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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2023 NP Accelerator R&D PI Exchange Meeting

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Background: High Reliable FRIB Machine Operation

- FRIB has officially completed CD4 on May 2, 2022, and now is under machine operation for users.
- The reliable machine operation is the first priority for user service.
- This project is to develop high Q and high gradient cavities with operational gradient > 10 MV/m, for cryomodule replacement in future due to cavity performance degradation in long term operation.
- **Project final goal: Cavity performance, 12 MV/m @ Qo ≥ 2.0E+10**
- This project has four objectives.
- Several challenging transformative preparation developments are presented in this program.

Outline

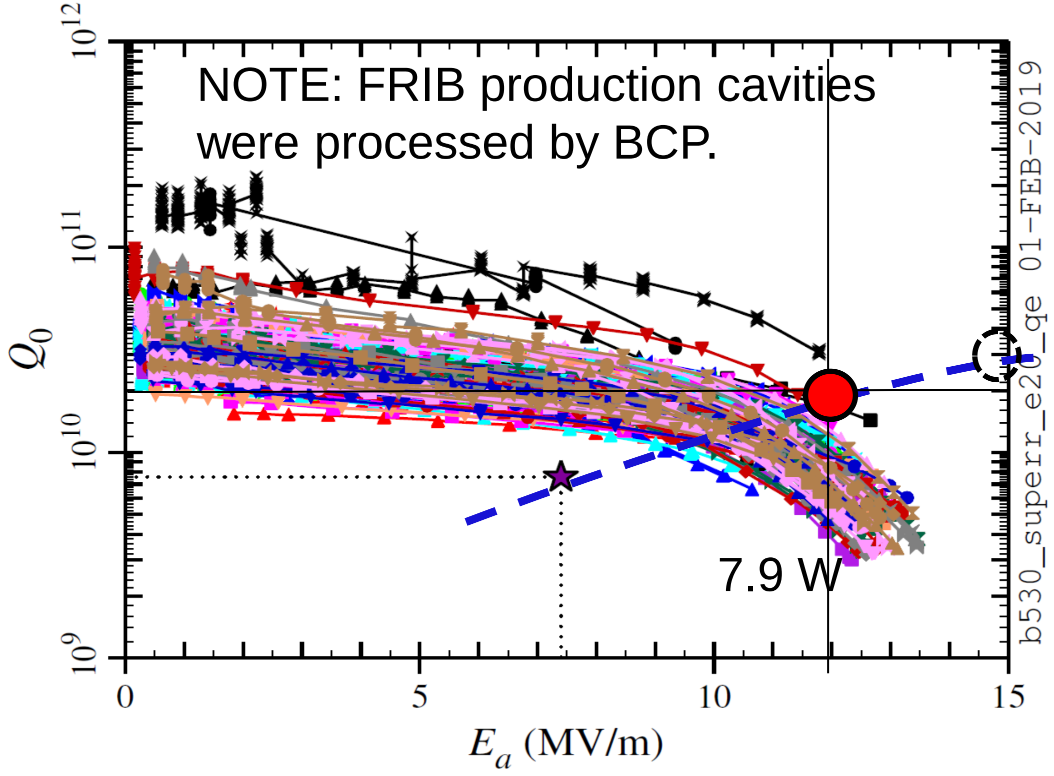
- Background of the Project
- Project and R&D Status
  - Objective 1
  - Objective 2
  - Objective 3
  - Objective 4
- Resource and Budget Status
- Summary

High Q&G 0.53HWR R&D for FRIB 0.53 HWRs

- So far, FRIB SRF cavities are operated stably at 5 - 8 MV/m.
- Field emission (FE) and high field Q slope (HFQS) are major issues to be resolved, for high Q&G performance.
- Qo has to be improved by a factor 2 - 4 for the high gradient operation at Eacc = 12 – 15 MV/m.

FRIB production 0.53HWR performance limitations

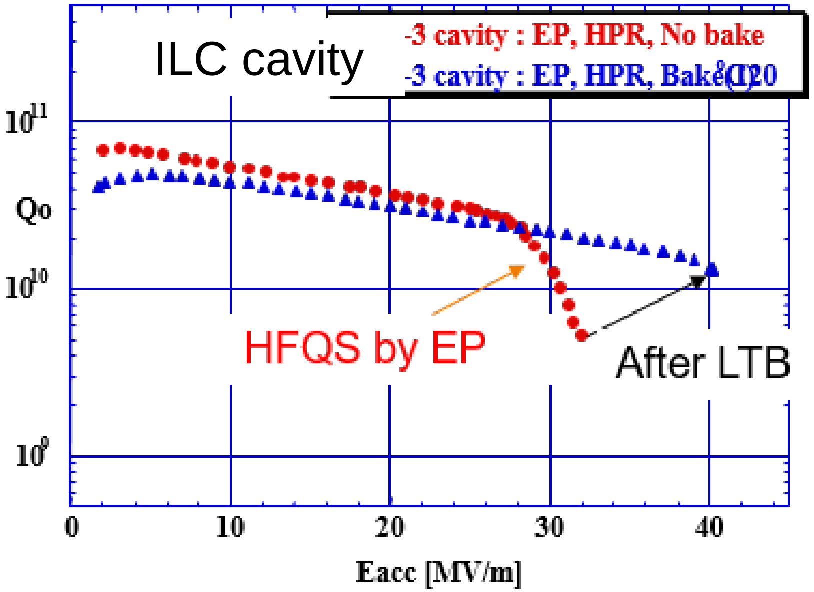
Type	HWR 0.53
Total number of certificated cavities	148
1. Quench < Bp = 85 mT	2 (0.1 %)
2. Field emission X-ray below Bp = 85 mT	109 (74 %)
3. High Field Q Slope	37 (25 %)



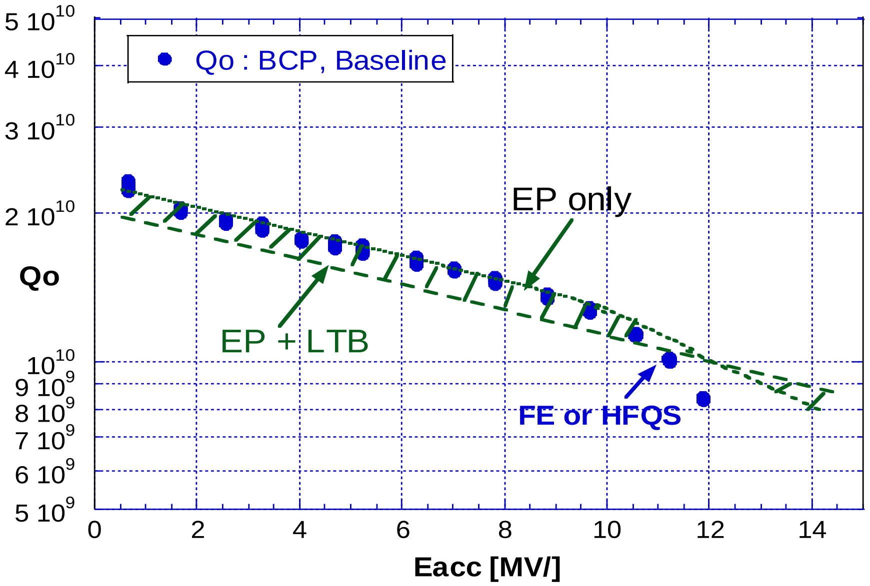
FRIB 0.53HWR production cavity performance

Objective 1: Apply EP+LTB to FRIB 0.53HWRs

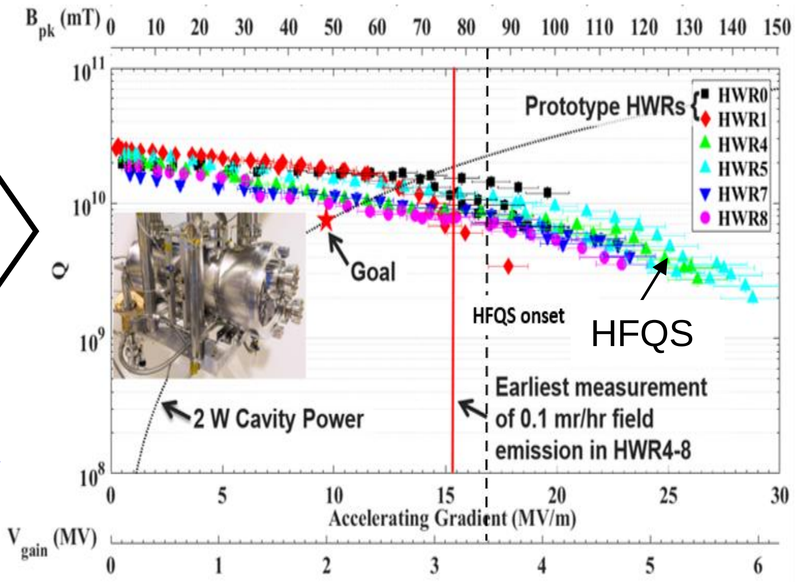
- Apply electropolishing (EP) and low temperature bake (LTB) to FRIB 0.53HWRs to mitigate FE and HFQS.
  - Successful EP (no LTB) experience with HWR at ANL, showing a promising result.
  - ILC cavities show that HFQS is eliminated by the LTB post EP.



