Nb_3Sn at Fermilab: Exploring Performance

Sam Posen

19th International Conference on RF Superconductivity

July 4, 2019

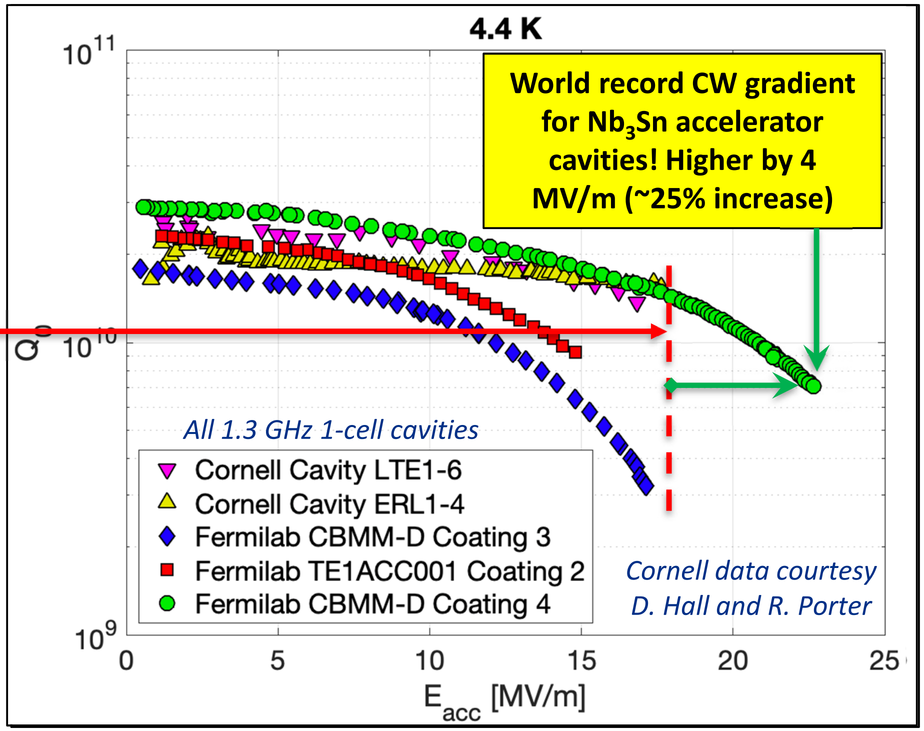
1. **Progress in Nb_3Sn Film Quality**
2. Defects to Avoid in Nb_3Sn
3. Progress in Demonstrating Practicality of Nb_3Sn Cavities

Progress in Nb_3Sn Film Quality

- At TTC 2019 in Vancouver, we showed that we had made a Nb_3Sn cavity that reached 22.5 MV/m, **a new record CW accelerating gradient for Nb_3Sn (25% increase)**

TTC Workshop, Vancouver, Feb 2019

Previous CW accelerating gradient limit ~17-18 MV/m



Still trying to nail down which of changes we made to the coating parameters were the important ones

Since TTC, we have repeated the coating as closely as we could and found there are some major differences in film properties…

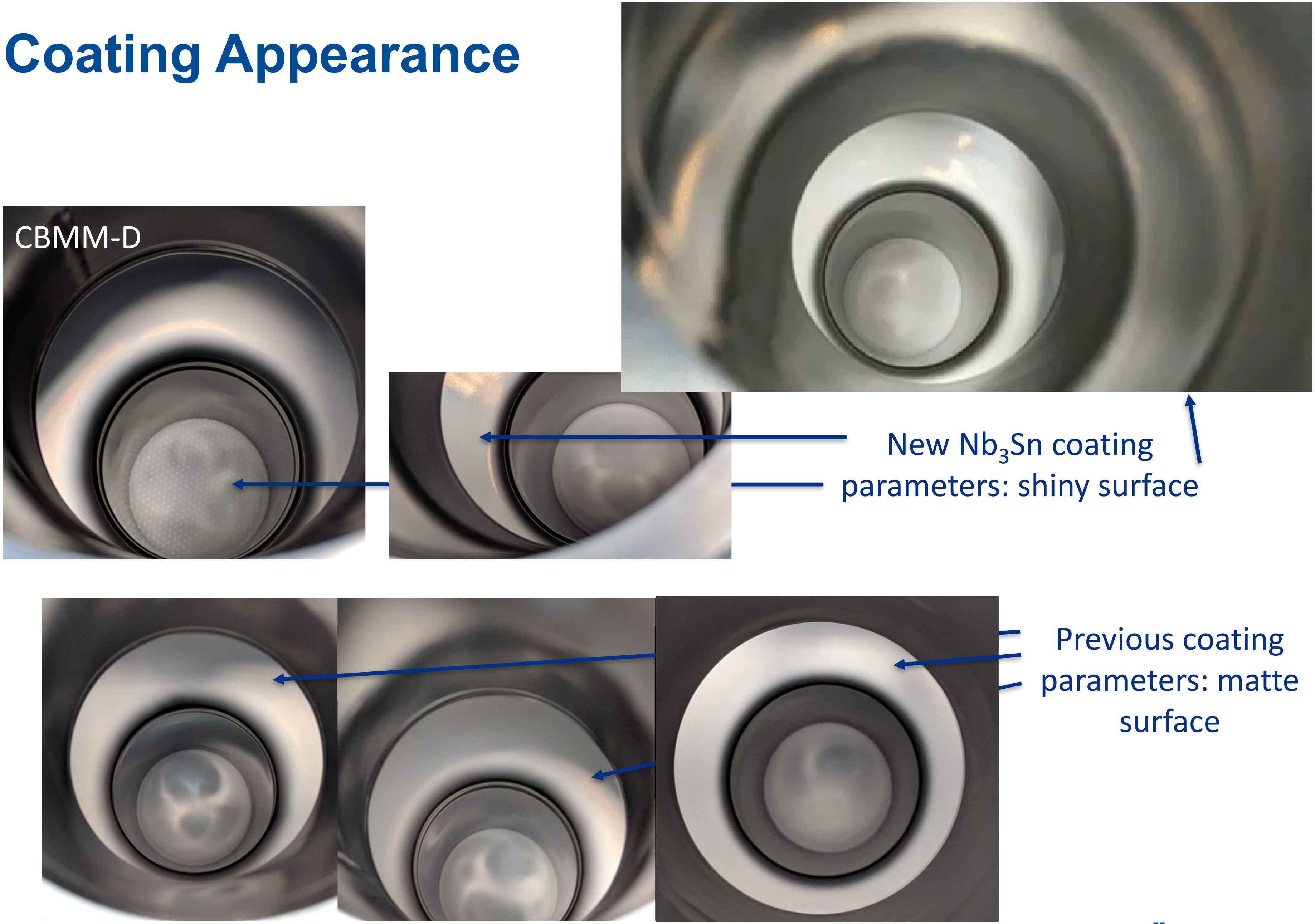
Fermilab

Matte vs Shiny Nb_3Sn Surface

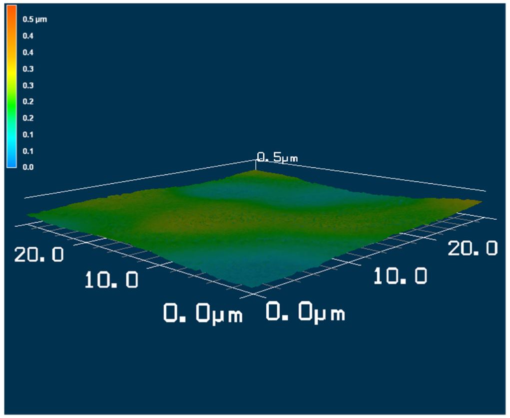
Left: Previous Nb_3Sn Coating Parameters

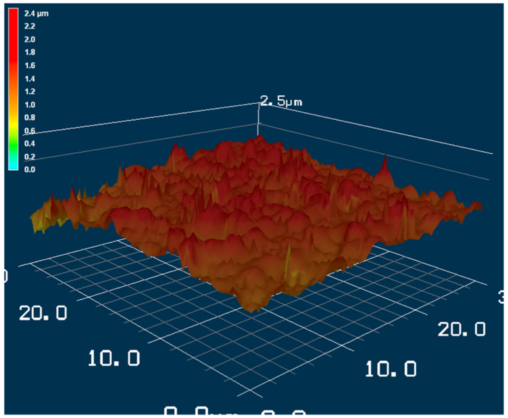
Right: New Nb_3Sn Coating Parameters result in mirror-like coating

