Development of Transformative Preparation Methods to Push up High Q&G Performance of FRIB Spare HWR Cryomodule Cavities

PI: K. Saito on behalf project group

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2024 NP Physics Accelerator R&D PI Exchange Meeting

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Outline

- **Project Goals**
- **Objectives, Status, Deliverables, and Publish**
  - ✓Objective 1: Improve the FRIB53 cavity gradient performance, using EP, and LTB
  - ✓Objective 2: Push up Qo performance by reducing the ambient magnetic field
  - ✓Objective 3: Develop wet N-doping for higher Q performance
  - Objective 4:Ongoing within 12month extension, develop HNO_3-free BCP to resolve the HFQS in the conventional BCP'ed cavities

Objectives 1-2 have already been reported in the 2023 NP Accelerator R&D PI Exchange meeting, and just few slides will be shown to recap the results. In this report, most of the time will be spent on objectives 3 and 4 results.

- **Education**
- **Issues and Resolutions**
- **Budget**
- **Summary**

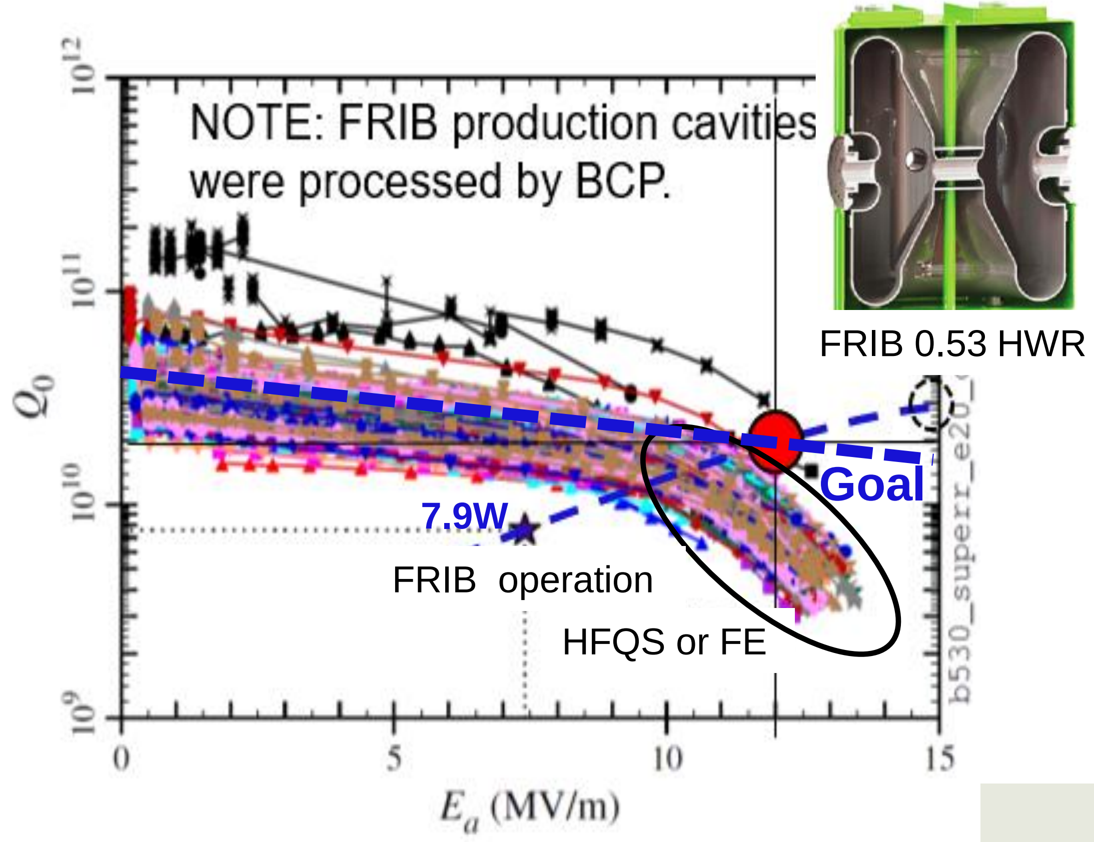
Project Goals

- FRIB reliable operation for users is the first priority. A plan to build a high gradient spare cryomodule to be swapped in the future cavity degradation.
- The FRIB production cavities processed by buffered chemical polishing (BCP) are limited by high field Q-slope (HFQS), or field emission (FE). The cavity performance has to be improved.
- Well known in TESLA R&D that HFQS is mitigated by low temperature bake (LTB) with electropolished (EP) cavity case.

- **Project Goal-1 (Objective 1 and 2)**: Improve the operateable FRIB cavity performance, by applying EP and LTB, instead BCP.

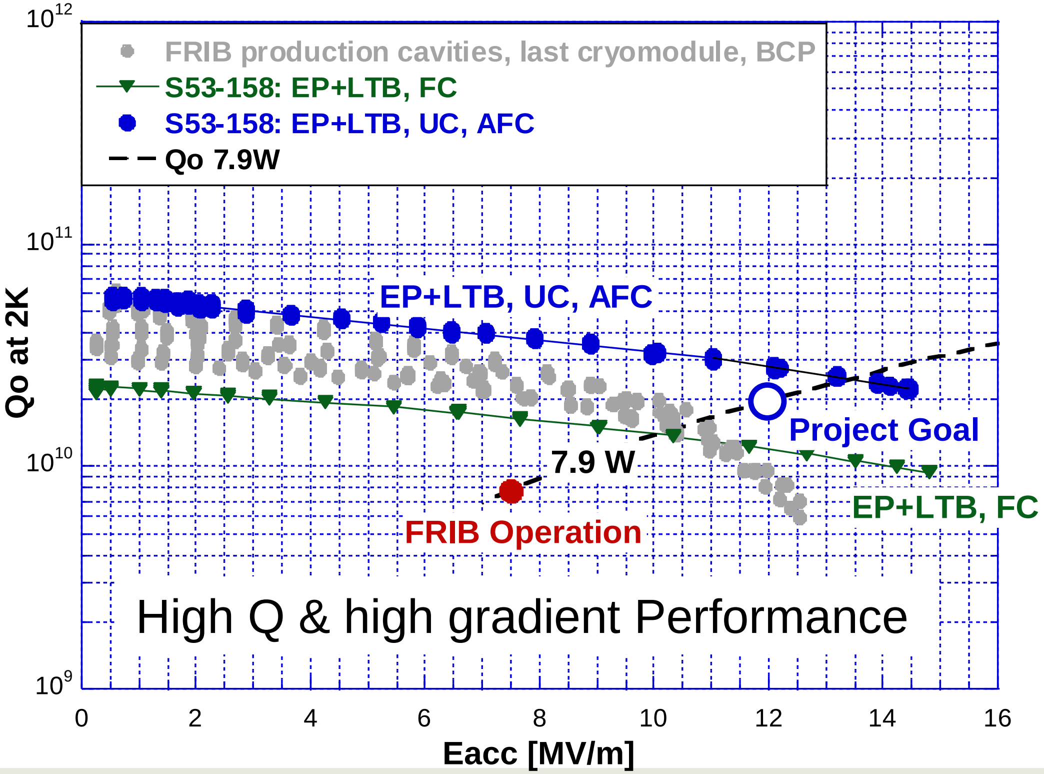
Cavity Performance Goal:
Qo = 2.0E+10 @ Eacc = 12 MV/m

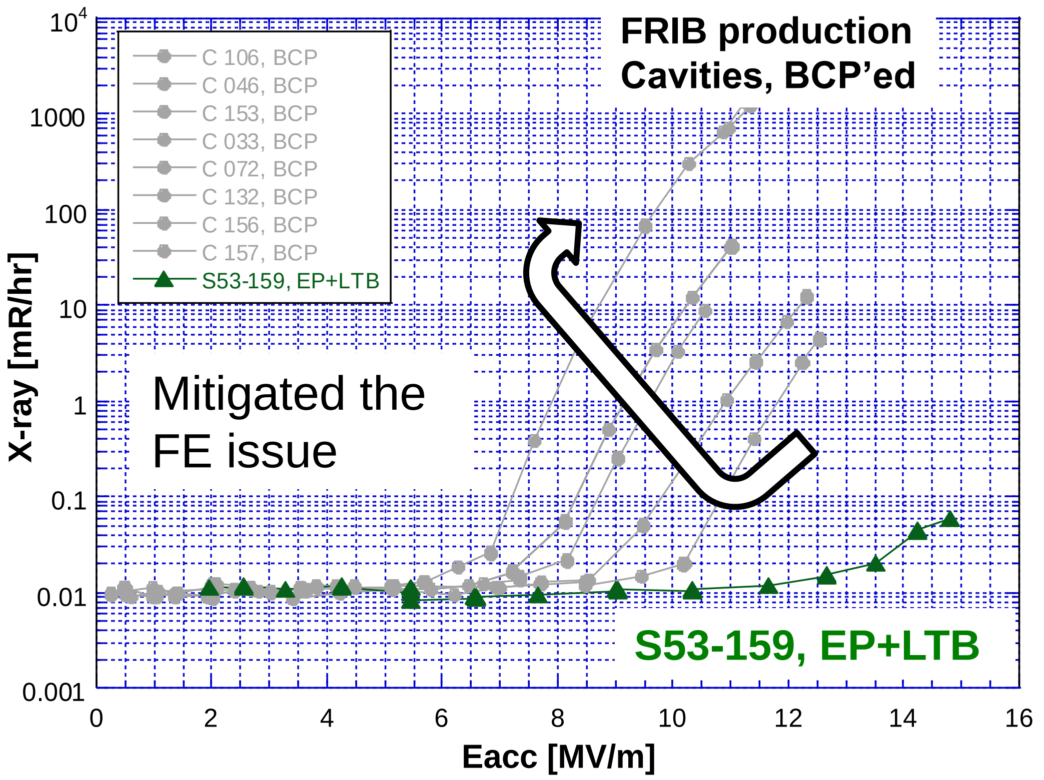
- **Project Goal-2 (Objective 3 and 4)**: Develop transformative surface treatment methods for further high cavity performance.



Project Goal-1 Completed by Objectives 1 and 2

- EP + LTB pushed up the **gradient to 15 MV/m**, and Uniform Cooldown (UC)+Active field cancellation (AFC) improved **Qo** further **to 2.8x10^{10} at 12MV/m. Achieved goal-1.**
- **Field Emission (FE) was also greatly mitigated**, due to a smoother surface finishing by EP.





EP at FRIB for FRIB 0.53 HWR

LTB for FRIB 0.53 HWR

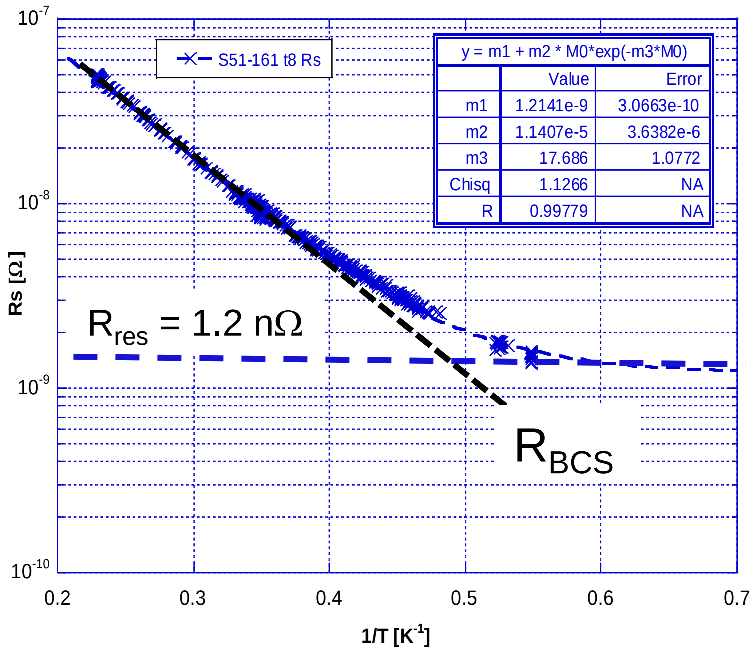
Effort for High Q: Reduce Ambient Magnetic Fields

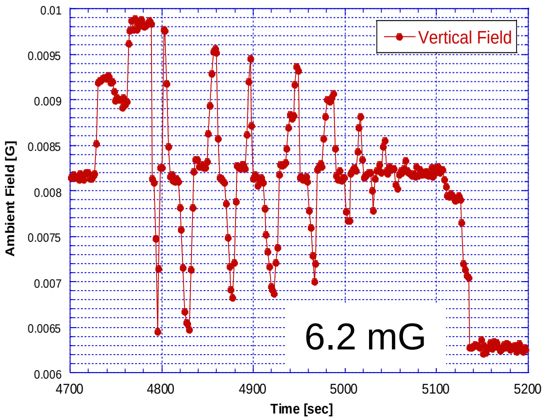
- Magnetic flux trapping is a major cause of residual surface resistance (R_{res}).

  $$Qo = \frac{107.4}{R_s},\ R_s = R_{res} + R_{BCS}(T, f) = R_{res} + C\cdot \frac{f^2}{T}\cdot \exp(-\Delta/k_B T)$$

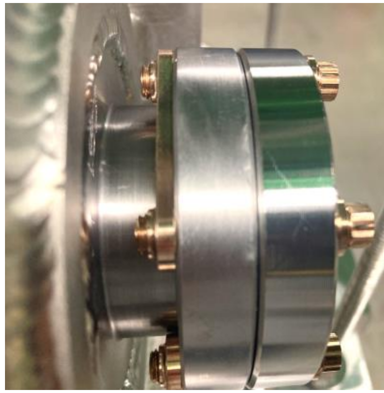
  R_{res} (~ 4 nΩ) >> R_{BCS} (~ 1nΩ at 2K), $Qo\ (2K) \sim \frac{107.4}{R_{res}}$, at 322 MHz.

- Reduce the ambient magnetic field:
  - Developed uniform cooldown (UC)+active field cancellation (AFC) to reduce magnetic flux produced by Seebeck effect at different material joints, nearby cavity.
  - Degaussing process at ~ 20K during UC.
  - Utilized NC25 bolts/nuts (Copper/Nickle alloy, perfectly none magnetization), for all cavity ports, instead of SUS.
- Reached R_{res} ~ 1 nΩ
  - UC+AFC reduces the ambient field to 3 - 6 mG, and R_{res} = 1.5 – 2.3 nΩ.
  - Degaussing or use of NC25 bolts/nuts decreases R_{res} to ~ 1 nΩ even with 6 mG of the magnetic field.





