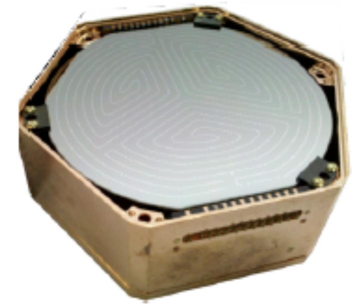


SuperCDMS SNOLAB

CD2/CD3 Review

1.1.6 Tower Wiring and Electronics

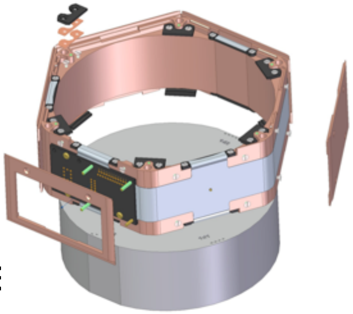
Per Hansson Adrian

Jan. 24-25, 2018

Key Deliverables for WBS 1.1.6

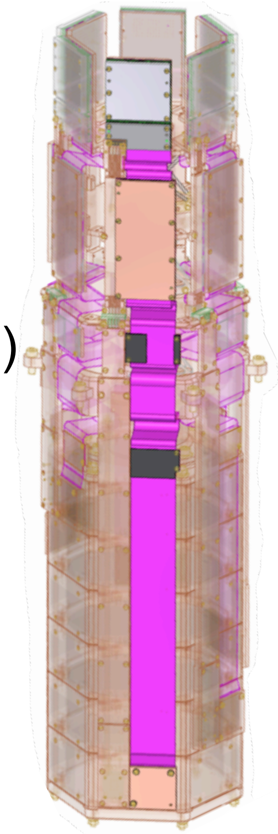
WBS 1.1.6.1 Horizontal flex cable

- Interface to detectors



WBS 1.1.6.2 Vertical flex cable

- Superconducting wiring with cryogenic electronics mounted on stiffe
- Connect tower to room temperature cabling (part of WBS 1.5)



WBS 1.1.6.3 HEMTs (High Electron Mobility Transistors)

- Provide ionization readout and amplification

WBS 1.1.6.4 SQUIDs (Superconducting Quantum Interface Device)

- Provide Transition Edge Sensor (TES) resistance sense and amplification

Electrical interfaces to vacuum coax assembly

- Vacuum coax assembly part of WBS 1.1.5

Flow-down of Science Goals to Technical Requirements

- Ultimately tower electronics requirements are derived from modeling the detector and electronics together
  - Energy resolution goals and requirements levels presented in TDR includes modeling of the readout electronic performance
  - Technical requirements on the tower electronics contributions is extracted from these models
  - Requirements are extracted using ideal circuit behaviors and unaffected by warm electronics

Science Goals

SG-1 Search for dark matter particles with masses below 10 GeV/c^2 using complementary target nuclei (germanium and silicon) and complementary techniques (iZIP and HV) that will provide an understanding of residual backgrounds.

SG-2 Design for the possibility of future upgrades that would further increase the low-mass sensitivity of the experiment to the level where solar neutrinos are detected.

Technical Requirements

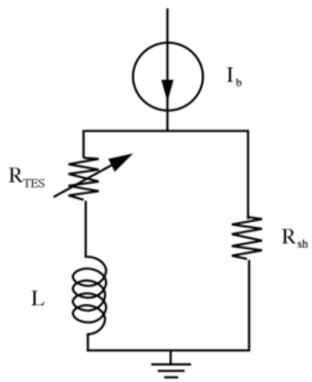
	Required	Goal
HV detectors		
Phonon energy resolution (σ) for Ge (Si)	50 (35) eV_t	10 (7) eV_t
Minimum bias voltage	50 V	100 V
iZIP detectors		
Phonon energy resolution (σ) for Ge (Si)	100 (50) eV_t	50 (25) eV_t
Charge energy resolution (σ) for Ge (Si)	300 (330) eV_{ee}	160 (180) eV_{ee}
Bandwidth for DAQ/trigger system	50 MB/s	100 MB/s

Flow-down of Science Goals to Technical Requirements

Phonon Signal

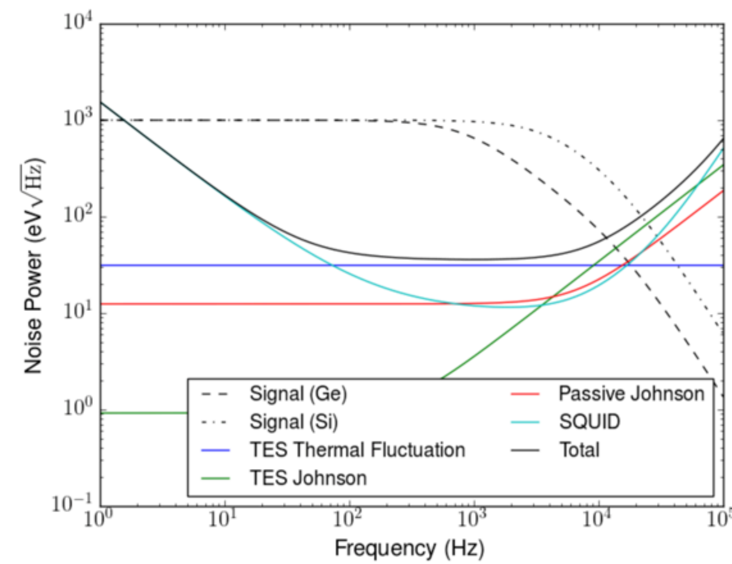
- Overall design goal is to be limited by intrinsic TES noise

- Sets overall SQUID noise spectral requirements
  - White noise region: <4.5pA/√Hz
  - @ 100Hz: <10pA/√Hz



Parameter	Design Value CDMS-HV	Design Value iZIP
Crystal Temperature	<30 mK	
TES Parameters		
Length	200 μm	155 μm
Normal State Resistance	150 mΩ	
Operating Resistance	50 mΩ	
Loop Inductance	$\ll$ 500 nH	
Shunt Resistance	5 mΩ	
Parasitic Resistance	$<$ 5 mΩ	
α $\left(\frac{R_0}{T_c}\frac{dR}{dT}\Big\vert_{I_0}\right)$	$\sim$ 150	
$\vert\beta\vert$ $\left(\frac{R_0}{I_0}\frac{dR}{dI}\Big\vert_{T_c}\right)$	$<$ 0.3	
T_c	40-45 mK	40-60 mK
Risetime (L/R)	2-3 μs	2-4 μs
Falltime (τ_{TES})	30-40 μs	10-40 μs

- Additionally, component requirements on "TES signal loop" comes from voltage bias and stability (electro-thermal oscillations)
  - Parasitic resistance small compared to TES resistance
  - Shunt resistance small compared to TES resistance
  - "TES loop" inductance small to limit L/R time (avoid electro-thermal oscillations and limited bandwidth)



Flow-down of Science Goals to Technical Requirements

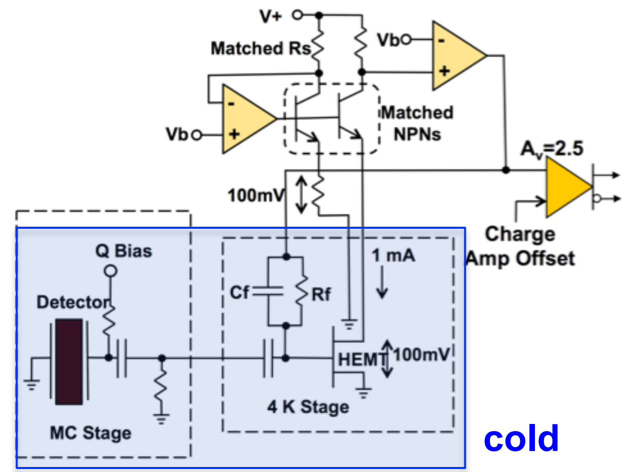
Ionization signal

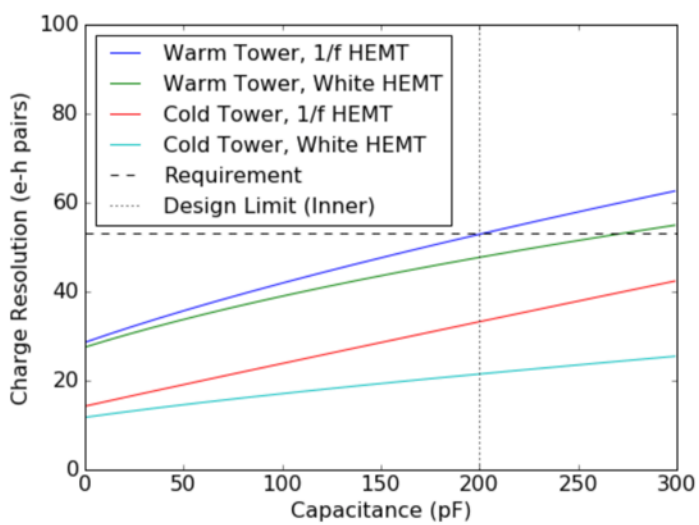
- Energy resolution determined by readout electronics noise and bandwidth

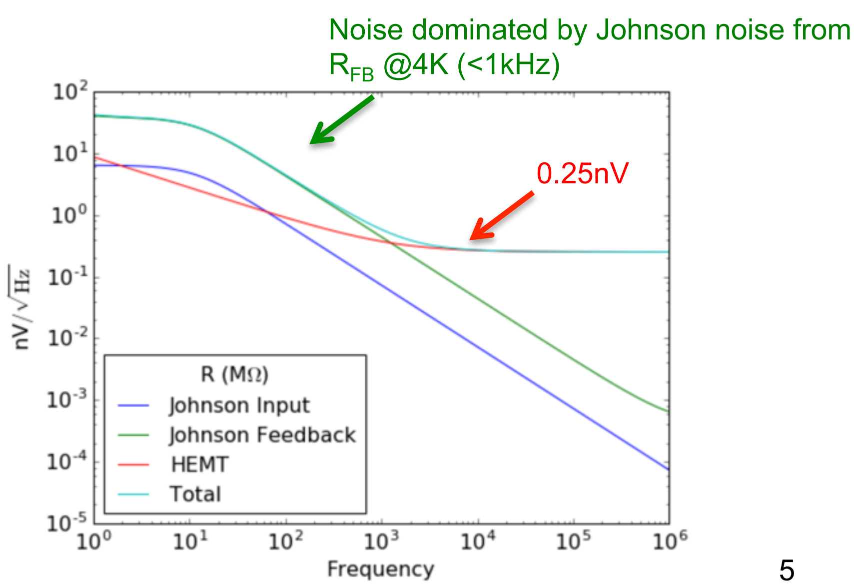
- Requirements extracted by modeling circuit component contributions
  - HEMT 1st stage amplifier (characterized noise spectra)
  - Warm electronics monitoring feedback considered to be ideal

- Power dissipation requirement met with HEMT (<100μW/device)

- Design resolution goal met and comfortably within requirement with
  - Stray capacitance <20pF (@HEMT input, C_{det} fixed at 200pF)
  - HEMT input noise spec: <0.25nV/√Hz (white) and <3nV/√Hz @100Hz
  - Feedback resistors >400MOhm







