Fermilab Millikelvin Facility: The first 1.5 years

Donna Kubik

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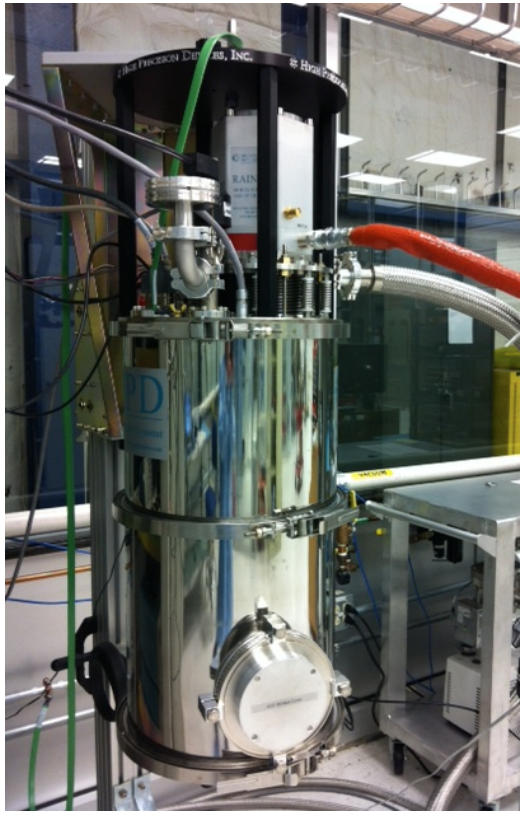
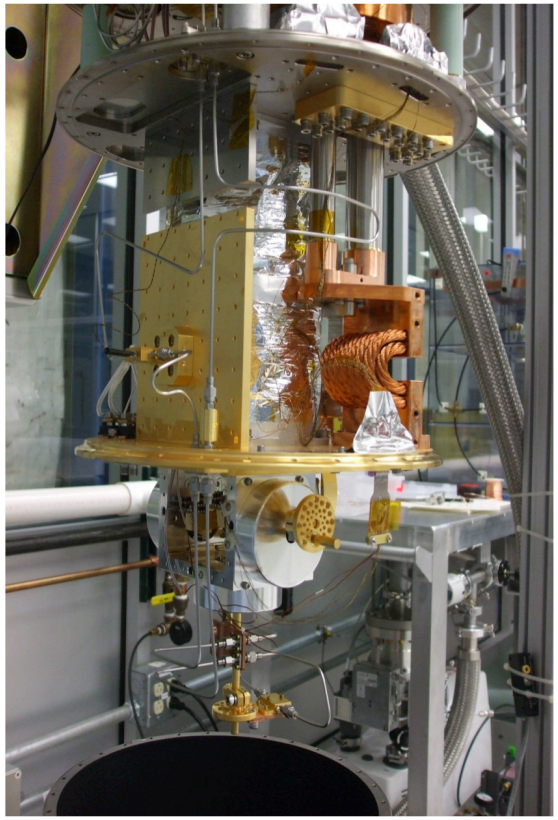
Fermilab Millikelvin Facility

- The millikelvin facilty is based on an adiabatic demagnetization refrigerator (ADR) from High Precision Devices, Inc.
- It is comprised of a cryogen-free pulse-tube Cryomech cryocooler using the ADR to reach cryogenic temperatures.
- The cryostat stage base temperatures are approximately 60 K, 3 K, 500 mK, and 50 mK.
- The two millikelvin stages can regulate anywhere from 3 K to their base temperatures of 500 mK and 50 mK.





← 60 K (25 W)

Pulse-tube cooler

← 3 K (0.7 W)

← 500 mK (1 J @ 1 K)

← 50 mK (117 mJ @100 mK)

ADR

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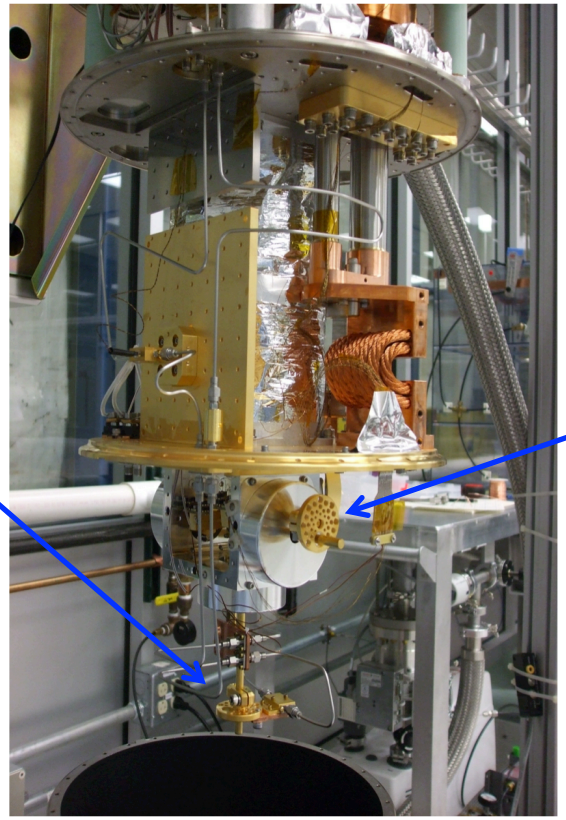
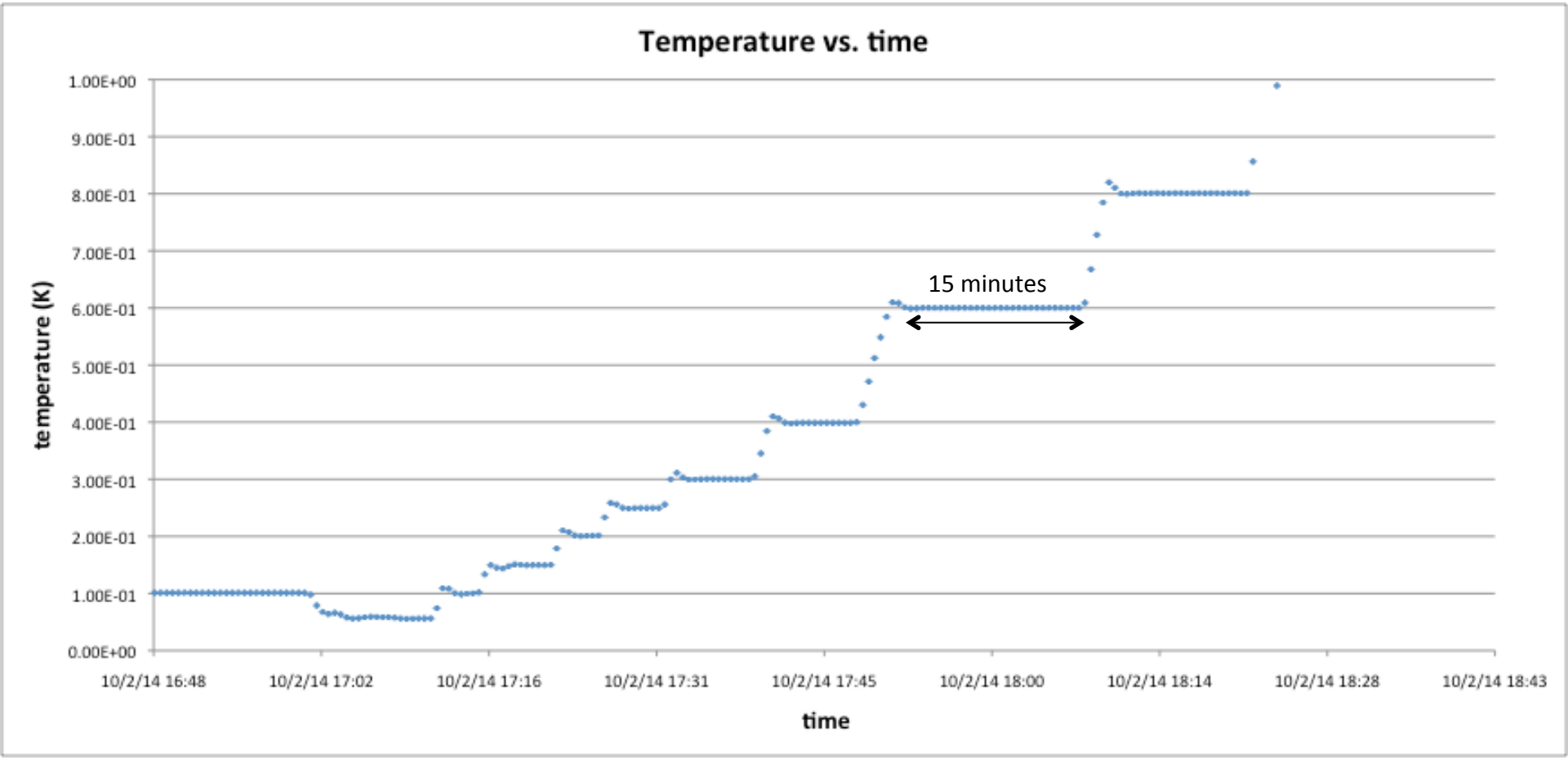


The Millikelvin Facility has been booked 100% of the time

The appeal of the ADR is its temperature ability, agility, and stability

Temperature stability: RMS = 0.2 mK



ADR ENHANCEMENTS & PERFORMANCE STUDIES

ENHANCEMENTS

- LabView ramp controls and continuous recording of ADR parameters
- More-efficient transition to temperature (PID) regulation
- N2 system to speed up ADR warmup

PERFORMANCE STUDIES

- Thermal capacity as f(temperature)
- Efficiency of heat sinking of cables: normal and superconducting
- Stray magnetic field measurement

SUPERCONDUCTING DETECTOR R&D

- Fermilab MKID R&D (ongoing)
- SPT-3G Nb resonators (ongoing)
- Tsukuba STJ R&D (6 weeks)

CRYOGENIC MATERIALS R&D

- SCDMS thermal conductivity test (3 weeks)

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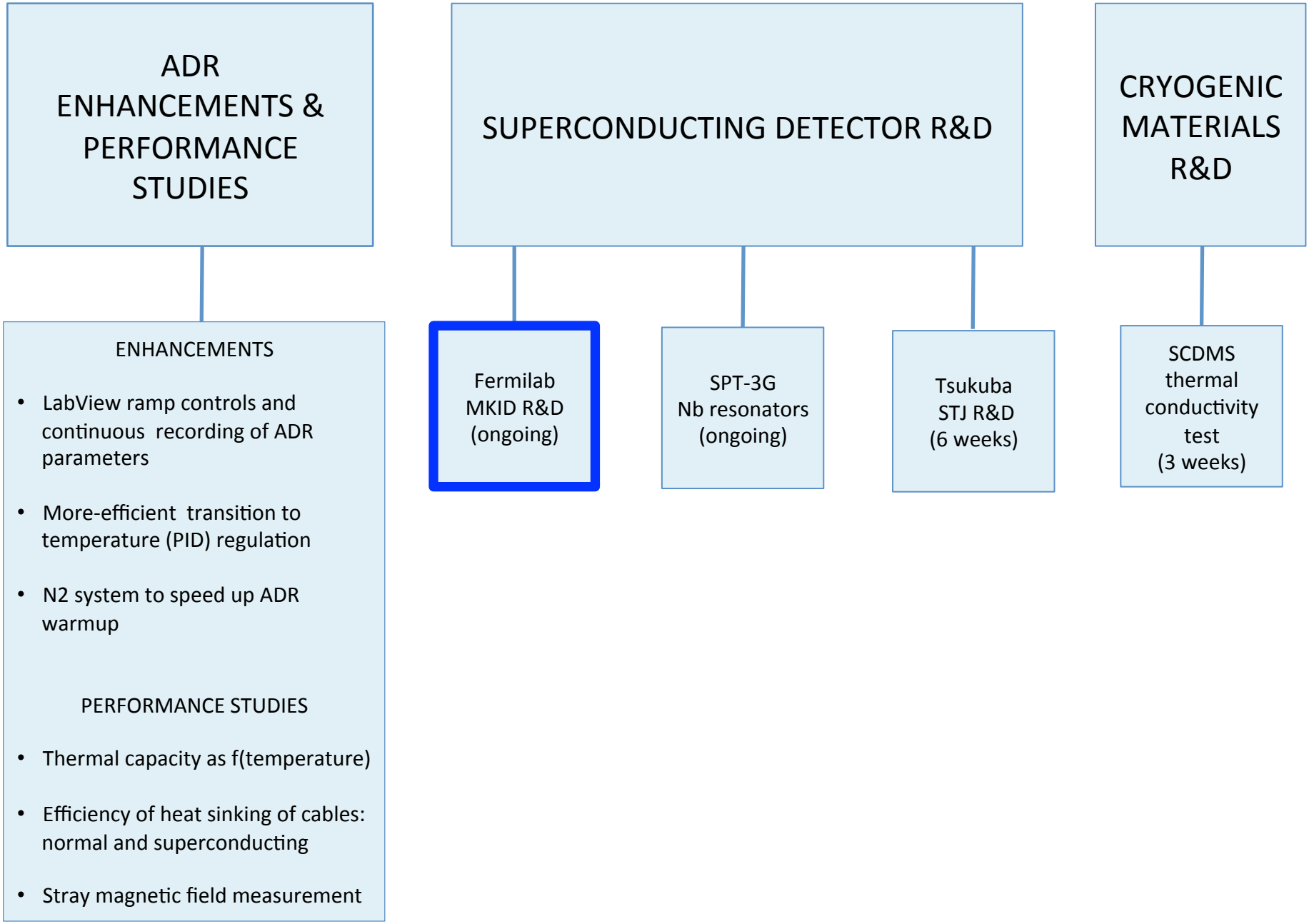
Outline

- Summary of each project that has used the millikelvin facility
  - Project overview
  - Suitability of the ADR
  - Future use of the ADR



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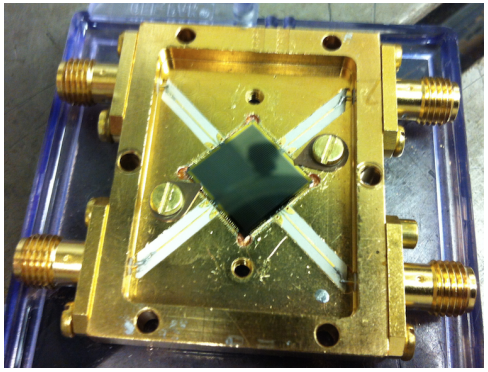
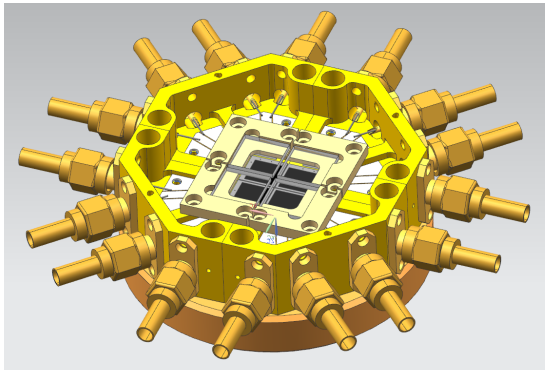
MKIDs: Project overview

- In collaboration with UCSB, develop a large Microwave Kinetic Induction Detector (MKID) array to deploy on a telescope in Chile.
  - Starting with Array Camera for Optical to Near-IR Spectrophotometry (ARCONS), a 2024-pixel array; goal is to increase array size to ~50,000 pixels.



