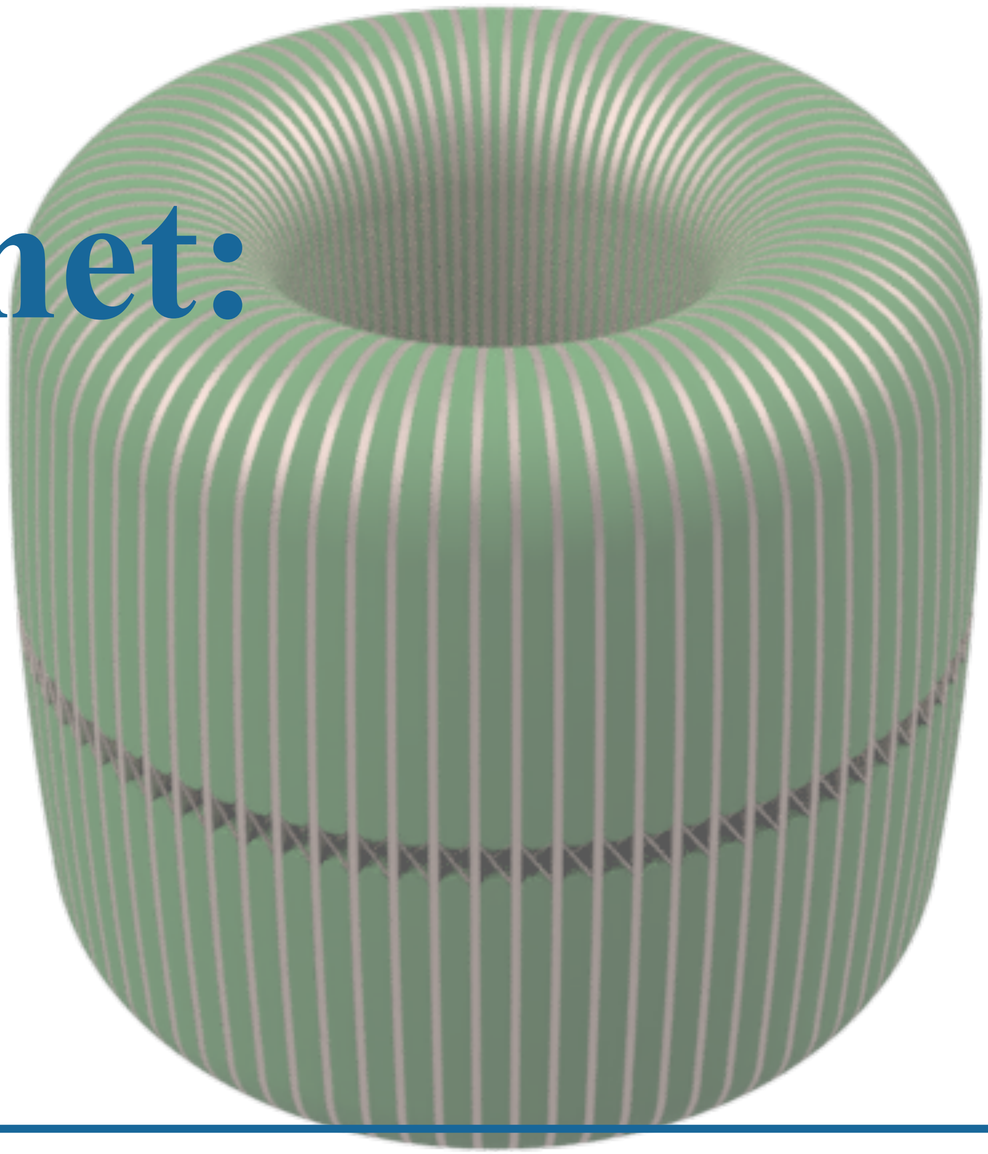
# ABRA-10 cm Magnet: Lessons Learned



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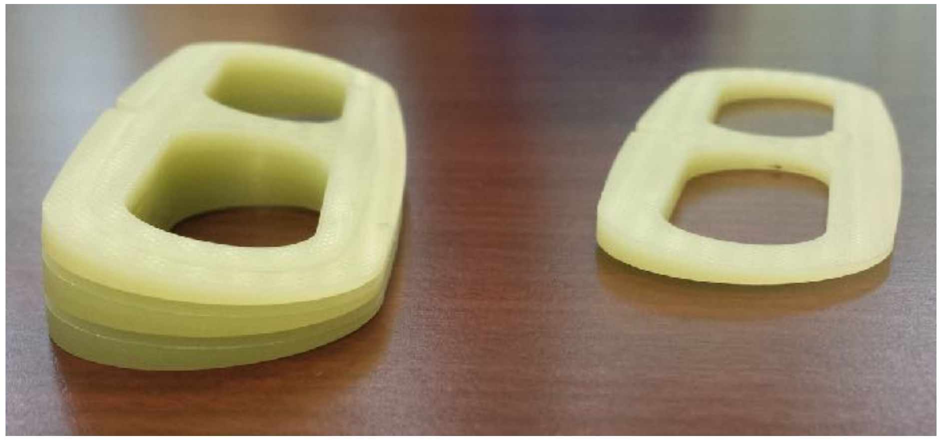
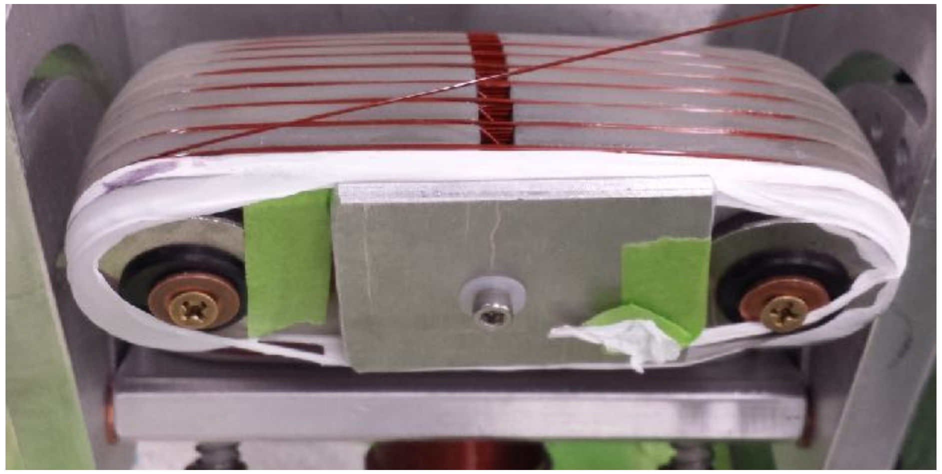
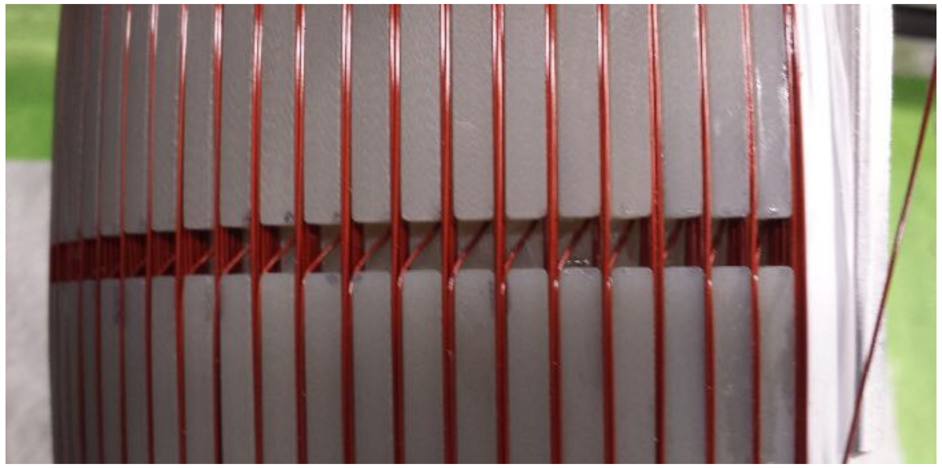
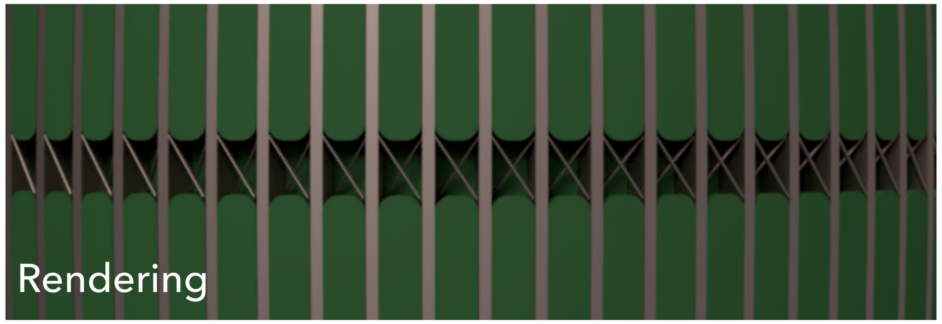
# MAGNET WINDING DESIGN

