# WG1 TTC: Impact of Baking on the Performance of Low-beta, Low-frequency QWRs at 4 K

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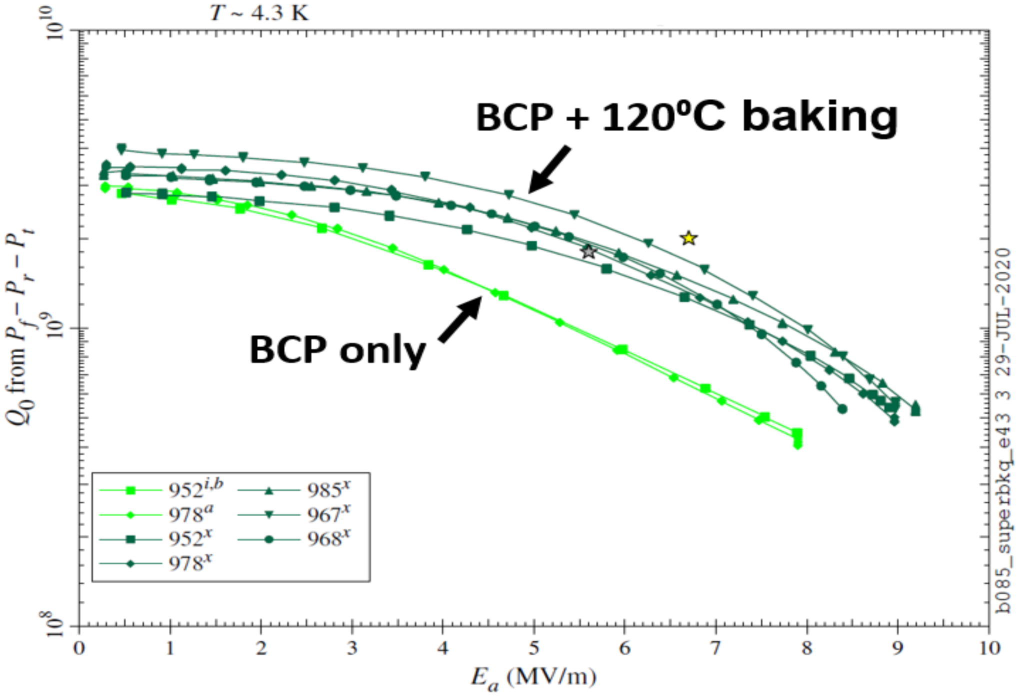
# Introduction

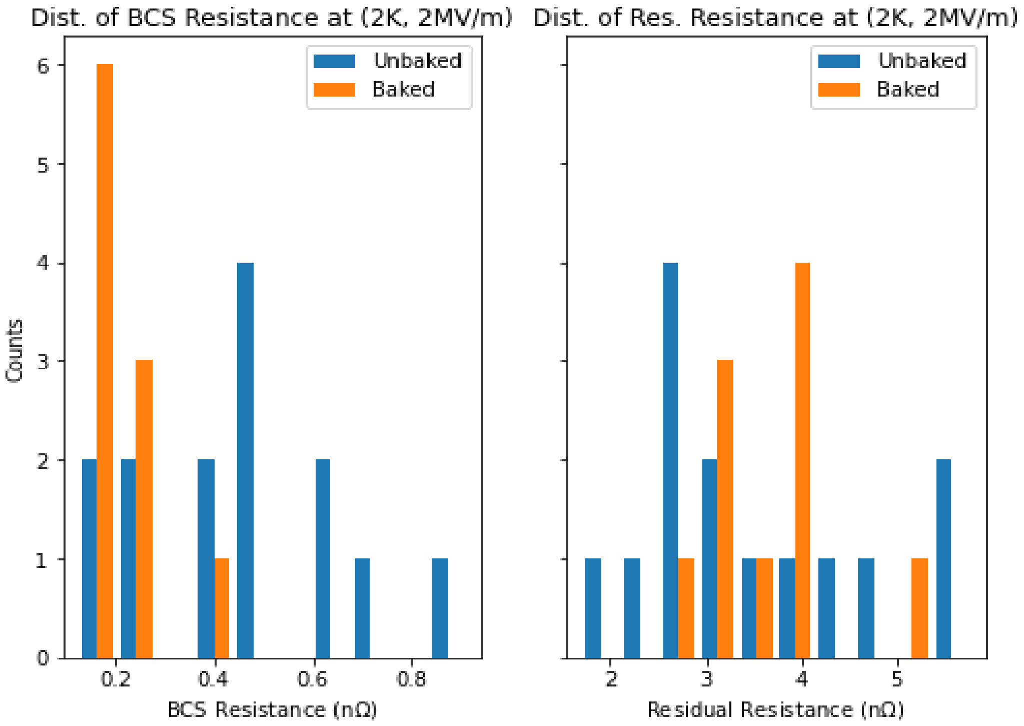
- FRIB linac contains 94 quarter-wave resonators with $\beta = 0.085$ (QWR, $f$ = 80.5 MHz, $T$ = 2 K, 4.3 K); prep: buffered chemical polishing (BCP)
- BCP + in-situ low-temperature bake (LTB,120 C, 48hrs) improves medium field $Q$-slope (MFQS) at 4.3 K




- Cause for reduction in MFQS? How to utilize it?
- Examine the BCS resistance in three different baking scenarios
  - In-situ LTB: 120 C 48hr
  - Furnace LTB: 120 C 48hr
  - Furnace medium temp. bake (MTB): 350 C 3hr