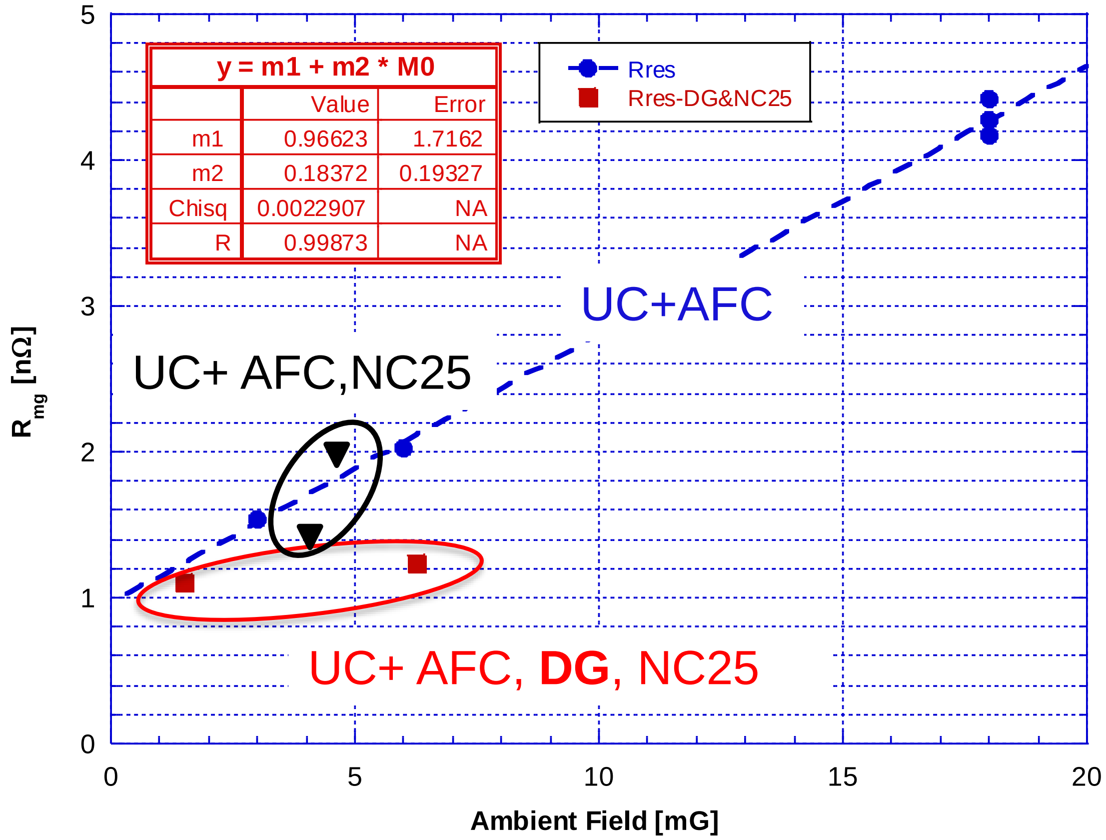
Degaussing at ~ 20 K



NC25 bolts/nuts, instead SUS ones

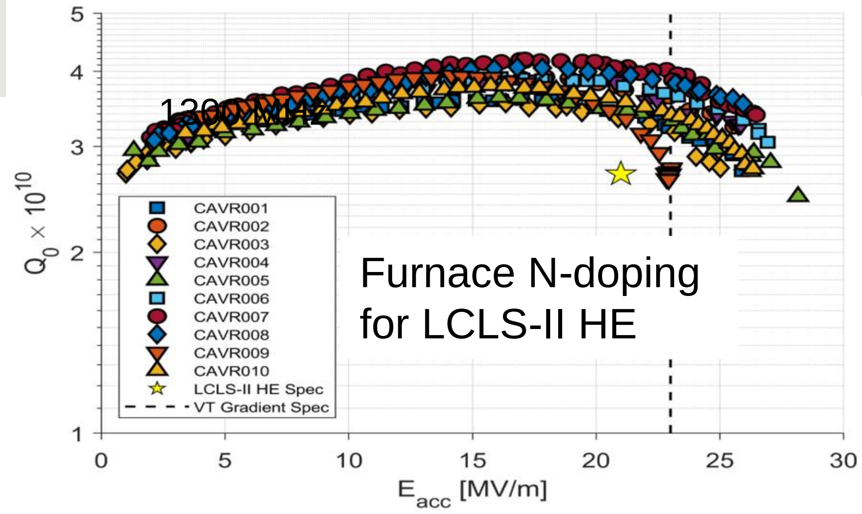
Lessons Learned on Flux Trapping

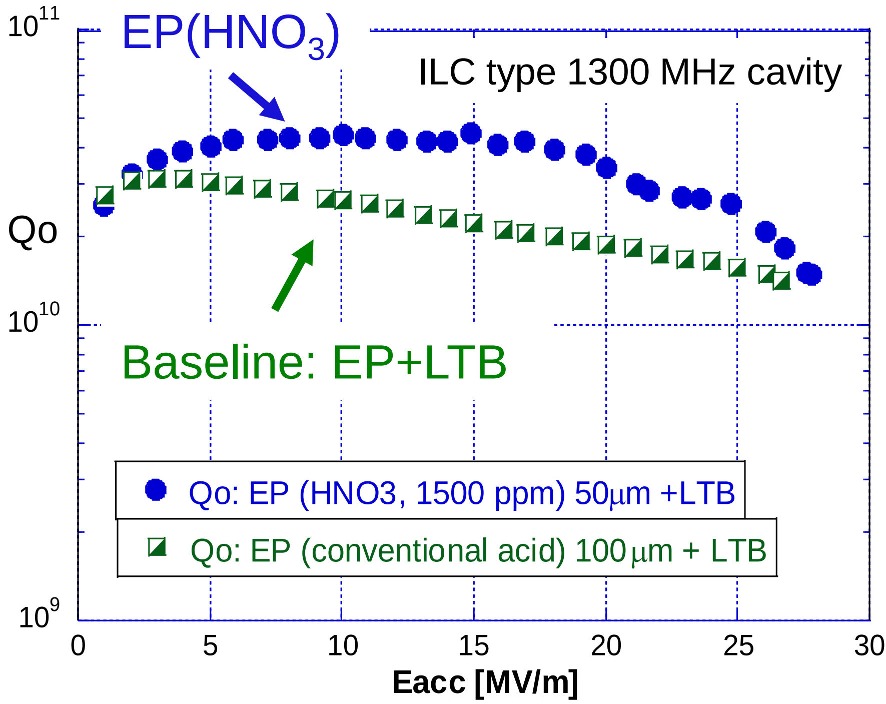
- Ambient field (H_{amb}) contribution (R_{mg}) on R_{res} is well known:
  $R_{mg}[n\Omega] = C \times \sqrt{f\,[\mathrm{MHz}]} \times H_{amb}\,[mG]$
- The data fitting result in for FRIB 0.53 HWRs:
  $R_{mg}\ [n\Omega] = 0.184 \times H_{amb}\ [mG]$
- **In fast cooldown (FC), R_{res} = 4.3 nΩ, and 80% the R_{res} is due to flux trapping.**
- Degaussing At ~ 20K during cooldown is effective to reduce the R_{res} to ~ 1 nΩ.
- R_{res} ~ 1nΩ, limit of the ambient field control.
- Ambient field is well controlled now.



Objective 3: Wet Nitrogen-Doping, EP(HNO_3)

- N-doping might push up Qo for FRIB 0.53HWRs.
  - Impossible the 800 – 900 °C furnace treatment included in the current furnace N-doping recipe, for FRIB cavities (spares) dressed Ti jacket on it.
- **Motivation of wet N-doping, EP(HNO_3):**
  - EP(HNO_3) (called as nitrogen doping EP) was developed by PI 20 years ago for Hydrogen-free EP.
  - EP(HNO_3): Electropolishing using new acid by adding 1500 ppm nitric acid (HNO_3) to the conventional EP acid: for example10 cc 64% nitric acid to 4L EP acid.
  - Discovered a Qo enhancement effect in EP(HNO_3)'ed cavity, which might be due to wet N-doping effect (?).
- **Objective 3: Apply EP(HNO_3) to FRIB 322 MHz HWRs**
  - Verify wet N-doping
  - Investigate cavity performance
  - Analyze role of wet doped nitrogen
- **Impact on SRF Community**
  - Many responses on the paper published in LINAC2024. Might be a highlight in SRF2025, next fall in Tokyo?





Verification of Wet N-Doping

- **Scientific Motivation** of wet N-doping: the electro-chemical reaction potential in EP is 0.35 eV, which corresponds to 3500^{O}C. N-doping might be caused during EP(HNO_3).
- **Verifications of Wet N-doping**

V-1. N_2 and O_2 outgassing in degassing process:

Outgassed more N_2 and less O_2, because the doped nitrogen atoms occupied the original oxygen doping sites, thus suppressed O doping.

V-2. LTB effect at 4.3K:

Smaller Qo enhancement in EP(HNO_3)'ed cavity, than the conventional EP'ed one because oxygen contributes to the enhancement is less.

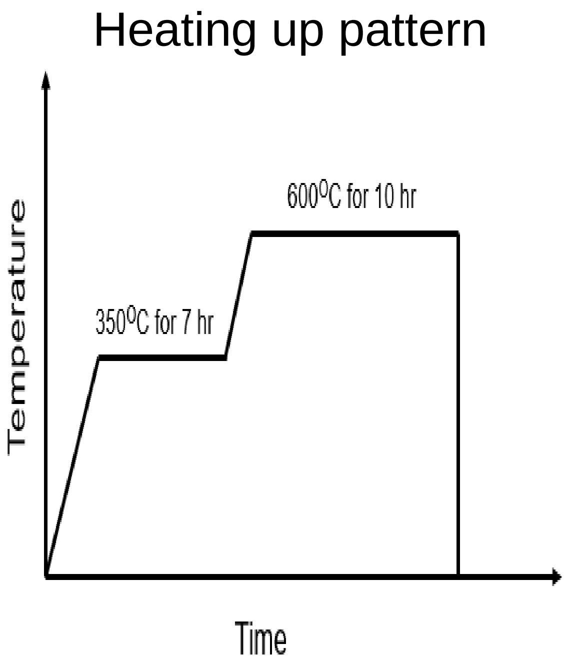
V-3. Estimation of doped N and O from RRR:

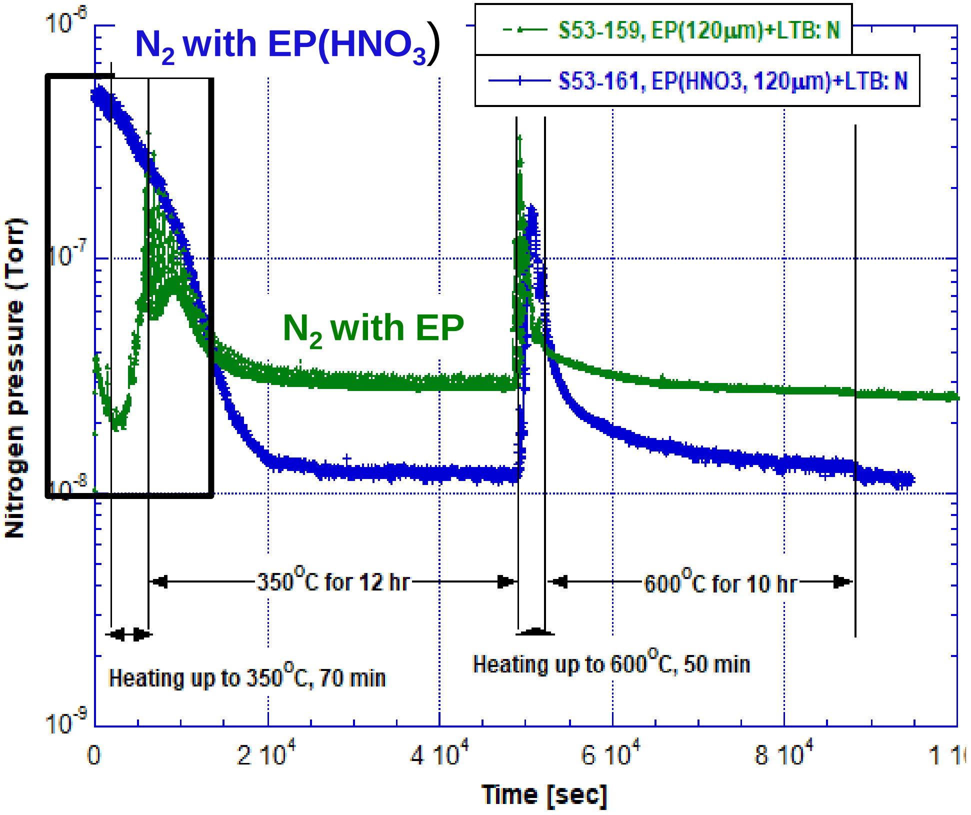
A greater amount of N, but a smaller amount of O.

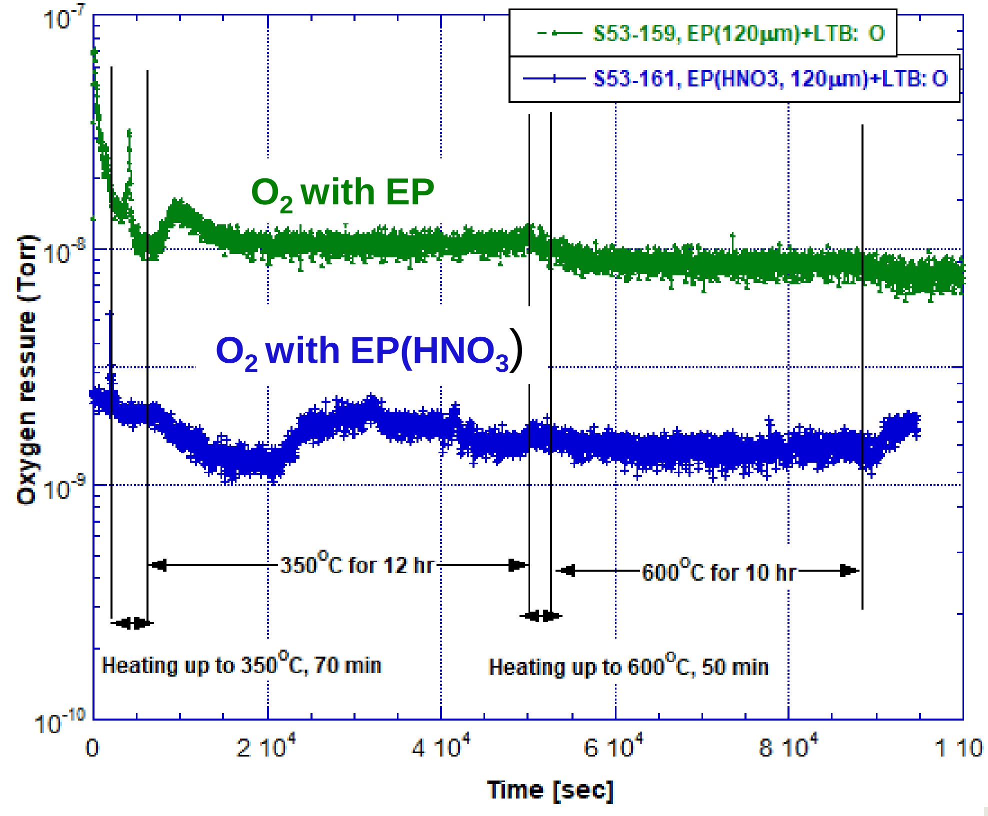
❖ ***Direct verification by SIM is not ready because of no sample attachment on the cavity.***

V-1: Enhanced N_2 and Depressed O_2 Outgassing

- Expect enhanced N_2 outgassing and decreased oxygen outgassing during hydrogen degassing process: 600°C 10hr.
- Observed the enhanced N_2 outgas during heat up to 350°C, on the other hand depressed O_2 in all process.



