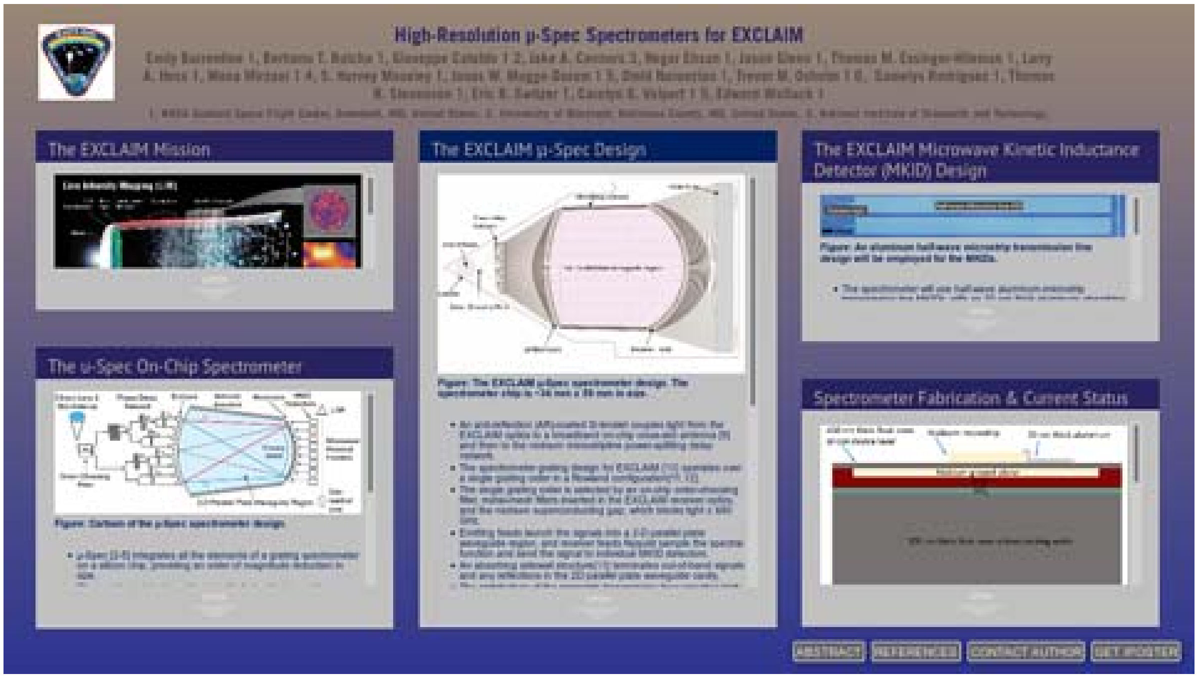
High-Resolution μ-Spec Spectrometers for EXCLAIM



High-Resolution μ-Spec Spectrometers for EXCLAIM

The EXCLAIM Mission

The μ-Spec On-Chip Spectrometer

The EXCLAIM μ-Spec Design

Figure: The EXCLAIM μ-Spec spectrometer design.

The EXCLAIM Microwave Kinetic Inductance Detector (MKID) Design

Spectrometer Fabrication & Current Status

Emily Barrentine 1, Berhanu T. Bulcha 1, Giuseppe Cataldo 1 2, Jake A. Connors 3, Negar Ehsan 1, Jason Glenn 1, Thomas M. Essinger-Hileman 1, Larry A. Hess 1, Mona Mirzaei 1 4, S. Harvey Moseley 1, Jonas W. Mugge-Durum 1 5, Omid Noroozian 1, Trevor M. Oxholm 1 6, Samelys Rodriguez 1, Thomas R. Stevenson 1, Eric R. Switzer 1, Carolyn G. Volpert 1 5, Edward Wollack 1

1. NASA Goddard Space Flight Center, Greenbelt, MD, United States, 2. University of Maryland, Baltimore County, MD, United States, 3. National Institute of Standards and Technology, Boulder, CO, United States, 4. Science Systems and Applications, Inc., Lanham, Maryland, United States, 5. University of Maryland, College Park, MD, United States, 6. University of Wisconsin, Madison, WI, United States.

