The Fundamental Science of Nitrogen-Doping of Niobium Superconducting Cavities

Dan Gonnella

B Exam

May 20, 2016

Outline

- Motivation
- Introduction to Superconducting RF
- Nitrogen-Doping of SRF Cavities
- BCS Resistance Studies
- Residual Resistance Studies
- High Field Limits
- Transition to Full Cryomodule
- Conclusions

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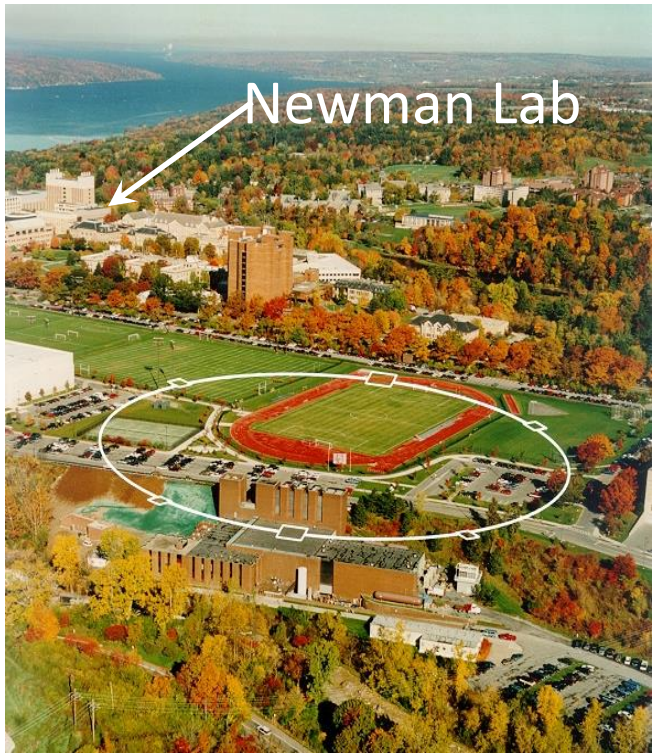
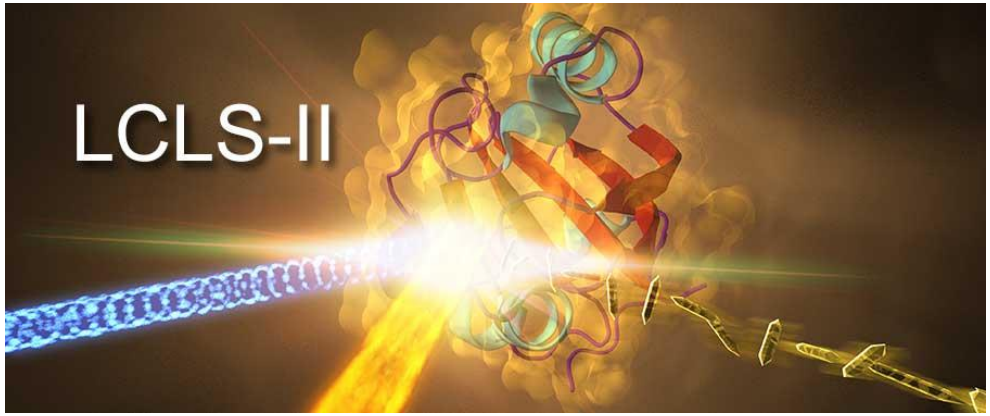
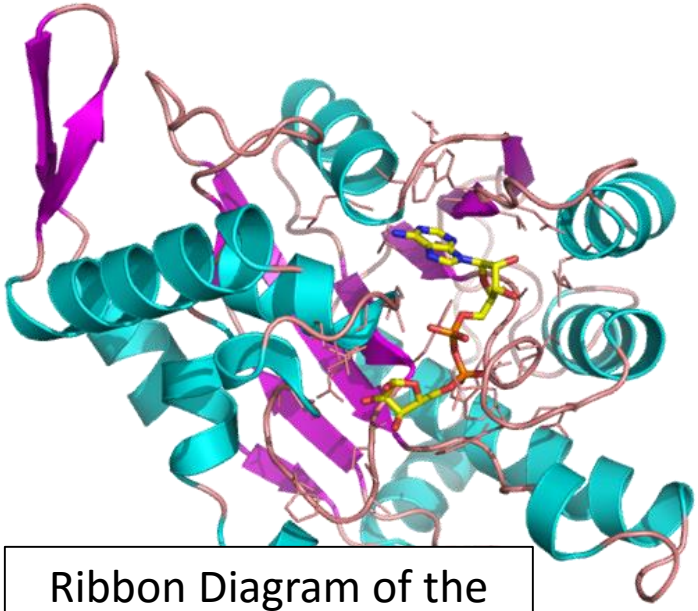
Motivation



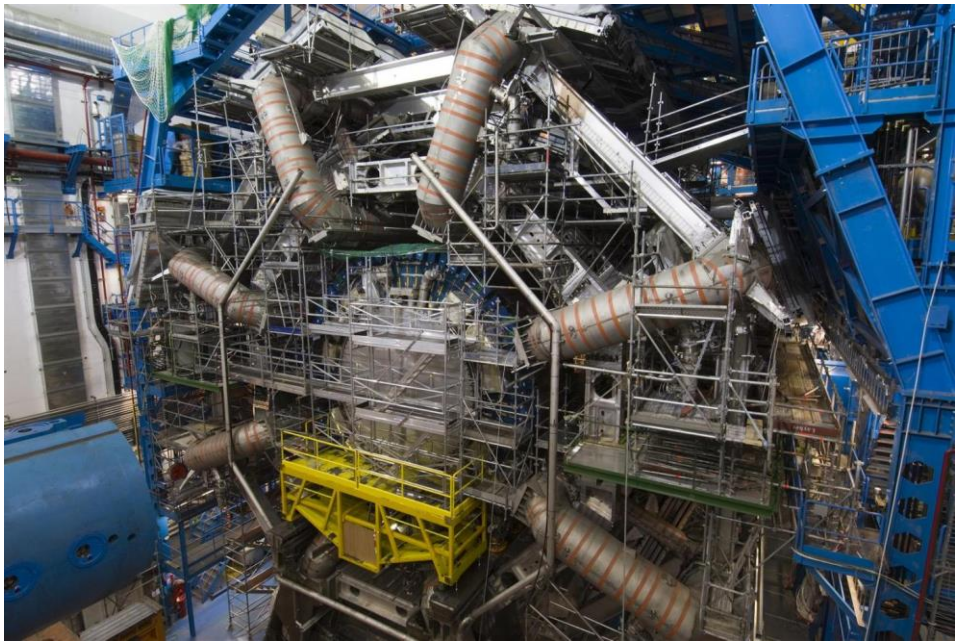


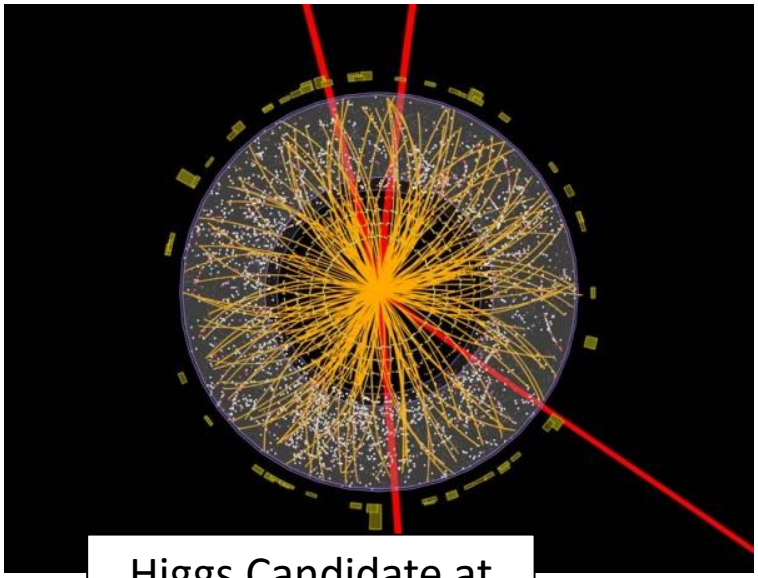


Ribbon Diagram of the PARG-protein

Images from Cornell, CERN, and SLAC

Motivation



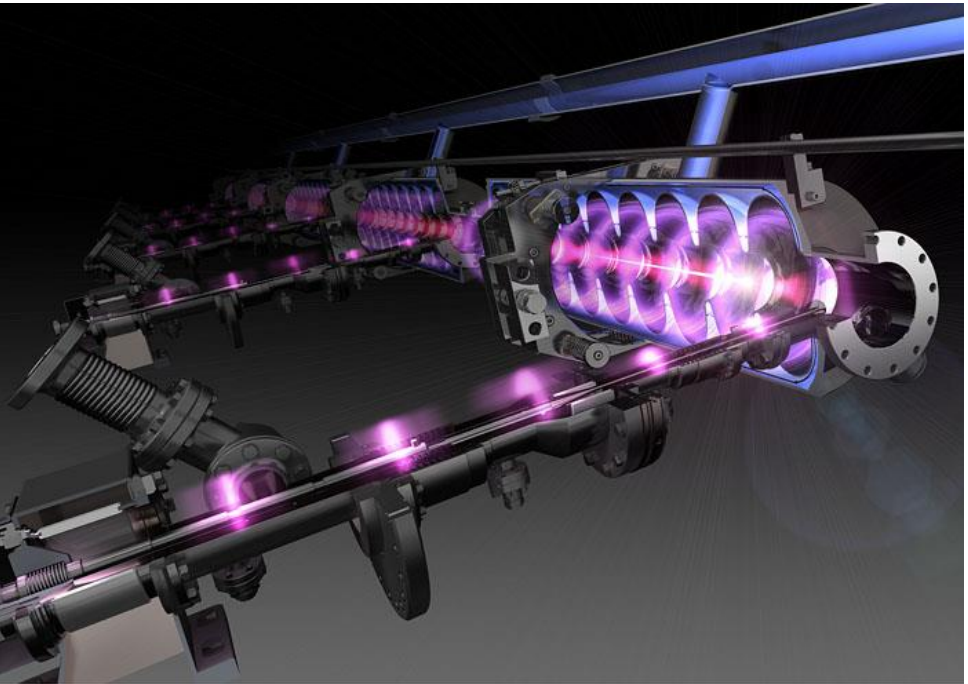


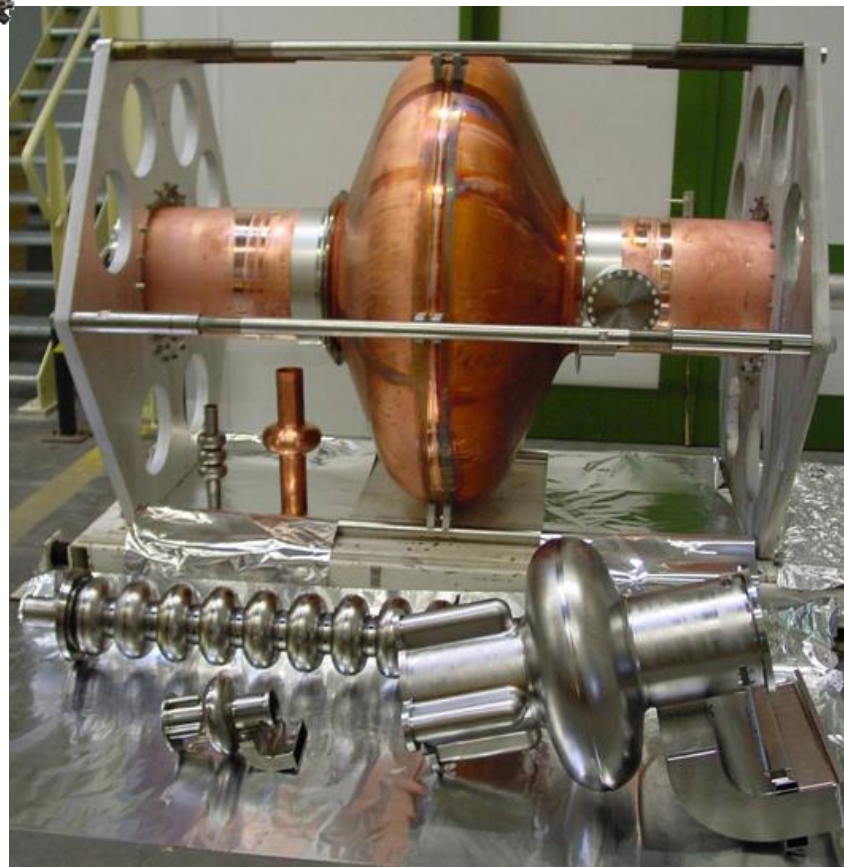
Higgs Candidate at the ATLAS Detector

Images from Cornell, CERN, and SLAC

Motivation

These accelerators are powered by SRF cavities!





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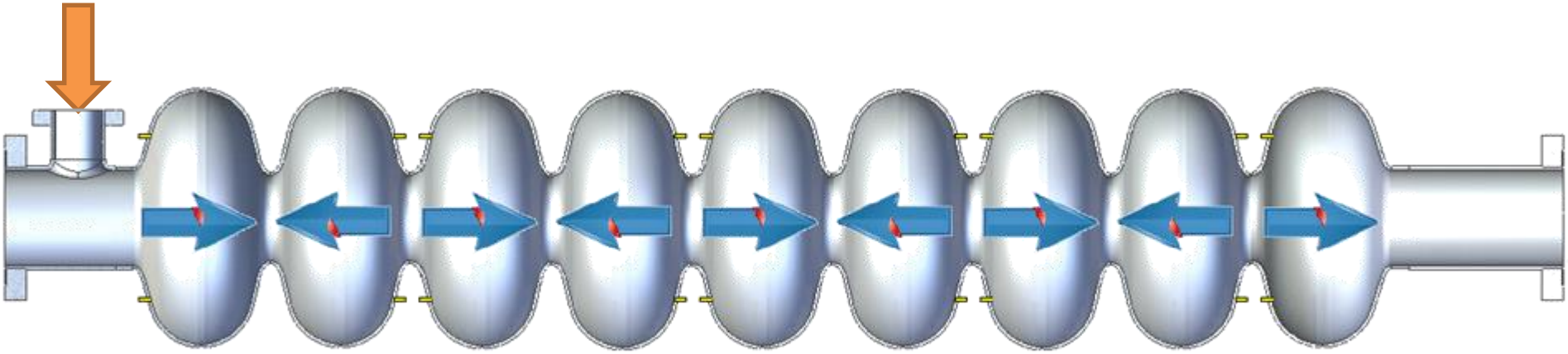
How Does a Cavity Work?

Input RF power at 1.3 GHz



Slowed down by factor of approximately $4x10^9$

Image courtesy of S. Posen

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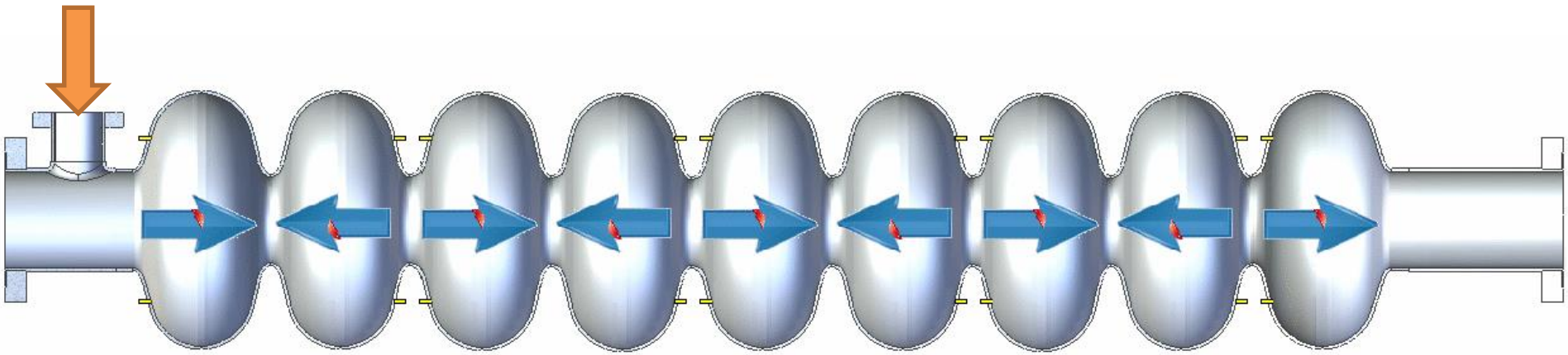


Slowed down by factor of approximately $4x10^9$

Image courtesy of S. Posen

Normal Conducting vs Superconducting

Copper RF Cavity

$Q_0 \sim 10^4$

At 20 MV, dissipated power in cavity walls is **15 MW**

Niobium SRF Cavity

$Q_0 > 10^{10}$

At 20 MV, dissipated power in cavity walls is **15 W**

Cryogenic costs increase the wall power to **15 kW**

Images from ILC

SRF Cavities

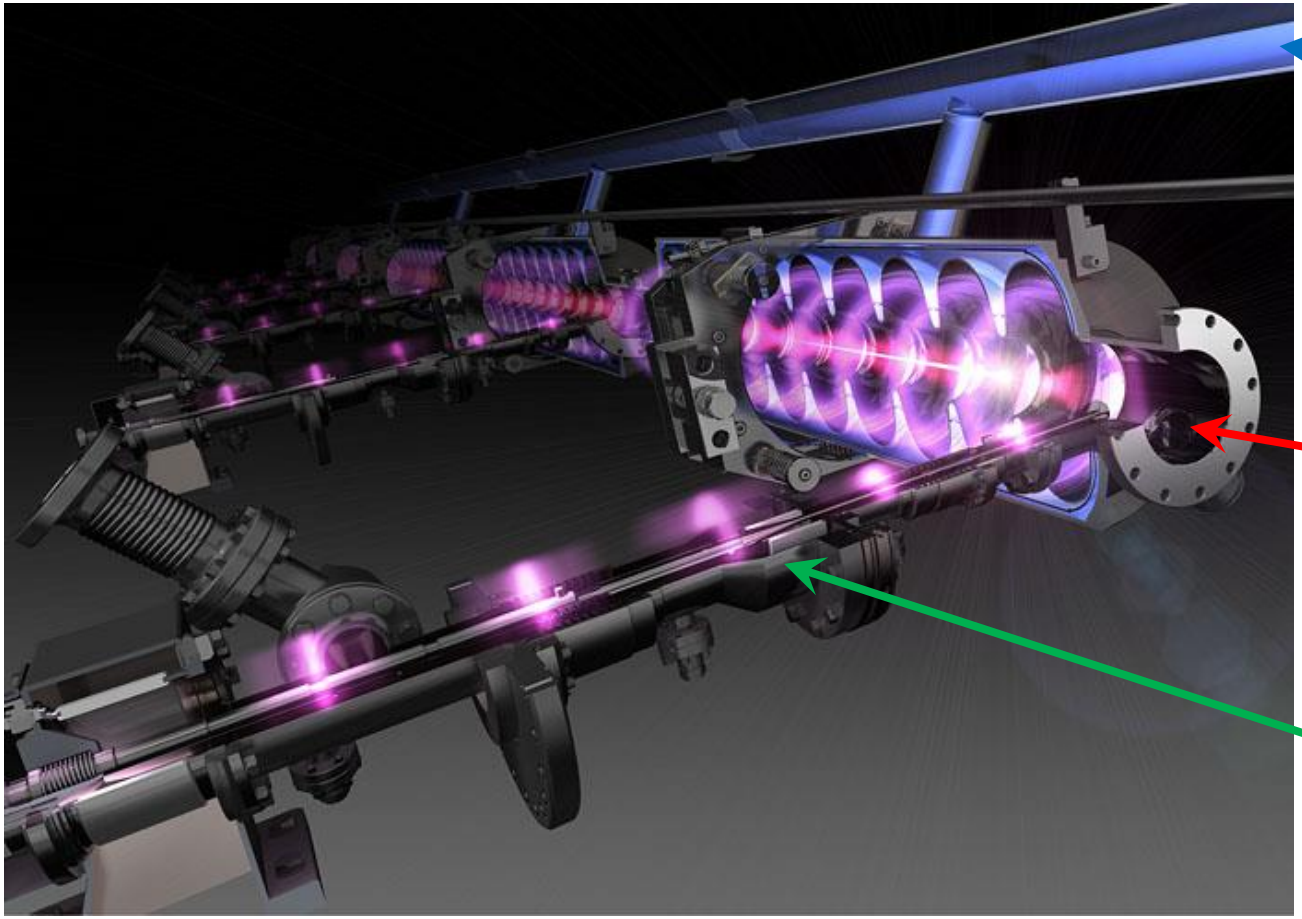
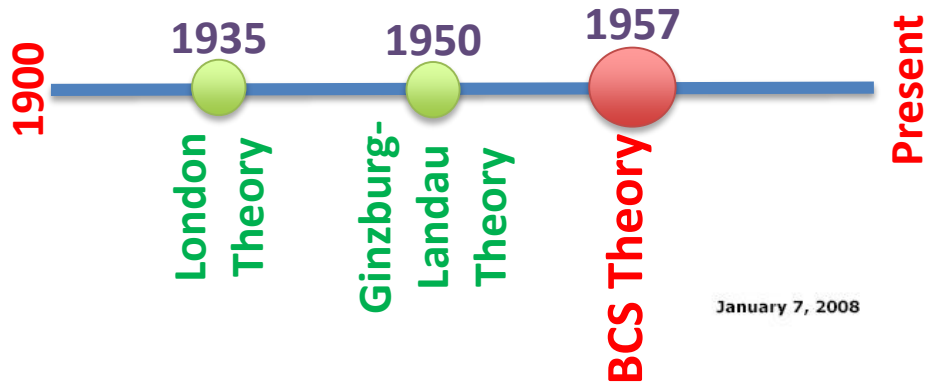


Image from linearcollider.org

Superconductivity

Bardeen, Cooper, and Schrieffer

Microscopic Theory proposed in 1957

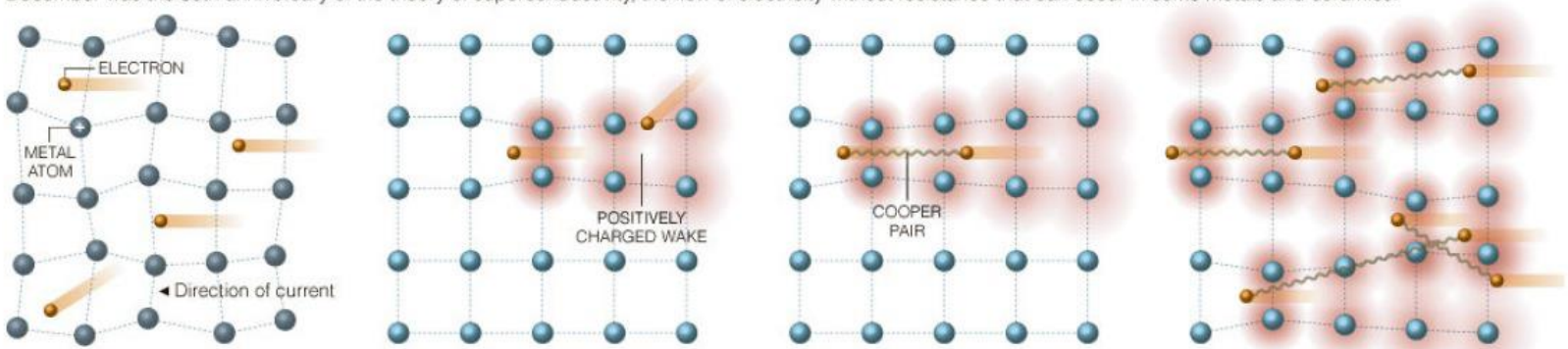


The New York Times

January 7, 2008

Low-Temperature Superconductivity

December was the 50th anniversary of the theory of superconductivity, the flow of electricity without resistance that can occur in some metals and ceramics.



ELECTRICAL RESISTANCE
Electrons carrying an electrical current through a metal wire typically encounter resistance, which is caused by collisions and scattering as the particles move through the vibrating lattice of metal atoms.

CRITICAL TEMPERATURE
As the metal is cooled to low temperatures, the lattice vibration slows. A moving electron attracts nearby metal atoms, which create a positively charged wake behind the electron. This wake can attract another nearby electron.

COOPER PAIRS
The two electrons form a weak bond, called a Cooper pair, which encounters less resistance than two electrons moving separately. When more Cooper pairs form, they behave in the same way.

SUPERCONDUCTIVITY
If a pair is scattered by an impurity, it will quickly get back in step with other pairs. This allows the electrons to flow undisturbed through the lattice of metal atoms. With no resistance, the current may persist for years.

Sources: Oak Ridge National Laboratory; Philip W. Phillips

JONATHAN CORUM/THE NEW YORK TIMES

Superconductivity

- Superconductors are characterized by a critical temperature, T_c, and a critical magnetic field, B_c
- Below T_c and B_c they have a zero resistance to DC fields and perfectly expel magnetic flux from their bulk (Meissner Effect)
- If the material goes above T_c or is exposed to fields larger than B_c, it will become normal conducting – in SRF we call this a quench

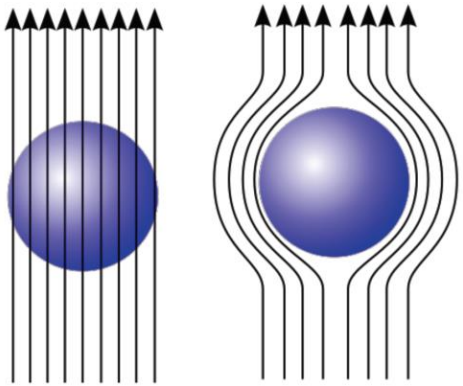
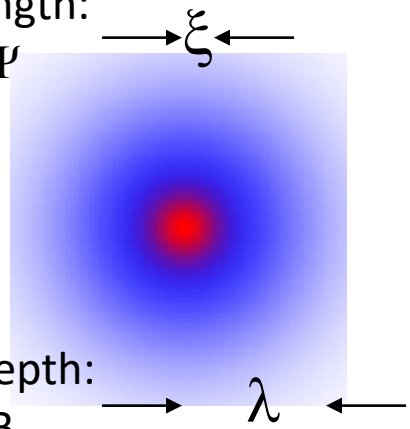


Image from Wikipedia

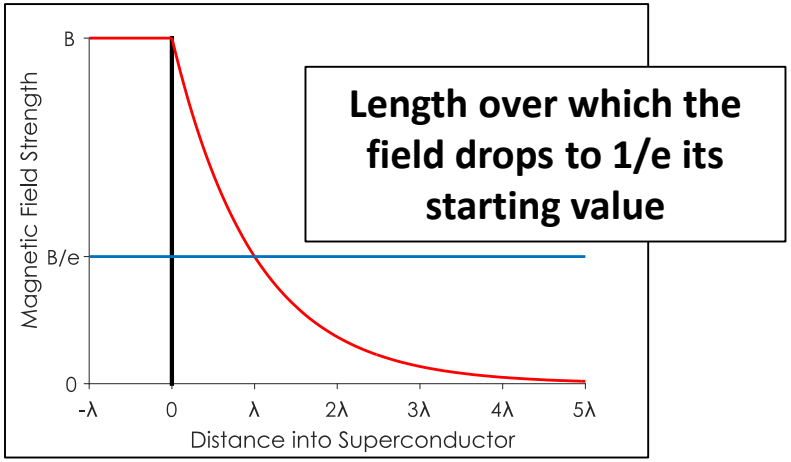
Important Parameters

Coherence length:
Decay of Ψ



Penetration depth:
Decay of B

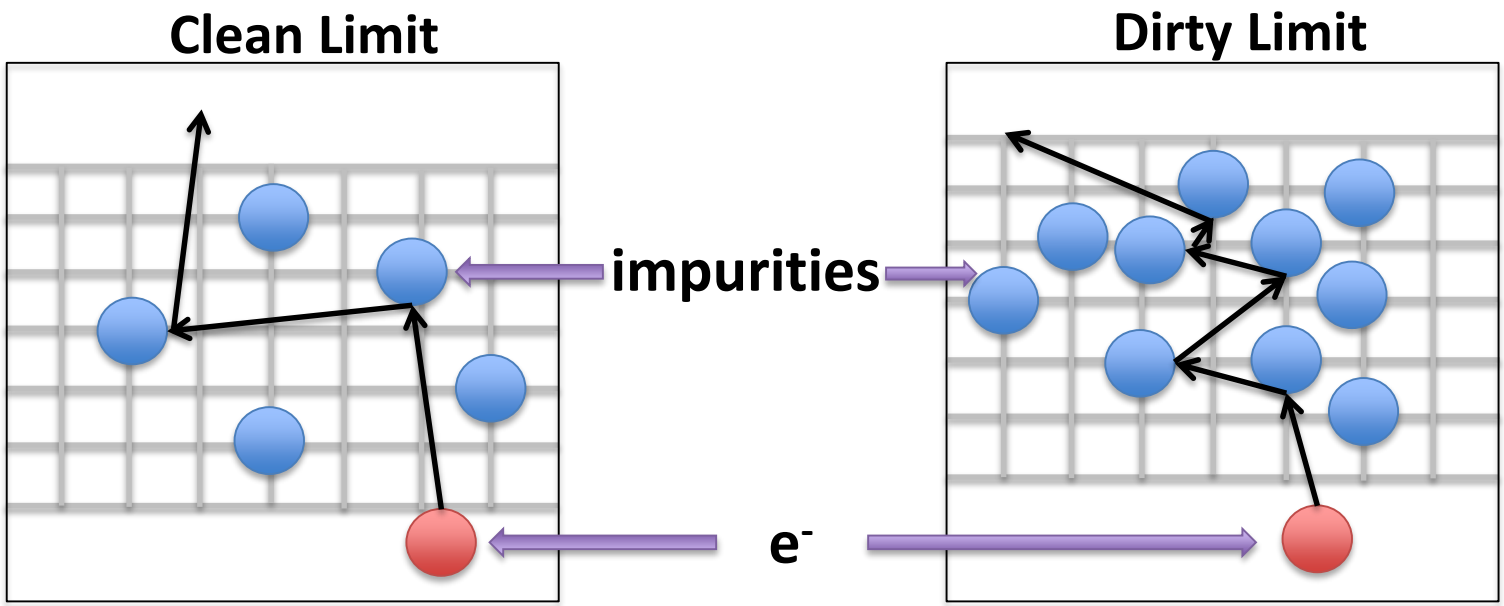
Penetration Depth (λ): Characteristic length over which the field decays into the superconductor



Coherence Length (ξ): Roughly size of the cooper pairs and normal conducting vortices

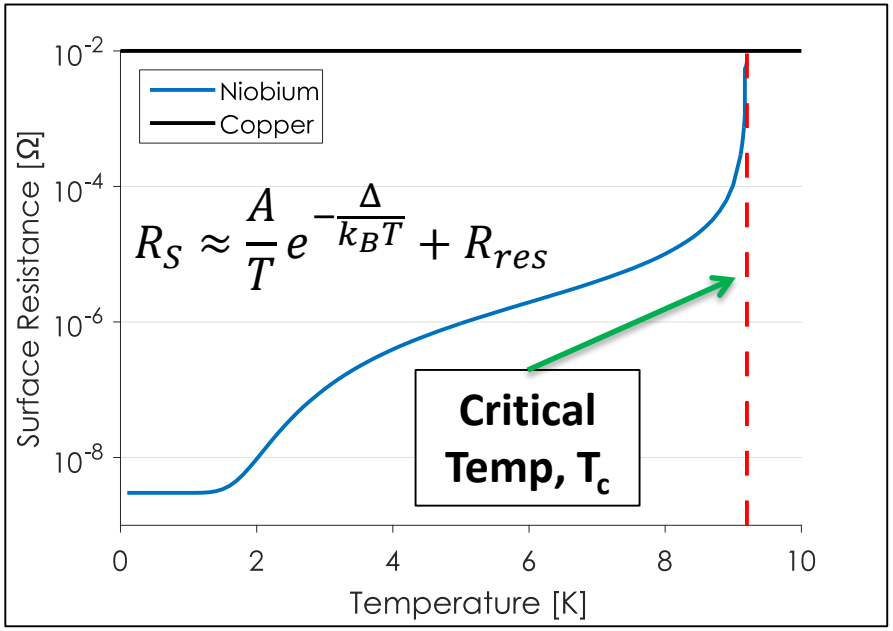
Energy gap (Δ/k_BT_c): Half the energy required to break a cooper pair

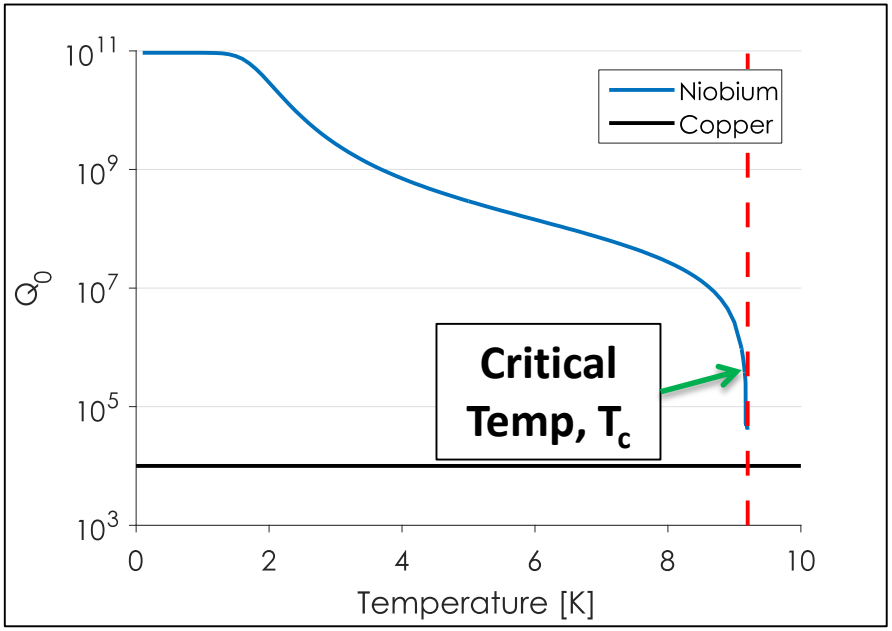
Mean Free Path



- Mean free path (ℓ) is the average distance an electron travels between hitting scattering sites
- For materials with high mean free paths, there are less impurities (clean limit)
- For materials with low mean free paths, there are many impurities (dirty limit)

Superconductivity and Q_0





- Under DC fields, superconductors have zero resistance but under RF, finite inertia of the cooper pairs leads to a small resistance (R_s)
- This surface resistance is related to the quality factor: $Q_0 = G/R_s$

Surface Resistance

The surface resistance can be broken into two components:

$$R_S = R_{BCS}(\lambda, \xi, \ell, \Delta, T_c, T) + R_{res}(?)$$

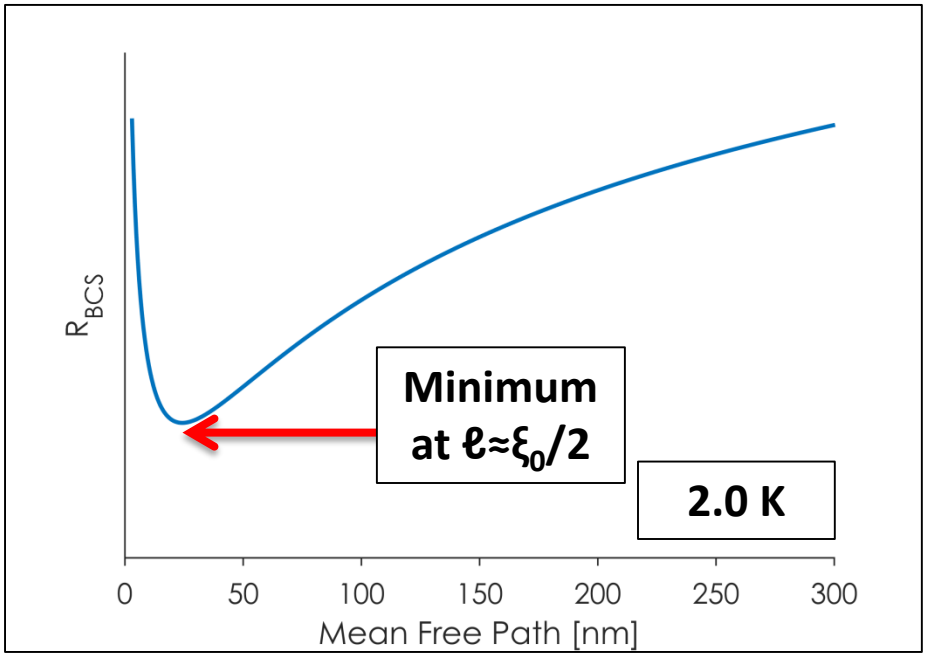
- The temperature dependent resistance is called the "BCS resistance"

$$R_{BCS} \approx \frac{A}{T} e^{-\Delta/k_B T}$$

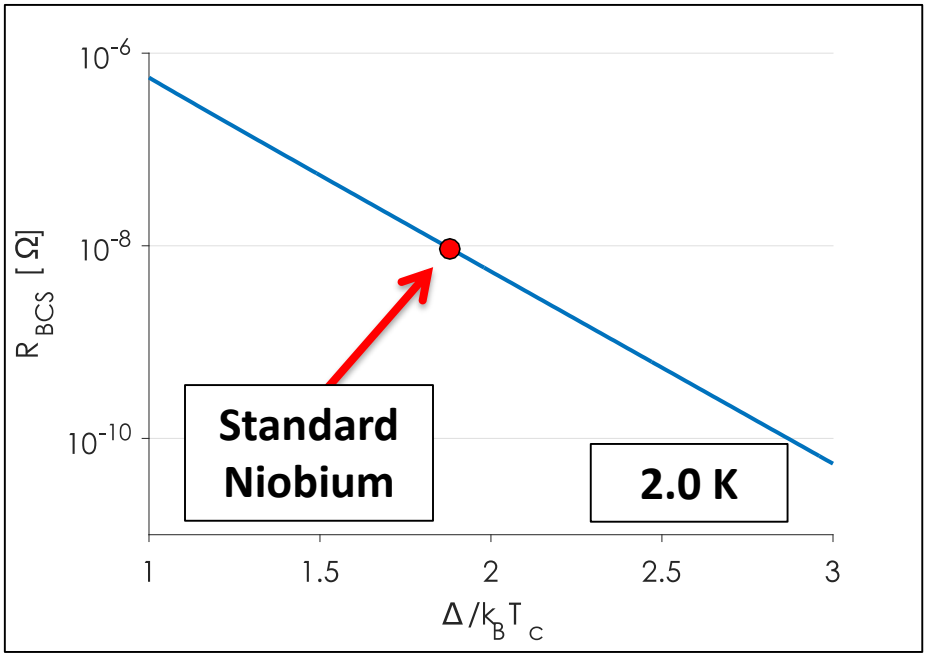
- The temperature independent portion is called the "residual resistance"

