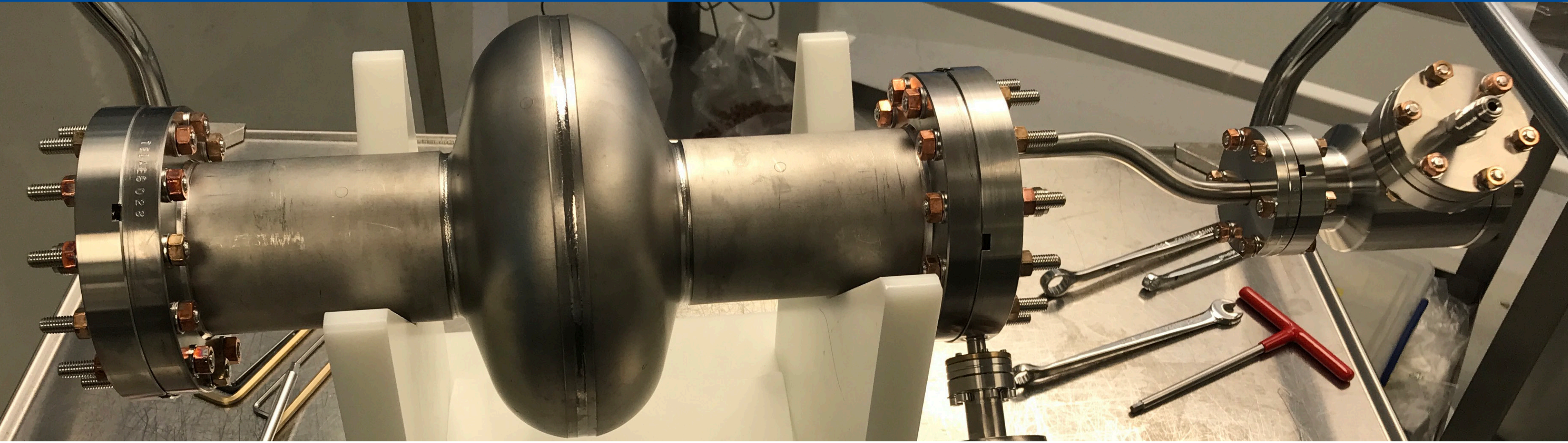

Analysis of Low RRR SRF Cavities

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In partnership with:

THE UNIVERSITY OF CHICAGO

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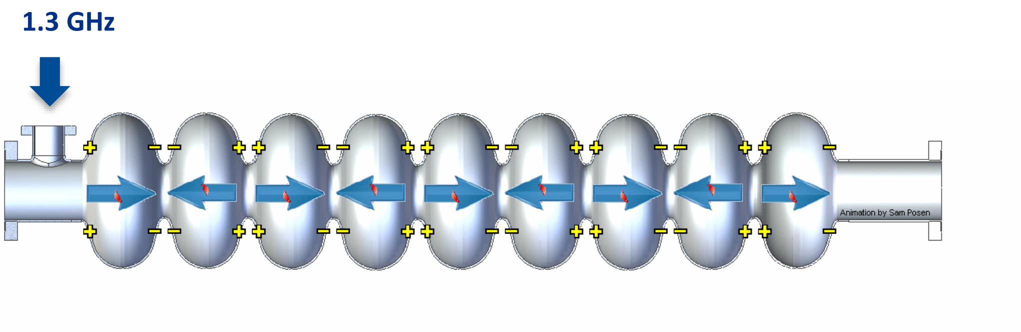
Introduction to Superconducting Radio Frequency (SRF) Cavities

- 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**



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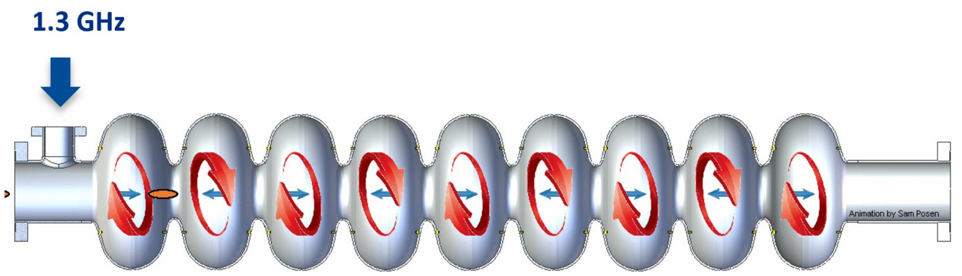


