Reducing Residual Resistance at Operating Fields: Potential, Challenges, and Future R&D Directions

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U.S. DEPARTMENT of ENERGY

OUTLINE

- Current Status of SRF R&D
- High Q, High Gradient
- Potential, Challenges, and Future R&D Directions

CURRENT STATUS OF SRF R&D

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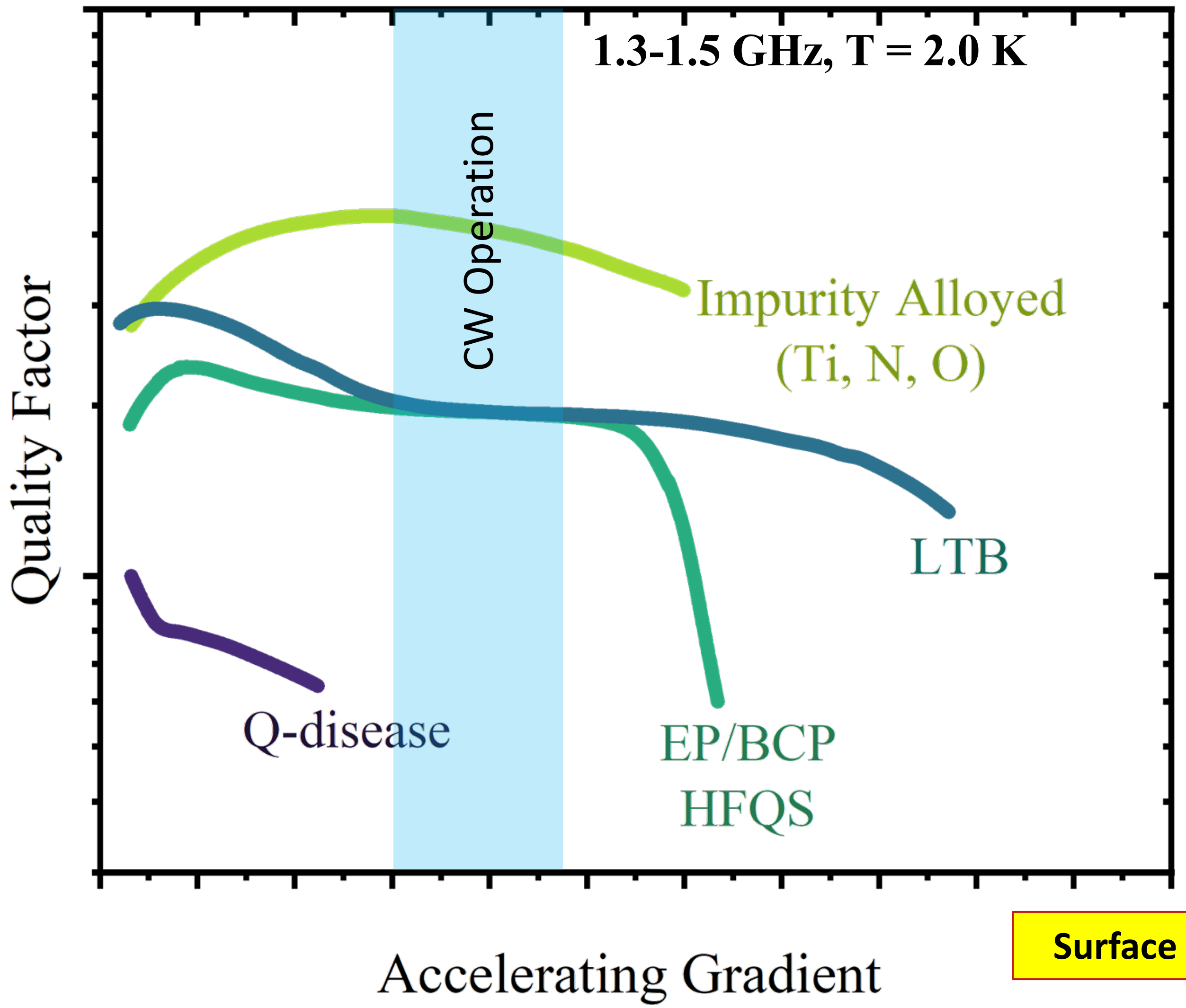
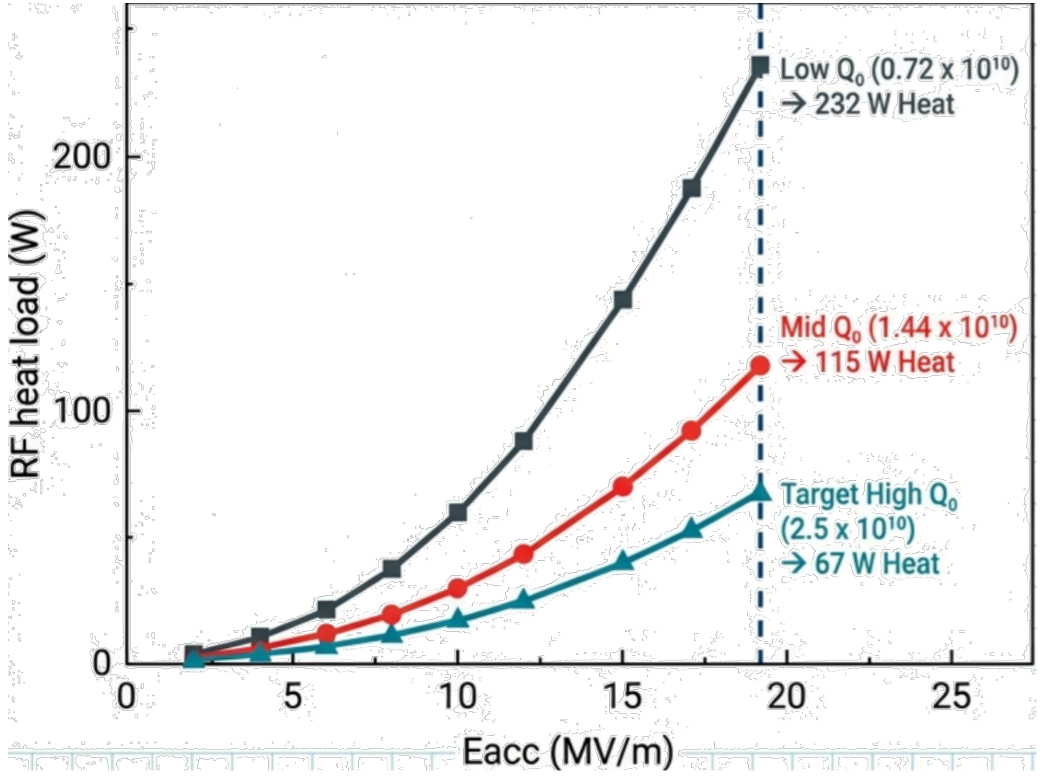