HFQS by EP is eliminated by LTB post EP



Expected FRIB 0.53 HWR performance



HWR cavity performance electropolished at ANL.

Objective 1: Apply EP+LTB, Procedure

Brand new FRIB 0.53 HWR SC53-159

↓

Borescope inspection

↓

Mechanical grinding

↓

Bulk EP, 120 μm

↓

Hydrogen degassing, 600 ^{O}C 10 hr

↓

Light EP, 20 μm

↓

Clean assembly

↓

Cold test

↓

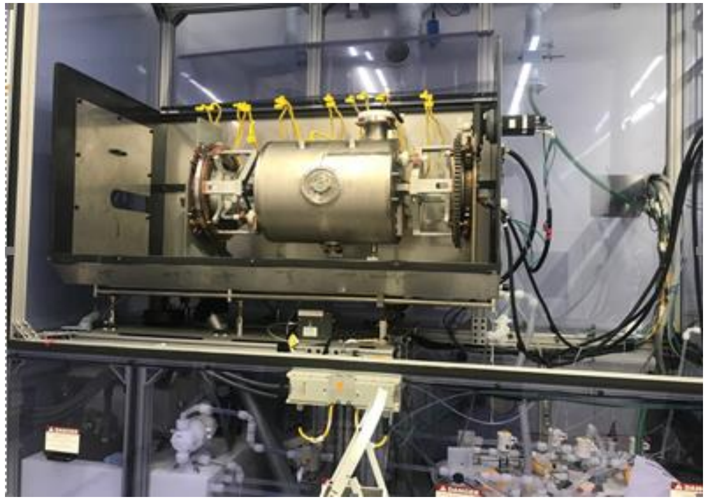
LTB

↓

Cold test

EP System at FRIB

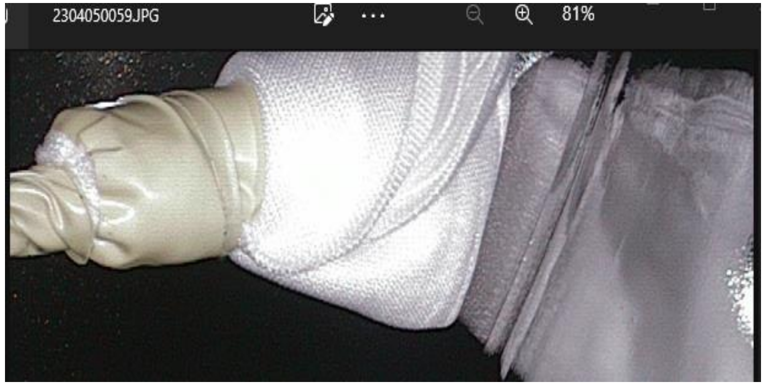
- EP System has been constructed in FRIB SRF Highbay for future high gradient cavities, i.e. energy upgrade 644 MHz cavity. System commissioning completed in Fall 2022.



EP system at FRIB

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

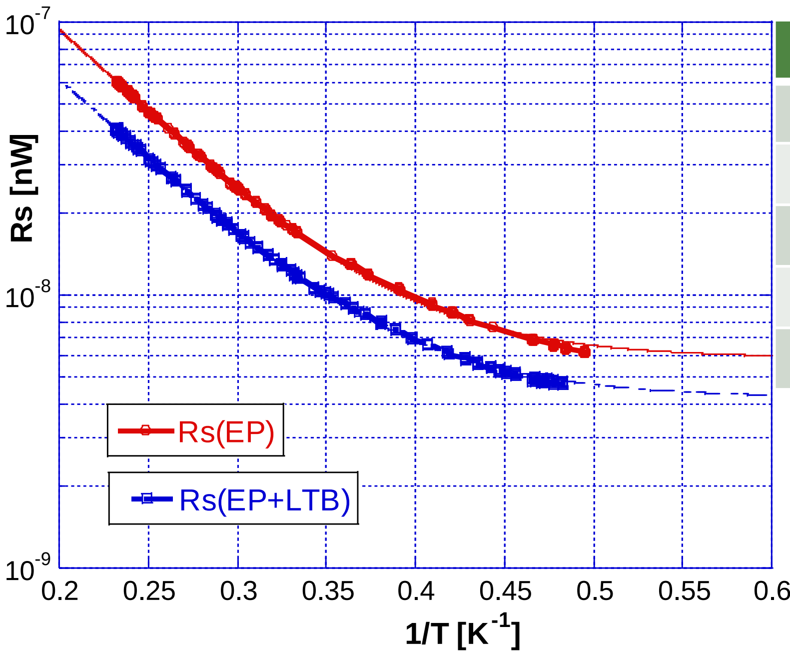
EP voltage [V]	Average Current [A]	Average current density [mA/cm²]	Acid temperature [°C]	Flow rate [L/min]	Rotational speed [turn/min]	Total EP time [hr]	Material removal	
16	269	29	Inlet 17 °C Outlet 27°C	2.6	1	8.5	From total charge 119.9 µm	From weight deference 122.9 µm



Mirror like electropolished surface

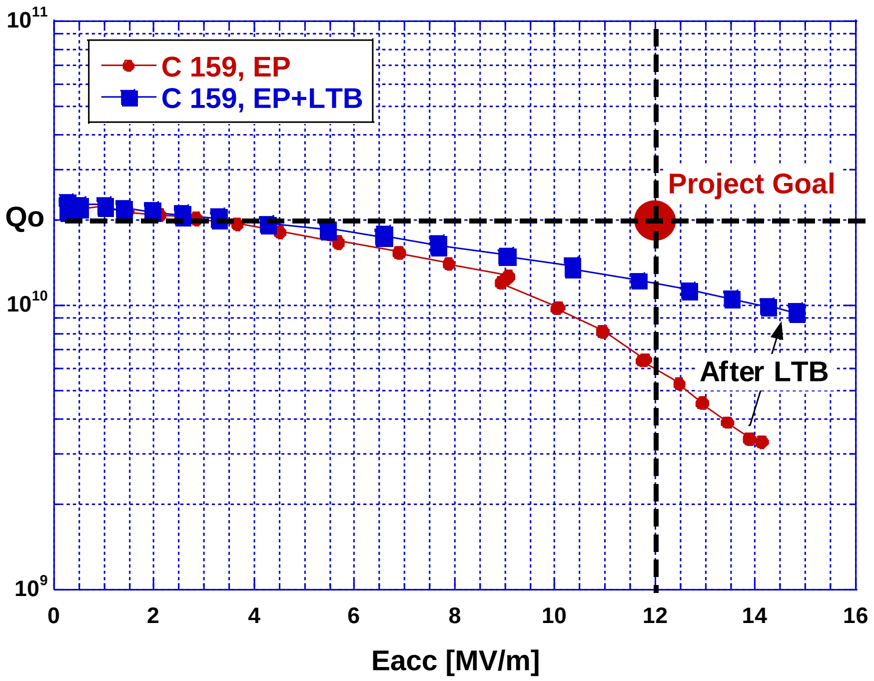
Objective 1 Results: Completed on June, 2023

- EP produced HFQS, as expected.
- EP+LTB reduced BCS surface resistance, as expected. Residual surface resistance also decreased by 1.7 nΩ . LTB post EP eliminated HFQS, as expected.
- High gradient performance up to 15 MV/m (quench) by EP+LTB
- Demonstrated first in the world that LTB post EP is effective for medium beta cavities.
- Need to increase Qo for the high gradient operation.



