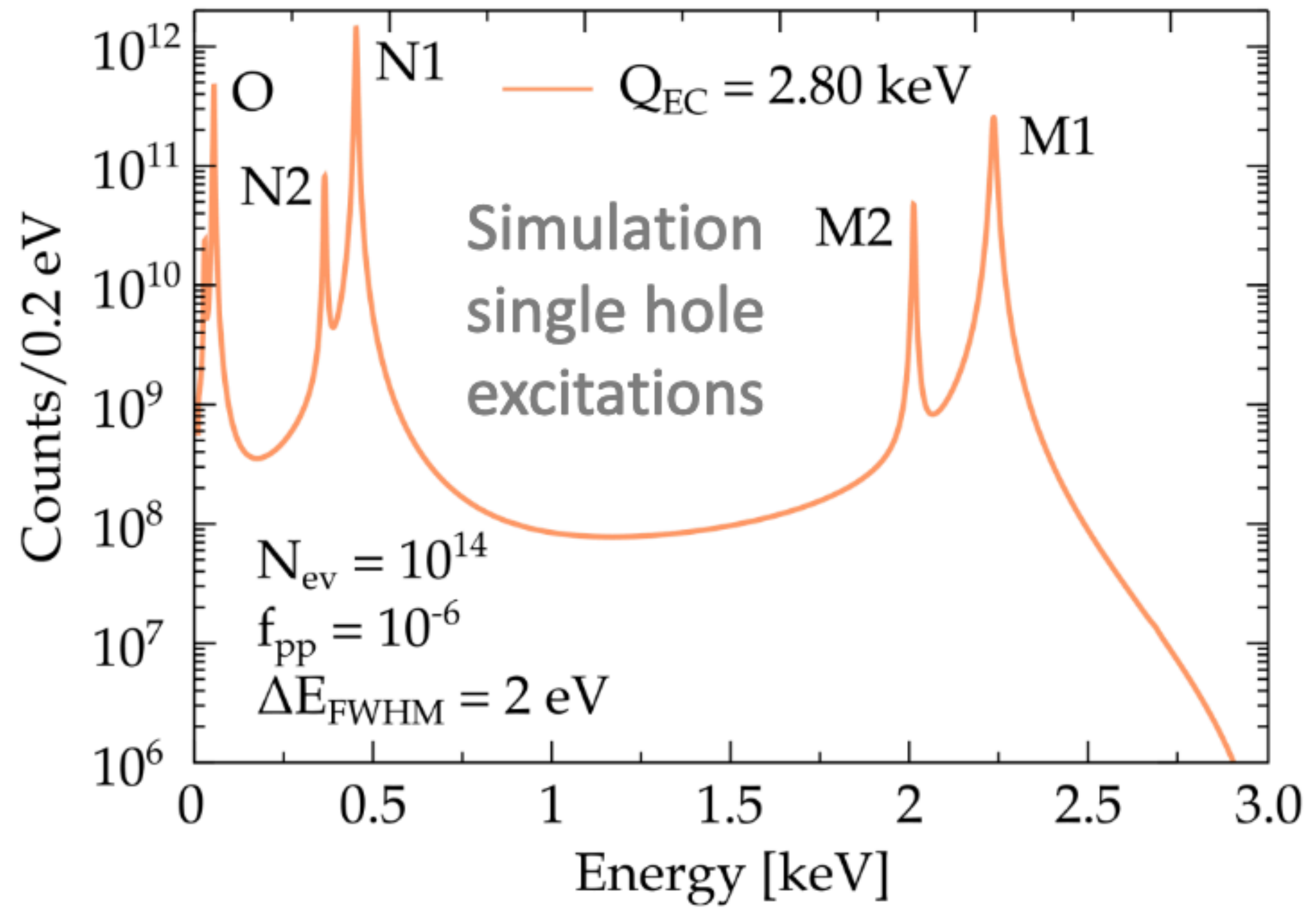
$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}\boxed{(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2}} \times \sum n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

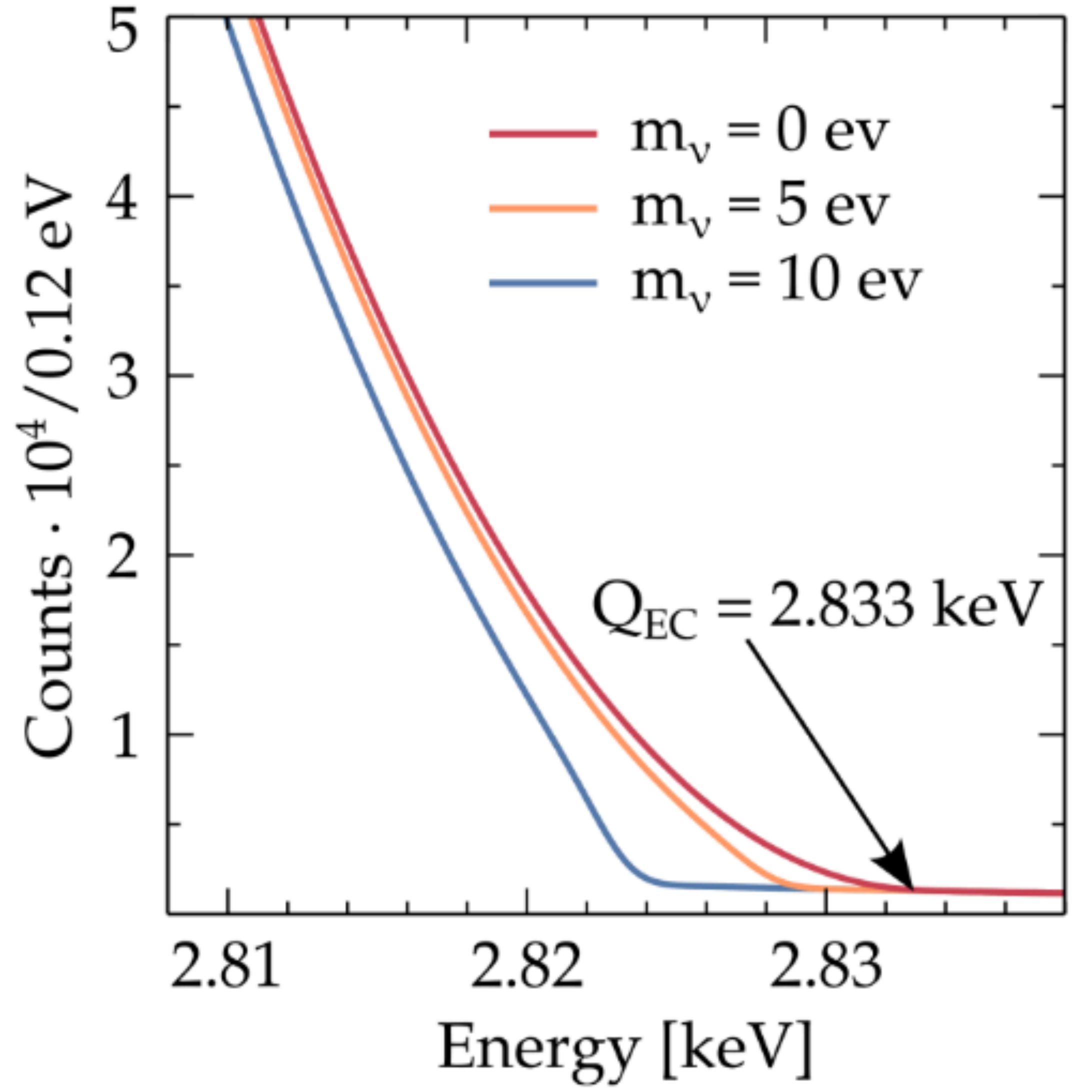
Q~2.8keV, capture only from shell ≥ M1
De Rujula & Lusignoli, Phys. Lett. B 118 (1982) 429

same phase space factor as usual β decay
(total de-excitation energy E_c instead of E_e)

Breit-Wigner shape

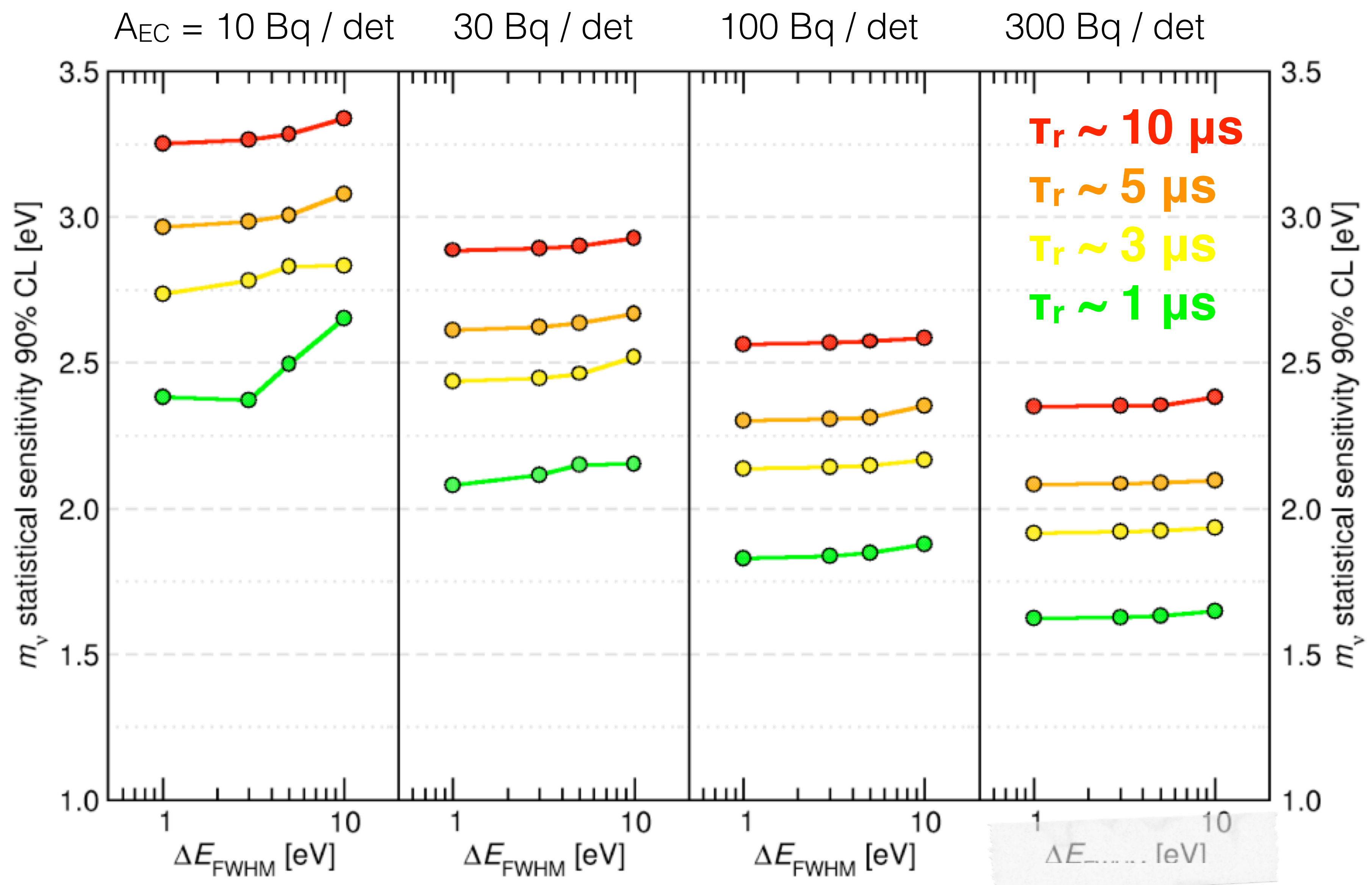
- Calorimetric measurement of Dy* de-excitation spectrum;
- “good” event rate and ν mass sensitivity depends on Q-value and capture peak position (roughly ~$1/(Q-E_{M1})^3$);
  - proximity of M1 line to end-point enhance statistics
- $\tau_{1/2}$ ~ 4570 years → few active nuclei needed;
  - avoid to spoil detector performances.





The HOLMES experiment in a nutshell

- **Direct neutrino mass measurement** with statistical sensitivity around 1 eV
- Usage of **Transition Edge Sensor (TES) based micro-calorimeters** with ^{163}Ho implanted Au absorber:
  - 6.5 x 10^{13} nuclei / det
  - A_{EC} ~ 300 Bq / det
  - ΔE ~ 1 eV, Δt ~ 10 μs
- **Multi steps approach:**
  - **64 chs prototype, activity ~ 1 Bq (showed in this talk)**
    - Probe of the full chain, assessment of implanted Ho effect on detector signals, first low statistic spectrum (analysis tool etc)
  - **64 chs array, implanted with maximum achievable activity**
    - t_m = 1 month, m_ν first m_ν extraction with sensitivity O(10 eV)
  - **1000 channels arrays:**
    - 6.5 x 10^{16} total nuclei
    - O(10^{13}) events / year
    - m_ν ~1 eV



sub-ev sensitivity region: $N_{ev} >> 10^{13}$

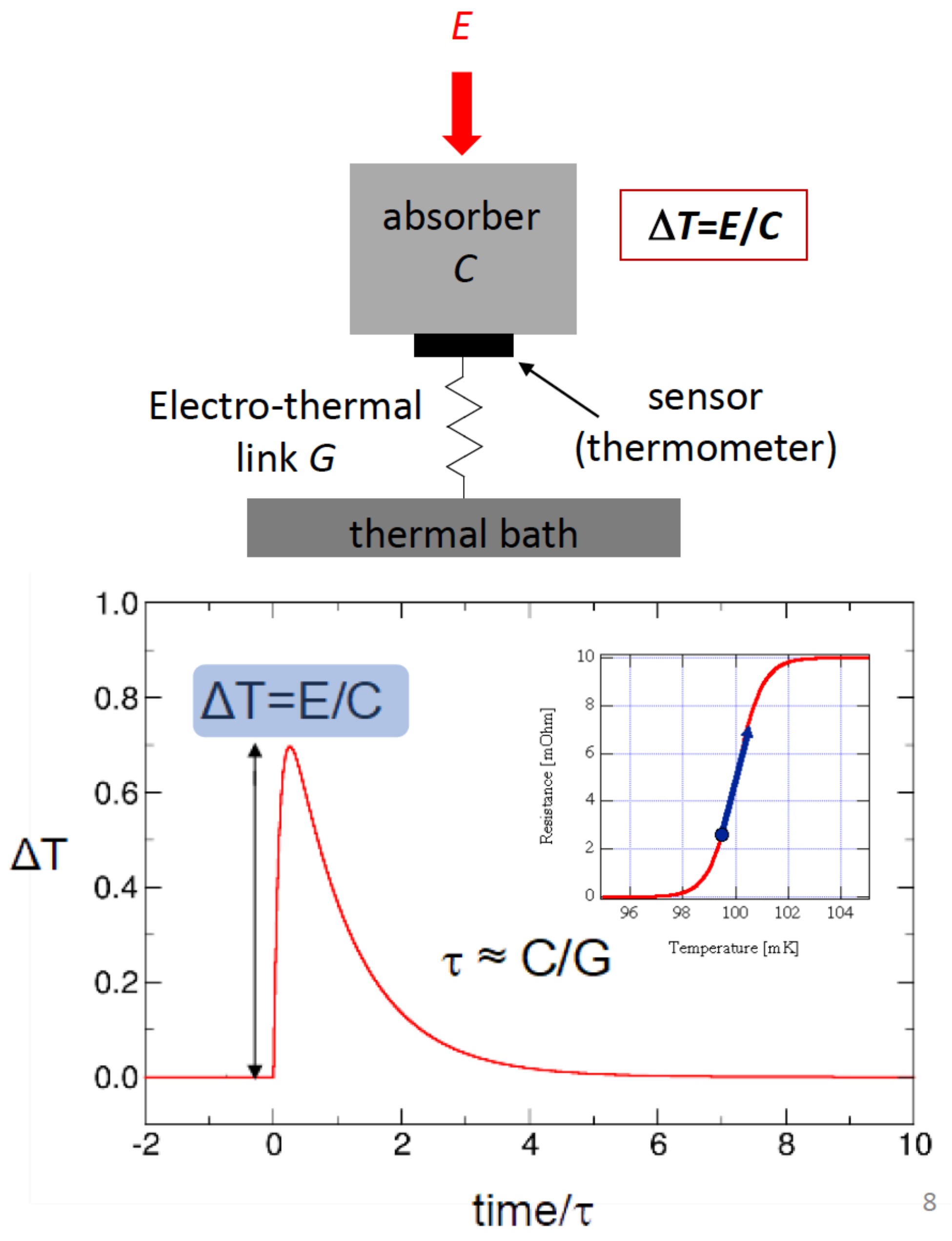
HOLMES detectors: TES-based micro-calorimeters

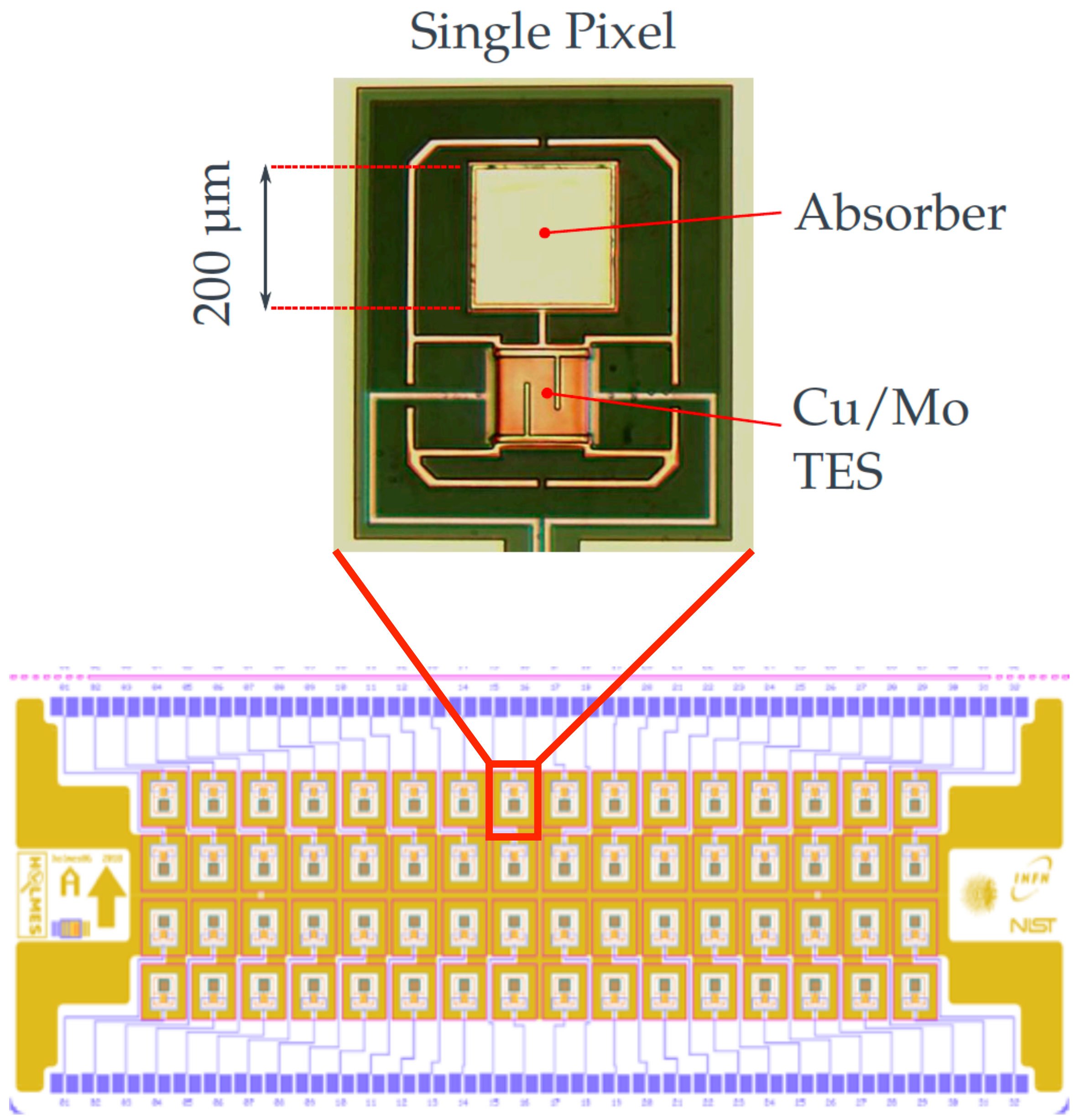
Transition edge sensors based μ-calorimeters:

