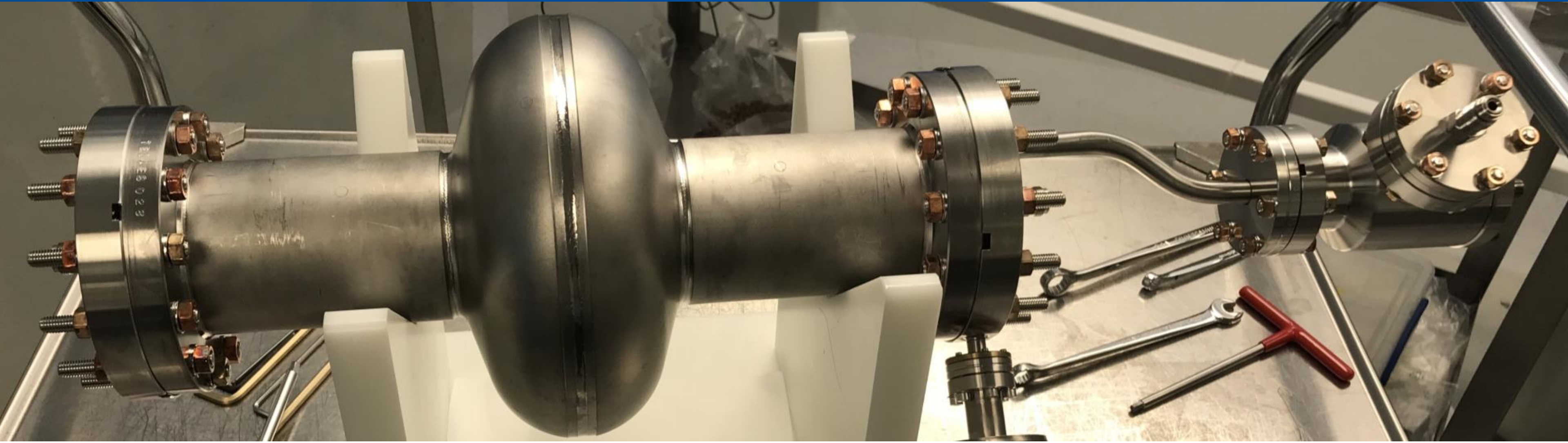


Analysis of Low RRR SRF Cavities

Katrina Howard, Daniel Bafia, Young-Kee Kim, Anna Grassellino

TTC2022 Aomori

11 October 2022

In partnership with:

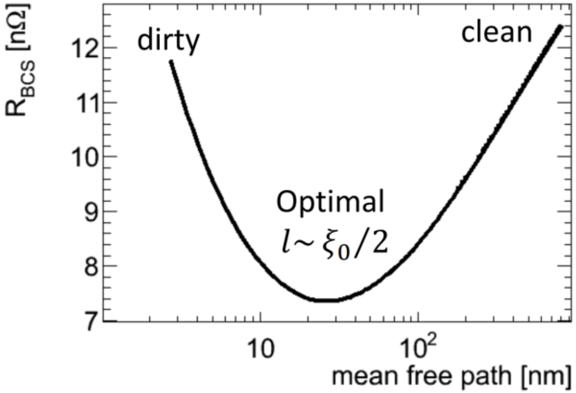
THE UNIVERSITY OF CHICAGO

Motivation for Low RRR Investigation

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

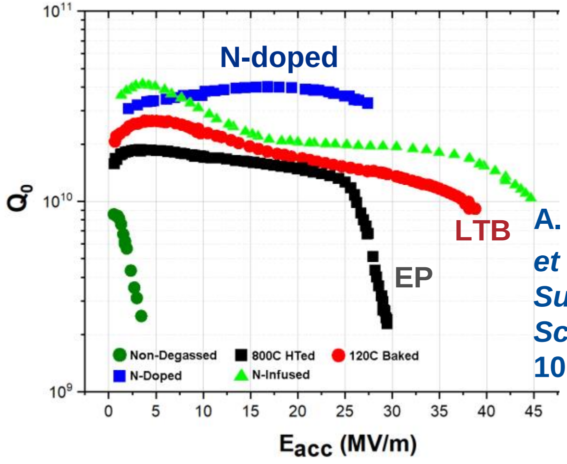
- Many SRF studies follow a “clean bulk dirty surface” technique to optimize the BCS resistance by adding extrinsic impurities
  - Low temperature bake and N-doping are current focus
- RRR = residual resistance ratio
  - Decreased by impurities in Nb
- What role do intrinsic impurities serve?
  - Lower the mfp so may experience low BCS resistance behavior
  - Might perform similar functions as extrinsic impurities which have been shown to improve performance
- Goal: use understanding of intrinsic impurities to design future surface treatments for high gradient and quality factor