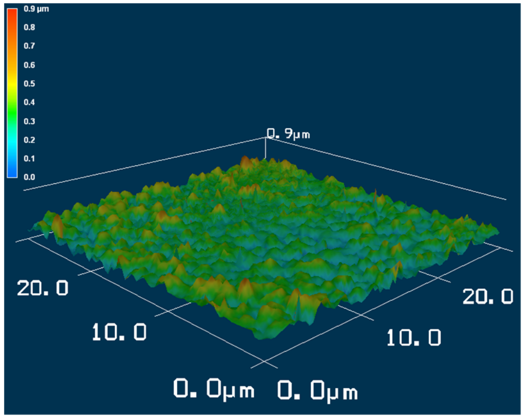
Coating Appearance



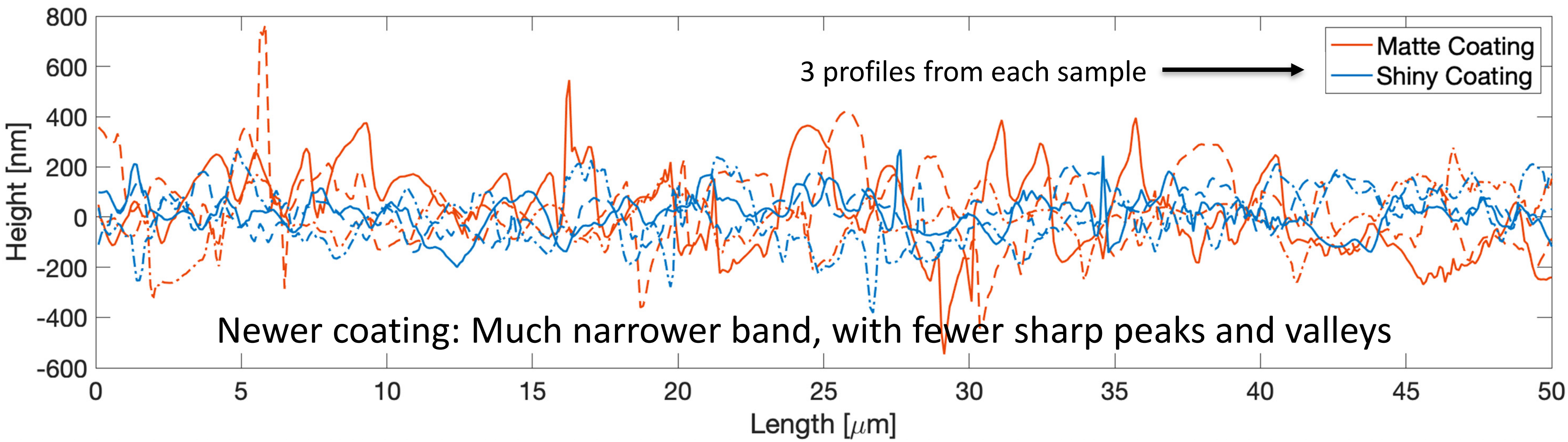
Fermilab

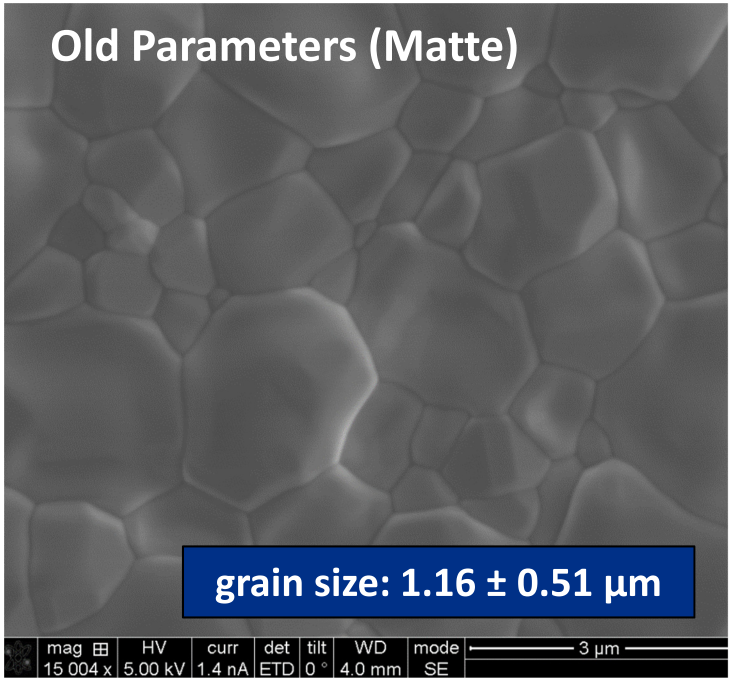


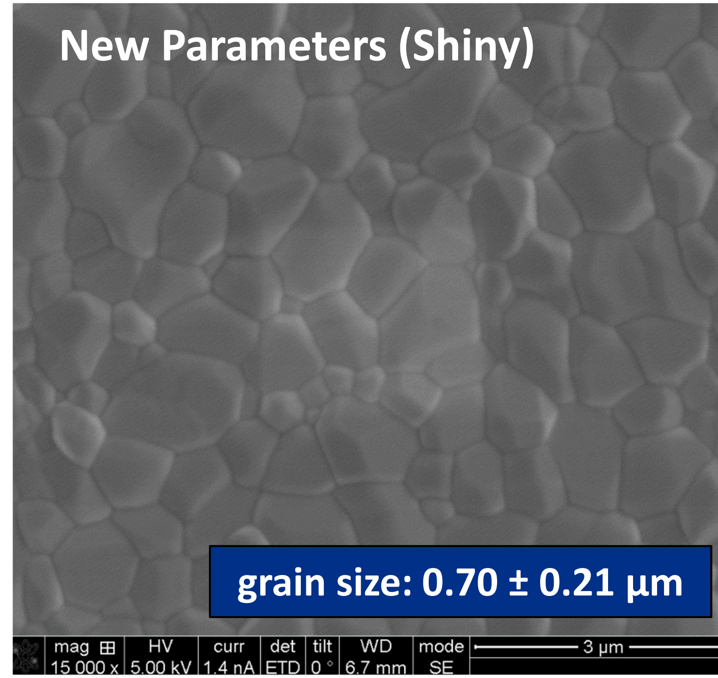


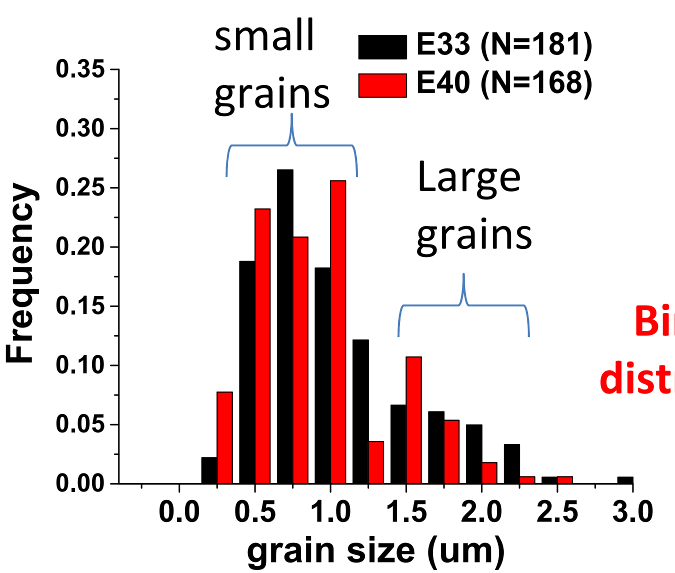


	Nb sample, EP, before coating	After coating, old parameters (matte)	After coating, new parameters (shiny)
R_a (mean deviation)	40 nm	130 nm	63 nm
R_q (RMS deviation)	48 nm	174 nm	81 nm



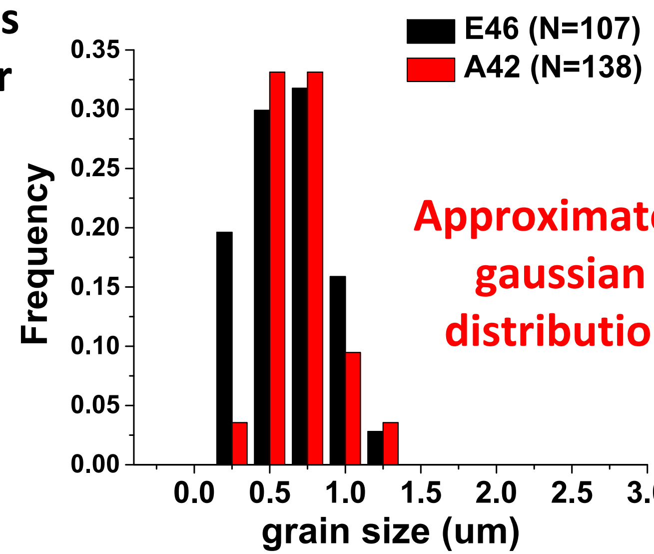






Bimodal distribution

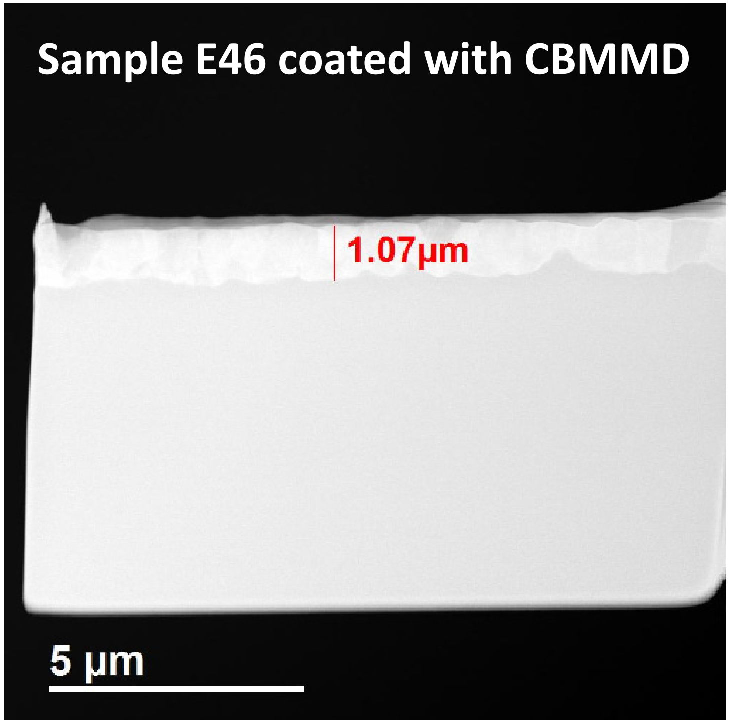
New coatings have smaller grain size

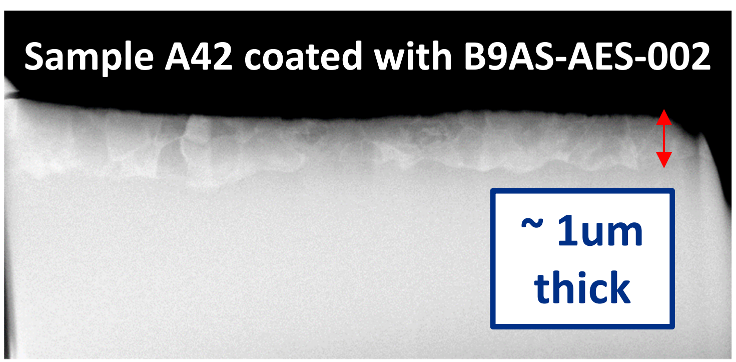


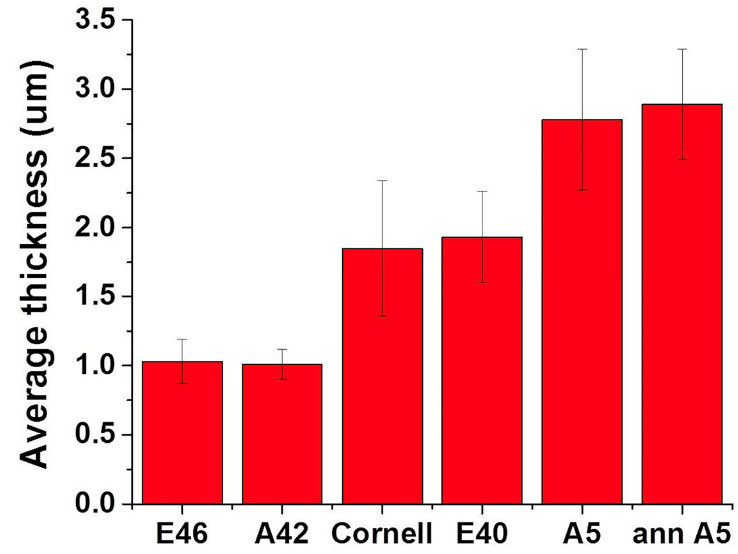
Approximately gaussian distribution

Microscopy by J.-Y. Lee, Northwestern U./Fermilab
David Seidman Group, Northwestern U. Materials Science & Engineering Dept

Film Thickness via FIB Liftout

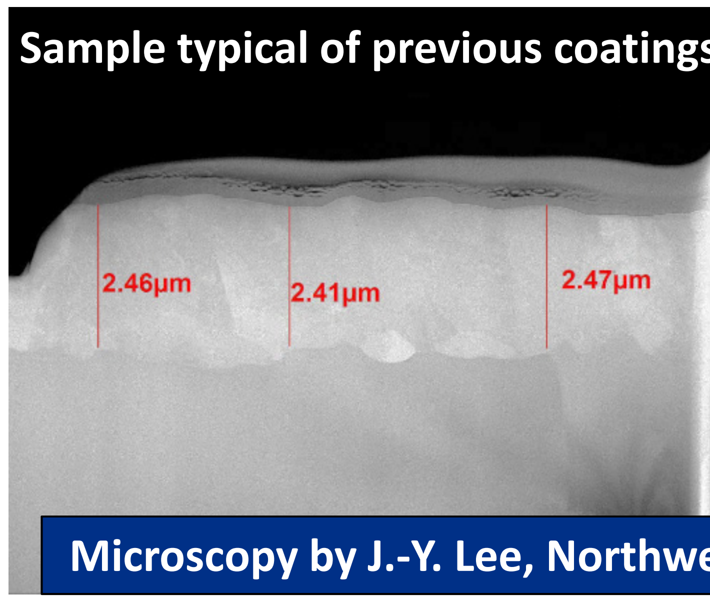






New coatings with shiny films

Old parameters with matte films

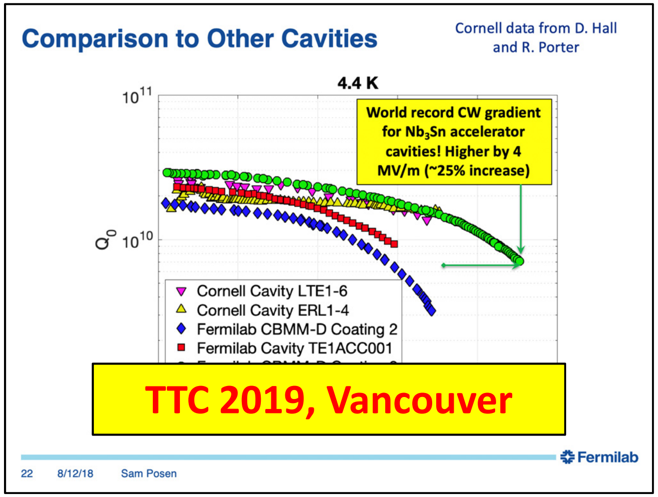


Microscopy by J.-Y. Lee, Northwestern U./Fermilab

Summary of Observations

- Shiny appearance consistent with reduced surface roughness
- Newer films also have smaller grains and are thinner
- Some possible reasons for reaching higher maximum fields:
  - Thinner films – Nb_3Sn has poor thermal conductivity, possibly reduce overheating
  - Smaller surface roughness – less magnetic field enhancement

- Maximum fields higher than 18 MV/m – now observed in a second cavity! More details in section 3…



1. Progress in Nb_3Sn Film Quality
2. **Defects to Avoid in Nb_3Sn**
3. Progress in Demonstrating Practicality of Nb_3Sn Cavities

Defects to Avoid in Nb_3Sn – Thin Regions

- Thin regions identified as cause of Q degradation in early Cornell cavity via microscopy of T-map hot spot cutouts [**Y. Trenikhina et al. SuST 2018**]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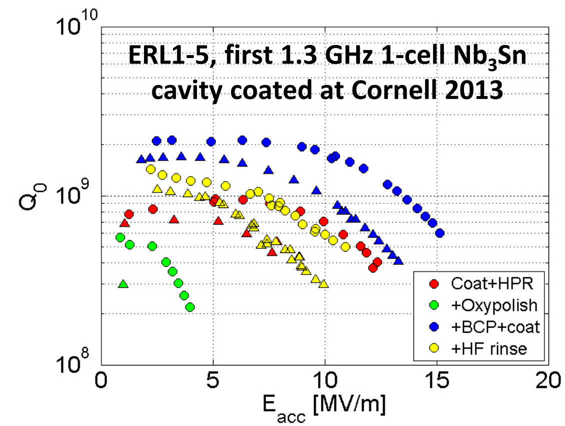
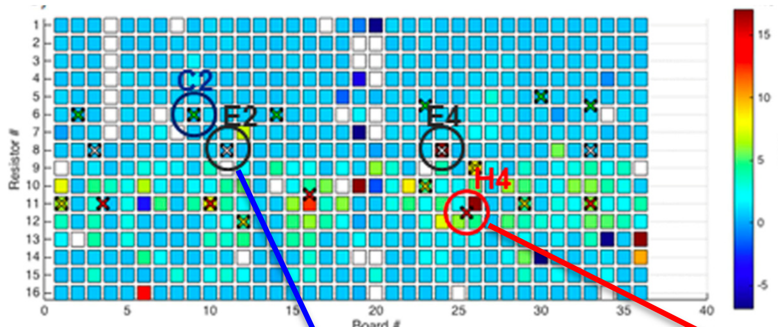
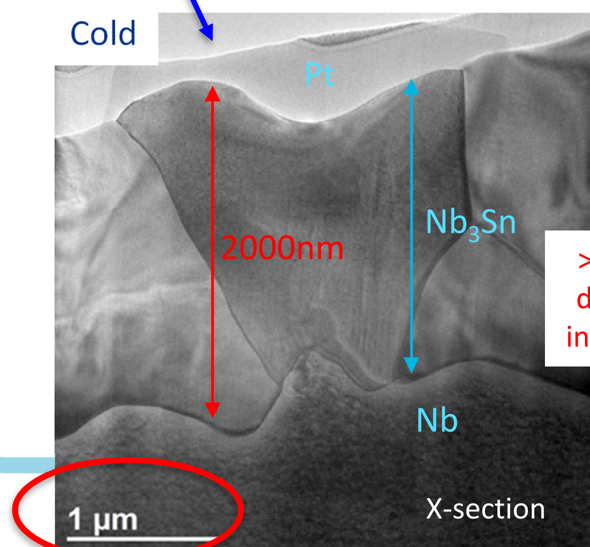
Superconductor Science and Technology
Supercond. Sci. Technol. 31 (2018) 015004 (13pp)
https://doi.org/10.1088/1361-6668/aa9694