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THE EXCLAIM MISSION

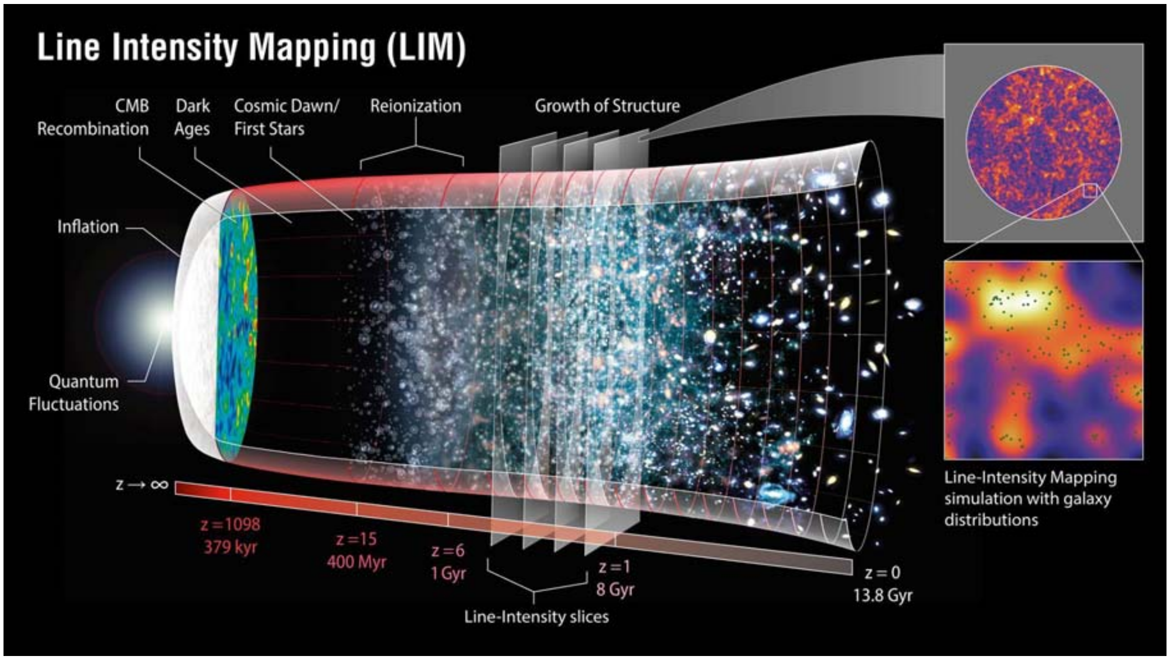


Figure: Line intensity mapping will probe our understanding of cosmology during the era of the growth of structure [15].

- The EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM) [1], is a high-altitude balloon-borne telescope designed to deepen our understanding of star formation processes, and the cosmological era during which the growth of structure took place .
- EXCLAIM will measure the integrated line emission from galaxies and the intergalactic medium from the nearby universe out to redshifts of z~3.5, using a technique called intensity mapping.
- Using this intensity mapping approach, rather than detecting individual galaxies, EXCLAIM will measure the statistics of brightness fluctuations of redshifted, cumulative line emission.

