Analysis of Low RRR SRF Cavities

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In partnership with:

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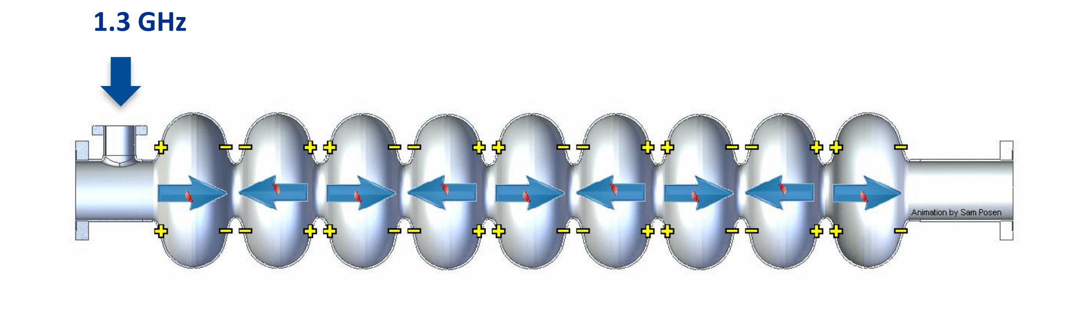
Introduction to Superconducting Radio Frequency (SRF) Cavities

- SRF cavities are resonant structures made from high purity niobium that generate the accelerating electric field along the beamline inside particle accelerators
- Purity measured by residual resistance ratio (RRR)
- Cavity performance determined by first ~100 nm of material
- Goals of SRF studies is to design surface profile to increase:
  - quality factor (efficiency)
  - accelerating gradient

$$Q_0 = \frac{G}{R_s} \sim$$ **Number of oscillations to dissipate stored energy**



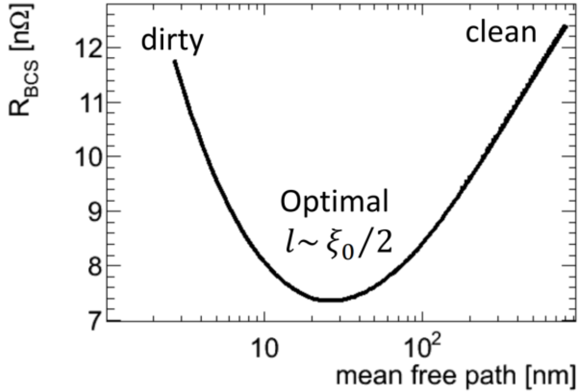
Motivation for Low RRR Investigation

$$R_s(T) = R_{res}(< 1.5\ K) + R_{BCS}(T)$$

Temperature Independent (↑ R_{res}) **Temperature Dependent** (↑ R_{BCS})

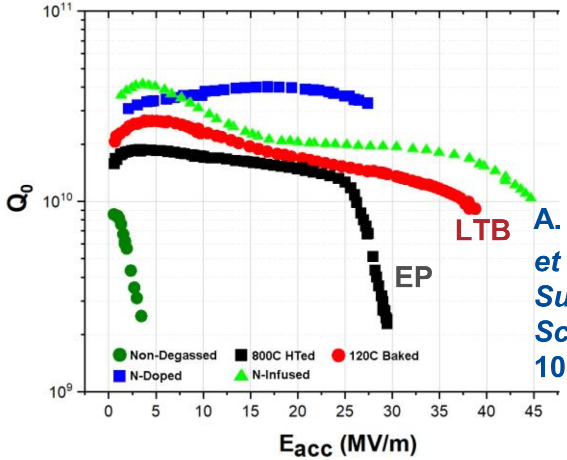
- Many SRF studies follow a “clean bulk dirty surface” technique to optimize the BCS resistance by adding extrinsic impurities
  - Low temperature bake diffuses oxygen into surface
- What role do intrinsic impurities serve?
  - Lower the mfp so may experience low BCS resistance behavior
  - Might perform similar functions as extrinsic impurities which have been shown to improve performance