Performance-defining properties of Nb_3Sn coating in SRF cavities

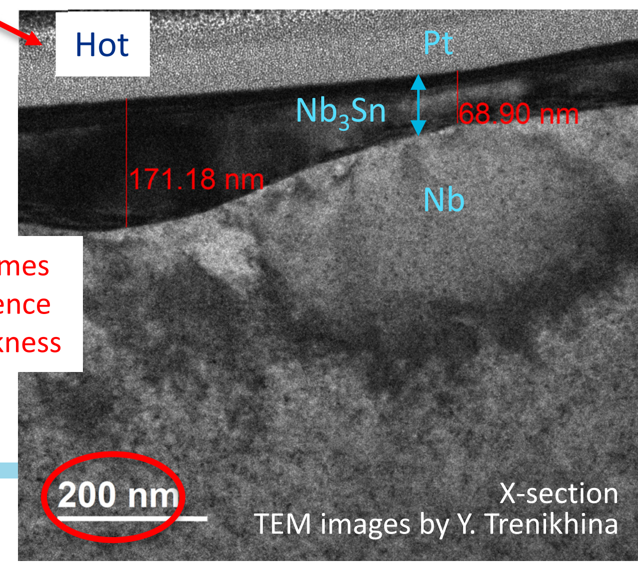
Y Trenikhina[1], S Posen[1], A Romanenko[1], M Sardela[2], J-M Zuo[2], D L Hall[3] and M Liepe[3]







>10 times difference in thickness



Defects to Avoid in Nb_3Sn – Thin Regions

- TEM studies in collaboration with Northwestern show frequent orientation relationship in thin regions [**J.-Y. Lee et al. SuST 2019; SRF'19 MP009**]
- 9-cell sample host cavity study shows thin regions tend to form when tin flux is low [**T. Spina et al. SRF'19 MOP059**; manuscript in preparation]
- Avoidable defect: not typically observed in coatings with good performance

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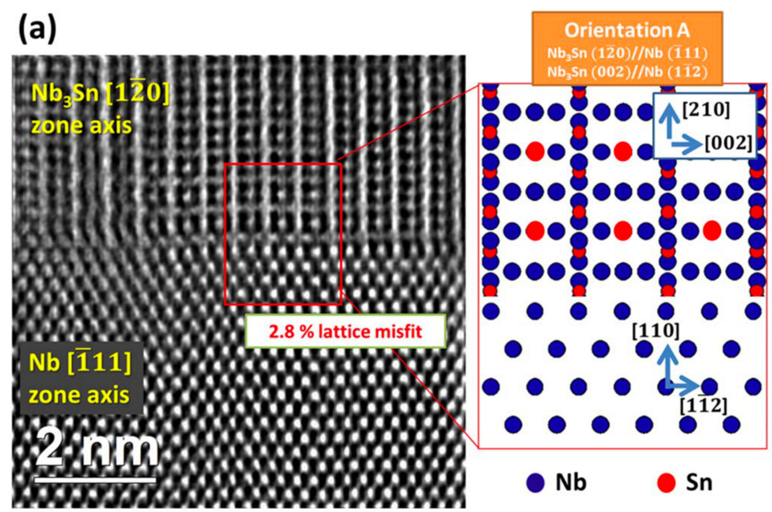
Superconductor Science and Technology
Supercond. Sci. Technol. **32** (2019) 024001 (16pp)
https://doi.org/10.1088/1361-6668/aaf268

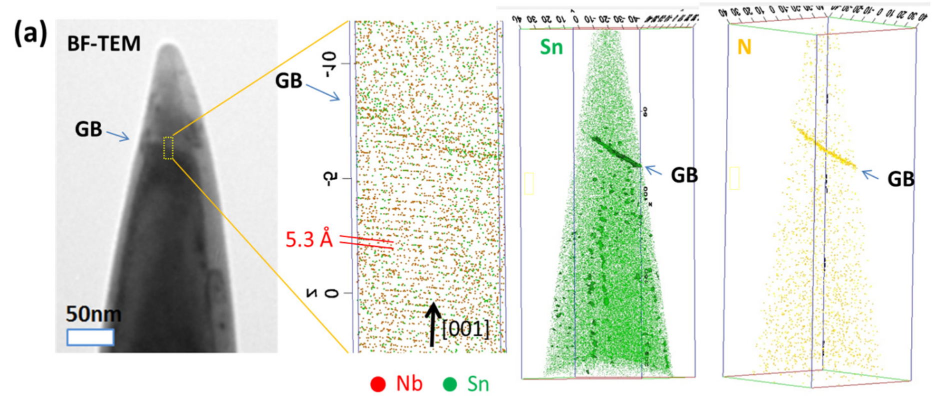
Atomic-scale analyses of Nb_3Sn on Nb prepared by vapor diffusion for superconducting radiofrequency cavity applications: a correlative study

Jaeyel Lee[1,2,6], Sam Posen[2,6], Zugang Mao[1], Yulia Trenikhina[2], Kai He[1,3], Daniel L Hall[4], Matthias Liepe[4] and David N Seidman[1,5,6]

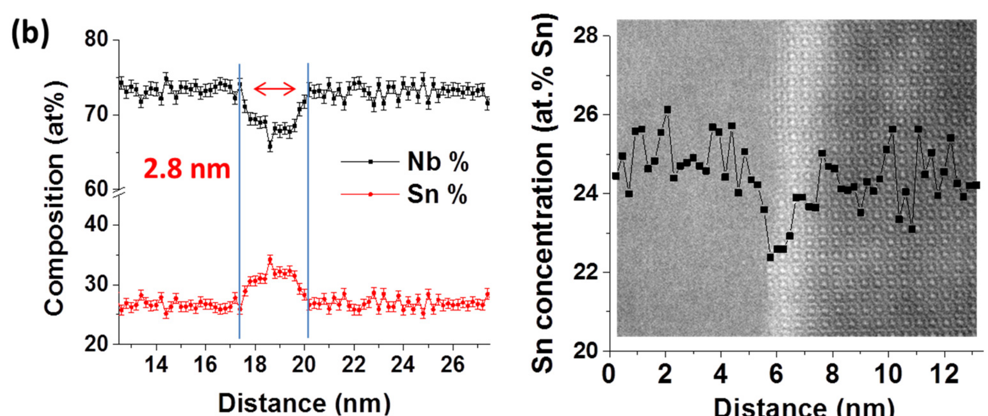


Defects to Avoid in Nb_3Sn – Tin Segregation in GBs

- Witness samples coated with cavities with Q-slope analyzed by TEM and APT show tin segregation in grain boundaries with size ~ξ
- Avoidable defect: clean GBs observed in samples from cavities with strong performance
- **[J.-Y. Lee et al. SRF'19 MP008; arXiv:1907.00476]**, studies of impact on superconductivity in progress as part of CBB



Atom probe tomography (APT) tip preparation and analysis



Poor performance coating showing tin segregation at GB

High performance coating showing minor Sn depletion

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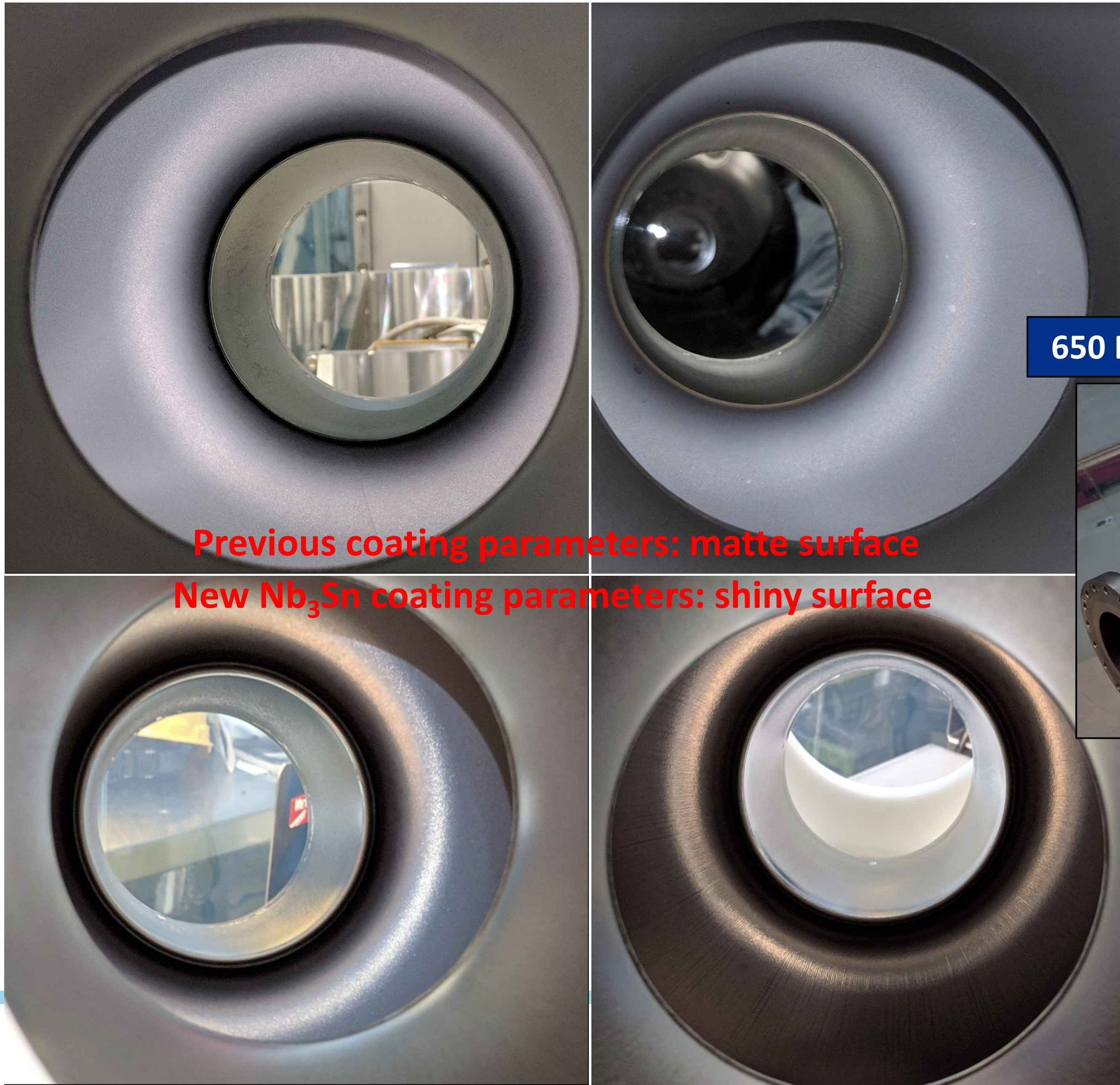
3. **Progress in Demonstrating Practicality of Nb_3Sn Cavities**

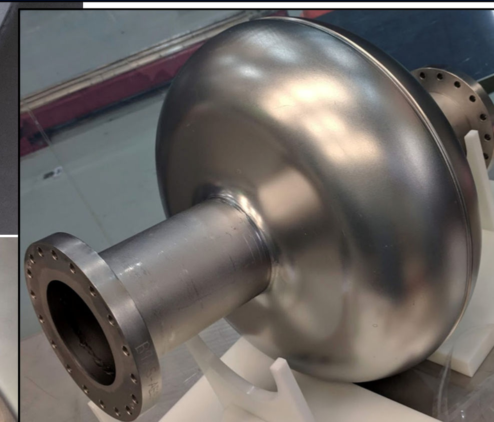
Can We Successfully Coat at Frequencies <1 GHz?



