Argonne NATIONAL LABORATORY

Development of Superconducting Detectors for X-ray Science

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Accelerator & Detector Research and Development Program PI Meeting
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U.S. DEPARTMENT OF ENERGY

Outline

- Why Superconducting Detectors?
- Overview of SC Detectors
  - Transition Edge Sensors
  - Superconducting Tunnel Junctions
  - Resonator based detectors
- Microwave Kinetic Inductance Detectors
  - A path towards higher count rates and larger solid angle coverage.

Superconductors Detectors for APS Detector R&D- Why?

- **Detector R&D is heavily focused on pixel array detectors**
  - Crowded field (PSI, Cornell, BNL, FNAL, etc.)
  - APS/ANL is at a significant legacy disadvantage.
- **Limited R&D on spectroscopic/fluorescence detectors**
- **Leverages local facilities and existing projects.**
  - ***This is a long-term R&D project aimed to develop a unique and competitive R&D program at the APS.***

What are the applications for this type of detector?

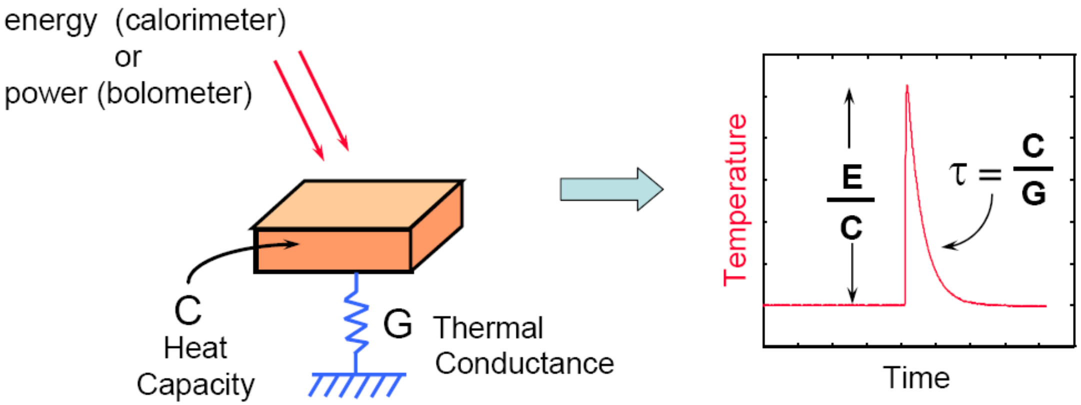
- **X-ray absorption fine structure (XAFS)**
  - Allows broadband and efficient measurement compared to crystal analyzers.
  - Sub-band fluorescence lines ($K\alpha_1$ and $K\alpha_2$ or $K\beta_1$ and $K\beta_5$)
    - Spin-dependent XAFS studies.
- **XRF: fluorescence line overlap in complex biological samples**
  - X-ray Fluorescence Tomography
- **Energy Dispersive XRD**
  - **If we can make thick absorbers, this could be potentially interesting, but this is a long shot.**
- **At the end of the day, detector must work reliability and be user-friendly.**

Two major classes of Superconducting Detectors

- Thermal Detectors (i.e., Transition Edge Sensors)
- Quasiparticle Detectors

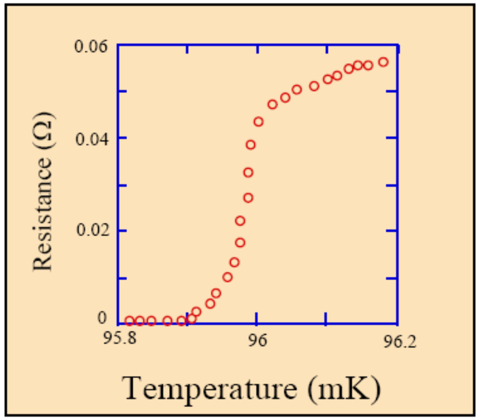
Transition-Edge Sensors (TES)

Thermal sensors

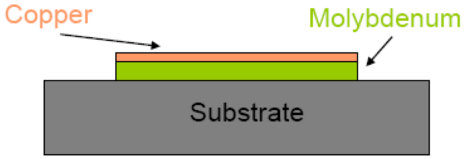


1/e response time =
100 μs - 1 ms

- Transition-Edge Sensor (TES) = thin-film biased in superconducting-normal transition
- Use strong dR/dT in transition as thermometer

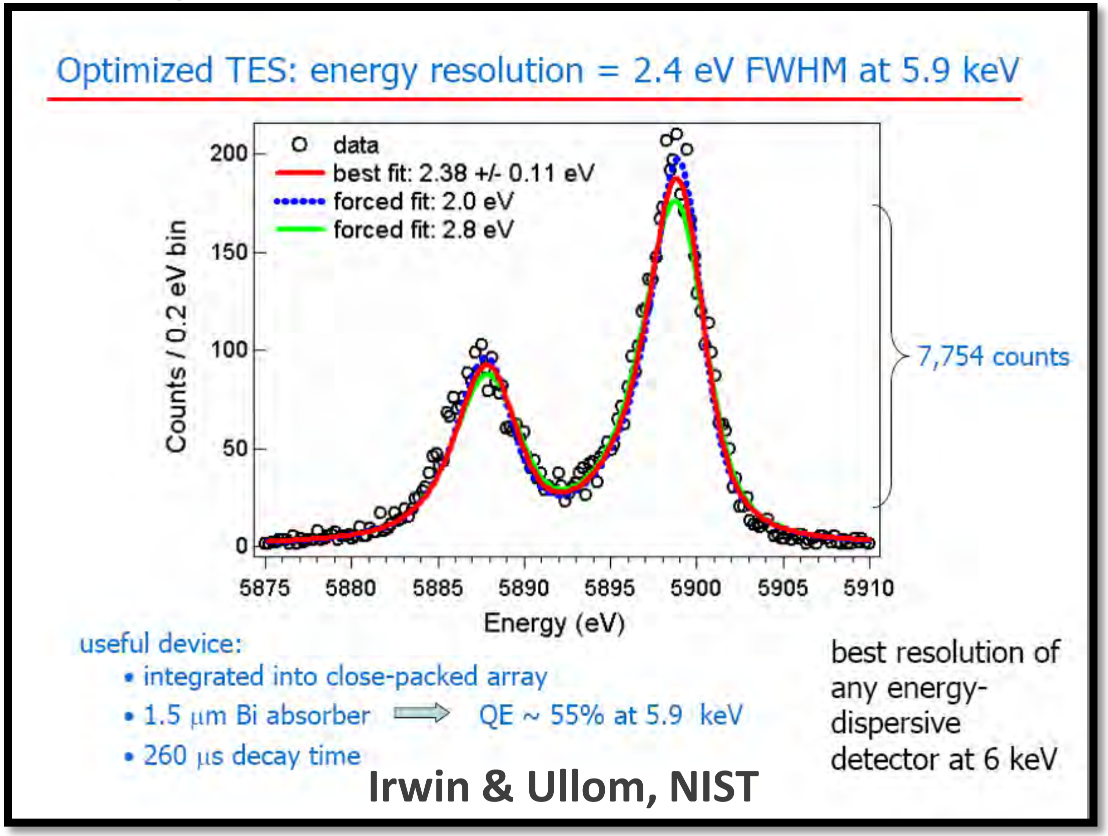


- molybdenum-copper:
  robust and temperature stable
  Molybdenum $T_c \sim .92$ K
  Copper normal



Kent Irwin, NIST

Transition-Edge Sensors (TES)



- TES have the best energy resolution (not Fano limited)
- However, TES require relatively complex cryogenic electronics which makes multiplexing difficult.

