R&D at JLAB Towards High Performance Superconducting RF Cavities

Pashupati Dhakal

03/14/2018

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Nuclear Science Seminar, MSU

Jefferson Lab

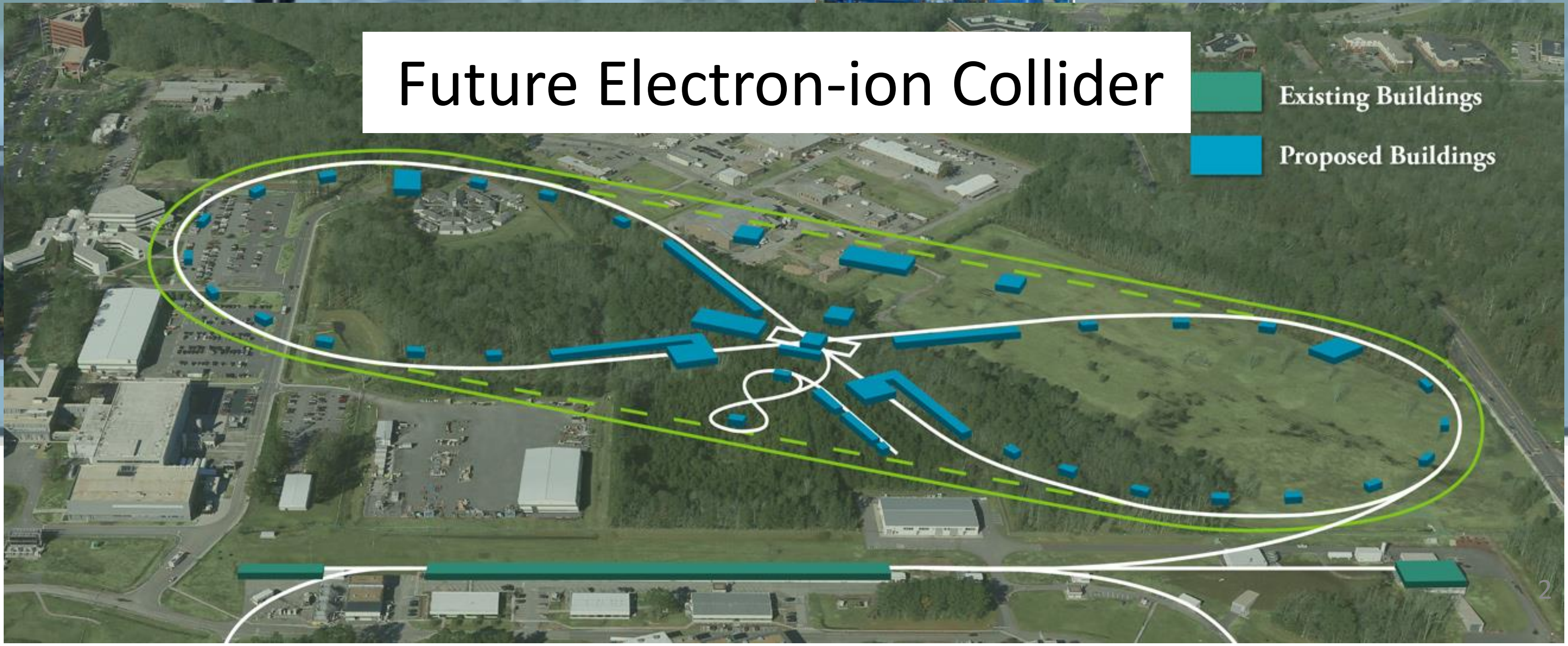
Injector

Accelerator

7/8 of a mile around

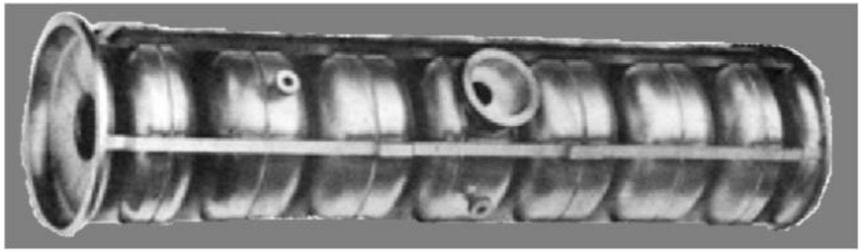
magnets

Future Electron-ion Collider



HISTORICAL MILESTONES

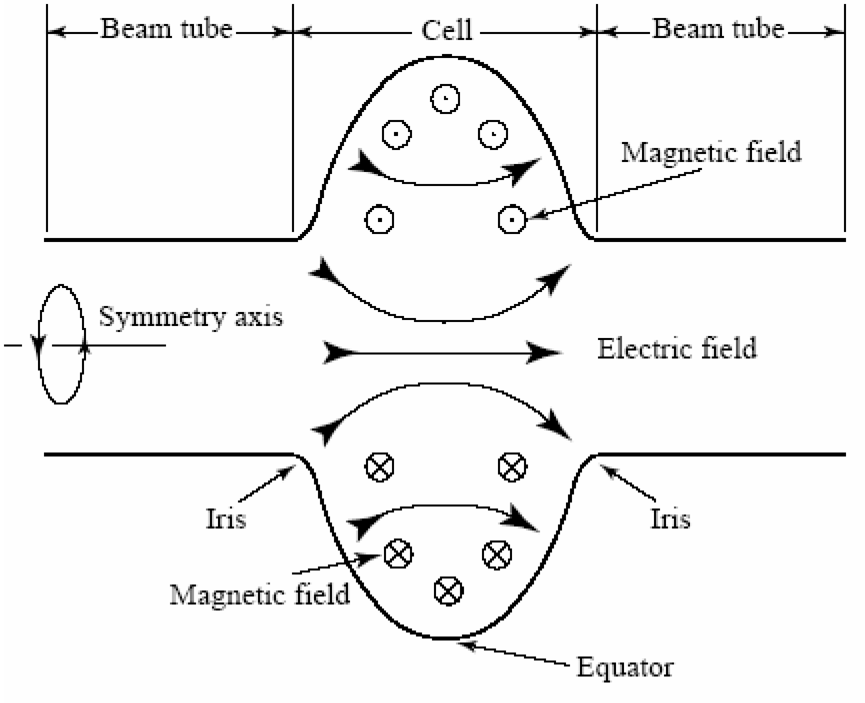
1908 : **Kamerlingh Onnes** (Liquefied Helium)
1911 : **Kamerlingh Onnes** (Discovery of superconductivity)
1928-34 : **Meissner** (Discovered superconductivity of Nb)
1924 : **Gustaf Ising** (First Publication of RF acceleration)
1928 : **Rolf Wideroe** (Build first RF accelerator)
1947 : **Luis Alverez** (USA) (Build first DTL 32 Mev protons)
1947 : **W. Hansen** (USA) (Build first 6 MeV e-accelerator, Mark I)
1961 : **W. Fairbank** (Stanford) (First proposal for superconducting accelerator for e^-)
1964 : **Fairbank, Schwettman and Wilson** (Stanford) (First acceleration of e^- with SC lead cavity
1970 : **J. Turneaure** (Stanford) , **Epeak = 70 MV/m and Q ~ 10^{10}** in 8.5 GHz cavity
1968-81 : **M. McAshan, A. Schwettman, T. Smith, J. Turneaure, P. Wilson** (Stanford) Developed and Constructed the Superconducting Accelerator

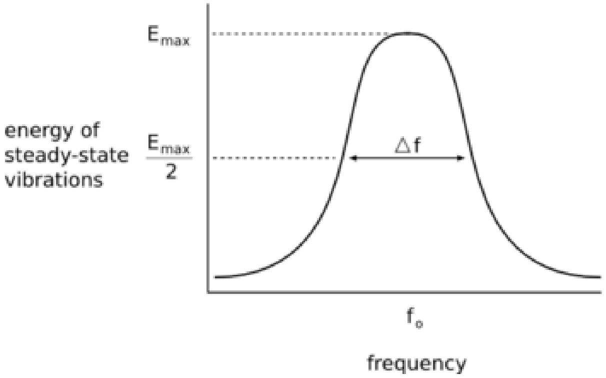


Since then, many superconducting accelerators were built and many more are constructing and making plans for many new facilities.

SRF CAVITY

- A resonant cavity is the high-frequency analog of a LCR resonant circuit.
- RF power at resonance builds up high electric fields used to accelerate charged particles.
- Energy is stored in the electric & magnetic fields.





$$Q = \Delta f/f$$

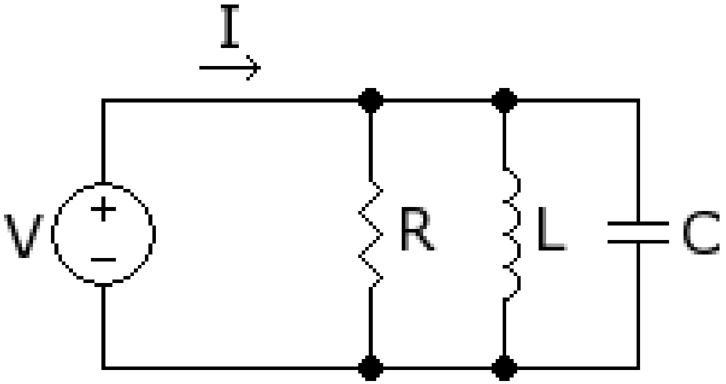


FIGURE OF MERITS

Surface current (∞ H) results in power dissipation proportional to the surface resistance (R_s)

$$\frac{\mathrm{dP_c}}{\mathrm{ds}} = \frac{1}{2} R_s |H|^2$$

Total power dissipation in cavity wall $P_c = \frac{1}{2} \int_S R_s |\mathbf{H}|^2 \, \mathrm{d}s$

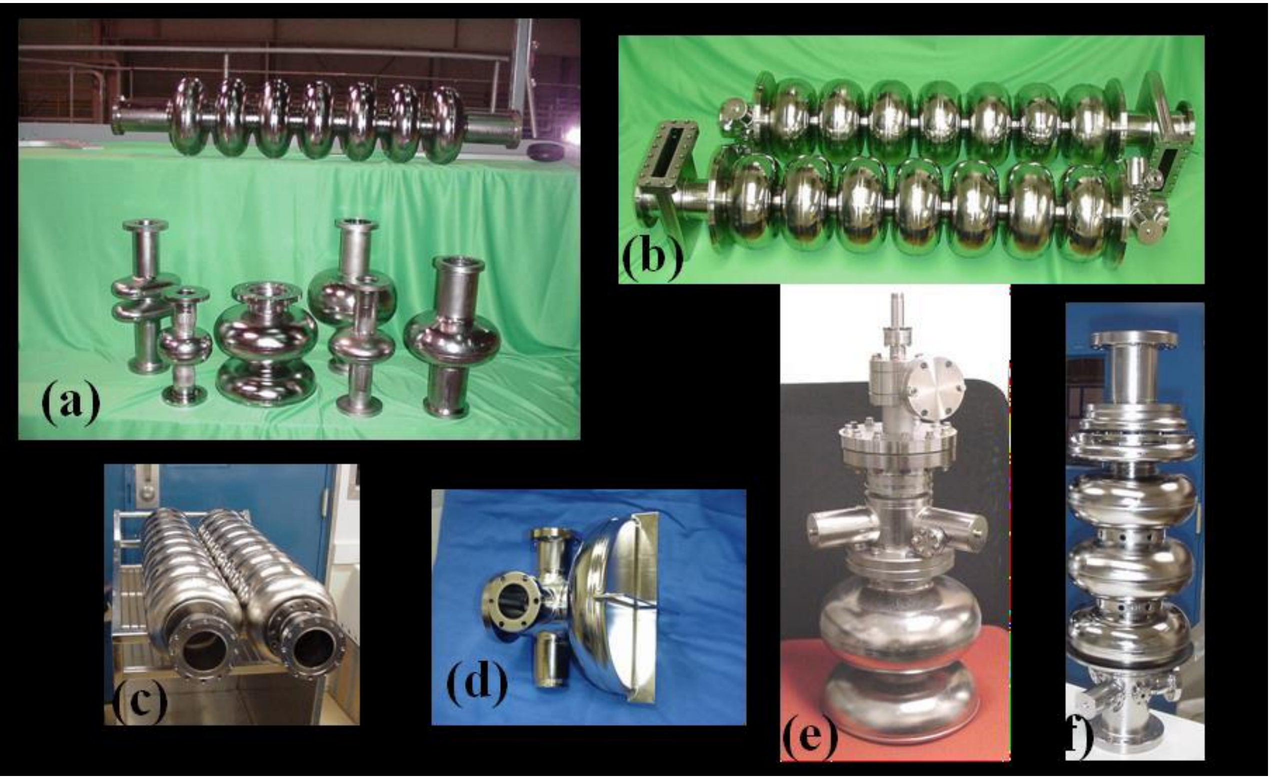
Stored energy in cavity $U = \frac{1}{2} \mu_0 \int_V |\mathbf{H}|^2 \, \mathrm{d}v$

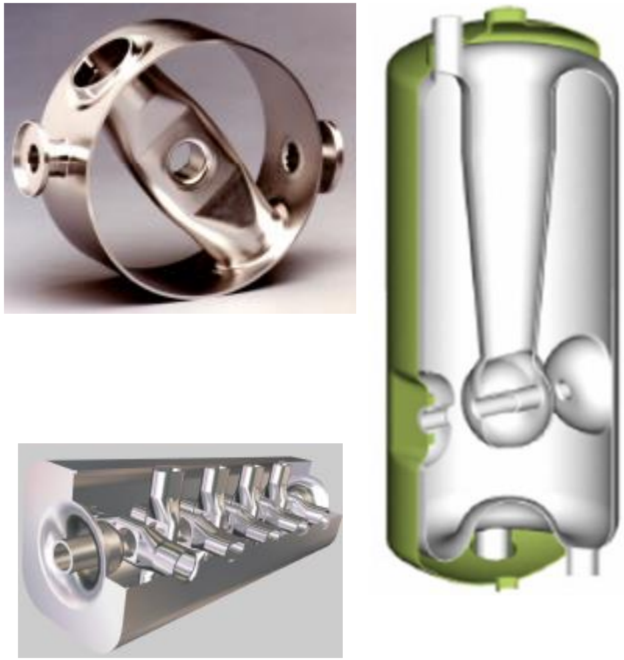
Cavity quality factor $Q_0 = \frac{\omega_0 U}{P_c} = \frac{\omega_0 \mu_0}{R_s} \frac{\int_V |\mathbf{H}|^2 \, \mathrm{d}v}{\int_S |\mathbf{H}|^2 \, \mathrm{d}v} = \frac{G}{\boxed{R_s}}$ $G = \omega_0 \mu_0 \frac{\int_V |\mathbf{H}|^2 \, \mathrm{d}v}{\int_S |\mathbf{H}|^2 \, \mathrm{d}v}$

$Q_0 \sim 10^4$ for normal conducting and $Q_0 \sim 10^{10}$ for superconducting cavities.

SRF CAVITY

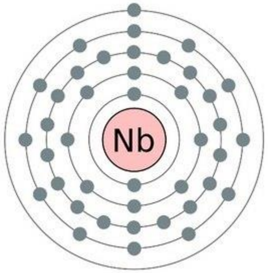
- Building bocks of modern particle accelerators.
- Mainly made from superconducting bulk Niobium.

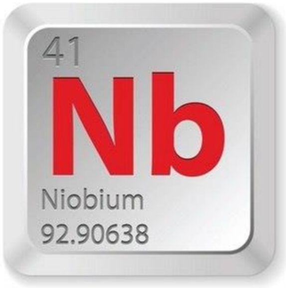




Shape and size varies on the type of applications

WHY NIOBIUM?



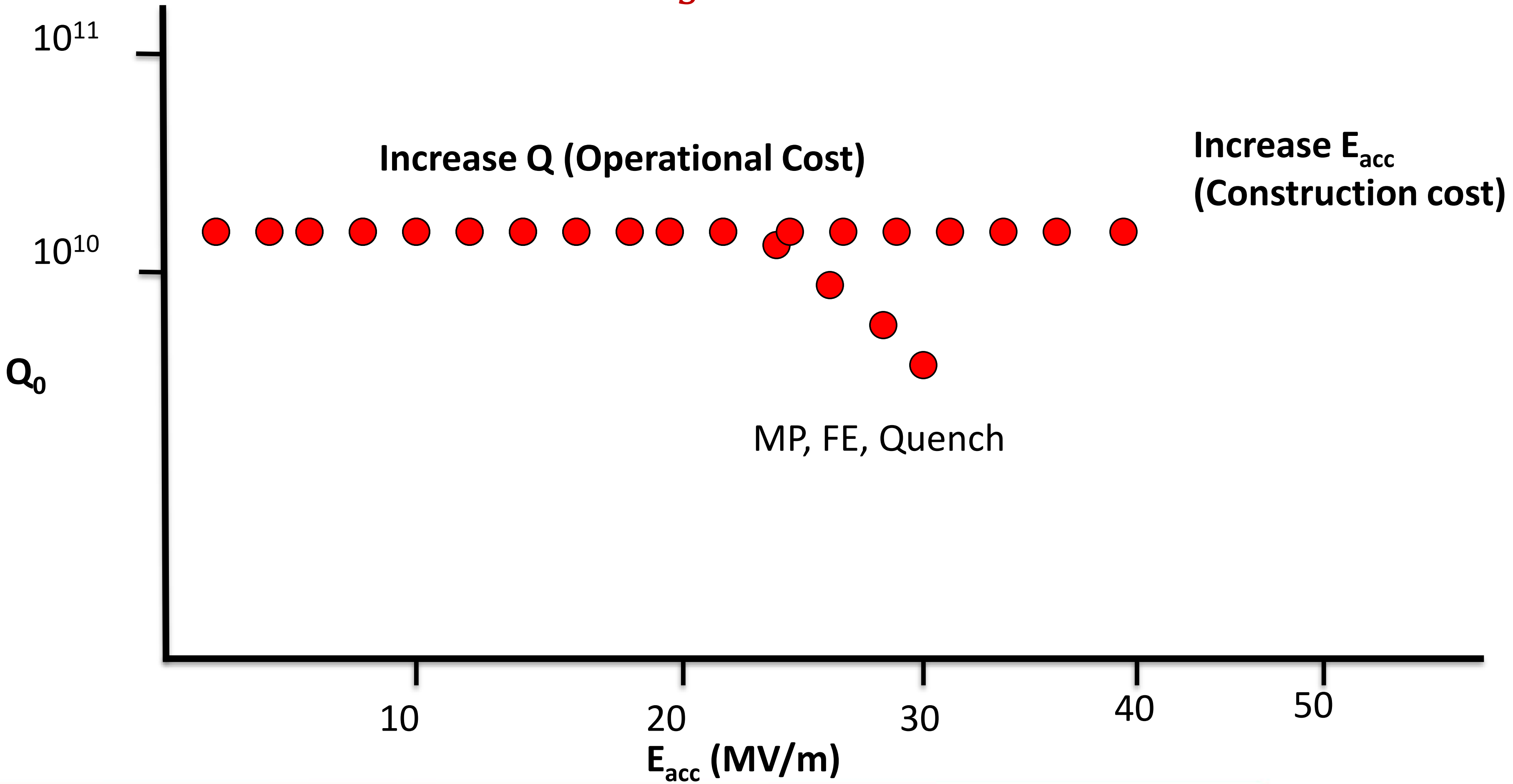


- Elemental superconductor with highest T_c (= 9.25K)
- Highest critical field (H_c ~ 200 mT).
- Chemically quite inert, however it is covered with thin oxide layers.
- It can be machined and deep drawn easily and available as bulk and sheet material of many shape, size and purity.
- It has minor disadvantage because it getters gas like hydrogen, oxygen which are found to be detrimental to SRF cavity performance.