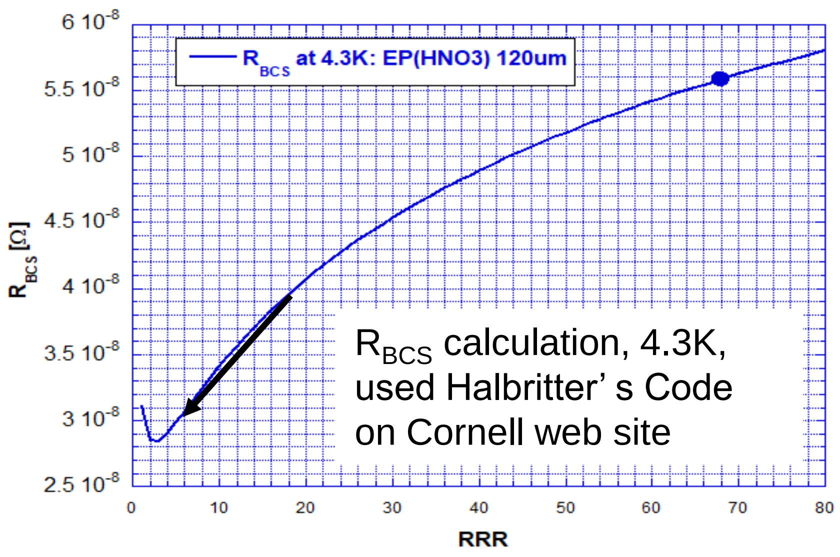




Why Qo Enhancement at 4.3K with Contaminated Surface

R_{BCS} (~ 40 nΩ) >> R_{res} (~ (1 – 4) nΩ) at 4.3K @ 322MHz.

Qo (4.3K) ~ $\frac{107.4}{R_{BCS}}$ at 4.3K @ 322 MHz

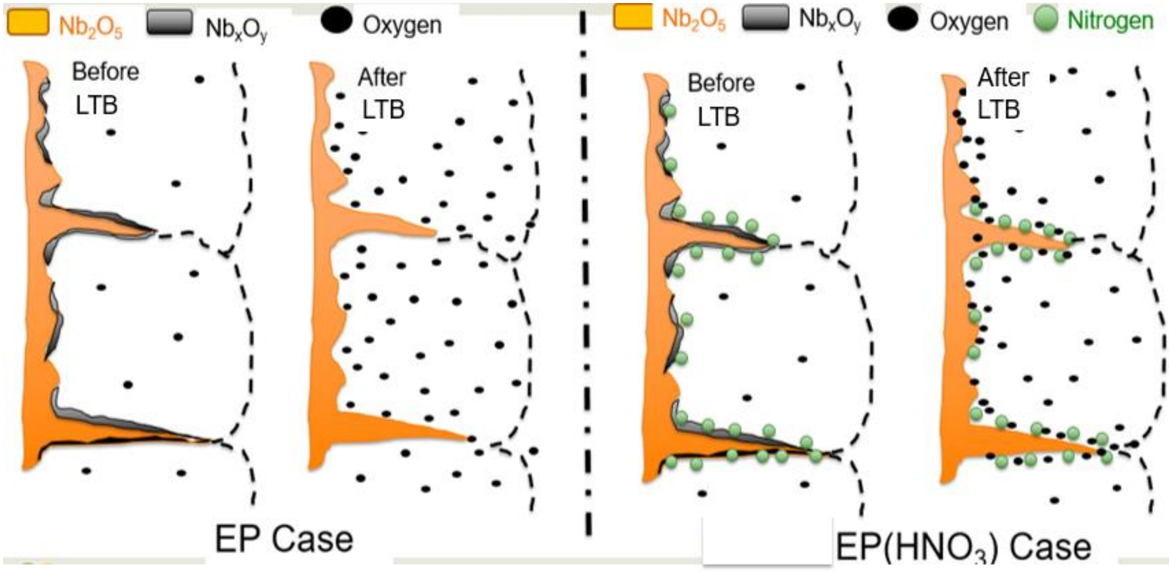


- BCS surface resistance (R_{BCS}) decreases by contamination on SRF surface: shorter mean-free path (ℓ) or lower RRR, $\ell \propto RRR$.

  Qo enhances by contamination on SRF surface

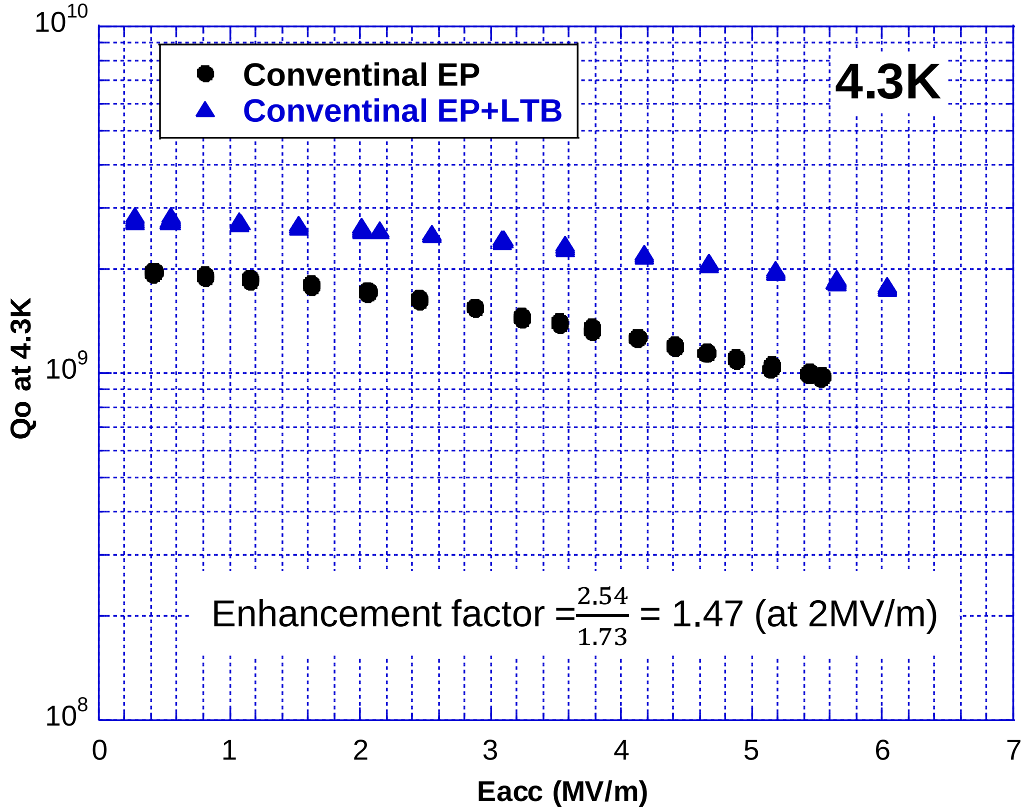
  - In-situ LTB (120°C, 48 hr) post EP diffuses oxygen existing on top surface into the RF penetration depth (~ 40 nm), and contaminates this area. Thus a visible Qo enhancement happens at 4.3K by LTB.

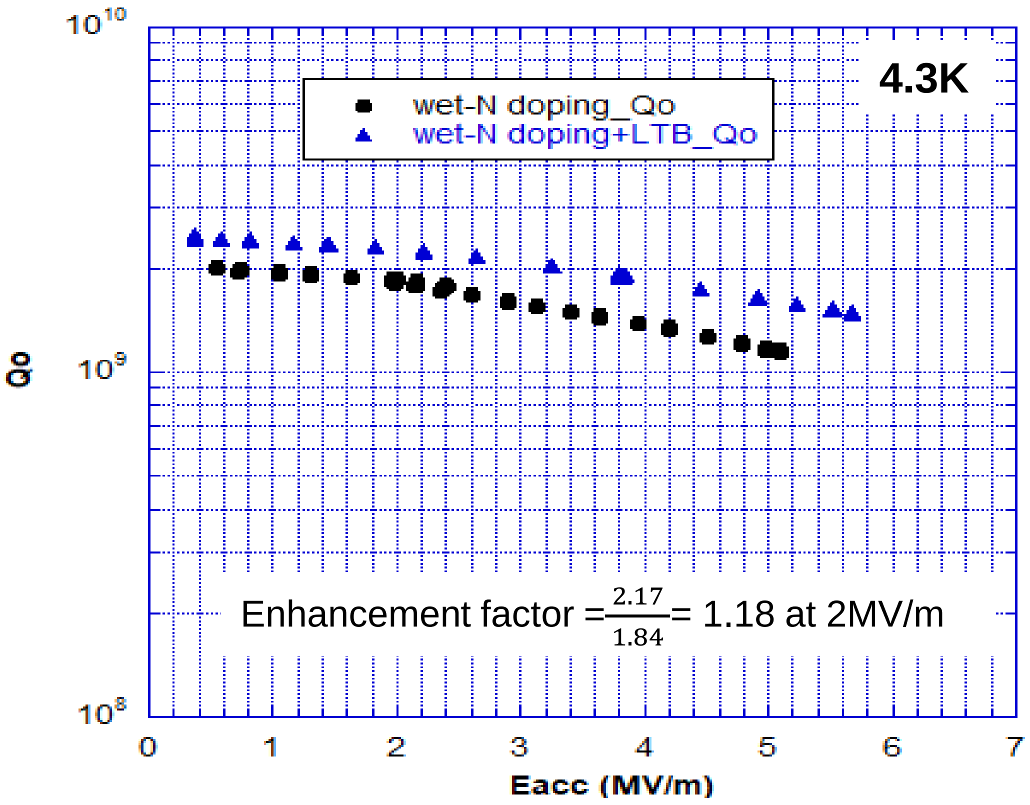
- Wet N-doping case:
  - Nitrogen is doped on top surface, especially at grain boundaries, and does not diffuse during LTB (for e.g. 0.16 nm at 140°C for 40 hr). Wet doped nitrogen itself has no contribution to the Qo enhancement.
  - Amount of oxygen by EP(HNO_3) is less than the conventional EP. Qo enhancement by LTB should be smaller than EP.



V-2: Suppressed Qo Enhancement at 4.3K

- Observed the expect smaller Q_o enhancement by LTB in EP(HNO_3).
- As expected, EP(HNO_3)+LTB produces a smaller Qo enhancement at 4.3K than EP.
- Qo enhancement factor (Qo before LTB/Qo after LTB) should be proportional to the amount of oxygen concentration.





How to Estimate O and N Concentrations on Top surface, from RRR

- $R_s\,(T)$ measured at Eacc = 2 MV/m is fitted by: $R_s(T) = R_{\mathrm{res}} + R_{\mathrm{BCS}}(T) = R_{\mathrm{res}} + \frac{A}{T}\exp(-\frac{\Delta}{K_B T})$.

  Calculate R_{BCS}(4.3K) and R_{BCS}(2K)

- Determine of RRR: **Exact BCS theoretical calculation used Halbritter' s code** at 4.3K and 2K, and compare the fitted values.

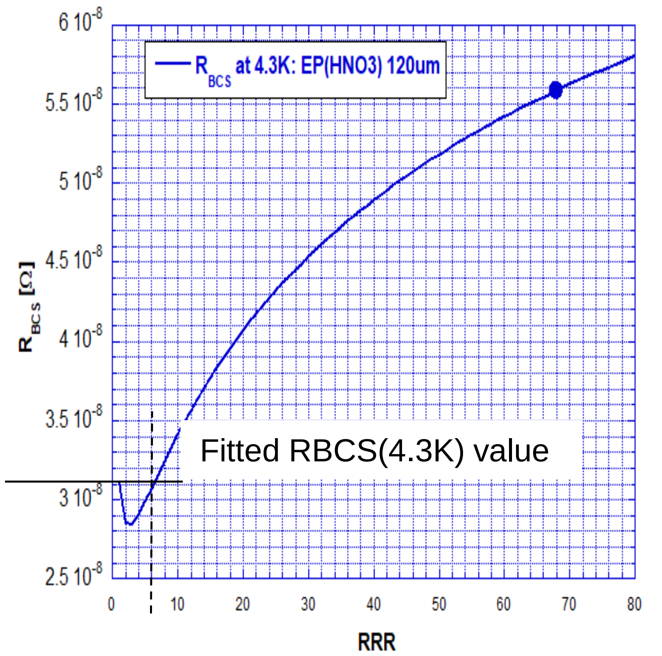
- Nitrogen and oxygen concentrations: inferred from RRR (for Nb bulk) using the formula:

$$\frac{1}{\mathrm{RRR}} = \frac{c_{\mathrm{O}}}{5800} + \frac{c_{\mathrm{N}}}{2273} + \frac{c_{\mathrm{H}}}{16322} + \frac{c_{\mathrm{C}}}{8911} + \frac{c_{\mathrm{Ta}}}{604690} + \frac{1}{1249}$$ [1].

