Progress in Nb_3Sn developments for CEBAF-style quarter cryomodule

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Outline

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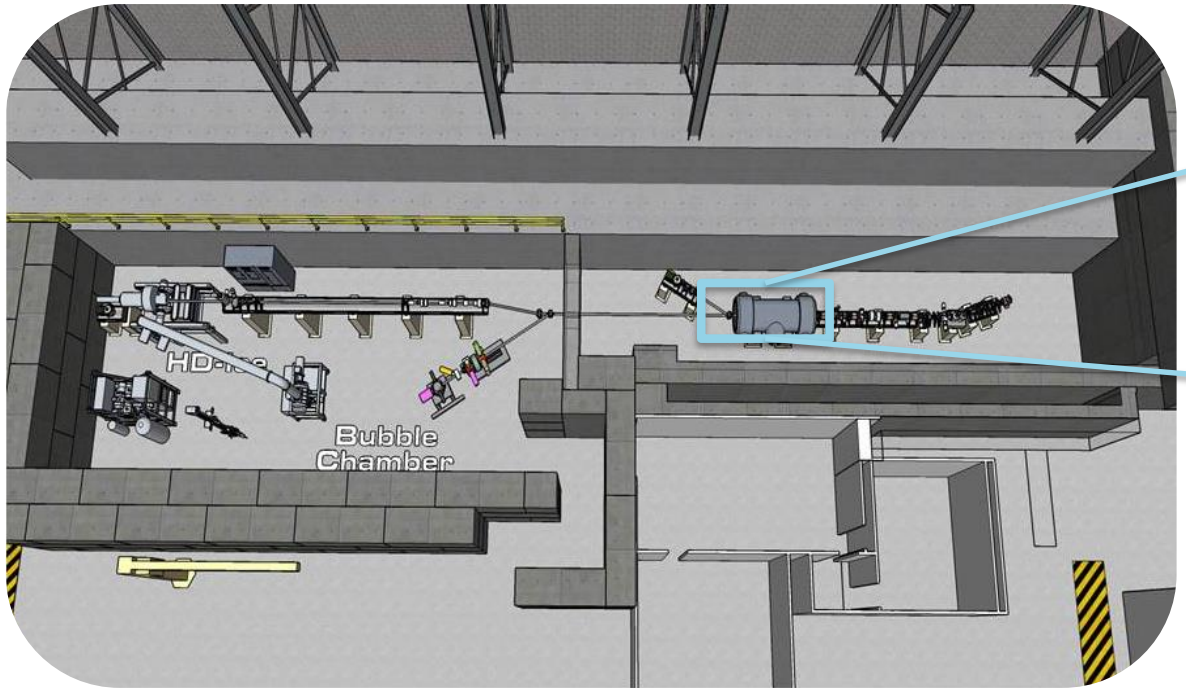
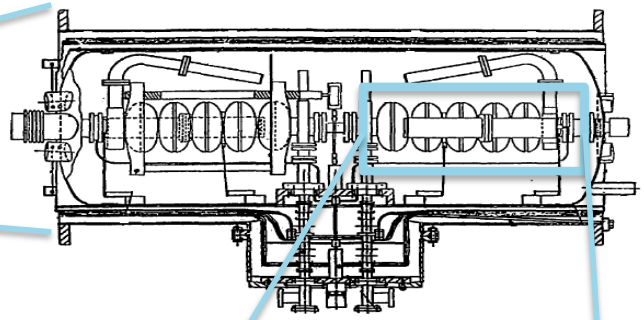
- Best performance in CEBAF cavities
- Degradation after pair assembly
- Mechanical simulations
- Cavity re-coating results
- Recent post-pair results
- Conclusion

Introduction

- The main goal of this study is to investigate operation of Nb_3Sn-coated cavities in accelerator environment.
- To save cost, we agreed to use a spare CEBAF injector cryomodule.
- The two niobium cavities in the spare CEBAF injector cryomodule will be replaced with two Nb_3Sn-coated cavities.
- The cryomodule with Nb_3Sn-coated cavities will be then used in Upgrade Injector Test facility (UITF), a small electron accelerator at Jefferson lab.

Upgrade Injector Test facility (UITF)

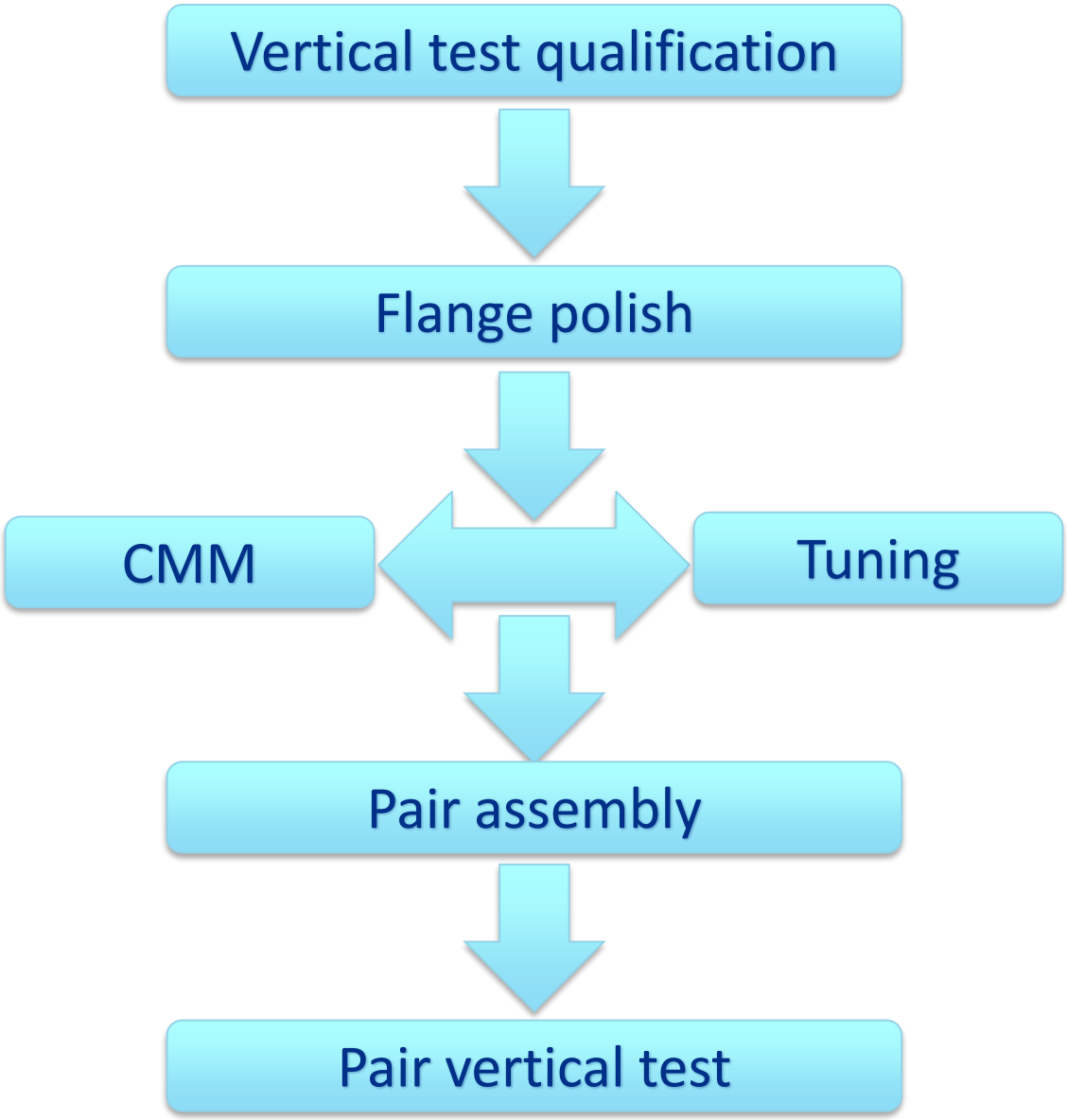


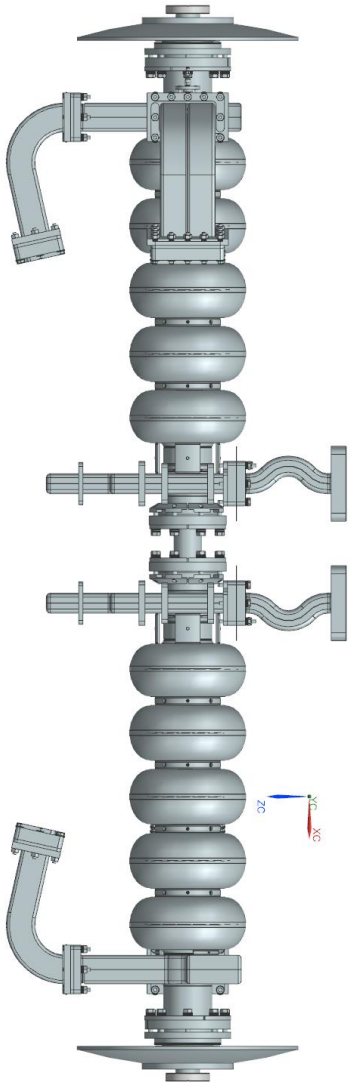


- 10 MeV accelerator for target and electron gun research
- Maximum energy set by the radiation shielding
- The required energy reach translates into E_{acc} = 10 MV/m in each cavity.