Sup

Organization

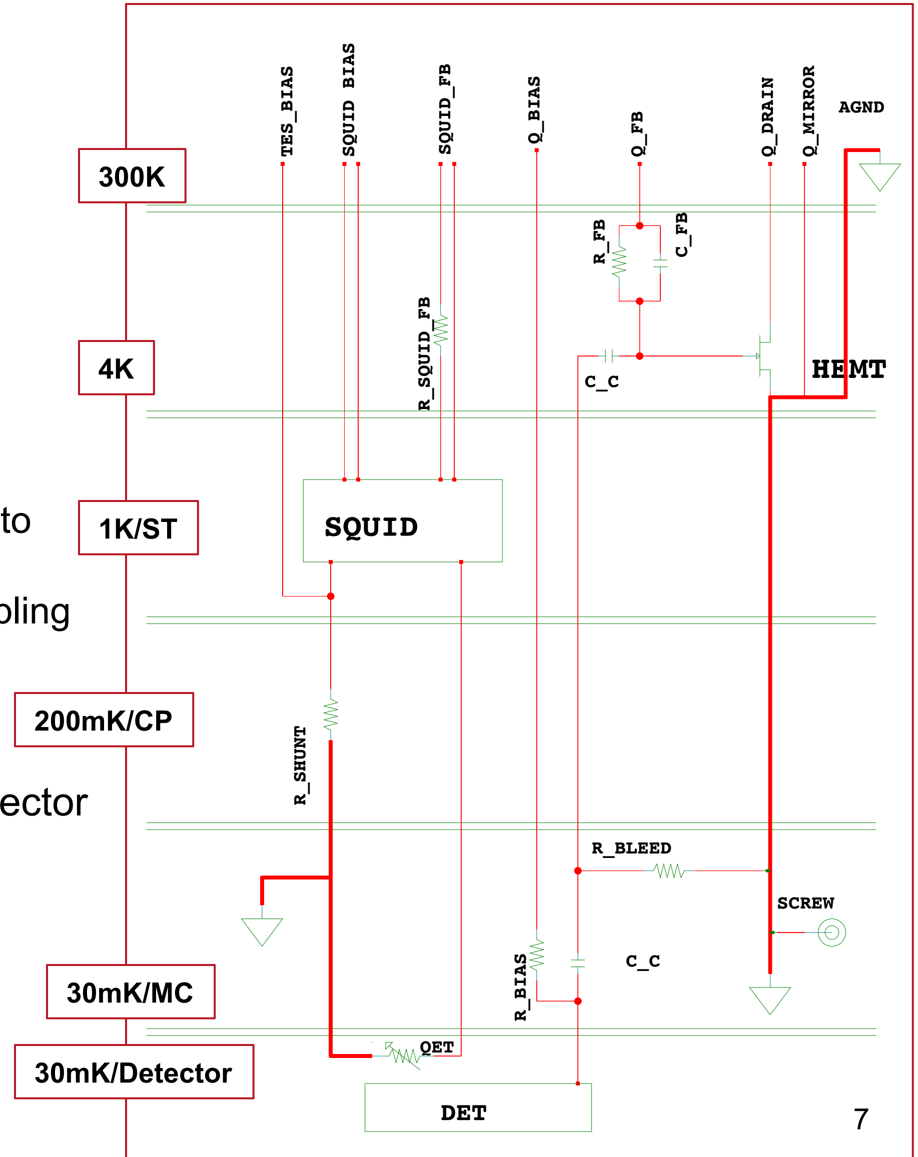
L3 Manager: Per Hansson Adrian (SLAC)
Deputy: Martin Huber (CU Denver)

- Electronics layout
  - In-house layout group at SLAC led by Tung Phan
- Electronics assembly
  - In-house electrical shop at SLAC
  - Wirebonding and micro-assembly expertise: Matt Cherry (SLAC & SuperCDMS) and Jasmine Hasi (SLAC)
- Electronics support
  - SLAC TID-AIR Electrical Systems group
  - Physicists in SuperCDMS
- Technician support
  - Matt McCulloch (SLAC)
  - Leo Manger (SLAC)
  - Bob Conley (SLAC)

Tower Wiring Overview

iZIP

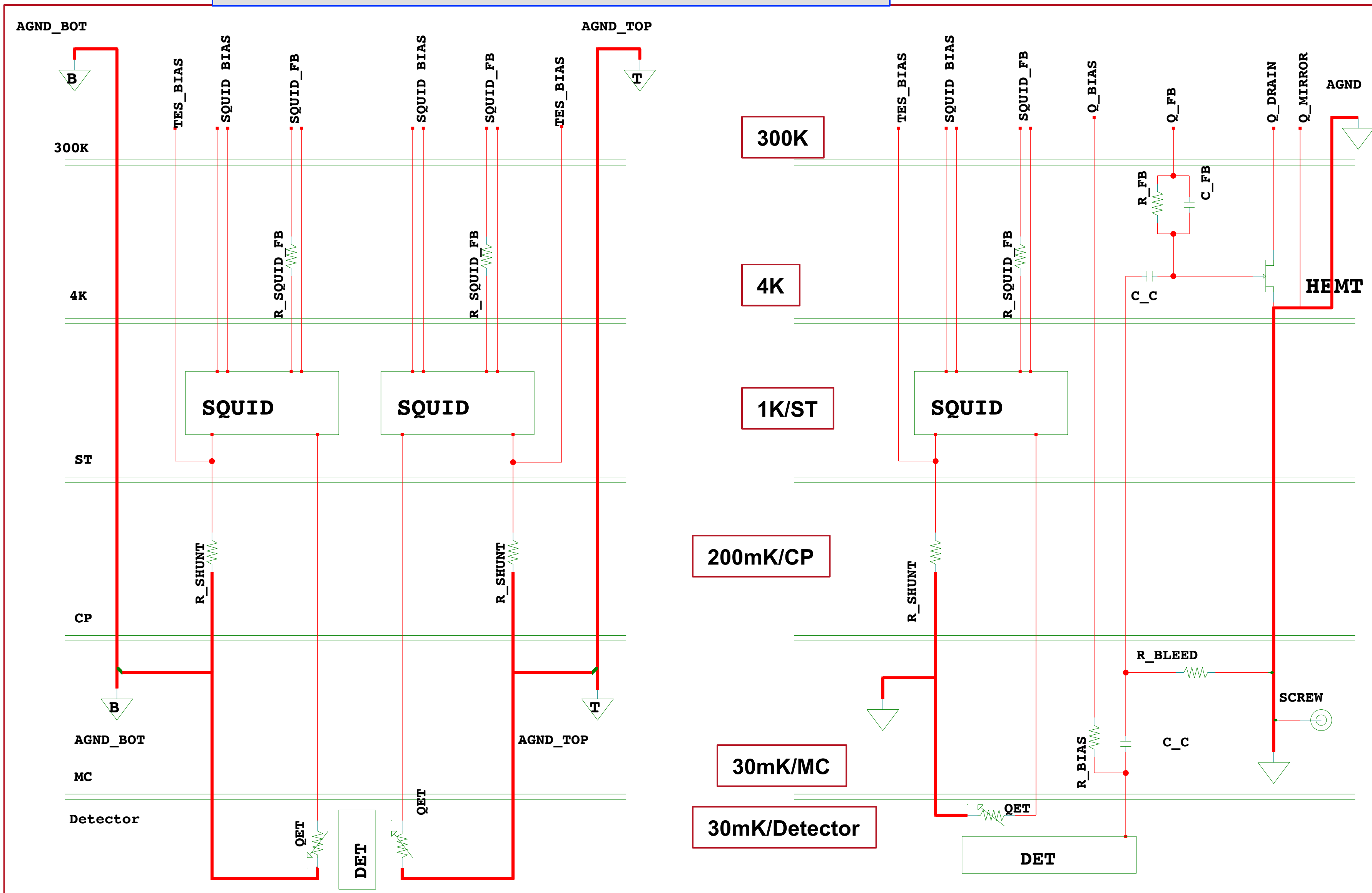
- Wiring extends from 4K down to detector temperature: must provide low thermal conductance
- Key components
  - SQUID readout of phonon channels
  - HEMT readout of ionization
  - LEDs to neutralize trapping sites
- Location of electrical components optimized
  - Bias and bleed-through resistors at 30mK to minimize noise (and avoid charge-up)
  - Ionization feedback resistor at 4K (de-coupling cap. prevents lower)
  - Ground referenced to detector stage
- Total of 12 phonon, 4 ionization channels/detector
- All material/components need to fit inside radiopurity budget



Tower W

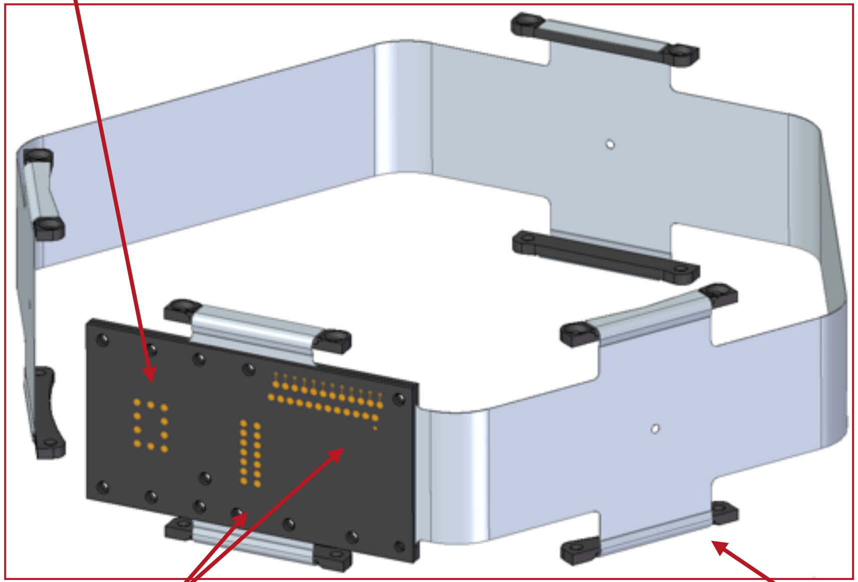
- HV vs iZIP
  - Bias detectors by floating top/bottom to ±50V
  - No ionization channels
  - Almost identical cold hardware

iZIP



Horizontal Flex Cable

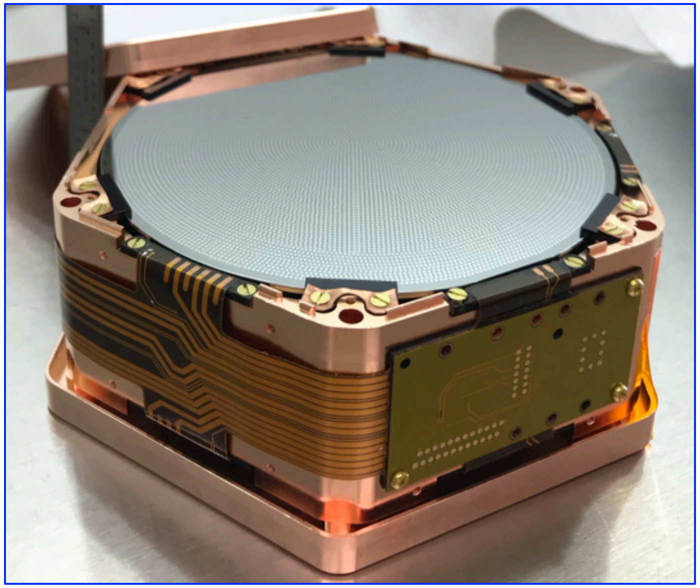
- Connects from detector wirebonds to vertical flex and vacuum coax
- Mount points for LEDs



Connectors to interface with vertical flex cable

Wirebonds to detector and LEDs on Detector Interface Boards (DIBs)

