Photomixer R&D:
A cryogenic THz calibration system

Emily Perry (LBNL/UC Berkeley)
BREAD Collaboration Workshop (Harvard University)
14-16th January 2026

Group involved:
Noah Kurinsky (SLAC), Betty Young (SCU), Emily Scott (SCU), Sidney Stevens (SLAC), Tonya Pershel (SLAC), Chiara Salemi (LBNL/UC Berkeley), Erin Engelhardt (LBNL/UC Berkeley) & Brennan Coffey (UC Berkeley).

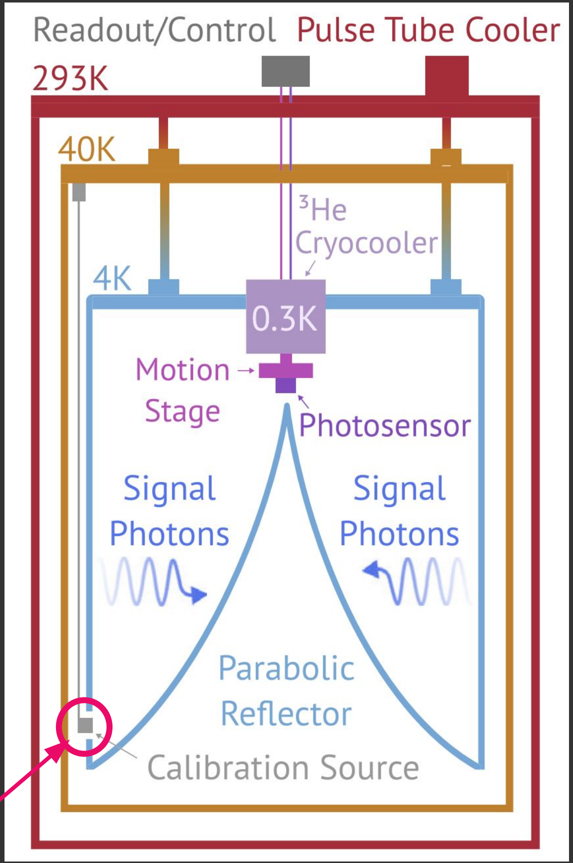
Motivation

CHALLENGE: The calibration of ultra-sensitive THz/meV detectors in cryogenic environments is difficult.

SOLUTION: A system is being developed using a photomixer and hollow circular waveguides to deliver tunable frequency THz photons to cryogenic sensors.

IMPACT: Motivated by the need to calibrate SQUATs, which are sensitive to single THz photons and meV phonons. Robustness to allow transfer to detectors such as BREAD.

This work



PHYSICAL REVIEW LETTERS 128, 131801 (2022)

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Why Produce THz via Photomixing?

Bakman Laser Technologies

System is a broadband source which is **cryogenically compatible** and **directly** supplies the signal (THz photons) many detectors are trying to measure. Other criteria this source meets:

- Precise frequency: resolution 500 MHz (0.0005 THz)
- Tunable: range from ~200-2000 GHz (0.2-2 THz)
- Robust design and good coupling mechanisms for integration into various systems (waveguides, free space, space efficient)
- “On and off” mechanism

Other sources include:

- Bandpass filtered blackbody source: *pros: broadband, good coupling… cons: precision (filters), not tunable* [MURAJ V7 NO.2]
- Monochromatic laser: *pros: precision, power… cons: single freq, precise alignment needed [BREAD paper]*
- Frequency multipliers (e.g. Schottky diode): *pros: precision, power, costs, tunable cons: single freq, complexity and delicacy, conversion losses at high THz freq [Appl. Phys. Express 17 070101]*

  & more…

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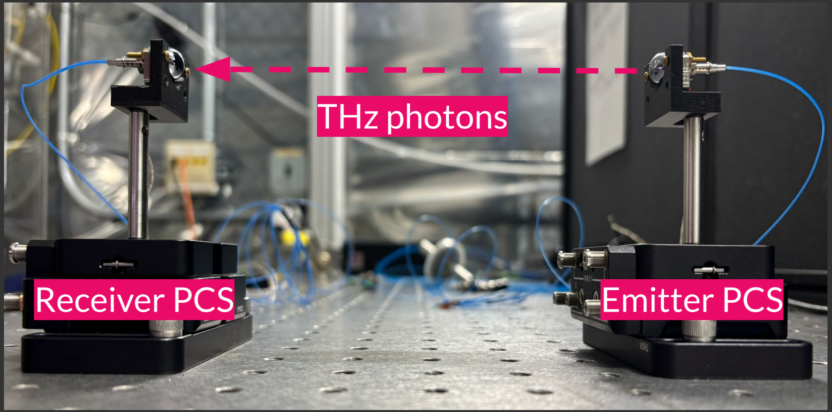
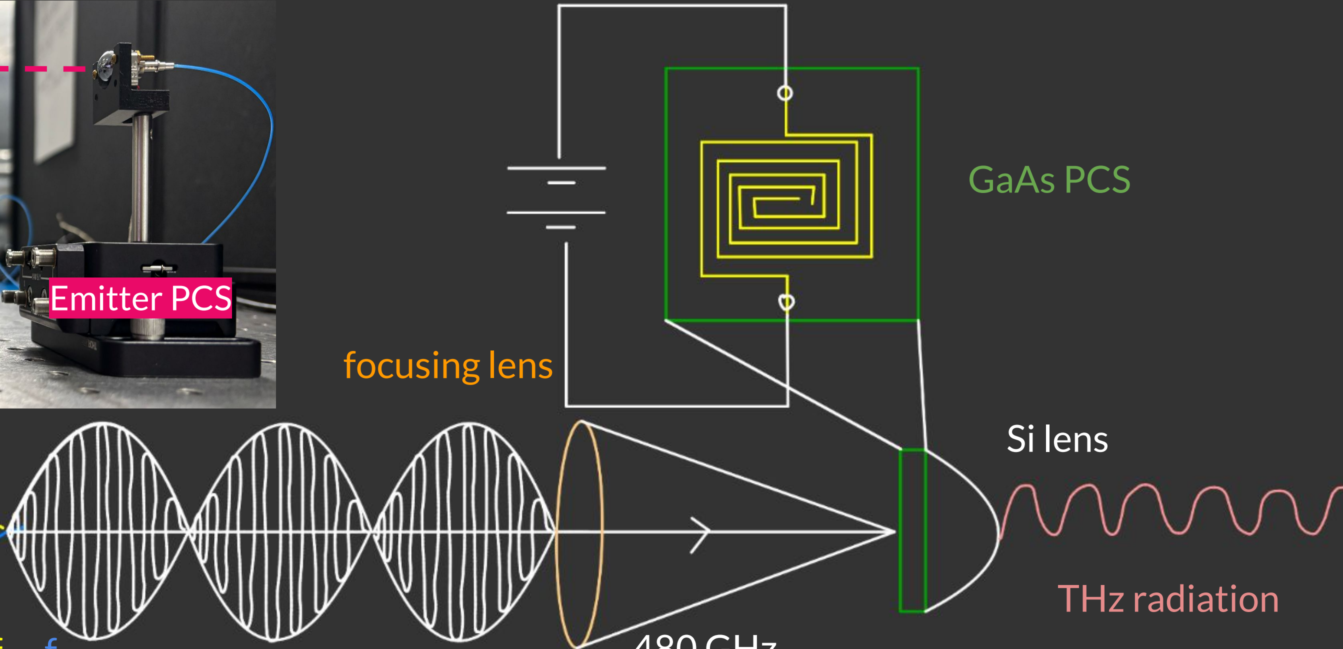
Principle of Operation

Emission of THz:

2 lasers (f_1 & f_2) overlap, same polarization → Beat note formed and focused on GaAs photodetector → Photodetector response modulated at $f_{THz} = f_1 - f_2$ → Photocurrent converted to EM wave at THz frequency by antenna





Principle of Operation

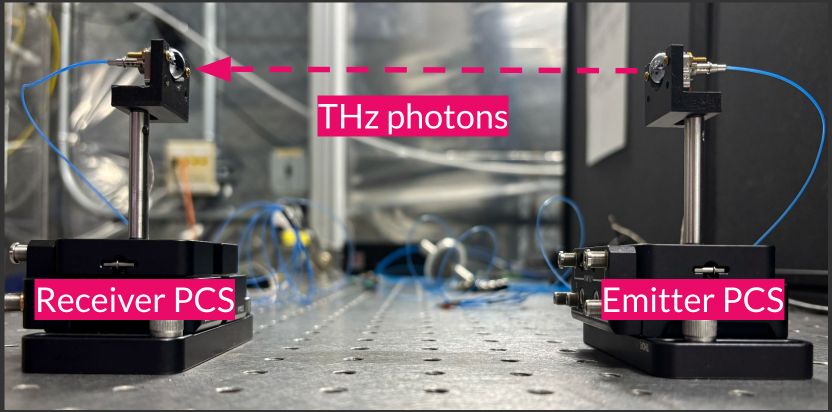
Q. Why are there 2 PCS heads?

A. For eventual emitter → sensor (e.g. SQUAT) the second PCS head is not needed.
For demonstration of THz photomixing at cryogenic temperatures we can use the second head as a detector! Will transition to source-only in near future.

→Current test set up is an interferometer!