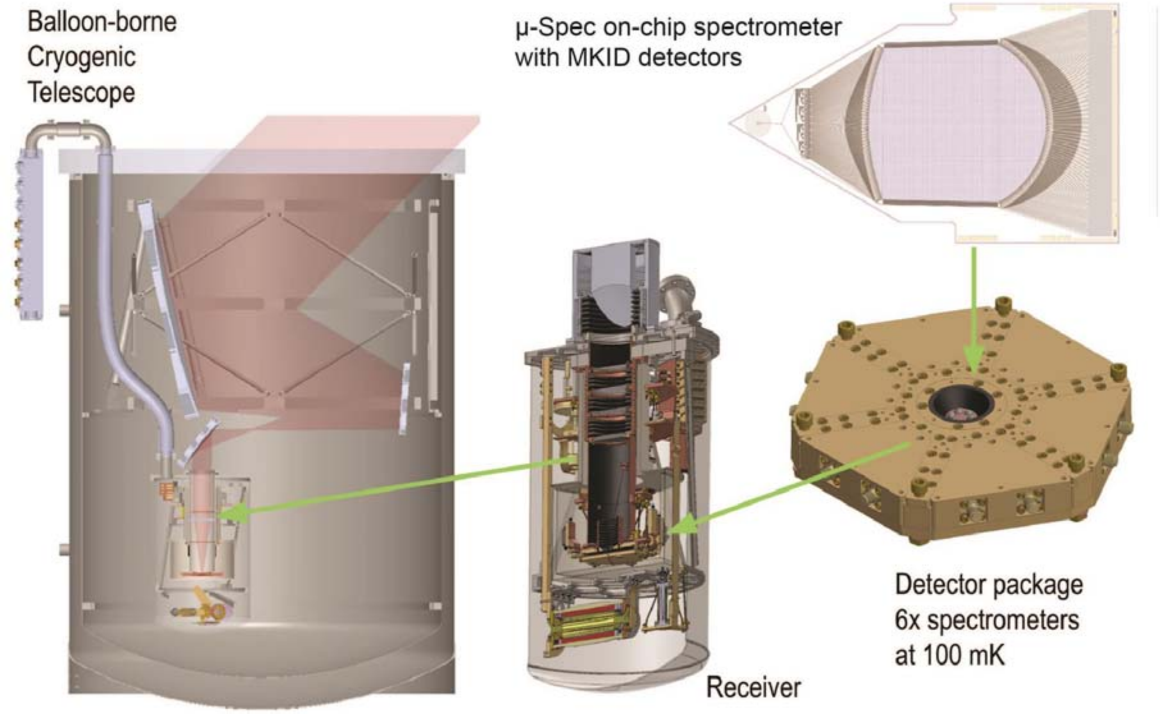


Figure: Overview of the EXCLAIM balloon-borne Instrument.

- The instrument will employ an array of six superconducting integrated grating-analog spectrometers (µ-Spec) with superconducting microwave kinetic inductance detectors (MKIDs) in an all-cryogenic telescope (1.7 K).
- The cryogenic telescope enables the instrument to reach high senstivity in the low background between atmospheric emission lines.
- The EXCLAIM program began in April 2019, and the first balloon flight is expected in Summer/Fall 2022.

THE U-SPEC ON-CHIP SPECTROMETER

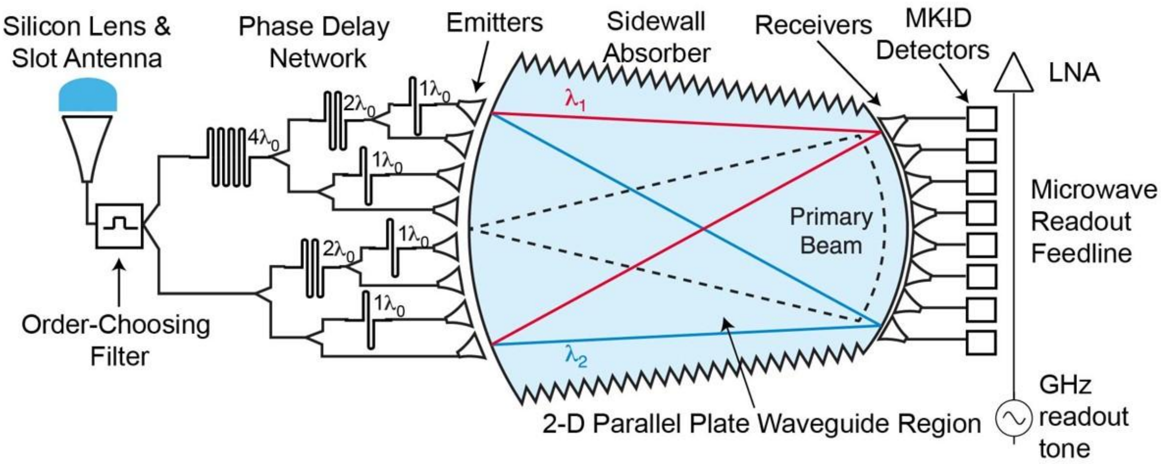


Figure: Cartoon of the µ-Spec spectrometer.