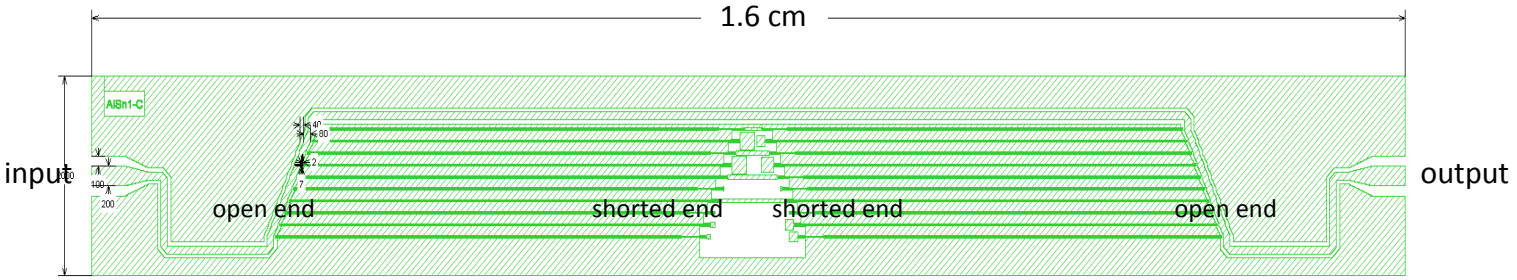
ARCONS

x10, x100

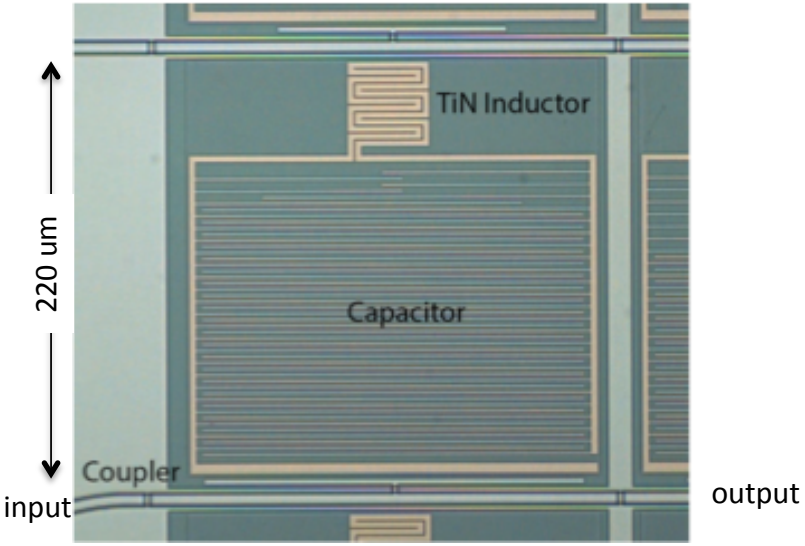


ARCONS-10, ARCONS-100

Two families of MKIDs

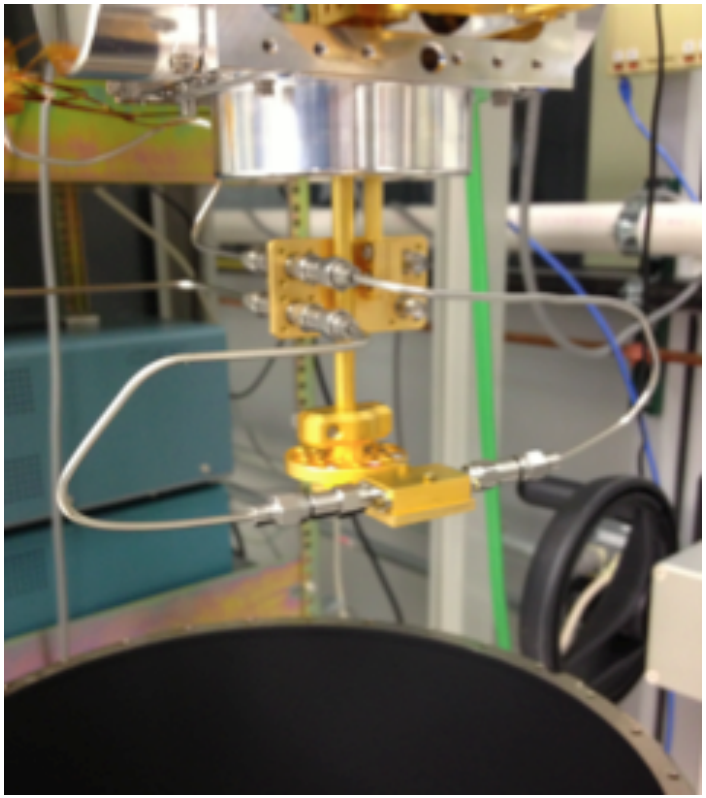


Coplanar waveguide MKIDs (CPW MKIDs)
20 resonators

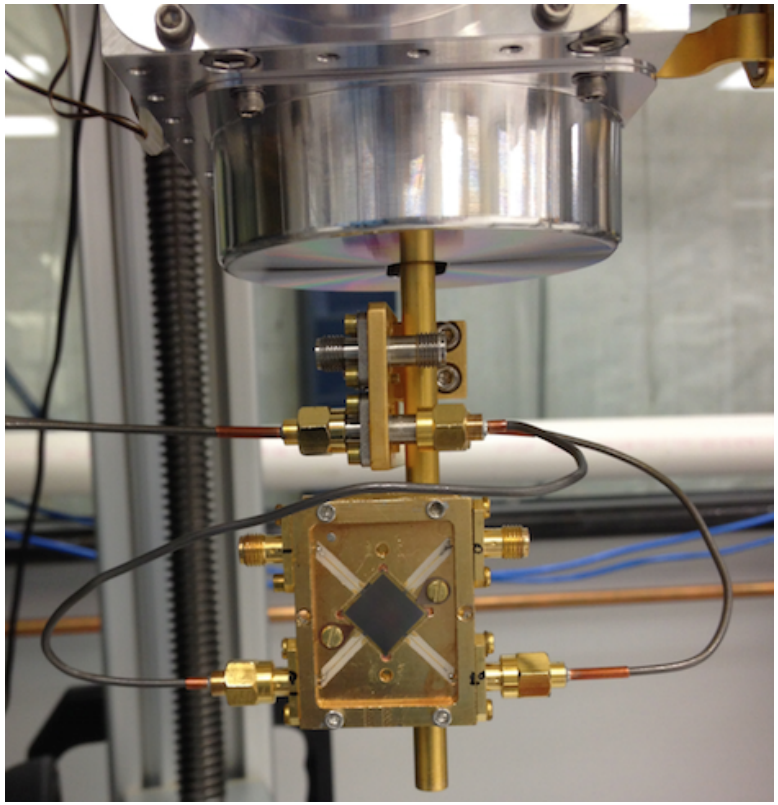


Lumped element MKIDs (LEKIDs)
1 resonator → arrange many into array

MKID testing



CPW MKID installed in FNAL ADR
Al on Sapphire



LEKID installed in FNAL ADR
TiN on Silicon

MKIDS: Suitability of the ADR

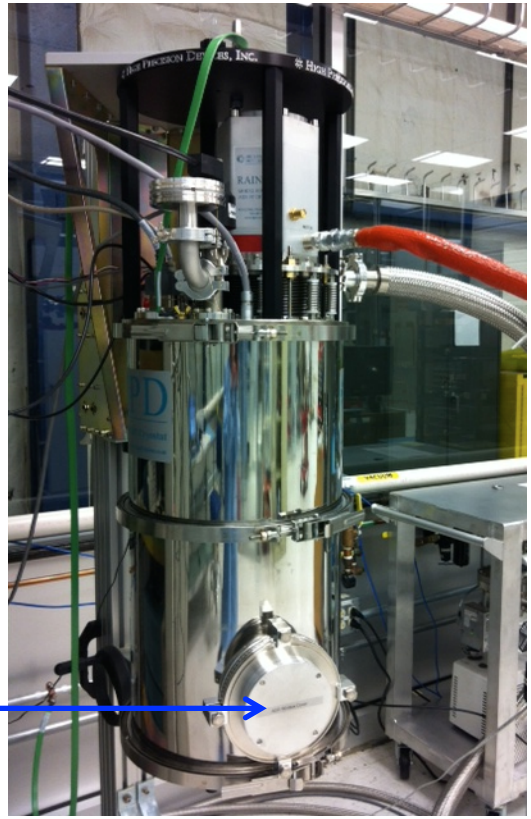
- The choice of material for the resonator and the optimal operating temperature is driven by two things
  - To minimize the energy gap in the superconductor.
  - To minimize the number of quasiparticles the superconductor.
  - The quasiparticle density in a superconductor is strongly dependent on temperature: Below ~$0.1T_C$, the quasi-particle density is about what it would be at 0 K and is very small. So, want to operate $<0.1T_C$.

Material	T_c (K)	Δ (meV)	0.1 * T_c (K)
Al (ANL MKID)	1.2	0.18	0.12
Ta	4.47	0.67	0.45
TiN (ARCONS)	5.6	0.84	0.56
Nb	9.3	1.40	0.93

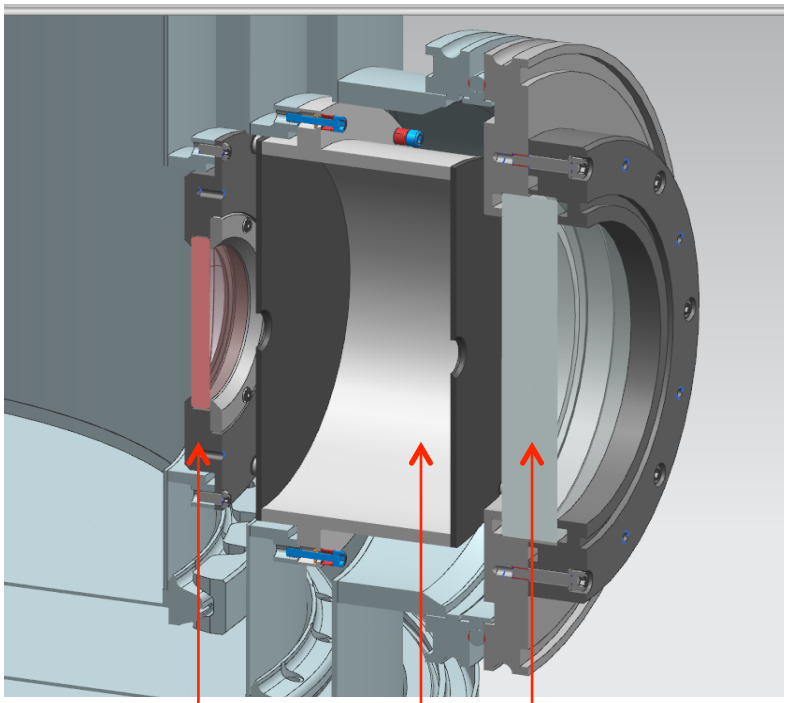
- These temperatures are achievable with the ADR.

MKIDs: Future use of the ADR

- To study response to light, cryostat optics have been installed on the ADR.
- The ADR will be taken to the telescope with ARCONS!



Optics attach to cryostat here



ADR Cryostat Optics

ADR ENHANCEMENTS & PERFORMANCE STUDIES

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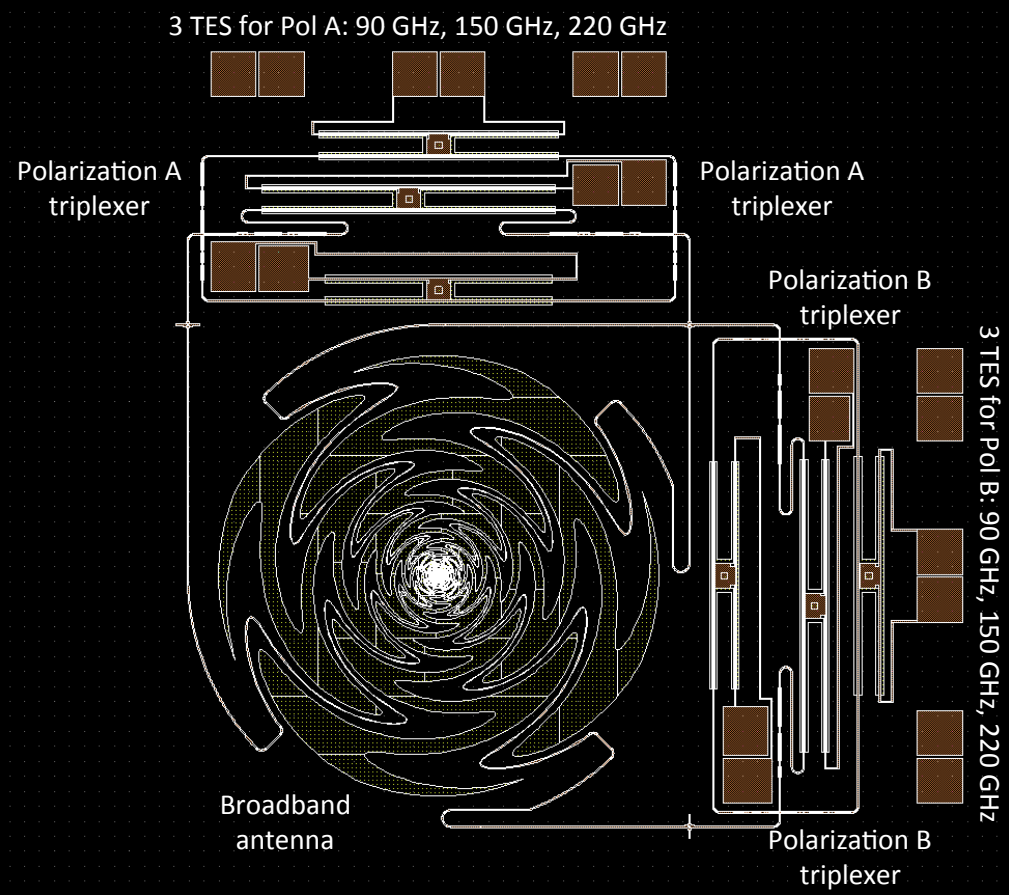
SPT-3G: Project overview

- To study loss in Nb, which is a key parameter in the SPT-3G detector design.
- All the microwave transmission is in Nb structures: antenna, microstrip, in-line filters: all parts that transmit the microwaves to the TES island, where the heat is deposited and measured by the TES.