- Magnet made from 80 identical Delrin wedges
  - High frequency properties (loss) of Delrin unknown
- NbTi (CuNi) wire wound into grooves
  - Winding scheme is 14 wraps in 7 layers then jump forward to next groove (e.g. clockwise)
  - Process is then reversed in the last wind to lay 2 more winds in one layer into each groove and moving backward to the previous groove (e.g. counter clockwise)
  - 16 wraps (8 layers) in each groove, total of 1280 wraps, one trip clockwise, one trip counter-clockwise.
  - Counter-winding gives no net azimuthal current
  - ~0.25 miles of wires
- Each layer is glued in with ECCOBOND 24 two component epoxy
  - Careful epoxying is important to making sure wires do not move when cooling, charging, or after charged
  - A sudden move of a wire (like a crack), can cause a localized heat and trigger a quench

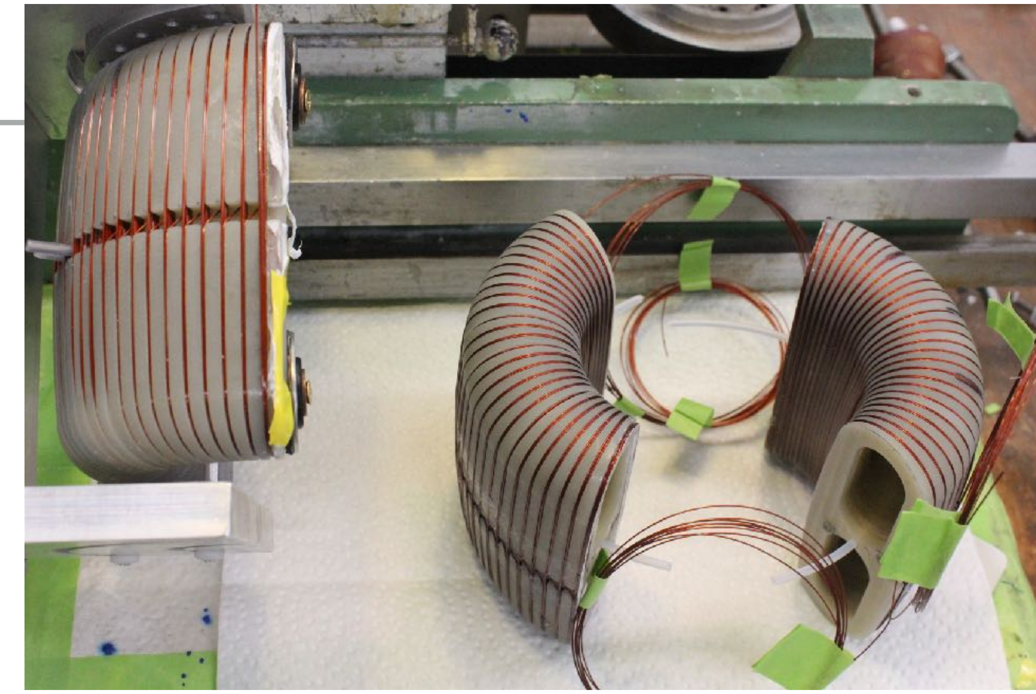




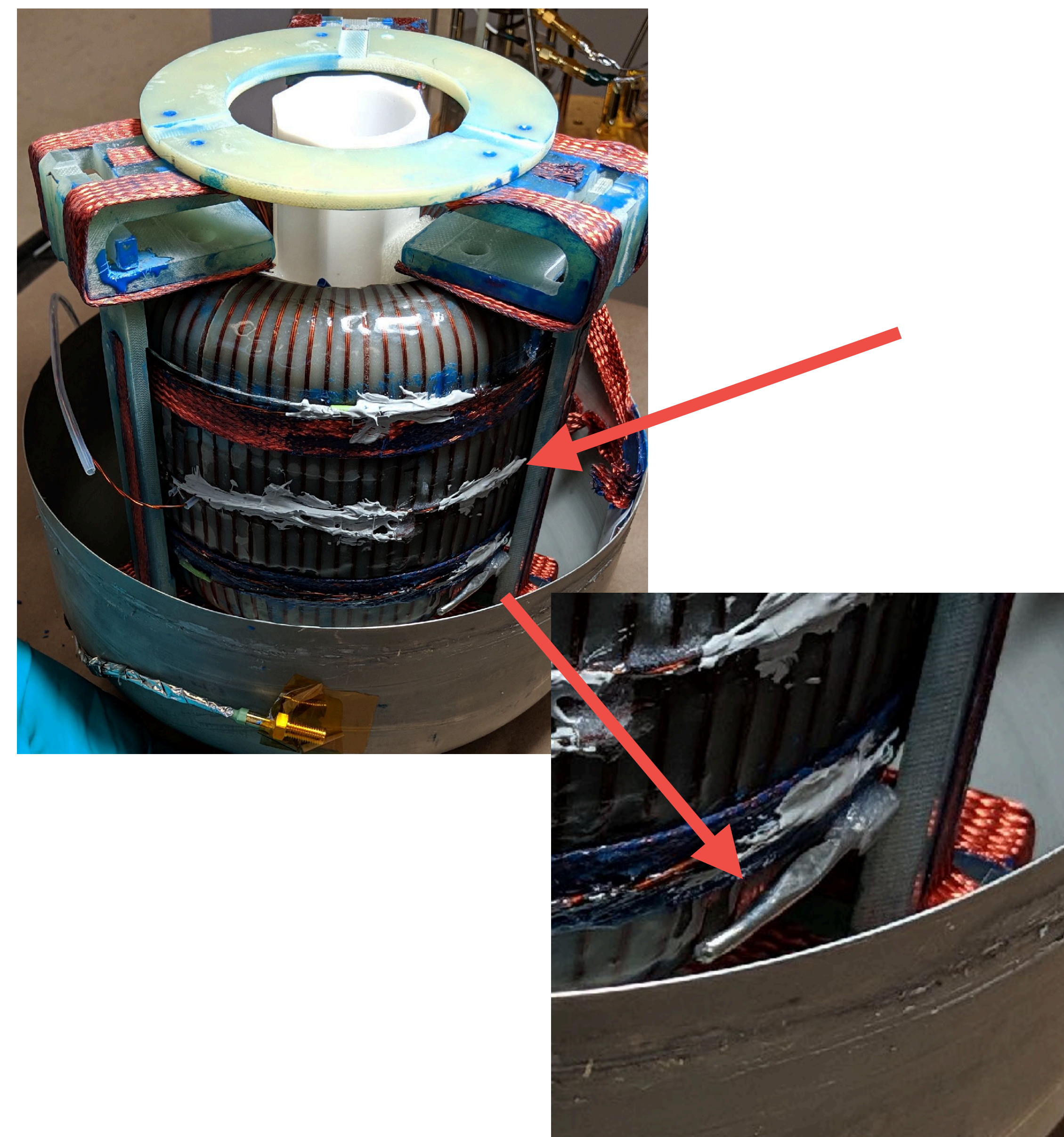




# MAGNET WINDING PROCEDURE

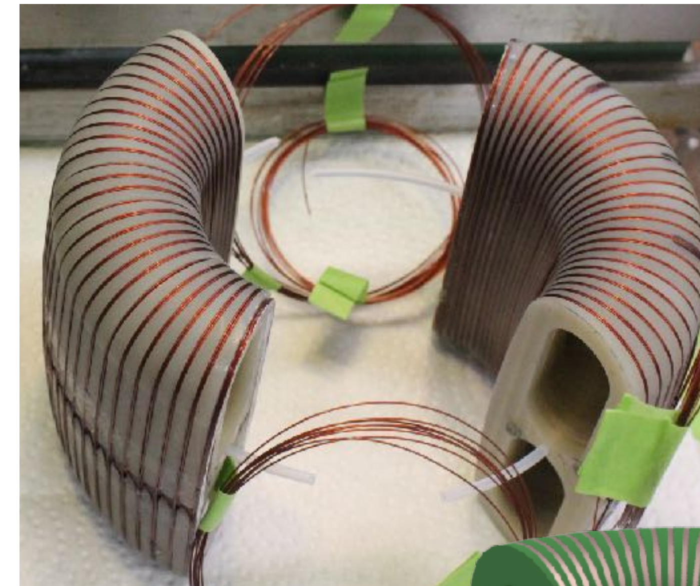


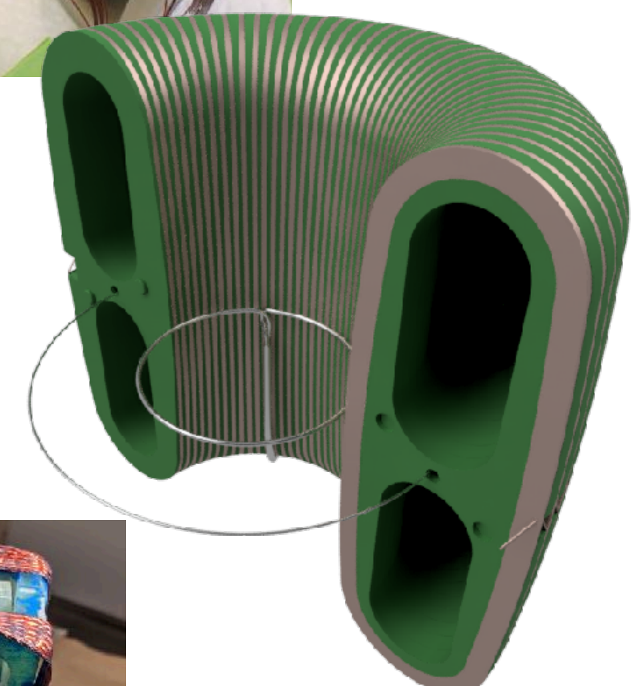
- Magnet was wound in three (roughly) equal parts
  - With three separate strands of NbTi wiring
  - Magnet sectors then glued together
- The sections of wire then had soldered together
  - The procedure for soldering wires is to twist the two wires together, scrape the ends, cover in solder, and crimp
  - The excess twisted-pair wire is then wrapped around the outside of the magnet and glued down
  - This is (probably) the source of one of the biggest problems we encountered: stray magnetic fields!
- Difficult to model the stray magnetic fields
  - Hard to put into COMSOL
  - Difference in scales: 10 cm magnet vs ≲ mm scale wires. See more from Chiara's talk on COMSOL.

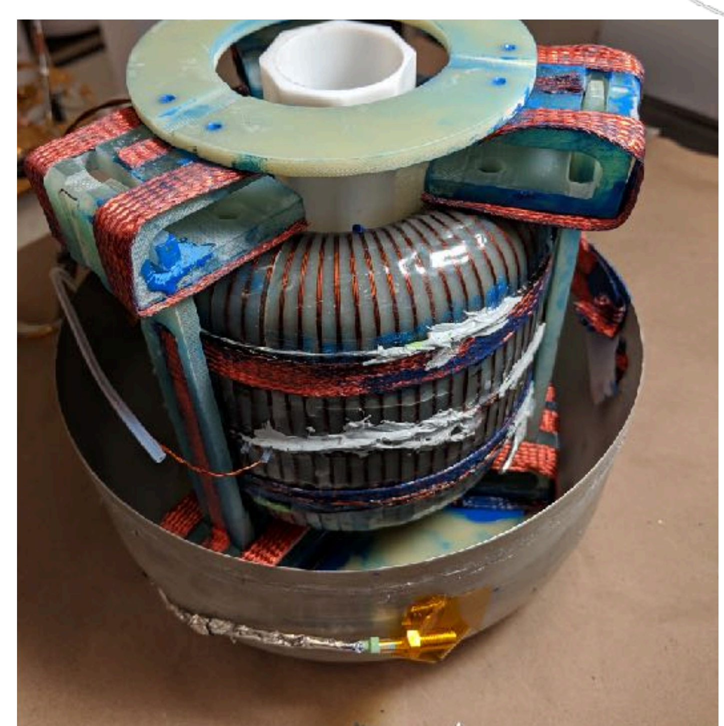