TES array at NSLS (NIST Beamline)

LTD-13 2009 Stanford

A soft-X-ray TES spectrometer for the National Synchrotron Light Source

P 175

NIST

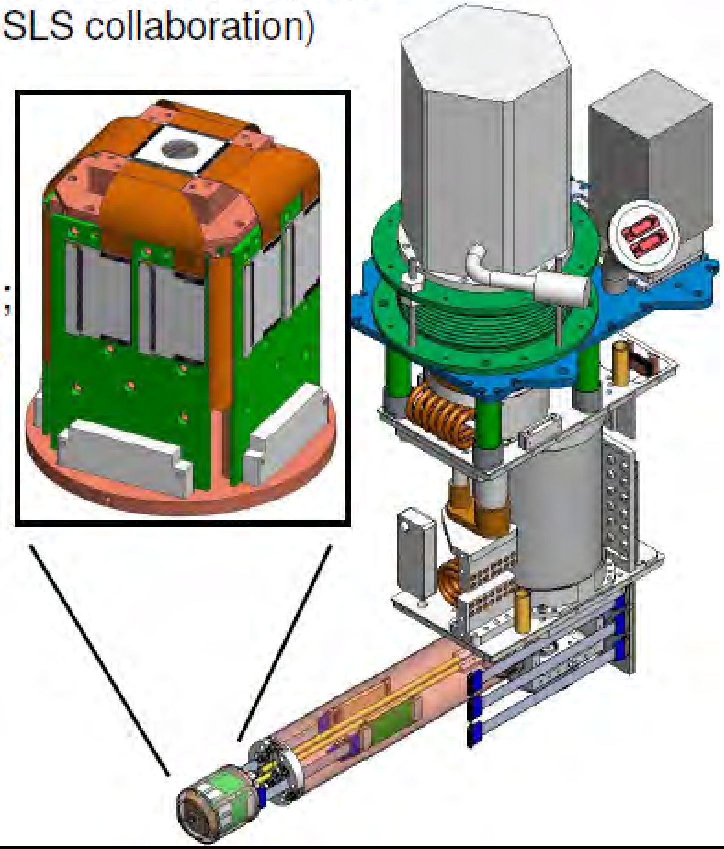
Randy Doriese *NIST, Boulder, CO, USA*
(for the NIST/NSLS collaboration)

Applications:

- XAS
- XES
- combined: DOS measurements; unoccupied *and* occupied states

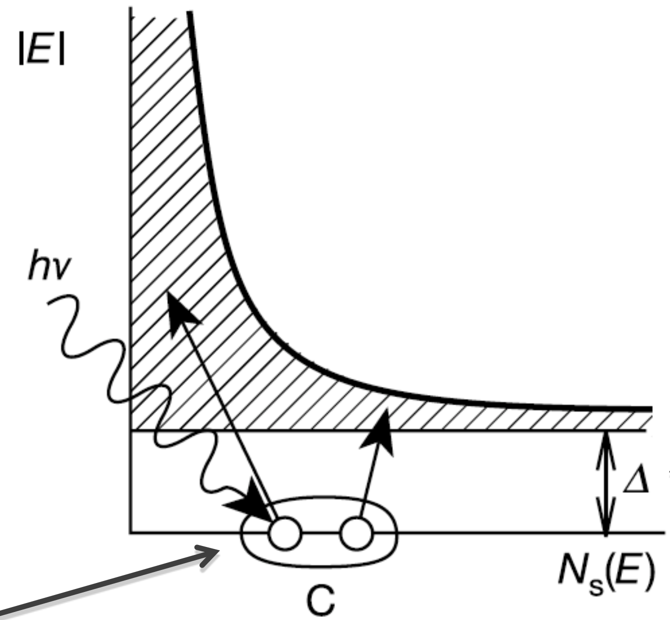
Proposed specifications:

- 256 pixels
- 200 – 1500 eV energy range
- ΔE_{FWHM} ~ 1 eV
- 10 mm^2 total collecting area
- ~ 25 kHz total count rate



Quasiparticle detectors

- Use small Superconducting Energy Gap
- Break Cooper Pairs
- Use Cooper Pairs as detection mechanism (like electron hole pairs in a semiconductor)



Silicon Energy Gap: 3.67 eV

SC Energy Gap

- Tantalum: 0.67meV

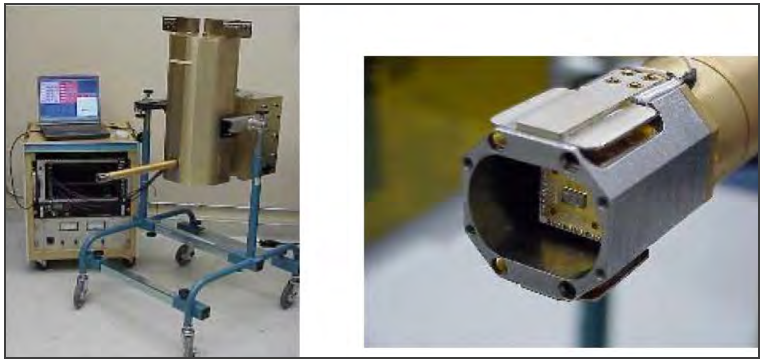
Cooper Pair

Theoretical Resolution

$$R = \frac{1}{2.355}\sqrt{\frac{\eta h\nu}{F\Delta}}$$

How can the excess of quasiparticles be sensed?

- **Superconducting Tunnel Junctions**
  - Measure changes in the tunneling current across a thin oxide barrier between two superconducting electrodes **(i.e., Josephson junction)**
    - Both Copper Pairs and quasiparticles tunnel
      - Copper Pair tunneling is suppressed with a magnetic field.
    - Excess quasiparticles from X-ray result in a current pulse. (Room temp. current amplifiers)
  - **Dedicated soft x-ray STJ array at ALS ABEX beamline (Friedrich et al)**
    - 36-element (Total area ~ 1.44 mm2); Solid Angle ~ 10-3
    - ~15eV at 1keV
    - Maximum Count rate ~ 1MHz



  - **Challenges:**
    - Tunnel junction fabrication is non-trivial
    - No clear multiplexing scheme.
      - Important since single pixels have limited size
        - » Limited by quasiparticle mean free path!!
          - » e.g., Tantalum ~ 250 microns.

An Alternative to STJs ---
Microwave Kinetic Inductance Detectors

Consider the electrodynamics of superconductors…..