T-dependent surface resistance, EP and EP+LTB

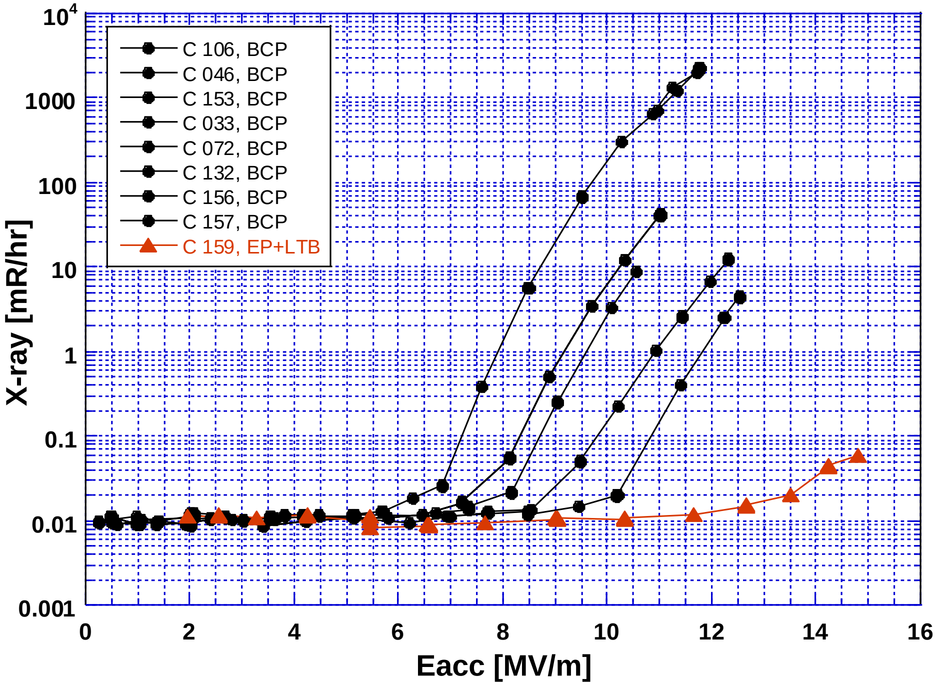
	EP	EP + LTB
A [ΩK^{-1}]	2.14E-5	1.30E-5
Δ/k_B [K]	19.42	19.03
Rres [Ω]	5.90	4.24
R_{BCS} [Ω]	1.30	0.954
Qo @ 2 MV/m	1.49E+10	2.07E+10



Eacc vs Qo performance, EP and EP+LTB

Objective 1 Result: Mitigation of FE

- EP smooth surface finishing pushed up the FE onset, and mitigated FE very much, as expected.
- In this R&D, HPR took place the robotic system developed after FRIB production. This result will include such a HPR optimization.



Field emission behaviors, BCP and EP+LTB

Objective 1 Summary

- Objective 1 was successfully completed in early June, 2023. The result was published in SRF2023 conference, June 25-30, Grand Rapids, MI.
- Flat Qo performance reached up to 15 MV/m (quench) by EP+LTB: innovation of a processing method for high gradient performance for medium beta cavities.
- The same result as ILC cavities that LTB post EP eliminates the HFQS has been confirmed first in the world with a medium beta cavity: Technical and Scientific contributions
- Field emission is greatly mitigated by EP.
- Qo needs to be enhanced more for high gradient operation, for example at 12-15 MV/m.

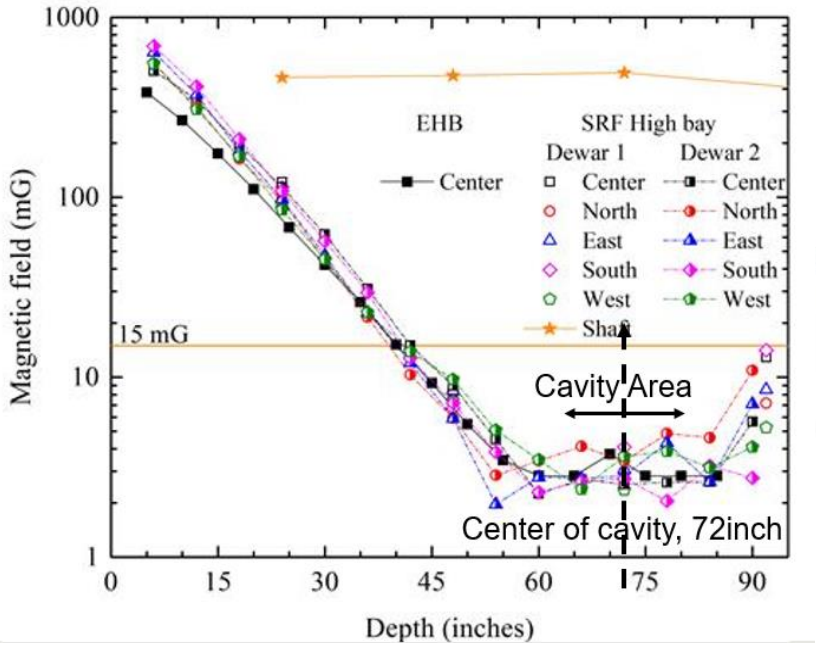
Objective 2: Reduce Ambient Field to Enhance Qo

- Requirement for Qo to be improved more for high gradient operation.
- BCS surface resistance at 2 K is small enough at frequency 322 MHz of FRIB 0.53 HWR, for example ~ 0.5 nΩ with EP+LTB. **Residual surface resistance (R_{res}) is dominant in the surface resistance (R_S)** at 2K. For higher Qo, the causes of R_{res} have to be understood, to reduce it.
- **Ambient magnetic field** around cavity is well known as a cause of R_{res}.
- **Objective 2: Investigate the ambient magnetic field** influence
  - Reduce the ambient field in VTA Dewar as much as possible by installing a **local magnetic shield** on the cavity.
  - Investigate **thermoelectric current effect**
    - ❖ Many deferent material connections of Ti/Nb, Ti/SUS, Nb/NbTi, etc. around cavity. These produce thermoelectric currents by Seebeck effect, if temperature difference is large during cooling down, and results in lower Qo due to flux trapping.

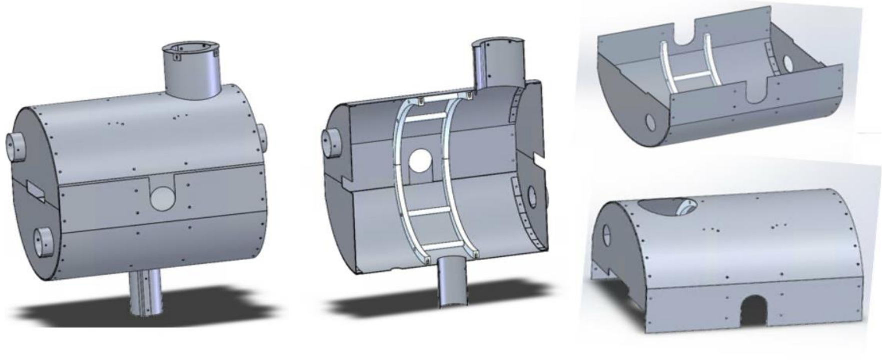
Local Magnetic Shield Design and Fabrication

- A local magnetic shield (MGS) was designed to reduce the ambient field in VTA Dewar < 0.1 mG
- The MGS was fabricated using Permalloy.
- In FRIB acceptance test, this design goal was confirmed at RT. Attenuation 99.6%.

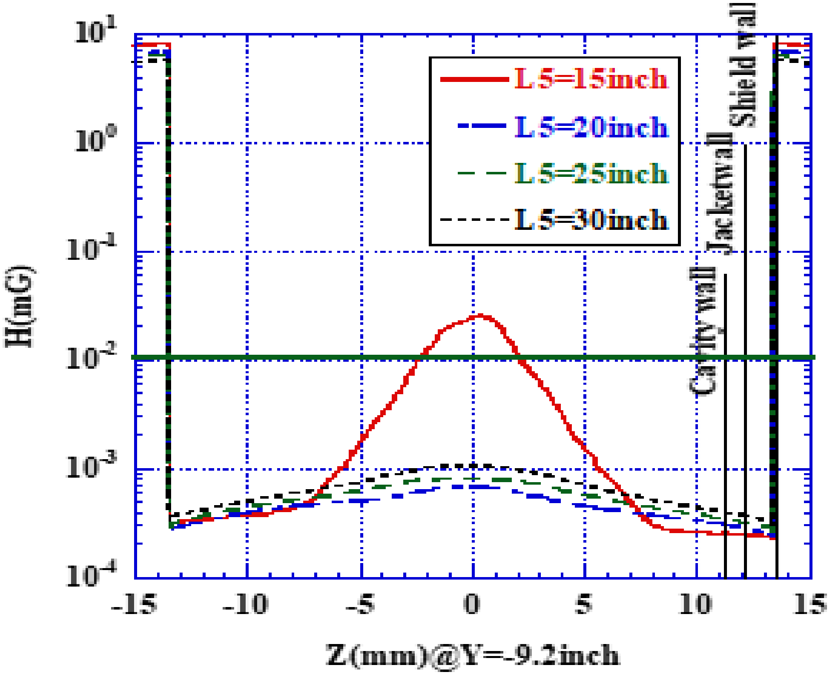
Ambient field in the Dewar is 2 – 5 mG at effective zone, at RT.