BCS resistance vs mfp



A. Miyazaki SRF2021 Tutorial

Q vs gradient for different surface treatments



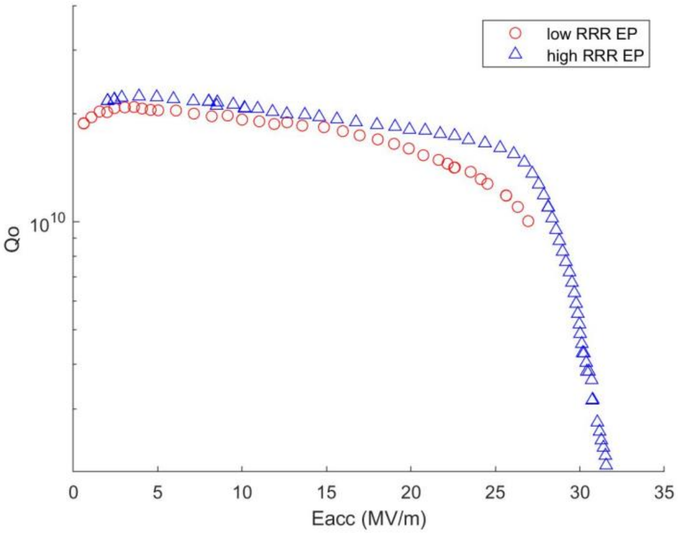
A. Grassellino *et al* 2013 *Supercond. Sci. Technol.* 26 102001

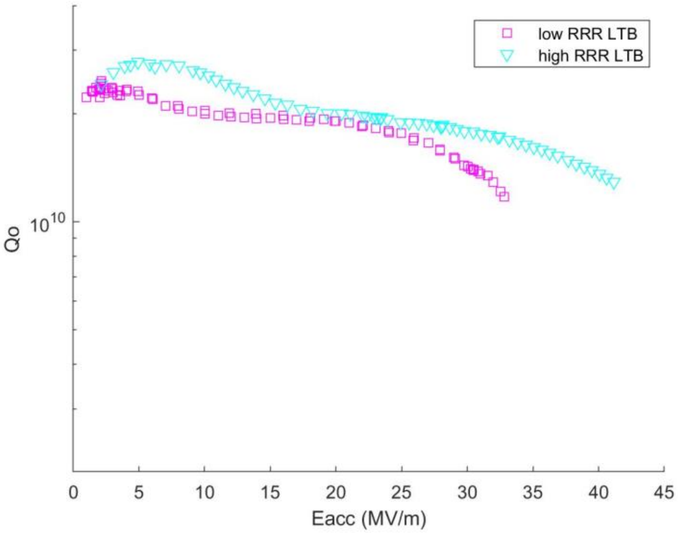
Low RRR Analysis Components

- Baseline testing on 1.3 GHz TESLA-shaped single-cell low RRR (= 61) cavity in electropolished (EP) condition
  - Quality factor vs accelerating gradient at 2 K and low T (< 1.5 K)
  - Residual resistance vs gradient
  - BCS resistance vs gradient
  - Frequency vs temperature
- Repeat testing after surface treatment
  - Low temperature bake (120 ℃ x 48 hours)