Tuning sensitivity

Pair assembly





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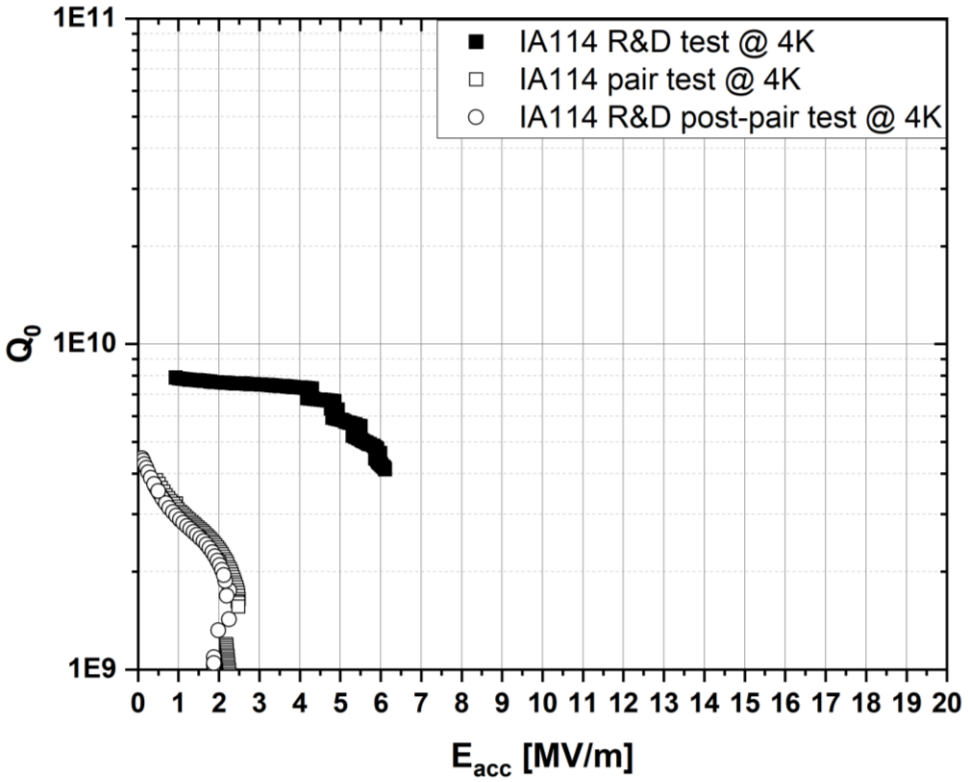
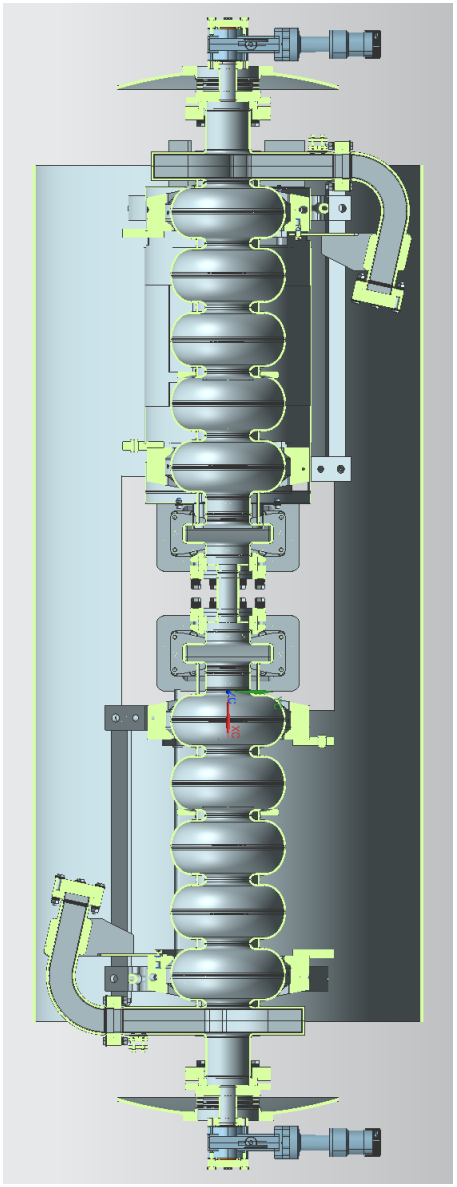
First pair assembly and test





- To test the procedures, two older Nb_3Sn-coated cavities were used in the first pair assembly
- Significant degradation was observed in both cavities during the vertical test of the cavity pair

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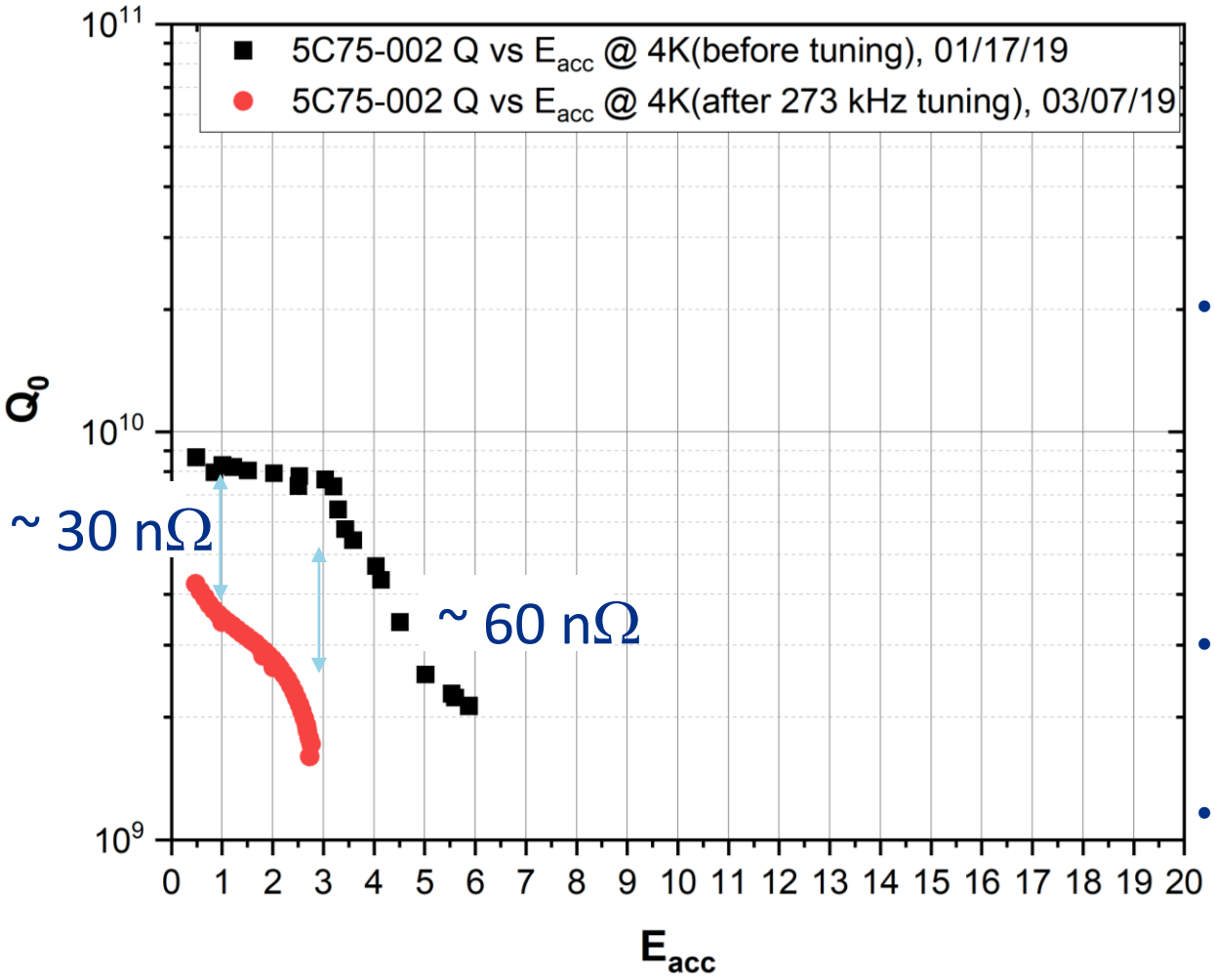
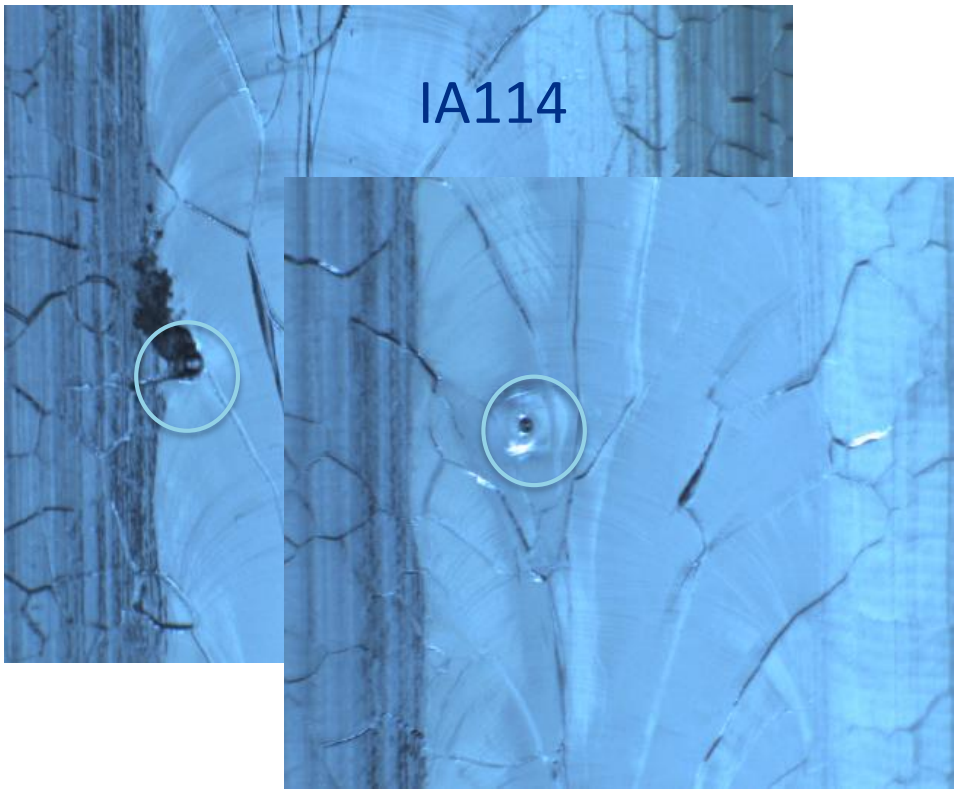
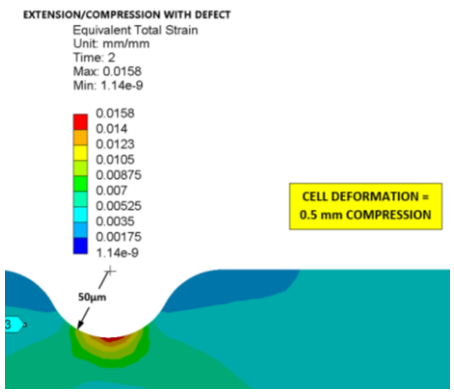
Tuning sensitivity