- One SPT-3G pixel
- 3 bands
- 2 polarizations/band

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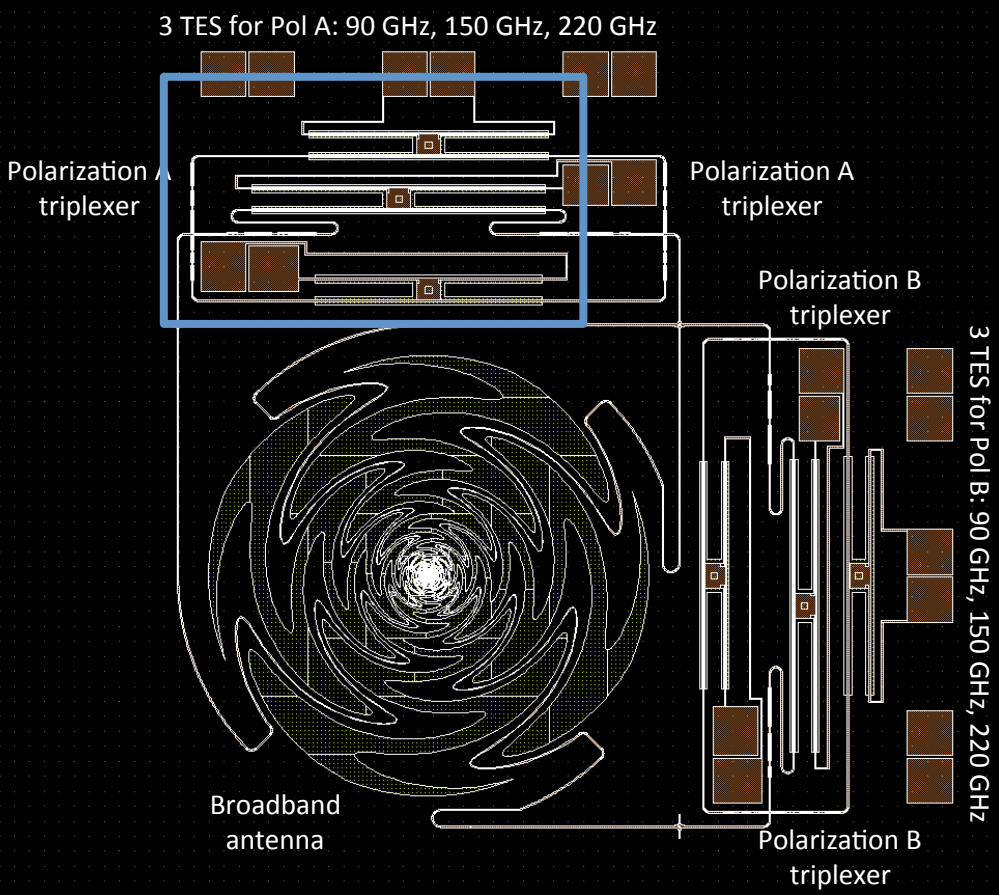
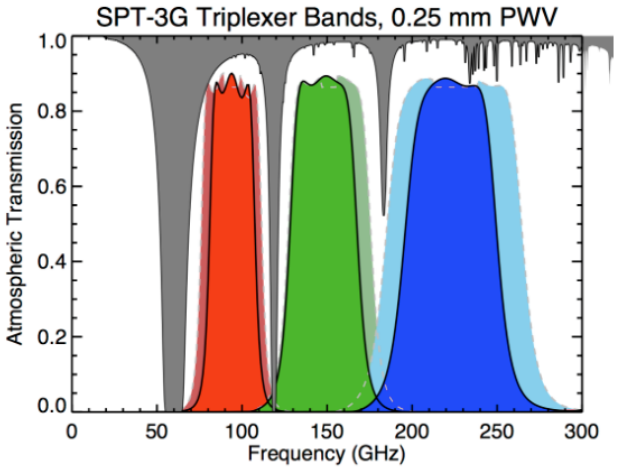
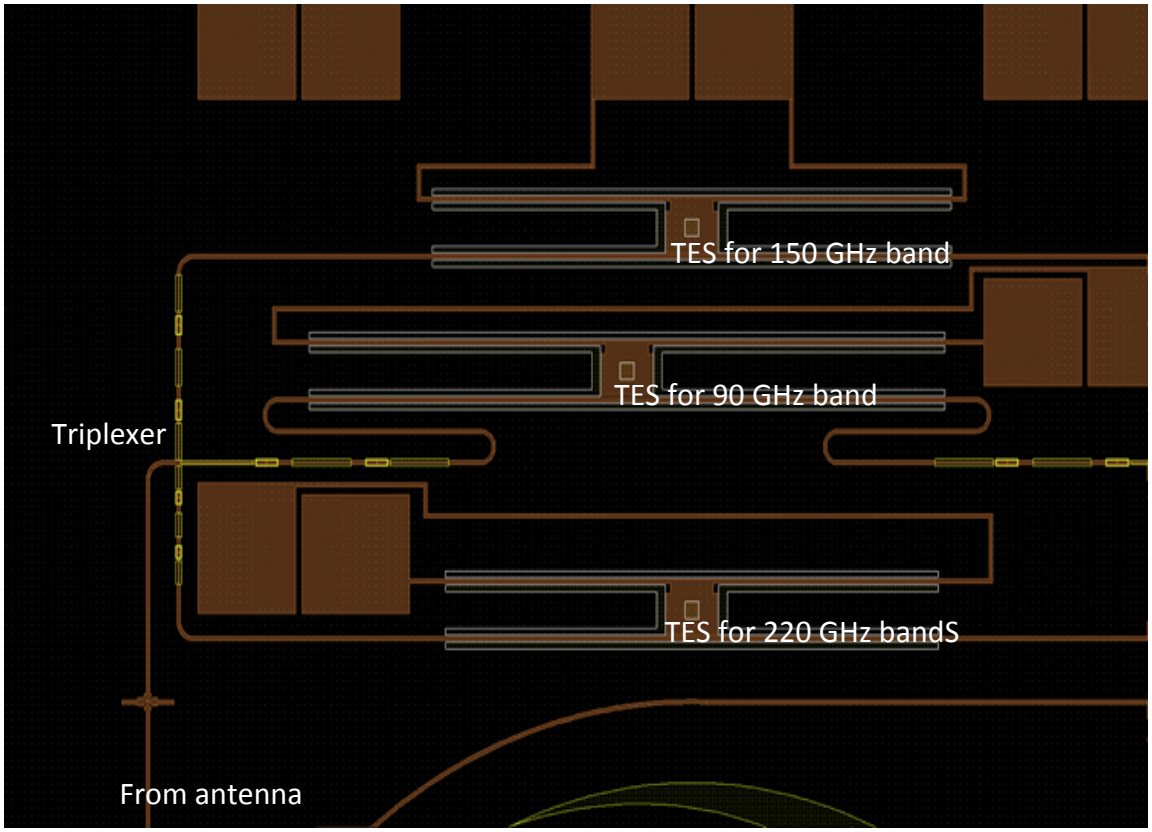


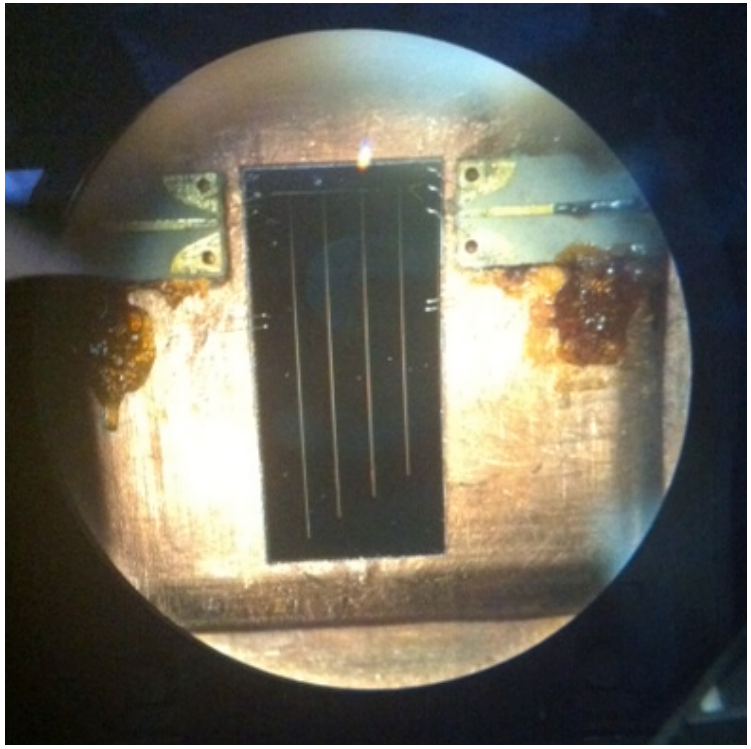
- One SPT-3G pixel
- 3 bands
- 2 polarizations/band

Zoom in on one side of input to TES





Fabrication tool



Four half-wavelength Nb resonators

- By fabricating ½-wave resonators using the same recipe as that planned for the SPT pixels, one can evaluate the recipe without fabricating and testing the much more complicated pixel geometry.
- The resonators operate at frequencies of 6-10 GHz, much easier to test than the 90 GHz – 220 GHz frequencies of the SPT detectors
- The resonator tests indicate excellent microstrip performance at 6-10 GHz frequencies.
- It is thought that the microstrip will not perform well at 100-300 GHz if it doesn't perform well at 6-10 GHz frequencies.

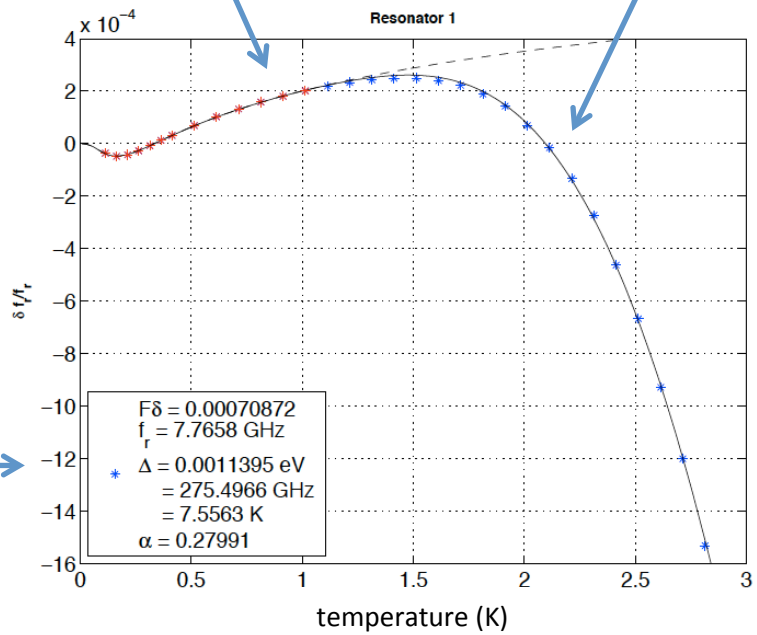
SPT-3G: Suitability of the ADR

- The origin of loss in Nb + dielectric can be studied by measuring the fractional resonant frequency change as f(temperature) for Nb CPW resonators (shown on next slide) and comparing the results to theory.
- Measurements from 50 mK to 3 K are required to cover SPT observations; perfect for the ADR!

TLS (Two-Level Systems) theory

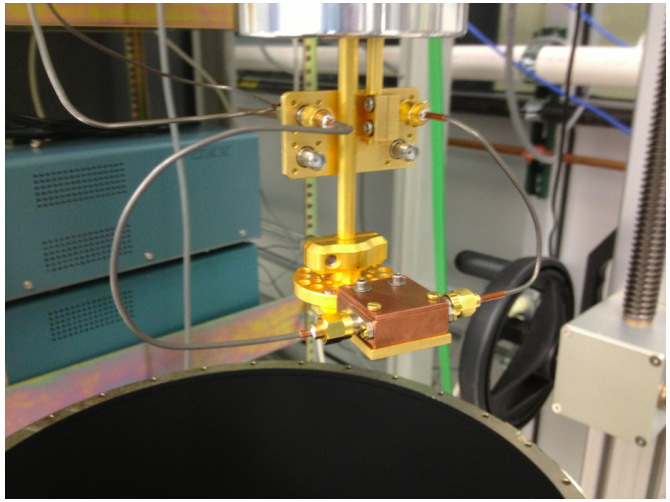
Mattis-Bardeen theory

$$\frac{f-f_0}{f_0} \approx \frac{F\delta}{\pi}\left[Re\psi\left(\frac{1}{2}-\frac{\hbar\omega}{j2\pi k_B T}\right)-log\frac{\hbar\omega}{2\pi k_B T}\right]-\frac{\alpha}{4}\left[\sqrt{\frac{2\pi k_B T}{\Delta_0}}e^{-\frac{\Delta_0}{k_B T}}+2e^{-\frac{\Delta_0}{k_B T}}e^{-\frac{\hbar\omega}{2k_B T}}I_0\left(\frac{\hbar\omega}{2k_B T}\right)\right]$$

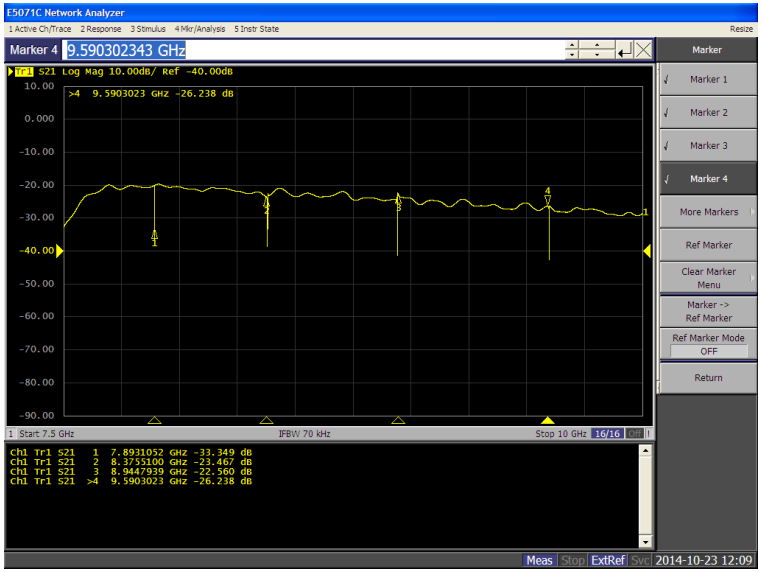


Fit for loss,
gap energy,
kinetic inductance fraction,
calculate T_c

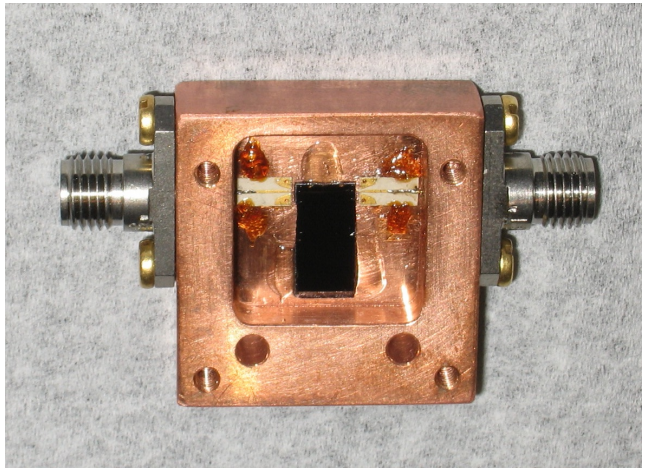
SPT-3G: Suitability of ADR



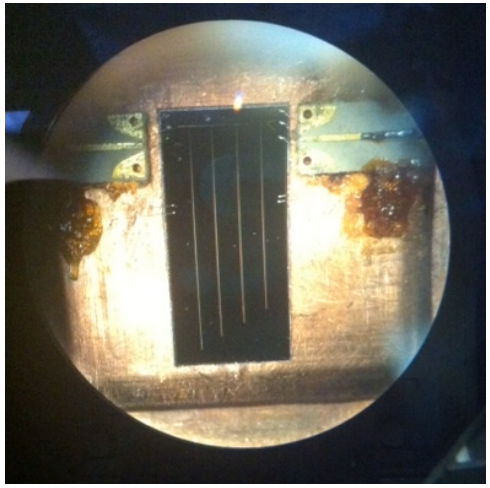
Nb resonators installed in ADR



Four resonances



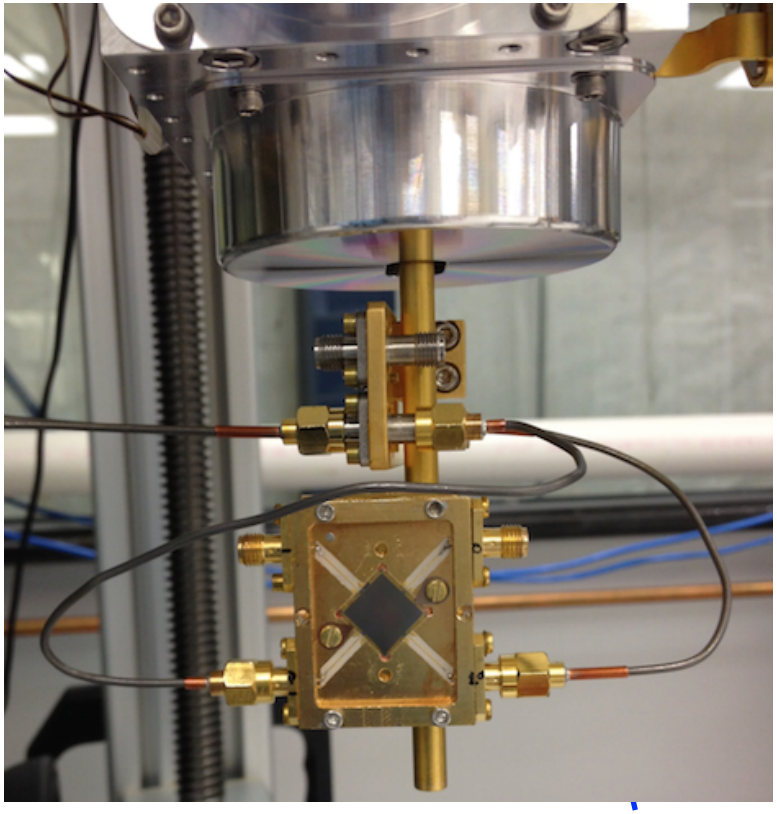
Resonator chip in detector mounting box.



