FY25 Strategic University Research Partnership (SURP)

Origins of frequency scatter in large-format arrays using Kinetic Inductance Detector (KID) based technology

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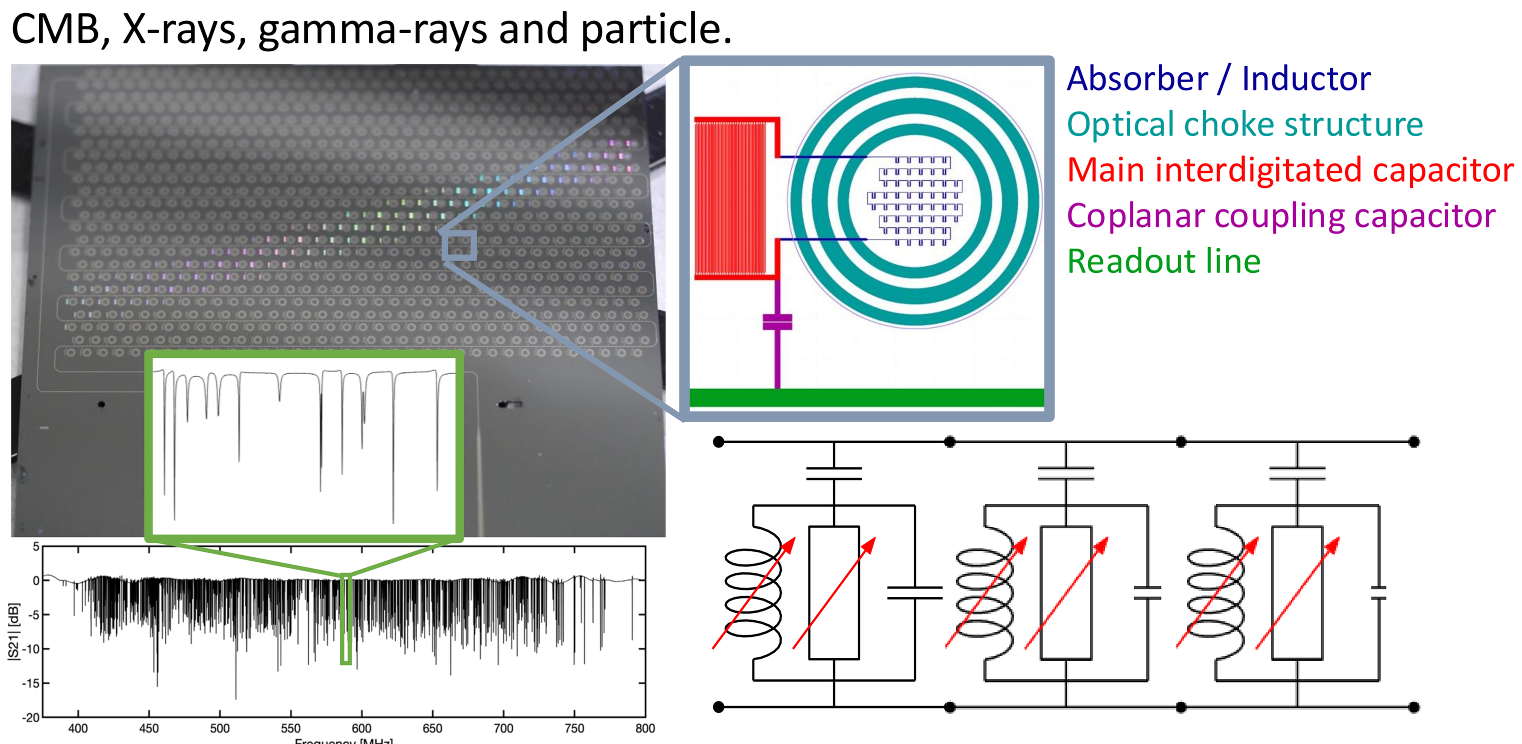
Kinetic Inductance Detectors

Kinetic Inductance Detectors (KIDs) have found widespread application in the field of astrophysics and remote sensing as: large arrays of sensitive detectors in the mm through far-infrared; large arrays of photon-counting energy-resolving detectors at near-IR through optical wavelengths; phonon-mediated detectors for dark-matter experiments; multiplexing element for detectors for CMB, X-rays, gamma-rays and particle.



