Efforts Towards First Applications of Nb_3Sn SRF Cavities

Sam Posen

SRF Conference 2021

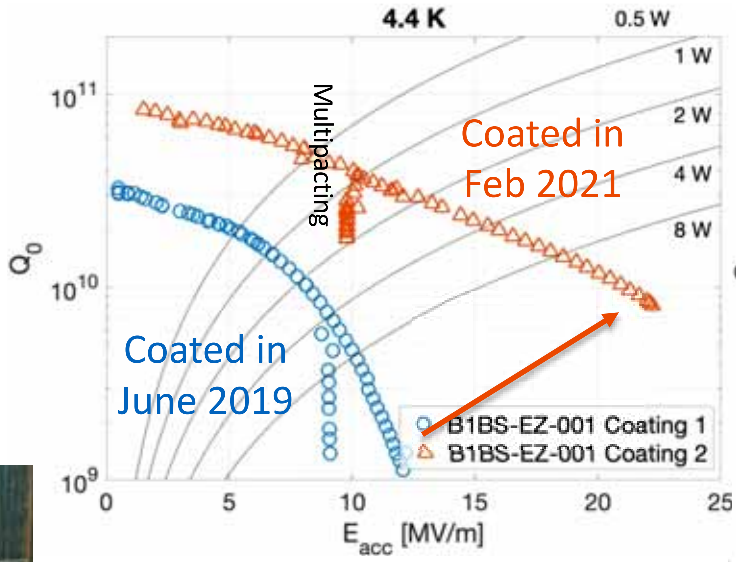
2 July 2021

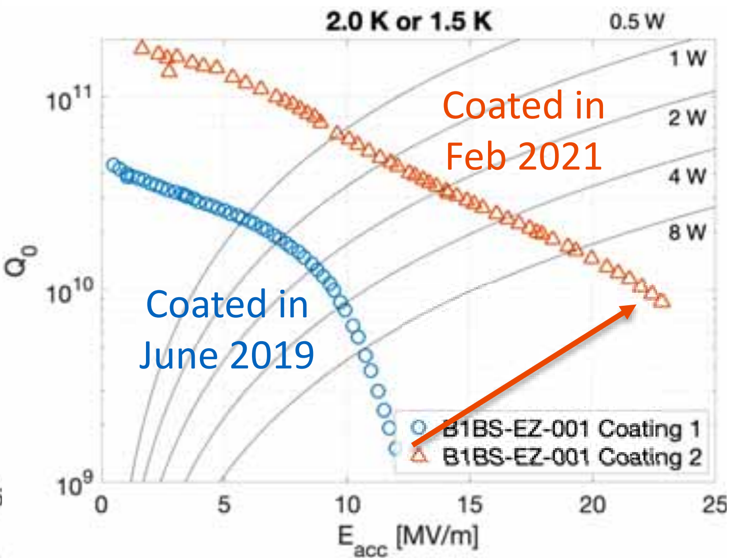
1. **Details of Conduction Cooling Progress at Fermilab**
2. Multicell Nb_3Sn Cavities
3. Multi-Tesla B-Field Cavities
4. Cavity Coating Facility Development
5. Nb3SnSRF'20

See also Gigi Ciovati's talk from Wednesday!

New Coating of Conduction Cooling Cavity

- Removed from cond. cooling setup for second coating attempt
- Substantial performance improvement



