Conduction Cooling Studies for Nb3Sn SRF Cavities

Developing the use of commercial cryocoolers for compact accelerators

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U.S. DOE award DE-SC0008431 supports Nb3Sn coating studies and RF testing R&D

NSF Award 1734189 supports research on compact high frequency cavities

Outline

- Motivation for conduction cooling
- Assembly design at Cornell
- Primary RF test results
- Analysis & Diagnostics
- Next steps for the future

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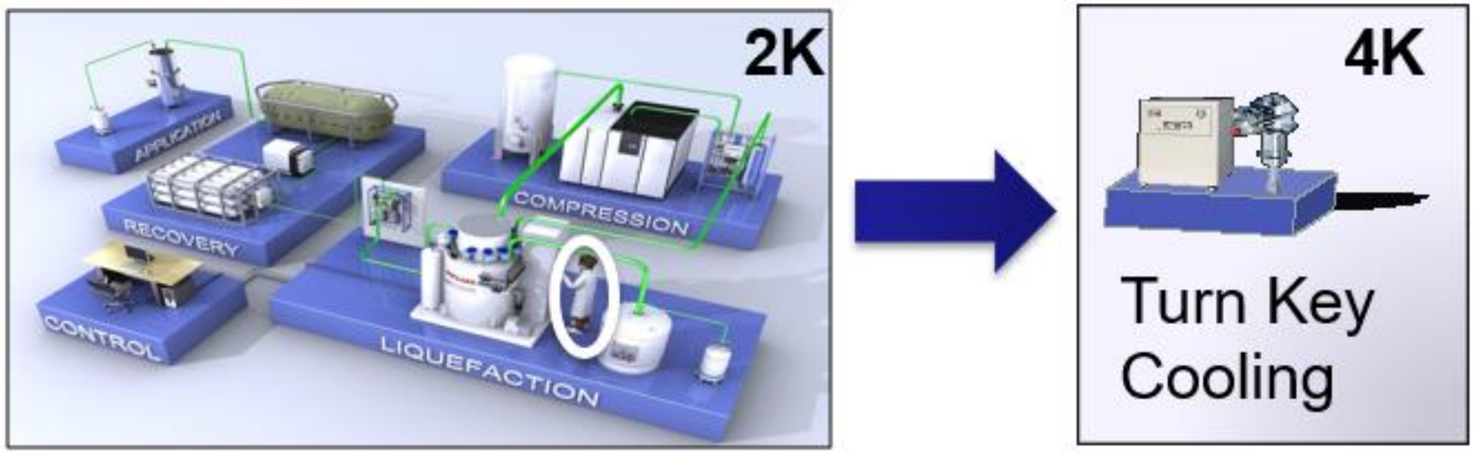
Motivation

- U.S. DOE report "Accelerators for America's Future" outlines various applications of compact accelerators
  - Spans across industry, medical fields, national security, etc.
  - Examples include wastewater treatment, medical procedures & sterilization, cargo inspection, …
- Small-scale operations of SRF cavities face major barrier in complex cryogenics infrastructure
- Cryocoolers provide a cheaper and simpler ("turn-key") alternative
- Nb_3Sn cavities offer more efficient operation at 4 K – primary operation temperature

→ Successful operation of Nb_3Sn SRF cavities using cryocoolers can help make SRF technology more accessible for such applications.



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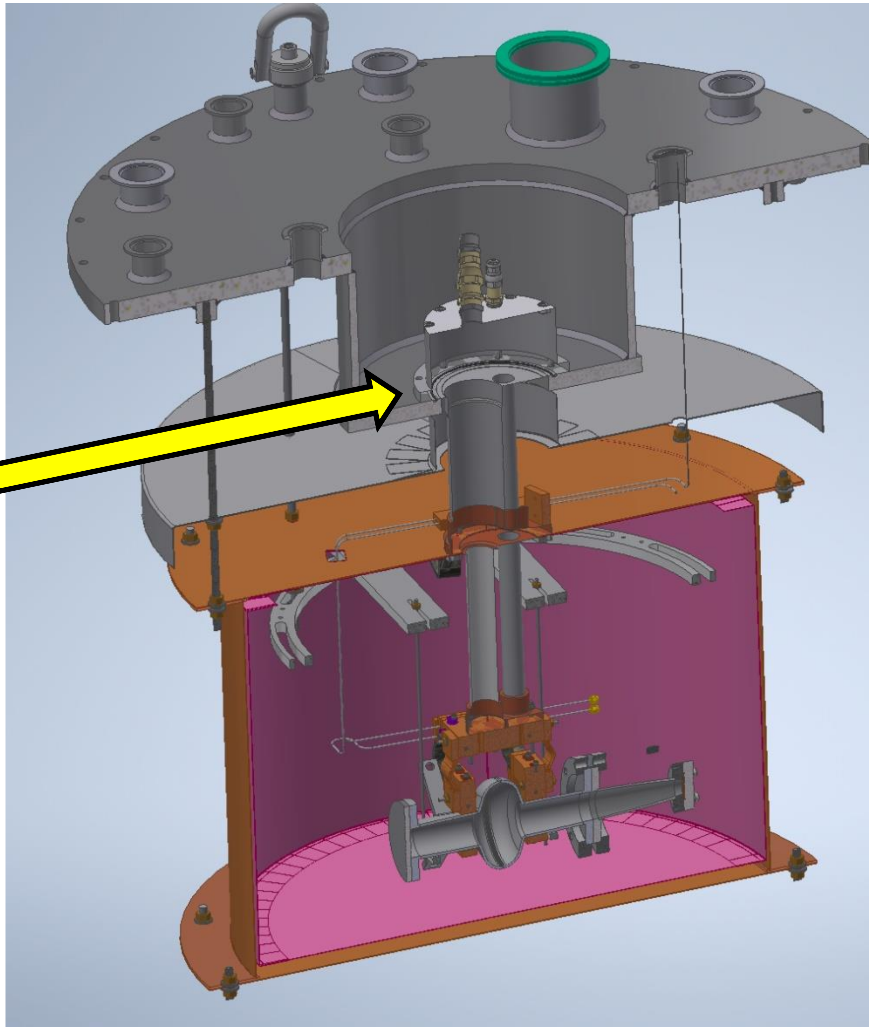
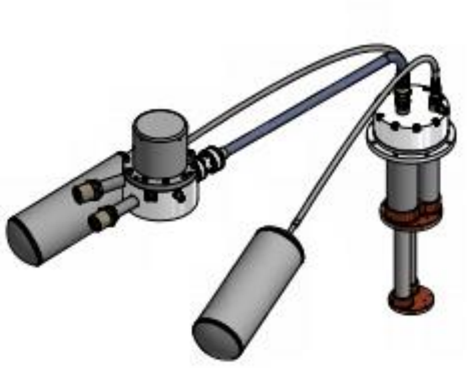
Assembly Design

- Cryocooler: Cryomech model P420 with remote motor
  - 2nd stage: 1.8 W @ 4.2 K
  - 1st stage: 55 W @ 45 K
  - Motor & reservoirs removed from primary assembly