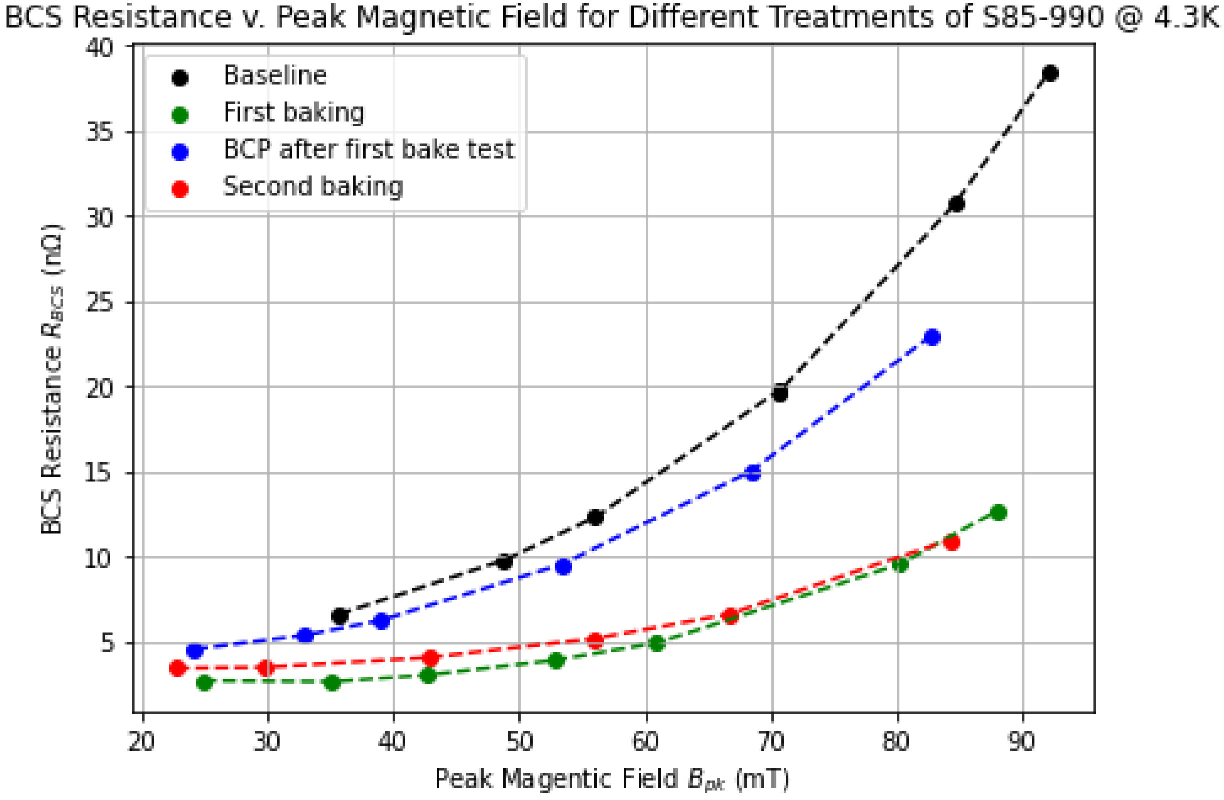
# Goal and Methodology

- Goal: isolate BCS resistance and the effect of baking
- Note: FRIB QWRs use indium gasket as RF seal
  - Seating of gasket has impact on residual resistance
    - » Residual resistance is dominant component for FRIB QWR at 2 K
- In rough approximation, ignore BCS contribution at 2K
  - $R_s(2K, B_{pk}) \approx R_{res}(B_{pk})$
  - $R_{BCS} \approx R_s(4.3K, B_{pk}) - R_{res}(2K, B_{pk})$



# Effect of BCP Reset

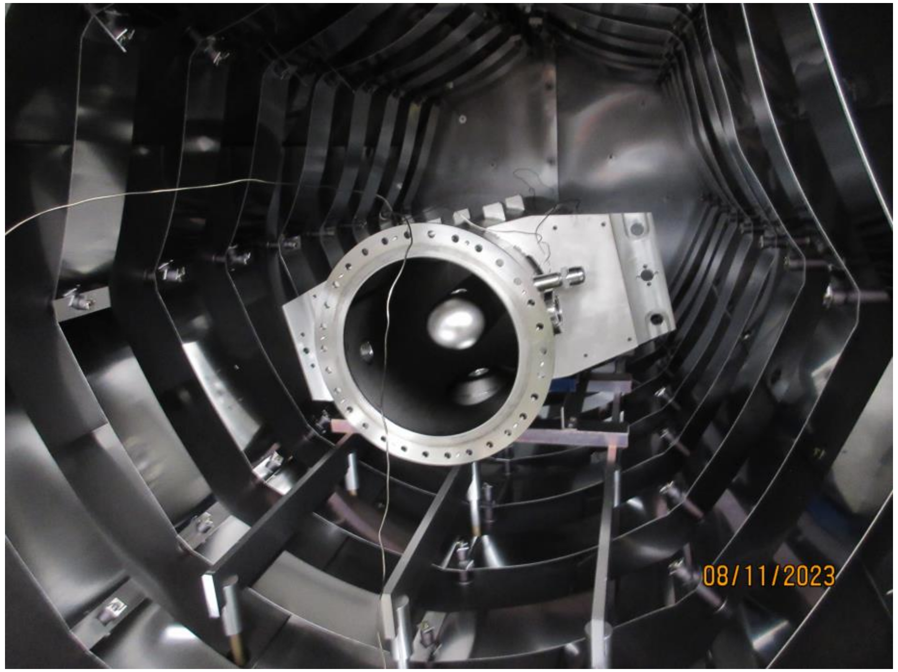
- Hypothesis: improvement in MFQS is due to improved thermal impedance
  - Shown anodized cavity has increased performance ~4 K [1]
- First case to look at: S85-990
  - Baseline
  - BCP + 120C in-situ bake
  - Post-test BCP, then retest. Performance within variation for un-baked cavities
  - BCP + 120C in-situ again
- Effect of first bake reset by BCP
  - Then recovered by second bake
- Conclusion: improved MFQS not necessarily due to improved thermal impedance