- absorber coupled to superconductive sensor in transition region, energy release in absorber → temperature increase in TES → variation of TES resistance;
- 2 μm Au thickness for full absorption of e⁻ and photons
- "side car" configuration to avoid TES proximization and allow G engineering for a optimal τ control

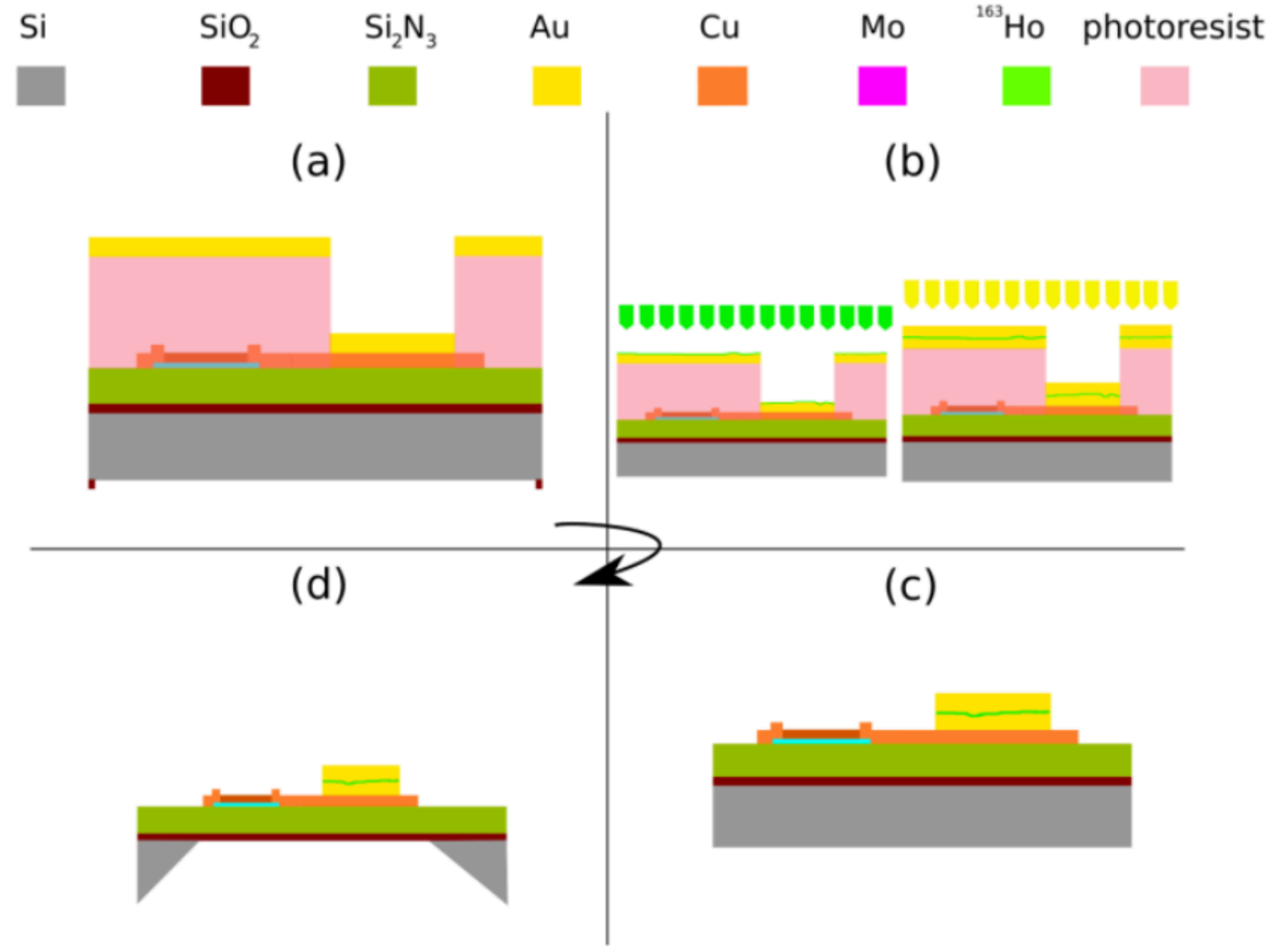
Multi step production procedure:

- Up to first 1um of Au at NIST;
- Ho implantation in Genova;
- absorber completion, bonding and membrane release in Milano.





64 chs array



The Ho source production and preparation

^{163}Ho does not exist in nature: it is produced at nuclear reactor by:

- ^{162}Er (n,γ) ^{163}Er, σ_{therm} ~ 20 b
- ^{163}Er + e$^-$ → ^{163}Ho + ν_e ($\tau_{1/2}$ ~ 75 m)

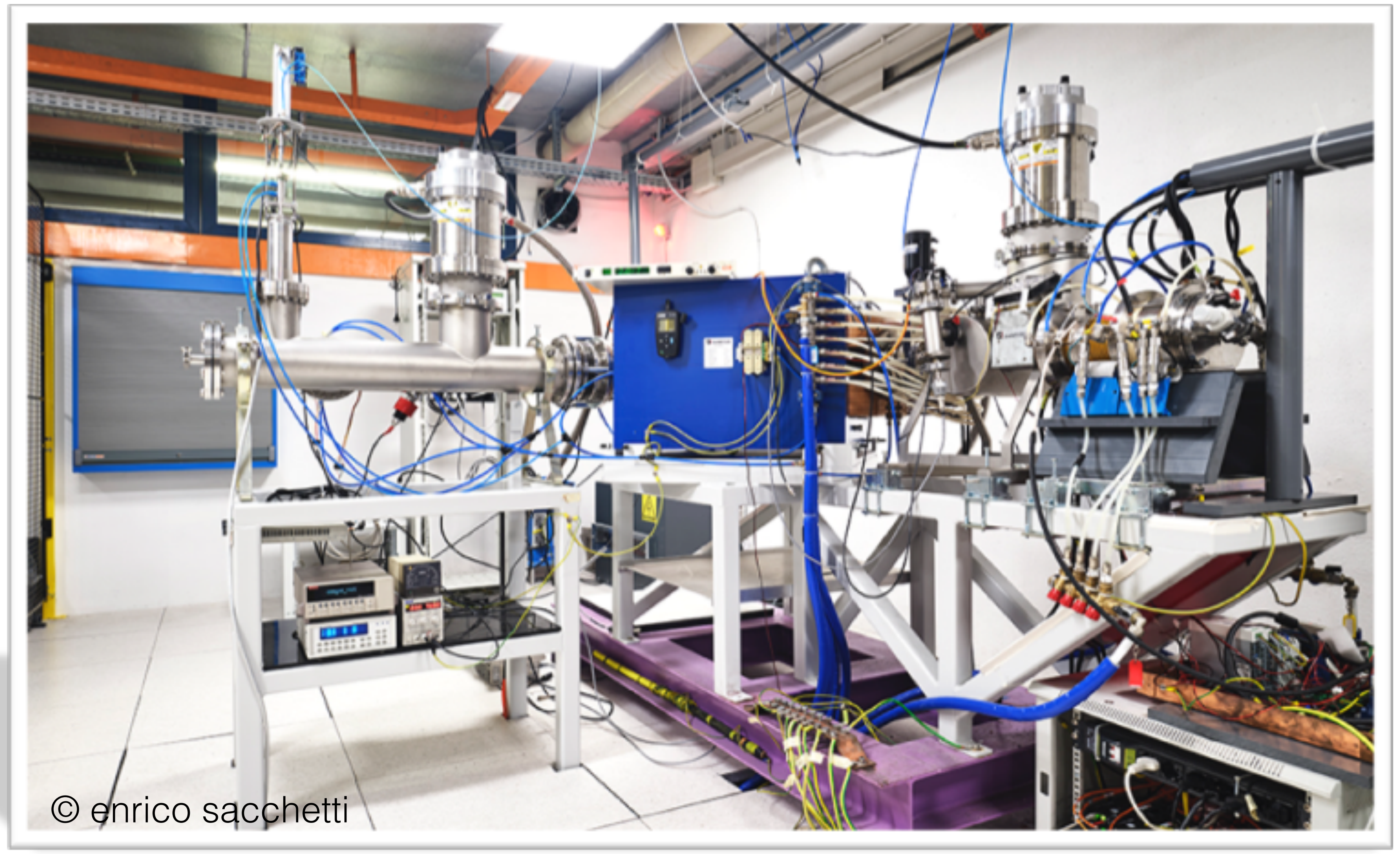
“Dirty” process: many other isotopes are created together with ^{163}Ho. The worst one is ^{166m}Ho:

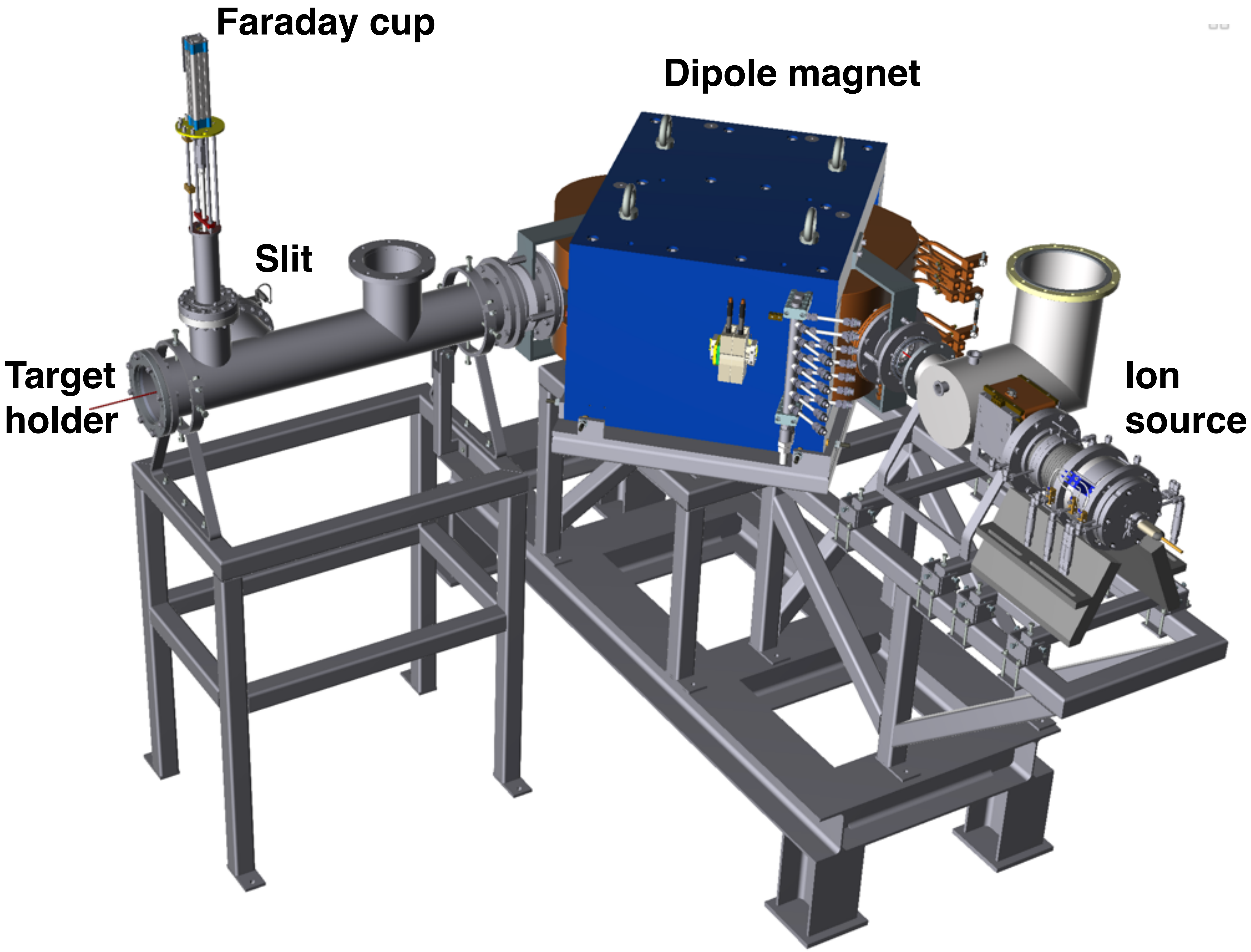
- ^{165}Ho (n,γ) ^{166m}Ho
- It shows a β decay which can be source of background in HOLMES roi ($\tau_{1/2}$~ 1200 years).

- For this reason purification of sample is needed.
  - A radiochemical separation removes everything but Ho. It is done at PSI: after this process, a 163Ho/165Ho/166mHo with proportion 60/40/0.1 Ho(NO_3)$_3$ is obtained
- **A mass separation is mandatory to remove ^{166m}Ho (and even ^{165}Ho).**

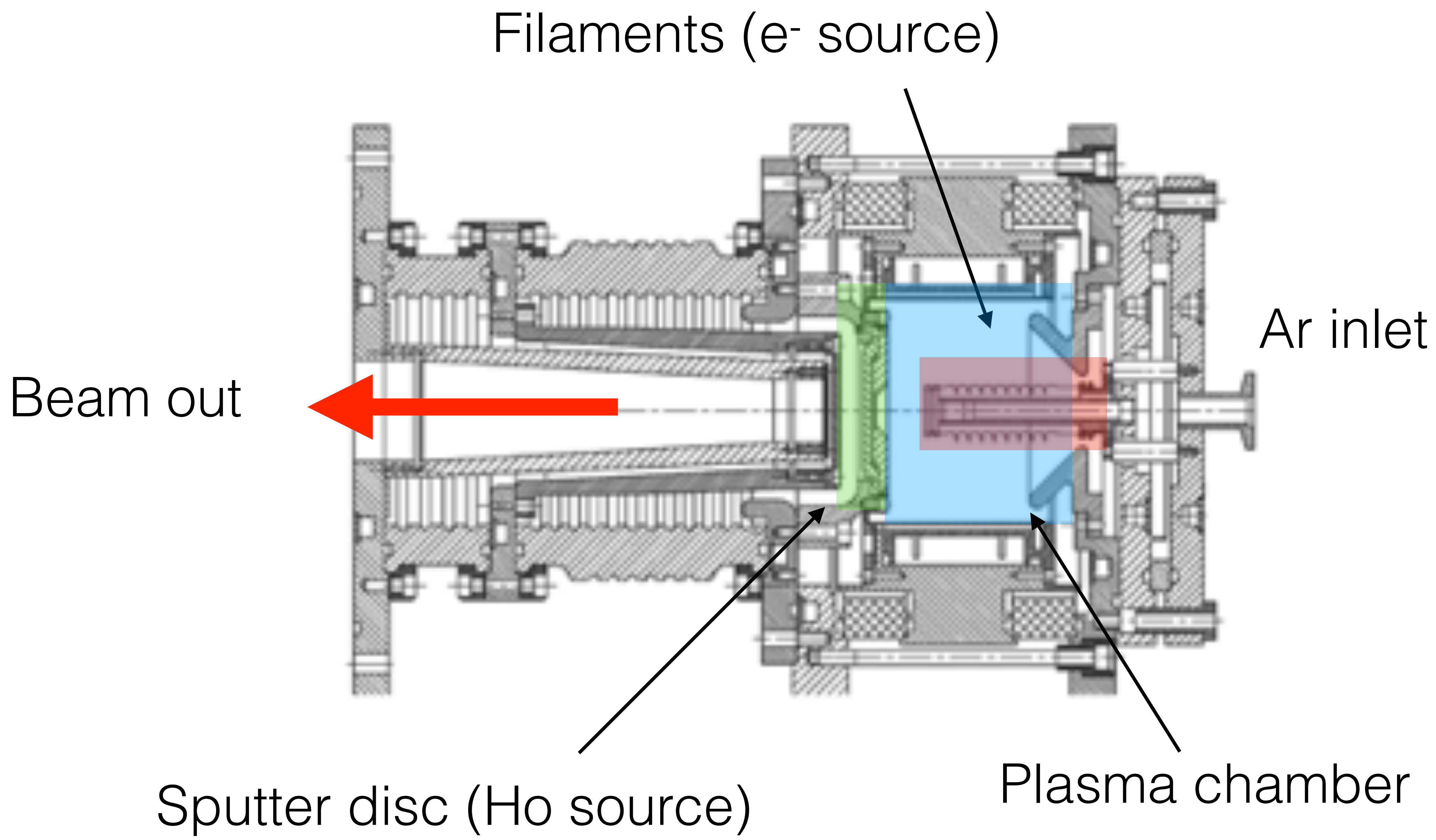
The ion implanter

- an Ar Penning **sputter ion source** (50 keV max acceleration energy);
- a **magnetic dipole mass analyzer** (max. B field: 1.1 T);
- a **Faraday cup** and a **slit** for beam diagnostic / geometrical selection;
- a **target holder**, able to hold target && measure beam current during implantation run.