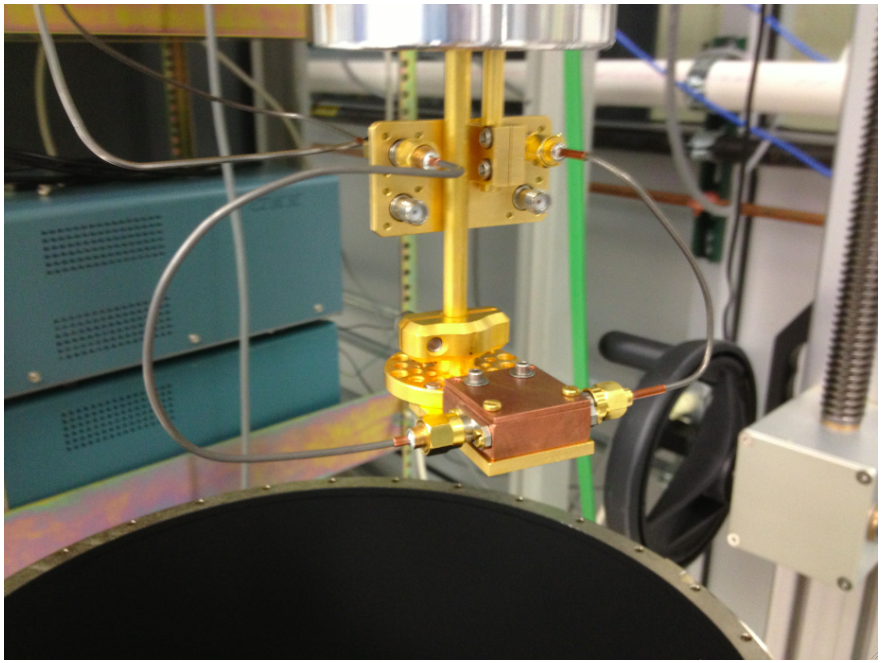
Four half-wavelength Nb resonators

Problem

- Had to remove MKID to install SPT resonator and vice versa.
- But both projects would like to be ongoing.



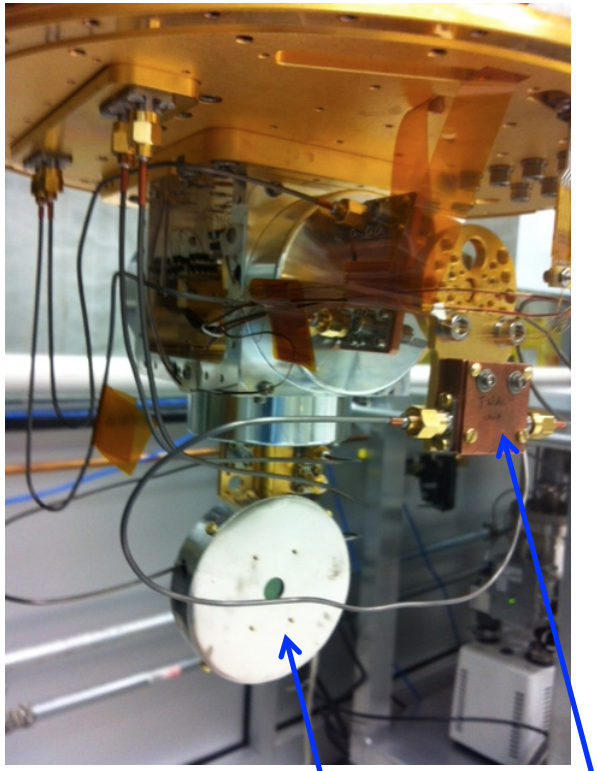
MKID



SPT resonator

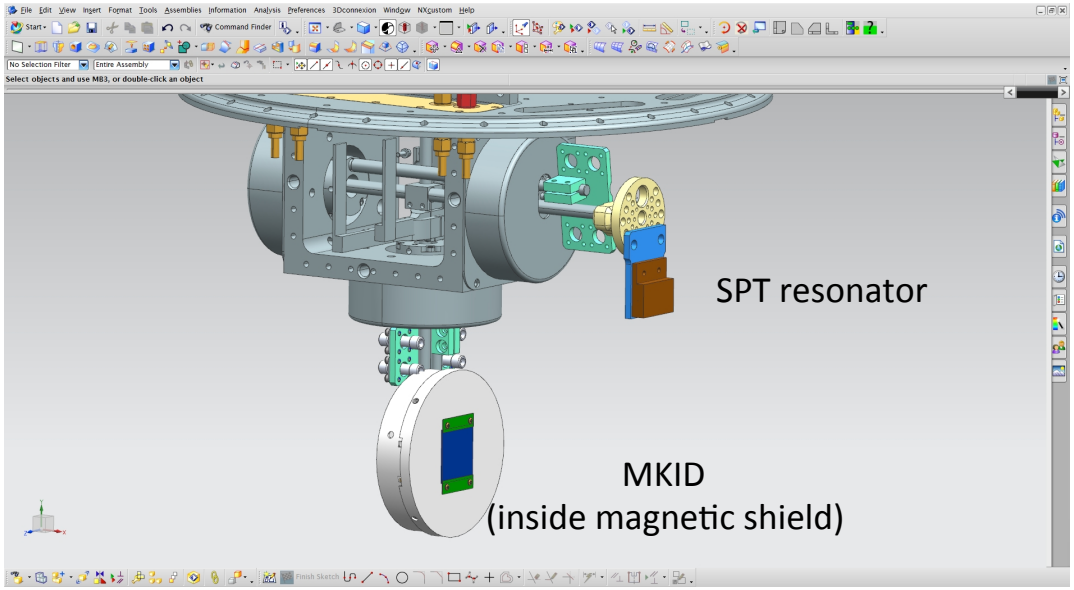
Solution

- We installed a second channel in the ADR dedicated to the SPT resonator; this enables switching between MKID and ANL resonator testing without taking time to warming up & cool down ADR.



MKID
(inside magnetic shield)

SPT resonator



SPT-3G: Future use of the ADR

- Would like to investigate a number of possible microstrip material configurations:
  - Nb-SiOx-Nb (baseline)
  - Nb-a:Si-SiOx-a:Si-Nb (a:Si passivation)
  - Nb-AlO-SiOx-AlO-Nb (AlO passivation)
  - Nb-AlO/SiO2-Nb (AlO/SiO2 nano-laminate via ALD)
- Would also like to test:
  - material stability, so repeated resonator testing over time.
  - fabrication repeatability

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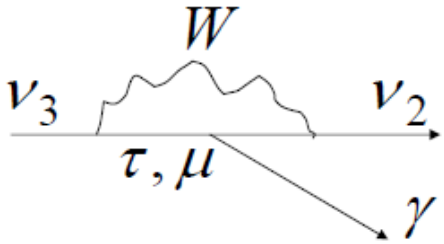
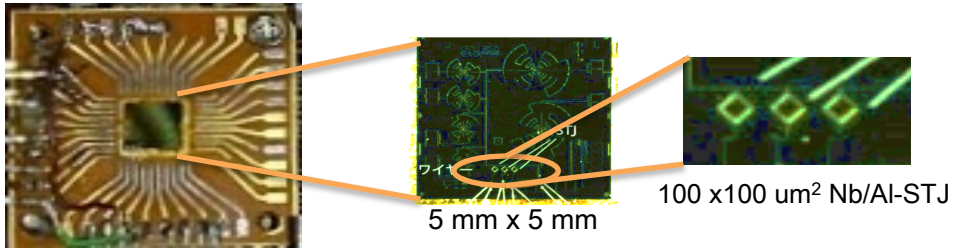
STJ: Project overview

- The goal of the STJ experiment is to use a space-based array of STJ (Superconducting Tunnel Junction) photon detectors to detect photons emitted in cosmic relic neutrino decay to measure neutrino mass.



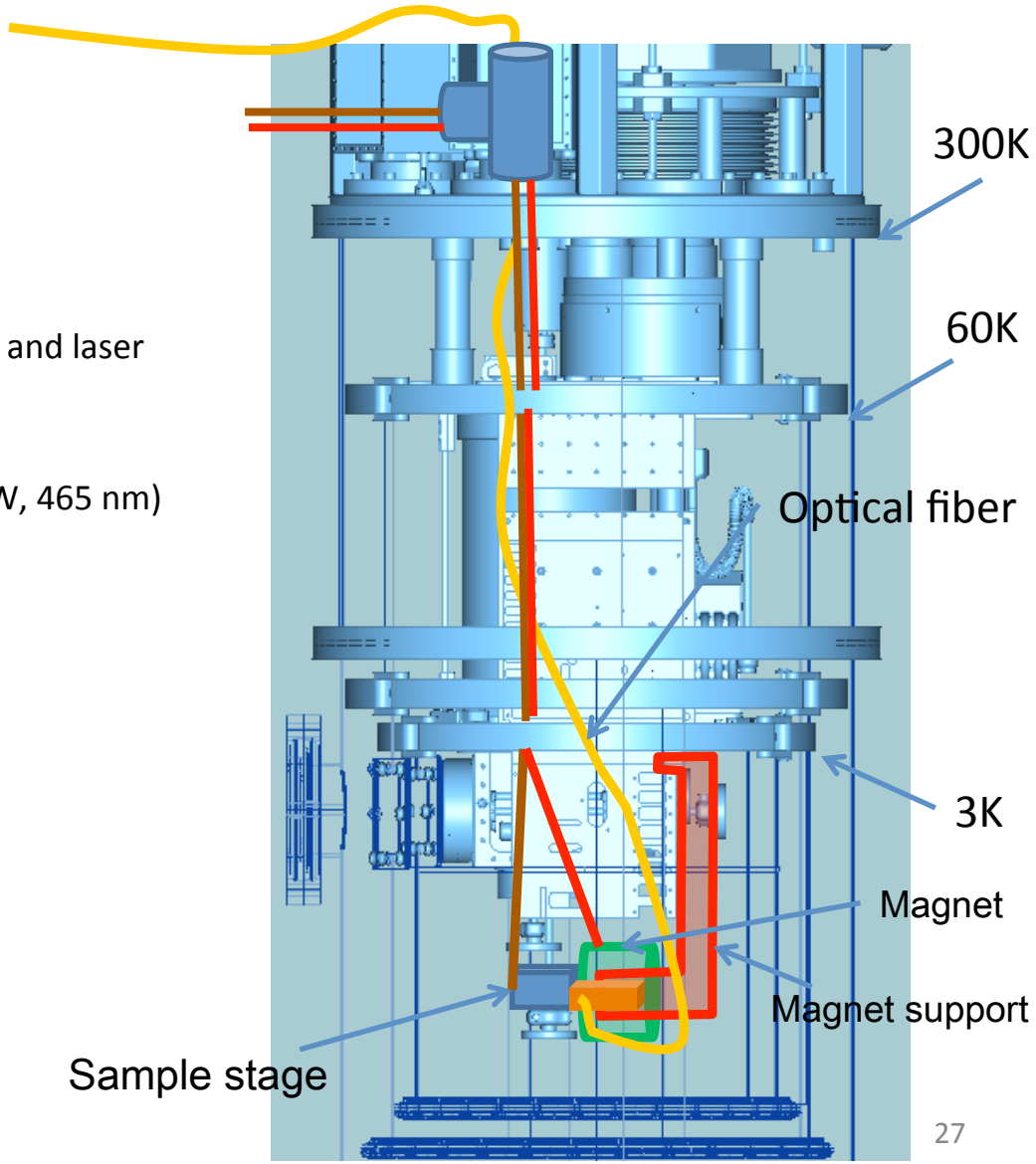
- Assuming m_3 is between 50 meV and 150 meV, the decay photon energy in the ν_3 rest frame is between 10 meV and 25 meV

- The Tsukuba group used the FNAL millikelvin refrigerator to characterize a Nb/Al-STJ and a Hf STJ (See slide 25 for details)



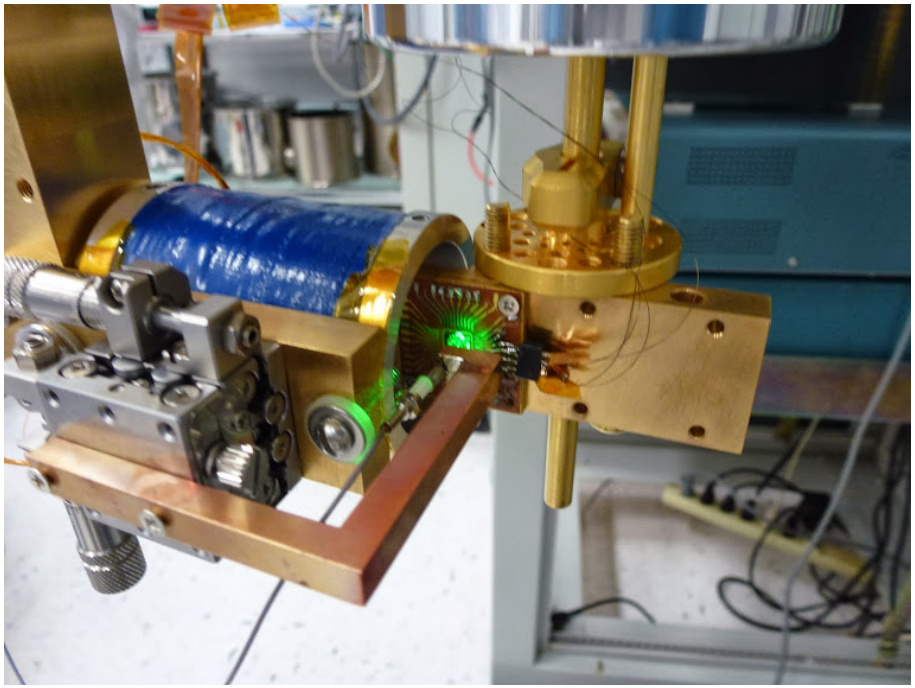
STJ: Project overview

- They installed:
  - A Nb/Al-STJ on the FAA
  - A superconducting magnet, XY stage, and laser fiber holder cooled by the 3 K stage.
  - A fiber for the laser (Class 3B, 149 mW, 465 nm) illuminated the STJ.