BCS resistance vs mfp



A. Miyazaki SRF2021 Tutorial

Q vs gradient for different surface treatments



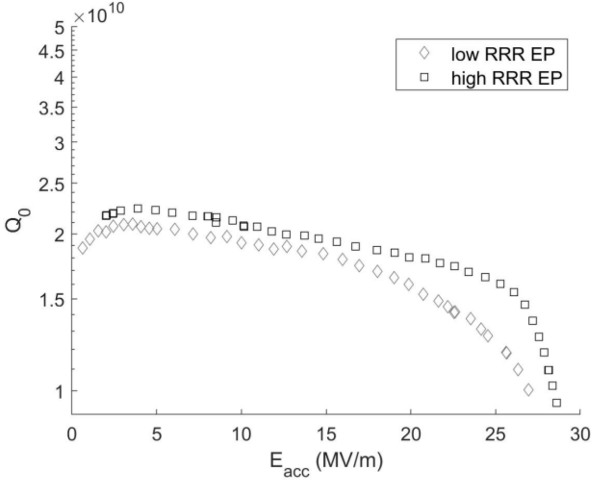
A. Grassellino *et al* 2013 *Supercond. Sci. Technol.* 26 102001

Low RRR Analysis Components

- 1.3 GHz TESLA-shaped single-cell low RRR (= 61) cavity with primary impurity Ta, according to sheet metal specifications, but not detected on SIMS at Fermilab
- Baseline testing in electropolished (EP) condition
  - Quality factor vs accelerating gradient at 2 K and low T (< 1.5 K)
  - Residual and 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) required multiple tests due to flux issues

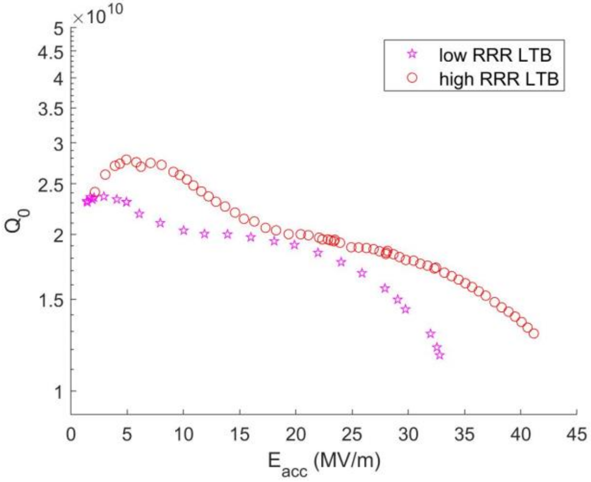
Cavity testing facility at Fermilab

Quality Factor vs Accelerating Gradient at 2 K



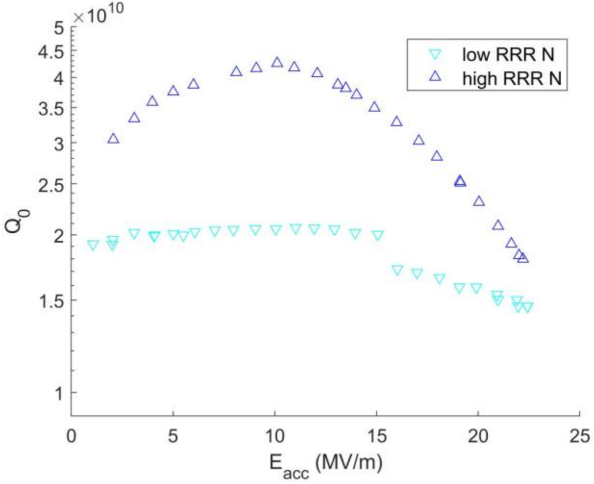
Electropolished

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



Low Temperature Bake

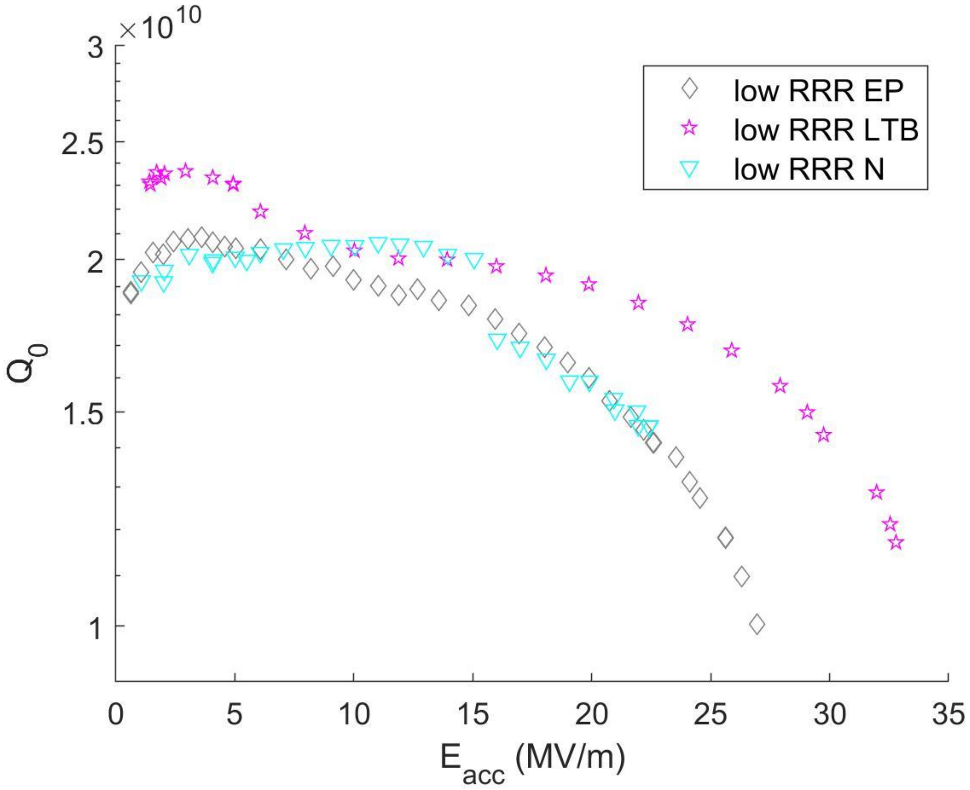
- Low RRR experiences reduced response to LTB treatment