Prototype Cu horizontal flex



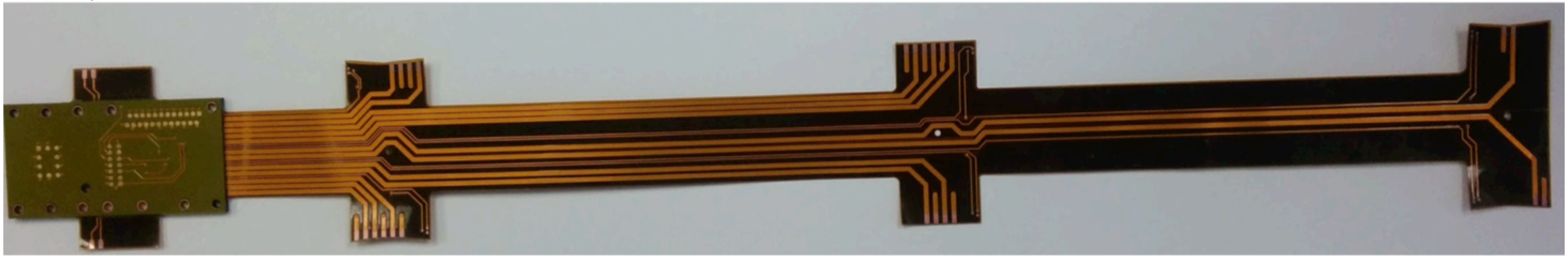
Horizontal Flex Cable Design

Rigid flex PCB (~13”x1.6”)

- **Superconductive**: two inner layers are fully tin-plated (<<1mOhm parasitic)
- **Superconductive low resistance connectors**: fuzz buttons (<1mOhm)
- **Low inductance**: wide traces/full ground plane (~34nH <<500nH)
- No components on rigid board for improved handling/packaging

Two almost identical versions: HV has split ground plane to enable floating each side

Prototype Cu horizontal flex

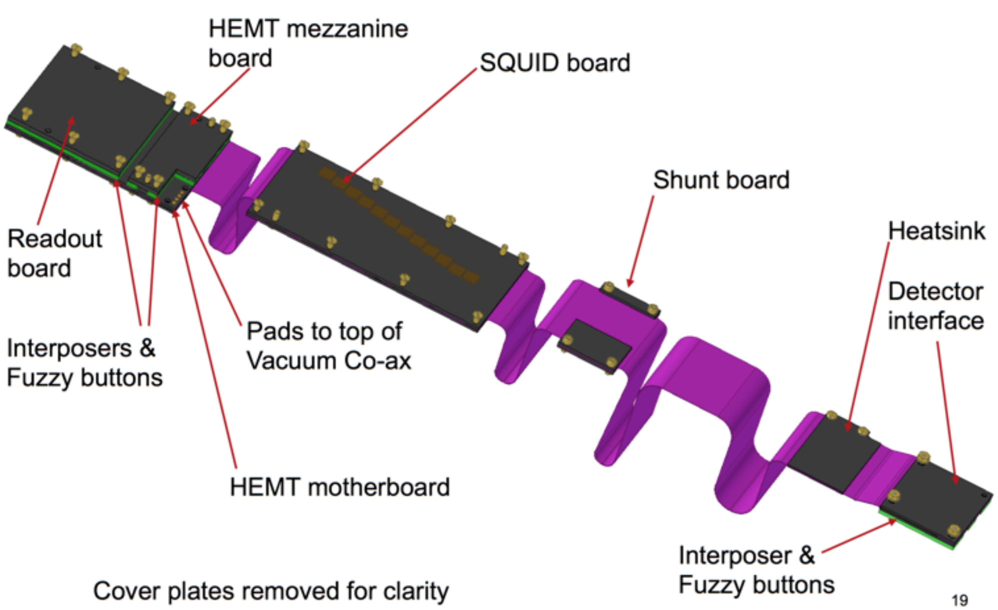


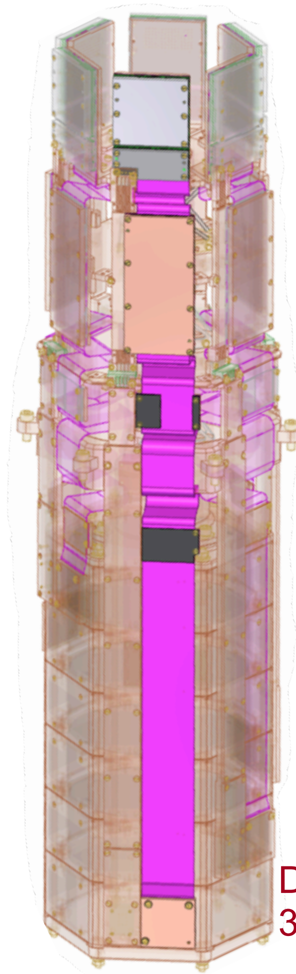
- Prototype copper cable version built and used in testing
- Tin-copper design meets all requirements and is out for fabrication
  - Improvements: Radiopure connectors, superconducting to minimize parasitic resistance, lower inductance

Preproduction Horizontal Flex in Fabrication

Vertical Flex Cable

Superconducting wiring with cryogenic electronics mounted on stiffener boards



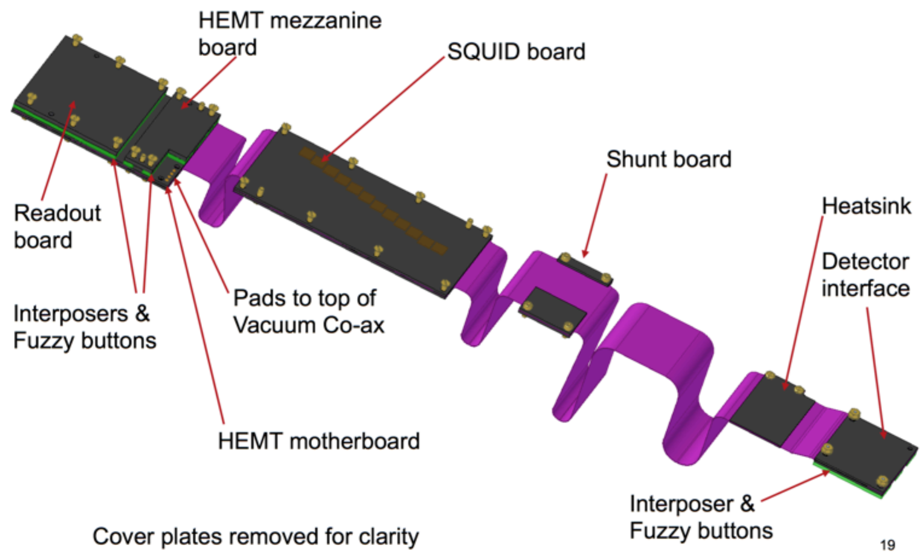


Vertical Flex Cable Design

Rigid flex circuit design

- **Superconducting**
  - NbTi traces for low thermal conductivity
  - Meets parasitic resistance <1mOhm requirement
- **Cirlex rigid boards**
  - Multilayer sections to house components and interconnections
  - Radiopurity constraint prevent use of FR4
- **Cu-plated through-holes**
  - Etch Cu from sections between rigid boards
  - Interfaces with conventional PCB fabrication process
- **Low inductance**
  - Wide traces and ground planes for TES signal
  - Meet "TES loop" requirement (contributes <50nH to required <<500nH)

Overall complexity and non-standard materials makes this challenging



- Circuit for ionization readout on mezzanine board
  - Flexibility of circuit design (upgrades)
  - Easier Q/A screening

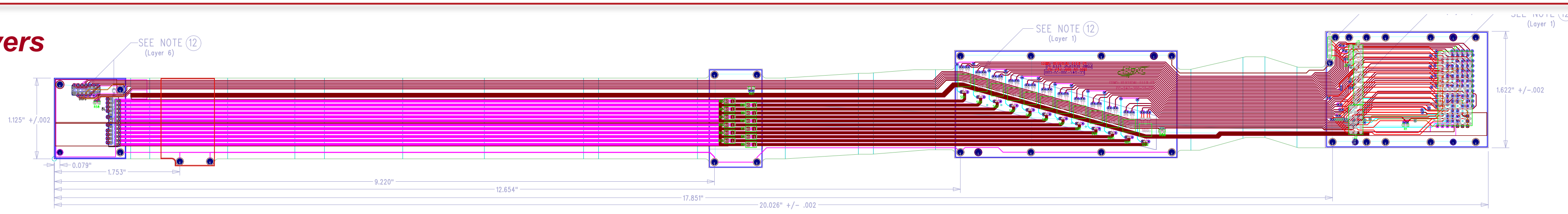
⇒ **Single design for iZip and HV towers**

Vertical Flex Cable Design Details

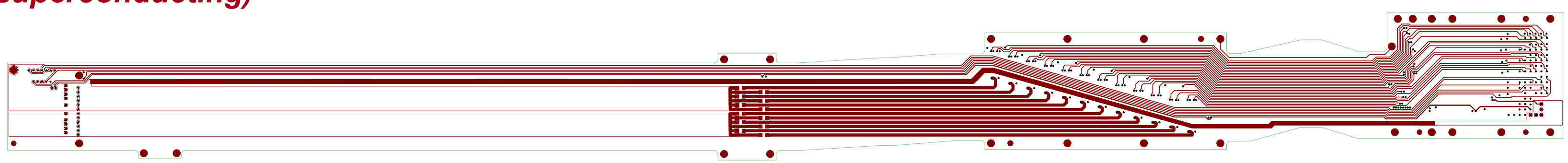
Rigid-flex circuit design

- 2-layer flex (super-conducting)
- 6-layer rigid board sections (2x Cirlex core)

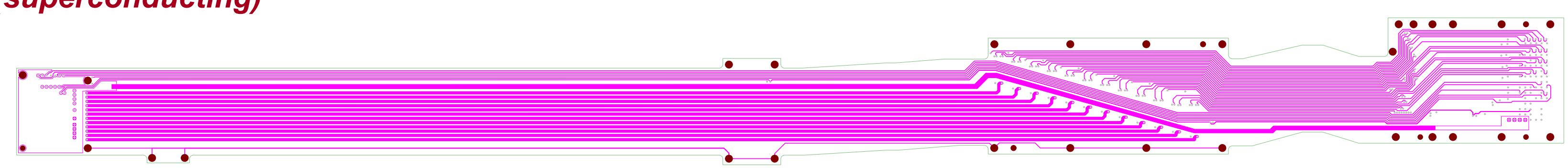
All layers



Layer 3 (superconducting)



Layer 4 (superconducting)



Vertical Flex Cable: Development and Progress since last review

Successful fabrication of Ti-15-3-3-3 prototype vertical flex cable (Basic Electronics Inc.)