Ambient field in a FRIB VTA Dewar



Magnetic Shield design



The ambient field is reduced below 0.1 mG by putting a sleeve around port.

Local Magnetic Shield and Procedure of Objective 2

MGS installed on the SC53-159.

Objective 1 LTB, warmed up after cold test

↓ Cavity kept under vacuum for 4 months

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MGS shield installation

↓

Cold test, fast cooldown

↓

Warm up to 250K

↓

Cold test, uniform cooldown

↓

Warm up to 300K

↓

Detached MGS

↓

Cold test, without MGS. uniform cool down

↓

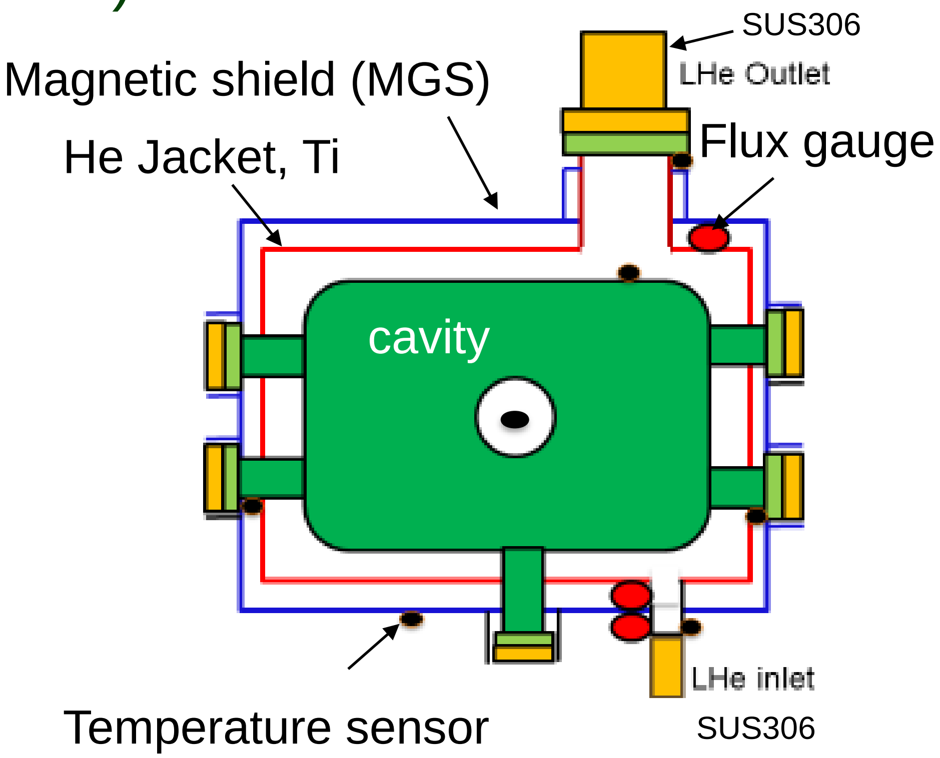
Warm up 250 K

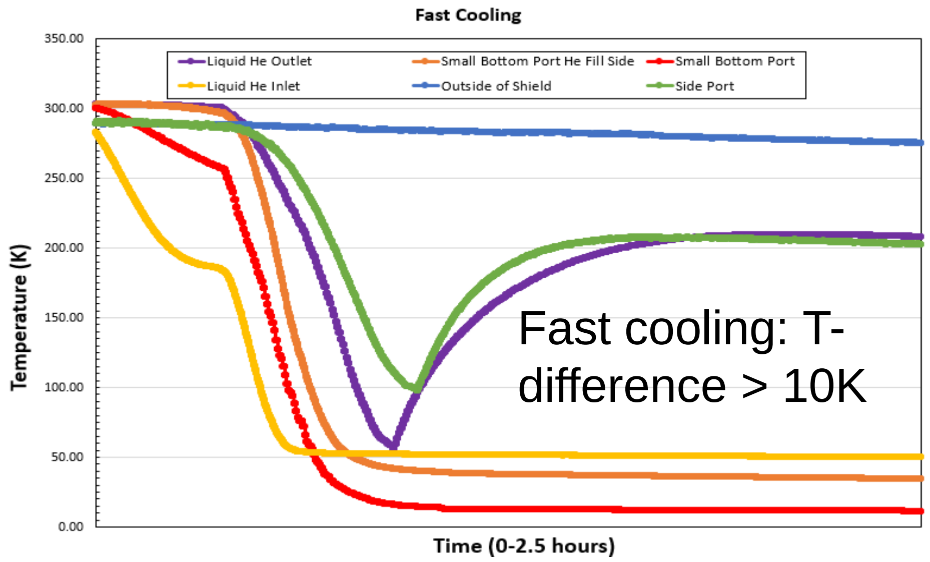
↓

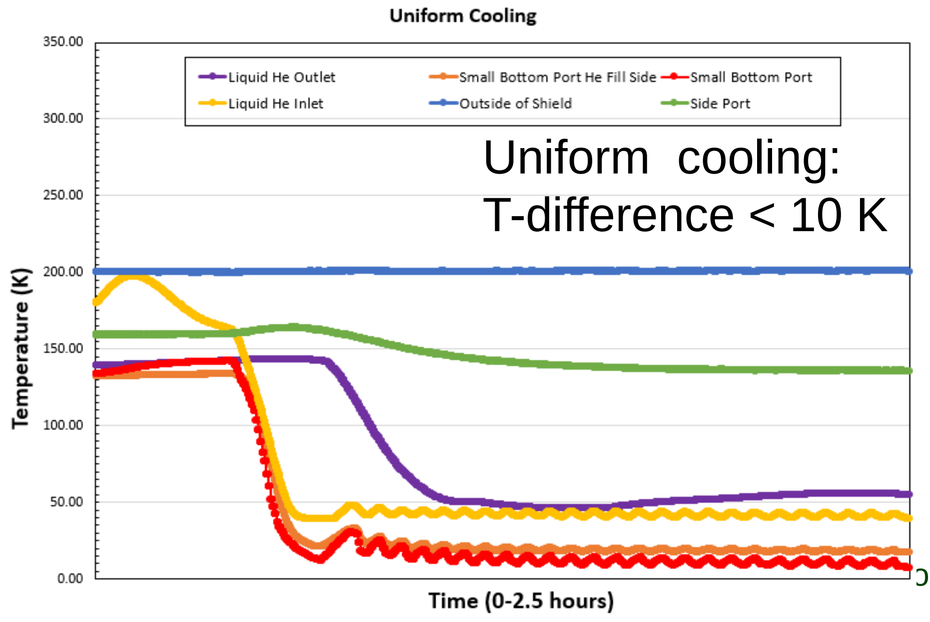
Cold test, without MGS, uniform cool down and active ambient field cancellation

Active Monitoring of Temperature and Flux, Fast and Uniform Cooling

- 7 temperature sensors around cavity, and 3 flux gauges.
- Fast cooling (Temp. difference at top and bottom of cavity >10 K)
- Uniform cooling (Temp. difference. top and bottom of cavity < 10 K)