- To test potential sensitivity of Nb_3Sn coated cavities to mechanical deformations, a 5-cell CEBAF cavity was coated and tuned
- The tuning amount was 273 kHz similar to what is expected during cavity preparation for pair assembly
- Significant degradation was observed after tuning
- Cavity performance post-tuning was similar to that of the cavities after pair assembly

Effect of surface imperfections

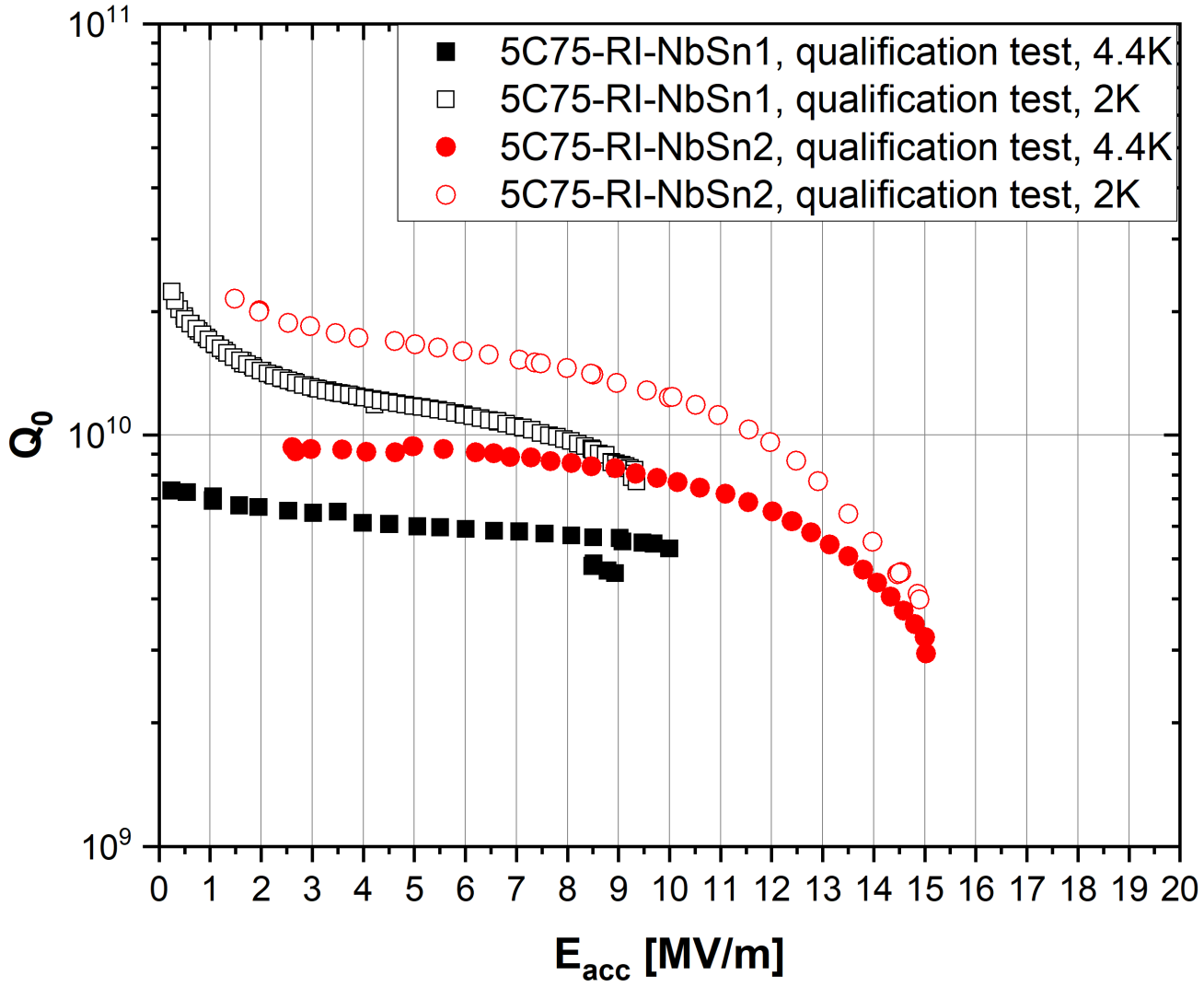


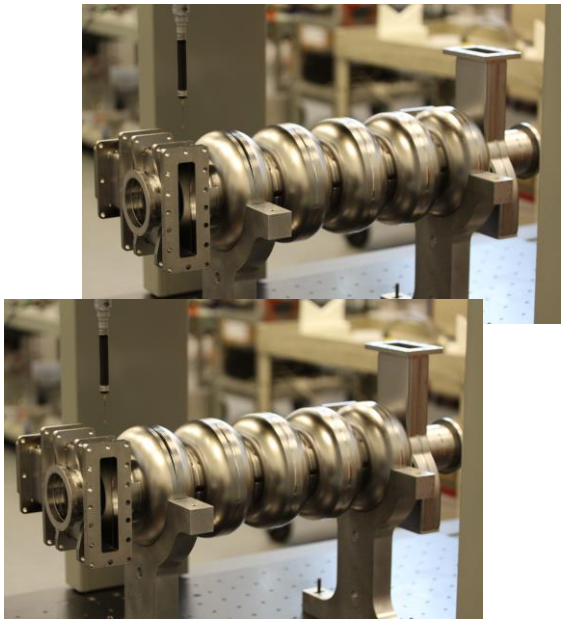


- We also realized that older CEBAF cavities built in 90s are not the best starting substrates for Nb_3Sn coating due to the defects in the weld regions
- Defect in the weld regions are likely to be worse coated due to reduce Sn and $SnCl_2$ flux during coating.
- They could also serve as a weak points during mechanical deformation that cause large than expected effect in the films

