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Developing a New Generation of Integrated μ -Spec Far-Infrared Spectrometers for EXCLAIM

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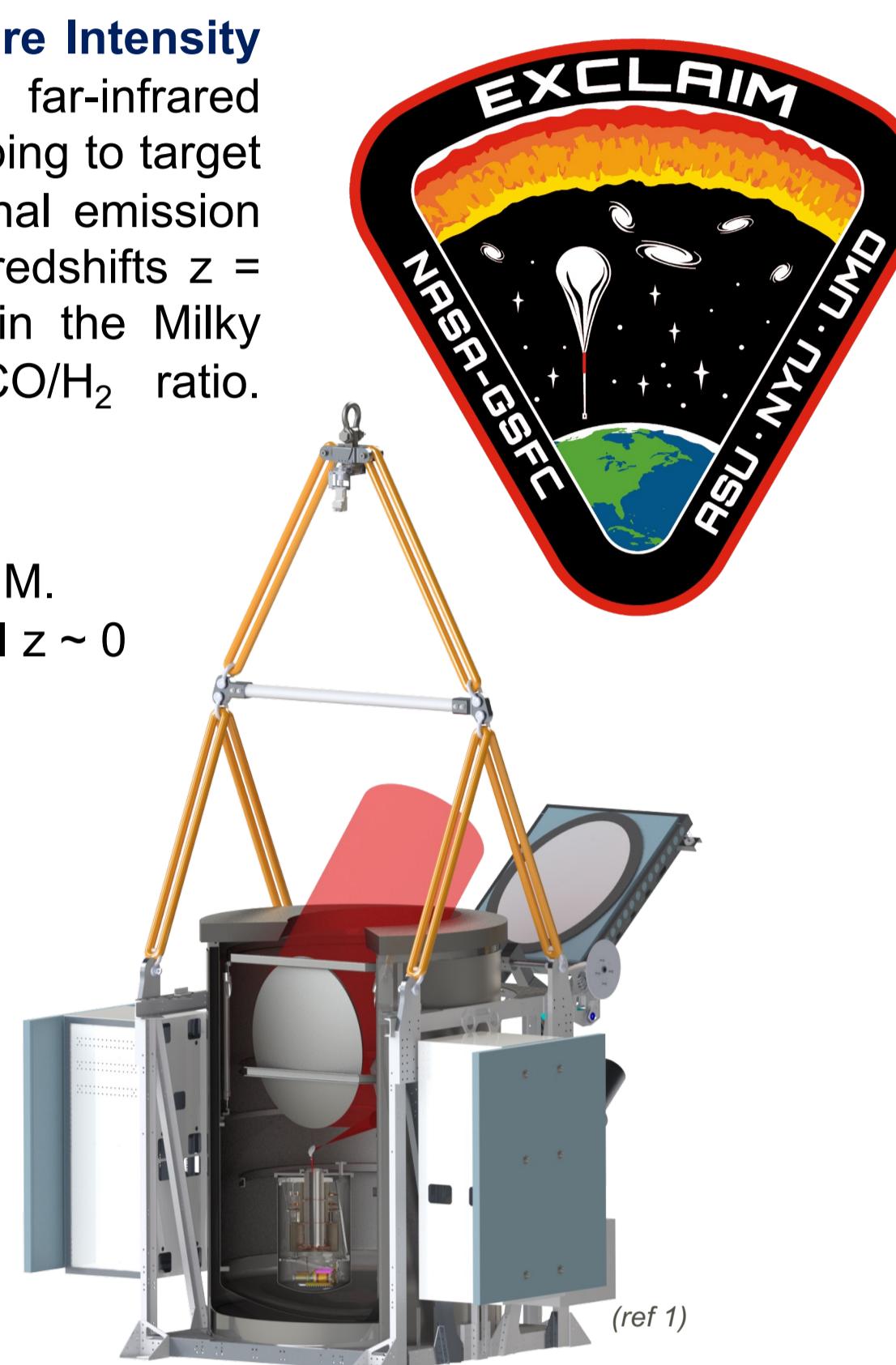
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1 EXCLAIM MISSION

The Experiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) is a balloon borne far-infrared astronomy mission that uses line intensity mapping to target extragalactic measurements of the CO rotational emission ladder at redshifts $z < 1$ and CII emission at redshifts $z = 2.5\text{--}3.5$. EXCLAIM will additionally map [CI] in the Milky Way to probe the commonly assumed CO/H₂ ratio.