These rapid advances are driven by the KID's ability to be multiplexed into large arrays through frequency domain multiplexing. The KID's readout frequency can be set by design. Thus, by giving each pixel a unique readout frequency, 1000's of KIDs can be coupled to a single readout line. This results in an enormous simplification of the readout compared to competing detector technologies, which is crucial given their cryogenic operation.

Objective

For future missions it will be crucial to maximize the number of pixels per line and readout bandwidth. However, a key limitation for the multiplexing density of modern KID arrays is the scatter of frequencies with respect to their design value. Measurements show "random" offsets from the design frequencies by as much as 1%. This scatter will affect pixel dynamic range, induce electrical cross-talk, and ultimately lead to a reduction in the science-usable yield of the arrays.

Determine the physical origin of readout frequency scatter in large arrays of Kinetic Inductance Detector

Recommendations and Impact

These results mark significant progress toward isolating the mechanisms responsible for frequency scatter and guiding strategies to mitigate them in future large-format arrays. Two conclusions are immediately implementable:

- For the purposes of cooldown-to-cooldown variations, magnetic shielding that maintains a high quality factor for regular operation is sufficient, with no further improvements required. In addition, a well-documented measurement setup is now available to test other detectors.
- Similarities in the lithography profile allows for a (limited) improvement in the frequency design to limit yield reduction from scatter, by eliminating designs with dramatically worse performance. However, the shift of the peak across wafers currently makes it impossible to achieve significant gains by simply adjusting the design to offset lithographic errors. A dedicated investigation into the origin of the peak and increasing the stability of the peak location can now occur.

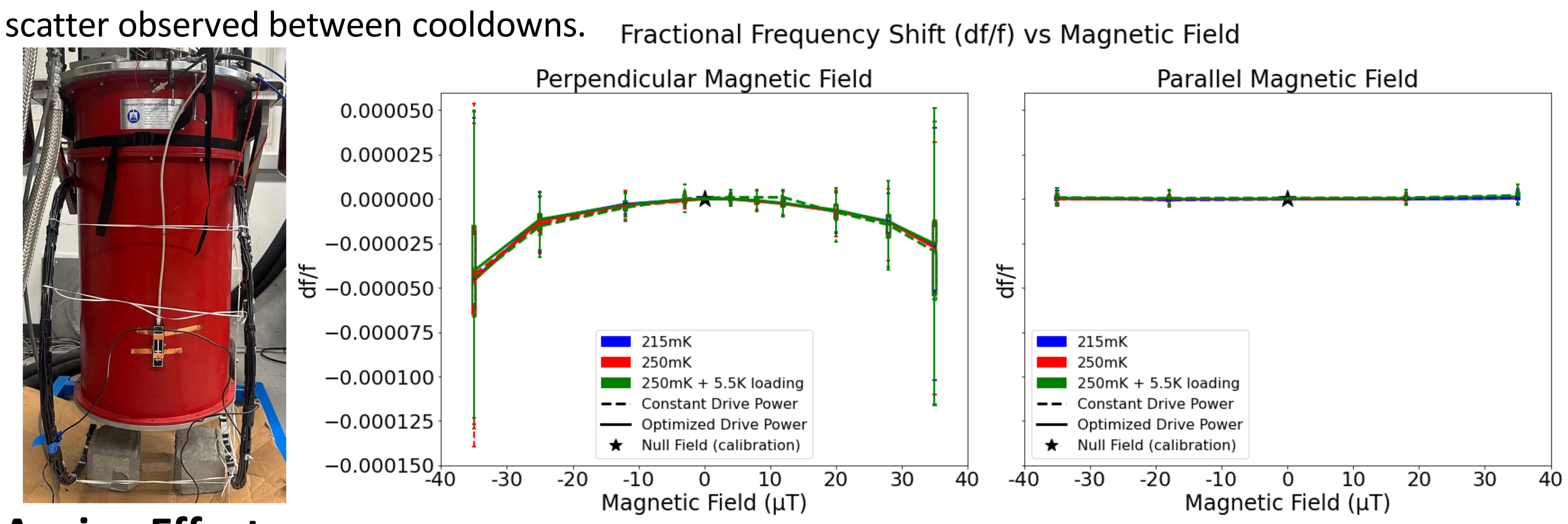
The continuing efforts of this SURP aim to ultimately increase the pixel density per readout bandwidth and enable larger scale detector arrays with reduced \$/pixel. Given the ever wider spread of KID-technology as detectors of multiplexing components, including for upcoming missions like PRIMA and HWO, this will provide JPL a key competitive advantage in the implementation of this technology.