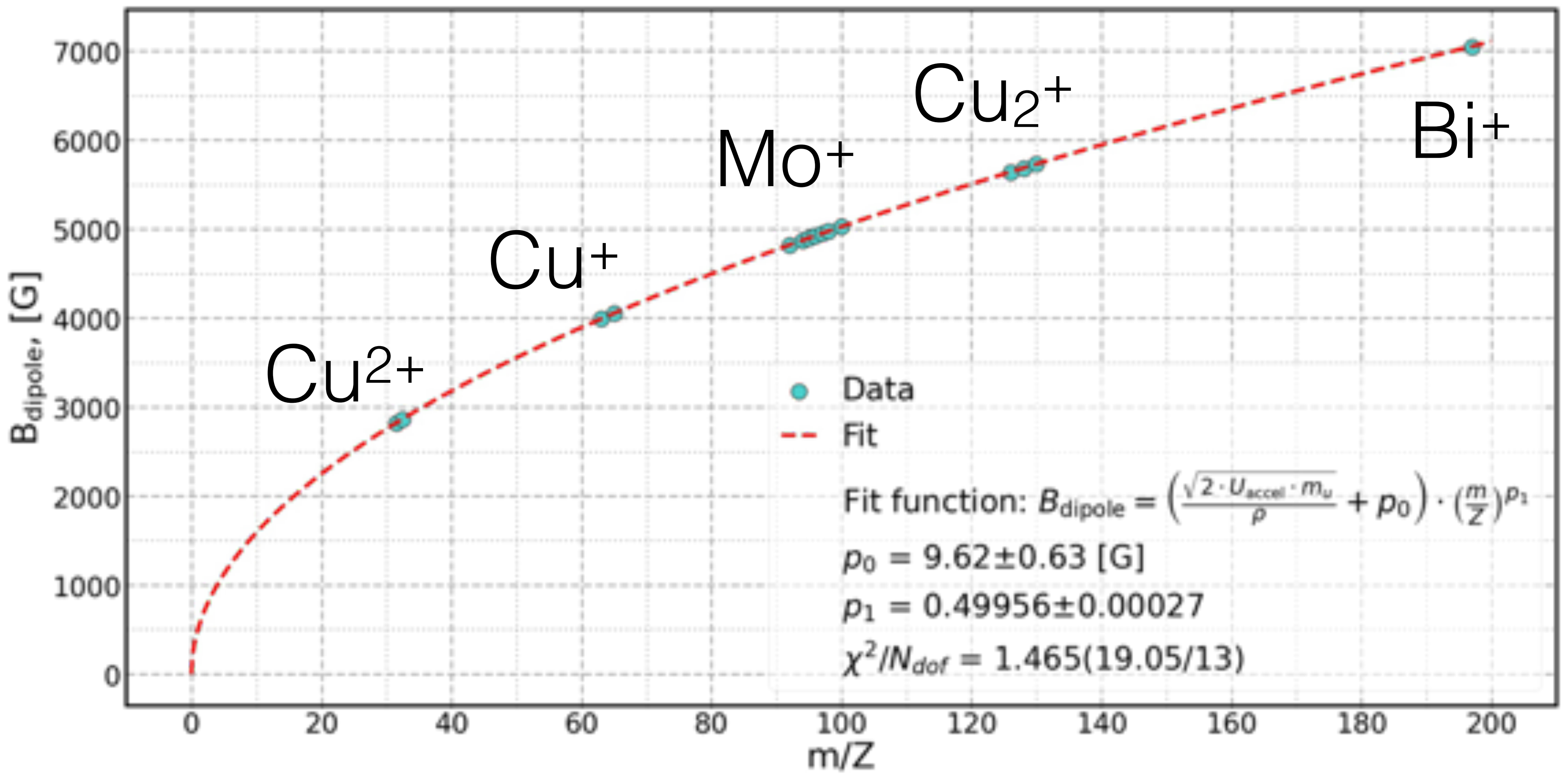
The ion source and sputter target

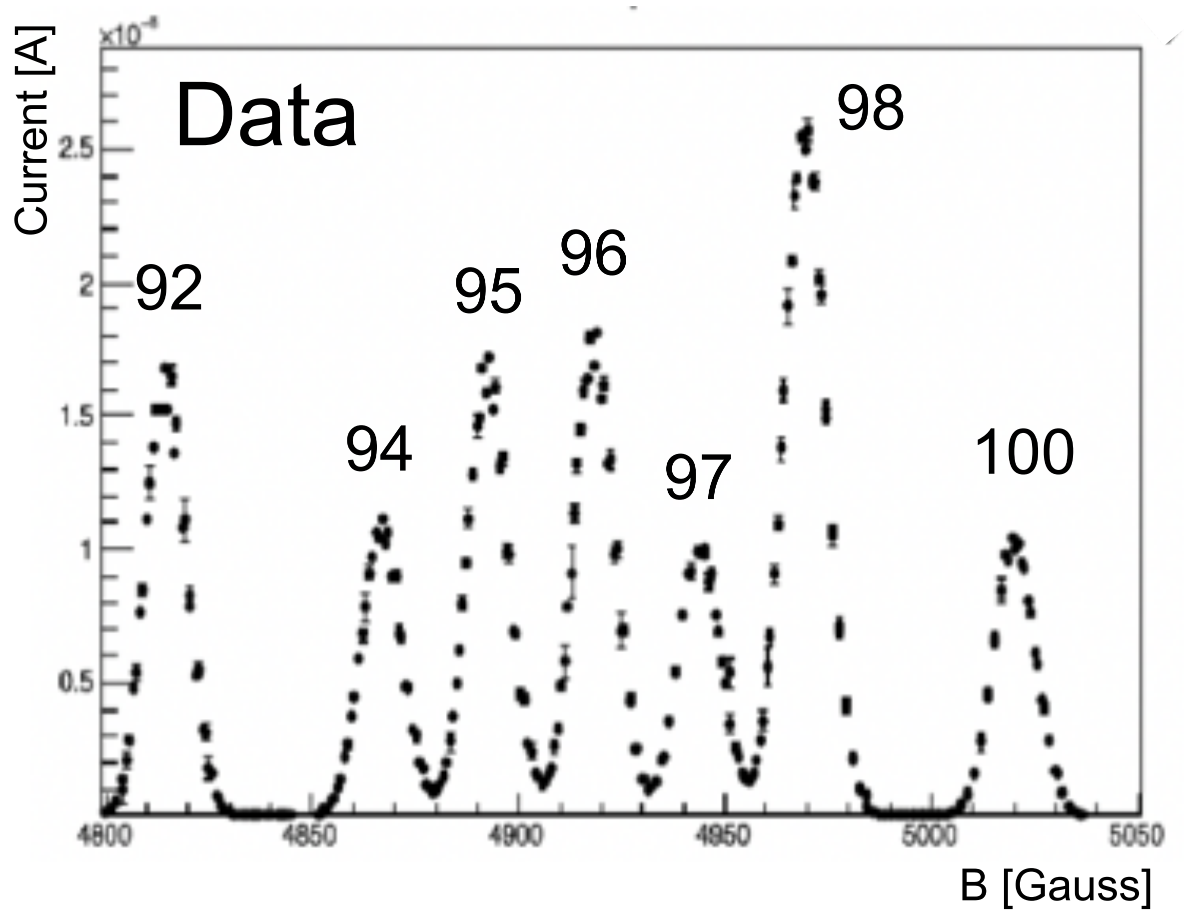


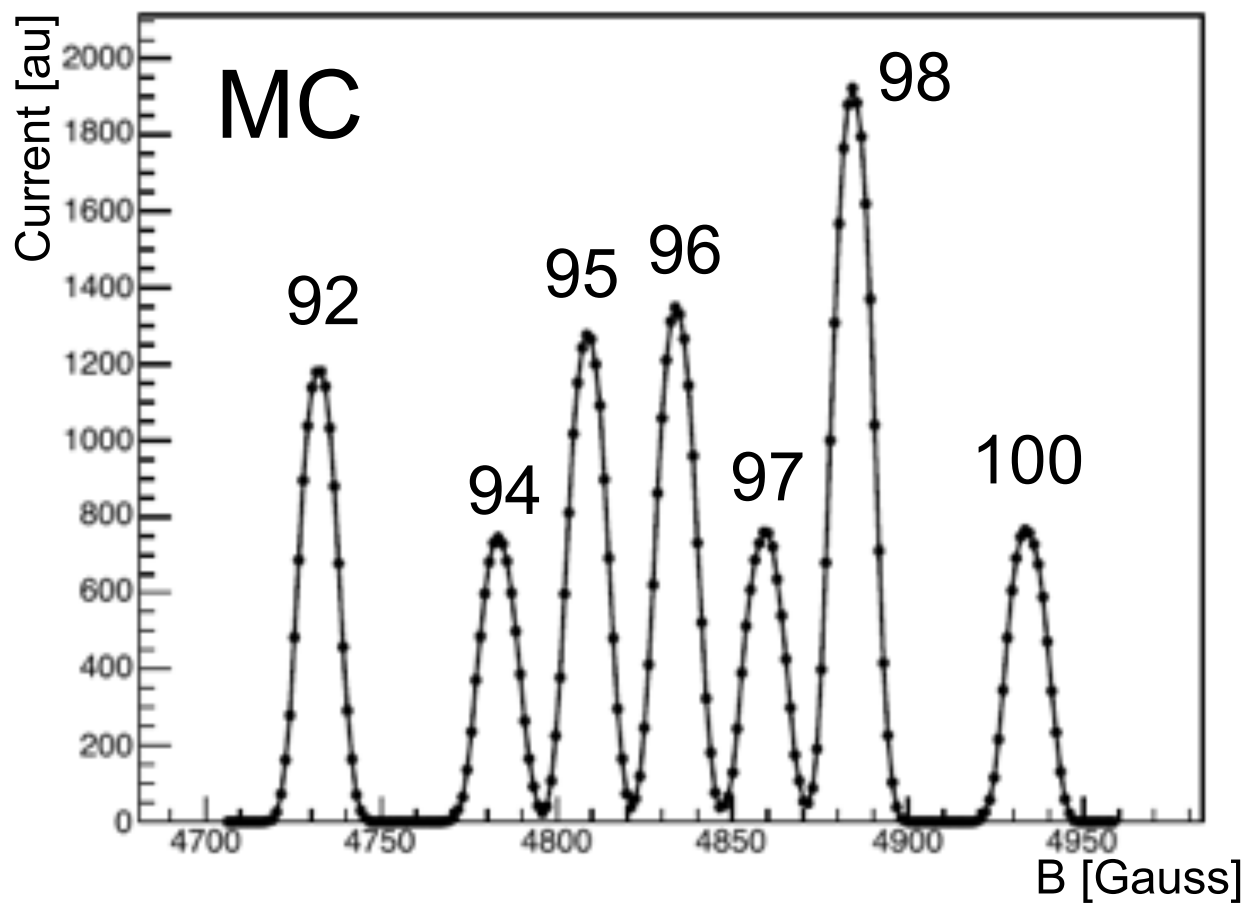
The sputter target consists of a Zr/Bi (98%/2%) sintered matrix on which a $^{163}Ho(NO_3)_3$ solution is "dripped" and dried. In this way it was possible to obtain an uniform distribution of the source inside the target.

Implanter commissioning: calibration and MC

The machine is calibrated analyzing multiple peaks from Cu, Au, and Bi (which are present inside the source/target). A small misalignment was found and taken into account during implantation process.







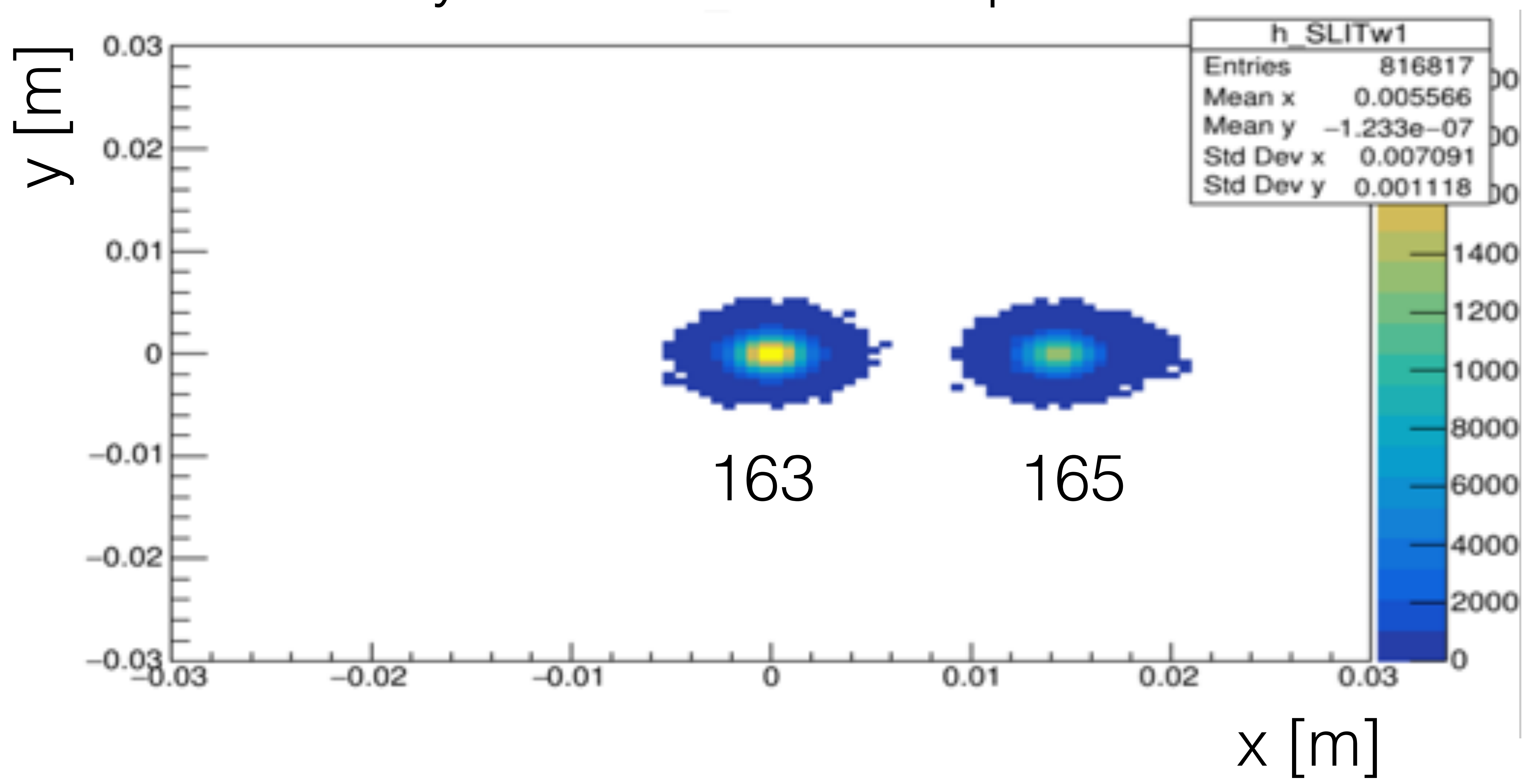
Multiple isotopes element (like Mo) are used to extract beam size **(σ ~ 1.3 / 1.5 mm)** and cross check MC simulation reliability.

Implanter commissioning: 163/166 separation

Our solution contains ^{163}Ho/^{165}Ho/^{166m}Ho with relative abundance: 60/40/0.1

163 vs 165/166 a.m.u. separation evaluated by MC simulation (and validated on data, see later) → ^{165}Ho is expected to be about 15 mm far from ^{163}Ho at slit plane → ^{166m}Ho is expected to be ~ 22 mm away from ^{163}Ho.

x-y distribution at slit plane

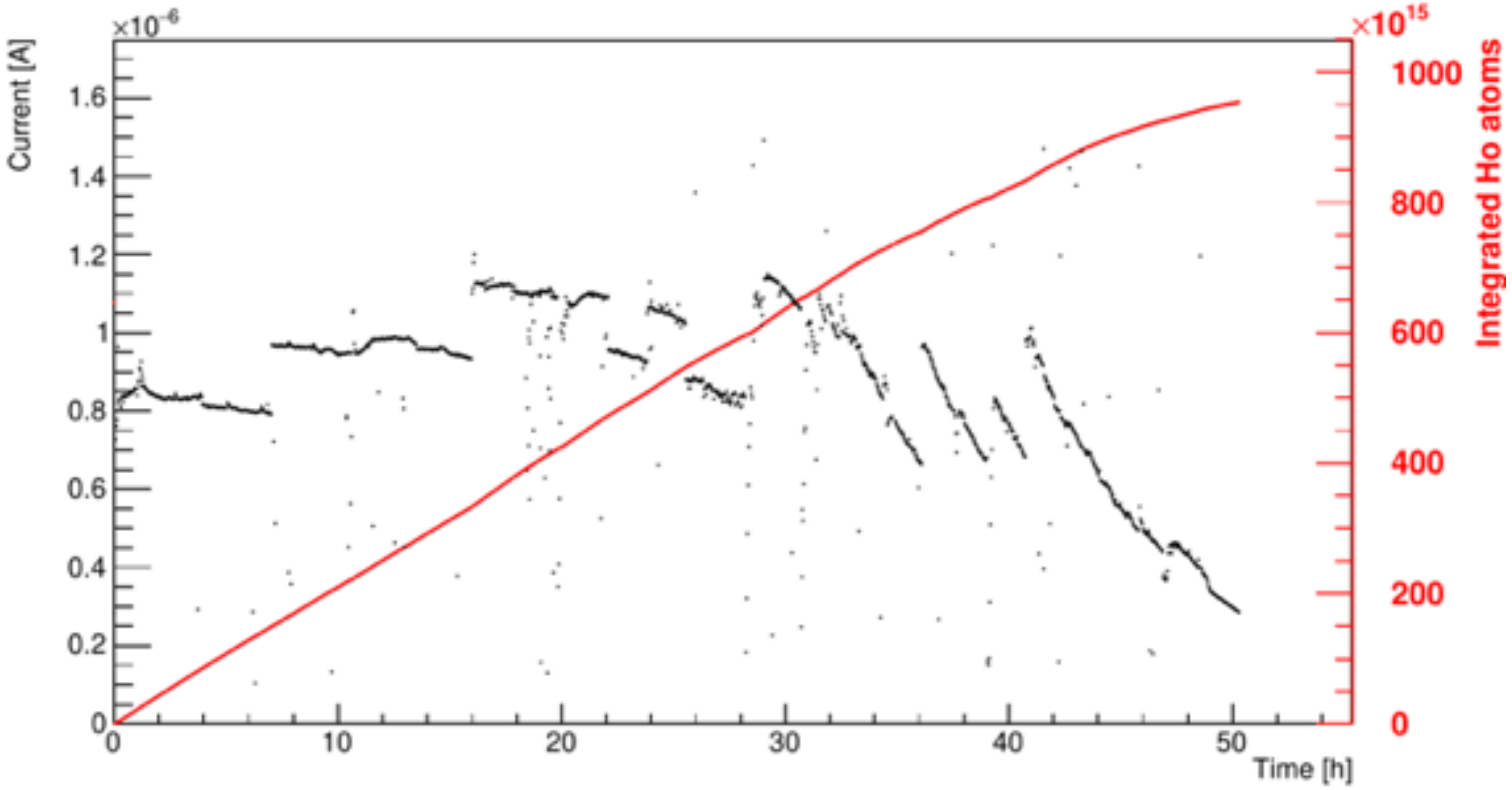


Extraction efficiency

Extraction efficiency is evaluated using ^{165}Ho loaded target, by acquiring long run (> 50 h running time) up to a total consumption of the target and comparing integrated charge with ^{165}Ho content.