Ci : concentration in ppm

[1] H. Umezawa; https://www.jstage.jst.go.jp/article/jcsj/52/2/52_79/_pdf/-char/ja

Exact BCS theoretical calculation using Halbritter' s code on the Cornell web site



❖Supposed: only oxygen contaminant in EP: $\frac{1}{31} = \frac{C_{O1}}{5800}$, C_{01}= 187, EP+LTB: $\frac{1}{6} = \frac{C_{01}^*}{5800}$, C_{01}^*= 967

❖Oxygen for EP(HNO_3, 120μm): $C_{02} = \frac{187 \times 0.8}{1.47}$ = 150, from enhancement factor C_{01}: C_{02} = 1.47 : 1.18

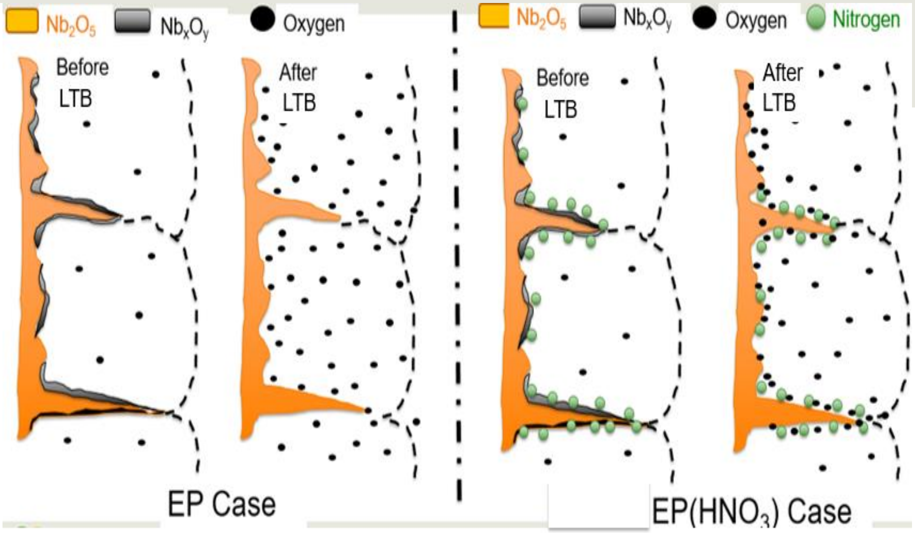
❖Nitrogen for EP(HNO_3, 120μm): $\frac{1}{17} = \frac{150}{5800} + \frac{C_{N2}}{2273}$, C_{N2}= 75

❖Oxygen for EP(HNO_3, 120μm)+LTB: $\frac{1}{10} = \frac{C_{o2}^*}{5800} + \frac{75}{2273}$, C_{o2}^* = 389

Processing	Qo enhancement factor at 4.3K after LTB	RRR	O [ppm]	Oxygen ratio	N [ppm]
Conventional EP(120)	1.47	31	187	5.2	0
Conventional EP(120)+LTB		6	967		0
EP(HNO_3,120)	1.18	17	150	2.6	75
Ep(HNO_3,120)+LTB		10	389		75

V-3: Estimated O and N Concentration

- EP(HNO_3) dopes nitrogen, and **suppress oxygen doping** on the top surface.
- **Wet doped nitrogen stays at the doped site** and **no diffusion** during LTB.
- Oxygen diffuses but this wet **doped nitrogen disturbs the oxygen diffusion**: Oxygen not diffuse enough deep.



Estimated O and N Concentration on Top Surface

Processing	Qo enhancement factor at 4.3K by LTB	RRR	Oxygen [ppm]	Oxygen ratio	Nitrogen [ppm]
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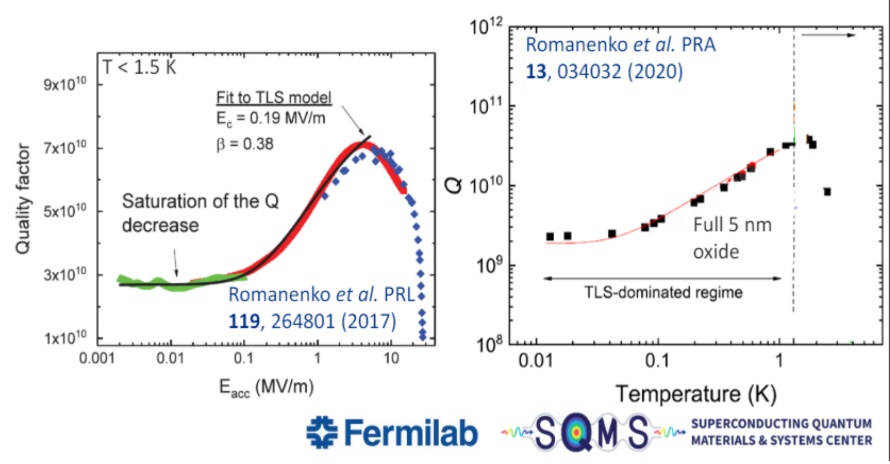
Conventional EP(120)+LTB		6	967		0
EP(HNO_3,120)	1.18	17	150	2.6	75
EP(HNO_3,120)+LTB		10	389		75
Degassing + EP(HNO_3, 25)	1.15	17	146	2.6	76
Degassing + EP(HNO_3, 25) + LTB		10	386		76
EP(HNO_3, 25+50)	1.49	18.2	190	2.4	50
EP(HNO_3, 25+50) + LTB		10	452		50

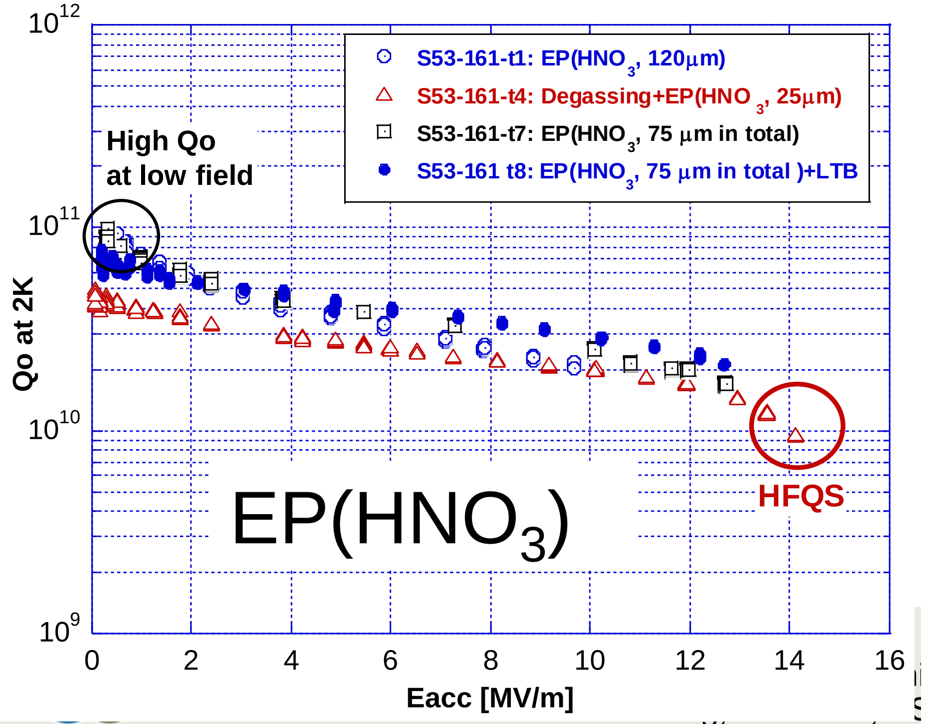
Performance at 2K and Hydrogen Q-Disease

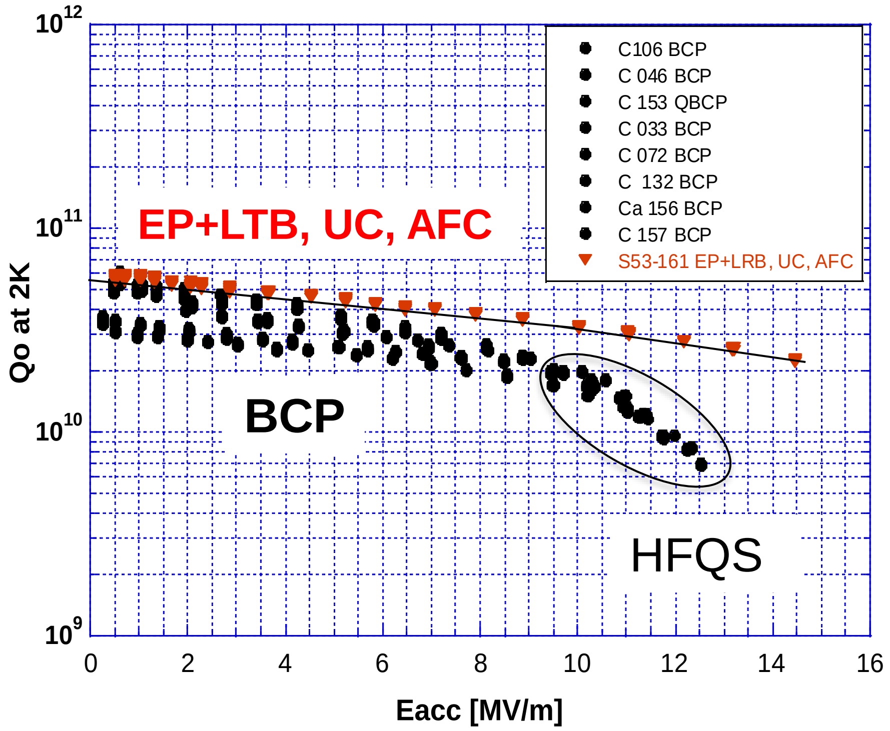
- **Extremely high Qo at low field : Qo =(8-9) E+10**, which might be beneficial to SRF quantum computer technology.
- Pushed up HFQS onset field > 12 MV/m from 9 MV/m (BCP) .
- **Steep MFQS (medium field Q slope) compared to EP**.
- **Achieved the project Goal – 1 by EP(HNO_3)**: Qo = $2x10^{10}$ @ 12 MV/m
- NO Hydrogen Q-disease, up to 75 μm EP(HNO_3) in total of material removal so far, after degassing.



Hydrogen Q-Disease

Processing	Hydrogen Q-disease	Symptoms
EP(HNO_3 120 μm)	Yes	Very light
Degassing + EP(HNO_3, 25 μm)	No	-
EP(HNO_3, 50μm, in total 75μm)	NO	-

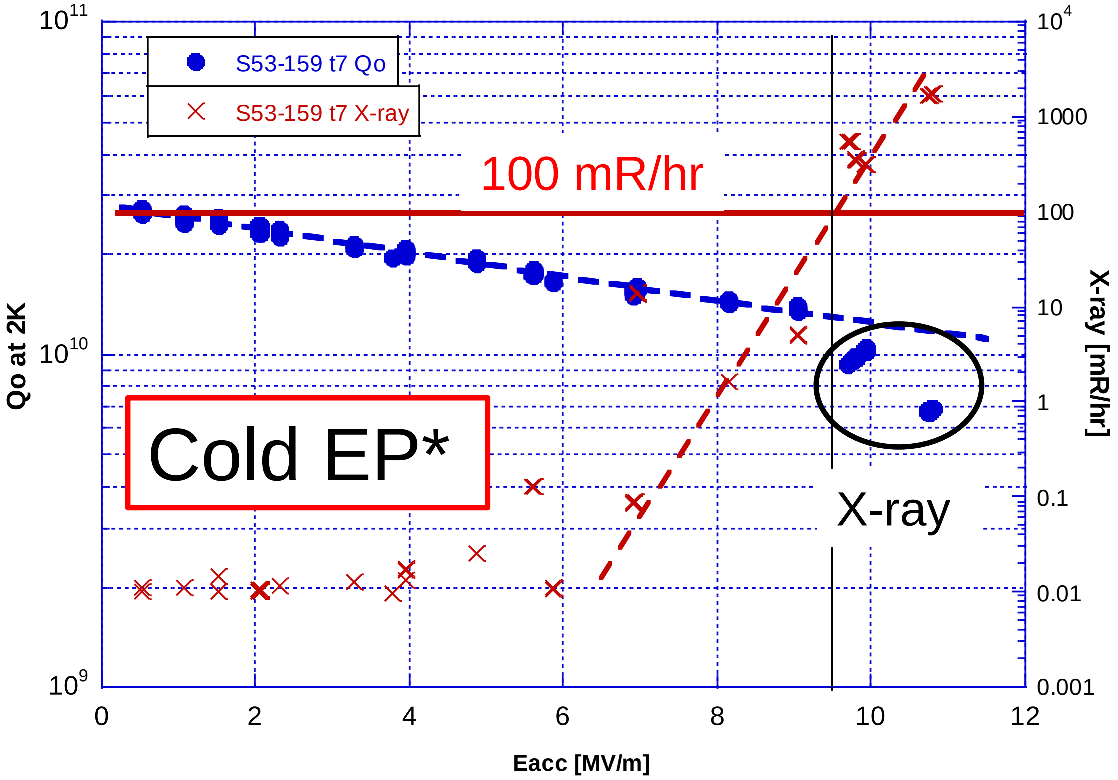


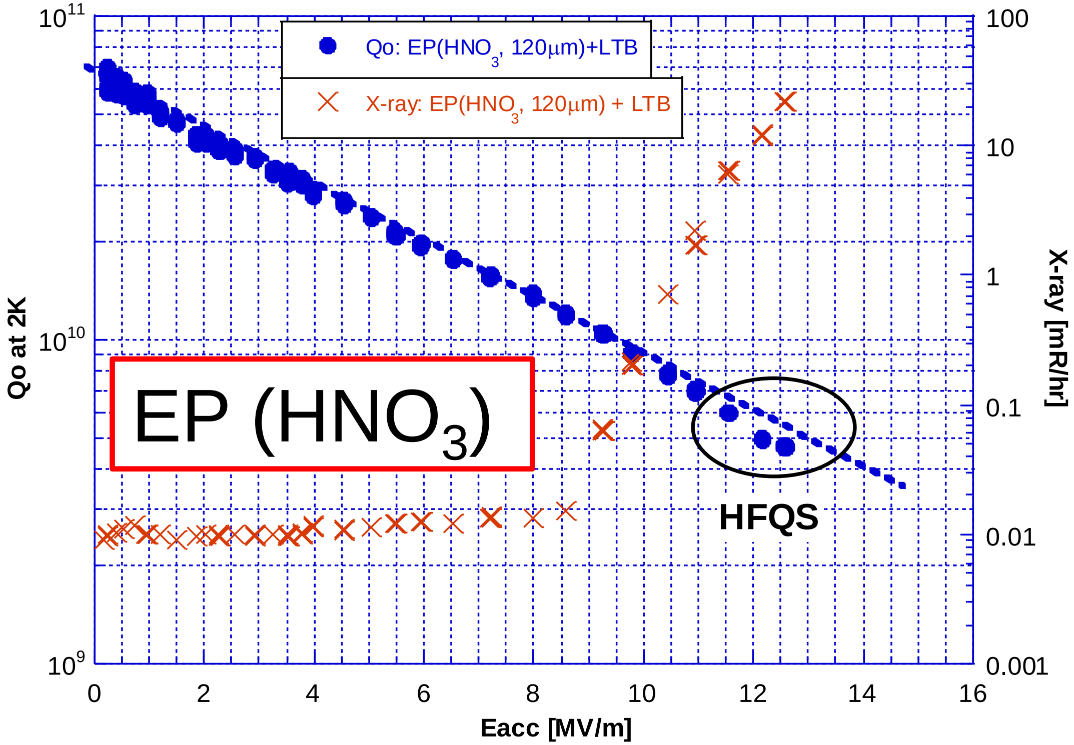


HFQS Not Mitigated by LTB with EP(HNO_3)

- EP(HNO_3) produced the HFQS not mitigated by LTB, similar to BCP.
- Wet-doped nitrogen disturbs oxygen diffusion during LTB, so oxygen did not move to enough depth. This makes LTB impossible to mitigate HFQS.

Heat loads do not appear on Qo vs Eacc curve up to the dose 100 mR/hr of X-ray in FRIB VTA test.