# CALIBRATION SYSTEM

- Calibration wire from solid NbTi (we think) wire running through the body of the toroid (inside PTFE liner)
- Twisted pair soldered to SMA connector and plugged into RG196 coax cable, into 30 dB attenuator at 100mK, into 20 dB attenuator at 4K, to RT BNC connector
- Clearly not tenable approach long term
  - Too much resistance coupled into the circuit
- Future approaches can remove some of the 110 dB of calibration attenuation and put into weak inductive coupling







# MAGNET MOUNTING

- Magnet mounted in G10 structure
- The magnet has to be cooled to go superconducting
  - Thermal path goes through 1 cm thick aluminum puck (mistake), through the tin coated copper shield, through coated Litz cables, to the magnet
  - Copper Litz cable is definitely a major problem for next generation
- Pickup loop mounted to PTFE cylinder
  - PTFE nice material, but difficult to mount rigidly. PTFE does not glue well, differential contraction, etc.
- Cool down takes 2~3 days from 300K to 10K, and 5~7 days to 1K
  - Mostly due to poor thermalization path

1 cm Aluminum Puck
(Not electrically connected to shield)

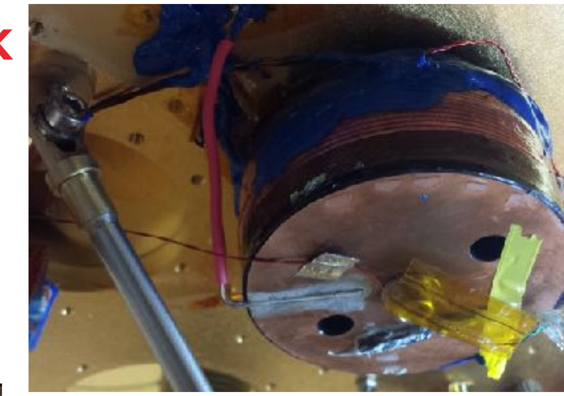
Tin coated copper shield
Tin: ~100μm
Copper: ~1 mm

Magnet upside down

# MAGNET MOUNTING

- Magnet wire runs out of superconducting shield up to the 4K plate to a superconducting switch
  - Wire between magnet and switch is unbroken length of NbTi (CuNi) wire
  - Magnet wire was definitely made too short and could not be (easily) extended
  - This lead to base temperature of the magnet being stuck around 1K (close to that of the still), even while MC was around 100 mK
- Magnet wire is wrapped around the superconducting switch
  - Switch is poorly thermalized to 4K plate and wrapped in heater (resistive wire)
  - Can be heated above superconducting transition