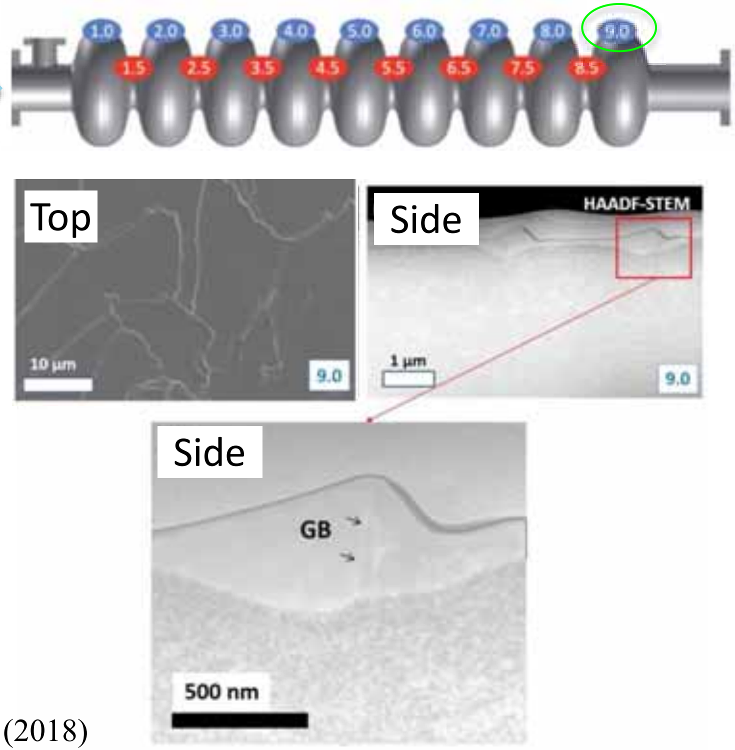


- Suspected cause for Q-slope degradation was thin regions
- Added extra $SnCl_2$ nucleation agent relative to previous coating to attempt to improve uniformity

Thin Regions Occur When Tin Flux is Low

- Proposed mechanism: interfacial energy dominates when layer is very thin during early growth – encourages epitaxy if time duration is too long
- Possibly explanation for previous results, including degradation observed at Wuppertal but not Cornell – if the tin flux was too low at Wuppertal (e.g. they discuss 10s of hours long coatings)

One Sn-source coating





T. Spina et al. *Supercond. Sci.* 34 (2020)

J. Lee et al. *Supercond. Sci. Tech.* 32 (2019)

Y. Trenikhina et al. *Supercond. Sci. Tech.* 31 (2018)

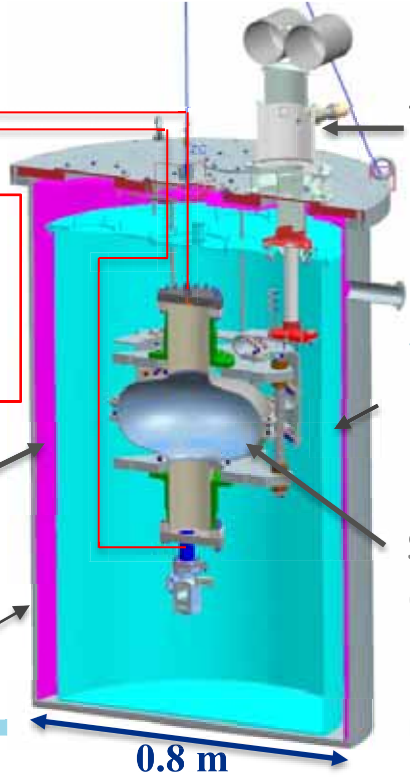
Fermilab

Fermilab conduction-cooled SRF cavity measurement setup

R.C. Dhuley *et al.*, ***IOP Conf. Ser.: Mat. Sci. Eng.***, 2020. https://doi.org/10.1088/1757-899X/755/1/012136
R.C. Dhuley et al., ***IEEE Trans. Appl. Supercond.***, 2019, https://ieeexplore.ieee.org/abstract/document/8651336
R.C. Dhuley, M.I. Geelhoed, J. Thangaraj, ***Cryogenics***, 2018, https://doi.org/10.1016/j.cryogenics.2018.06.003

Euclid Techlabs

RF system
- 10 W cw @ 650 MHz, 1.3 GHz
- Resonance locking
- P_f, P_r, P_t, τ_L measurements



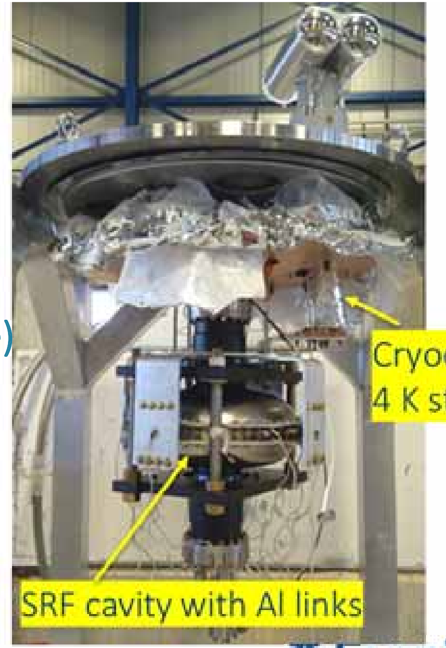
Two-stage cryocooler
- 55 W @ 45 K
- 2 W @ 4.2 K

Thermal shield
(cooled by the 45 K stage)

Magnetic shield
(<15 mG)

SRF cavity with Al link
(cooled by the 4 K stage)