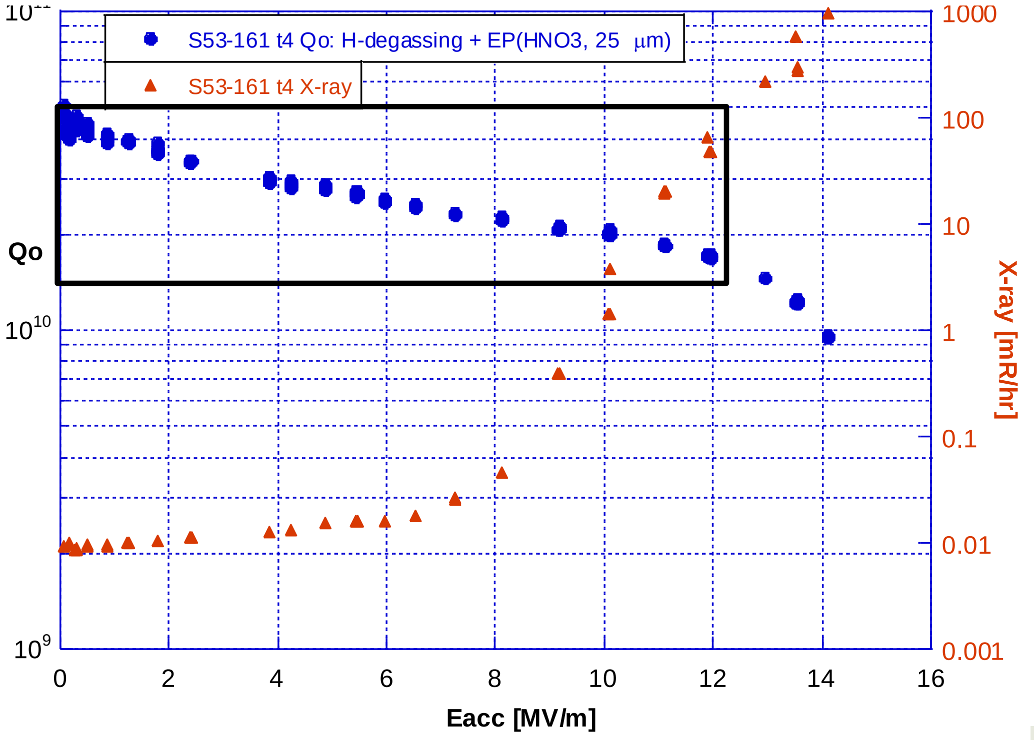


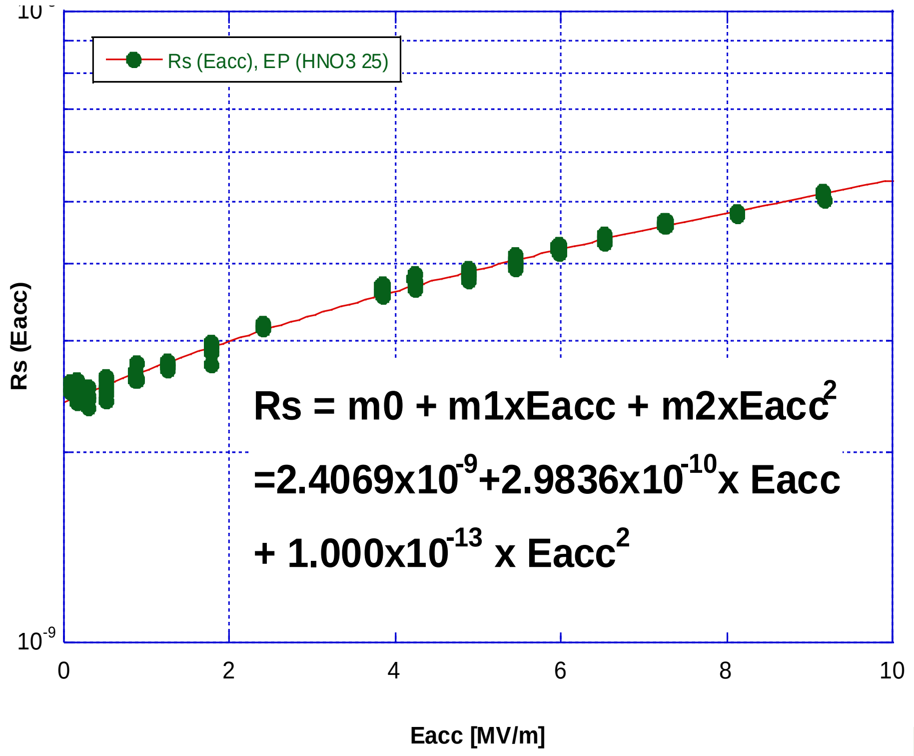


* Recent R&D has discovered the cold EP has no HFQS up to 12-13 MV/m with FRIB 0.53 HWRs (322 MHz).

Analysis of Medium Field Q-Slope (MFQS)

- R_s is well fitted for all results by:
  R_s (Eacc) = 107.4/Qo(Eacc) = m0 + **m1x Eacc** + m2x $Eacc^2$
- m0: residual surface resistance, sensitive to cooldown condition.
  m1 x Eacc: produces MFQS.
  m2 x $Eacc^2$: thermal feedback, well known.





Feature of MFQS among EP(HNO_3), BCP, and EP

- EP (HNO_3): m1 = (2 – 4) $\times 10^{-10}$, close to BCP ~ 2 $\times 10^{-10}$
- Conventional EP: m1 = 6 x 10^{-11}, much smaller than EP (HNO_3) or BCP.
- ***Difference in m1 value might be explained by the characteristics of weak links, i.e. the insulators at grain boundaries doped nitrogen by BCP or EP(HNO_3).***

Processing	m0 : relate to Rres, sensitive to cooldown condition	m1 : relates to MFQS, hysteresis loss, or flux trapping	m2 : relates to thermal feedback, well known
BCP, FRIB production cavities, no LTB	**3.06 e-9**	**1.87 e-10**	**1.44 e-11**
EP(HNO_3, 120), UC+AFC	**1.09 e-9**	**3.82 e-10**	**2.18 e-12**
EP(HNO_3, 25, after degassing), UC+AFC	**2.41 e-9**	**2.98 e-10**	**1.00 e-12**
EP(HNO_3,75), UC+AFC (degaussing), NC25	**1.24 e-9**	**2.65 e-10**	**7.81 e-12**
EP(HNO_3, 75) + LTB, UC+AFC (degaussing), NC25	**1.54 e-9**	**1.70 e-10**	**4.36e-12**
EP (120), S53-159, FC	**4.85 e-9**	**5.70 e-11**	**3.82 e-11**

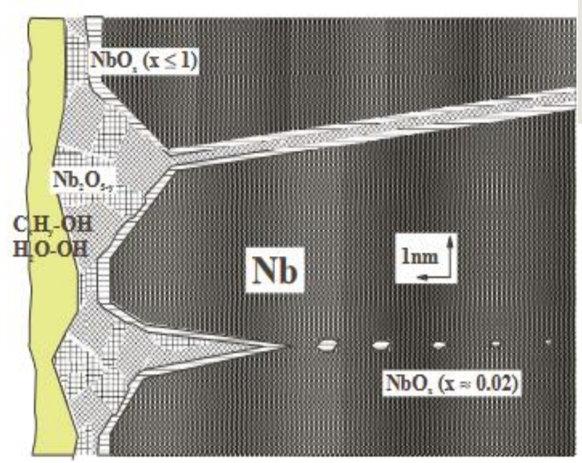
HOM Measurement Planned for MFQS Loss Mechanism

- **Additional test items in objective 3 to understand MFQS**
  - Hysteresis loss in MFQS predicts:

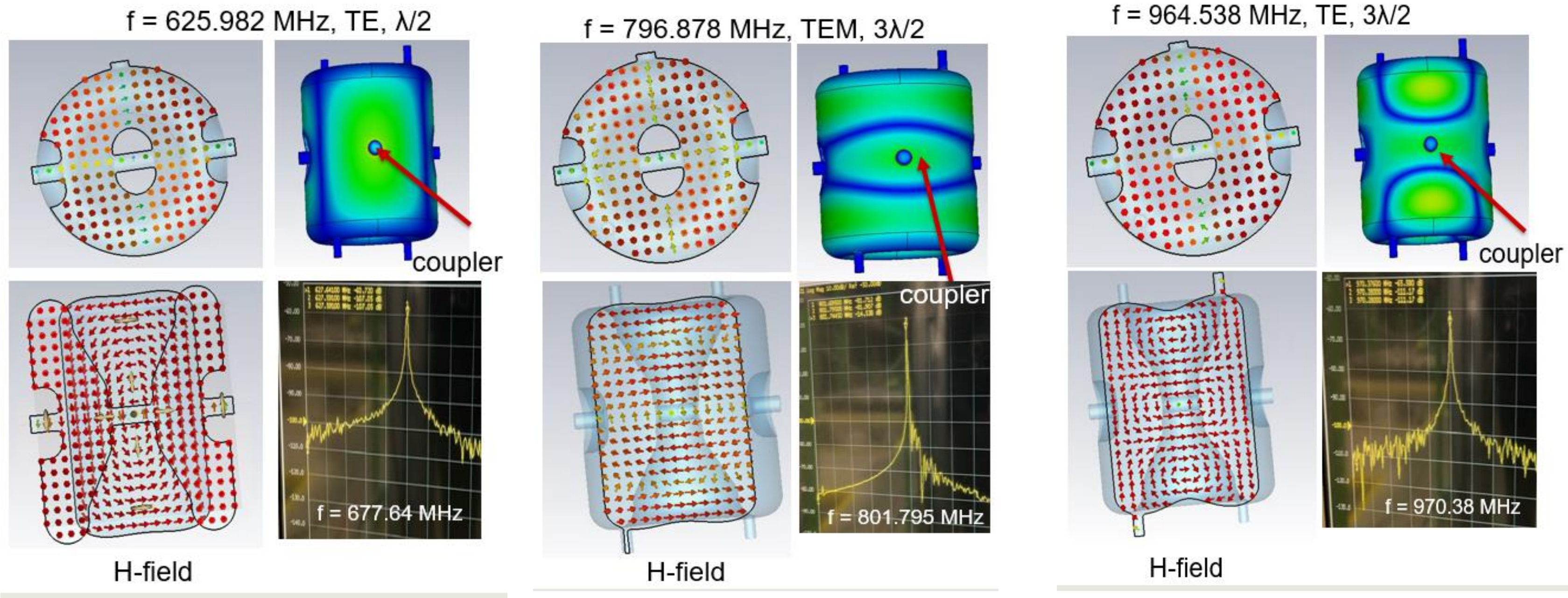
    m1 proportional to cavity frequency [2],

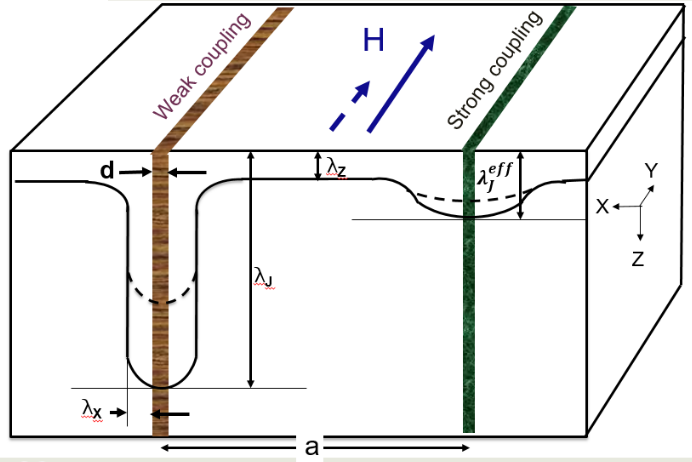
$$R_{hys} = m1 \propto f$$

[2] G. Ciovati and J. Halbritter, SRF2005



- HOM measurement is planned to investigate the frequency dependence on m1.
  - HOM measurement is ready.

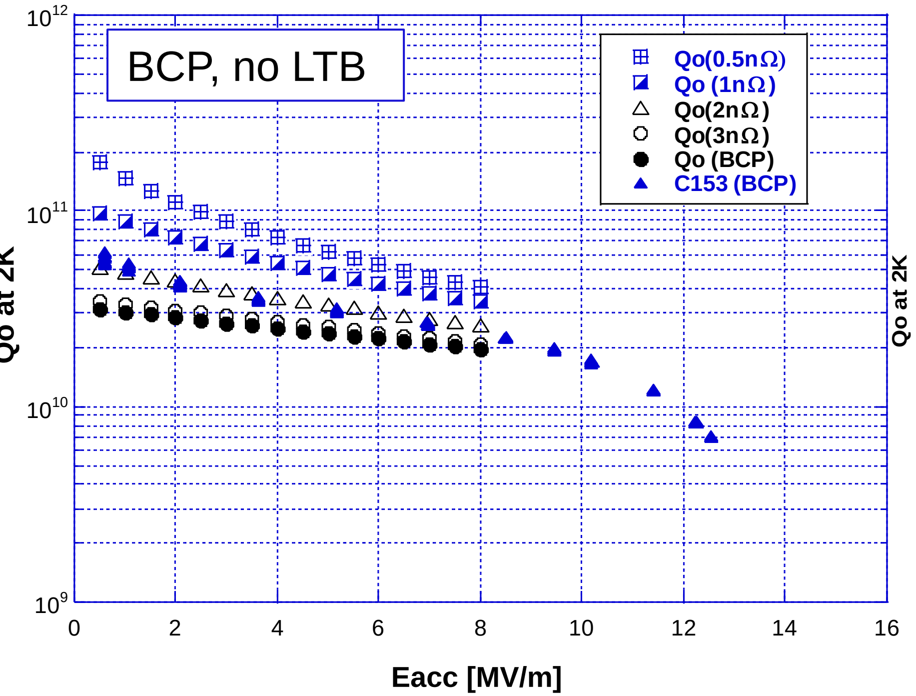


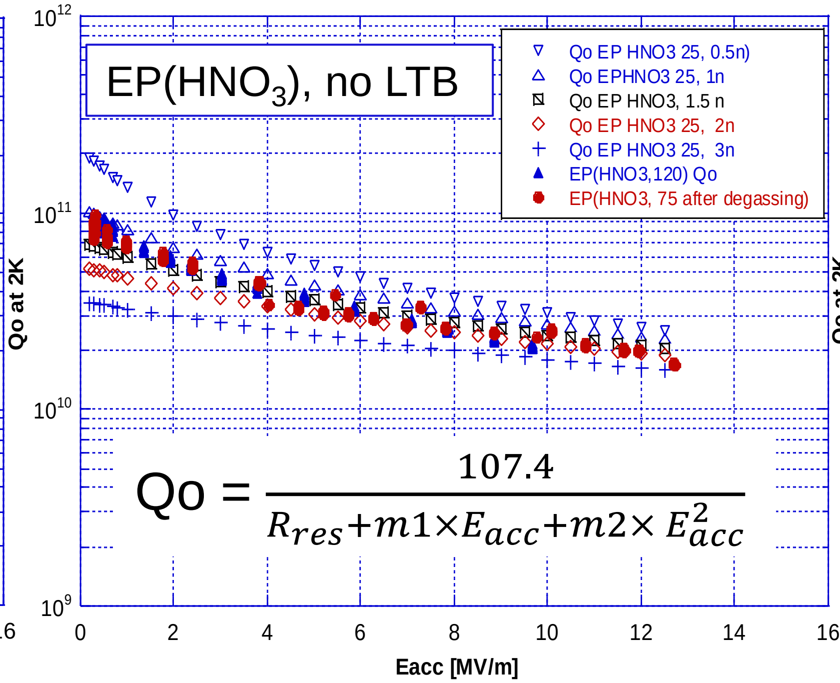


Weak/strong link at grain boundaries produce hysteresis loss due to Josephson flux penetration