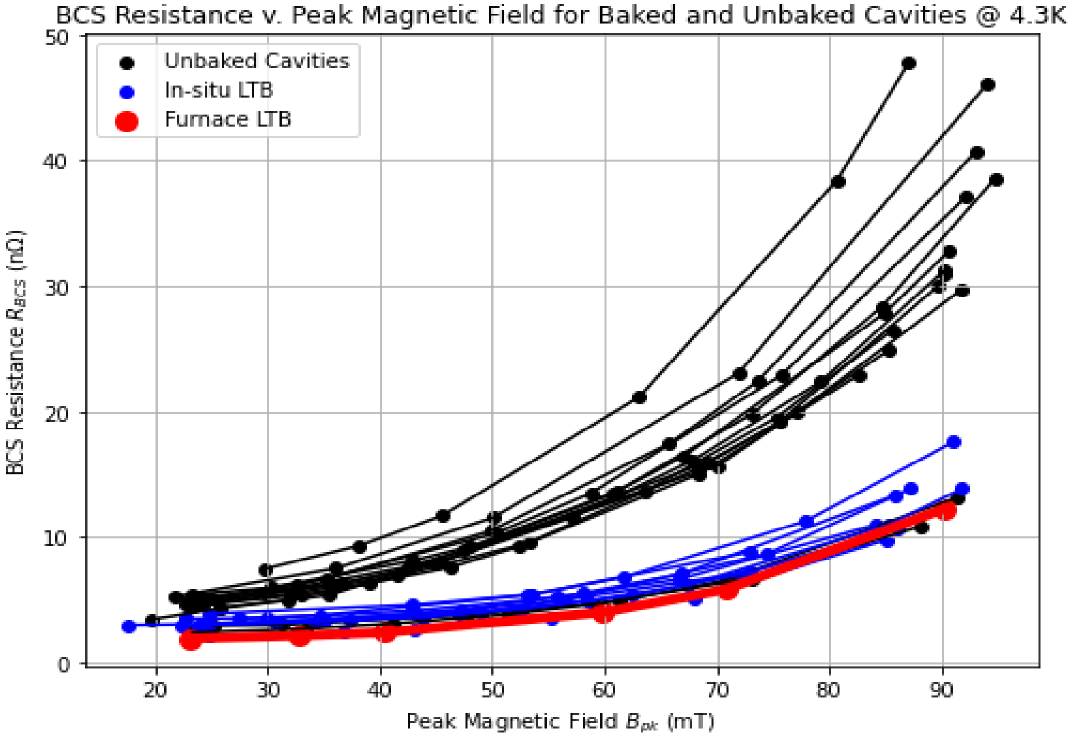

**[1]** M. Checchin, et. al., *Proc. Of SRF2013*

# In-situ vs. Furnace LTB

- Test furnace LTB and compare the result with in-situ LTB
  - Resulting Q-curve is in red
- Can see that furnace configuration yields similar MFQS improvement
  - Bottom flange (Ti) and tuning plate (Nb) are not baked in furnace baking