Survey size: $\sim 300 \text{ deg}^2$ area (wide)
Scan: $\sim 7^\circ$ in azimuth at fixed elevation 45°
Beam size: 76 cm projected aperture $\approx 4^\circ$ FWHM.
Redshifts: CO $0 < z < 0.6$, CII $2.5 < z < 3.5$, CI $z \sim 0$
Cross correlation: BOSS quasars
Spectrometer: MKID on-chip μ -Spec
Detectors: Antenna-coupled MKID
Flight duration: conventional (e.g. 1-day) flight
Flight location: NM, USA
Cryogenics: 3500 l LHe Bucket dewar
Balloon class: $\sim 2400 \text{ kg dry mass}, 34 \text{ MCF}$
Holding time: $\sim 2000 \text{ l LHe fill gives } 18 \text{ hr of } 1.7\text{K operation at float}$
Cold optics: superfluid fountain-effect pumps cool the optics to 1.7 K (Kogut+ 2021)
Heritage: ARCADE/PIPER



2 SPECTROMETER OVERVIEW

Number of spectrometers	6
Spectrometer spectral band	555 – 714 μm (420 – 540 GHz)
Spectrometer grating order, M	2 (single order)
Spectrometer resolving power, R	512 at 472 GHz (center frequency) 535 to 505 over spectral band
Spectrometer efficiency	24%
KID NEP (at input to each KID)	$8 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$ at 0.16 fW (at KID) at 5 to 26 Hz acoustic frequency
Number of receivers/KIDs per spectrometer	355
KID readout band	3.25 to 3.75 GHz
Operating temperature	100 mK

Above: Some key information about EXCLAIM's spectrometers.¹

Right: The main contributing components to the overall efficiency of the EXCLAIM spectrometers and their individual efficiencies estimated from design.²

The slot antenna coupling and the Rowland receiver array coupling (part e. in center spectrometer figure) have the largest impact on the spectrometers' efficiency. Coupling to antennas in the Rowland region dominates overall losses.

Efficiency Contributions	Design Estimate
Slot Antenna Coupling	$53 \pm 5.5\%$
Order-Choosing Filter Transmission	$\geq 98.7\%$
Reference coupler	96.84%
Rowland Circle Receiver Coupling	$\sim 50\%$
MKID Coupling	> 99%
Transmission Line Loss	$\geq 94\%$
Total Efficiency Estimate	$\geq 24\%$

4 STRAY LIGHT

Based on results from the R=64 μ -Spec prototype, special design attention has been placed on mitigating the effects of stray light in the EXCLAIM spectrometers.

Changes include:

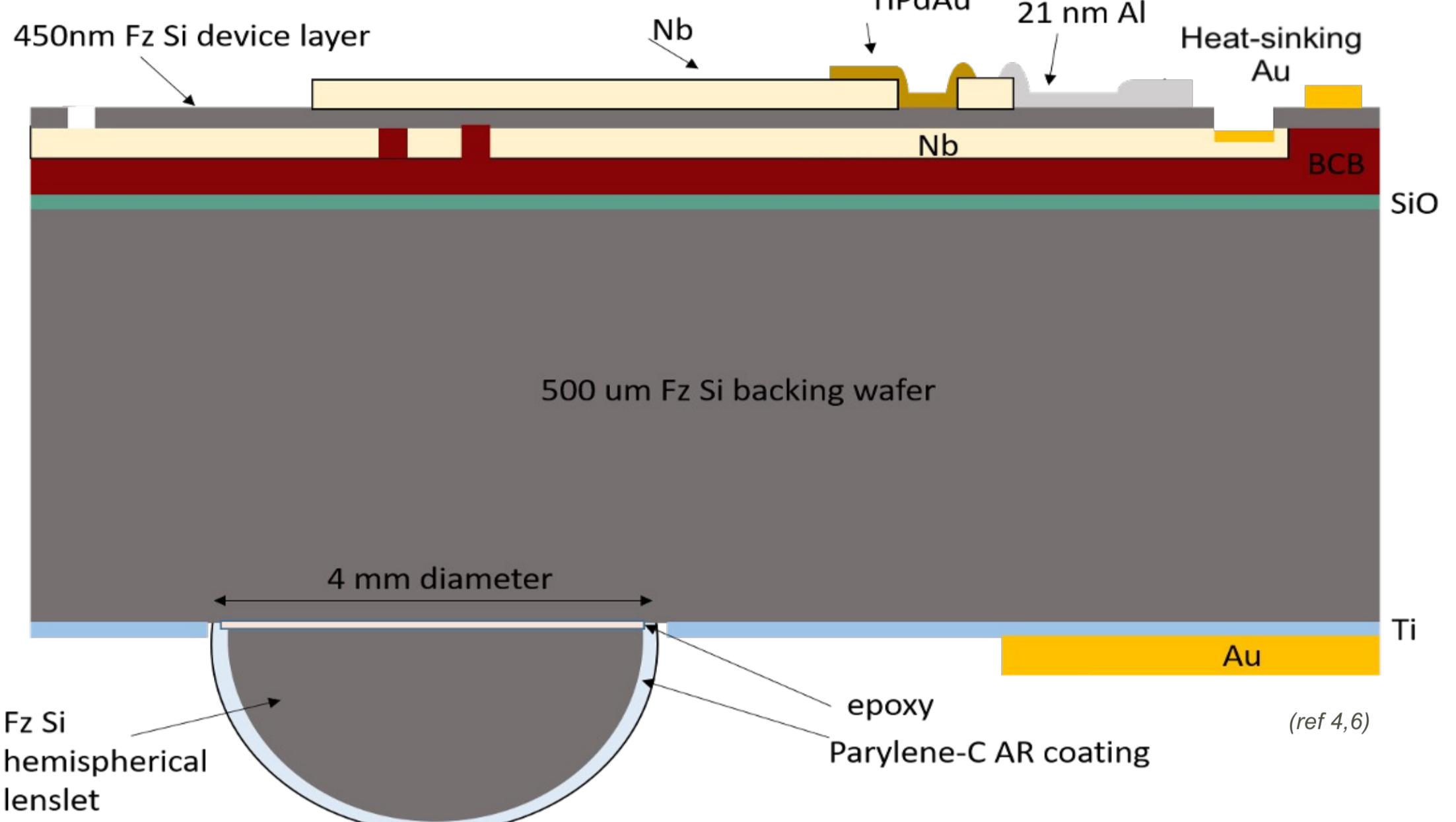
- The addition of a thin Ti coating layer with a thickness designed to target a sheet resistance optimized to terminate stray light in the Si backing wafer.
- The addition of a layer of normal-metal Au solely under the portion of the spectrometer housing the KIDs, to act as a trap for cosmic-ray excited phonons.
- An RF design that minimizes ground plane cuts.
- Al feedlines for readout that absorb thermal radiation > 90 GHz.
- And others in the table below:

Individual Stray Light/Cross Talk Terms	Maximum Expected Value, Equivalent In-band Power at MKID Input [aW]	Mitigation Features in Current Baseline Design
In-band Higher-Order Diffraction	0	Focal Plane Design; Sidewall absorber
In-band Diffraction Reflected	200 (non uniform distribution*)	Sidewall absorber
Out-of-band Diffraction	68 (non uniform distribution*)	Optical filters off chip; Nb gap; Baffle Structures/Receiver Optics Design; Sidewall absorber
In-band Optical Chain Thermal Emission Diffraction	48	Baffle Structures/Receiver Optics Design;
In-band Optical Cross-Talk Due to Spectral Function	0	Focal Plane Design
Spectrometer Backing Wafer	0.7	Optical filters off chip; Baffle Structures/Receiver Optics Design; Backside Ti Coating
Spectrometer Top Package	0	Optical filters off chip; Baffle Structures/Receiver Optics; Package blackening
Thermal On-Chip RF Line	60	Thermal blocking filters; RF chain configuration
RF cross-talk – Physical coupling	0	Microstrip architecture and thin Si dielectric (only 450 nm); resonator frequency spacing
RF cross-talk – Lorentzian coupling	20	High Internal QI; Readout system accuracy
Total Budget Estimate	378	

ABSTRACT

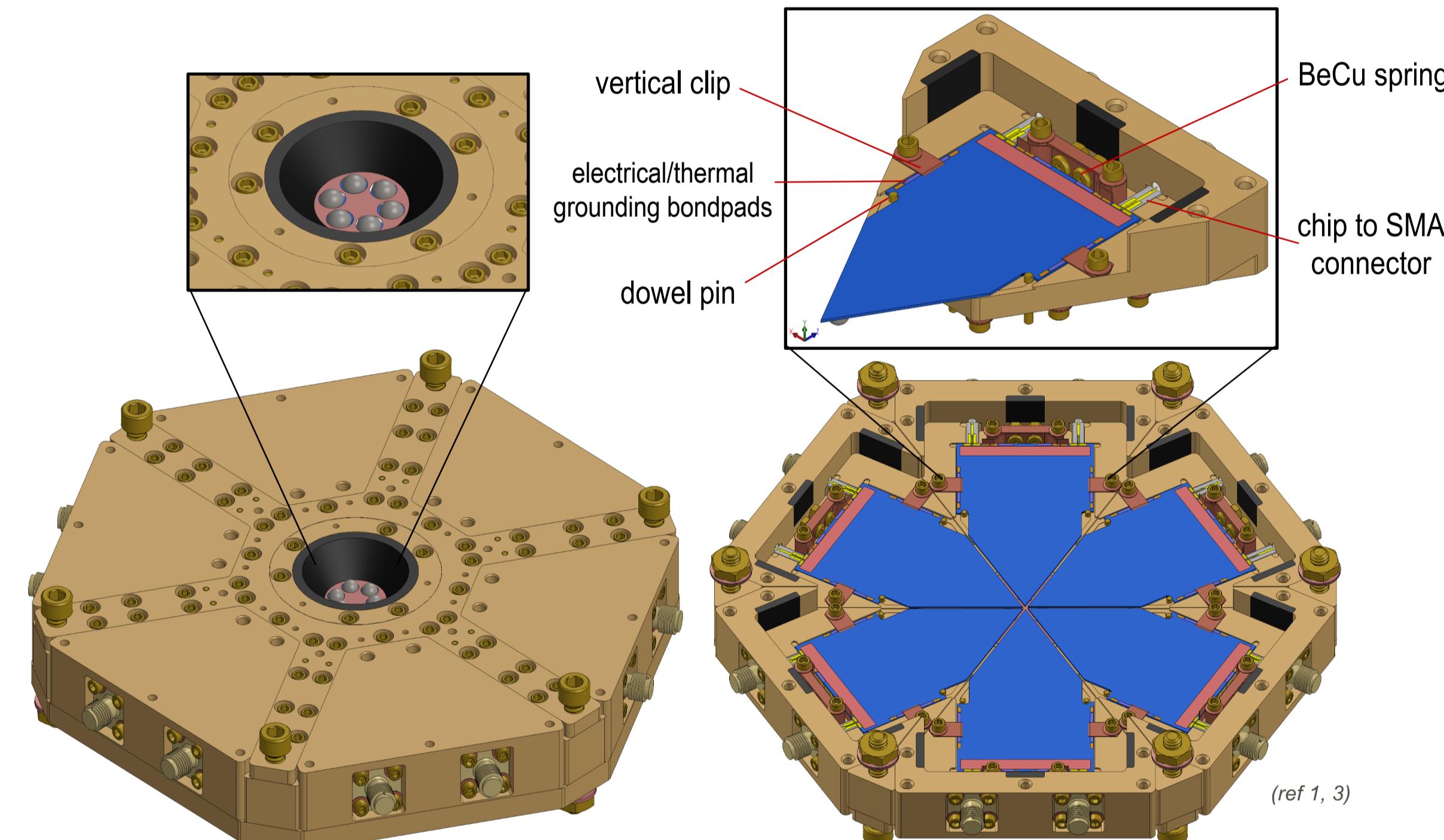
The current state of far-infrared astronomy drives the need to develop compact, sensitive spectrometers for future space and ground-based instruments. Here we present details of the μ -Spec spectrometers currently in development for the far-infrared balloon mission EXCLAIM. The spectrometers are designed to cover the 555 – 714 μm range with a resolution of $R = \lambda/\Delta\lambda = 512$ at the 638 μm band center. The spectrometer design incorporates a Rowland grating spectrometer implemented in a parallel plate waveguide on a low-loss single-crystal Si chip, employing Nb microstrip planar transmission lines and thin-film Al kinetic inductance detectors (KIDs). The EXCLAIM μ -Spec design is an advancement upon a successful $R = 64 \mu$ -Spec prototype, and can be considered a sub-mm superconducting photonic integrated circuit (PIC) that combines spectral dispersion and detection. The design operates in a single $M = 2$ grating order, allowing one spectrometer to cover the full EXCLAIM band without requiring a multi-order focal plane. The EXCLAIM instrument will fly six spectrometers, which are fabricated on a single 150 mm diameter Si wafer. Fabrication involves a flip-wafer-bonding process with patterning of the superconducting layers on both sides of the Si dielectric. The spectrometers are designed to operate at 100 mK, and will include 355 Al KID detectors targeting a goal of NEP $\sim 8 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$. We summarize the design, fabrication, and ongoing development of these μ -Spec spectrometers for EXCLAIM.