SRF CAVITIES

Performance is measured as Q_0 (E_{acc}) Curves.

Q-factor (Q_0): $Q_0 = \frac{G}{R_S}$, G constant shape dependence



SURFACE RESISTANCE

$$R_S = R_{BCS} + \boxed{R_0 + R_{Fl}}$$

$\mathbf{R_{BCS}}$ defines by BCS resistance on the Bardeen-Cooper-Schrieffer theory of superconductivity:

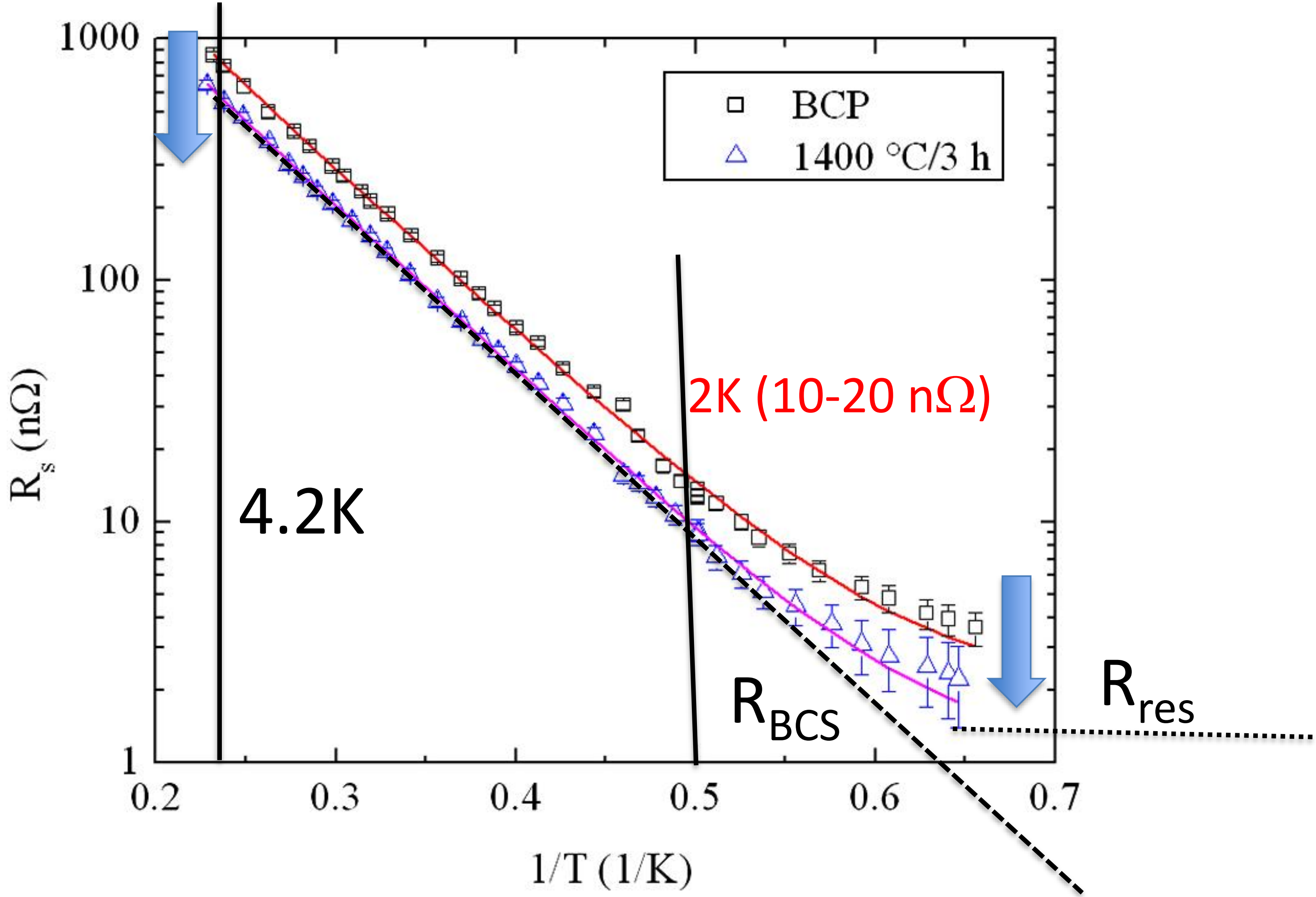
$$R_{BCS} = \left(\frac{1}{T}\right) A(\lambda_L, l, \Delta, \xi_0, f_0, T_c) e^{-\frac{\Delta}{k_B T}}$$

$\mathbf{R_0}$ defines the residual resistance depends on the purity, sub gap states, dislocations, imperfections ....

$\mathbf{R_{fl}}$ defines the resistance due to the trapped flux during the cooldown (vortex dissipation).

High Q→ minimize R_s

SURFACE RESISTANCE



SURFACE RESISTANCE

- Minimizing R_0 via heat treatments, chemical and mechanical polishing.

- Minimizing R_{BCS} via material diffusion (reduce mfp to optimal value). No clear evidence on increase in gap (Δ) yet.

- Minimizing R_{FL} via better magnetic shielding and/or better cooldown technique that minimize the trapping of residual magnetic field.

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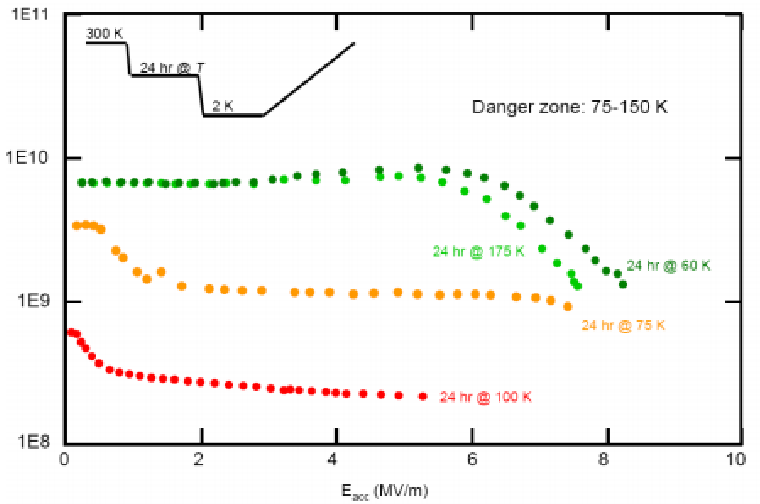
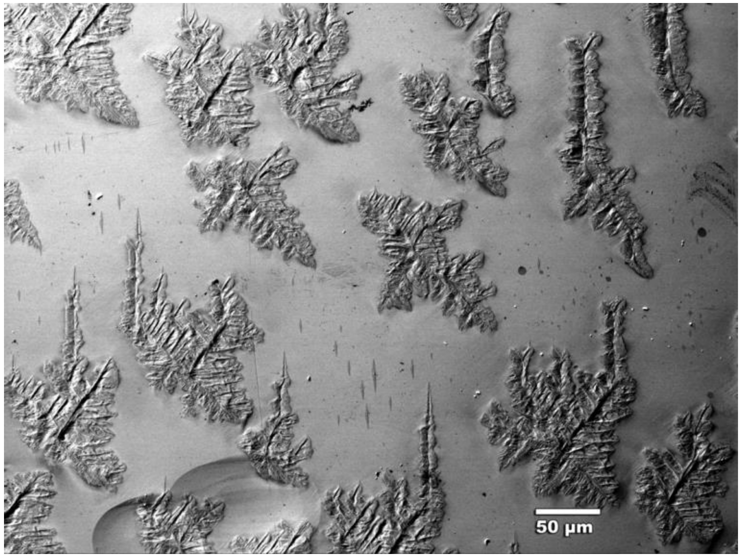
Q-DISEASE





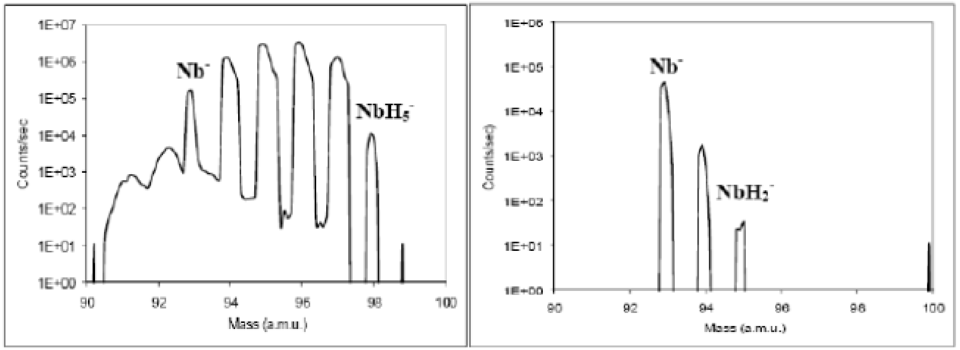
Hydrides precipitates

The hydrogen dissolved in bulk niobium under certain conditions (holding at temperature 75-150K for extended period of time) during cool down precipitate as a lossy hydride at the niobium surface.

Hydrogen can be mitigated by

- rapid cooldown through the danger temperature zone
- degassing hydrogen by heating the Nb cavity in vacuum

- Work started to understand the role of high field Q-slope with hydrogen (niobium hydrides) and **passivation of Nb surface during heat treatment**.
- The improvement on Q have been observed following the heat treatments with lower hydrogen concentrations.



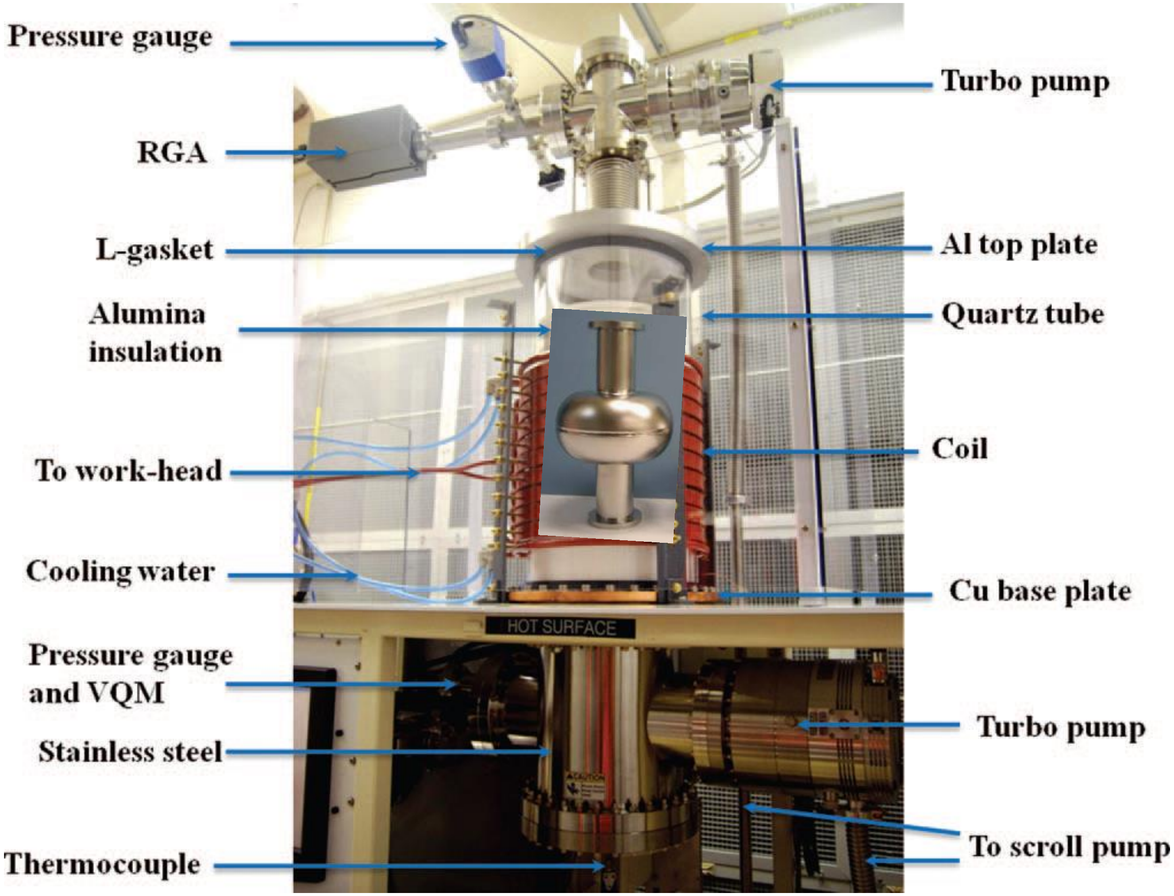
800C/ 3hrs heat treatment removes gross hydrogen

Ciovati et al, PRSTAB ***13****, 022002 (2010)*

Issue: residual gas absorbed during the cooldown, need post furnace surface removal via BCP or EP.

INDUCTION FURNACE

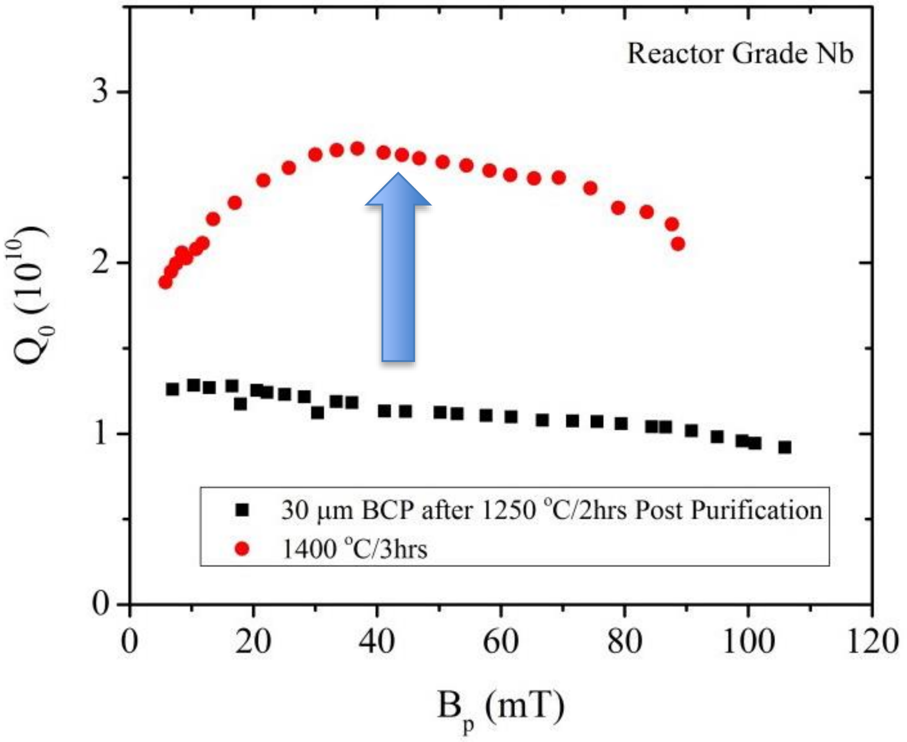
- New dedicated clean induction furnace was designed and installed in order to explore the surface passivation parameters.
- The furnace is capable to going higher than 2000C in UHV environment.
- The furnace is equipped with gas (N2, O2, Ar, H2) handling system.