Best performance in CEBAF cavities

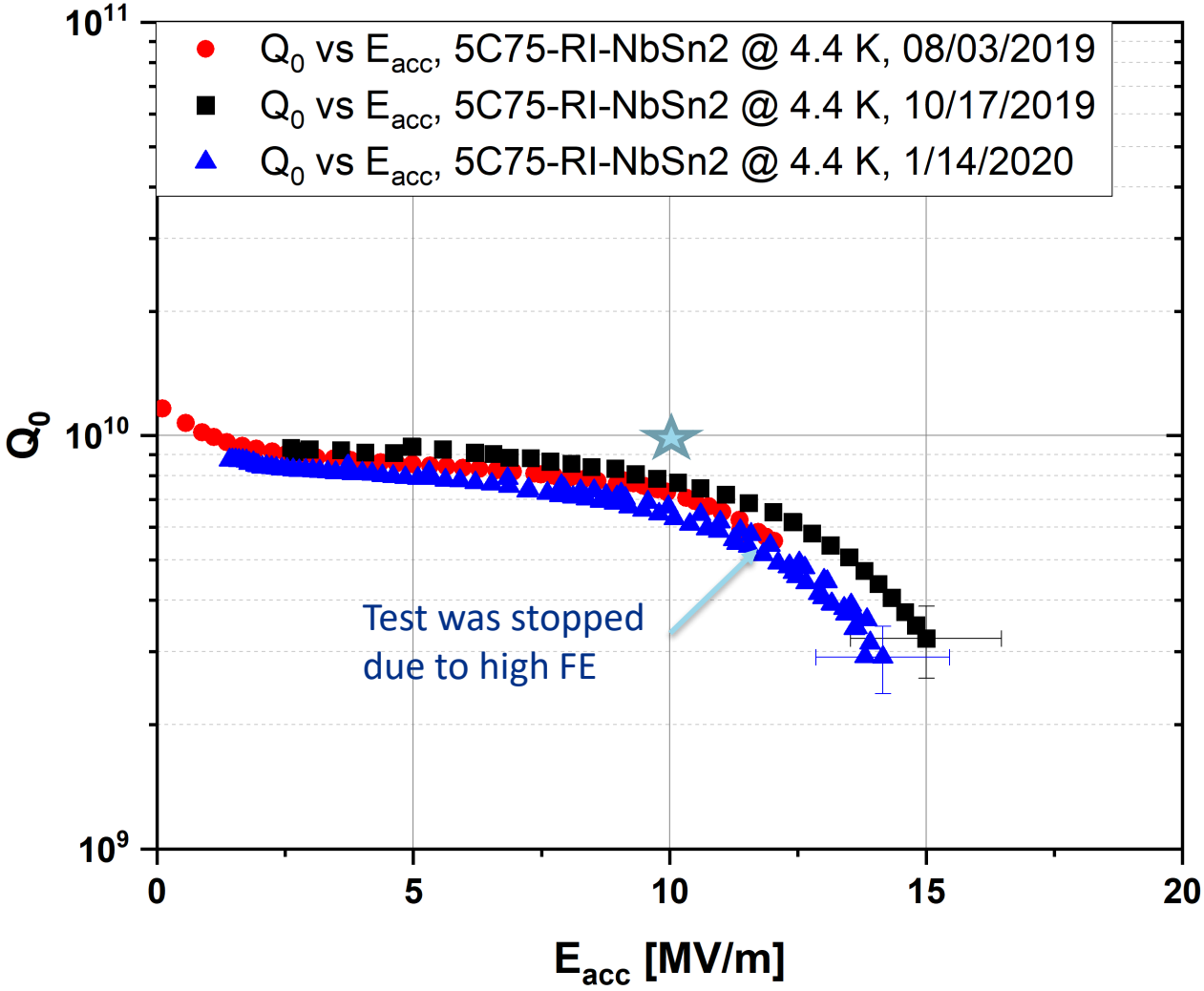
Excellent performance in Nb_3Sn-coated C75 cavities





- The best Nb_3Sn-coated cavity reached 15 MV/m

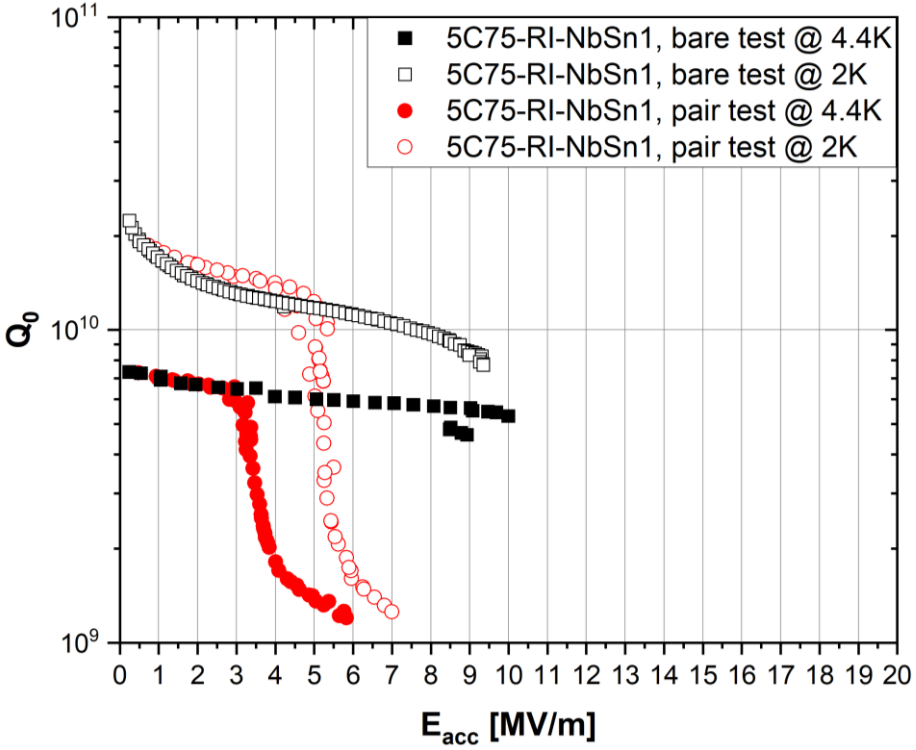
Performance change after 5 months and shipment

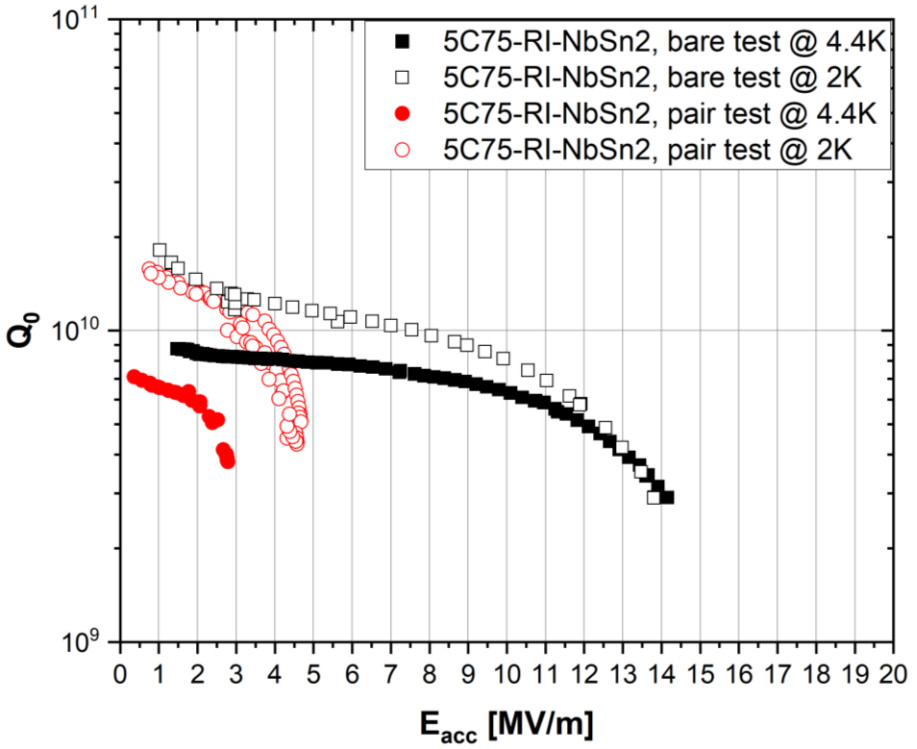


- One of the coated cavities was tested at Jefferson Lab
- The cavity was transported to Fermilab and re-tested at Fermilab
- After three months on the shelf, the cavity was re-tested at Fermilab
- No degradation was observed in these tests

Degradation after pair assembly

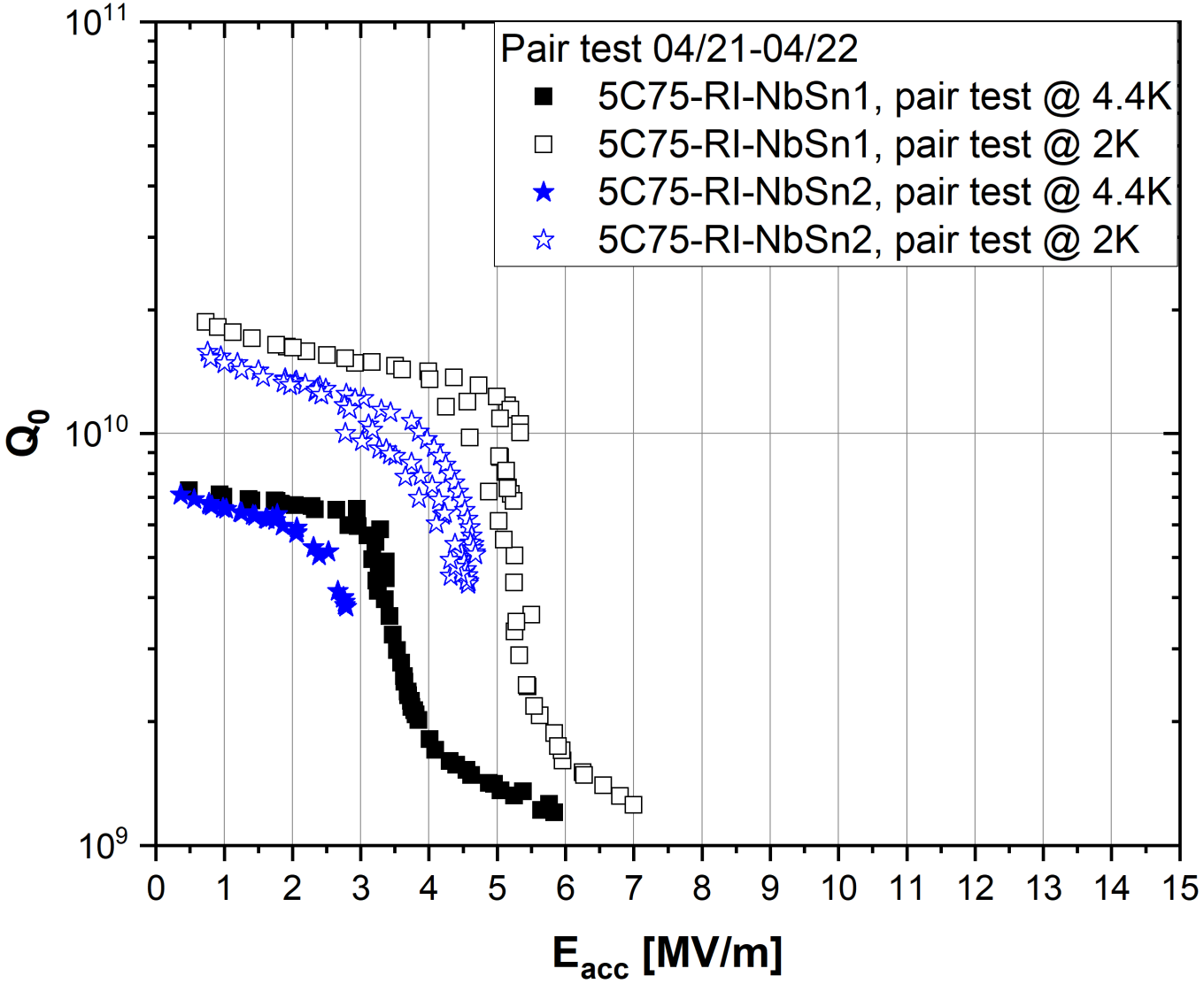
Degradation after pair assembly (again)