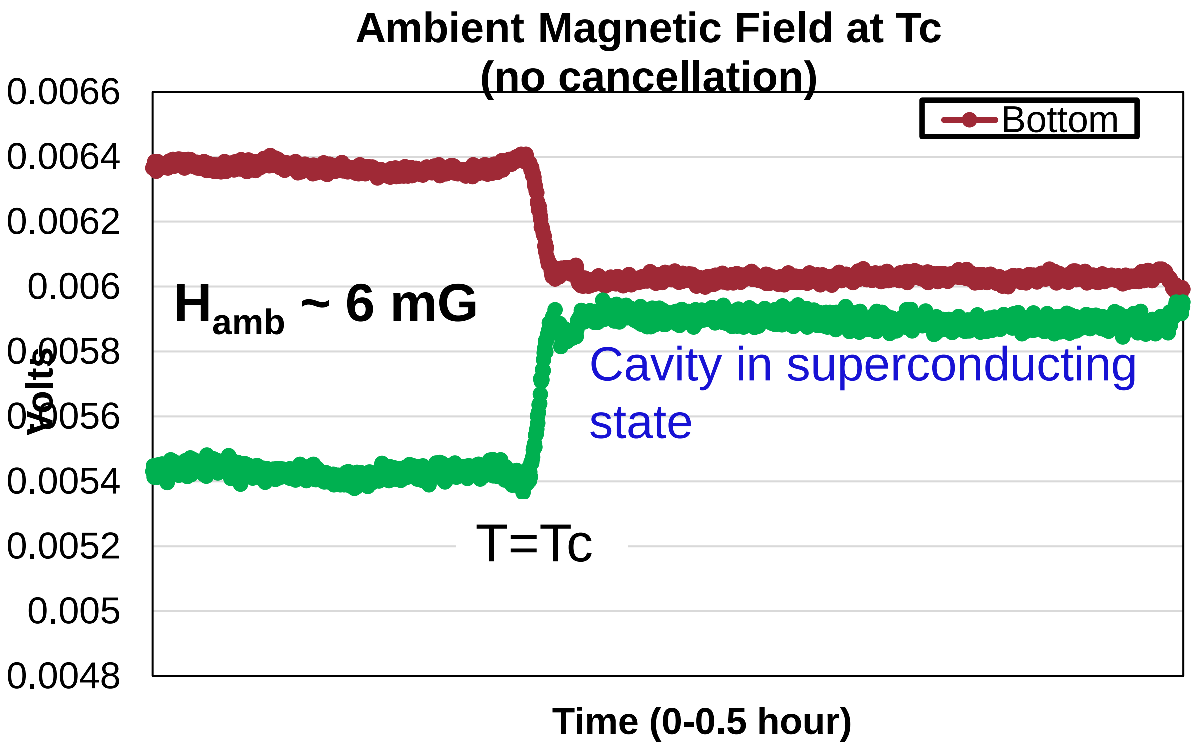




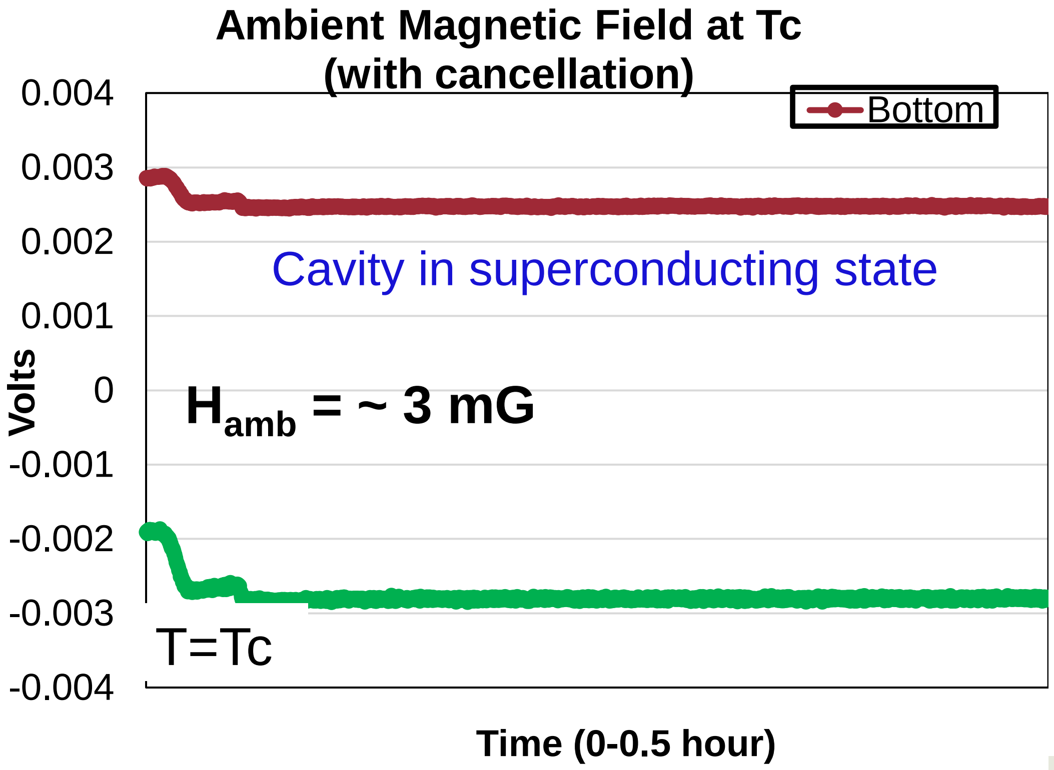
Ambient Magnetic Field around T_C by Uniform Cooling, Active Field Cancellation

- Ambient field was ~ 6 mG by uniform cooling.
- ~ 3 mG by Uniform cooling and active field cancellation.