4K

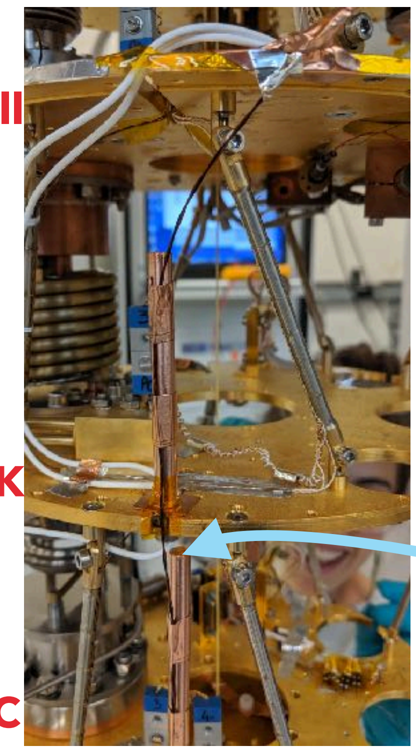


Superconducting Charging Switch

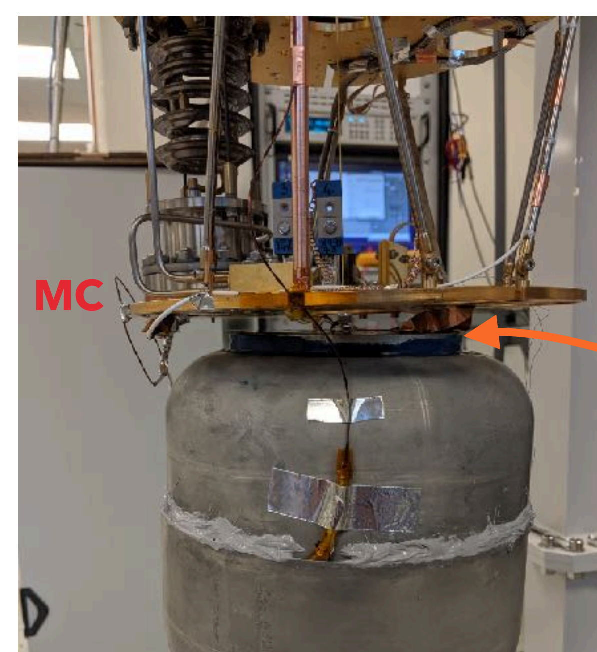
Still

100mK

MC

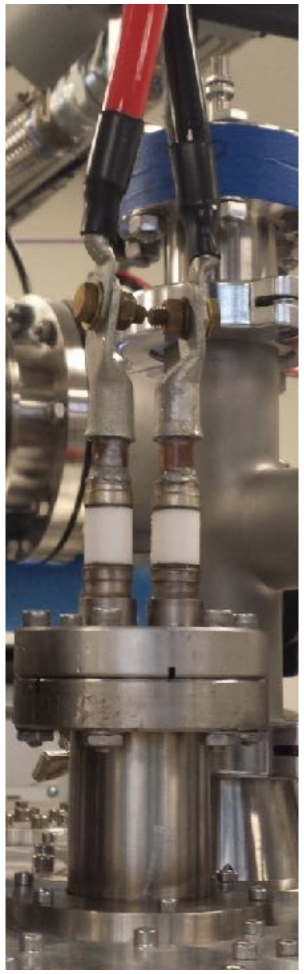


Twisted Pair NbTi (CuNi) Magnet Wire (Thermalized to plates.)



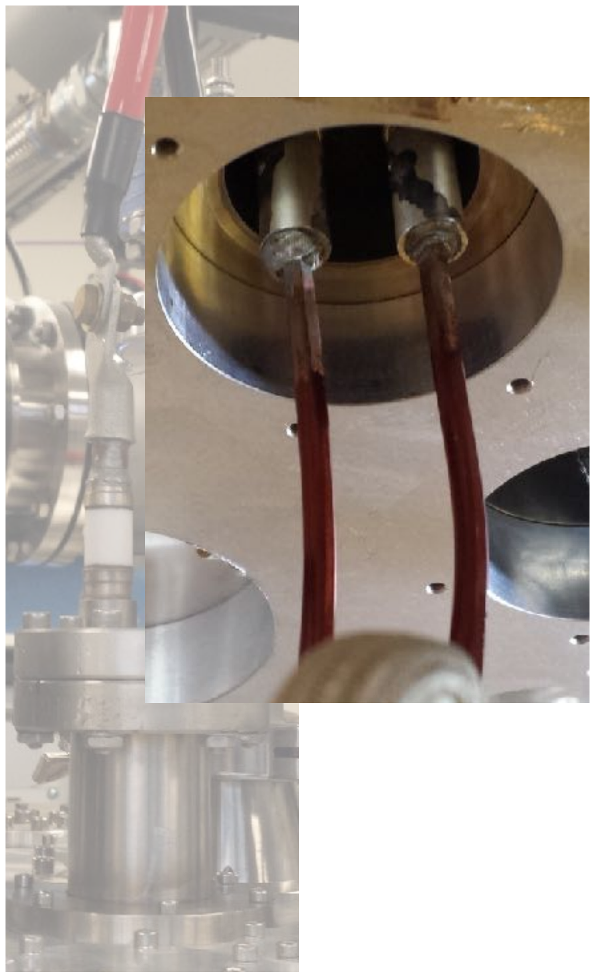

Temporary mounting

# MAGNET LEADS FROM 300K TO 4K



Vacuum feedthroughs can be attached to charging cables

# MAGNET LEADS FROM 300K TO 4K

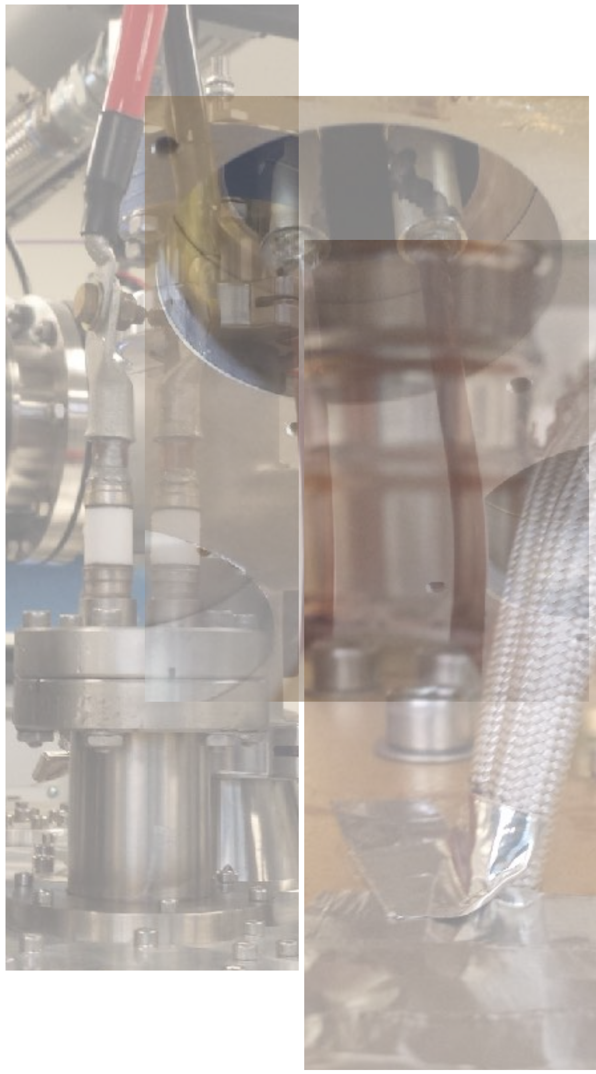


Charging leads are ~5 mm thick copper leads

# MAGNET LEADS FROM 300K TO 4K

Copper leads wrapped in kevlar sleeves and not touching 70K plate

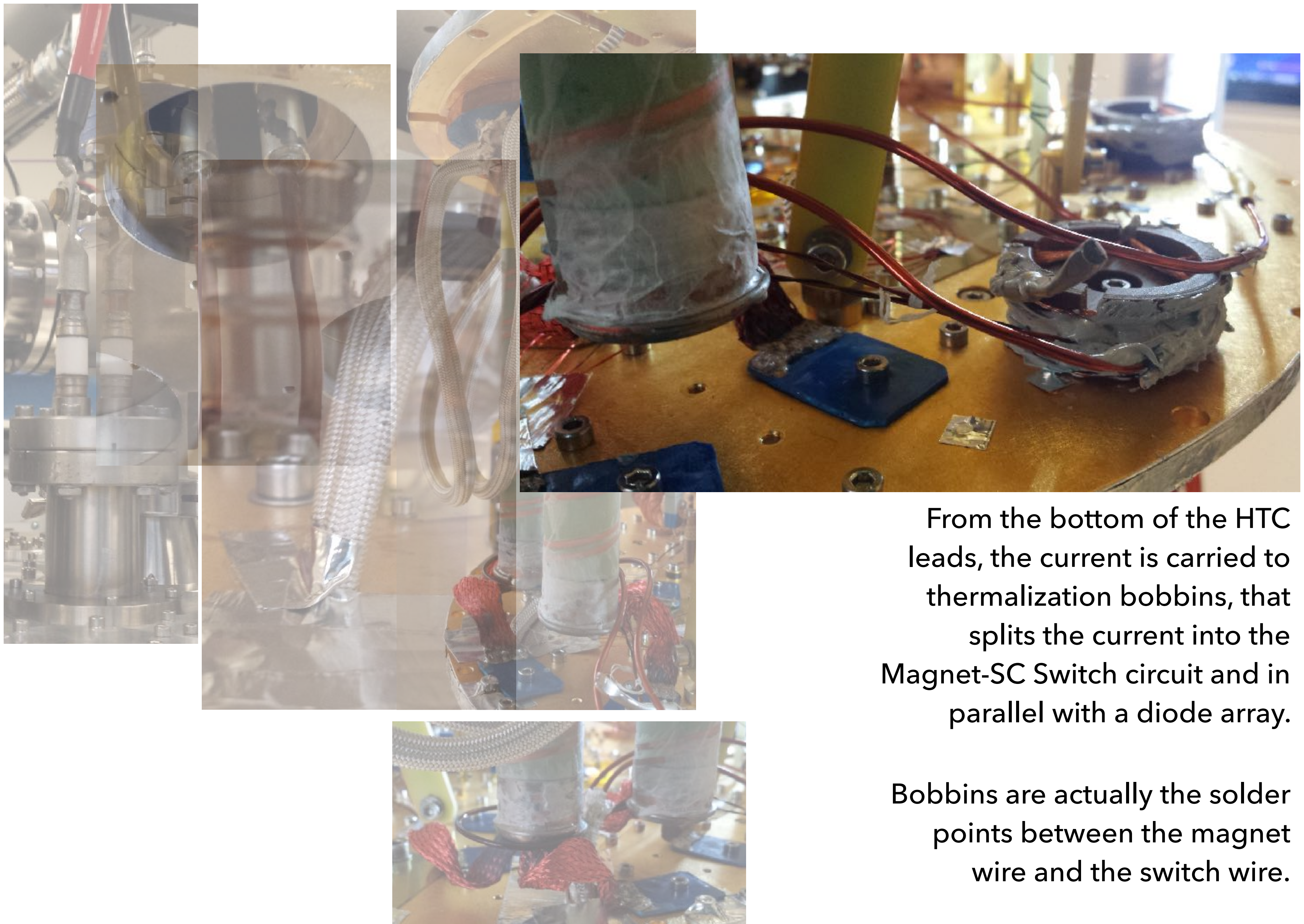
# MAGNET LEADS FROM 300K TO 4K



Copper leads are ~18" long before coupling to 70K plate (to minimize heat leak to 70K plate). Copper leads coupled to top of HTC leads.