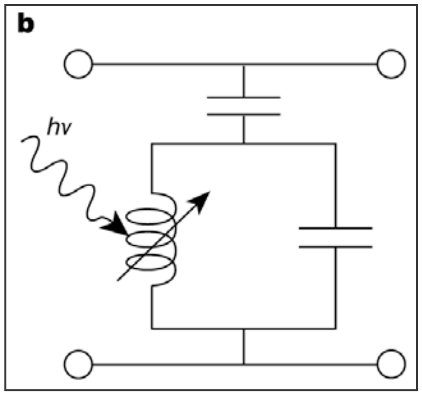
- Superconductors have zero resistance for DC currents, but finite impedance for AC currents
- Consider an AC electric field applied near a superconductor's surface
  - Energy is required to accelerate or decelerate Cooper pairs in a superconductor → extra inductance → "kinetic inductance".
  - More generally, results in a complex surface impedance (or complex conductivity)
    - $Z_s = R_s + i\omega L_s$
      - R_s → surface resistance from thermally generated quasiparticles
      - However for $T \ll T_c$, $\omega L_s \gg R_s$ (Primarily inductive effect)

➢ **Mattis-Bardeen theory → changing the population of Cooper pairs by breaking them with photons changes the kinetic inductance** (or more generally the complex impedance or conductivity)

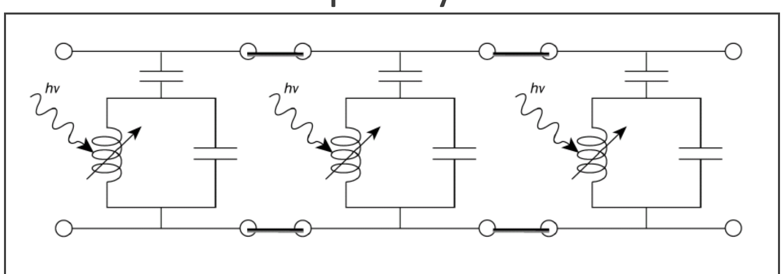
But how do you multiplex?

Microwave Kinetic Inductance Detectors

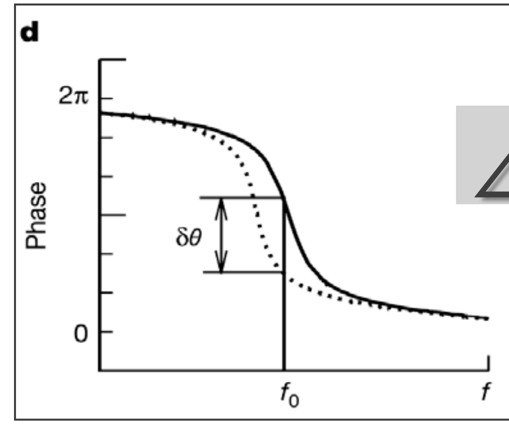
- Multiplex using microwave resonators
- Total Inductance is Geometric + Kinetic



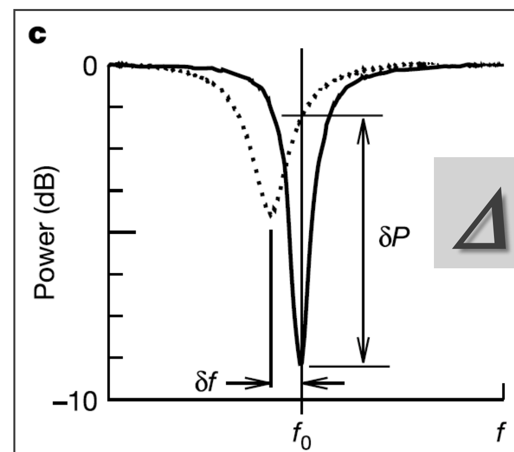
Lithographically vary geometric inductance/resonant frequency…



Observables….



ΔL_s



ΔR_s

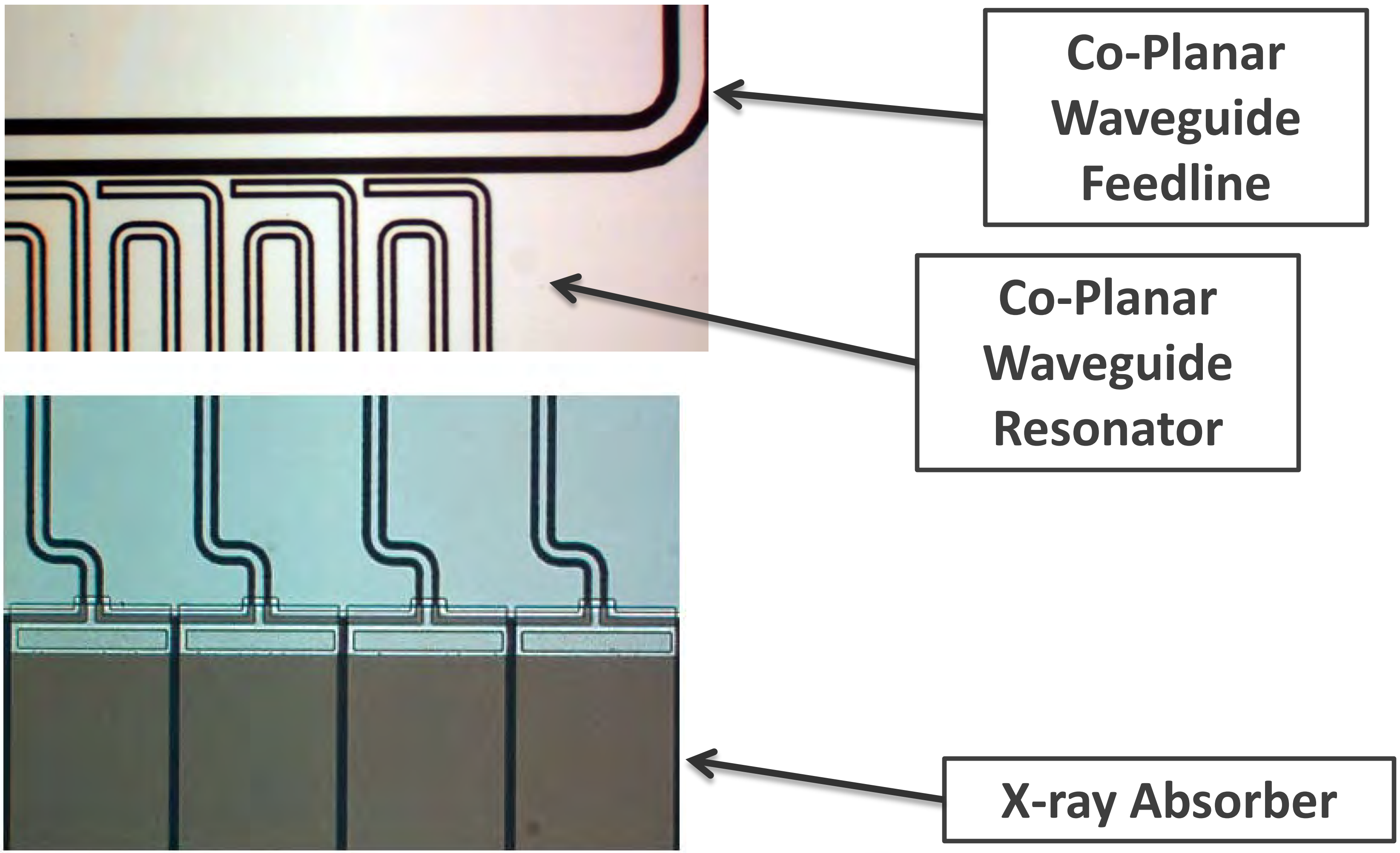
Ben Mazin et. al.