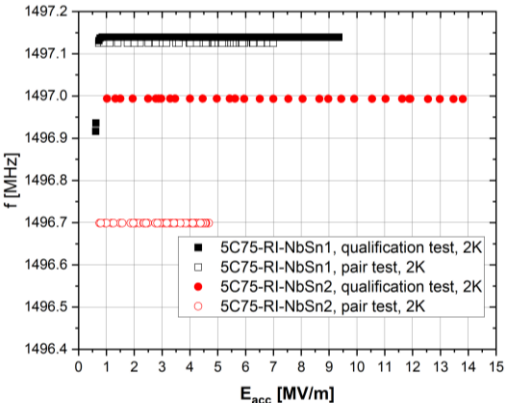


- Degradation was observed again after pair assembly in the vertical test as a pair
- The degradation was smaller than in the previous pair assembly, but still reduced cavity performance below acceptable level

Summary of the results post-pair assembly



- No warm tuning was done to cavities on the tuning bench
- Both cavities exhibited degradation in the vertical test after the pair assembly.



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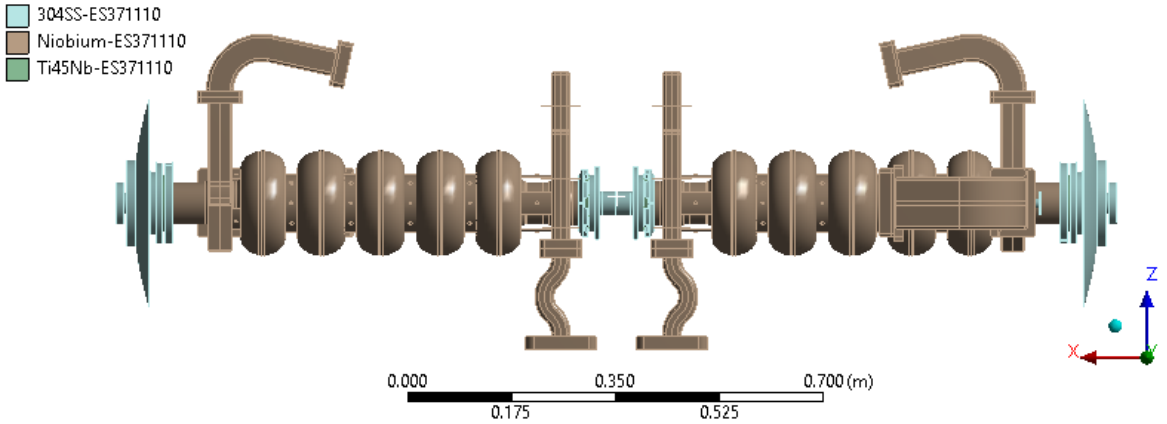
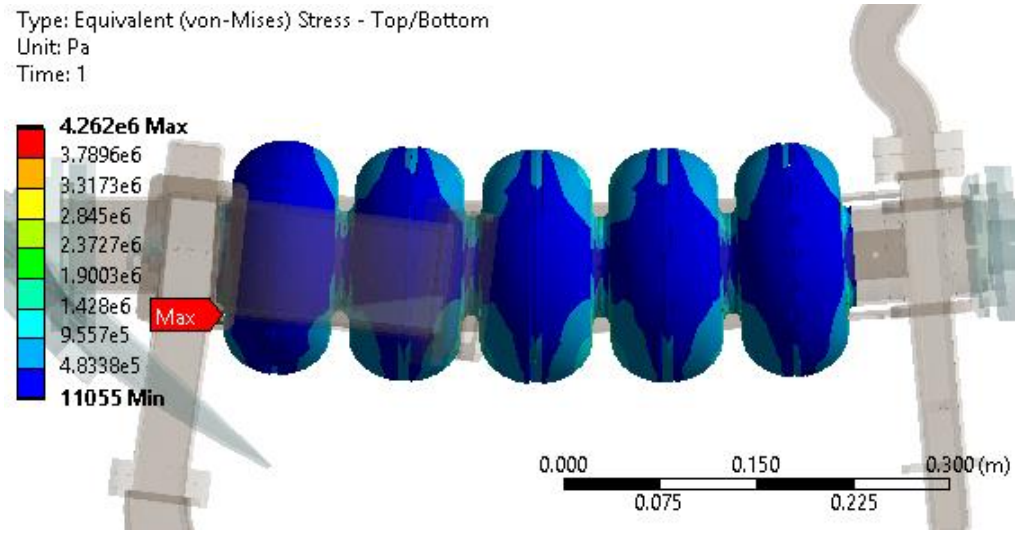
Mechanical simulations

Mechanical analysis

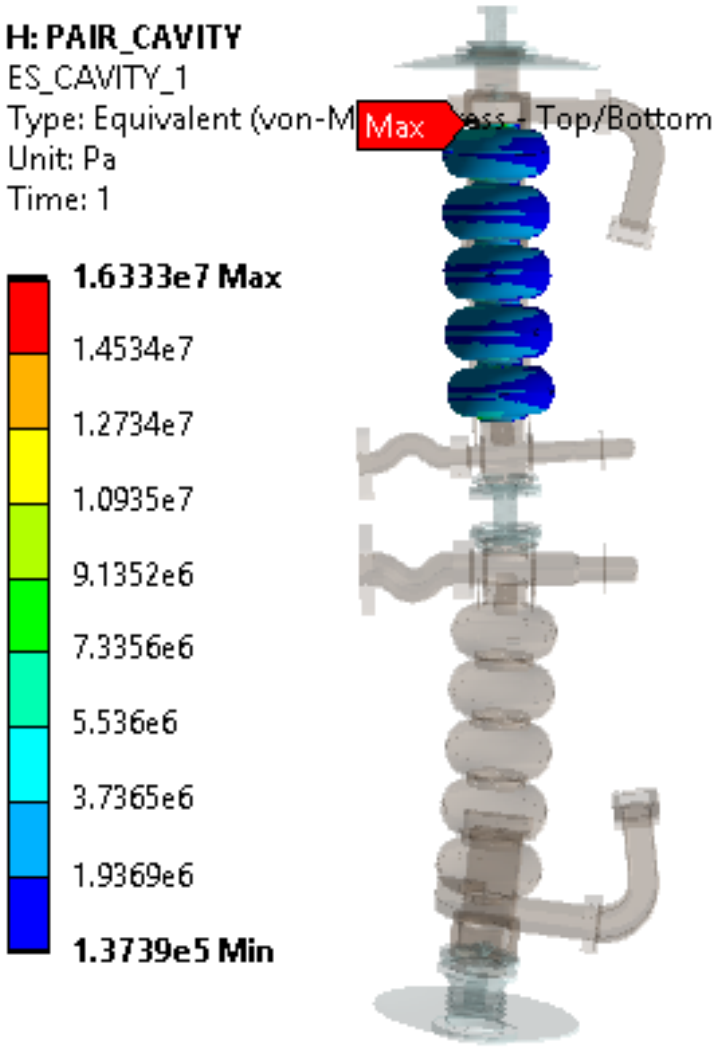




- Mechanical analysis was performed to evaluate stresses during various processing steps.
- Typical stresses are a few Mpa, which are significantly lower than even conservative 38 MPa yield strength of niobium