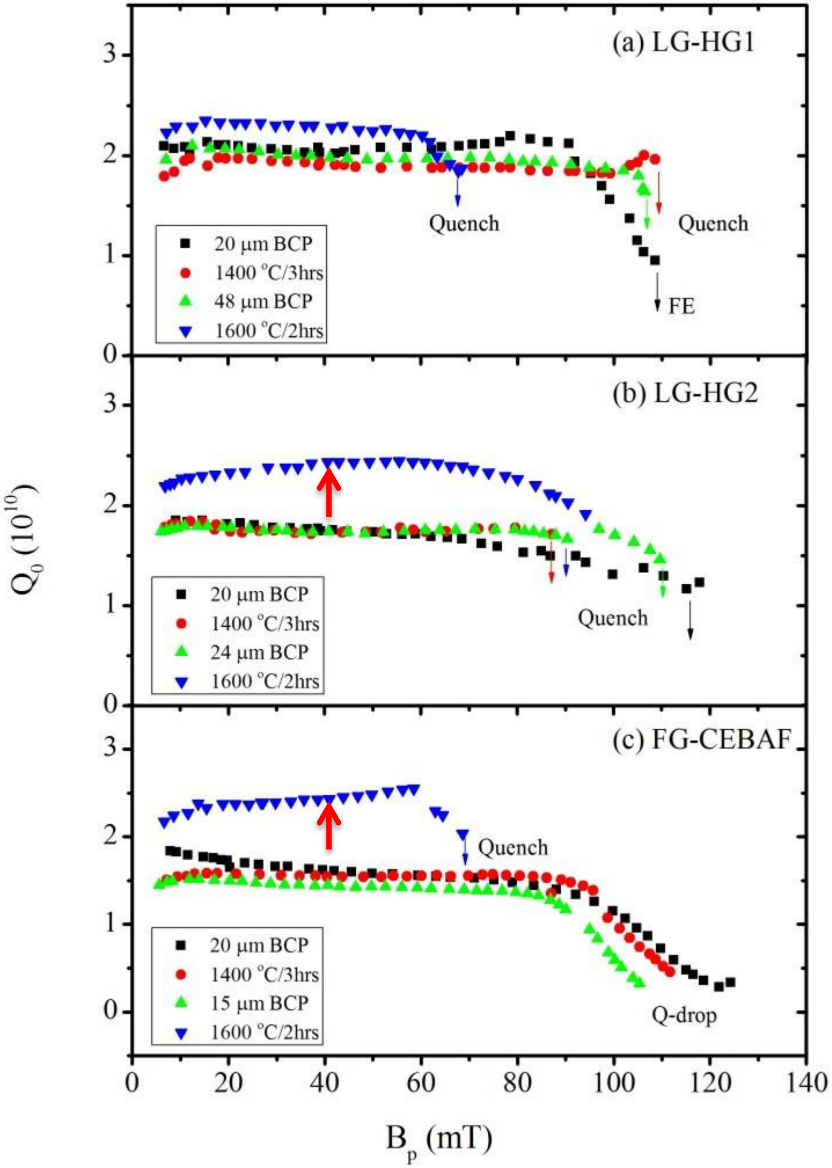


P. Dhakal et al., Rev. Sci. Inst. 83, 065105 (2012)

High Temperature Heat Treatments

T = 2.0K, f = 1.5 GHz





Increase in Q_0 was observed when the cavity was heat treated at high temperature (1400-1600C)mainly due to the reduction in residual resistance

CONCLUSION#1

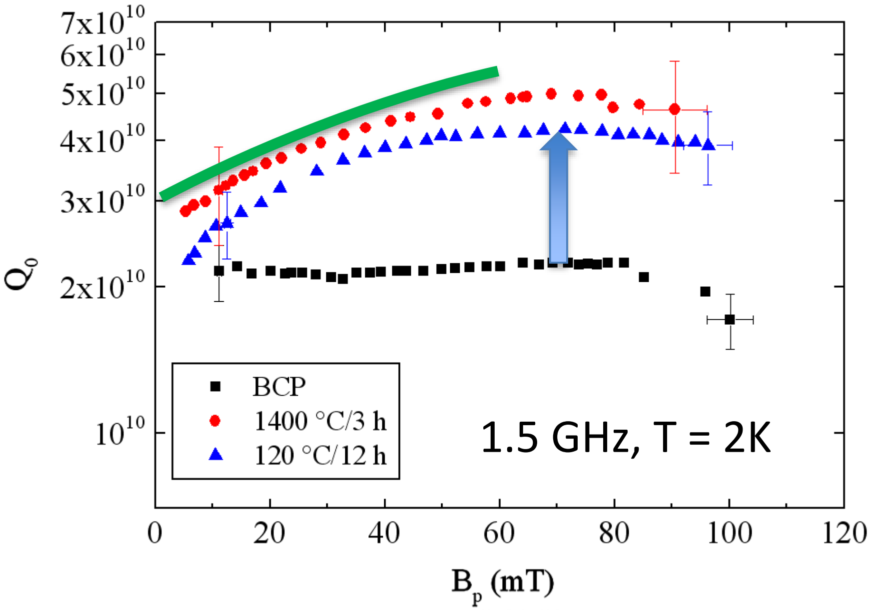
- High temperature heat treatment mainly used for hydrogen degassing and mechanical healing of SRF cavities.
- The reduced interstitial impurities and dislocations and defect sites plays role on residual resistance and can be minimized with high temperature heat treatment in clean environment.

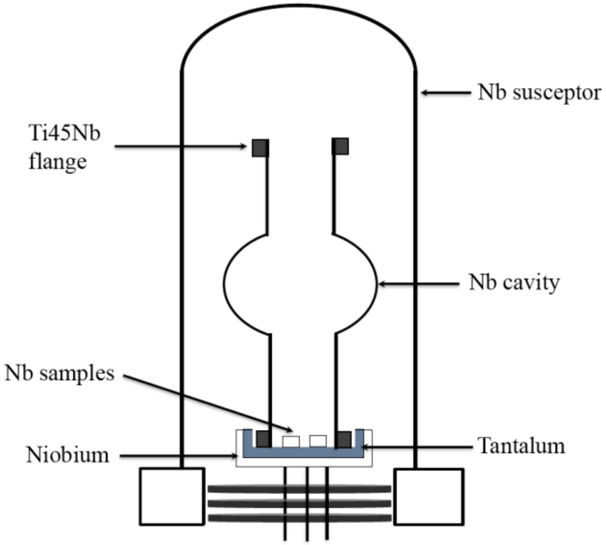
SURFACE RESISTANCE

- Minimizing R_0 via heat treatments, chemical and mechanical polishing.
- Minimizing R_{BCS} via material diffusion (reduce mfp to optimal value).
- Minimizing R_{FL} via better magnetic shielding and/or better cooldown technique that minimize the trapping of residual magnetic field.

TI-DOPING

- Exceptionally high Q was observed on 1.5 GHz cavity when cavity was heat treated at 1400C/3hrs in the presence of Ti source in furnace
- Investigation found that ~ 1 at.% of Ti was diffused with in ~2 μm on RF surface resulted in the increase in Q and more importantly the positive Q(E) dependence.

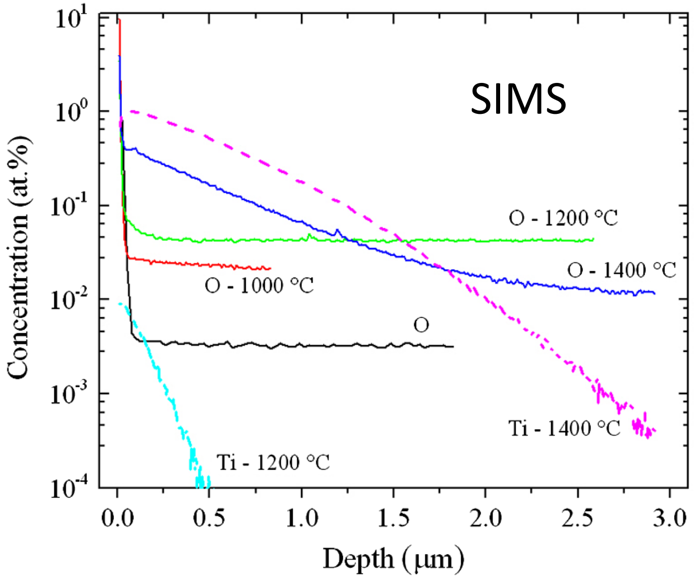


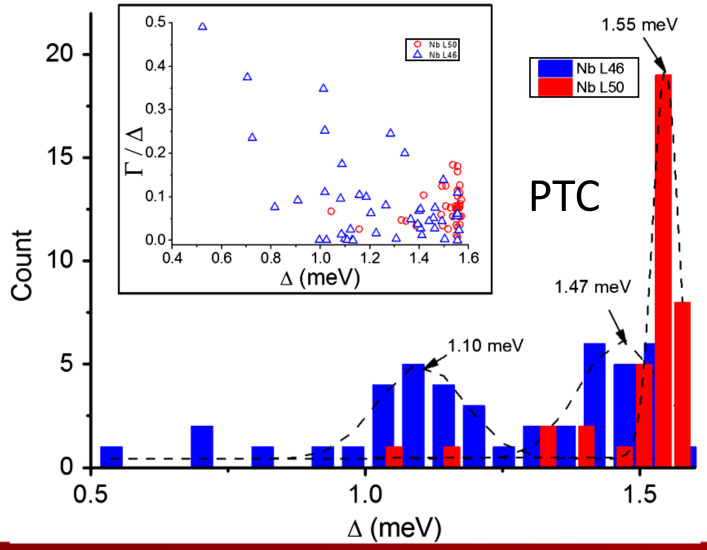


- **First demonstration of Q-rise via doping**
- **No electropolishing after doping**

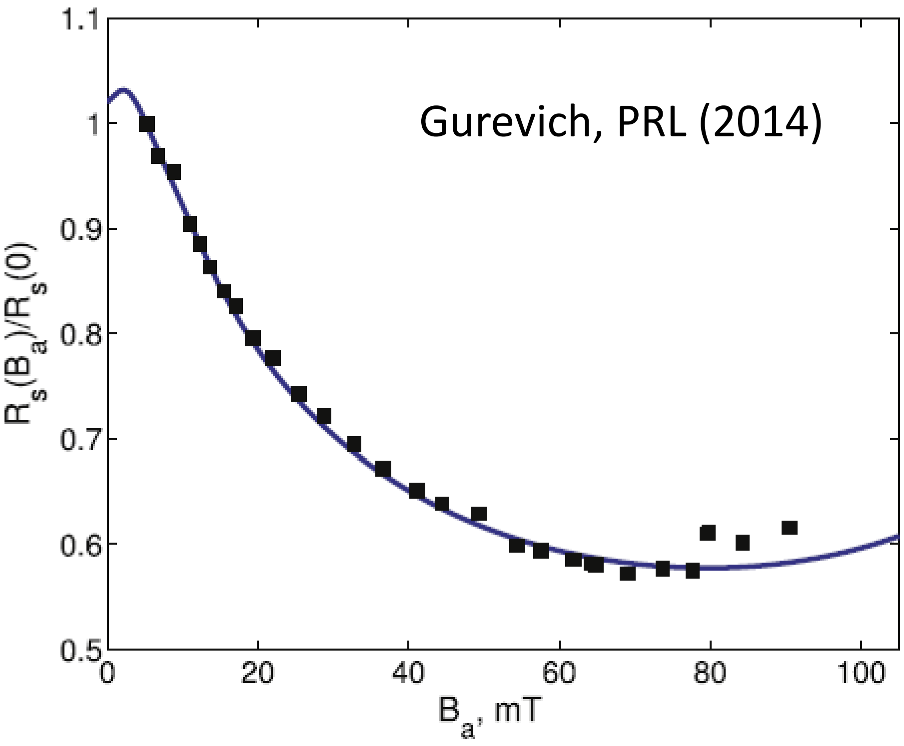
P. Dhakal et al., Phys. Rev. ST Accel. Beams 16, 042001 (2013)
P. Dhakal et al., IPAC'12, p. 2651 (2012)

TI-DOPING


SIMS


PTC

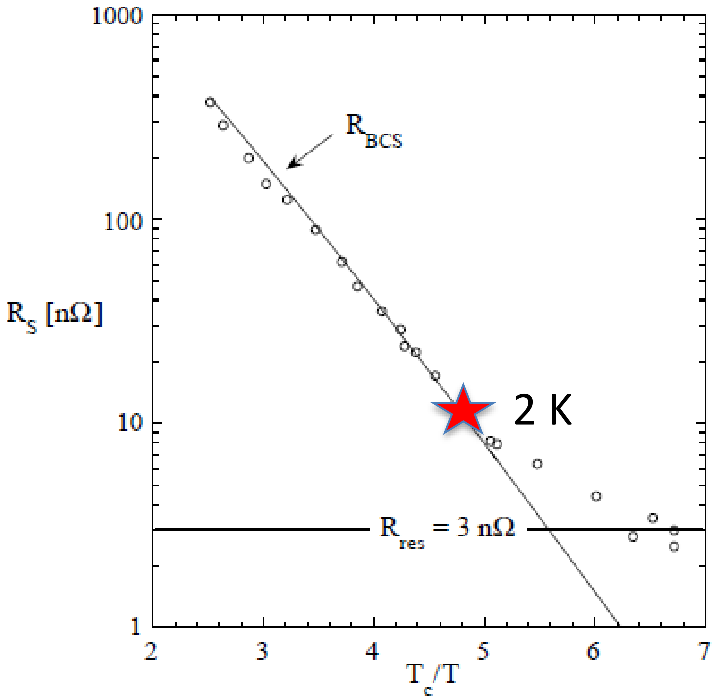
High Q was achieved due to the reduction in BCS Surface resistance due to Ti- doping


Gurevich, PRL (2014)

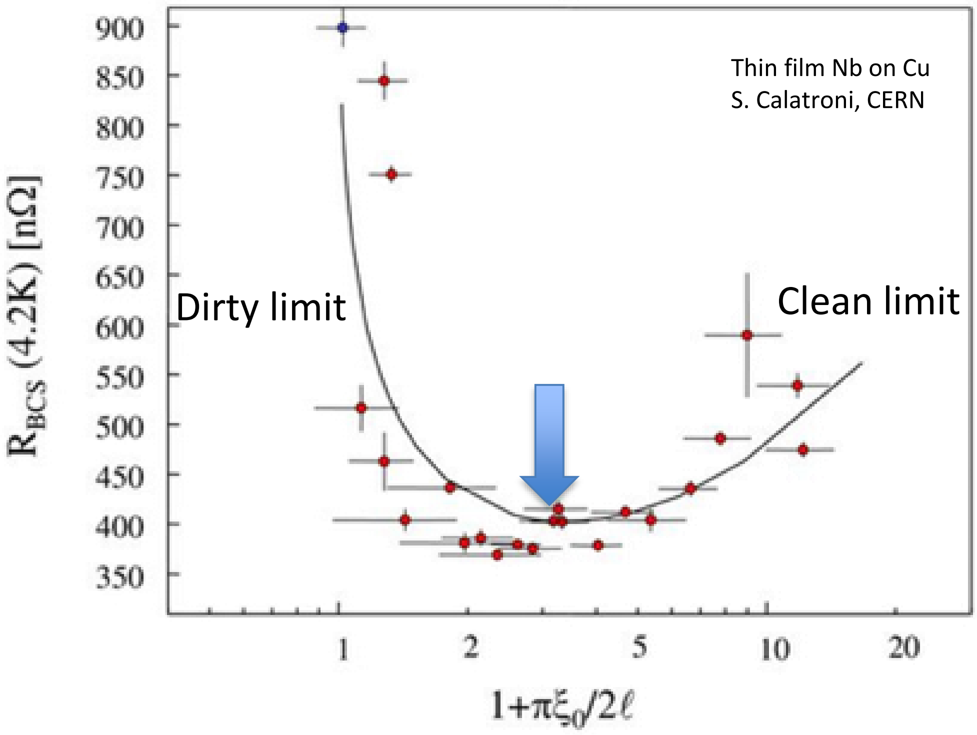
Reduced dissipation due to the current-induced broadening of the quasiparticle density of states in dirty limit.

Mean free path dependence of BCS surface resistance

$$R_{BCS} = \left(\frac{1}{T}\right) A(\lambda_L, l, \Delta, \xi_0, f_0, T_c) e^{-\frac{\Delta}{k_B T}}$$



2 K

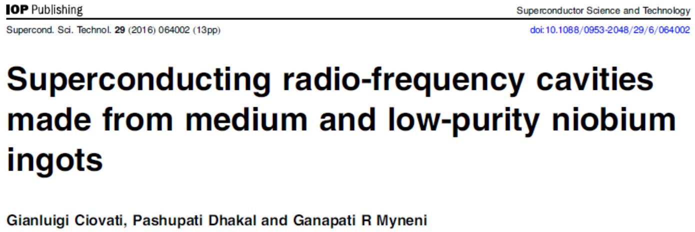


Thin film Nb on Cu
S. Calatroni, CERN

Dirty limit

Clean limit

Lower BCS resistance is expected in medium purity Nb, higher quality factor was observed in cavities made from medium and low purity niobium ingots



IOP Publishing

Superconductor Science and Technology

Supercond. Sci. Technol. **29** (2016) 064002 (13pp)

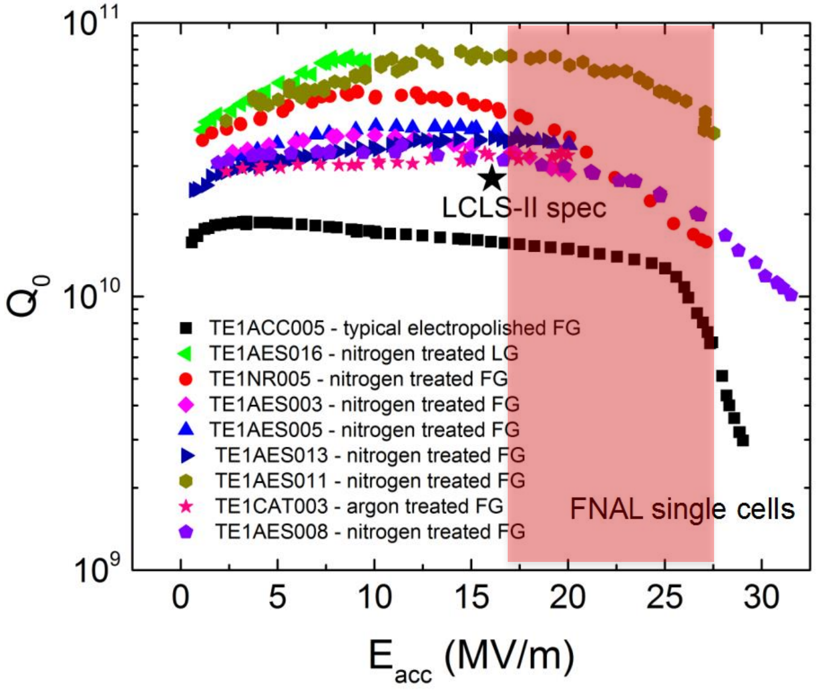
doi:10.1088/0953-2048/29/6/064002

Superconducting radio-frequency cavities made from medium and low-purity niobium ingots

Gianluigi Ciovati, Pashupati Dhakal and Ganapati R Myneni

N-DOPING

- Fermi Lab explored the surface passivation technique and found that the nitrogen doping followed by surface removal by EP produce the similar results those were obtained via Ti diffusion.
- Process include 800C heat treatment followed by Nitrogen injection for few mins (2-10) at 800 C.
- This has been grown so fast that it became “production recipe” for LCLS-II cavities.
- Even though the dramatic enhancement on Q has been observed the gradient of doped cavities are limited to medium gradient ~20 MV/m.