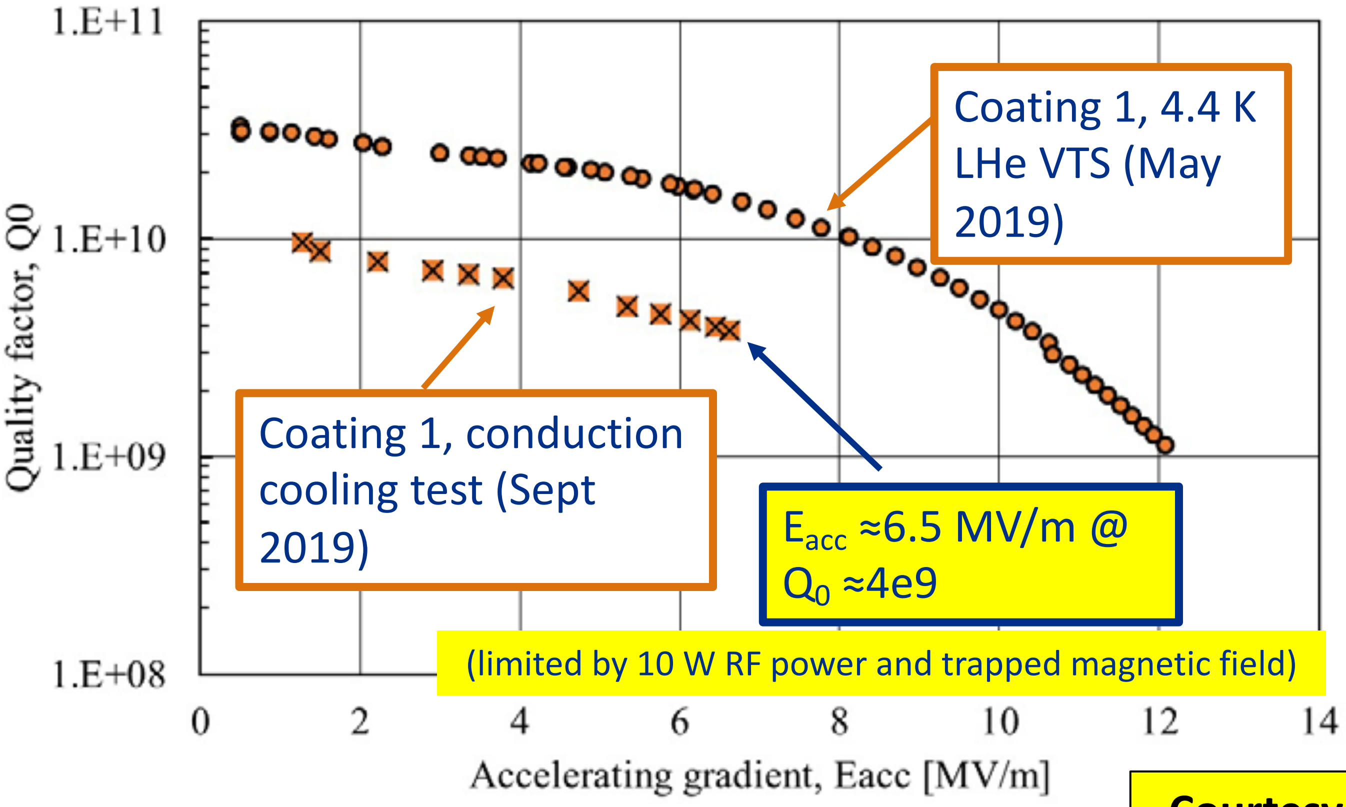
Vacuum vessel

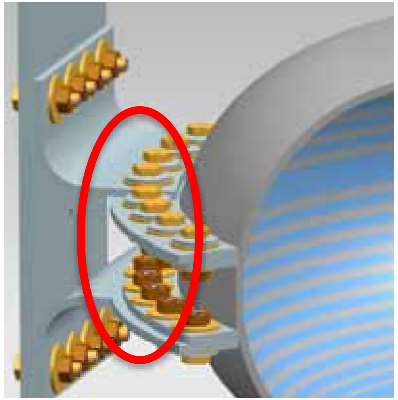


Courtesy Ram Dhuley, Fermilab

Results from 2019: E_{acc} vs. Q_0 for Nb_3Sn coated single cell 650 MHz SRF cavity

R.C Dhuley, S. Posen, M.I. Geelhoed, O. Prokofiev, J.C.T. Thangaraj, ***Supercond. Sci. Technol.***, 2020.
https://doi.org/10.1088/1361-6668/ab82f0