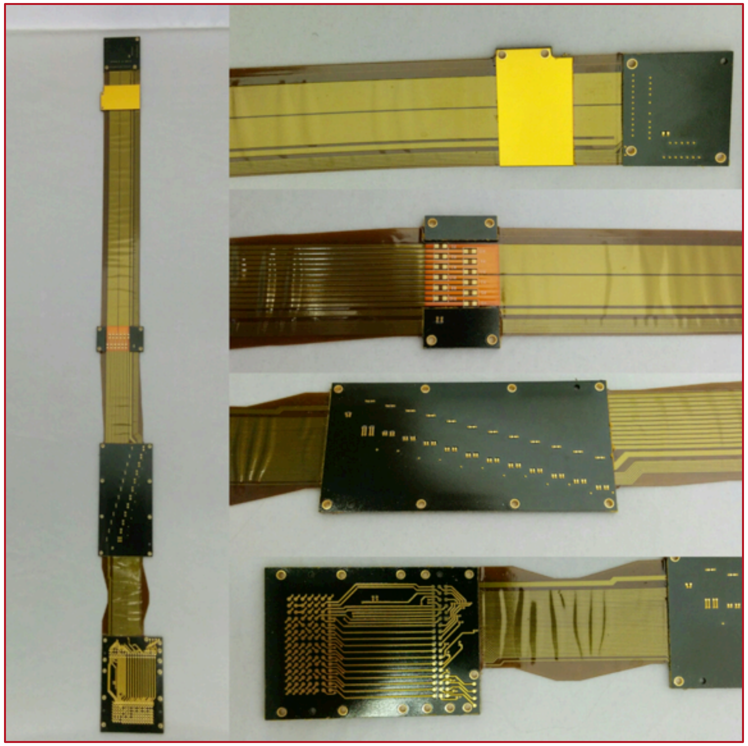
- Closed out open R&D for the project
- Electrical checkout and thermal behavior as expected; noise studies ongoing
- Engineering an improvement to mechanical integration on tower to account for difference in stiffness and ductility compared to model
- Yield still an important question going towards NbTi (4/7 show several open/high R channels, etch problem from plating)

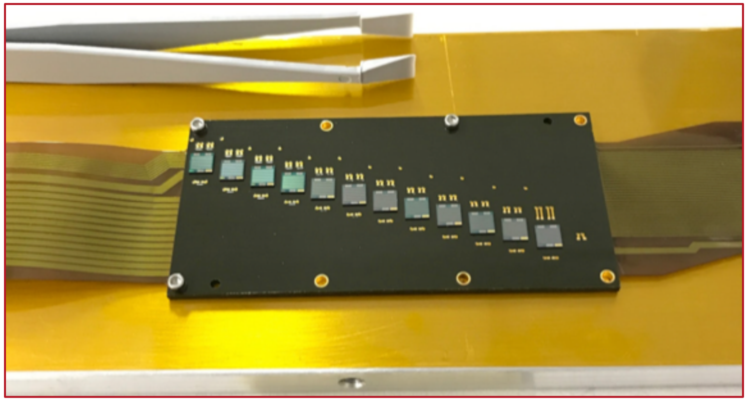
Demonstrated key performance requirements on superconducting flex cable

- Superconductivity and parasitic resistance (from e.g. plated through-holes)
- Measured expected inductance for TES signals satisfying design requirement
- Mounted SQUIDs, HEMTs and passive components and demonstrated noise performance

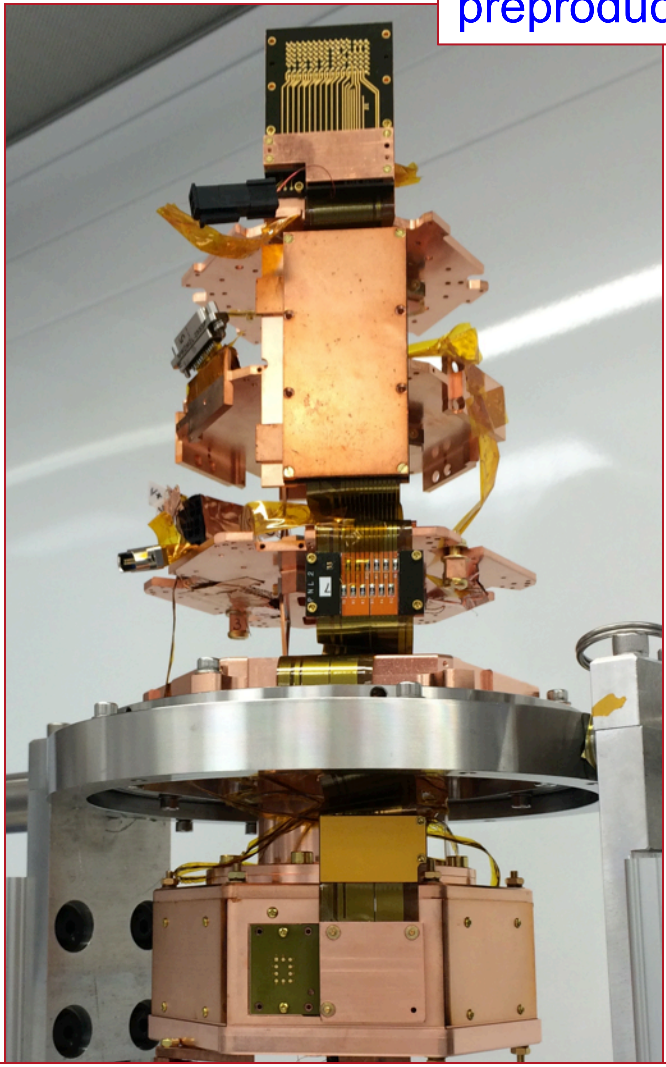
Fabrication ongoing for preproduction NbTi version; leveraging Ti prototype fabrication experience (PTH size and non-standard pads, drilling procedures, handling)

Ti Prototype Vertical Flex Cable





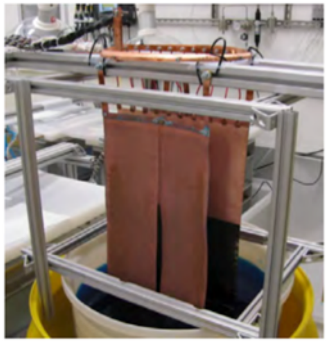
Assembled on preproduction tower

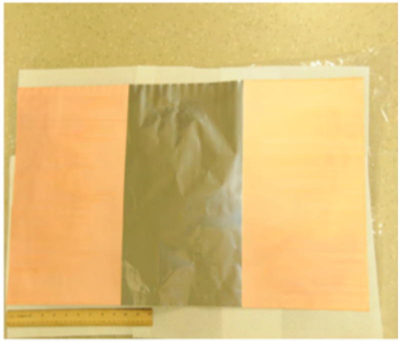


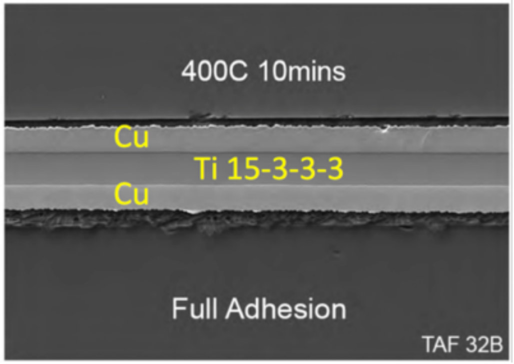
Minimum bend radius exceeded with no support – see M. Oriunno's talk for mitigation plan

Ti Test Flex Cable Results

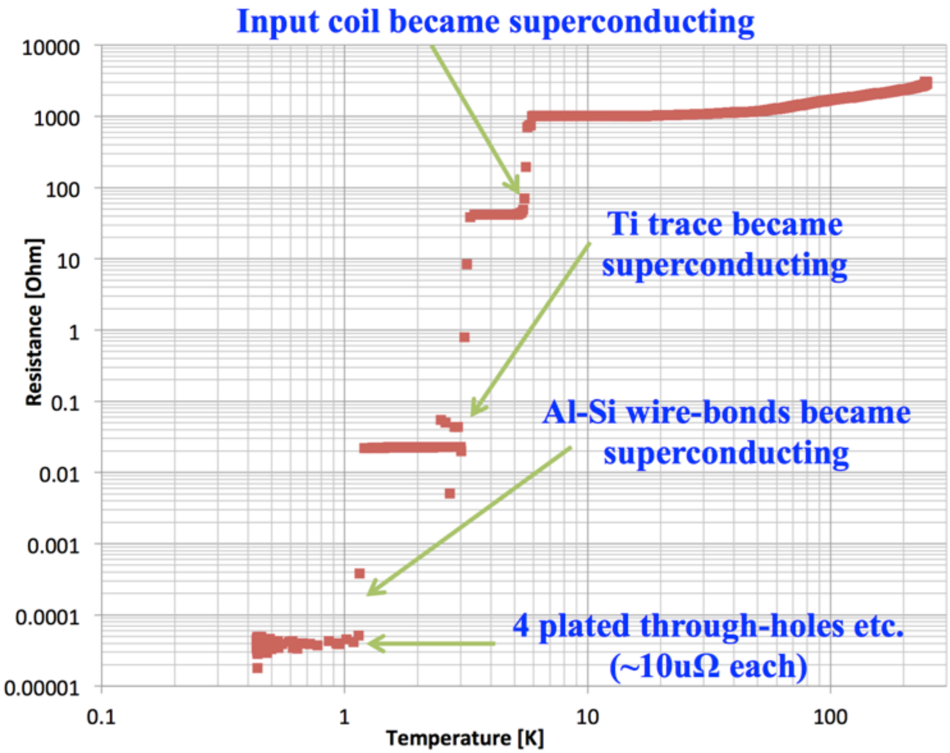
Pictures from Cu-plating process







Complete circuit:
SQUID+Ti traces+wirebonds+plated through holes

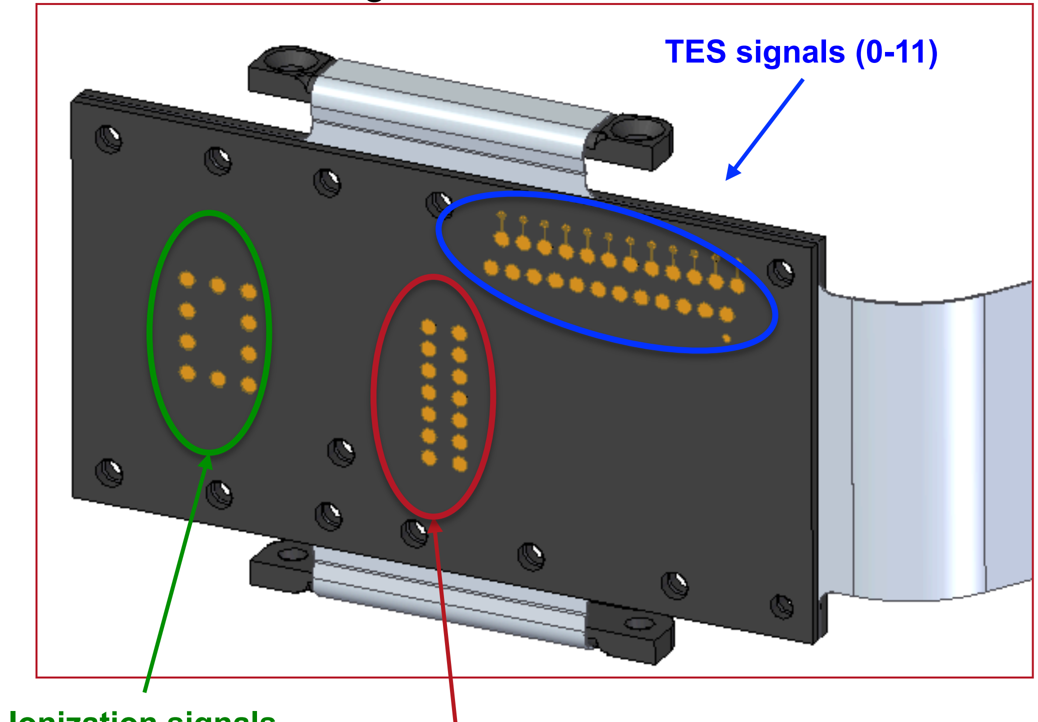


- Parasitic resistance requirement met at <1mOhm for TES signal loop (wirebonds+SQUID input coil+traces+through-holes)
- Measured expected Ti trace inductance (<20nH): verifies meeting full TES signal loop inductance

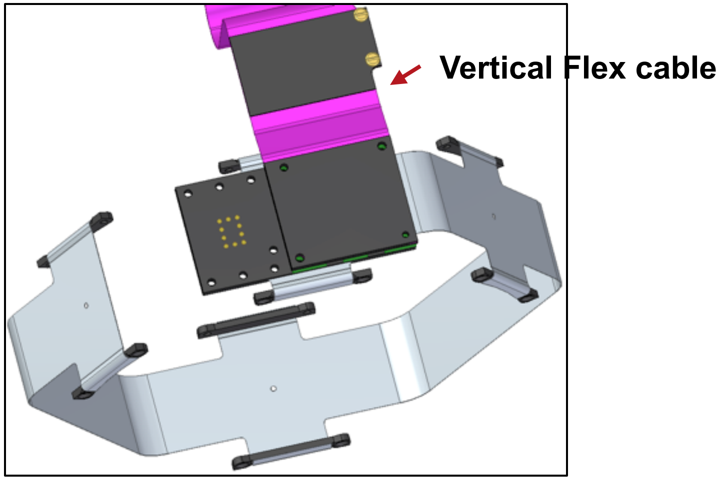
Meets requirements for resistance and inductance