UCSB
University of California, Santa Barbara

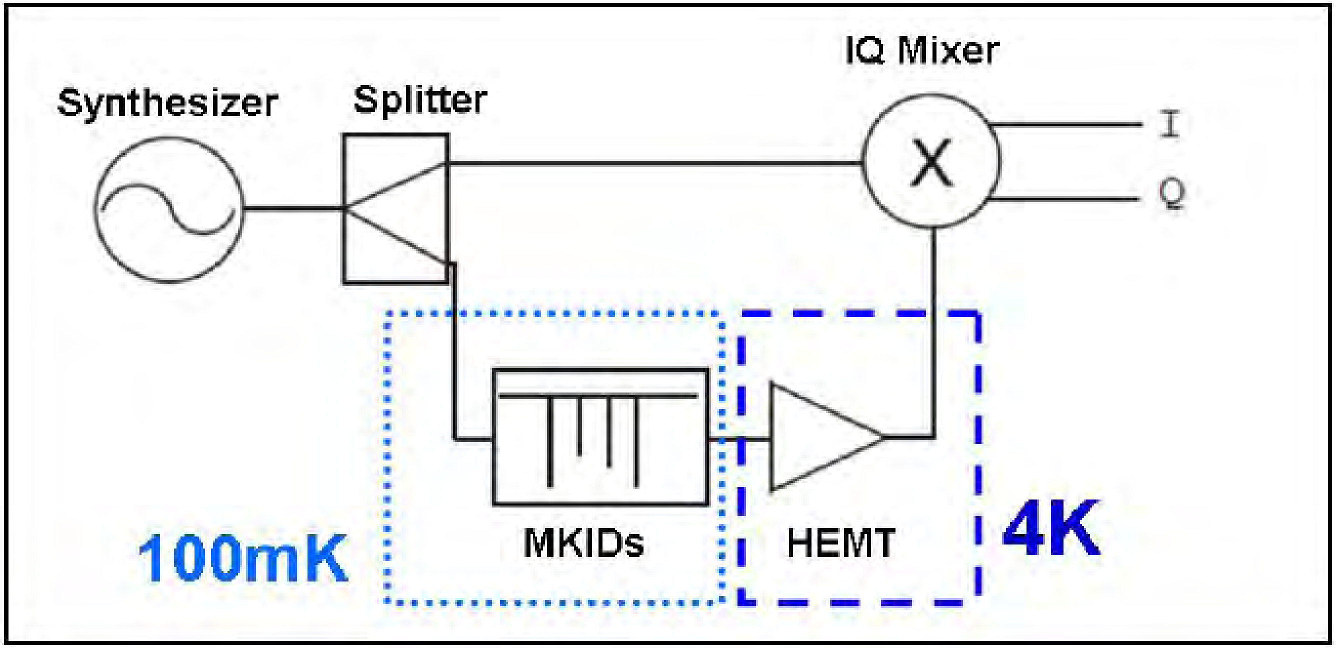
JPL
Jet Propulsion Laboratory
California Institute of Technology

‘Microwave’ refers to the readout frequency! (e.g., 3-10 GHz)

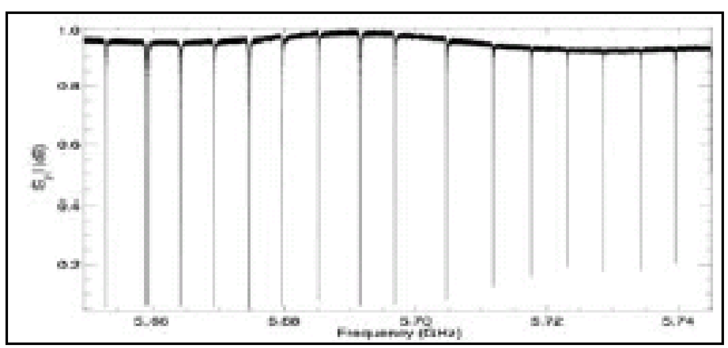
Anatomy of an MKID



MKIDs – Readout Scheme



Multiplexing is main advantage of MKIDs over STJs and TES



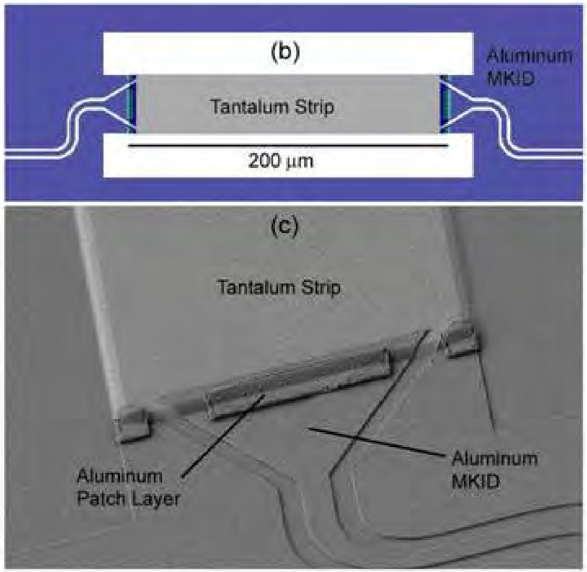
Should be able to readout ~4000 pixels

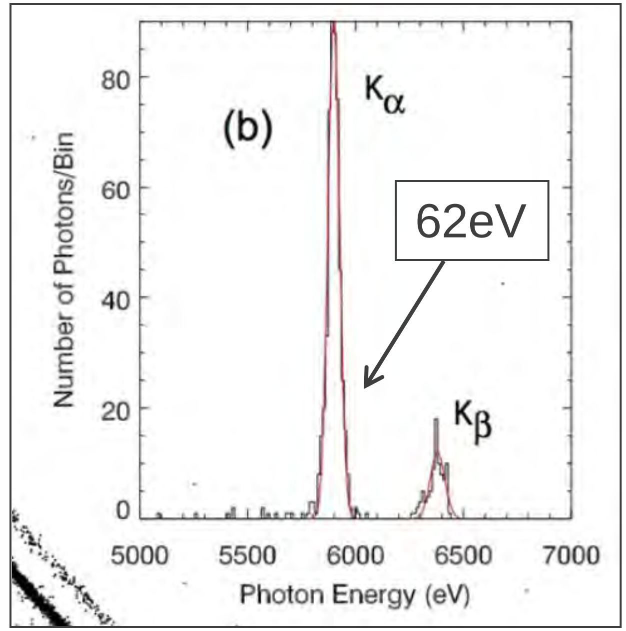
MKIDs – Count-Rate

The maximum count rate is roughly the inverse of the combined quasiparticle lifetime in the absorber (τ_a) and the resonator (τ_r).

- Rise time → Absorber diffusion time
- Fall time → Quasiparticle lifetime in the resonator
- e.g., tantalum absorber and aluminum resonator
  - **Measured lifetimes are: τ_a ~ 40 μs and τ_r ~ 190 μs (Mazin et al 2006)**
  - **This yields a maximum count rate of ~ 4000 Hz per element.**

What has been shown already?





Mazin et al 2006

Table 1: Fano Limits for Various Absorber Materials

Material	Atomic Number Z	Transition Temperature	Theoretical Energy Resolution at 6 keV	Attenuation Length at 6 keV
Lead	82	7.2 Kelvin	3.53 eV	1.86 μm
Tantalum	73	4.5 Kelvin	2.79 eV	1.79 μm
Tin	50	3.7 Kelvin	2.53 eV	2.60 μm
Indium	49	3.4 Kelvin	2.43 eV	2.77 μm
Rhenium	75	1.7 Kelvin	1.72 eV	1.31 μm
Molybdenum	42	.92 Kelvin	1.26 eV	2.94 μm
Osmium	76	.66 Kelvin	1.07 eV	1.18 μm

How Cold?

- **Want to operate T ~ T_c / 10 ~ 100mK**
  - Minimize quasiparticle recombination noise
- **How?**
  - Adiabatic Demagnetization Refrigerator (ADR) (dry)
  - Fixed hold time (~4 days hours, 2-3 hour recycle time)
    - Relatively simple cryogenic wiring (2 coax cables)
    - Challenge is to position detector as close to outside world as possible.