Previous coating parameters: matte surface

New Nb_3Sn coating parameters: shiny surface

650 MHz cavity B9AS-AES-002



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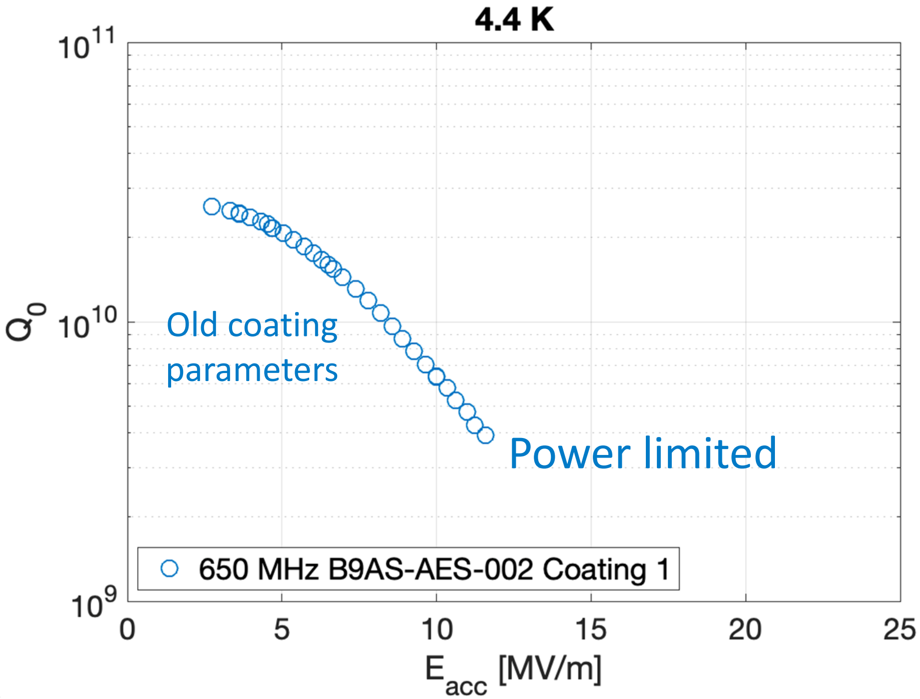
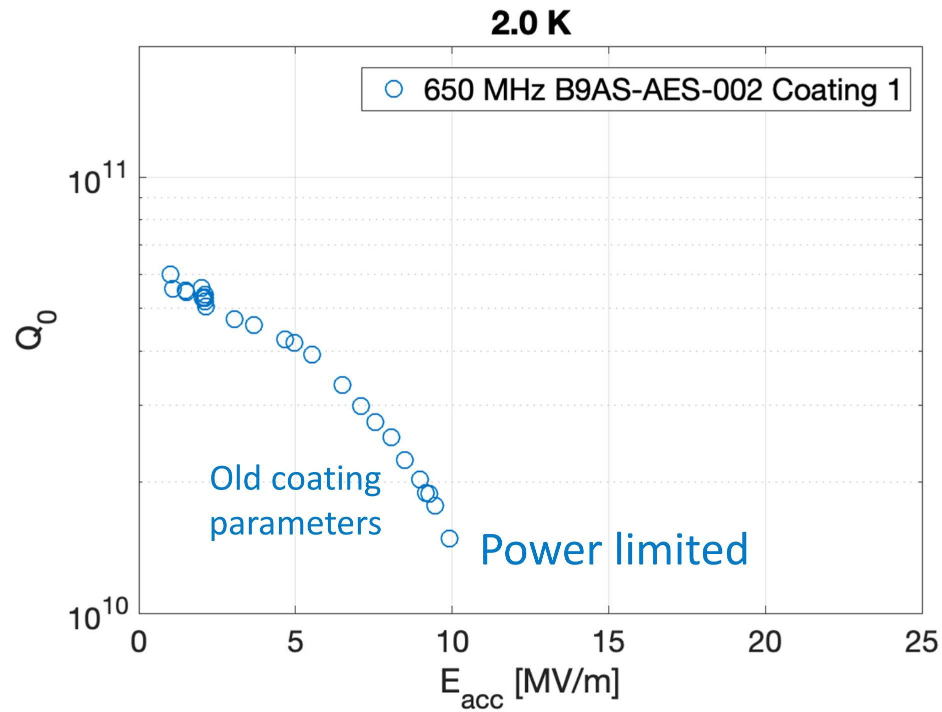
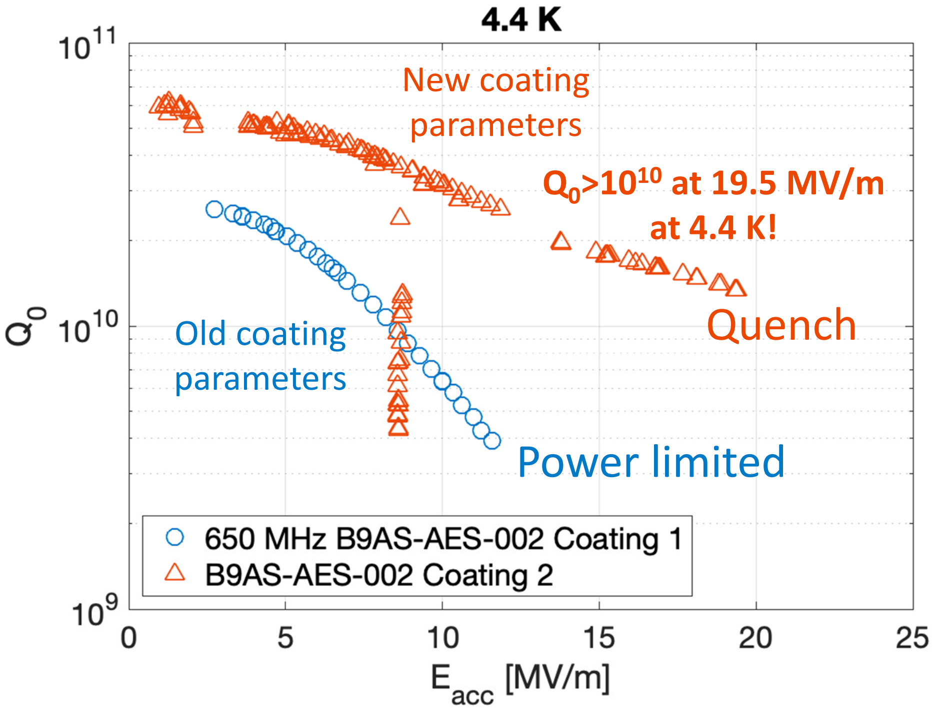


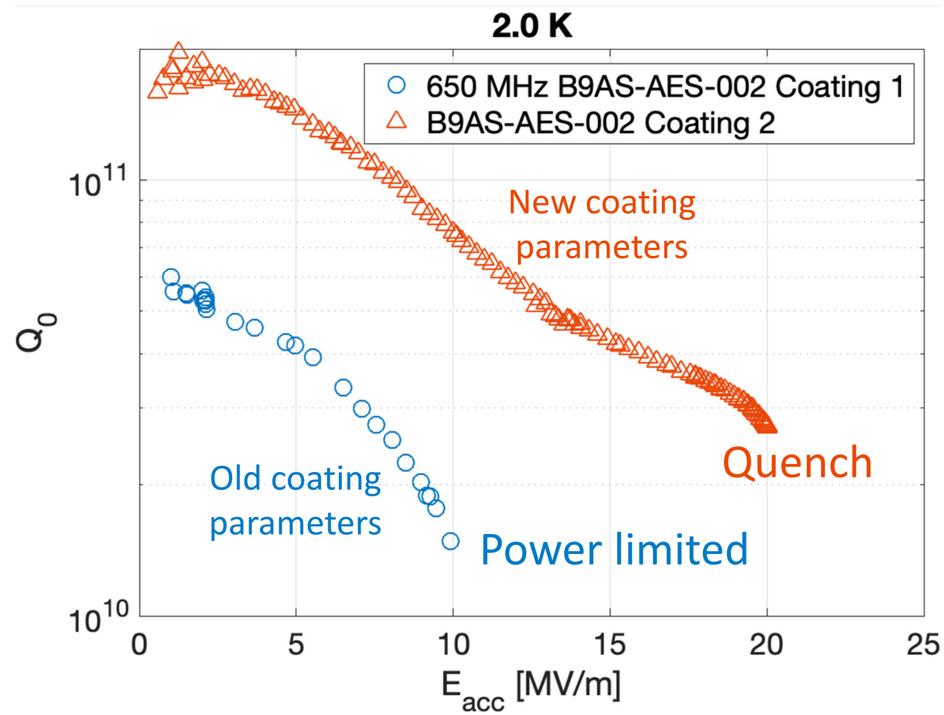


Blue: results presented at TTC2019

Can We Successfully Coat at Frequencies <1 GHz?