HTC leads made of high TC tapes wrapped around G10. Bottom of leads thermalized to 4K plate.

# MAGNET LEADS FROM 300K TO 4K



From the bottom of the HTC leads, the current is carried to thermalization bobbins, that splits the current into the Magnet-SC Switch circuit and in parallel with a diode array.

Bobbins are actually the solder points between the magnet wire and the switch wire.

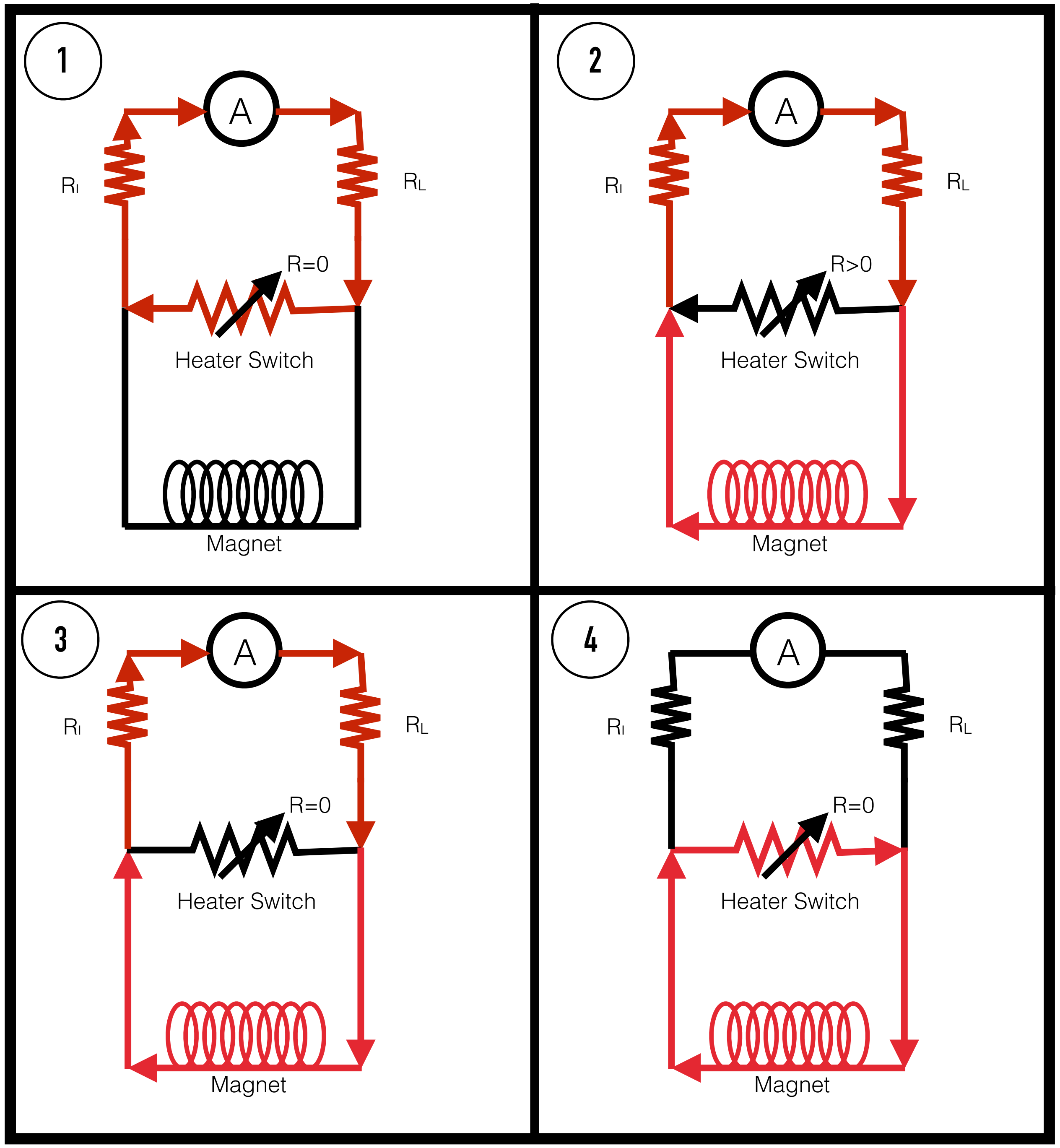
# MAGNET LEADS FROM 300K TO 4K

Diode array protects the magnet by dumping current once voltage exceeds ~10V.