Simulation are done by Sergey Cheban

Mechanical analysis

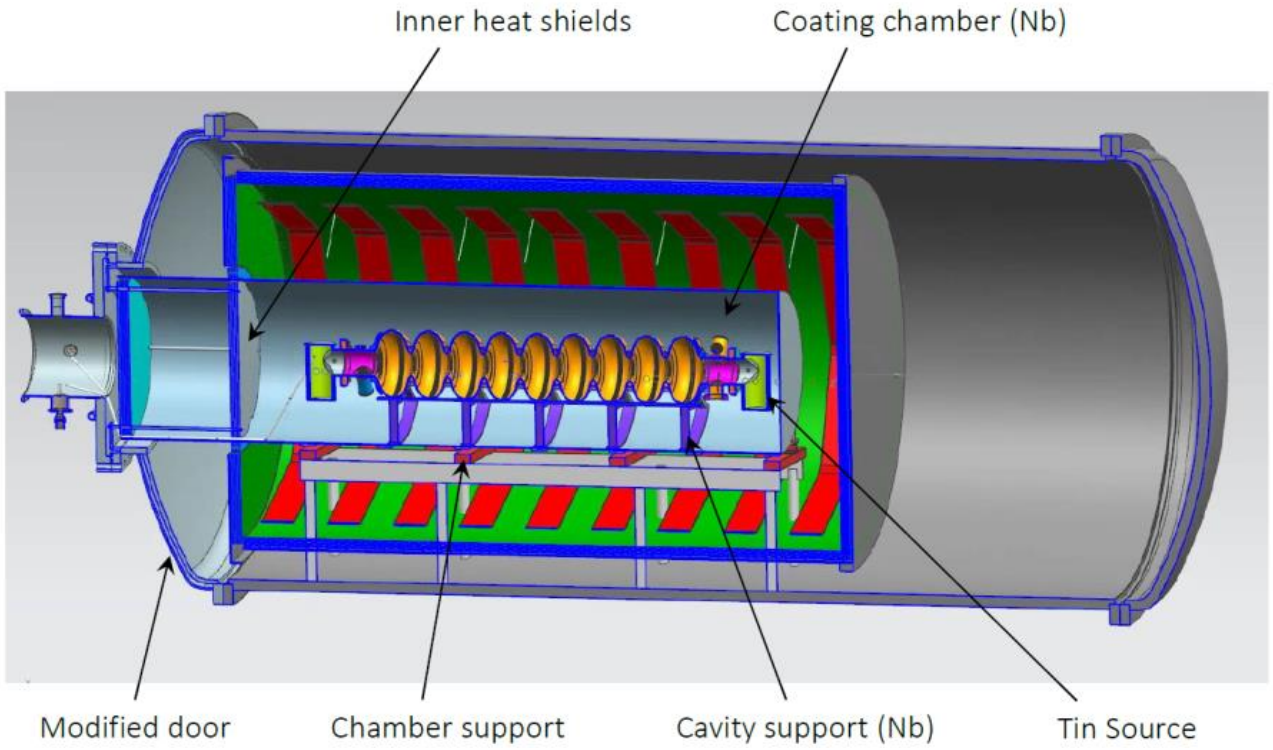


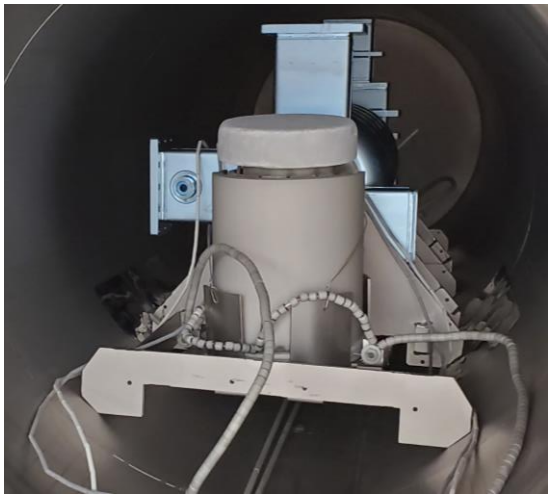
- The highest stress was found in the cavity testing configuration for vertical testing of the cavity pair.
- The maximum stress was calculated at about 16 MPa, which is still lower than the yield strength of 38 MPa.
- However, after the assembly in the cleanroom the cavity pair is lifted with the crane into the vertical testing dewar.
- If the acceleration exceeds about 3g, the stresses could exceed yield strength, especially, in areas that were thinned during fabrication and processing of the cavity.

Simulation are done by Sergey Cheban

Cavity re-coating results

5C75-RI-NbSn1 Nb3Sn re-coating at FNAL facility





- A record cw accelerating gradient of 24 MV m^{-1} for a cavity made with an SRF material other than Nb
- Two cavities that exhibit $Q_0 > 1 \times 10^{10}$ at 20 MV m^{-1} and 4.4 K
- $Q_0 \sim 9 \times 10^9$ at 15 MV m^{-1} and 4.4 K on a practical cavity structure commonly used in accelerators;

S Posen *et al* 2021 *Supercond. Sci. Technol.* **34** 025007

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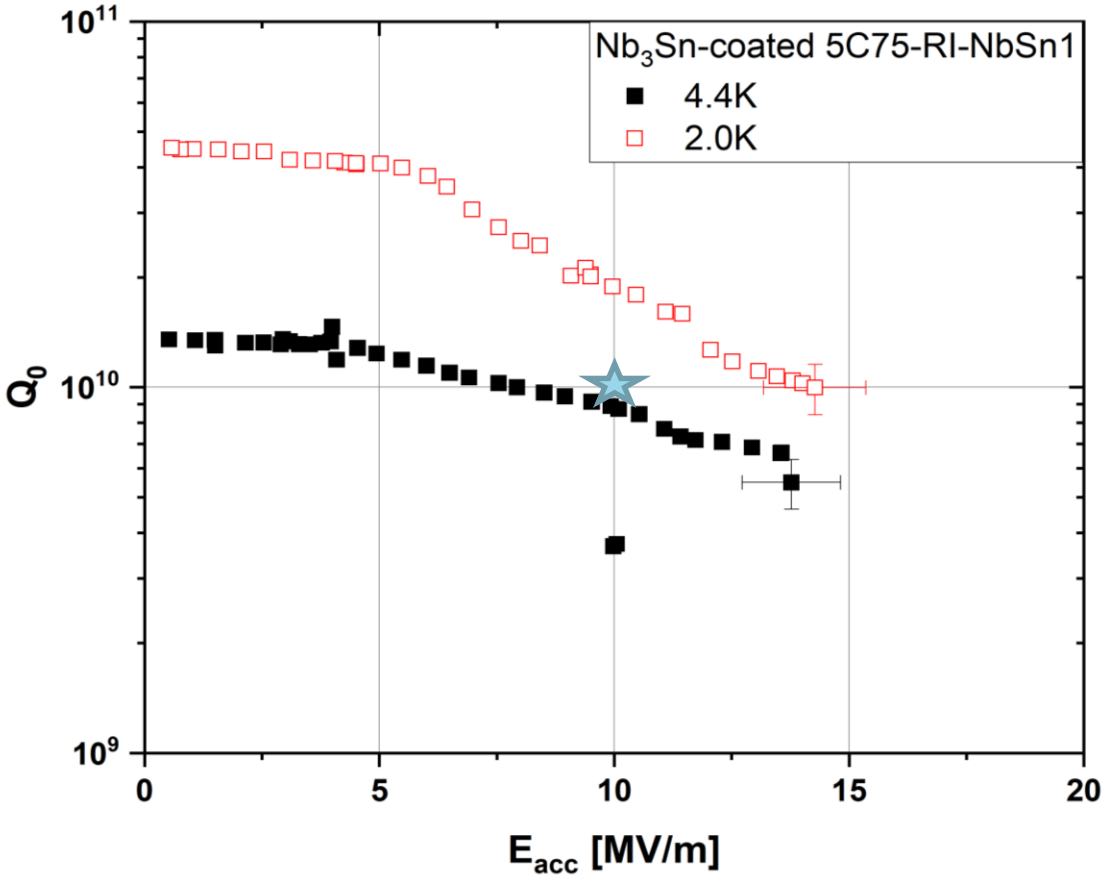
5C75-RI-NbSn1 Nb3Sn re-coating results



- CEBAF cavity was processed in preparation for Nb_3Sn coating at FNAL & ANL facilities for the first time
- The cavity was coated at FNAL using recipe developed for coating of 9-cell cavities
- The cavity showed excellent performance in the vertical test at Fermilab

C75-RI-004 Nb_3Sn coating at JLAB facility

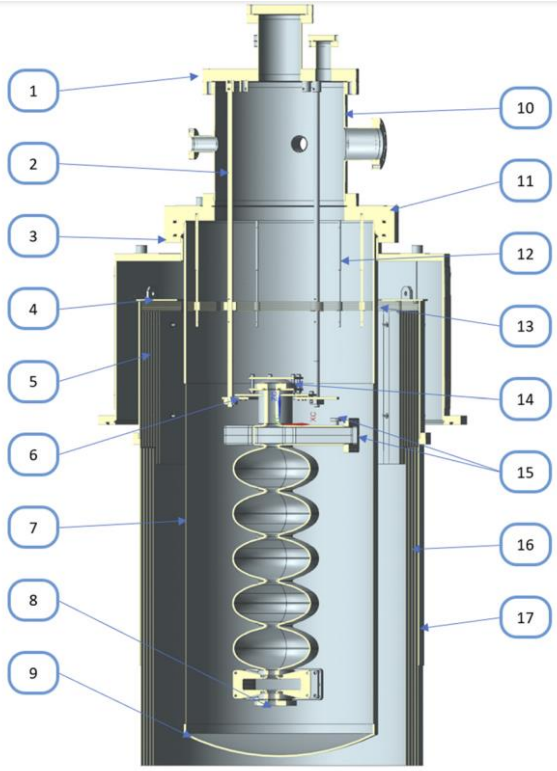


FIG. 1. A schematic of a coating chamber with a CEBAF 5-cell cavity inside the hot zone. (1) Multiport top plate custom-built by Lesker Company; (2) 0.5 in. OD niobium support rods; (3) water-cooled stainless steel (SS) door custom-built by Lesker Company; (4) SS support structure; (5) molybdenum heat shields; (6) 4 mm-thick niobium support plate; (7). 4 mm-thick niobium cylinder; (8) niobium crucible (not shown); (9) 4 mm-thick deep-drawn niobium dome, which is electron beam welded to the niobium cylinder; (10) multiport SS spool piece custom-built by Lesker Company; (11) water-cooled zero-length reducer custom-built by Lesker Company; (12) 1/4 in. niobium support rods; (13) niobium and molybdenum heat shields; (14) niobium cavity support structure; (15) niobium covers (not shown); (16) heat shields (a part of the furnace custom-built by T&M vacuum); (17) SS support structure (a part of the furnace custom-built by T&M vacuum).