Motivation for Low RRR Investigation

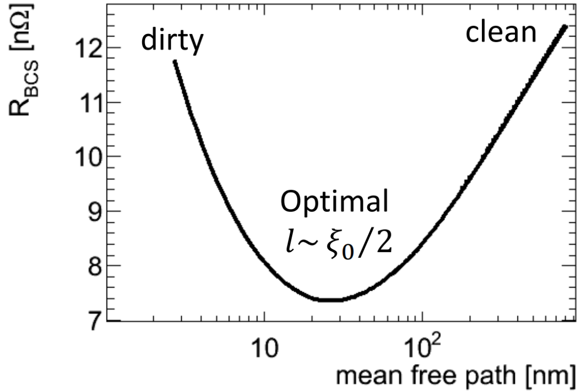
$$R_s(T) = R_{res}(< 1.5\ K) + R_{BCS}(T)$$

Temperature Independent (↑ R_{res})

Temperature Dependent (↑ R_{BCS})

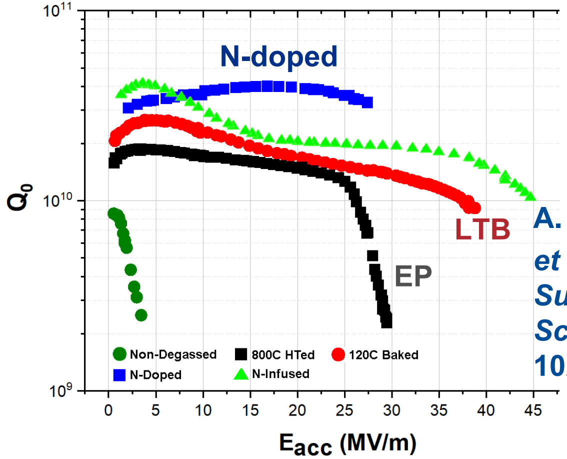
- Many SRF studies follow a “clean bulk dirty surface” technique to optimize the BCS resistance by adding extrinsic impurities
  - Low temperature bake diffuses oxygen into surface
  - N-doping introduces nitrogen into surface
- What role do intrinsic impurities serve?
  - Lower the mfp so may experience 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

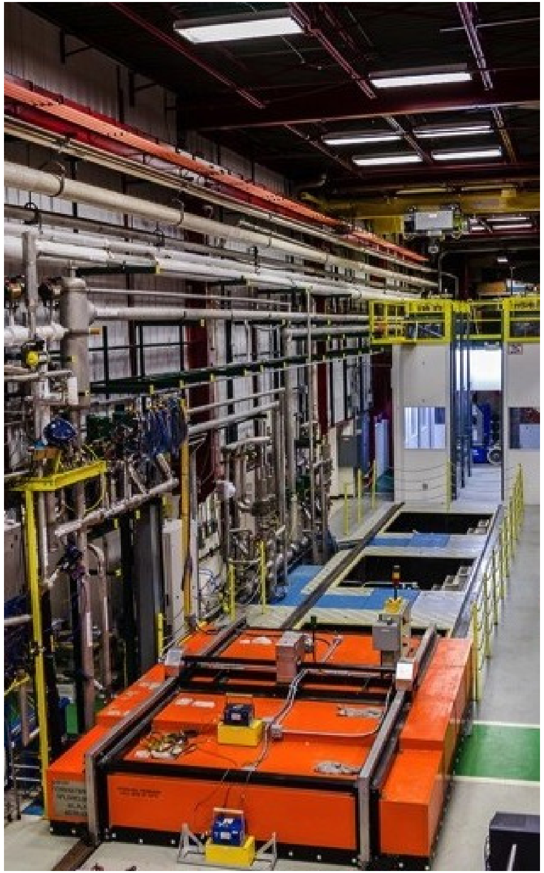
Q vs gradient for different surface treatments