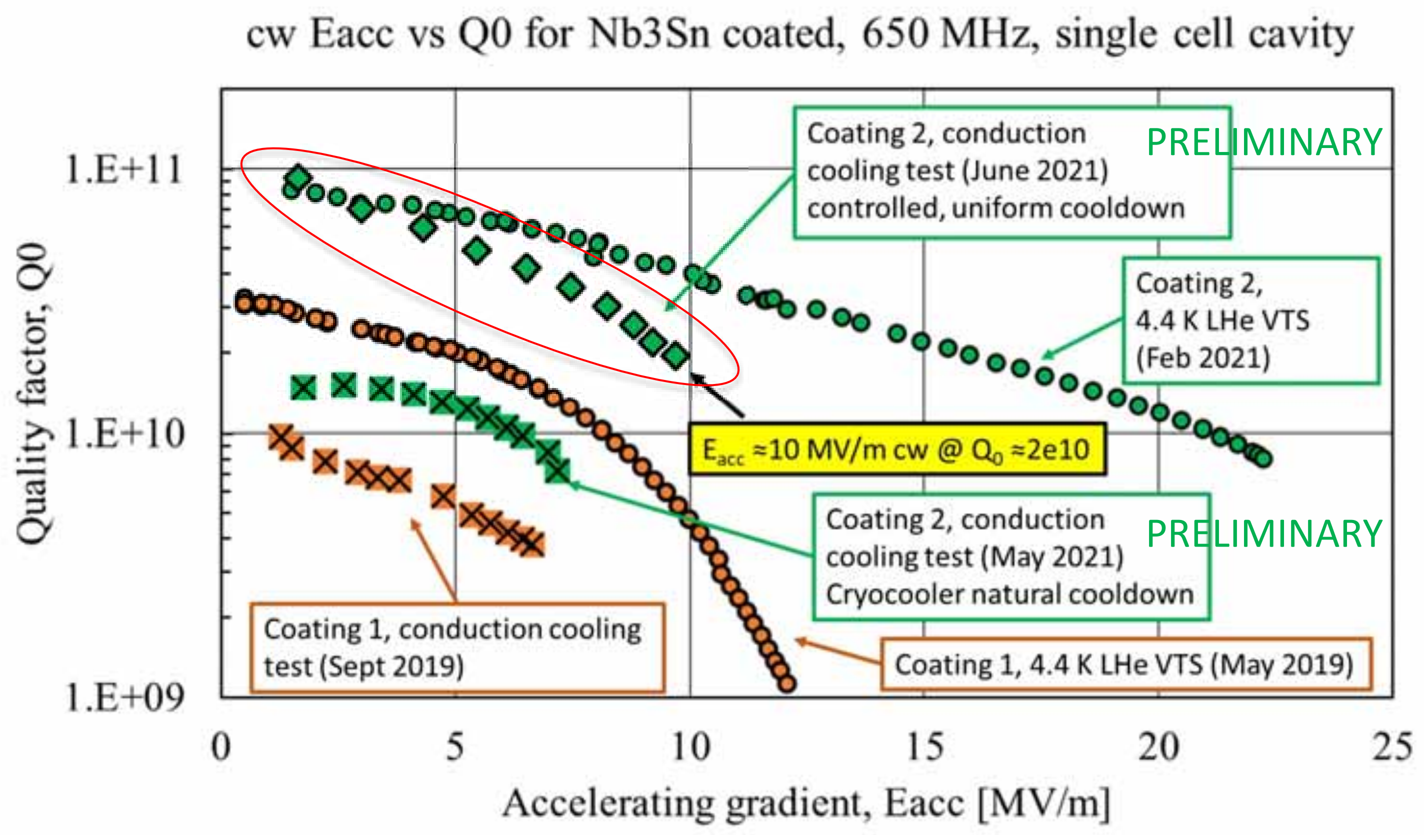




disc springs ~1 G led to large flux trapping

Courtesy Ram Dhuley, Fermilab

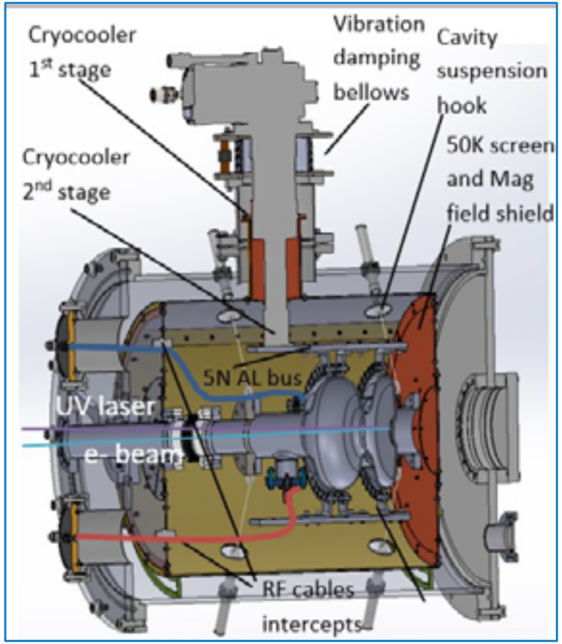
June 2021: the cavity attained ~10 MV/m cw @ Q0 ≈2e10 with conduction cooling



