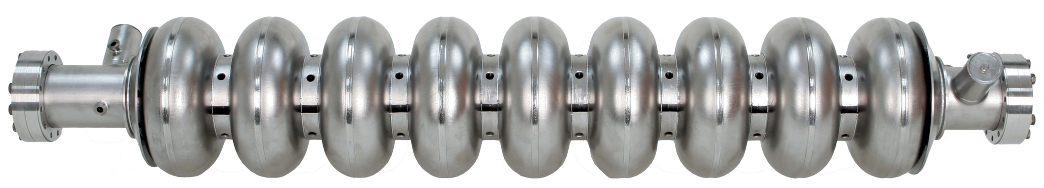
Characterizing the Dirty Layer in Superconducting RF Cavities

Anil Radhakrishnan, University of Illinois at Urbana-Champaign – Lee Teng Internship
Mattia Checchin, Technical Division, Fermi National Accelerator Laboratory

Motivation

Impurity enriched surface layer is shown to create improvement in accelerating gradients achievable in SRF cavities.

Theoretical investigations show the gradients can be further improved by tuning this layer.



Background

Cavities

RF cavities are devices used to accelerate charged particles in accelerators by creating a resonant electromagnetic field in RF range.

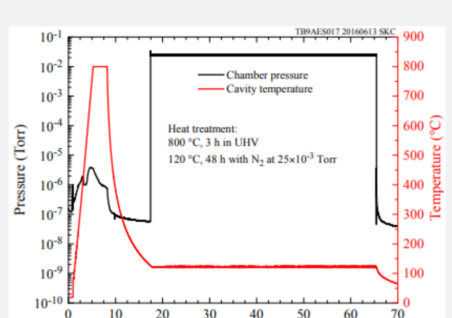
Superconducting cavities are used in most high-energy accelerators due to their reduced power consumption and high accelerating gradient (~45 MV/m).

Nitrogen Infusion

N-infusion modifies the first ~100 nm of the cavity by adding interstitial nitrogen.

Typical treatment involves:

- Cavities that are treated for 3 hours at 800 °C in HV.
- Nitrogen is then injected at 120 °C.

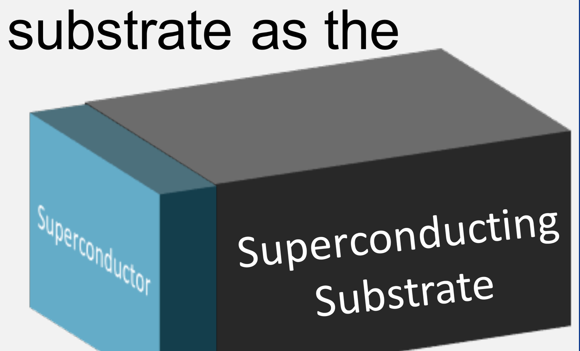


Kubo's Model

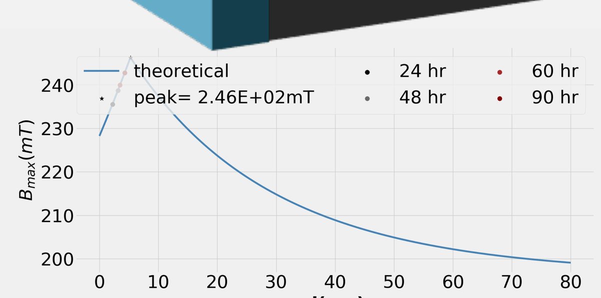
For theoretical analysis, we use a **Superconductor-Superconducting substrate** model proposed by Takayuki Kubo.

Nb surface after the low-temperature nitrogen infusion has a depth-dependent penetration depth which can be described by an S-S bilayer with a thin dirty Nb and a clean Nb substrate as the simplest model.