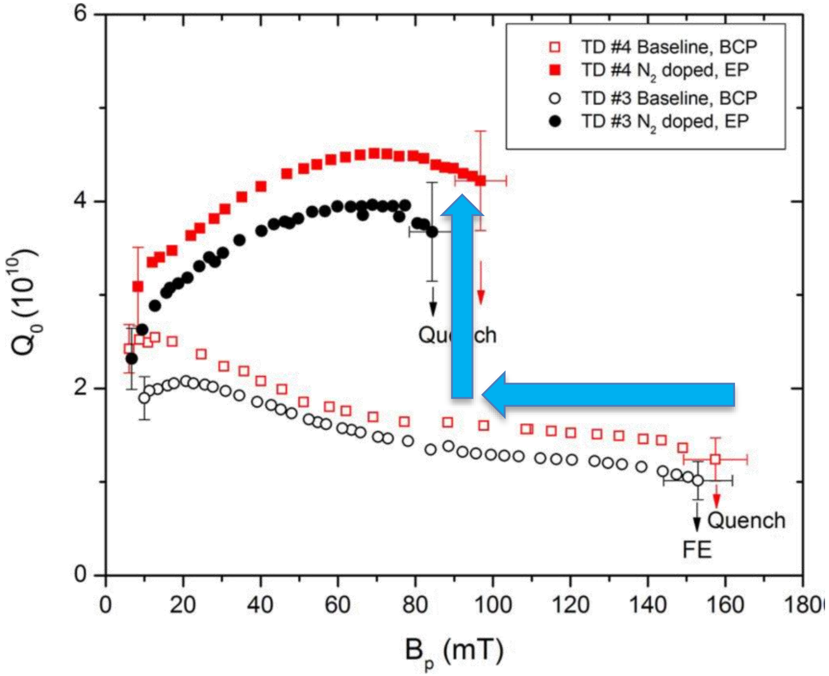


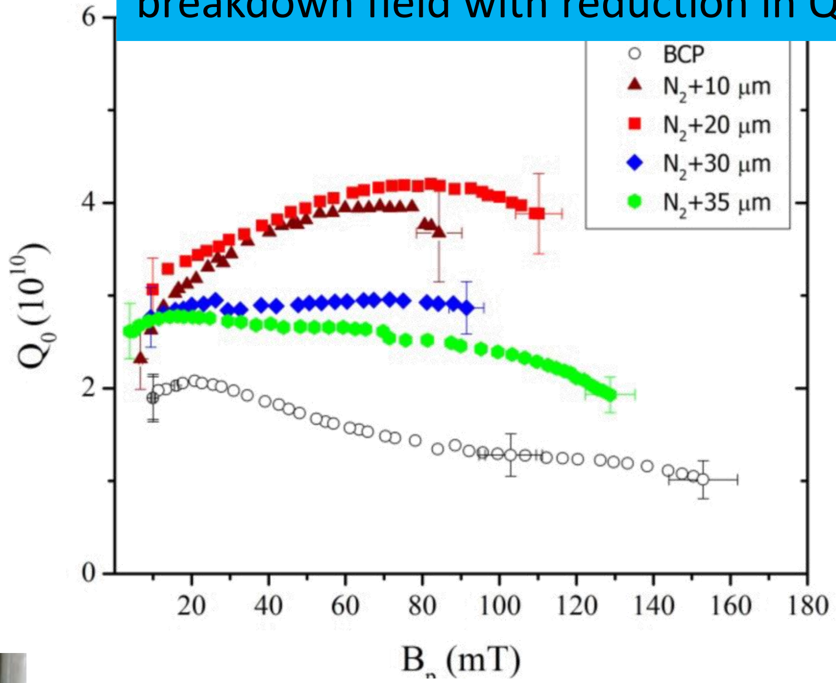
Grassalino et al., SUST 2013

Once again the same mechanism as Ti-doping R_{BCS} reduction due to N-doping

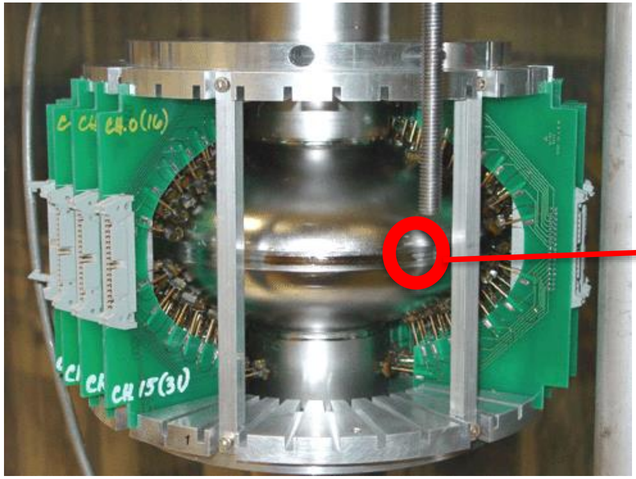
N-DOPING

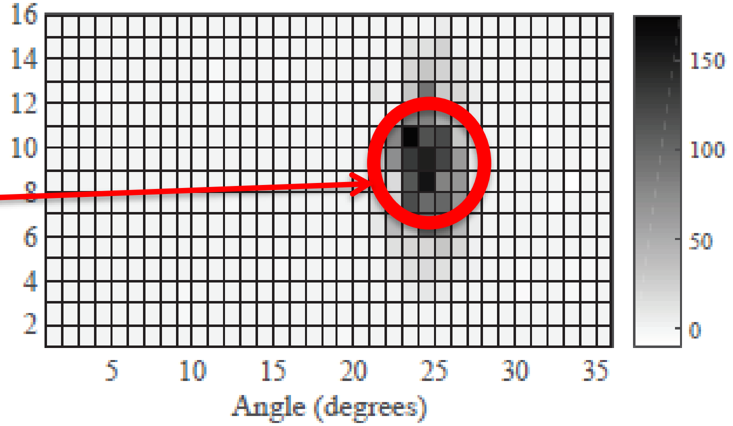
Successive electropolishing increase the breakdown field with reduction in Q_0.





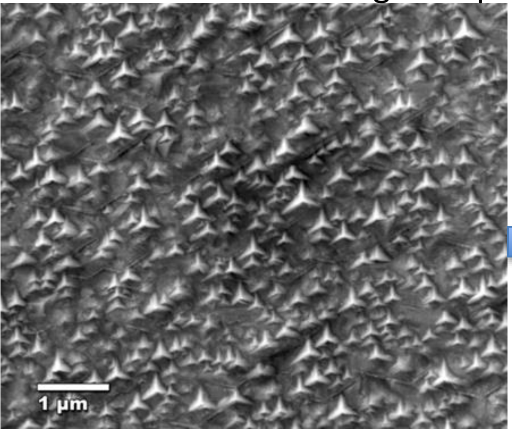
Temperature mapping quench location detection



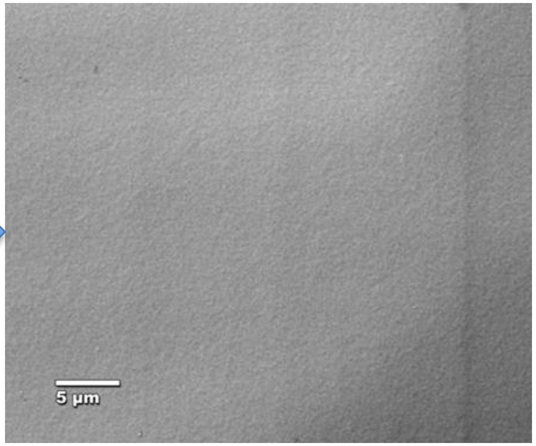


N-DOPING/COUPON STUDY

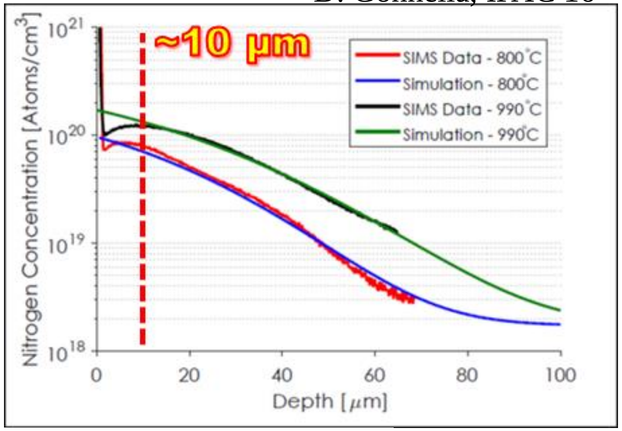
Nb-surface due to nitrogen doping

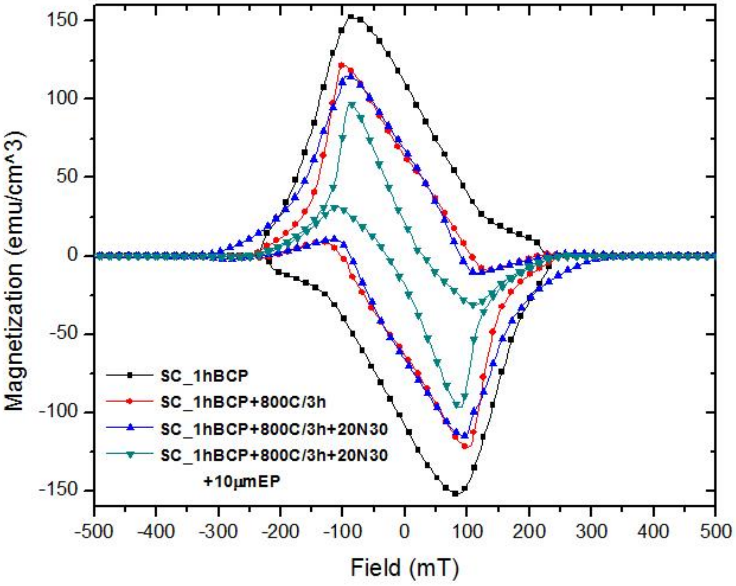


EP

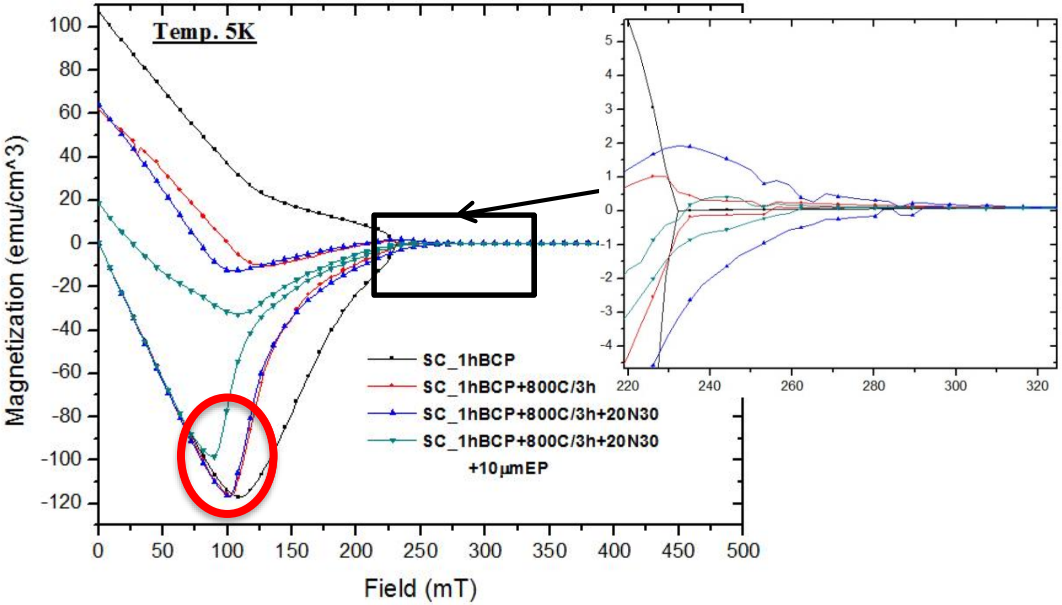


D. Gonnella, IPAC 16

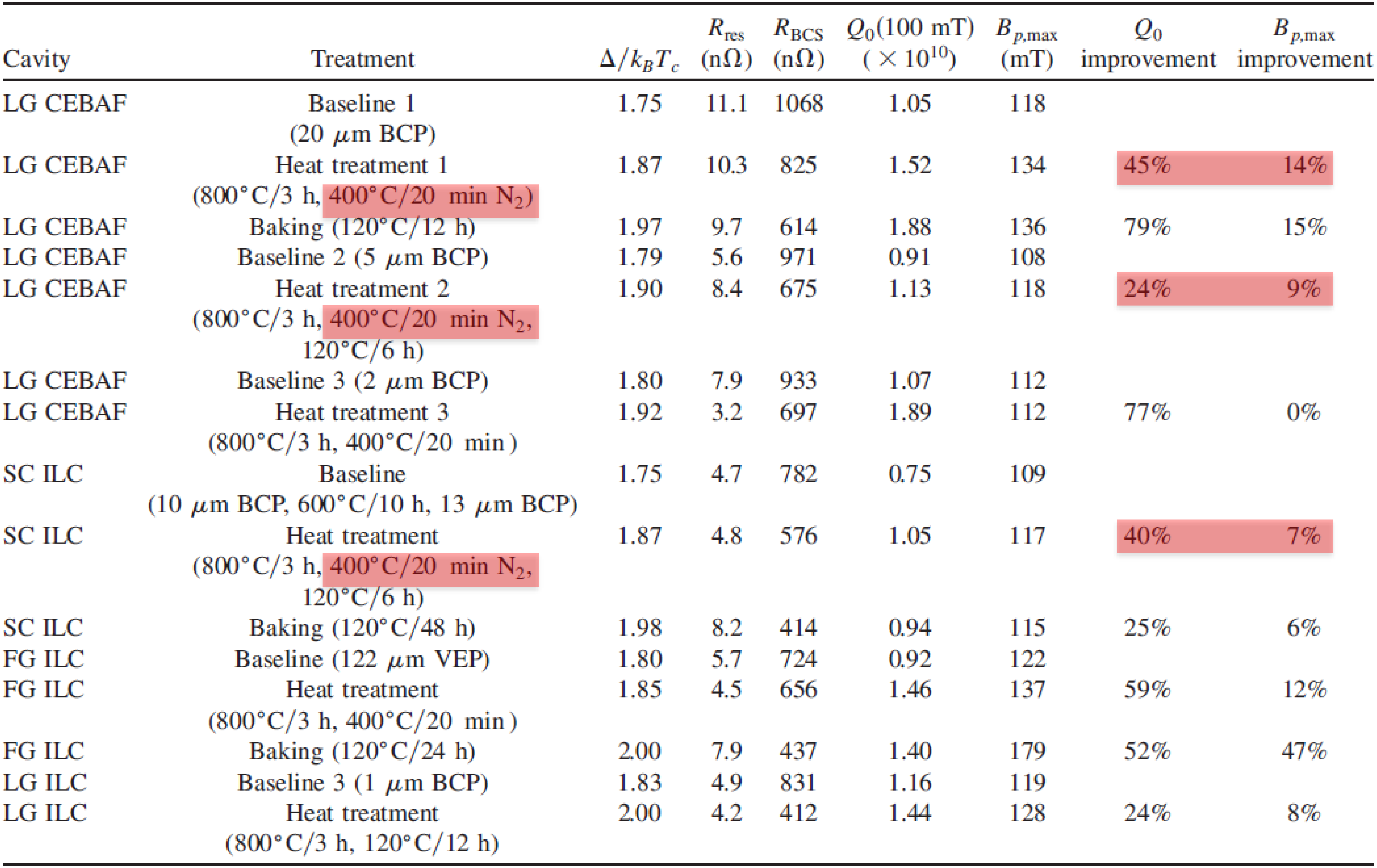




Successive EP remove the surface pinning



Earlier work on Nitrogen doping to achieve high Q with high E_{acc}



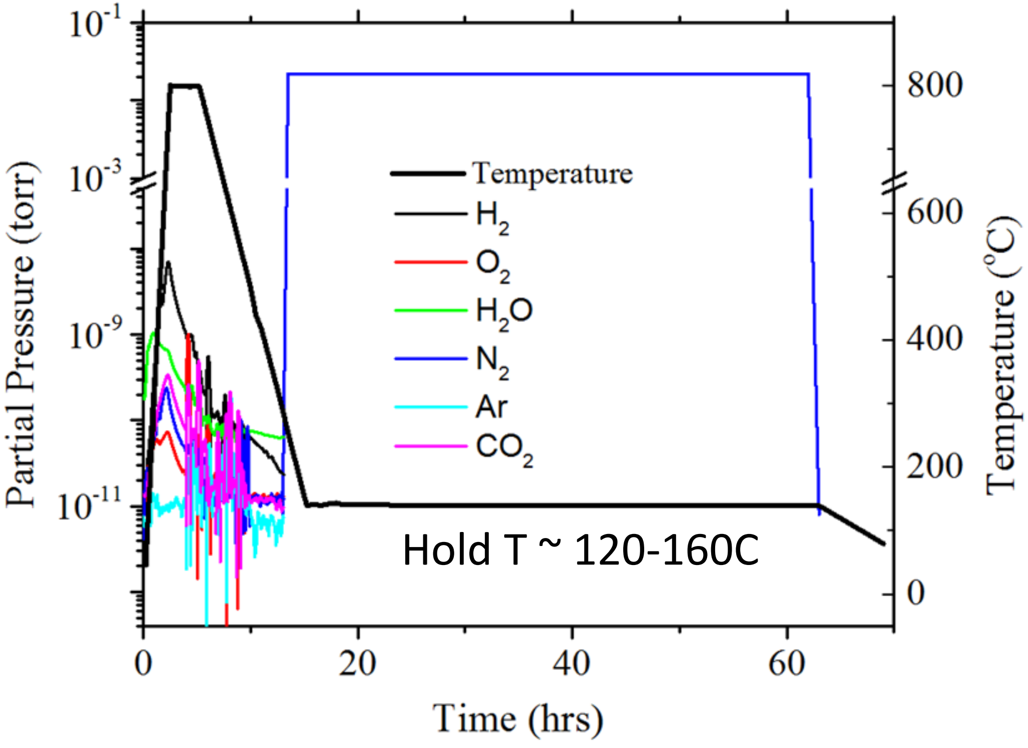
Cavity	Treatment	Δ/k_BT_c	R_{res} (nΩ)	R_{BCS} (nΩ)	Q_0(100 mT) ($\times 10^{10}$)	$B_{p,max}$ (mT)	Q_0 improvement	$B_{p,max}$ improvement
LG CEBAF	Baseline 1 (20 μm BCP)	1.75	11.1	1068	1.05	118		
LG CEBAF	Heat treatment 1 (800°C/3 h, 400°C/20 min N_2)	1.87	10.3	825	1.52	134	45%	14%
LG CEBAF	Baking (120°C/12 h)	1.97	9.7	614	1.88	136	79%	15%
LG CEBAF	Baseline 2 (5 μm BCP)	1.79	5.6	971	0.91	108		
LG CEBAF	Heat treatment 2 (800°C/3 h, 400°C/20 min N_2, 120°C/6 h)	1.90	8.4	675	1.13	118	24%	9%
LG CEBAF	Baseline 3 (2 μm BCP)	1.80	7.9	933	1.07	112		
LG CEBAF	Heat treatment 3 (800°C/3 h, 400°C/20 min)	1.92	3.2	697	1.89	112	77%	0%
SC ILC	Baseline (10 μm BCP, 600°C/10 h, 13 μm BCP)	1.75	4.7	782	0.75	109		
SC ILC	Heat treatment (800°C/3 h, 400°C/20 min N_2, 120°C/6 h)	1.87	4.8	576	1.05	117	40%	7%
SC ILC	Baking (120°C/48 h)	1.98	8.2	414	0.94	115	25%	6%
FG ILC	Baseline (122 μm VEP)	1.80	5.7	724	0.92	122		
FG ILC	Heat treatment (800°C/3 h, 400°C/20 min)	1.85	4.5	656	1.46	137	59%	12%
FG ILC	Baking (120°C/24 h)	2.00	7.9	437	1.40	179	52%	47%
LG ILC	Baseline 3 (1 μm BCP)	1.83	4.9	831	1.16	119		
LG ILC	Heat treatment (800°C/3 h, 120°C/12 h)	2.00	4.2	412	1.44	128	24%	8%