An efficiency ε ~ 0.2 % was found. It is low but enough to proceed with first implantation.

Studies are ongoing to improve the source extraction efficiency.



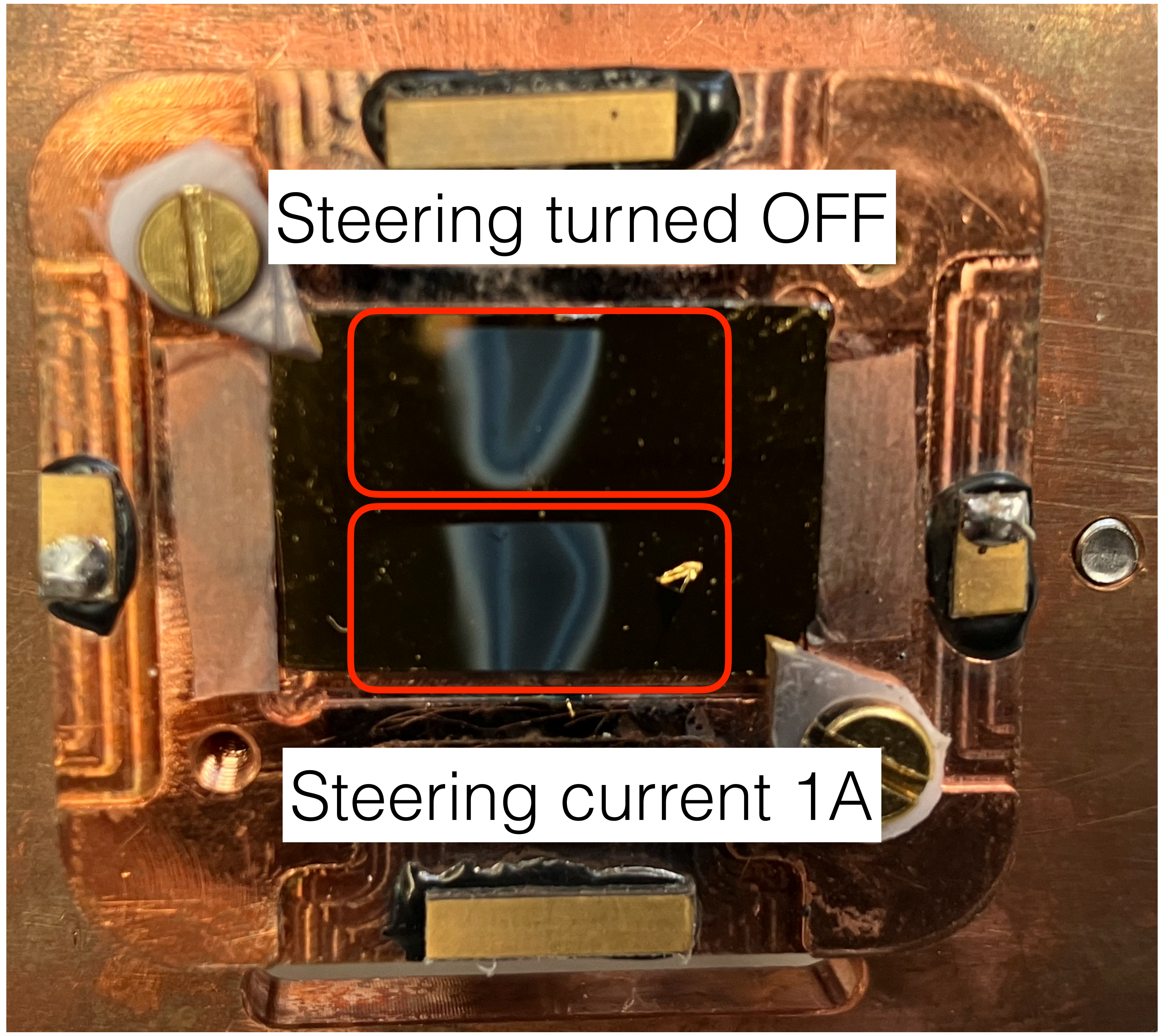
Jumps in beam current plot are due to different source configuration (sputtering and discharge voltage)

Beam profile and vertical alignment

In the current implanter setup the only diagnostic tool is a Faraday Cup, which is not the best tool for alignment purposes.

Thus, beam profile and alignment were checked with high current implantation runs using gold plated silicon substrate as targets and looking for the beam “shadow”.

We found beam profile is not exactly gaussian - mainly in y direction. This is under study with MC simulation.



First arrays implantation

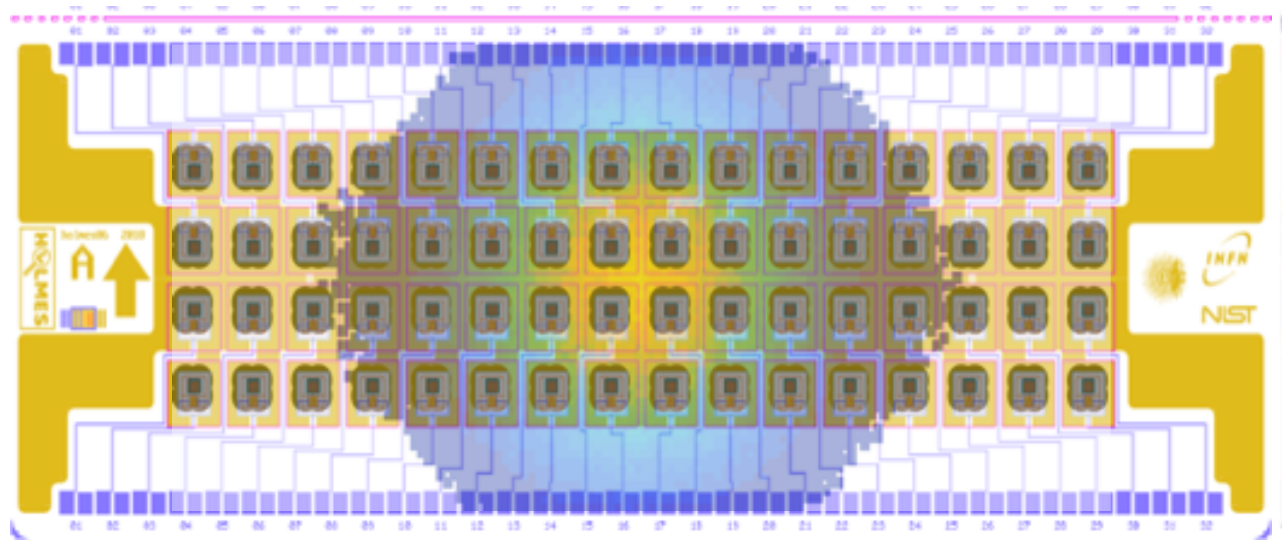
We did 2 sets of implantation runs on 2 arrays:

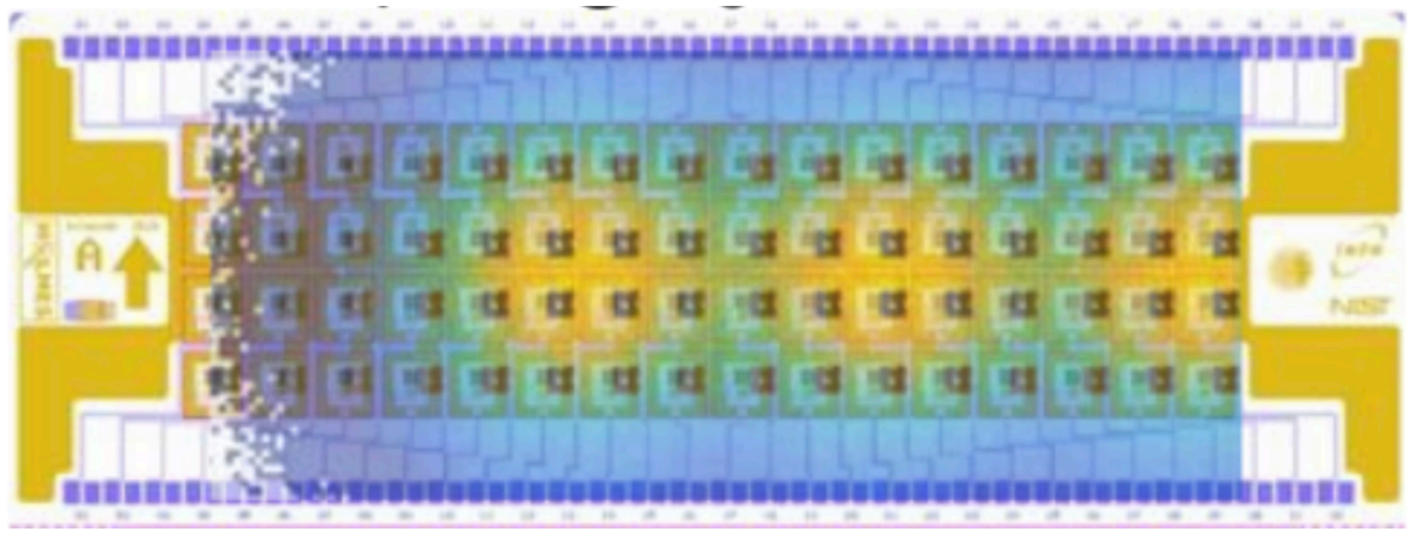
1) single spot in the center of the array, for beam profile evaluation and assessment of the effect of Ho implantation on detector properties;

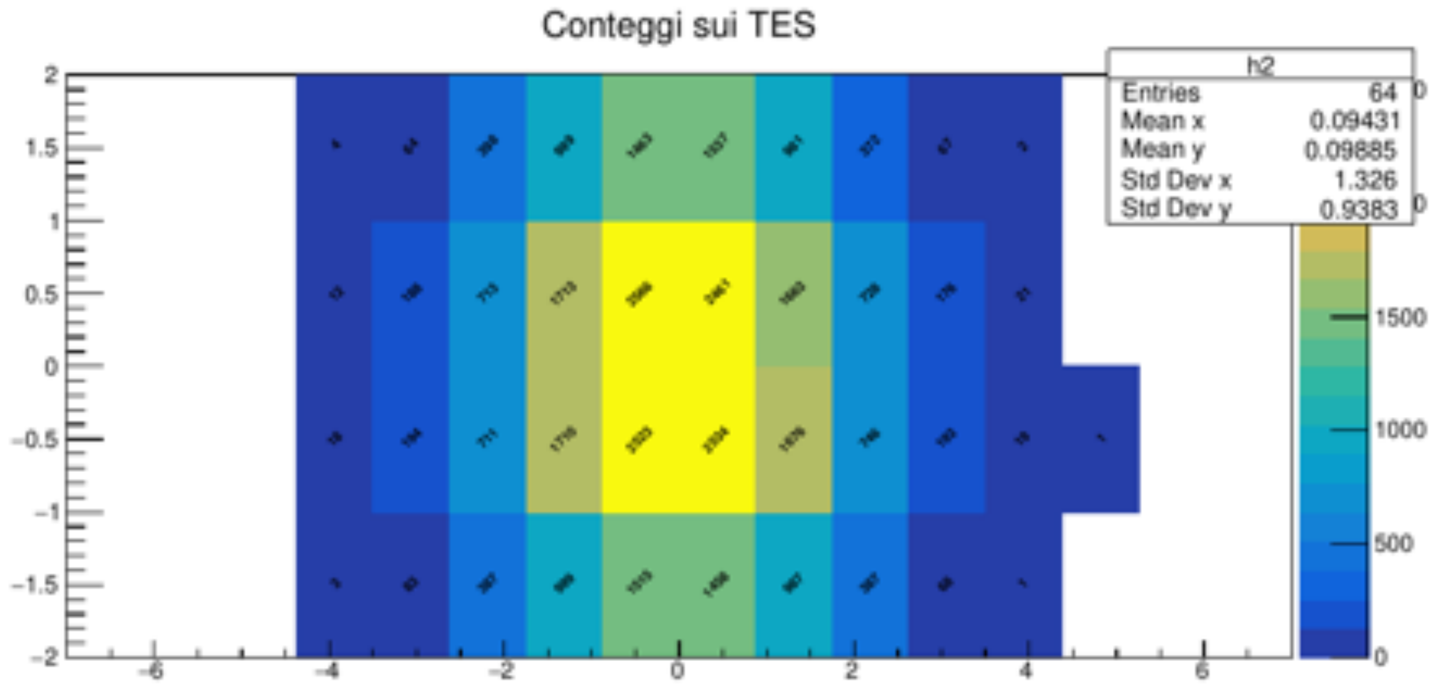
2) multiple (3 positions) spots to check implantation uniformity

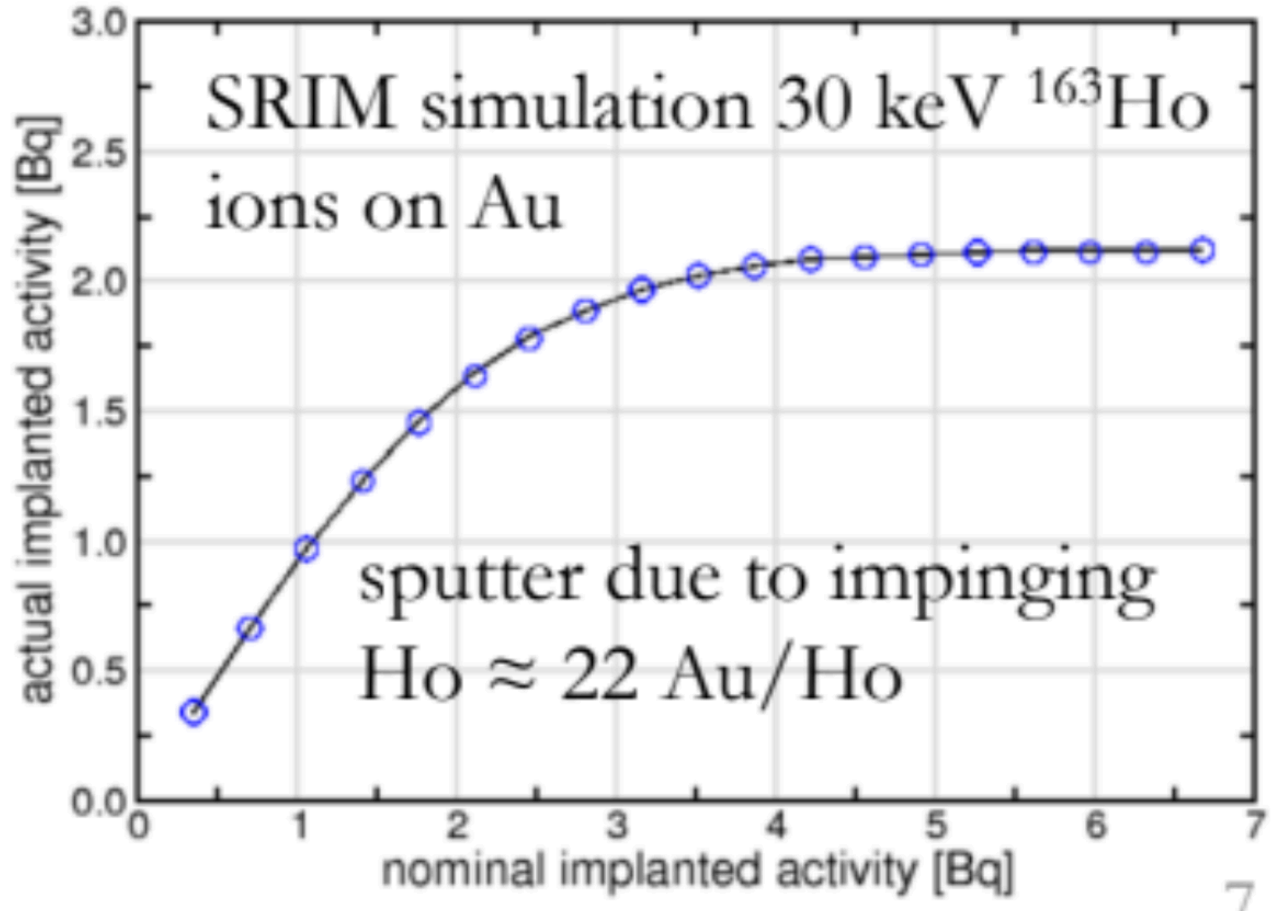
Geometrical efficiency was evaluated by means of MC simulations.

From SRIM simulation, we expect a saturation effect in the maximum achievable activity.