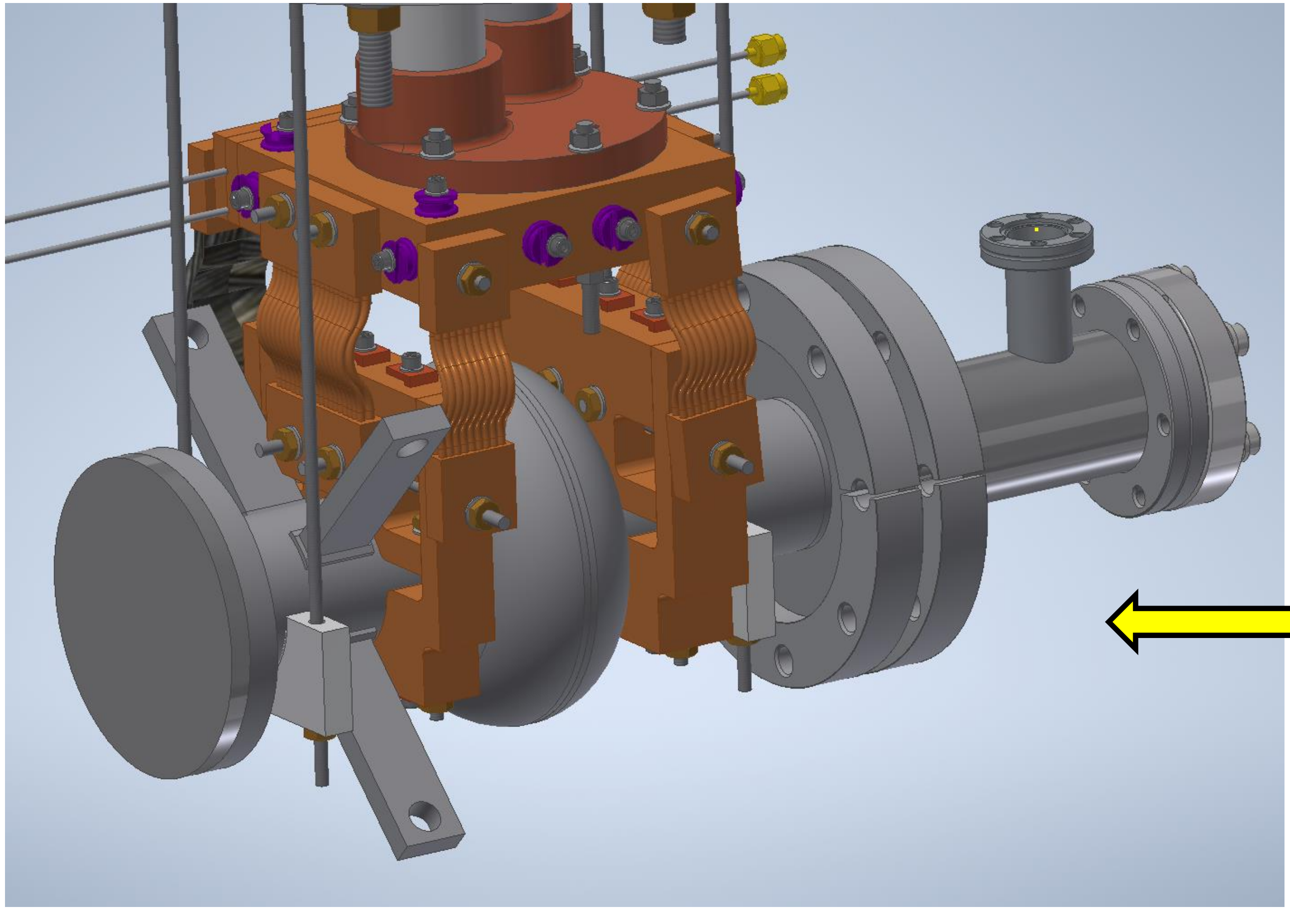


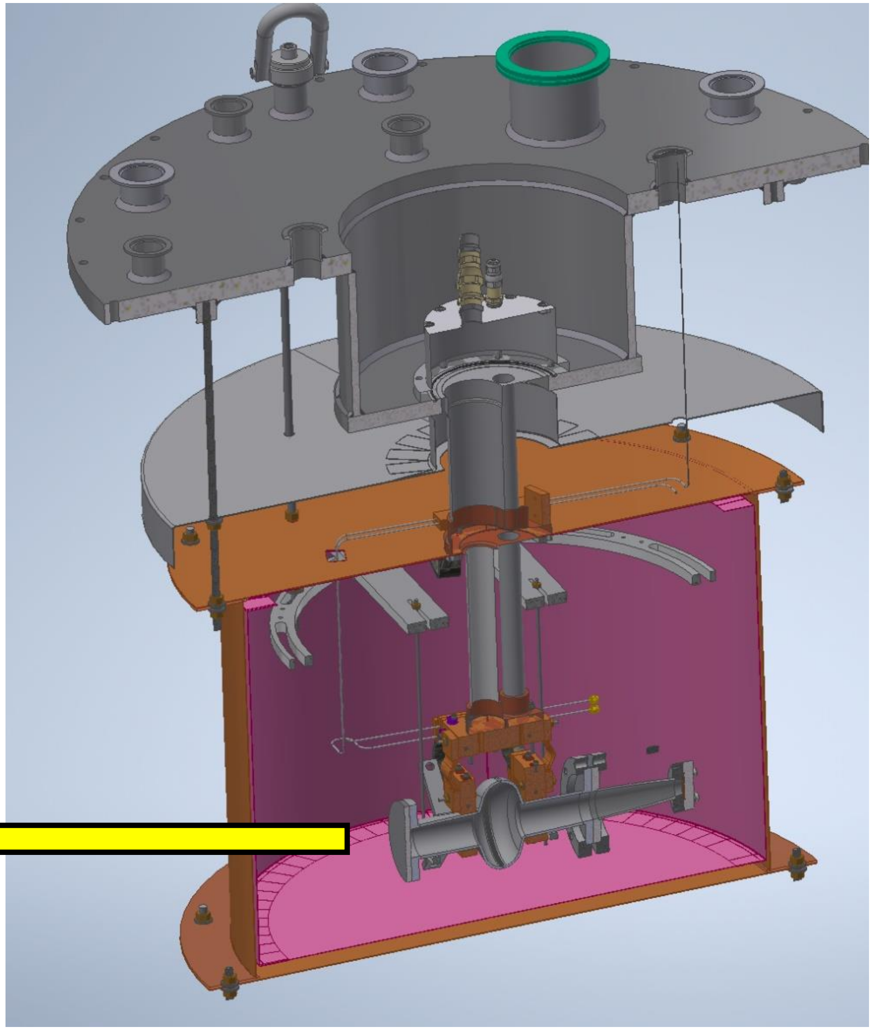


Primary compressor unit
- "Turn-key" operation
- Straight-forward system monitoring

Assembly Design

- Cavity: Nb_3Sn-coated 2.6 GHz
- Thermal Connection: Copper braided straps
- Cernox sensors on 2nd stage, beam clamps, equator





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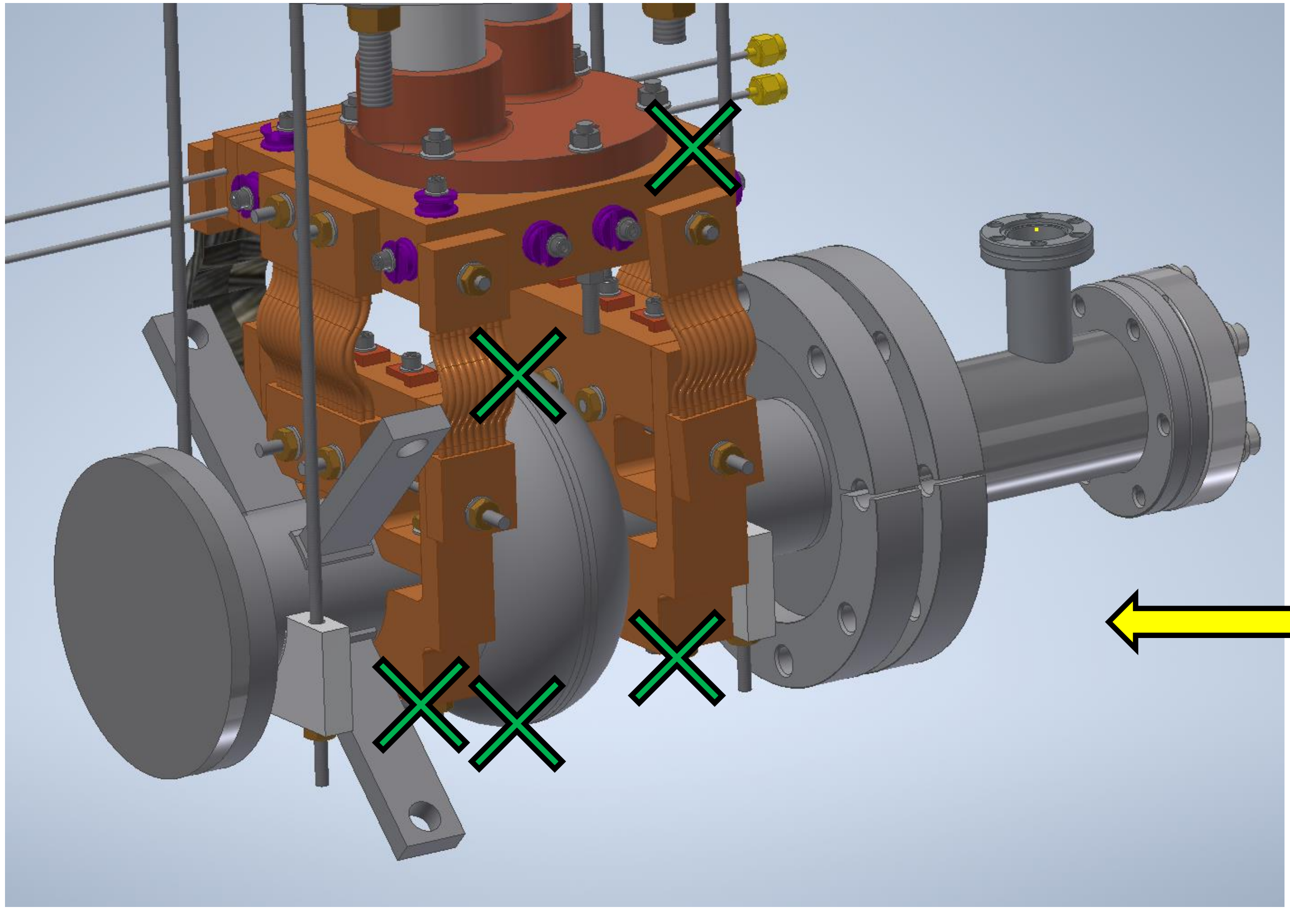

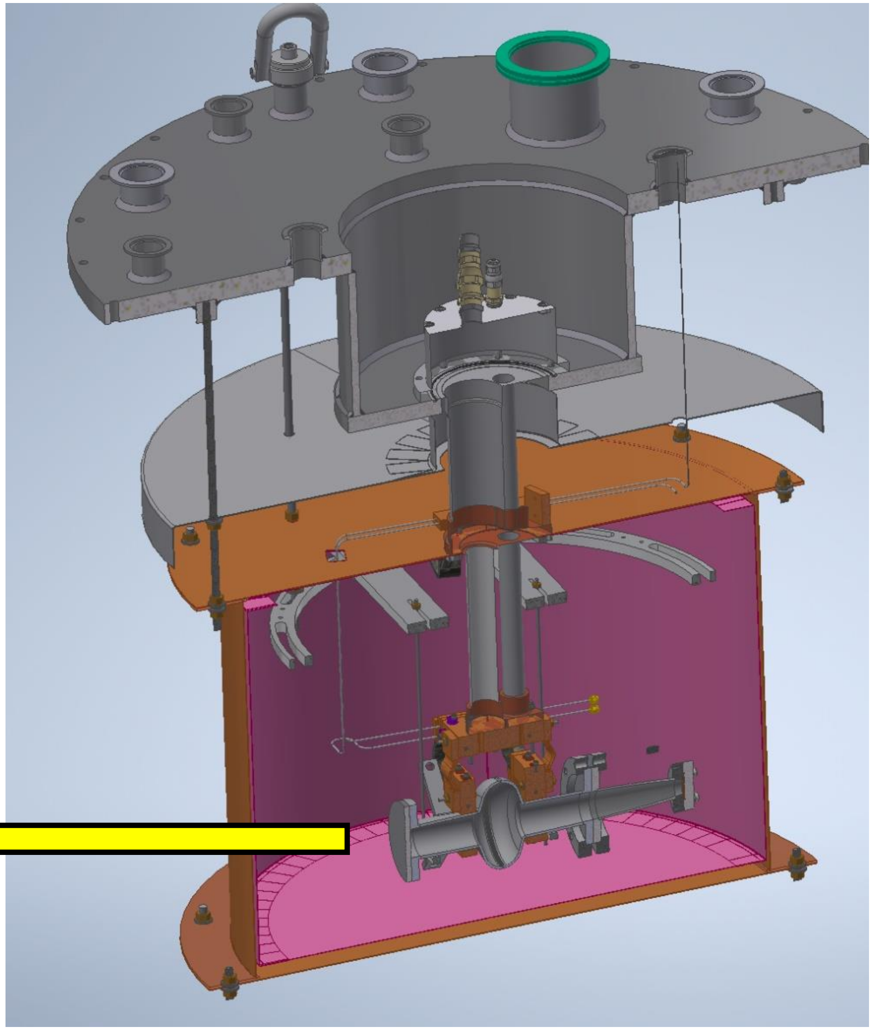

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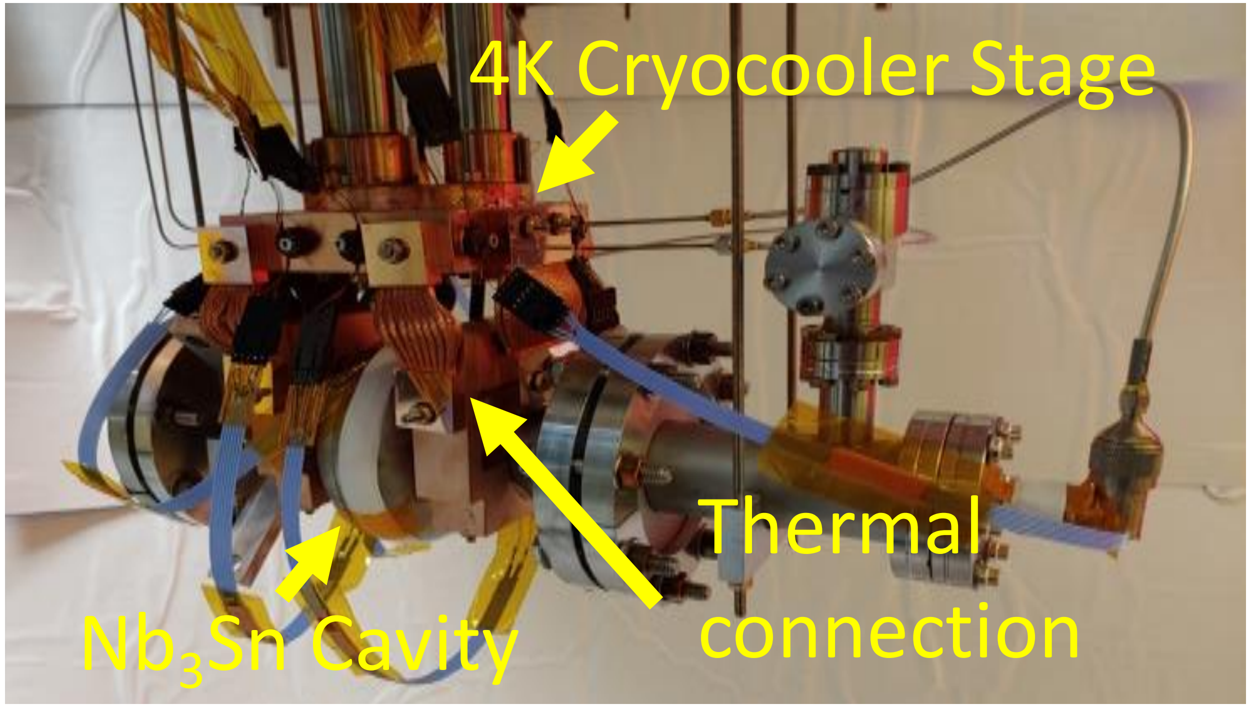