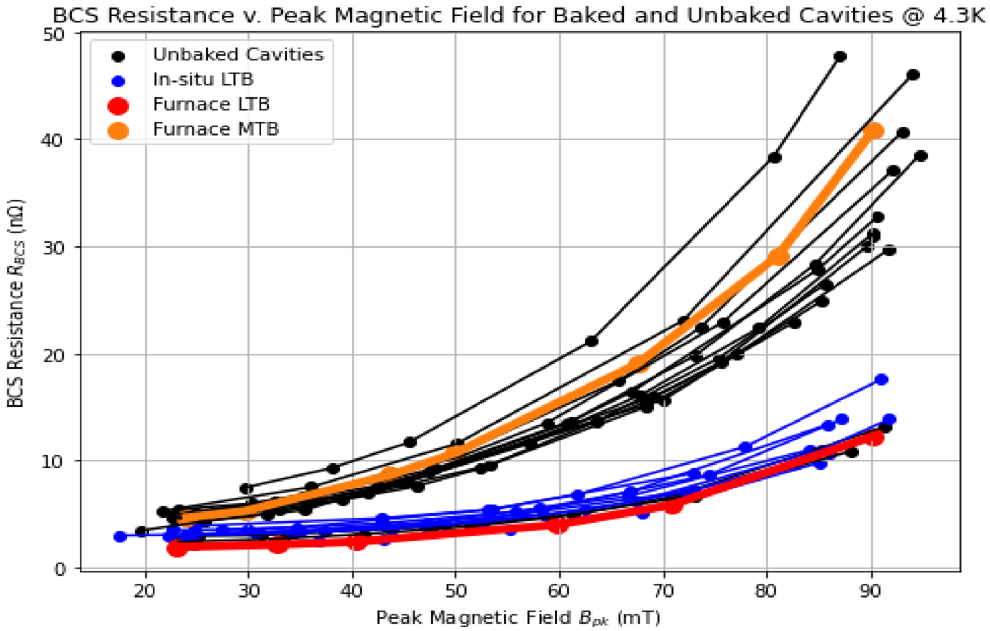


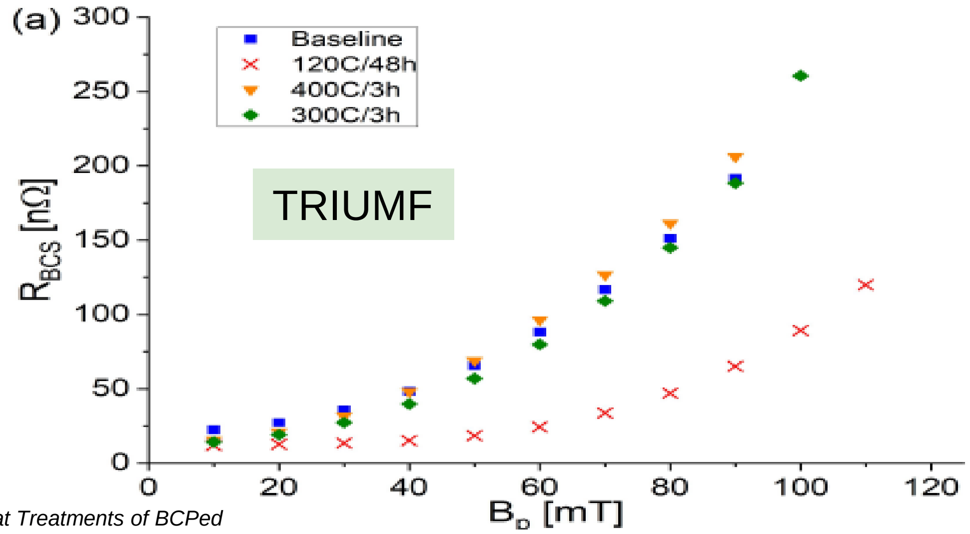

*Furnace bake setup. Image courtesy of B. Barker*



# Furnace MTB

- Test for our first furnace MTB (350 C, 3hr)
- Isolate BCS resistance at 4.3 K, compare with other bake tests
  - Included are baseline tests, dots
- Performance is more in-line with unbaked cavity at 4.3 K
  - Trend agrees with findings of mid-T bake at 4 K by TRIUMF [2]
    - » Results shown from 220 MHz multimode QWR and HWR
- Cannot preform in-situ MTB due to indium seal for bottom flange

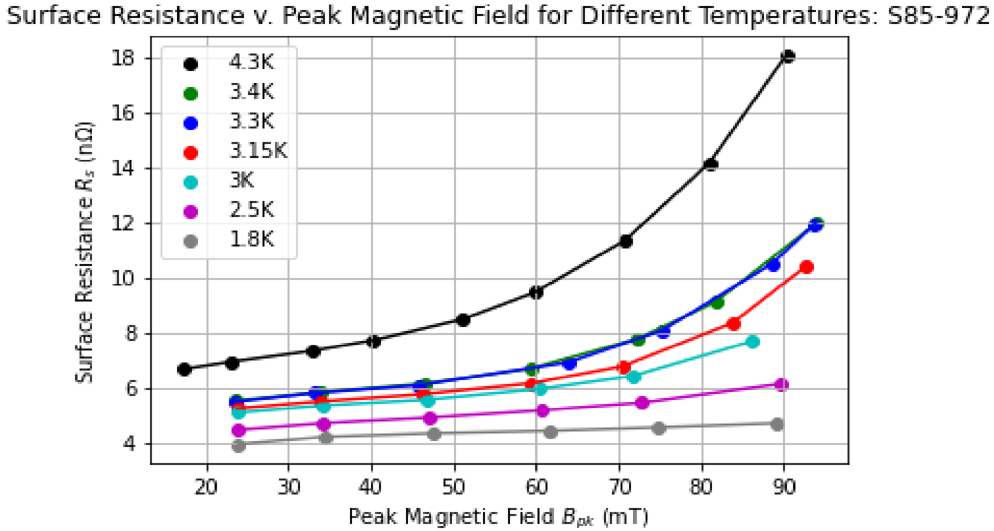



**[2]** P. Kolb et. al., *Mid-T Heat Treatments of BCPed Coaxial Cavities at TRIUMF*, 2023, https://doi.org/10.48550/arXiv.2306.12588

# Rs v. Field and T

- Previously: had testing availability to take CW data at multiple temperatures for furnace LTB
  - Cryogenic stability: $\pm 0.01\ K$ on average
  - Interested in transition in trend from quadratic and linear as T decreases
    - » Expected sharp transition in curve through $T_\lambda$, as seen in other geometries/freq. [3]




- Next steps: use simple fitting model at first [4]: $c_0 + c_1 b + c_2 b^2$
  - $c_1$ is associated with hysteresis losses, $c_2$ carries thermal feedback and pair-breaking losses information [5]
- Redo this measurement when available
  - Measure another LTB cavity with more data sets below $T_\lambda$
  - Measure an un-baked cavity to compare with; reduction of $c_1$ would suggest diffusion of oxygen away from surface [6, 7] as explanation of MFQS reduction


**[3]** C. C. Compton, et. Al, *Phys. Rev. Accel. Beams* **8.042003**, 2005

**[4]** K. McGee, et. al.,, *Phys. Rev. Accel. Beams* **24.112003**, 2021, https://doi.org/10.1103/PhysRevAccelBeams.24.112003

**[5]** G. Ciovati, J. Halbritter, *Physica C: Superconductivity*, Issues 1-2 Vol. 441, pp 57-61, https://doi.org/10.1016/j.physc.2006.03.053.