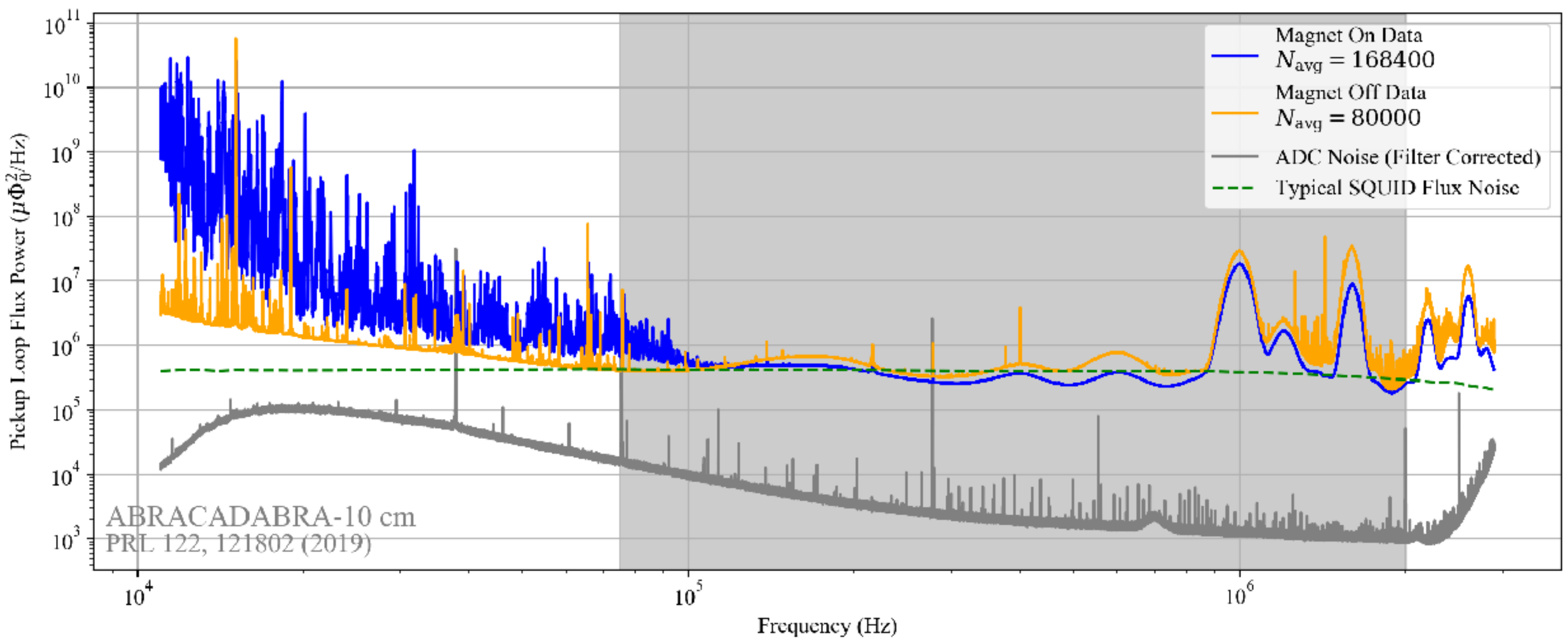
# MAGNET CHARGING

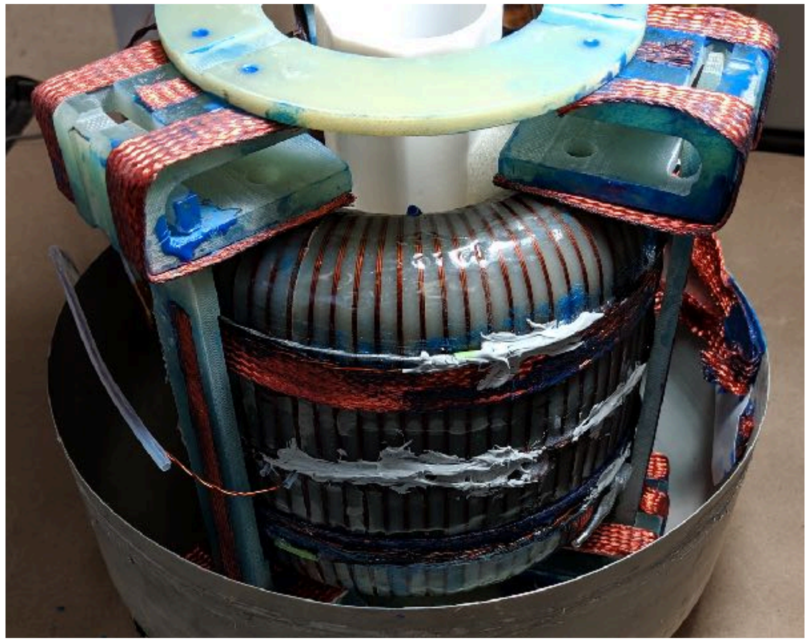
- Start with the magnet and switch superconducting

1. Push current into the leads, current begins going through the superconducting switch (instead of pushing against the inductance of the magnet)
    - Make sure the limit the excess voltage on the current source, to limit the power dissipated across the magnet
2. Turning on the heater causes the superconducting switch to go normal, and the current decays into the magnet with an LR time constant (~2 seconds)
    - The switch will keep itself normal conducting due to the self heating of the current, so the heater can be turned off as soon as the charging begins
3. Allow the superconducting switch to cool back down and go superconducting
4. Turn off the current source and the current remains in the magnet running through the switch



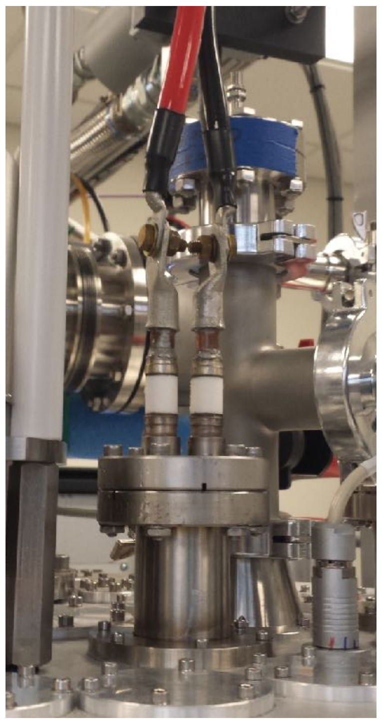
# LESSONS LEARNED – STRAY FIELDS



- Below ~100kHz signal is dominated by vibrational noise, made much worse by the turn on of the magnet
  - Above 100kHz, this noise is subdominant, but (likely) still present
- Possibility 1: This is due to poorly laid excess wires on the outside of the toroid
  - Need to lay wire paths very carefully and minimize/eliminate excess wire. Work with company to make sure magnet is wound to spec.
- Possibility 2: This is due to stray fields from the wires on the inner side of the toroid
  - Need field simulations to check this. Also careful wire laying design (see nEDM approaches).
- ~~Possibility 3: This is due to crosstalk from wires outside the shield.~~ Tested this, seems unlikely.

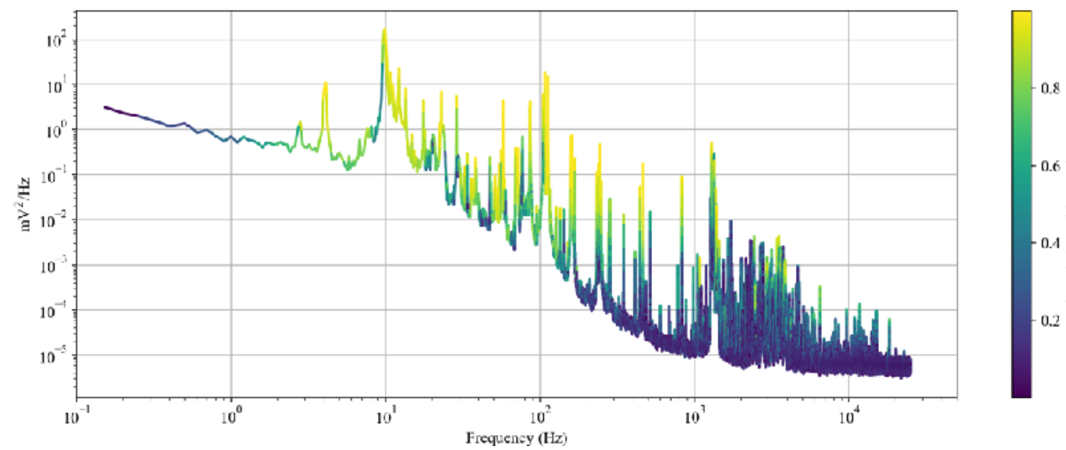
# LESSONS LEARNED – MAGNET CROSSTALK



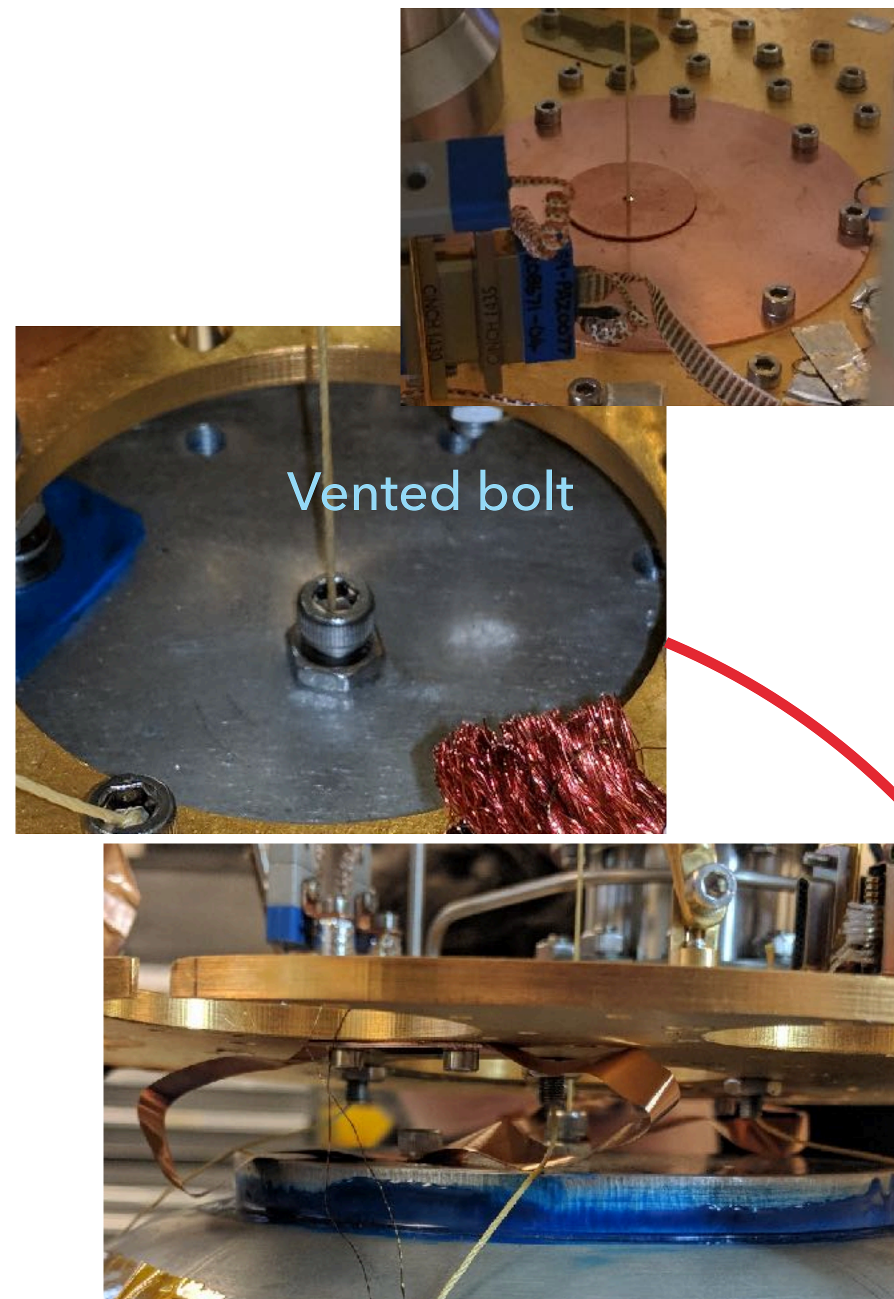

- Touching the magnet leads overloads the SQUIDs
- Shorting the magnet leads overloads the SQUIDs
- Anything having to do with the magnet leads overloads the SQUIDs
- Shielding the magnet leads improves the noise on the SQUIDs