The BCS Resistance

R_{BCS} vs Mean Free Path

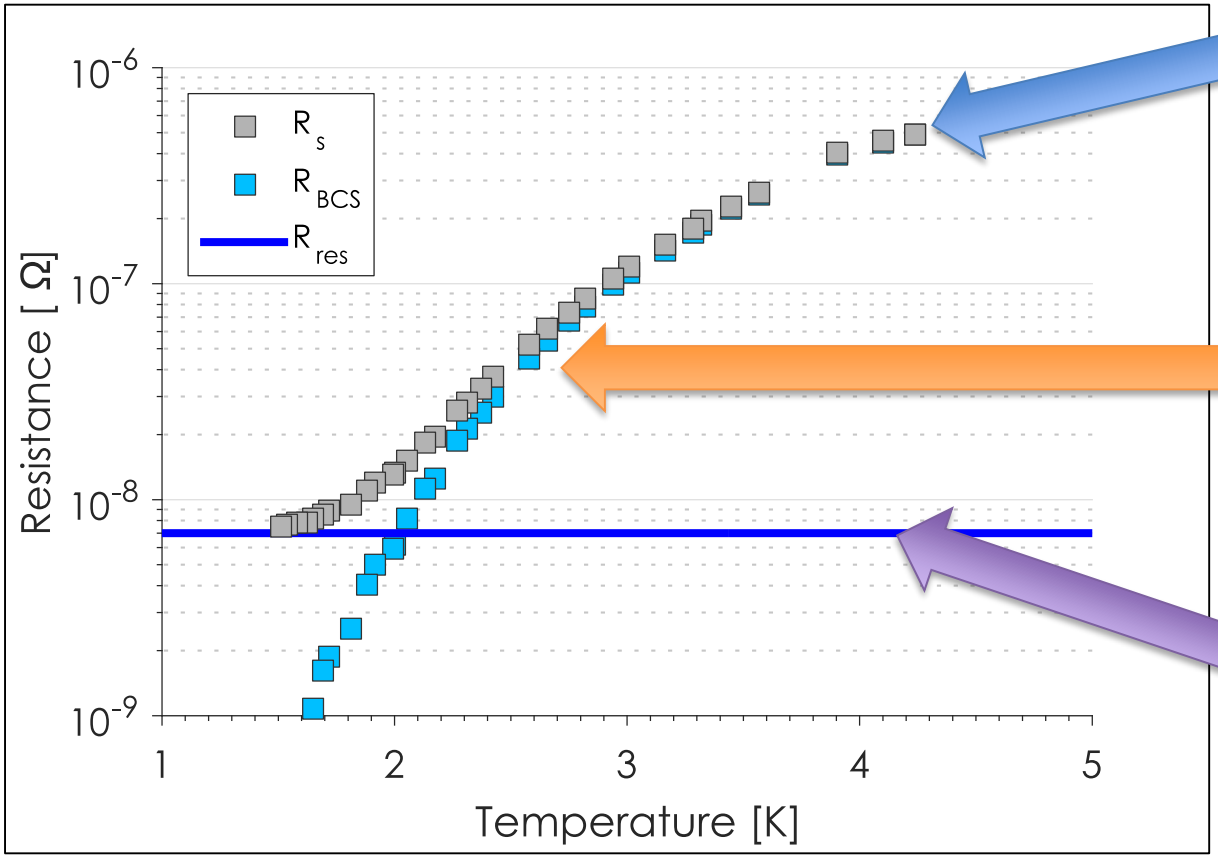


R_{BCS} vs Energy Gap



- Larger energy gap leads to lower R_{BCS}
- R_{BCS} has a minimum at a mean free path of ~$\xi/2$
- It is very important to design the mean free path to reach optimal R_{BCS}

Surface Resistance



At High Temperatures, R_{BCS} Dominates

At Intermediate Temperatures, Both are Important

At Low Temperatures, R_{res} Dominates

Requirements for Low Loss

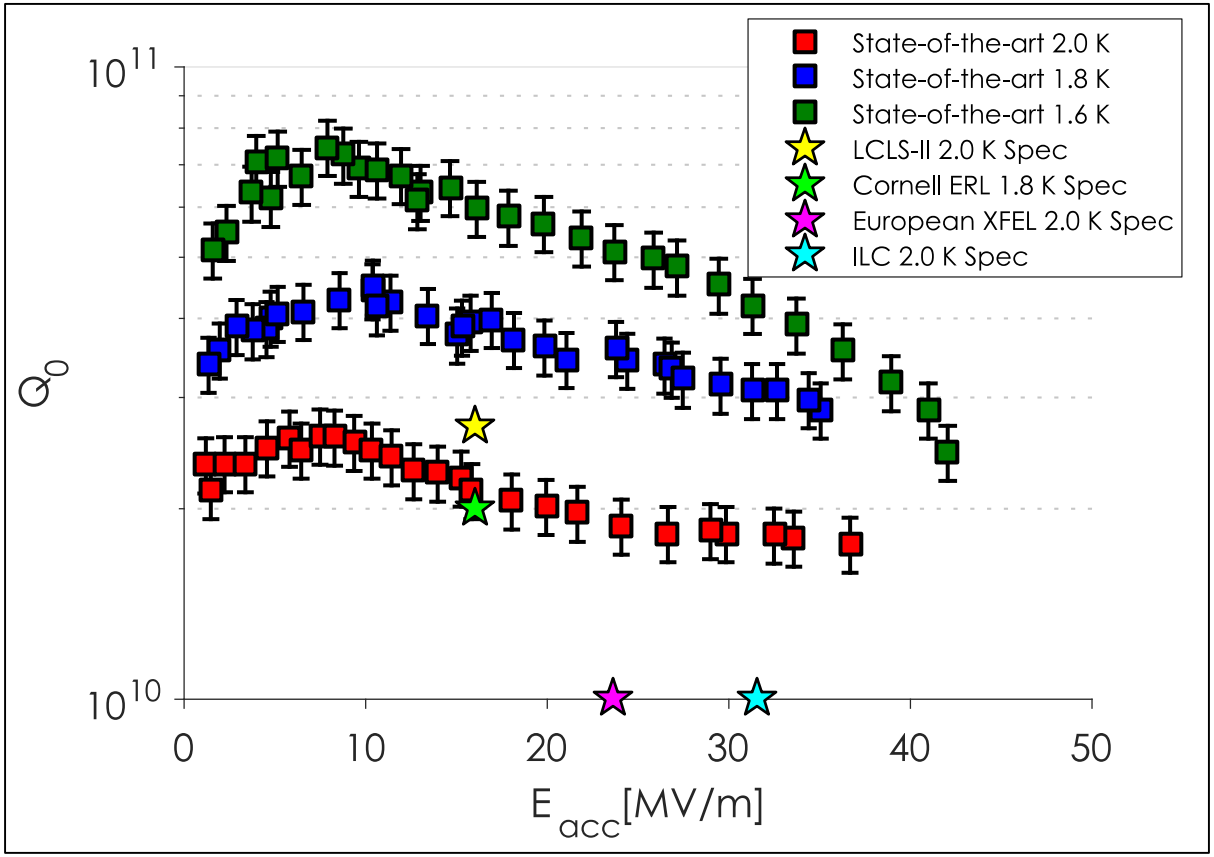
- New light sources such as the proposed Cornell Energy Recovery Linac (ERL) and the SLAC Linac Coherent Light Source II (LCLS-II) require "CW" operation
- Economic viability requires the cavities to have low loss

Low Loss → **Less Power Dissipated**

Cheaper Cryogenic Plant
Less Wall Power Costs

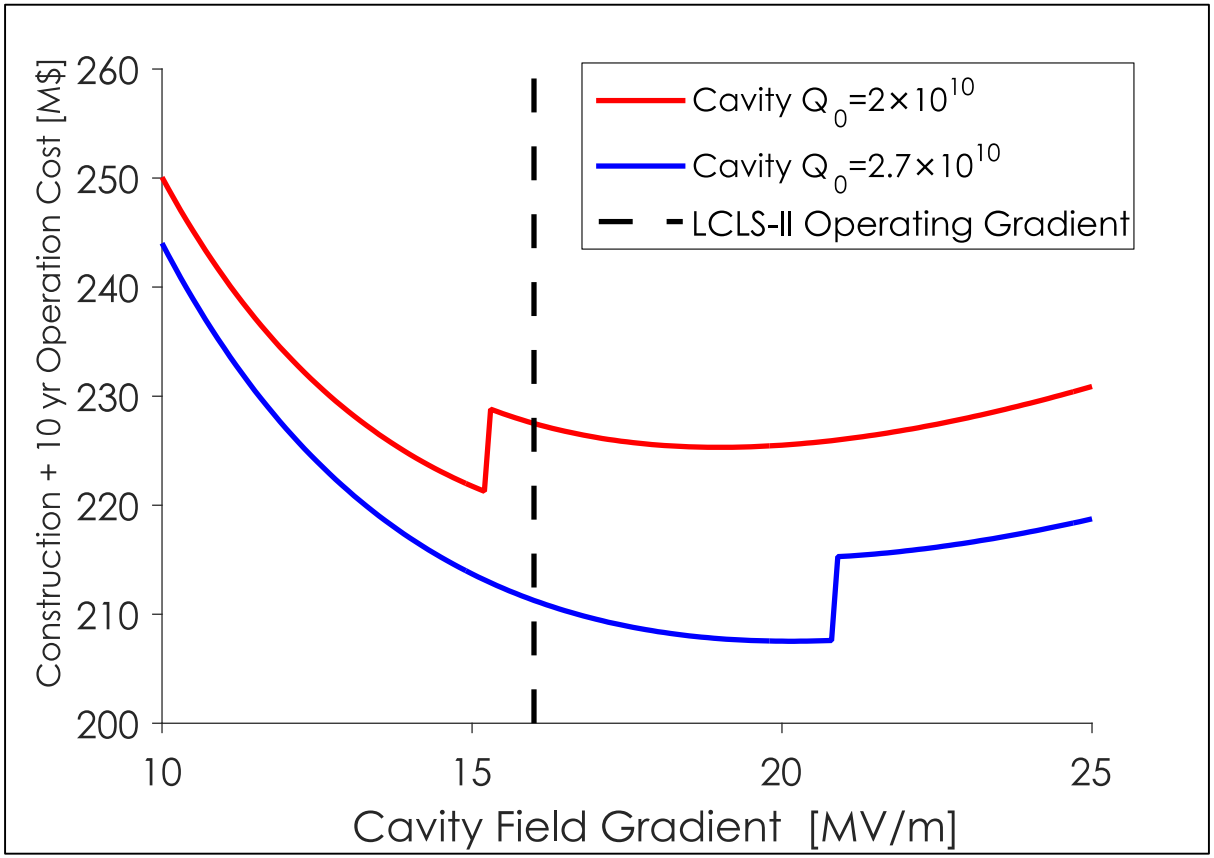
$$P_{diss} \propto 1/Q_0$$

The Need for High Q



Standard cavity preparation methods can reach Q's of **$2x10^{10}$** at 16 MV/m and 2 K

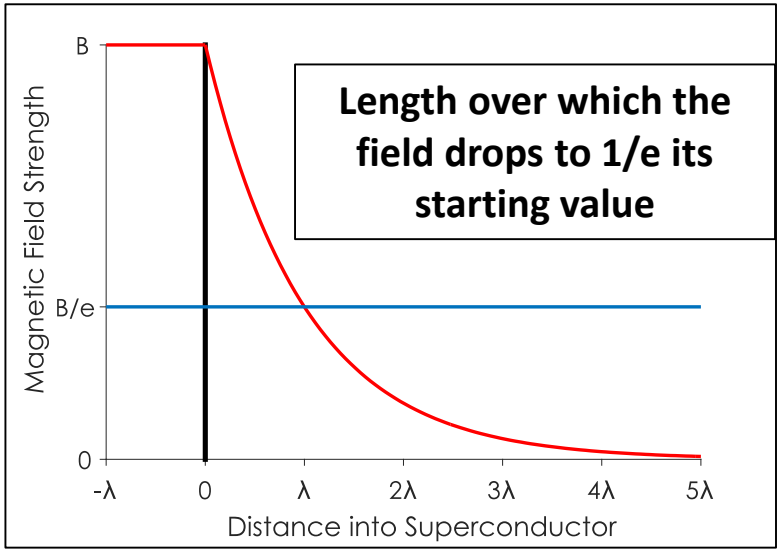
The Need for High Q



If Q_0's of 2.7×10^{10} can be achieved, the cost of LCLS-II can be significantly lowered!

To reach higher Q's and better efficiency at 2 K, both R_{res} and R_{BCS} need to be optimized

Penetration Depth (λ): Characteristic length over which the field decays into the superconductor



- We care about the layer that will see the RF field
- The penetration depth is typically on the order of ~40 nm
- Ultimately this is the layer that is important for RF performance

The first ~200 nm need to be optimized

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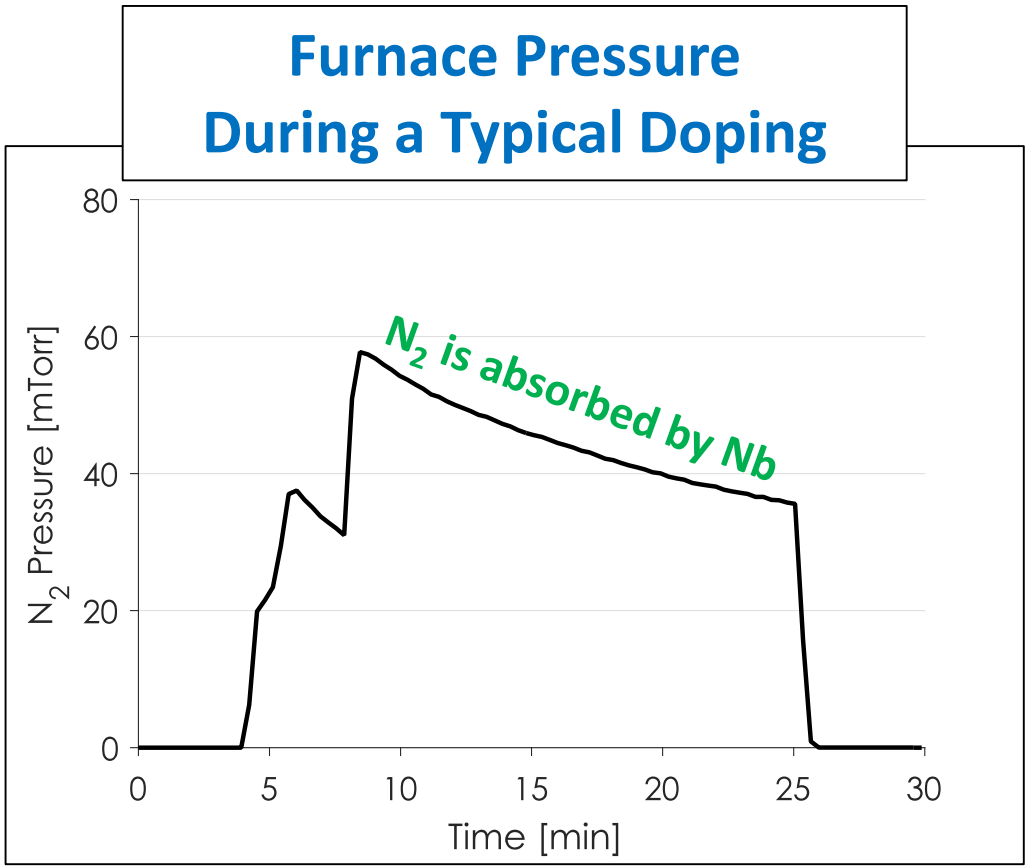
Nitrogen-Doping of SRF Cavities

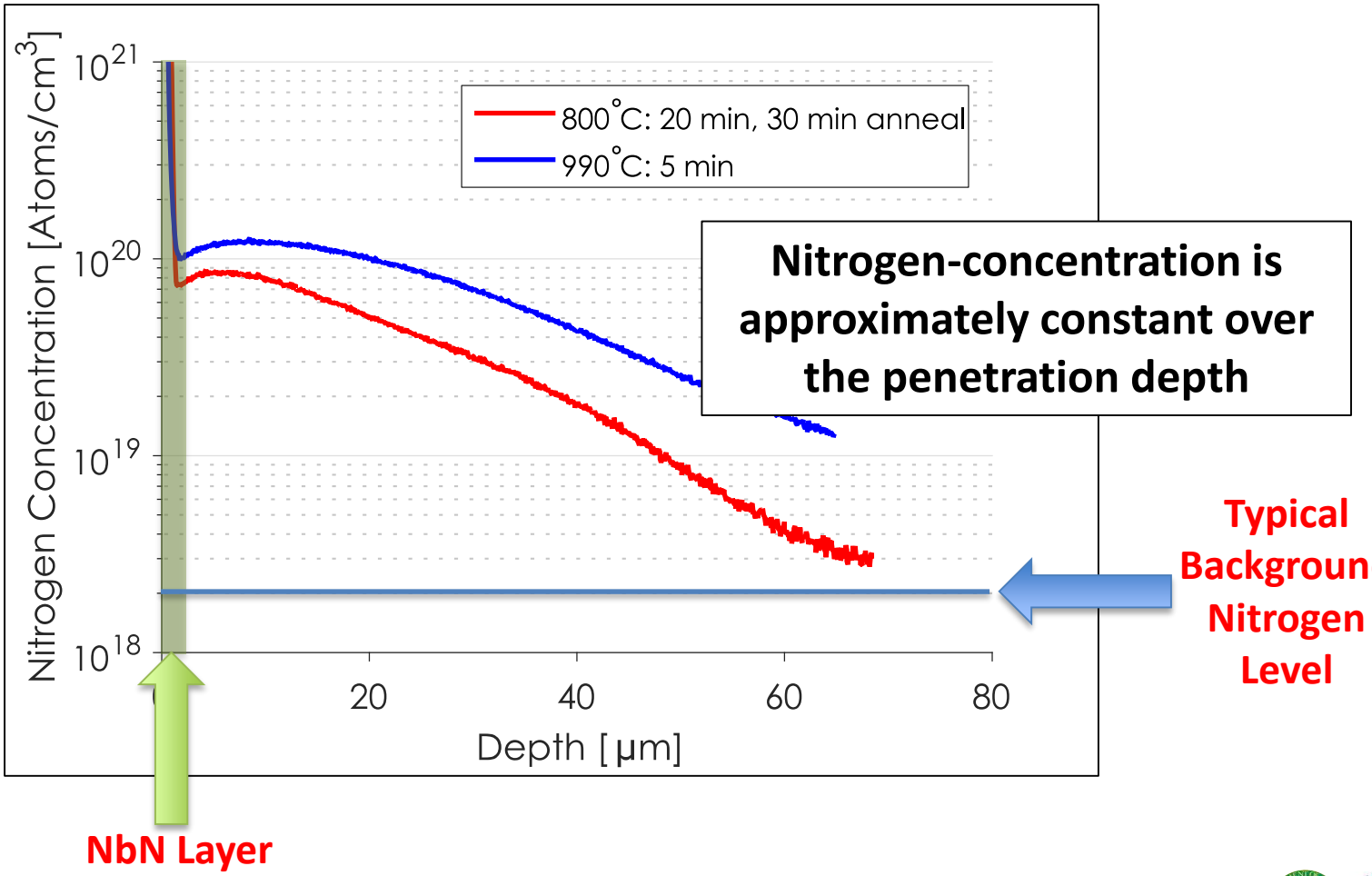


Me Putting a Cavity in the UHV Furnace for N-Doping

A typical doping consists of:

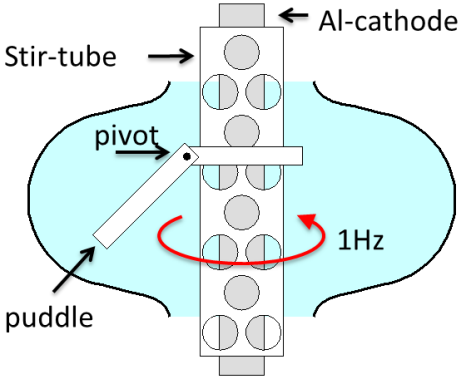
- Degas at 800°C for 3 hours in vacuum
- Doping at 700-1000°C in some mTorr of N_2
- Final chemistry, typically a few µm

Typical N-Doping



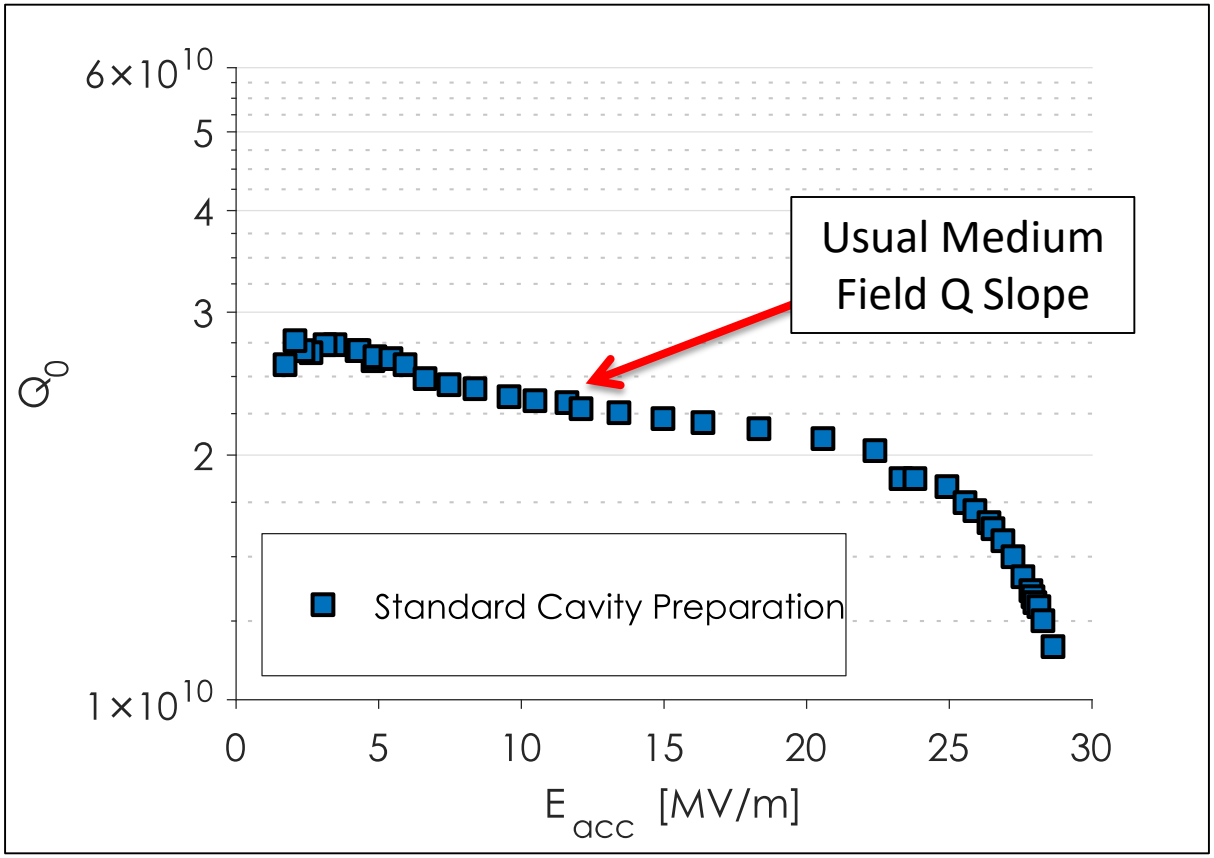
Removal of Lossy Nitride Layer

At Cornell, we use a vertical electropolish (VEP) to remove the NbN layer and reach the optimal doping level



Me Getting Ready to Set up a Cavity on the VEP System

Nitrogen-Doping of SRF Cavities



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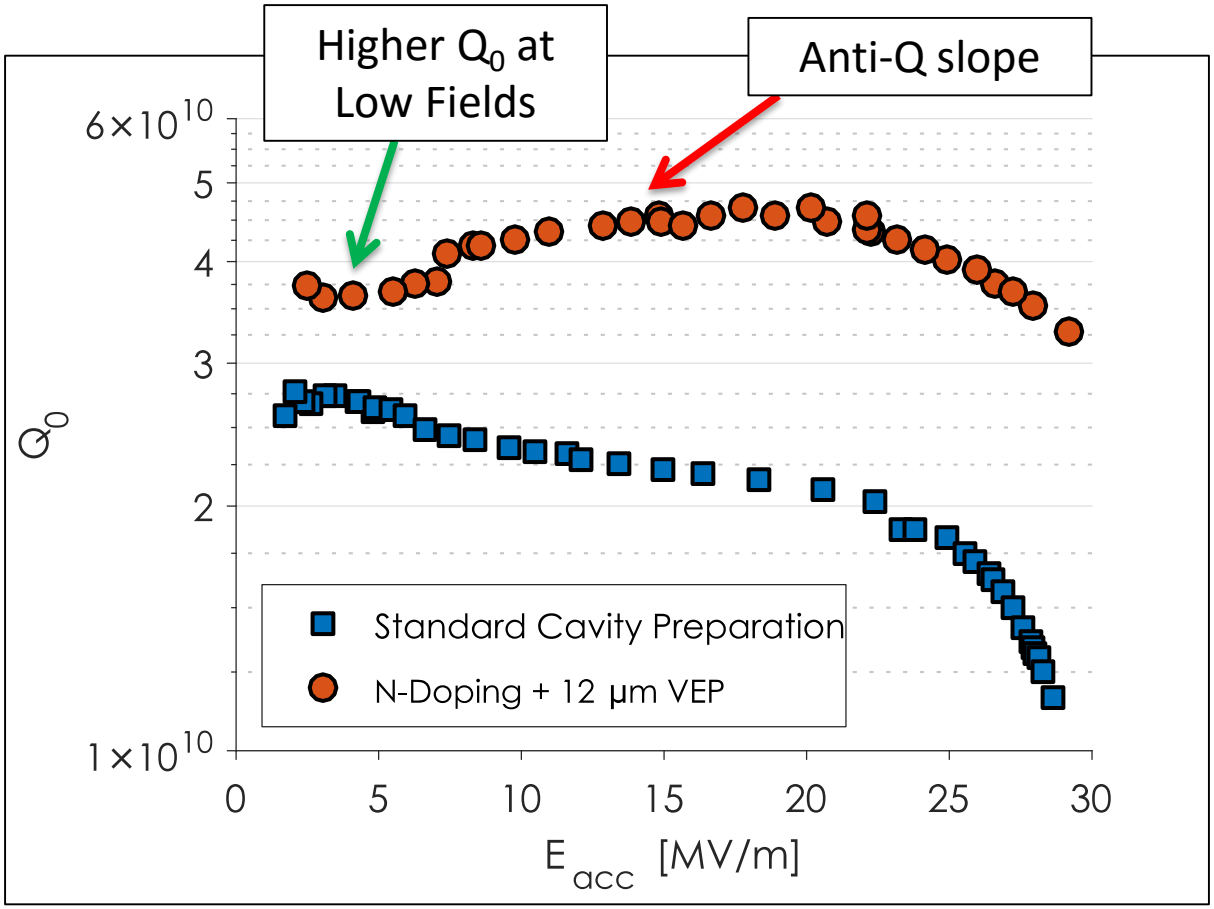
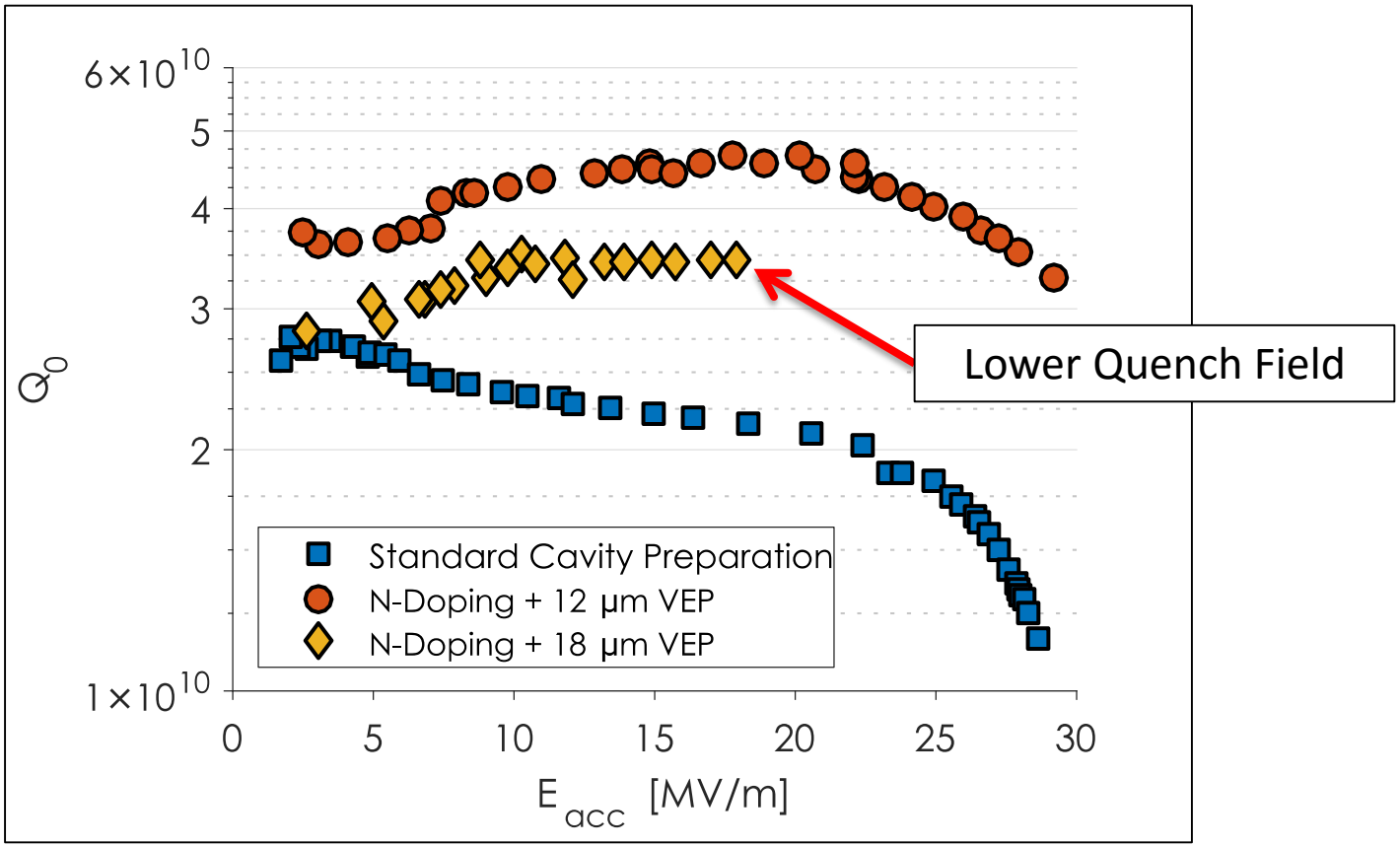


Drastic improvement in Q_0!

Nitrogen-Doping of SRF Cavities



Sometimes this brings with it a reduction in the maximum fields reachable

Fundamental Questions

4 Fundamental Questions:

- What leads to Q_0 improvement in nitrogen-doped cavities and can it be optimized?
- How do ambient magnetic fields affect doped cavities?
- What are the maximum fields reachable in doped cavities?
- Can cavity performance be maintained in a cryomodule?