N-doped

- Low RRR has significantly lower Q_0 at low and mid gradients
- Experienced multipacting quenches above 16 MV/m

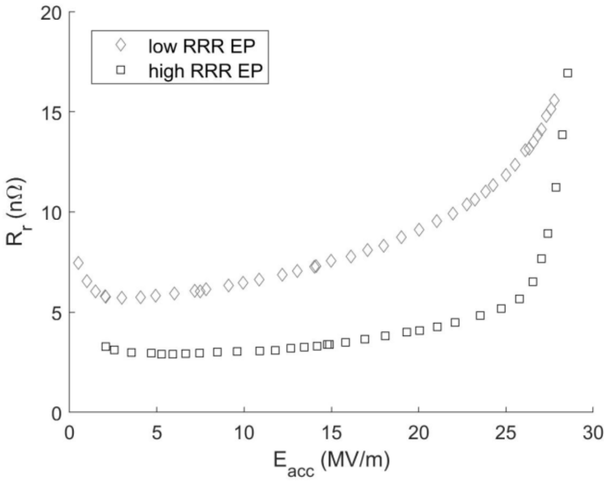
Quality Factor vs Accelerating Gradient at 2 K

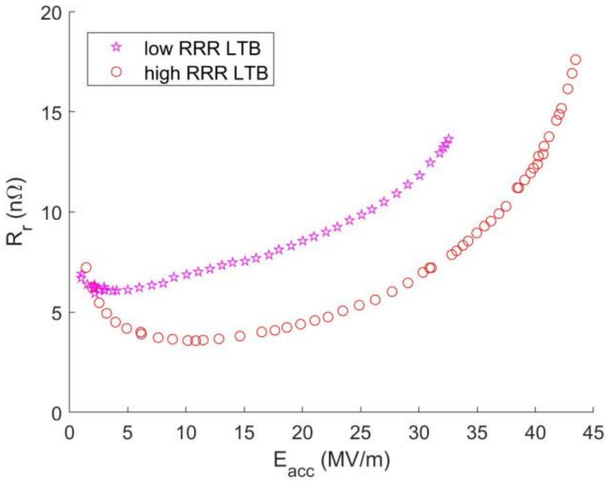


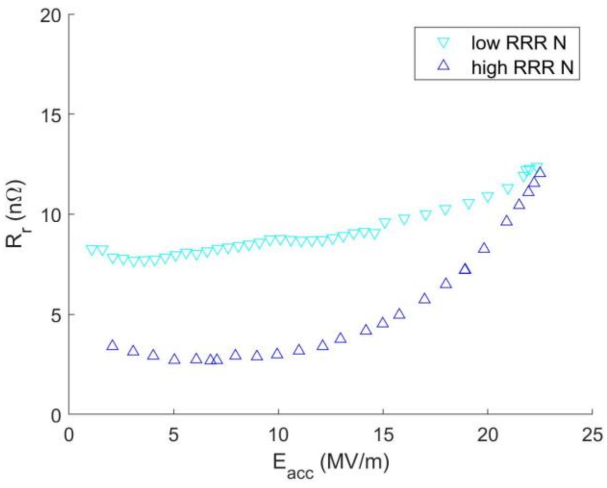
- Performance of all cavities is similar at medium gradients
- LTB delays Q_0 slope and reaches highest Q_0 and gradient
- Low RRR does not experience strong anti-Q_0 slope
- N-doping reaches lowest gradient

