Toward large field-of-view X-ray spectrometers with Magnetic Microcalorimeters

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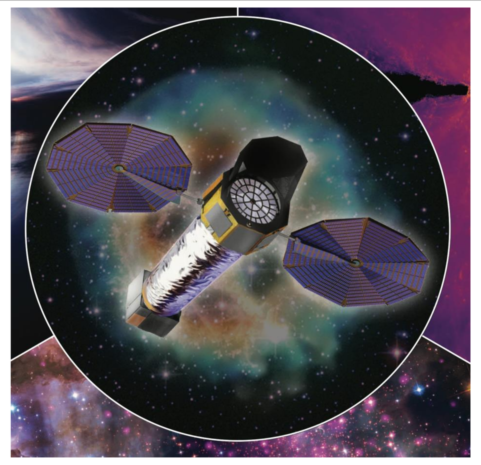
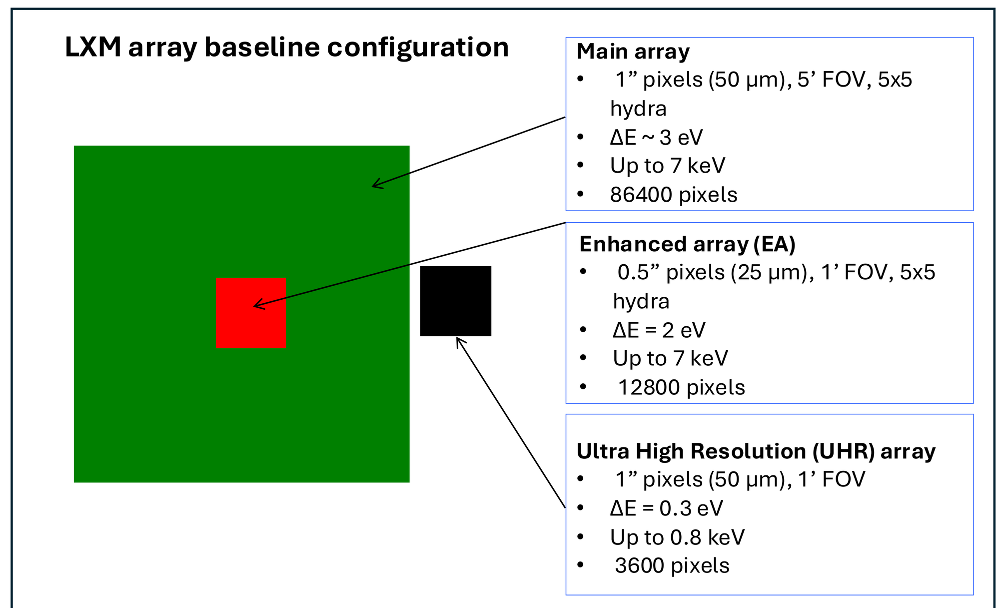


Lynx

: Revolutionary X-ray observatory mission concept

(1) Seeing the dawn of the black holes
(2) Revealing what drives galaxy formation and evolution
(3) Unveiling the energetic side of stellar evolution and stellar ecosystems

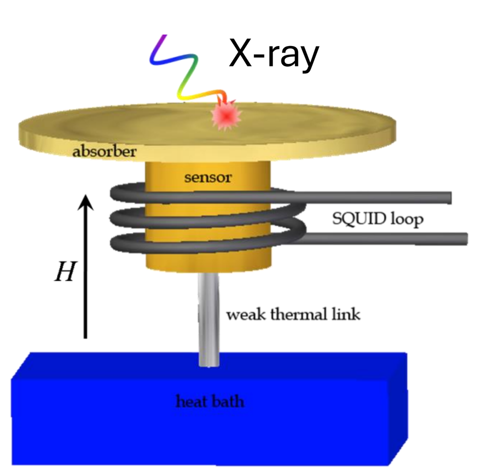
■ Lynx X-ray Microcalorimeter detector (LXM)



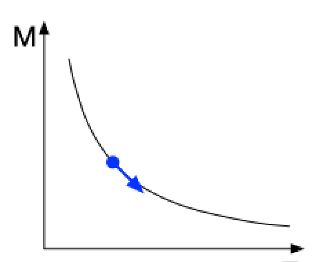
- *Astro 2020 Decadal* endorsed a Lynx-like X-ray mission as a *New Great Observatory* that should be a part of the mission and technology maturation program development this decade
- Key instrument is an imaging spectrometer called the Lynx X-ray Microcalorimeter (LXM) which is a very large microcalorimeter array with > 100 kilo-pixels
- Magnetic Microcalorimeter (MMC) is a leading technology option for the detectors