Cavity testing facility at Fermilab

Quality Factor vs Accelerating Gradient at 2 K





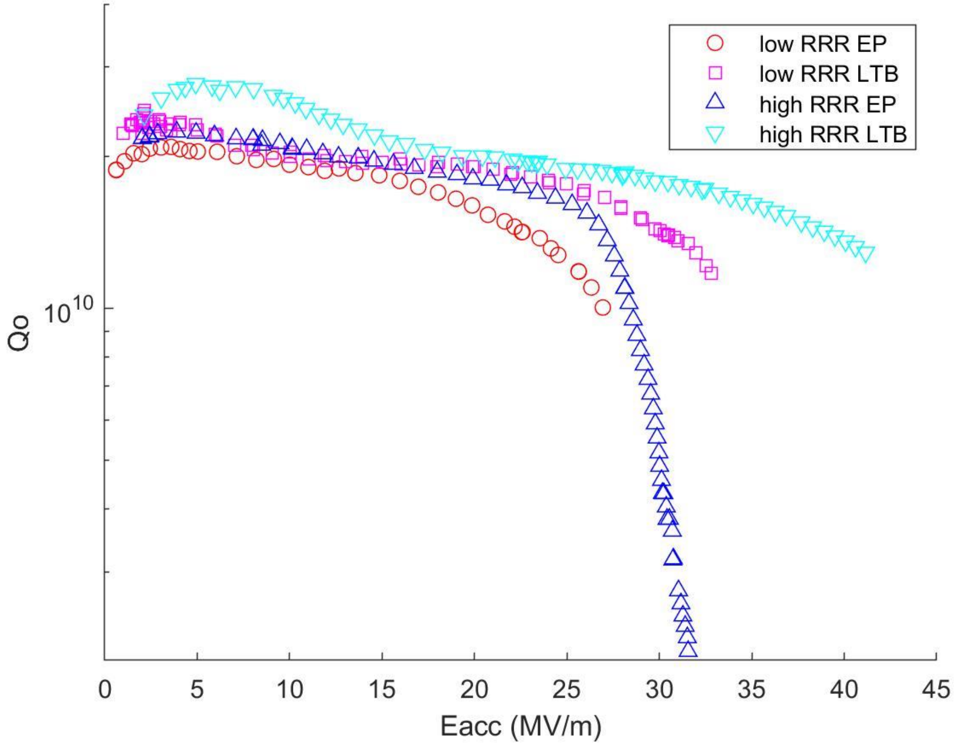
Electropolished

- **Low RRR has slightly lower Q_0 at all gradients and does not reach as high gradient**
- **Q_0 slope begins sooner but less sharp**

Low Temperature Bake

- **Low RRR does not experience “bump” of anti Q_0 slope at low gradient**
- **Performance is extended from EP but not as far as high RRR**