$$P_{\mathrm{RF}} = (E_{\mathrm{acc}})^2 \left(\frac{R_s}{G}\right)\left(\frac{1}{R/Q}\right)$$

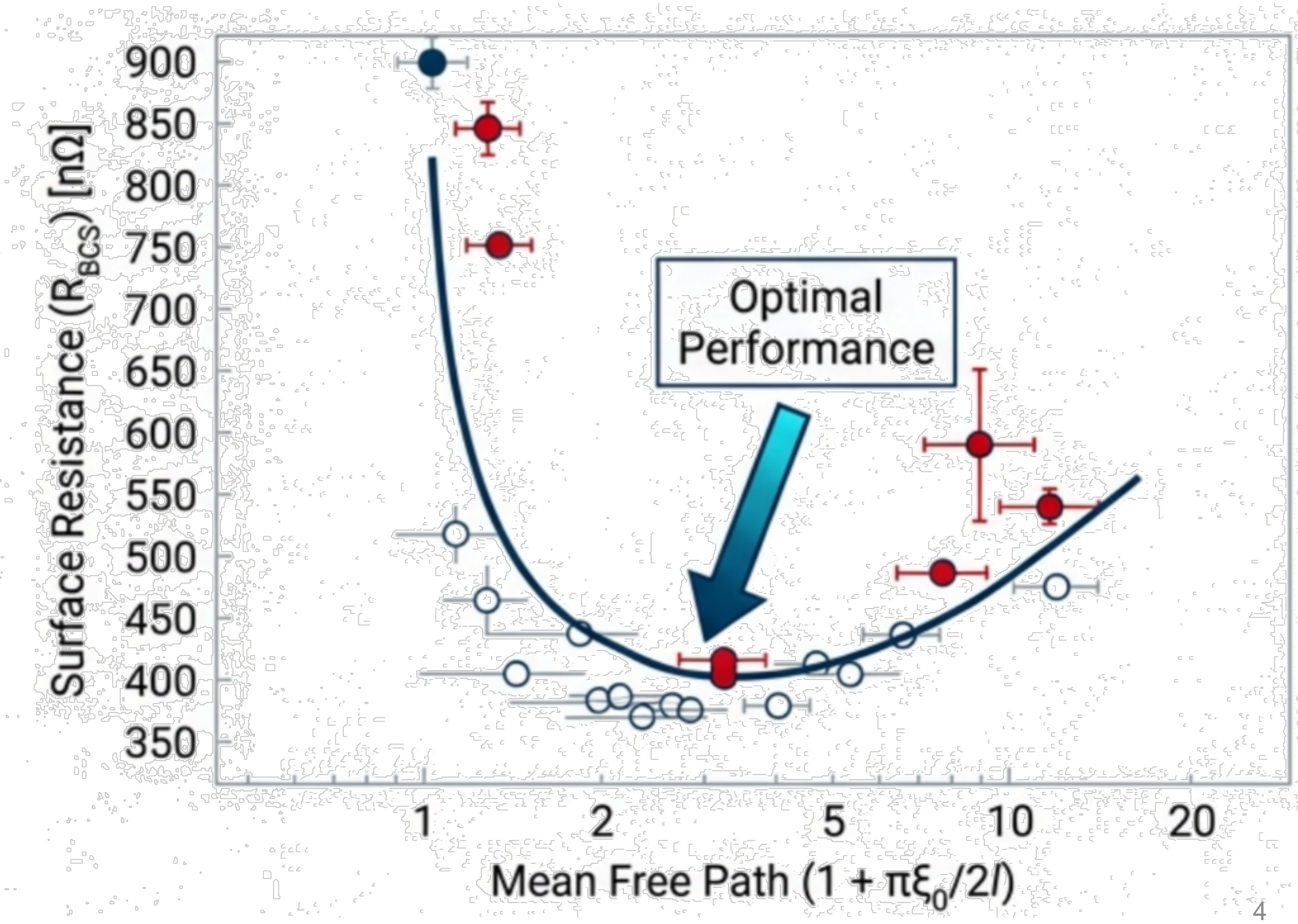


Surface resistance is not just a material parameter; it is an operating expense.

SURFACE RESISTANCE

$$R_s(T, B_{rf}) = R_{BCS}(T, B_{rf}) + R_0(B_{rf})$$

- **Counter-Intuitive Physics:** Pure Niobium is not the theoretical optimum.
- **The Mechanism:** By introducing impurities (doping), we shorten the electron mean free path.
- **The Result:** Resistance reaches a minimum when the coherence length matches the mean free path ($\xi_0/\ell \approx 1$).



RESIDUAL RESISTANCE (R_0)

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$R_{interstitial}$: Caused by material impurities (H, N, C). Addressed by high RRR.

$R_{interface}$: Substrate effects, typically for bi-metallic structures.