Probably not enough nitrogen

Ciovati et al. Phys. Rev. ST Accel. Beams 13, 022002 (2010)

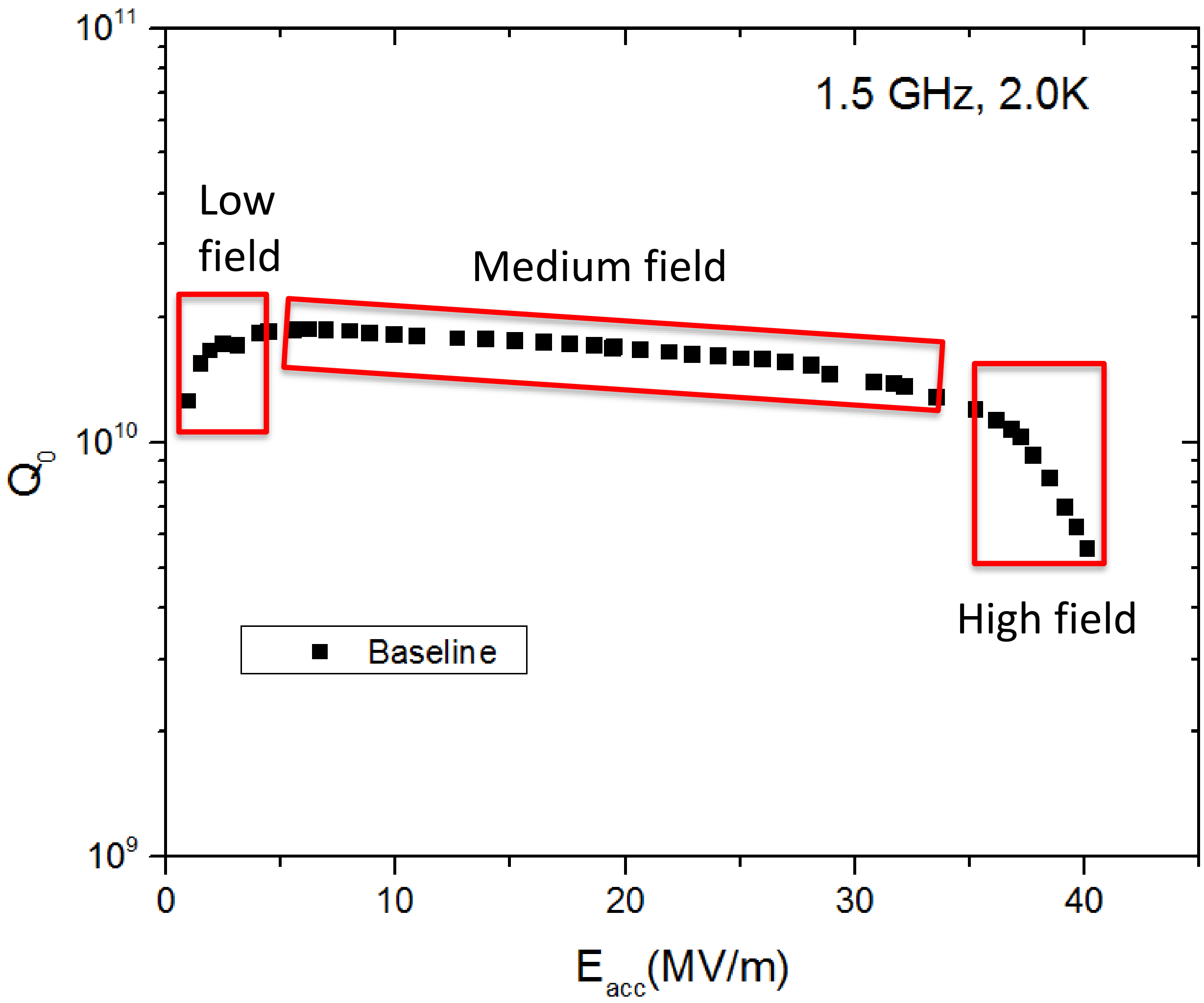
LOW TEMPERATURE BAKING IN N2

- The vacuum heat treatment procedure started with the 800 °C/3 h degassing step followed by lowering the temperature to the (120-160 C) range.
- furnace reaches ~ 200-300 °C, at which point the nitrogen partial pressure is increased to ~25 mTorr.
- Once the temperature has fallen to the desired value (120-160 °C), which is within ~2 hours, the temperature is held for ~46 hours