Courtesy Ram Dhuley, Fermilab

Conduction Cooled Nb_3Sn Application Effort: UED

- Led by Euclid, with FNAL and BNL partners, funded by DOE BES SBIR program
- Ultra-compact & -efficient ultrafast electron diffraction
- Cavity BCP'd at Argonne, now being prepared at Fermilab for vertical test in next weeks, then Nb_3Sn coating + test



euclid BEAMLABS Fermilab BROOKHAVEN NATIONAL LABORATORY

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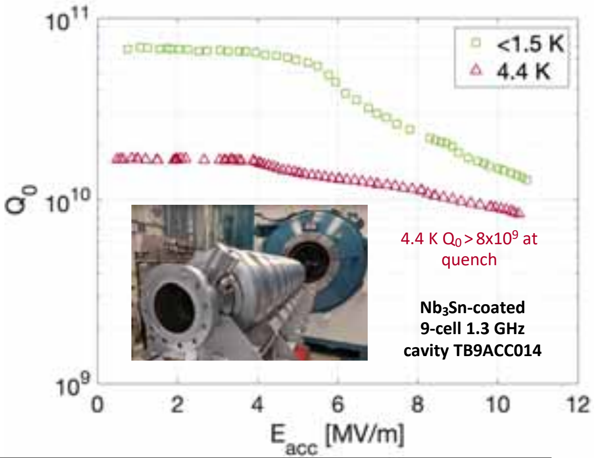
2. **Multicell Nb_3Sn Cavities**
3. Multi-Tesla B-Field Cavities
4. Cavity Coating Facility Development
5. Nb3SnSRF’20

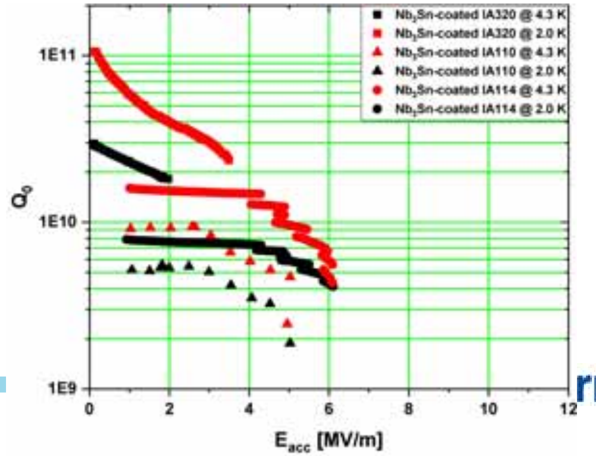
From SRF 2019 and Before

- First coatings of 1.3 GHz 9-cell (S. Posen et al., Fermilab) and 1.5 GHz 5-cell (G. Eremeev et al., JLab) cavities
- Achieving 5-10 MV/m in vertical test – useful accelerating fields!
- Exciting progress in cavity structures typical for accelerator applications