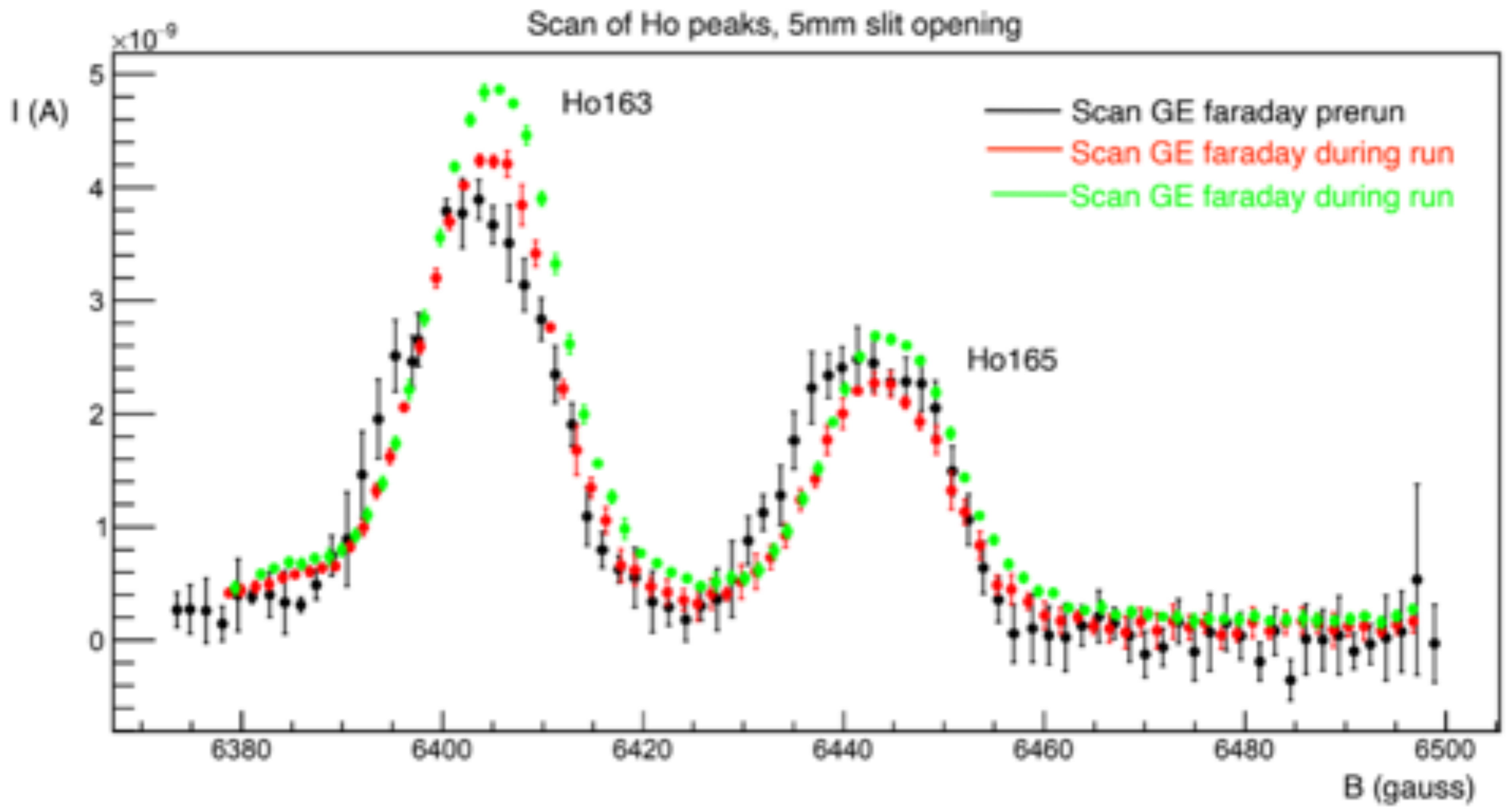




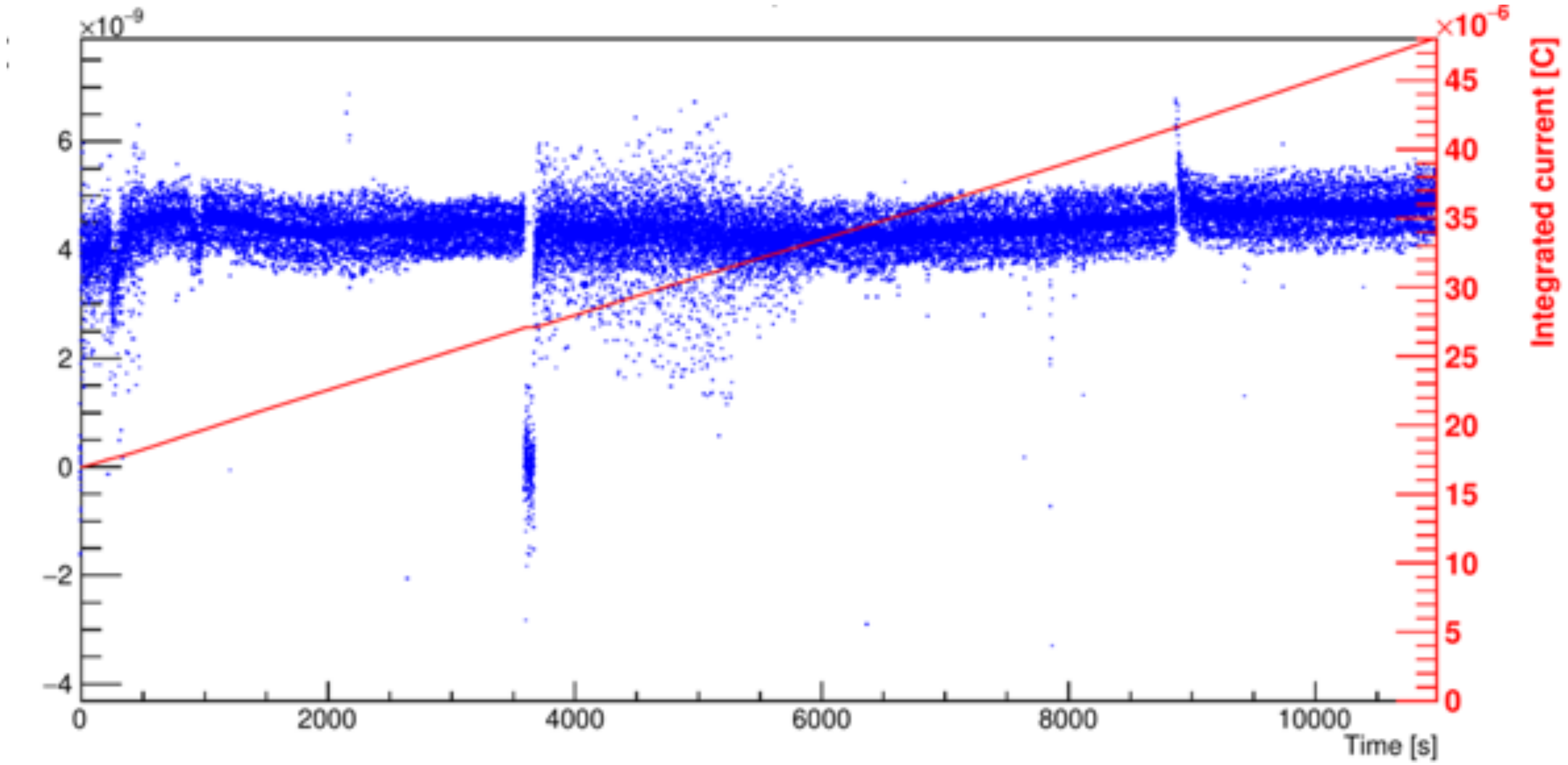




First arrays implantation



^{163}Ho / ^{165}Ho mass separation (^{166m}Ho content is too low to be measured) was measured on data during implantation runs: we found a separation of ~ 45 Gauss, corresponding to 15 mm, as expected from MC simulations.



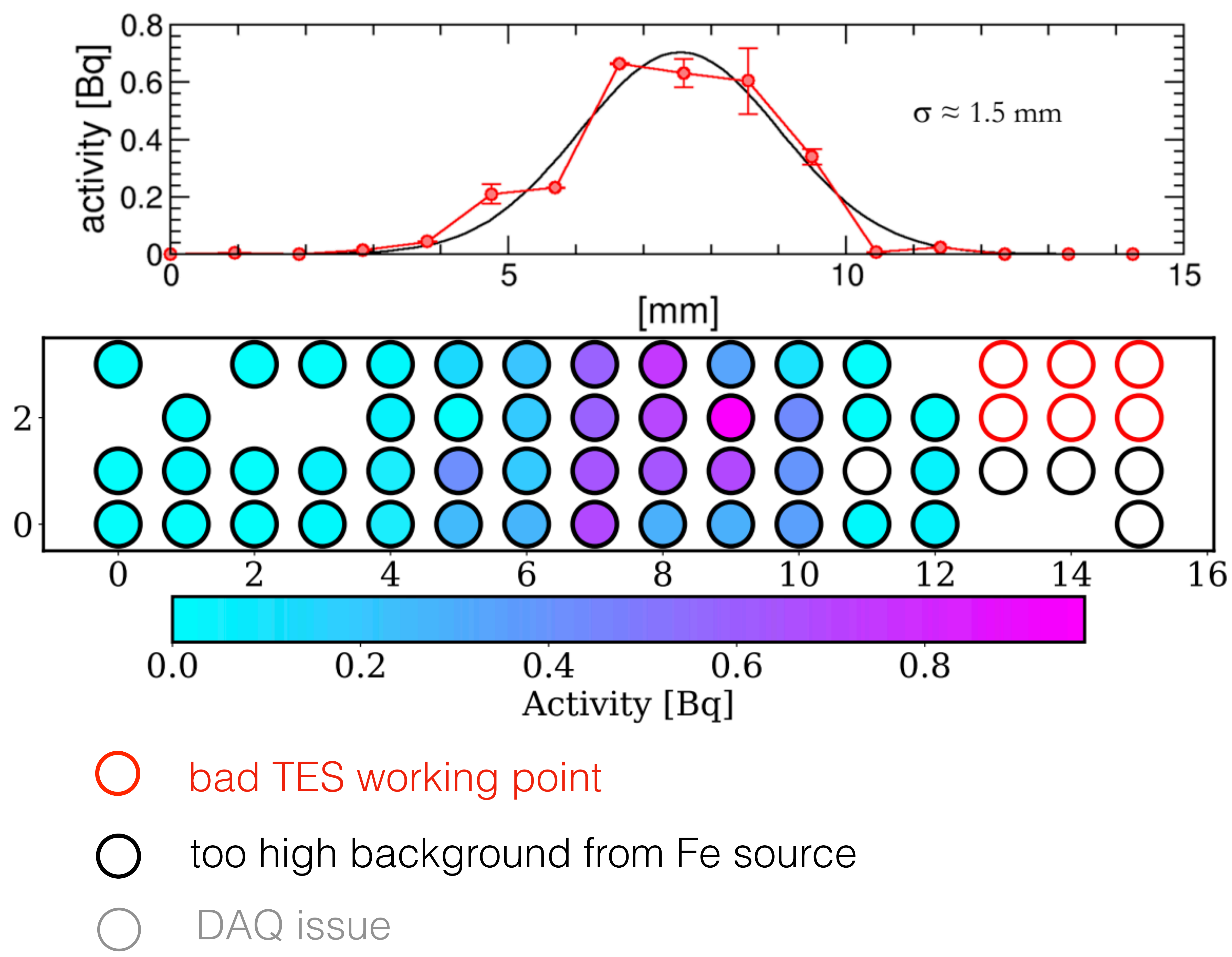
Thanks to the specially designed target holder, which acts even as a Faraday Cup, we are able to measure beam current on-line during implantations.
We expected to have an activity of ~ 2Bq in central TES after a run of ~ 3hours at 5nA beam current.

First arrays implantation

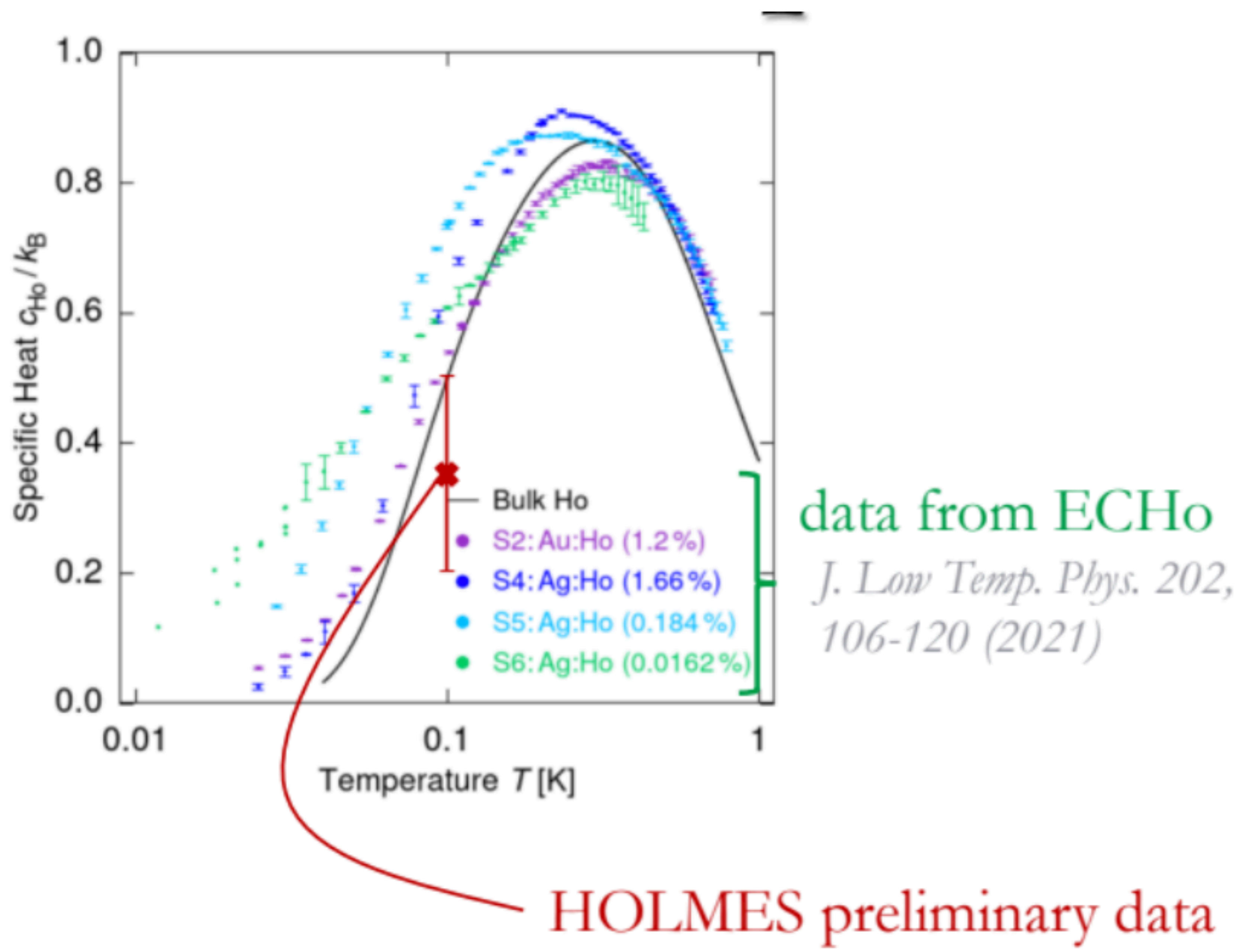
Finally, implanted detectors were measured in HOLMES setup. Activities on each TES were measured and a factor 2 discrepancy with respect to expectation was found. This is still under investigation.

From the activity raw map it is possible to evaluate beam size: we found a σ ~ 1.5 mm, in good agreement with expectation.

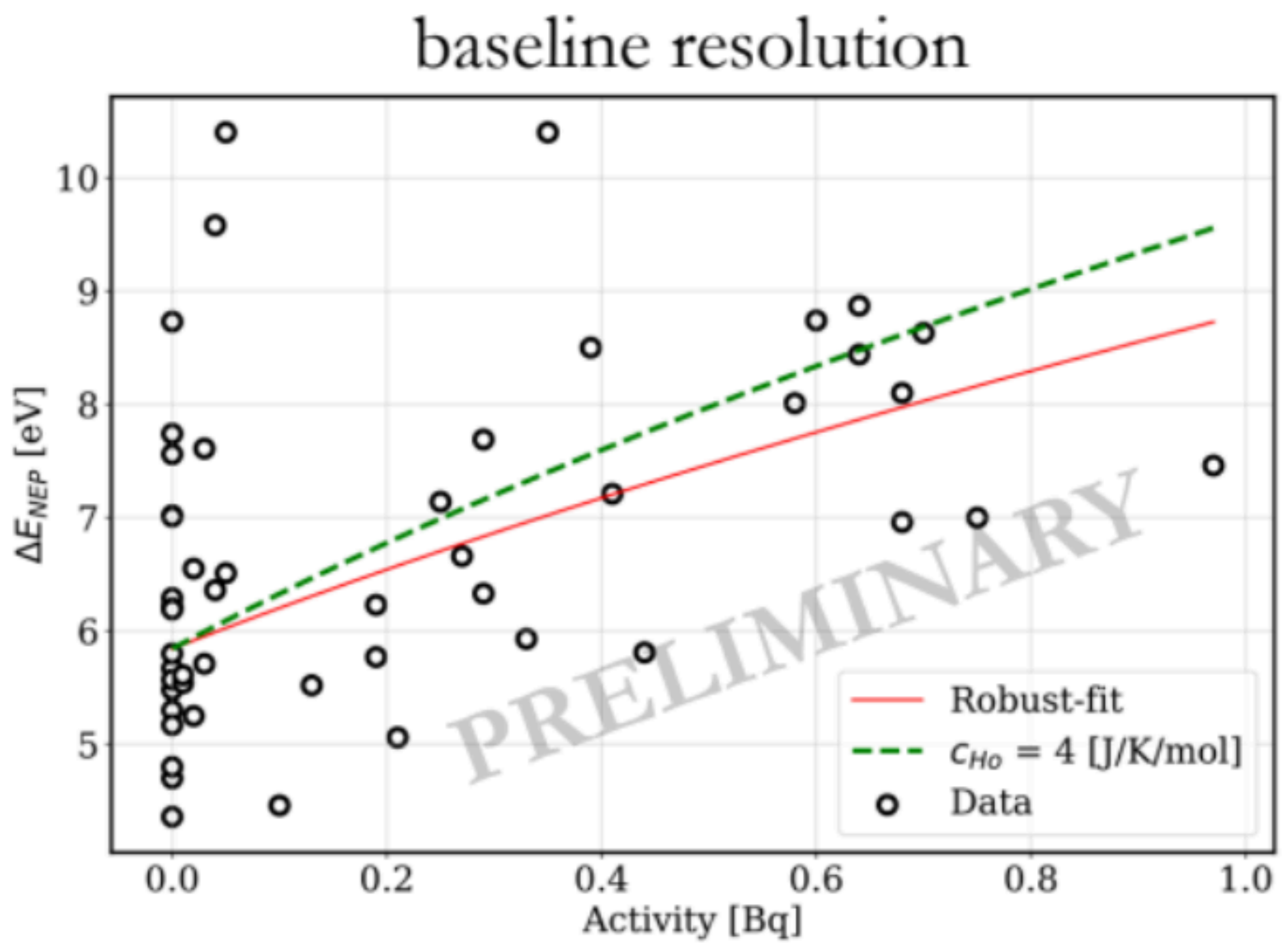
Analysis of the multiple spots array is still on going.