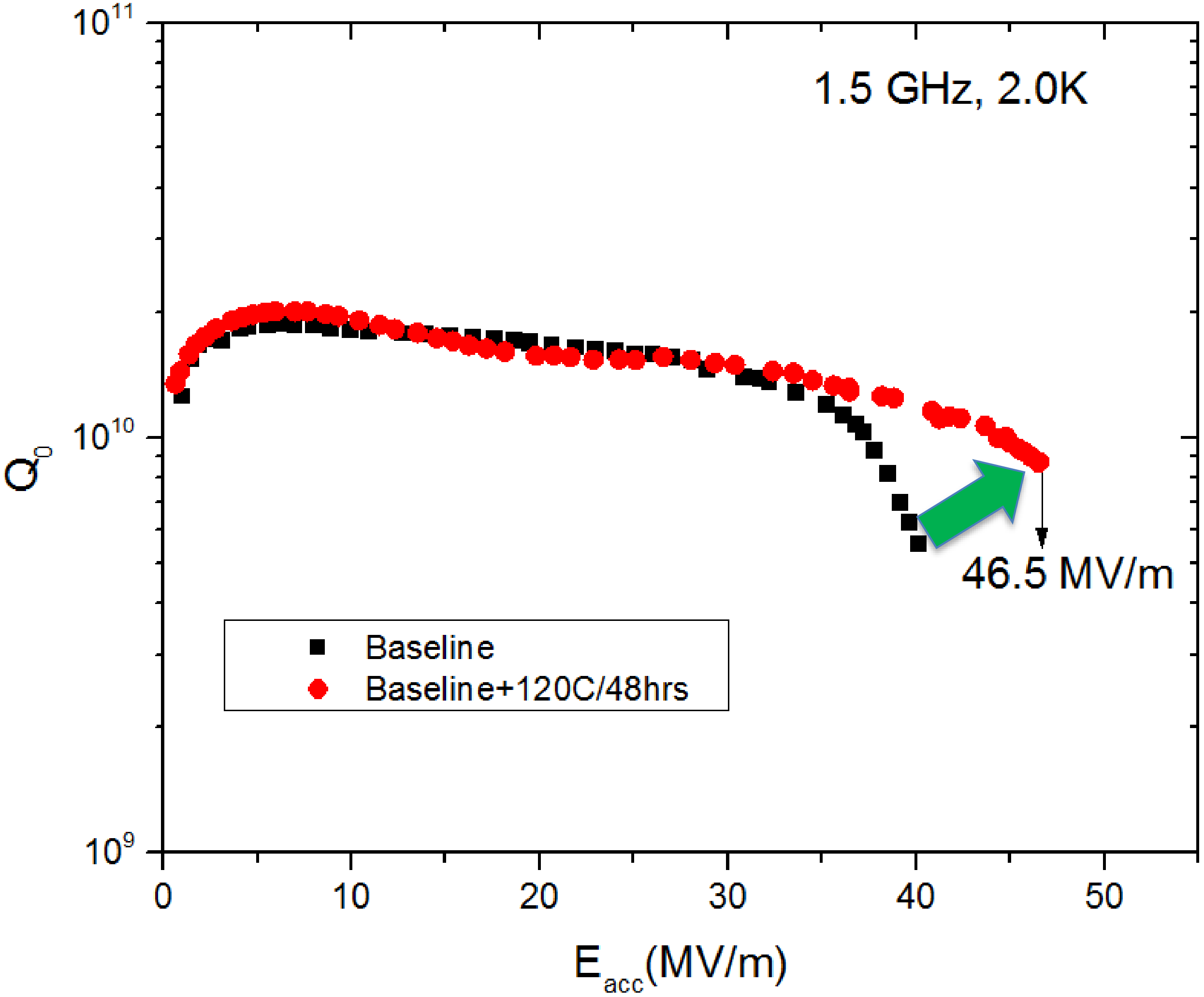
P. Dhakal et al., PRAB, 2018

LOW TEMPERATURE BAKING IN N2

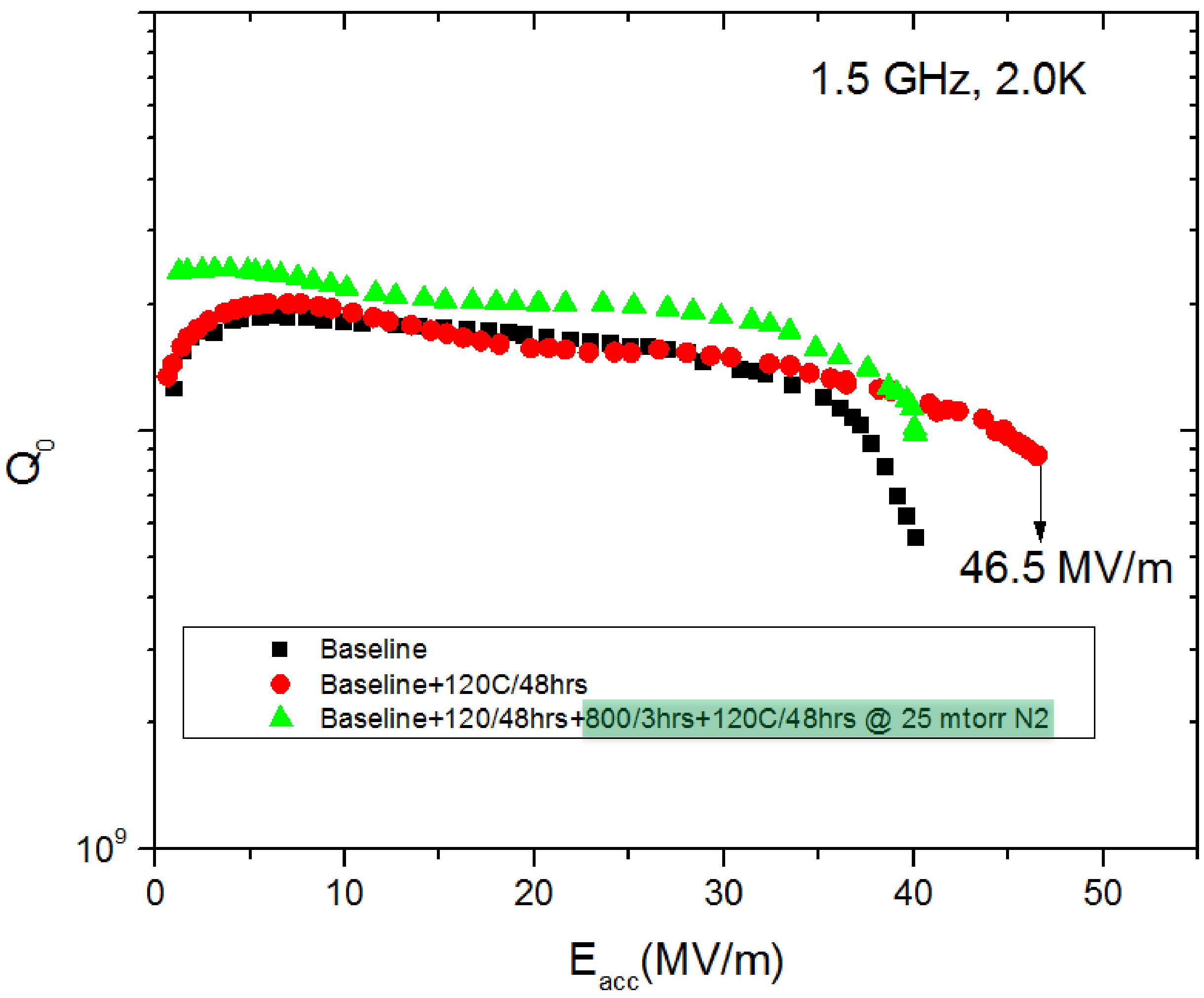


Standard ILC EP recipe

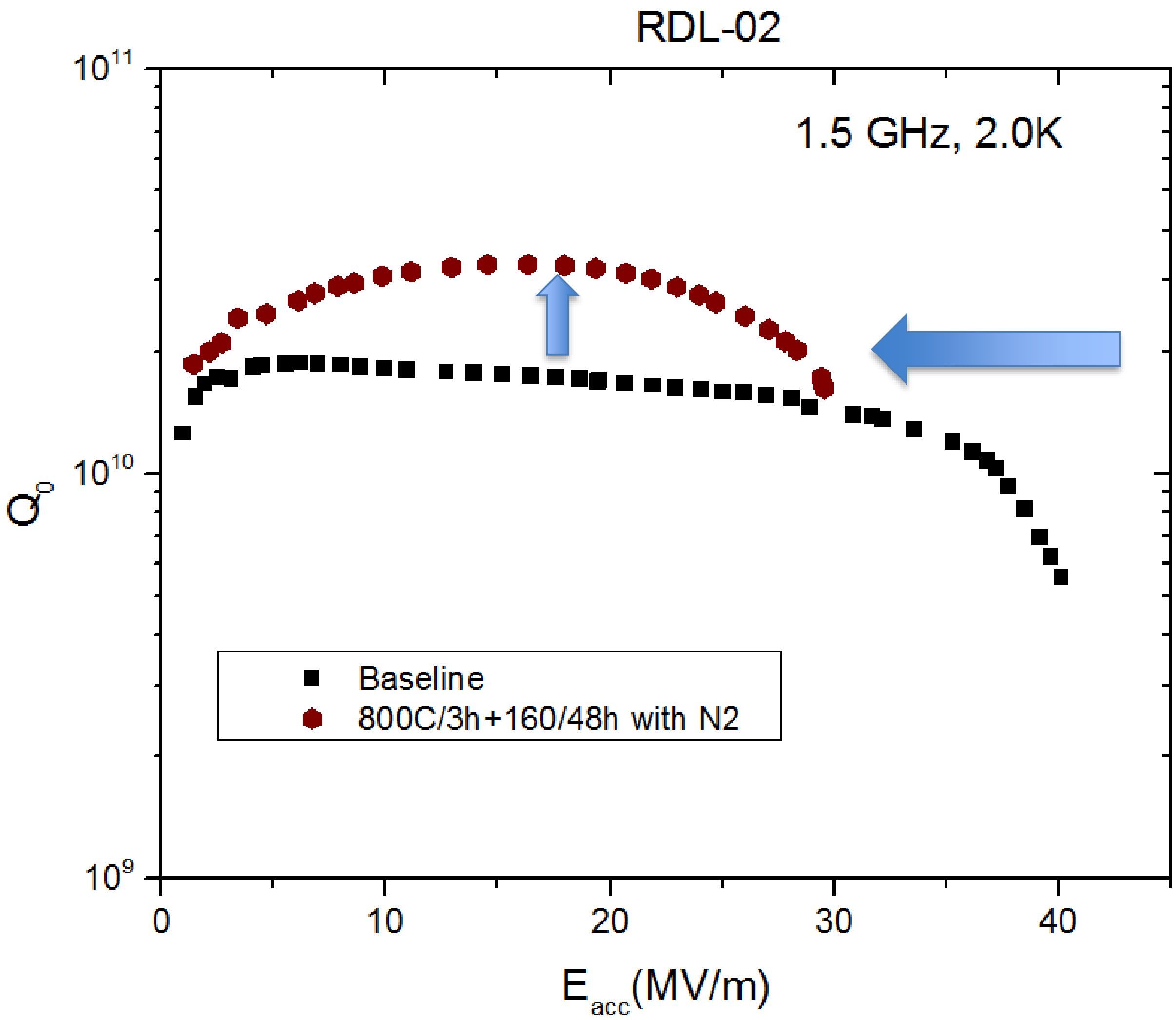
LOW TEMPERATURE BAKING IN N2



LOW TEMPERATURE BAKING IN N2

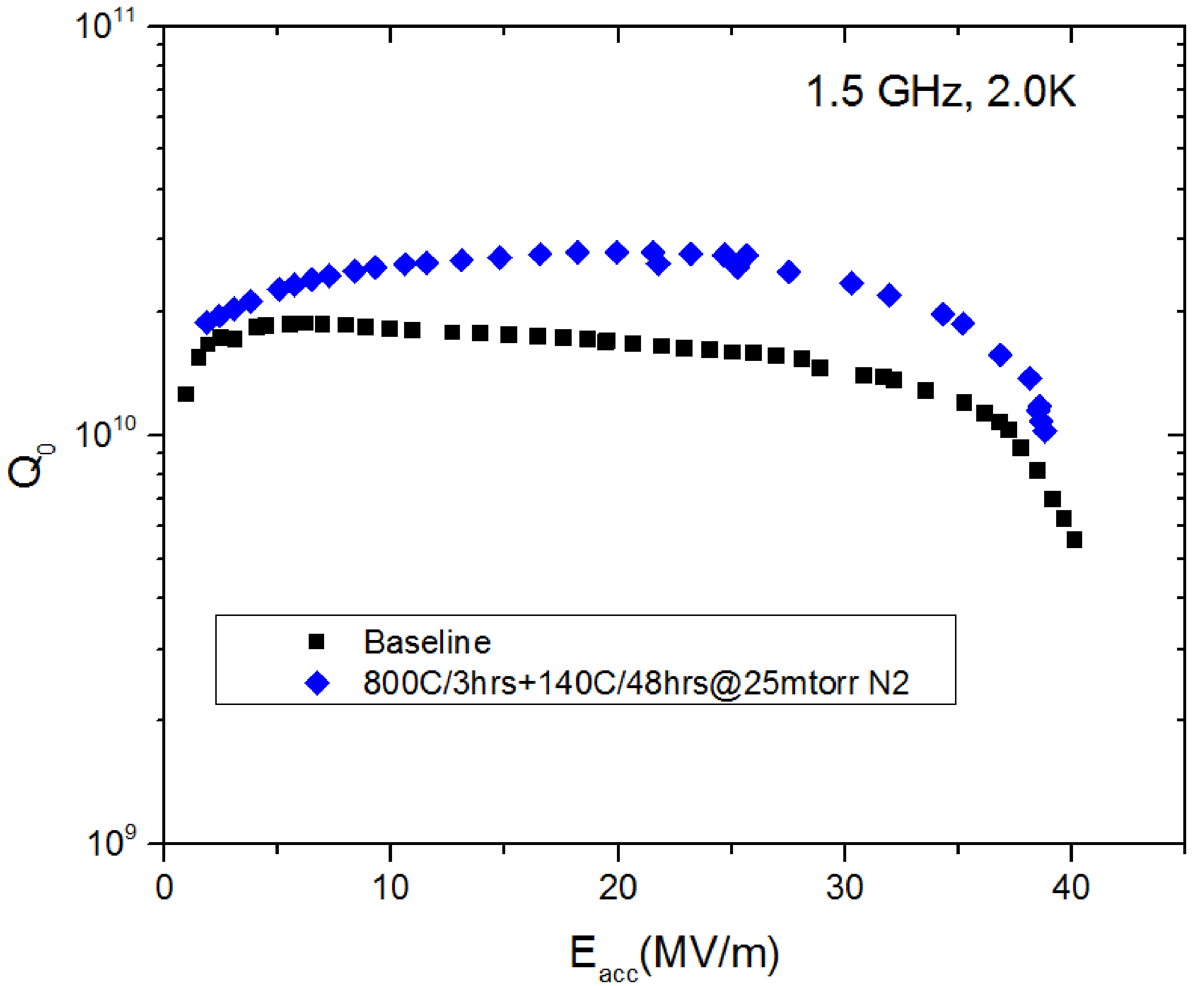


LOW TEMPERATURE BAKING IN N2



Higher temperature is beneficial for Q in medium field however, the gradient decreases.

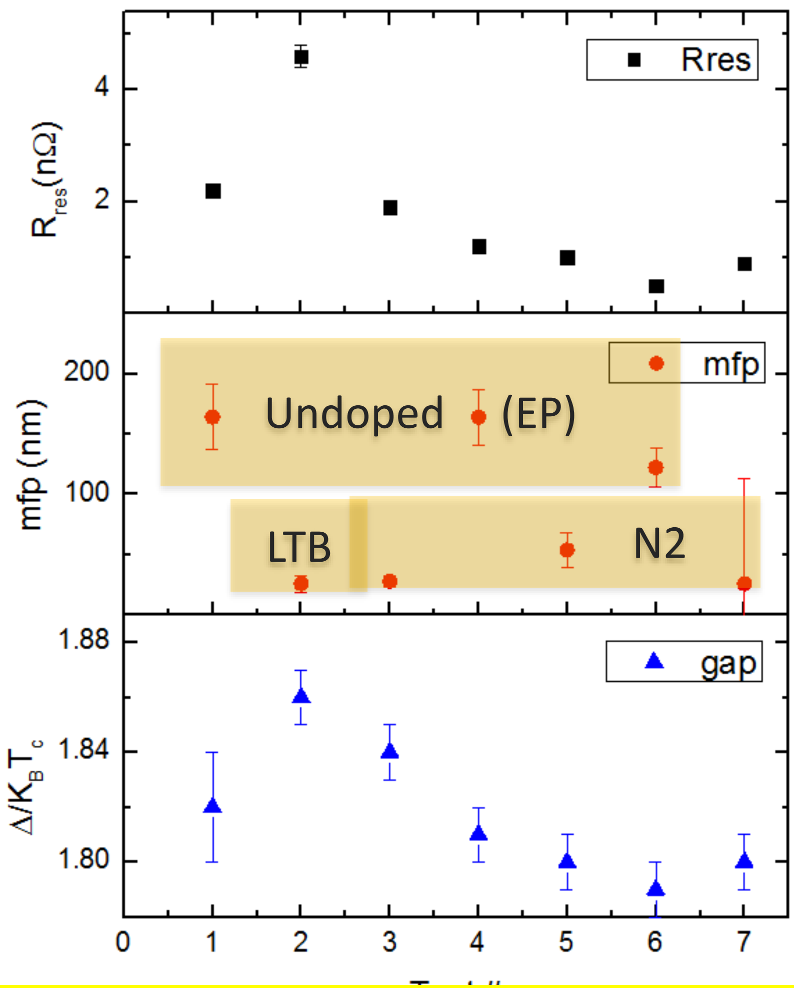
LOW TEMPERATURE BAKING IN N2



High Q with no E_{acc} degradation, process still need optimization.

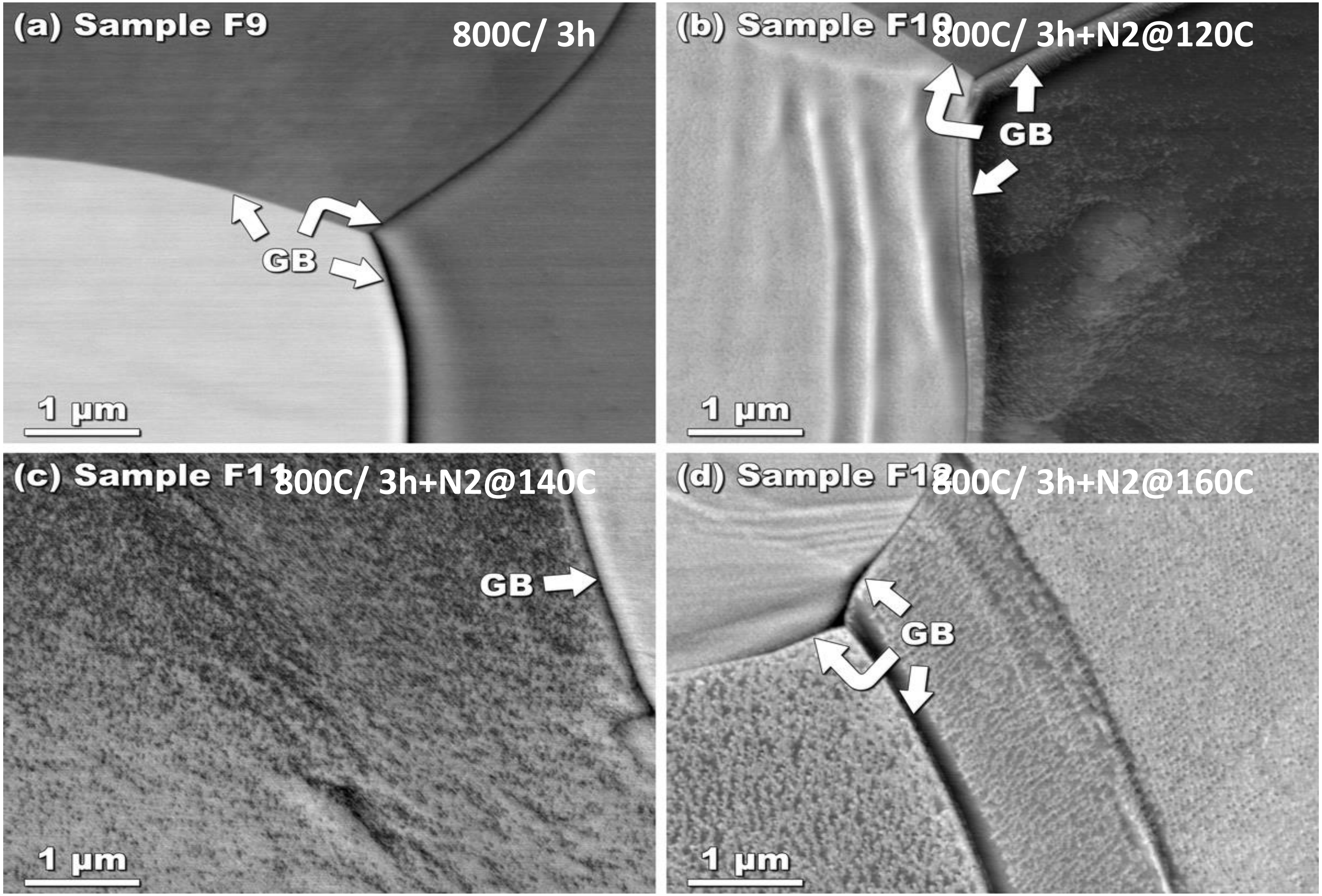
LOW TEMPERATURE BAKING IN N2

Test	Δ/K_BT_c	mfp(nm)	R_{res}(nΩ)
Baseline	1.82±0.02	164±27	2.2±0.1
+120C/48h	1.86±0.02	26±7	4.6±0.2
+800C/3h+ 120C/48h@ 25mtorr N2	1.84±0.02	28±5	1.9±0.1
+10 um EP	1.81±0.02	164±23	1.2±0.1
+800C/3h+ 160C/48h@ 25mtorr N2	1.80±0.02	54±14	1.0±0.1
+10um EP	1.79±0.02	122±16	0.5±0.1
+800C/3h+ 140C/48h@ 25mtorr N2	1.80±0.02	26±87	0.9±0.1



Lower mfp after N2 infusion is similar to doped and conventional low temperature baked cavity, still need more careful investigation if this can give us the lowest BCS resistance and its field dependence

SAMPLE COUPONS STUDY



800C/ 3h

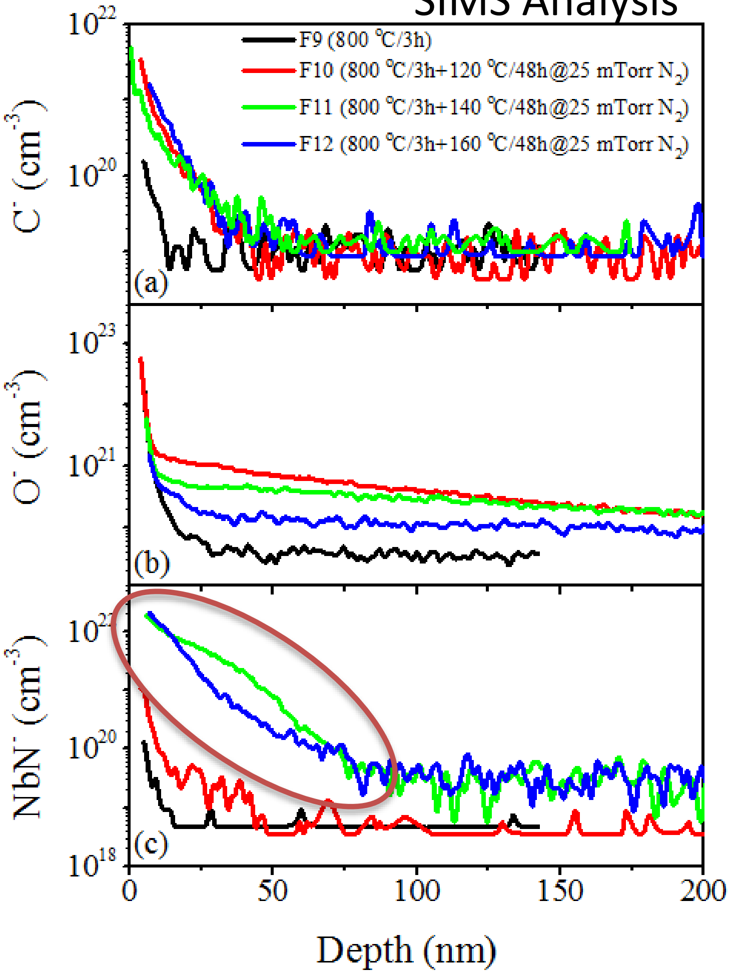
800C/ 3h+N2@120C

800C/ 3h+N2@140C

800C/ 3h+N2@160C

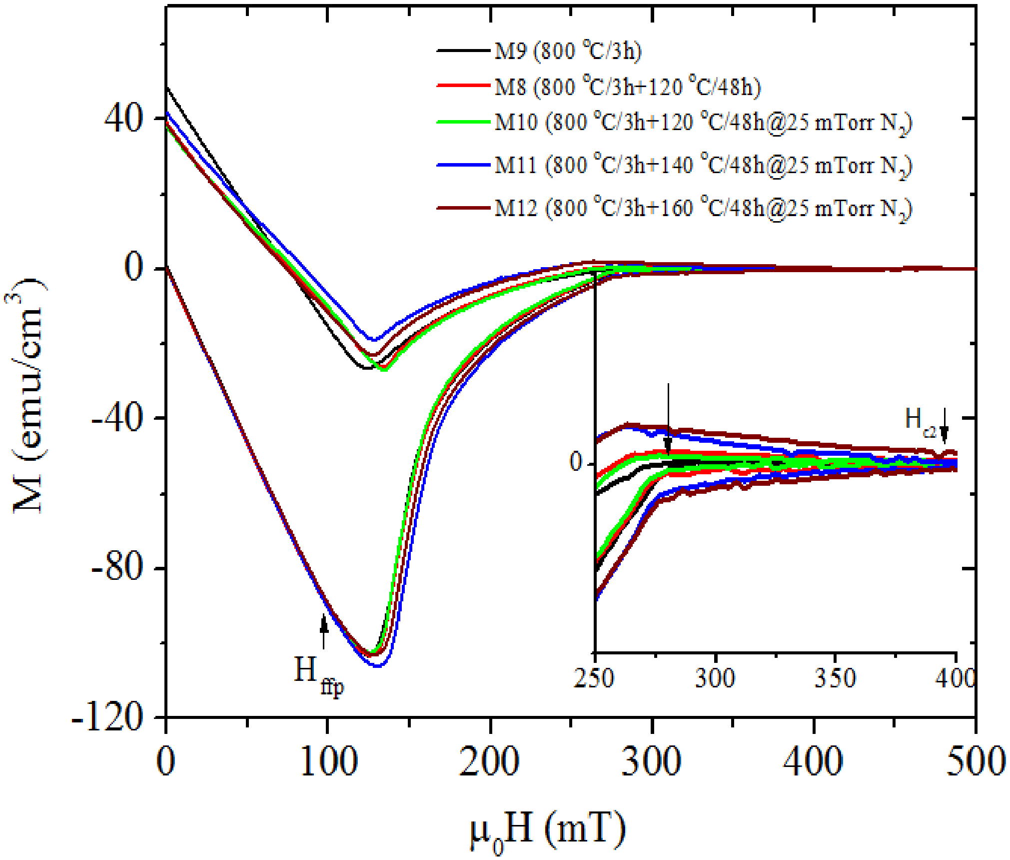
SAMPLE COUPONS STUDY

SIMS Analysis



Higher surface N2 concentration

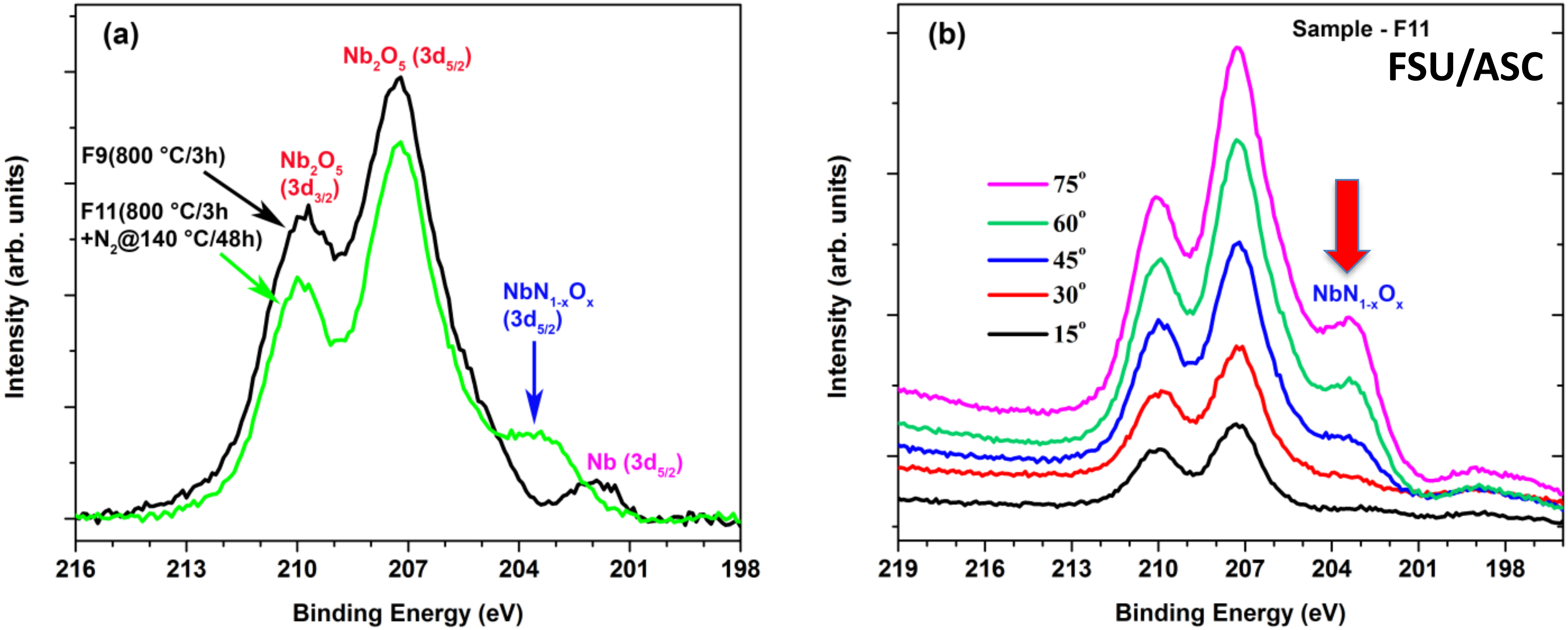
Magnetization

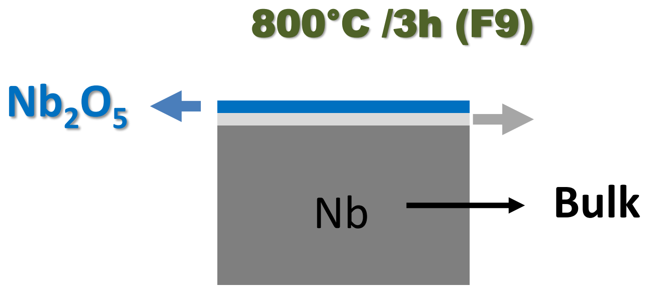


No change in bulk properties

P. Dhakal et al., PRAB, 2018

SAMPLE COUPONS STUDY



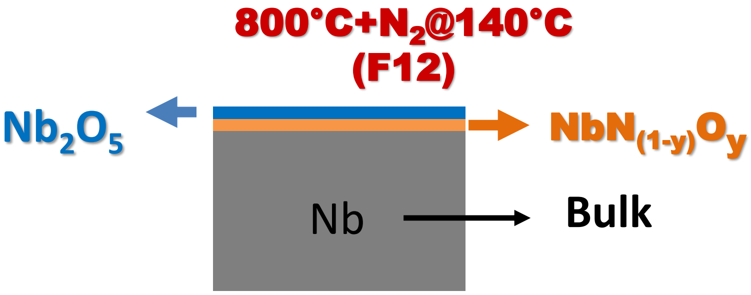


800°C /3h (F9)