Me Assembling a Single-Cell Cavity in the Clean Room

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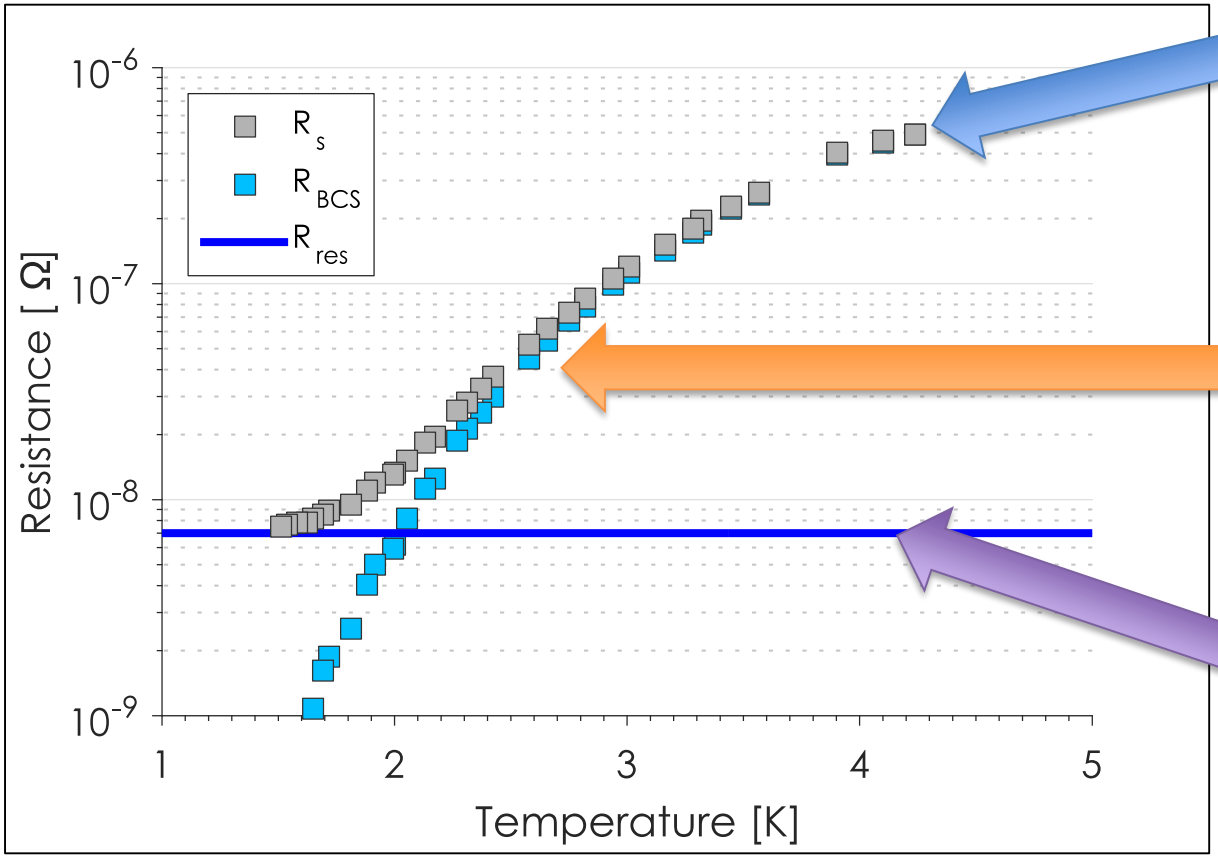
BCS Resistance Studies



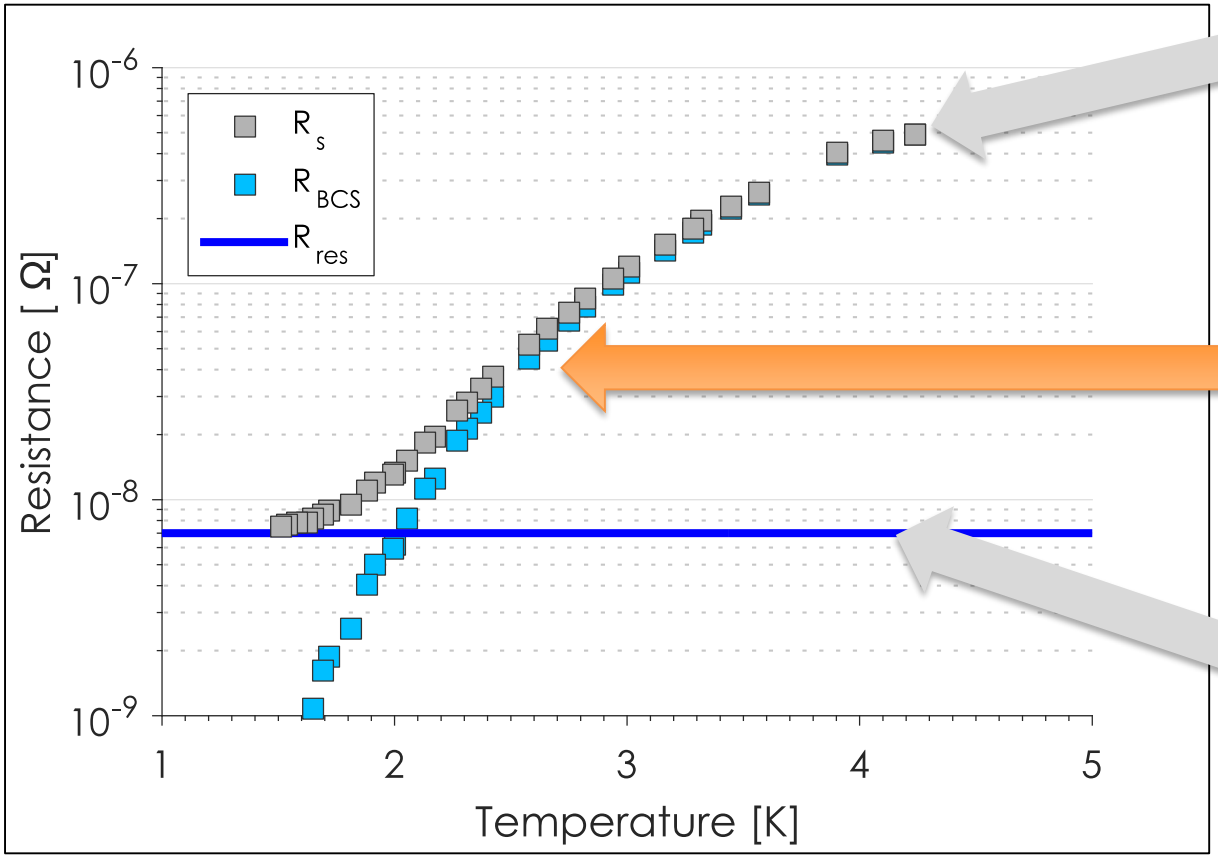
At High Temperatures, R_{BCS} Dominates

At Intermediate Temperatures, Both are Important

At Low Temperatures, R_{res} Dominates

$$R_S = R_{BCS}(T, \dots) + R_{res}$$

BCS Resistance Studies



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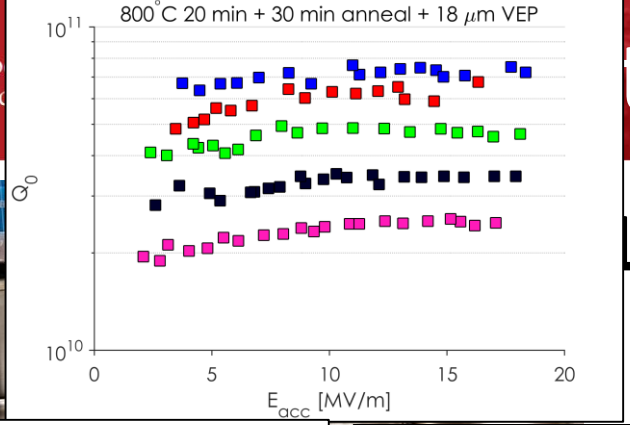
Cavities Prepared & Tested

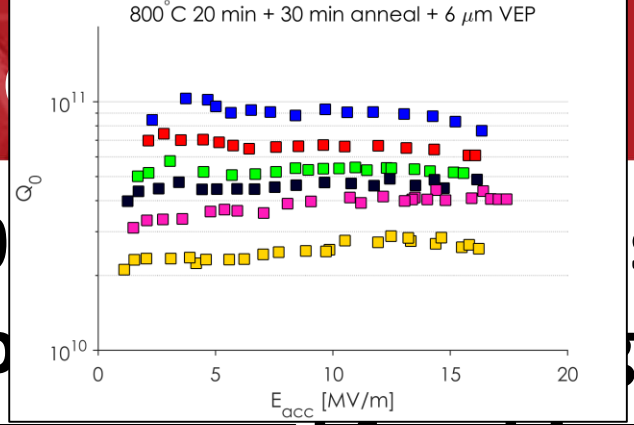
10 cavities of various levels of nitrogen-doping were prepared for this work

Cavity Name	Doping Temp [°C]	Doping Time [min]	Anneal Time [min]	Pressure [mTorr]	Final VEP [µm]
LT1-3	990	5	0	20	5
LT1-2	900	20	30	60	6, 12, 18
LT1-2	800	20	30	60	6
LT1-3	800	20	30	60	12
LT1-1	800	20	30	60	18
LT1-4	800	20	30	60	24
LT1-5	800	20	30	60	30, 40

Cornell Lab
Sciences an

Tested





s levels

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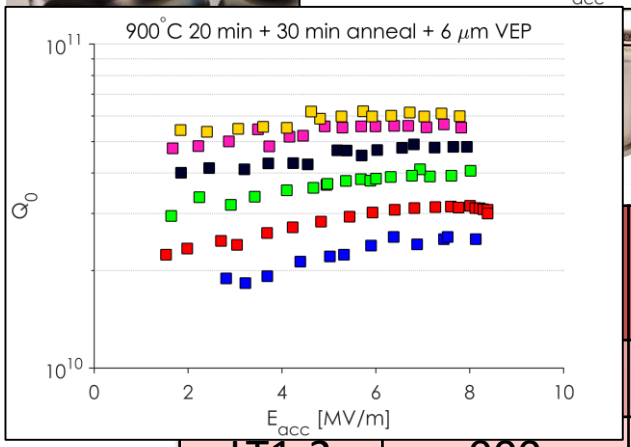
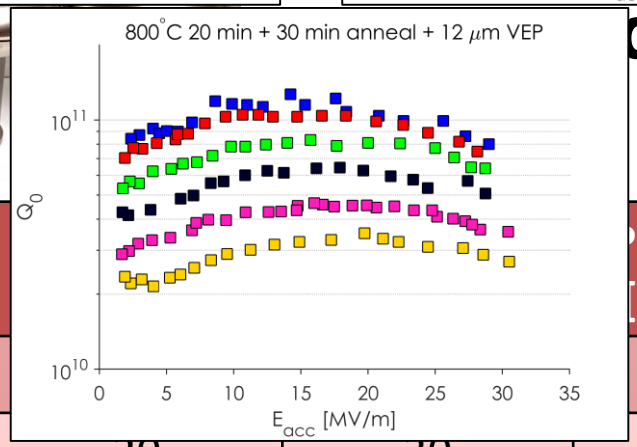
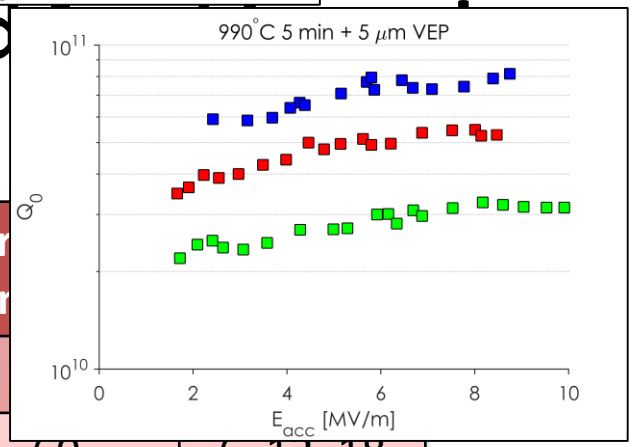
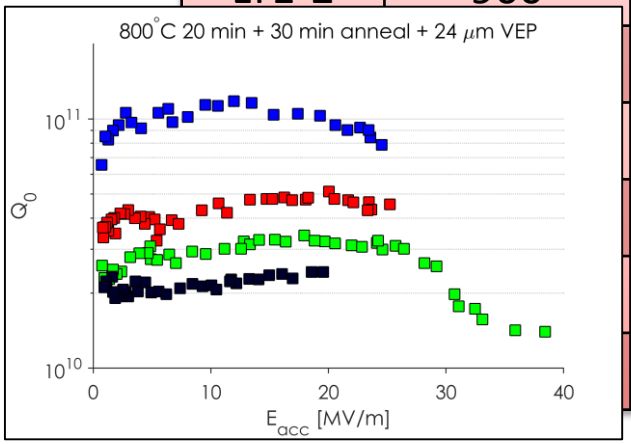
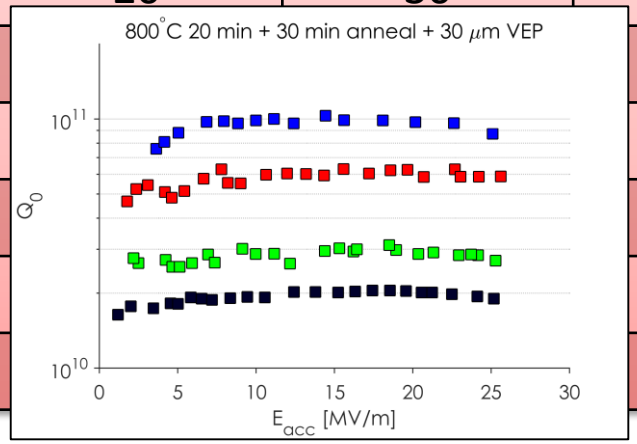


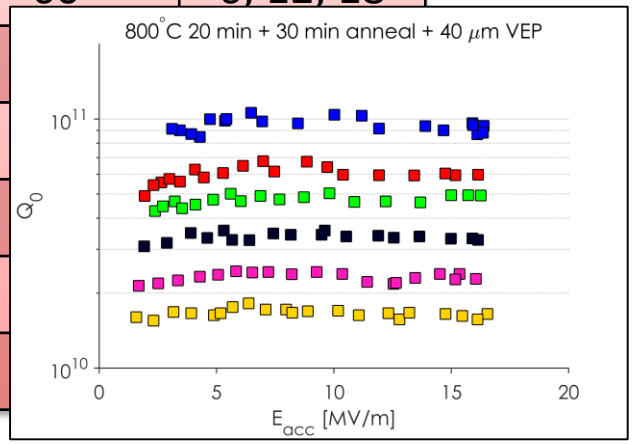




LT1-2	900	20	30	60	6, 12, 18

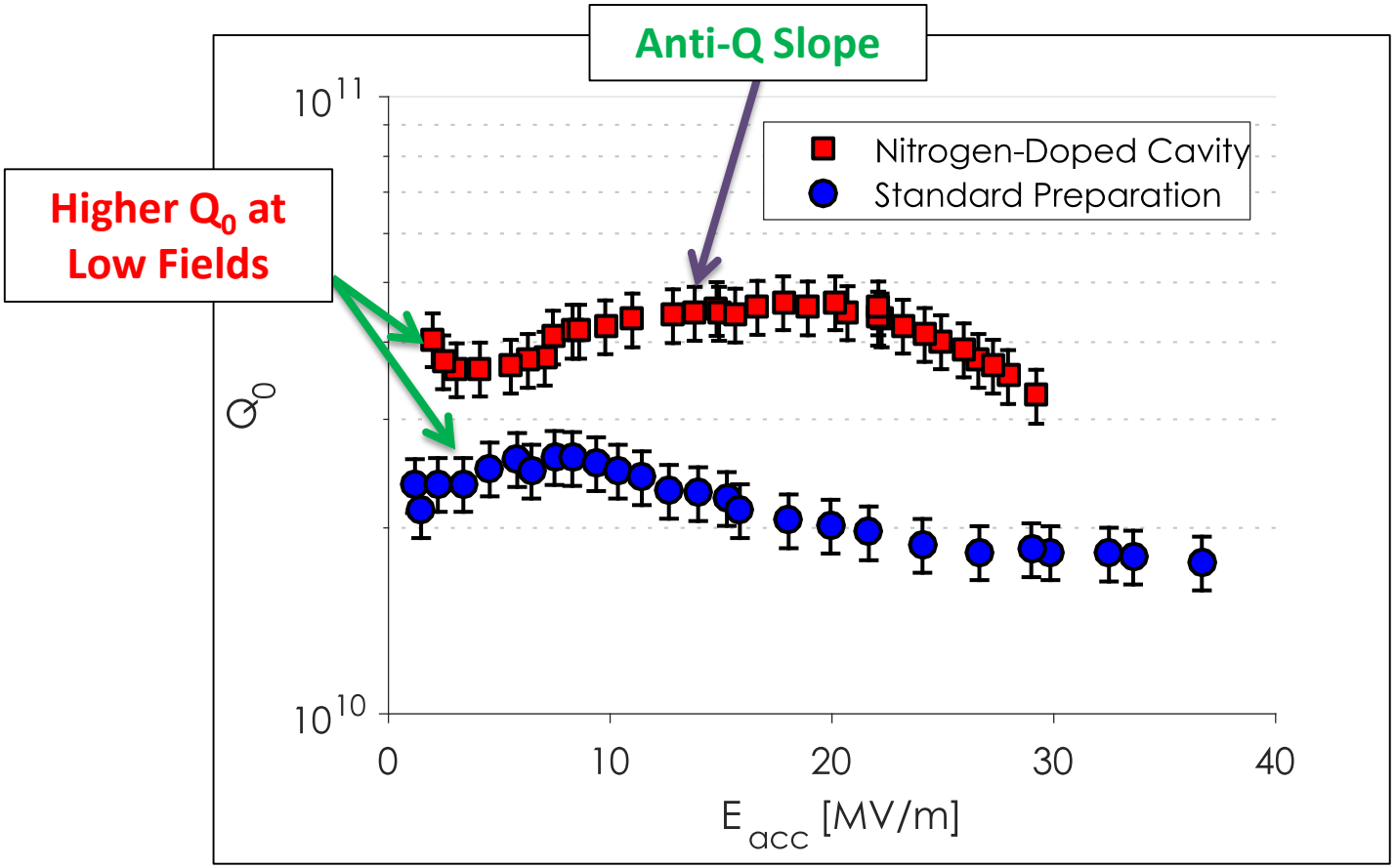




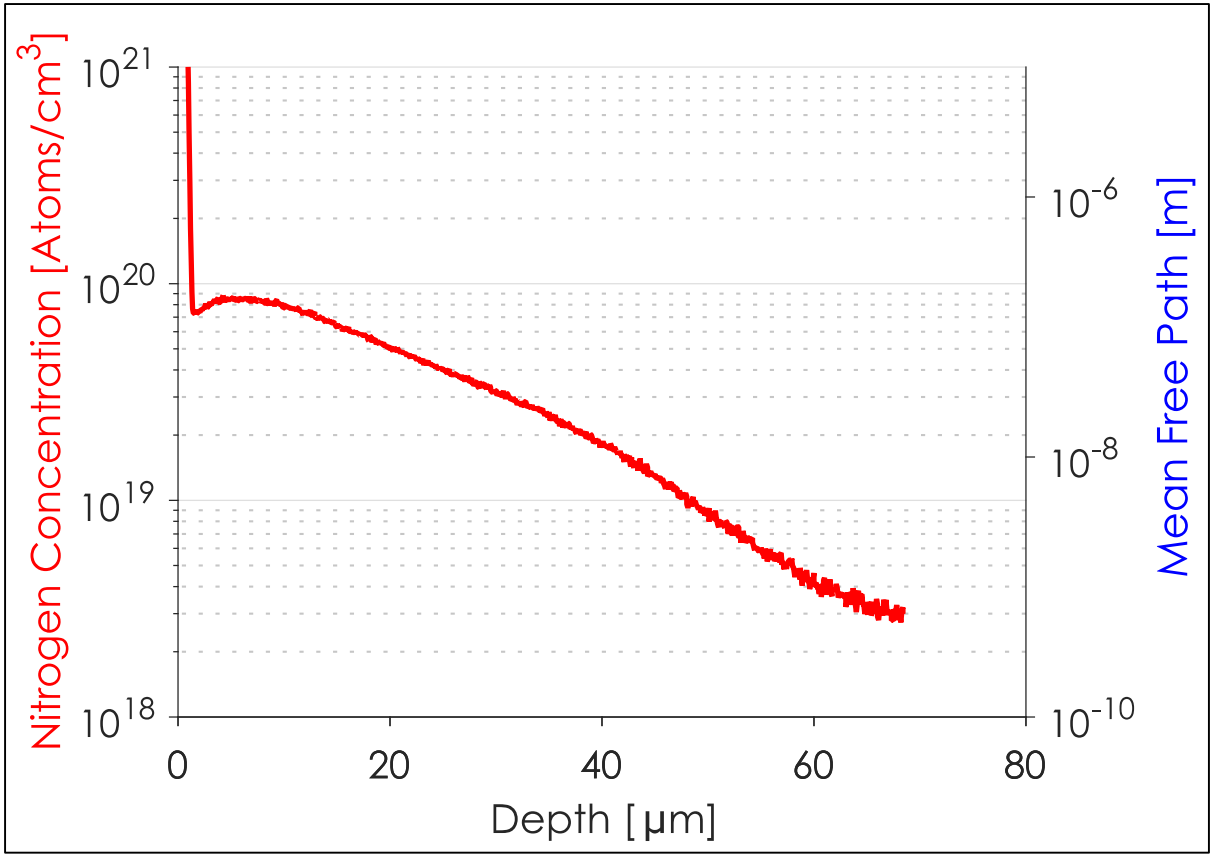


BCS Resistance Studies

1.3 GHz Single Cell ILC shaped cavity: bulk VEP, 800°C bake in vacuum for 3 hours, 20 min in 60 mTorr of N_2, 30 minute anneal



Effect of Doping on Material Properties



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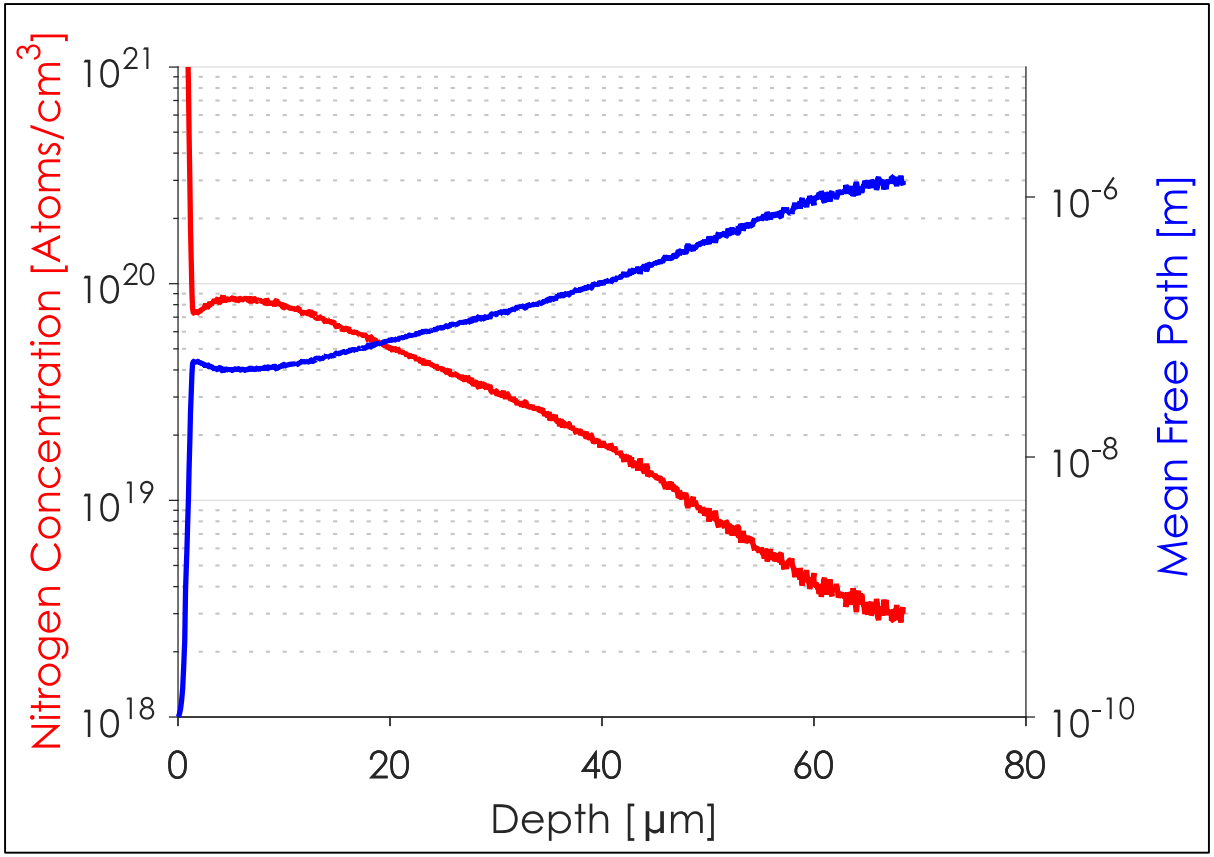
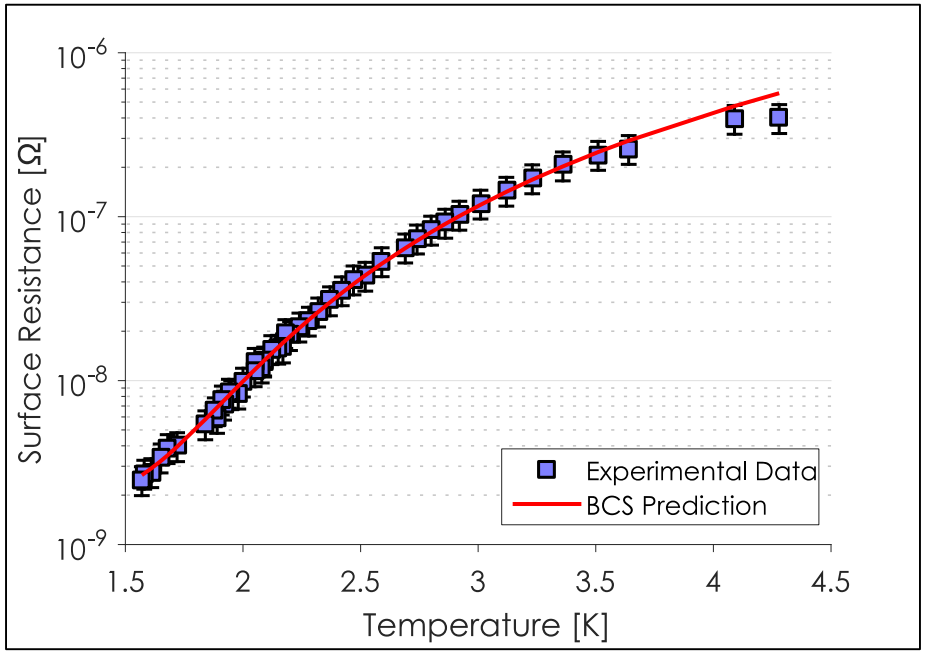


- Nitrogen acts as an impurity and lowers the mean free path of the niobium
- This lowering will significantly impact R_{BCS}

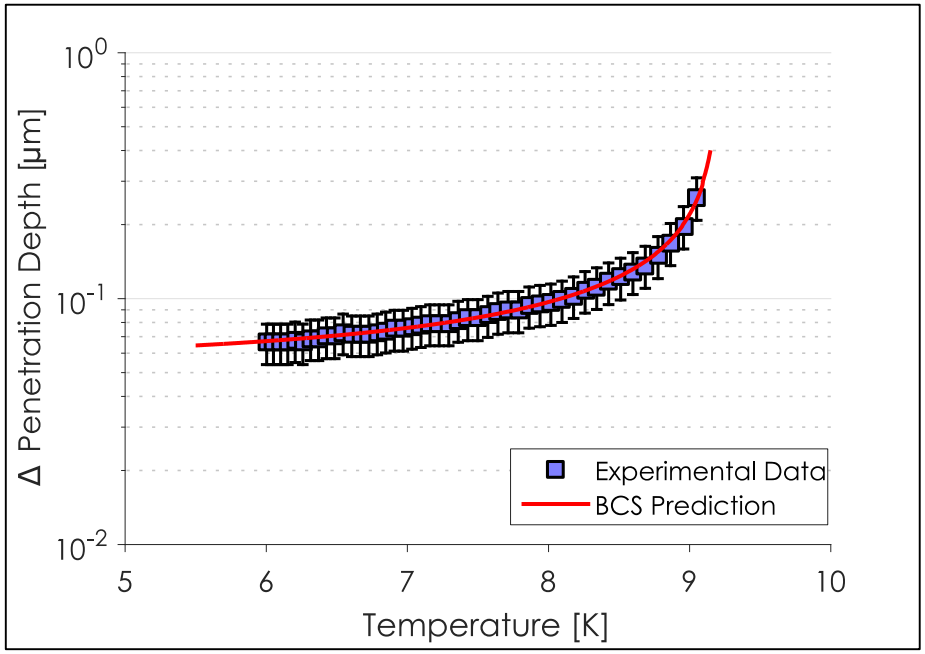
Extraction of Material Properties

- SRIMP, a code written by Halbritter, can be used to calculate R_{BCS} based on material parameters
  - T_c, Mean Free Path, Δ/k_BT_c, clean coherence length, and clean penetration depth

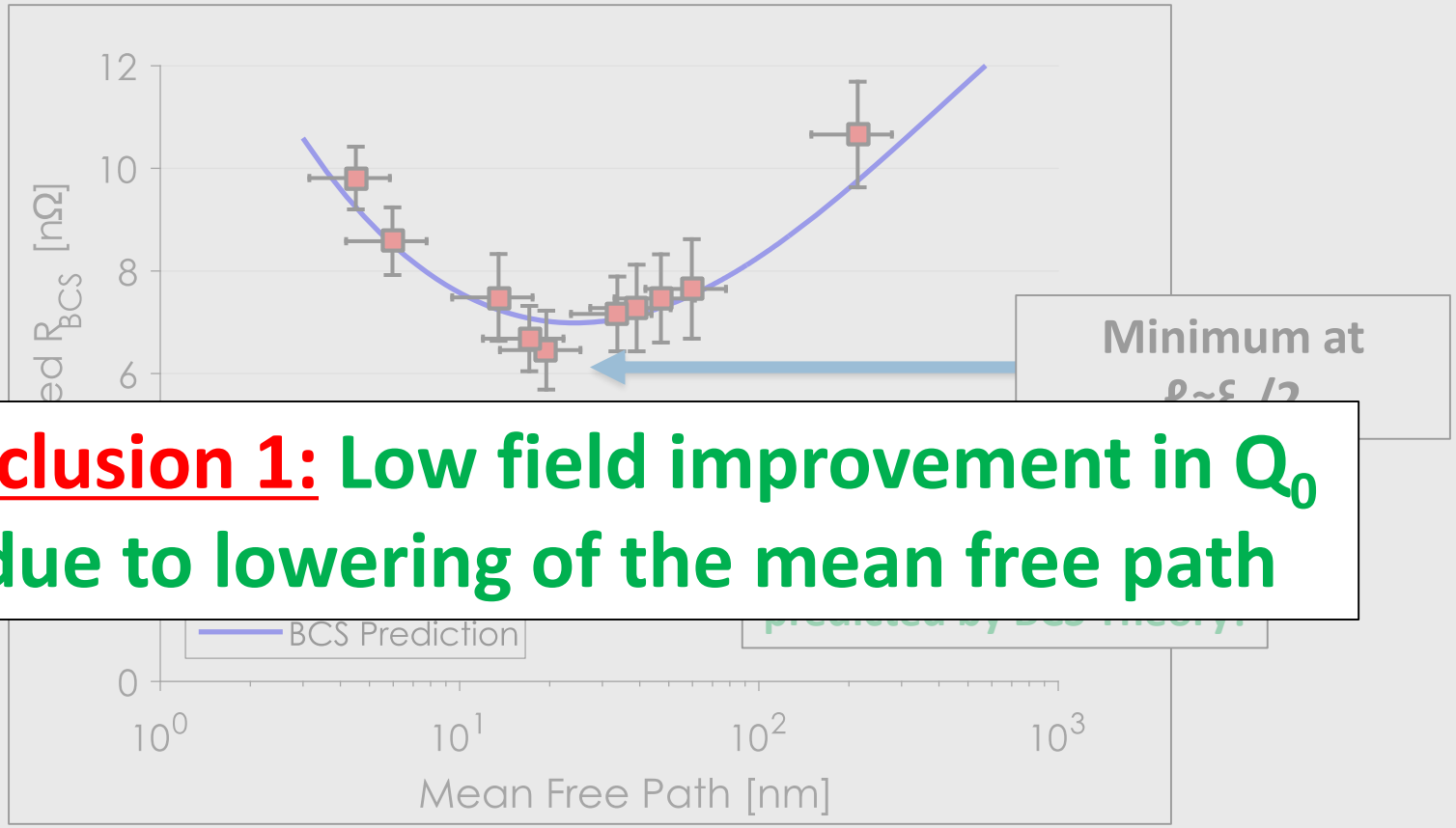
Surface Resistance vs Temperature



Penetration Depth vs Temperature



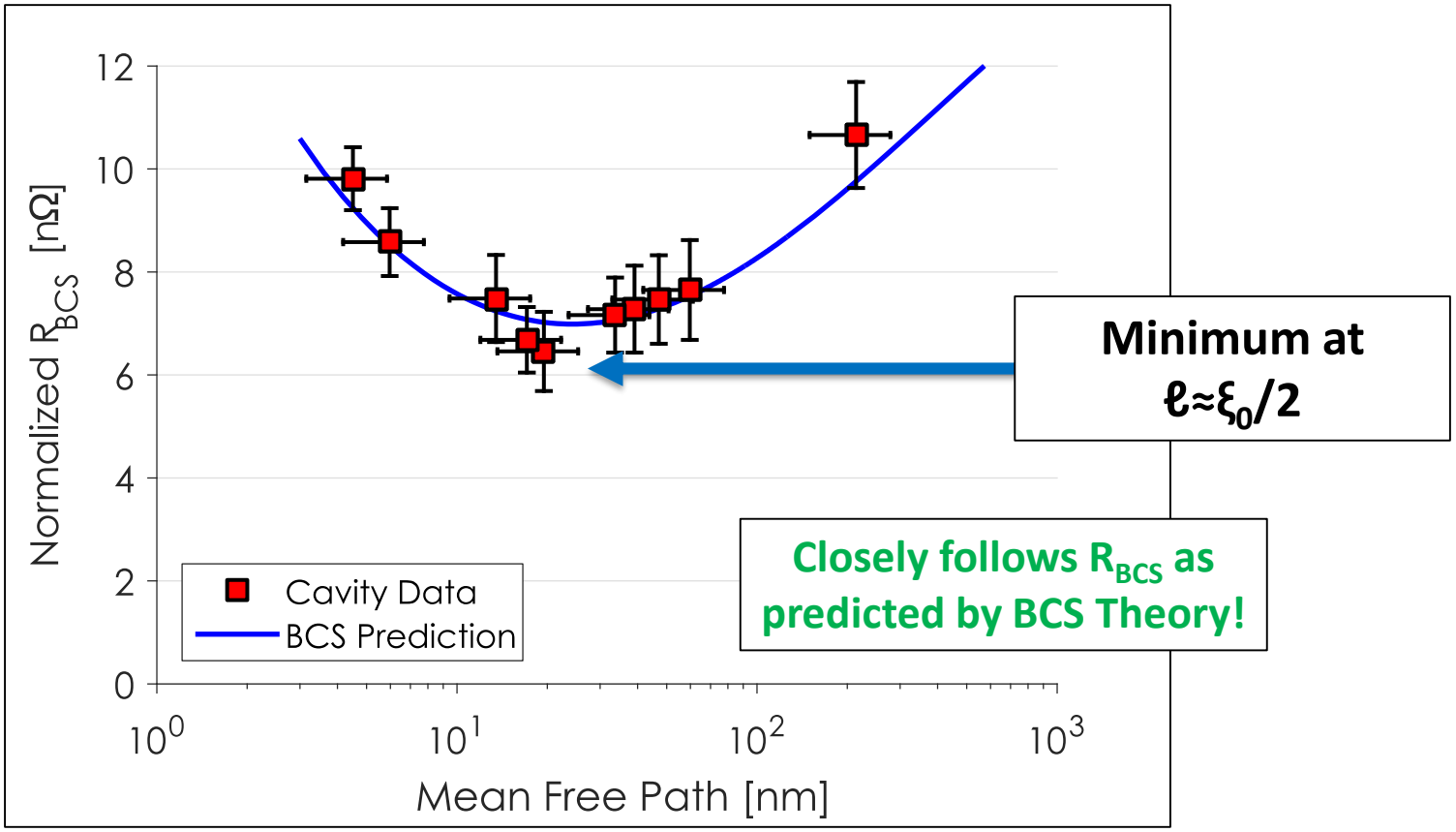
Effect of Doping on Low Field R_{BCS}



Conclusion 1: Low field improvement in Q_0 is due to lowering of the mean free path

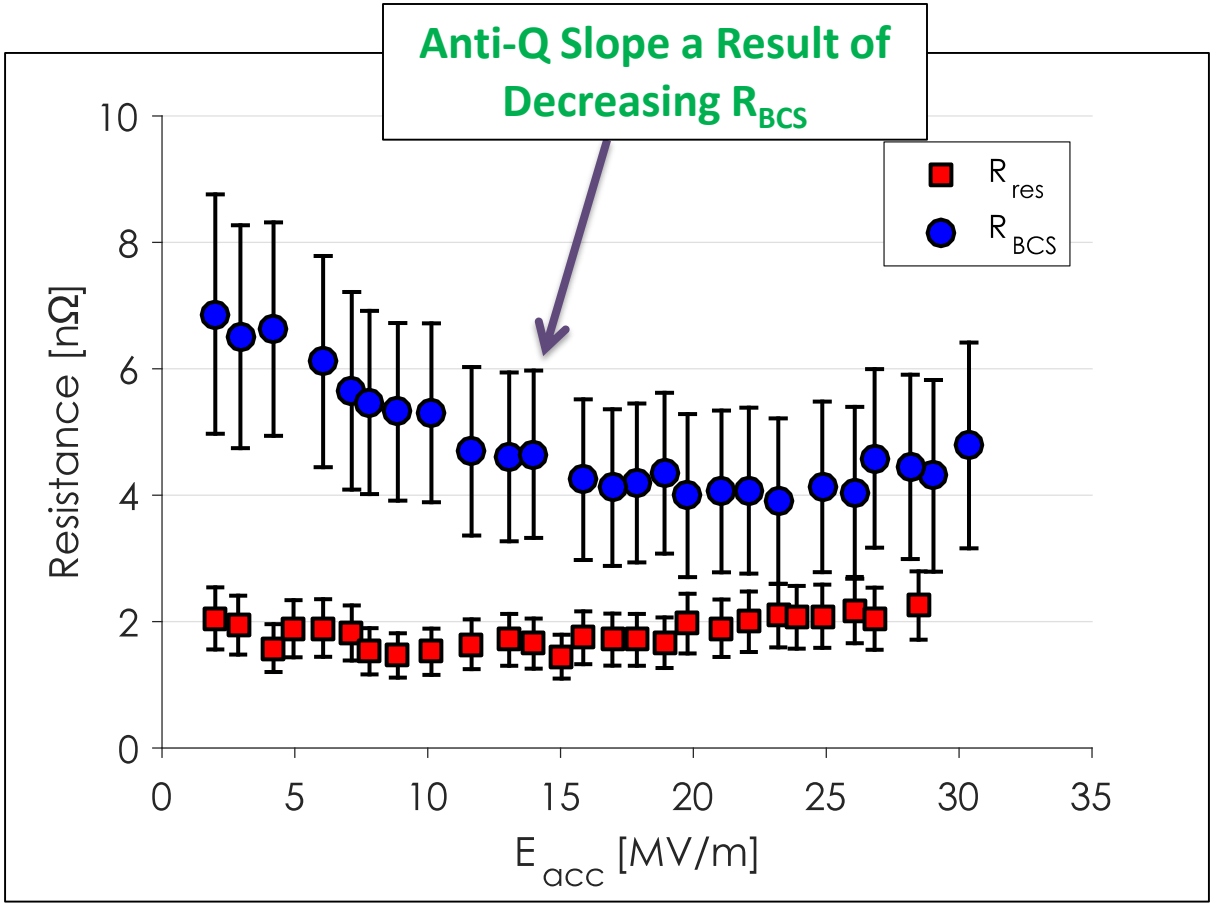
This lowering of the mean free path causes the R_{BCS} to approach the minimum as predicted by BCS theory

Effect of Doping on Low Field R_{BCS}



This lowering of the mean free path causes the R_{BCS} to approach the minimum as predicted by BCS theory