$R_{suboxide}$: Surface oxides (NbO_2, NbO). Addressed by annealing.

$$R_0 = R_{interstitial} + R_{suboxide} + R_{TLS} + R_{interface} + R_{flux} + R_{surfacedefects} + \ldots$$

R_{TLS}: Two-Level Systems due to Nb_2O_5 (at $T < 1$ K). Addressed by Annealing/Capping.

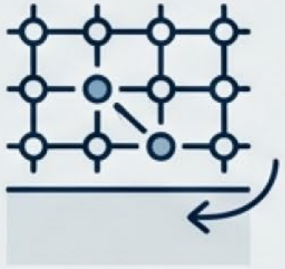
$R_{surface\ defects}$: Surface damage. Addressed by Chemical/Mechanical Polishing.

R_{flux}: Trapped Flux. Addressed by shielding and cooldown protocols.

HIGH Q_0, HIGH GRADIENT

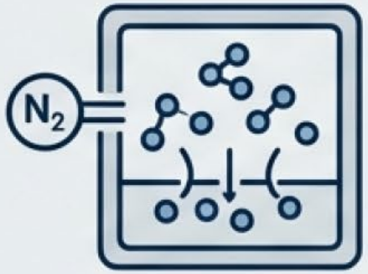
The Recipe: Surface Alloying within the RF Penetration Depth

Titanium Doping



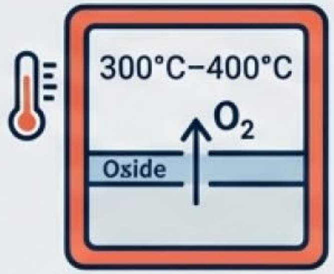
Surface alloying with Ti.

Nitrogen Doping/Infusion



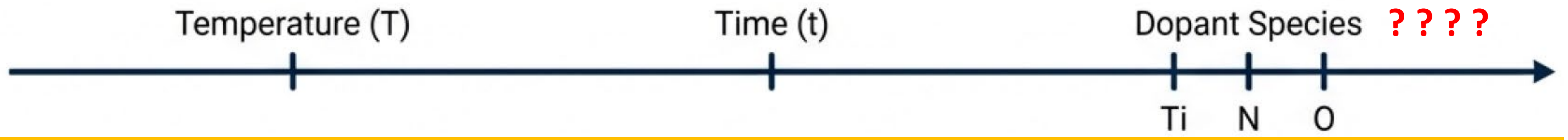
High-temperature furnace treatment with N_2 gas.

Oxygen (Mid-T Bake)



Baking at 300°C–400°C to diffuse native oxide layers.