Quality Factor vs Accelerating Gradient at 2 K

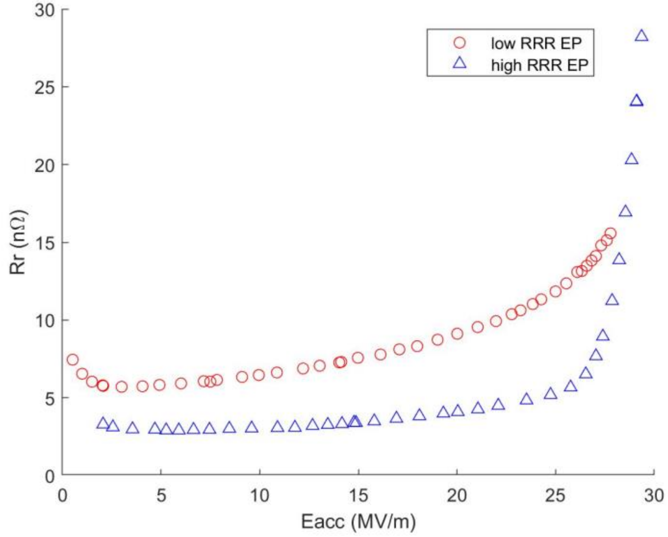


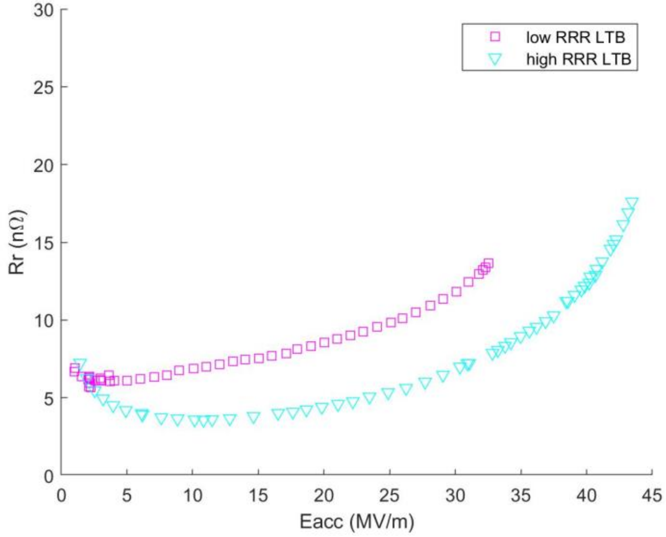
LTB improves performance of low RRR cavity but in a different way than we see in high RRR cavities

- Performance of all cavities is similar at medium gradients
- LTB delays Q_0 slope in low RRR but less extreme difference than high RRR
- Low RRR does not experience anti Q_0 slope after LTB

Residual Resistance vs Accelerating Gradient

$$R_{res} = \frac{G = 270\ \Omega}{Q_0(low\ T)}$$





Electropolished

- **Low RRR almost always a few nΩ higher than high RRR**

Low Temperature Bake

- **Similar at low field but then low RRR steadily increases**
- **Parallel at high field**

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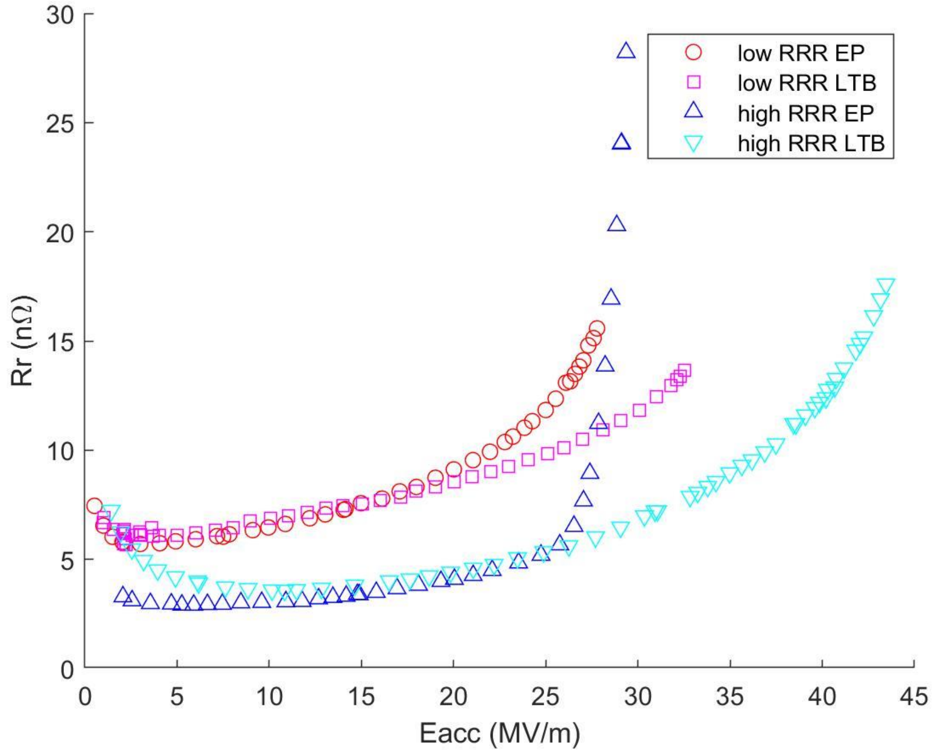
Residual Resistance vs Accelerating Gradient