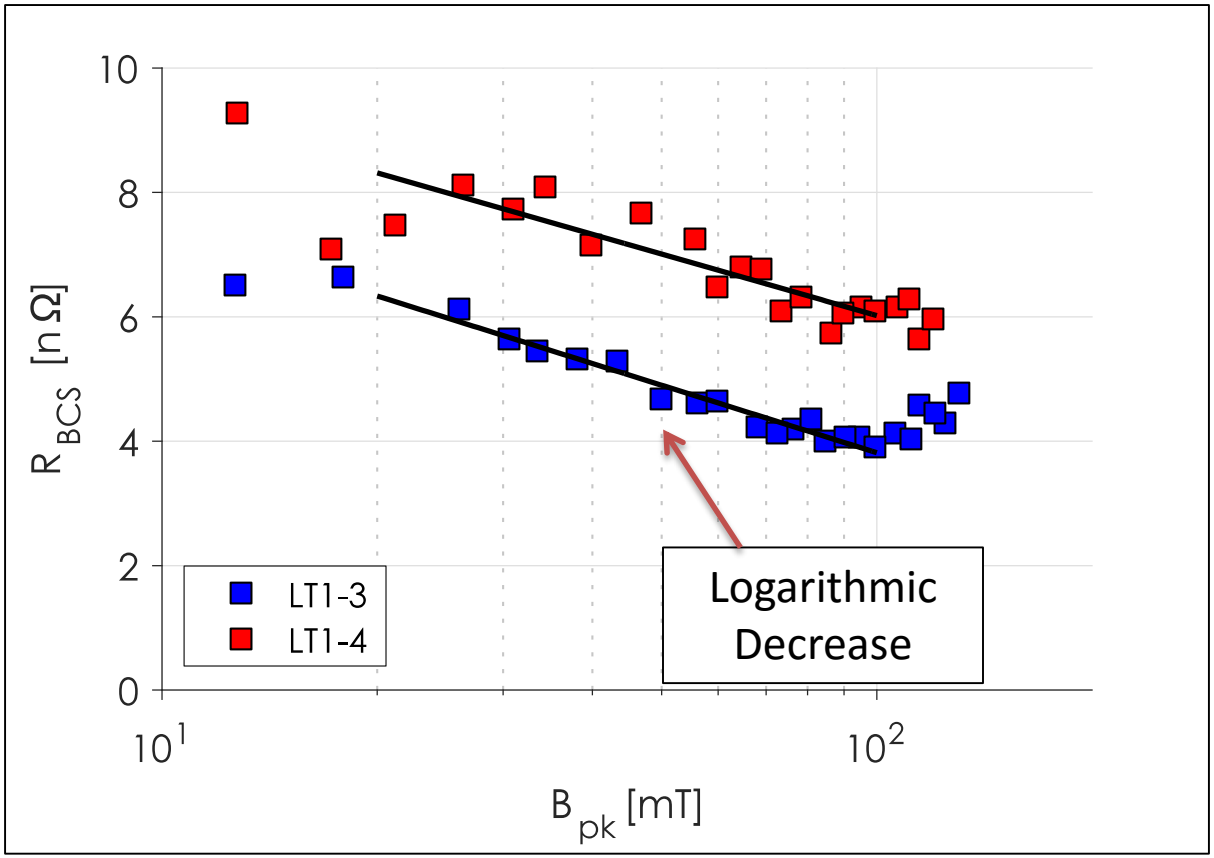
Example of Deconvolution



$$R_s = R_{res}(E_{acc}) + R_{BCS}(E_{acc}, T)$$

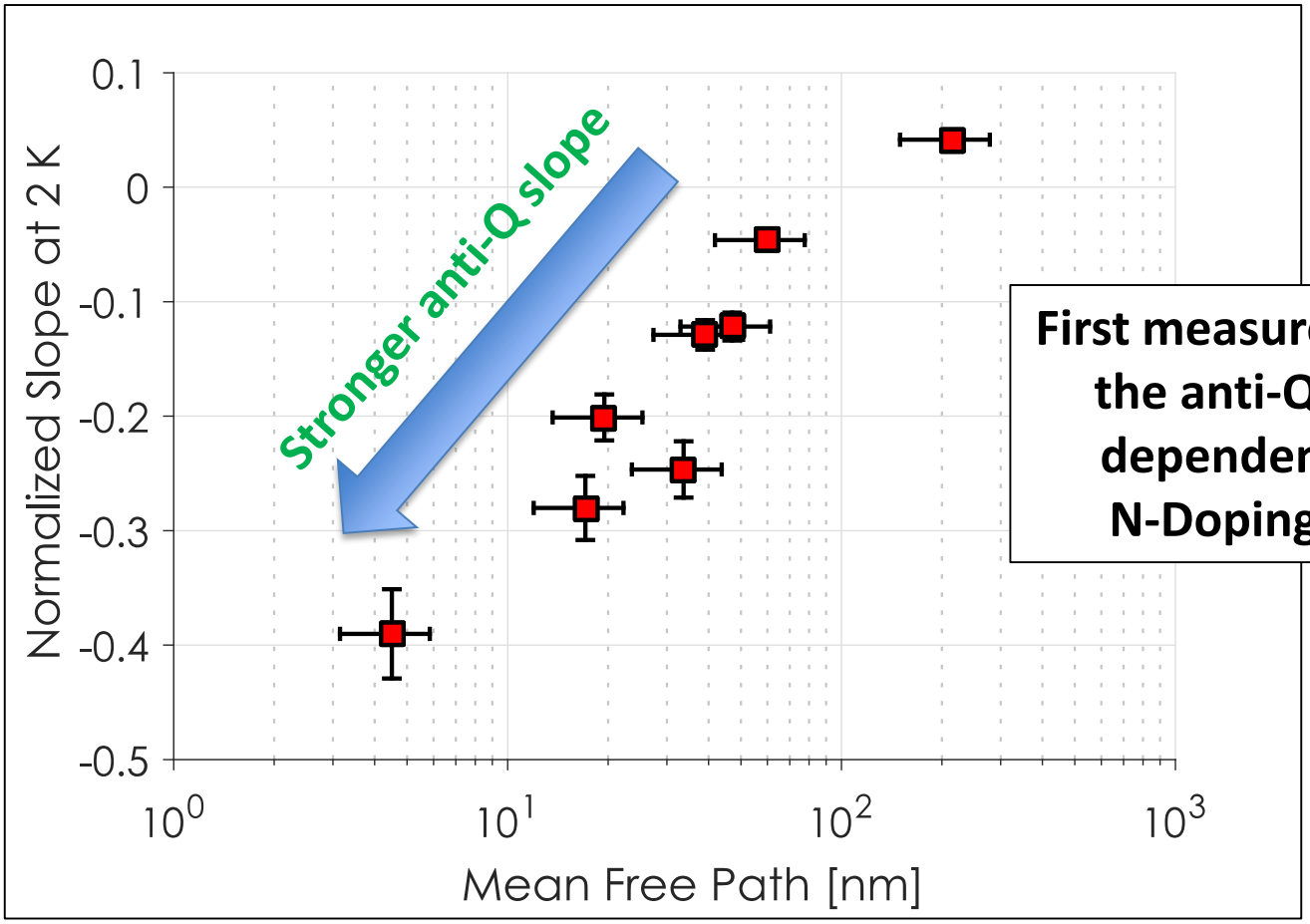
First shown in *A. Romanenko et. al, Appl. Phys. Lett. 102, 252603 (2013)*

Field Dependence of R_{BCS}



Conclusion 2: **R_{BCS} decreases roughly as the logarithm of the magnitude of the RF field**

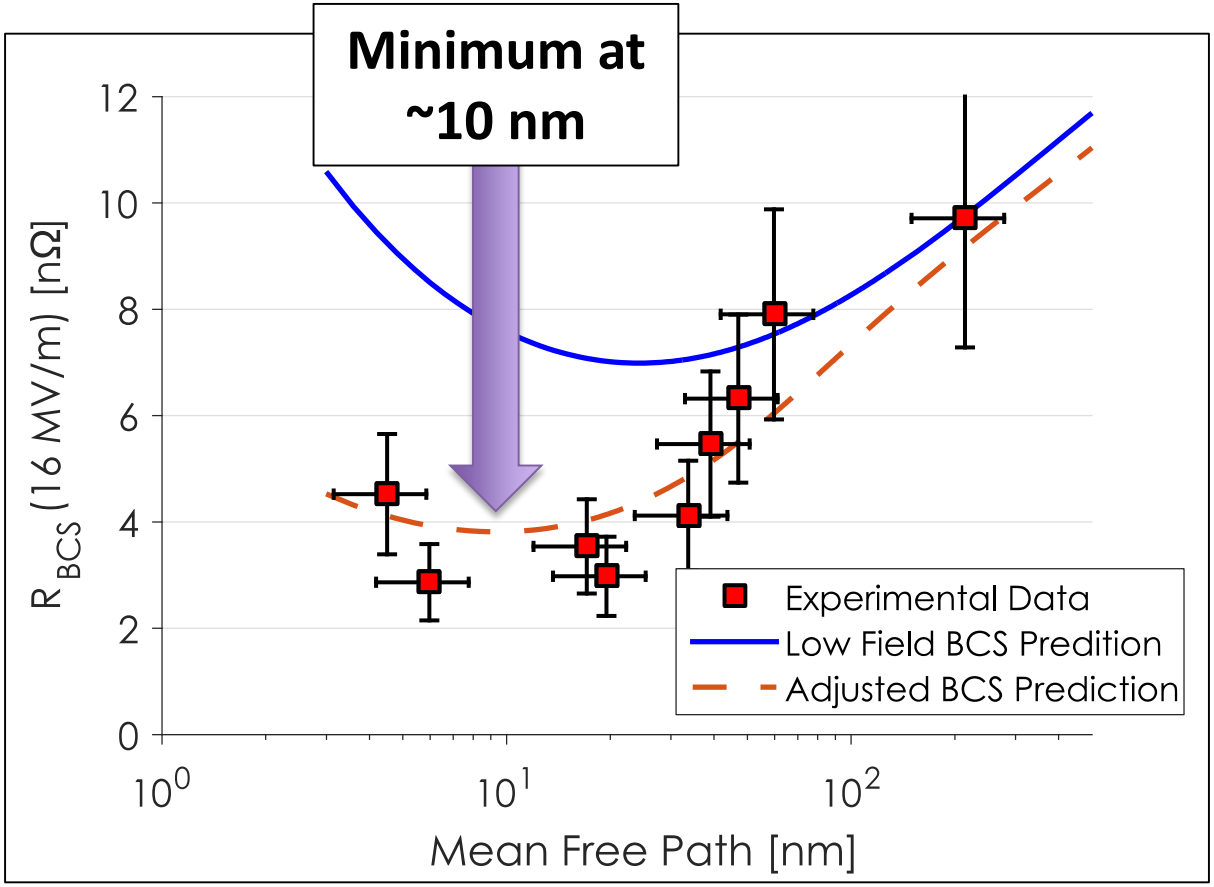
Field Dependence of R_{BCS}



First measurement of the anti-Q slope dependence on N-Doping level

Conclusion 3: **Stronger doping (lower mean free path) leads to a stronger anti-Q slope**

Optimal Doping Level



R_{BCS} at 16 MV/m is lowest at ℓ≈10 nm

This is shifted from the low field prediction

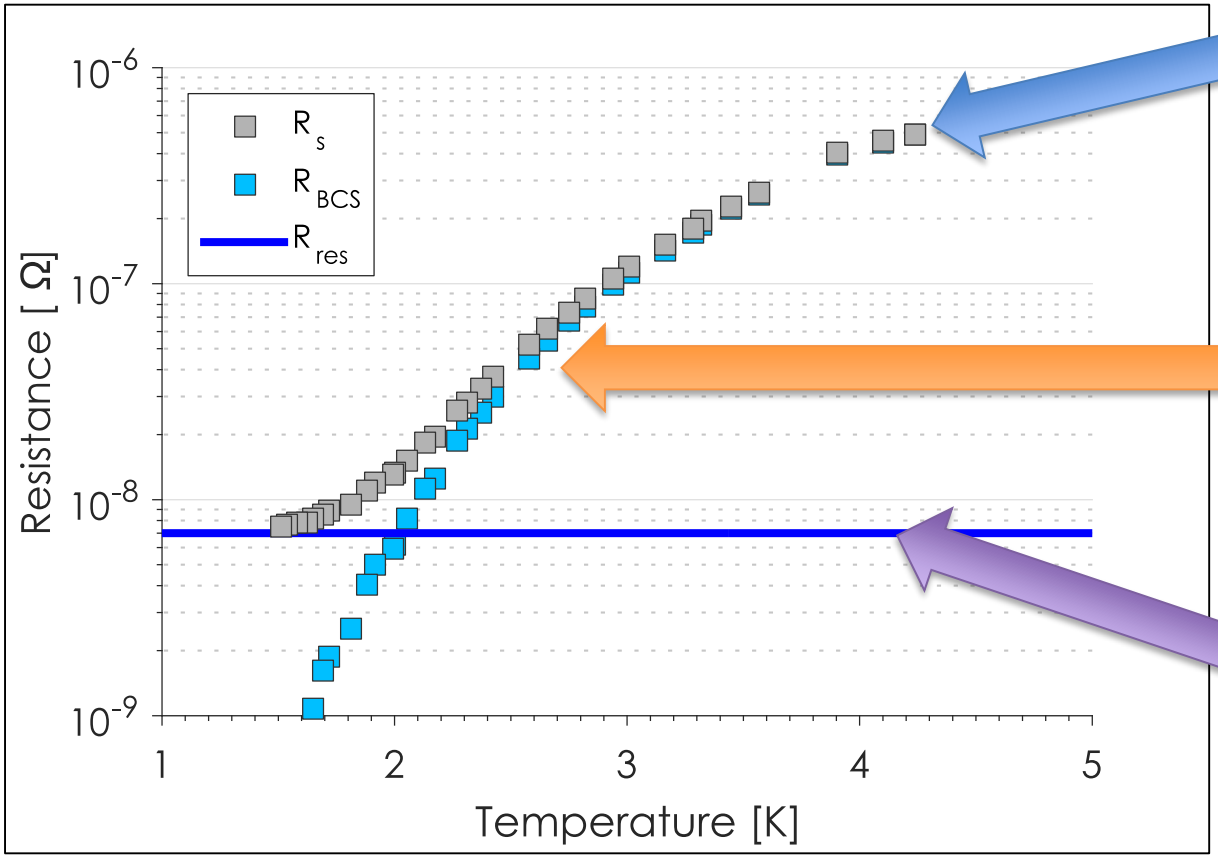
BCS Resistance Studies

1. Low field improvement in Q_0 is due to the lowering of the mean free path leading to a lower R_{BCS}
2. R_{BCS} decreases roughly as the logarithm of the magnitude of the RF field
3. Stronger doping (lower mean free path) leads to a stronger anti-Q slope

Outline

- Motivation
- Introduction to Superconducting RF
- Nitrogen-Doping of SRF Cavities
- BCS Resistance Studies
- Residual Resistance Studies
- High Field Limits
- Transition to Full Cryomodule
- Conclusions

Residual Resistance Studies



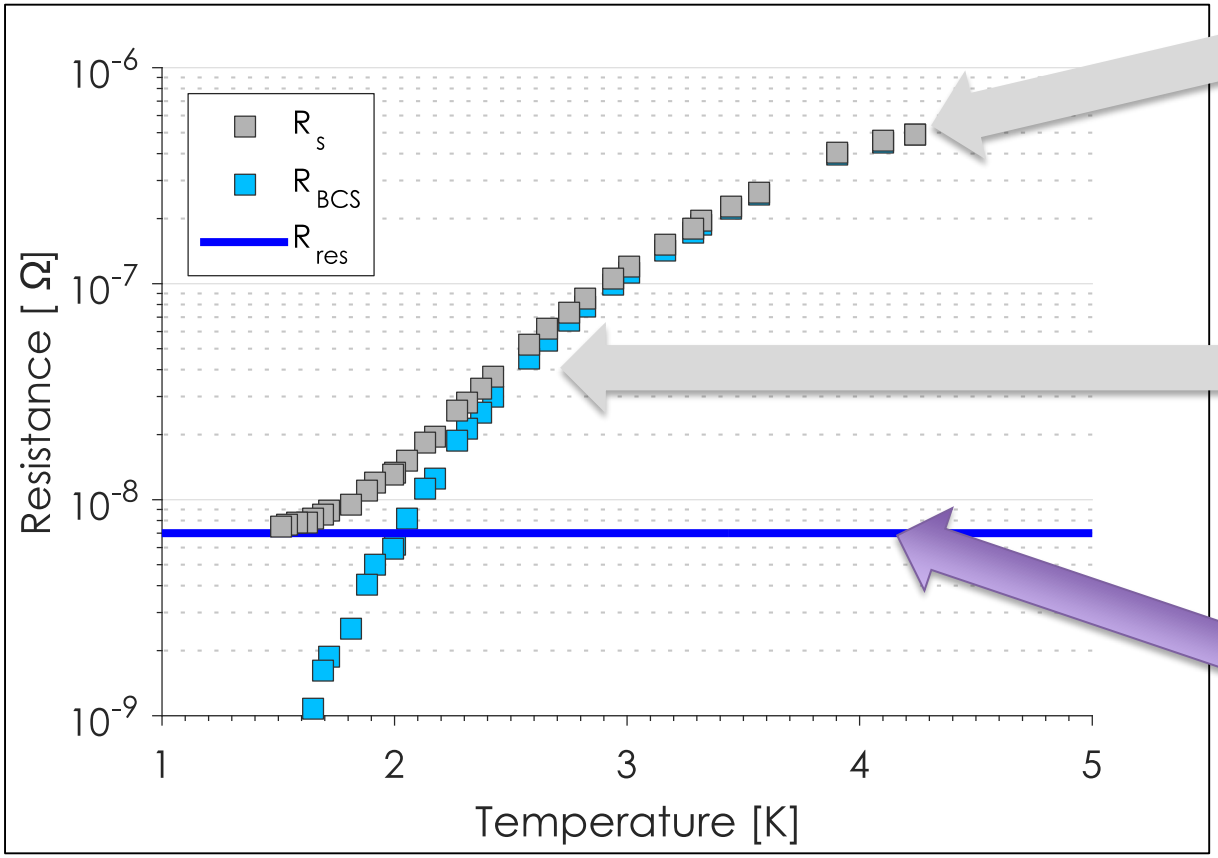
At High Temperatures, R_{BCS} Dominates

At Intermediate Temperatures, Both are Important

At Low Temperatures, R_{res} Dominates

$$R_S = R_{BCS}(T, \dots) + R_{res}$$

Residual Resistance Studies



At High Temperatures, R_{BCS} Dominates

At Intermediate Temperatures, Both are Important

At Low Temperatures, R_{res} Dominates

$$R_S = R_{BCS}(T, \dots) + R_{res}$$

What contributes to R_{res}?

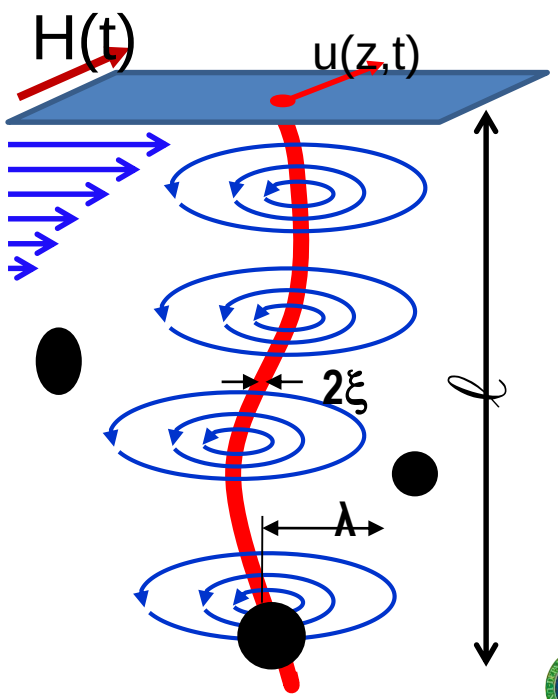
Residual resistance is made up of several components:

- Normal Conducting Inclusions
- Oxides
- Hydrides
- Trapped Magnetic Flux

In well prepared cavities, R_{res} has been shown to be due primarily to trapped magnetic flux

Trapped Magnetic Flux

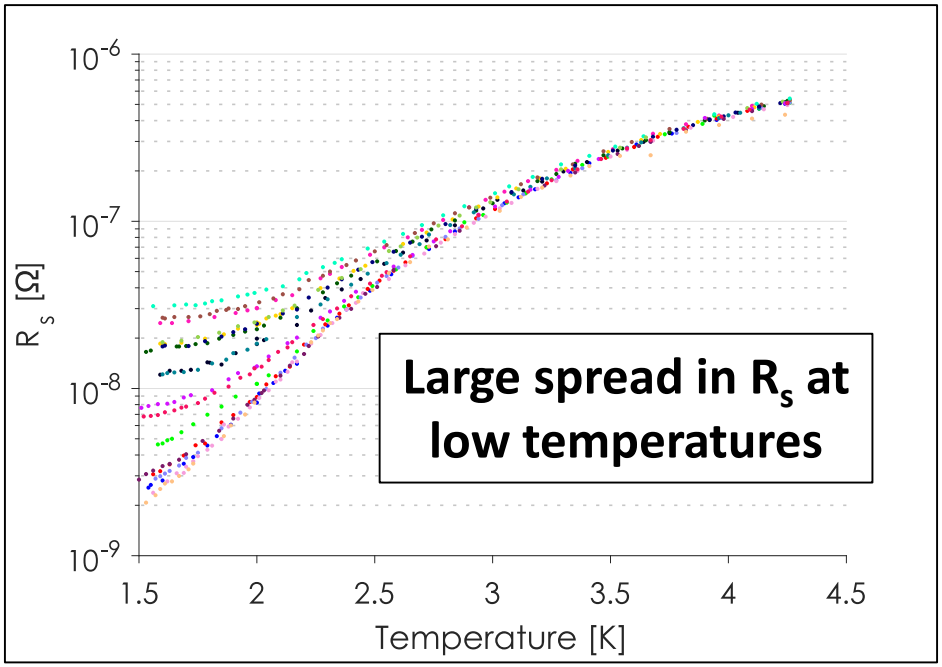
- In a perfect superconductor, magnetic flux will be perfectly expelled from the bulk
- Because SRF cavities aren't "perfect," magnetic field lines can be trapped at impurities
  - This is heavily dependent on material and cool down dynamics



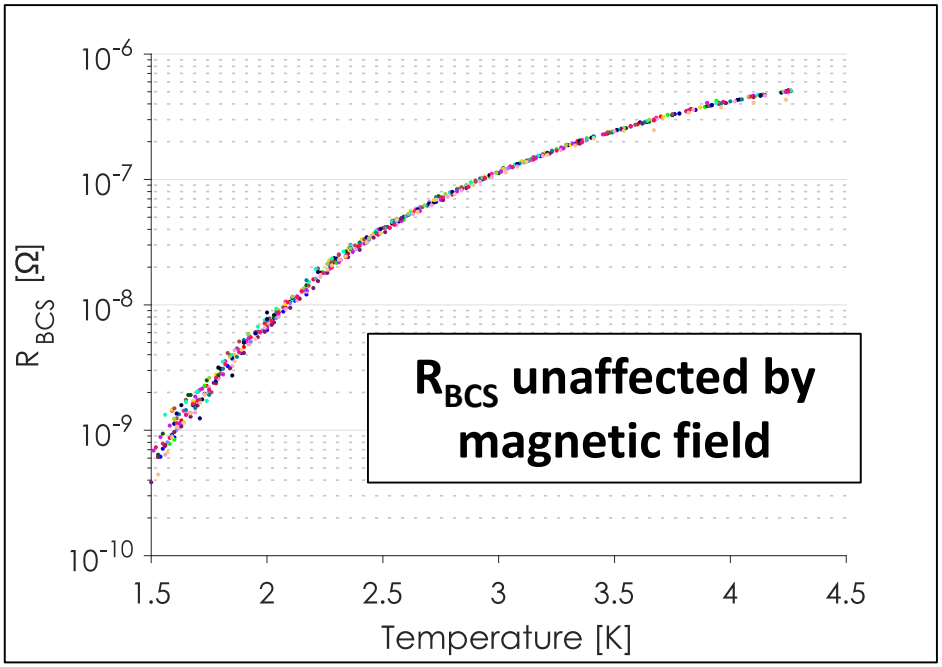
Trapped flux lines oscillate under RF leading to additional losses

Trapped Magnetic Flux

R_s vs T



R_{BCS} vs T



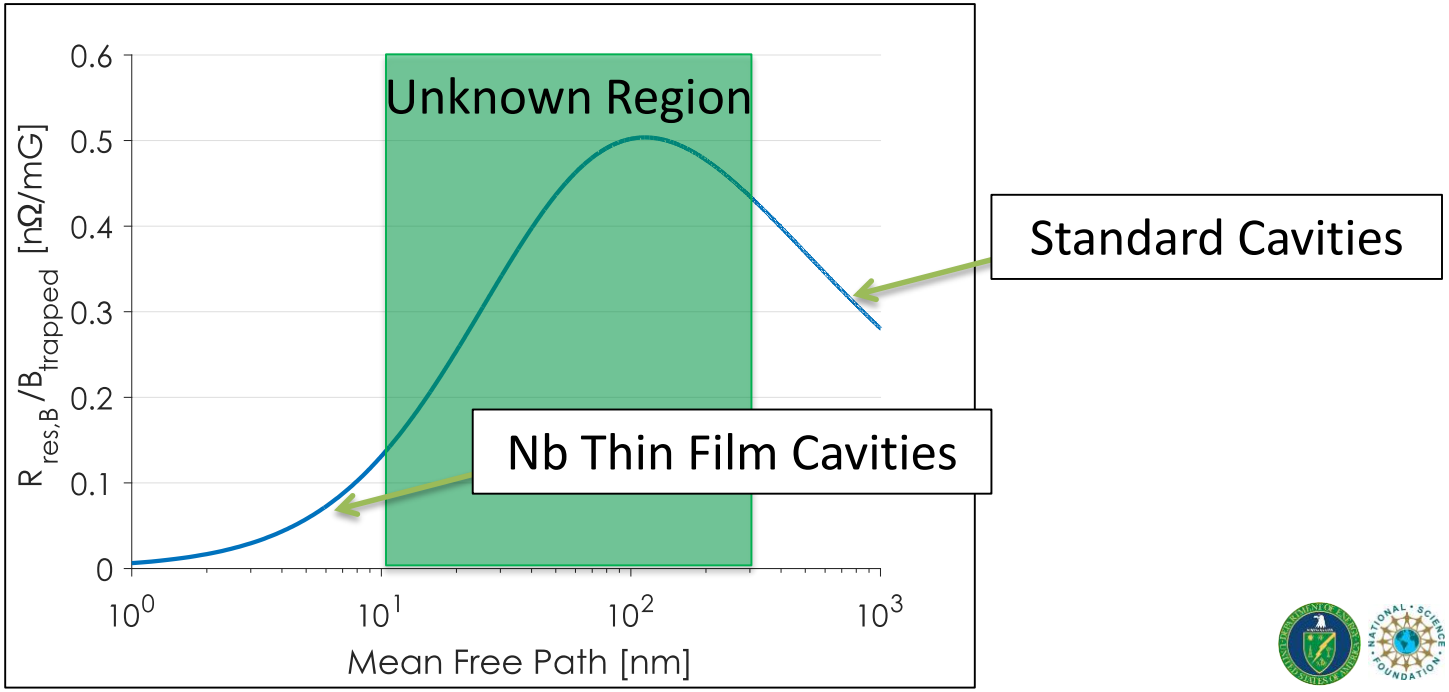
Spread in surface resistance is due only to a changing residual resistance, R_{BCS} is unaffected

Theoretical Considerations

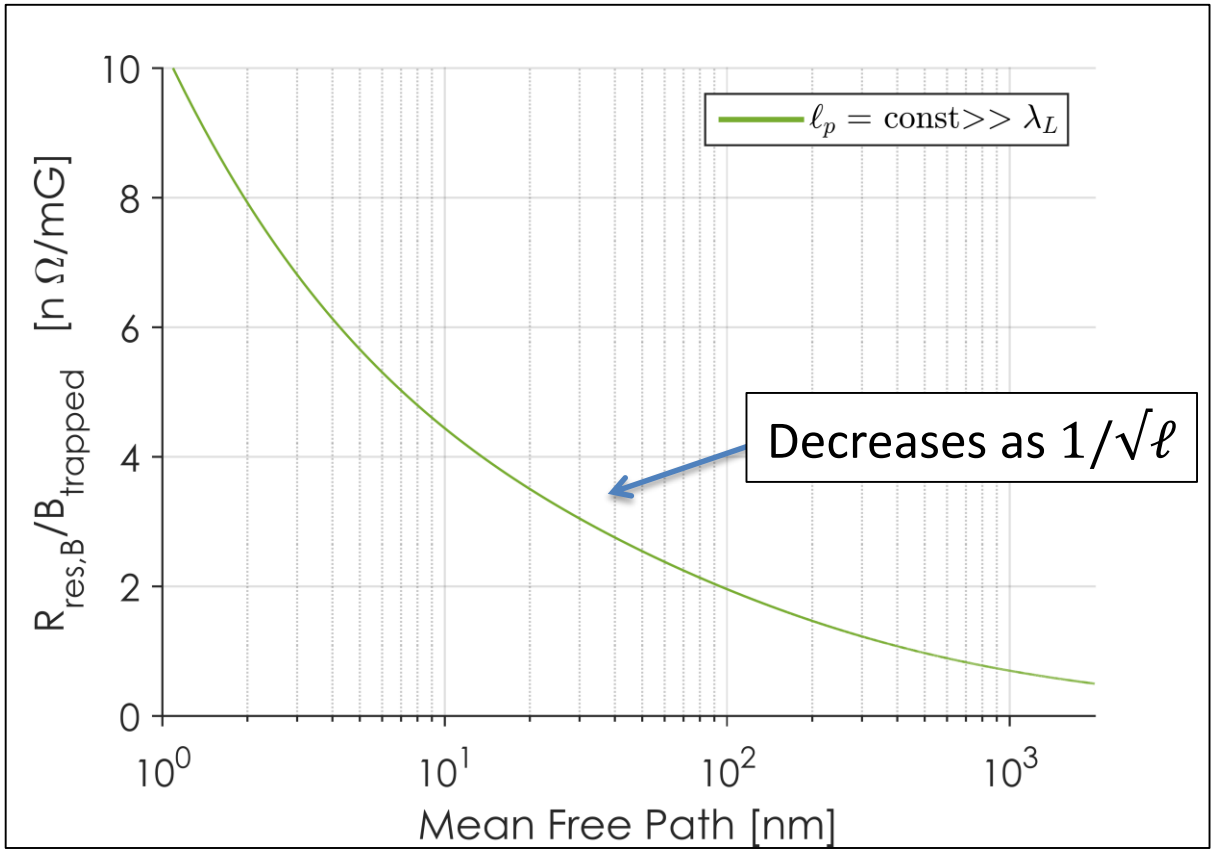
A simple model for calculating residual losses from trapped flux:

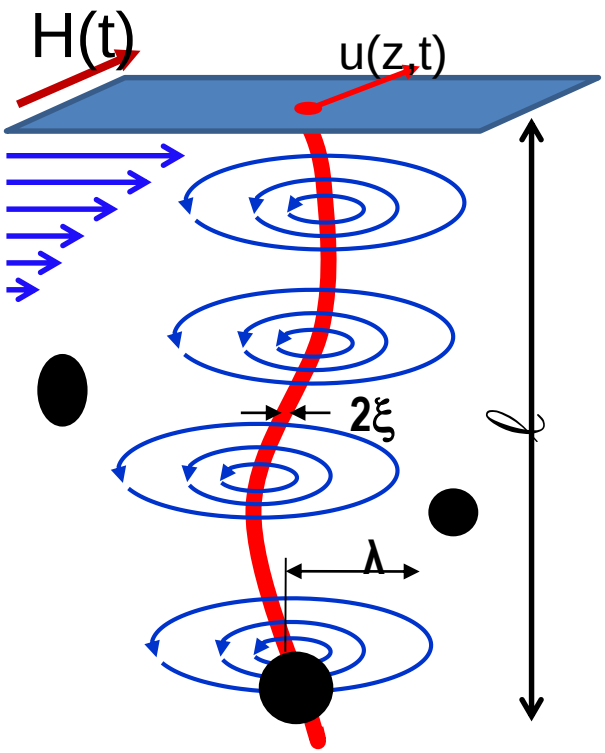
$$AB_{trapped} = N\phi_0$$

$$R_{res,B} = NR_n \frac{\pi\xi^2}{A} B_{trapped} = \frac{\pi\xi^2 R_n}{\phi_0} B_{trapped}$$



Theoretical Considerations

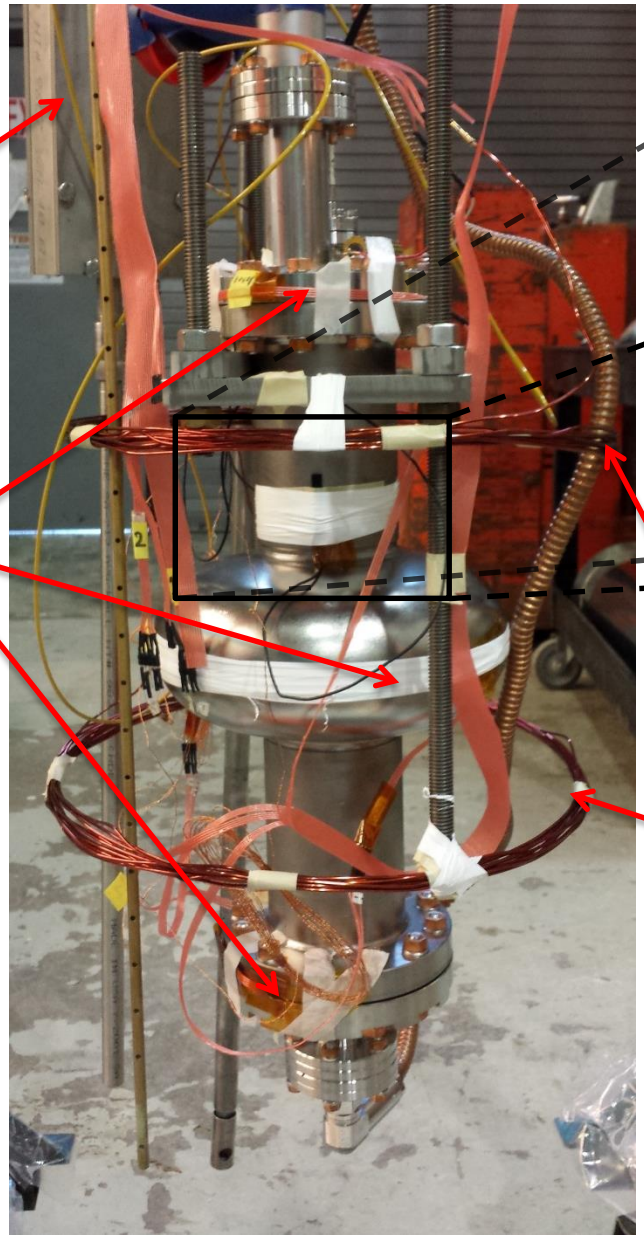


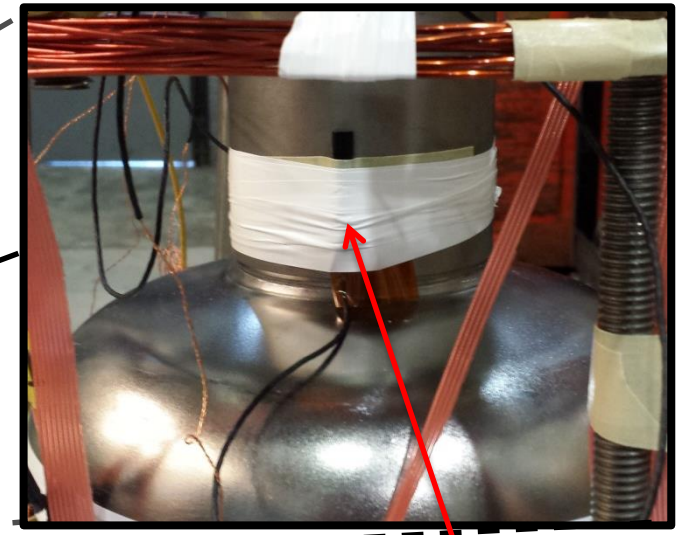


A. Gurevich and G. Ciovati, PRB 87(5):054502 (2013)

- Gurevich et. al. computes the sensitivity of residual resistance to trapped flux from London theory
- This highly dependent on material parameters and the mean spacing between pinning sites