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

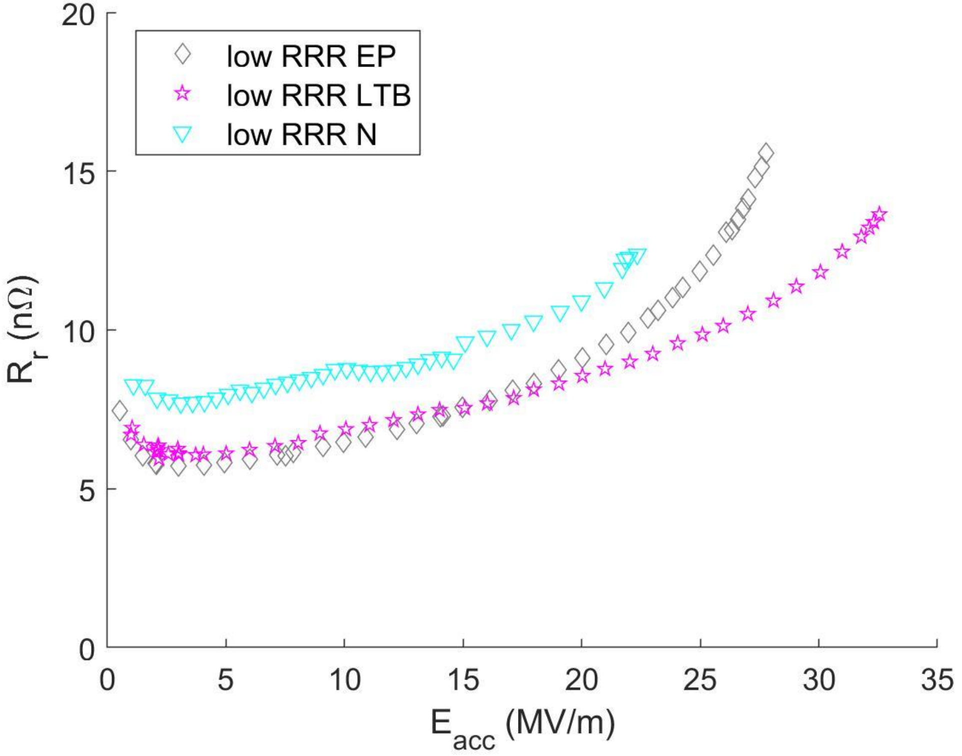
- **Low RRR R_r larger at mid and high fields**

N-doped

- **Low RRR R_r larger at low and mid fields**
- **Low RRR more constant with gradient**

Residual Resistance vs Accelerating Gradient

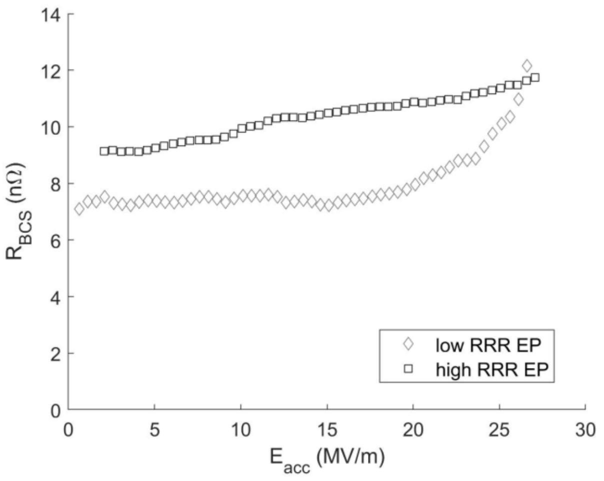
$$R_{res} = \frac{G = 270\ \Omega}{Q_0(low\ T)}$$

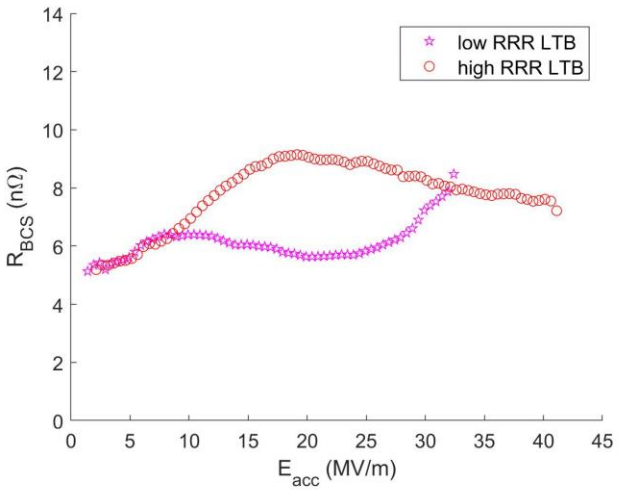


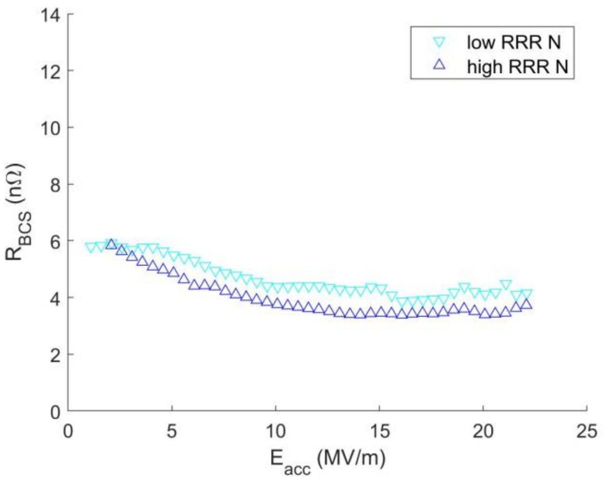
- Low RRR EP and LTB R_r equal at low and mid fields
- N-doped R_r always slightly larger than EP and LTB
- LTB treatment enables smallest increase with gradient