Interface between Horizontal, Vertical Flex & Vacuum Coax Assembly

Horizontal flex rigid board

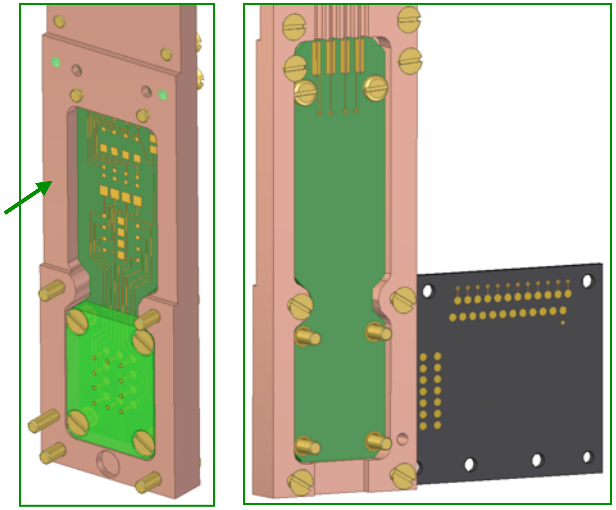


Vertical flex interface



Vacuum coax interface

All charge components at MC stage on PCB



- All connections on tower uses Fuzz Buttons

All PCBs and interposers for fuzz buttons in hand

Fuzz Button Connectors

Conventional connectors do not meet requirements for tower

- Need low radioactivity throughout tower
- Need low parasitic resistance for TES signal (<1mOhm)

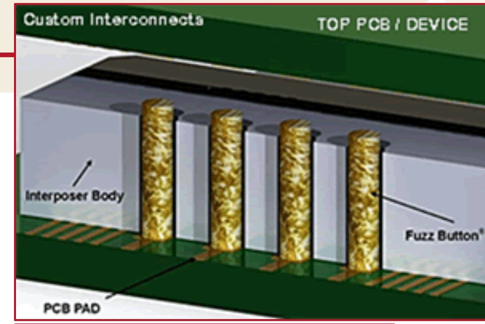
Use Fuzz Buttons from Custom Interconnect Inc.

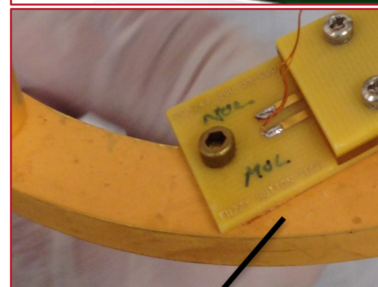
- Based on fine magnet wire turned into springy interconnections
- 0.002” Au/Mo wire for superconductivity
- Placed in Cirlex interposers that “sandwich” two PCBs (with gold-plated pads)

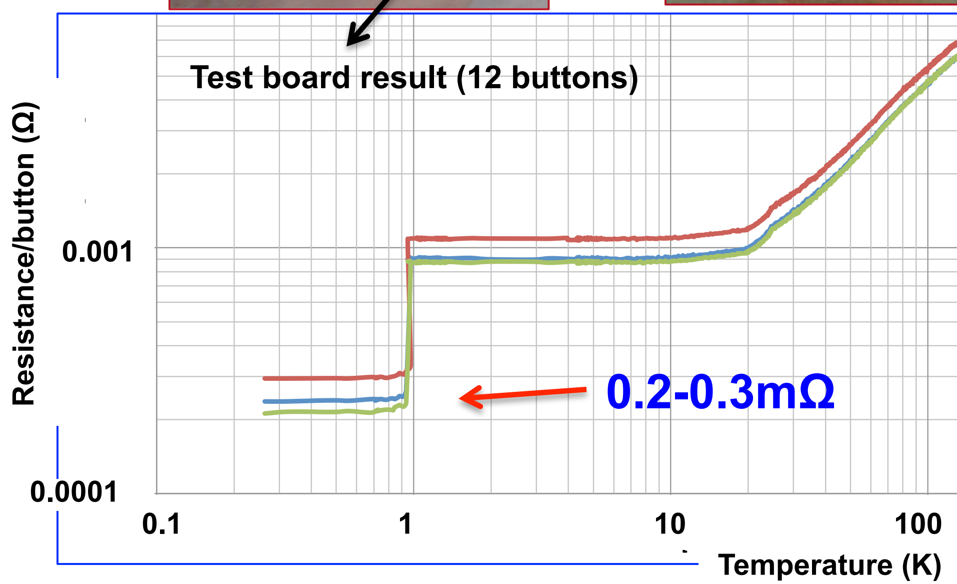
Test program verified meeting our requirements

- All samples go superconducting
- Small cold resistance increase between after m de-mate cycles (safe cycle study)
- Spring force and length contraction showed not issue for SuperCDMS

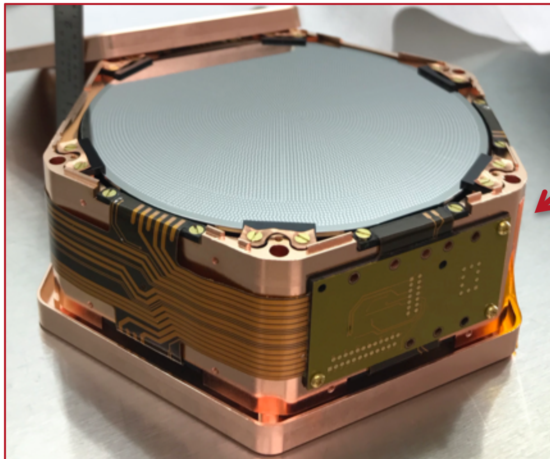
Satisfies low parasitic resistance for TES signals





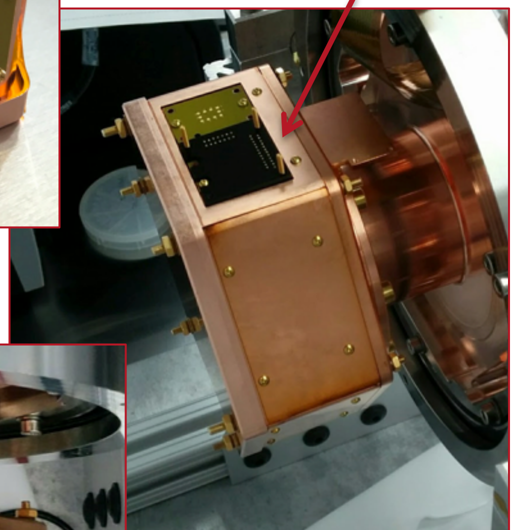


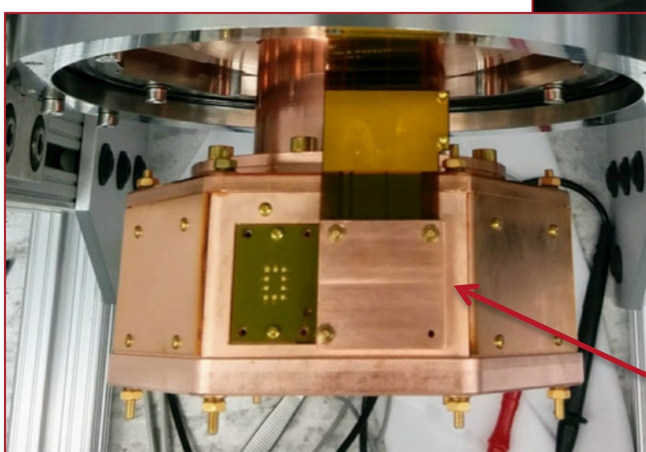
Interface between Horizontal, Vertical Flex & Vacuum Coax Assembly



Horizontal flex

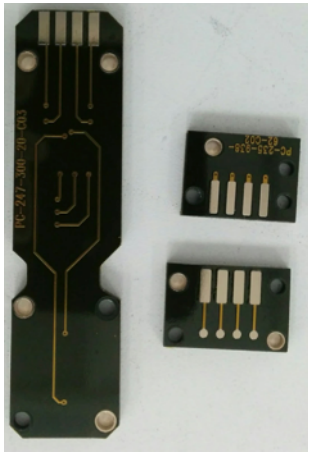
w/ interposer to vertical flex





Vertical flex connected
(MC board has Cu cover)

Vacuum coax PCBs for preproduction towers



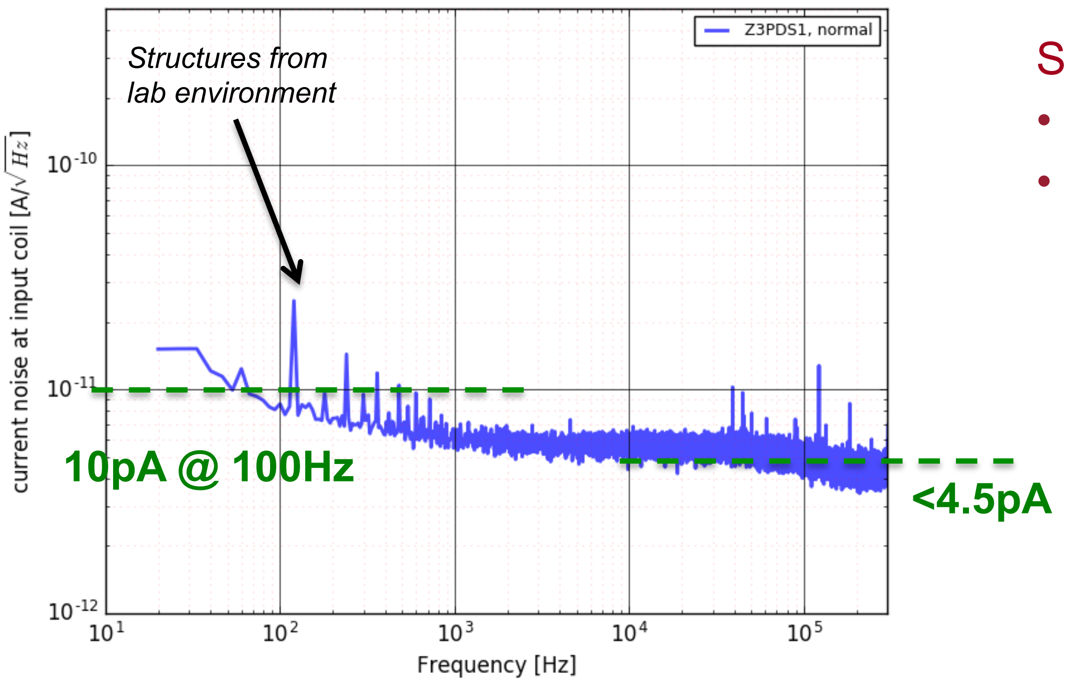
Preproduction interposers

SQUID Status

SQUIDs manufactured by NIST (M. Huber, CU Denver, coordinates)

- Critical requirement is noise level low enough making TES intrinsic noise dominate
- Prototype SQUIDs for SNOLAB have been tested and shown to meet requirements

SQUID noise with G115 Ge detector using flex cables and DCRC D.0



SQUID noise requirements

- <4.5 pA/√Hz in white noise region
- <10 pA/√Hz at 100 Hz

Meets noise requirements.