- The focal plane comprises of three different arrays, each of which is optimized for different science goals
- The Main array and EA designed for 4 µm thick Au absorbers while the UHR array is designed for 1 µm thick Au absorbers
- In the past year, we have developed a process to fabricate these dual-thickness absorbers

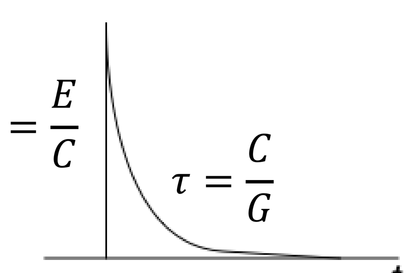
■ Principle of MMCs



- Paramagnetic sensors: **Au:Er$_{900\ ppm}$**, Ag:Er, etc.
- Detector signal: $\delta M = \dfrac{\partial M}{\partial T}\delta T = \dfrac{\partial M}{\partial T}\dfrac{E_{x\text{-}ray}}{C_{total}}$



$$T - T_0 = \frac{E}{C}$$

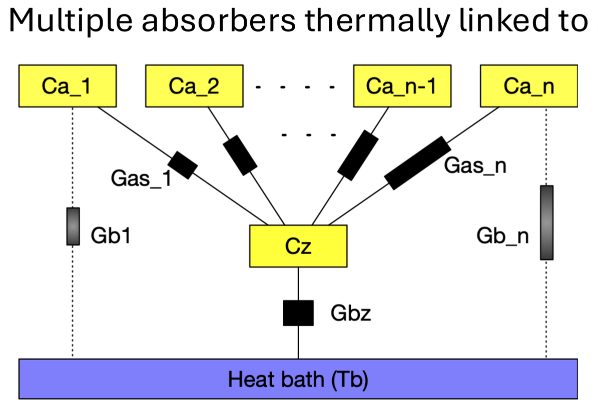


$$\tau = \frac{C}{G}$$

MMC advantages:
- MMCs have potential for greater energy resolution than TESs
  - Persistent current stored in superconducting Nb circuit for MMC bias, no Johnson noise associated with readout.
- More straightforward calibration due to broad smooth responsivity.
- Thermal design is simpler as no heat dissipated in MMC pixels.
- Uses microwave multiplexed SQUID readout similar to TESs.

■ Thermal multiplexing: "Hydra"

- Multiple absorbers thermally linked to a single sensor via paths with different thermal conductance

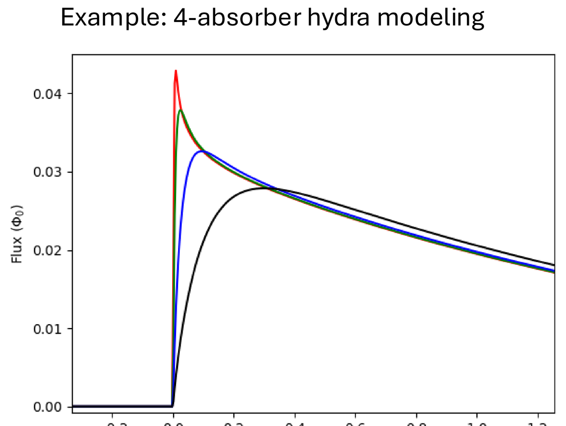


$$C_z\frac{dT_z}{dt} = -\left(\sum_{i=1}^{n} G_{as,i} + G_{bz}\right)T_z + \sum_{i=1}^{n} T_i G_{as,i} + P_{bz} + \sum_{i=1}^{n} P_{az,i}$$