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

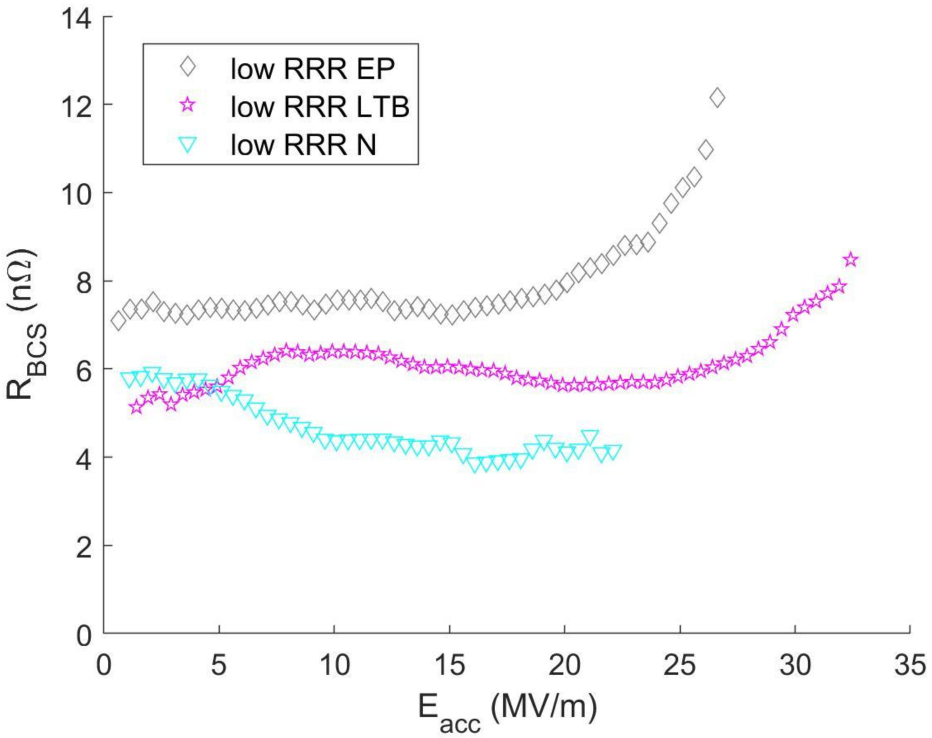
- Low RRR R_{BCS} is lower at mid fields

N-doped

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

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
  - Combined effects of intrinsic and extrinsic impurities
- 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
  - Low RRR N-doped appears very sensitive to trapped flux

Next Steps

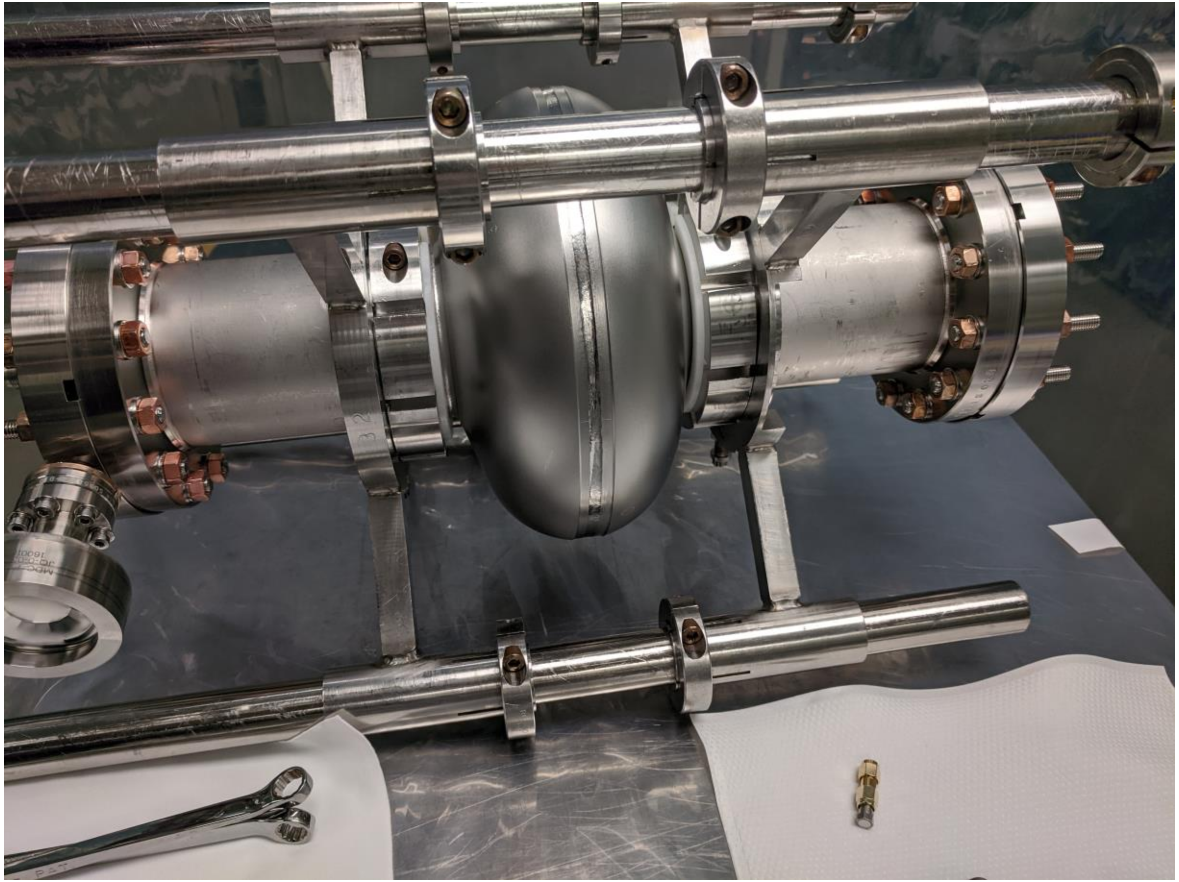
- Small EP (2 μm) on N-doped cavity to investigate underdoped behavior
- Sample study on low RRR material in EP, LTB, and N-doped conditions
  - Secondary-ion mass spectrometry to observe impurity profile
  - Microscopy to characterize surface