S. Posen et al., THFUB1

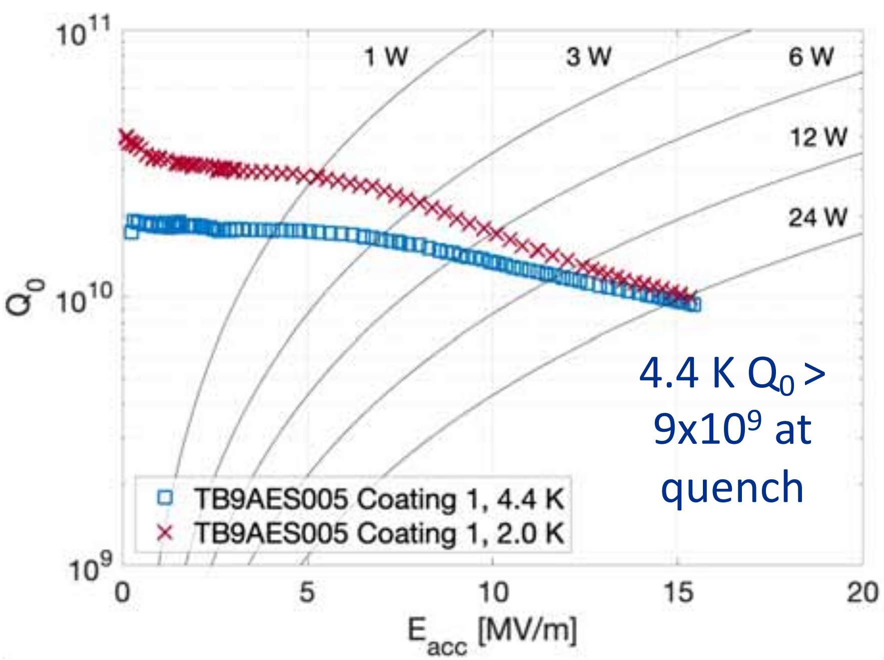


G. Eremeev et al., TTC 2018



Progress in 9-cell Nb_3Sn Cavities at Fermilab

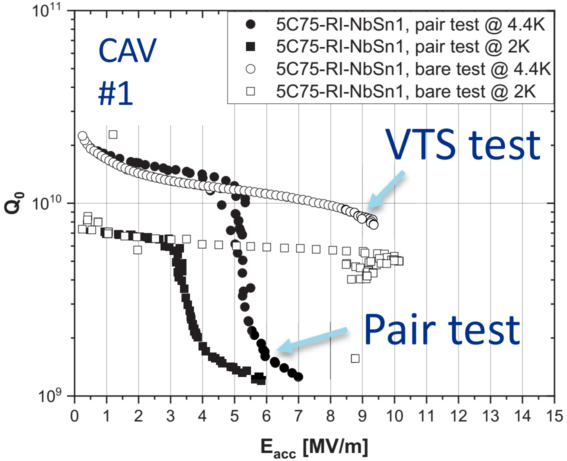
- Improved maximum gradient with high Q_0 out beyond 15 MV/m
- Not every coating is 15 MV/m, but even lowest performing coatings so far reach ~6 MV/m with high Q_0
- Already interesting for lower energy applications, working on reproducibility
- Now working towards horizontal test of 9-cell cavity

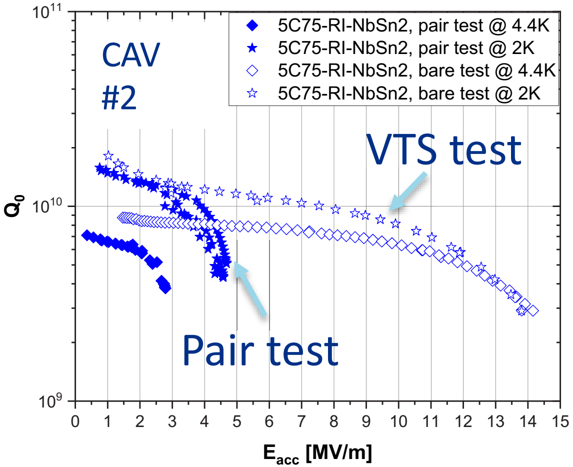


4.4 K Q_0 > 9×10^9 at quench

Fermilab

Push towards Nb_3Sn cryomodule





Record gradients in multicell cavities

Progress in the development of cryomodules with Nb_3Sn-coated multicell SRF cavities

Despite measures taken based on the previous experience, degradation was still observed in both cavities after the pair assembly

The cause of degradation in one cavity could be due to the mechanical deformation, consistent with the phenomenon reported previously [1]; the cause of degradation in the other cavity is under investigation

Studies are ongoing to better understand the cause of degradation and to re-work the cavities and the pair