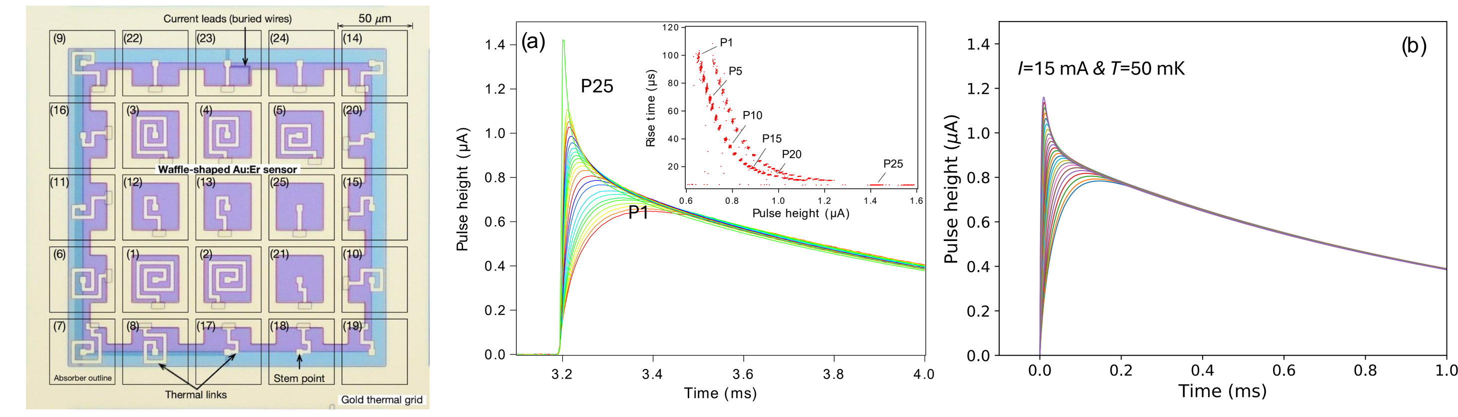
$$C_i\frac{dT_i}{dt} = G_{as,i}T_z - \left(G_{as,i} + G_{ab,i}\right)T_i + E_{photon} + P_{ab,i} - P_{az,i}$$

- The paramagnetic sensor has a weak thermal coupling to the heat bath (G_{bz})
- $C_i \sim C_z / n$
- Each absorber is thermally coupled to the sensor with a different thermal conductance ($G_{as,i}$)
  - If all G_{as} are identical, the pulse height is maximized (yielding the best energy resolution), but position sensitivity is lost
- Solving the heat equation reveals how the temperatures of the sensor and absorber change after a photon hits the absorber
  - $G_{as,i}$: defined to be evenly distributed between the minimum and maximum values of G_{as}
- - P(f), internal thermodynamic fluctuation, $P(f)=4k_bT^2G$