$$\lambda_{\text{superconductor}} > \lambda_{\text{substrate}}$$

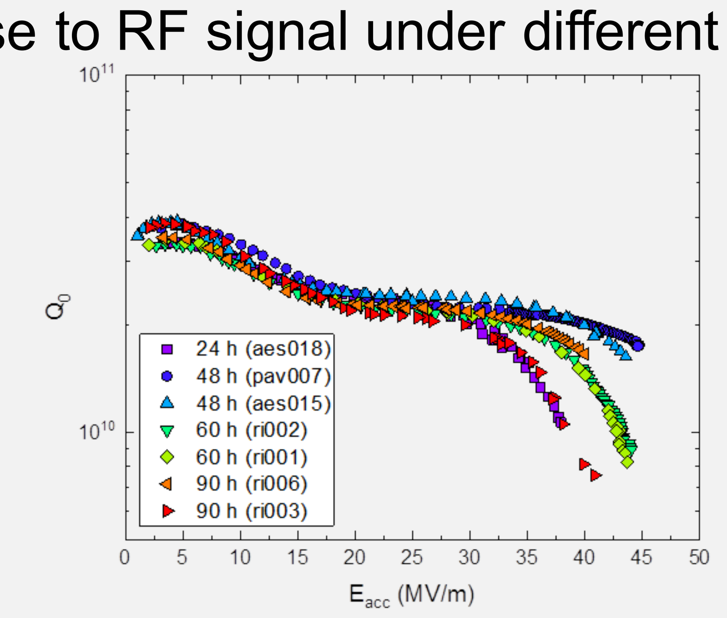


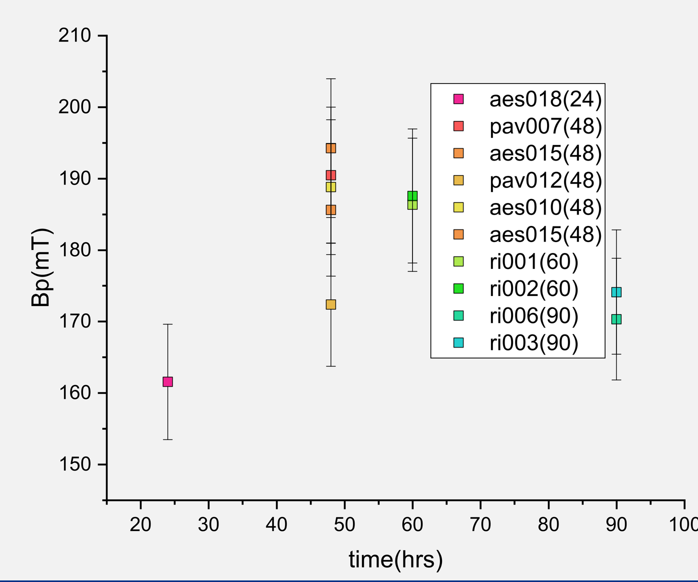
The model lets us calculate the maximum and optimal magnetic fields for a given thickness of superconductor, which is then used to find optimal thickness for best accelerating gradient.



Cavity Testing

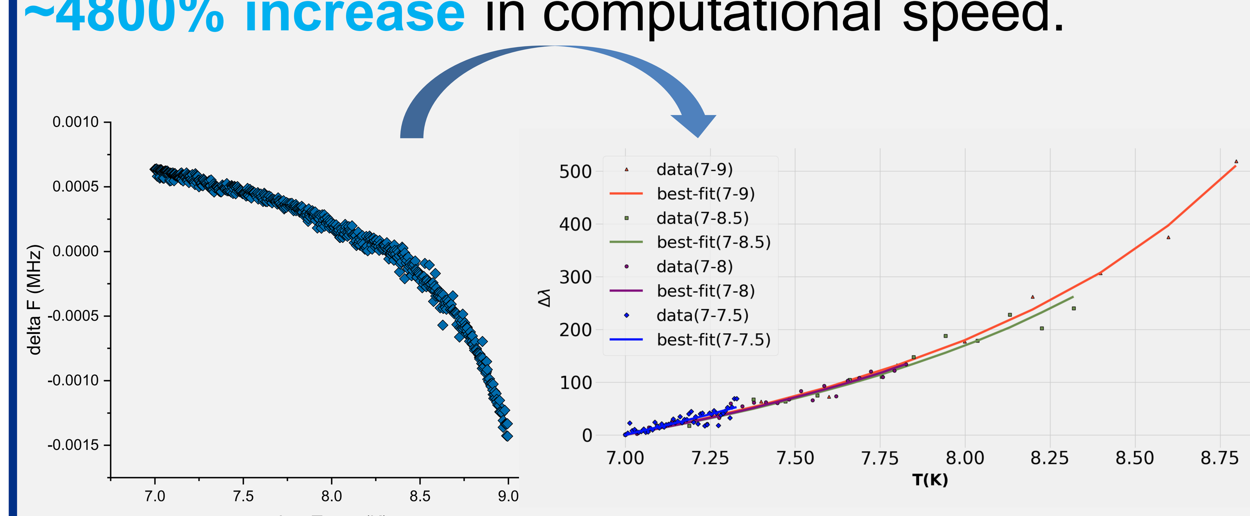
N-infused cavities prepared at the same temperature but different infusion duration were tested at the Vertical Test Facility to record their response to RF signal under different conditions.