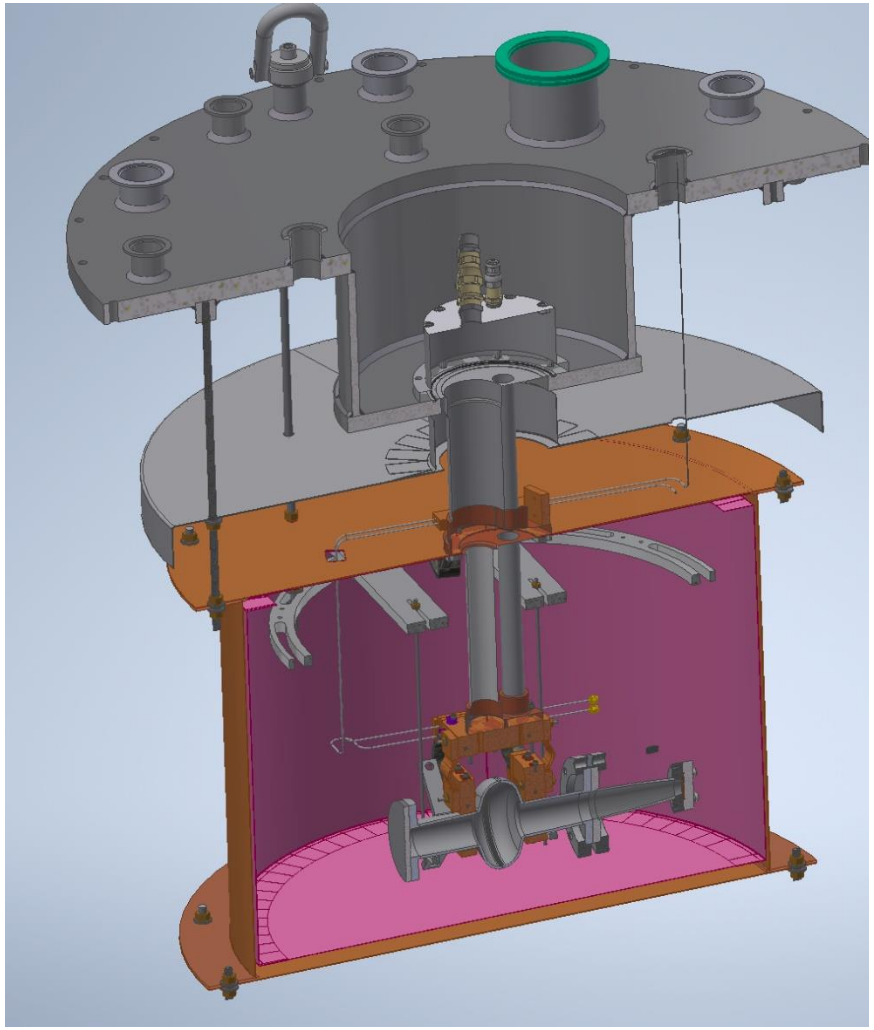

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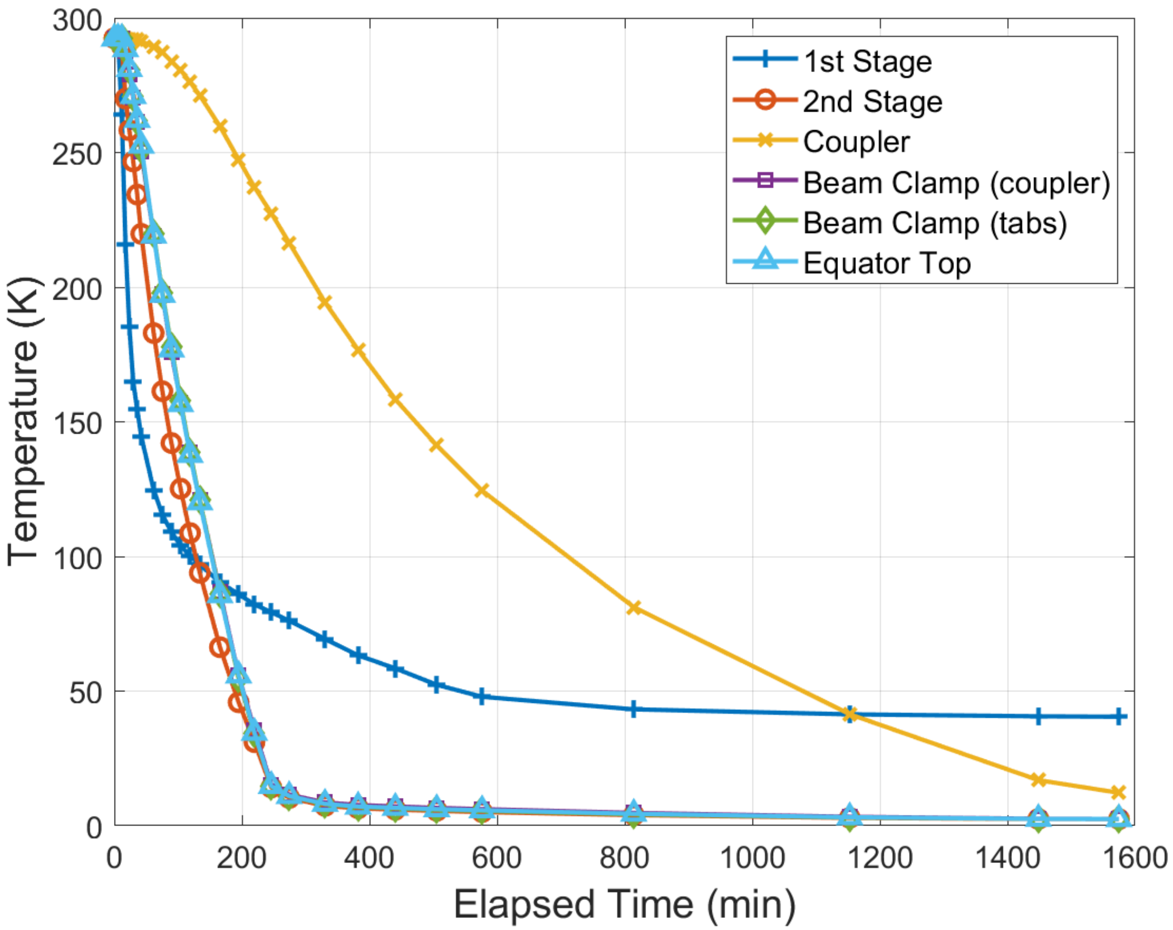
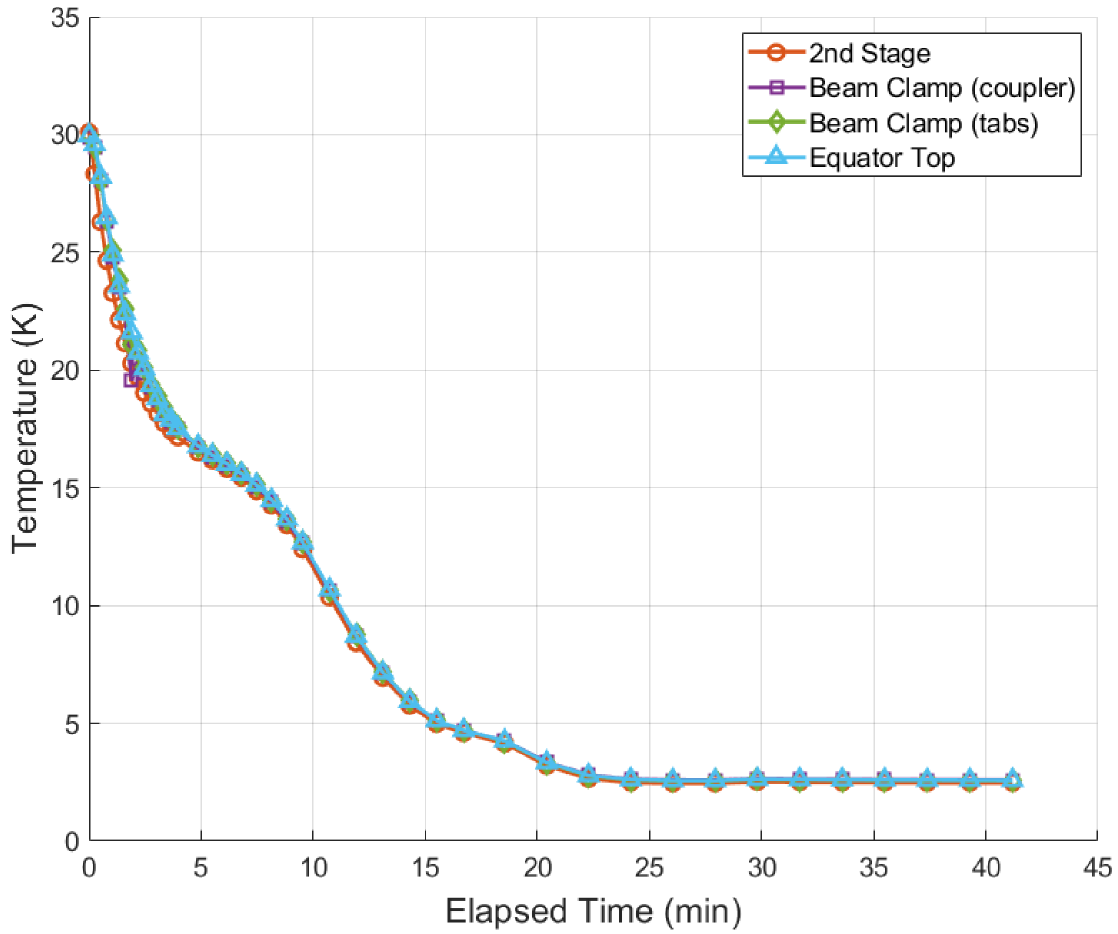
Initial Cooldown

- Initial cooldown from room temperature
- Cavity assembly cooled in approx. 4 hrs
  - Note: clamp and equator curves are overlapping
- 1st stage and coupler require more time