- The magnet wires are obviously strongly coupled to the pickup
    - Need to understand this coupling
    - Could look into method to charge and disconnect the warm leads from cold
    - Shielding leads

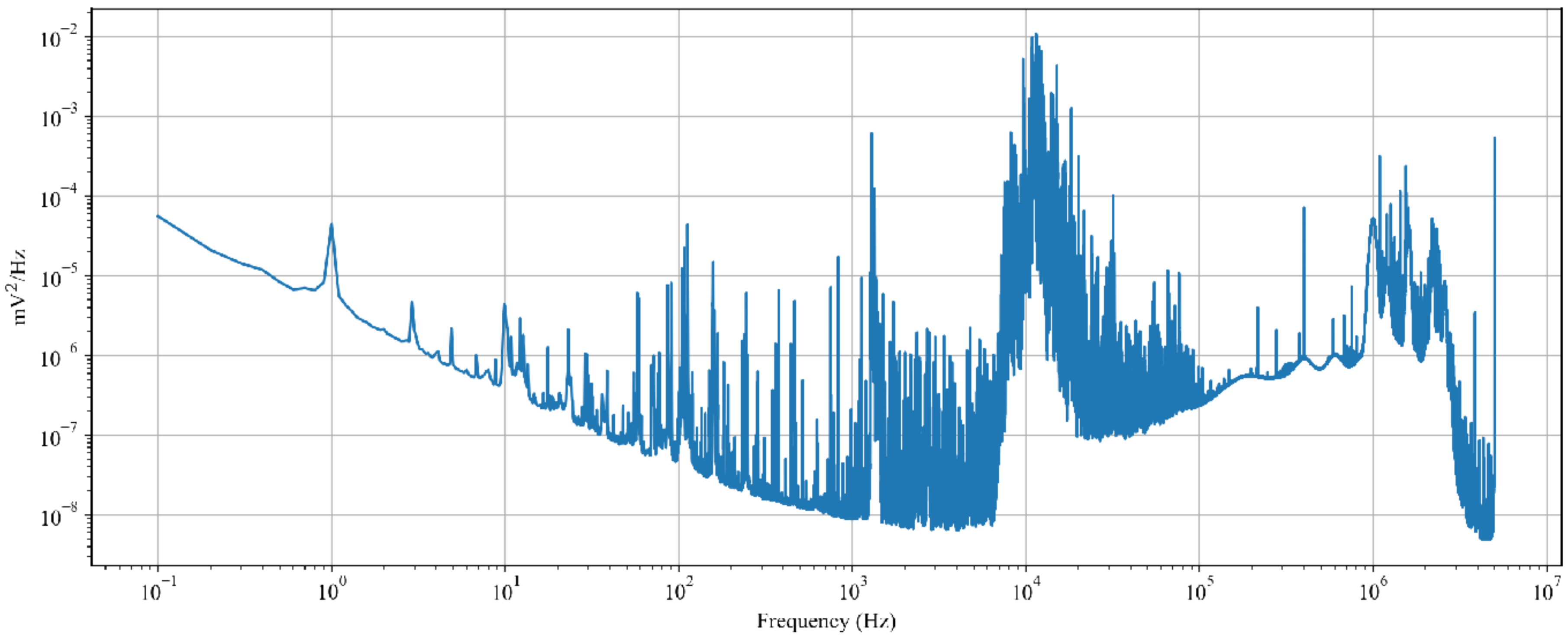
# SUSPENSION




- Low frequency noise (likely from vibrations) caused huge problems
- Hung ABRA from a 2m long pendulum
  - Supported by Kevlar thread with 120lb tensile strength
  - Connected to vented bolt
- Loose copper ribbon thermalization
  - Poor thermalization lead to ~1 week cool down time (from 300K to $T_{Magnet}$~1K)