Same combined laser beam sent down a longer optical path to detector PCS onto which the THz signal is incident

1. **Light Source**: laser
2. **Beam Splitter:** 2 beams, a probe and a test beam.
3. **Optical Paths:** probe beam travels a longer fixed path. Test beam travels along a changeable path
4. **Interference Pattern**



Principle of Operation

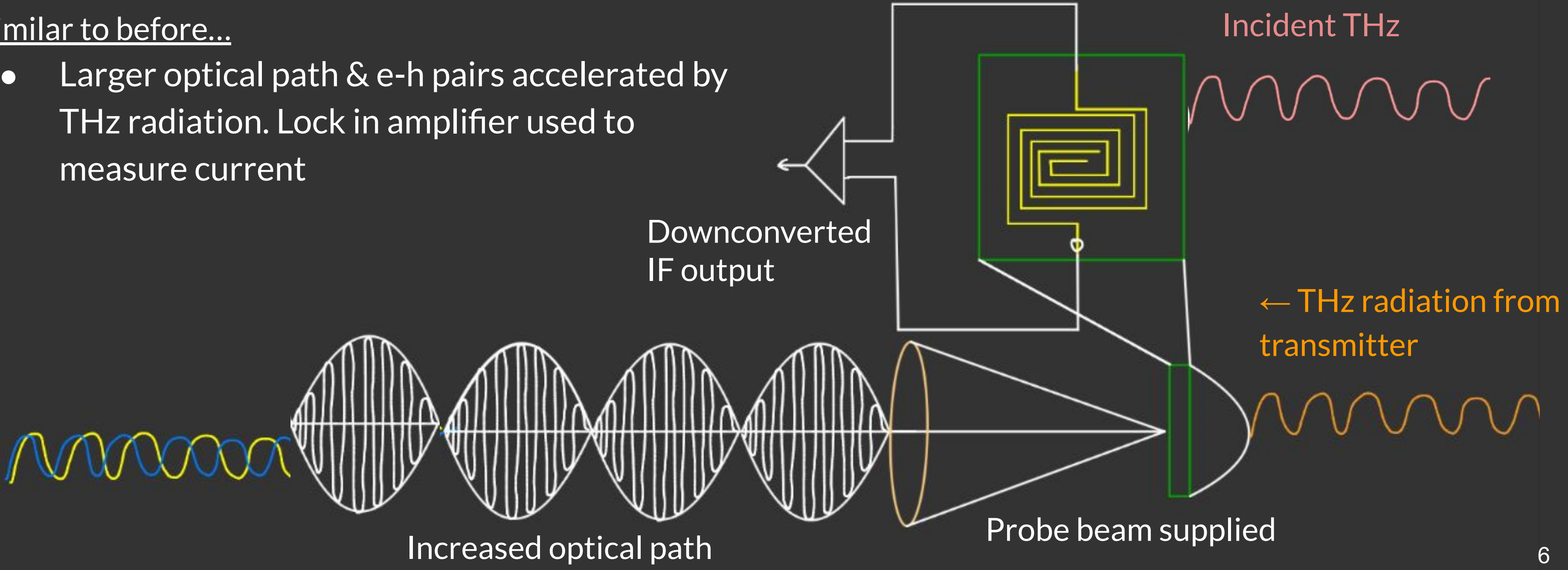
High frequency photomixing to detect THz (temporary)

Detection of THz with PCS:

2 lasers (f_1 & f_2) overlap, same polarization → Beat note formed and focused on GaAs photodetector → Photodetector response modulated at $f_{THz} = f_1 - f_2$ → e-h charge carriers are accelerated by the incident THz. Current generated proportional to the strength of the THz EF.

Similar to before…

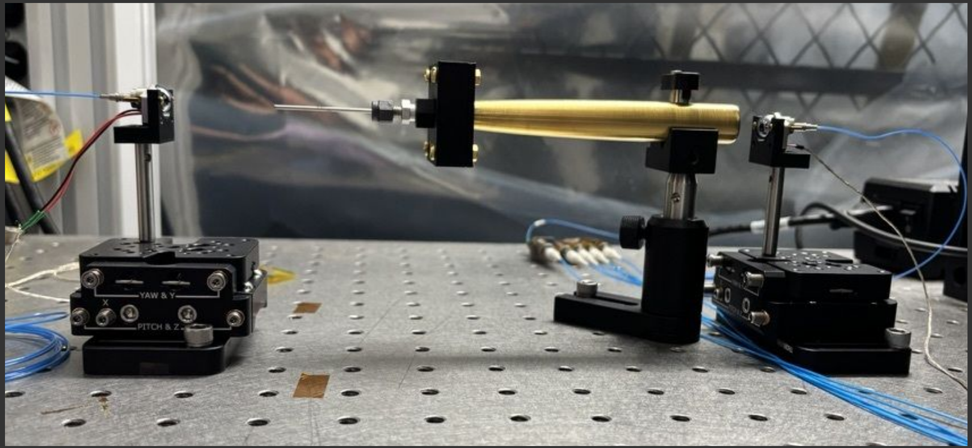
- Larger optical path & e-h pairs accelerated by THz radiation. Lock in amplifier used to measure current

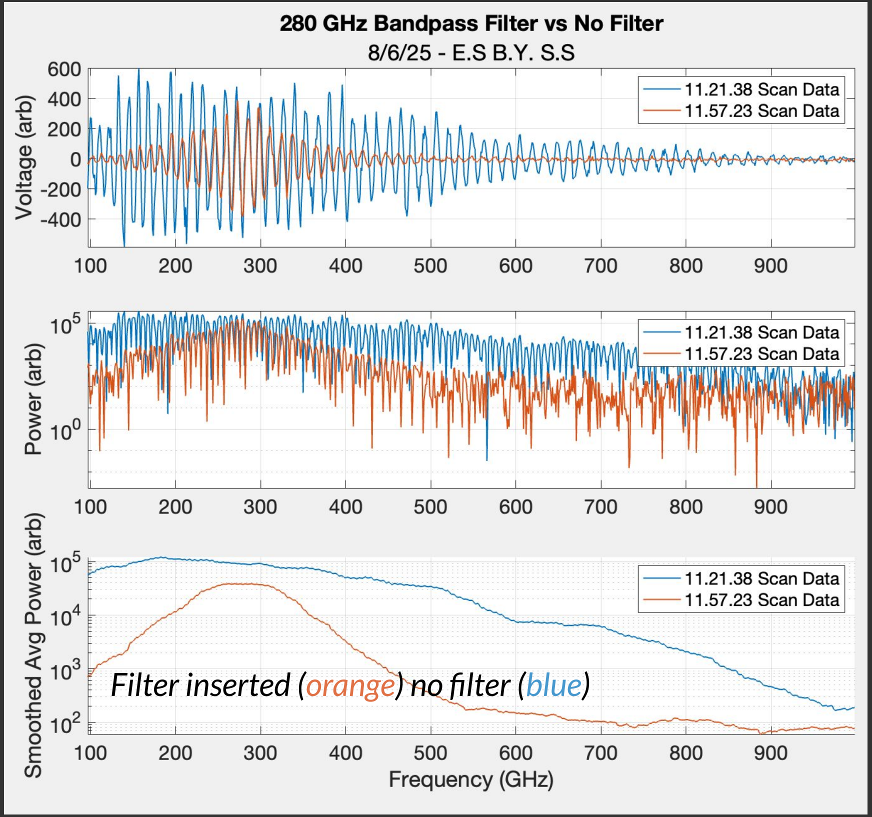


Bench Top R&D @ SLAC

Work includes:

1. **S/N improvements** → cable modifications, grounding schemes, Faraday cages
2. **Waveguides** → needed in final configuration
3. **Winston cone tests**
4. **Sourcing second system:** for improved alignment
5. Collaboration on **THz→SQUAT design**