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

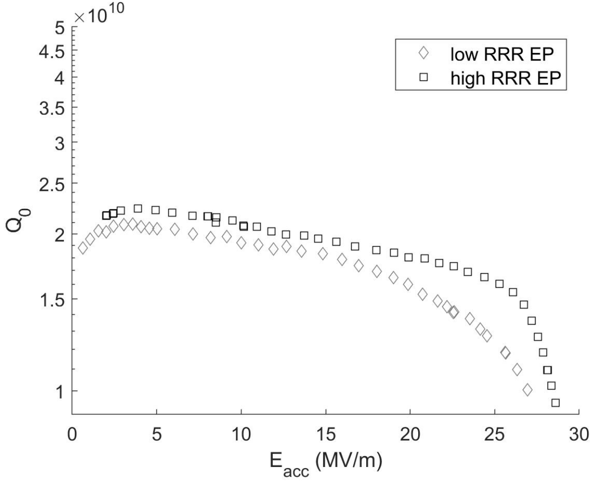
Low RRR Analysis Components

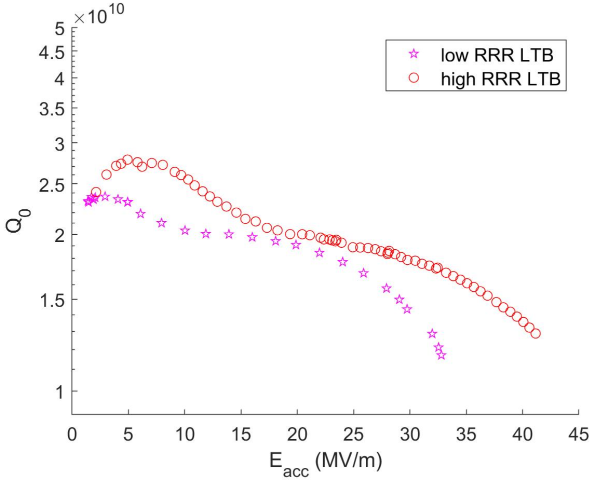
- Baseline testing on 1.3 GHz TESLA-shaped single-cell low RRR (= 61) cavity in electropolished (EP) condition
  - Quality factor vs accelerating gradient at 2 K and low T (< 1.5 K)
  - Residual resistance vs gradient
  - BCS resistance vs gradient
- Repeat testing after surface treatment
  - Low temperature bake (120 ℃ x 48 hours)
  - N-doping (2/6 recipe with 5 μm EP)

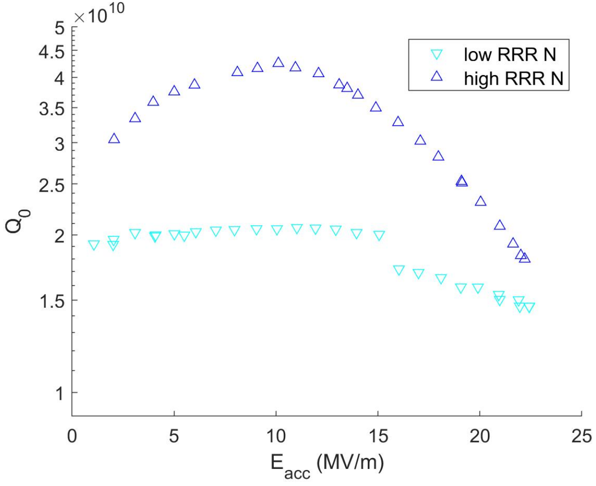


Cavity testing facility at Fermilab

Quality Factor vs Accelerating Gradient at 2 K







Electropolished

- **Low RRR has slightly lower Q_0 and reaches lower gradient**
- **Q_0 slope begins sooner but less sharp**