3 FABRICATION



- A bonded-wafer flip process is used to enable the spectrometer circuit to be fabricated on both sides of a single crystal silicon dielectric. The single crystal silicon dielectric layers provides fundamentally high transmission line efficiency, and high performance MKIDs. Care is also taken throughout the process to control the superconducting and dielectric interfaces to prevent the introduction of additional loss and noise.
- The Nb liftoff and Al wet etch processes allow for the patterning of these superconducting layer without roughening or etching into the single crystal silicon layer. These patterning process also allow for linewidths dimensions to be precisely controlled within design tolerances.
- The film quality and resistivity parameters of the metal layers are also monitored to ensure compliance with design tolerances.
- Sub-micron patterning steps are required for the slot antenna design and achieved using a Heidelberg laser write tool.

5 PACKAGE



Principles of Package Design:

- All six on-chip μ -Spectrometers fit without touching in one superstructure.
- The lenses of the individual spectrometers are aligned in the focal plane when cold.
- The spring and clip design secure the spectrometers and allow for thermal contraction when cold.
- Individual spectrometers can be easily interchanged if certain if certain design elements are retained, minimizing re-packaging steps and allowing future devices to also use the same package.
- Heat sinking occurs through a copper bus to an ADR, and is maintained at 100 mK.
- Blackening epoxy is applied where possible to mitigate stray light and reflections.
- Each spectrometer has two SMA connections for readout.

STATUS

- The EXCLAIM six-spectrometer superstructure package design is complete.
- The design phase for EXCLAIM's spectrometers is complete, and the first spectrometers are expected to be yielded in early fall of 2022 to begin to undergo characterization testing.
- EXCLAIM plans to take its first <24 hr flight from NASA's Ft. Sumner, New Mexico facility in Fall 2023.

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