- SQUID fabrication and Q/A testing ongoing; 3rd batch successfully meeting specifications and NIST is moving on
- Fabricating 410 in total (need 288 for four towers, ETA end of July)
- Detailed testing and screening plan ready at CU Denver before assembly at SLAC

HEMT Testing and Status

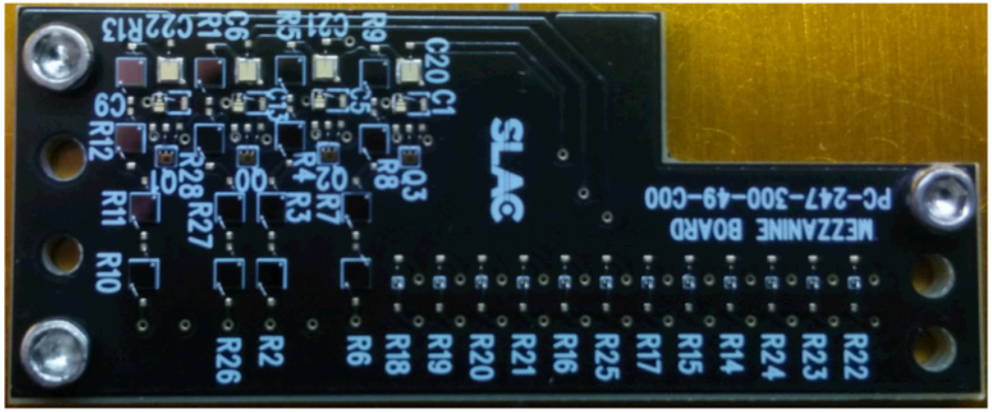
Ionization readout based on High Electron Mobility Transistor (HEMT) at 4K

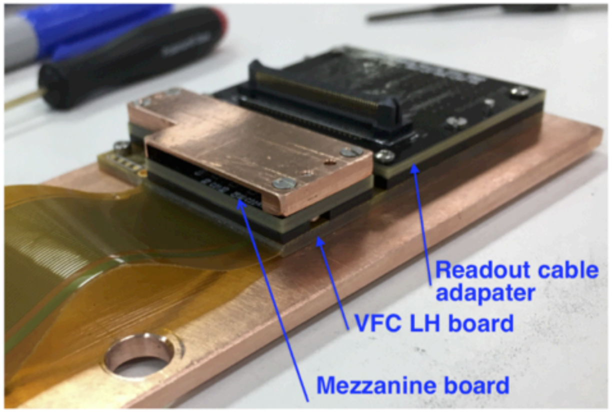
- Closed-loop w/ room-temperature feedback (FB resistor at 4K)
- Major improvements to Soudan are lower power (100uW) and noise compared to Soudan readout

All ionization circuitry on mezzanine boards

- Simplifies assembly, handling and screening
- Allows for future upgrade to active reset (expect ~x2 energy resolution improvement)

Mezzanine board housing the HEMT circuitry at 4K

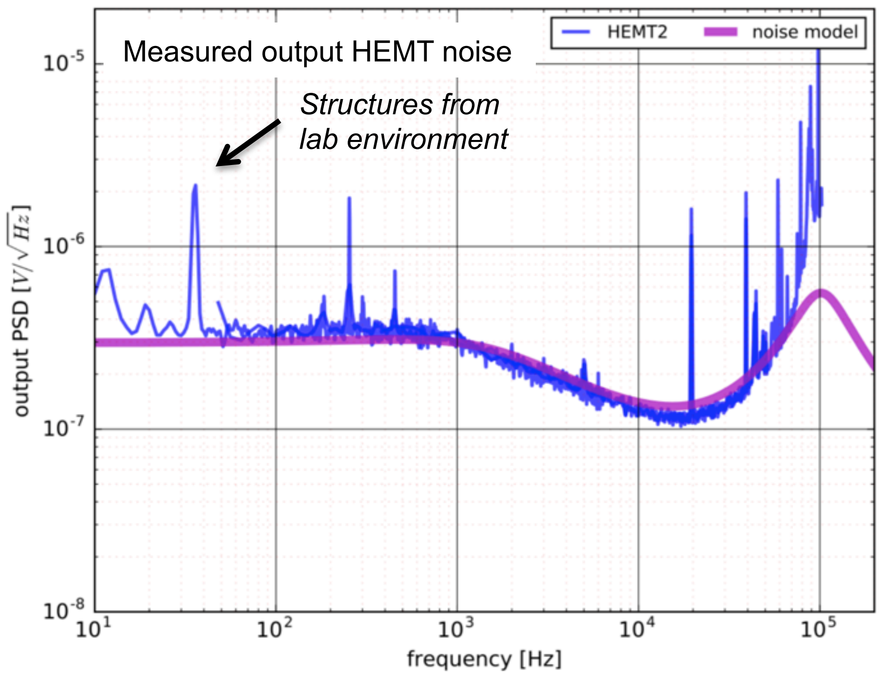


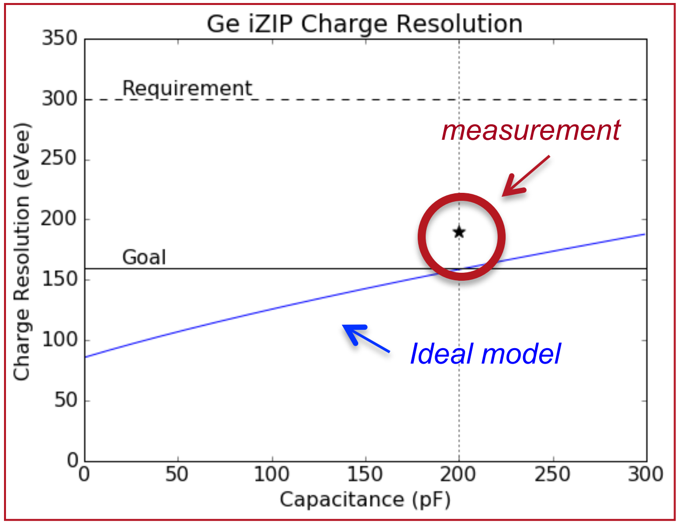


HEMT Testing and Status

Study HEMT noise using vertical flex cables and same warm readout circuitry as on DCRC

- Configuration without detector, bleed and bias resistor
- Considerations for full system is controlling stray capacitance and noise from RFI/EMI/microphonics





Model and measurement agree: shows promise that we can reach our goal

Complete set of HEMTs for project delivered (100)

- Fabricated by Y. Ying at LPN-CNRS, France; partially screened (good yield)
- 48 needed in total, rest used as mounted spares or for prototyping/testing
- Detailed screening planned at CalTech (I-V curves and passive component tests)

Background Control

Mitigations
Material surveys
Handling procedures
Final component assay

Main concerns

- Internal contamination
- Surface contamination
  - U, Th, K in dust and Pb210 from radon-daughter plateout.
  - Estimated exposure time to dust- and radon-laden air

Assay program for all material and components

- All materials screened for radiopurity (using the same lot when possible)
- >90% components for tower electronics assayed: remaining in queue for screening
- For all complicated assembled parts, dedicated survey samples are being screened (e.g. flex cables, PCBs)

Internal procurement control:

- Review before any fabrication for SNOLAB
- Background group experts part of every review panel

Design Maturity and Interface Control

100% (13/13) drawings/schematics for tower complete

- 3/3 Flex cables
- 5/5 Cirlex PCBs
- 5/5 Fuzz button interposers

Interface Control Documents (ICD)

- Tower to Readout Electronics
- Pinouts on connectors and wiring diagram
- Mechanical design and interfaces for PCBs and interposers

Project Management Risks & Risk Mitigations

Moderate Impact

Vertical Flex Cable Manufacturing

- *Risk:* If the vertical flex cable can not be manufactured then an alternate design will need to developed.
  - *Mitigations:*
    1. R&D
    2. Fabrication of Ti 15-3-3-3 prototype

Moderate Impact

SQUID chip availability

- *Risk:* If the SQUID chips do not provide the performance required then the tower electronics will be delayed and may have performance issues at cold temperatures
  - *Mitigations:*
    1. Early procurement
    2. Work closely with NIST to solve fabrication process issues

Risks and mitigations are being managed to minimize impact to the project

Internal Reviews

Review	Date	
SQUID Procurement Review	11/11/16	COMPLETE
Vertical flex cable design review (tin-Cu fab.)	11/16/16	COMPLETE
Preproduction vac. coax PCB fabrication review	5/12/17	COMPLETE
Preproduction fuzz button interposer fabrication review	5/12/17	COMPLETE
Preproduction horizontal flex review	6/16/17	COMPLETE
HEMT mezzanine PCB board review	6/30/17	COMPLETE
Preproduction vertical flex review	9/15/17	COMPLETE
HEMT Screening review	Early ‘18	

Major Tasks for Preproduction Towers 1&2

		FY17												FY18											
WBS	**Major task**	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
1.1.6.1	Preproduction horizontal flex fab.																								
1.1.6.2	Tin-copper preproduction vertical flex fab.																								
1.1.6.2	Prototype Ti vertical flex fab.																								
1.1.6.2	Preproduction NbTi vertical flex fab.																								
1.1.6.3	HEMT screening																								
1.1.6.4	SQUID fabrication & screening																								

- All major procurements for preproduction finished or in progress
- Remaining deliveries
  - Preproduction horizontal flex – Feb ’18
  - Preproduction NbTi vertical flex – Mar. ’18
  - SQUID fabrication – 3rd good batch end of 17’, 4th in spring ’18

Testing

- SQUID and HEMT screening
- Flex cable electrical checkout (warm and cold)

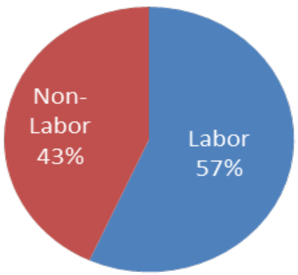
All major procurements finished or in progress.

Summary

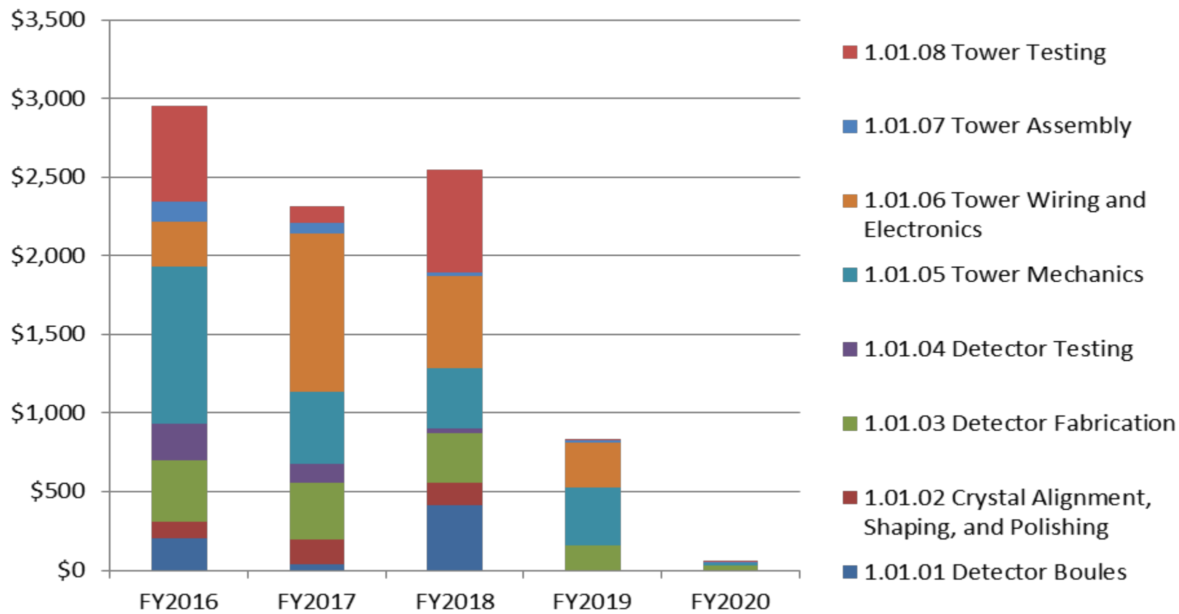
- Key accomplishments since last review
  - Finalized design of superconducting horizontal and vertical flex cables
  - Closed out R&D with delivery of a Ti superconducting flex cable meeting all requirements
  - All HEMTs required for project in hand, SQUID fabrication and Q/A ongoing with chips meeting requirements
- Design is mature
- All major procurements for Tower 1 & 2 are ongoing
- Ready for CD2/3

Questions?