Nb_2O_5

Nb

Bulk



800°C+N_2@140°C (F12)

Nb_2O_5

$NbN_{(1-y)}O_y$

Nb

Bulk

Nb_2O_5, and $NbN_{(1-y)}O_y$ exists within first 10nm in low temperature N infused sample

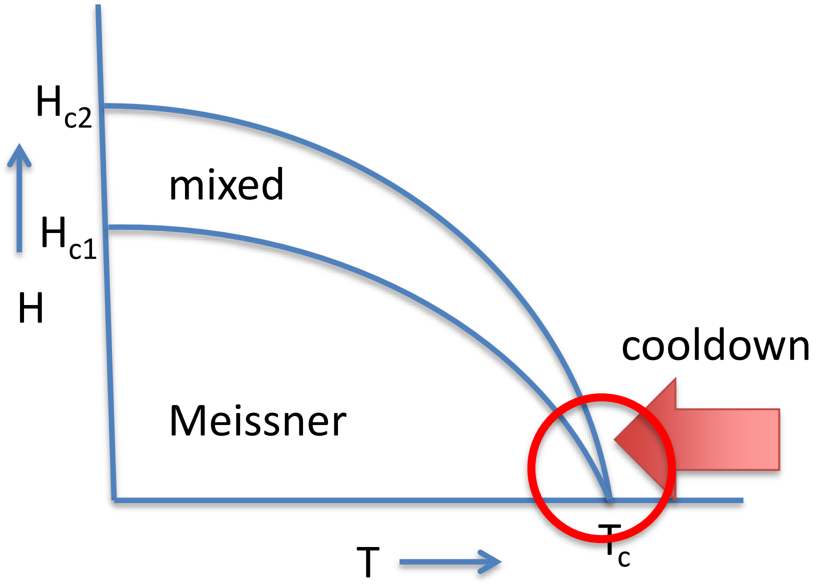
CONCLUSION#2

- R_{BCS} decreases due to reduction of mean free path as a result of material diffusion (Ti or N2) within the rf penetration depth.
- The Q-rise phenomenon can be explained by the reduced dissipation due to the current-induced broadening of the quasiparticle density of states in dirty limit.
- Accelerating gradient can be preserved when the cavity is heat treated at lower temperature in the presence of nitrogen.

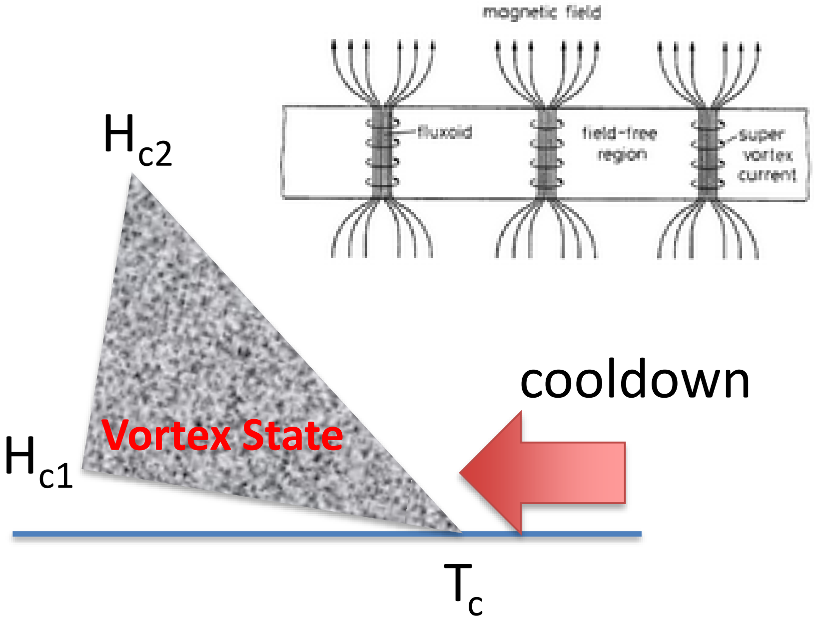
SURFACE RESISTANCE

- Minimizing R_0 via heat treatments, chemical and mechanical polishing.
- Minimizing R_{BCS} via material diffusion (reduce mfp to optimal value).
- Minimizing R_{FL} via better magnetic shielding and/or better cooldown technique that minimize the trapping of residual magnetic field.

FLUX TRAPPING



Phase diagram of Type-II superconductor

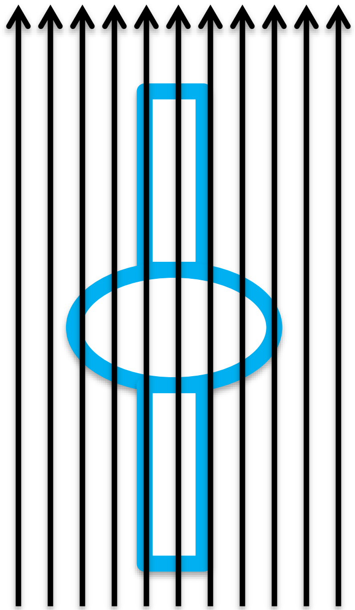


Flux will trap during the cooldown

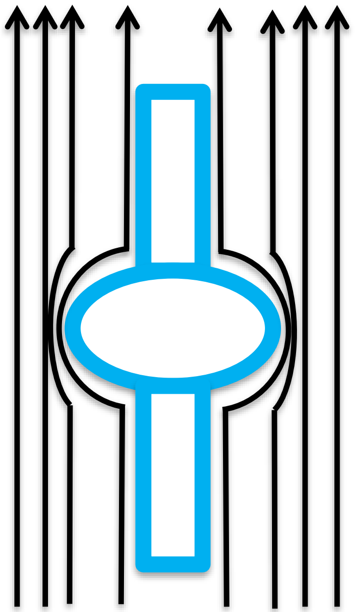
- Magnetic flux will be trapped during the cooldown
- It is found that the trapping depends on the temperature gradient during the cooldown

A. Romanenko et al., J. Appl. Phys 115, 184903 (2014).
T. Kubo, Prog. Theor. Exp. Phys. 2016, 053G01 (2016).

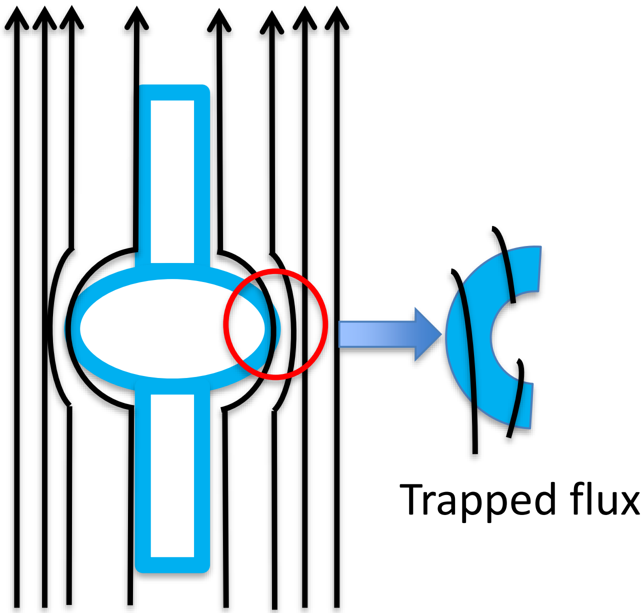
$T > T_c$

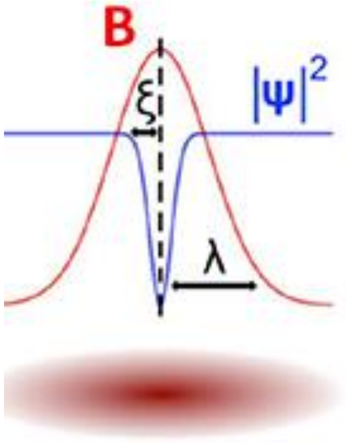


$T < T_c$
Complete Meissner Effect

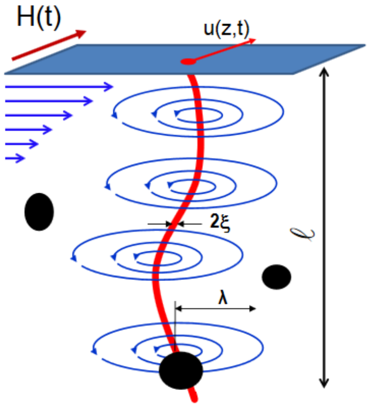


$T < T_c$
Incomplete Meissner Effect





Vortex



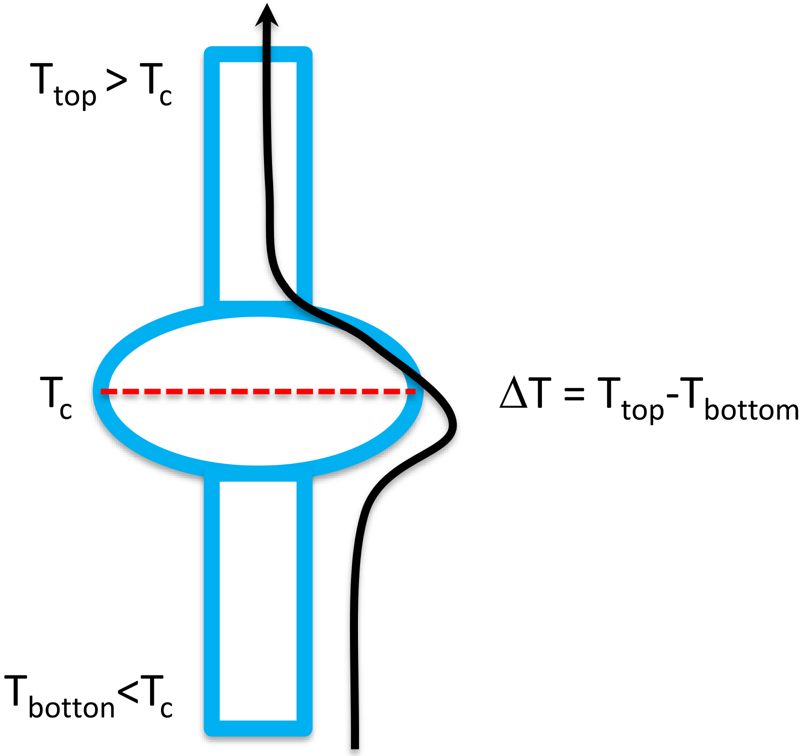
Vortex oscillation on RF field

Single vortex can dissipate a power ~ 2 μW and the increase in residual resistance can be ~ 2 nΩ/mG due to the vortex dissipation.

A. Gurevich and G. Ciovati Phys. Rev. B 87 054502 (2013)
A. Gurevich, Supercond. Sci. Technol. 30 034004 (2017)

VORTEX DISSIPATION

The amount of flux trapping is found to be dependent of the temperature gradient along the cavity during the cooldown.



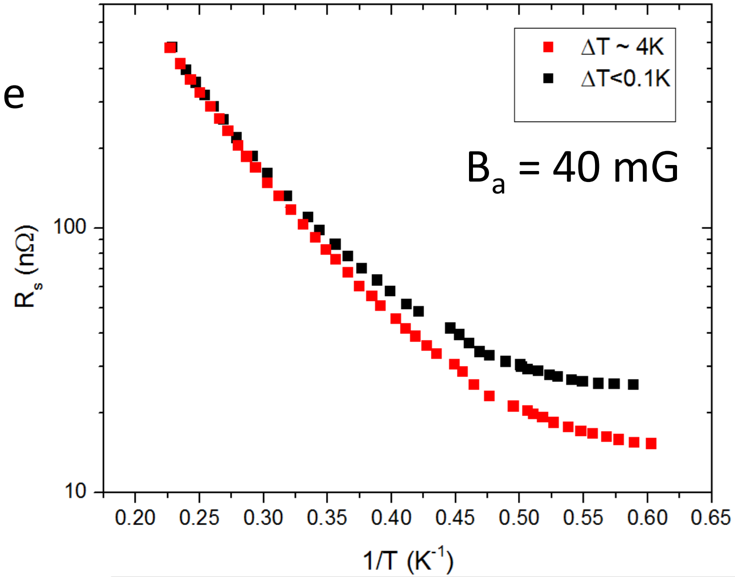
$T_{top} > T_c$

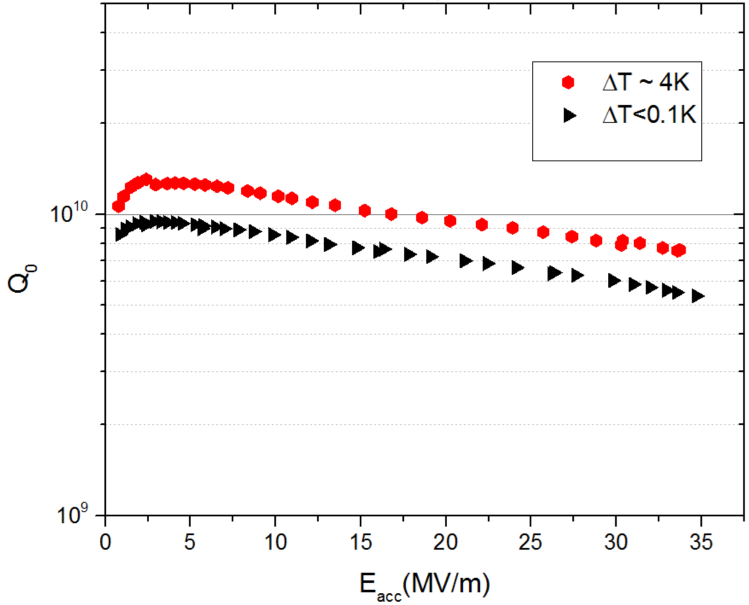
T_c

$\Delta T = T_{top}\text{-}T_{bottom}$

$T_{botton}<T_c$

Cavity cooldown from bottom and NC/SC boundary moves up



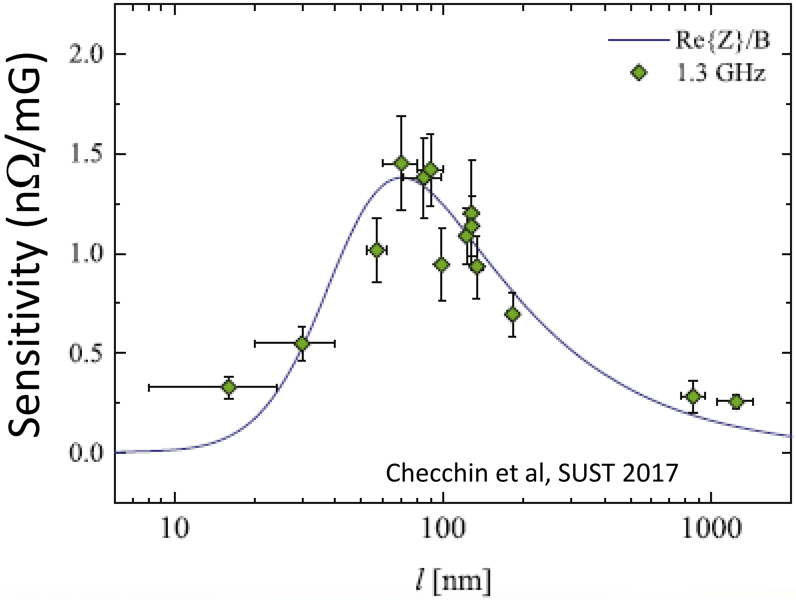


WHERE DOES THE FLUX TRAP?