650 MHz cavity B9AS-AES-002





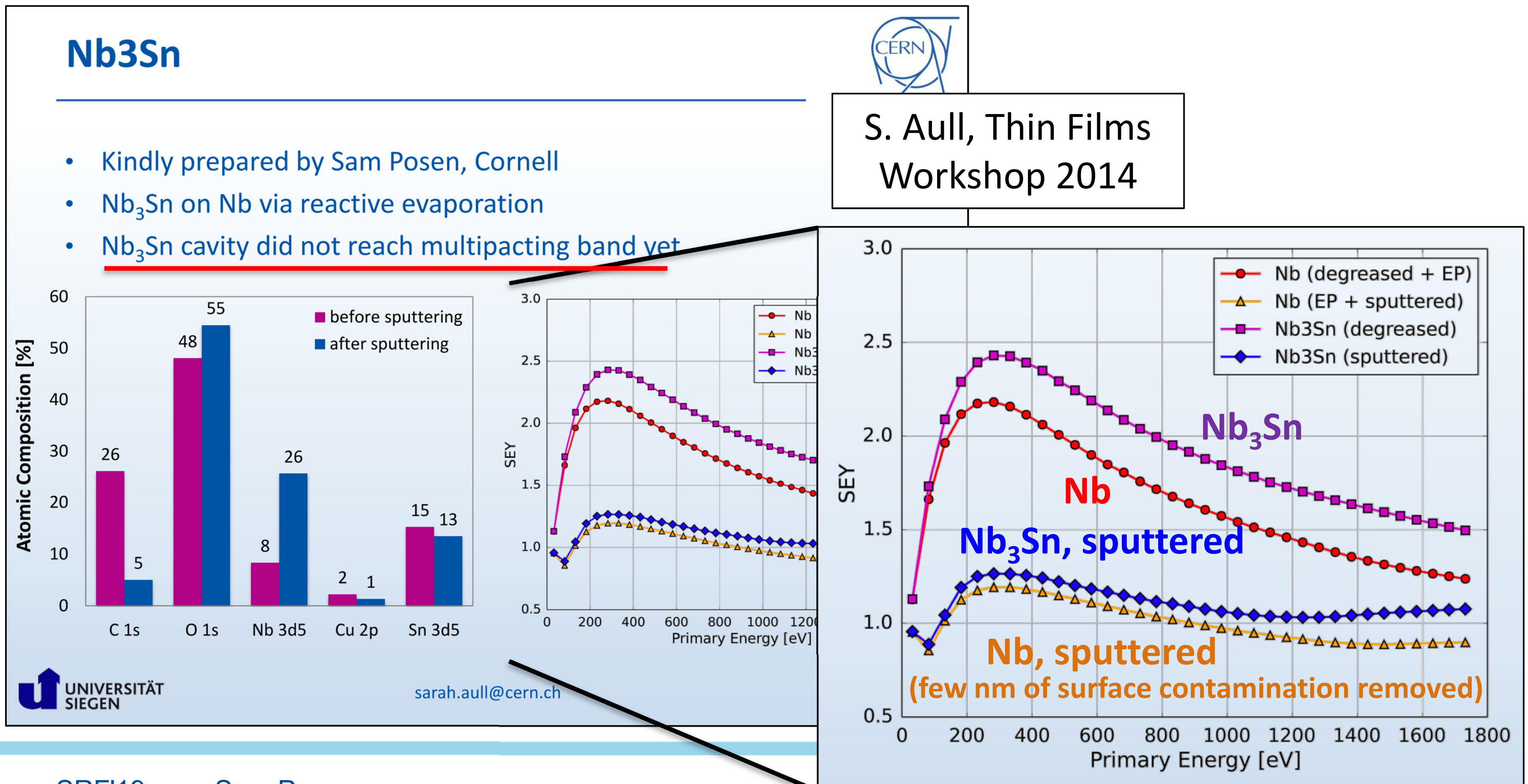
Blue: results presented at TTC2019

Yes, we can successfully coat a 650 MHz cavity

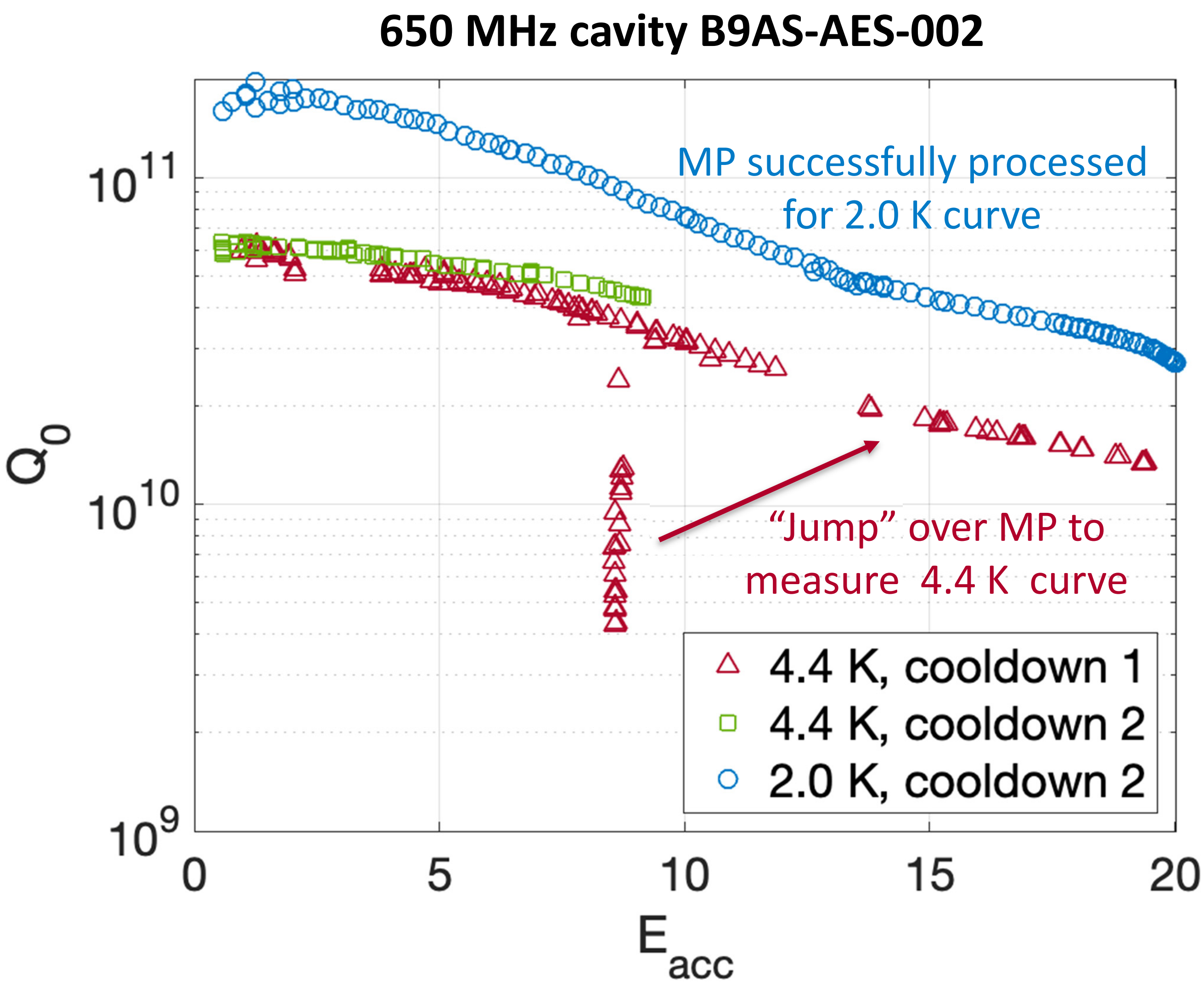
Red: new results with shiny coating

Can We Process Multipacting on Nb_3Sn Surfaces?

- Can we reduce SEY sufficiently on Nb_3Sn surfaces? We have seen baking degrade performance. And quenching causes trapped flux. Can we process without baking or quenching?



Can We Process Multipacting on Nb_3Sn Surfaces?



Yes, we can successfully process multipacting

Can We Tune a Cold Nb_3Sn Cavity?

- Nb_3Sn is a strain sensitive superconductor
  - E.g. Nb_3Sn wires must be pre-stressed so that they are closer to neutral loading at max field
- We strain our cavities in operation! What is the effect of frequency tuning?
- How does this affect our cavities? Residual resistance? BCS resistance? Max field?

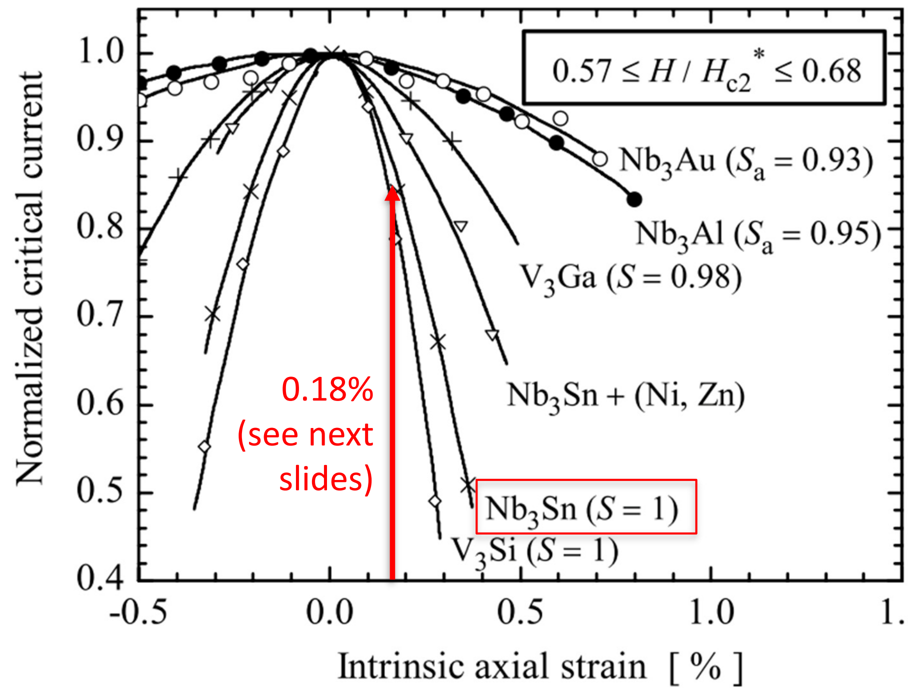
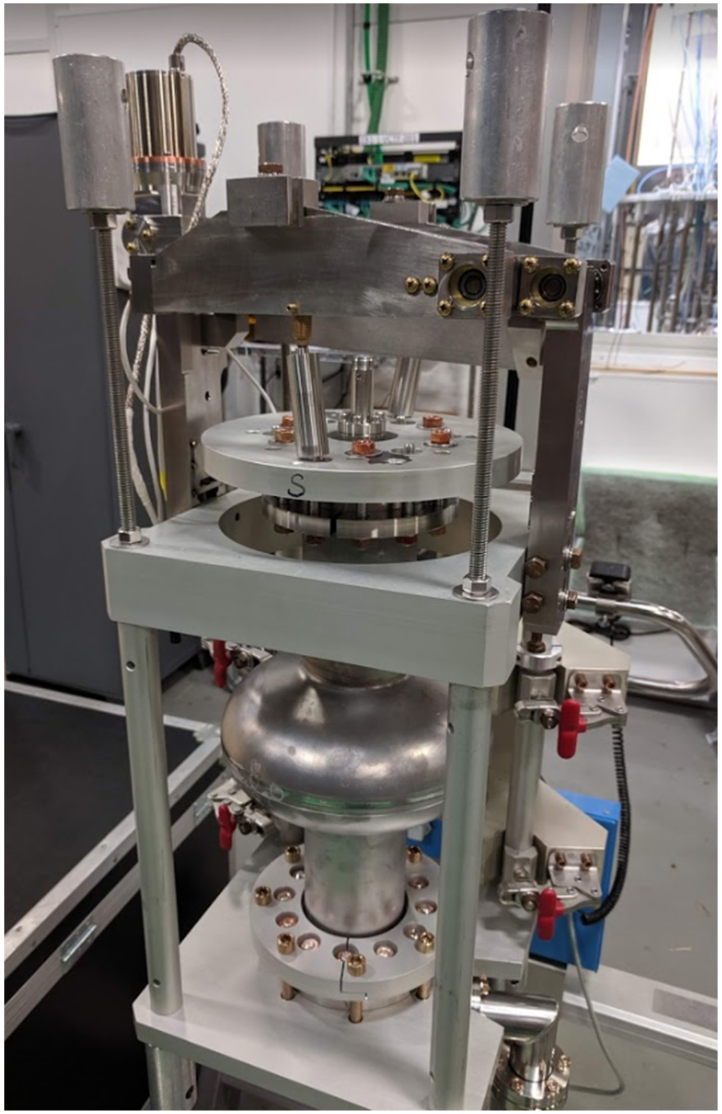
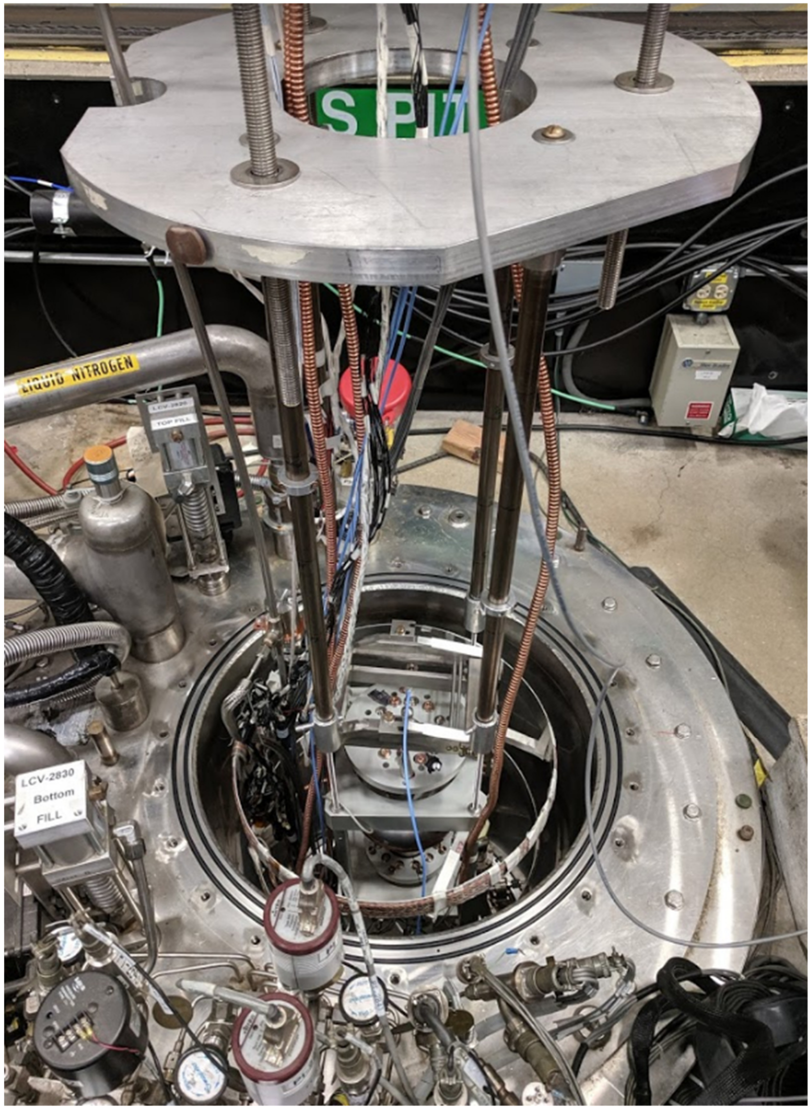


Figure 11. Strain sensitivity of the critical current for different A15 superconductors with varying amounts of disorder, after Flükiger *et al* [26] (*©1984 Plenum Press. Adapted with kind permission of Springer Science and Business Media and R Flükiger*).

A Godeke 2006 *Supercond. Sci. Technol.* **19** R68

Can We Tune a Cold Nb_3Sn Cavity?



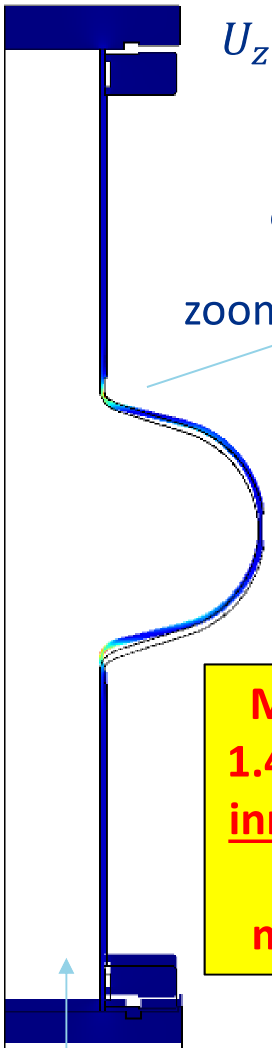


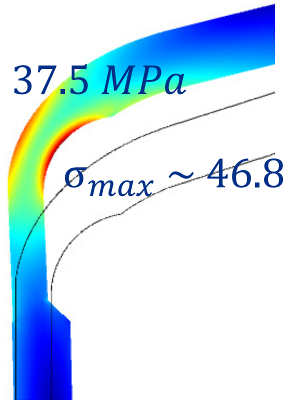
Special thanks to Y. Pischalnikov and J.-C. Yun

Expected Maximum Surface Strain

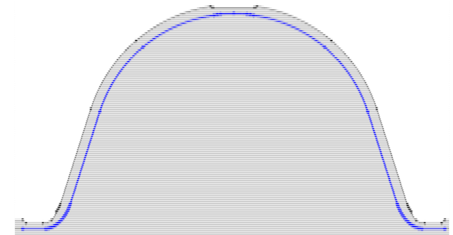
2K	ΔF, KHz	F, N
fixed/100 µm	230	2310

Stress&strain along inner surface (blue lines)