1.01 Detector Towers

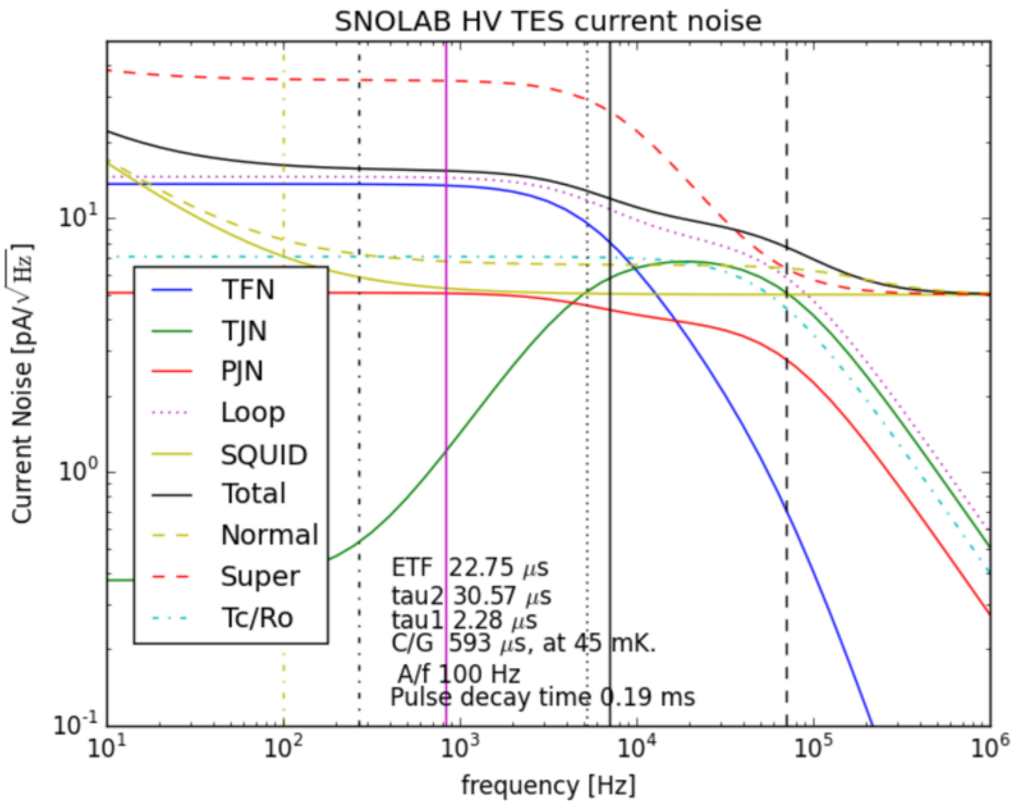


1.01 Detector Towers	
Resource Type	($K)
Labor	$4,935
Non-Labor	$3,760
Total BAC	$8,695

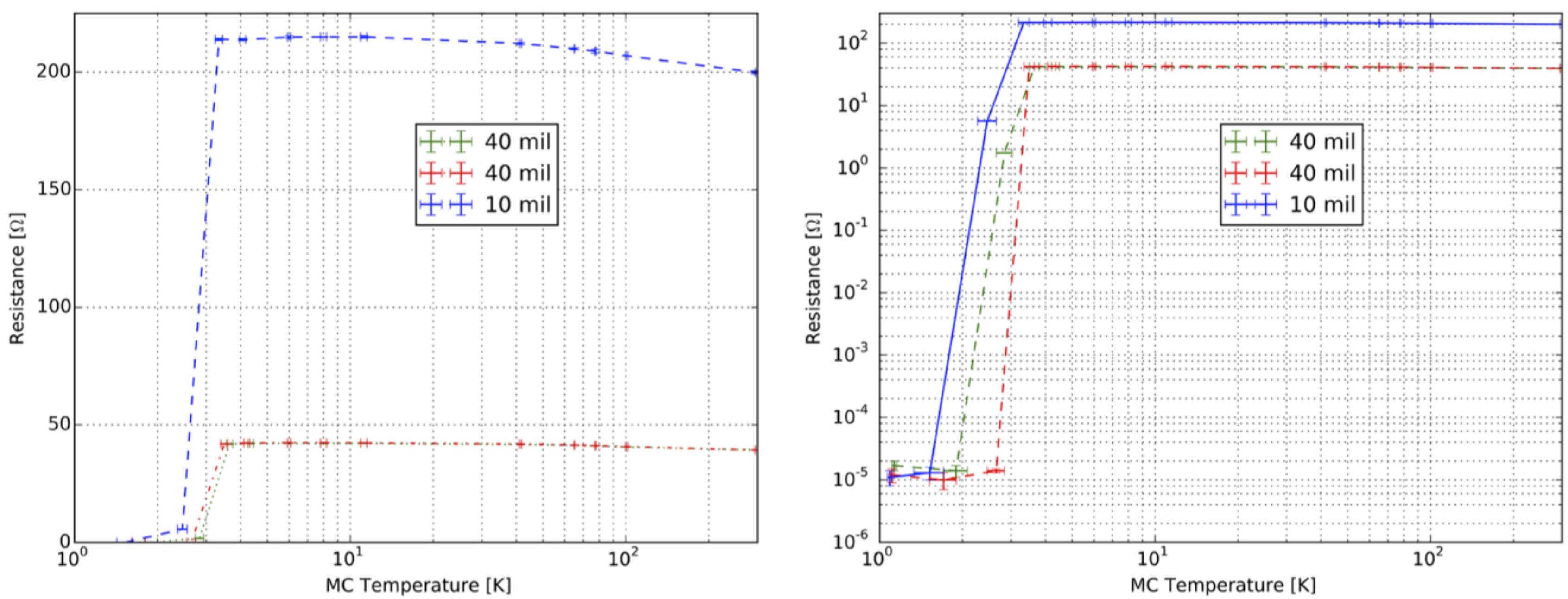


WBS	FY2016	FY2017	FY2018	FY2019	FY2020	Total
1.01.01 Detector Boules	$204	$35	$412	$0	$0	$650
1.01.02 Crystal Alignment, Shaping, and Polishing	$102	$157	$141	$0	$0	$401
1.01.03 Detector Fabrication	$394	$366	$318	$159	$31	$1,267
1.01.04 Detector Testing	$234	$123	$31	$0	$0	$387
1.01.05 Tower Mechanics	$999	$452	$384	$370	$18	$2,222
1.01.06 Tower Wiring and Electronics	$287	$1,013	$586	$287	$0	$2,173
1.01.07 Tower Assembly	$125	$62	$25	$10	$2	$223
1.01.08 Tower Testing	$606	$112	$650	$2	$1	$1,371
Grand Total	$2,951	$2,318	$2,547	$827	$52	$8,695

TES Signal Noise contributions



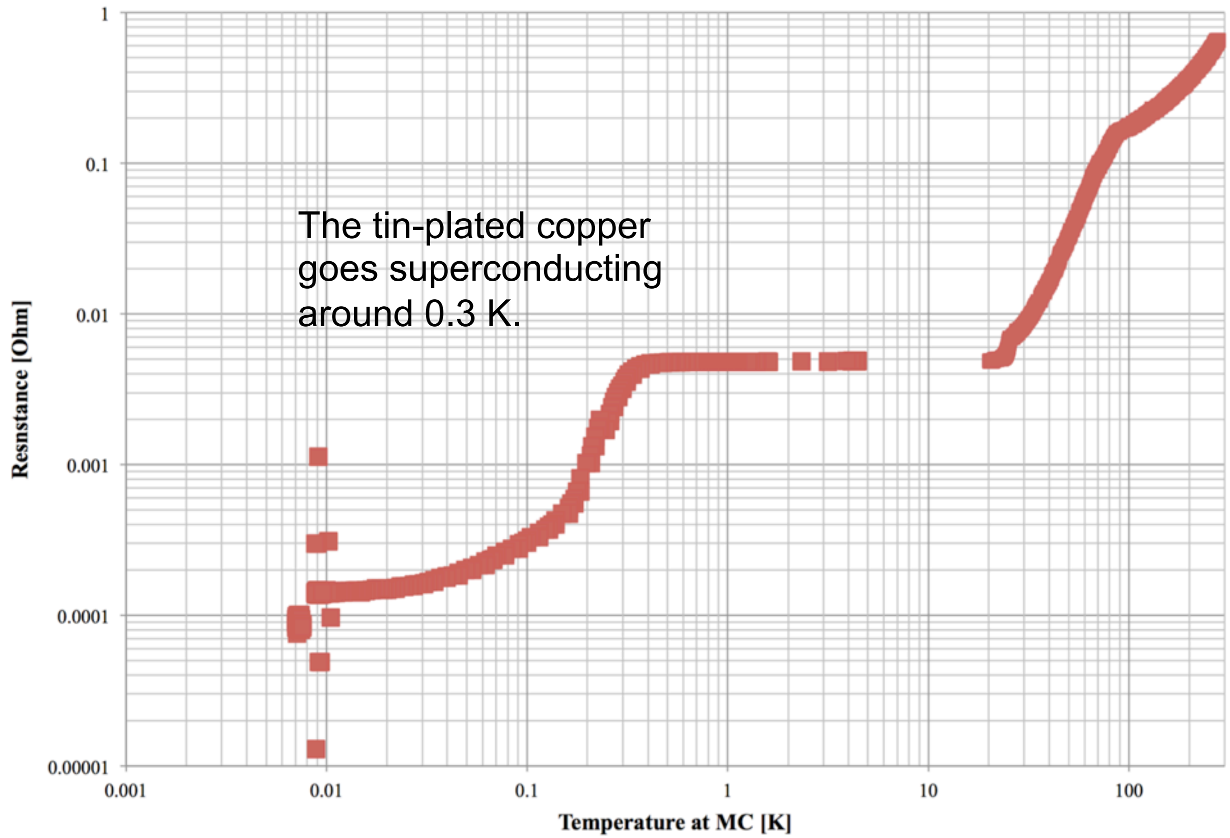
Trace Resistance of Ti-15-3-3-3 Vertical Flex Cable



- Including four plated through holes per trace, with linear (left) and logarithmic (right) vertical axes.
- Rise in resistance as Tc is approached from above.
- Parasitic resistance of the plated through holes and copper routing, Rp ≈ 10 μΩ, corresponding to 2.5 μΩ per hole