- Coating system comprises a commercial furnace and custom niobium reaction chamber, for coating Nb_3Sn films on the inner surface of SRF cavities.
- The system is capable of coating multicell accelerator cavities inside the niobium reaction chamber with the vacuum system separated from the furnace vacuum.
- 2 µm thick uniform Nb_3Sn films with the transition temperature of 18 K are grown on small samples and multicell cavities.
- Coated single cell cavities exhibit quality factors close to $3 \cdot 10^{10}$ at 4 K, about two orders of magnitude improvement over typical quality factor, and close to $5 \cdot 10^{10}$ at 2 K, a factor of three improvement of baseline tests of these cavities.
- Multicell cavities exhibit quality factors in excess of 10^{10} and reach above 10 MV/m, suitable for accelerator applications.

G Eremeev *et al* Rev. Sci. Instrum. 91, 073911 (2020)

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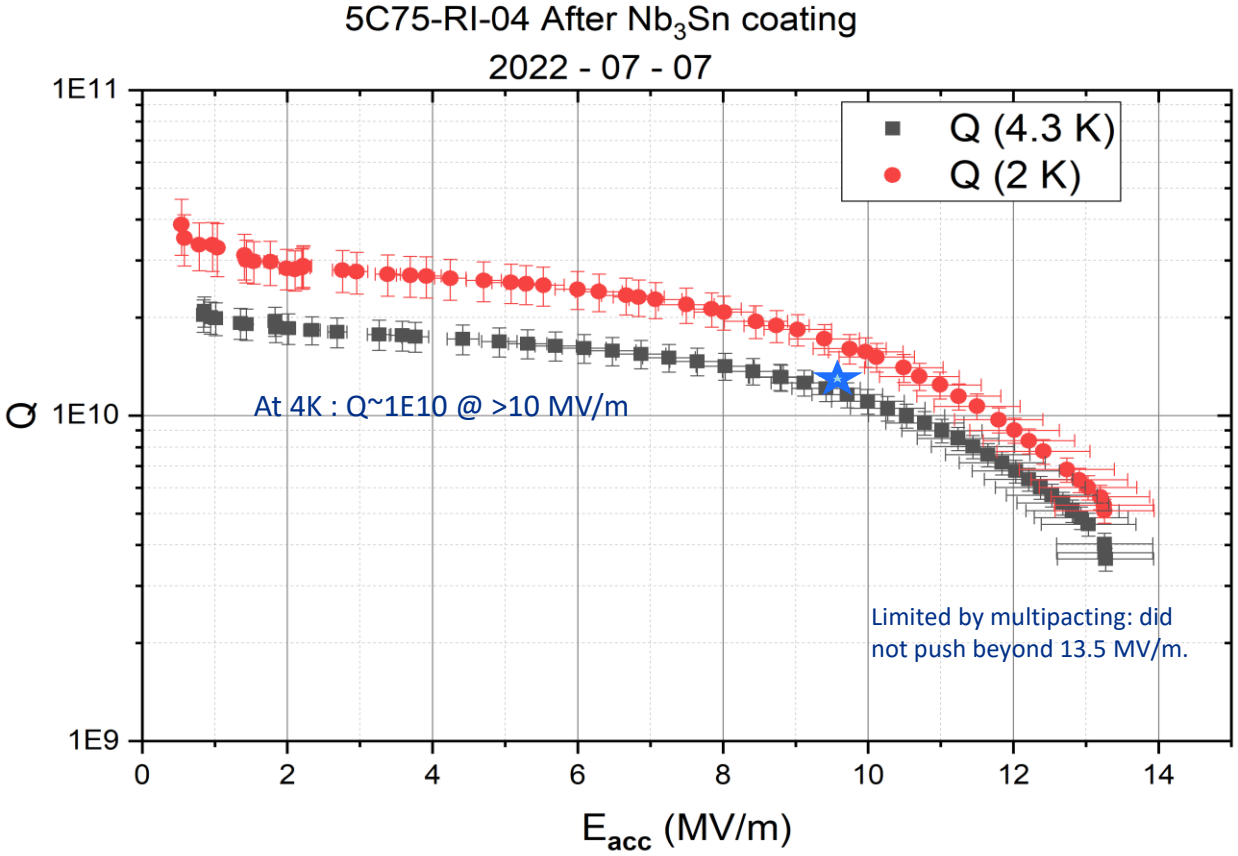
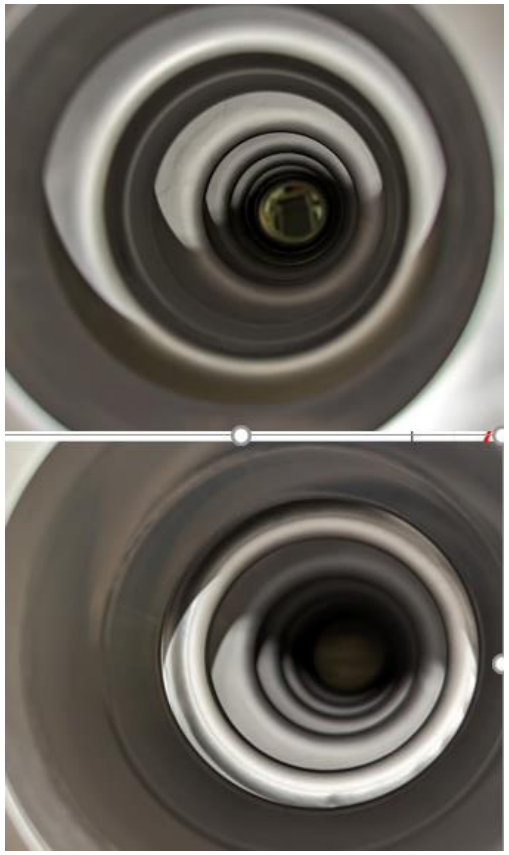
C75-RI-004 Nb_3Sn coating results

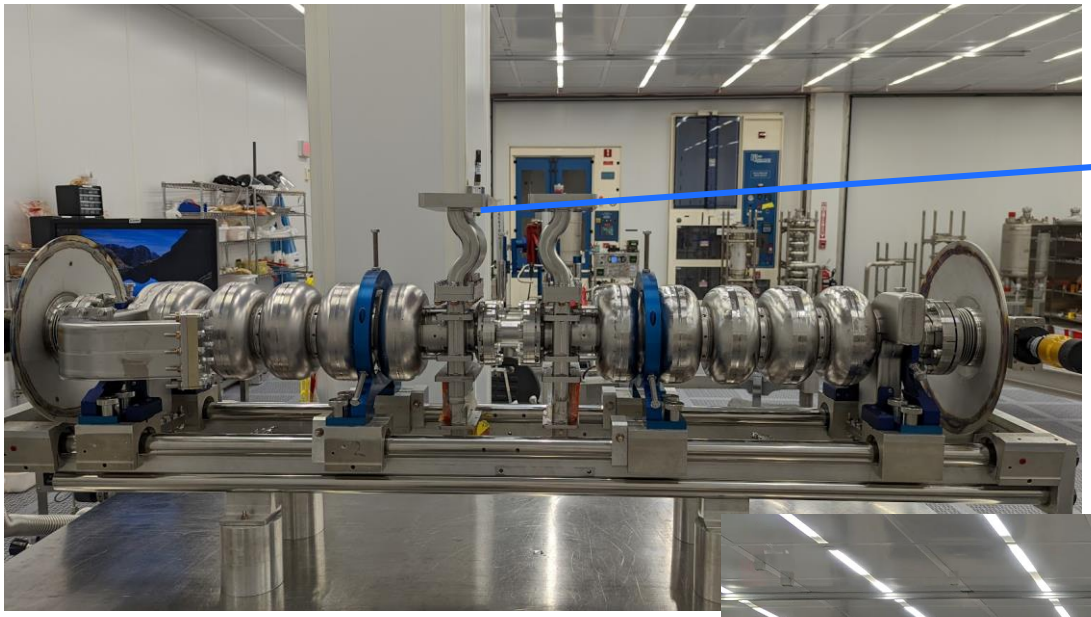


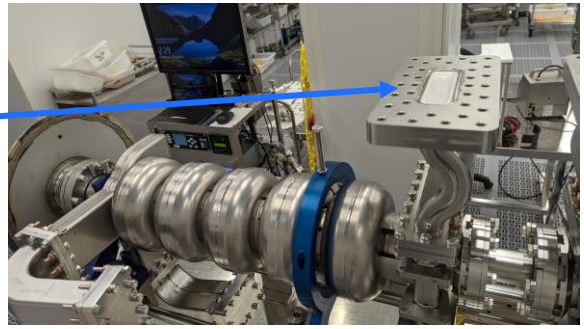


- CEBAF cavity made of large grain material was coated for the first time
- The cavity had excellent performance and was limited by multipacting at 13.5 MV/m.