Example: 4-absorber hydra modeling

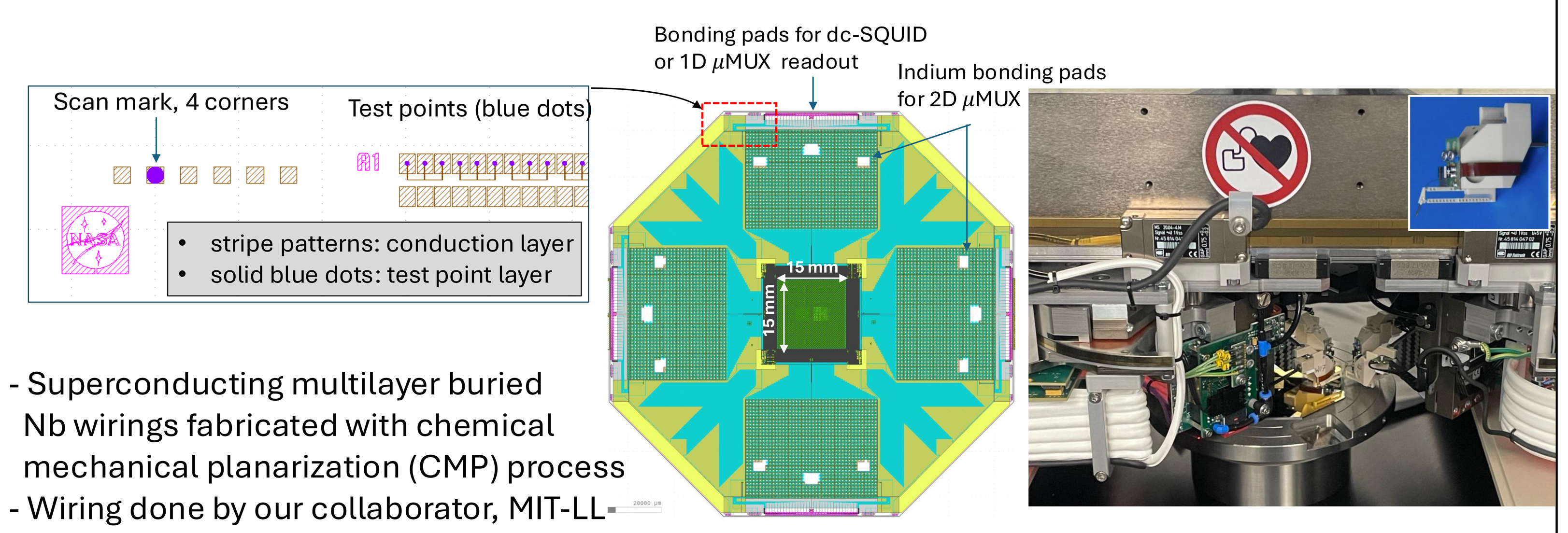


■ Demonstration 5x5 hydra - single sensor

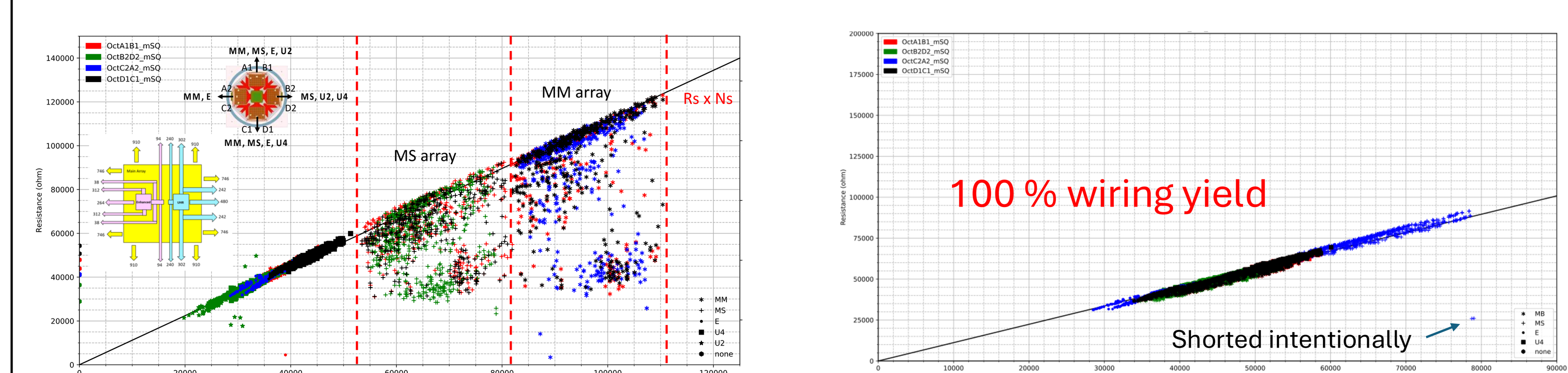


(a) 25 averaged pulse shapes and individual groups are clearly separated (onset)
(b) Simulated pulse shapes, showing good agreement with the measured data in (a), with a difference of approximately 10%
[W. Yoon et al., "Position-Sensitive Magnetic Calorimeters for Lynx", *J Low Temp Phys* 199, 916-922 (2020)]