Process Variables



- **Q-rise is due to the current-induced broadening of the quasiparticle density of states in dirty limit.**
  Gurevich, PRL 2014
- **High Q0 cavities are very sensitive to trapped magnetic flux during cooldown, often mask the benefit of high Q_0**

RESIDUAL RESISTANCE (R_0)

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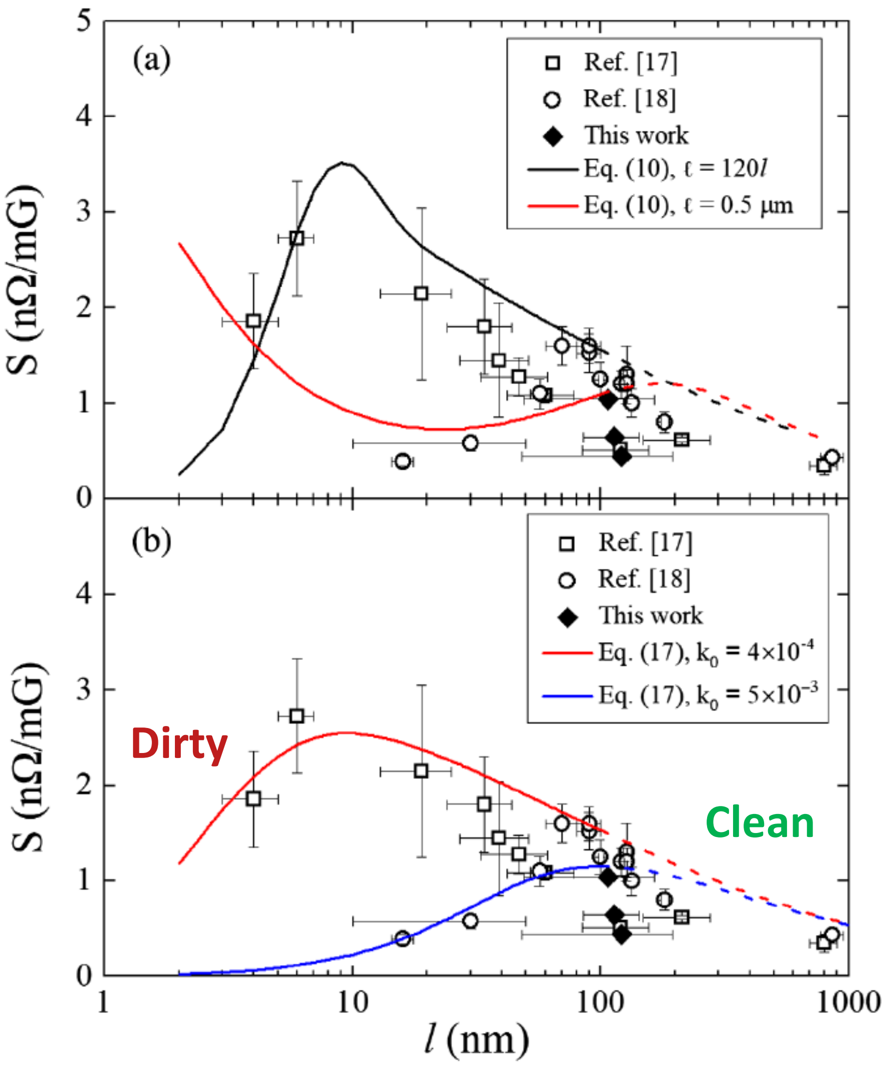
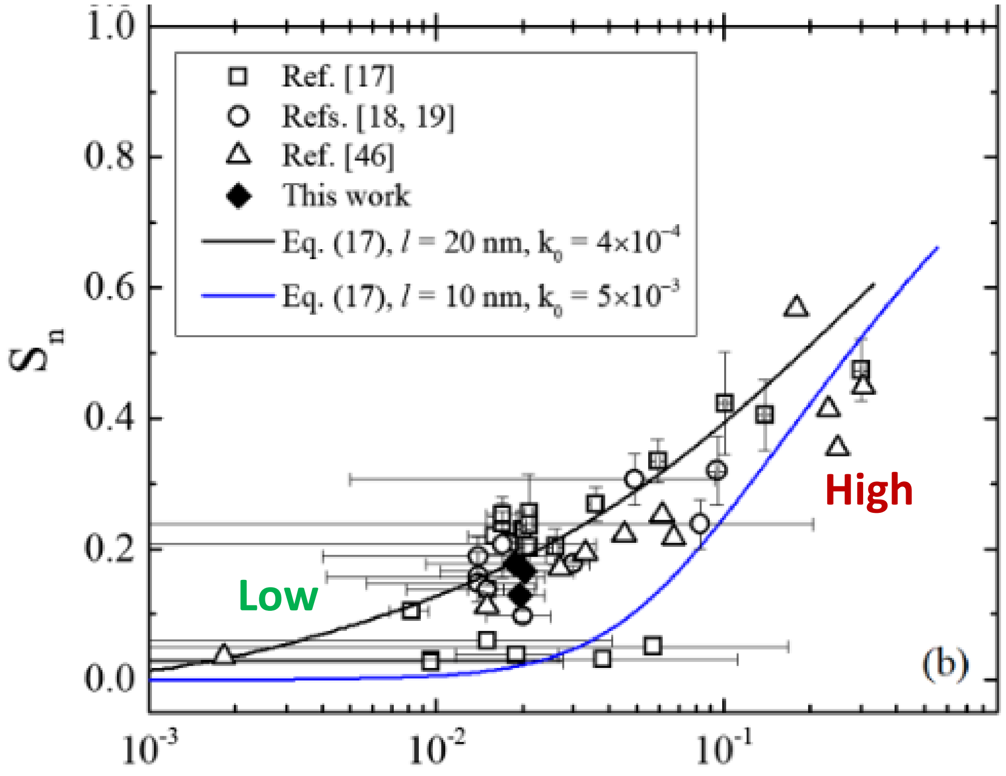
$$R_0 = R_{interstitial} + R_{suboxide} + R_{TLS} + R_{interface} + R_{flux} + R_{surfacedefects} + \ldots..$$