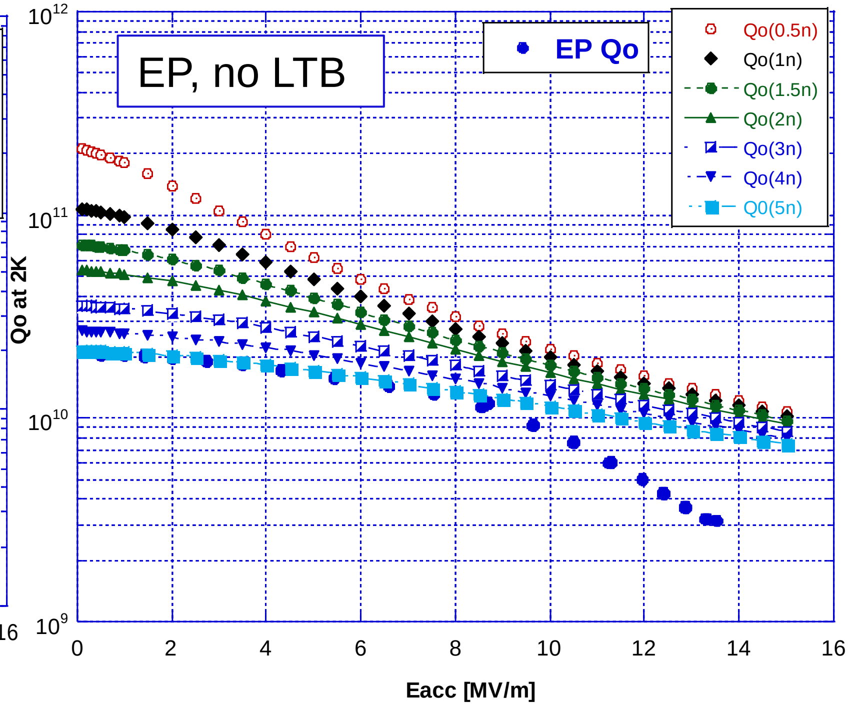
MFQS Dependence on R_{res}, FRIB 0.53 HWRs (322 MHz)

- Similar MFQS behavior with both EP(NHO_3) and BCP.
- This analysis strongly suggests:
  - ❖ **BCP also dopes nitrogen.**
  - ❖ The wet doped nitrogen characterizes the BCP'ed cavity performance. A very high Qo behavior at low field could happen with BCP also, at small Rres ~ 1nΩ.





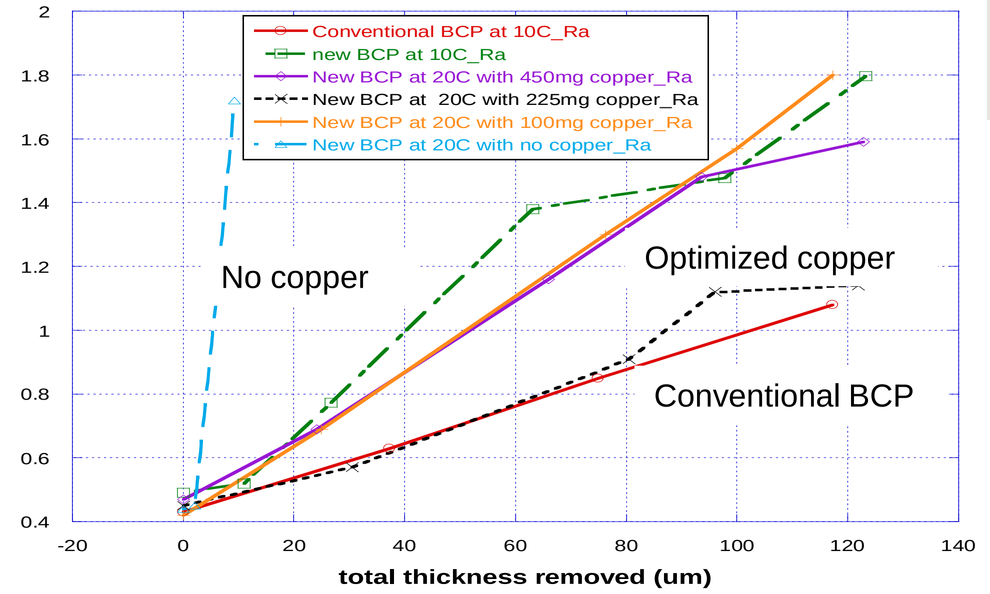
$$Qo = \frac{107.4}{R_{res} + m1 \times E_{acc} + m2 \times E_{acc}^{2}}$$

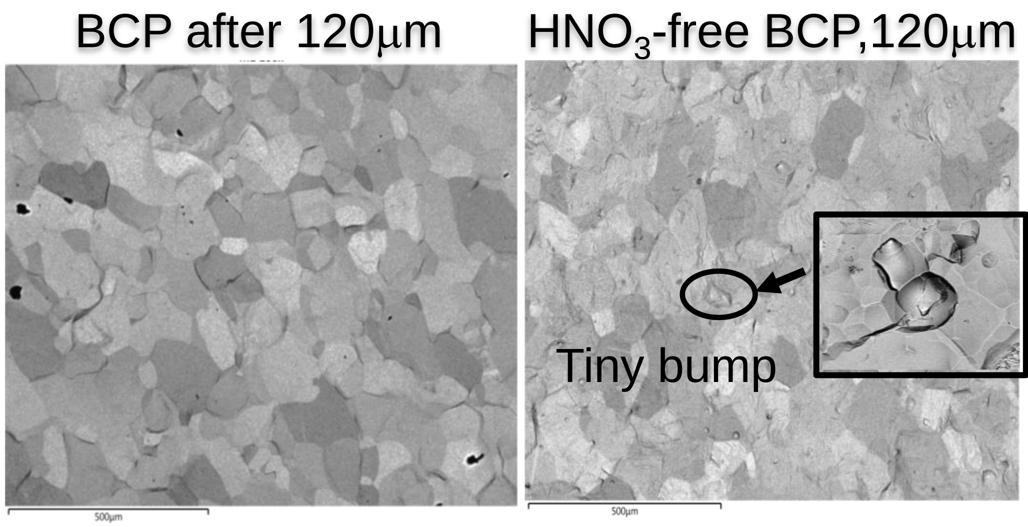


Objective 4: HNO_3-free BCP

- Understood that HNO_3 might be problematic in BCP'ed cavity performance.
- **HNO_3-free BCP acid**
  - Current BCP acid; HF(49%):HNO_3 (64%):H_3PO_4 (85%) = 1: 1: 2 v/v
  - Replacement of HNO_3 to H_2O_2 (50%) was tried, failed (too rough finishing), but succeeded when used copper as catalyst (MSU PhD work 2021, Didi Luo).

    Developed HNO_3-free BCP acid: HF(50%):H_2O_2 (50%): H_2O =15: 29: 11, + copper. H_2O_2 effectively 36.3%
  - Optimized copper (225 mg/L): comparable surface finishing to BCP, Ra ~ 1μm at 120μm material removals.
  - Etching speed: 2.5 μm/min, similar to BCP, but 5 times faster than EP.
  - Similar SEM (back scattering) Image both on BCP and HNO_3-fee BCP.
  - But HNO_3-free BCP has tiny bumpy irregularities due to preferential etching, which FE might be concerned. More optimization might be required.
  - No copper contamination on SEM images, if HPR was applied.
- **Safety for waste acid**
  - Highly concentrated hydrogen peroxide (effectively 36.3%) decomposes easily and causes a rise in pressure in the waste storage tank, raising concerns about damage to the container. The exhausted gas includes HF vapor. Needs a cure for waste acid: JSA matter.

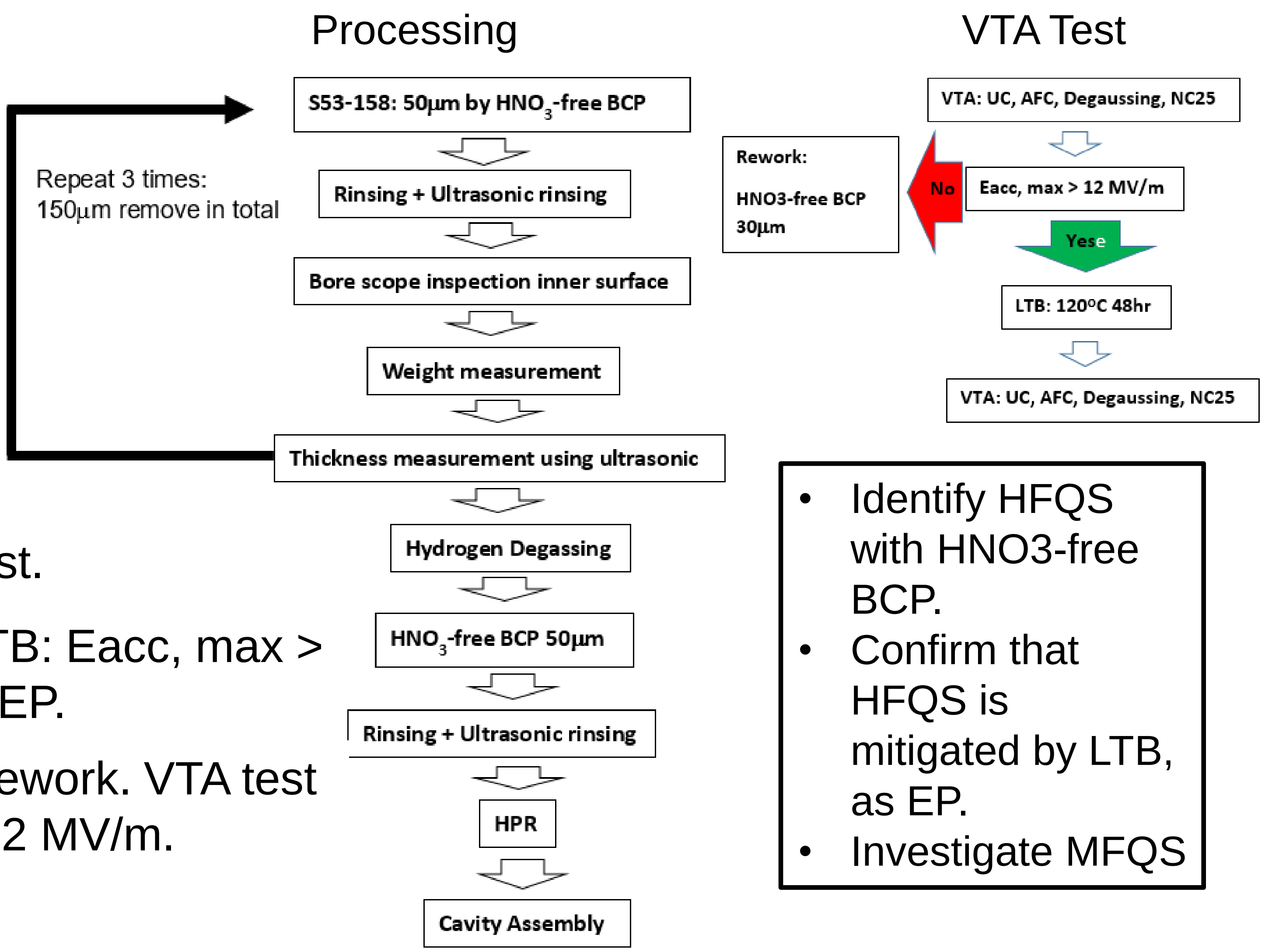




SEM Inage (back scattering)

Plan for HNO_3-Free BCP

- **Establishment of the processing**
  - 50μm removal for every three times, to establish the complete HNO_3-free BCP processing
  - Finally, 50μm will be removed as the final etching, after hydrogen degassing
  - Cavity assembly using NC25 bolts/nuts.
- **VTA Test**
  - Validate HNO_3-free BCP by VTA cavity test.
  - Cavity performance goal at 2 K, before LTB: Eacc, max > 12 MV/m. HFQS might happen similar to EP.
  - If the goal is achieved, apply LTB. If not, rework. VTA test after LTB, Goal at 2 K: Qo = 2.0E+10 @ 12 MV/m.



- Identify HFQS with HNO3-free BCP.
- Confirm that HFQS is mitigated by LTB, as EP.
- Investigate MFQS

- ***JSA process for the waste acid takes a time. The cavity processing and cavity test will be done within 12 month extension without any additional budget. Objective 4 to be completed by August 31/2025.***

Education Through This Project

Postdoc: Yuting Wu (female)

Gained hands-on technologies:

1. Cavity/Magnetic shield design skill using CST,
2. Cavity preparation skill on BCP and EP
3. Cavity testing skill at room temp. and cryogenic temp.
4. Microscopic surface analysis, SEM, XPS
5. Cavity data analysis

Invited talks:

1. TTC High Q and high G virtual meeting on 04/11/2024, Title Development of High Q and High Gradient β = 0..53 Half Wave Resonator
2. TTC High Q and high G virtual meeting on 09/12/2024, Title Development of Wet Nitrogen Doping to Enhance Q Performance
3. 5-min oral talk for excellent poster presentation in LINAC2024, August, 2024, Chicago, Title Development of Wet Nitrogen Doping to Enhance Q Performance of β = 0.53 Half-wave Resonators

Publishes (First author by blue):

1. SRF2023 contributed paper, Title Development of Transformative Cavity Processing – Superiority of Electropolishing on High Gradient Performance over Buffered Chemical Polishing at Low frequency (322 MHz)
2. LNAC2024 contributed paper, Title Development of Wet Nitrogen Doping to Enhance Q Performance of β = 0.53 Half-wave Resonators
3. Journal paper 1, to be submitted to APS/123-QED, Title: Development of High Q and High Gradient of β=0.53 Half Wave Resonator for FRIB High Gradient Spare Cryomodule.
4. Journal paper 2, to be submitted to APS/123-QED, Title: Development of Wet Nitrogen Doping to Improve Performance of Half-Eave Resonators"

Graduate Student: Spencer Comb (male), Master Defense to be in July, 2025

Gained hands-on technologies:

1. Magnetic shield design skill using CST,
2. Cavity preparation skill on BCP and EP
3. Cavity testing skill at cryogenic temp.
4. Microscopic surface analysis, SEM
5. Cavity data analysis
6. Seebeck coefficient measurement system design and measurements

Publishes (Co-author):

1. LNAC2024 contributed paper, Title Development of Wet Nitrogen Doping to Enhance Q Performance of β = 0.53 Half-wave Resonators
2. Journal paper 1, to be submitted to APS/123-QED. Title: Development of High Q and High Gradient of β=0.53 Half Wave Resonator for FRIB High Gradient Spare Cryomodule.
3. Journal paper 2, to be submitted to APS/123-QED, Title: Development of Wet Nitrogen Doping to Improve Performance of Half-Eave Resonators"

Issues and Resolutions

- Schedule Delay with Objective 3 - 4, and Solution
  - Lack of resource during 2024 Summer FRIB machine maintenance delayed schedule of objective 3 - 4.
  - Needs a long time for JSA process for safety on objective 4 (HNO_3-free BCP acid): sample test confirmations and documents.
  - Requested DOE extension for 12 months without additional budget, and accepted. Project end date: Aug.31, 2025.
- PI retirement on end of 2024, and Solution
  - PI, Kenji Saito to retire on end of 2024
  - C. Compton (Co-PI) will take over the PI responsibility, after Kenji.
  - Postdoc, Y. Wu will take leadership for real job with Object 4.
  - Kenji will make effort for the final report with C. Compton, through remote work.