■ Continuity test of all individual wirings using flying prober

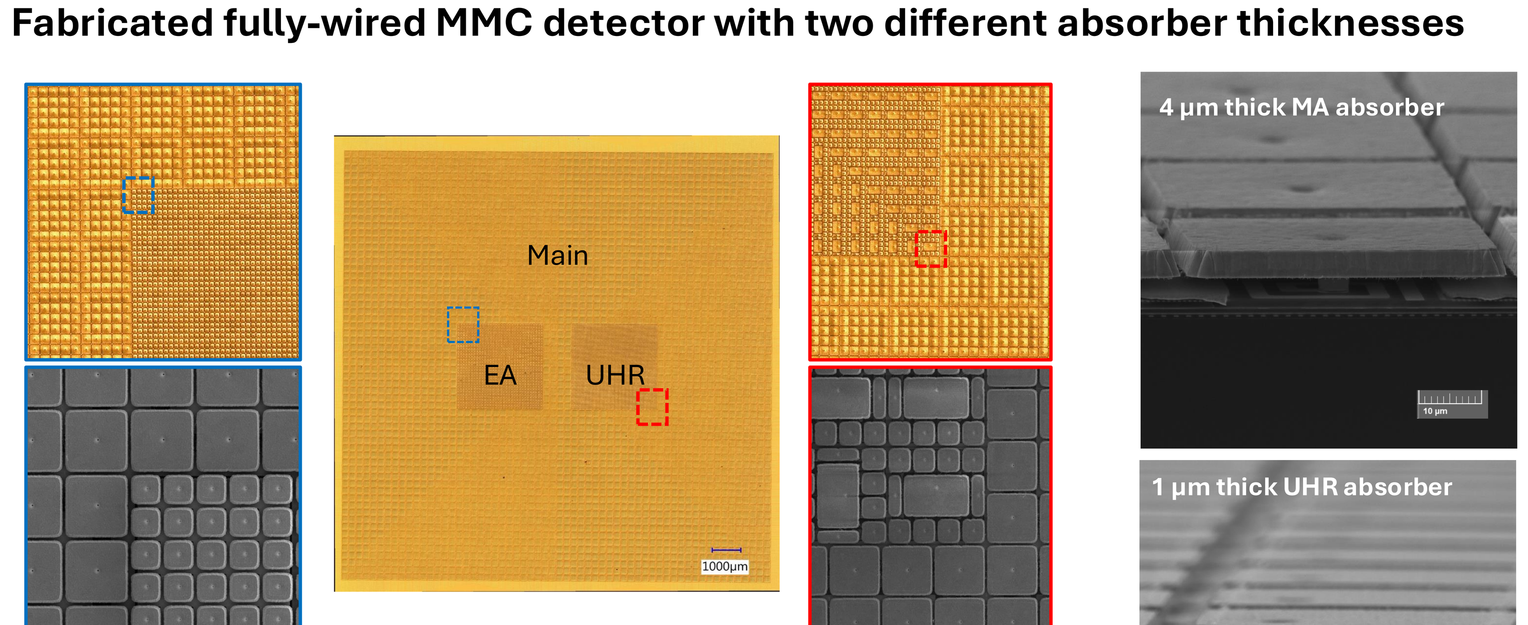


- Superconducting multilayer buried Nb wirings fabricated with chemical mechanical planarization (CMP) process
- Wiring done by our collaborator, MIT-LL
- The longest bias wiring length is approximately 70 m
- The total wiring length of the latest design is about 350 m !
→ A single broken wire has a substantial impact on yield, budget, and timeline!



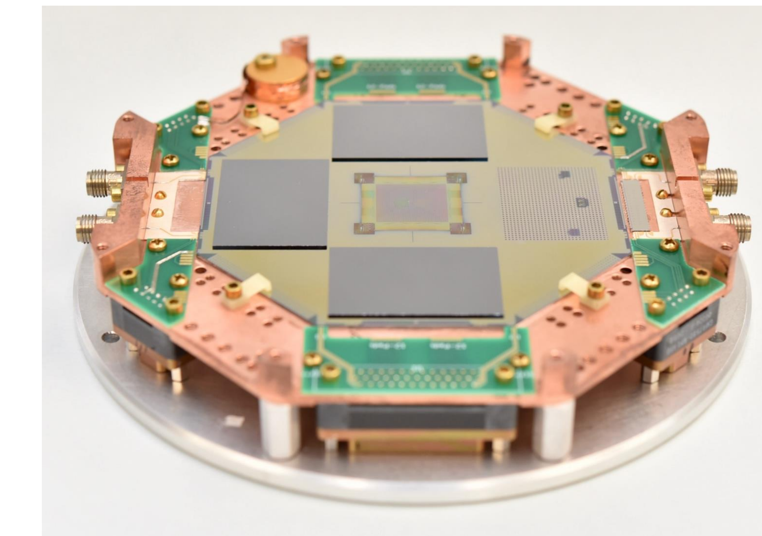
- Three observed major problems:
  (1) shorts to GND and open wires, (2) critical dimension variations, and (3) over-polishing of the top wiring
  ➔ Resolved these issues and achieved 100 % buried wiring yield!