$$R_{res} = \frac{G = 270\ \Omega}{Q_0(low\ T)}$$

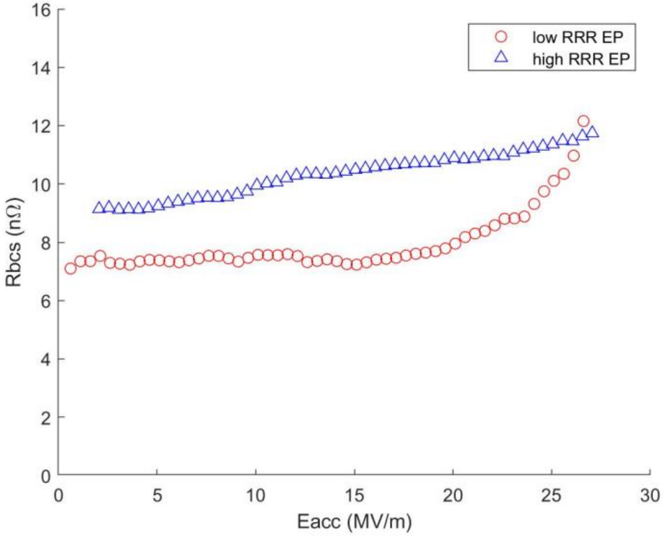


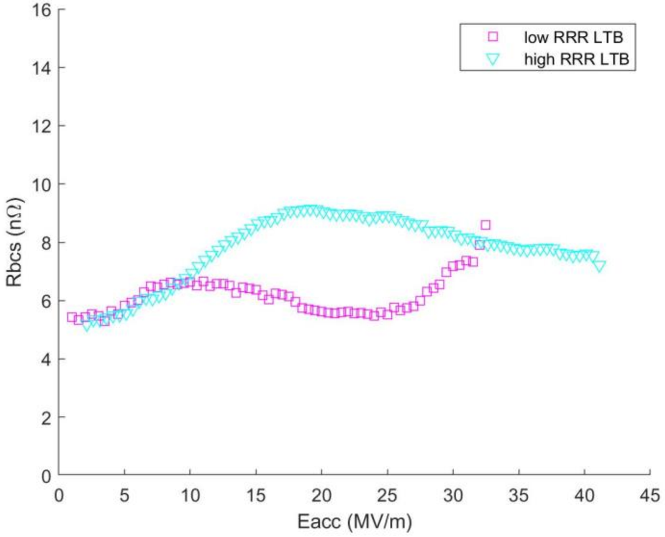
Low RRR and high RRR have similar residual resistance response to LTB

- Low RRR EP and LTB nearly equal until ~20 MV/m
- High RRR EP and LTB same at medium field
- Low RRR almost always larger residual resistance than high RRR

BCS Resistance vs Accelerating Gradient

$$R_{BCS}(2\ K) = R_s(2\ K) - R_{res}$$





Electropolished

- **Low RRR is significantly lower except at high field**

Low Temperature Bake

- **High and low RRR equal until ~10 MV/m**
- **Low RRR has lower BCS resistance at mid field**