[1] Eremeev et al, SRF'19

Courtesy Grigory Eremeev, Fermilab

1. Conduction Cooling & Applications
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3. **Multi-Tesla B-Field Cavities**
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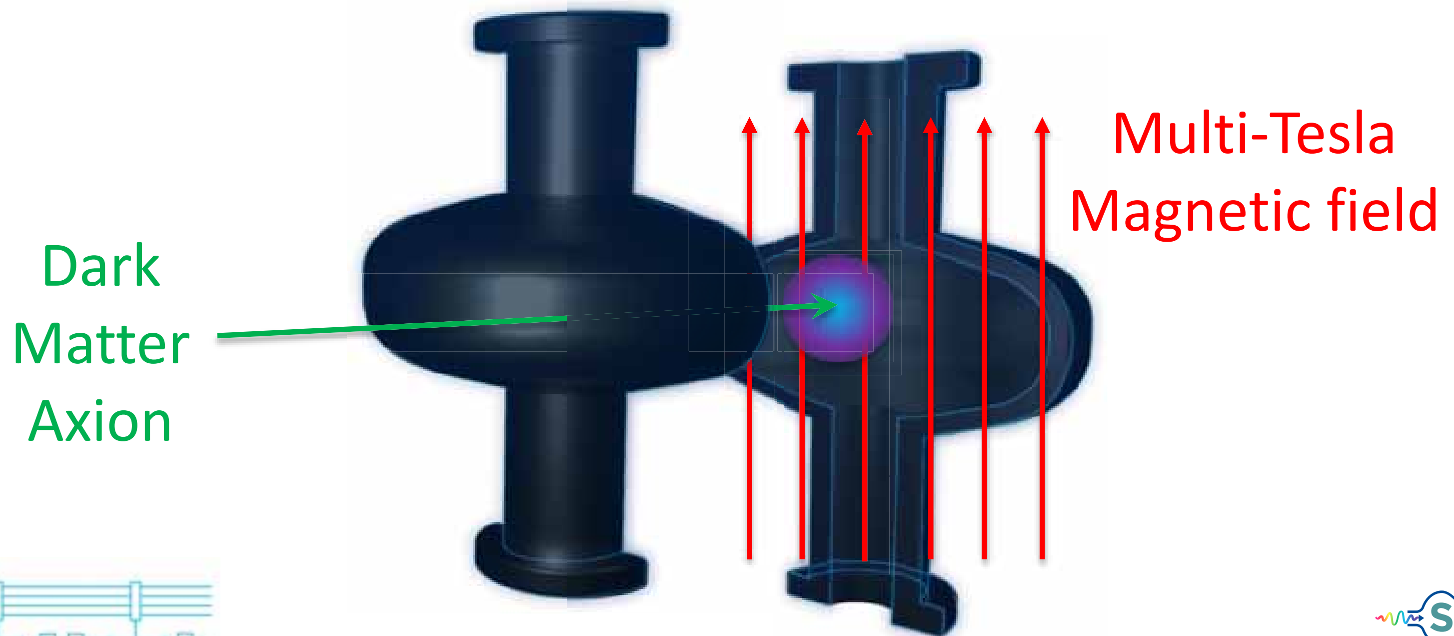
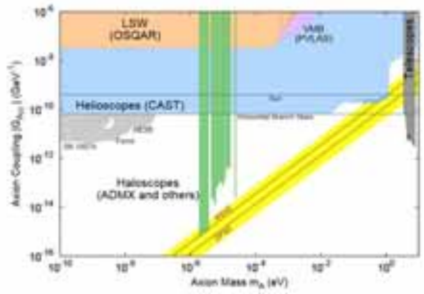
Nb_3Sn SRF for Quantum (part of SQMS Quantum Center)

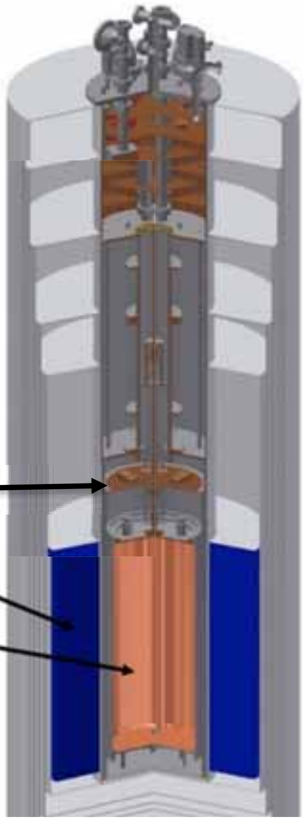
- **Haloscope**: dark matter axion conversion to microwave photon in magnetic field
- Cavity frequency must match axion mass to be sensitive to it
- Sensitivity improves with higher magnetic field, higher cavity Q_0



Current State of the Art Axion Searches

- Operating haloscopes like ADMX use normal conducting cavities (typically copper)
- They have reached desired exclusion limit for a small range of masses, but a very wide mass range remains
- Scan rate scales as $d\nu/dt \propto B^4V^2Q/2T_{sys}$
  - B (magnetic field), V (cavity volume), Q (cavity quality factor), T_{sys} (system noise temperature)
- Q improvement is promising path to improving rate of scanning substantially
- **Nb_3Sn is well suited due to its very high upper critical field, ~30 T** (for comparison: Nb ~0.4 T, NbTi ~15 T)