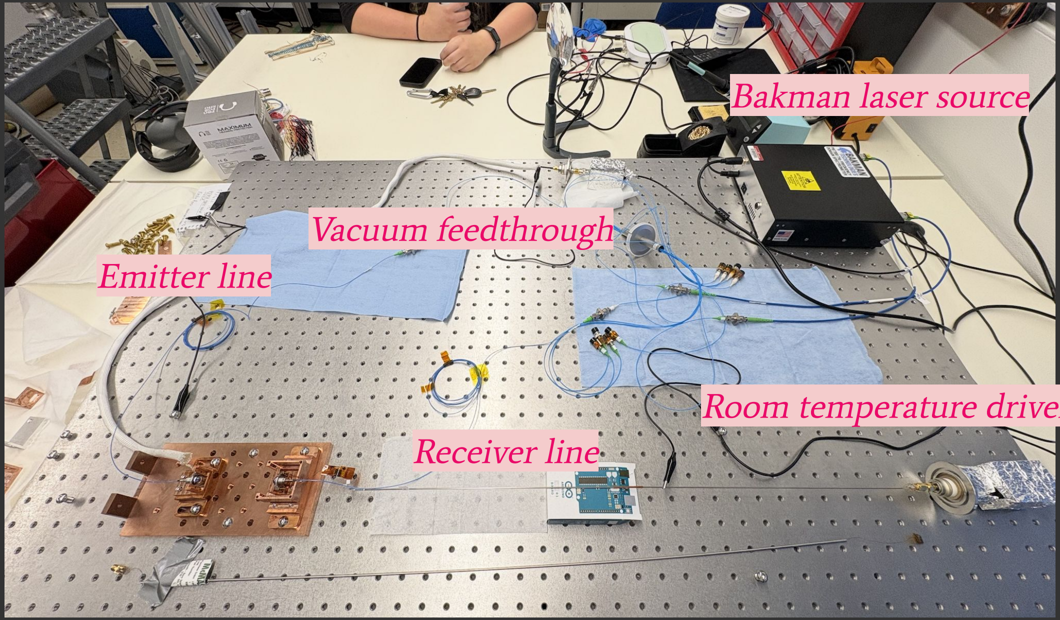


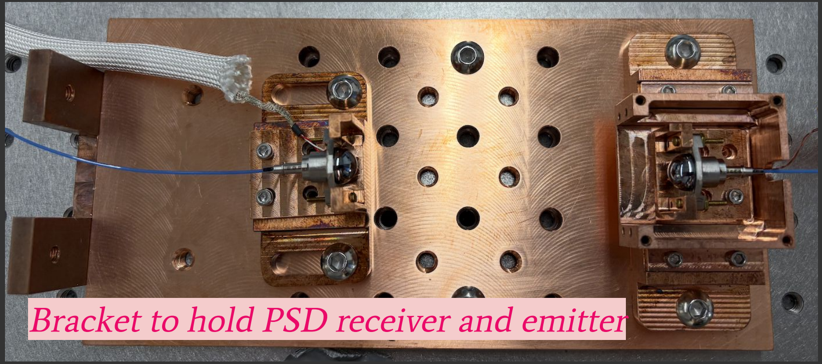
From Betty & Emily S. With a 12.6 +/- 0.2 cm PSD head spacing.

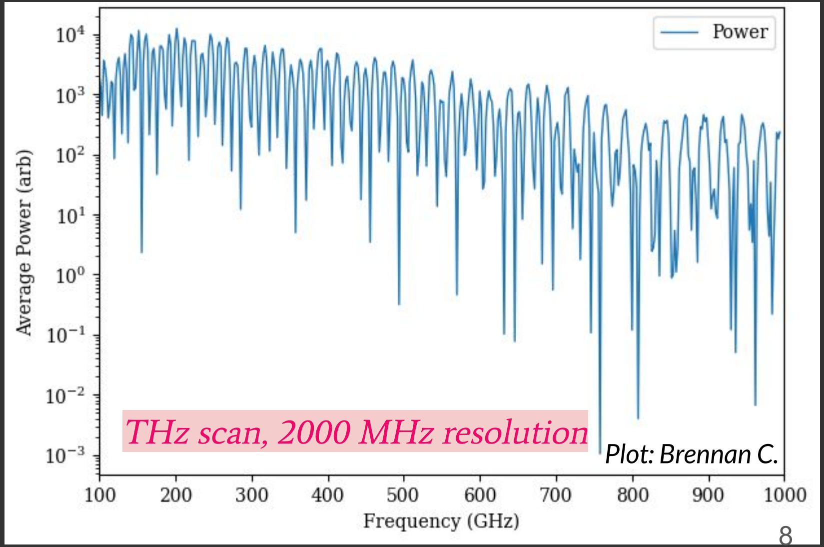
Bench Top Tests @ UC Berkeley

We have reproduced the set up at Berkeley!

Components switched out for cryogenically/fridge compatible versions where needed.







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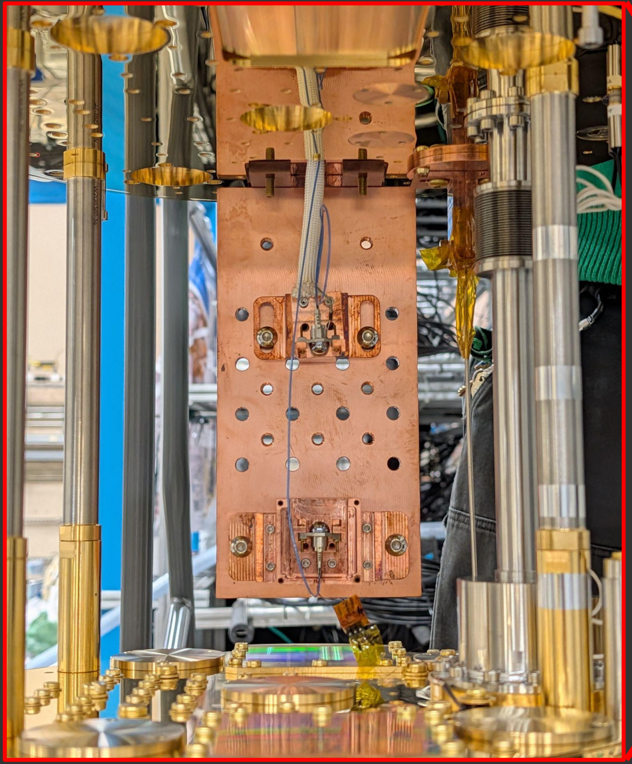
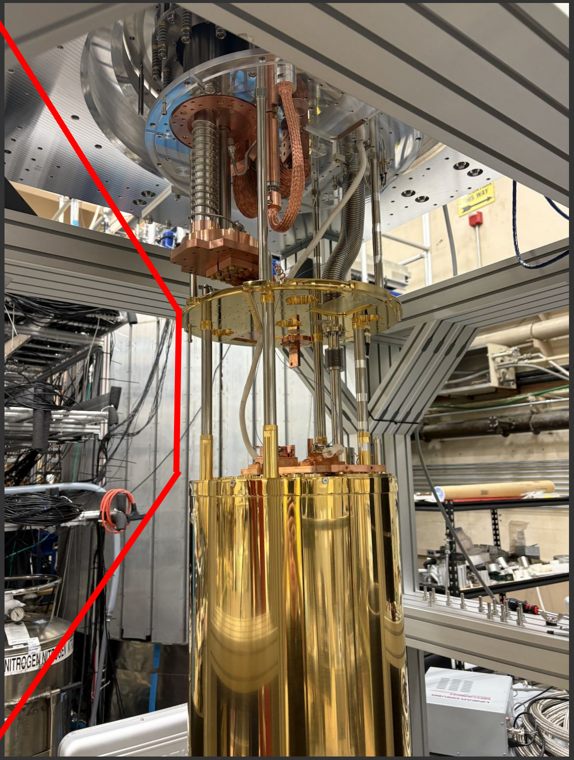
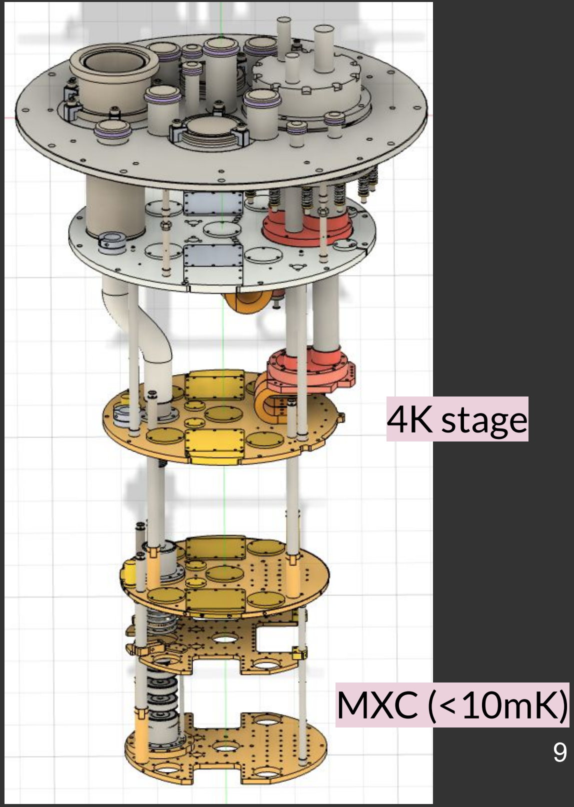
UC Berkeley Cryogenic Photomixer Only Tests @ 4K

Goal: Verification of photomixer cryogenic operation

Test: PCS setup at 4K stage to demonstrate THz can be delivered at cryogenic temperatures.







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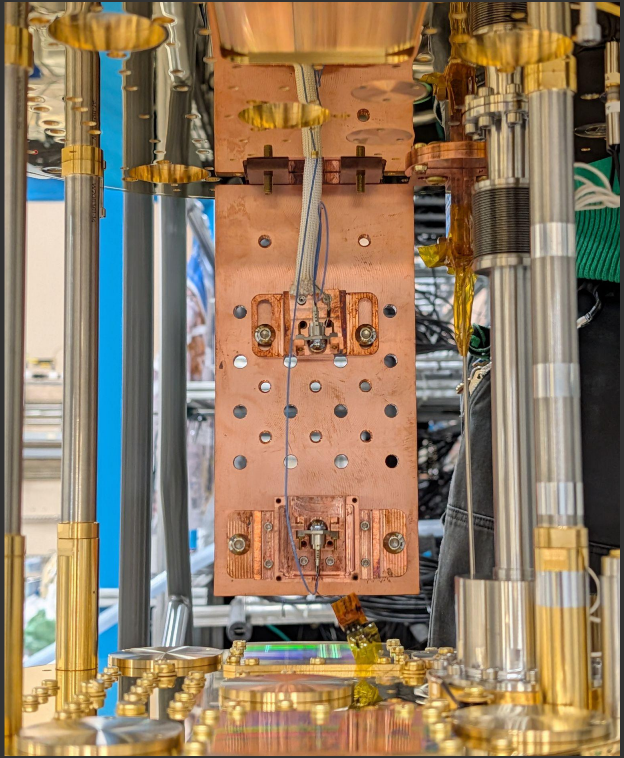

THz system moved to Bluefors LD400.