MKIDs @ Argonne for synchrotrons

- The goal is moderate energy resolution (< 20eV) with good count rate capabilities (> 200kcps)

- Leverages Argonne's micro/nano-fab facilities (CNM) and superconductivity expertise (MSD); Astronomical TES bolometer program(MSD & UChicago); and the APS RF expertise.

- Three Main Aspects:
  1. **Device Fabrication**
     - Fabrication is completely in-house
     - Relatively "simple"… patterning of metal (deposition, photolithography, etching)
       - Film quality is very important!
     - Initially aim a simple device, then progress to more complex designs (e.g., membrane-suspended)
  2. **Cryogenics and Device Characterization**
  3. **Readout electronics**
     - Initially the analog readout for characterization, then to FPGA-based array readout.

Conclusions

- Superconducting detectors have a place at synchrotrons.
- Superconducting detector development has started at the APS.
- MKIDs are a path towards high count rates and higher solid angle coverage.

Acknowledgements

- Tom Cecil
- Orlando Quaranta
- Lisa Gades
- Ben Mazin (UCSB)
- MSD Crew (TES development for astro)
  - Val Novosad (MSD)
  - Aaron Datesman (MSD)

Extra Slides

MKIDs – Speed and Resolution

G Vardulakis *et al*

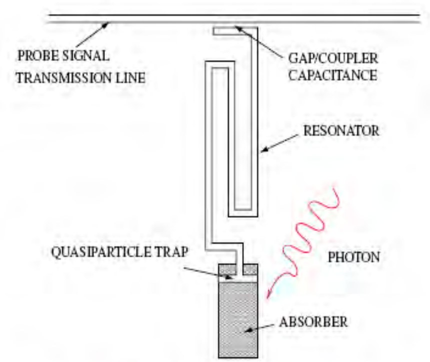
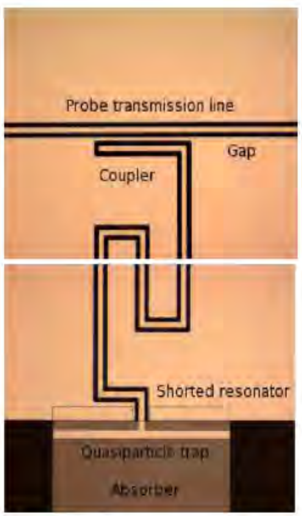
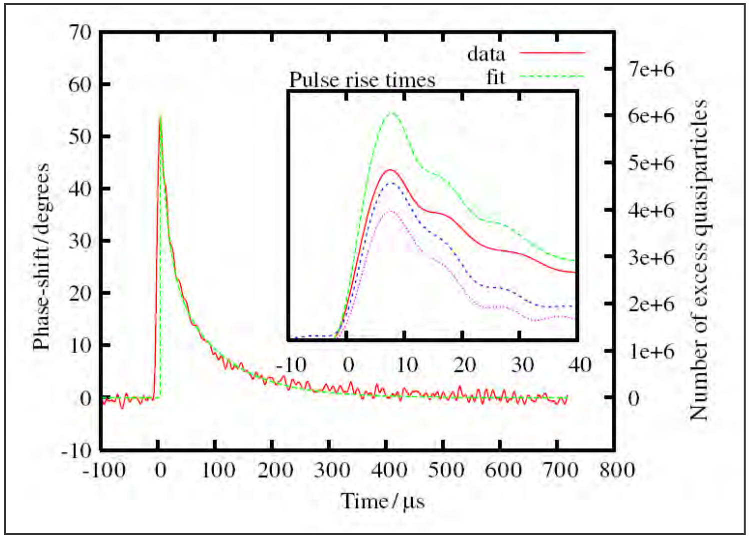
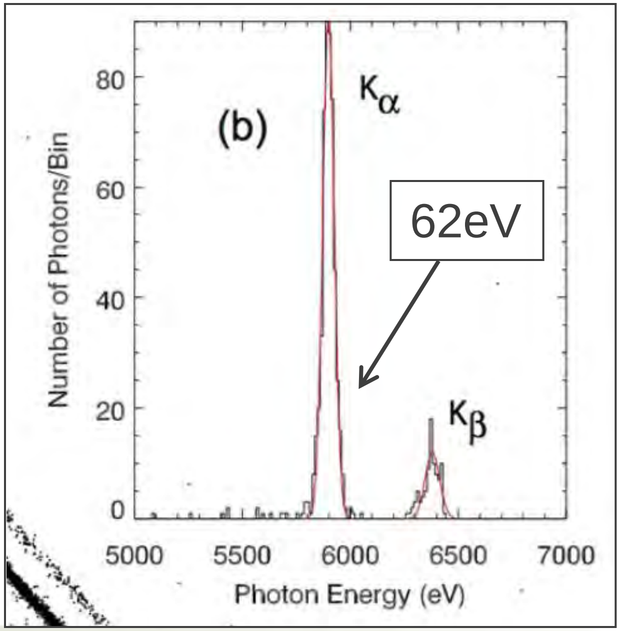


Figure 3. Schematic of a kinetic inductance detector (KID).



G Vardulakis *et al* Meas. Sci. Technol. **19** (2008) 015509





Mazin et al 2006

Quasiparticle Generation - A Cascade Process

Incoming Photon → absorbed, ionizing atom and releasing inner-shell electron

1. **First Stage:** **Rapid energy down-conversion (electron-electron interactions → secondary ionization and cascade plasmon emission)**
   - e.g. 10keV photoelectron down-conversion to a thermal population of electrons and holes at a characteristics energy ~ 1eV takes 0.1 ps (Kozorezov et al)
   - 1st stage ends when electron-phonon inelastic scattering rate dominates electron-electron interactions.
2. **Second Stage:** **~ 1eV down-convert to large number of Debye energy phonons**
   - Energy of phonon distribution exceeds energy of electron distribution
   - Debye energy of superconductors is larger than SC gap energy
   - Phonons with energy > 2 Δ will generate quasiparticles.

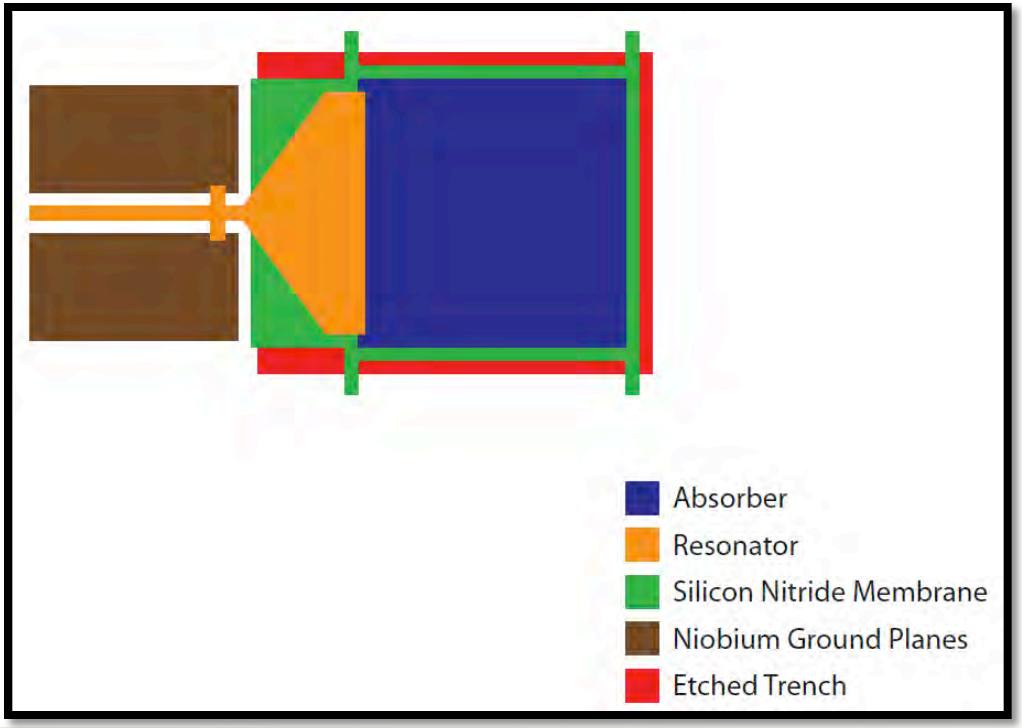
Finally, we have a mixed distribution of quasiparticle and phonons:

- $N_{qp} \sim E_{photon}/\Delta$
  - **But scaled down because large percentage of photon energy stays in the phonon system**
    - **For Tantalaum, 60% energy resides in qp system. (Kurakado) (Efficiency → η)**
      - $N_{qp} = \eta h\nu/\Delta$
      - **At 6keV and Ta absorber, Δ = 0.67 meV → 5 Million qp!!**

Phonon Trapping

- **Dominant phonon loss mechanism for Ta and Al is through the substrate.**
  - **Copper Pair breaking phonons Mean Free path ~ 50nm**
- ***Effective quasiparticle lifetime is lengthened by phonon trapping.***
  - **Acoustic match between superconducting film and substrate.**

➢ **Thus thicker films or membrane-suspended absorbers.**



Quasiparticle Dynamics – How big are they?

- Governed by a diffusion-recombination equation:

$$\frac{\partial n_{qp}}{\partial t} = D\nabla^2 n_{qp} - \frac{n_{qp}}{\tau_{qp}} - Rn^2_{qp}$$

  - D is the diffusion constant in absorber
  - τ_{qp} is recombination time (quasiparticle lifetime)
  - R is the recombination rate

➢ **Size of absorber is limited the quasiparticle mean free path:**

$$l \sim \sqrt{D\tau_{qp}}$$

➢ **For Tantalum *l* ~ 250 microns**

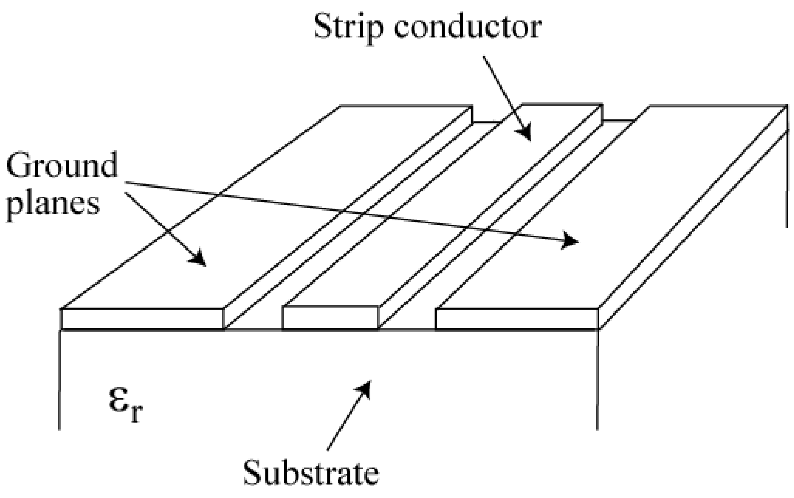
➢ **Can potentially be enhanced if absorbers are isolated from substrate (e.g., membrane); "phonon trapping"**

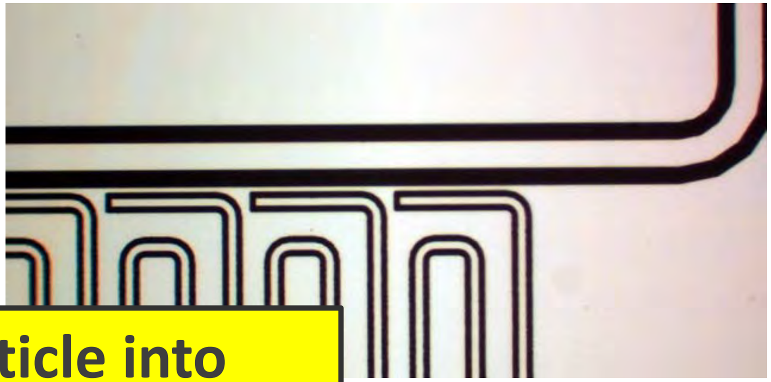
➢ **QP mean free path for many materials are unknown.**

➢ **We are explore materials with potentially longer mean free paths.**

Microwave Resonators

- MKID resonators are waveguide (CPW) transmission line
  - TEM mode propagation
  - Current flows at the edges of the central line and ground planes.
  - Quarter wavelength long
    - One end open (feedline is capacitively coupled)
    - Other end shorted to ground (absorber & qp trapping)
  - 3mm long at 10GHz.
- Each Resonator is coupled to the another CPW transmission line (feedline)
- Also lumped element MKIDs.