**[6]** A. Romanenko, *proc. of TTC 2020*, https://indi.to/mfBdR

**[7]** K. Saito, *Proc. Of SRF 2021, https://doi.org/10.18429/JACoW-SRF2021-WEPFDV004*

# Summary

- Found that LTB improves MFQS for FRIB $\beta = 0.085$, 80.5 MHz QWRs at 4.3 K
  - See from decomposition of $R_s$ that improvement comes from change in BCS
  - Furnace LTB has similar improvement to in-situ LTB
- MTB doesn't offer improved MFQS for FRIB QWRs
  - Difference in frequency, much lower
  - Difference in surface treatment: EP v. BCP
- When available, continue examination of trend of MFQS with temperature
- Developed a new recipe for spare FRIB QWRs production
  - Bulk BCP, 600 C H degas, light BCP, 120 C 48hr furnace LTB, and high pressure rinse

# Thank you! Questions?

# Full Citations

**[1]** M. Checchin, et. al., *Heat Transfer at the Interface Between Niobium and Liquid Helium For 6 GHz SRF Cavities, proc. Of SRF 2013*

**[2]** P. Kolb et. al., *Mid-T Heat Treatments of BCPed Coaxial Cavities at TRIUMF*, 2023, https://doi.org/10.48550/arXiv.2306.12588

**[3]** C. C. Compton, et. Al, *Phys. Rev. Accel. Beams* **8.042003**, 2005, https://doi.org/10.1103/PhysRevSTAB.8.042003

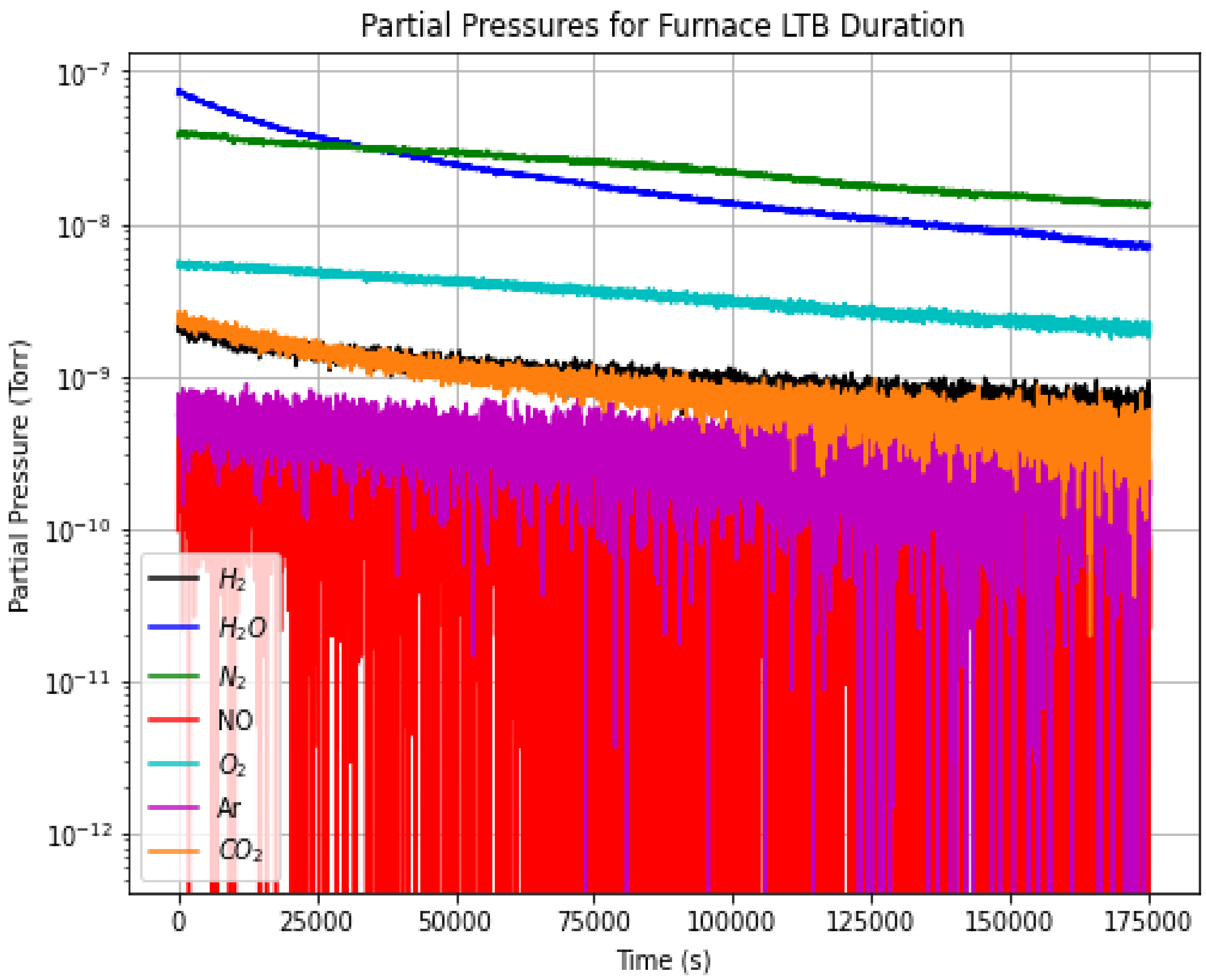
**[4]** K. McGee, et. al., *Medium-velocity Superconducting Cavity for High Accelerating Gradient Continuous-wave Hadron Linear Accelerators*, *Phys. Rev. Accel. Beams* **24.112003**, 2021, https://doi.org/10.1103/PhysRevAccelBeams.24.112003