First results (still in progress!): Ho impact on TES

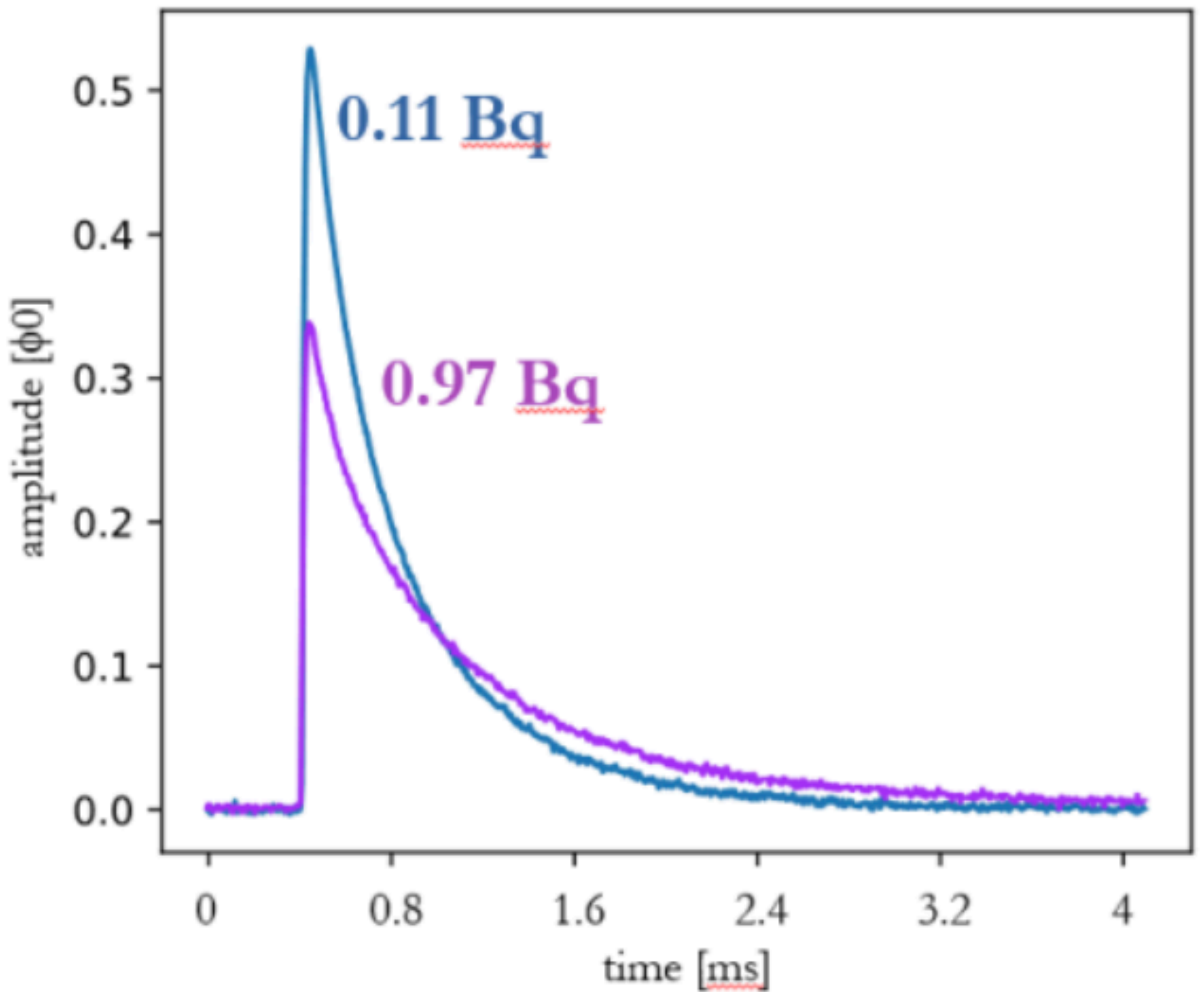


- Ho heat capacity is dominated by Schottky anomaly
- peak at ≈ 300 mK
- high activity manageable at $T \lesssim 30$ mK?
- to be explored by HOLMES



bulk Ho ≈ 4 J/K/mol *Phys. Rev.* 177:910, 1969

3 ± 1 (stat) ± 0.7 (sys) J/K/mol



- from pulses decay time:

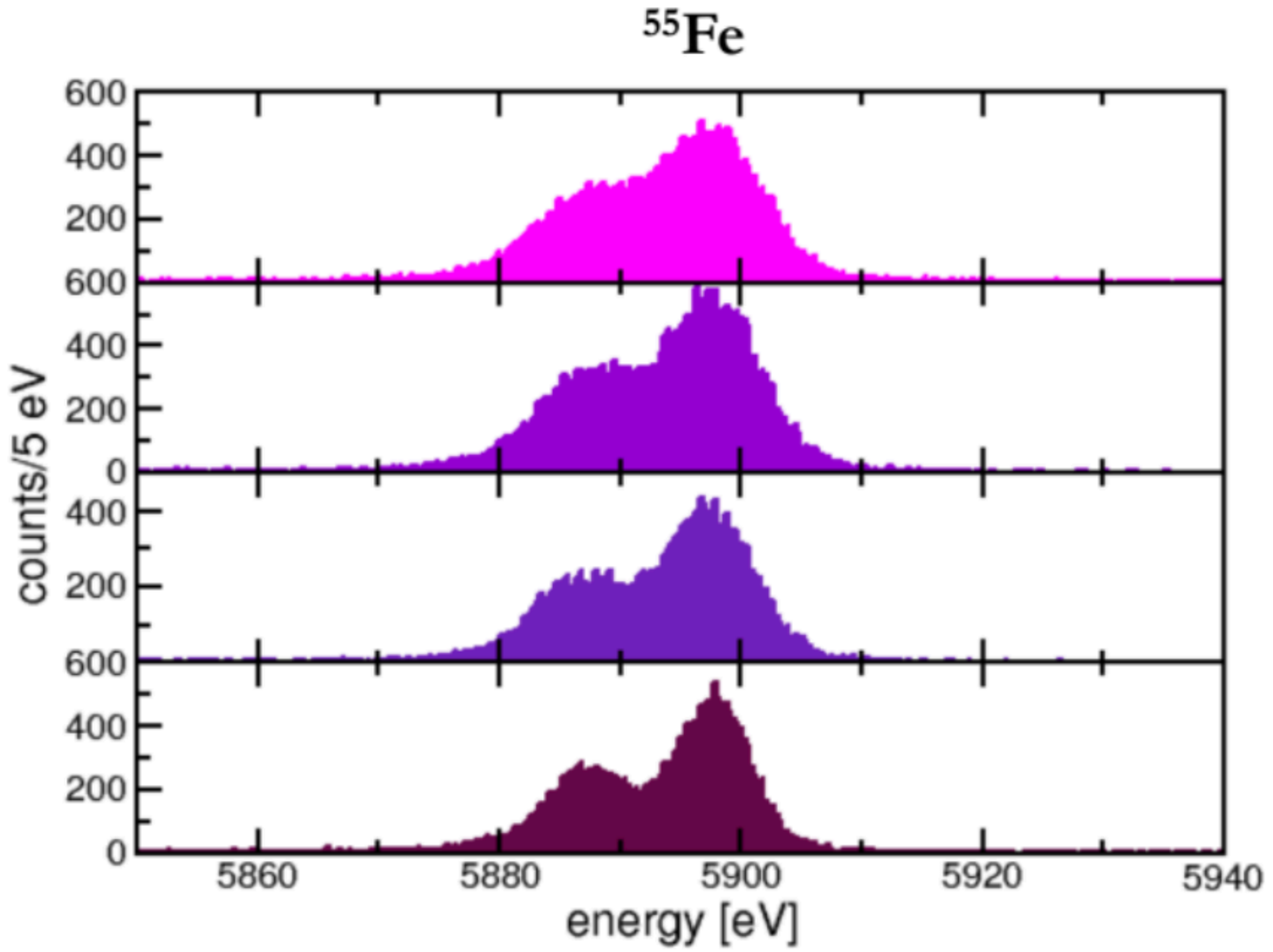
c_{Ho} = 2.5 ± 0.6 J/K/mol

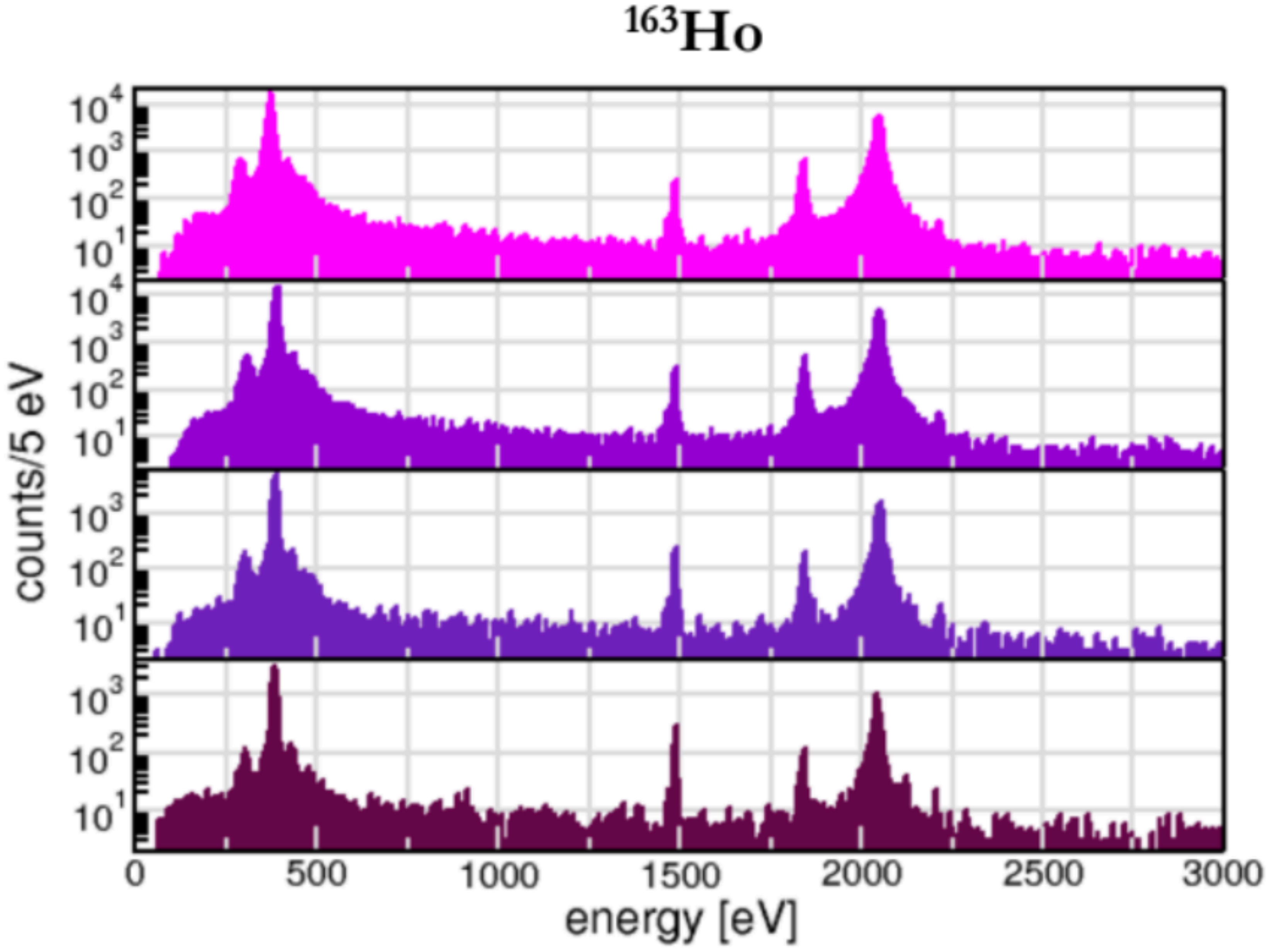
(still preliminary!!)

First results (still in progress!): Ho impact on TES

Data taken with ^{55}Fe calibration source

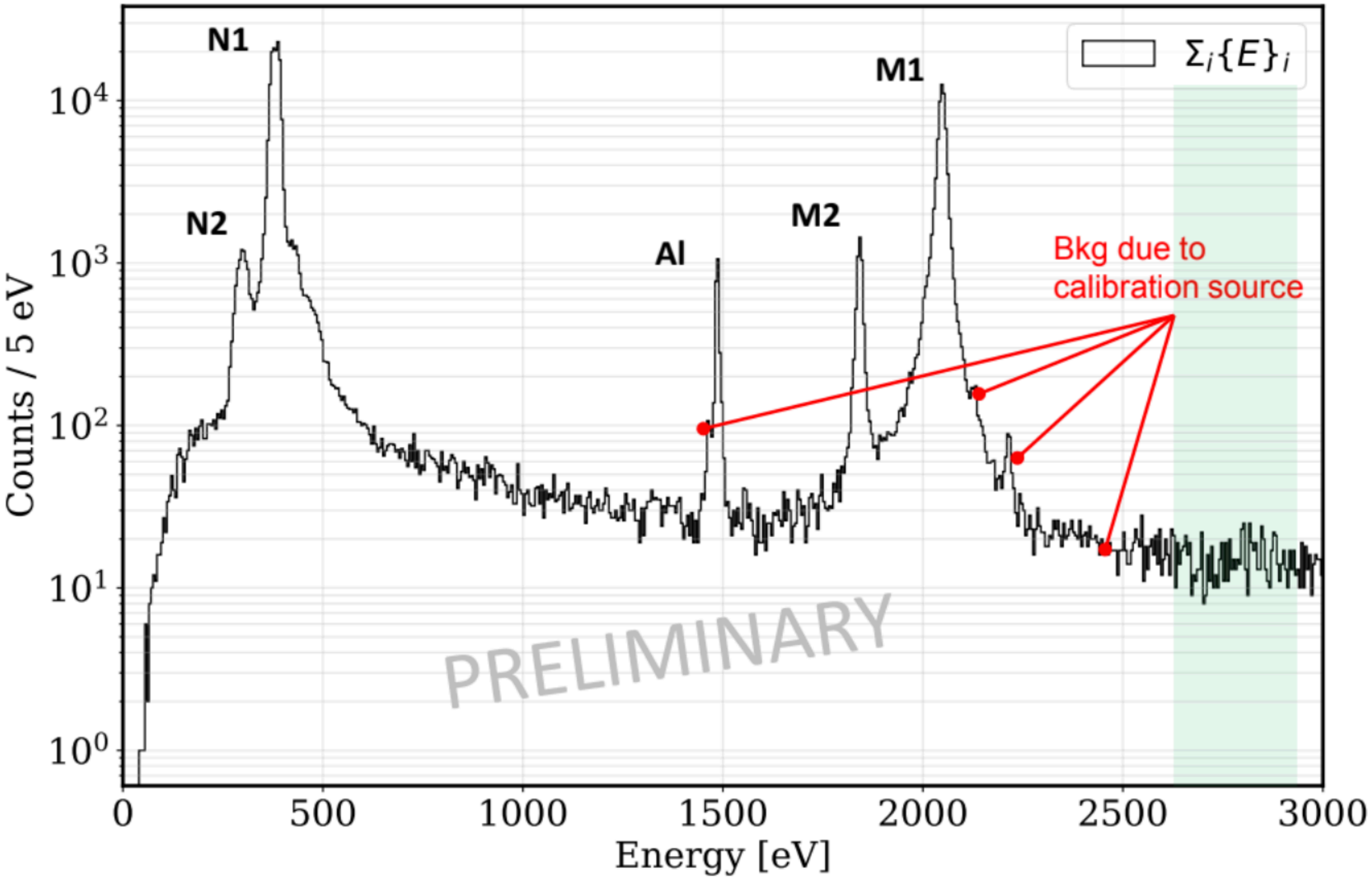
TES #	ΔE_{FWHM} @6 keV [eV]	^{163}Ho activity [Bq]
13	8.36 ± 0.09	0.97
17	7.78 ± 0.08	0.55
19	7.12 ± 0.08	0.21
21	5.76 ± 0.07	0.11





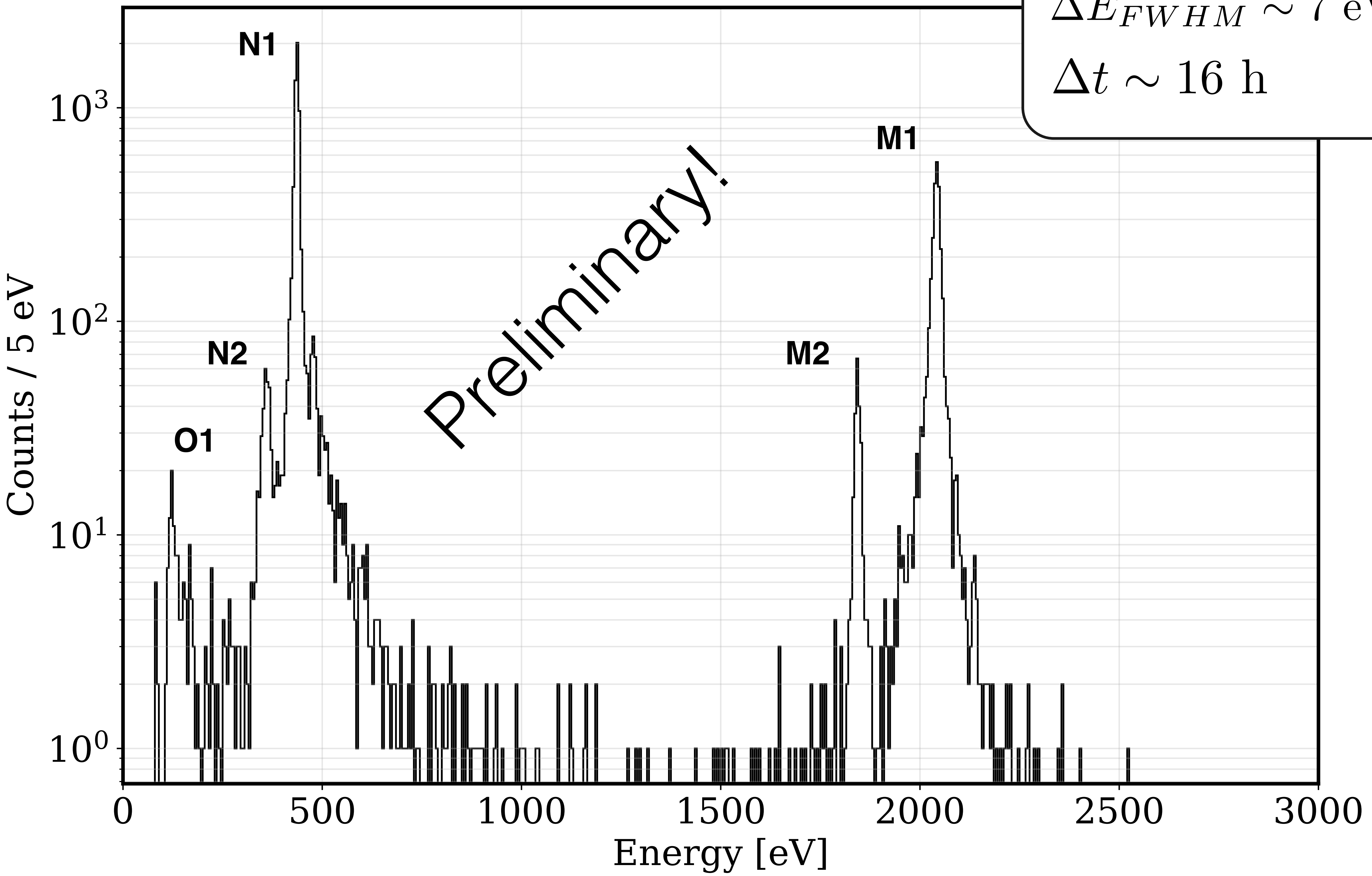
First results (still in progress!): ^{163}Ho spectrum