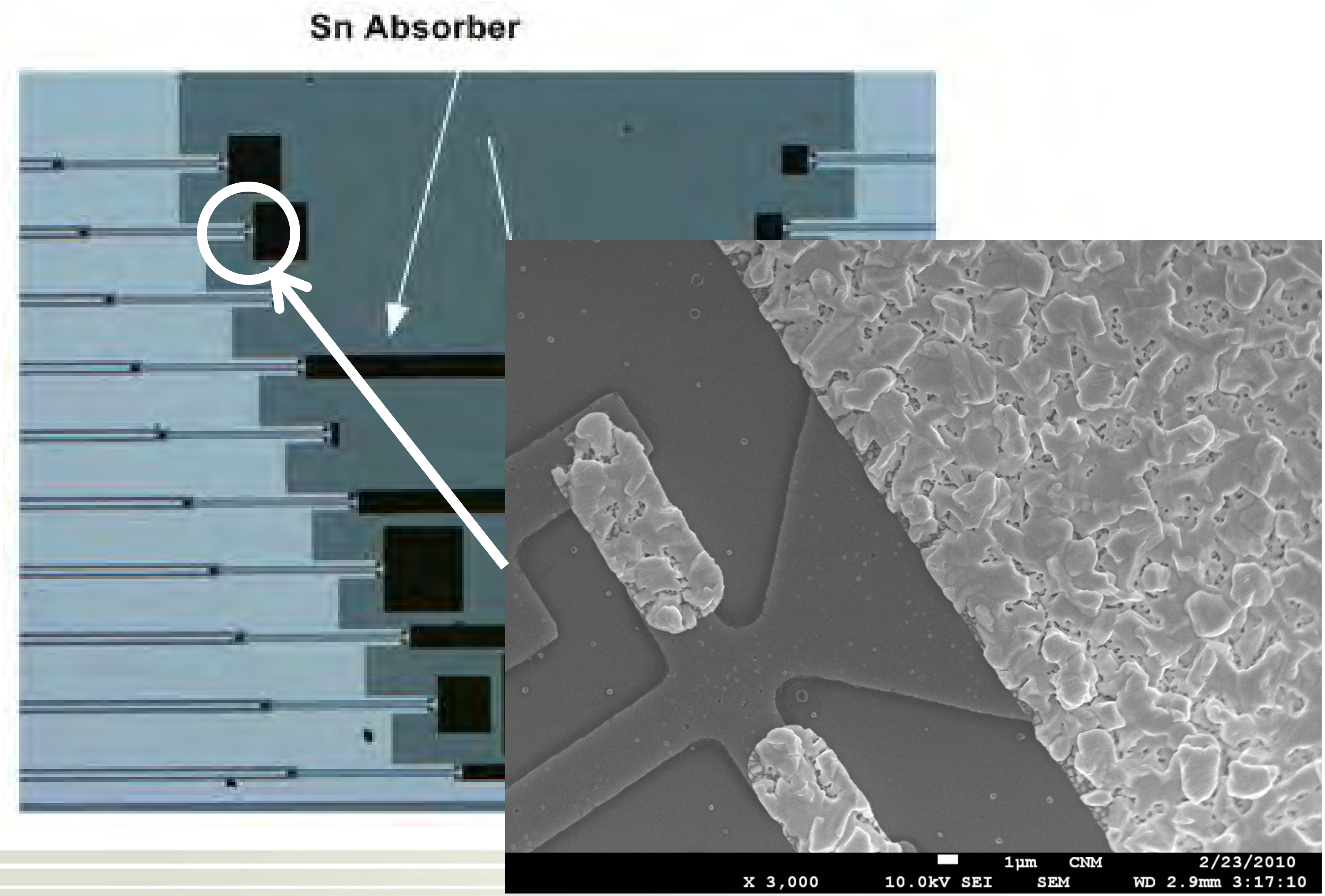




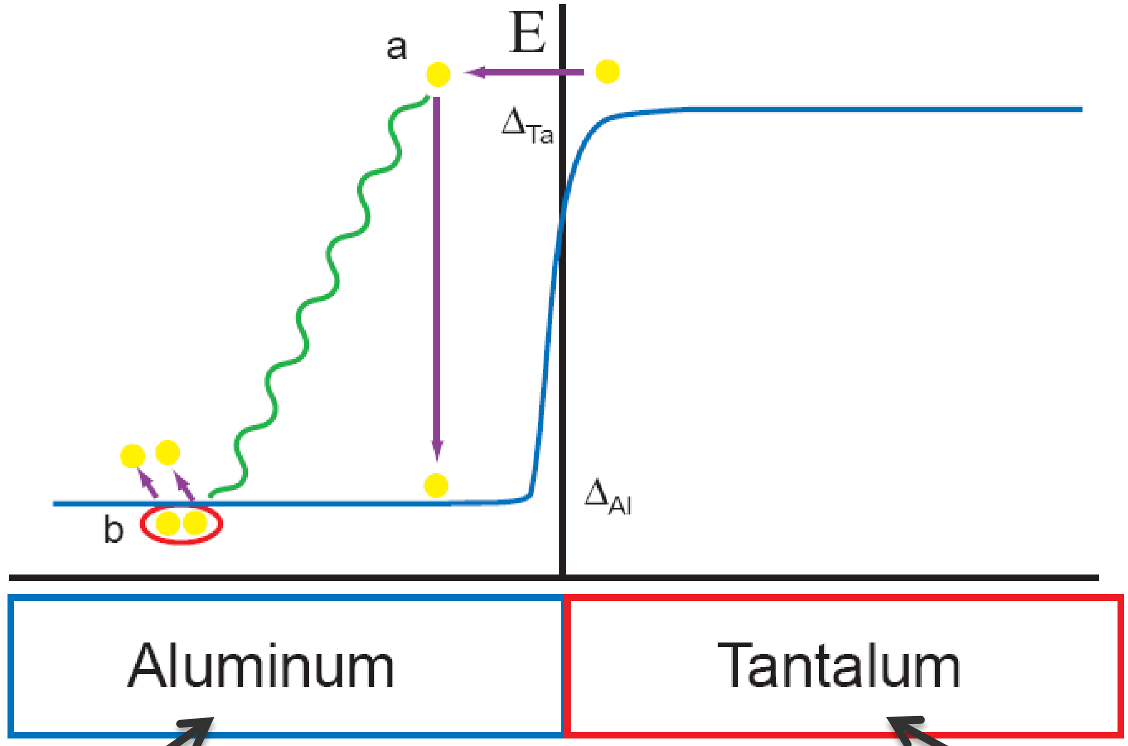
How do you get quasiparticle into resonator for detection?

Possible MKID arrangements

- Can make pixels and also strip detectors.



MKIDs – Quasiparticle Trapping

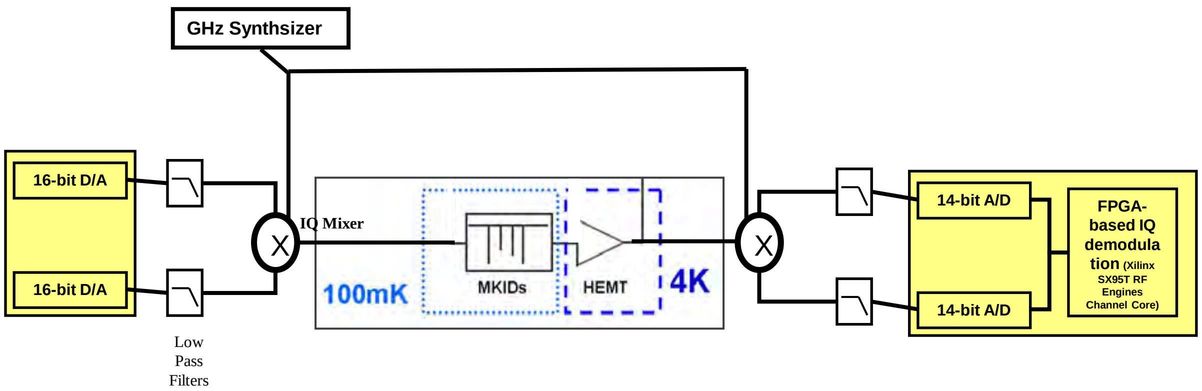


Co-Planar Waveguide Resonator

X-ray Absorber (quasiparticle diffusion)

MKID Array readout

- Room temperature electronics
  - Transfer complexity from cryogenic electronics (TES & SQUIDs) to room temperature.
  - Scalable system
- Array size limitation is room temperature electronics (512 is practical today)
  - Riding on Moore's Law for room temperature microwave integrated circuits developed for the wireless communications industry.