Testing has begun, system is very sensitive, working hard on optimising noise with:

- Careful grounding scheme
  - e.g. star grounding
- EMI reduction via
  - Cable design. Currently using thin (0.1mm) manganin twisted pair and SS shielding
  - use of optical fibers

We will also be conducting fridge cooling power measurements to understand if operation at 1K is feasible

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UC Berkeley Cryogenic Photomixer Only Tests @ 1K

Goal: Understanding of whether emitter PCS head can be operated at 1K. *In design stage*

Test: PCS emitter held at 1K and the receiver head at the MXC z-position (held at 1K).

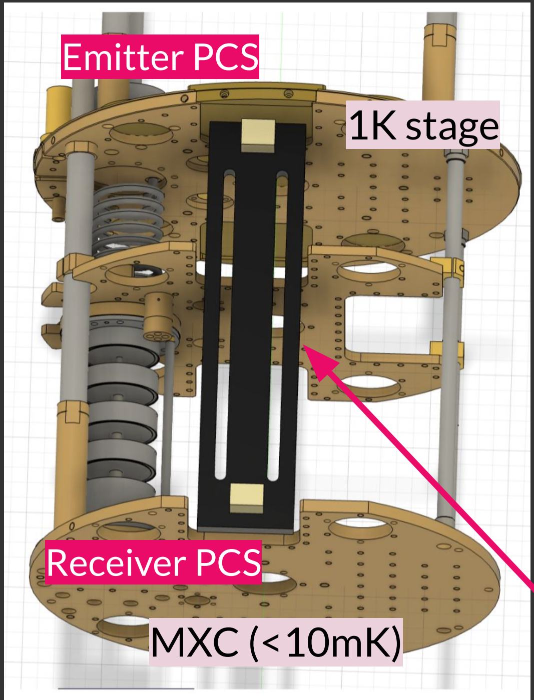

Diagram: Brennan C.

→ Test feasibility of operation at 1K (confirmation of heat load).
→ If successful will simplify the delivery of THz to SQUATs at 10mK.

Additional testing will include:

1. **Waveguides and bending radii limitations**
   Q. Can we successful deliver THz in systems where large bend may be needed (BREAD)?
2. **Filters**
   Q. If filters are needed to filter hot photons from higher temperature stages how is THz delivery affected?

Both waveguides and filters will be placed along bracket across stages

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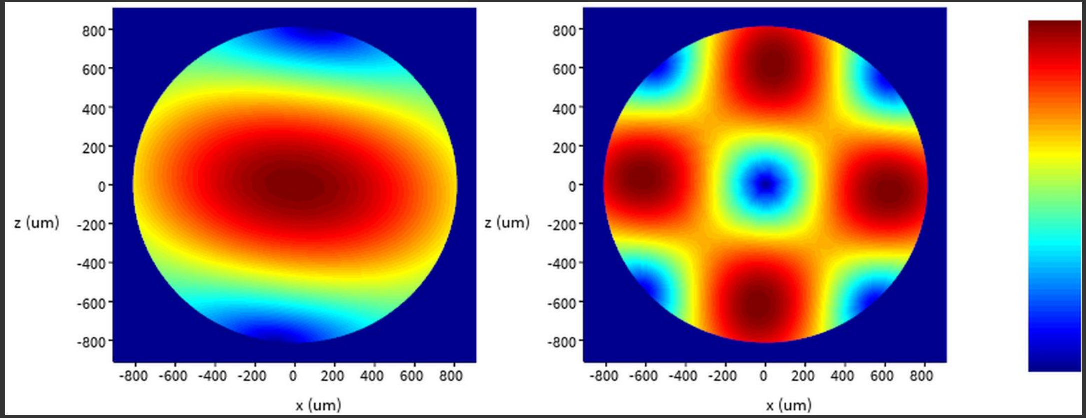
Simulations

FEEM: Finite Element Eigen Mode, FDTD: Finite Difference Time Domain

Simulations started with Ansys Lumerical [website] to study transmission of THz across our system

Utilizes FEEM & FDTD solvers, enables:

- Study of EM-field profiles in cross section of waveguides (range of modes & frequencies)
- Determination of loss & effective index
- Study transmission across vacuum gaps between consecutive waveguides
- Waveguide bending
- Filter inclusions



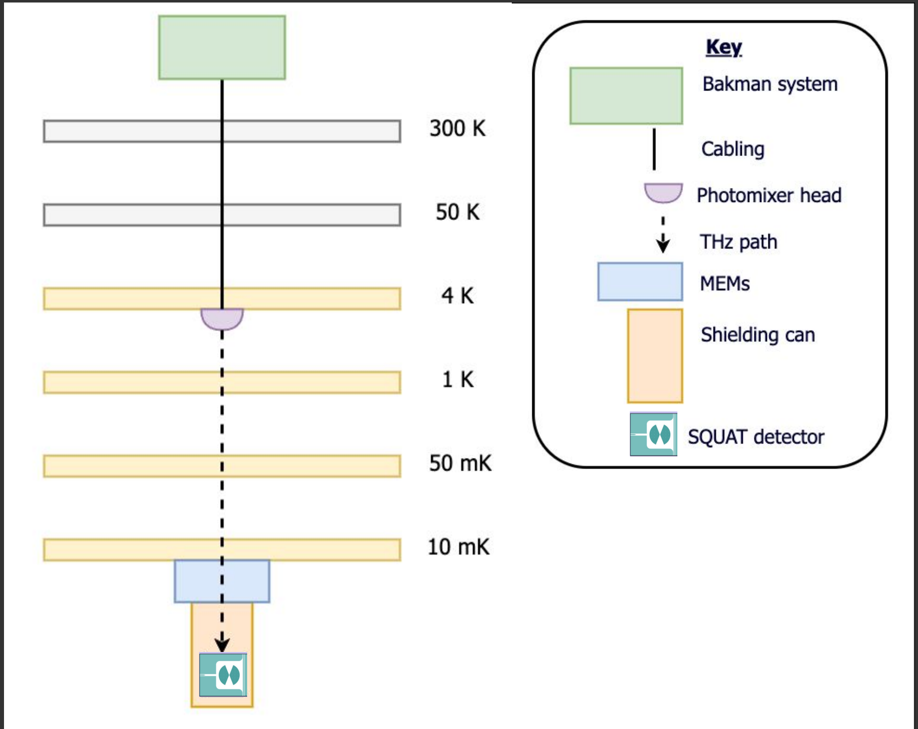
FEEM Visualization of the first (TE_{11}) and fourth (TE_{21}) transverse electric modes of a 1.6mm diameter copper waveguide carrying 1 THz frequency light.

Lead by Brennan Coffey (UC Berkeley)

Future Work: THz to SQUATs

Design work being done in collaboration with SLAC

- Design considerations:
  - Thermal shorting
  - Waveguide or free-space coupling
  - Blackbody radiation filtering
  - Beam considerations: diffraction, etc
  - Robustness necessary for transfer to other systems (e.g BREAD)
  - Integration with MEMS scanner for steering [talk, Sidney Stevens]



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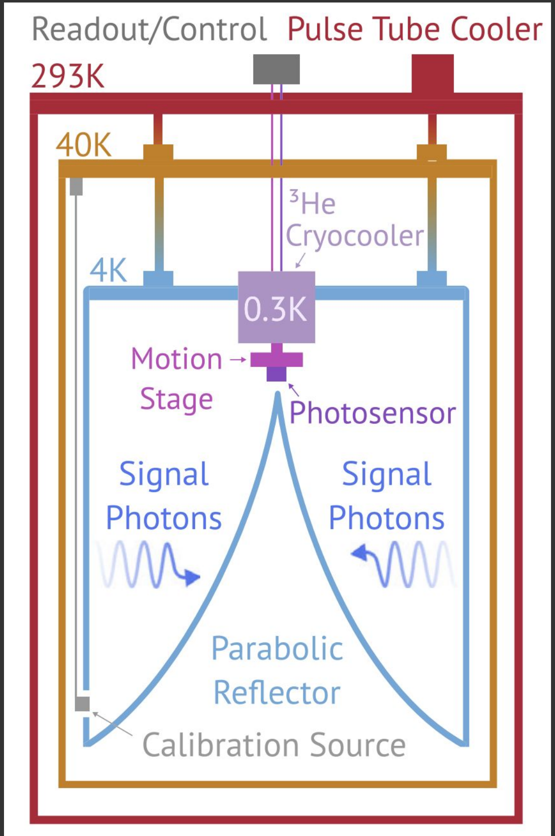
Application case: BREAD Calibration System



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We aim to make this system robust such that it can be integrated into detectors such as BREAD

Question for this audience:

What would we need to do to make this system suitable for BREAD?

Examples:

- How could we couple the THz calibration system?
- What power output is needed from the THz system (few photons?)
- Are additional components needed (e.g. production of polarised photons to mimic axion coupling production?)
- Others?