STJ: Project overview

- They studied:
  - Leakage current as f(temperature)
  - Suppression of Josephson current as f(magnetic field)
  - IV curves
  - Noise
  - Response to 465 nm DC and pulsed laser



The STJ is located in the 50-Gauss fringe field of the superconducting magnet. The STJ is shown illuminated by the alignment laser.

STJ: Suitability of ADR

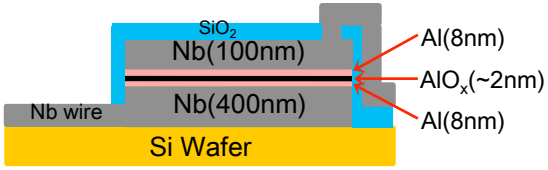
- The operating temperatures of major STJ's are covered by the ADR:
  - Nb/Al-STJ
  - Ta/Al-STJ
  - Al-STJ
  - Hf-STJ
- The criteria for operating temperature is the same as for MKIDs: $<0.1T_c$
- Also consider temperature with minimum leakage current.

Material	$T_c(K)$	$\Delta(\mathrm{meV})$
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.16	0.021

STJ: Past, Present, Future

- February, 2014 (3 weeks)
- Measured: STJ response to visible light via an optical fiber
- Nb/Al-STJ design: processed at KEK with 100um x 100um junction size

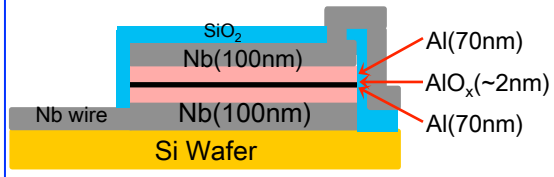
  (Nb 100nm/Al 8nm/AlOx/Al 8nm/ Nb 400nm)



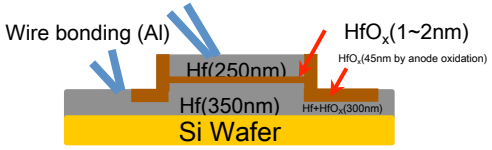
Nb/Al-STJ

- August, 2014 (3 weeks)
- Measured: Newly-designed Nb/Al-STJ response to visible light
- Nb/Al-STJ design: processed at AIST with 20um x 20um ~ 100um x 100um junction sizes

  (Nb 100nm/ Al 70nm/AlOx/Al 70nm/Nb 100nm)
- Test a Hf-STJ at 50~100 mK.

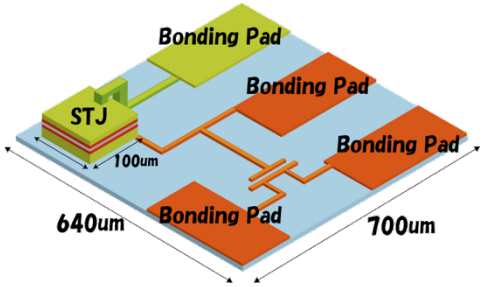


Nb/Al-STJ



Hf-STJ

- February, 2015 (2~3 weeks)
- Measure: Nb/Al-STJ response to visible light with a SOI based cold amplifier, or HEMT based cold amplifier
- New STJ designs: SOI-STJ (Nb/ Al-STJ on the SOI wafer with CMOS FETs)
- Test a Hf-STJ at 50~100 mK



SOI-STJ

ADR ENHANCEMENTS & PERFORMANCE STUDIES

ENHANCEMENTS

- LabView ramp controls and continuous recording of ADR parameters
- More-efficient transition to temperature (PID) regulation
- N2 system to speed up ADR warmup

PERFORMANCE STUDIES

- Thermal capacity as f(temperature)
- Efficiency of heat sinking of cables: normal and superconducting
- Stray magnetic field measurement

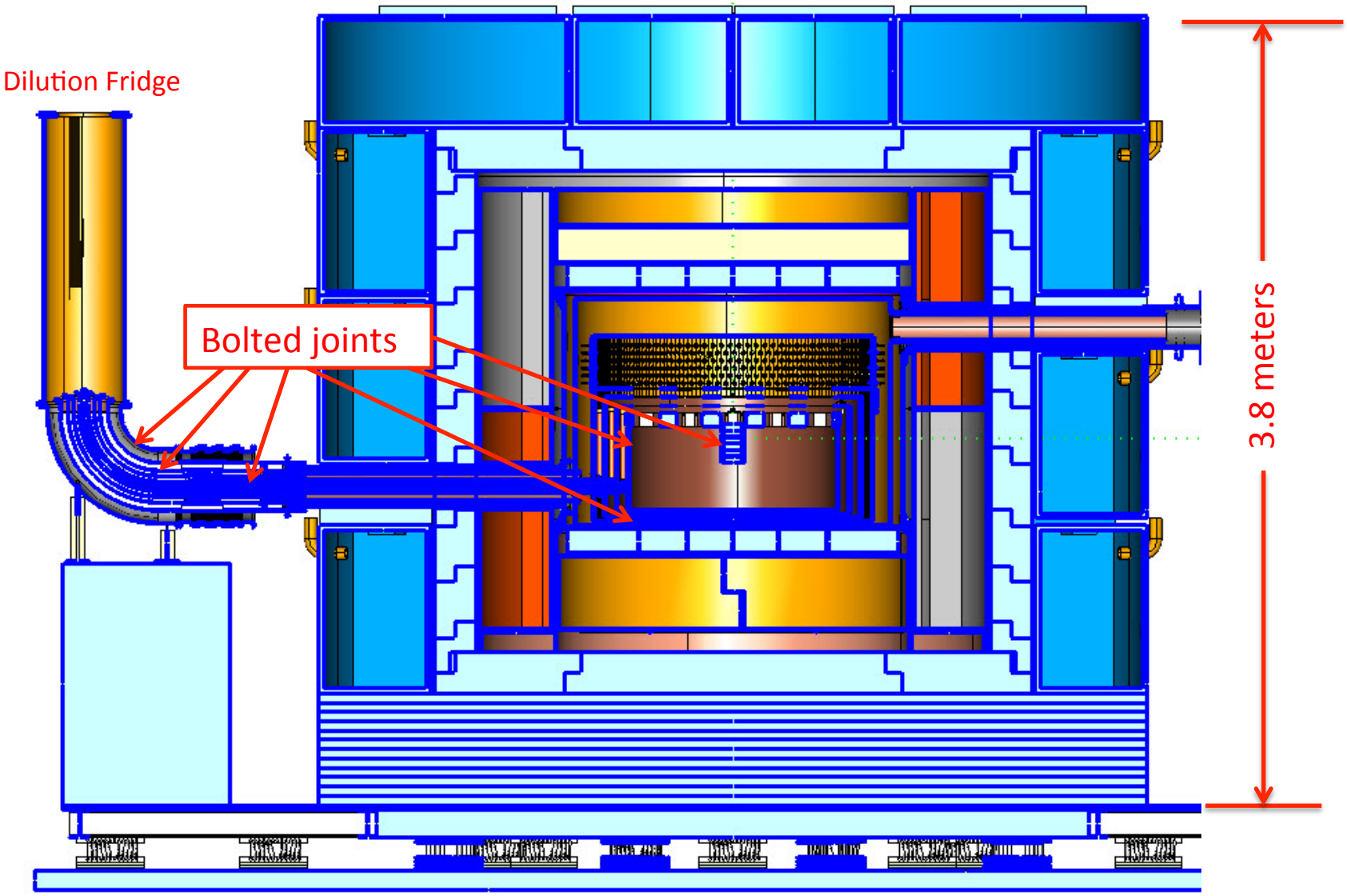
SUPERCONDUCTING DETECTOR R&D

- Fermilab MKID R&D (ongoing)
- SPT-3G Nb resonators (ongoing)
- Tsukuba STJ R&D (6 weeks)

CRYOGENIC MATERIALS R&D

- SCDMS thermal conductivity test (3 weeks)

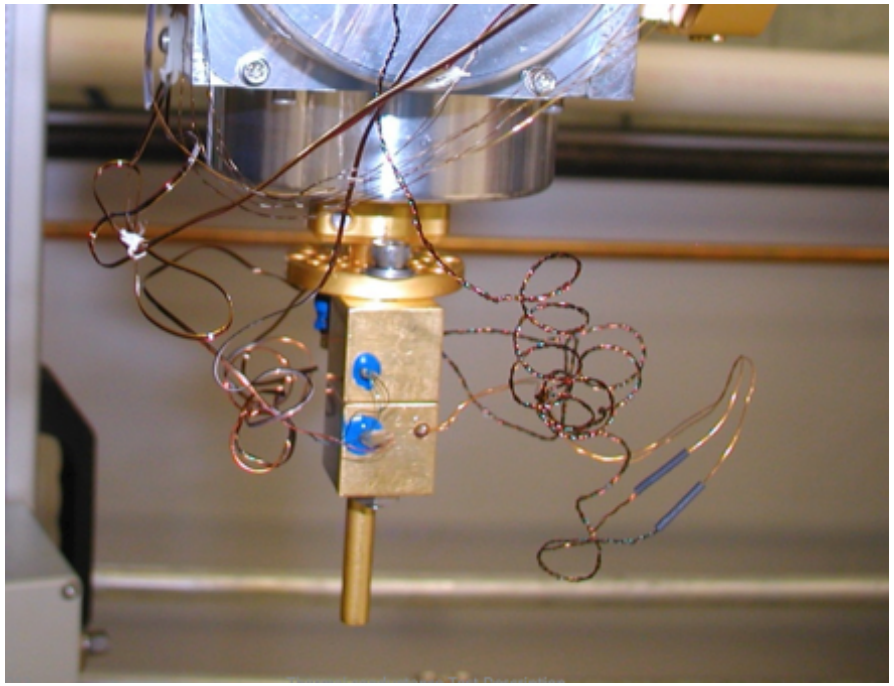
SCDMS: Project overview



SCDMS cryostat

SCDMS: Project overview

- SuperCDMS (SCDMS) detectors are cooled by conduction.
- Bolted joints are required for assembly.
- Joint resistance dominates the conductance.
- Published tests are few and vary widely.
- Soudan conductance would be inadequate for SCDMS.
- Measured the conductance of several bolted joints.
- Testing done in ADR confirmed the design basis.

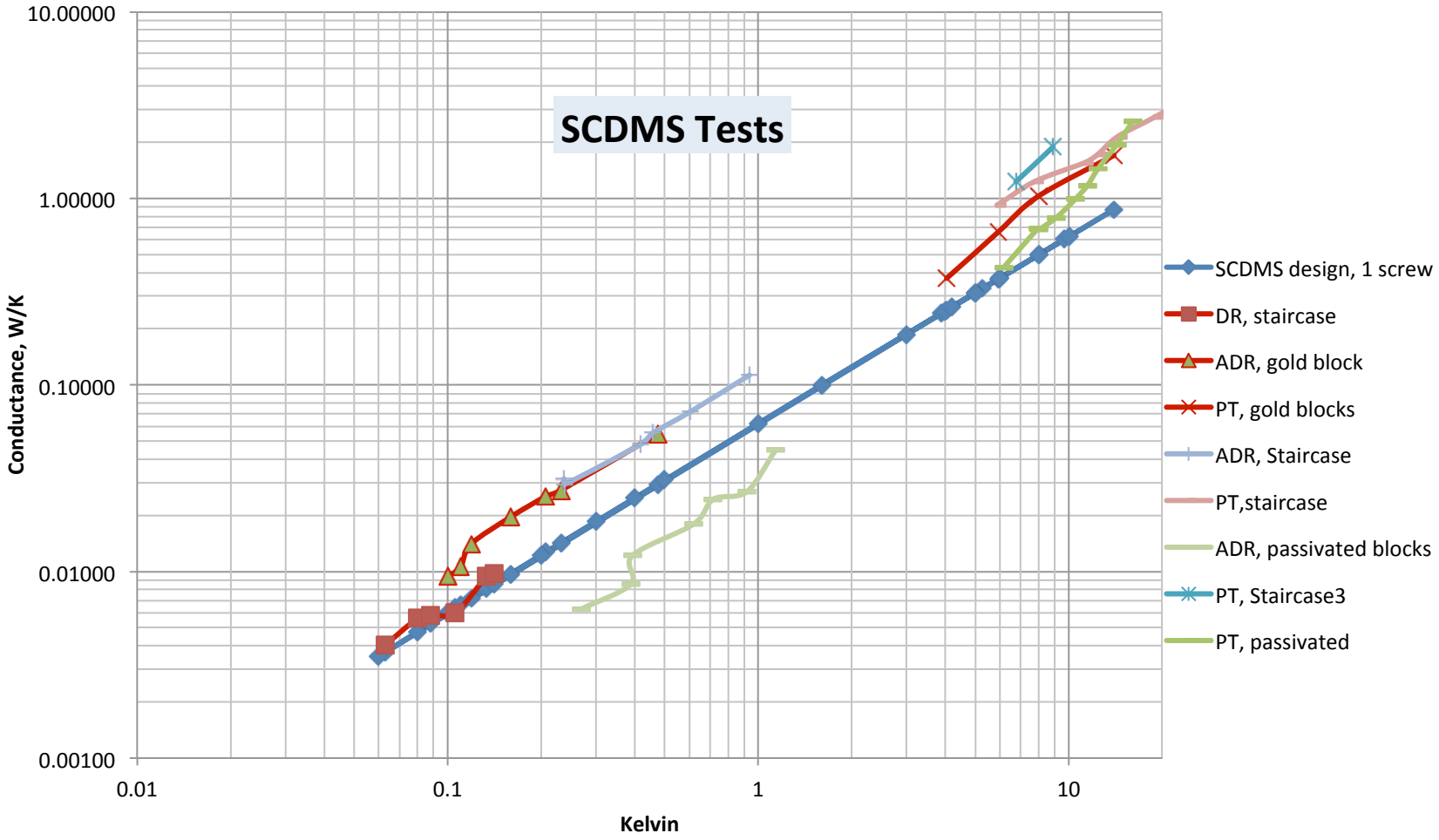


Bolted joint between gold-plated Cu blocks tested in ADR

SCDMS: Suitability of the ADR

- Testing over a range of temperatures was necessary:
  - SCDMS will have bolted joints at 50K, 4.5K, 700mK, 100mK, 20mK.
- Testing at 4K to 10K was done with the PT 415 cryocooler at PAB.
- Testing from 100 mK to 1.2 K was done in the ADR.
- The versatile temperature range and ease of use was attractive
- The test results will soon be published

Three ADR tests 0.1K to 1K

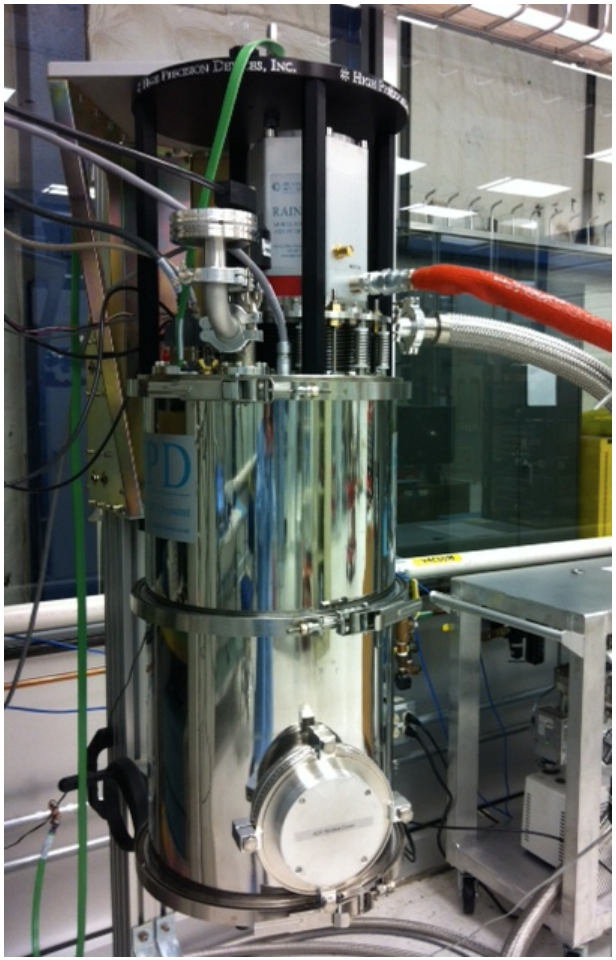


SCDMS: Future use of the ADR

- If SCDMS is approved, it will be desirable to further refine the joint design and test in the ADR.