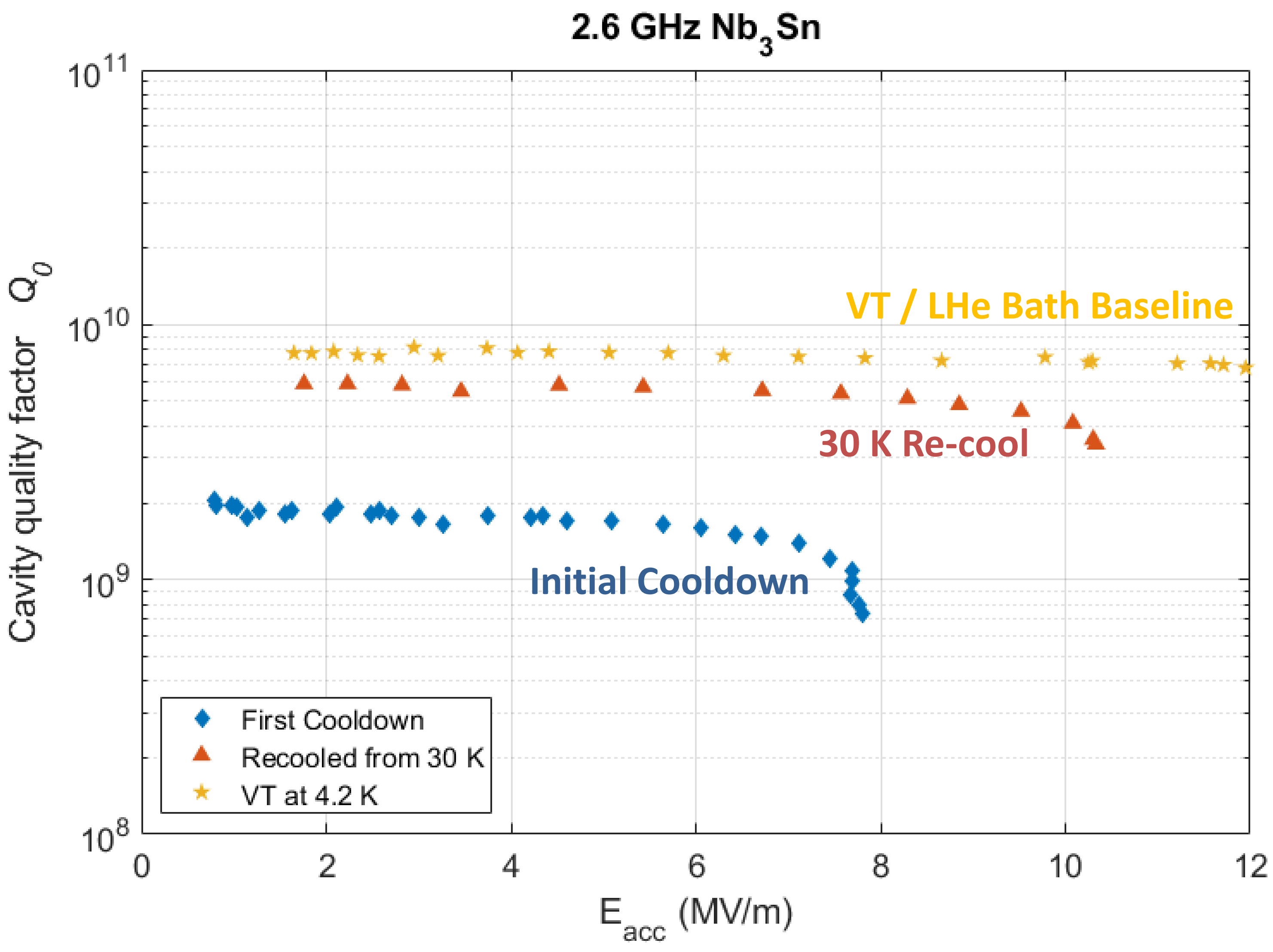
Temperature Cycle – 30 K Re-cool

- Cavity warmed up to 30 K, then cooled back down
- Not showing 1st stage or coupler for clarity
- Other temperature cycles completed from 20 K and 40 K – similar process
- Remaining analysis focuses on 30 K re-cool



RF Test Results: Q_0

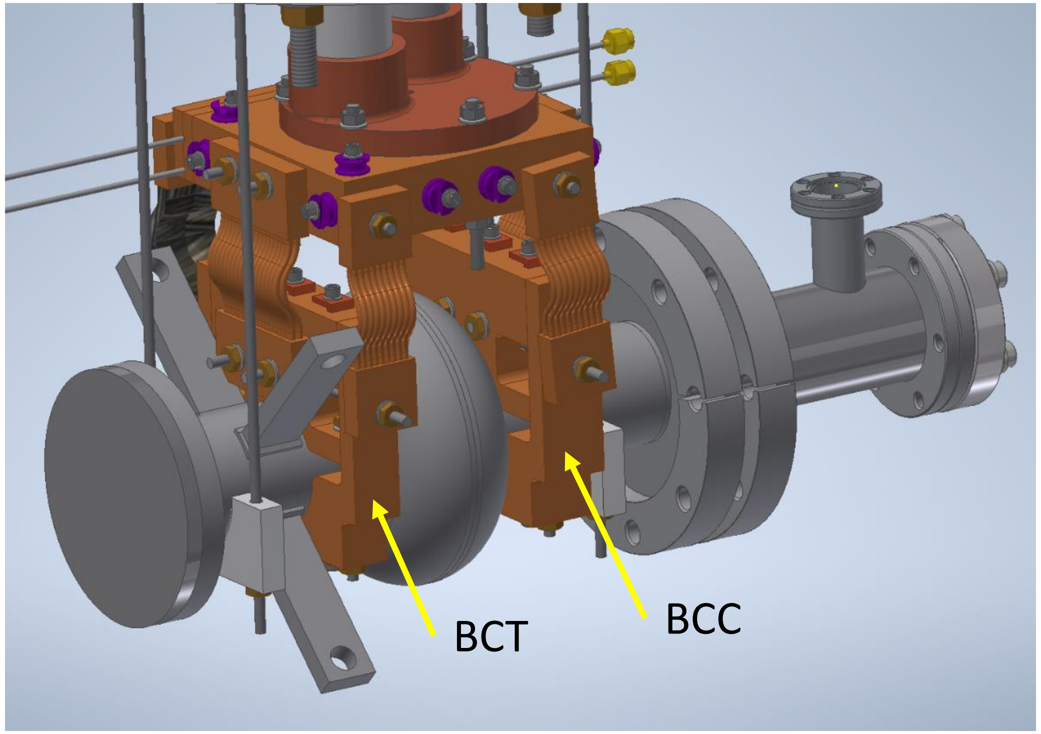
- **4.2 K VT (LHe Bath)** baseline test
  - Quench near **18 MV/m**
  - Low-field Q_0 ~ **8E9**
- **Initial Cooldown** test
  - E_{acc} stable up to **8 MV/m**
  - Low-field Q_0 ~ **2E9**
- **30 K temperature cycle** test
  - E_{acc} stable past **10 MV/m**
  - Low-field Q_0 ~ **6E9**
  - Q_0 within factor of ~2 of 4.2 K VT
  - Pdiss = **0.78 W** at 10 MV/m
    - Comfortably under 1.8 W
  - Continuous operation
    - dT/dt < 1 mK/s

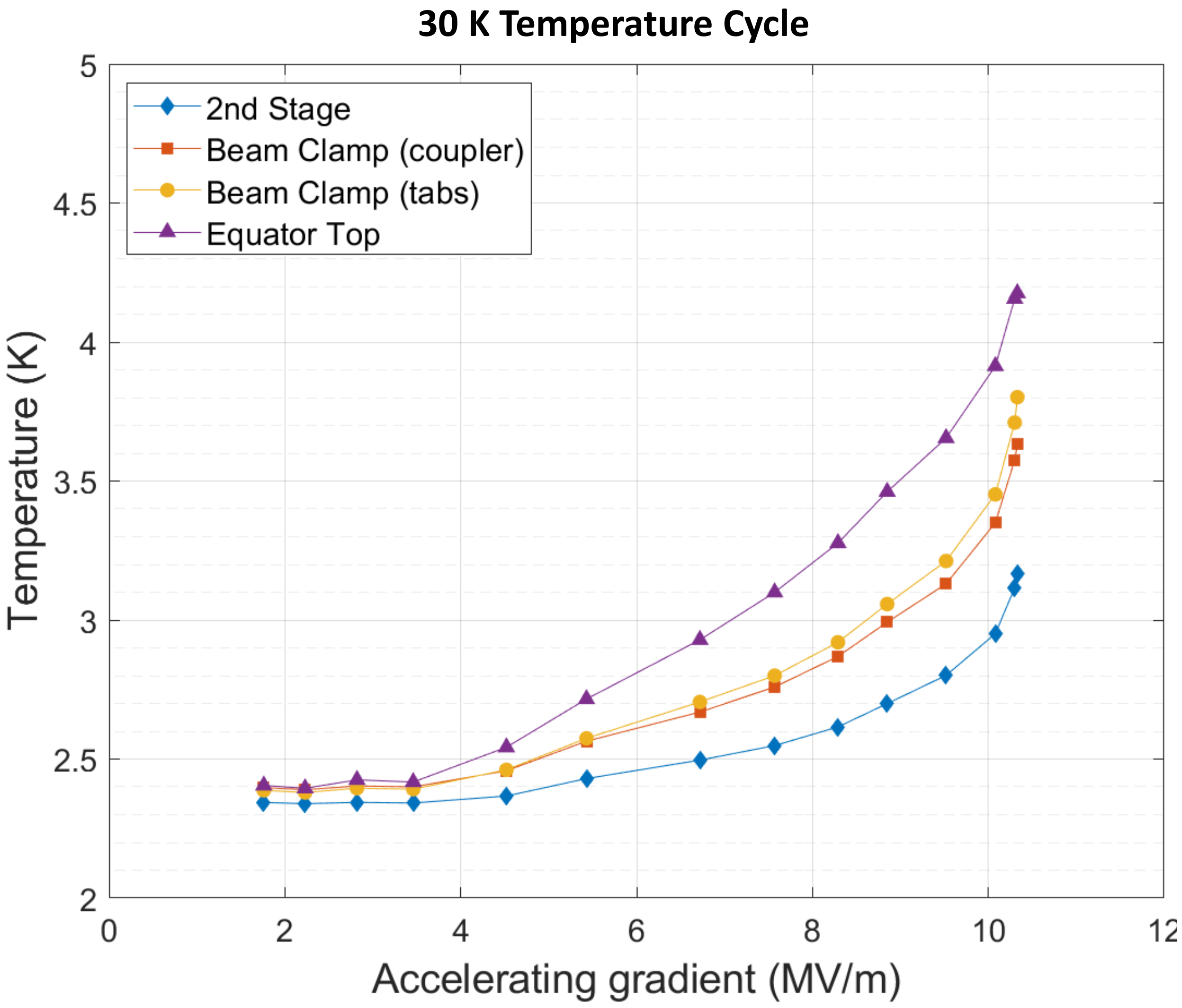


RF Test Results: Temperatures

- 30 K Temperature Cycle
- Minimal heating under 4 MV/m
- Cavity just under **4 K** at **10 MV/m**
- Max cavity temp ~ **4.2 K**