FLUX TRAPPING (LOW FIELD)





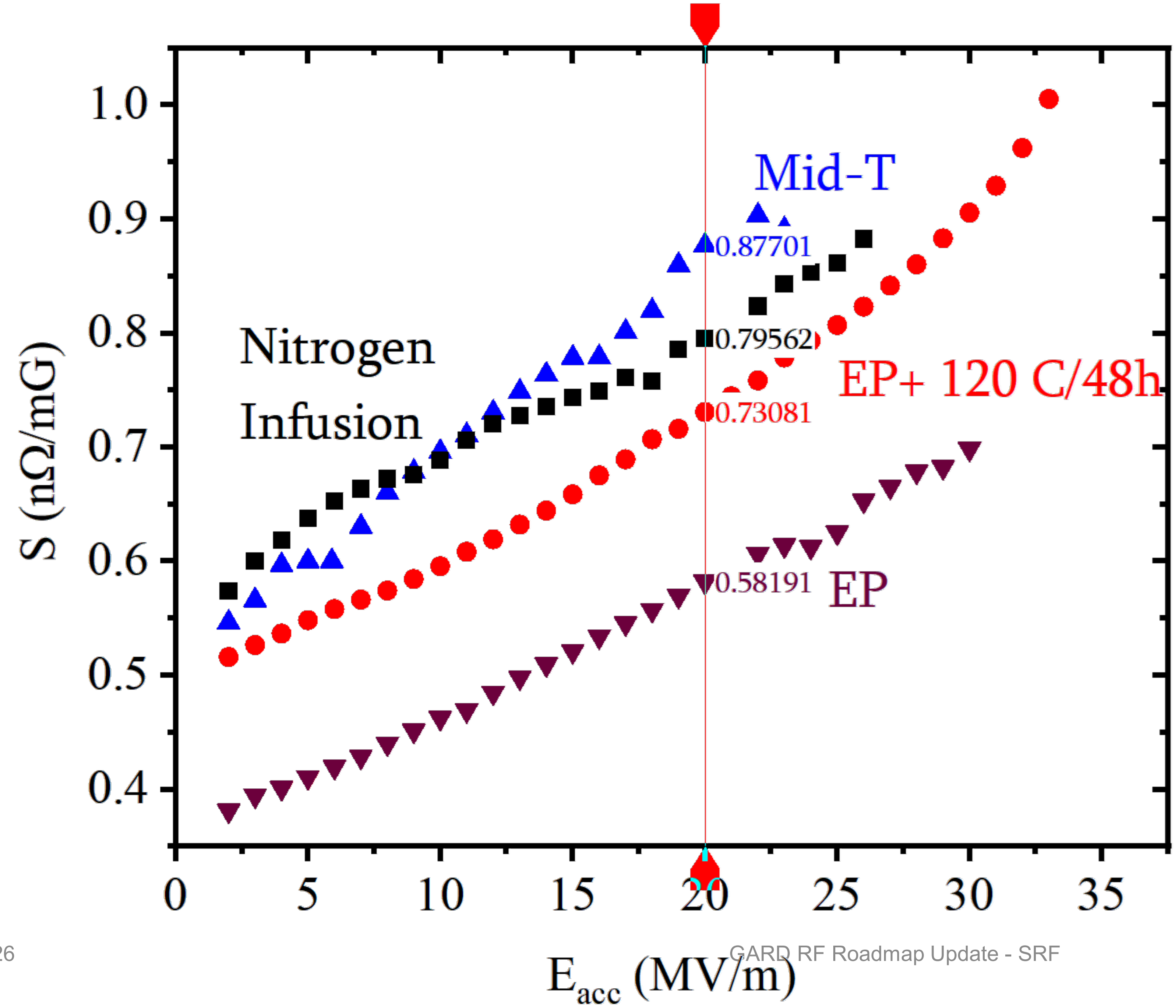
$$\chi = \omega\eta\lambda^2/\epsilon$$

Flux trapping sensitivity depends on

- ❑ Mean free path
- ❑ Pinning strength/type
- ❑ Frequency
- ❑ Orientation of flux lines with respect to rf field