Origins of Frequency Scatter Measured

Magnetic Fields

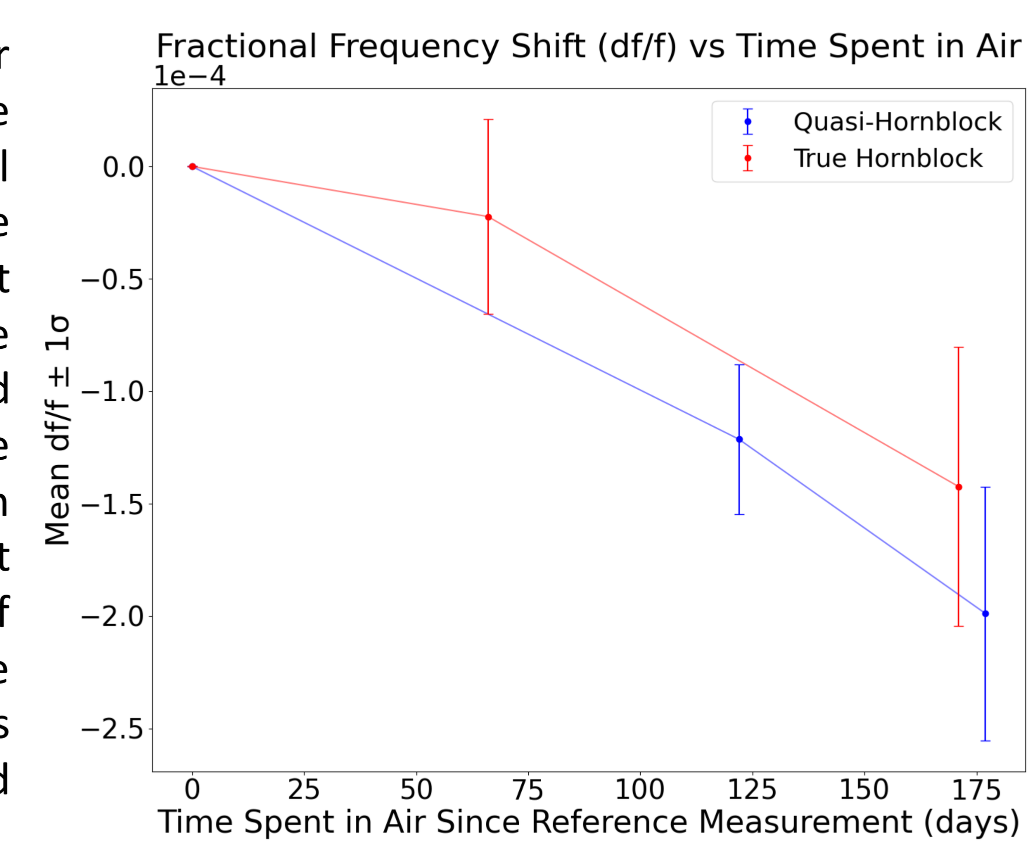
Magnetic fields were initially suspected as a major contributor to cooldown-to-cooldown variations in resonator frequency. To test this hypothesis, we upgraded our measurement system with a Helmholtz coil capable of applying controlled DC magnetic fields in either perpendicular or parallel orientations relative to the detector plane during the superconducting transition. The coils are placed outside the cryostat and the mu-metal shield was removed from the system. The net field was measured outside the vacuum shield during the measurements and calibrated by placing the magnetometer close to the array whilst warm.