Please come and say hi or email me with thoughts!

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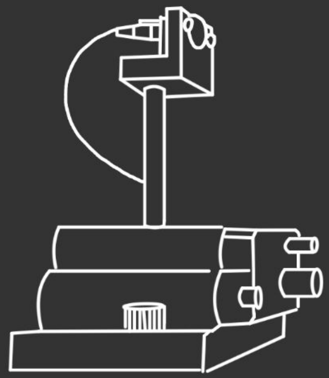
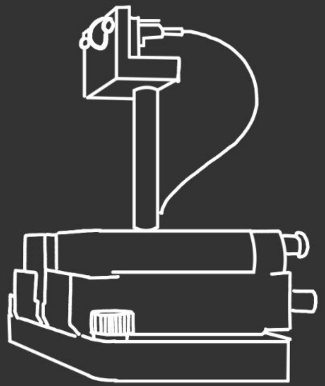
Summary

- A THz system is being developed using a photomixer and hollow circular waveguides to deliver tunable frequency THz photons to cryogenic sensors.
    - *Benefits: broadband, tunable, robust, direct source of THz*
- Current status/near-term testing plans:
    - Cryogenic testing of photomixing system is underway in dilution fridge
        - 4K testing to verify operation at cryogenic temperatures
        - 1K testing to confirm operation at 1K and test waveguides and filter inclusion in chain
- Goal: calibration with SQUATs by summer 2026.



THANK YOU!



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Backup

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Other THz Sources

A monochromatic laser:

- Inject photons via a small hole in the barrel (in BREAD) for in-situ photosensor's detection efficiency and the overall system's response
- **Pros:**
  - High precision resolution (exact freq.)
  - Large signal power, could be beneficial in overcoming noise during initial verifications
  - Can test the coherent standing waves formed between the reflector and a horn antenna
- **Cons:**
  - Narrow spectral range, time in-effective
  - Requires precise alignment, which could be difficult in-situ
  - Costs

Discussed in BREAD paper [link]

NB: A table top room-temperature spectrometer at UChicago is available to characterize sources and filters [link].

Other THz Sources (proposed in InfraBREAD IF/THz)

Bandpass-filtered blackbody source:

- Inject photons via a small hole in the barrel (in BREAD) for in-situ photosensor's detection efficiency and the overall system's response. Also modelled directly above focus for InfraBREAD
- **Pros:**
  - Broadband Flexibility: using different filters can provide calibration across large freq.
  - Good coupling options: generally easier than laser integration. Simple set up
  - Helpful for finding "true" focal point of detector within 50µm in axial direction [MURAJ]
- **Cons:**
  - Limitations on frequency precision from filters, not tunable
  - Lower signal power (maybe not a con)
  - Slower on/off. Larger body so harder to get uniform temp.
  - Heat load considerations (15-40K vs 10mK)

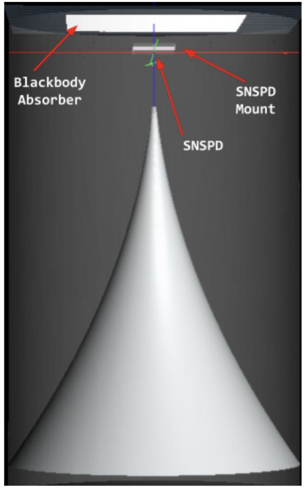

Figure 5: A scale model of the blackbody-based calibration method implemented in FRED Optical Engineering Software. The blackbody emitter, SNSPD, and SNSPD mount are labeled accordingly. Although not directly visible in the image, the SNSPD sits in the center of the bottom surface of the SNSPD mount.

Proposed/modelled in InfraBREAD [CPPC seminar,, MURAJ, SK]

NB: A table top room-temperature spectrometer at UChicago is available to characterize sources and filters [link].

Discussed in BREAD paper [link]

Other THz(?) Sources (used in GigaBREAD)

monopole pin antenna (GigaBREAD is IF/THz range)

- Current Methods: It uses a monopole pin antenna inserted in front of the conversion surface to inject blind test signals at specific frequencies.
- Antenna Calibration: A vector network analyzer (VNA) is used to calibrate the horn antennas axial position based on reflection measurements.
- Validation: It validates measurements by comparing the DAQ/amplifier chain output against reflectivity measurements done with a network analyzer.

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Other THz Sources

Safumi Suzuki and Masahiro Asada 2024 Appl. Phys. Express 17 070101

Frequnecy Multiplers

- FMs(such as Schottky diode-based doublers or triplers) can be used as calibration sources by changing microwave sources into the THz.
- Typically high-precision microwave synthesizer generating signal → passed through a chain of multipliers → desired "calibration photons" for injection.
- A frequency multiplier typically uses a non-linear component, such as a Schottky diode, to distort an incoming microwave signal. This distortion generates higher-order harmonics. By using waveguides and filters, a specific harmonic (e.g., the 2nd harmonic for a "doubler" or 3rd for a "tripler") is isolated to be used as the calibration source.
- Pros:
  - High precision frequency
  - Cost
  - Tunability: output can be swept across a broad range of frequencies
  - High power (maybe not a pro)
- Cons:
  - Complexity: requires RF chain, delicacy in multipliers operating in the high THz range often use fragile "whisker-diode"
  - Conversion Loss: Multipliers are relatively inefficient; each stage of multiplication results in a significant loss of power (typically 10–15 dB), resulting in very faint signals at high THz frequencies.

Simulations

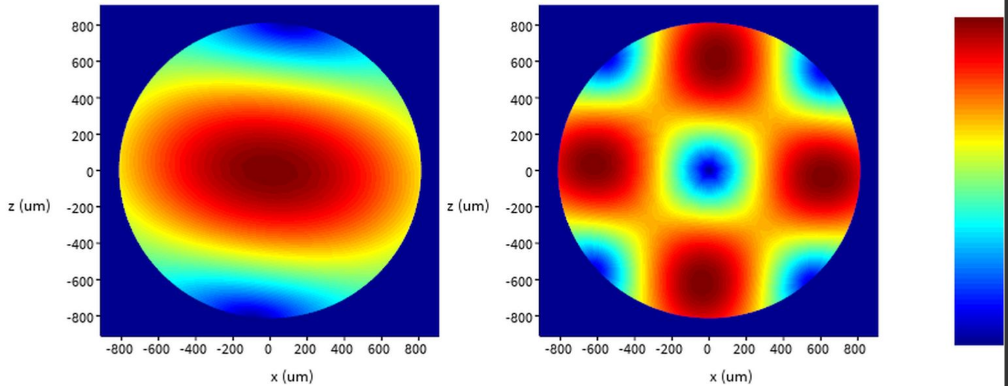
FEEM: Finite Element Eigen Mode, FDTD: Finite Difference Time Domain

Simulations started with Ansys Lumerical [website].

Example: Modal and transmission analysis of THz in waveguides using the FEEM & FDTD solvers.

- FEEM pros: determinations of loss, effective index, and EM-fields in a 2D cross-section of our waveguide across a range of modes at a given frequency.
- Used in conjunction with FDTD's Modal Expansion Monitor to explore transmission behavior across variable-sized vacuum gaps between consecutive waveguides.

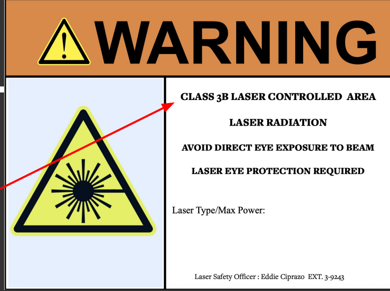
Additional simulations will explore:
Waveguide bending radii & filters.



FEEM Visualization of the first (TE_{11}) and fourth (TE_{21}) transverse electric modes of a 1.6mm diameter copper waveguide carrying 1 THz frequency light.

Lead by Brennan Coffey (UC Berkeley)