Low Temperature Bake

- **Low RRR experiences reduced response to LTB treatment**

N-doped

- **Low RRR has significantly lower Q_0 at low and mid gradients**

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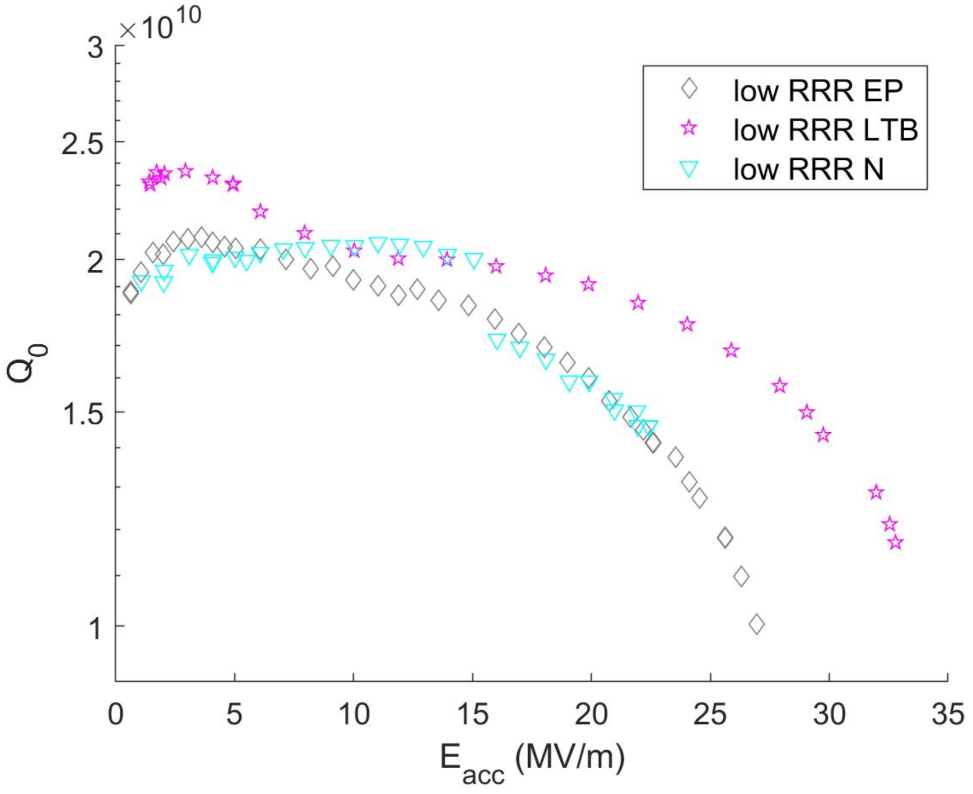
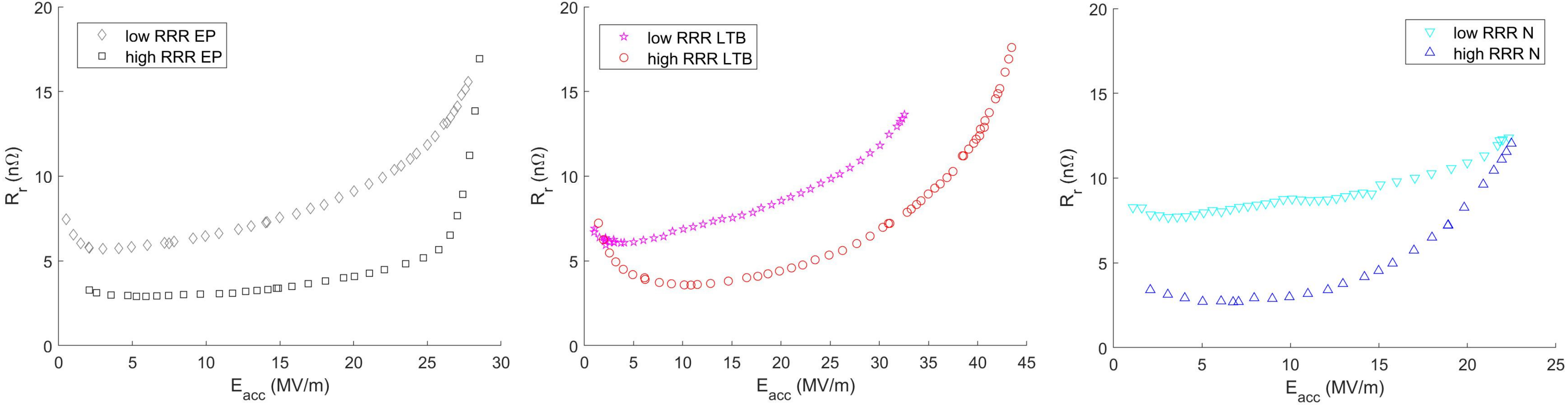
Quality Factor vs Accelerating Gradient at 2 K



- Performance of all cavities is similar at medium gradients
- LTB delays Q_0 slope and reaches highest Q_0 and gradient
- Low RRR does not experience strong anti-Q_0 slope
- N-doping reaches lowest gradient