Parallel fields produced no measurable effect. Perpendicular fields induce a frequency shift well described by $df/f = (A*B_{perp})^2$, where $A = 1.6x10^{-4}$ [1/μT], and a 3μT field change gives ~$2.3x10^{-7}$ shift. In a shielded cryostat (<μT variations) we observe scatter between cooldowns ~$5x10^{-4}$. This suggests that magnetic field effects are detectable but ultimately play a minor role in producing the frequency scatter observed between cooldowns.



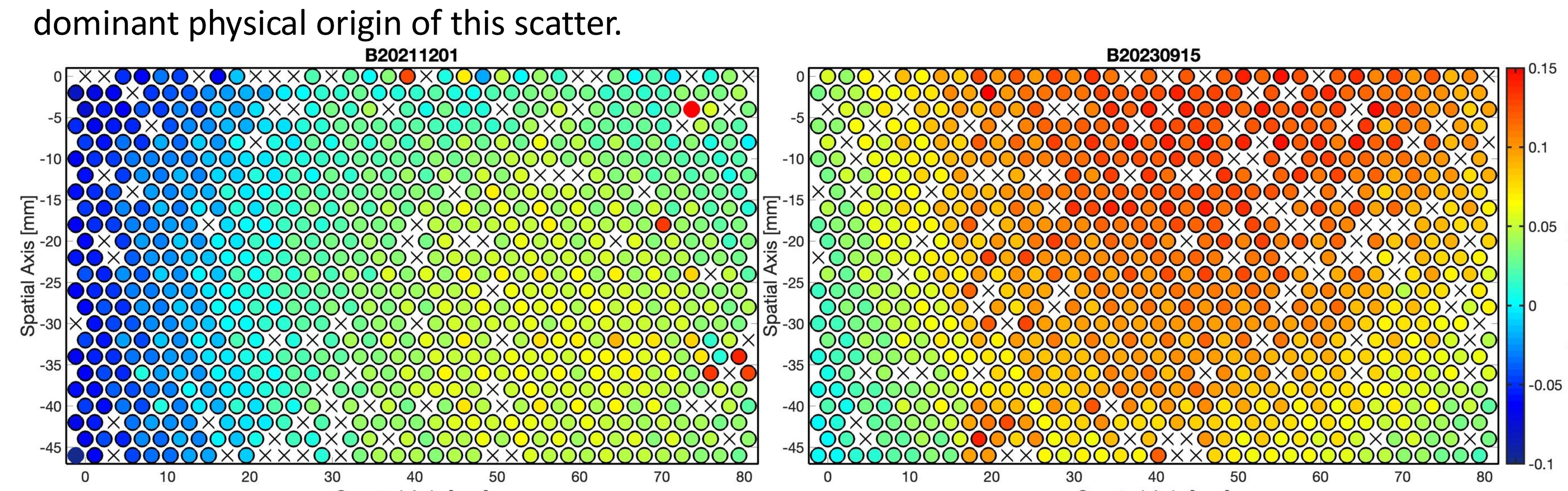
Ageing Effects

Aluminum oxidation, was identified as another possible source of frequency scatter. We compiled an inventory of ~3 years of historical TIM array measurements under otherwise identical test conditions. Analysis revealed that the longer resonators are exposed to air, the greater the frequency shifts (order of 10^{-4}) and scatter. No saturation was identified within the longest timescale (~180 days). This correlation with air exposure supports the idea that aluminum oxidation is a physical origin of frequency scatter, highlighting the importance of careful storage and handling protocols. This data is also a key starting point for continued monitoring of these arrays in time.



Lithographic Fabrication Effects

Fabrication non-uniformities were studied using LED mapping techniques. By selectively illuminating subsets of detectors and comparing illuminated versus dark responses, we mapped resonators to their precise physical locations and compared measured frequencies to their design values. We identify systematic deviations across the array of order 1%. The deviations follow a parabolic spatial patterns with a similar length scale in both wafers studied. However, the parabola has a varying "point of origin" on the wafers. Inspection of these wafers is a key next step to correlate physical features with the measured frequency shifts and determine which lithographic effects is the dominant physical origin of this scatter.



Publications:

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