- DAQ time: 48.5 h
- Sum over 4 pixels
- High background due to 55Fe calibration source



First results (still in progress!): ^{163}Ho spectrum

Single TES spectrum without calibration source

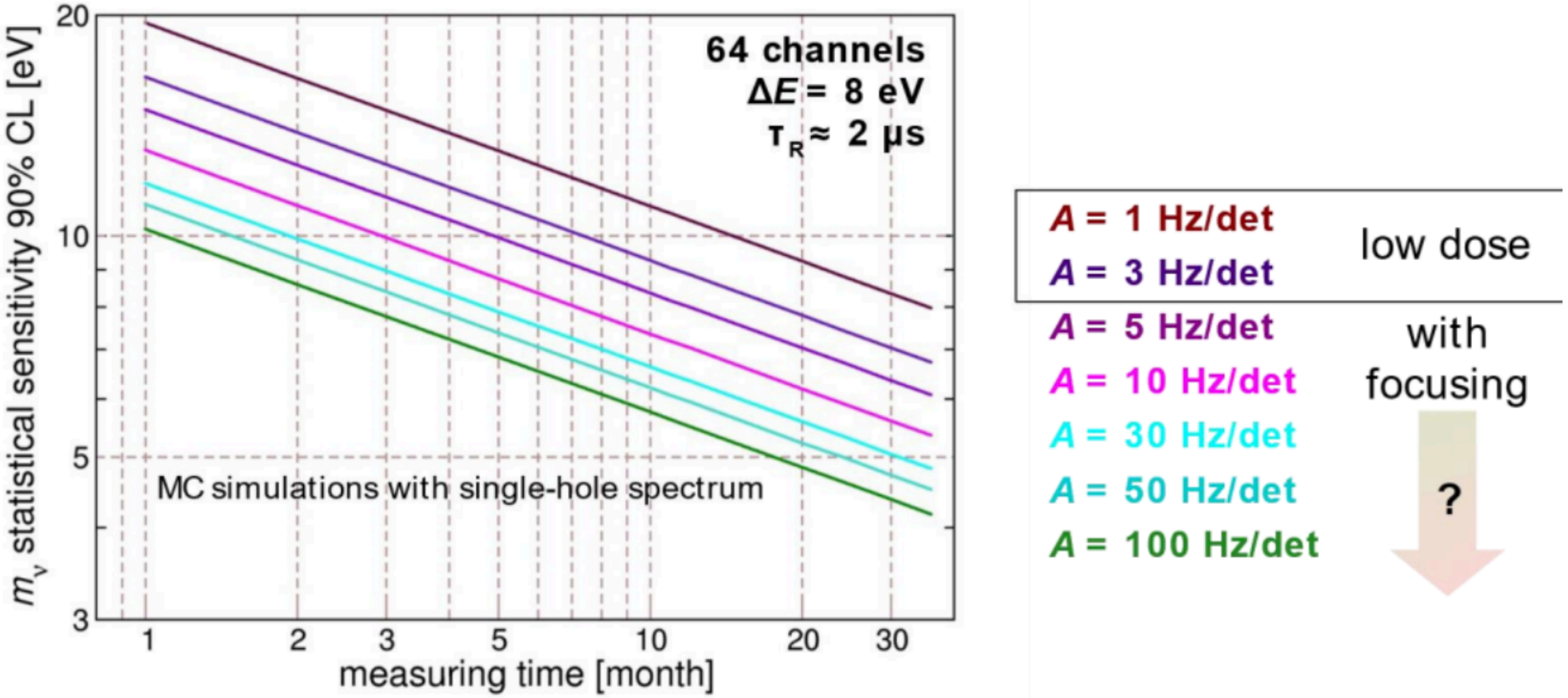


$\Delta E_{FWHM} \sim 7$ eV

$\Delta t \sim 16$ h

Next steps

- In the next month, we will implant a new array with the maximum achievable activity and we will perform the first long run, which will bring us to our first limit on neutrino mass with an expected sensitivity around 10 eV.
- Then, we will upgrade the implanter facility by adding a focusing stage and a co-evaporation chamber.

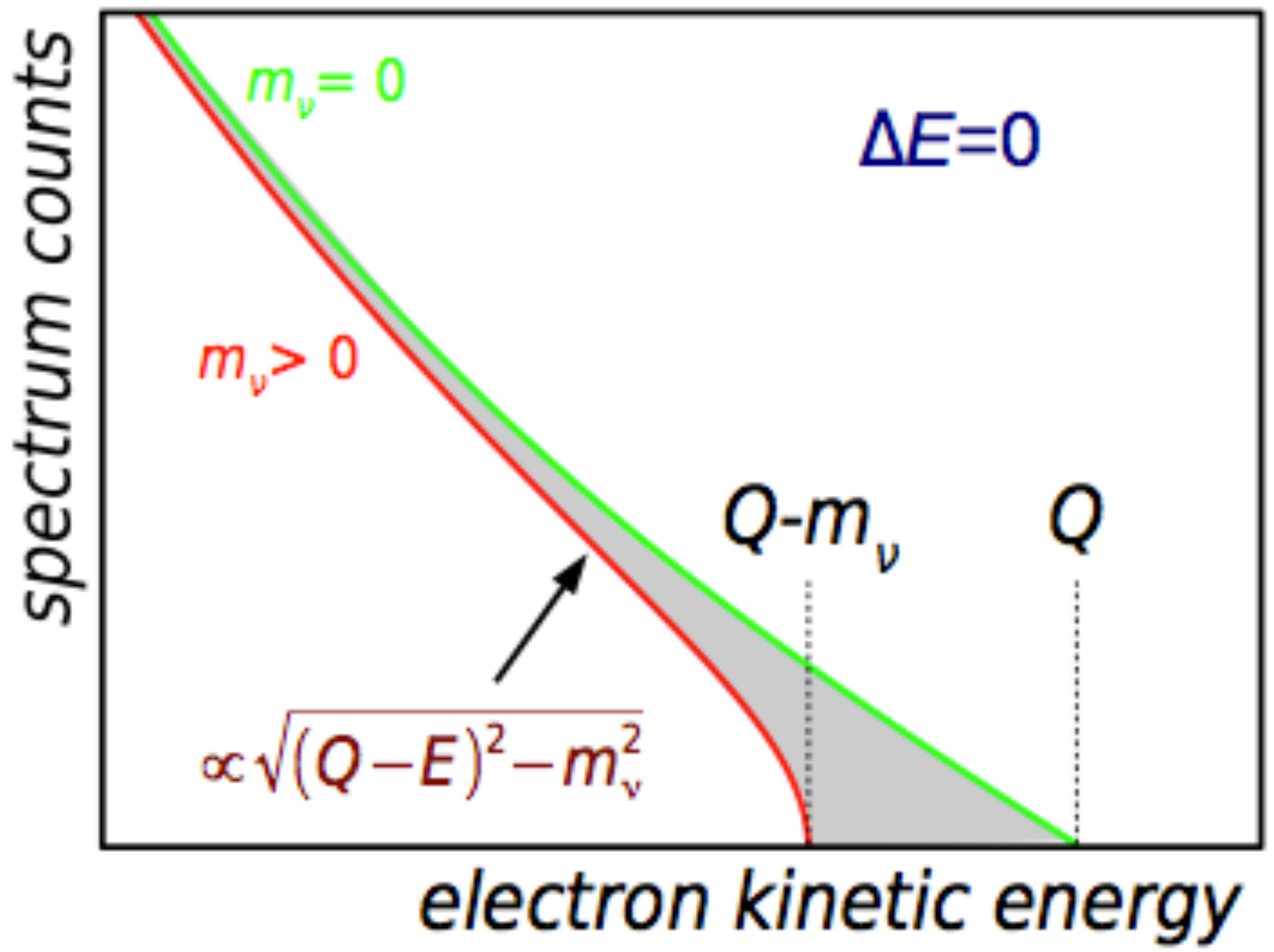


Back-up

Direct neutrino mass measurements

Study of kinematics of weak decay with ν emission:

- **low-Q β decays isotopes** (^{3}H, ^{187}Re, ^{163}Ho…) needed ("good" statistics close to end point scales as $1/Q^3$);
- **model independent**: it relies only on E, p conservation
- ν mass appears as a **distortion in the Kurie plot**
- 2 different approaches:
  - **spectrometric;**
  - **calorimetric.**

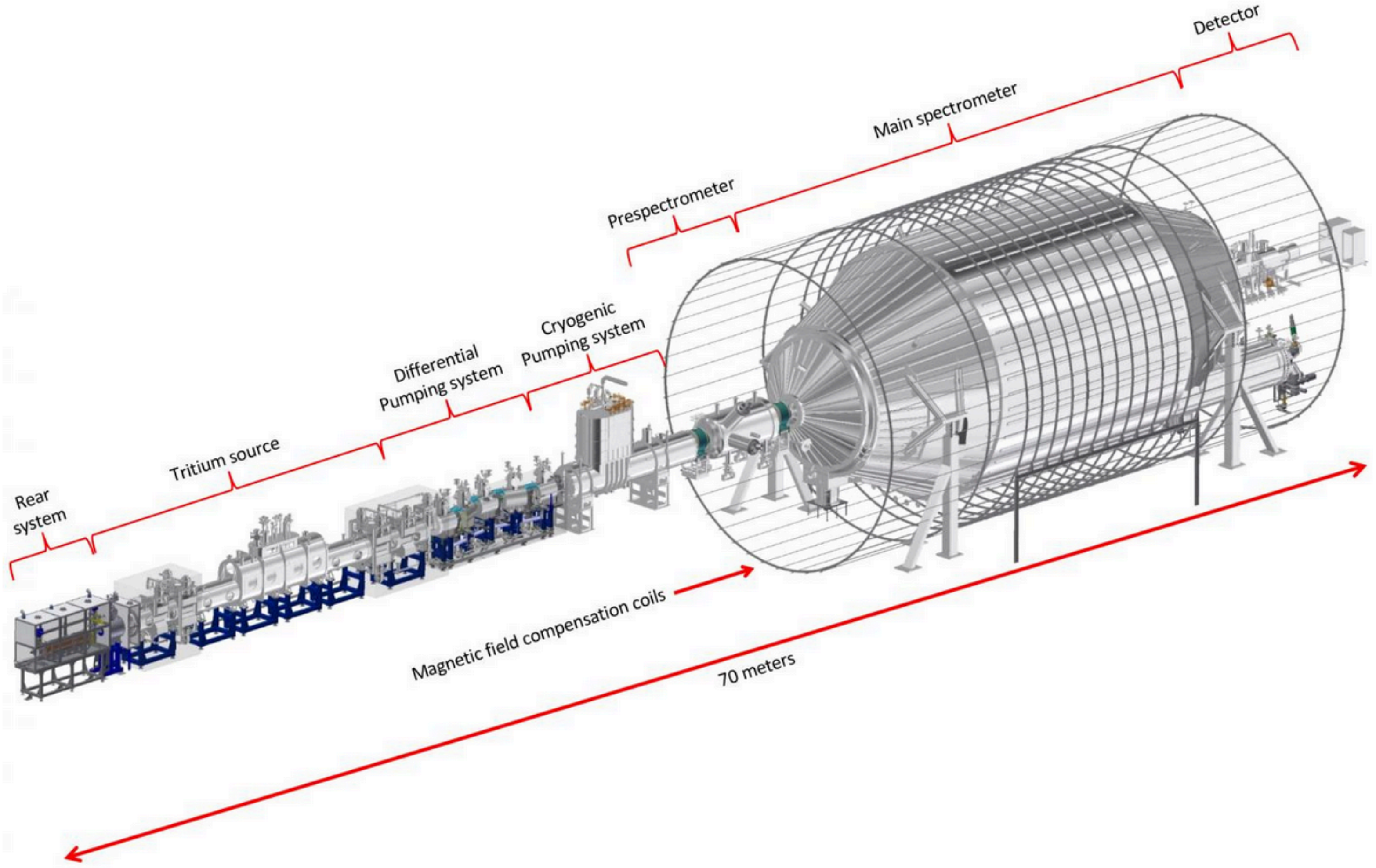


Spectrometry vs calorimetry

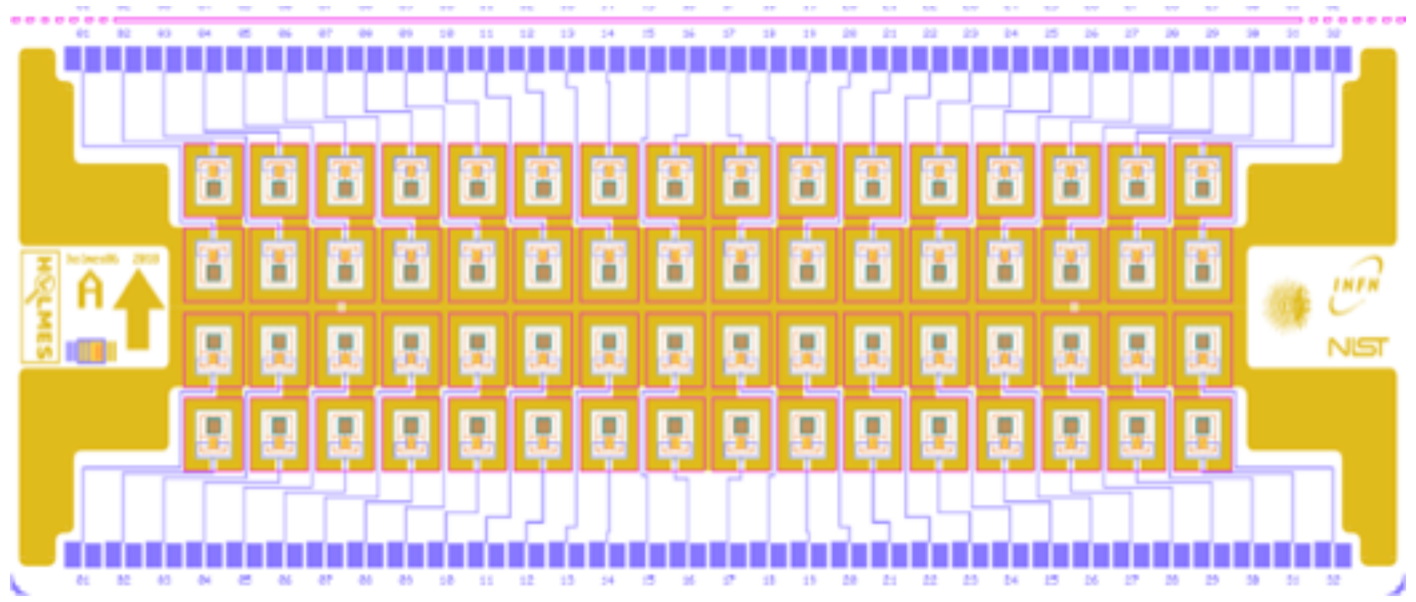
- **Spectrometry**: source $\not\subset$ detector (KATRIN like).
  - High statistics allowed, no pile-up issue.
  - Main systematics sources:
    - **decay on excited states**;
    - **energy losses in source**.
- **Calorimetry**: source $\subset$ detector (HOLMES approach)
  - Circumvent many systematics, thanks to calorimetric approach (all energy is confined in absorber and measured);
  - **But this implies pile-up issue!**
  - Needed a trade off between activity and detector properties + pile-up rejection algorithm.

The best current limit on a direct measurement comes from KATRIN (m_ν < 0.8 eV, expected 0.3 eV sensitivity), but this technique has reached its technological and mechanical limit.
Calorimetric seems to be a viable alternative way.