Conclusions

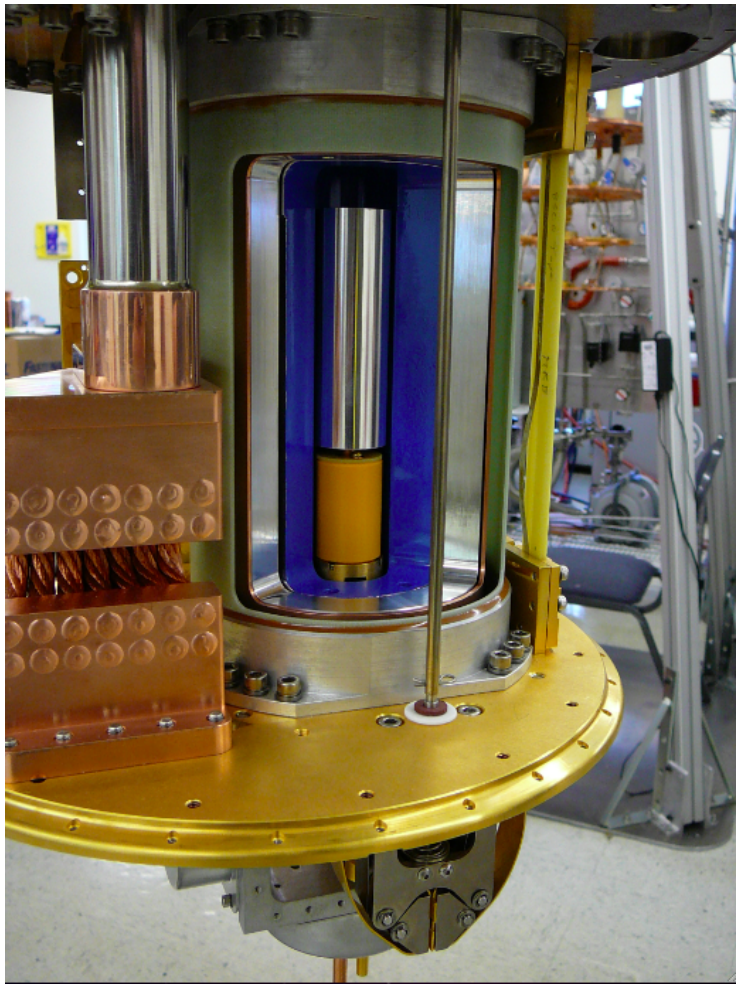
- Summary of each project that has used the millikelvin facility
  - Project overview
    - The ADR is attractive for a wide variety of applications.
  - Suitability of the ADR
    - Ability to reach 100 mK (and even lower)
    - Ability to readily change temperature from a few K to 100 mK (or less)
  - Future use of the ADR
    - There is continued demand for time on the ADR.



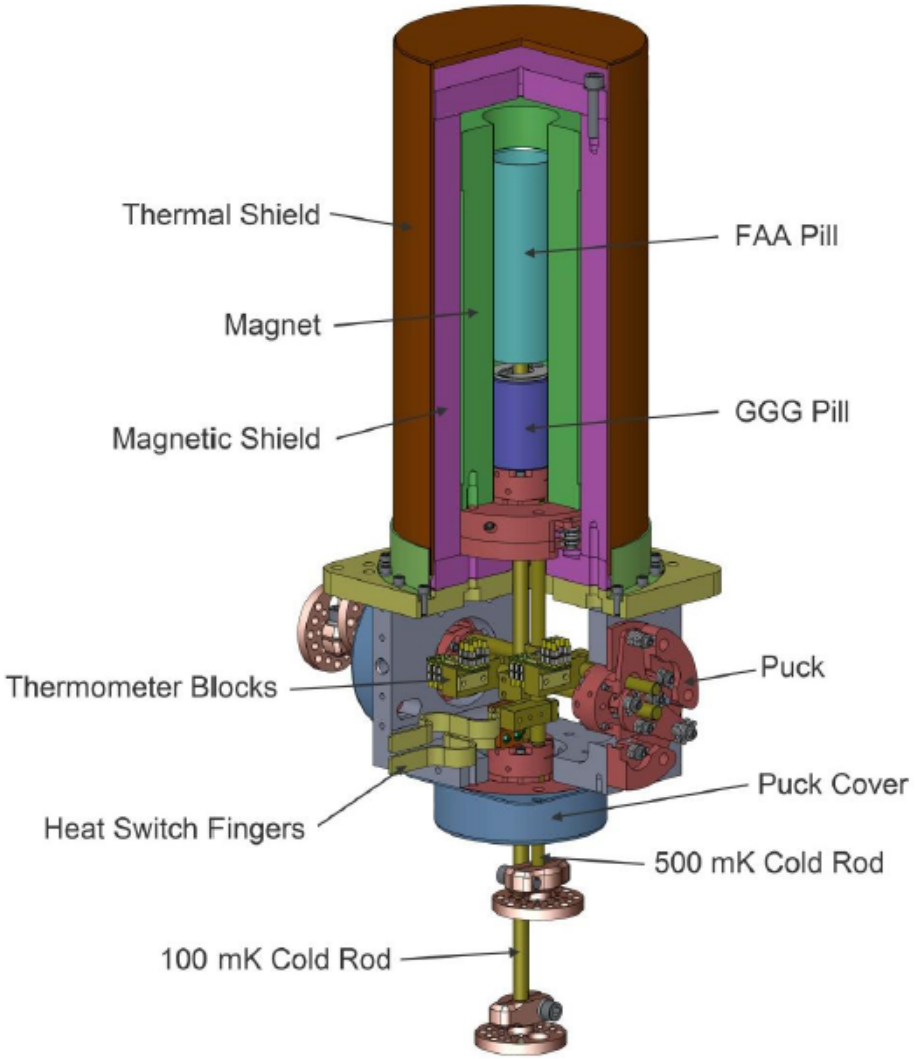
Thank you.

extra slides

Mockup of ADR

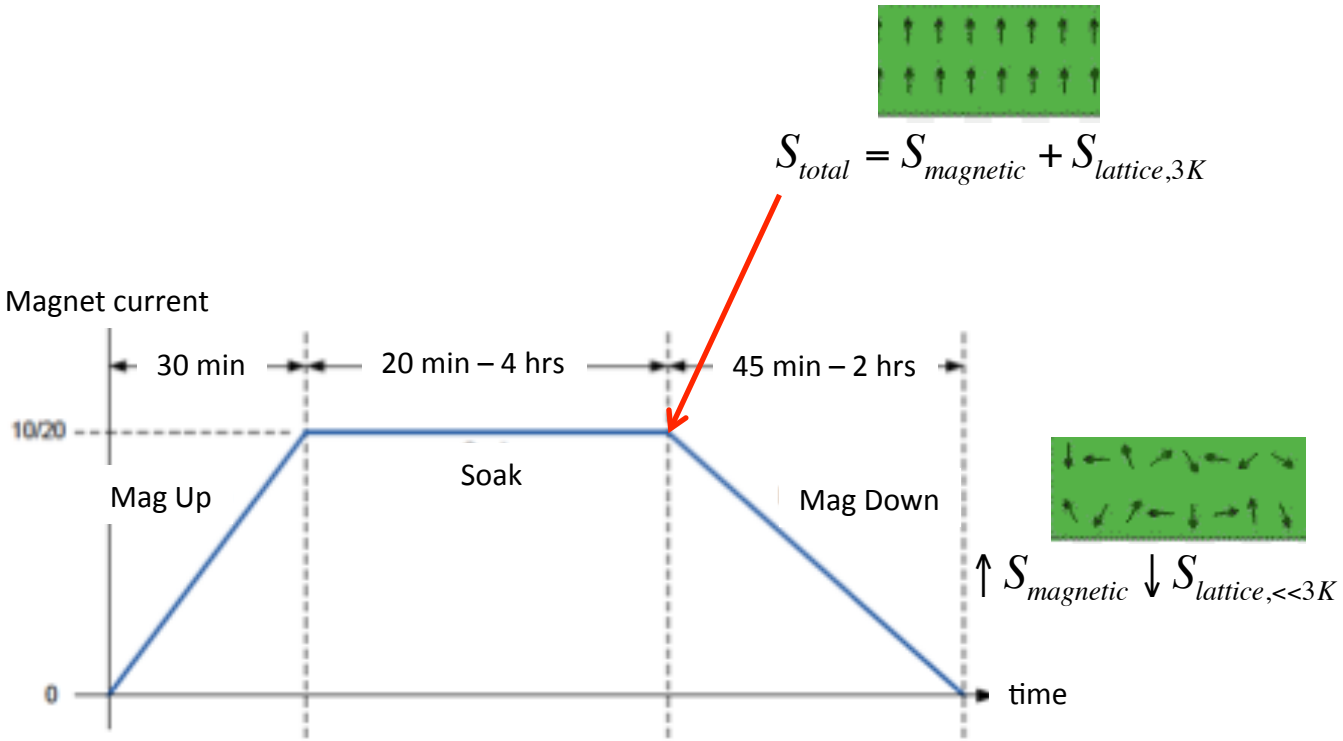


Mockup of ADR at HPD

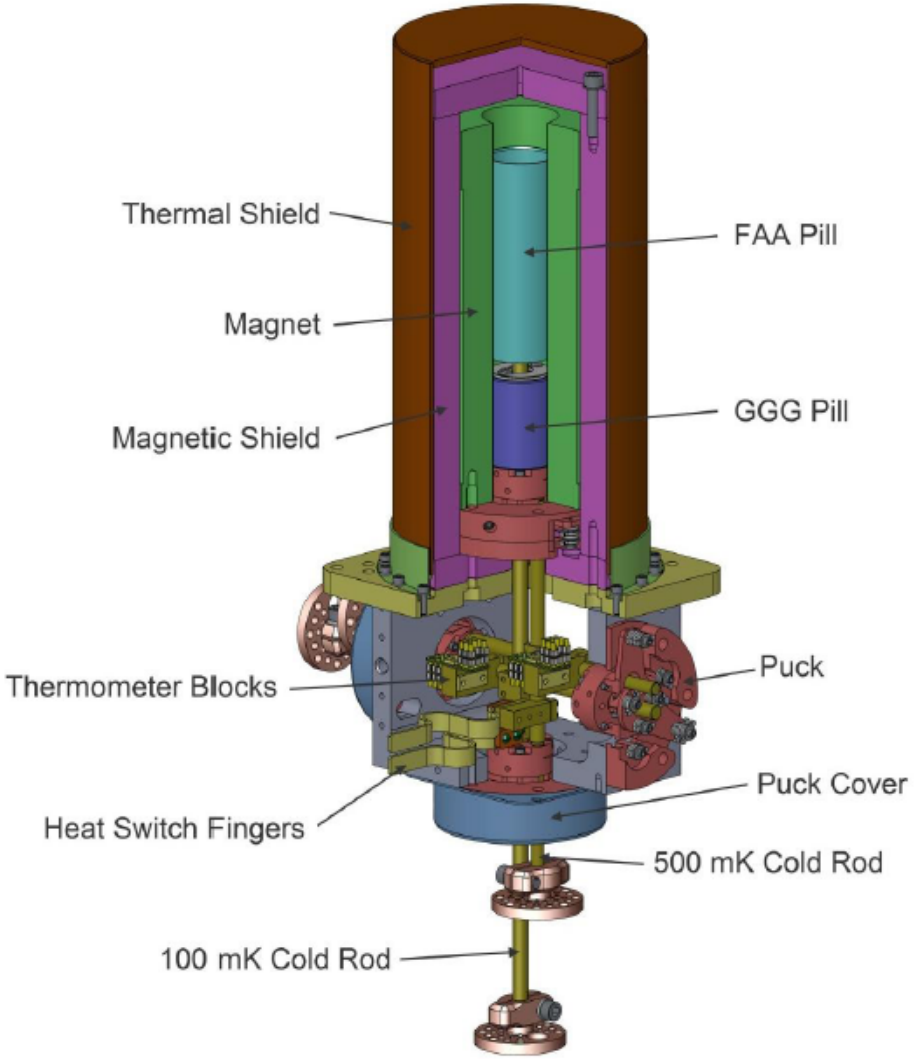


ADR

Adiabatic demagnetization

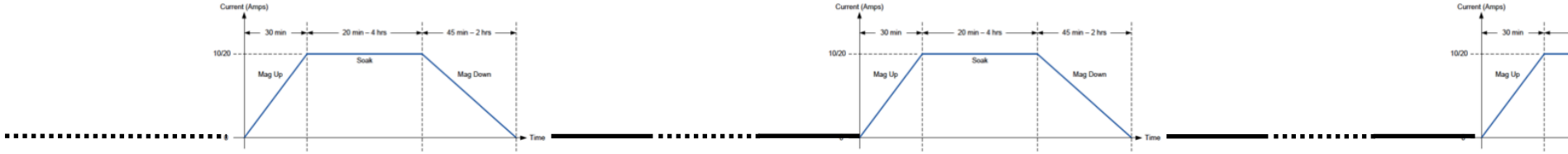


ADR specifications



- The ADR generates the coldest stage temperatures (500 mK and 50 mK).
- The ADR contains a superconducting 4 T magnet, a Gadolinium Gallium Garnet (GGG) paramagnetic salt pill, a Ferric Ammonium Alum (FAA) paramagnetic salt pill, a Hiperco 50 magnetic shield, and a Kevlar suspension system.
- The ADR generates cooling through adiabatic demagnetization of the paramagnetic salt pills.
- The Kevlar suspension isolates the salt pills from warmer stage temperatures while supporting experimental payloads of 2 kg or less.
- No-load GGG cooling capacity is ~1.0 J from base temperature to 1 K
- No-load FAA cooling capacity is ~100 mJ at 100 mK