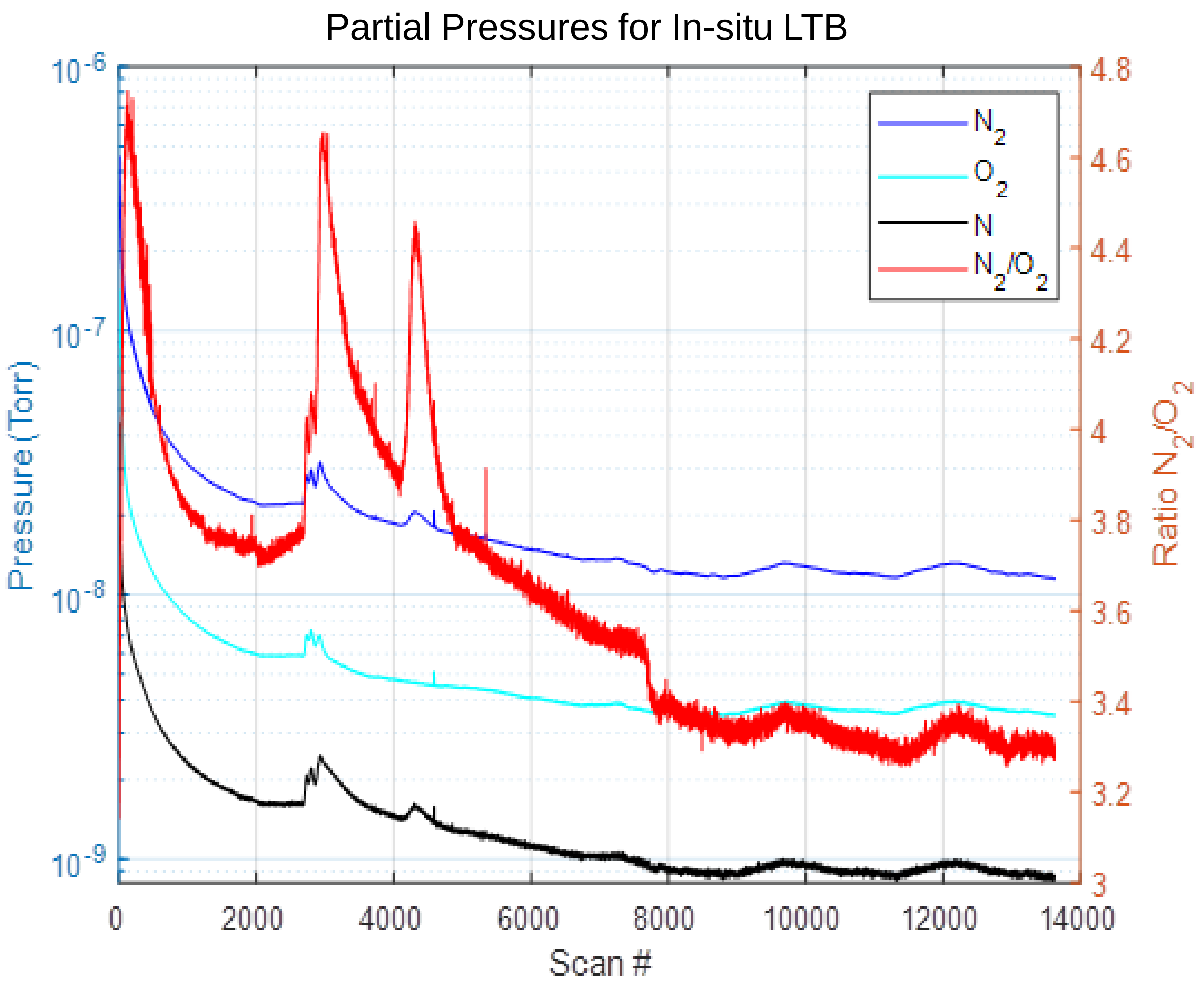
**[5]** G. Ciovati, J. Halbritter, *Analysis of the Medium Field Q-slope in Superconducting Cavities Made of Bulk Niobium, Physica C: Superconductivity,* Vol. 441, pp 57-61, https://doi.org/10.1016/j.physc.2006.03.053.

**[6]** A. Romanenko, *New Low-T Sample Studies Highlighting the Important Role of Oxygen Diffusion*, *proc. of TTC 2020*, https://indi.to/mfBdR

**[7]** K. Saito, *A New Model for Q-Slope in SRF-Cavities: RF Heating at Multiple Josephson Junctions to Weakly-Linked Grain Boundaries or Dislocations, Proc. Of SRF 2021, https://doi.org/10.18429/JACoW-SRF2021-WEPFDV004*