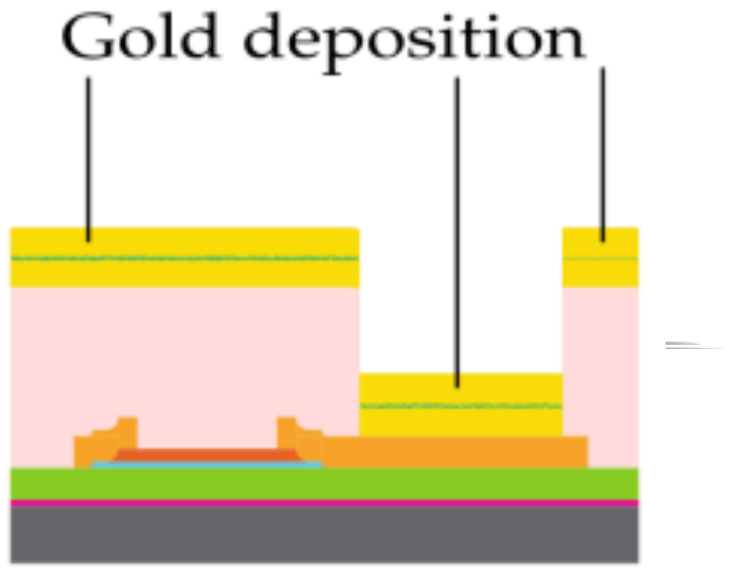
KATRIN detector

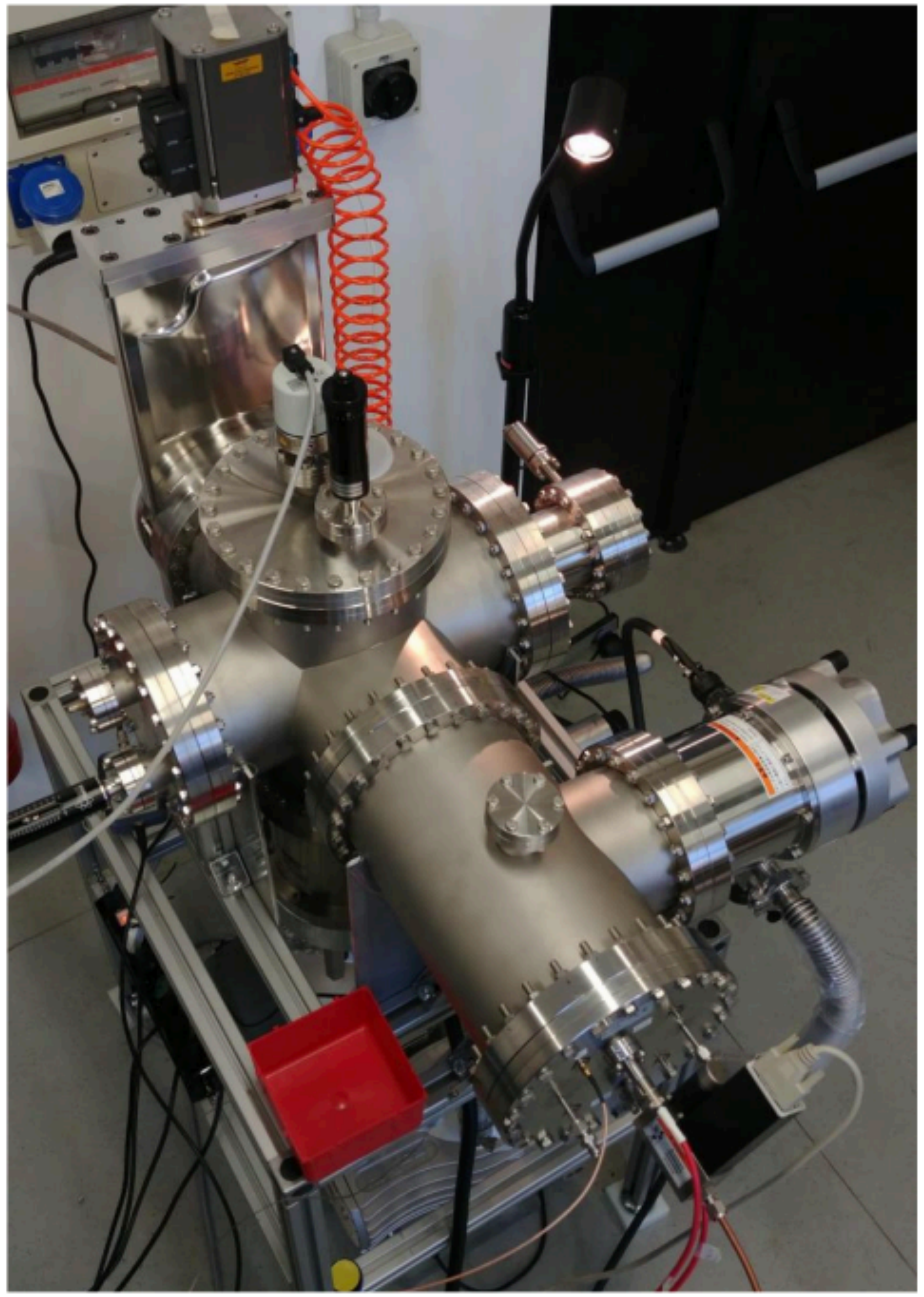


HOLMES detector

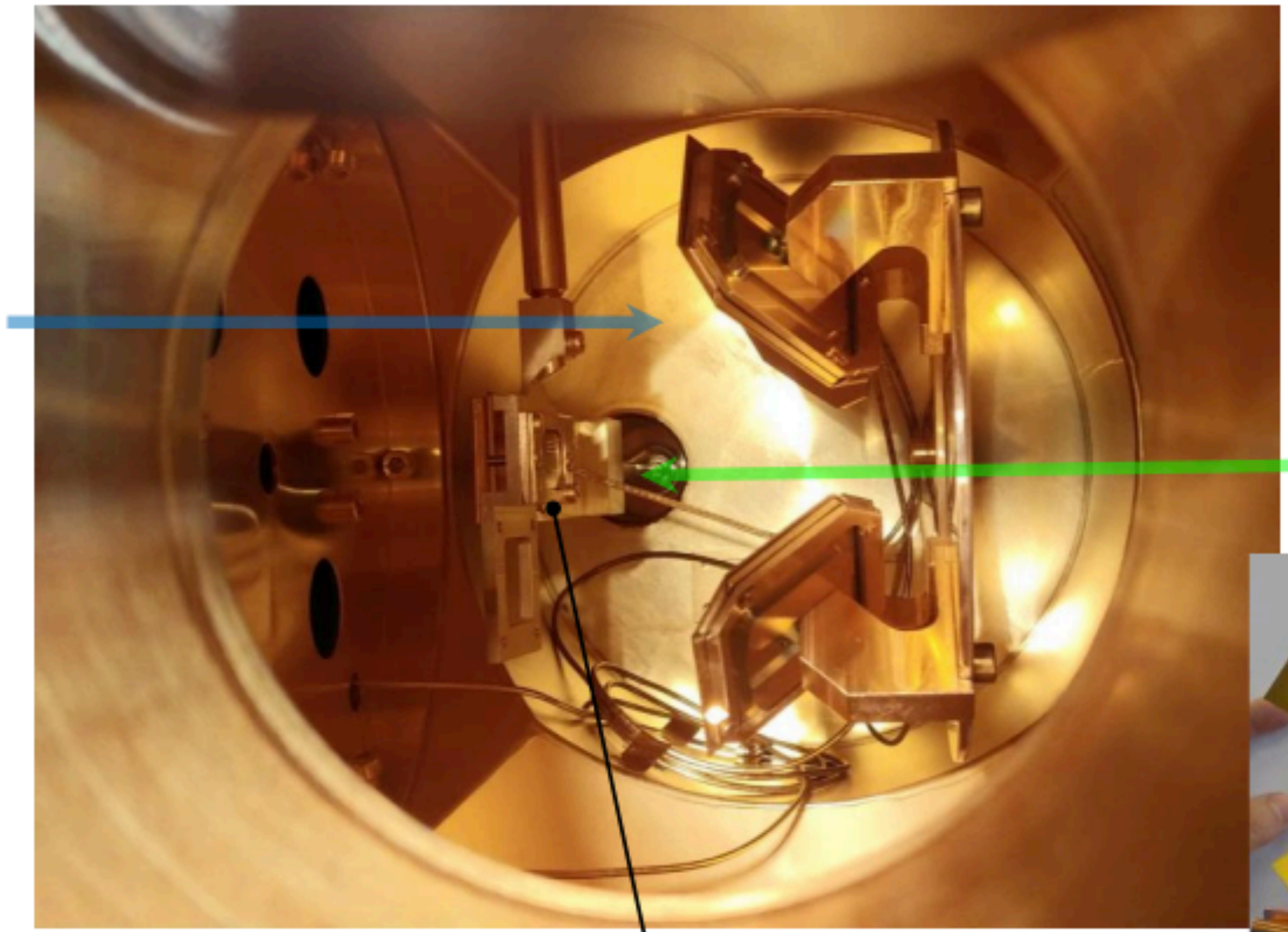


Full encapsulation @Milano-Bicocca

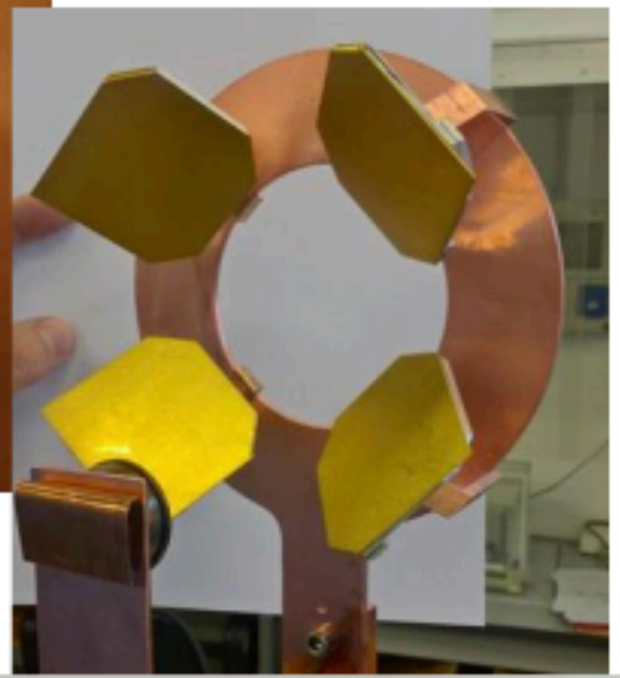




Ar ion beam (for sputtering)



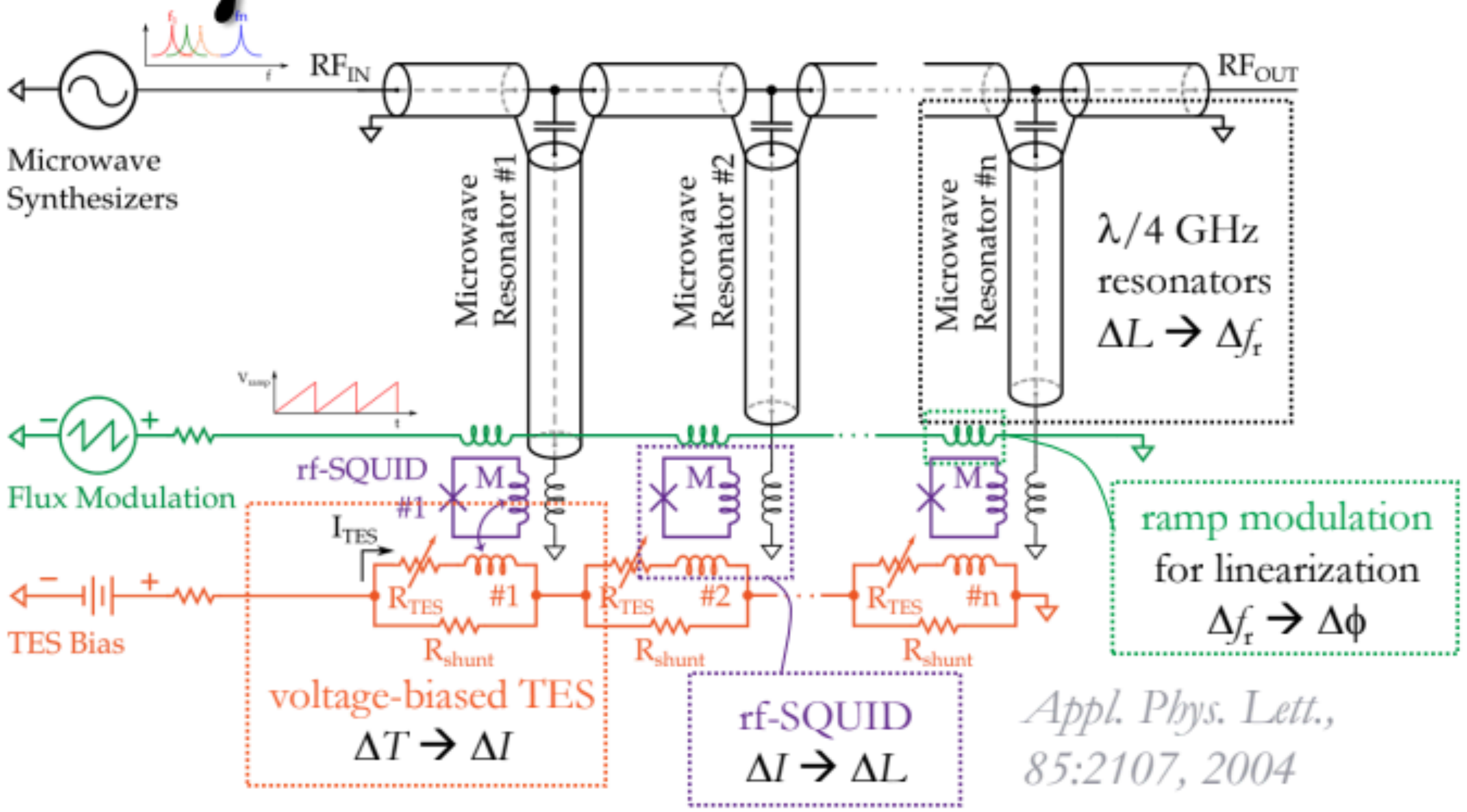
^{163}Ho (not implemented yet)



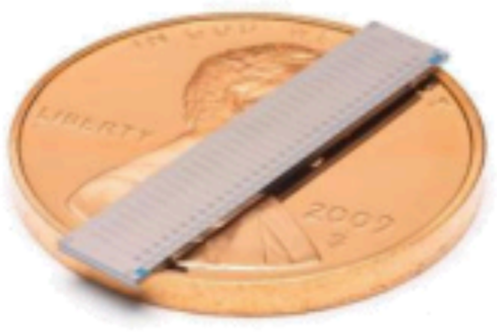
TES array

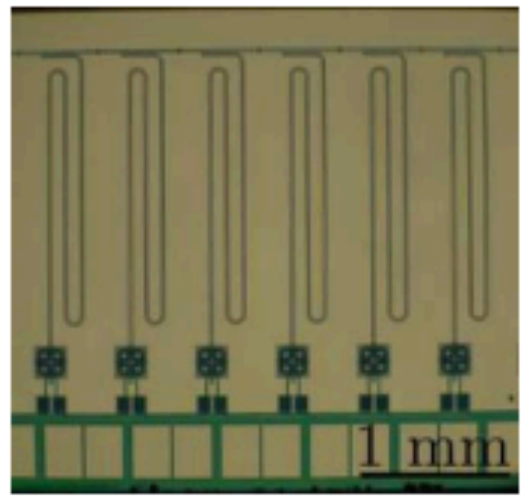
- 1 μm layer to fully encapsulate the ^{163}Ho
- ≈ 27 hours to complete the process
- soon will be integrated with the ion-implanter to compensate sputter and avoid oxidation

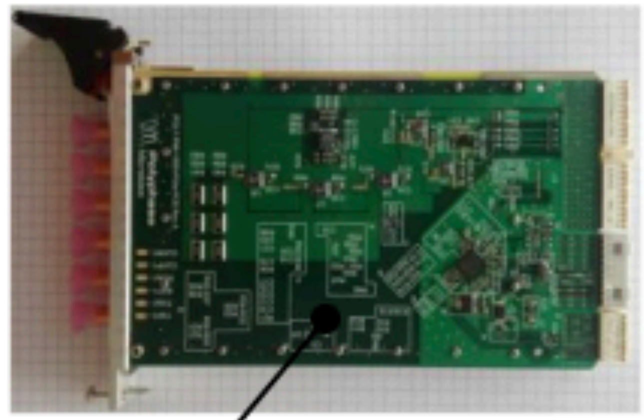
µwave mux readout & DAQ



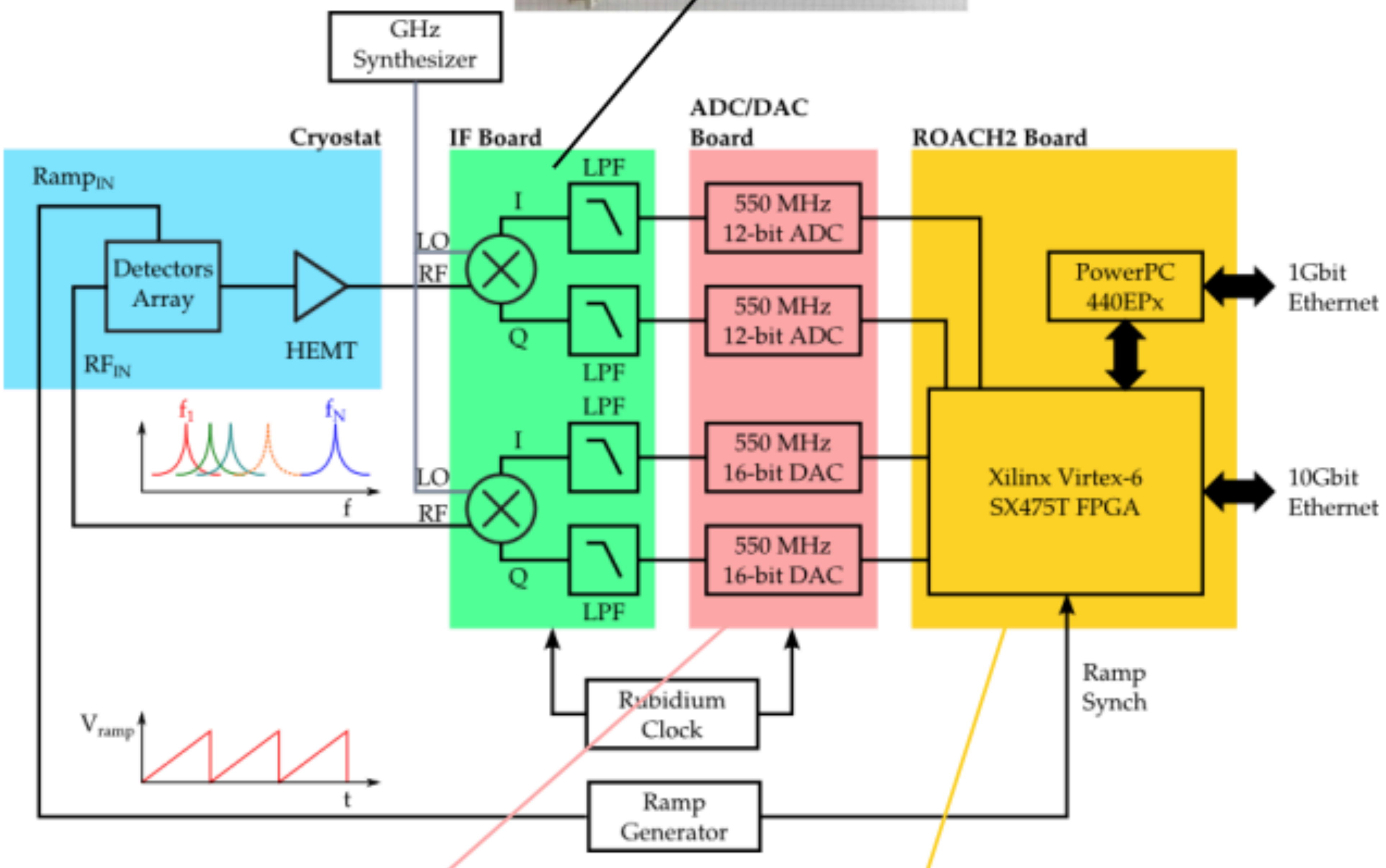
Appl. Phys. Lett., 85:2107, 2004







64 channels already available



- $f_{ramp} = f_{samp}$ (= 500 kHz)
- allows to readout many detectors with one common RF line and HEMT amplifier: 1 HEMT (4-8 GHz) = 256 TESs *JINST 14 P10035 (2019)*