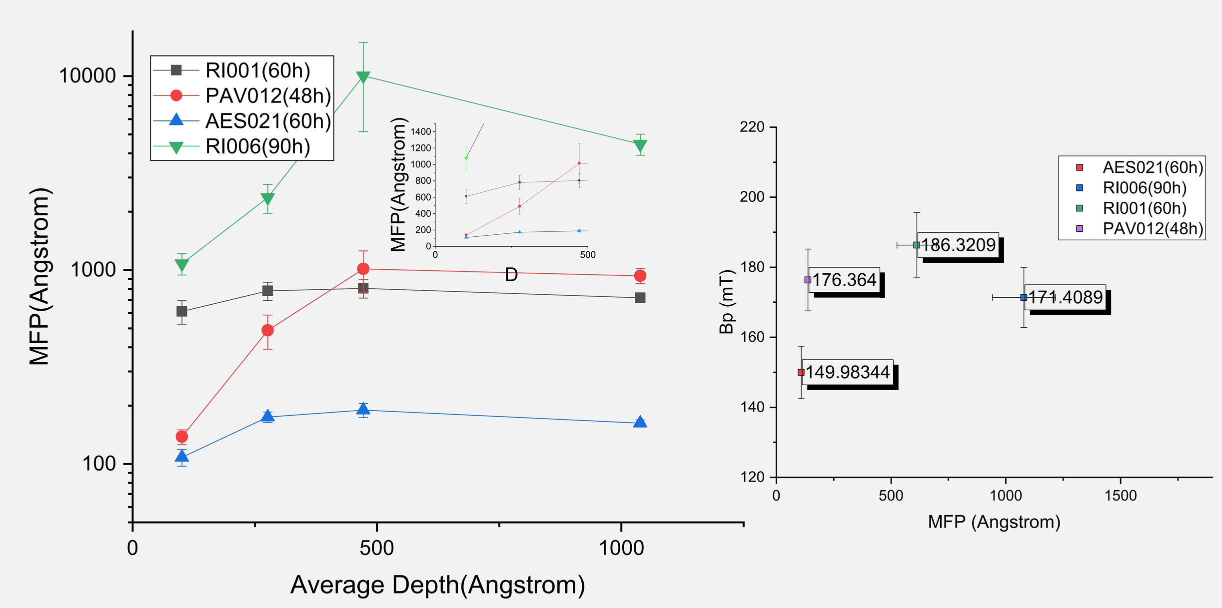
BCS Fitting

The data processing and BCS fitting was performed in Python after implementing a wrapper for Halbritter program in C. The module is capable of easily handling bulk data and resulted in a **~4800% increase** in computational speed.



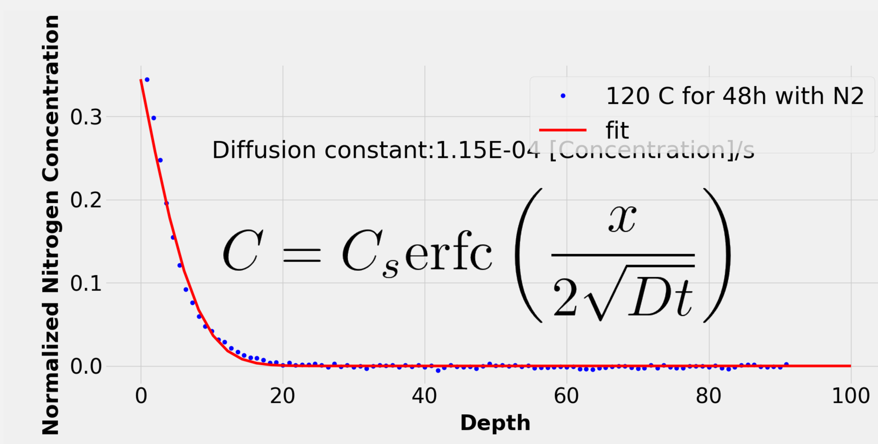
$$\Delta f = -\frac{\mu_0 \pi f_0^2}{g} \Delta\lambda \qquad \frac{\lambda(T)}{\lambda_0} = \frac{1}{\sqrt{1+\left(\frac{T}{T_c}\right)^4}}$$

The BCS fit of this data lets us extract parameters like mean free path (MFP), which are useful for characterizing the superconducting material.