ADR cycle



Initial cooldown to 3K ~20 hours

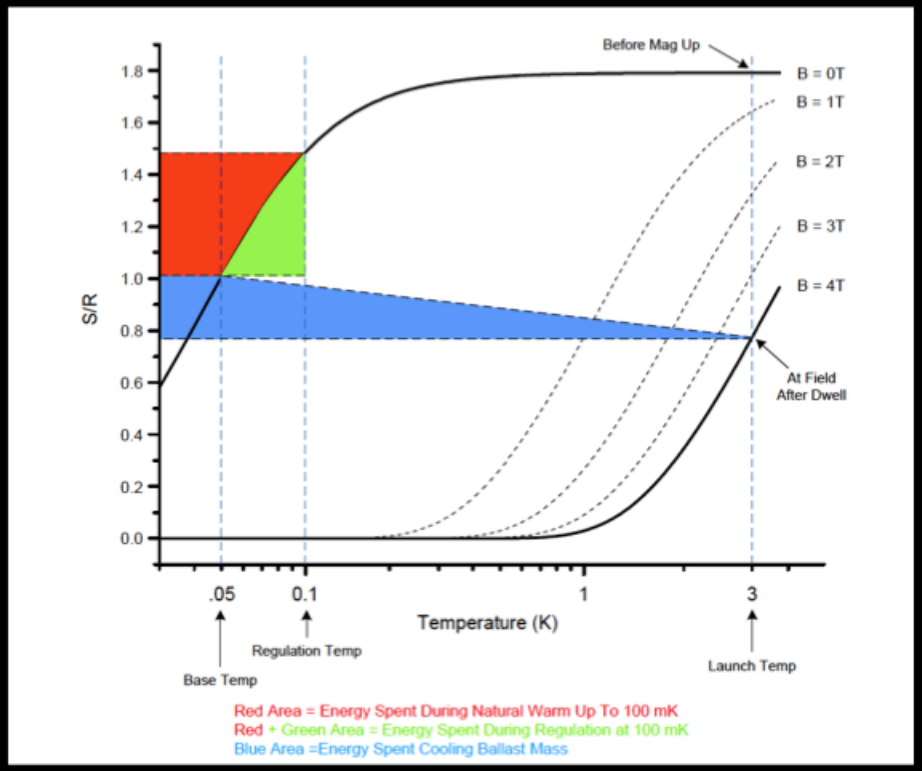
Mag cycle 2.5 - 6.5 hours

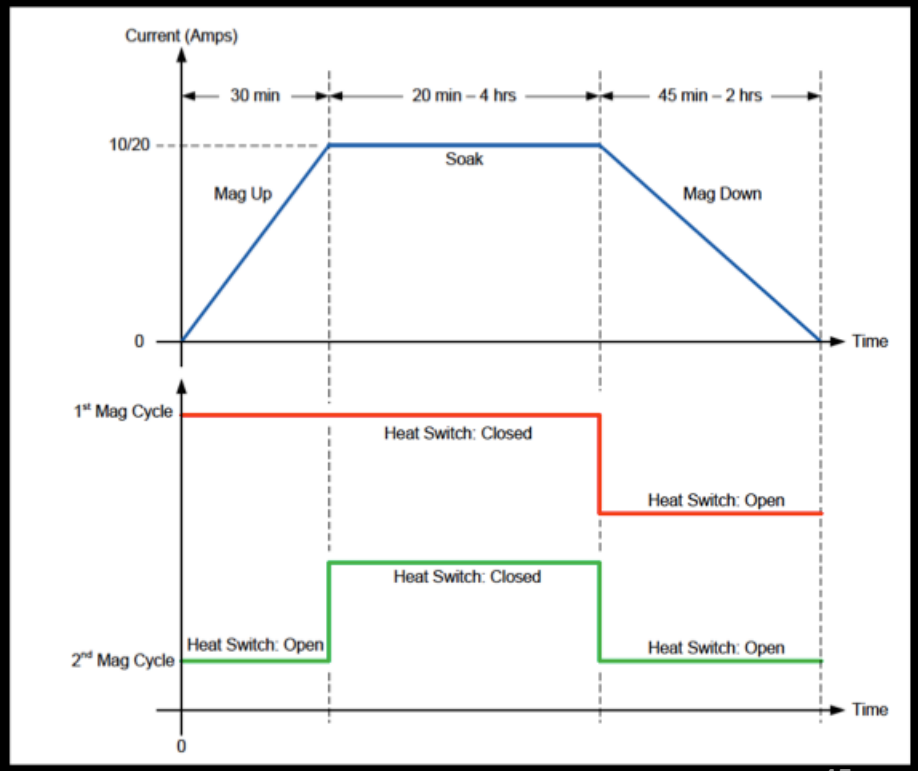
Do your experiment a few-150 hours (depending on temperature & heat load)

Mag cycle 2.5 - 6.5 hours

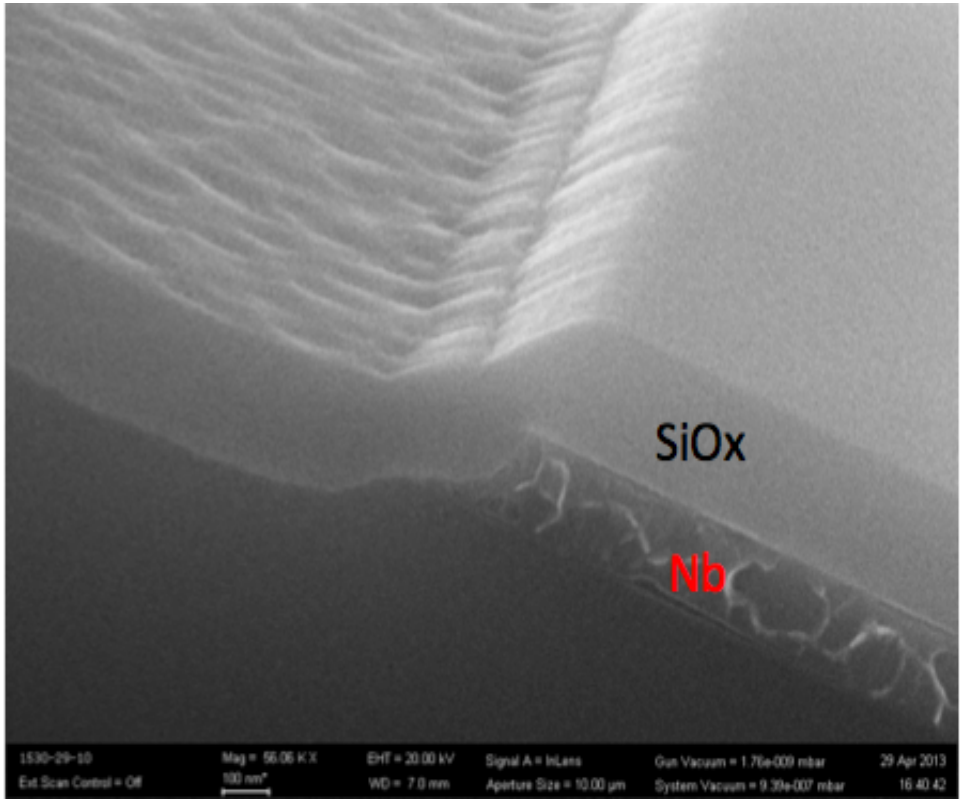
Do your experiment a few-150 hours (depending on temperature & heat load)

MAG cycle

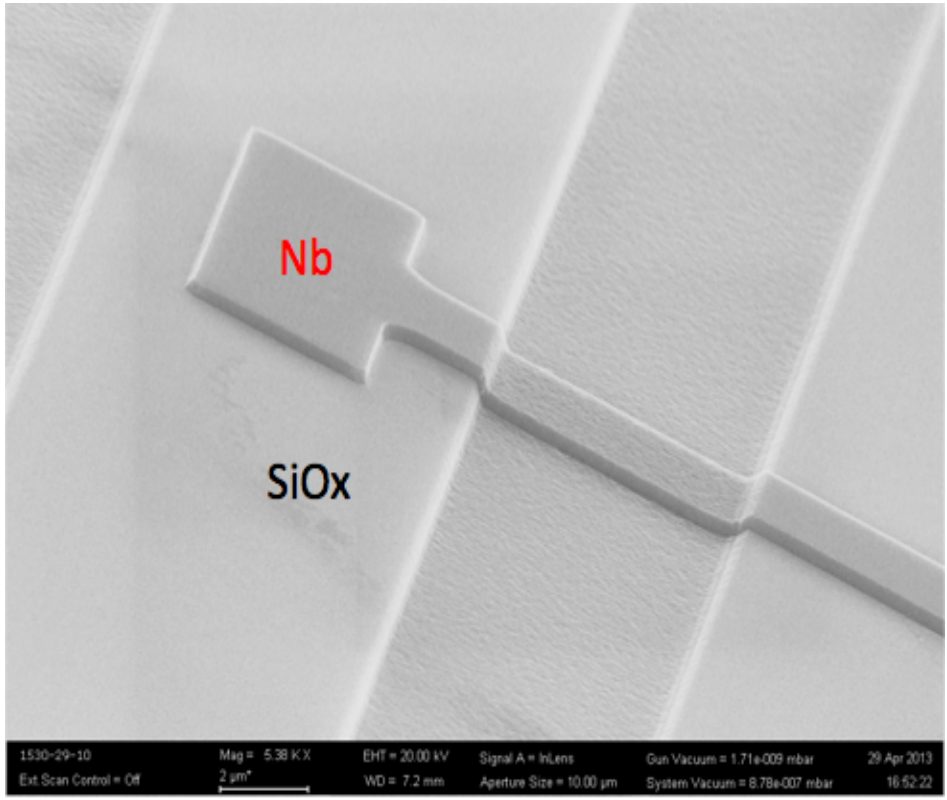

Before Mag Up
B = 0T
B = 1T
B = 2T
B = 3T
B = 4T
At Field
After Dwell
S/R
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
.05
0.1
1
3
Temperature (K)
Base Temp
Regulation Temp
Launch Temp
Red Area = Energy Spent During Natural Warm Up To 100 mK
Red + Green Area = Energy Spent During Regulation at 100 mK
Blue Area =Energy Spent Cooling Ballast Mass


Current (Amps)
30 min
20 min – 4 hrs
45 min – 2 hrs
10/20
Soak
Mag Up
Mag Down
0
Time
1st Mag Cycle
Heat Switch: Closed
Heat Switch: Open
Heat Switch: Closed
2nd Mag Cycle
Heat Switch: Open
Heat Switch: Open
Time
0

Improved Step Edge Coverage



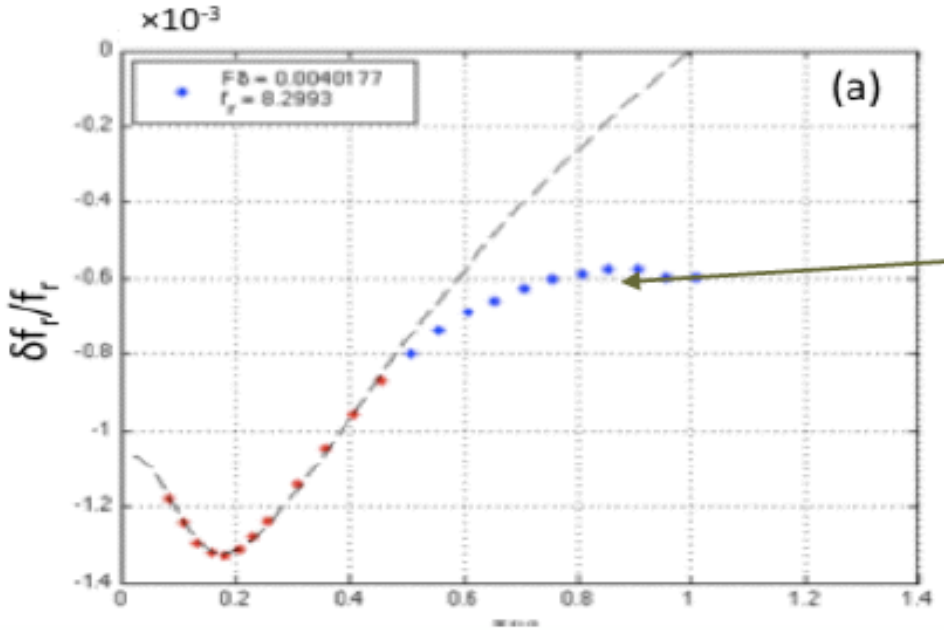
SEM image at the step edge of Nb ground plane.



SEM image of an Nb microstrip capacitivly coupled to a CPW transmission line (only the coupling end is shown).

Non-TLS states

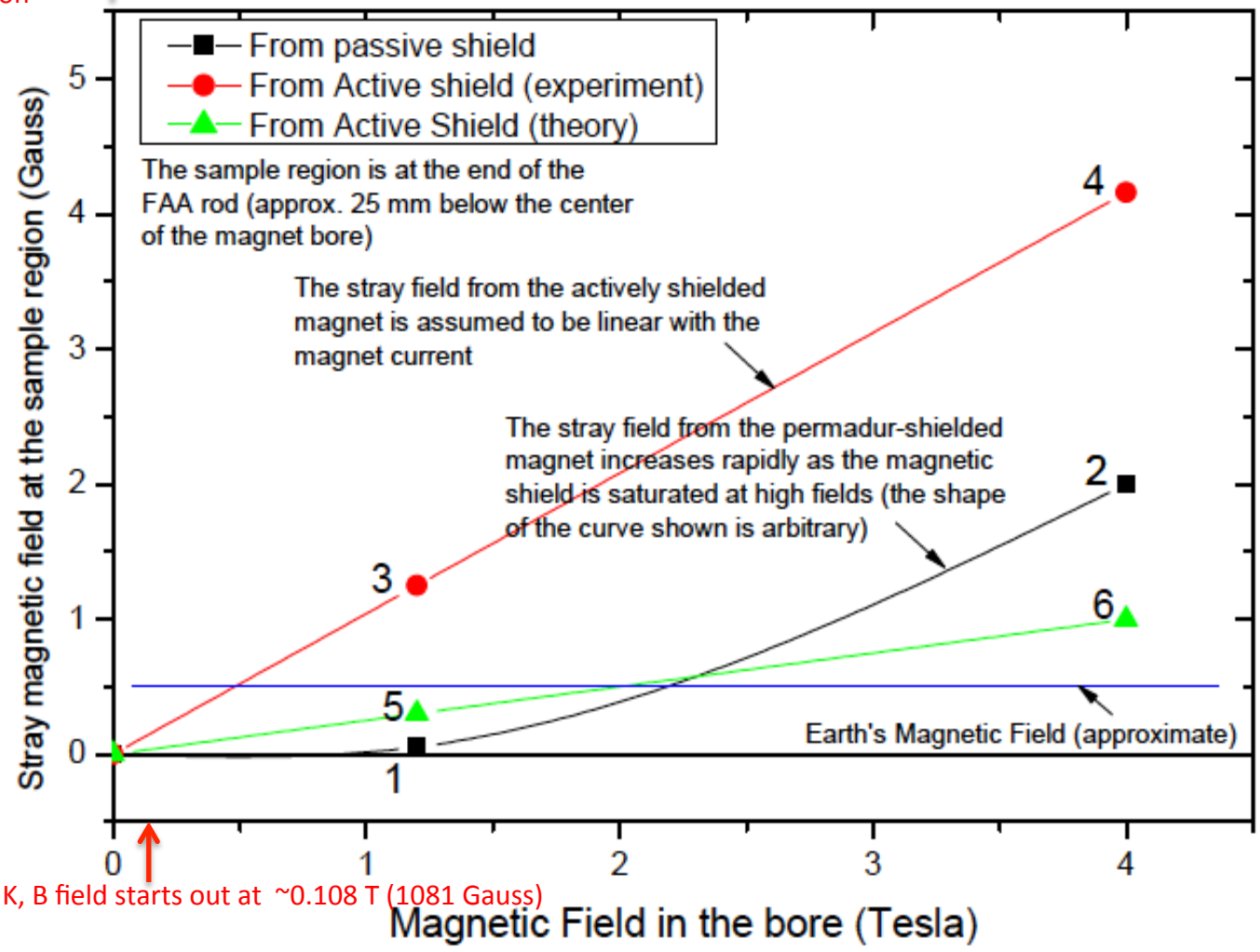
- δ_{TLS} lower limit on loss tangent at higher frequencies (150 GHz, 220 GHz)
- There can be other loss mechanisms (e.g. Cooper pairs with gap $E_{gap} < hf$)



Deviation from TLS model coming from thermally breaking Cooper pairs.