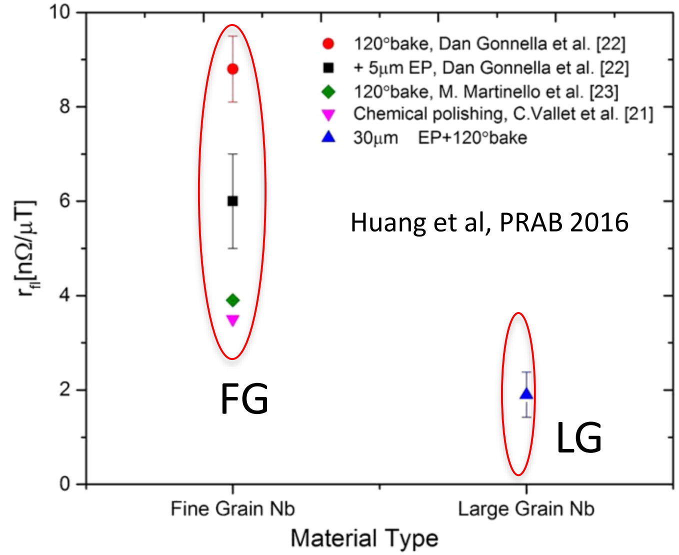
- Magnetic flux traps during cavity cooldown on impurities sites, hydrides and oxides precipitates, lattices imperfections and surface contaminations.
- Grain Boundaries and dislocations.
- The normal precipitates acts as an attractive pinning centers.
- The pinning by grain boundaries takes place through the electron scattering mechanism.
- Both **Abrikosov** and **Josephson** vortices contribute to RF loss.

FLUX TRAPPING IN SRF CAVITIES

- Earlier measurement on SRF cavities showed dRs/dBa ~ 0.4 nΩ/mG.
- dR_{res}/dB_a measured in a fine-grain, electropolished bulk Nb cavity was 0.6 nΩ/ mG and the difference in R_{res} between "fast" and "slow" cool-down was ~1.5 nΩ .
- Much higher values of $dR_{res}/dB_a \cong$ 3-4 nΩ/ mG as well as larger increase of R_{res} for "slow" cool-down compared to "fast" cool-down were obtained for fine-grain, nitrogen-doped Nb cavities
- Values of dR_{res}/dB_a between ~0.06 nΩ/mT and ~0.2 nΩ/ mG were reported for a large-grain bulk Nb cavity treated by electropolishing (EP) and baking at 120 °C in ultra-high vacuum and cooled in temperature gradients ranging between ~1 K/m and ~70 K/m



Checchin et al, SUST 2017

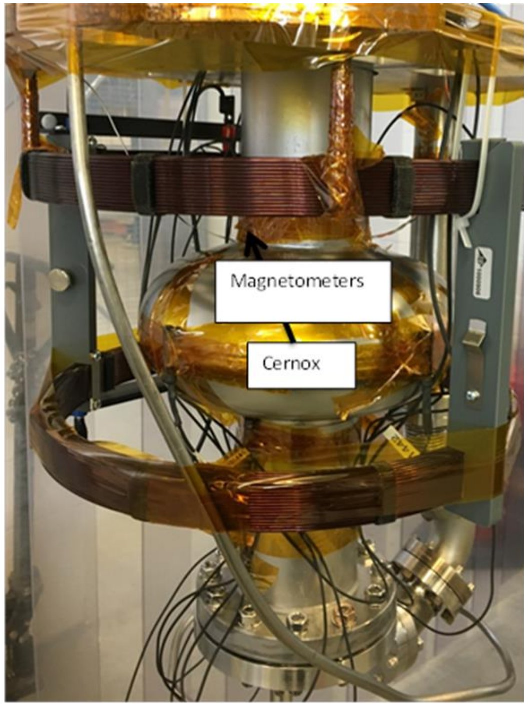


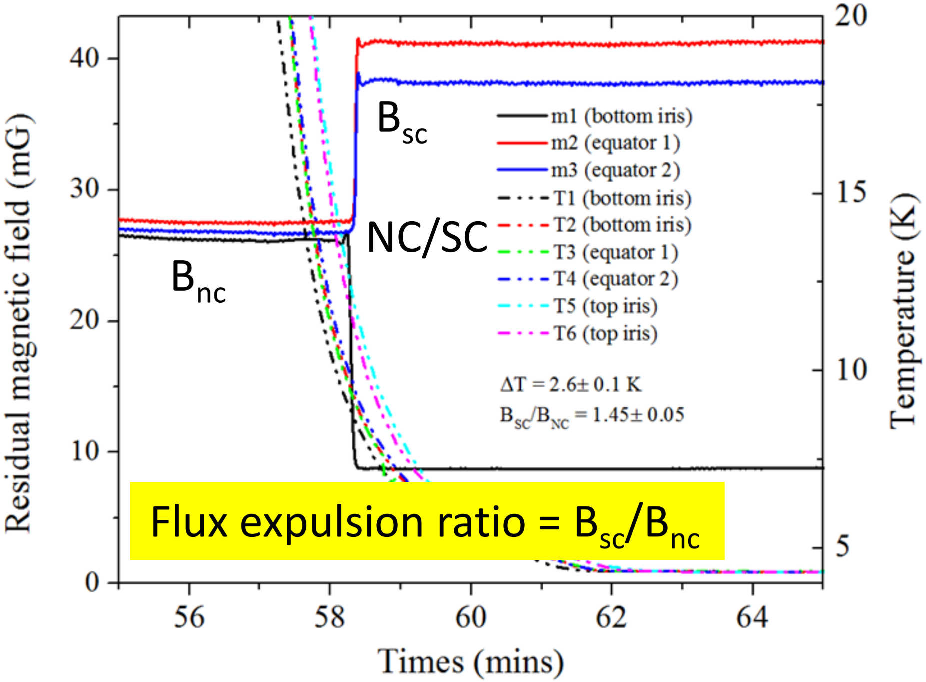
Huang et al, PRAB 2016

FLUX TRAPPING IN SRF CAVITIES

- We measure the flux expulsion and flux trapping studies on LG cavities with different impurities in order to see the correlation of purity (bulk RRR) and surface preparations (EP, LTB and N-doping).
- Q0(T) data were taken from 4.3-1.6K to extract the residual resistance as a function of residual field (applied) in Dewar in two condition of slow ($\Delta T_{iris\text{-}iris}$ <0.1K) and fast ($\Delta T_{iris\text{-}iris}$ >4K) (**total 40 cooldown and rf tests**).

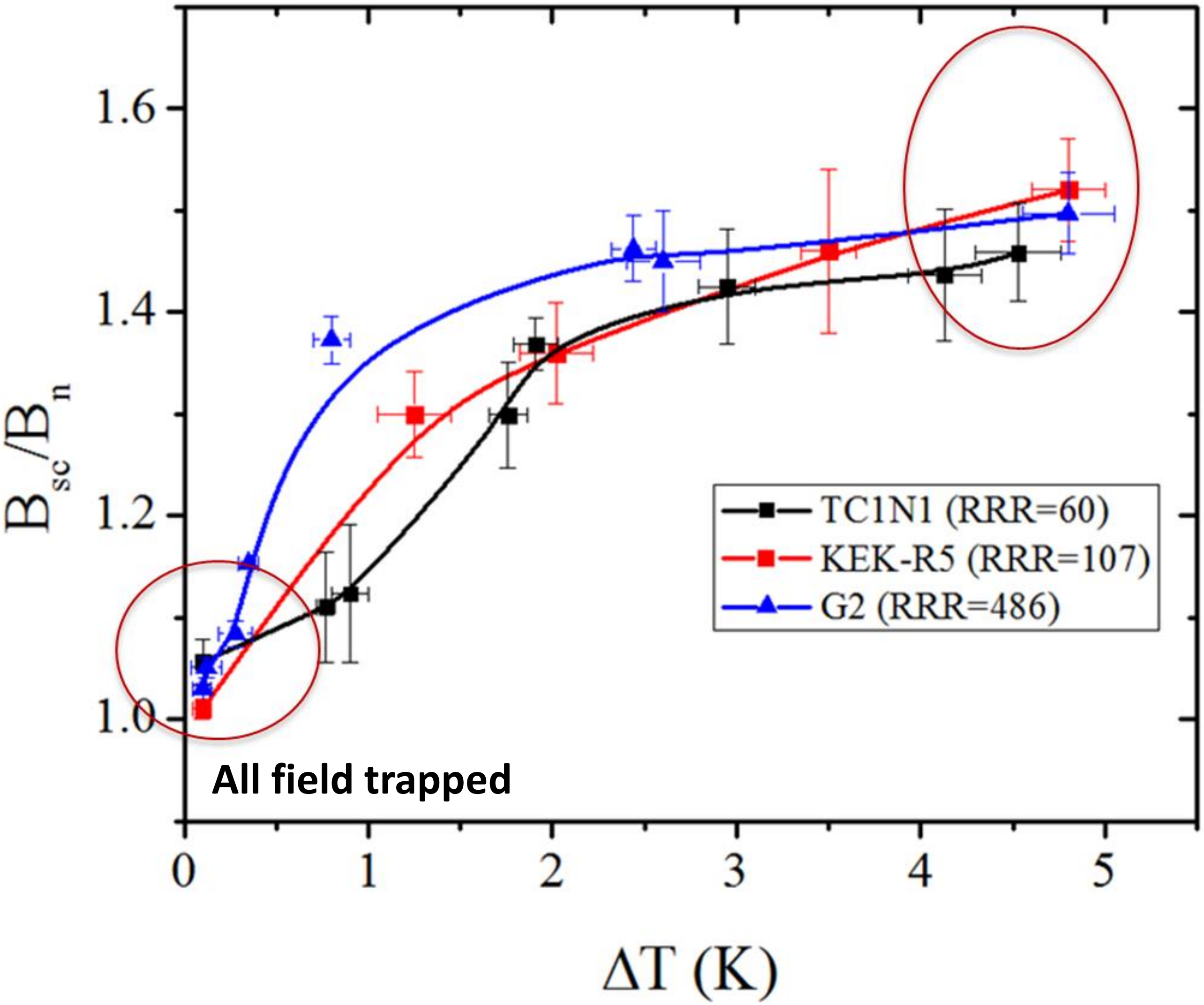
Magnetometer placed at equator, parallel to the cavity axis





Flux expulsion ratio = B_{sc}/B_{nc}

FLUX EXPULSION ON LG CAVITIES

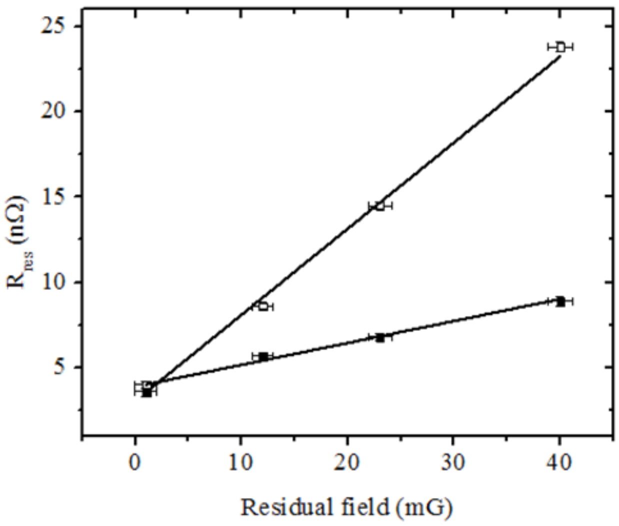


Partially trapped
Perfect expulsion
1.5-1.7 depending on shape of cavity

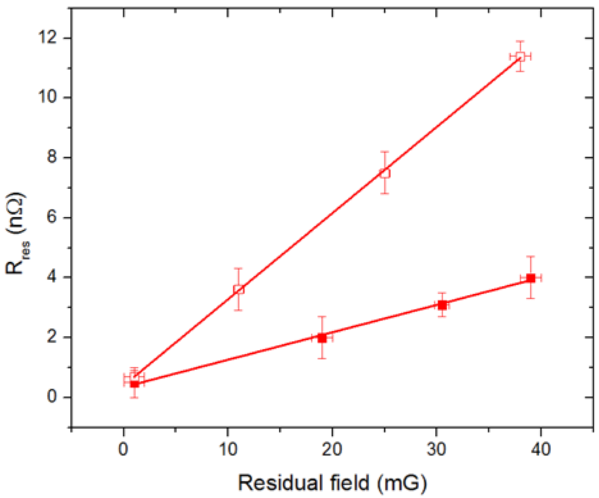
All field trapped

FLUX TRAPPING ON LG CAVITIES SURFACE (EP)

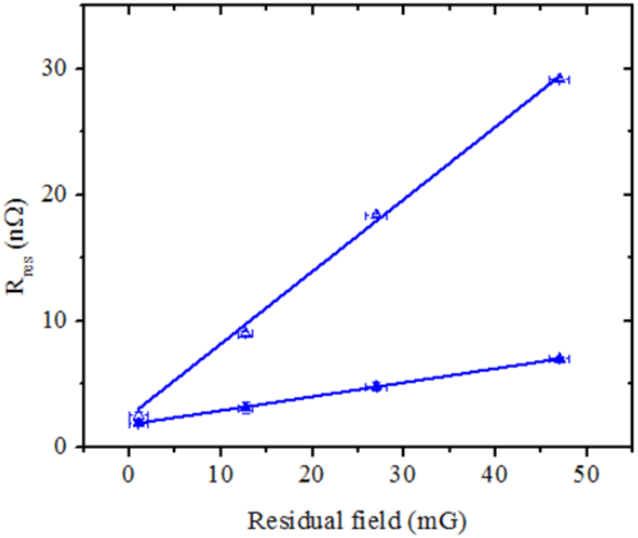
RRR = 60



RRR = 107

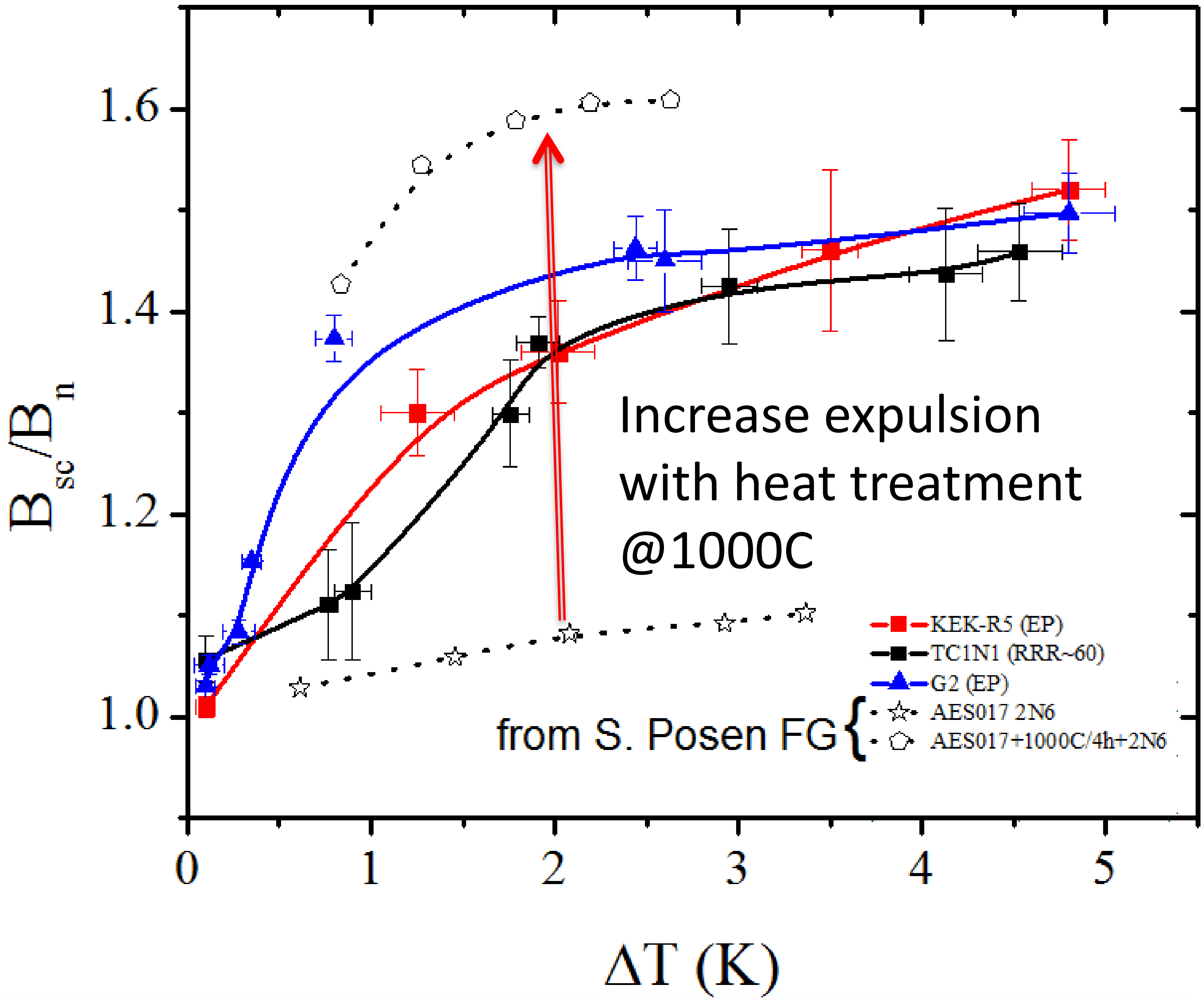


RRR = 486



Cavity	ΔT>4K(B_{sc}/B_n ~ 1.5) dRres/dBa nΩ/mG	ΔT<0.1K(B_{sc}/B_n ~ 1) dRres/dBa nΩ/mG
TC1N1 (RRR=60)	0.13 ±0.01	0.51 ±0.02
KEK-R5 (RRR=107)	0.10 ±0.02	0.28 ±0.04
G2 (RRR=486)	0.11 ±0.01	0.57 ±0.02

FLUX Expulsion FG/LG



Increase expulsion with heat treatment @1000C

from S. Posen FG

CONCLUSION #3

- The flux trapping sensitivity is lower on cavities made from large grain niobium compared to the fine grain counterparts subjected to the same surface treatments.
- Cavities made from large grain niobium show good flux expulsion regardless of the RRR of host materials suggest the interstitial impurities may have less effect on flux expulsion/trapping.
- Grain boundaries and segregation of impurities (including N2 in doped cavities) may be the primary host for flux pinning/trapping.

Thank you for your attention.