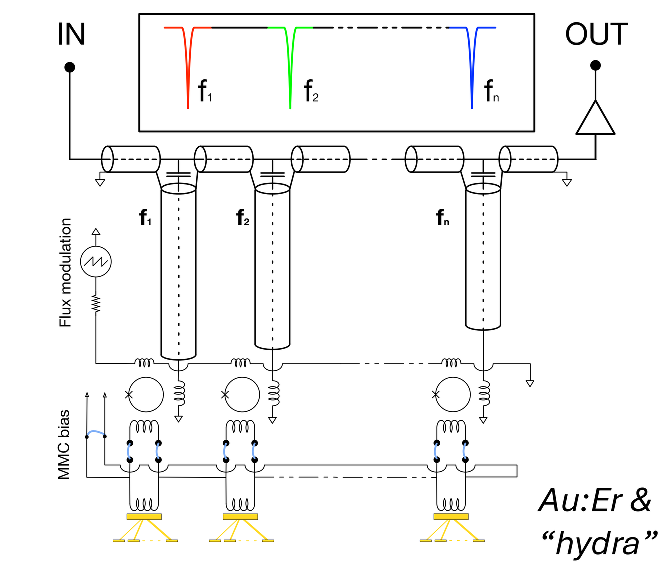
■ Fabricated fully-wired MMC detector with two different absorber thicknesses



- Developed a process for fabricating two different absorber thicknesses on the same detector:
  - Main array and Enhanced main array: 4 µm thick Au absorber
  - UHR array: 1 µm thick Au absorber
- Various design concept studies for the Main array
  (1) Superconducting Nb meander coil + Au:Er sensor
  (2) "Sandwich": Additional superconducting Nb plane above (1)
  (3) "Bipolar": Superconducting Nb/Al integrated persistent current heat switches connecting two Nb meander half-coils

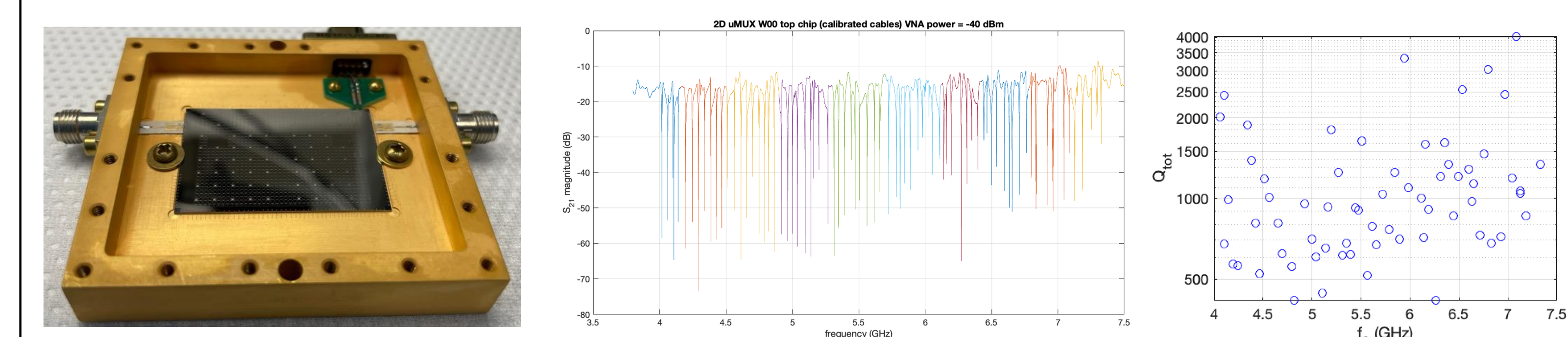
■ Flip-chip indium bump bonding and transmission test of 2D resonator chips





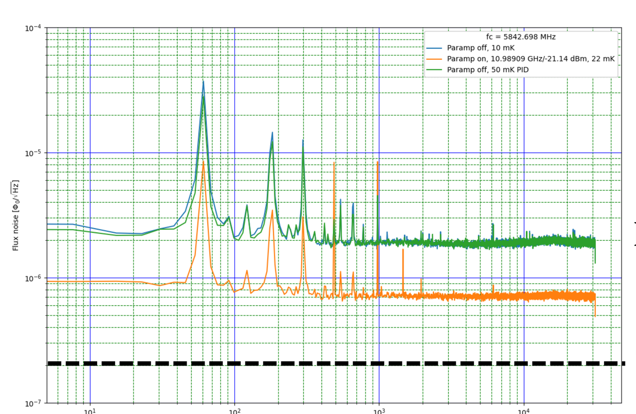
- Bump-bonded three prototype superconducting 2D microwave resonator chips onto the MMC detector using superconducting indium
- MMC signal will be read out by 2D µMUX chip and amplified by KI-TWPA and HEMT