Uniform cooling, Nov. 10

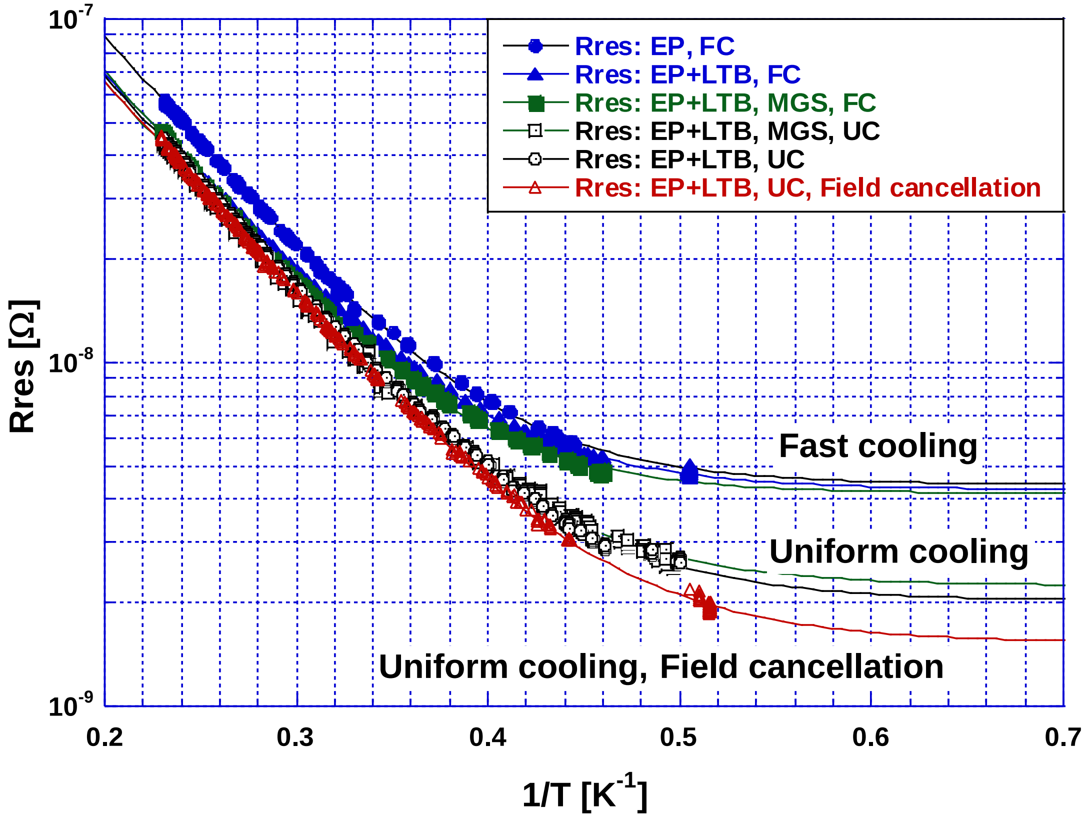


Uniform cooling and active field cancellation, Nov. 13

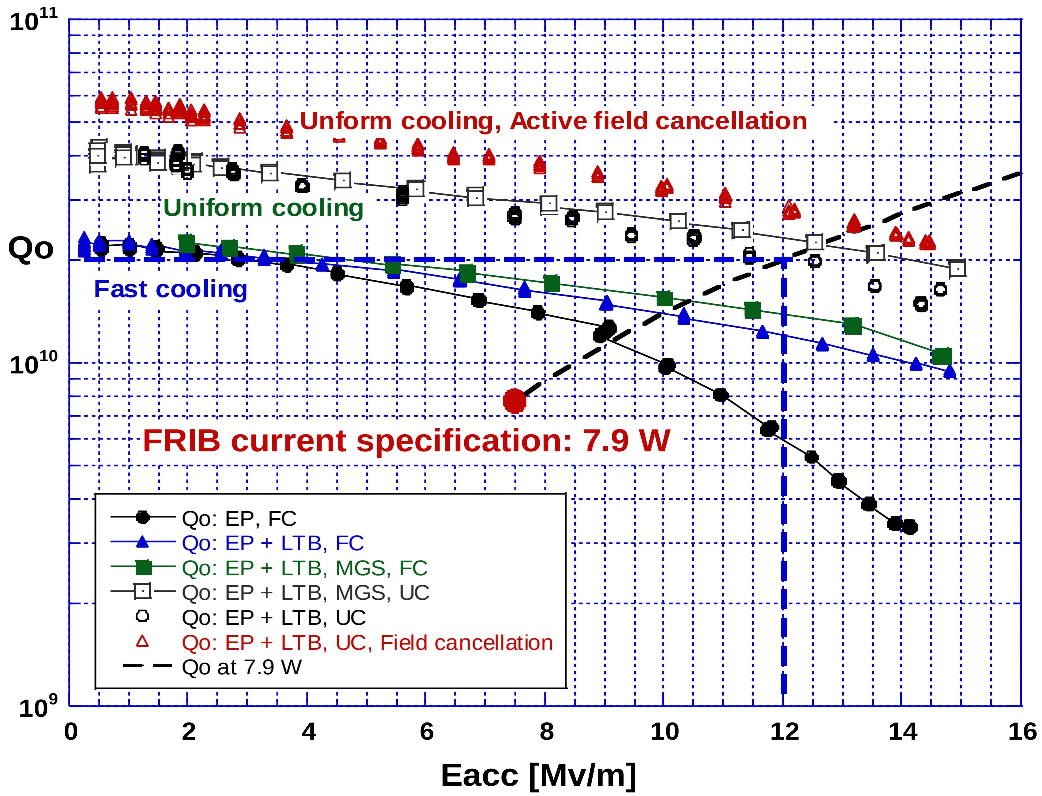


MGS, Fast and Uniform Cooling, Active Field Cancellation

- Local magnetic shield improved the residual surface resistance a little.
- Uniform cooling worked well to reduce the residual surface resistance up to ~ 2 nΩ.
- High Q&G performance was achieved up to 15 MV/m (quench) in all cases.
- Active field cancellation up to 3 mG produced the highest Qo performance, Rres= 1.5 nΩ.
- **The goal: $Q_0 \geq 2.0$ E+10 at 12 MV/m has been reached.**



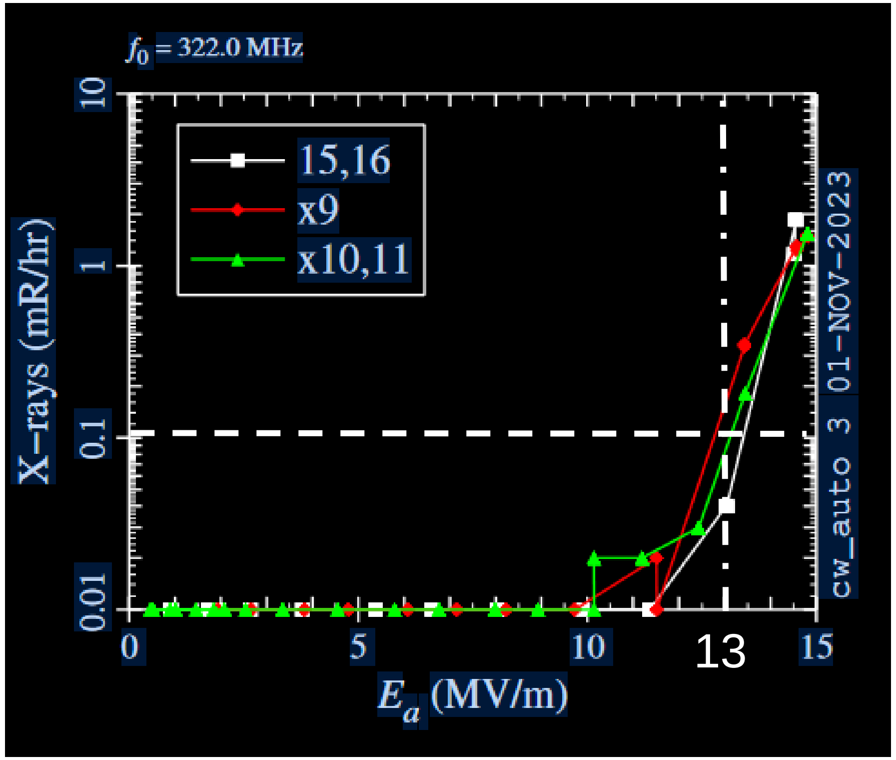
Comparison of surface resistance, uniform cooling works to reduce the residual surface resistance



Comparison of cavity performance, uniform cooling pushes up high Q performance.

Field Emission Behavior

- Field emission behavior is similar to the case of EP in all other experiments in objective 2.
- X-ray is less than 0.1 mR/hr below 13 MV/m. From point of FE view, 13 MV/m is FRIB usable gradient.
- Need to improve FE for higher gradient operation >13 MV/m.



Field emission behavior in a Objective 2 experiment

Ambient Field Contribution (R_{mg}) on Rres

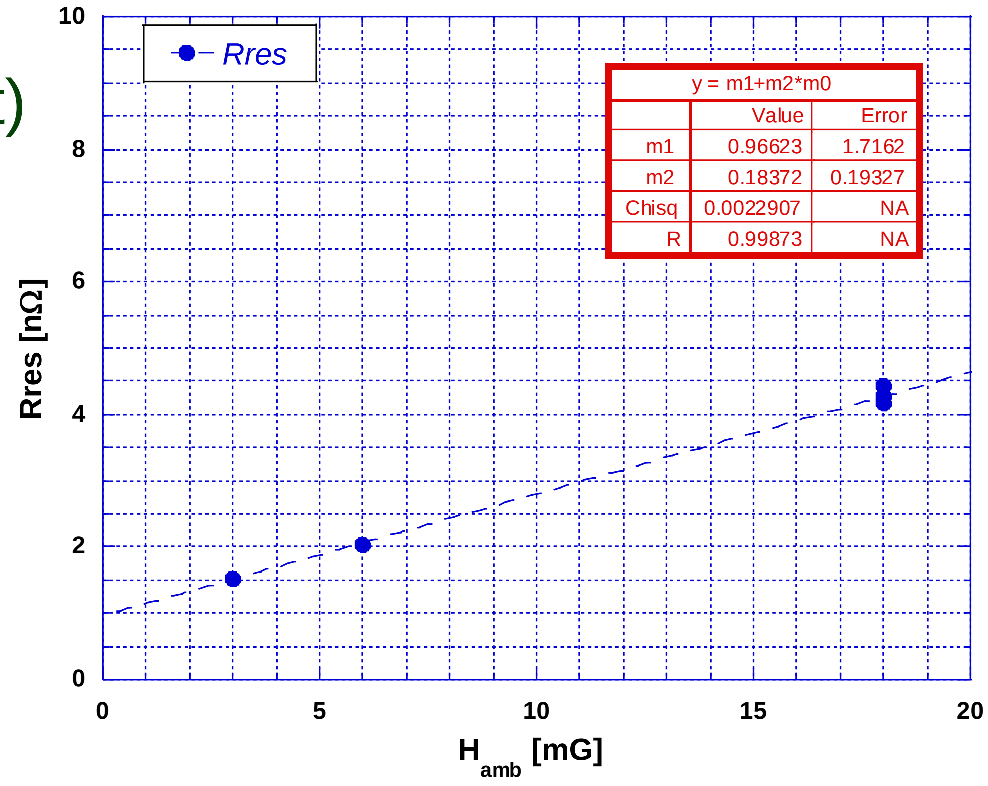
- Ambient field (H_{amb}) contribution (R_{mg}) on Rres is well known:

  $R_{mg}(n\Omega) = C\times\sqrt{f[MHz]}\times H_{amb}[mG]$,

  at 1300 MHz, $C\sqrt{f}$= 0.43 (KEK measurement result)

- The data fitting result 0.184 is consistent with the frequency dependence of R_{mg}.