P. Dhakal et al., PRAB, 23, 023102 (2020)
A. Gurevich, SUST , 30, 034004 (2017)

FLUX TRAPPING-FIELD DEPENDENCE



At operating gradient, the benefit of high Q_0 is minimized due to large flux trapping sensitivity

FLUX EXPULSION/TRAPPING/RECRYSTALLIZATION

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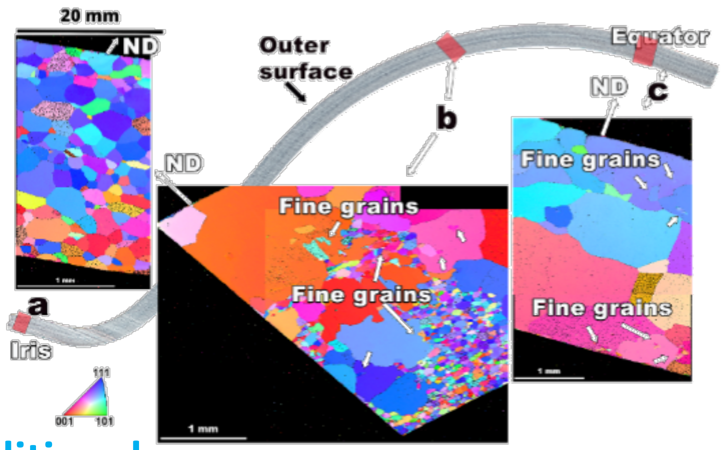
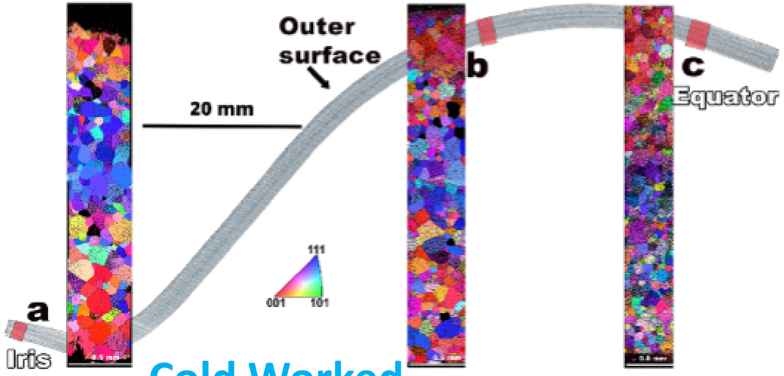
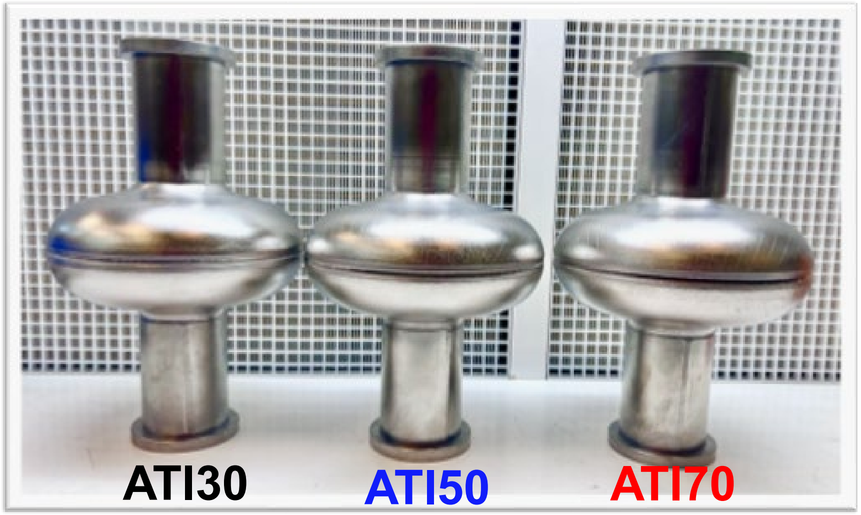