■ 2D microwave multiplexing chip (NIST)



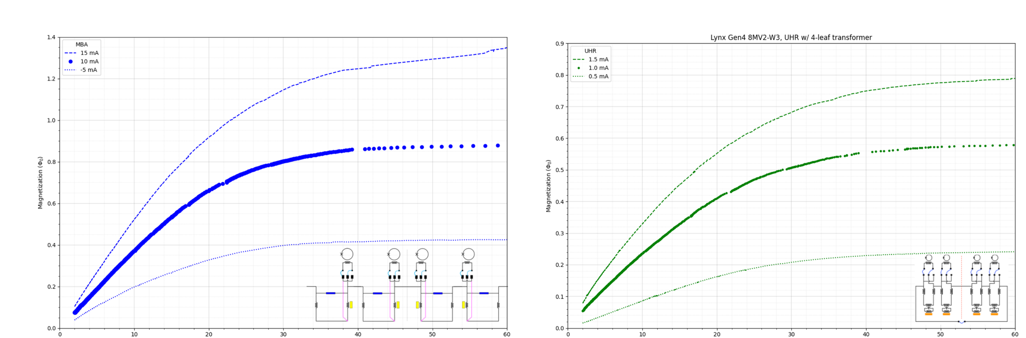
- 77 resonances are observed, 68 resonances are identified as good single peaks
- Resonance frequency range: 4 - 8 GHz

µMUX noise measurement, flux ramp modulation with KI-TWPA (JPL)



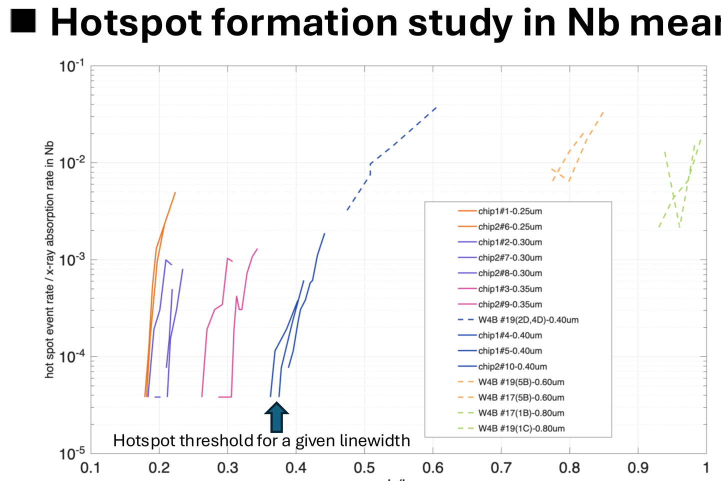
KI − TWPA off, 1.9 $\mu\mathrm{Phi}_0/\sqrt{\mathrm{Hz}}$
KI − TWPA on, 0.7 $\mu\mathrm{Phi}_0/\sqrt{\mathrm{Hz}}$ (~1240 $\hbar$)
Target < 0.2 $\mu\mathrm{Phi}_0/\sqrt{\mathrm{Hz}}$ (~100 $\hbar$)

■ Magnetization curves (M ∝ 1/T)



- MBA, Au:Er sensor partially deposited, 12/25 area
- UHR, Demonstrated that the multi-turn transformer is working

■ Hotspot formation study in Nb meander coil



Loss of superconductivity in narrow regions ("Hotspot")
- due to the interplay between the applied current and X-ray photons directly hitting the Nb coil
- it provides an important indication for determining our next wiring geometry

For detailed hotspot threshold modeling, see" Hotspot formation in sub-micron width Nb superconducting coils for MMC X-ray detectors", **2EPo1A-01**

■ Summary and Outlook

- Successfully fabricated full-scale Lynx detector array with two different absorber thicknesses
- Obtained a low-noise spectrum with flux-ramp modulation and KI-TWPA
- Innovative bipolar design and integrated transformers with MMCs work as expected
- Will focus on measuring high energy resolution X-ray spectra shortly
- Optimizing the coupling of the MMC array, and the µMUX & KI-TWPA readout