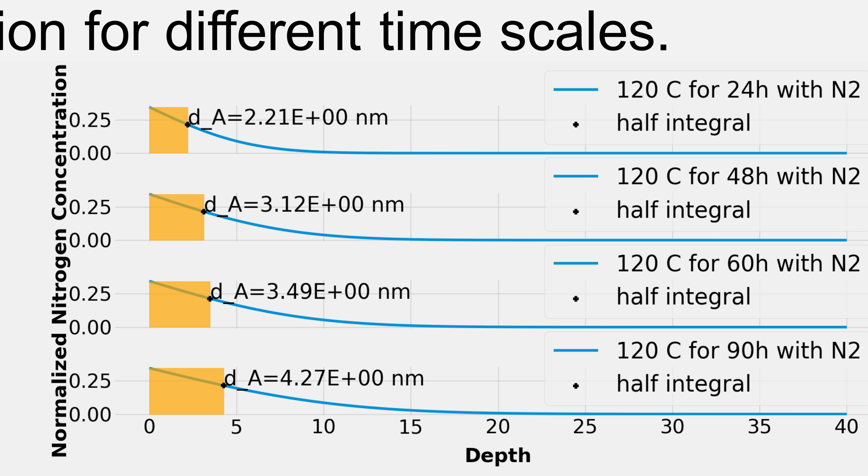


Theoretical Grounding

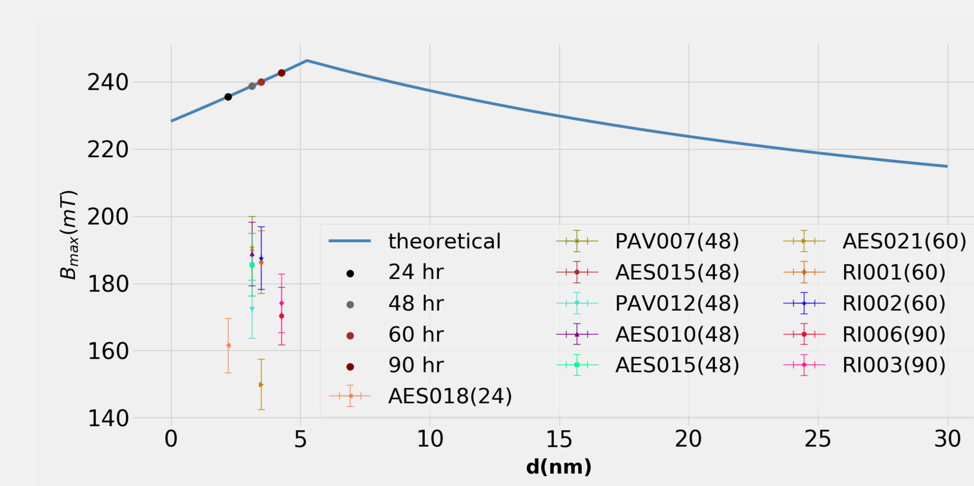
To obtain the thickness of the superconductor, nitrogen concentration data was fit with Fick's law.



The parameters obtained were used to simulate diffusion for different time scales.



The **half concentration point** is taken as depth of film in the simulation. The experimental data is then overlaid on it



Conclusions

- An efficient software for BCS theory based data analysis was developed. This allowed for:
  - Effortless handling of bulk data.
  - ~4800% increase in computational speed.
- The MFP at surface and the N_2 concentration profile was used to compare the maximum quench field achieved in N-infused cavities with a theoretical model.
- Predicted quench field values were higher than what experimentally measured. Such a discrepancy can be explained by:
  - Local defects in the cavity limiting the gradient.
  - The model being developed in the London limit.
  - Simulating diffusion profiles with only one diffusion constant from concentration profile at 48 hours.

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[1] Kubo, T. "Multilayer coating for higher accelerating fields in superconducting radio-frequency cavities: a review of theoretical aspects." *Superconductor Science and Technology* 30, 023001 (2017).
[2] Halbritter, J. "On the penetration of the magnetic field into a superconductor." *Z. Physik* 243, 201–219 (1971).

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