Discussion Topics

- How was RRR and impurity concentration determined when the sheet metal was made?
  - Cell material from Tokyo Denkai (Ta Wt % .0193, RRR = 61) and beam tube material from Wah Chang (Ta % .1)
- How might oxygen behave differently in a Nb lattice with more impurities?
- How can intrinsic impurities affect the sensitivity to trapped flux?
- Why is BCS resistance for N-doped low RRR not lower than high RRR, as observed in EP and LTB tests?

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. This work was supported by the University of Chicago.

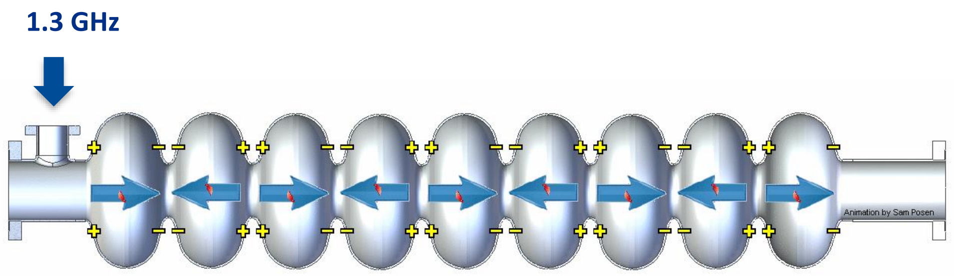
Extra Slides



Introduction to Superconducting Radio Frequency (SRF) Cavities

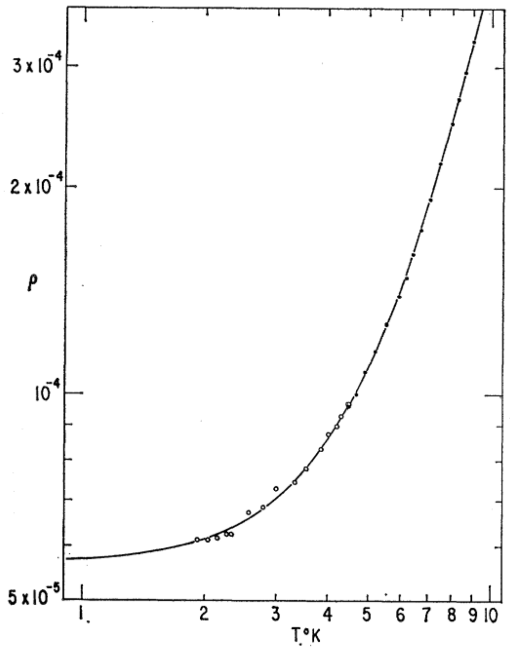
- SRF cavities are resonant structures made from high purity niobium that generate the accelerating electric field along the beamline inside particle accelerators
- Purity measured by residual resistance ratio (RRR)
- Cavity performance determined by first ~100 nm of material
- Goals of SRF studies is 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**



Measurement of Purity of Niobium = RRR

- Residual resistance ratio (RRR) is the ratio between DC (not RF) resistivity of material at room temperature to its residual value at low temperature
- RRR and mean free path have a direct relationship
    - High mfp → high RRR
    - Low mfp → low RRR
- Theoretical limit of Nb = 35,000
    - high RRR for SRF is ~300
- RRR is lowered by impurities in the Nb
    - grain boundaries
    - elements: Ta, N, O, C, H, Zr, etc.