PRINCIPLES OF OPERATION

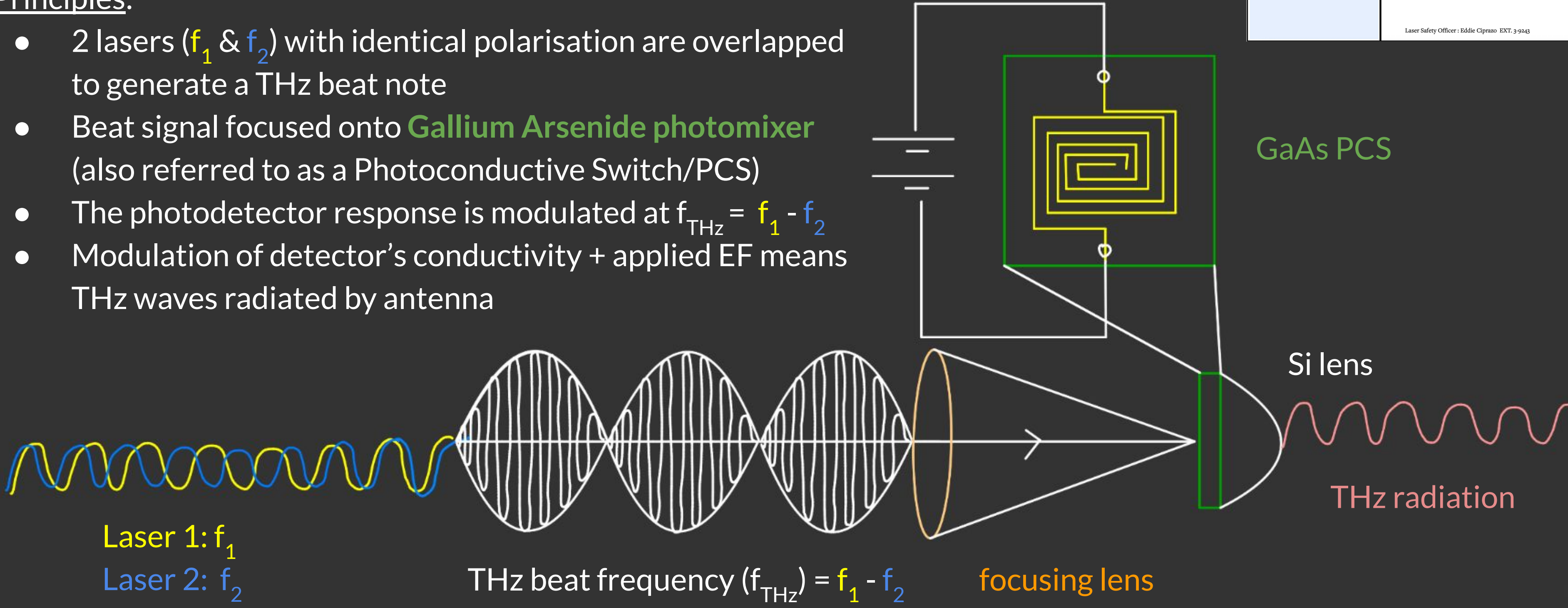


High frequency photomixing to generate and detect THz radiation.

CLASS 3B LASER CONTROLLED AREA

Principles:

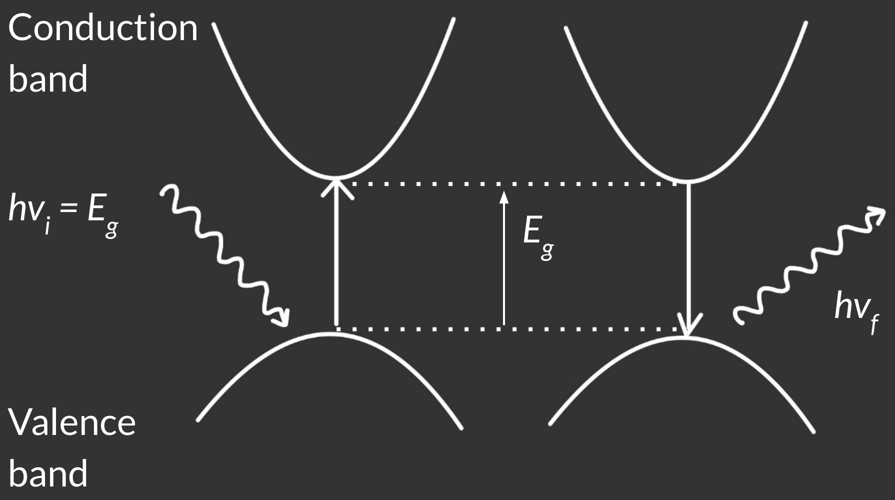
- 2 lasers (f_1 & f_2) with identical polarisation are overlapped to generate a THz beat note
- Beat signal focused onto **Gallium Arsenide photomixer** (also referred to as a Photoconductive Switch/PCS)
- The photodetector response is modulated at $f_{THz} = f_1 - f_2$
- Modulation of detector's conductivity + applied EF means THz waves radiated by antenna

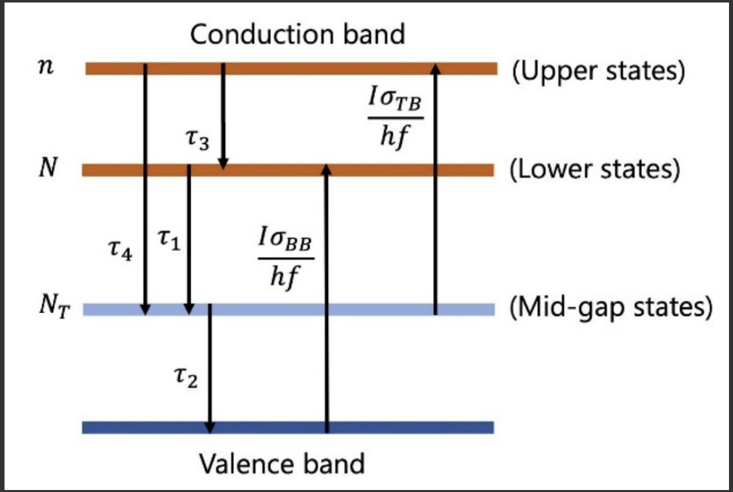


HOW PCS's WORK

Photoconductive switching:

- The photons from the combined laser beams are absorbed by the LTG-GaAs semiconductor, generating electron-hole pairs
- LTG-GaAs a very short carrier lifetime
  → generation and recombination of charge carriers is quick
  → enables electrical conductivity to oscillate with the beat freq.





L N F Dela Rosa et al 2024 Semicond. Sci. Technol. 39 075010

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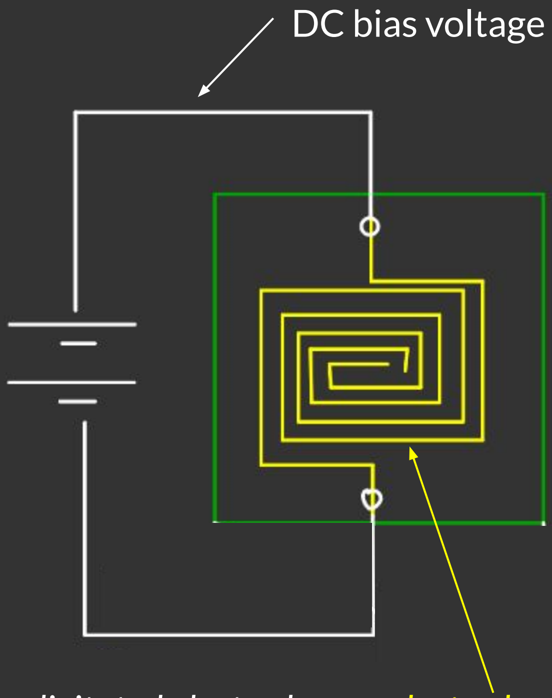
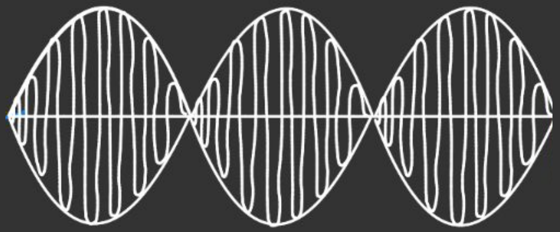


Photocurrent generation:

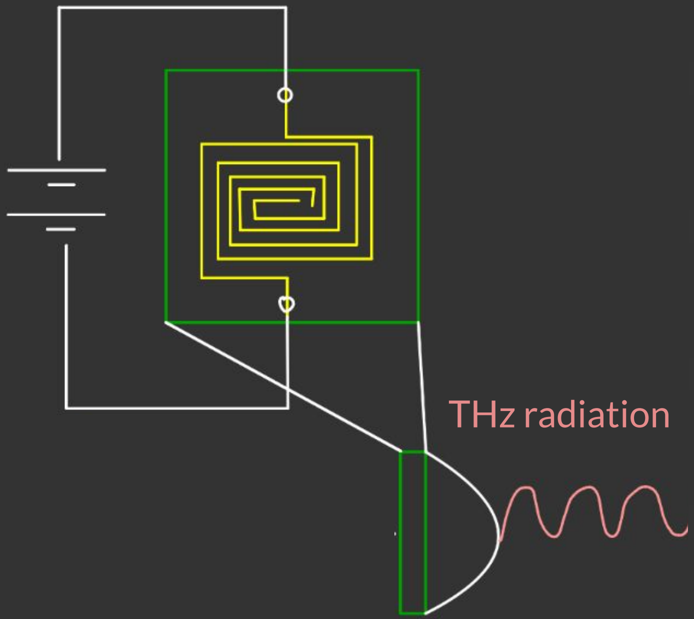
- DC bias voltage applied to the interdigitated electrodes* drives charge carriers, creating a photocurrent.
- Because the # carriers is modulated at the beat freq (f_{THz}), the photocurrent also oscillates at f_{THz}



THz beat frequency (f_{THz}) = $f_1 - f_2$

interdigitated electrodes are electrodes with a "finger locked" pattern. Provides a high surface area in a small volume, ideal for sensing applications.

HOW PCS's WORK



Photoconductive switching:

- The photons from the combined laser beams are absorbed by the LTG-GaAs **semiconductor**, generating electron-hole pairs
- LTG-GaAs a very short carrier lifetime
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  → enables electrical conductivity to oscillate with the beat freq.

Photocurrent generation:

- DC bias voltage applied to the interdigitated electrodes* drives charge carriers, creating a photocurrent.
- Because the # carriers is modulated at the beat freq (f_{THz}), the photocurrent also oscillates at f_{THz}

THz radiation:

- Photocurrent travels to the integrated antenna, which converts the electrical current into a corresponding electromagnetic wave at the terahertz frequency.
- The antenna radiates this signal into free space, and a silicon lens is attached to the back of the device to improve signal coupling.