Residual Resistance vs Accelerating Gradient

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



Electropolished

- Low RRR R_r larger at low and mid fields

Low Temperature Bake

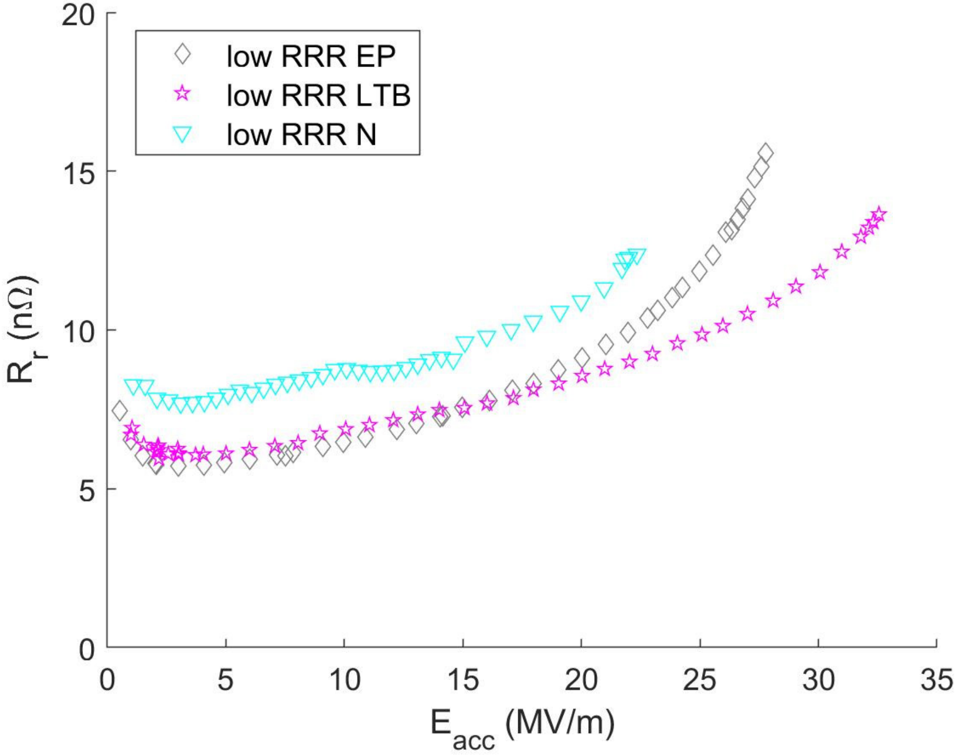
- Low RRR R_r larger at mid and high fields

N-doped

- Low RRR R_r larger at low and mid fields

Residual Resistance vs Accelerating Gradient

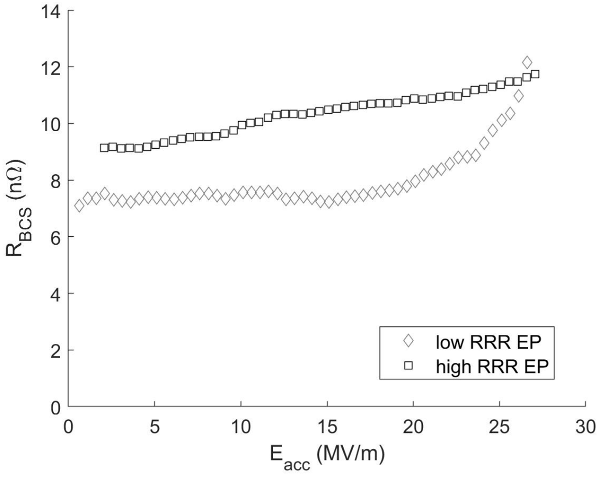
$$R_{res} = \frac{G = 270\ \Omega}{Q_0(low\ T)}$$