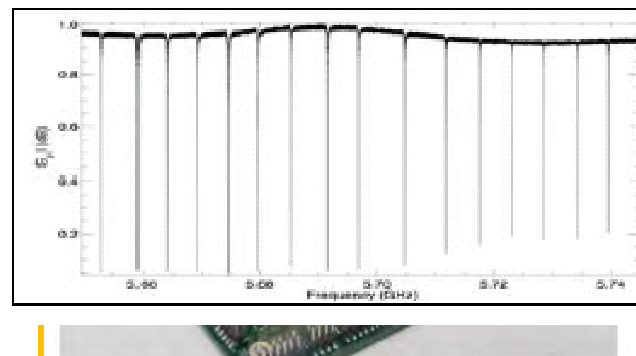
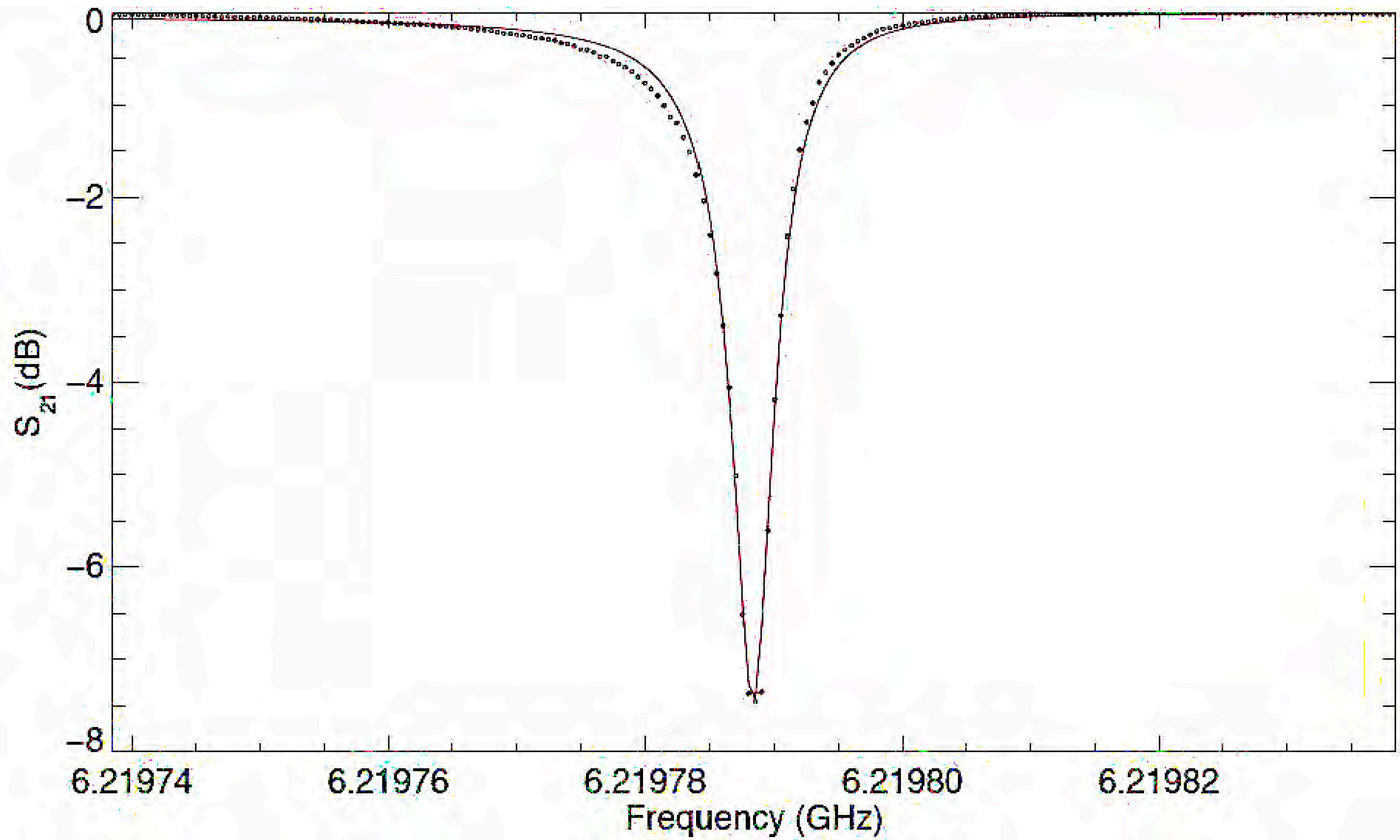


Figure 4. The CASPER ROACH board.



0
−2
−4
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−8
S_{21} (dB)
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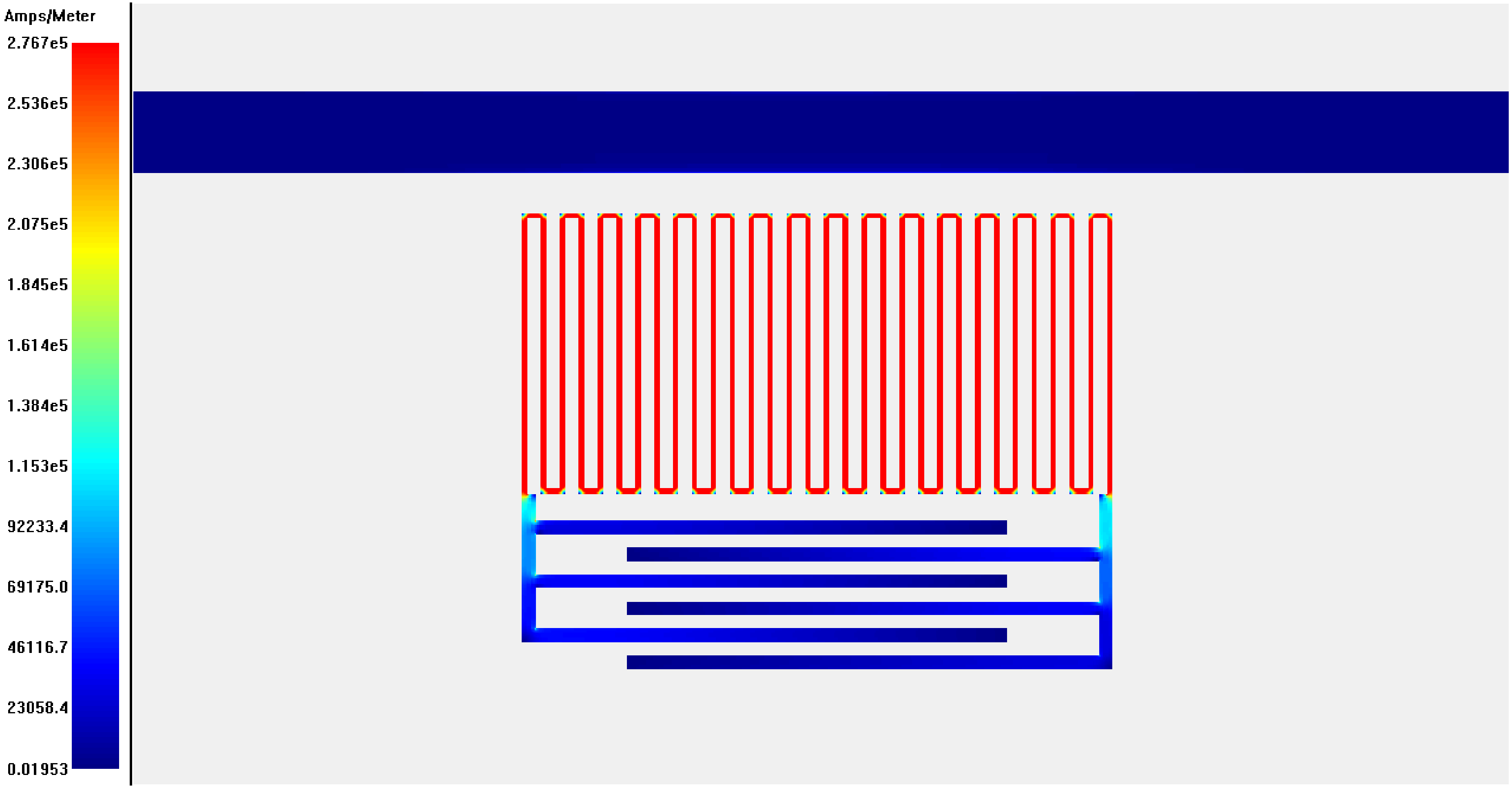
6.21976
6.21978
6.21980
6.21982
Frequency (GHz)


Amps/Meter
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2.536e5
2.306e5
2.075e5
1.845e5
1.614e5
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46116.7
23058.4
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