- µ-Spec [2-5] integrates all the elements of a grating spectrometer on a silicon chip, providing an order of magnitude reduction in size.
- Phase delay is introduced by a synthetic ‘grating’ consisting of meandered superconducting niobium transmission lines on a silicon substrate.
- A 2-D parallel plate waveguide region serves as a spatial beam combiner and focal plane, which Nyquist-samples the spectral response, the sinc^2 function.
- The low loss of single-crystal silicon [6-8], compared to deposited dielectrics, provides high-efficiency and high-resolution.
- We use Microwave Kinetic Inductance Detectors (MKIDs) due to their ease of fabrication, multiplexing capability, and ability to reach ultra-low sensitivity.

THE EXCLAIM Μ-SPEC DESIGN

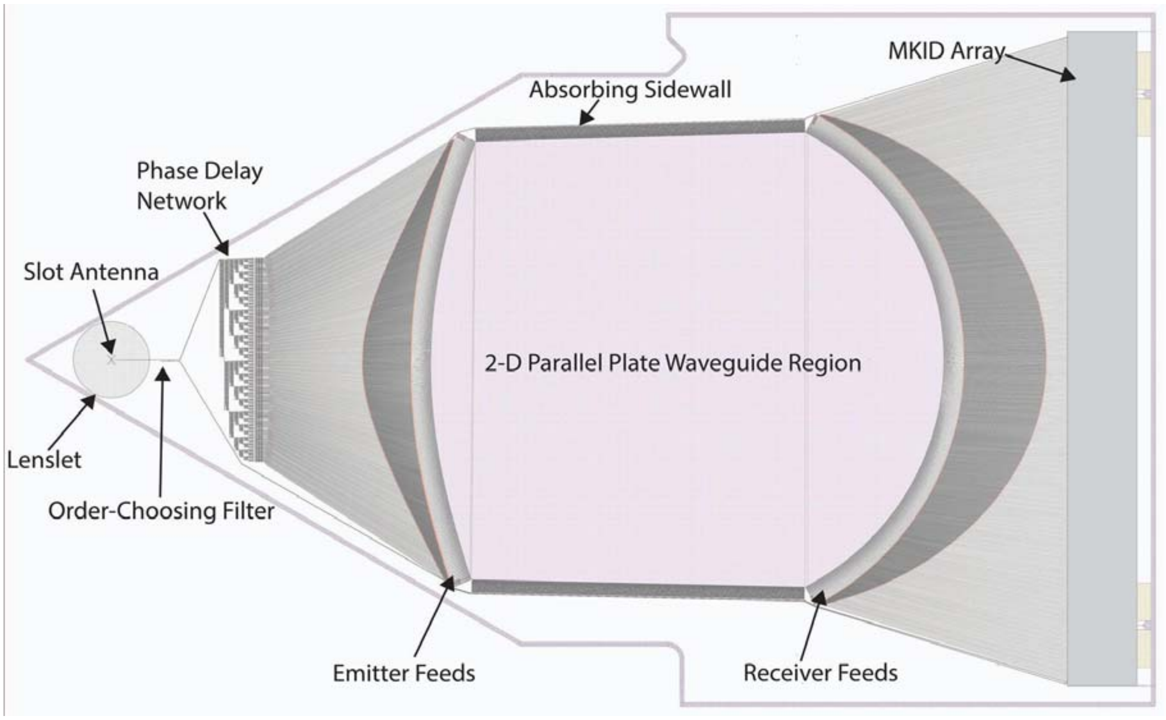


Figure: The EXCLAIM μ-Spec spectrometer design. The spectrometer chip is ~34 mm x 59 mm in size.

- An anti-reflection (AR)-coated silicon lenslet couples light from the EXCLAIM telescope optics to a broadband on-chip cross-slot antenna [9] and then to the niobium microstripline power-splitting phase delay network.
- The spectrometer grating design for EXCLAIM [10] operates over a single grating order in a Rowland configuration[11,12].
- The single grating order is selected by an on-chip order-choosing filter, metal-mesh filters inserted in the EXCLAIM receiver optics, and the niobium superconducting gap, which blocks light ≥ 680 GHz.
- Emitting feeds launch the signals into a 2-D parallel plate waveguide region, and receiver feeds Nyquist sample the spectral function and send the signal to individual MKID detectors.
- An absorbing sidewall structure[13] terminates out-of-band signals and any reflections in the 2D parallel plate waveguide cavity.
- The architecture of the microstrip transmission lines provides high immunity to stray light and cross-talk, due to the thin 450-nm-thick silicon dielectric layer, and the protective niobium ground plane.
- A thin-film titanium coating will be deposited on the back of the spectrometer chip to terminate stray light.
- Each spectrometer will provide a resolving power, R ~ 512, over the 420–540 GHz spectral band.
- The expected efficiency of the spectrometer from the input of the lenslet to the input of each MKID is ~ 25-30% and is dominated by losses in the coupling to the slot-antenna-lenslet and coupling to the receiver feeds.