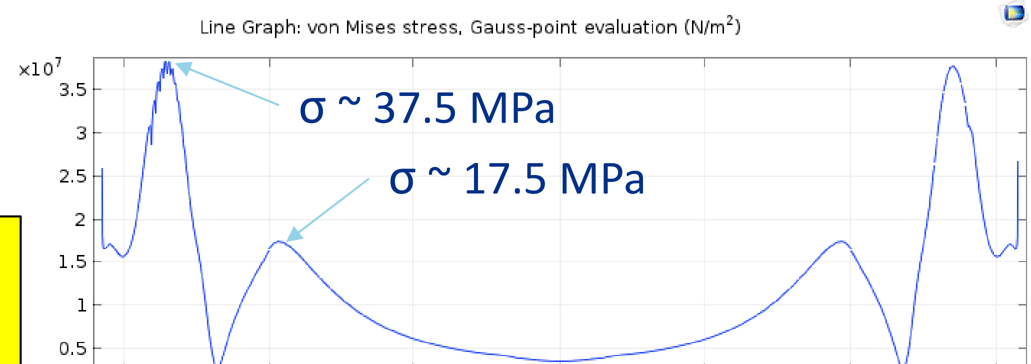


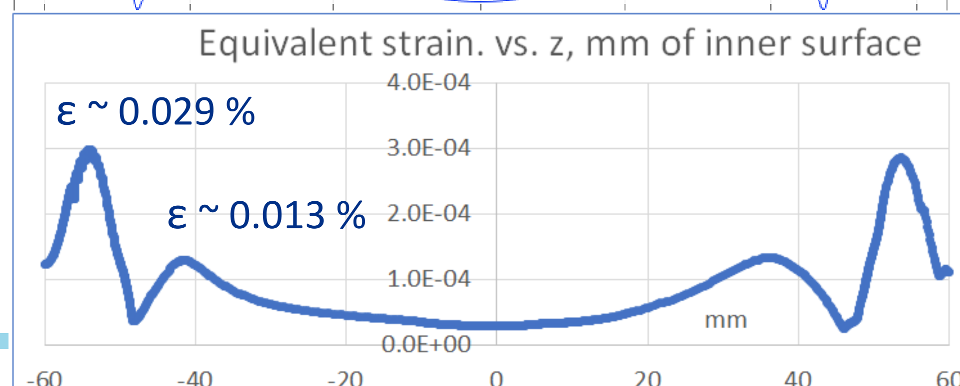


Max range of tuner is 1.4 MHz: Peak strain on inner surface ~0.18% at iris, ~0.08% in high magnetic field region

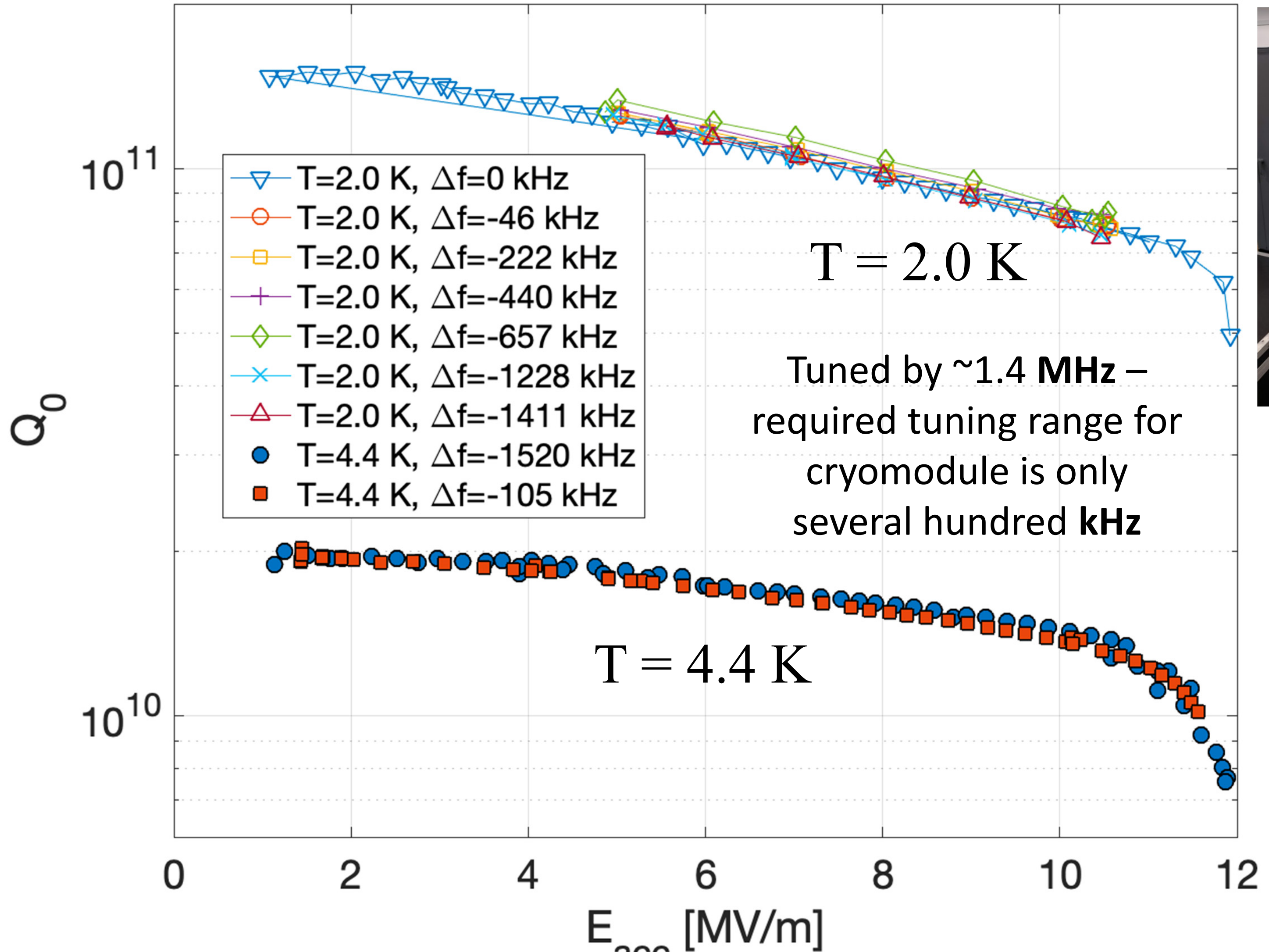


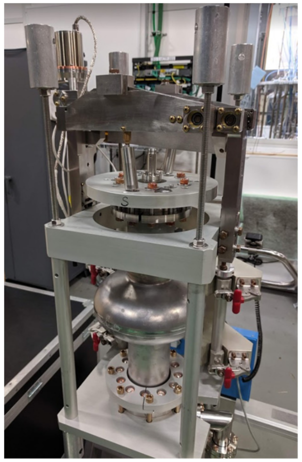
Simulations by Timergali Khabiboulline and Ivan Gonin





Can We Tune a Cold Nb_3Sn Cavity?

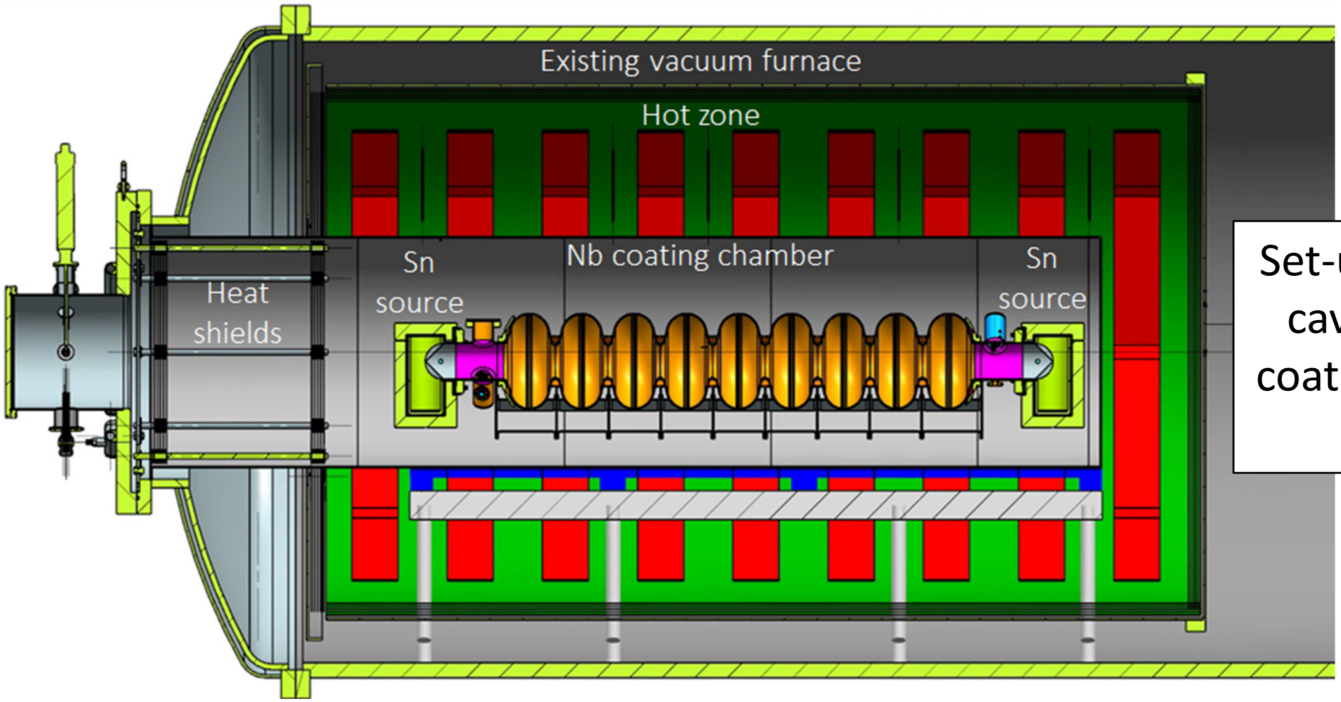




Yes, we can tune a cold Nb_3Sn cavity without degrading R_{res} or R_{BCS} — at least up to the fields measured

Can We Successfully Coat an Accelerator-Style Structure?

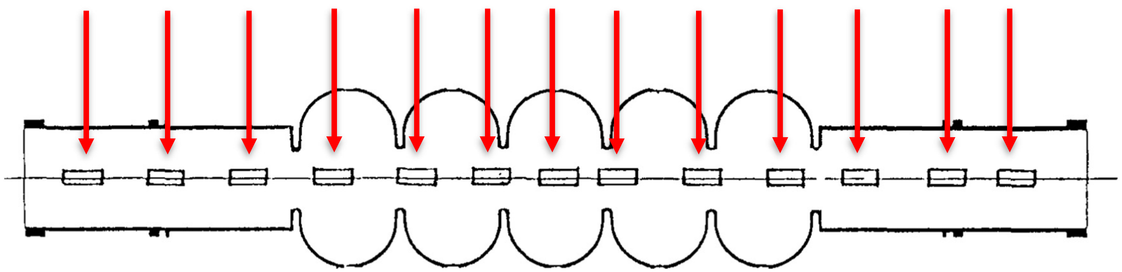
- Showing a strong performance in our most widely applied structure would be a fantastic milestone
- We decided to coat a real 9-cell ILC cavity, including all its features that are tricky for coating (e.g. HOM cans and F-hooks, NbTi flanges and conical end-dishes)



Set-up of a 9-cell ILC cavity in Fermilab coating furnace (two tin sources)

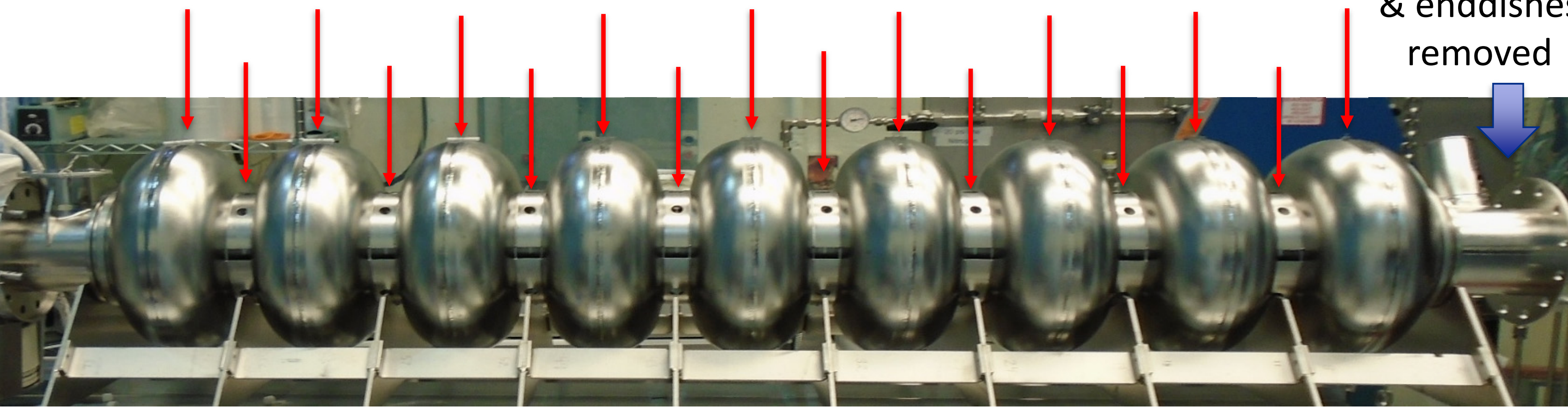
Preparation: Nb_3Sn 9-Cell Sample Host Cavity

Major thanks to Argonne team for figuring out how to chemically treat this unusual cavity!!