HOW DO WE DETECT THZ?

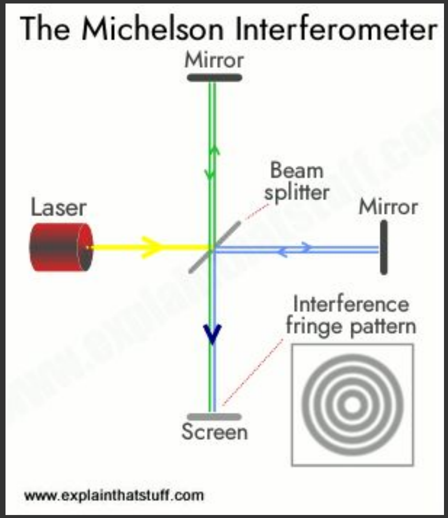
- The THz system uses a **coherent detection technique**

	Coherent	**Incoherent**
Signal inputs	Amplitude (A) & phase (ϕ) - measures the entire complex amplitude	Intensity (I) & power (P)
Operating principle	Involves a receiver that uses a local oscillator (a laser) that is synchronized with the phase and frequency of the original transmitted signal & mixes the 2.	The receiver does not need to synchronize with the transmitted signal phase. It detects the signal based on its magnitude or power. Does not detect phase changes
Advantages	**Noise cancelling**, greater sensitivity, retains phase information	Simplicity, bulk deployment (low cost), more robust
Applications	Air traffic control radar and long-haul fiber-optic communication	Navitagation, radar detection

HOW DO WE DETECT THZ?

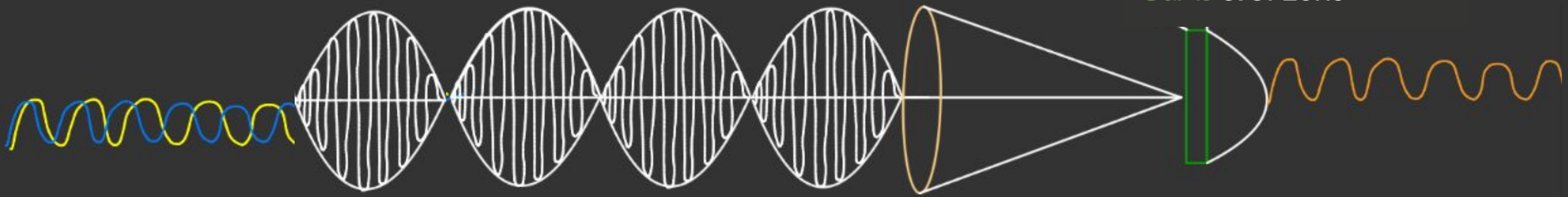
How is coherent detection achieved with the THz system?

- **homodyne detection:** same combined laser beam sent down a longer optical path to detector PCS onto which the THz signal is incident



Basically an interferometer!

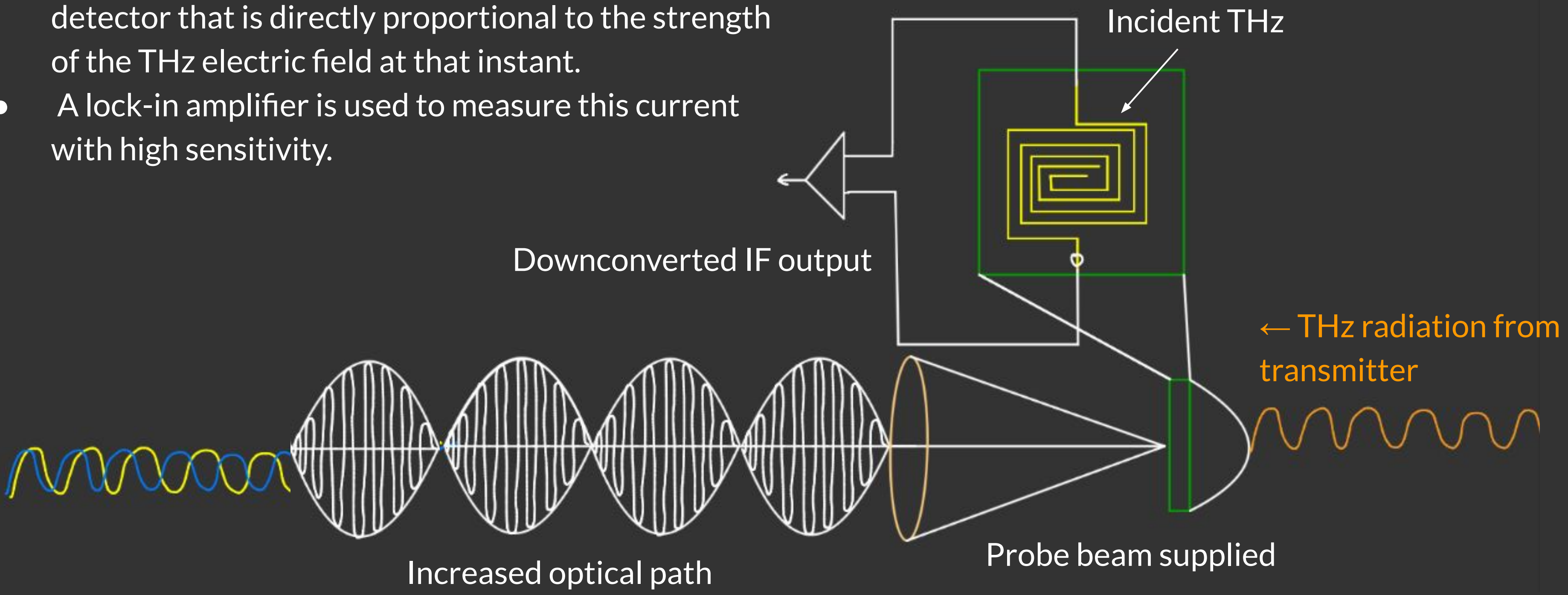
- **Light Source**: A light source, often a stable laser, provides the light.
- **Beam Splitter**: division of light into 2 beams: a probe beam and a test beam.
- **Optical Paths:** The probe beam travels a longer fixed path. The test beam travels along a path that is changed (by distance)
- **Interference Pattern**: Waves recombined producing interference pattern of bright and dark fringes.



HOW DO WE DETECT THZ?

Similar to before...

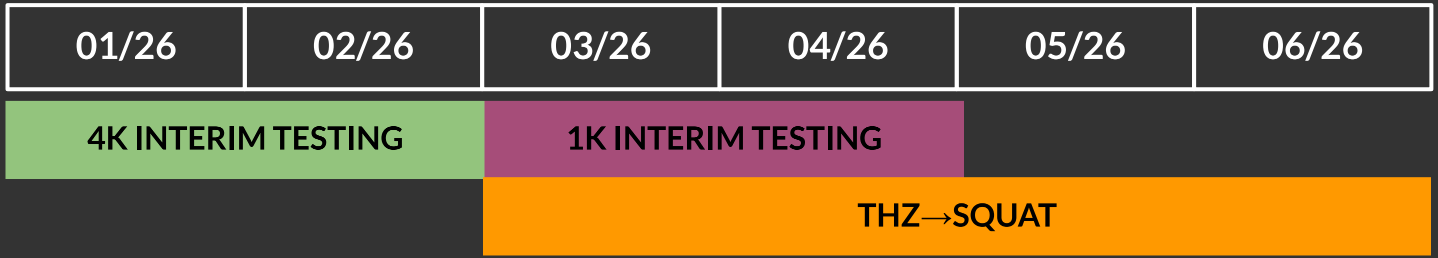
- Probe beam causes electron-hole pairs to be generated as before
- But this time these charge carrier are accelerated by the incident THz radiation
- This acceleration produces a small current in the detector that is directly proportional to the strength of the THz electric field at that instant.
- A lock-in amplifier is used to measure this current with high sensitivity.



OTHER CALIBRATION METHODS

Method	Description	Pros	Cons
THz calibration system	Supply THz via photomixing directly to SQUATs at cryogenic temperatures	Directly supplying signal you want to measure. Broadband, robust Crogenically compatible (starts in fridge)	R&D needed for design, expensive
Josephson junction injectors	JJ controlled by a current circulated through two or more attached microinjectors. This allows for manipulation of the junction's energy profile.	High sensitivity, exact manipulation Crogenically compatible (starts in fridge)	Modelling complications/extensive amount required because of spread of JJ prop (critcal current). Not tunable
Filtered black bodies	They can incorporate filters that precisely shape the spectral output of the blackbody to mimic or isolate specific types of noise, as seen in this AIP article.	Reproduction of noise profile Crogenically compatible (starts in fridge)	Slower on/off. Not tunable
Frequency multipliers	Involve calibrating microwave components to generate higher, precise frequencies for qubit control	Minimal hardware, cost reduction. Also supplying signal here	frequency multiplication is that the phase noise of the input signal is also multiplied by the same factor

Timeline of R&D



4K INTERIM TESTING:

- Installation of THz system in LD400 and initial room & cold temperature testing/alignment

1K INTERIM TESTING:

- Modification of existing 4K set up (waveguide etc.)
- Room & cold temperature testing/alignment
- Understand feasibility of 1K emitter positioning

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Roll off at higher frequencies?