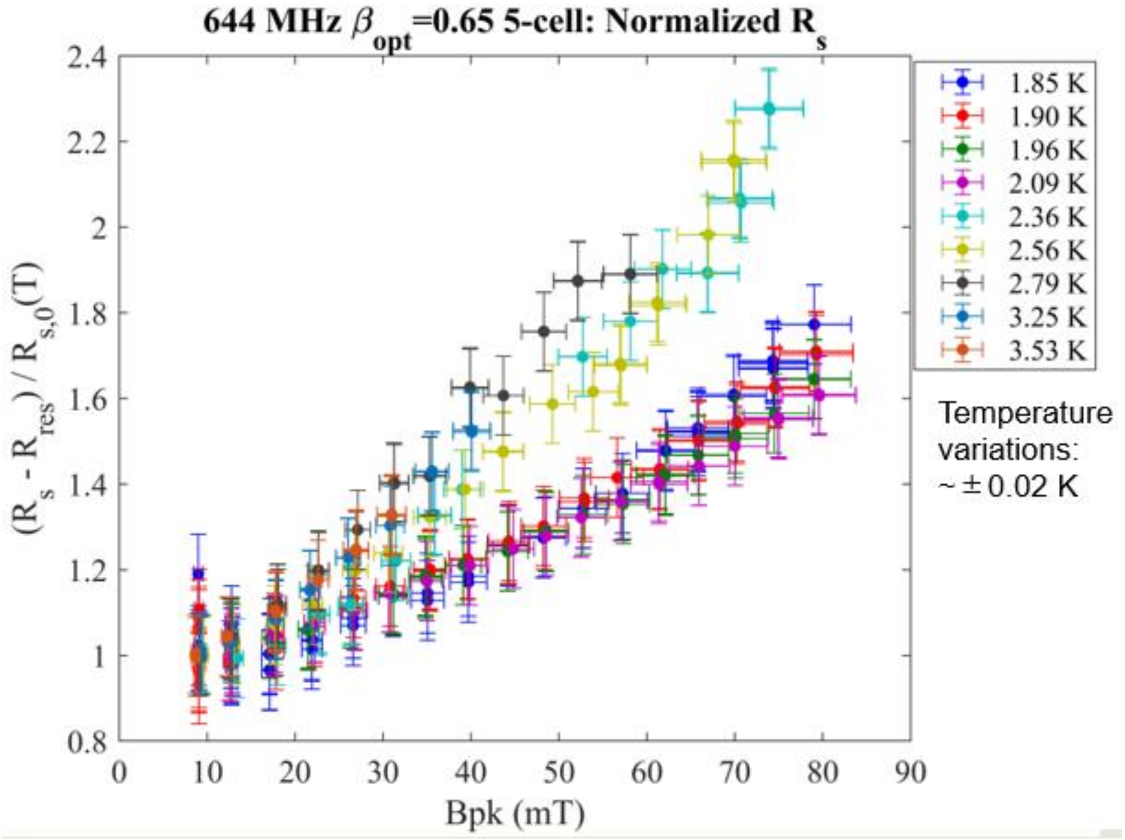
# Extra Slides: Partial Pressure Readouts for LTBs (Furnace left, in-situ right)



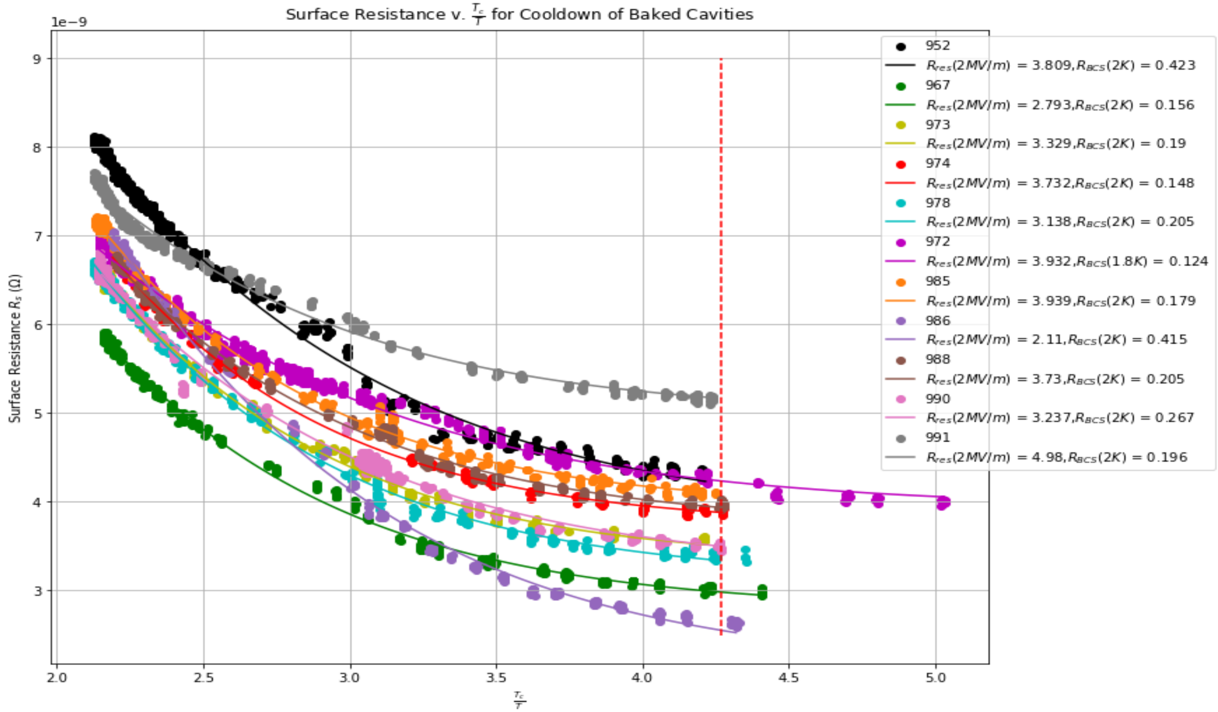
# Extra Slides: Motivation

- Case of EP+In-situ LTB FRIB $\beta = 0.65$ 644 MHz upgrade cavity
  - Simple model of normalized resistance using a constant residual resistance
  - CW data over MF region, see two distinct bands for Q-slope as function of field
    - » $T > T_\lambda$ and $T < T_\lambda$
- See shift in slope as LHe transitions to superfluid
  - Suggests MFQS can be improved by further improving thermal impedance
- Plethora of QWR LTB and baselines for FRIB
  - Reproduce and refine analysis with more updated model