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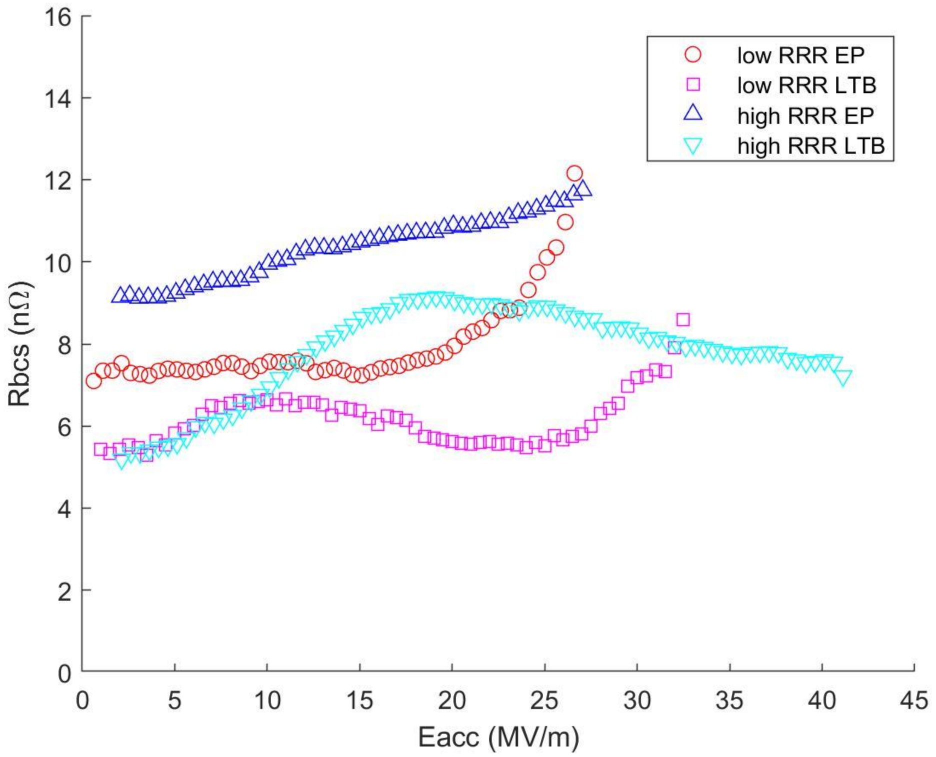
BCS Resistance vs Accelerating Gradient

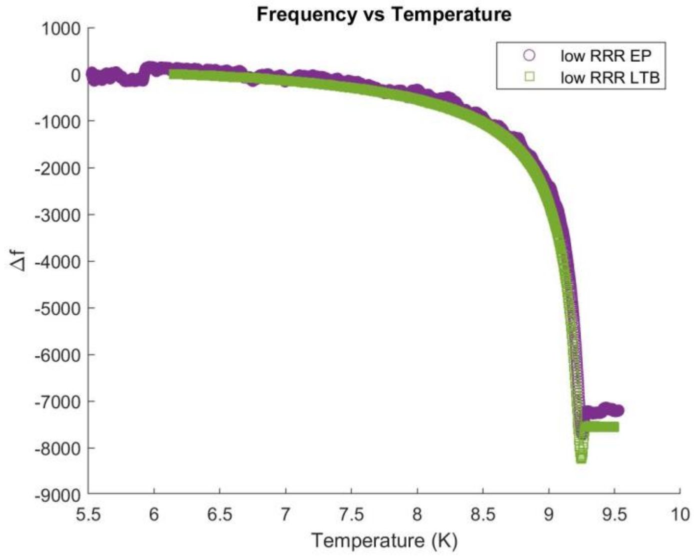
$$R_{BCS}(2\ K) = R_s(2\ K) - R_{res}$$

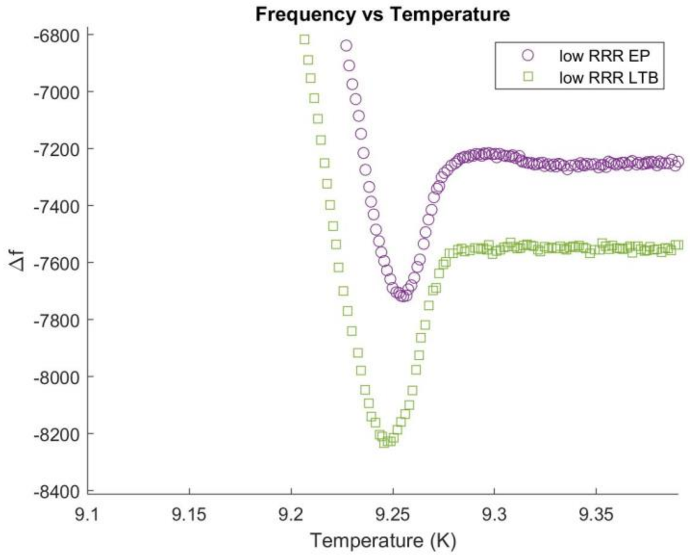


Low RRR exhibits low BCS behavior

- EP → LTB causes downright shift in BCS resistance
- Low RRR BCS is lowest at mid field
- Any benefit of dirty surface is lost at high field