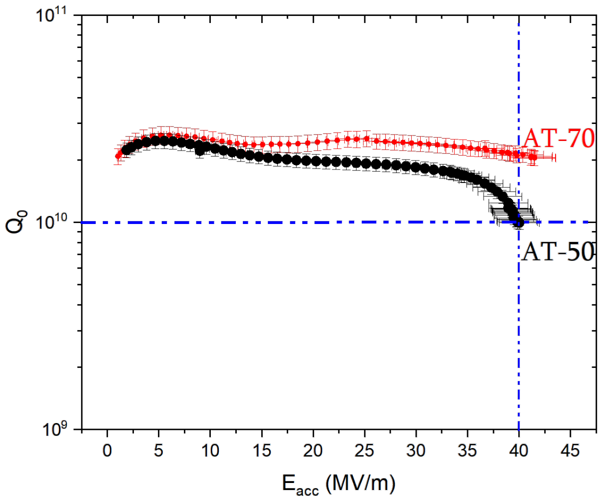
Traditional

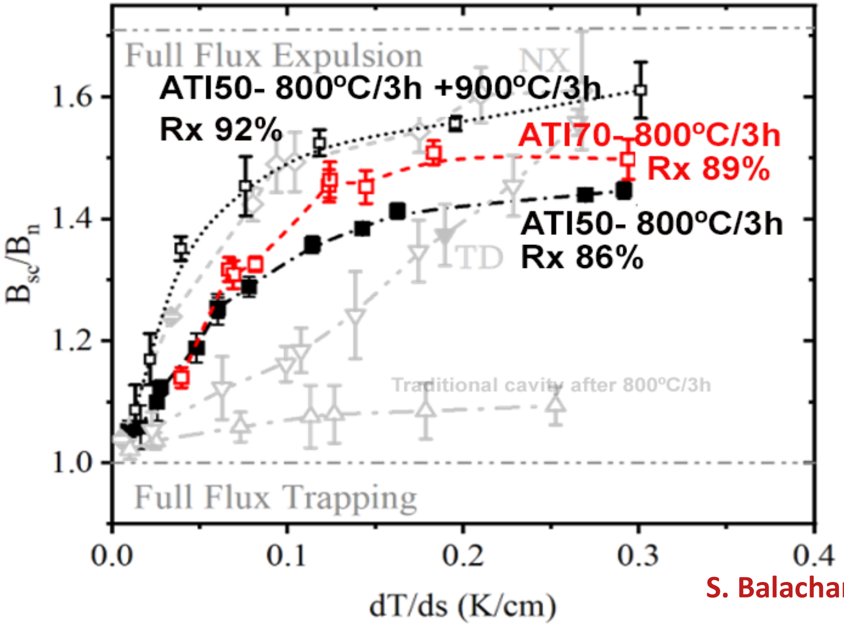
Cavities fabricated from cold-worked Nb sheets, followed by heat treatment at 800°C shown to ***Improved flux expulsion*** *compared to traditional methods*



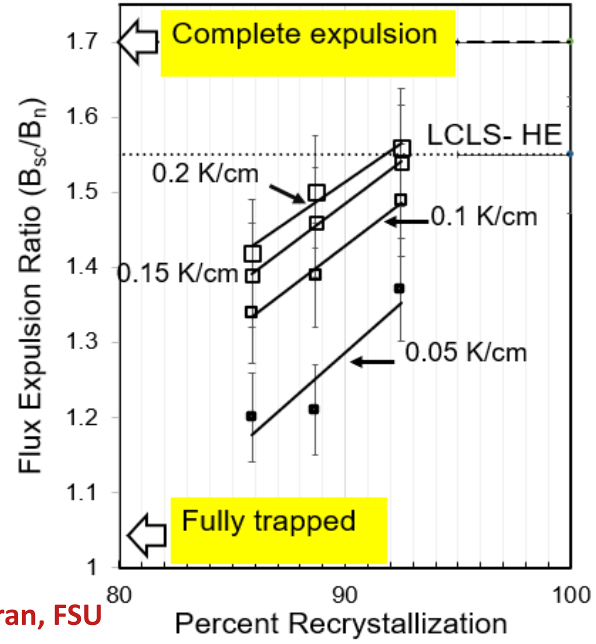
Cold Worked







S. Balachandran, FSU



Khanal et al., Superconductor Science and Technology 38 (1), 015015 (2024).
Bennet et al., IEEE Transactions of Applied Superconductivity, 35(5), 1-5 (2025)

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The main source of surface resistance at operating gradient is due to residual flux trapping during cooldown