Deliverable, 10/14 Successfully Completed

Deliverable Item	Status	Achieved Date	Comment
1) High gradient performance with FRIB 0.53HWRs by EP: Objective -1	√	May 2023	Eacc, max = 15 MV/m
2) Mitigate field emission for FRIB 0.53HWRs by EP: Objective - 1	√	May 2023	NO X-ray up to 12 MV/m
3) Mitigate HFQS by LTB post EP with FRIB 0.53 HWR: Objective - 1	√	May 2023/Nov. 2024	EP with 322MHz has no HFQS
4) Publish objective – 1 result	√	July 2023	SRF conference
5) Push up more high Qo performance by reducing ambient field: Objective - 2	√	Feb. 2024/Oct. 29024	Uniform cooldown and Active field cancellation, degassing, and use of NC25 bolts/nuts Smallest Rres = 1nΩ
6) High Q and high gradient performance by EP+LTB, improving cooldown: Objective - 2	√	May 2024	**Achieved first goal achieved. Qo = 2.8 x10^{10} at 12 MV/m**
7) Publish objective - 2 result	Ongoing Journal paper		To be submitted APS
8) Develop wet N-doping by EP(HNO_3): Objective - 3	√	July. 2024	**Achieved second Goal**
9) Give answer why HFQS is not mitigated by LTB post BCP, opened question more than 25 years in SRF community: Objective - 3	√	Sep. 2024	**First answer based on reality**
10) Demonstrate the high Q and high G performance by the wet N-doping: Objective - 3	√	Nov. 2024	Very high Qo at low field. **Achieved first goal**
11) Publish objective - 3 result	√ Ongoing Journal paper	Aug. 2024	LINAC2024 contributed paper. To be submitted APS
12) Develop HNO_3-free BCP surface treatment method: Objective - 4	**Ongoing under 12 months extension without no budget request**	To be May-June 2025	Transformative processing method
13) Confirm the cavity performance, similar to EP			EP might be replaced to HNO_3-free BCP
14) Publish objective - 4 result		To be July 2025	

Budget Status

	FY 23 ($k)	FY 24 ($k)	FY 25 (12 month extension)	Totals ($)
a) Funds allocated	359,000.00	345,000.00	No Cost Extension	704,000.00
b) Actual costs to date	140,386.70	610,063.41	643,437.07 (to date)	60,562.93 (remaining)

- Remained budget expense:
  - Postdoc contract ($ 46K) for extension 12 month, until April, 2025.
  - Nitrogen gas analysis have been quoted, $14K, delivery February 2025
  - ❖ Graduate student is supported by other DOE grants (ASET), $30K.

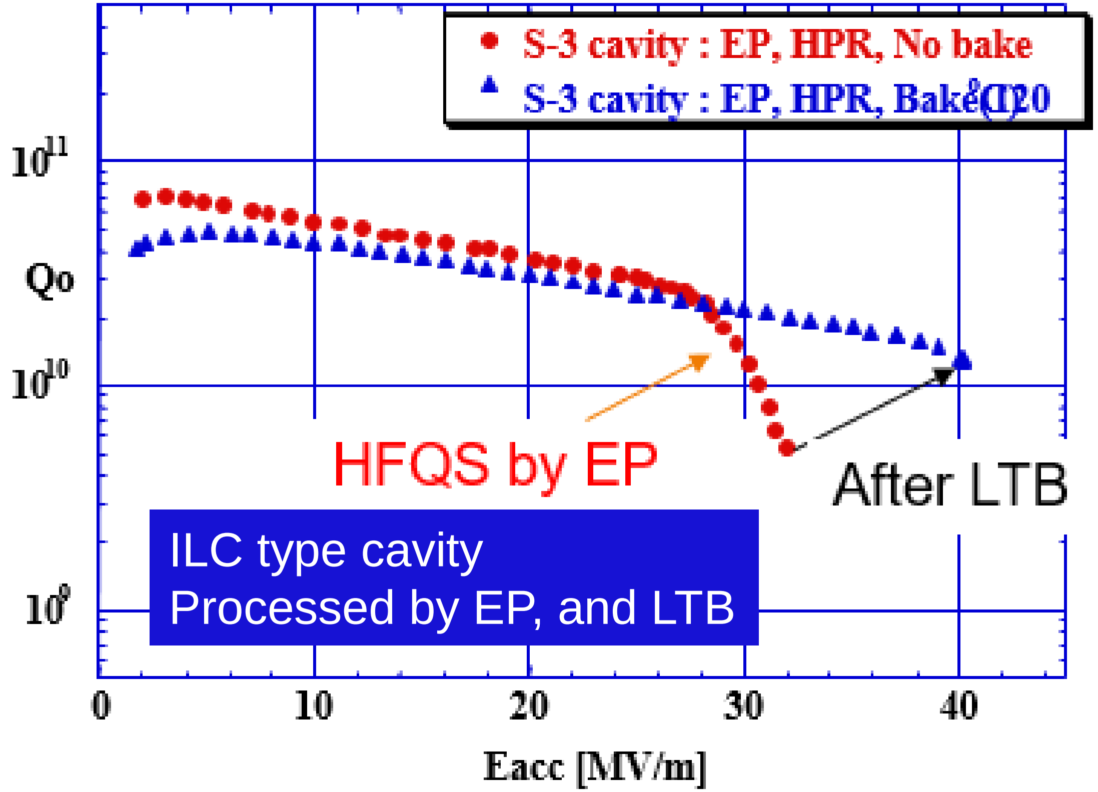
Summary

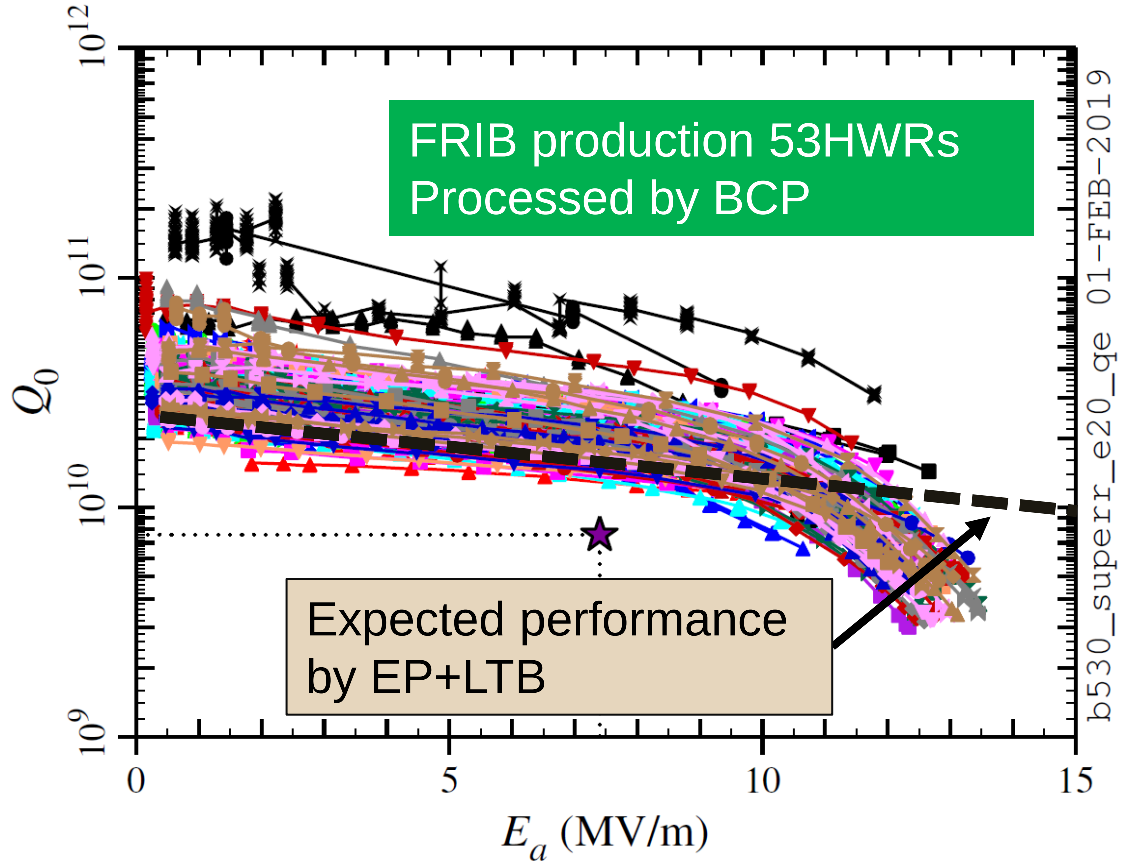
- This project applied the processing method (EP, LTB) developed by the TESLA R&D, to FRIB medium beta cavities. In addition, the cooldown method to push up Qo performance was developed, and thus the cavity performance was greatly improved: Qo = 2.8 $x10^{10}$ @ 12 MV/m. Achieved the goal.
- Wet N-doping has been developed and it was understood that the wet-doped nitrogen characterizes the EP(HNO_3)/BCP'ed cavity performance.
- Objective 4 still continues within 12 months extension. In this R&D, HNO_3-free BCP is possible to produce the similar cavity performance with EP. If succeed, EP might be replaced to HNO_3-free BCP, because of the faster etching and easier application for cavities with complex geometrical shapes.
- This project is very productive and produced many important technologies and scientific contributions.
- Finally, we greatly appreciate supports from DOE on this project.

Backup Slides

Strategy for Objective 1

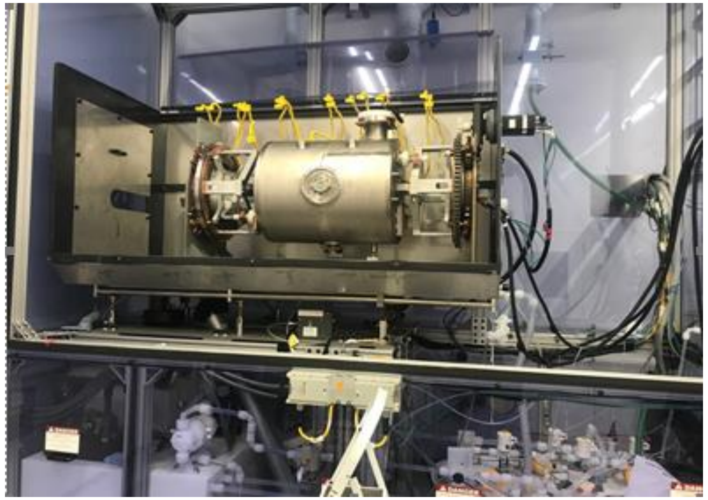
- Buffered Chemical Polished (BCP)'ed cavities can't mitigate High Field Q-Slope (HFQS) by low temperature bake (LTB, 120^{O}C for 48 hr)), but Electropolished (EP)'ed cavities can.
- Apply EP and LTB to FRIB 53HWRs in order to push up high gradient performance



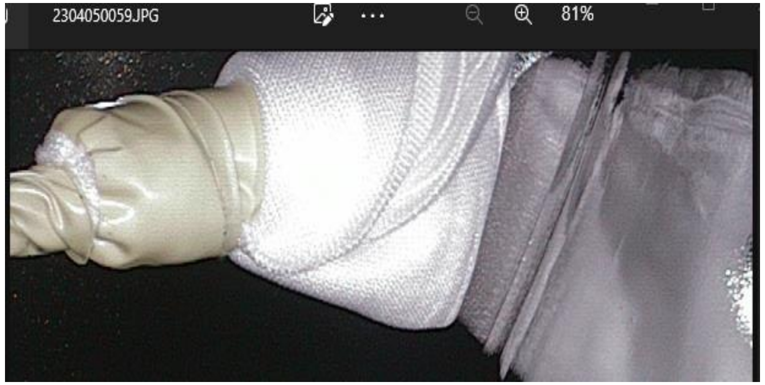


EP System at FRIB

- EP System has been constructed in FRIB SRF Highbay for future high gradient cavities, i.e. energy upgrade 644 MHz cavity. System commissioning completed in Fall 2022.



EP system at FRIB



Mirror like electropolished surface

EP condition for this R&D HWR (SC53-159)

EP voltage [V]	Average Current [A]	Average current density [mA/cm^2]	Acid temperature [°C]	Flow rate [L/min]	Rotational speed [turn/min]	Total EP time [hr]	Material removal	
							From total charge	From weight deference
16	269	29	Inlet 17 °C Outlet 27°C	2.6	1	8.5	119.9 µm	122.9 µm

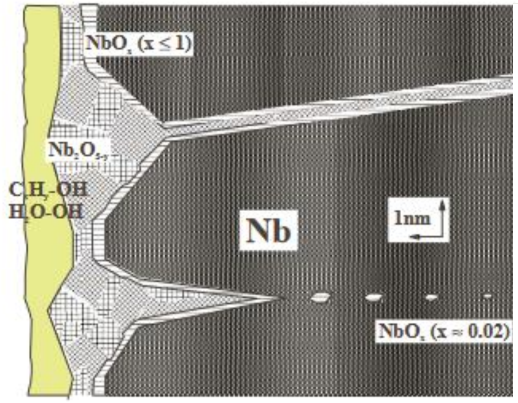
Loss Mechanism of MFQS: Hysteresis loss

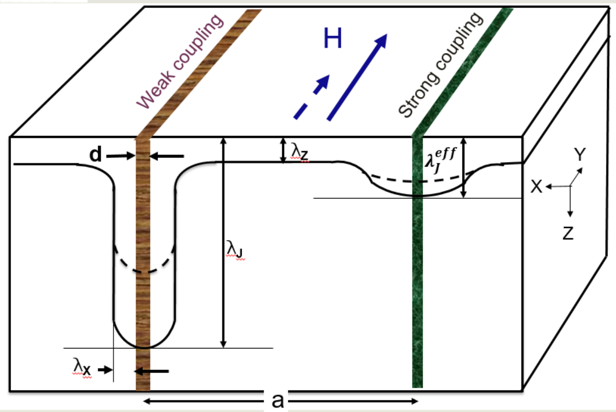
- The surface resistance linearly proportional to Eacc is produced by the ***hysteresis loss*** due to Josephson fluxons (JF) at weak/strong-links **at grain boundaries**, *J. Halbritter*.

$$R_{hys}\left(B_p\right) = \frac{4}{3\pi}\frac{\omega}{2J_{cJ}[1+(\frac{\omega}{\omega_0})^2]^{3/2}}\frac{2\lambda}{a_J}B_C\left(\frac{B_p}{B_C}\right) = R_{res}^1\left(\frac{B_p}{B_C}\right)$$

For e.g. 1.5 GHz BCP'ed cavities, $a_J \sim 100nm$,

$$J_{CJ} \sim 8\times 10^{11}\frac{A}{cm^2},\quad and\ \omega_0 \sim 0.06\ GHz$$





- The small J_{cJ} currents yield small H_{cJ} fields, where consequently **Josephson fluxons (JFs) penetrate** into long Josephson junctions **at grain boundaries**.
- Above H_{CJ}, the rf losses will be dominated by

Hysteresis losses R_{hys} $\propto$ $\boldsymbol{\omega H_{RF}}$ due to nucleation, annihilation, and pinning.