Nb sample with RRR = 16,500
Resistivity versus temperature
G. W. Webb 1969

Cavity Material Details

Cell material

Customer 御納入先　Messrs. AES. Inc. 殿

Surveyor 御立会者 殿

MATERIAL TEST RESULTS
試 験 成 績 表

No. 27306

Date 日付 Feb 21, 2012

TOKYO DENKAI CO., LTD.
東 京 電 解 株 式 会 社

Material 材質: Nb　Article 品名: Sheet

Specification No. 仕様書番号

Lot No.	Size 寸法 mm	Quantity 数量 pcs or gr		T.S 引張強さ N/mm²	Y.S 耐力 N/mm²	Elong 伸び %	Hardness かたさ Hv	E.V. エリクセン値
			Spec 規格 min					
			Spec 規格 max					
3856	-1 : 3t × 100 × 445 (mm) -2 : 3t × 50 × 160 (mm) -3 : 3t × 50 × 260 (mm) -4 : 3t × 104 × 104 (mm) -5 : 3t × 600 × 750 (mm)	1 pc 6 pcs 6 pcs 6 pcs 1 pc	Test Results 試験結果 Longitudinal	209	93	57	66.0	
			Transverse	216	103	52		

Chemical Composition (in Wt%) 化学成分

Lot No.	Element 成分	Ta	W	Ti	Fe	Si	Mo	Ni	Zr	Hf
	Spec 規格 min									
	Spec 規格 max									
3856	Test Results 試験結果	0.0193	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Element 成分	O	N	H	C
Spec 規格 min				
Spec 規格 max				
Test Results 試験結果	<0.001	<0.001	<0.0005	<0.001

Remarks 備考 Starting Ingot No. NC-1709
Heat No. HT8-102
RRR Value of Sheet: 61

Inspection Section Manager 課長
Engineer 担任

T.S.=Tensile Strength Y.S.=Yield Strength E.V.=Erichsen Value

Beam tube material

PRODUCT CERTIFICATION

IN REGARD TO YOUR

Purchase Order No.:	PO 04-0024-S
Sales Order No.:	122136
Item No.:	4
Description:	Niobium Sheet
Dimensions:	0.125" Thk x 24" W x 24" L
Specifications:	ASTM B393-99 (Gr. R04200) Type 1, and P.O.
Date:	May 19, 2004
Quantity:	2 pcs.
Weight:	47.4 lbs.
Heat No.:	505250
SFC No.:	1265734

THE TEST REPORT FOLLOWS:
Material Condition: Annealed

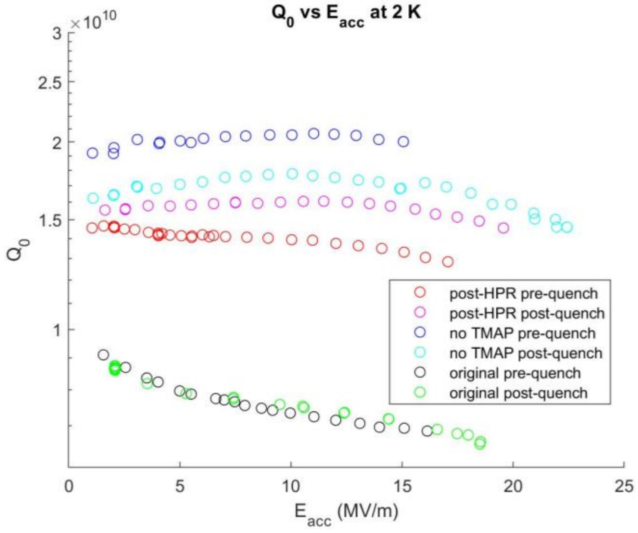
INGOT CHEMISTRY IN PERCENT

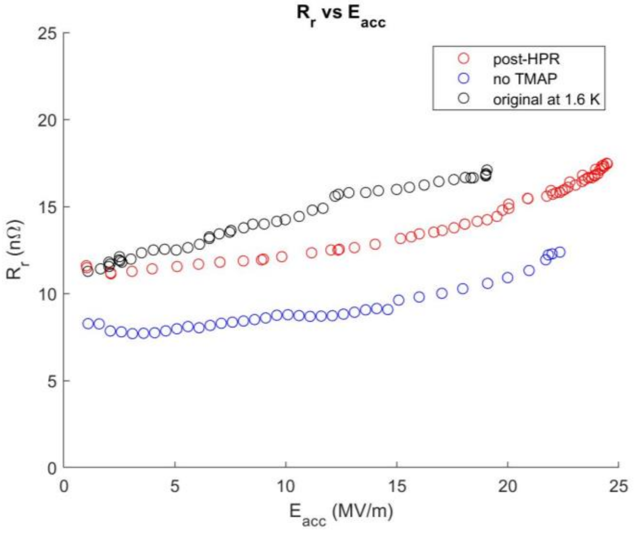
Element	Alpha Spec.	Spec. Max.	TOP	BOTTOM
C		0.01	0.002	0.002
Fe		0.005	<0.0035	<0.0035
H		0.0015	<0.0003	<0.0003
Hf		0.02	<0.0050	<0.0050
Mo		0.010	<0.0030	<0.0030
N		0.01	0.006	0.004
Ni		0.005	<0.0020	<0.0020
O		0.015	0.010	0.005
Si		0.005	<0.0050	<0.0050
Ta		0.1	0.04	0.03
Ti		0.02	<0.0040	<0.0040
W		0.03	<0.0030	<0.0030
Zr		0.02	<0.0050	<0.0050
Nb	BALANCE			