Recent post-pair results

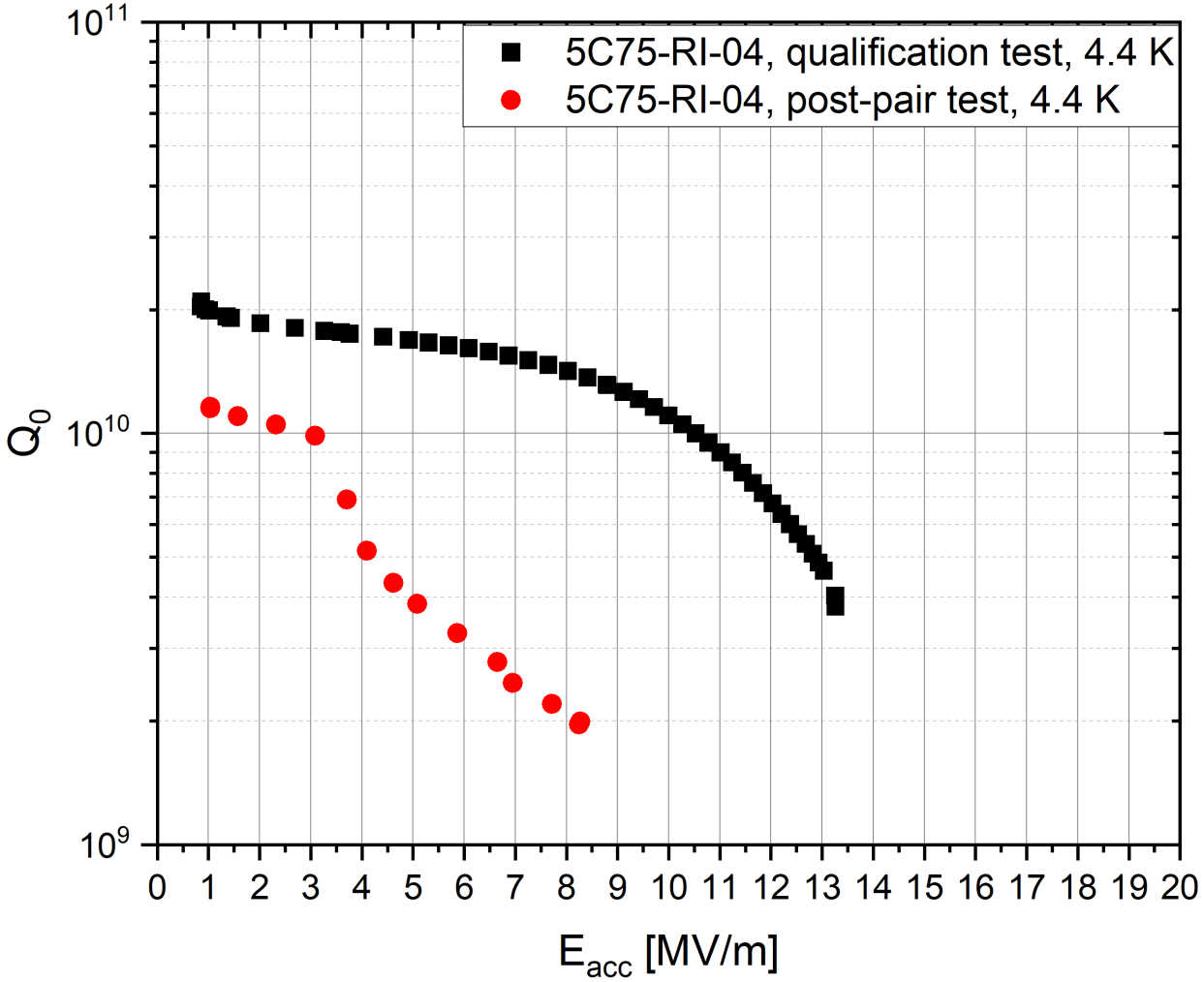
Pair assembly





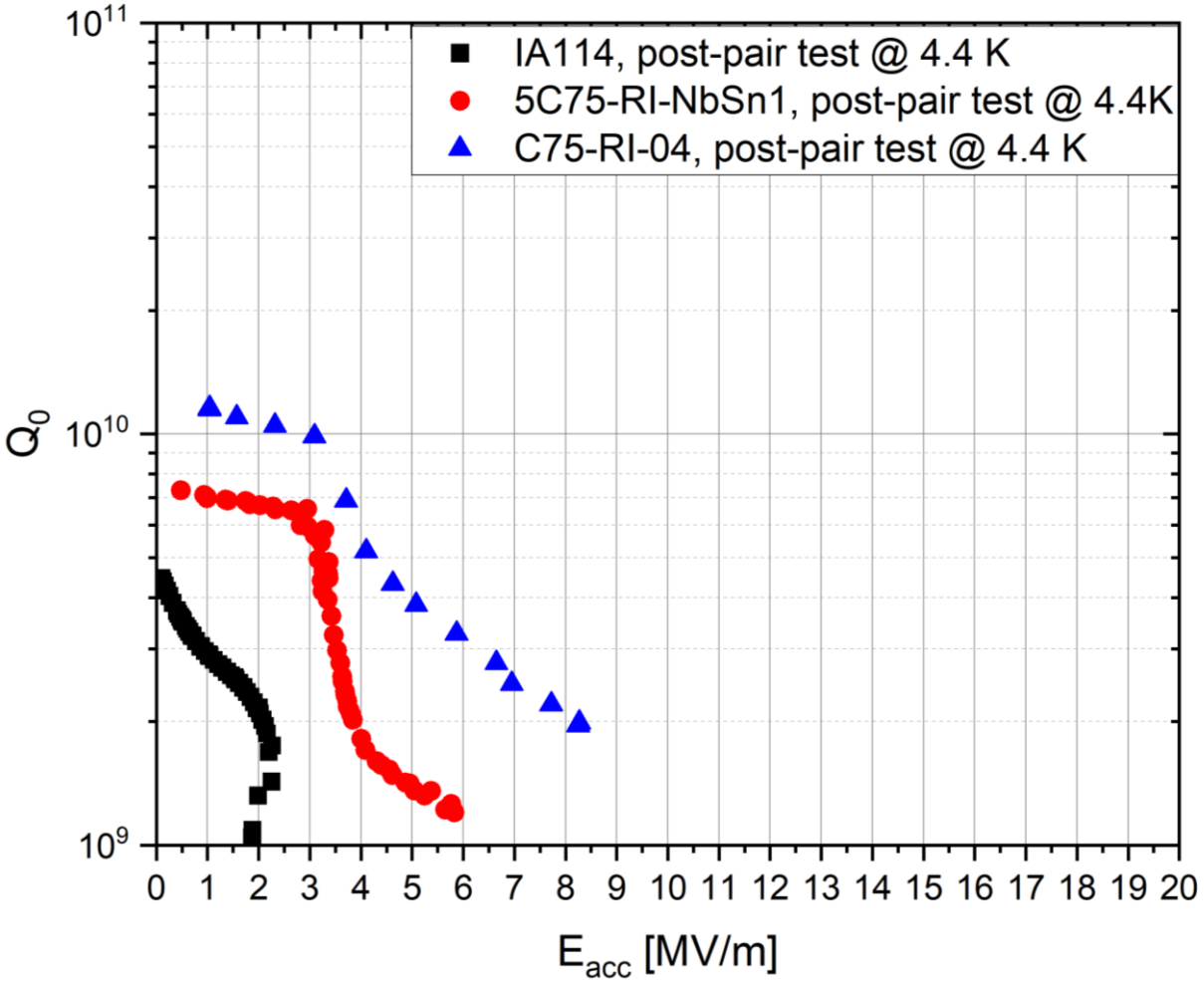
- Following a leak in one of the dogleg, the pair was disassembled.

Vertical test results after pair assembly



- The performance still degraded even with the latest changes in the preparation procedures
- While Q_0 exceeds 10^{10} at low gradients, there is still a strong Q-slope above E_{acc} z 3 MV/m
- The cavity reach the highest to-date gradient above E_{acc} = 3 MV/m post pair assembly

Comparison with previous post-pair results



- As we eliminate processing steps that could lead to deformation, we see improvement in the performance
- We plan to measure the second cavity from this pair and define the path forward based on the result

Conclusion

- Nb_3Sn cavities are very sensitive to mechanical deformation
- Elimination of tuning and vertical tests as a pair reduced cavity degradation after pair assembly
- With the recent change in the CM assembly for Nb_3Sn cavity, the performance is still not fully retained from vertical qualification test to cryomodule assembly

Acknowledgements

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- ✓ M. Liepe, R. Porter, et al.
- ✓ D. Bice, B. Tennis, A. Grassellino, A. Romanenko, S. Posen, et al.
- ✓ T. Reid, M. Kelly.
- ✓ JLab technical staff
- ✓ Fermilab technical staff