- Even H_{amb} = 0, R_{res} of 1 nΩ remains, which is unexplainable by flux trapping, so far.



Ambient field dependence on residual surface resistance measured in Objective 2 experiments

Understanding of Residual Surface Resistance (R_{res})

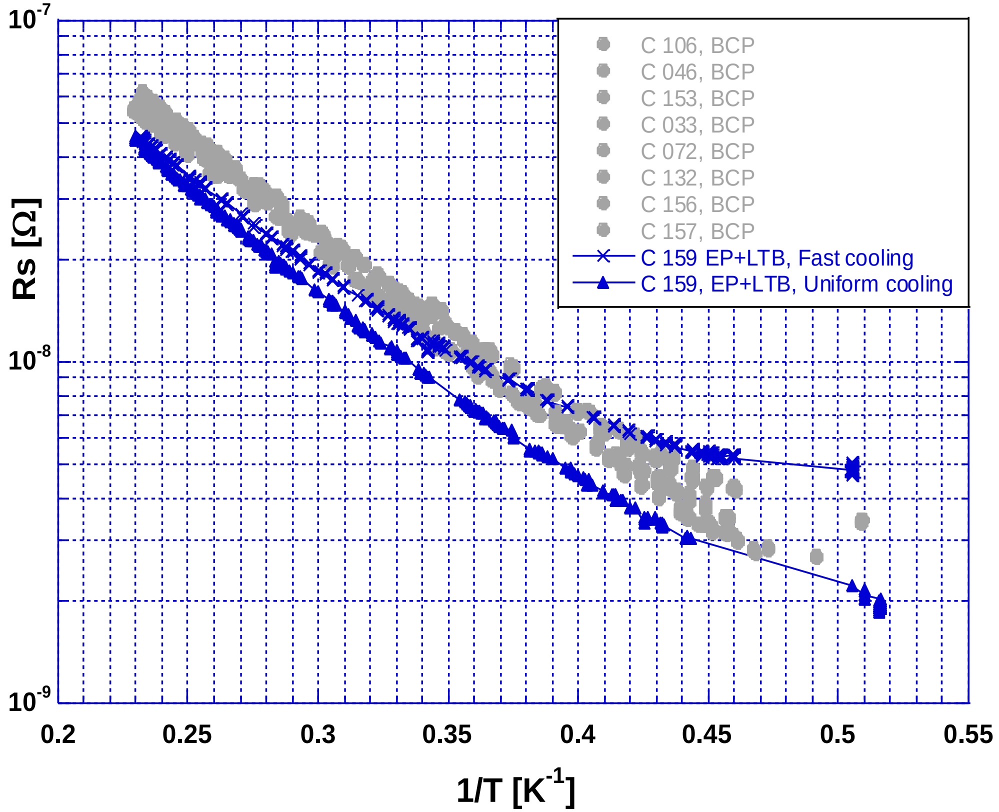
- 80% of the Rres is due to flux trapping in case of fast cooling.
- The remaining 20% (1 nΩ) cause is not yet known.
- Improvement of remaining 1 nΩ enhances extremely Qo to $1x10^{11}$.
- For high Q performance at high gradient, Qo slope has to be improved, one of which methods is to enhance thermal conductivity of niobium material, use more higher RRR material (current RRR=300), or post Ti purification before jacketing vessel on the cavity.

Understanding of R_{res} and Expected Qo

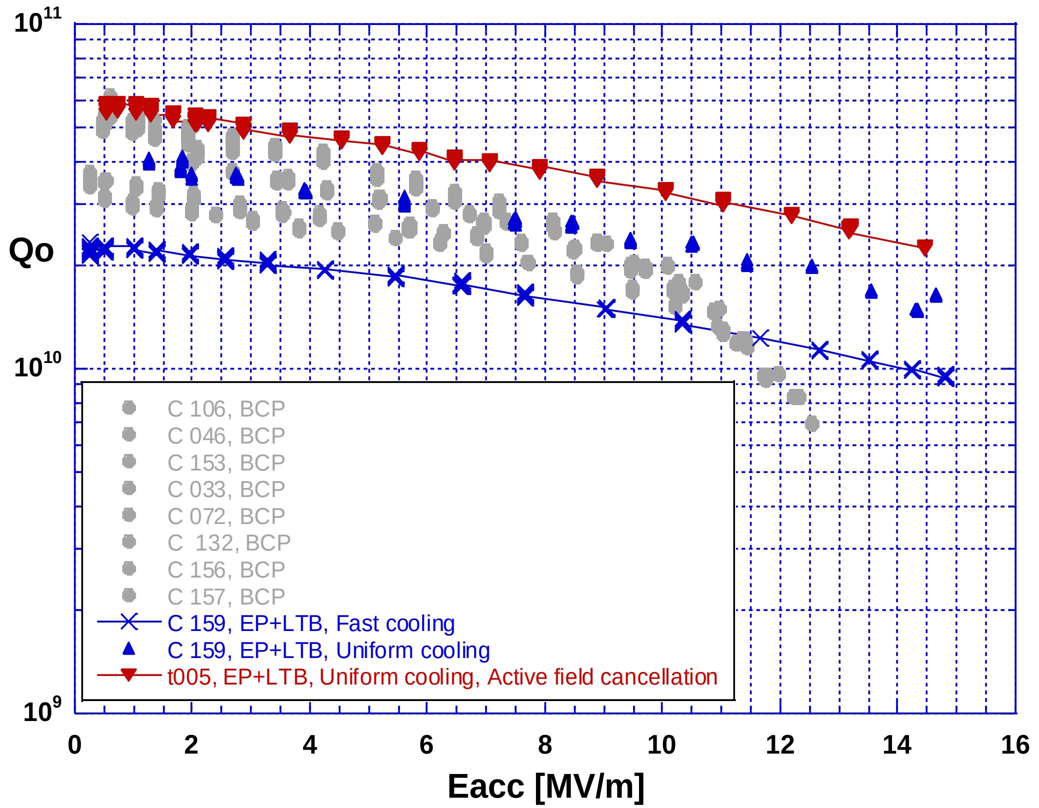
	Fast cooling	Uniform cooling	$H_{amb} = 0$	$R_{res} = 0$
R_{BCS} [nΩ] at 2K	0.5	0.5	0.5	0.5
R_{res} [nΩ]	4.3	2.0	1.0	0
R_S [nΩ]	4.8	2.5	1.4	0.50
Qo	2.2×10^{10}	4.3×10^{10}	7.7×10^{10}	2.2×10^{11}
1/Qo slope	2.5×10^{-13}	1.3×10^{-13}	1.3×10^{-13}	1.3×10^{-13}

Comparison BCP and EP+LTB

- EP+LTB produces a lower BCS surface resistance than that BCP.
- EP+LTB produces a flat Qo performance and pushes the gradient, while BCP'ed cavities are limited by HFQS or FE.



T-dependent surface resistance between BCP and EP+LTB



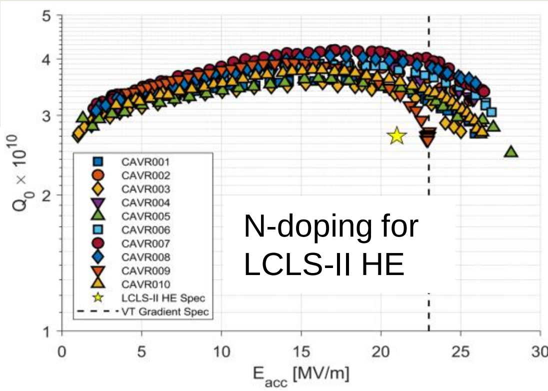
Eacc vs Qo performance between BCP and EP+LTB

Objective 2 Summary

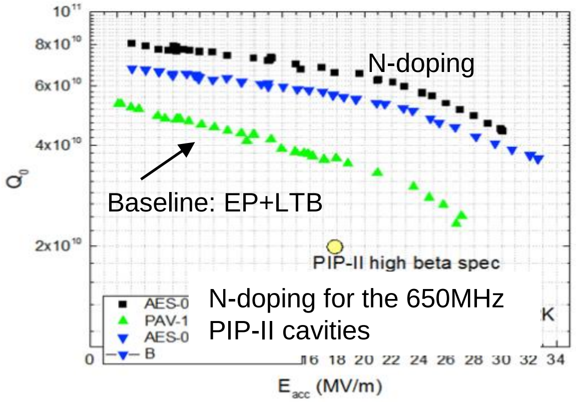
- Objective 2 was successfully completed in November, 2023.
- Local magnetic shield improved the Qo performance a little.
- Flux trapping is dominate of the residual surface resistance, 80%.
- Uniform cooling works to reduce the thermoelectric current effect.
- The final goal of this project has reached:12 MV/m @ Qo $\geq$ 2.0E+10, operational gradient > 10 MV/m (12 MV/m) with an operational margin > 30 % (60 %).
- To reduce the thermoelectric current effect more, investigation of Seebeck effect is important with various different material connection used in cryomodule, for example Nb/Ti, Ti/SUS,…..