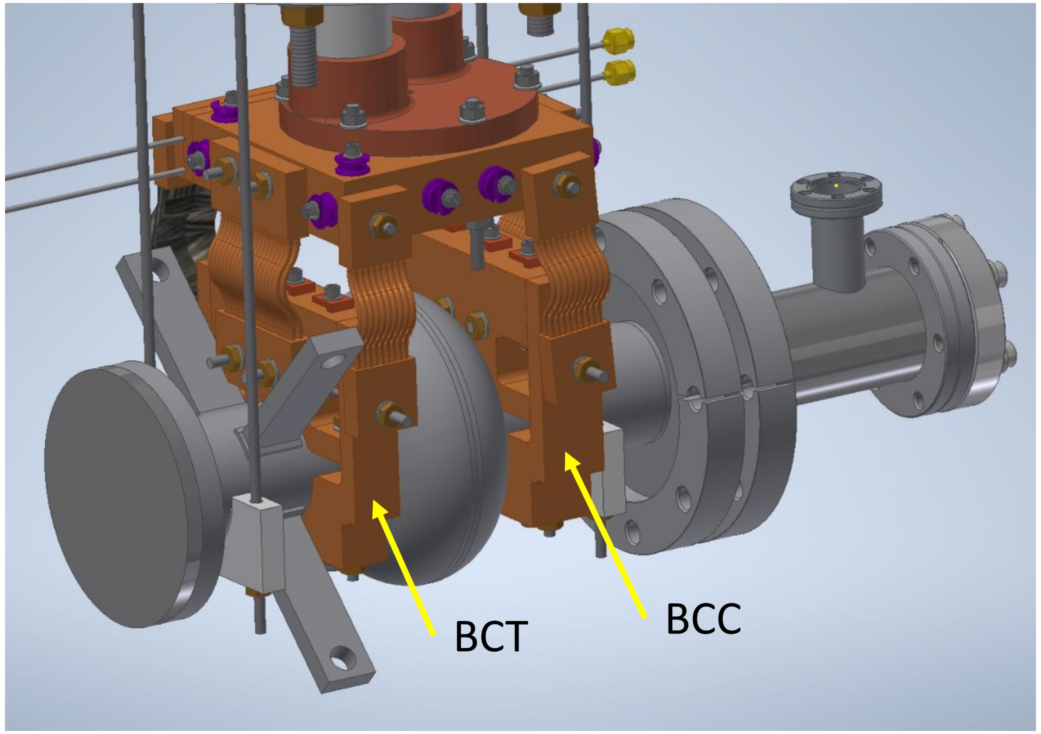
➔ **Stable operation at 10 MV/m at 4.2 K**

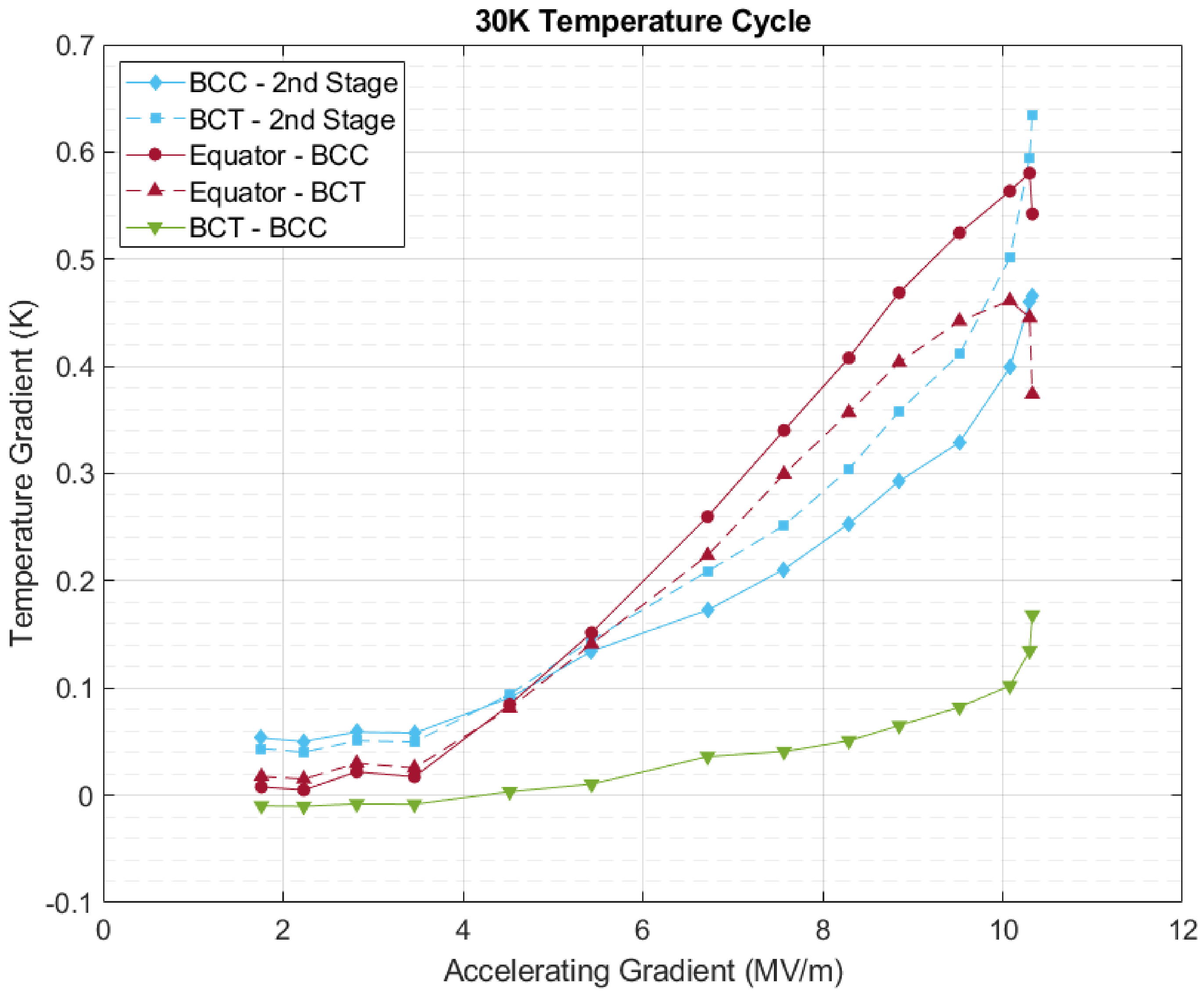




RF Test Results: Temperatures

- BCT slightly warmer than BCC
- Two gradient stages are approx. equal
  - ~0.1 K difference at 10 MV/m
- Good baseline to use as comparison





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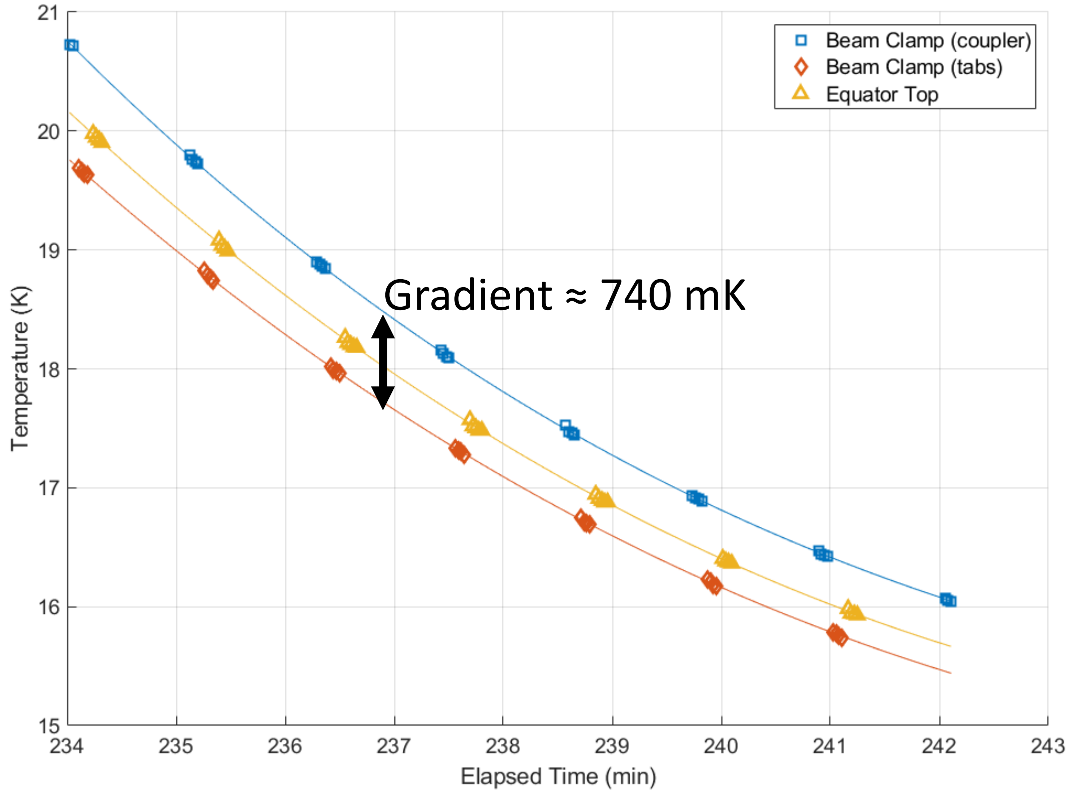
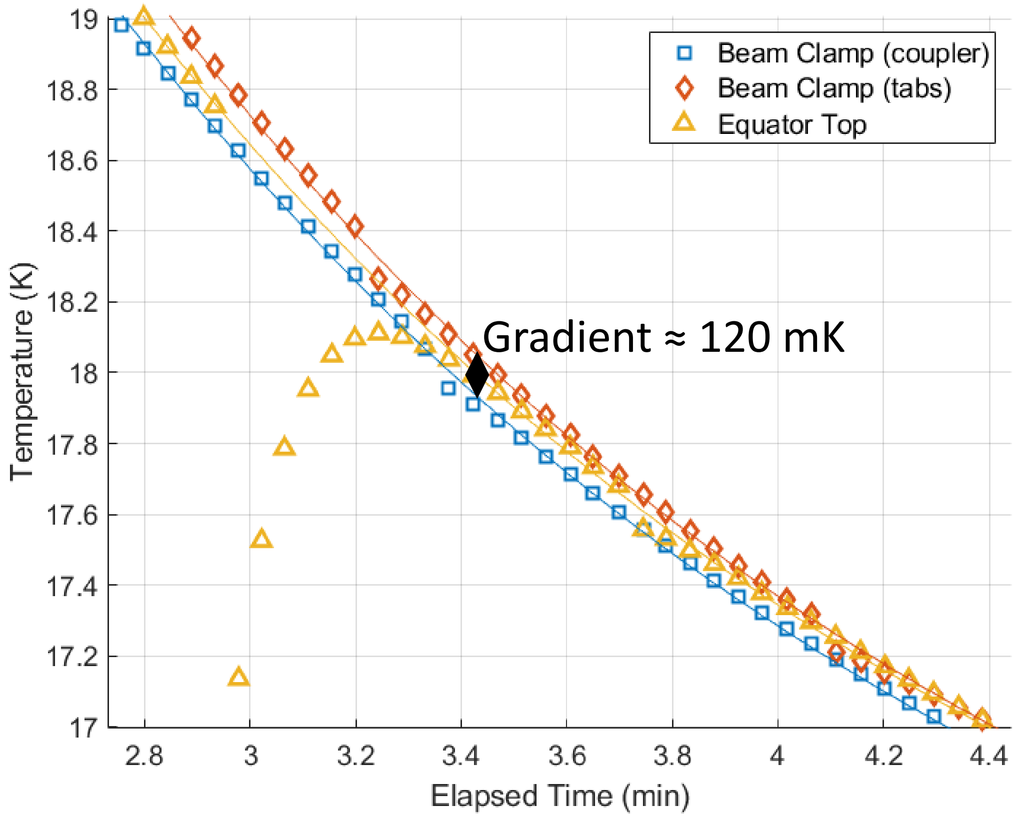
Cooldown Gradients