Table: EXCLAIM μ-Spec Spectrometer Design Parameters

EXCLAIM Spectrometer Parameters	
Spectrometer Design	µ-Spec, antenna-coupled diffraction-grating analog, Rowland configuration
Number of spectrometers	6
Spectral Range	420-540 GHz
Spectrometer Grating Order	2 (operates over a single order)
Resolving Power, R = λ/Δλ	512
Spectrometer Efficiency	~25-30% (from the silicon lenslet input to the MKID inputs)
Spectrometer materials	Niobium microstripline, single-crystal silicon dielectric

THE EXCLAIM MICROWAVE KINETIC INDUCTANCE DETECTOR (MKID) DESIGN

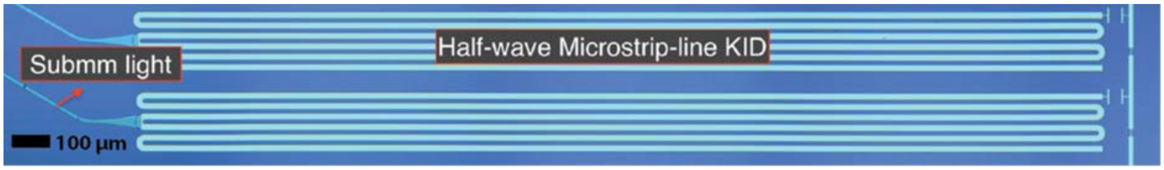
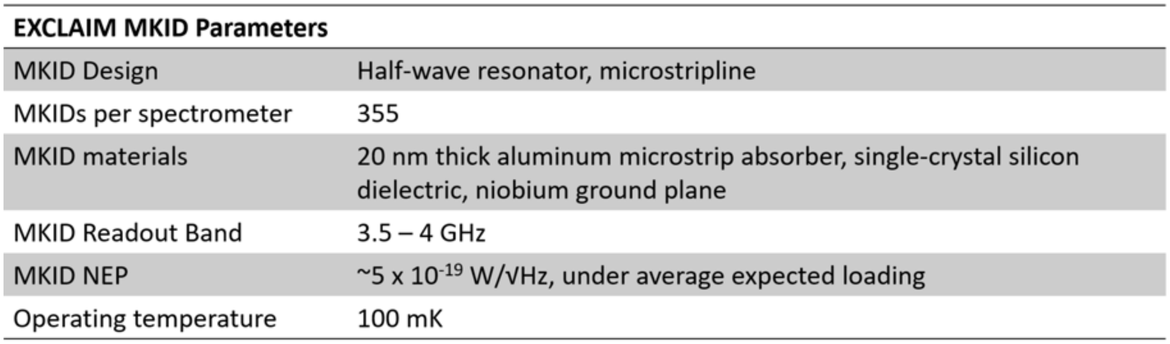


Figure: An aluminum half-wave microstrip transmission line design will be employed for the MKIDs.

- The spectrometer will use half-wave aluminum-microstrip transmission-line MKIDs, with an 20-nm-thick aluminum absorbing layer and a niobium ground plane.
- The MKIDs will operate at ~100 mK, and provide near background-limited sensitivity.
- Each spectrometer will feature 355 MKIDs, all read out on a single microwave readout line.