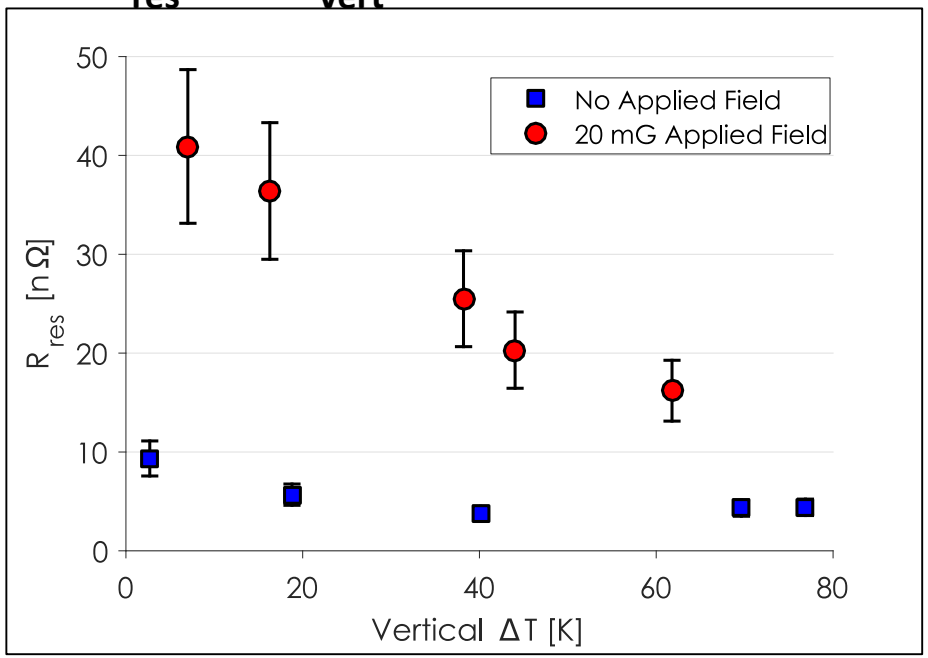
Experimental Setup



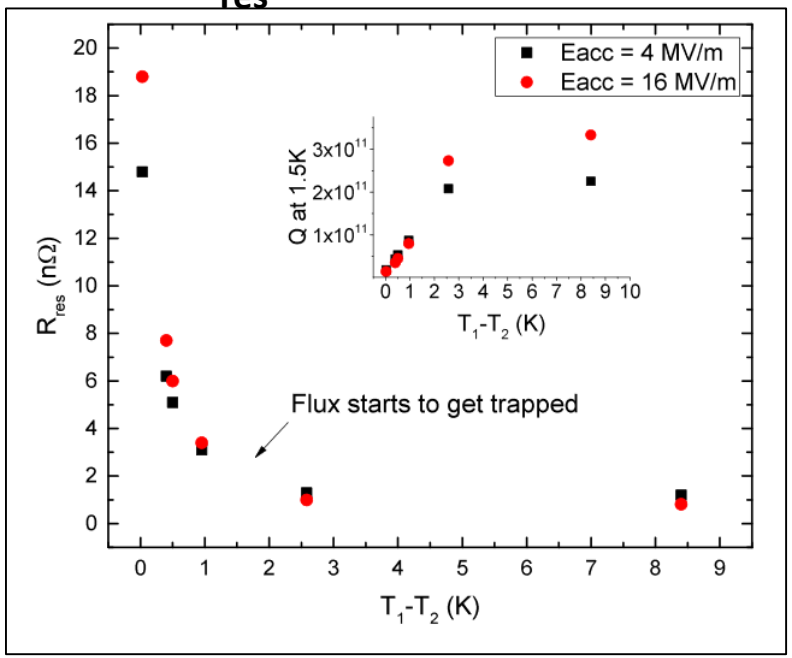


Impact of Cool Down

R_{res} vs ΔT_{vert} in the Cornell HTC



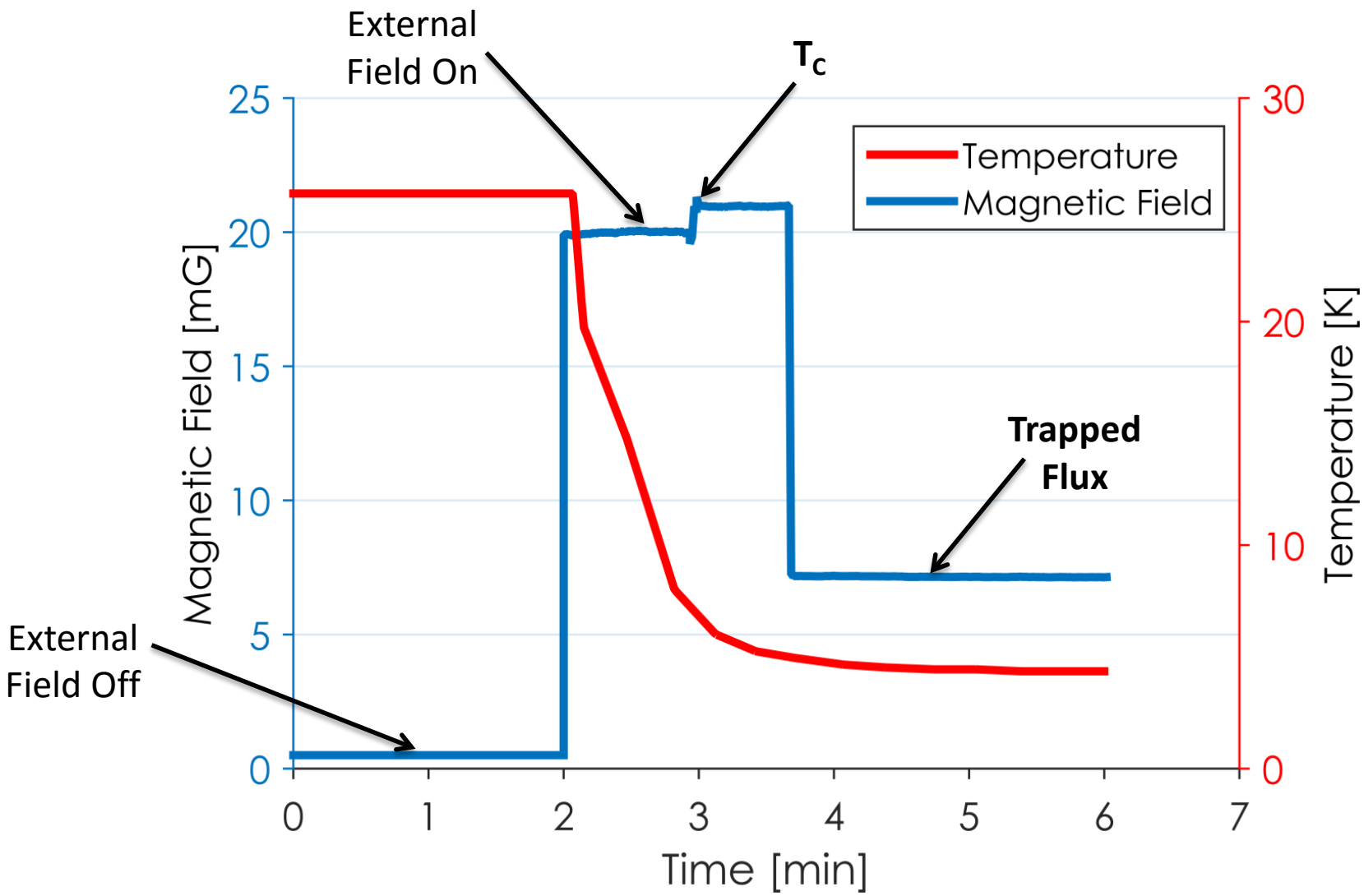
R_{res} vs ΔT at FNAL



A. Romanenko et al.
Appl. Phys. Lett. 105, 234103 (2014).

Conclusion 1: Larger temperature gradients during cool down lead to better flux expulsion and thus less trapped magnetic flux

A Typical Cool Down



Cavities Tested

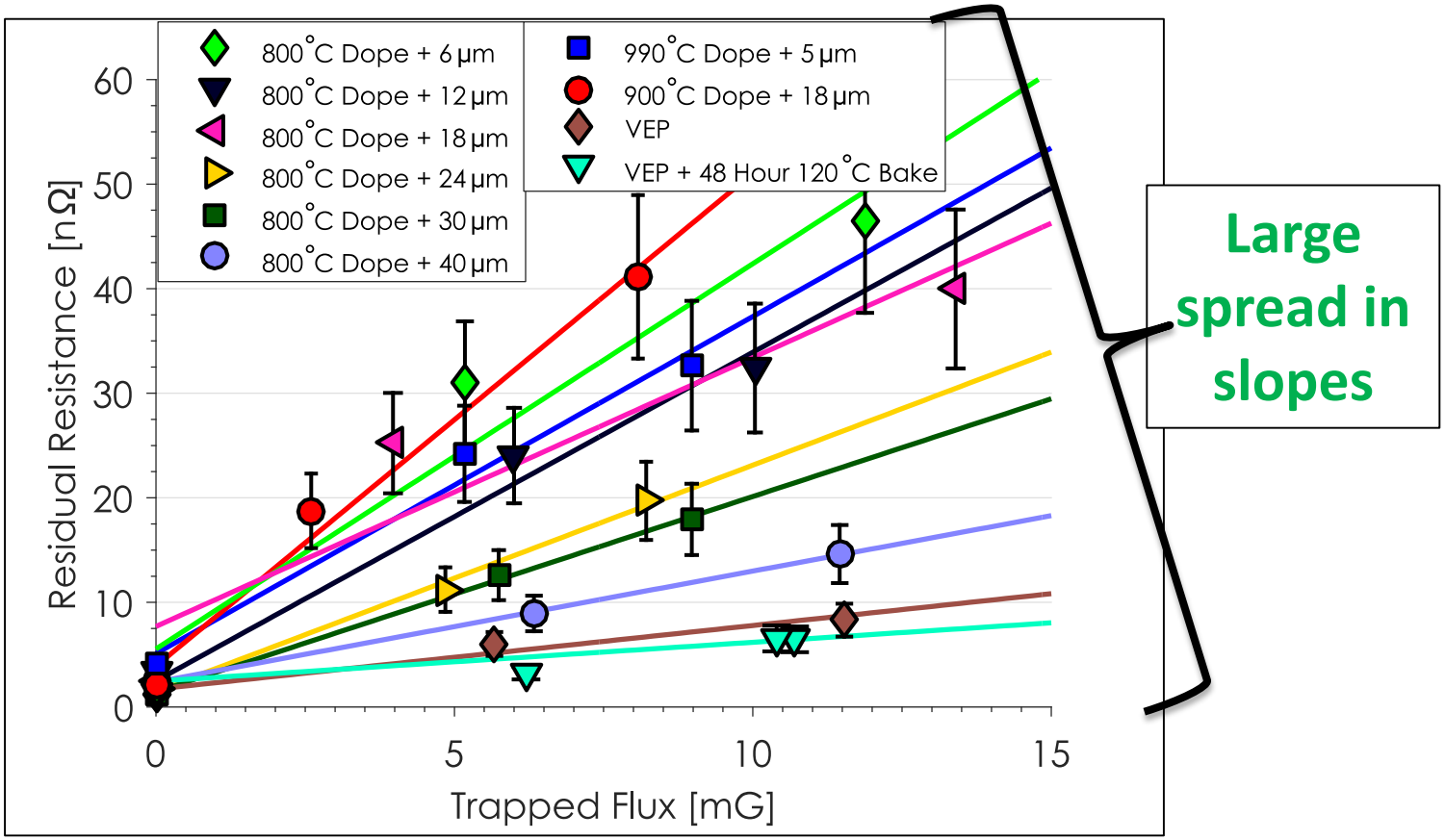
- 10 single-cell cavities were prepared with a variety of techniques.
  - 8 nitrogen doped cavities of varying doping levels
  - 2 “standard” treated cavities: one EP cavity and an EP+120^{0}C baked cavity

The Experiment

- Each cavity was cooled in a variety of magnetic fields leading to different amounts of trapped magnetic flux.
- Mean free path was extracted for each cavity.
- Sensitivity to trapped magnetic flux was found.

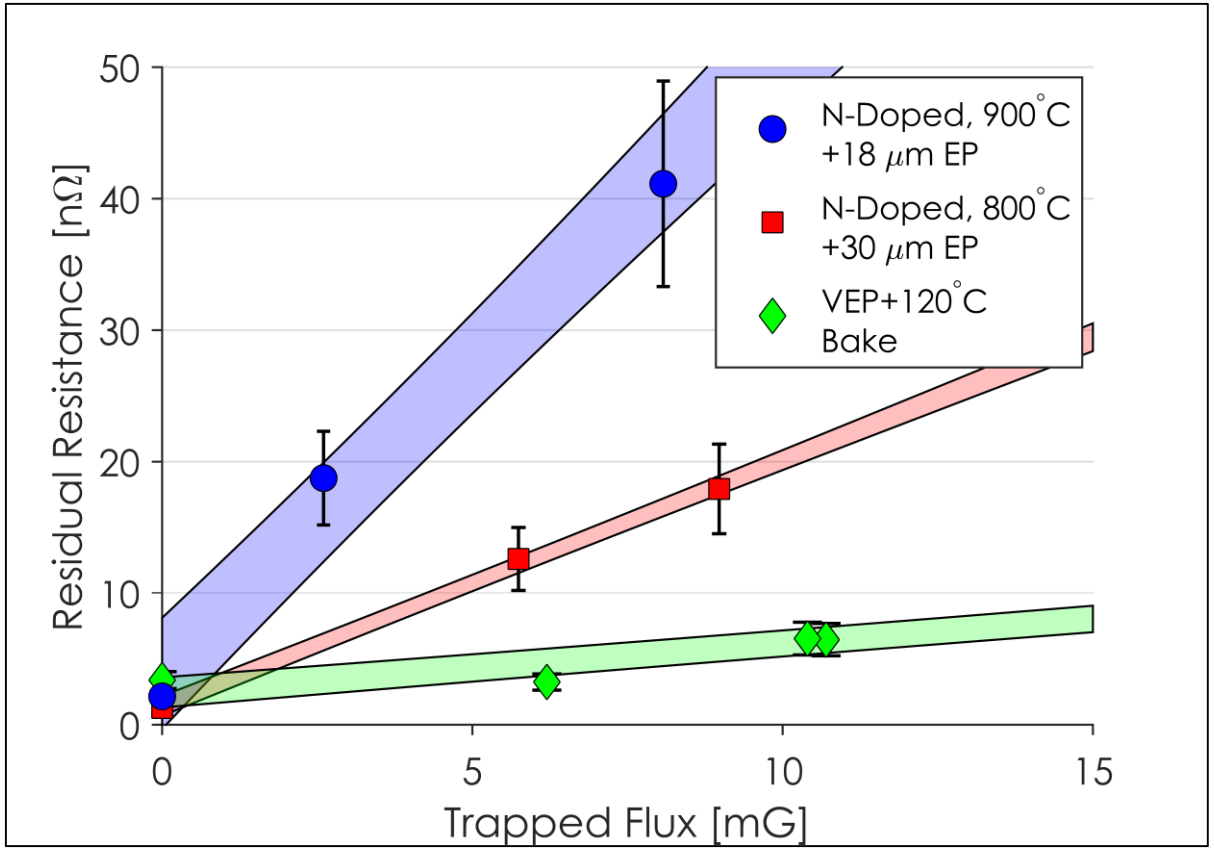
Me Assembling the Magnetic Field Experiment

R_{res} vs Trapped Flux



Conclusion 2: **Cavities with different preparations show very different sensitivities of residual resistance to trapped flux!**

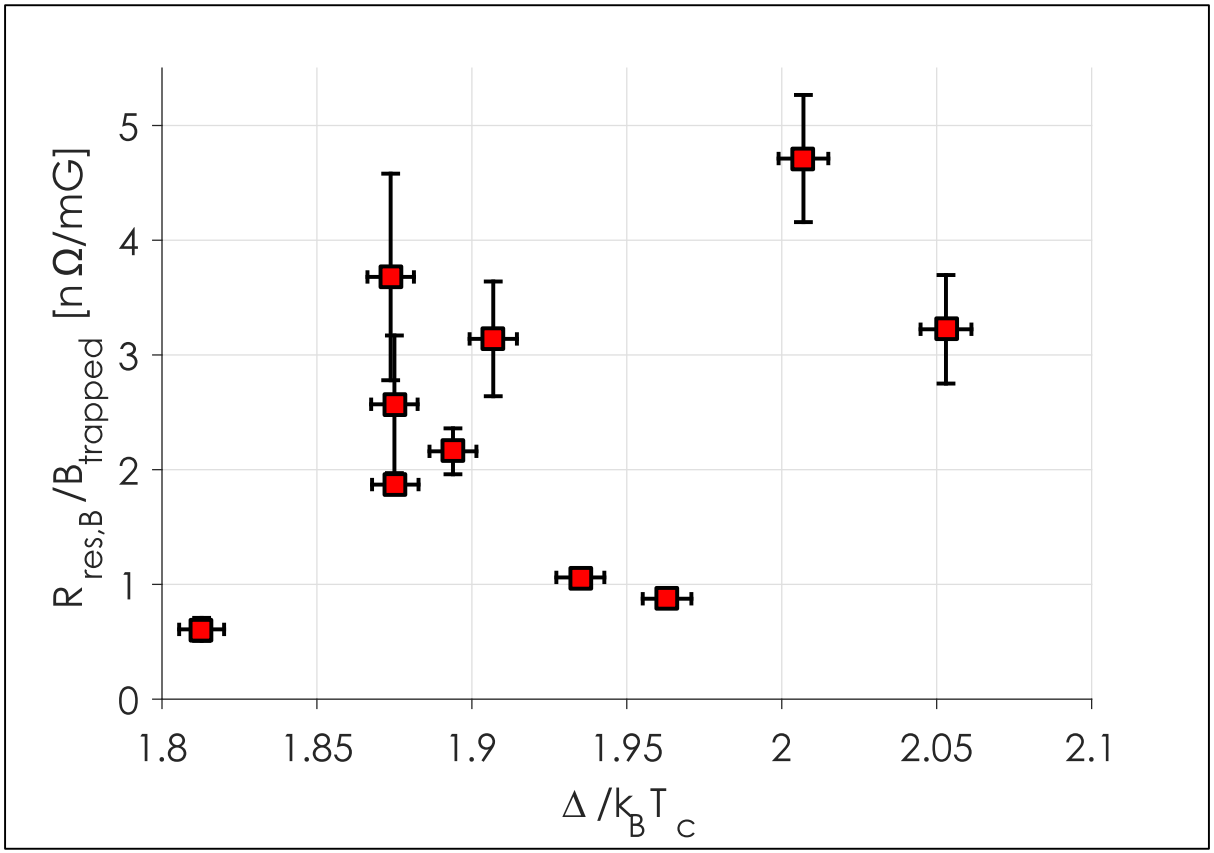
R_{res} vs Trapped Flux



All nitrogen-doped cavities tested showed a higher sensitivity than both the EP and EP+120°C baked cavities

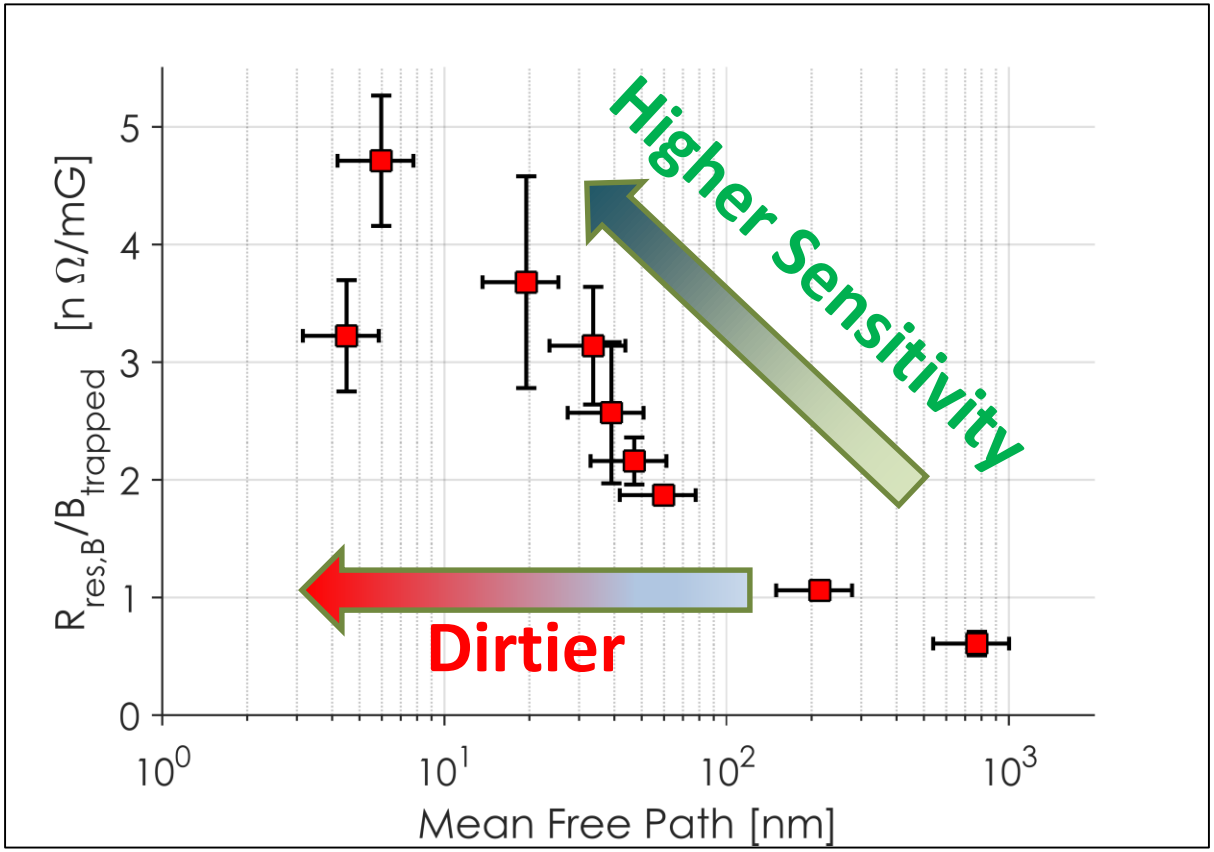
$$\frac{R_{res,B}}{B_{trapped}} = \frac{dR_{res}}{dB_{trapped}}$$

Sensitivity vs Energy Gap



No correlation between $R_{res,B}/B_{trapped}$ and Δ/k_BT_c

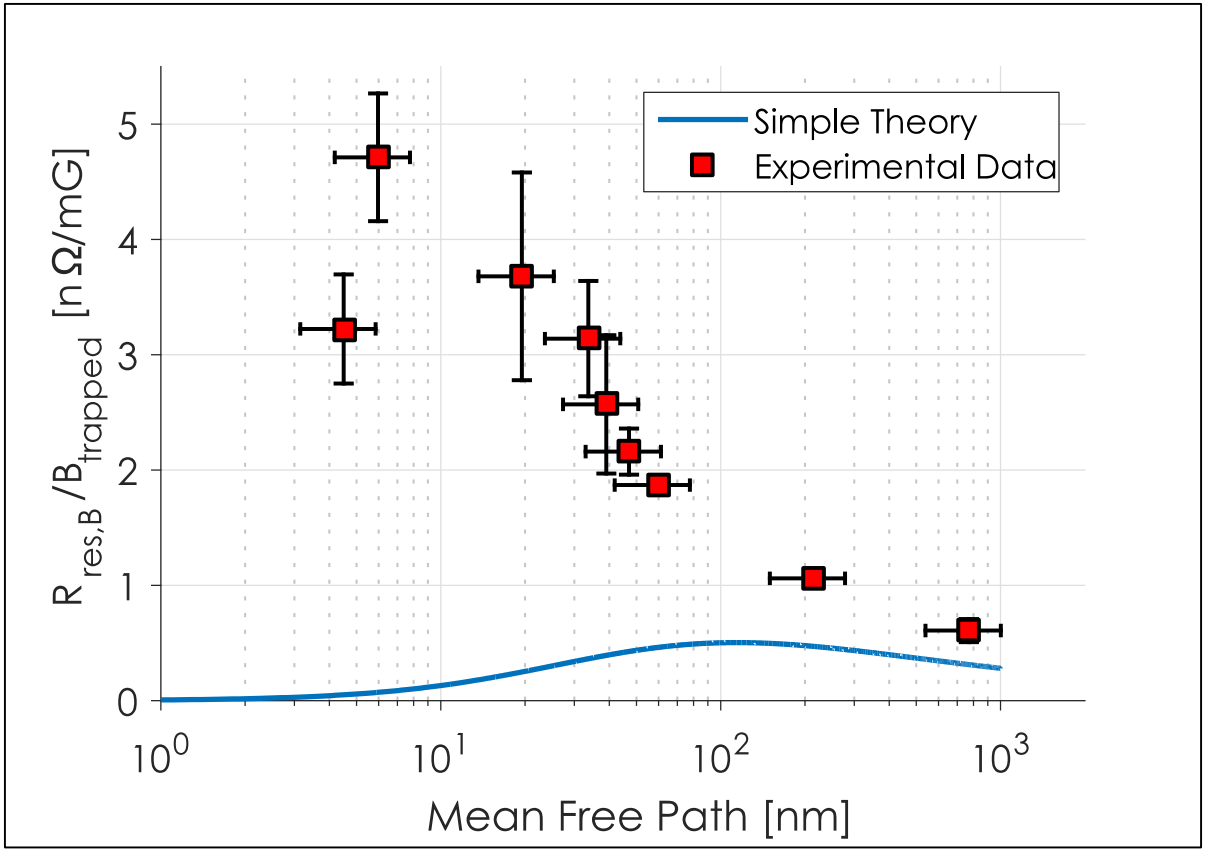
Sensitivity vs MFP



Conclusion 3: Shorter mean free paths lead to larger sensitivities down to ~10 nm, then shorter mean free paths lead to smaller sensitivities

Sensitivity vs MFP

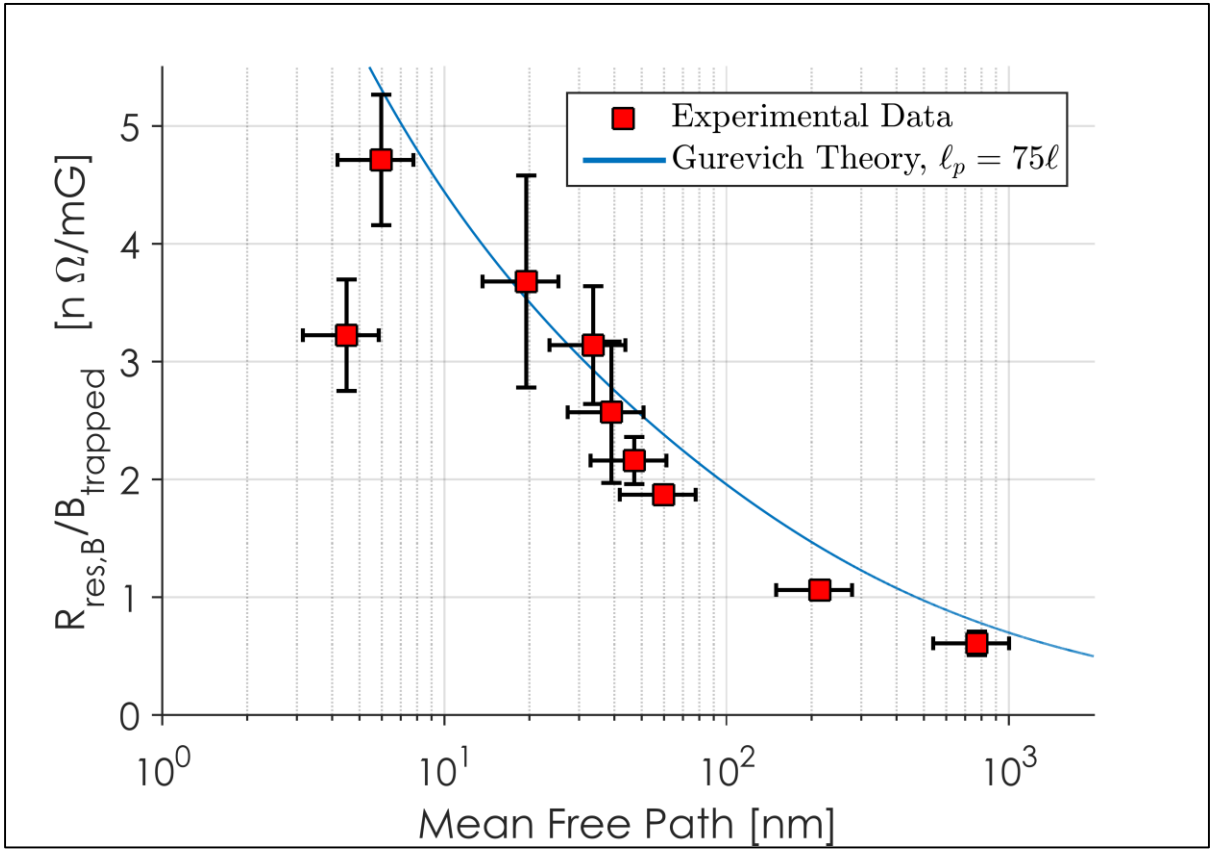
Simple Theory



Poor agreement with the simple theory of residual losses from trapped flux

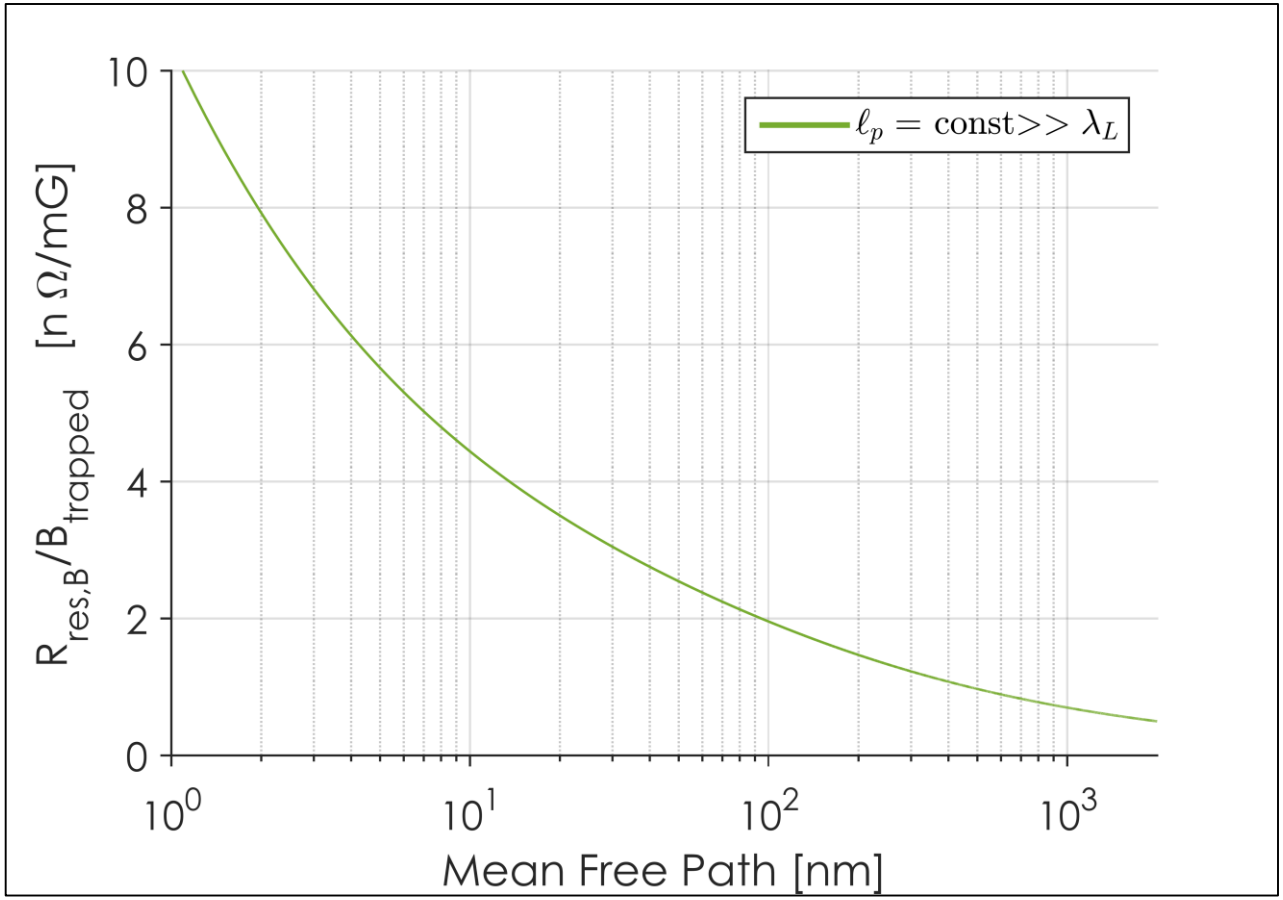
Sensitivity vs MFP

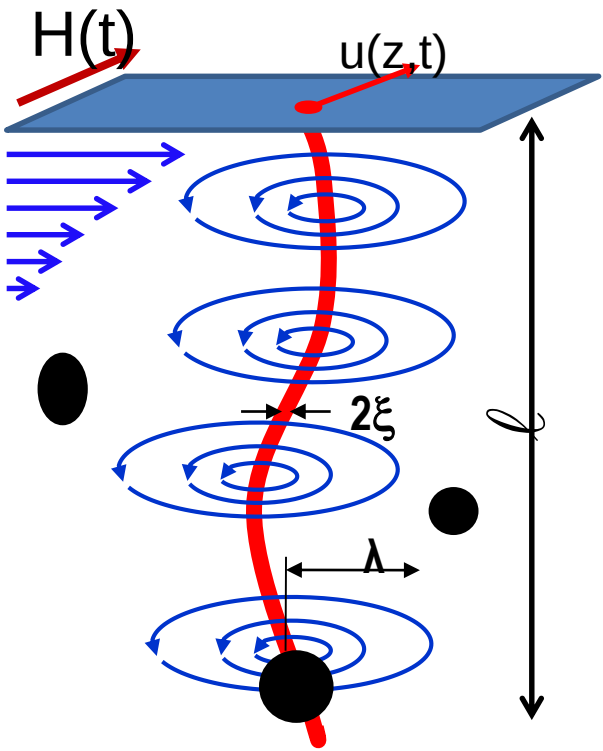
Gurevich's Theory



Good agreement in the clean limit but not in the dirty limit

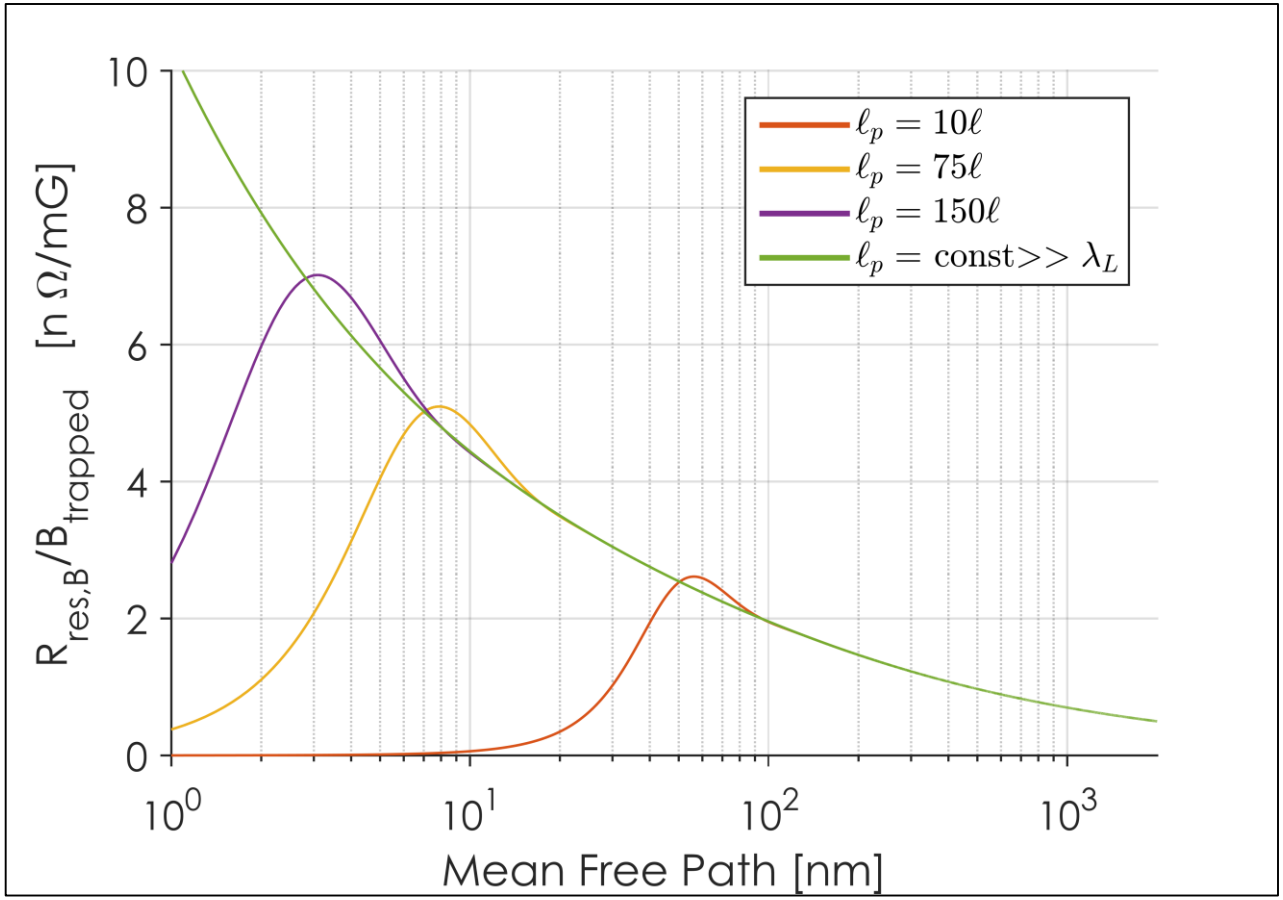
Theoretical Considerations

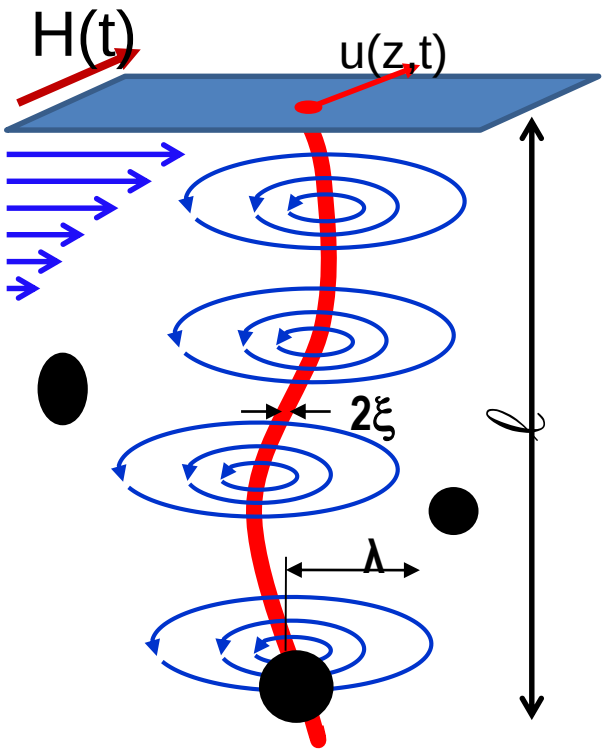




Is this interpretation of mean spacing between pinning sites correct?