- Why does temperature cycling offer better performance?
- Look at thermal gradients at Tc
- Thermal gradients → Thermal currents → Trapped flux → Higher R_0

Initial Cooldown

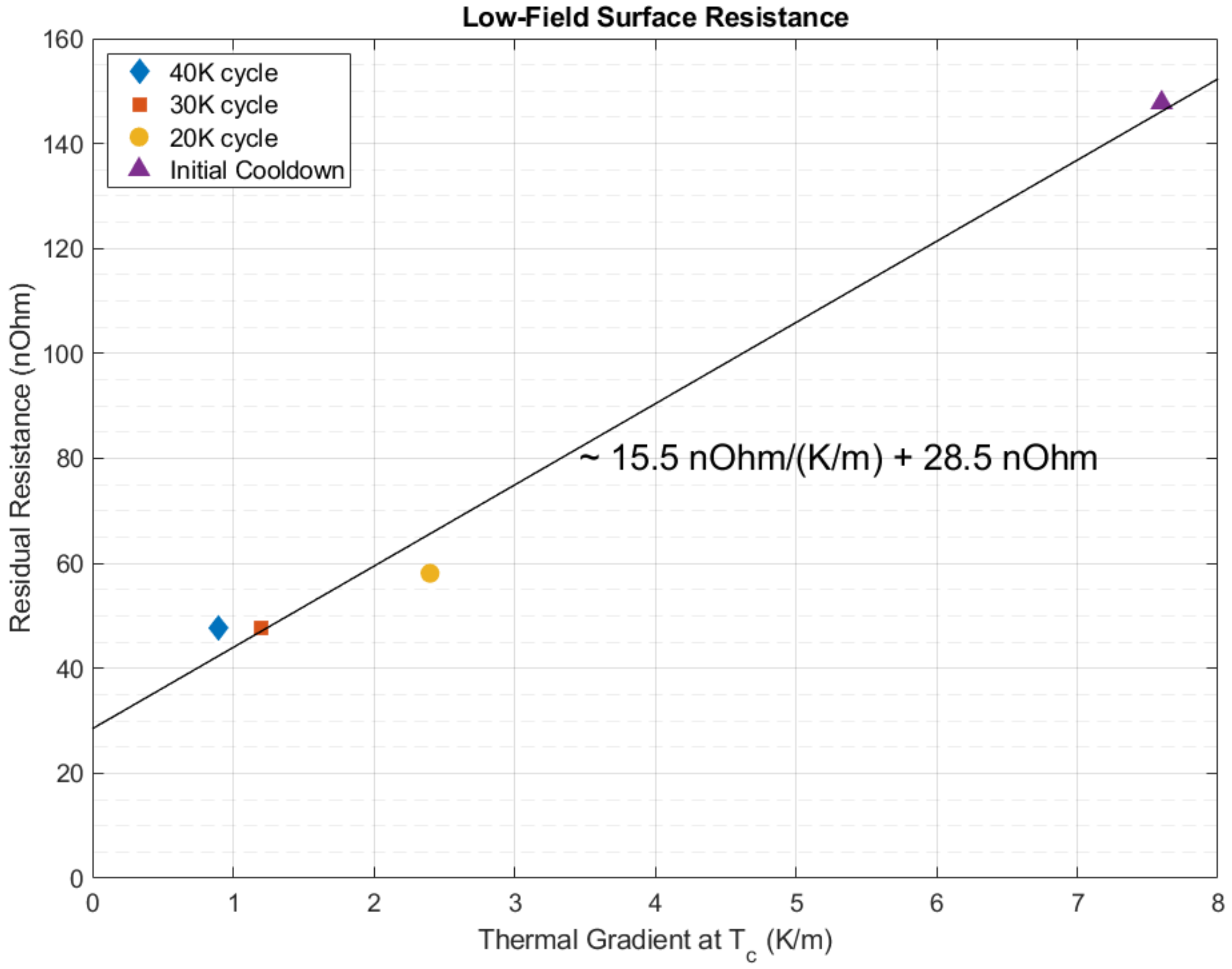


30 K Temp Cycle



R_0 Comparison

- Linear fit slope: **15.5 nΩ/(K/m)**
- Compare to results from R. Porter*
  - Low-field sensitivity: 0.75 nΩ/mG
  - Conversion factor: 6.2 mG/(K/m)
    - Assume same value for 1.3 & 2.6 GHz
  - ➔ **4.65 nΩ/(K/m)**
- Within factor of 3-4
- Ignores "vertical" gradient
  - Not a factor in VT due to symmetry

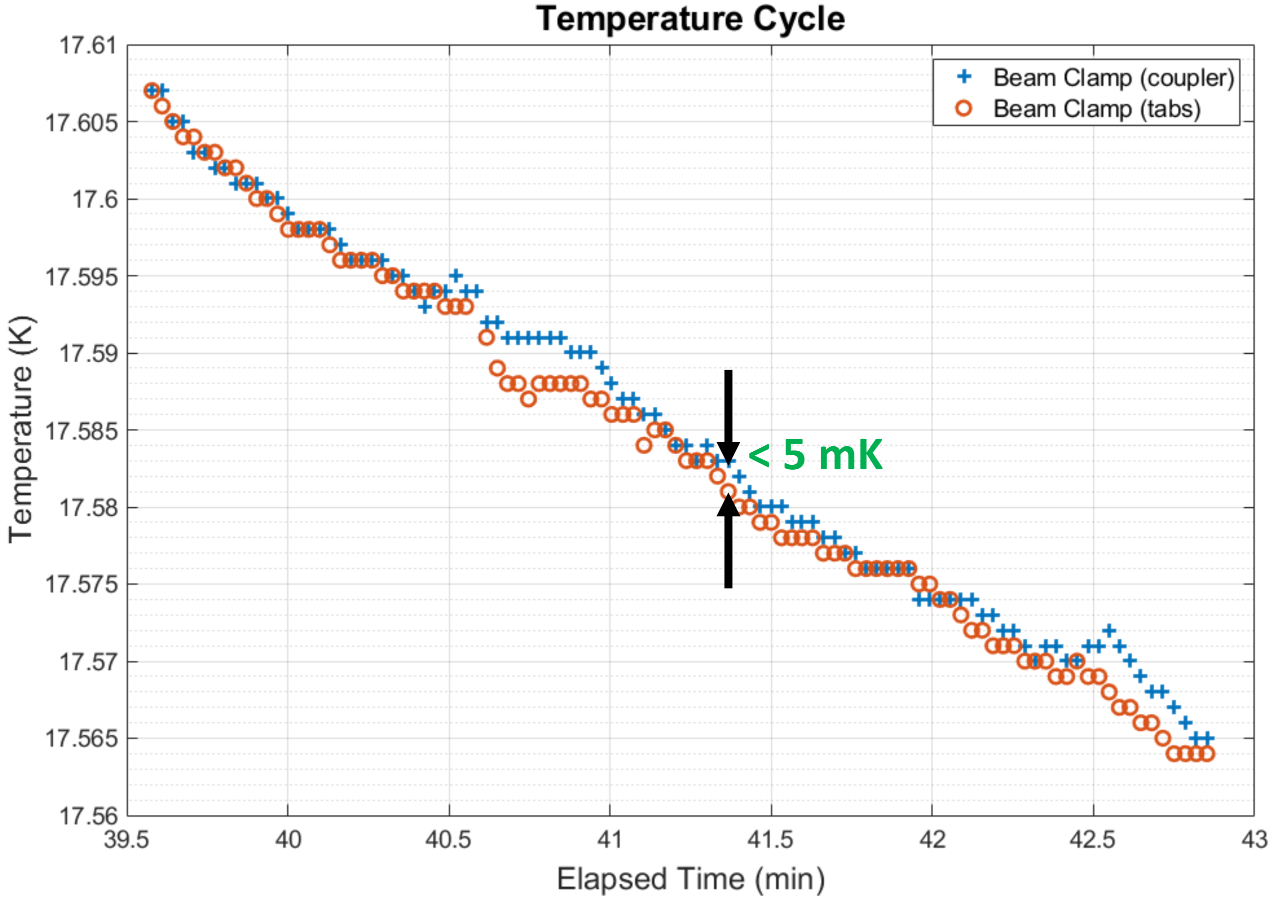


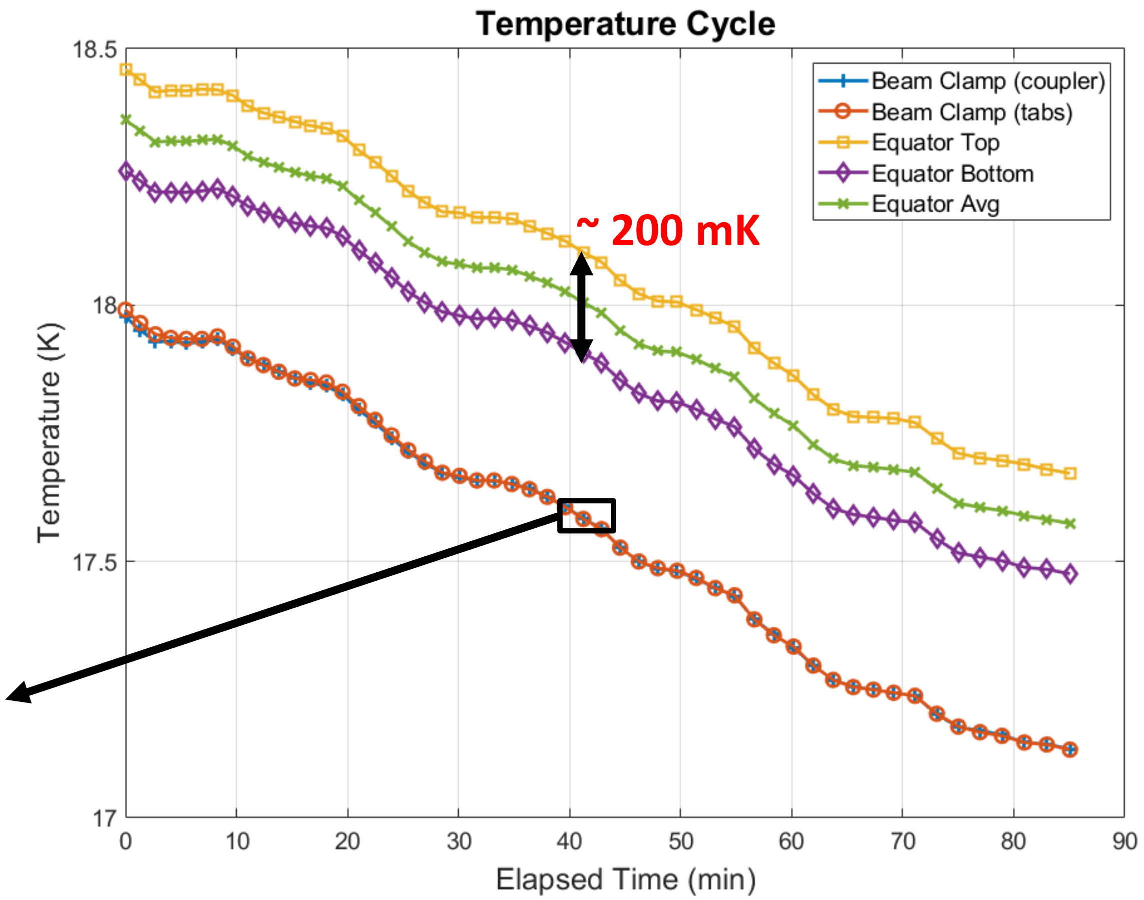
Conclusion: Reducing thermal gradients is crucial for high performance!