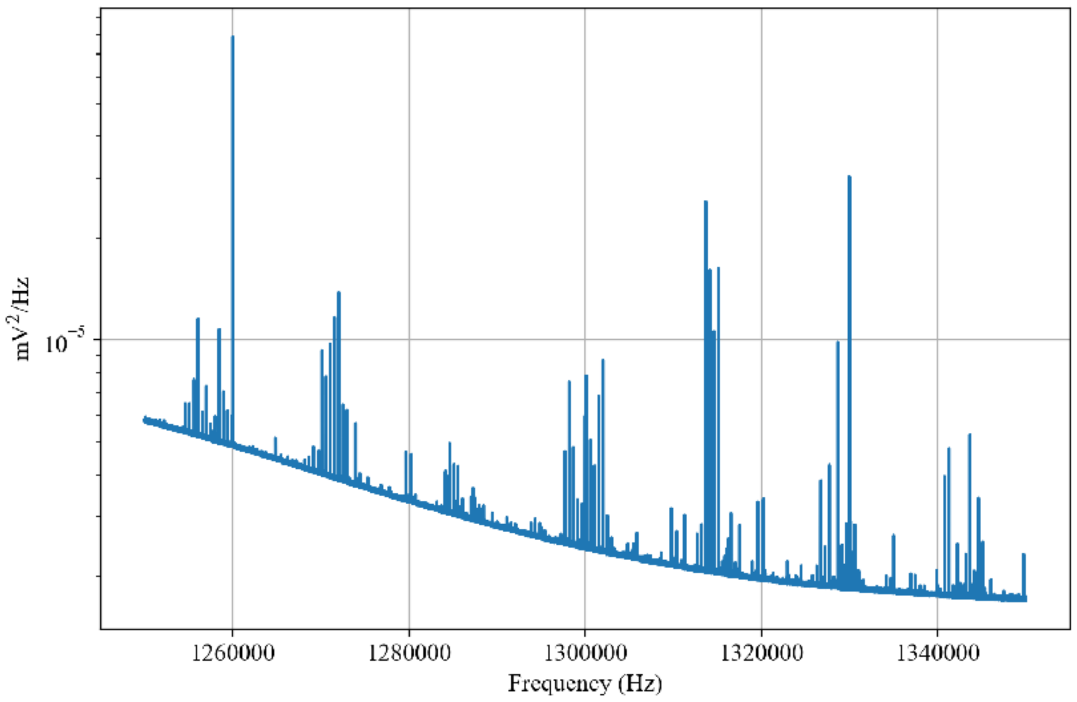


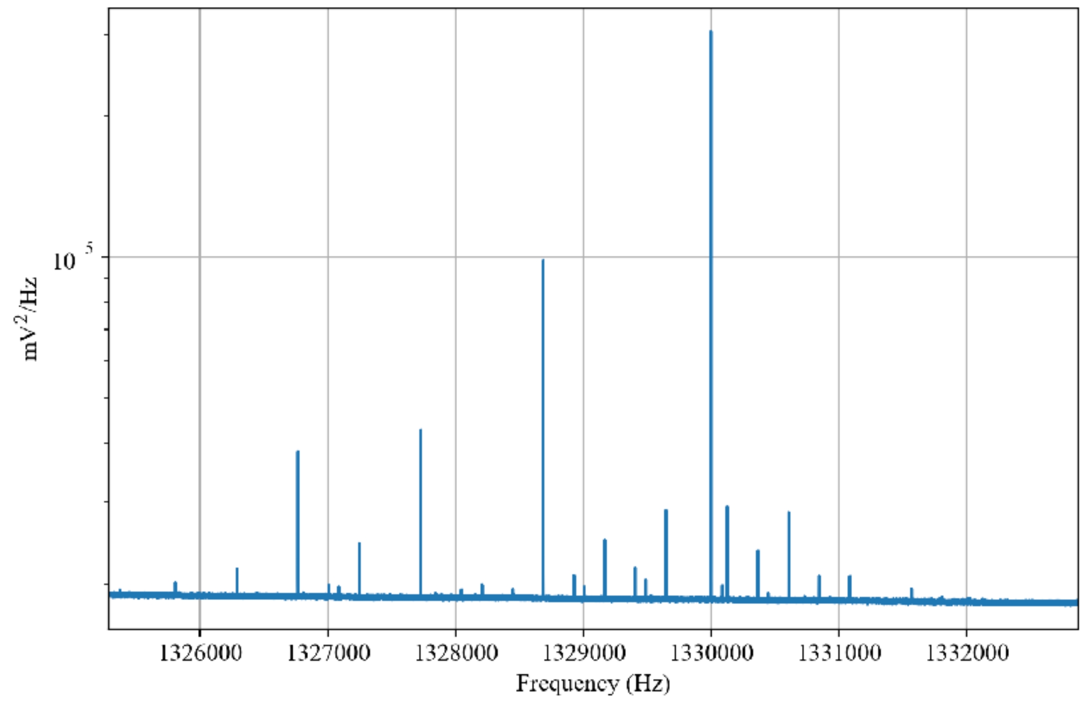

# THE NOT SO GOOD – LOW FREQUENCY NOISE




- We see lots of little narrow spikes
  - Present with magnet on or off
- Takes up <1% of frequency parameter space
- Nearly repeating structure
- Turns on and off randomly on ~week timescales
- Noise is coherent over >800s but <8hr
  - Spikes move around -> Taggable
- Seems to be environmental noise
  - Nearby labs, servers, etc
- Magnetic Shielding!

# THE NOT SO GOOD – SPIKES

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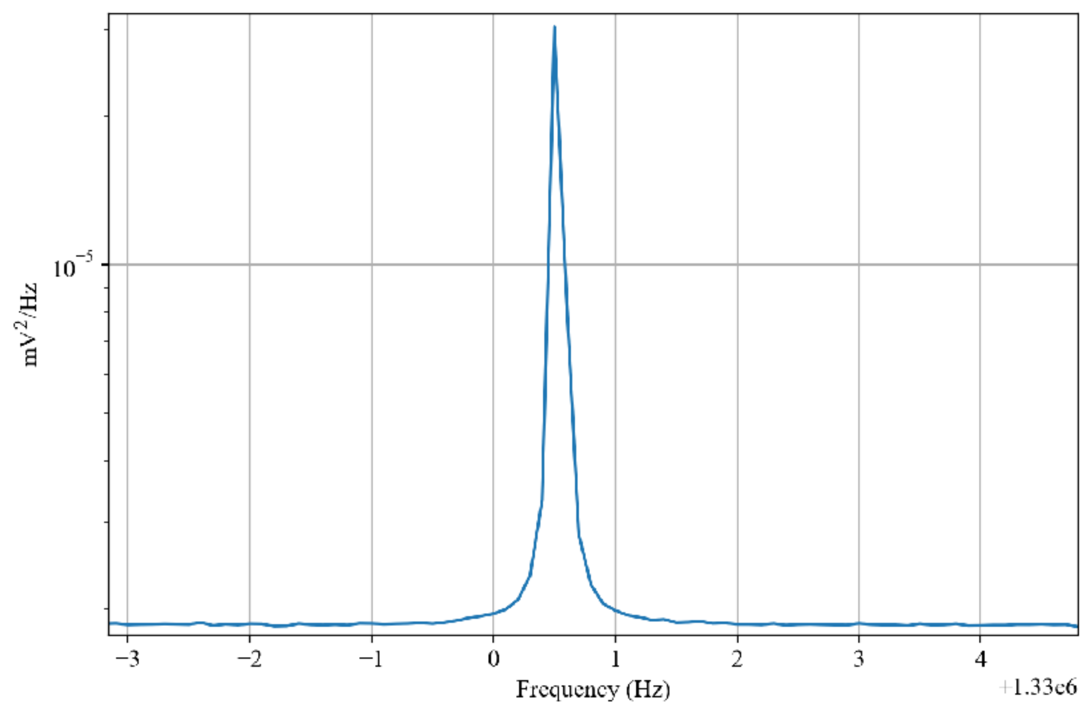
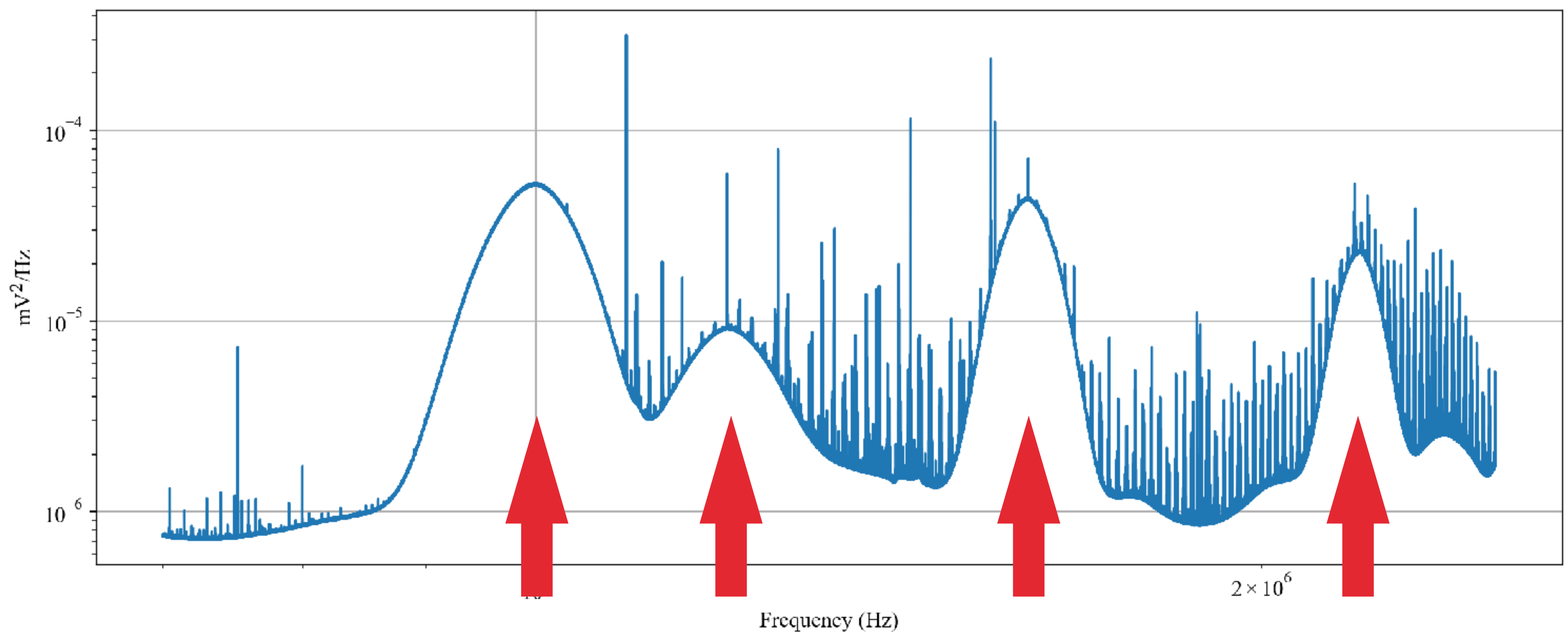


# THE NOT SO GOOD – BUMPS




- Noise baseline goes up by 1.5 orders of magnitude at various resonance frequencies
- Does not appear to be environmental noise
  - Scales with SQUID gain
  - Present with magnet on or off
- Seems more like resonances between the SQUID and network
  - Changed a little bit when we swapped out the pickup?

# DATA ACQUISITION APPROACH (ABRACADABRA ABACUS APPROACH)

- ABRA-10cm assumes a peak width of $\Delta f/f \sim 10^{-6}$
- Digitizer sampling at 10MS/s
- Collect 10s of data, FFT ($f_{max}$=5MHz, $\Delta f$=100mHz), contribute to running average PSD, repeat. Write to disk every 80 averages.
- Keep the time series data, smooth it, and downsample by factor of 10 to 1MS/s waveform
- Collect 100s of data, FFT ($f_{max}$=500kHz, $\Delta f$=10mHz), contribute to running average PSD, repeat. Write to disk every 16 averages.
- Keep the time series data, smooth it, and downsample by factor of 10 to 100kS/s waveform
- Write remaining time series to disk
  - Could build PSD with $f_{max}$=50kHz, $\Delta f$=400nHz
- Decreased disk space usage from ~26 TB to ~5 TB
- Currently (barely) running on a single core, with 32GB RAM