$T_c < 1K$; $E_{gap} < 3e\text{-}4$ eV
@150 GHz $hf = 6e\text{-}4$ eV

STJ requires 50 Gauss at sample region



At 100 mK, B field starts out at ~0.108 T (1081 Gauss)

Notes about the data points presented in the stray field plot.

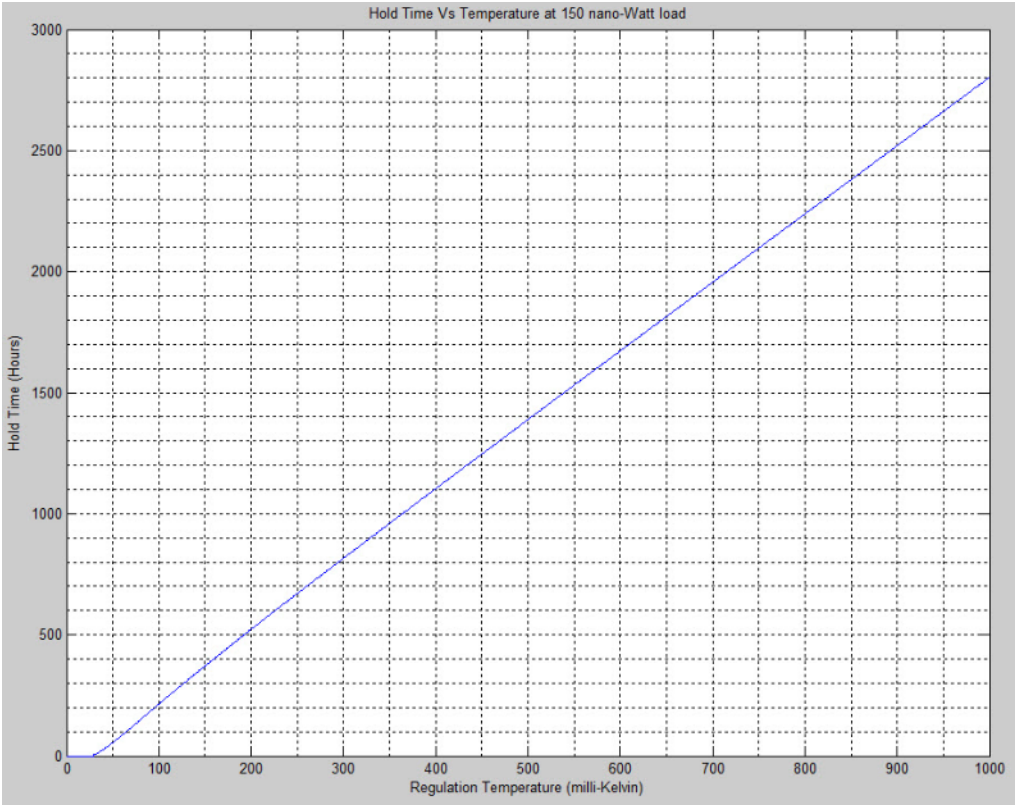
1. This point is measured from the field trapped in a superconducting magnetic shield with a T_c of 1 K (~6 Amps). Measurement by the John Martinis Group at UCSB.
2. This point is determined by a combined FEA analysis and magnetic field measurement taken outside of the cryostat by Vince Kotsubo and Doug Bennet at NIST.
3. This point is measured from the field trapped in a superconducting magnetic shield with a T_c of 1 K (~6 Amps). Measurement by the John Martinis Group at UCSB.
4. This point is extrapolated from point 3 assuming linearity of the stray field with current.
5. This point is extrapolated from point 6 assuming linearity of the stray field with current.
6. This point is calculated by AMI for for their actively-shielded magent design.

arcons

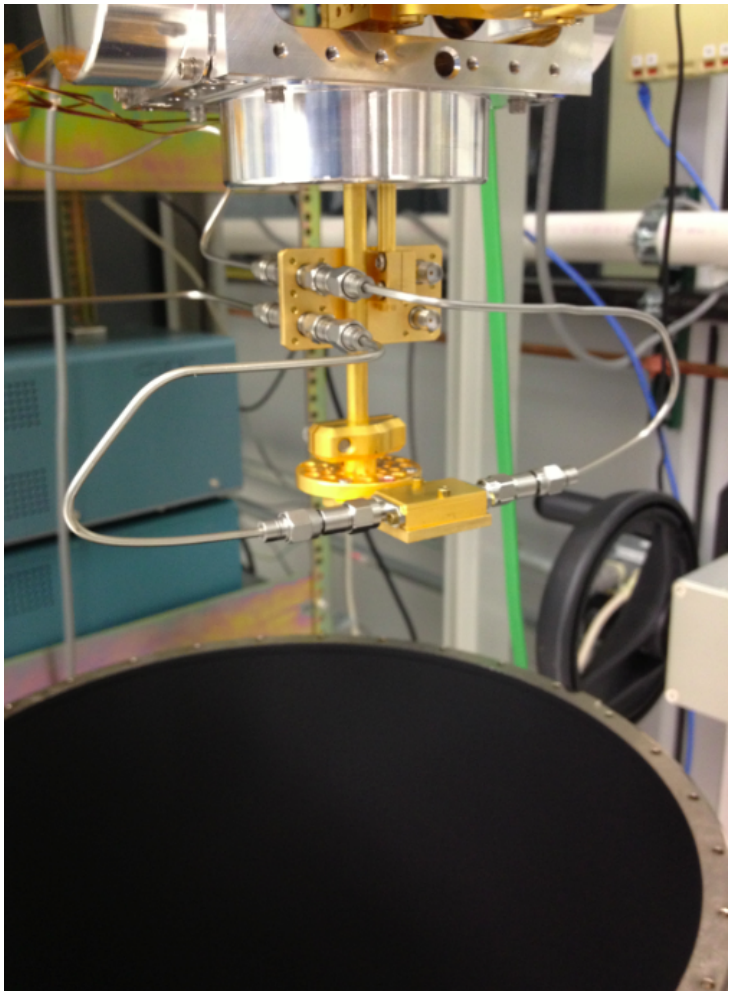
- 3-6 GHz
- 2MHz spacing

Hold time vs. temperature

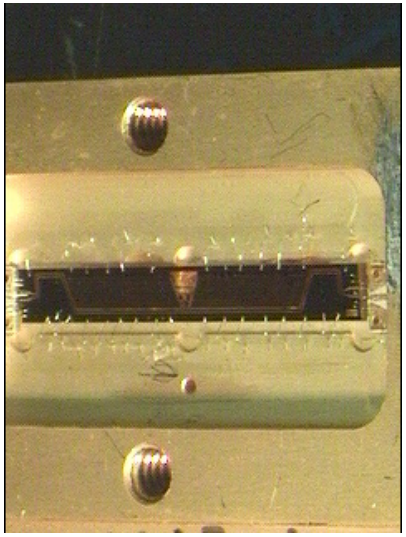
- HPD provided this graph of hold times vs. temperature.
- Note this assumes a small heat load 150 nW and regulation at 100 mK.

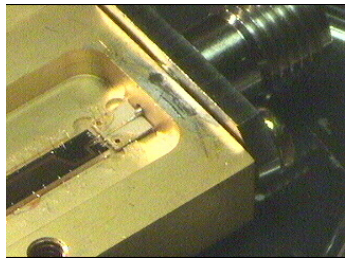


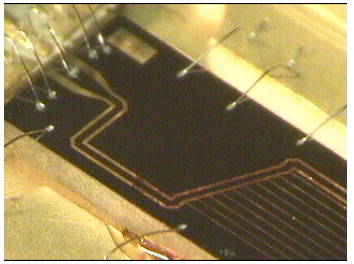
Testing ANL CPW MKID (20 resonators)



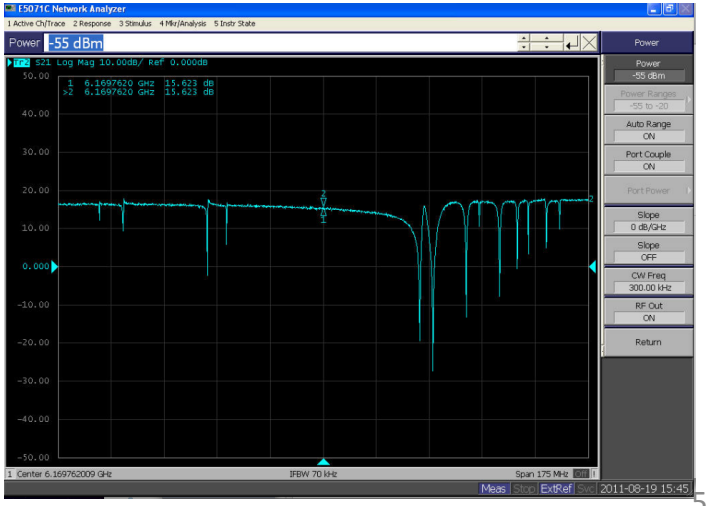
ANL CPW MKID installed in FNAL ADR





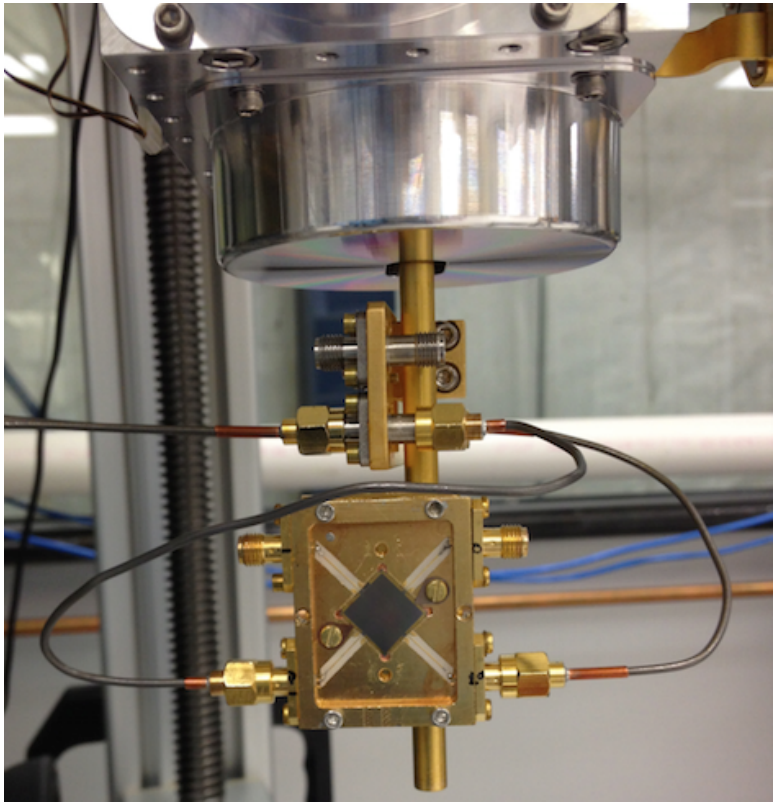


Al on Sapphire

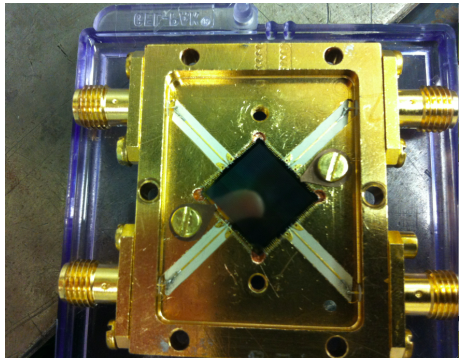


Center frequency = 6.17 GHz Span = 175 MHz

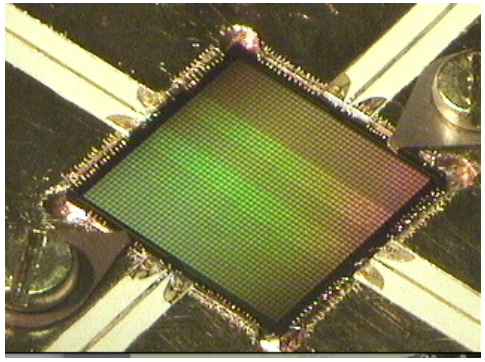
Testing ARCONS LEKID (2024 resonators)



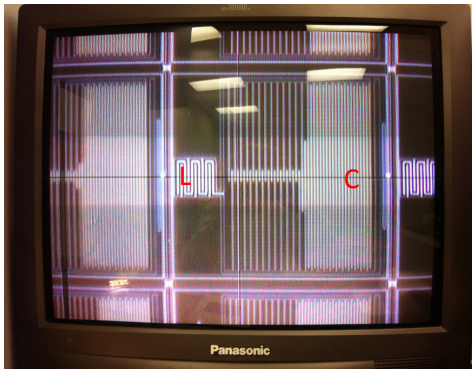
ARCONS LEKID installed in FNAL ADR



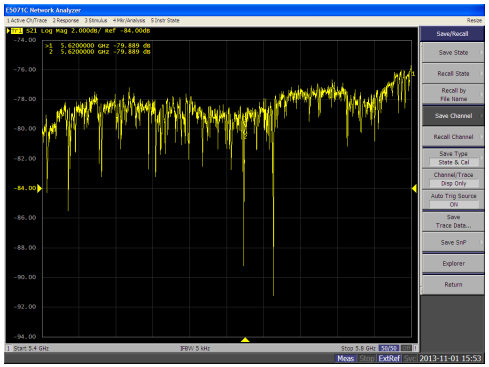
TiN on Silicon



2024 resonators



One resonator



Many resonances from a subset of the array (5.4 GHz - 5.8 GHz)

MKIDS: Suitability of the ADR

- First, the energy resolution of an MKID is proportional to the superconducting gap energy (Δ), so want to chose a material for the resonator with small Δ.
- Second, it is desirable to minimize the number of quasiparticles in the superconductor.
  - When a photon strikes the MKID, a number of quasiparticles are created based on the photon energy.
  - If there are already a large number of quasiparticles, it will be difficult to resolve how many were generated by the incident photon (producing change in surface impedance measured by MKIDs)
  - The quasiparticle density in a superconductor is strongly dependent on temperature: Below ~$0.1T_C$, the quasi-particle density is about what it would be at 0 K and is very small. So, want to operate <$0.1T_C$.

Material	T_c (K)	Δ (meV)	0.1 * T_c (K)
Al (ANL MKID)	1.2	0.18	0.12
Ta	4.47	0.67	0.45
TiN (ARCONS)	5.6	0.84	0.56
Nb	9.3	1.40	0.93

- These temperatures are achievable with the ADR.