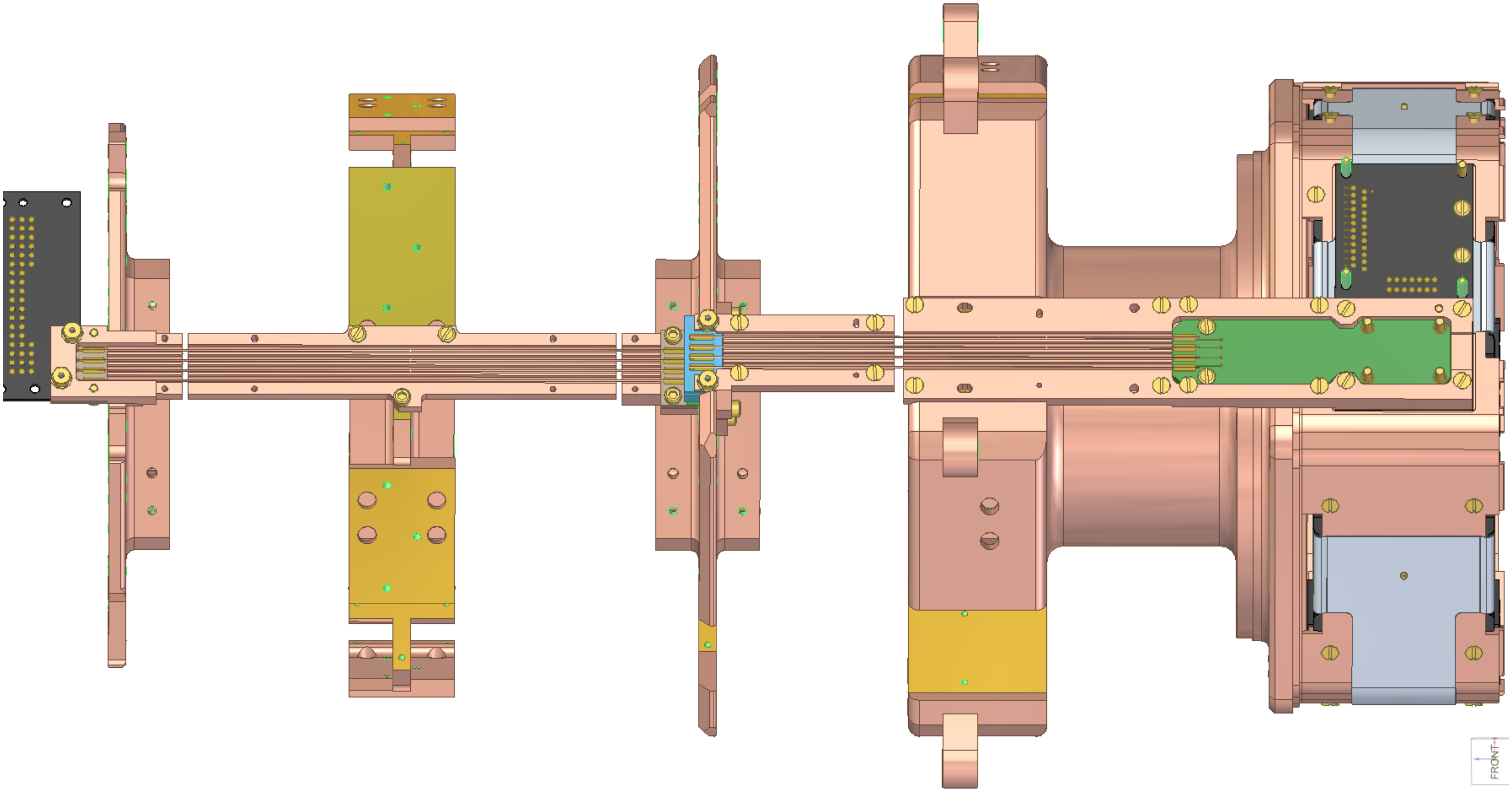
Horizontal Flex Trace Resistance

Resistance vs. temperature of tin-plated copper flex

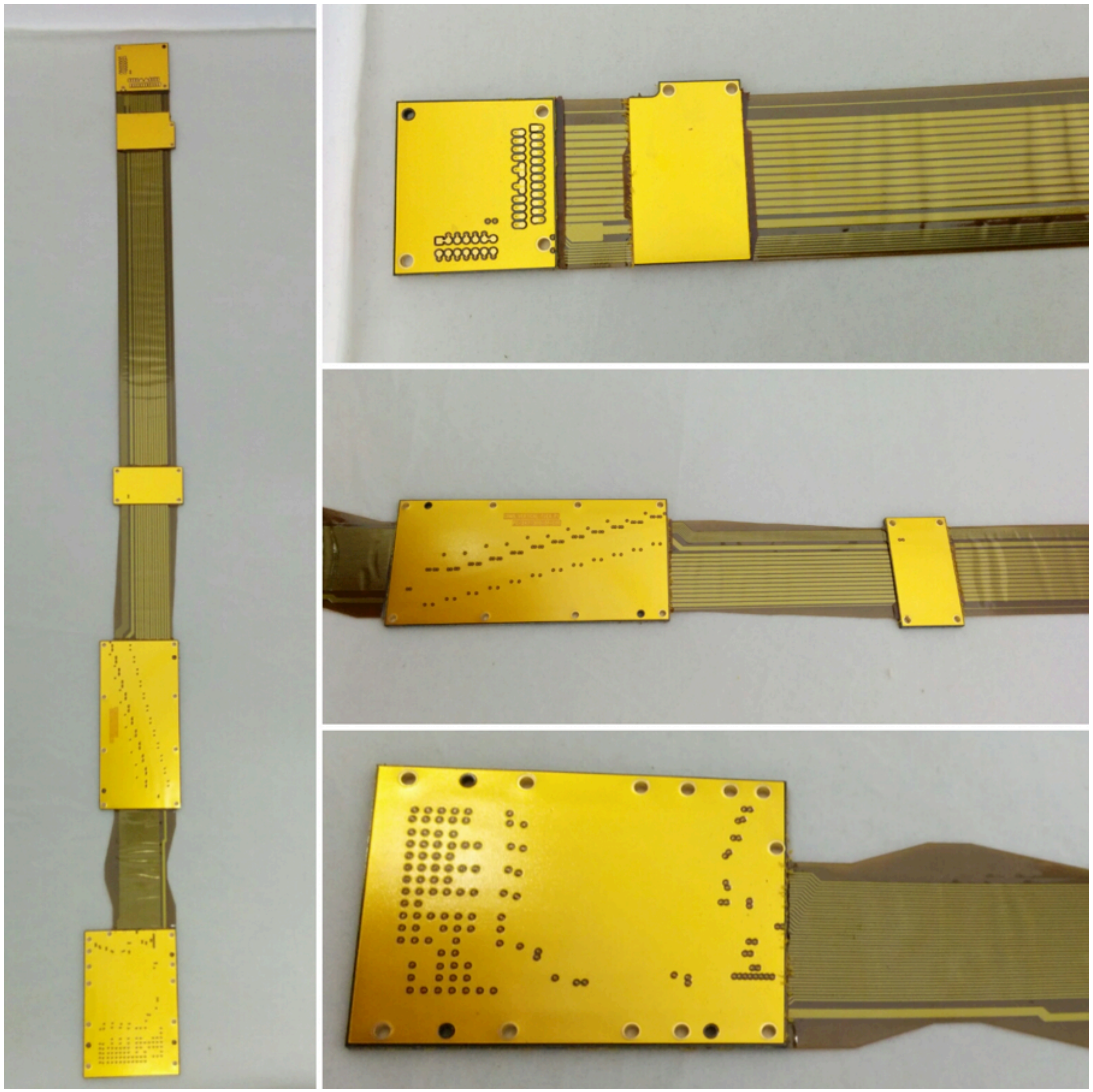


- Parasitic resistance of 100 µΩ (25 µΩ per plated through hole).
- Larger than that observed in both Ti 15-3-3-3 cables; may be related to the surprisingly low Tc of the tin-plated copper of this cable.

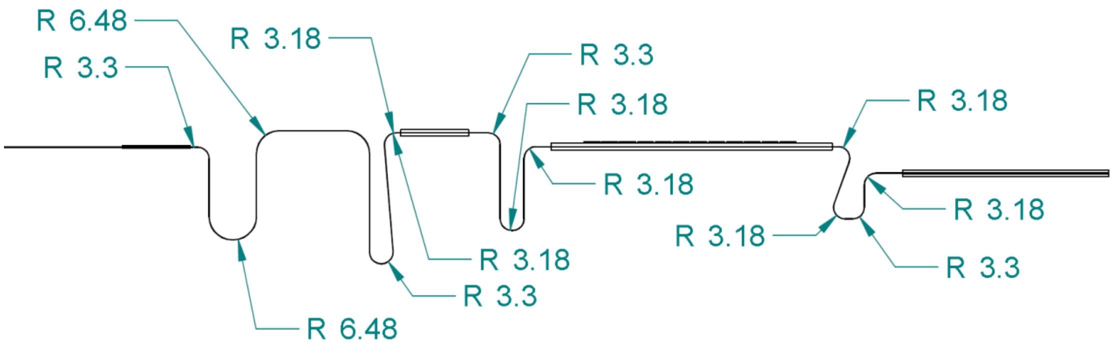
Tensioned NbTi Wires Bring iZIP Ionization Electrodes to 4K HEMT Front-End Electronics



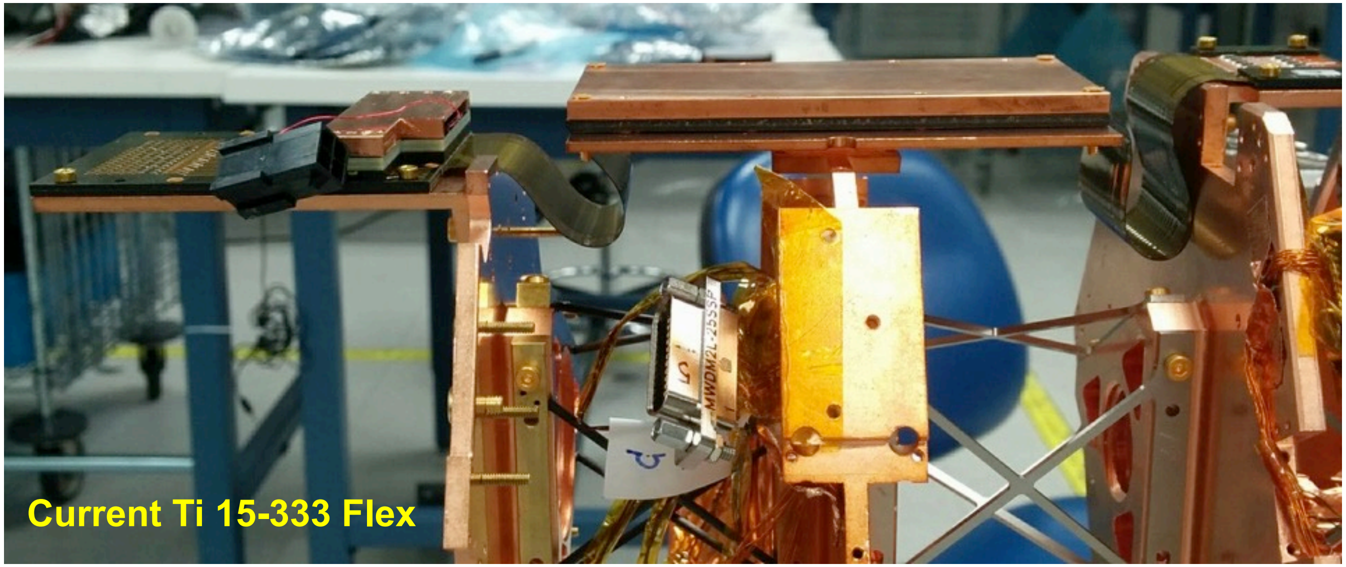
Ti Vertical Flex Cable



Integration VFlex Ti 15-333 – Lesson Learned



Baseline established with IPC-2223 Standard for Cu Flexible Circuits
Rmin = 10 x thickness [VFlex = 200 um] -> <u>Rmin = 2 mm</u>



VFlex Integration - Next steps

- The final flex cable is stiffer than expected. The current bending radii (3 mm) is challenging to achieve without mechanical fixtures to constrain the cable flexure.
- So far we have worked under the assumption of folding the cable on the tower during the installation, with the risk of stressing the flex cable beyond the minimum safe radius. It proved to be also a complex operation
- We will adopt the same strategy as for the rigid Vacuum Coax
- Development of fixtures where the cable is pre-folded and eventually thermal cycled with Liquid Nitrogen for Quality Control purpose, before the final installation on the tower.

VFlex Integration - Next steps

- Increasing the spacing between tower stages to increase the required radius of curvature

- Removing the folds to largely eliminate the need for bending the cable

- Utilizing Ti 15-3-3-3 conductor instead of NbTi if the NbTi proves to not be sufficiently ductile