* Presented at TTC'19

Improvement: Thermal Gradients

- Added 1 kOhm resistors to both beam clamps
  - Fine-tuned control during cooldown
- Successful implementation in recent test!
  - Beam clamps held within **1-2 mK** through Tc
  - Best cooldown previously had ~ **120 mK**

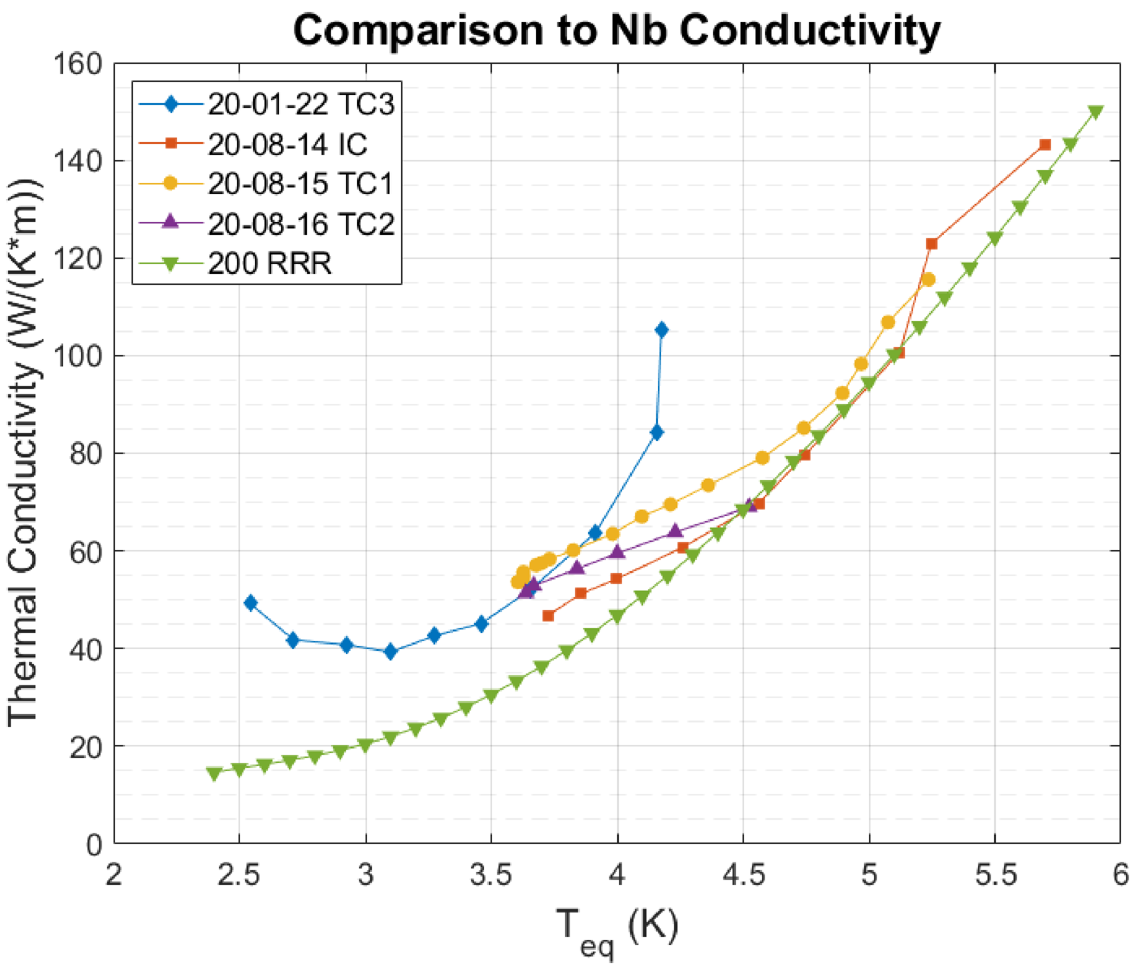


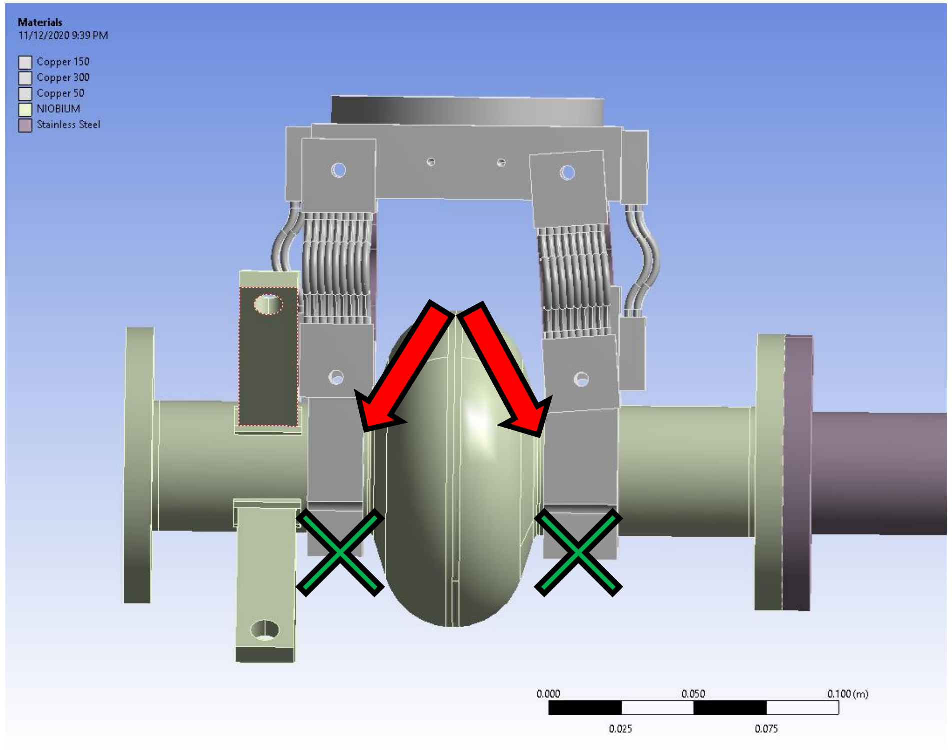


- Clamp-to-clamp gradient fixed
- "Vertical" gradient still an issue

Comparison to Nb Conductivity

- Calculated using P_{diss} and gradient between equator and beam clamps (averaged)
- Main contribution to gradient comes from niobium
  - Contribution from copper clamps is negligible



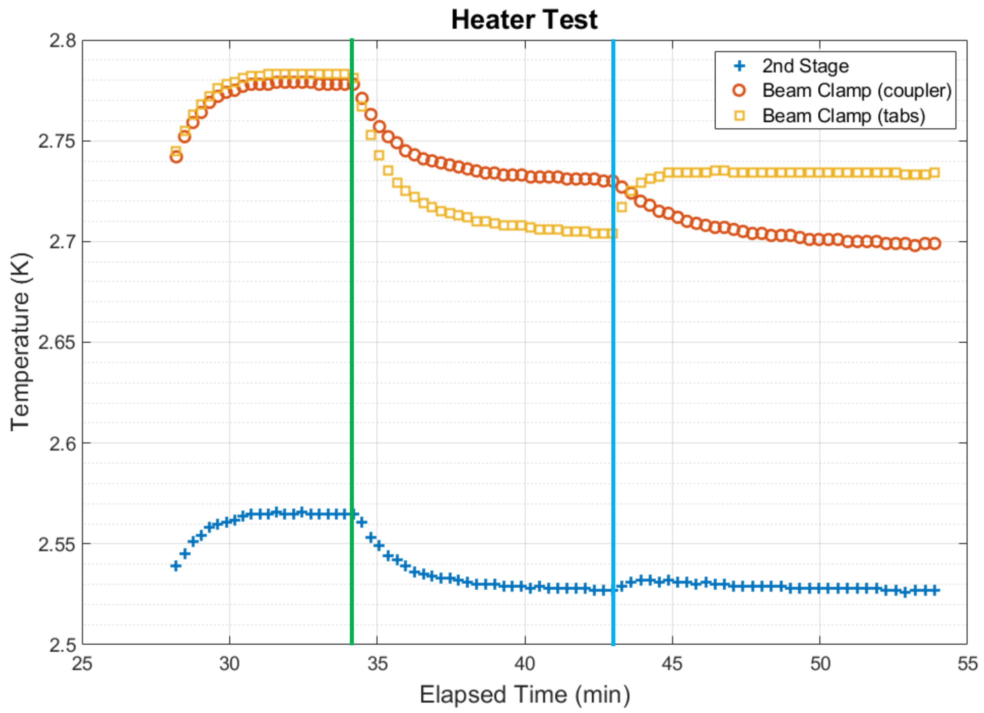


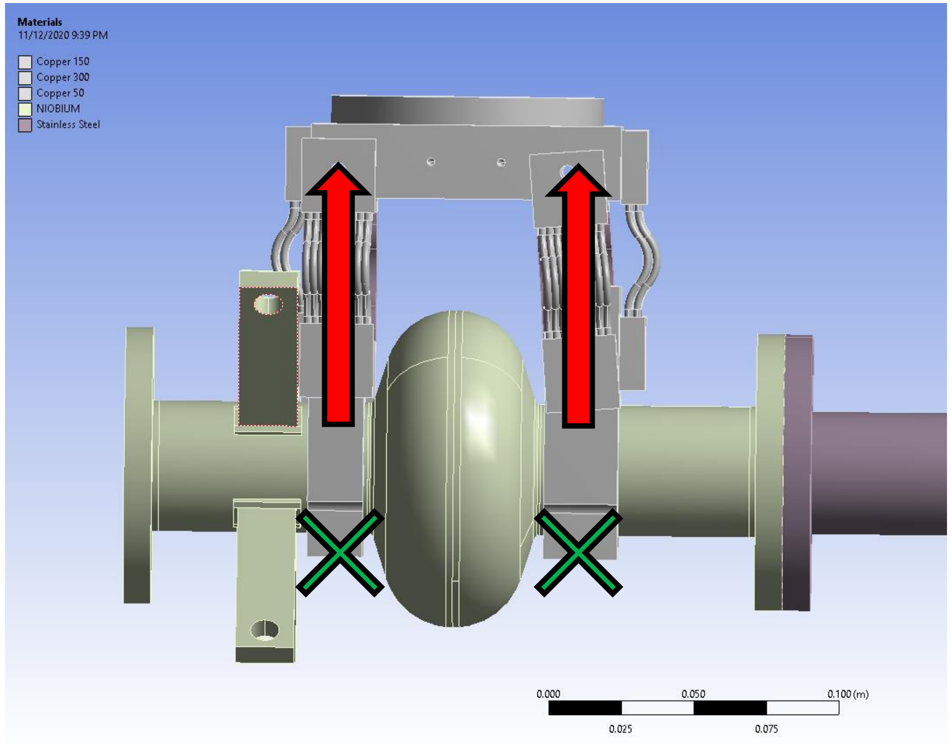
Conclusion:

Good thermal contact to beam clamps

Clamp Heater Test

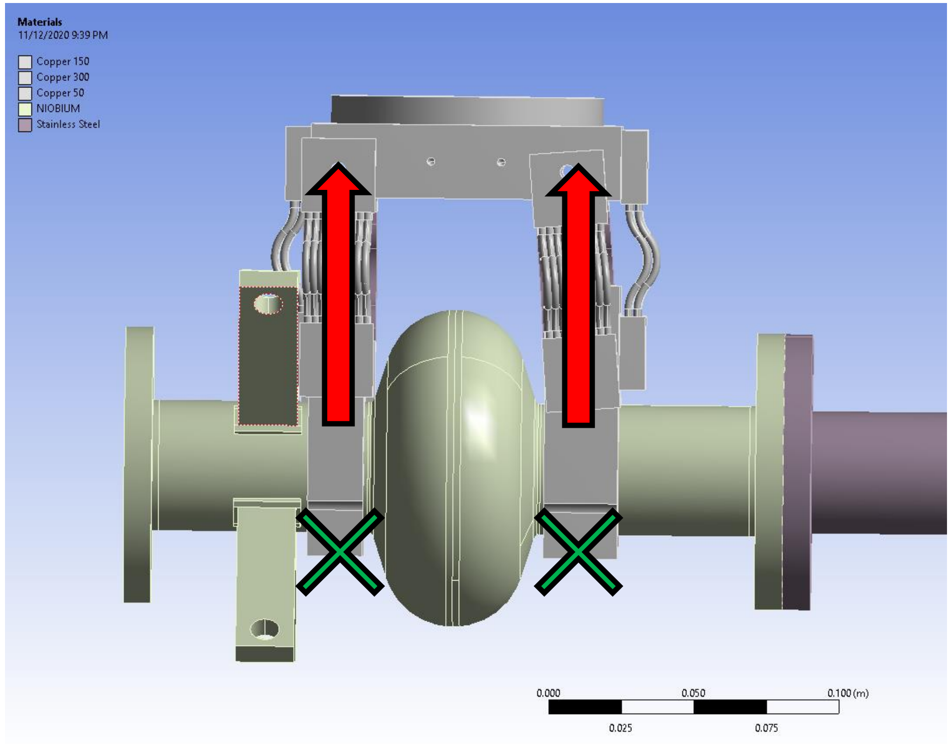
- RF off, system allowed to cool completely
- Calculate W/K using ΔGradient (heater on & off)
  - Gradient is between 2nd stage and clamps
- Setting A: 0.025 W on BCC only
- Setting B: 0.025 W on BCT only





Clamp Heater Test

- Setting A: 0.025 W on BCC only
  - ΔGradient = **0.044 K** → **0.57 W/K**
- Setting B: 0.025 W on BCT only
  - ΔGradient = **0.047 K** → **0.53 W/K**
- Compare to 30 K temp cycle test at 10 MV/m
  - P_{diss} / 2 = **0.39 W**
  - ΔGradient to BCC = **0.354 K** → **1.1 W/K**
  - ΔGradient to BCT = **0.468 K** → **0.83 W/K**
- Beam clamp temperature: roughly 2.7 K vs 3.4 K
  - Can expect ~ **30%** change due to Cu thermal cond.



Conclusion: Copper straps provide a reliable thermal pathway

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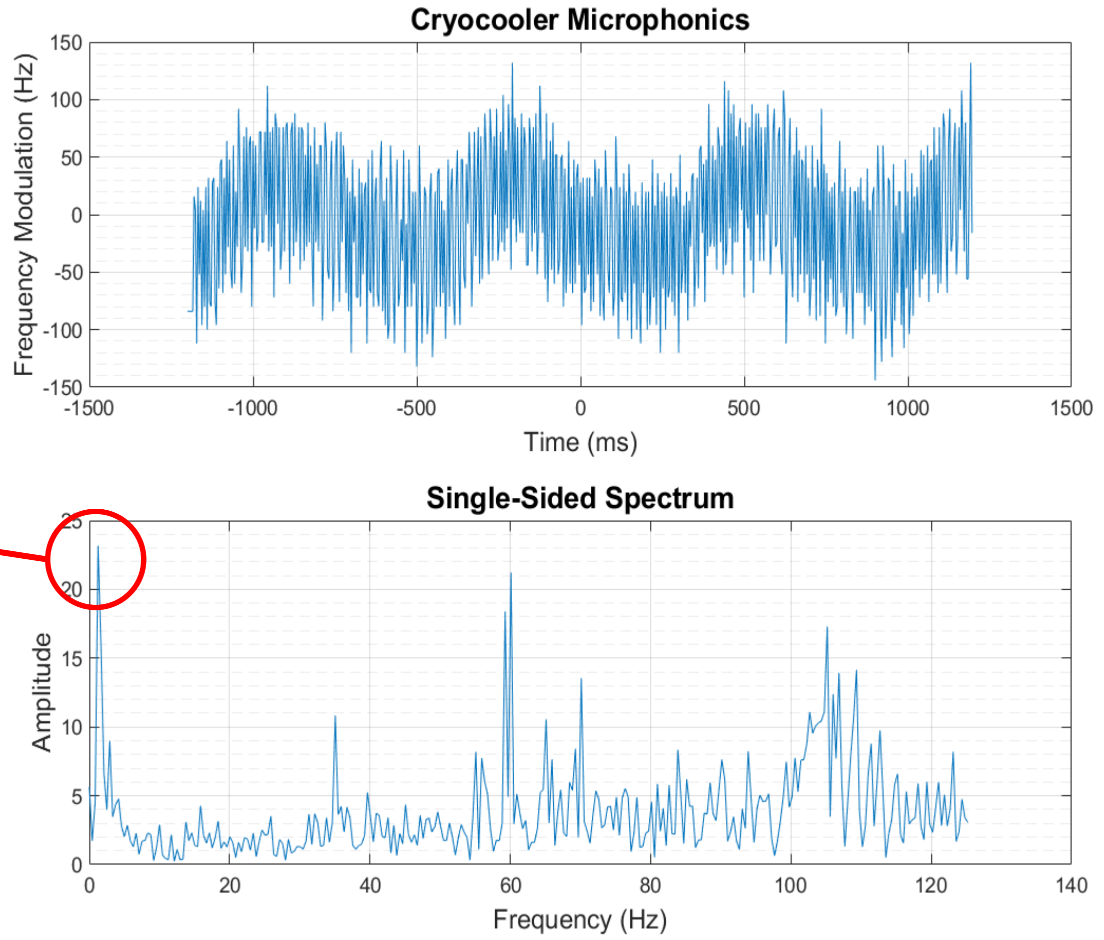
Next Steps: Near-term

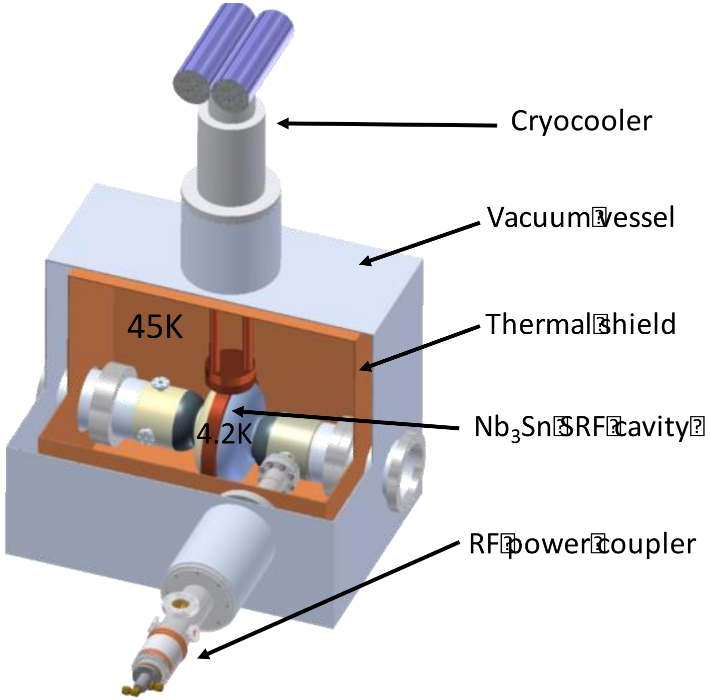
- Reduce ambient magnetic fields
  - Recent tests measured up to 60 mG near the cavity
  - Potential re-magnetization due to thermal cycling?
- Microphonics analysis & suppression
  - Large signal matches cryocooler pulse frequency
  - Strength of microphonics effects varies significantly
  - Reason for variation is currently unclear
  - Next tests will include vibrational sensors on top plate

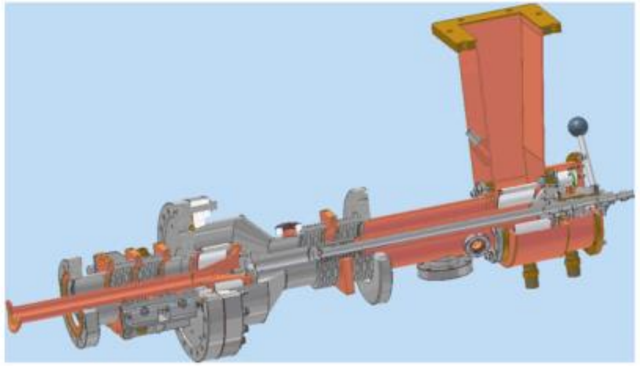


Next Steps: Long-term

- Three-year Stewardship Proposal – Accepted
- Main Objective: Develop new cryomodule with integrated cryocooler for 4K operation of Nb3Sn cavities
  - **1 MeV** energy gain w/ currents up to **100 mA** → input power up to **100 kW**
  - Requires low static & dynamic heat loads
  - Requires reliable microphonics control

Conceptual Illustration:





	Static	At 50 kW (CW, TW)
To 1.8 K	0.05 W	0.2 W
To 4.2 K	0.30 W	2.0 W
To 70 K	6.80 W	31 W

*Figure 4: **Left**: 3-D CAD model of the high-power Cornell ERL injector RF input coupler. Right: Static and dynamic heat loads of the coupler. [18, 19]*

Summary

- Demonstrated successful continuous operation at 10 MV/m
  - Max dissipated power well within 1.8 W
- Key finding: small gradients essential for performance
  - Demonstrated successful clamp-to-clamp gradient control during cooldown
- Ambient field reduction and microphonics control offer potential for further improvement in performance
- Next long-term project: implementation in full-scale cryomodule

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