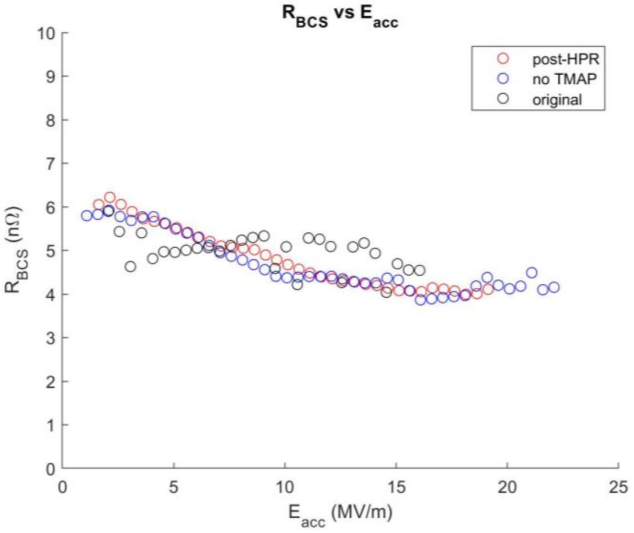
Certified By: R Louie, QA Supervisor \es 05/19/04

Wah Chang Is A Registered / Certified ISO 9001:2000 Company.

N-doped Tests





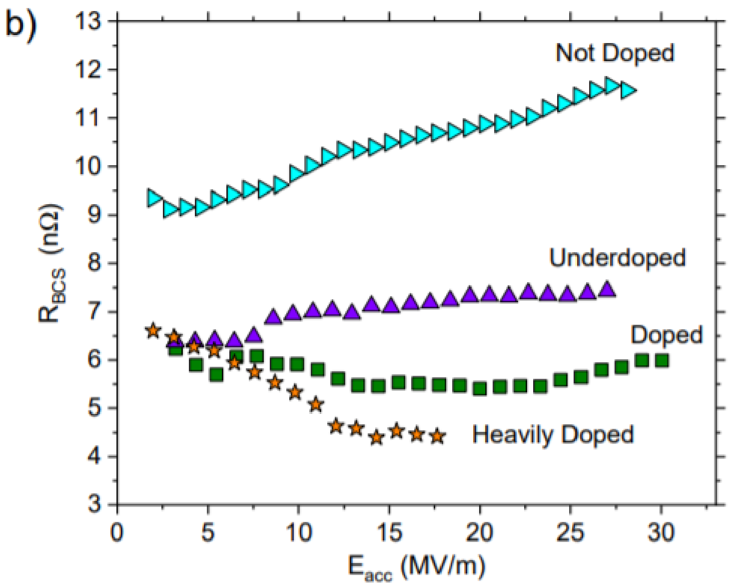


- Original test with flux peak is outlier
- Notice increase in Q after quench in post-HPR test → still having flux issues?

- Very large residual resistance
- Most trapped flux in original test
- Distinct offset between last 2 tests

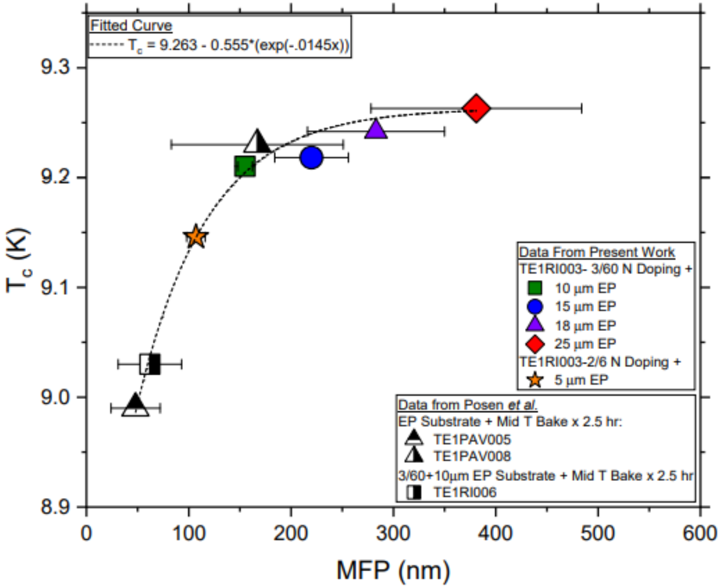
- Same BCS resistance in all tests suggests this is a flux issue!

Effect of Doping Severity



N-doping severity effect on BCS resistance

Daniel Bafia's Thesis Fig 6.7b



N-doping severity effect on mfp and Tc

Daniel Bafia's Thesis Fig. 6.6

Fermilab