Objective 3: Wet N-doping

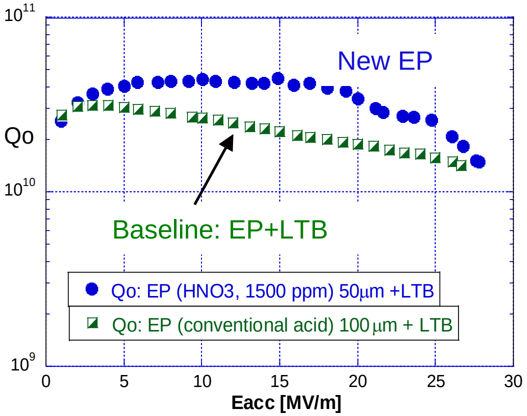
Challenge to A Transformative Processing

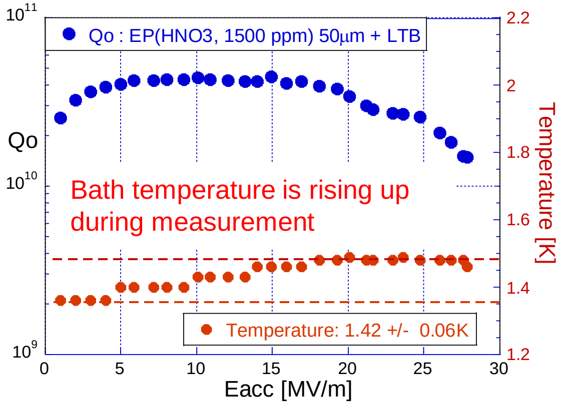


- Objective 3: Explore transformative processing for more high Q performance.
- N-doping might push up Qo performance, for FRIB 0.53HWRs, up to ~10 MV/m (85mT) at least, even a low frequency 322 MHz.
- FRIB spare cavities have a Ti jacket, and impossible to perform 800 – 900 ^{O}C heat treatment included in current N-doping recipe.
- PI found out a Qo enhancement phenomenon in a new EP method at KEK 20 years ago, which might work to FRIB 0.53 HWR.



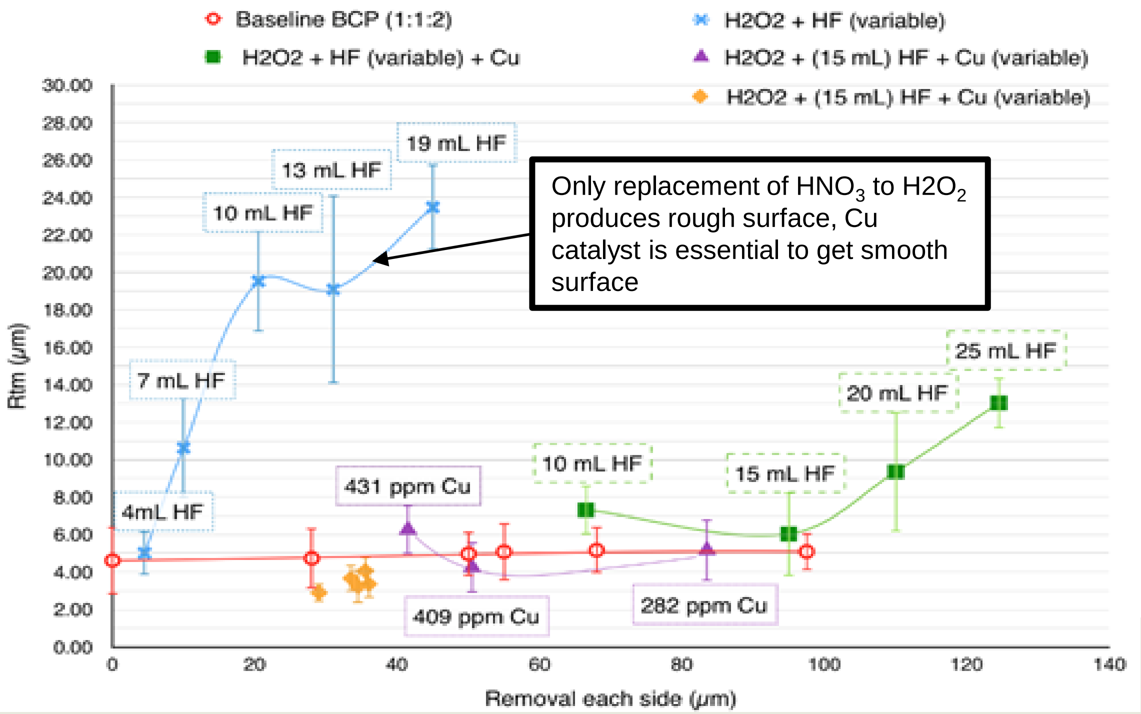
- **Objective 3: Apply the new EP (Wet N-doping).** Use EP acid with 1500 ppm HNO_3 into the current electrolyte.
- This method will provide a H-free EP also, H-degassing process will be able to be omitted.
- Objective 3 is to be done during Q5





Objective 4: HFQS-free BCP
Challenge to Another Transformative Processing

- Why post BCP LTB does not eliminate the HFQS with BCP'ed cavity is a opened question for more than 20 years in the SRF community.
- A MSU PhD program (2019) concluded that N-contamination from HNO_3 in BCP acid could be the cause.
- In this program, a new BCP acid with Copper catalyst and replace the HNO_3 to H_2O_2 was successfully developed for small Nb samples. This new BCP could leave an Oxygen contamination on Nb surface similar to EP, therefore the HFQS could be eliminated by LTB.
- **Objective 4: Apply this new BCP method to FRIB HWR.**
  - New BCP+LTB could produce high Q/G performance similar to EP+LTB
  - BCP is much simpler than EP for complicated cavity geometry.
  - If successful, it will be a very important technical and scientific contribution.
- Objective 4 is to be done during Q5-Q6



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

Resources for This 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: 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

Budget Status

	FY 2023 ($)	FY 2024 ($)	Totals ($)
a) Funds allocated	359,000.00	345,000.00	704,000.00
b) Actual costs to date	140,386.70	39,256.80	179,643.50
c) Uncosted commitments	84,803.09	224,209.07	309,012.16
d) Uncommitted funds (d=a-b-c)	133,810.21	81,534.13	215,344.35

- The unused cost $105K in FY2023
  - Delayed hiring Postdoc one year, $75K
  - Graduate student is supported by other DOE grants (ASET), $30K.
- This unused cost to be used for the materials newly necessary to this project R&D.
  - Temperature sensors (6) and flux gauges (3) have been ordered, $20K, delivery in March, 2024.
  - NC25 bolts/nuts (perfect non magnetized material) are quoted, $40K, delivery end of February, 2024.
  - Magnetic thin sheets are ordered, $2K, delivery end of December, 2023
  - Nitrogen gas analysis have been quoted, $14K, delivery end of April 2024.
  - HIP bonded samples for Seebeck Effect study are under Quote, ~ $30K, delivery mid May, 2024.
- Totally ~ $106K will be spent in FY 2024Q1 for these materials.

Summary

- So far, first two objectives of four have been successfully completed. The project schedule is on track.
- Two innovations have been developed in first two objectives.
  - EP+LTB processing recipe for high G cavity performance on HWRs
  - EP+LTB+Uniform cooling method for High Q&G HWRs.
- Final project goal: Eacc = 12 MV/m @ Qo ≥ 2E+10 has been achieved.
- Remained two objectives challenging more high Q will be completed during Q5-6.
- Lessons learned
  - For higher gradient > 15 MV/m, needs more effective mechanical grinding prior to EP. ⇨ Apply other mechanical grinding method like barrel polishing.
  - Investigation of Seebeck effect to push up Qo performance.