Q_0-RISE & FREQUENCY DEPENDENCE

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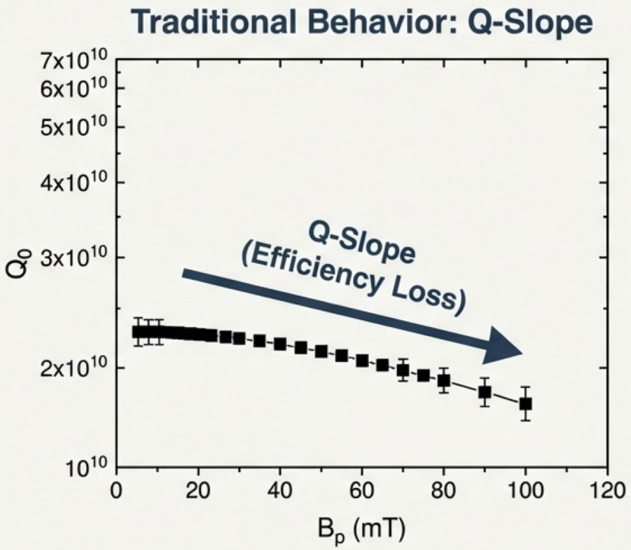
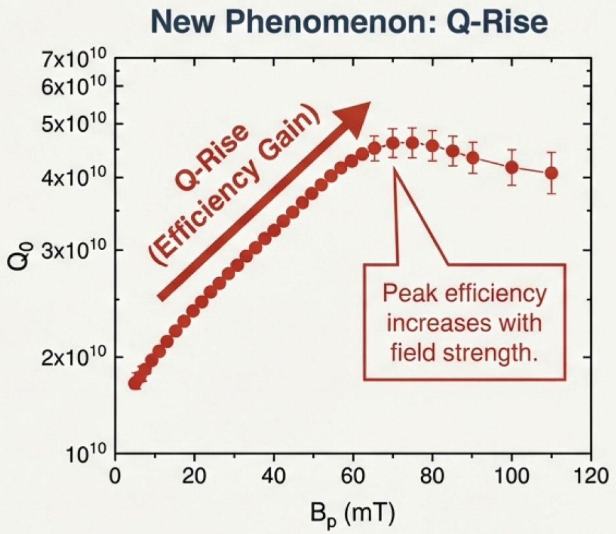


The Threshold



No Q-Rise observed (e.g., 650 MHz)

900 MHz
2.0 K

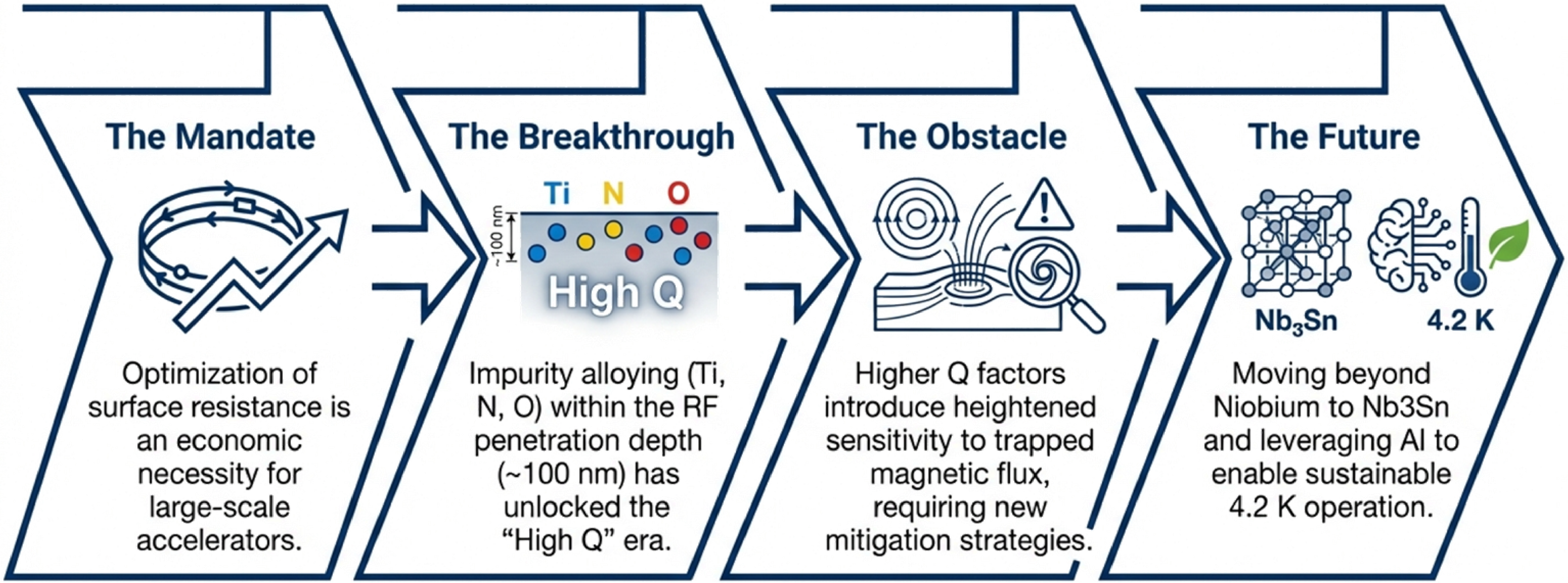
Q-Rise Enabled (e.g., 1.3 GHz)

Theoretical Model: Non-Equilibrium Superconductivity

A race between the RF drive and electron relaxation.

Gurevich, SUST (2023)
Kubo & Gurevich, PRB 100, 064522 (2019)
Kaplan et al., PRB 14, 4854 (1976)

The Path to Next-Generation SRF Performance



Mastering nanoscale surface physics to enable miles long discovery

Questions?