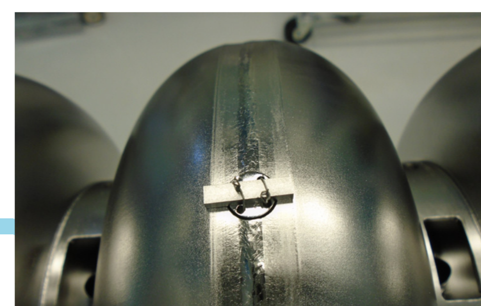
U. Wuppertal - 3 GHz 5-cell, 13 samples located along axis

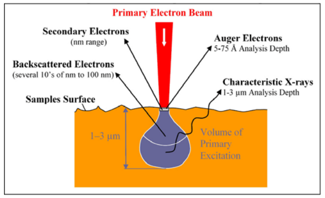
NbTi flanges & enddishes removed



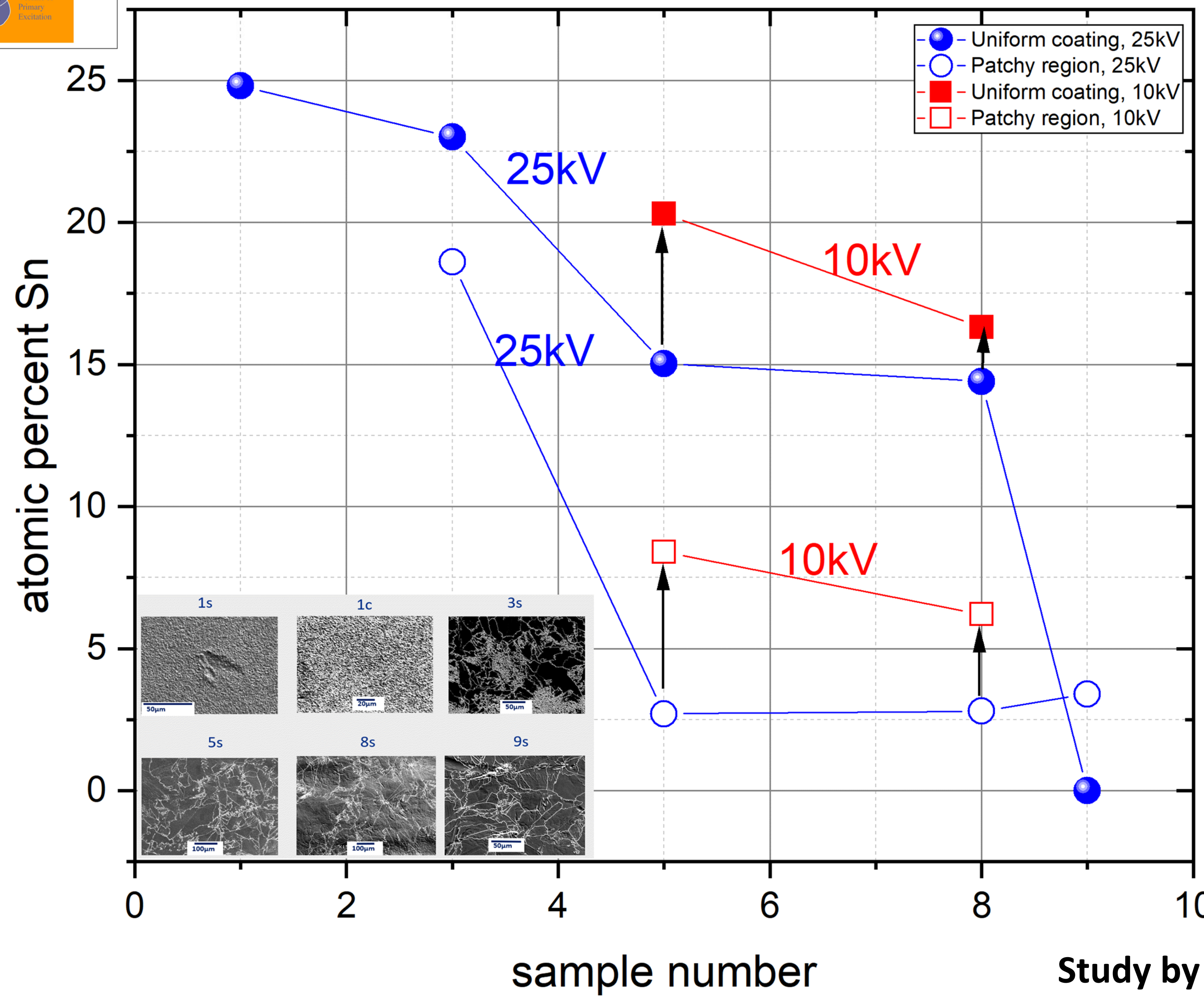
Fermilab - 1.3 GHz 9-cell, 17 samples located at equators and irises

(no useful cavities were harmed in the making of this study… cavity that was cut had very bad weld defect)