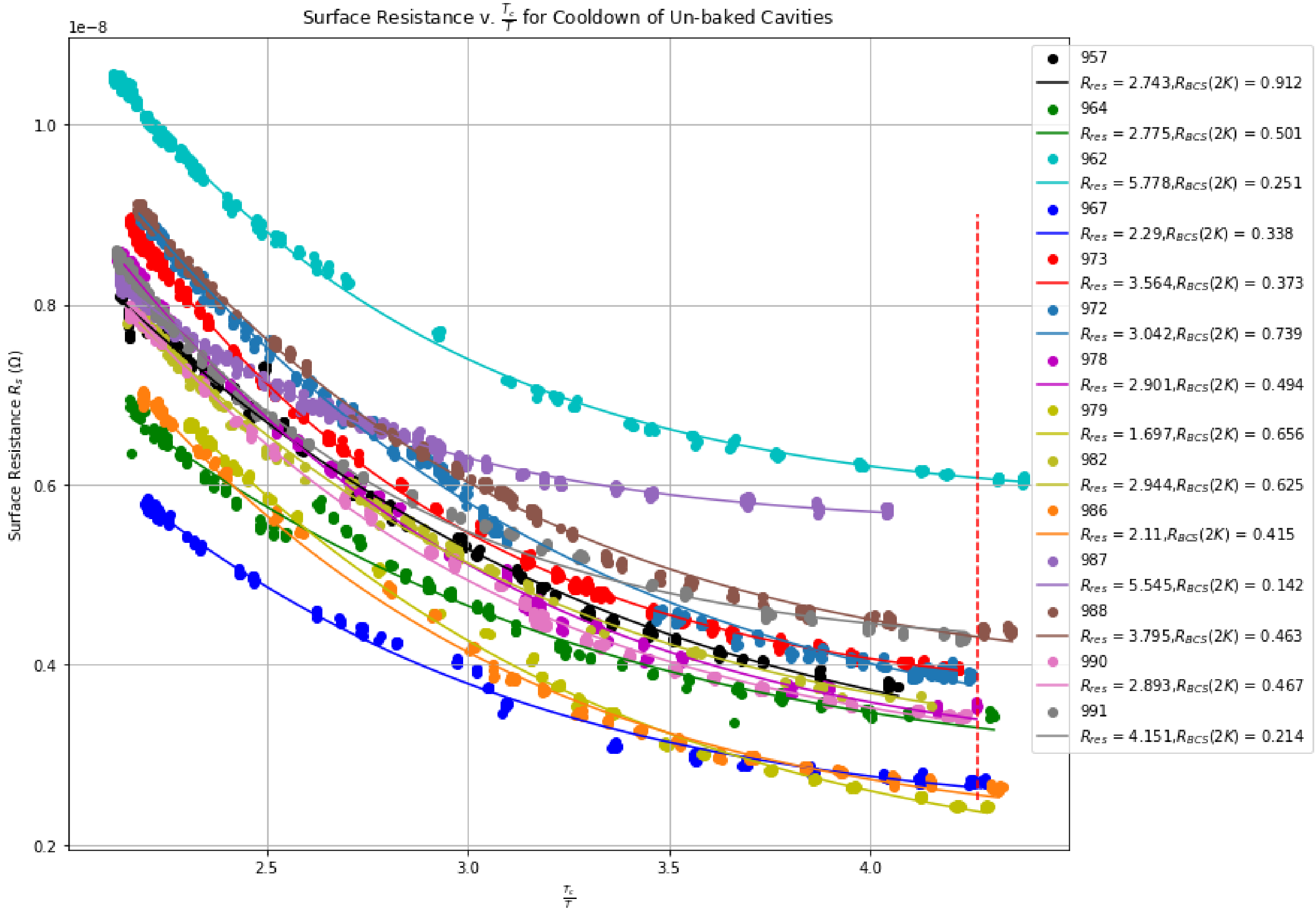


# Extra Slides: Data Treatment

- Previously: taking residual resistance to be a constant
  - In reality, residual resistance changes with cool down sensitivity and that $R_{res} = R_{res}(B_{pk})$
- Want: isolate the BCS resistance at 4.3K to examine change in MFQS
  - How: From idealized model: $R_{BCS}(2K, 80.5MHz) \approx 0.04\, n\Omega$
- For 11 baked cavities: $R_{BCS,avg} = 0.199\, n\Omega$ at 2K-1.8K
- For 13 baked cavities: $R_{BCS,avg} = 0.506\, n\Omega$ at 2K
- First order approx: ignore BCS at 2K for QWR
  - $\rightarrow R_s(2K, B_{pk}) \approx R_{res}(B_{pk})$



# Extra Slides: Unbaked Cooldown



# Extra Slide: 2 K Q-curves