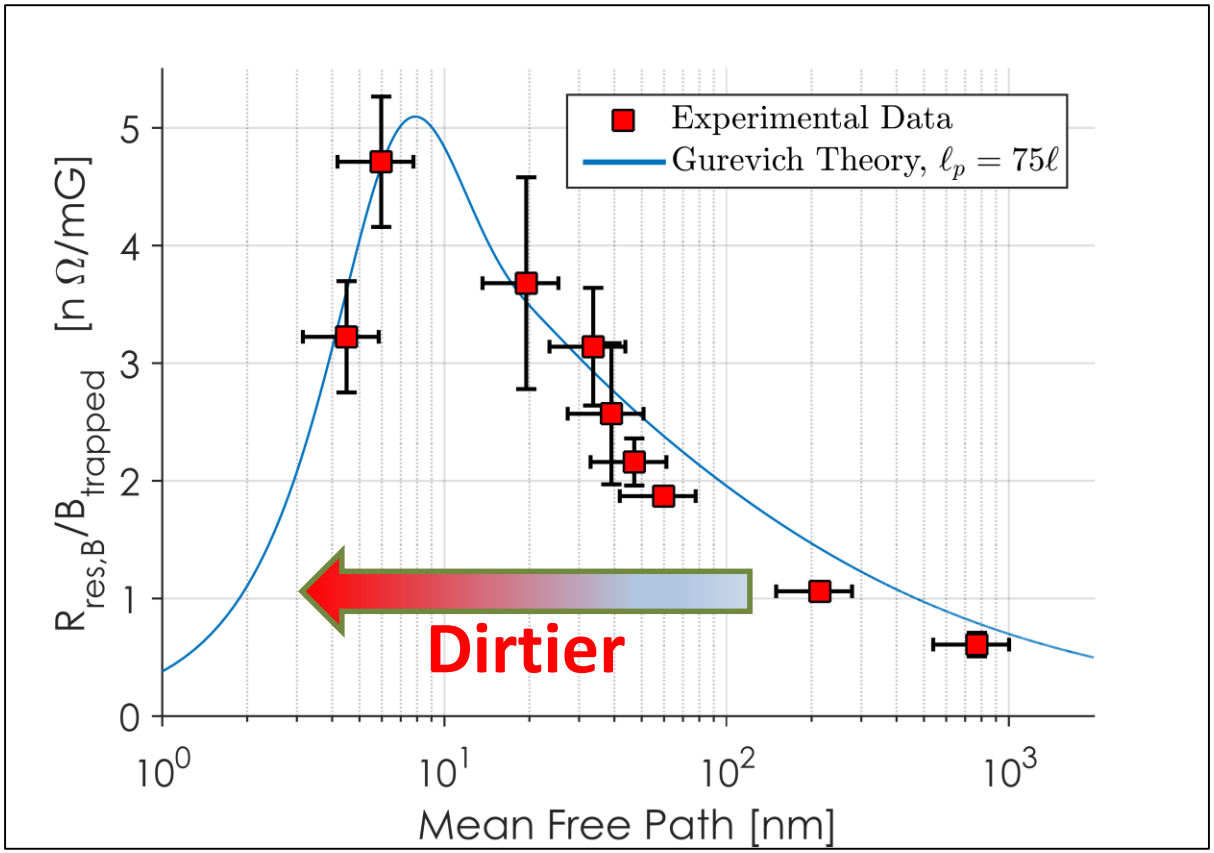
Theoretical Considerations





By introducing a proportionality relation between ℓ_p and ℓ, a "bell shape" dependence is found

Sensitivity vs MFP



Conclusion 4: Experimental data shows good agreement with Gurevich's theory of residual losses due to vortex oscillations

Residual Resistance Studies

1. Larger temperature gradients during cool down lead to better flux expulsion and thus less trapped magnetic flux
2. Cavities with different mean free paths show very different sensitivities of residual resistance to trapped flux
3. Shorter mean free paths lead to larger sensitivities down to ~10 nm, then shorter mean free paths lead to smaller sensitivities
4. Experimental data shows good agreement with Gurevich's theory of residual losses due to vortex oscillations

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- Residual Resistance Studies
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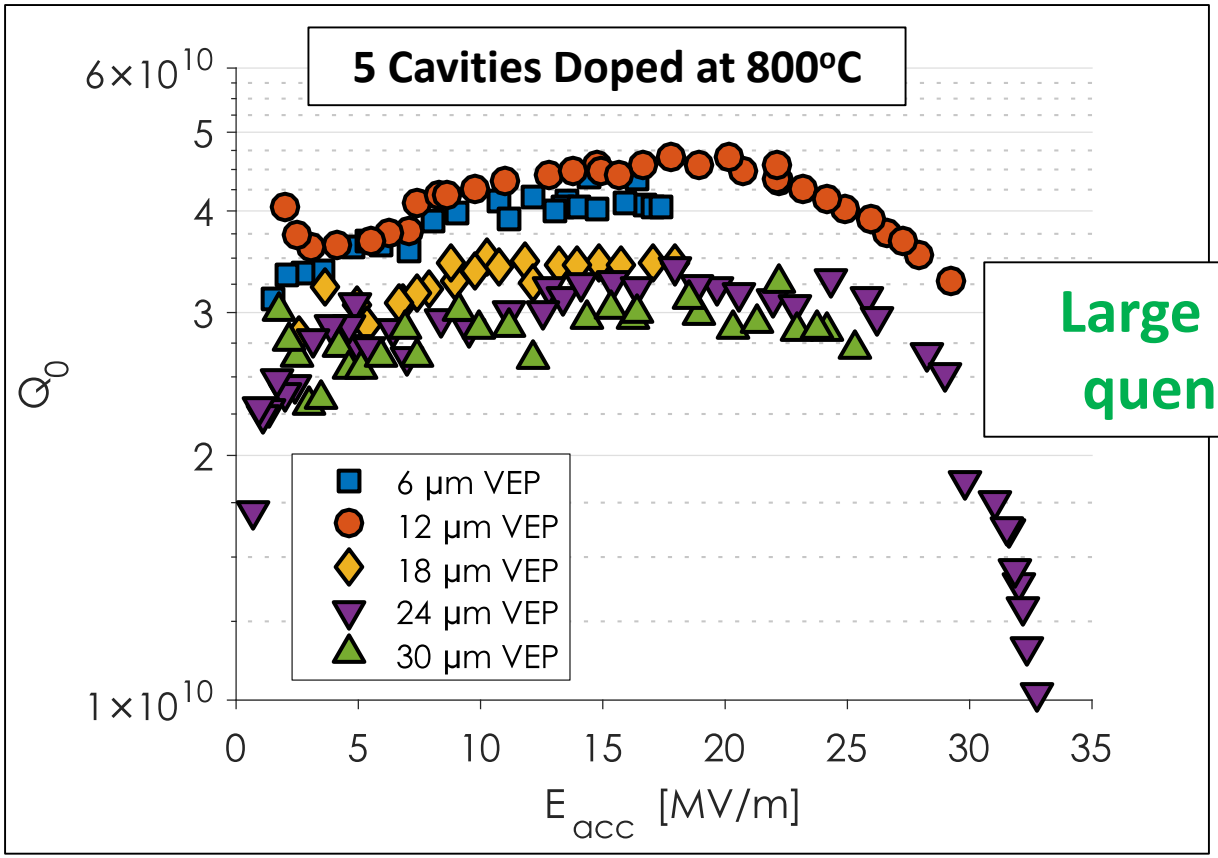
- Transition to Full Cryomodule
- Conclusions

High Field Limits

- Nitrogen-doped cavities on average quench at lower fields than un-doped cavities



Large spread in quench fields

Critical Fields in Superconductors

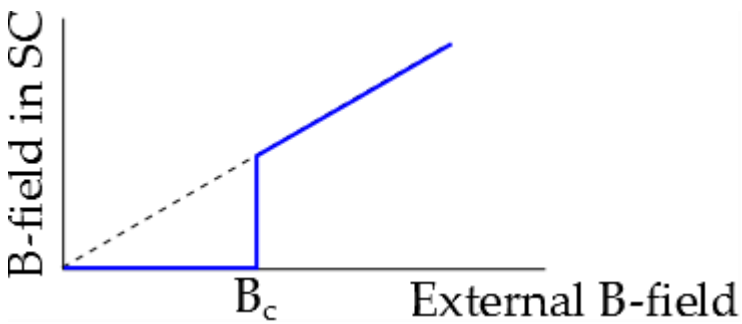
- Ginsburg-Landau Theory uses two length scales to characterize superconductors:

λ – Penetration Depth

ξ – Coherence Length

$\kappa_{GL}=\lambda/\xi$

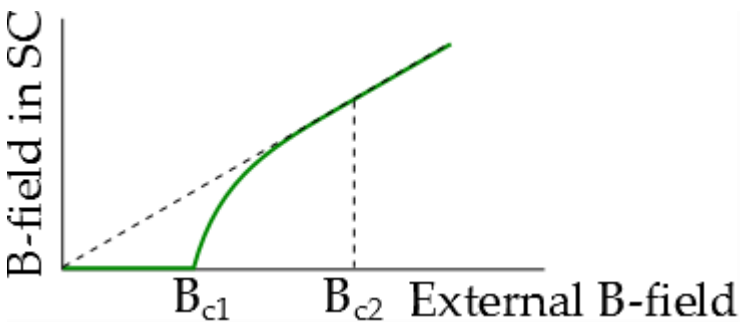
Type I – $\kappa_{GL} < 1/\sqrt{2}$



Superconducting when $B<B_c$

Normal Conducting when $B_c<B$

Type II – $\kappa_{GL} > 1/\sqrt{2}$

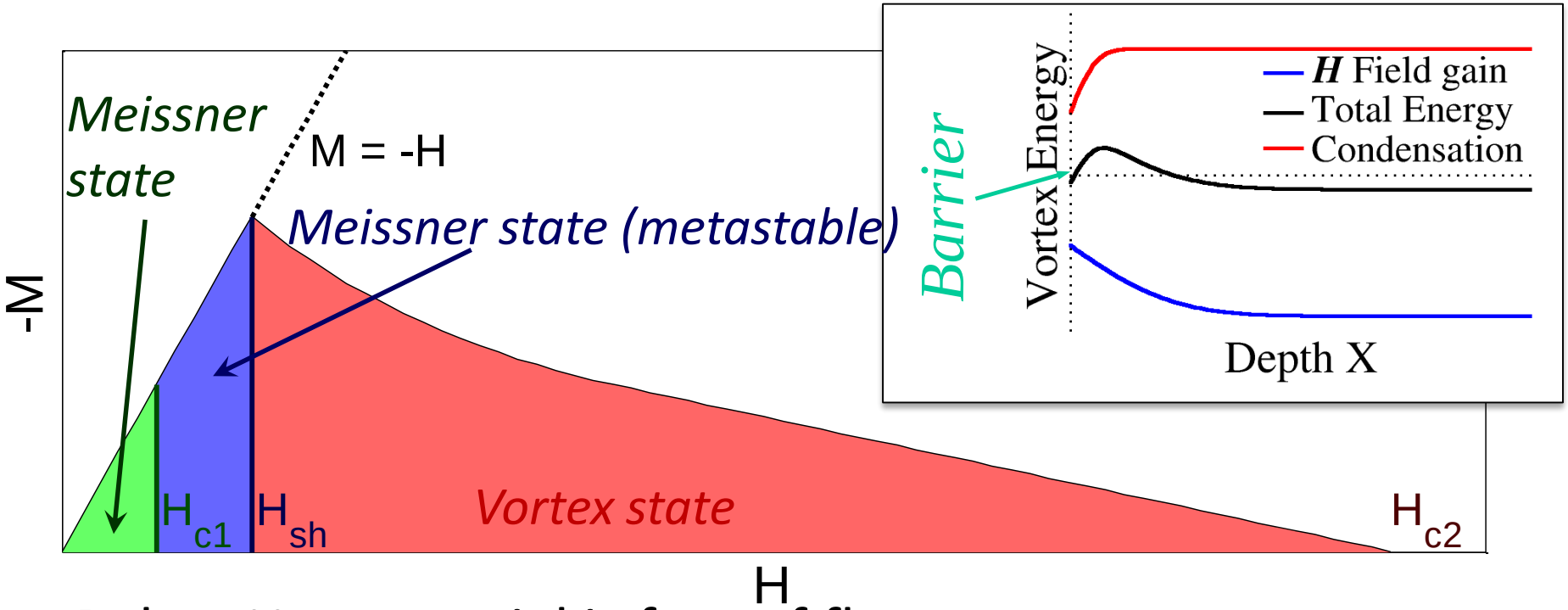


Superconducting when $B<B_{c1}$

Mixed State when $B_{c1}<B<B_{c2}$

Normal Conducting when $B_{c2}<B$

The Superheating Field

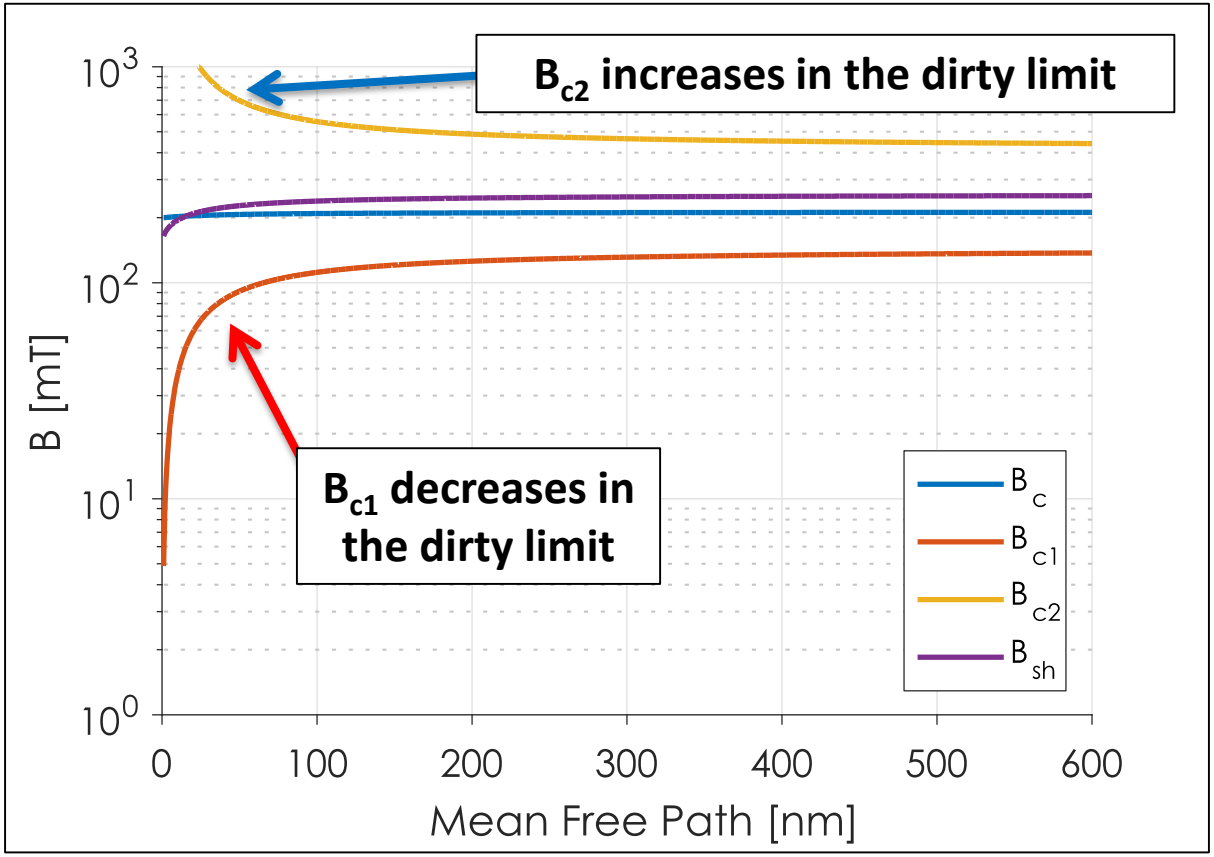


- Below H_{c1}, material is free of flux
- Favorable for flux to be deep in bulk above H_{c1}
- BUT surface energy barrier allows metastable state!
- **Ultimate SRF limit: superheating field H_{sh}**

Slide adapted from S. Posen

High Field Limits

Nitrogen-doping significantly lowers the mean free path of niobium – this lowering will also cause large changes to the critical fields



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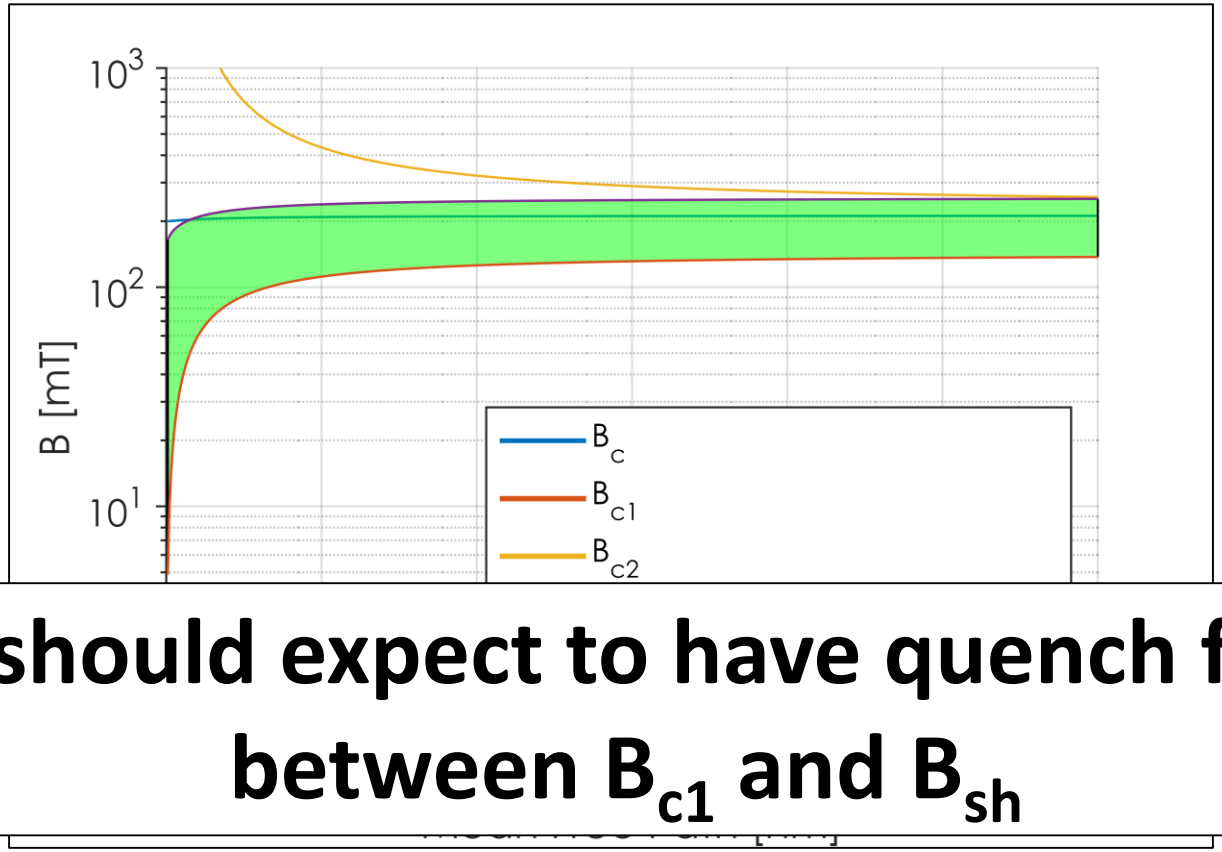
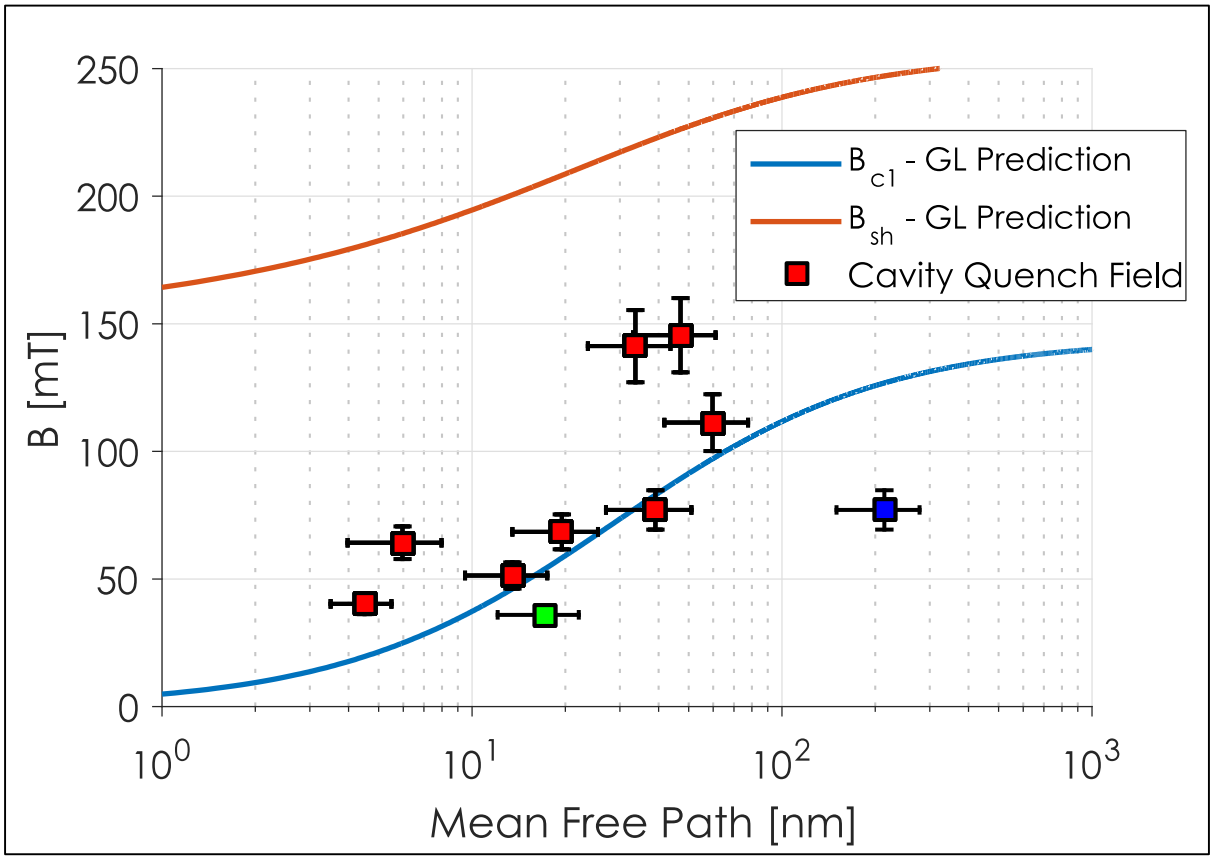


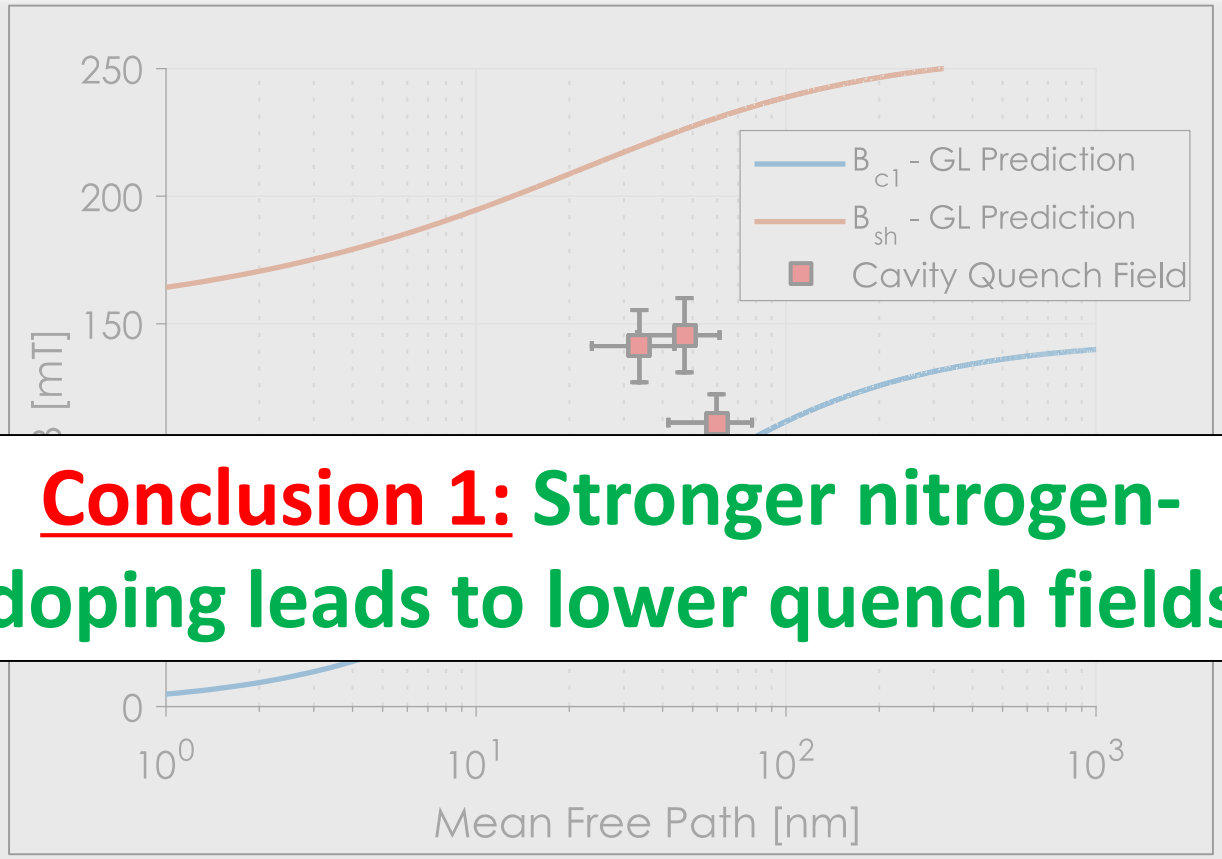
We should expect to have quench fields between B_{c1} and B_{sh}

High Field Limits



- Most of the nitrogen-doped cavities tested quench at or above B_{c1}
- 80% of Cornell's single-cell cavities operate in the metastable region!

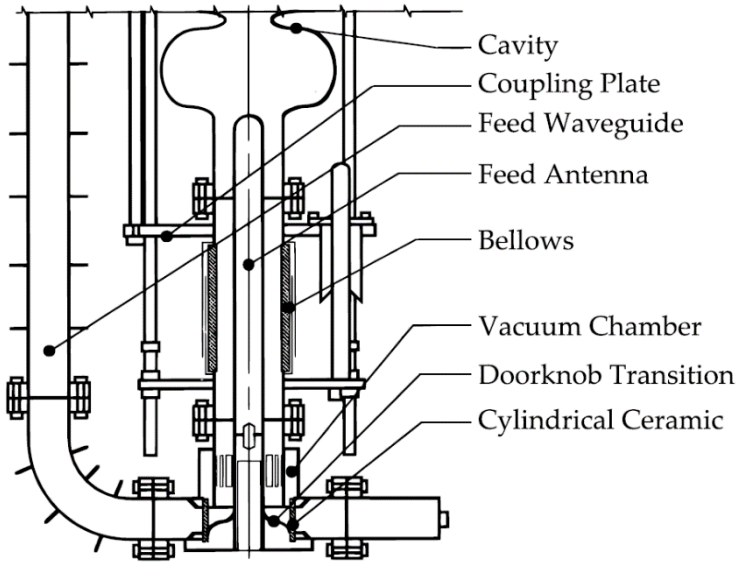
High Field Limits



Conclusion 1: Stronger nitrogen-doping leads to lower quench fields

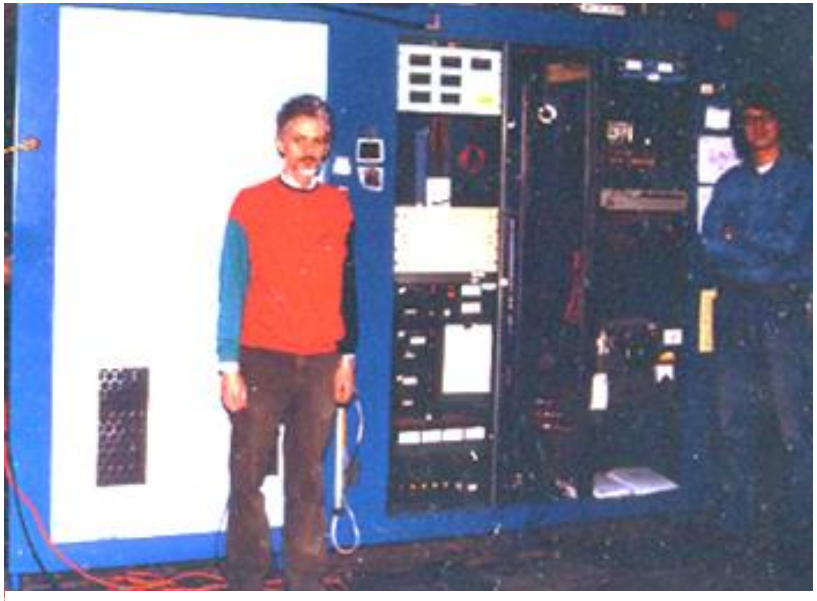
- Most of the nitrogen-doped cavities tested quench at or above B_{c1}
- 80% of Cornell's single-cell cavities operate in the metastable region!

High Field Limits



Cornell has a 2 MW Klystron which can be used to find the fundamental quench field of a cavity

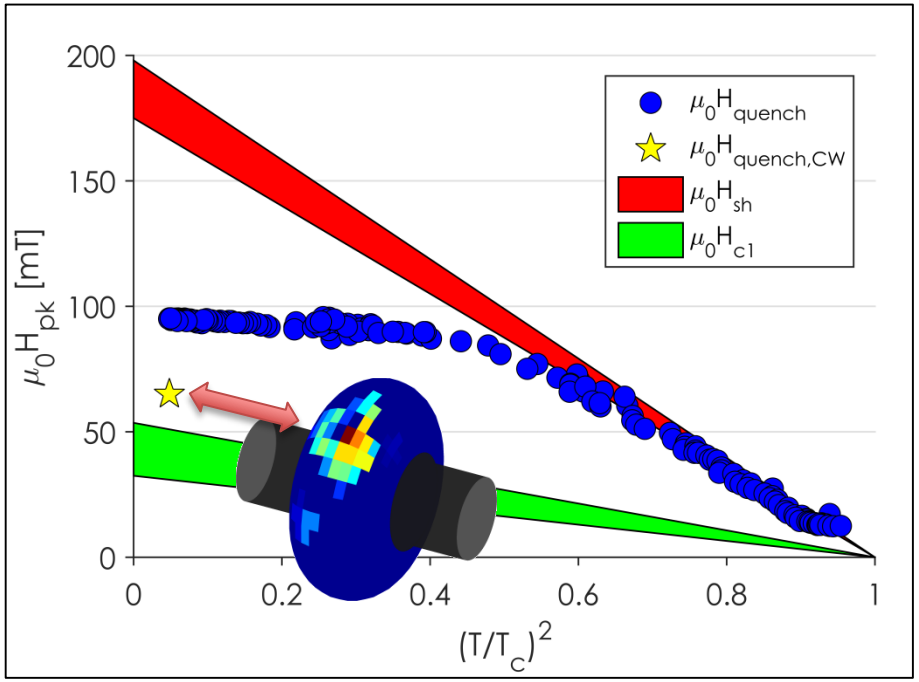
By pulsing a cavity with >1 MW of power, thermal effects that usually lead to quench in CW can be mitigated



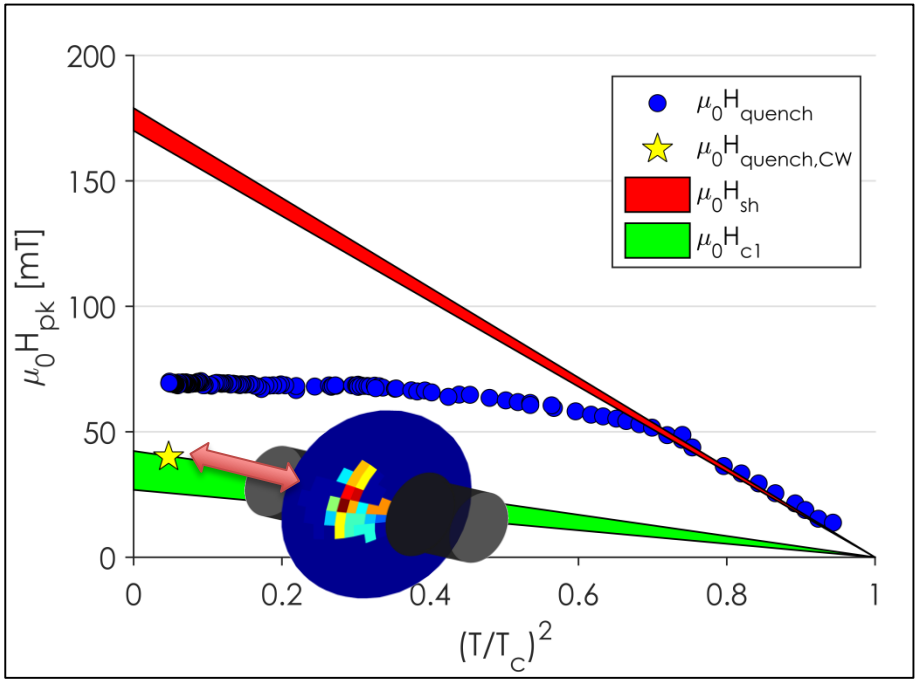
Boeing 1.5 MW Klystron

High Field Limits

900°C Doped Cavity



990°C Doped Cavity

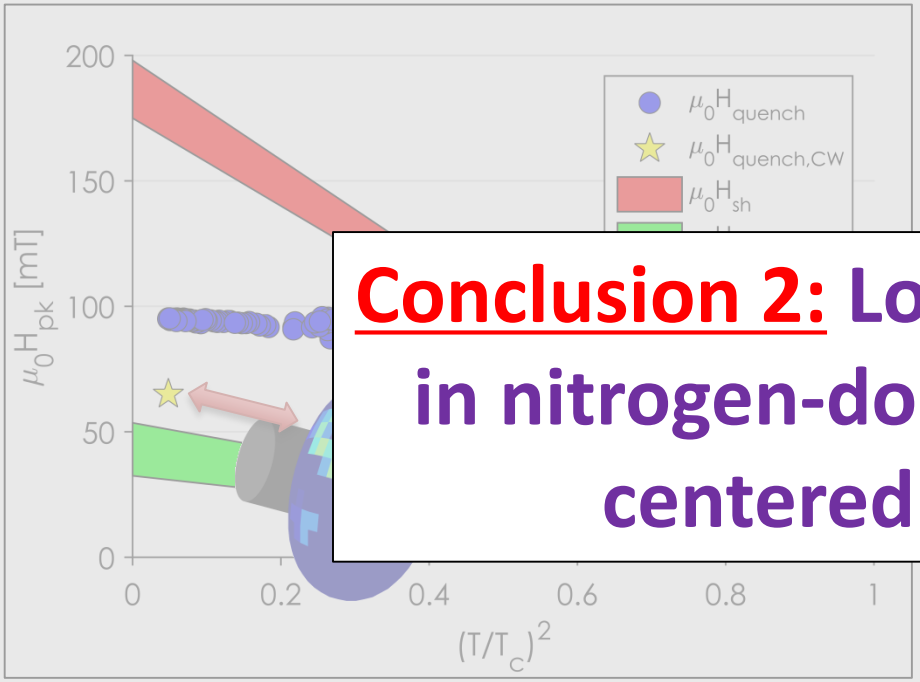


For both cavities:

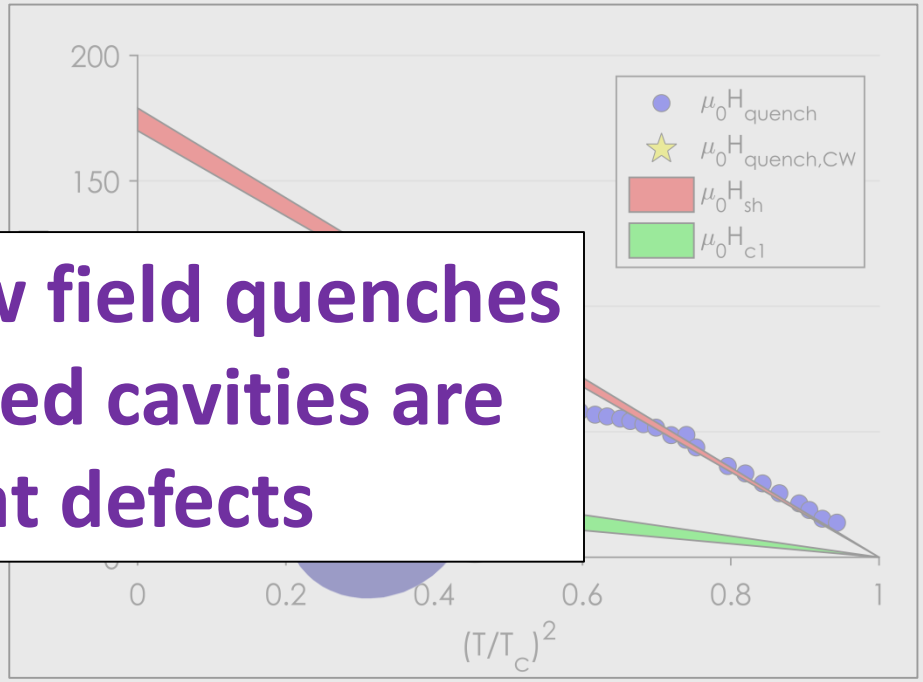
- At high temperatures, quench field follows the superheating field
- At low temperatures, quench field deviates from the superheating field, indicative of a **quench at a defect**

High Field Limits

900°C Doped Cavity



990°C Doped Cavity



Conclusion 2: Low field quenches in nitrogen-doped cavities are centered at defects

For both cavities:

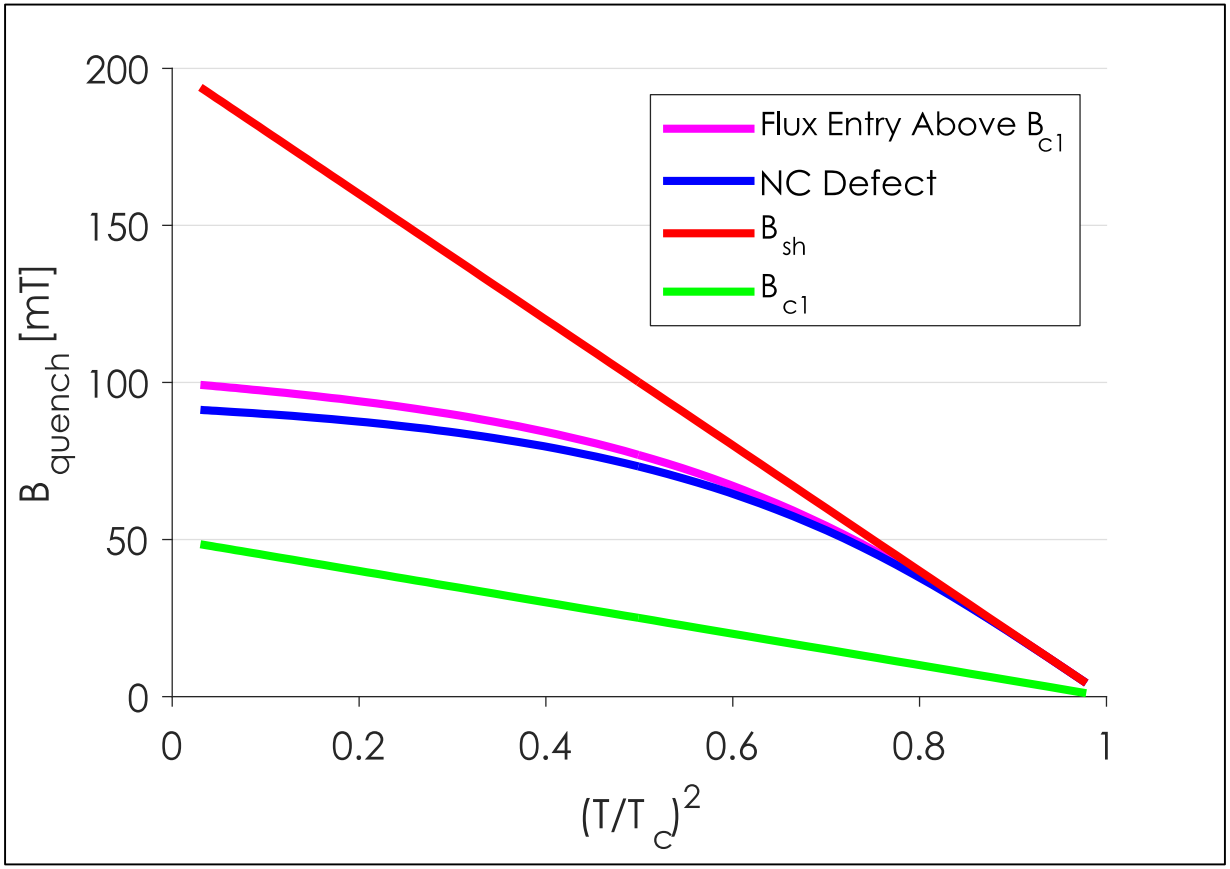
- At high temperatures, quench field follows the superheating field
- At low temperatures, quench field deviates from the superheating field, indicative of a **quench at a defect**

High Field Limits

This leaves two possibilities:

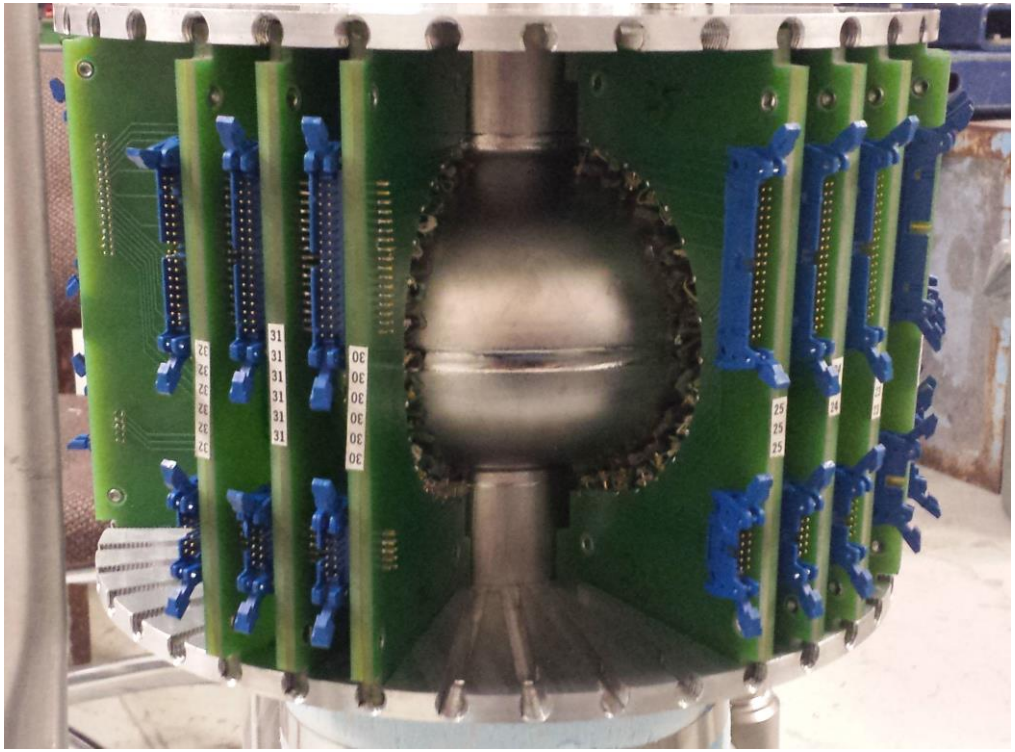
- Quench due to thermal runaway at NC defect
- Quench due to flux entry above B_{c1}

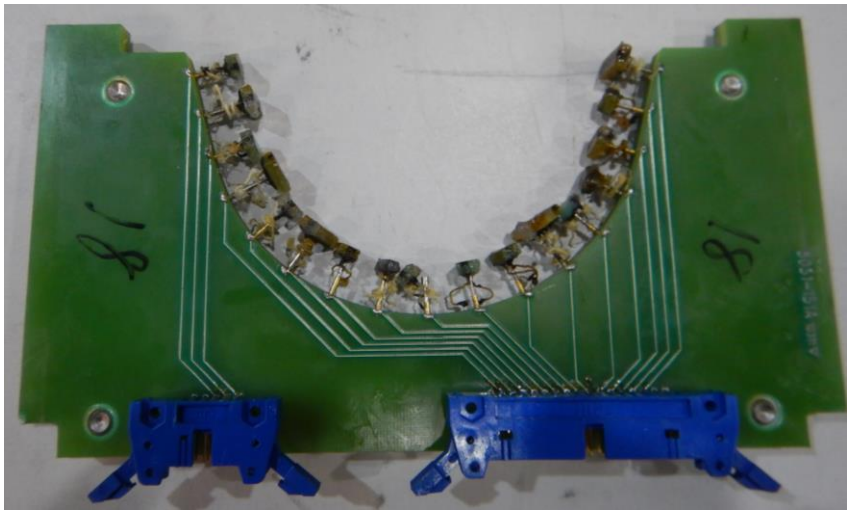
High Field Limits

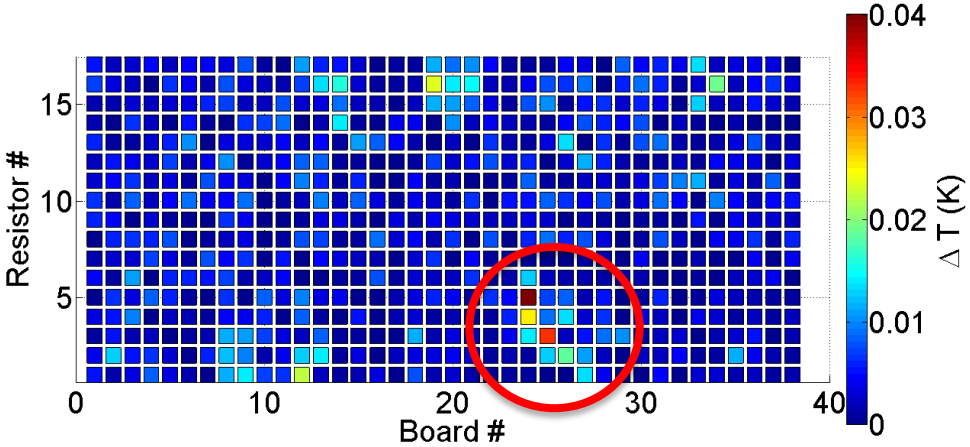


Quench field simulation shows that it is difficult to tell the two cases apart

Temperature-Mapping

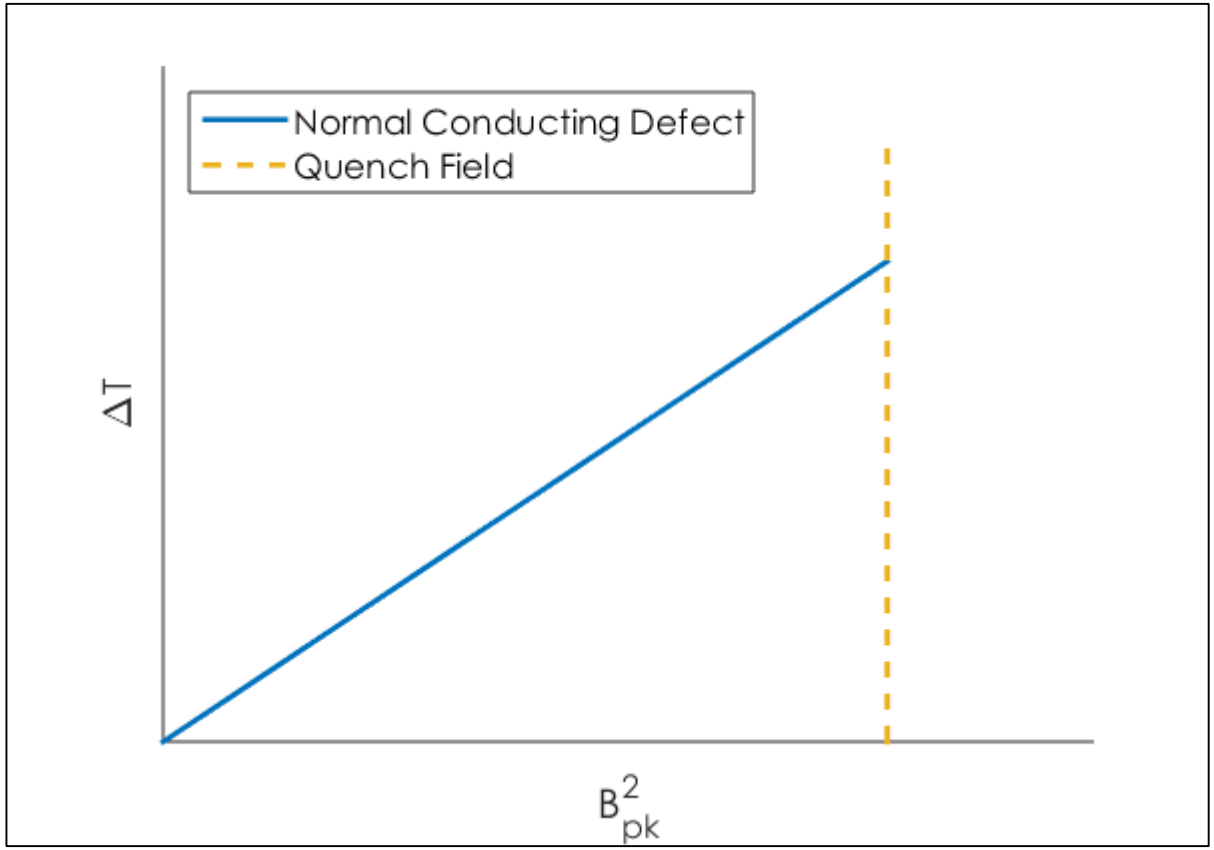






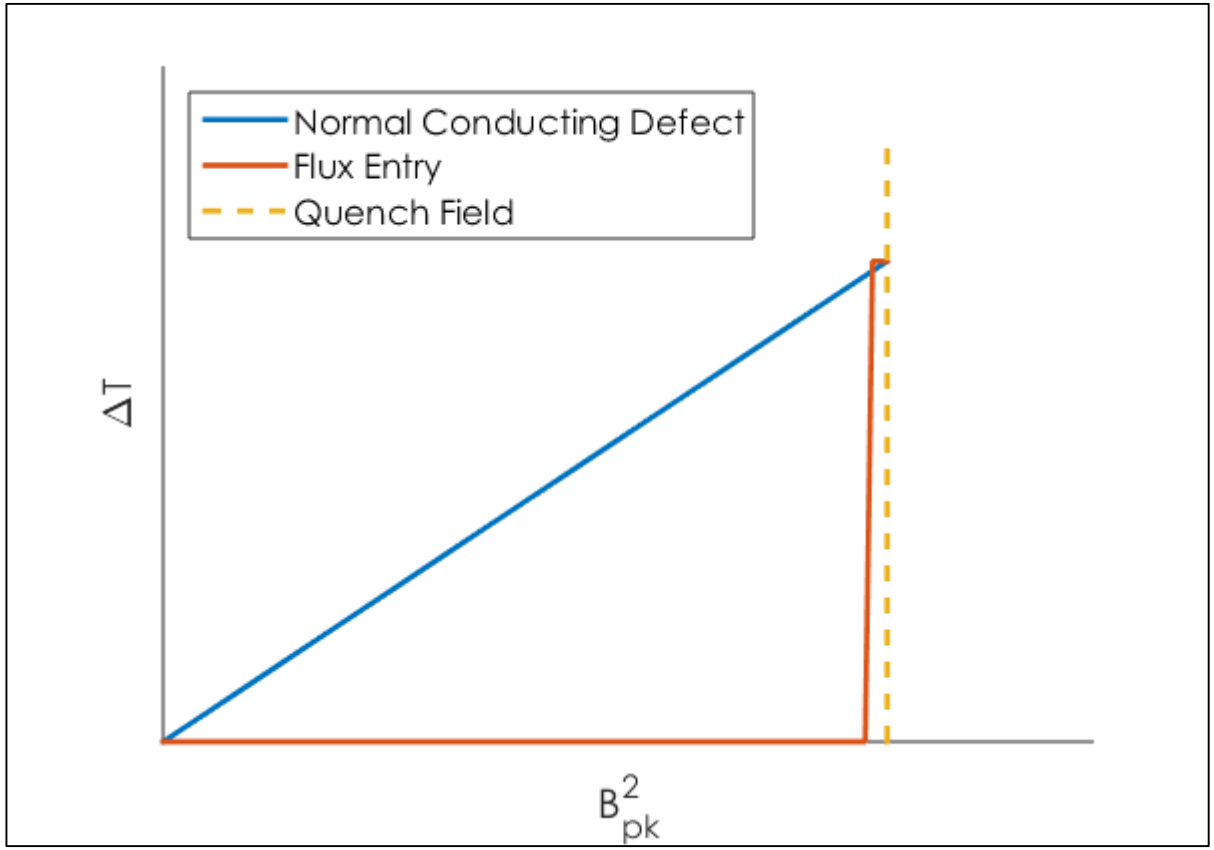
- Temperature-mapping consists of placing a series of resistors around the cavity
- Heating on the cavity surface can be measured during operation

High Field Limits



- Normal conducting defect results in "Ohmic" heating – ΔT increases linearly with B^2

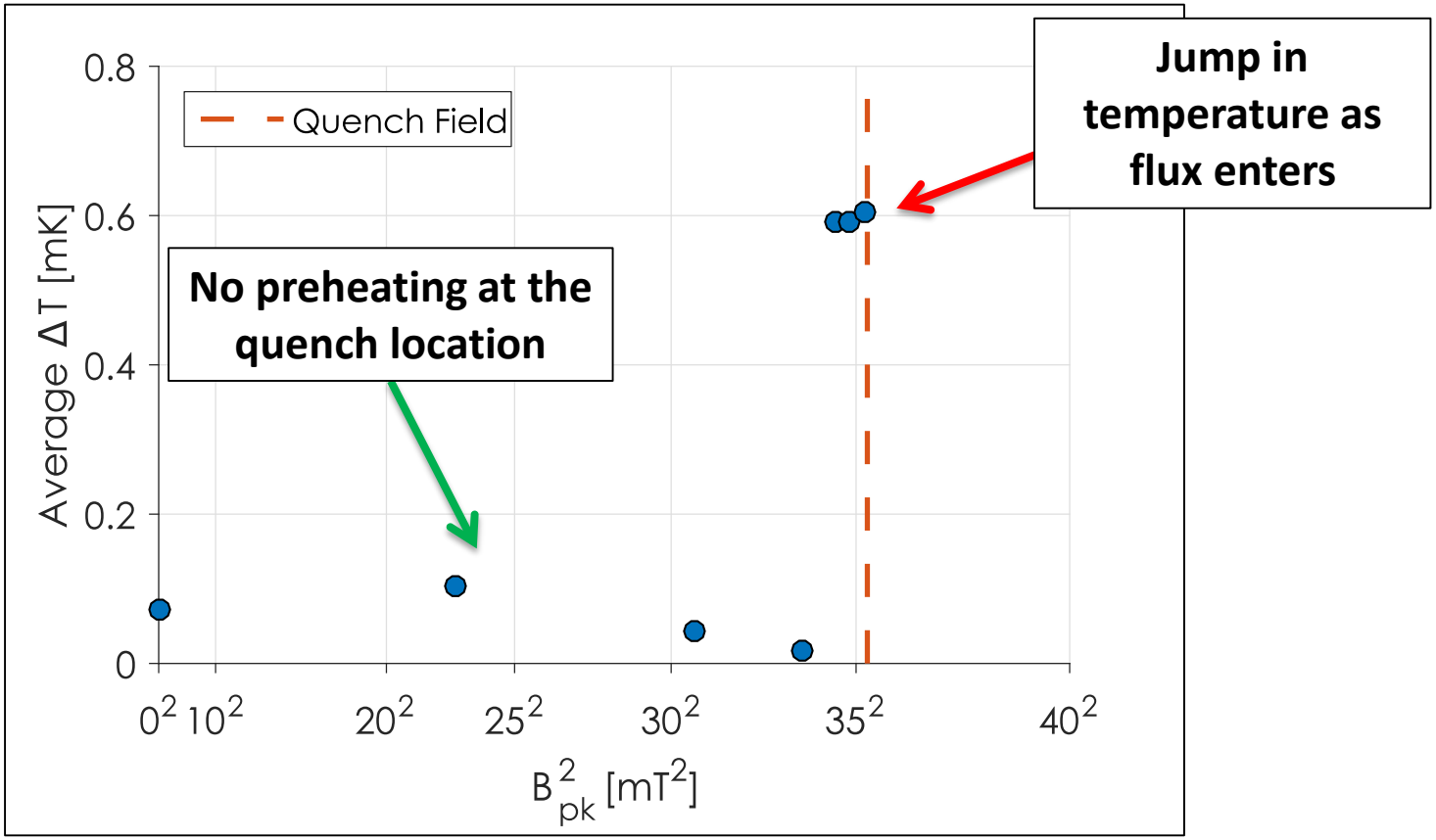
High Field Limits



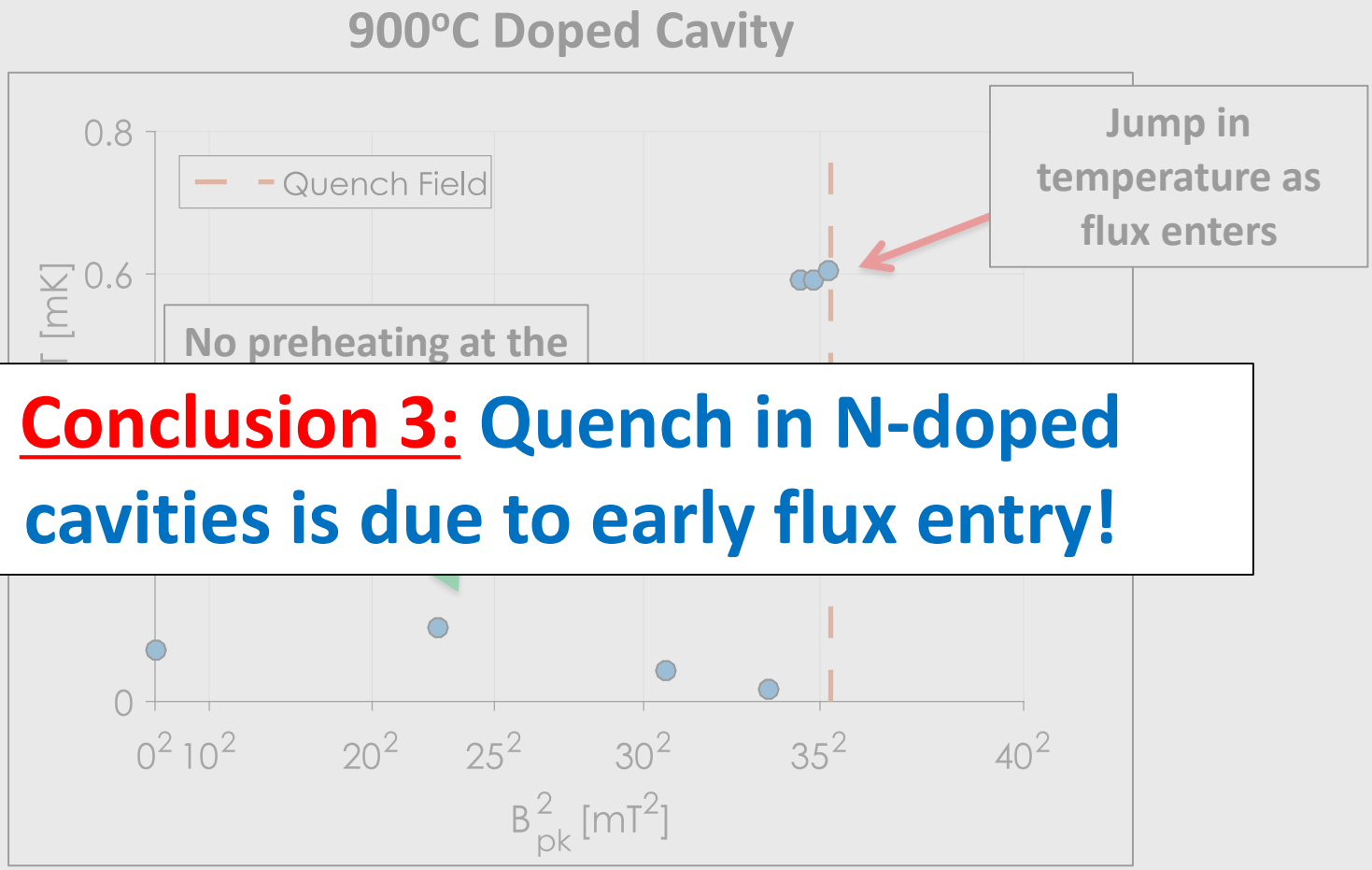
- Normal conducting defect results in "Ohmic" heating – ΔT increases linearly with B^2
- Flux entry above B_{c1} would show no preheating until just prior to the quench

High Field Limits

900°C Doped Cavity



High Field Limits



Conclusion 3: Quench in N-doped cavities is due to early flux entry!

High Field Limits

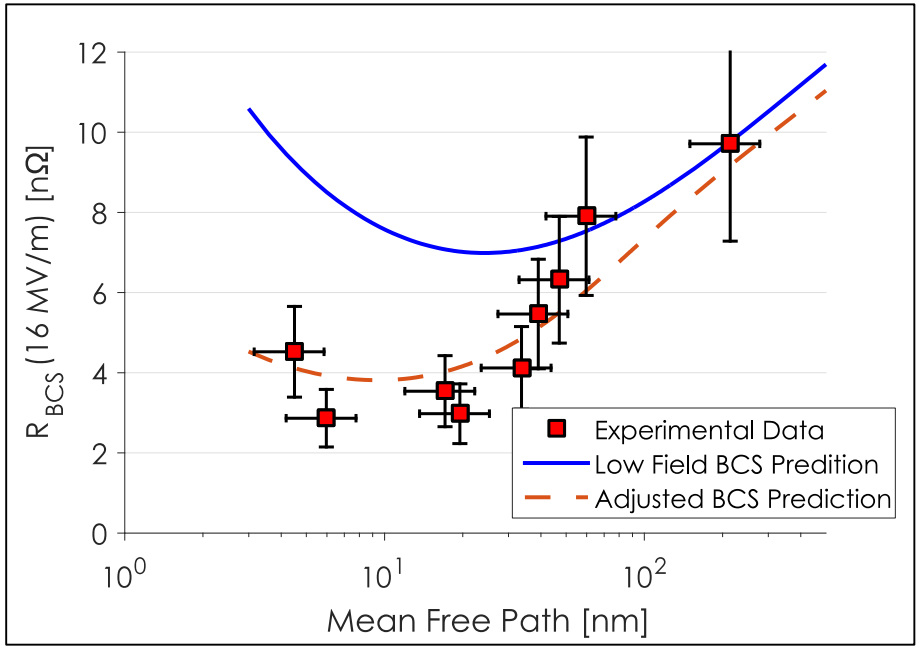
- Nitrogen-doped cavities have lower mean free paths and thus lower B_{c1}

1. **Stronger nitrogen-doping leads to lower quench fields**
2. **Low field quenches in nitrogen-doped cavities are centered at defects**
3. **Strong evidence for quenches in N-doped cavities being due to early flux entry!**

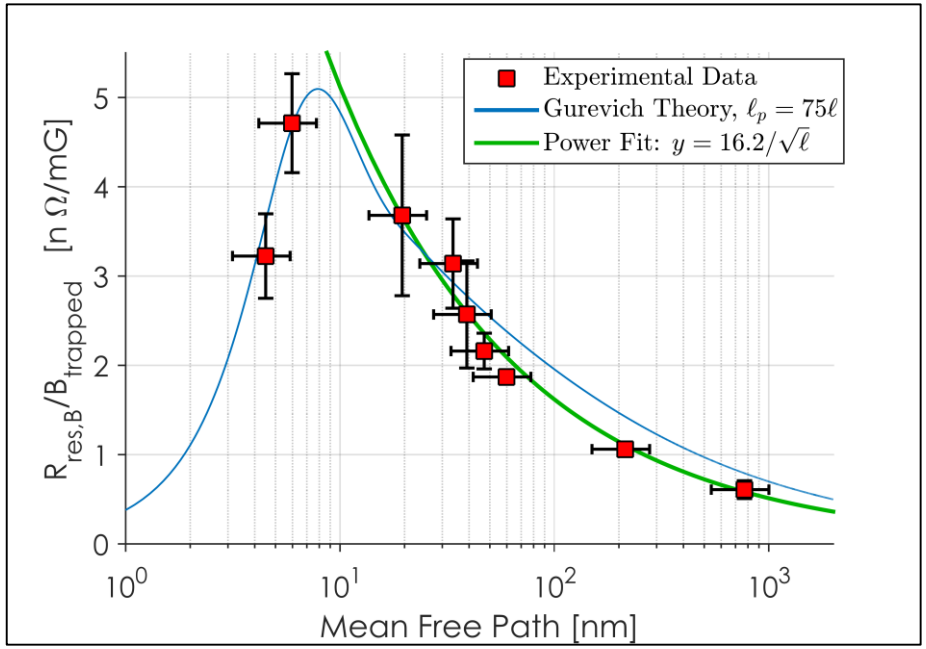
Is there an optimal doping level?

Is There an Optimal Doping?

R_{BCS}(16 MV/m) vs Mean Free Path

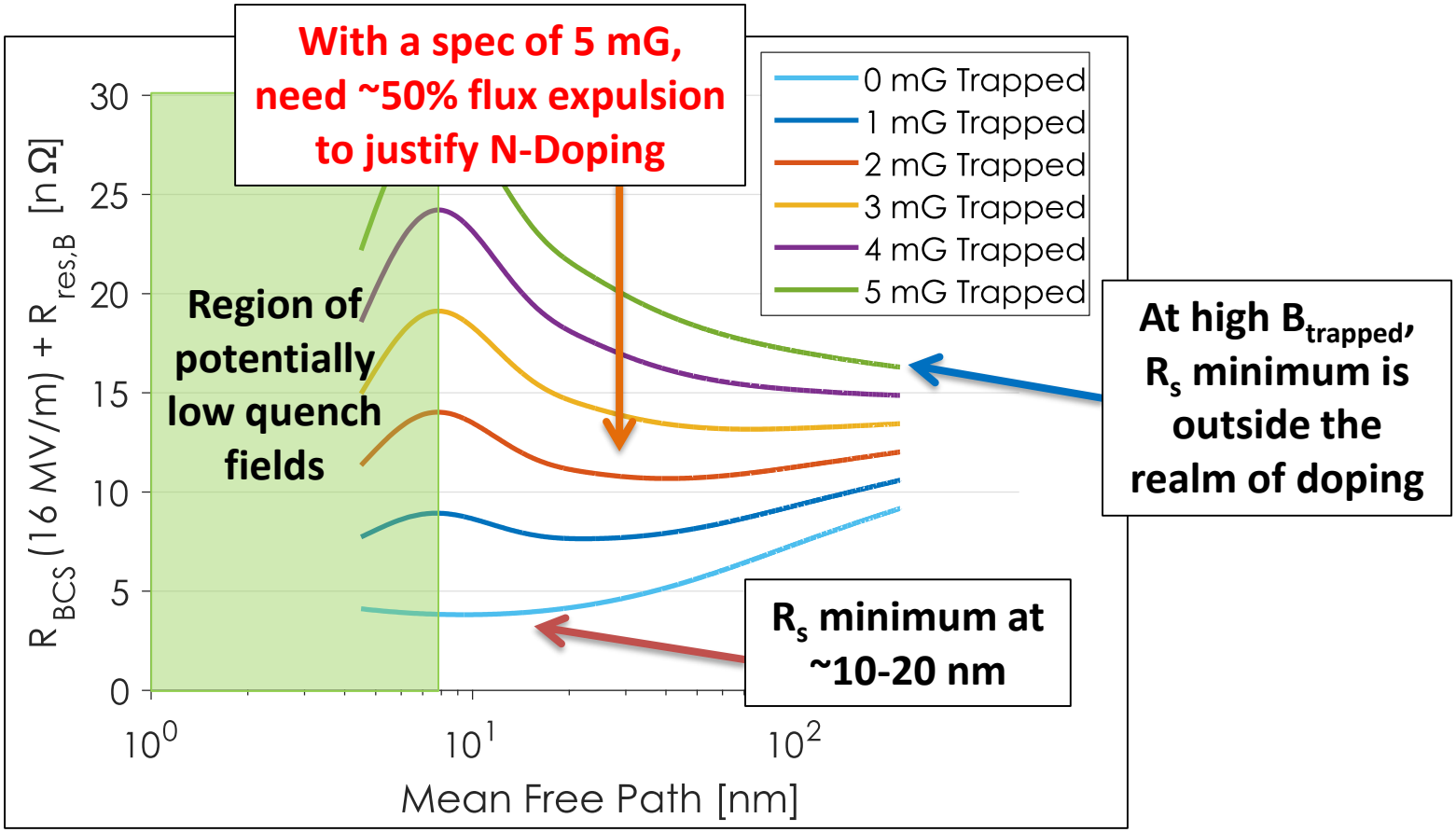


$R_{res,B}/B_{trapped}$ vs Mean Free Path



Can we combine these and find an "optimal doping level" at which the sum of R_{BCS}(16 MV/m) and $R_{res,B}$ are minimized?

Is There an Optimal Doping?

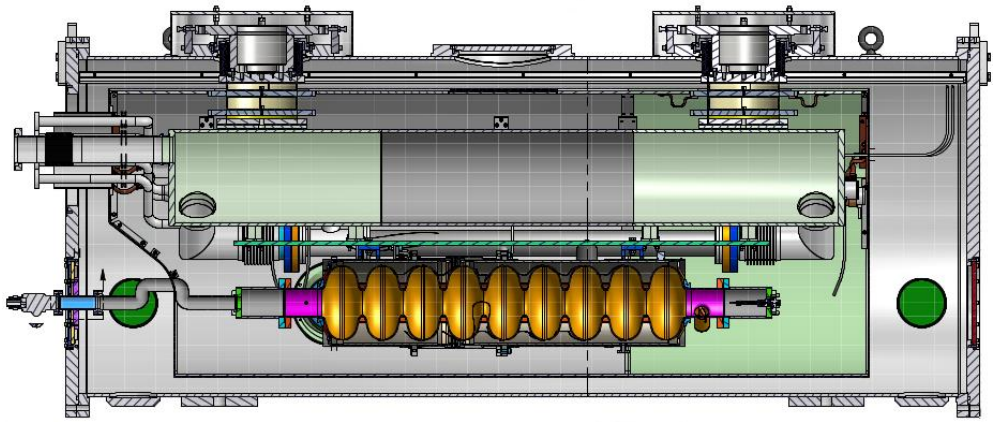


- With lower amounts of trapped magnetic flux, moderate doping is better
- With higher amounts of trapped magnetic flux, lower doping is better

Outline

- Motivation
- Introduction to Superconducting RF
- Nitrogen-Doping of SRF Cavities
- BCS Resistance Studies
- Residual Resistance Studies
- High Field Limits
- Transition to Full Cryomodule
- Conclusions

The Cornell HTC



The Cornell Horizontal Test Cryomodule (HTC) is a full cryomodule capable of holding one 9-cell cavity

The HTC is a close representation of a short section of the full LCLS-II Cryomodule

Me Next to the Fully Assembled HTC

Transition to Full Cryomodule

2 Main Concerns between VT and HT:

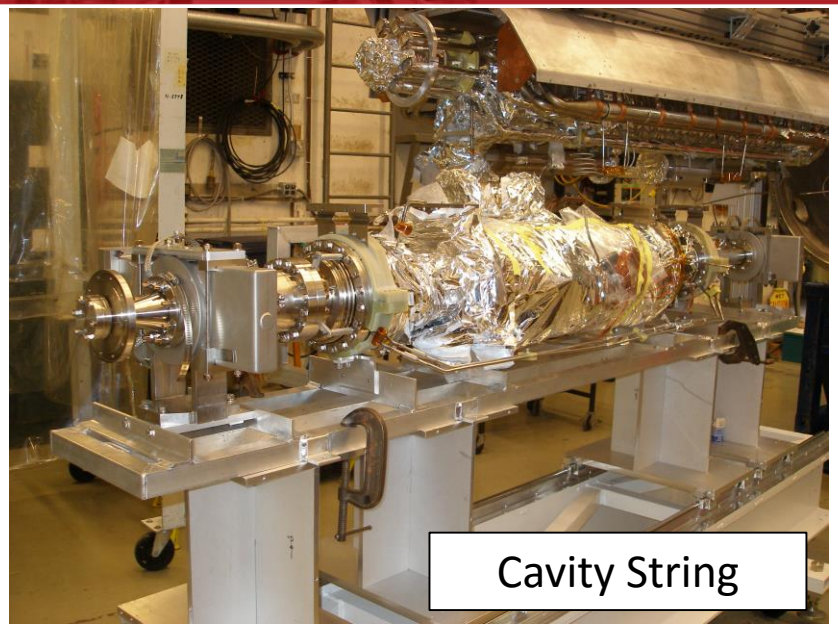
- Does assembling in a cryomodule degrade Q_0?
- Can we adequately cool nitrogen-doped cavities in a cryomodule to reach high Q_0?