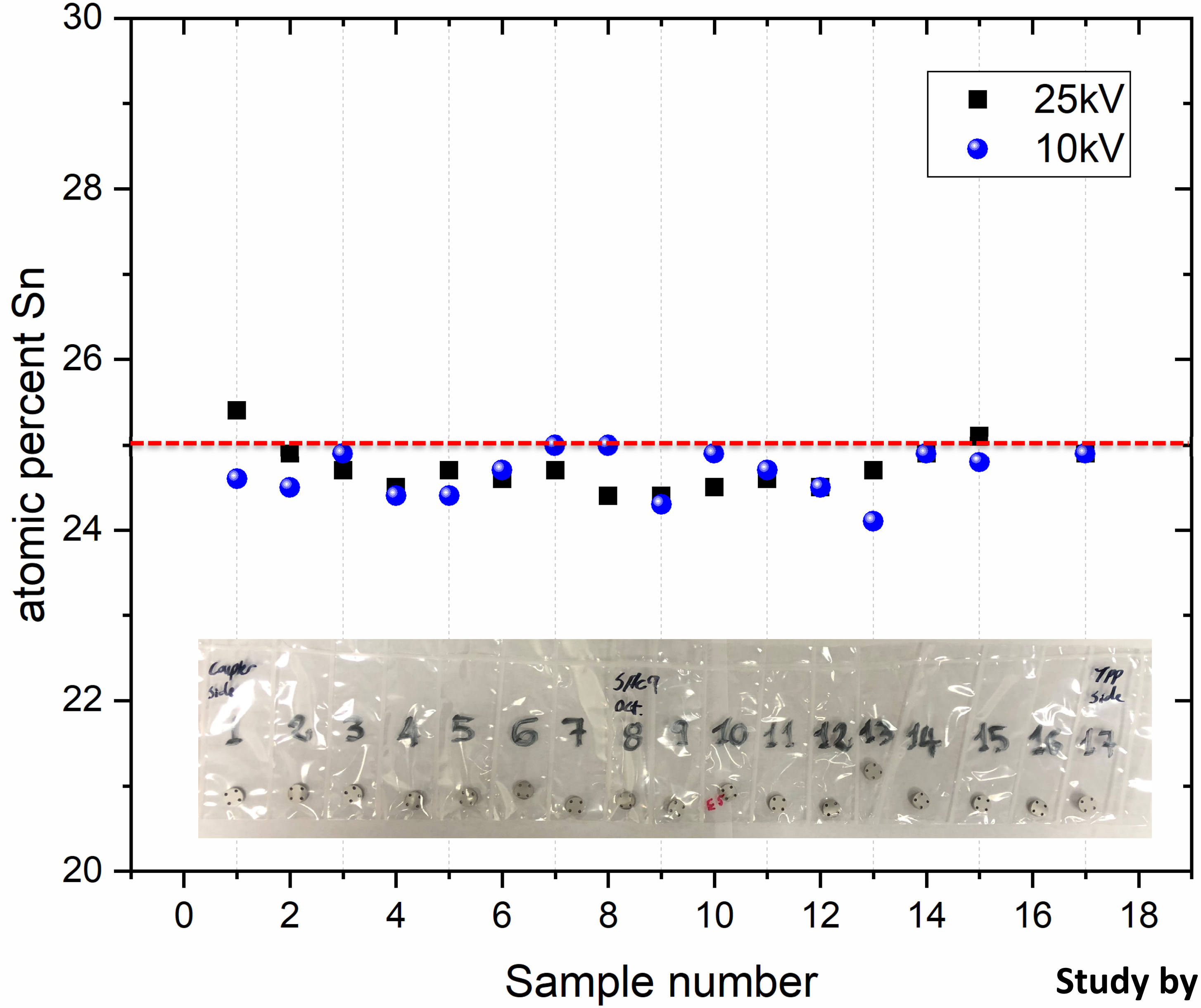
Sample Host 1st coating: One Sn source



Study by T. Spina
see MOP059

Sam Posen

2nd Coating, Two Tin Sources



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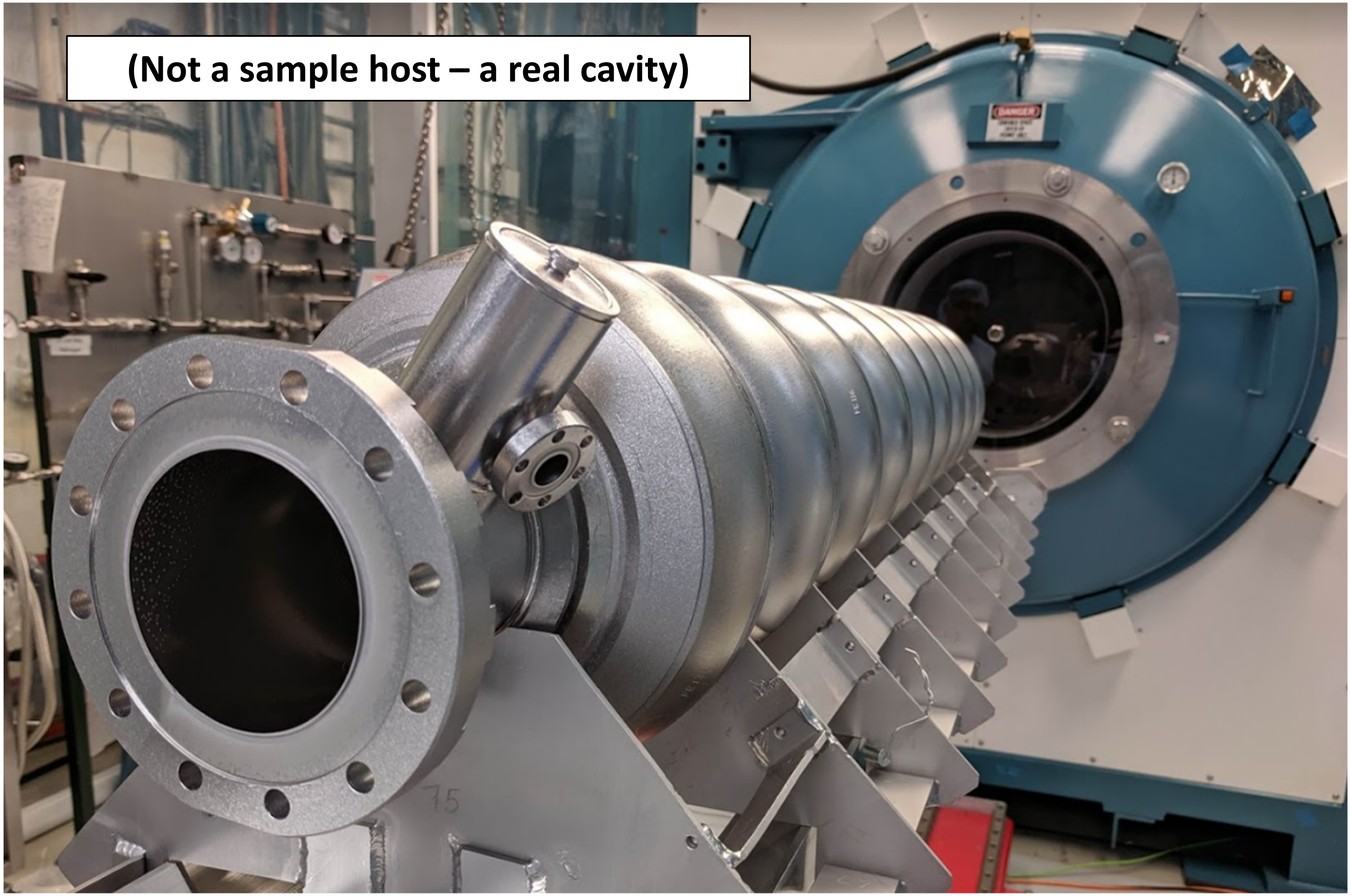
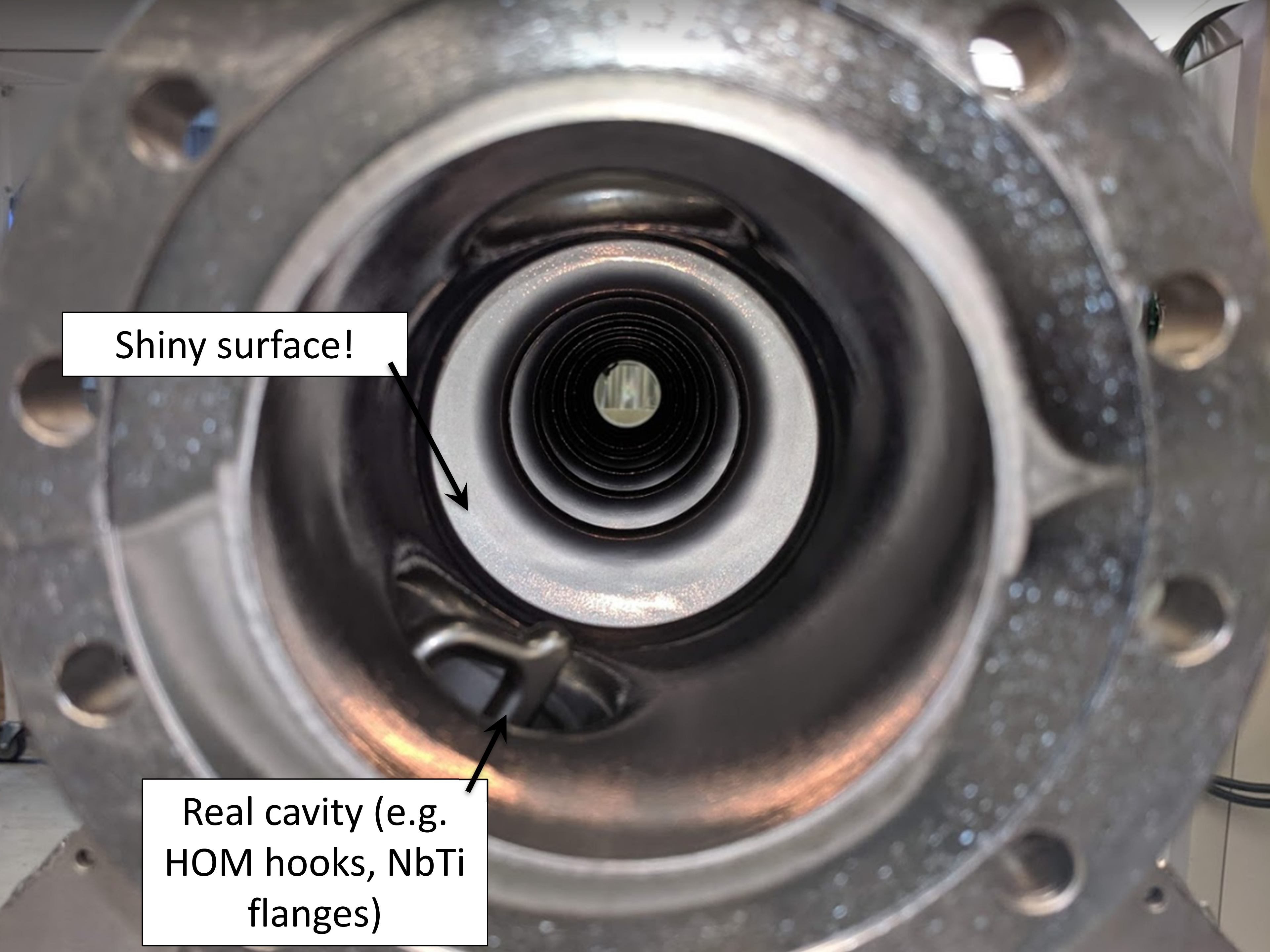
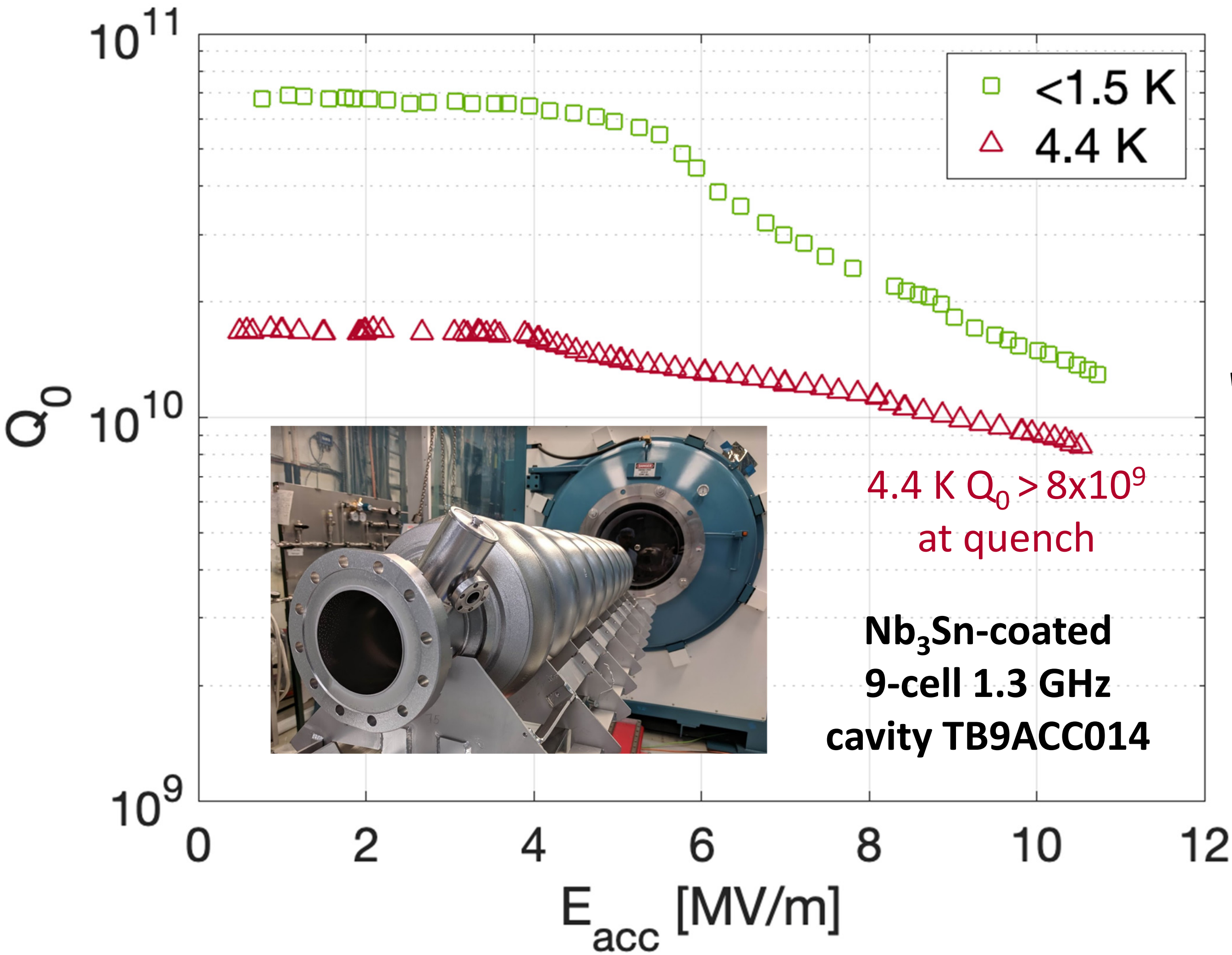
9-cell Cavity TB9ACC014 After Coating



Fermilab


Shiny surface!
Real cavity (e.g. HOM hooks, NbTi flanges)

Can We Successfully Coat an Accelerator-Style Structure?



Cavity was not field flatness tuned nor was flatness checked prior to test. Cavity will be tested again after these steps.

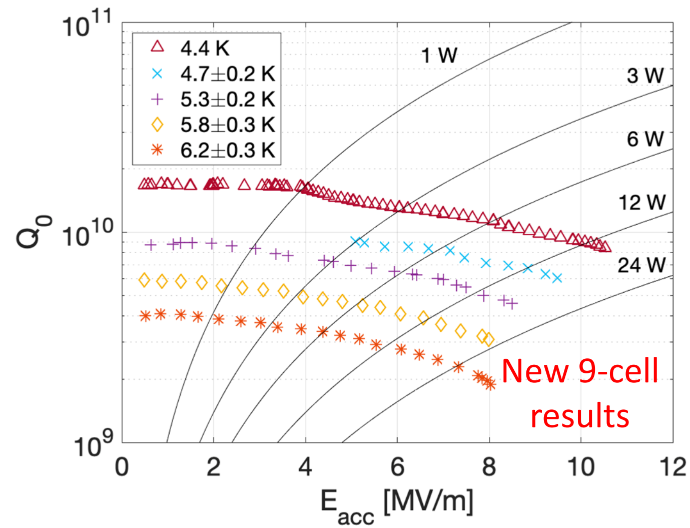
Includes correction for stainless steel flanges 2x0.8 nΩ

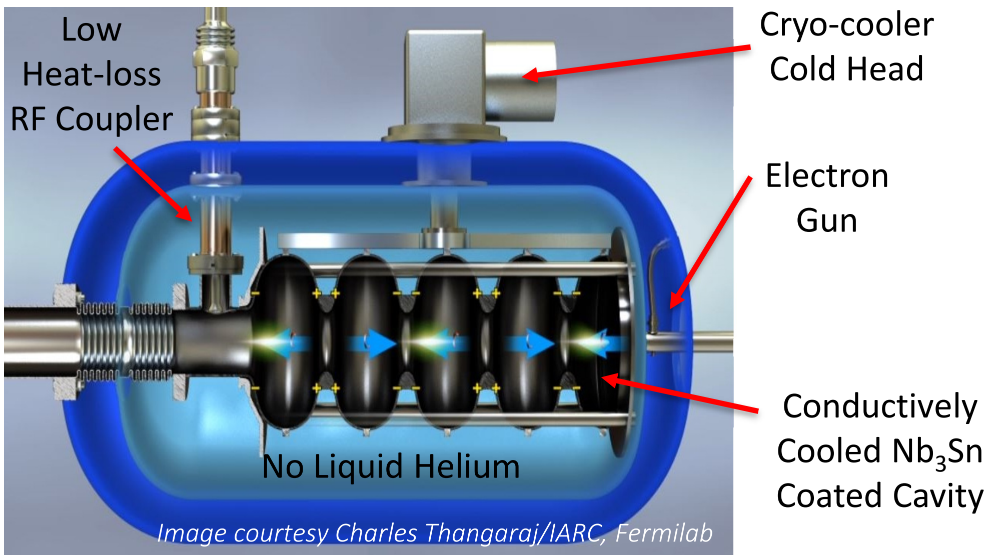
Excellent performance in a practical accelerator structure – record accelerating voltage ~10 MV in Nb_3Sn cavity

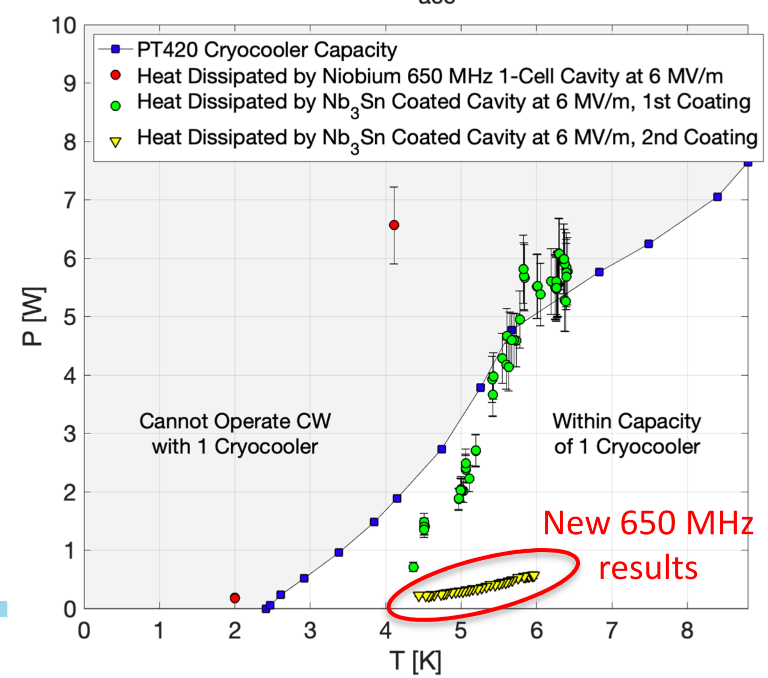
Time for Compact SRF Accelerators via Nb_3Sn!

- With the significant progress in Nb_3Sn, it is time to seriously think about a new class of CW compact high power industrial-class SRF accelerators enabled by watt-scale dissipation at T > 4 K with Nb_3Sn (cryocoolers!)
- Many applications to explore (wastewater, isotopes, hospitals, compact light source…)
- Fermilab/IARC ~10 MeV accelerator with conduction cooling in active development

VTS measurements at T >4.4 K in He gas

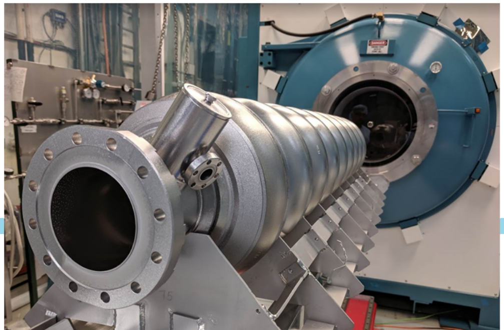






Summary

- New Nb_3Sn film development: lower surface roughness, thinner films
- Experiments help us understand defects to avoid in Nb_3Sn
- Excellent progress in demonstrating practicality of Nb_3Sn cavities
  - We showed that we can coat at 650 MHz and achieve $Q_0 > 10^{10}$ at 20 MV/m at 4.4 K
  - We showed that we can process multipacting if needed
  - We showed that we can tune a cold cavity without degradation
  - We showed that we can coat an accelerator-style structure and achieve the kind of performance needed for compact accelerator applications



Acknowledgements

- Dedicated efforts of Brad Tennis
- SRF processing team at FNAL and ANL, FNAL VTS testing team, FNAL machine shop and welding experts
- FNAL resonance control team for tuner setup
- Division & lab management for strong support and creating an environment where this type of R&D can thrive
- Fruitful collaboration with D.N. Seidman and J.-Y. Lee at Northwestern University
- Pioneers in Nb_3Sn SRF coatings (including Siemens, Wuppertal, KfK)
- Helpful discussions with Alex Romanenko, Anna Grassellino, Sergey Belomestnykh, Hasan Padamsee, Curtis Crawford, Matthias Liepe, Grigory Eremeev, Daniel Hall, Ryan Porter, Uttar Pudasaini, and the FNAL SRF science team
- Support from US DOE Office of High Energy Physics with partial support from ERDC