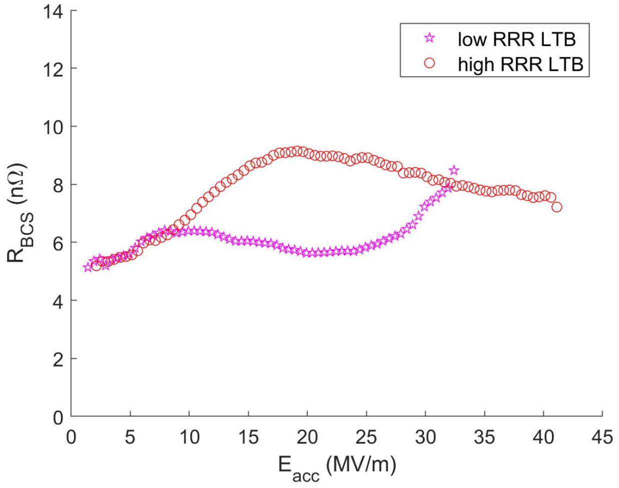


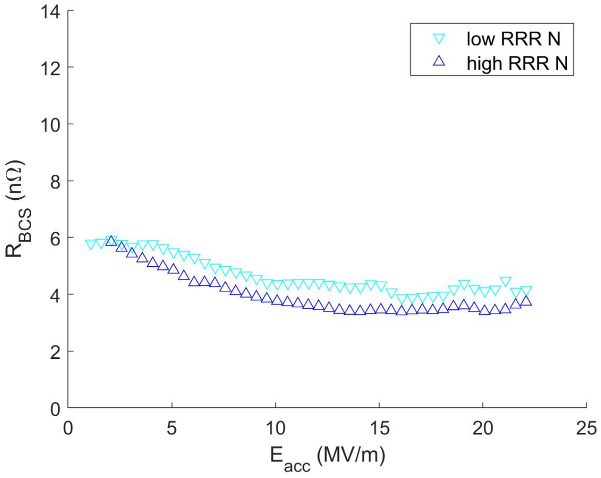
- Low RRR EP and LTB R_r equal at low and mid fields
- N-doped R_r always slightly larger than EP and LTB
- LTB treatment enables smallest increase with gradient

BCS Resistance vs Accelerating Gradient

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







Electropolished

- **Low RRR R_{BCS} is lower at low and mid fields**

Low Temperature Bake

- **Low RRR R_{BCS} is lower at mid fields**

N-doped

- **Similar R_{BCS} behavior**
- **Decreasing with gradient suggests anti-Q_0 slope**

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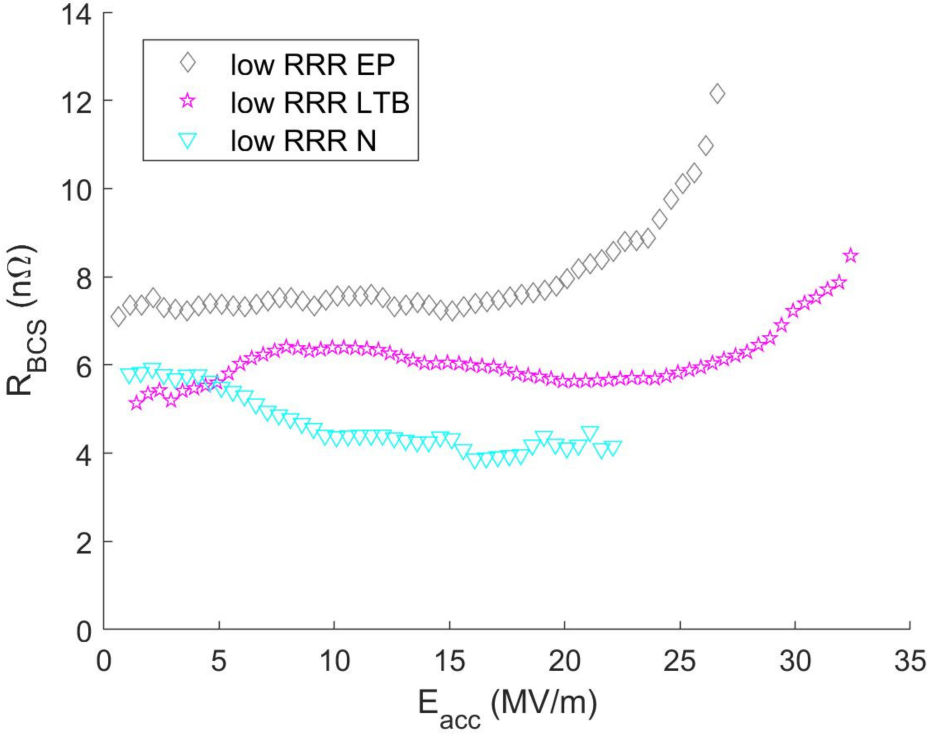
BCS Resistance vs Accelerating Gradient

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



Low RRR exhibits low BCS behavior

- Low RRR R_{BCS} is lowest at mid field
- Any benefit of dirty surface is lost at high field in EP and LTB
- N-doped has lower R_{BCS} than EP and LTB

Summary

- Low RRR shows:
  - Consistently high residual resistance
  - Low BCS resistance, especially at mid gradient
- Low RRR in EP and LTB conditions behave differently than high RRR
  - Intrinsic impurities do have significant impact on RF behavior
  - Combination of oxygen and intrinsic impurities enables higher quality factor and accelerating gradients
- N-doping is robust in producing similar BCS resistance in different purity SRF cavities

Next Steps

- High pressure rinse and retest N-doped cavity to avoid multipacting and trapped flux
- 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

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