Me Assembling the HPC for HTC9-4

Cornell Technicians working on the String Assembly

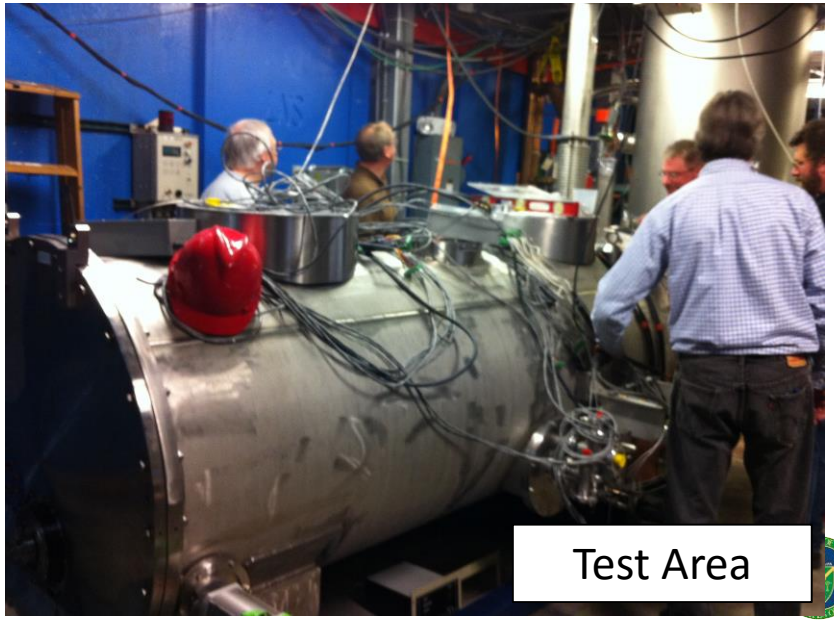
HTC Assembly

Solenoid Assembly



Cavity String

Fully Assembled Cryomodule

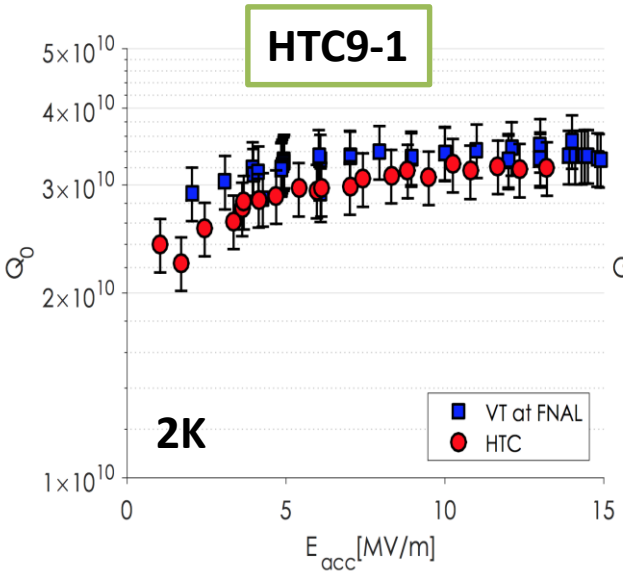


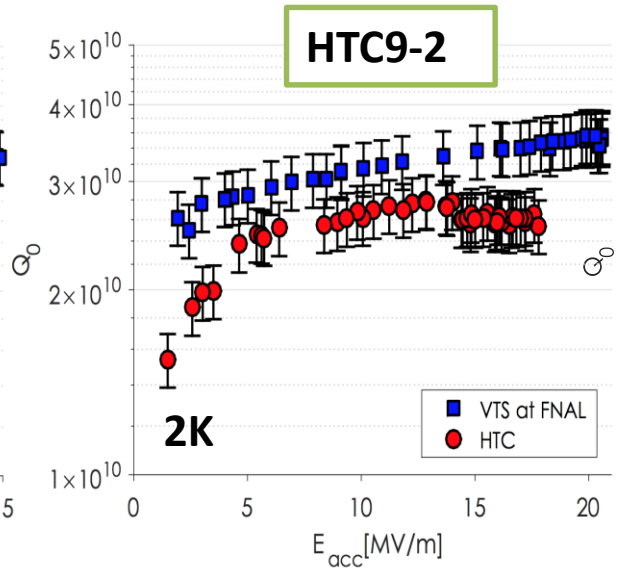
Test Area

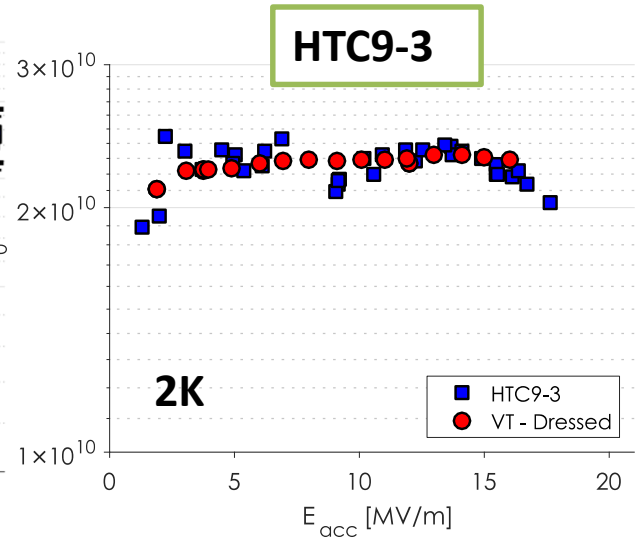
Organization of HTC Tests

Test	Cavity	Prepared By	RF Coupler	Helium Vessel	Other
HTC9-1	ACC012	FNAL	High Q	ILC	
HTC9-2	AES011	FNAL	High Q	ILC	
HTC9-3	AES018	Cornell	High Q	LCLS-II	Solenoid
HTC9-4	AES018	Cornell	LCLS-II	LCLS-II	
HTC9-5	AES030	JLab	LCLS-II	LCLS-II	Tuner, HOM Couplers

Change from VT to HT

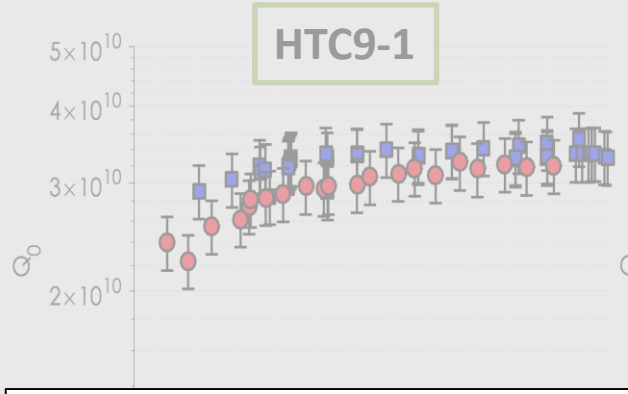


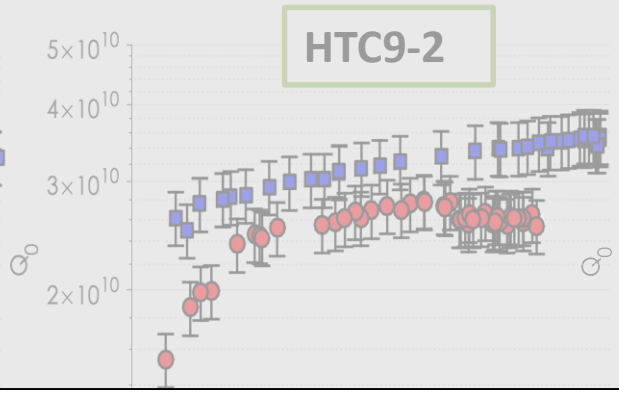


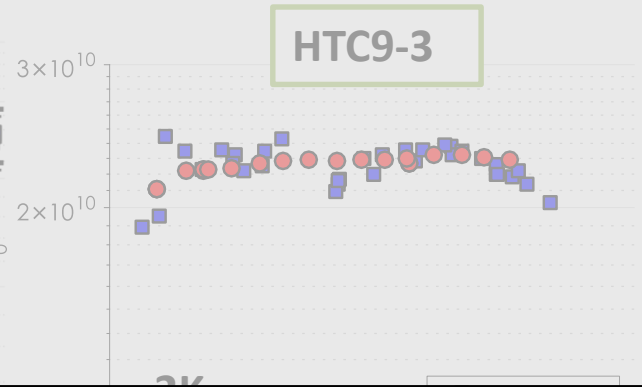


Cavity	Lhe Tank	HTC Test	VT Result	HT Result	$\Delta R_{VT\text{->}HT}$ [nΩ]
TB9ACC012	ILC	HTC9-1	$(3.5\pm0.4)\times10^{10}$	$(3.2\pm0.3)\times10^{10}$	1 ± 2
TB9AES011	ILC	HTC9-2	$(3.4\pm0.3)\times10^{10}$	$(2.7\pm0.3)\times10^{10}$	2 ± 2
TB9AES018	LCLS-II	HTC9-3	$(2.2\pm0.3)\times10^{10}$	$(2.2\pm0.2)\times10^{10}$	0 ± 1
TB9AES031	LCLS-II	HTC9-5	$(2.3\pm0.3)\times10^{10}$	$(2.3\pm0.3)\times10^{10}$	0 ± 1

Change from VT to HT







Conclusion 1: No significant change in performance when cavity is installed in a cryomodule

Cavity	Lhe Tank	HTC Test	VT Result	HT Result	$\Delta R_{VT\text{->}HT}$ [nΩ]
TB9ACC012	ILC	HTC9-1	$(3.5\pm0.4)\times10^{10}$	$(3.2\pm0.3)\times10^{10}$	1 ± 2
TB9AES011	ILC	HTC9-2	$(3.4\pm0.3)\times10^{10}$	$(2.7\pm0.3)\times10^{10}$	2 ± 2
TB9AES018	LCLS-II	HTC9-3	$(2.2\pm0.3)\times10^{10}$	$(2.2\pm0.2)\times10^{10}$	0 ± 1
TB9AES031	LCLS-II	HTC9-5	$(2.3\pm0.3)\times10^{10}$	$(2.3\pm0.3)\times10^{10}$	0 ± 1

Optimal Cooling Scheme

What is the best way to cool cavities in a cryomodule?

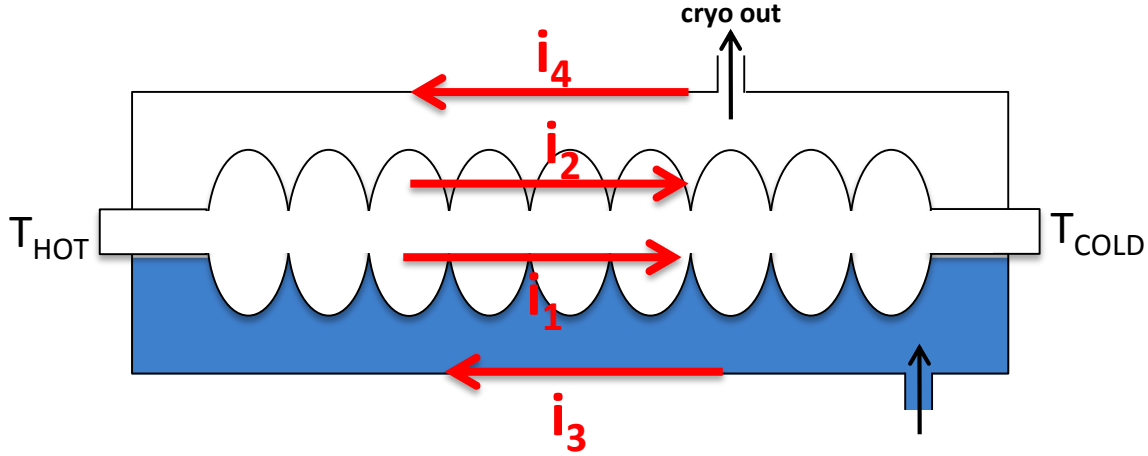
Cooling in HT

Flux Expulsion

Large temperature gradients lead to more efficient flux expulsion

Large ΔT → GOOD

Thermoelectric Currents



- Temperature gradients across a bimetal junction will result in a current flowing due to the Seebeck effect

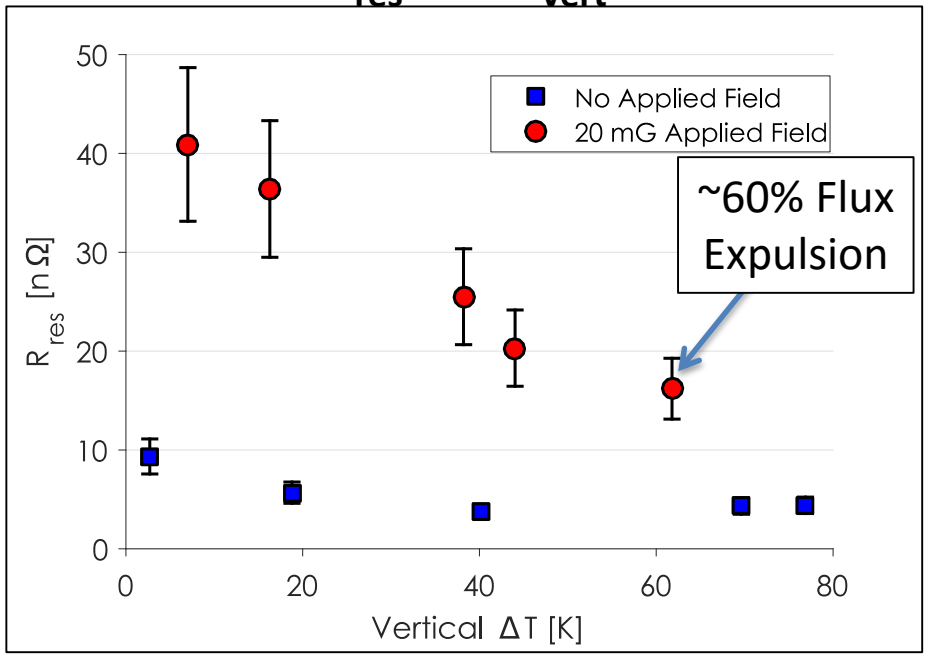
$$I = \left(\int_{T_1}^{T_2} [S_{Nb} - S_{Ti}] dT \right) \Delta T_{horiz} / R$$

- This current will result in an additional magnetic field

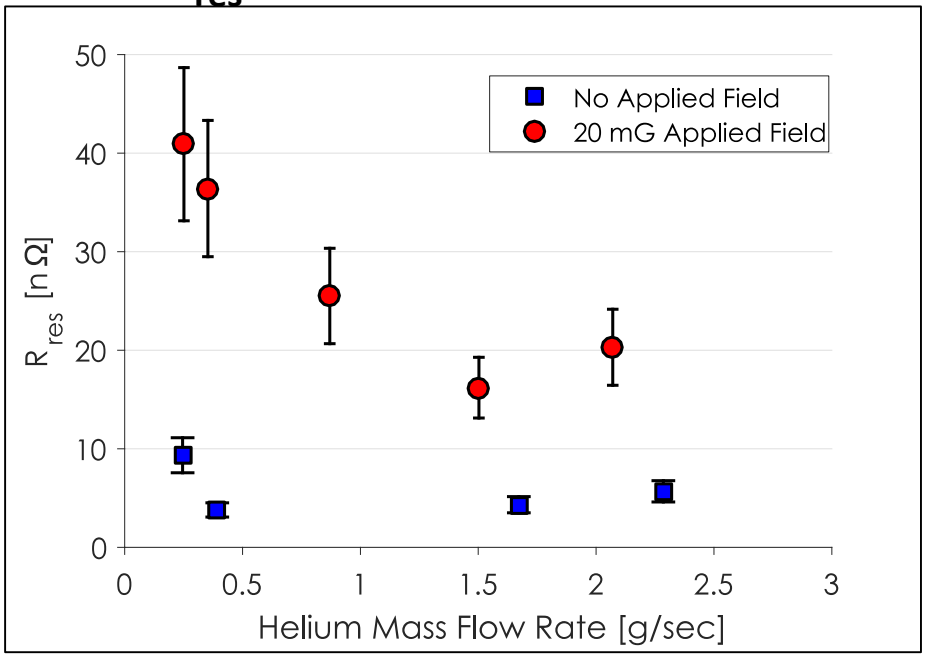
Large ΔT → BAD

Flux Expulsion in HT

R_{res} vs ΔT_{vert}

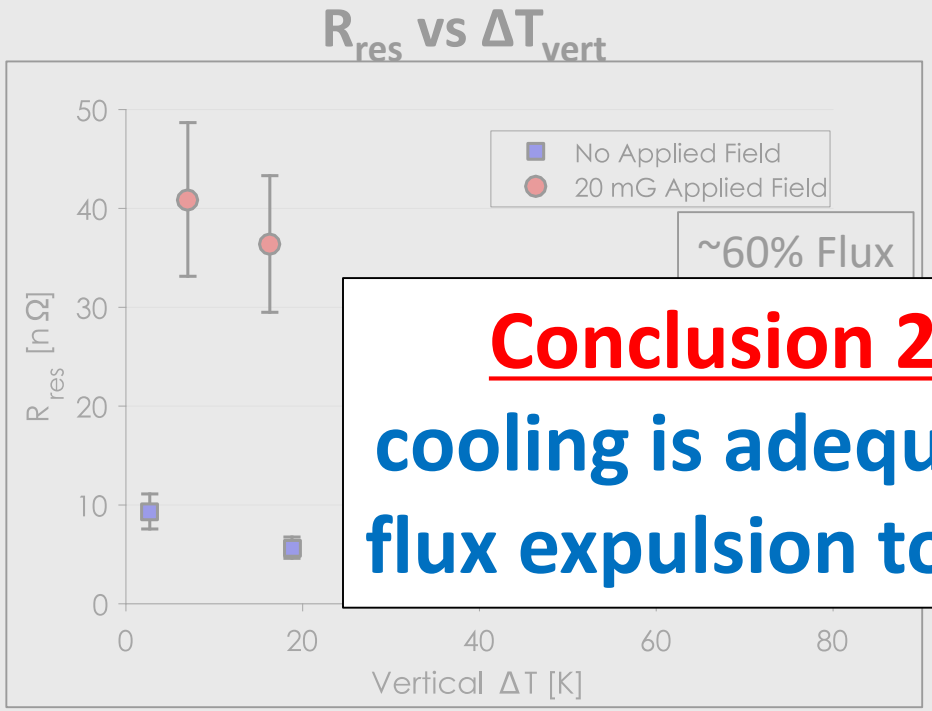


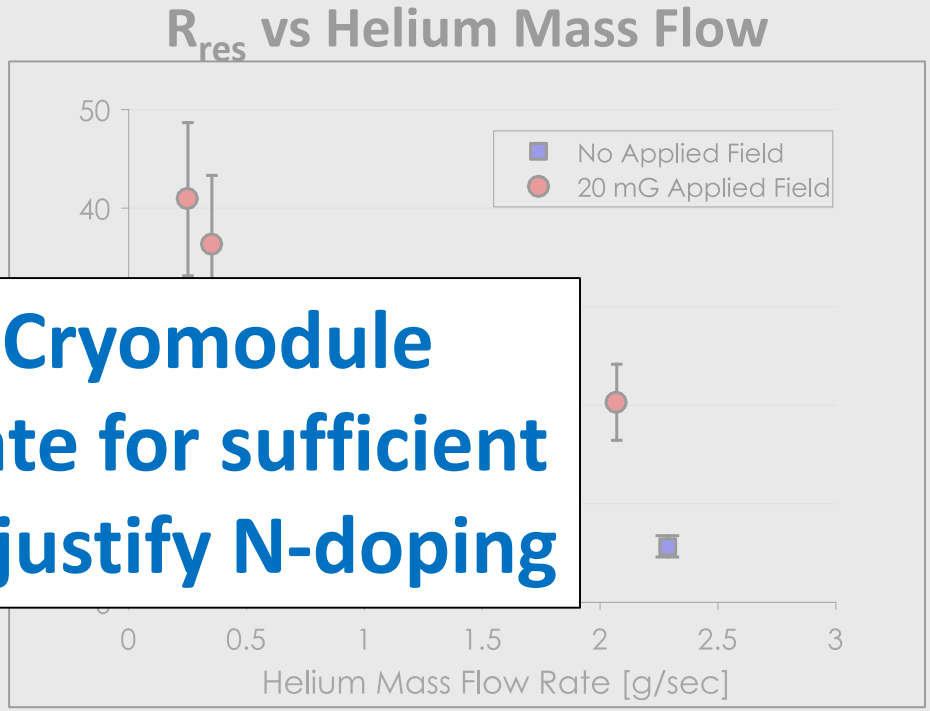
R_{res} vs Helium Mass Flow



- Large vertical temperature gradients are necessary for flux expulsion
- Helium mass flow rate directly leads to vertical gradients

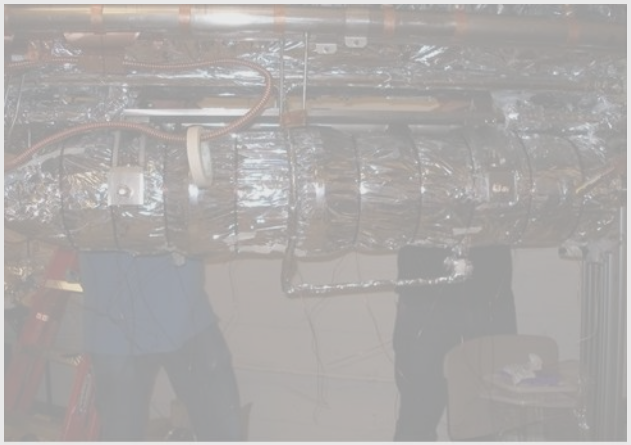
Flux Expulsion in HT





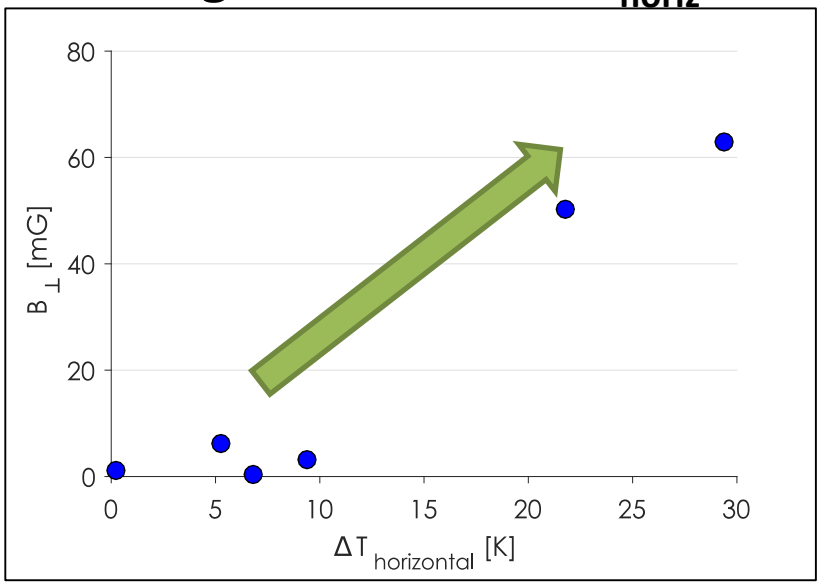
Conclusion 2: Cryomodule cooling is adequate for sufficient flux expulsion to justify N-doping

- Large vertical temperature gradients are necessary for flux expulsion
- Helium mass flow rate directly leads to vertical gradients

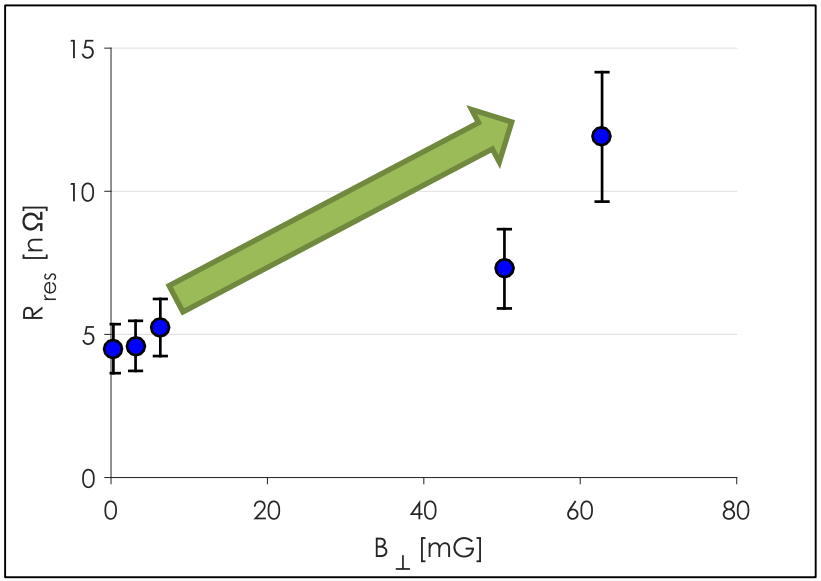


Thermoelectric Currents

Magnetic Field vs ΔT_{horiz}

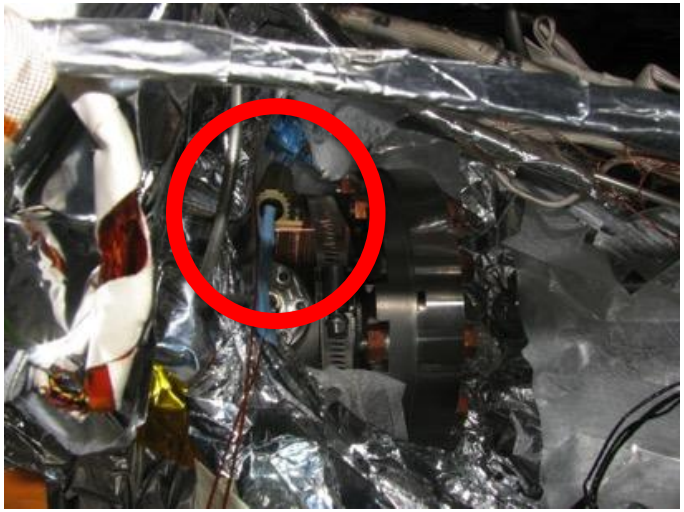


R_{res} vs Magnetic Field

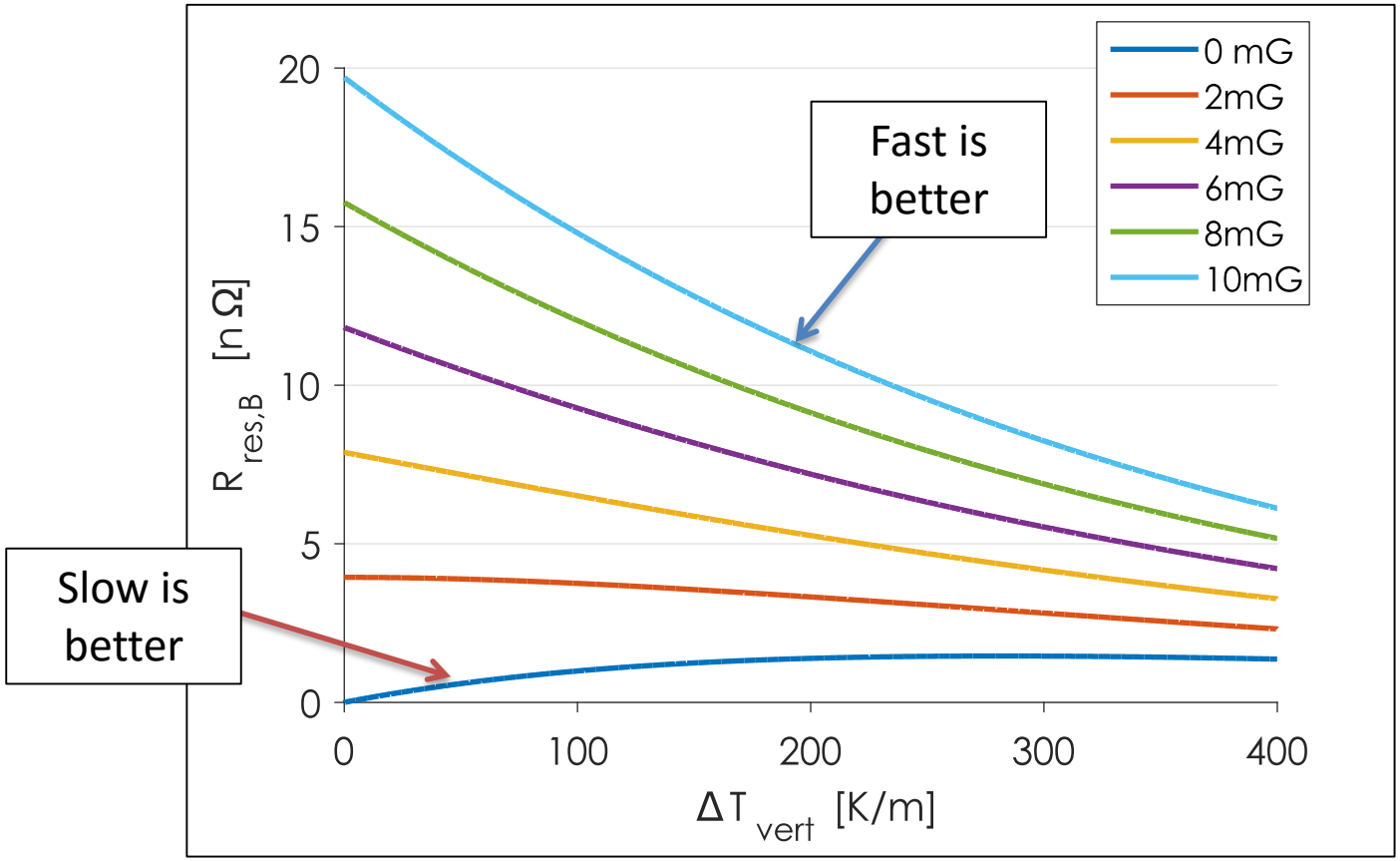


For ILC tank

- Larger horizontal temperature gradients lead to larger induced magnetic fields from thermoelectric currents
- These larger fields led to larger residual resistance in the cavity



Optimal Cooling Scheme



Conclusion 3: In small ambient magnetic fields, slow cool down should be used, in large ambient magnetic fields, fast cool down should be used

Transition to Cryomodule

1. Assembly in a cryomodule does not inherently degrade cavity performance
2. Cavities can be cooled with large enough vertical temperature gradients to enable efficient flux expulsion in a cryomodule
3. Slow cool down is better in small ambient fields – fast is better in large ambient fields

Outline

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- Residual Resistance Studies
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- Conclusions

Conclusions

4 Fundamental Questions:

- What leads to Q_0 improvement in nitrogen-doped cavities and can it be optimized?
- How do ambient magnetic fields affect doped cavities?
- What are the maximum fields reachable in doped cavities?
- Can cavity performance be maintained in a cryomodule?

Conclusions

What leads to Q_0 improvement in nitrogen-doped cavities and can it be optimized?

1. **Low field improvement in Q_0 is due to the lowering of the mean free path leading to a lower R_{BCS}**
2. **Anti-Q slope is a result of a decreasing R_{BCS} which decreases roughly as the logarithm of the magnitude of the RF field**
3. **Stronger doping (lower mean free path) leads to a stronger anti-Q slope**

Conclusions

How do ambient magnetic fields affect doped cavities?

1. Larger temperature gradients during cool down lead to better flux expulsion and thus less trapped magnetic flux
2. Cavities with different mean free paths show very different sensitivities of residual resistance to trapped flux
3. Shorter mean free paths lead to larger sensitivities down to ~10 nm, then shorter mean free paths lead to smaller sensitivities
4. Experimental data shows good agreement with Gurevich's theory of residual losses due to vortex oscillations

Conclusions

What limits the maximum field reachable in doped cavities?

1. **Stronger nitrogen-doping leads to lower quench fields**
2. **Low field quenches in nitrogen-doped cavities are centered at defects**
3. **Quenches in N-doped cavities are due to early flux entry at defects!**

Conclusions

Can cavity performance be maintained in a cryomodule?

- **YES!**
- I've demonstrated no significant degradation in Q due to assembly in the cryomodule
- Cavities in the cryomodule can be cooled with large enough temperature gradients to expel magnetic flux and reach high Q_0

Conclusions

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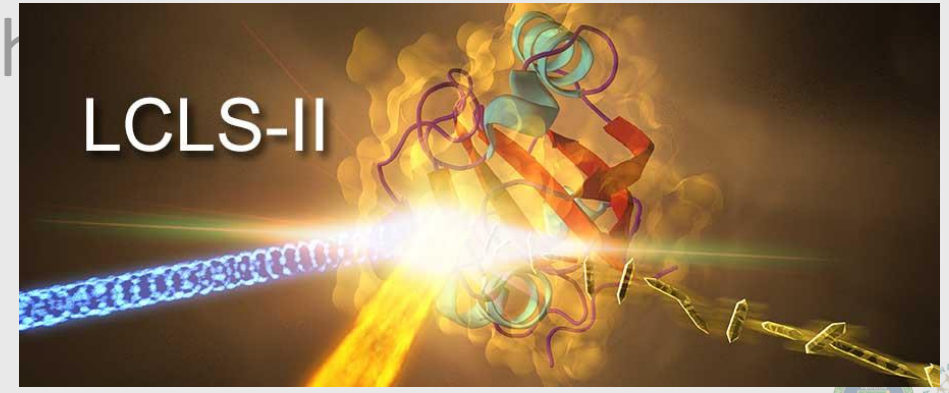
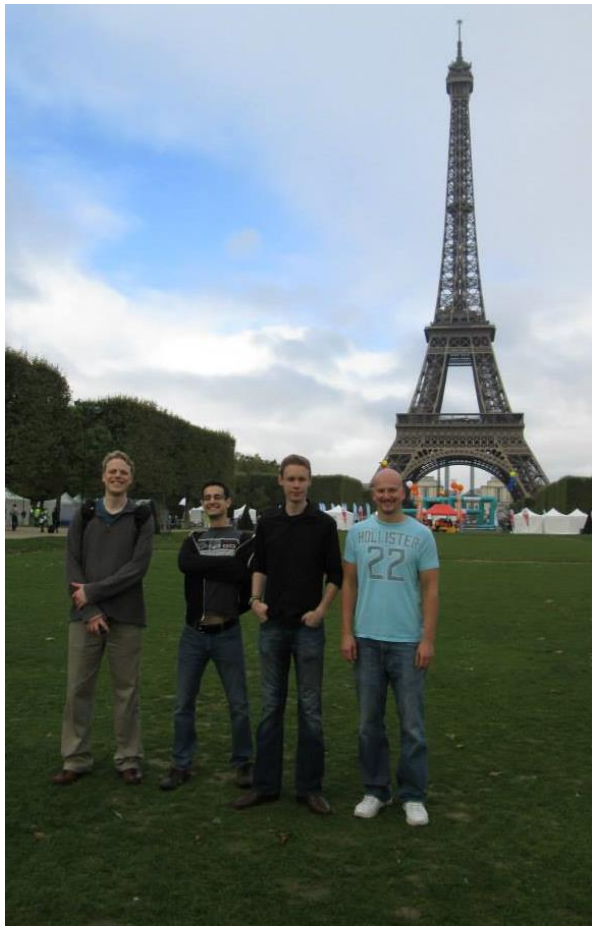
- radation in e
- oled with to expel magnetic flux and reach



Special thanks to Matthias Liepe, Sam Posen, Dan Hall, Nick Valles, James Maniscalco, Pete Koufalis and the Newman Staff!



Thanks for your attention!