Frequency vs Temperature

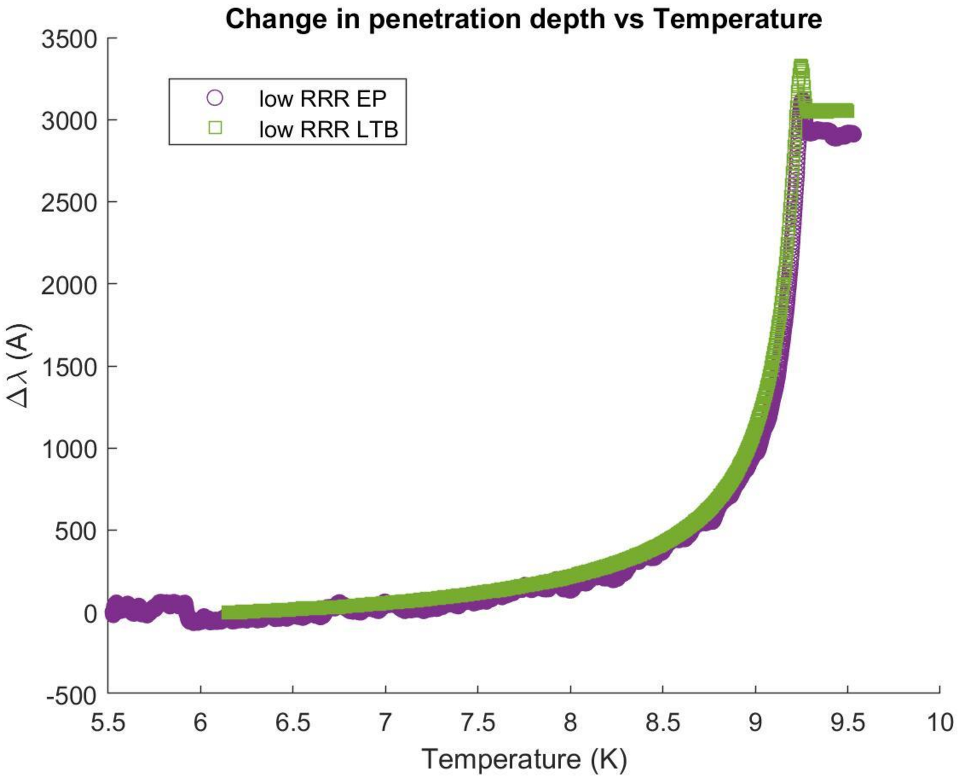




- **EP and LTB experience ~7.5 kHz change in resonant frequency through T_c**

- **Dip in EP and LTB → doped behavior**
- **Experimental T_c for both ~9.28 K**

Change in Penetration Depth vs Temperature

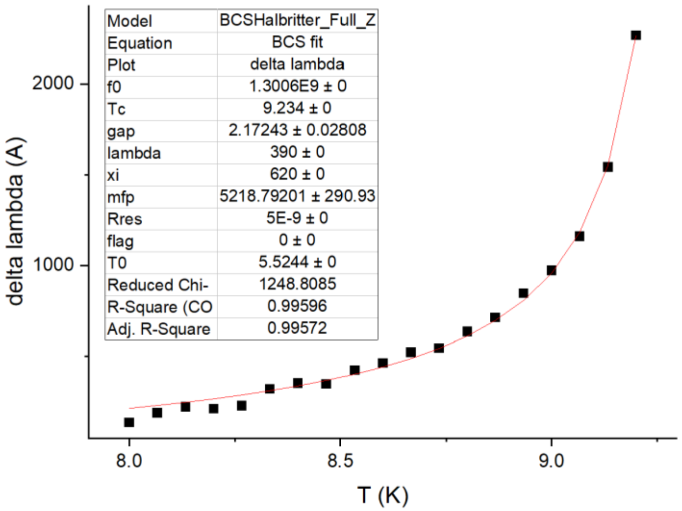


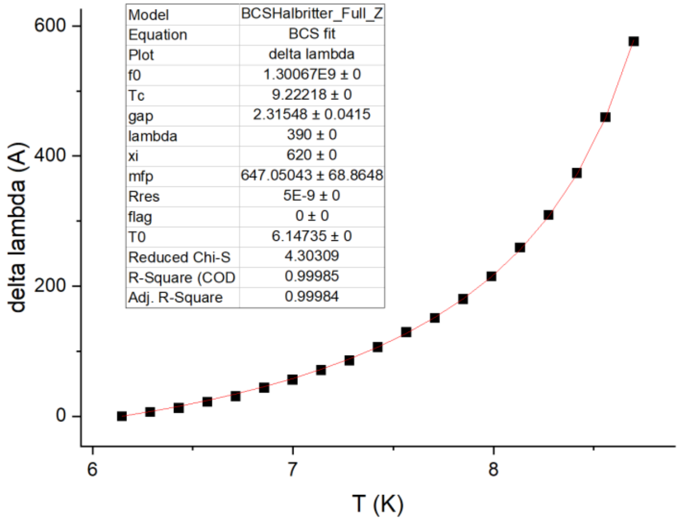
$$\Delta\lambda(T) = -\frac{G\Delta f(T)}{\mu_0 f^2(T_0)}$$

Need to convert to penetration depth to use fitting program to find mfp and gap

- G = 270 Ω (geometry factor)
- $\Delta f(T)$ = change in frequency vs temperature
- μ_0 = magnetic permeability
- $f(T_0)$ = constant resonant frequency at low temperature

Nonlinear Fitting using SRIMP Program





Electropolished

- mfp = 522 ± 29 nm
- gap = 2.17 ± .03

Low Temperature Bake

- mfp = 64.7 ± 6.9 nm → decrease suggests decreased BCS resistance
- gap = 2.32 ± .04 → increase suggests doped behavior

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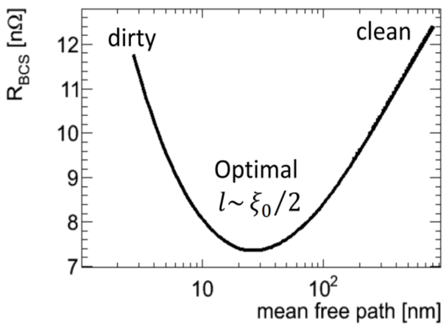
Summary

- Low RRR cavity in EP condition behaves differently than high RRR EP
  – Intrinsic impurities do have significant impact on RF behavior
- Low RRR cavity in LTB condition behaves similarly to high RRR LTB with some offset
  – Addition of oxygen into RF layer allows for higher quality factor and accelerating gradients without increasing the residual resistance from EP
  – How does oxygen behave differently in a Nb lattice with more impurities?
- Low RRR shows:
  – consistently high residual resistance
  – low BCS resistance, especially at mid gradient
  – dip on frequency versus temperature near Tc
  – decrease in mfp and increase in gap from EP → LTB

Recall:



Next Steps

- Processing additional data from LTB testing
  - Temperature-mapping to observe local heating and quench
- N-doping cavity
- Sample study on low RRR material
  - Process coupons to establish EP, LTB, and N-doped conditions
  - Secondary-ion mass spectrometry to observe impurity profile
  - Microscopy to characterize surface

Questions?

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