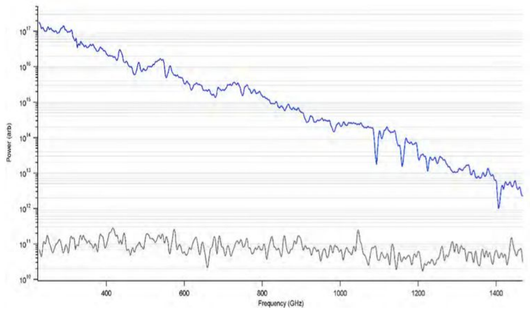

Figure 1.1.6: The data from the previous scan with a 60 point smoothing function applied to remove the interference pattern and shows the absorption features.

Photocarrier Lifetime:
When the THz frequency exceeds the reciprocal of the carrier lifetime, the material cannot respond fast enough. Results in a power drop

Parasitic Capacitance Capacitive Shunting:
Electrodes and substrate have inherent capacitance. At high frequencies, this capacitance acts as a short-circuit, diverting current away from the radiating antenna. Creates a fundamental frequency ceiling.

[Bakman Laser Technologies]

Optical Constraints: Antenna
Integrated antennas are usually optimized for a specific range

Emily Perry (eaperry@lbl.gov)

A Cryogenic THz Calibration System for Ultra-Sensitive Sensors: Design and Initial Tests

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Motivation

Delivering **broadband THz photons** into a cryogenic environment is a critical calibration challenge for THz/meV detectors, as fiber optics absorb THz radiation and tunable sources are limited. We are developing a system to **calibrate cryogenic THz/meV detectors** using hollow circular waveguides.

Our labs work on Superconducting Quasiparticle-Amplifying Transmons (SQUATs), which are sensitive to **single THz photons and meV phonons** by detecting tunneling events through readout of the qubit transition frequency. (Fig. 1)

The successful integration of THz photons with superconducting qubits would significantly enhance the sensitivity of **dark matter searches**, and could be used directly in experiments such as the Broadband Reflector Experiment for Axion Detection (BREAD), which will search for **low-mass axions**. (Fig. 2)

Here, we report progress toward a full-system setup to validate photomixer performance and test waveguide transmission in a 4K cryostat.

SQUAT Design

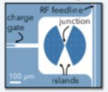


Figure 1 [1]

BREAD Schematic

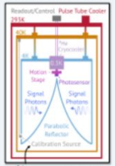


Figure 2 [2]

THz Photomixers

Bakman Technologies PB7300 Spectrometer

- Tunable, high-resolution, broadband (**0.1 – 1.9 THz**)
- Can be used to deliver THz photons to our SQUAT detectors
- Warm system used for Cu waveguide & filter characterization
- Cold system being prepped for cryogenic operation (Fig. 3)

	Warm Photomixers	Cold Photomixers
Operation Temperature	293 K	4 K
Si Lens Diameter	12.8 mm	10 mm
Si Lens Thickness	7.75 mm	7.3 mm
Si Lens Shape	Hyper-hemisphere	Hyper-hemisphere
Photomixer Thickness	0.5 mm	0.5 mm
Photomixer Spot Size	20 μm	20 μm
Beam Profile	Divergent 15° full	Collimated 6 mm FWHM

Preparing for Cryogenic Operation

Short Term Goal: Cryomixer Performance Validation

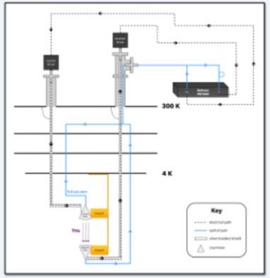


Figure 3: Experimental setup for testing photomixer performance in a 4K cryostat

Long Term Goal: SQUAT Calibration

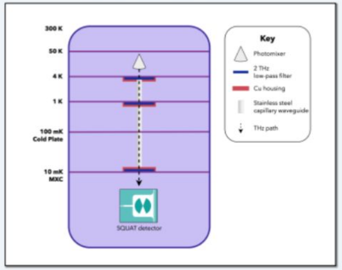
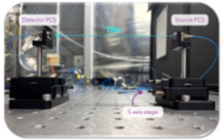
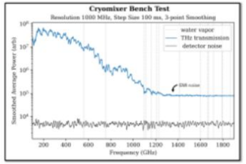


Figure 4: Calibrating SQUAT detectors in a dilution refrigerator

Results: Bench Testing Transmission



Cryomixer bench test setup with v1 cryomixer mounts.



Objective

- Validate room temperature performance of cryogenic photomixers

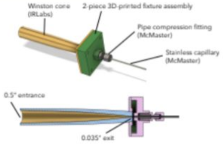
Results

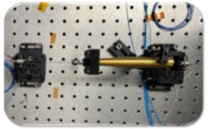
- Higher frequency signal (>1.2 THz) drops below electromagnetic interference (EMI) noise floor

Design Requirements

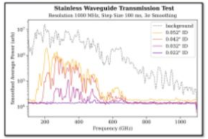
- Better shielding of electronic components to prevent pickup

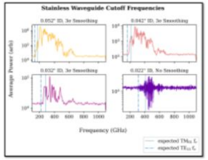
Results: Stainless Steel Capillary Waveguides





Experimental setup. Foil was placed in front of the detector to block stray THz radiation.





Winston Cone

- Concentrates incoming THz radiation to 0.035" exit diameter (non-imaging)
- High angular acceptance, though tip/tilt alignment is necessary

Results & Conclusions

- Successful transmission through waveguides
- Cutoff frequencies match expected values
- Drop in attenuation with ID likely due to misalignment

Design Requirements

- Optimal transmission across all frequencies will require some tip/tilt adjustment
- Full transmission not needed for calibrating low-threshold single photon detectors

Future Work

Finalize Cryomixer Mount Design

- Incorporate tip/tilt and translation
- Protect fragile Si lens without blocking beam

Continue Waveguide Characterization

- Break tests, loop radius tests

Improve Electromagnetic Interference Shielding

- Increase SNR at higher frequencies

v2 Cryomixer Mount

Grand Vision

- Use as reliable source for superconducting detectors (SQUATs and beyond)
- Explore other applications, e.g. Probe far-Infrared Mission for Astrophysics (PRIMA) telescope (1.3 – 12.5 THz) [Moullet 2023]

References

1. Superconducting quasiparticle-amplifying transmon: A qubit-based sensor for meV-scale phonons and single terahertz photons, Phys. Rev. Applied 22, 054009 (2024)
2. Broadband Solenoidal Haloscope for Terahertz Axion Detection, Phys. Rev. Letters 128, 131801 (2022)

Acknowledgments

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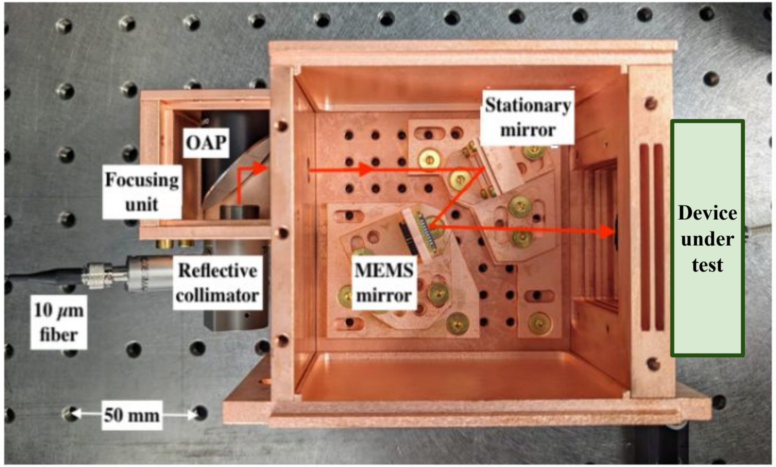
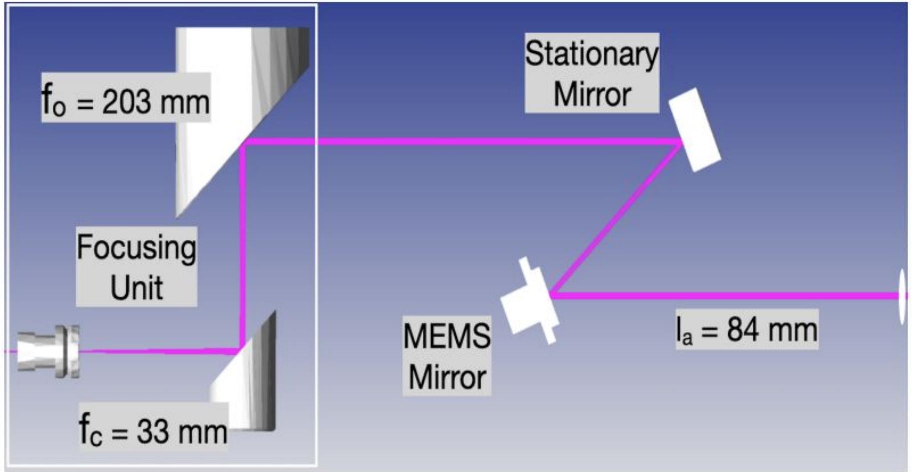
Slide from Sidney Stevens (link)

MEMS operation principle:

Light source → Custom focusing unit → steerable MEMS mirror → device under test





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