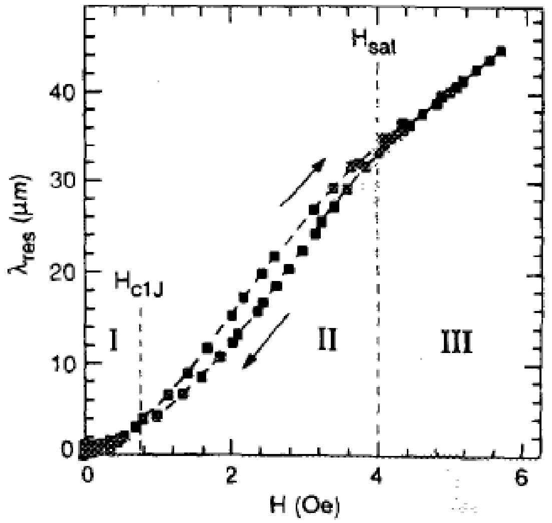
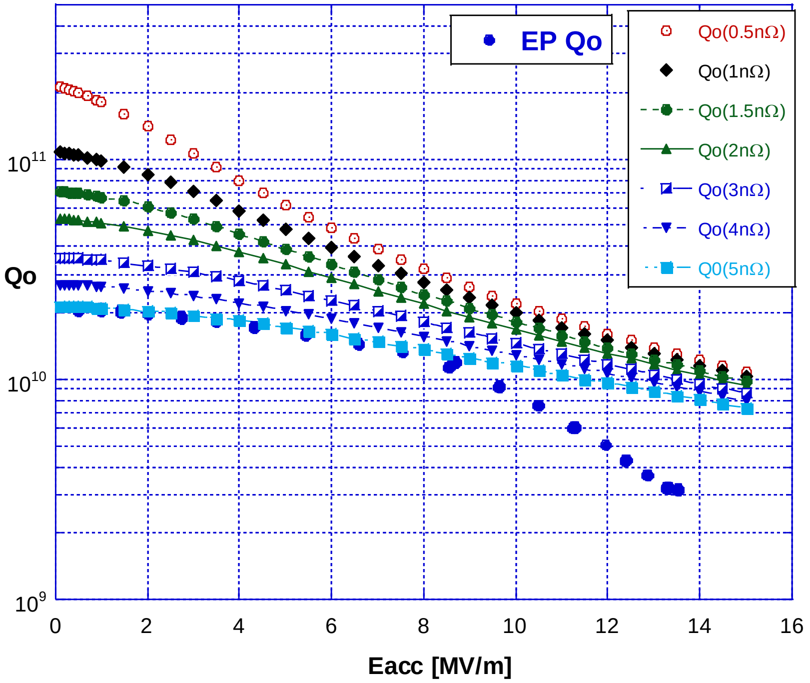
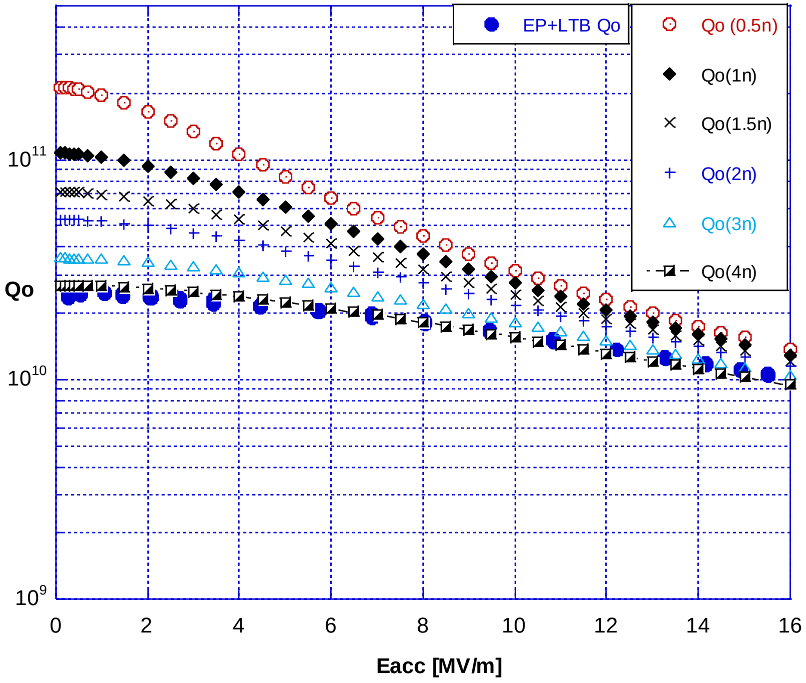


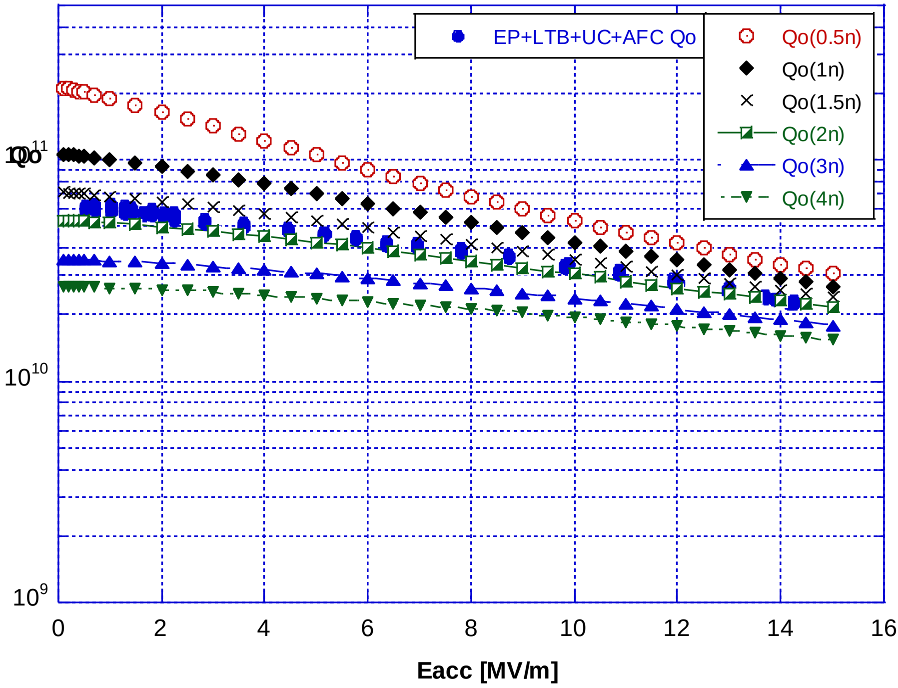
FIG. 1. "High"-field effects on the penetration depth at 85 K, displayed as $\Delta\lambda_{eff}$ vs B. Note the hysteresis due to flux inclusion at modest field values. The dashed lines are guides to the eye. Regime I is given by H^2 dependence, regime II by H dependence changing over to regime III with sublinear dependence on H.

Comparison of Qo with EP, EP+LTB, and EP+LTB+UC+AFC

- LTB eliminates HFQS and, which also reduces m1 (5.7e-11 to 1.84e-11), m2 (3.82e-11 to 2.75e-11), the impact appears in Qo at high fields.
- m1 and m2 is in similar value in EP, and a rounded Qo slope appears at low field with decreasing R_{res}.
- UC+AFC reduces m2 (2.75e-11 to 9.60e-12) by a factor 3, makes Qo curve flatter.







Summary: Role of Wet N-Doping

- Wet doped nitrogen disturbs the oxygen diffusion, and makes the cause of HFQS not mitigated by LTB.
- Wet N-doping features cavity performance, like BCP'ed.

Objective 3

HNO_3

EP(HNO_3)

1) The higher Qo at low field with the smaller R_{res}
2) Steep MFQS
3) HFQS not mitigated by LTB

BCP using the acid mixed HNO_3

Objective 4

Replace EP to HNO_3-free BCP

- Similar performance to EP'ed cavities.
- Easy application to complicated shaped cavities.

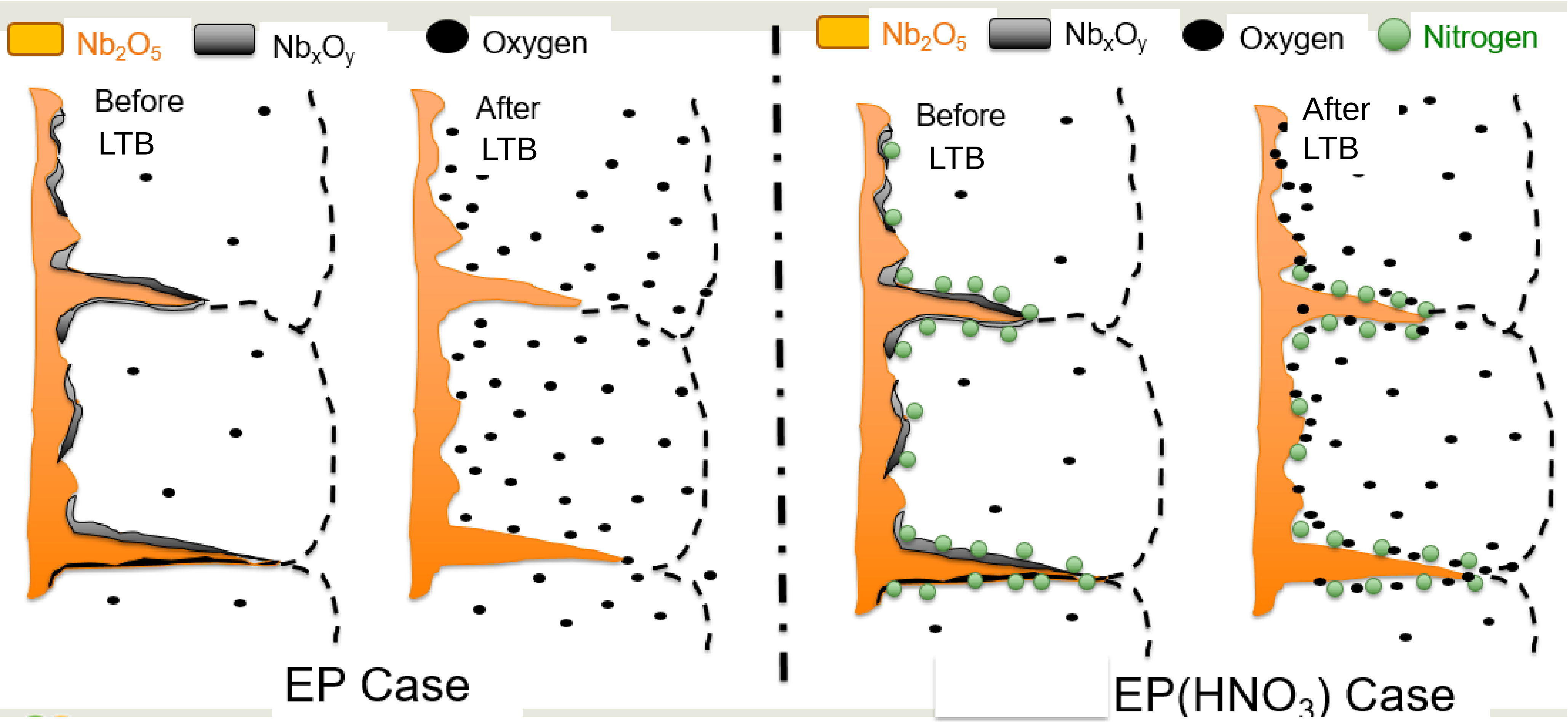
~~1) The higher Qo at low field with the smaller R_{res}~~
~~2) Steep MFQS~~
~~3) HFQS not mitigated by LTB~~

Replace HNO_3 to H_2O_2

HNO_3 free BCP

Resources for the Project

- **PI: Kenji Saito** (Professor and SRF Development Manager), overall.
- **Co-PIs:**
  - **Chris Compton** (Cryomodule Assembly Group Leader): cavity inspection mechanical grinding, magnetic shield fabrication, install, etc.
  - **Taro Konomi** (SRF Staff Physicist), ambient field simulation, magnetic shield design, cavity cold test
  - **Laura Popielarski** (SRF and Superconducting Magnet Deputy Manager), Cavity processing, managing bi-weekly meeting
- **Research Associate (Postdoc): Yuting Wu** started from Oct. 16th, 2023
- **Graduate student: Spencer Combs** supported by ASET program, joined from Fall, 2023
- Other resources
  - **Sam Miller** (Mechanical Engineering Department Manager): managing the mechanical design
  - **Alex Taylor** (Superconducting mechanical design engineer II): Magnetic shield mechanical design
  - **Joe Asciutto** (Engineer): cavity borescope and surface polishing
  - **Walter Hartung** (Senior SRF Physicist): Cavity cold test
  - **Wei Chang** (SRF high level application team leader): Cavity test
  - **Kyle Elliott** (Cavity Processing & Cold mass Assembly Group Leader): EP, BCP, and Cavity clean assembly,
  - **Ethan Metzgar** (Processing team leader):EP, BCP, Hydrogen degassing
  - **Brian Barke**r (SRF Process Engineer): EP, BCP, and Hydrogen degassing
  - **Dave Norton** (Accelerator Engineer I): Cavity test preparation
  - **John Schwartz** (SRF Engineer): Cavity frequency measurement
  - **Hiroyuki Ao** (Senior SRF Physicist)
  - **Sang-hoon Kim** (SRF System Engineer AND Test Group Leader): coordinating VTA schedule, cavity testing


Nb_2O_5
Nb_xO_y
Oxygen
Before LTB
After LTB
EP Case
Nb_2O_5
Nb_xO_y
Oxygen
Nitrogen
Before LTB
After LTB
EP(HNO_3) Case