Table: EXCLAIM MKID Design Parameters



EXCLAIM MKID Parameters	
MKID Design	Half-wave resonator, microstripline
MKIDs per spectrometer	355
MKID materials	20 nm thick aluminum microstrip absorber, single-crystal silicon dielectric, niobium ground plane
MKID Readout Band	3.5 – 4 GHz
MKID NEP	~5 x 10^{-19} W/√Hz, under average expected loading
Operating temperature	100 mK

SPECTROMETER FABRICATION & CURRENT STATUS

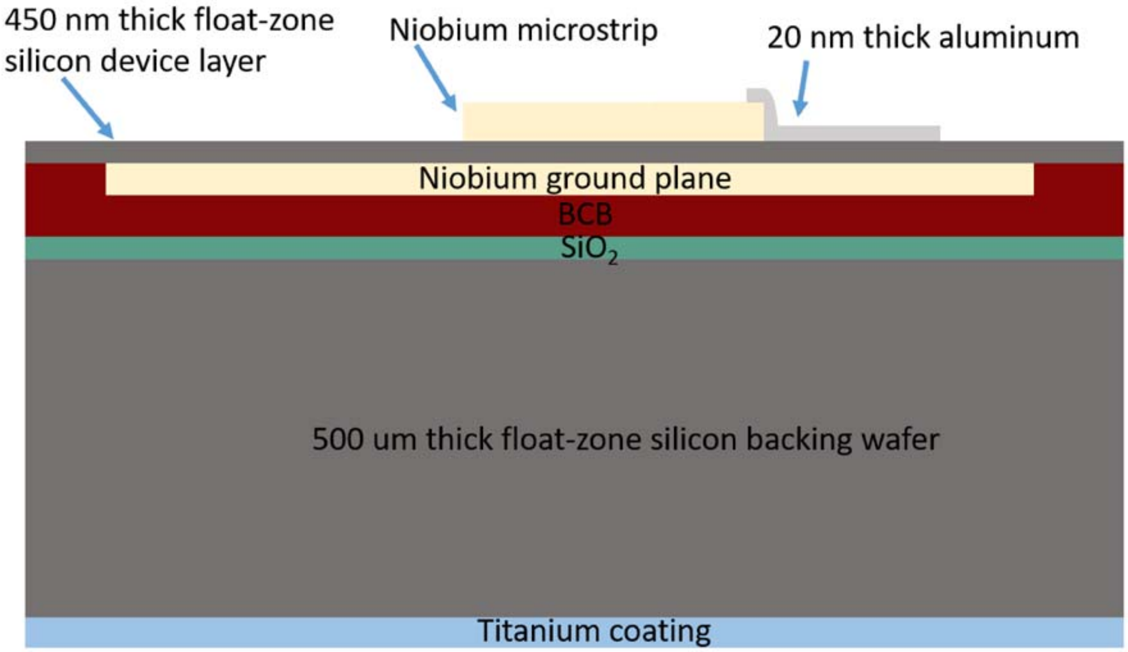


Figure: Cartoon stack-up (not to scale) of the EXCLAIM µ-Spec spectrometer chip.

- The EXCLAIM µ-Spec spectrometers will be fabricated following a single-flip wafer bonding process[14], in which a silicon-on-insulator wafer is bonded to a supporting backing wafer using a benzocyclobutene (BCB) thermoplastic, and the handle wafer is removed. This process allows us to fabricate the superconducting circuitry on both sides of the low-loss single crystal silicon device layer.
- The niobium transmission lines will be fabricated using a liftoff technique [14], which avoids roughening or etching through the single-crystal silicon dielectric, provides a clean and low-loss interface, and achieves the linewidth precision necessary to provide the spectrometer R ~ 512 resolution.
- Fabrication of the EXCLAIM µ-Spec spectrometers began in October 2020.

DISCLOSURES

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ABSTRACT

The EXperiment for Cryogenic Large-aperture Intensity Mapping (EXCLAIM) is a submillimeter (420-540 GHz) cryogenic balloon-borne astrophysics experiment which will use an intensity mapping approach to map carbon monoxide and singly-ionized carbon emission lines across cosmic time scales. The focal plane of the EXCLAIM instrument will feature six superconducting μ-Spec spectrometers. μ-Spec is a grating-analog spectrometer on-a-chip, which uses meandered superconducting Nb microstrip transmission lines on a single-crystal silicon dielectric to build a synthetic grating in a compact architecture. The spectrometer also features ultrasensitive Al/Nb Microwave Kinetic Inductance Detectors (MKIDs) in a microstrip transmission-line design. The spectrometers for EXCLAIM will operate with a resolution $R = \lambda/\Delta\lambda = 512$, and will each feature an array of 355 MKIDs. We report on these spectrometers under development for EXCLAIM, including an overview of the spectrometer design and fabrication status.

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