Dilution fridge

8 T magnet

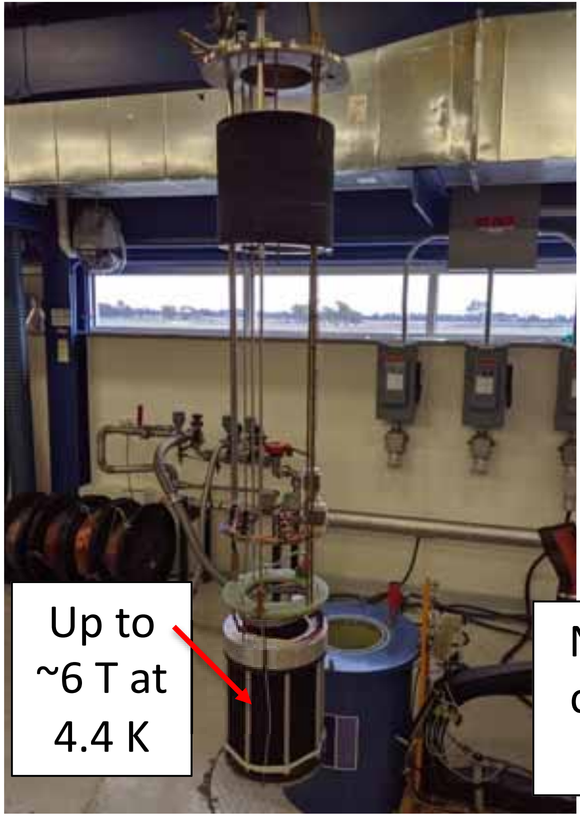
Copper cavity

From ADMX

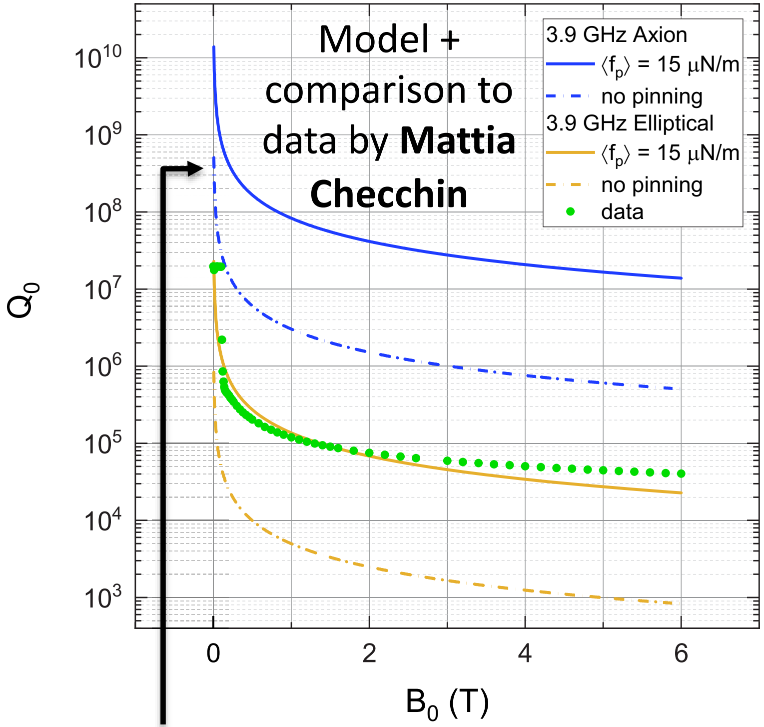
https://arxiv.org/pdf/1405.3685.pdf & https://indico.cern.ch/event/606690/contributions/2655459/attachments/1498473/2332791/Axion_Overview_TAUP_2017_Final.pdf

Evaluation of Nb_3Sn for Haloscopes

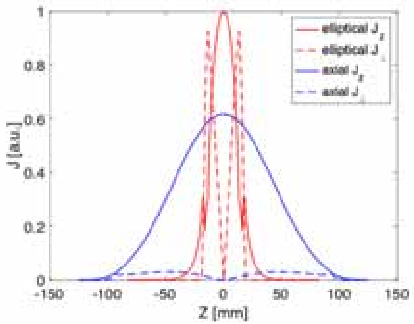
- First evaluation of Nb_3Sn SRF cavity in vortex state – test on 3.9 GHz cavity coated as part of accelerator R&D
- Use existing test stand typically used to evaluate magnet wires at multi-telsa fields
- In parallel, fabricated cavity with improved geometry for operating in magnetic fields

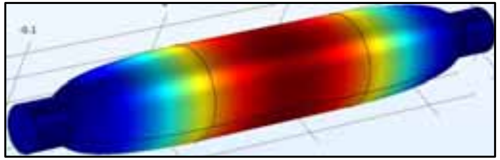


SRF Cavity in Multi-Tesla B-fields for Axion Searches



- Data from initial experiments with 3.9 GHz elliptical cavity matches model well
- New cavity shape directs current parallel to applied field to reduce JxB term, model predicts Q_0 improvement to ~10^6-10^7 range
- Cavity machined, to be coated with Nb_3Sn next – also fabrciated NbTi and Al cavities!



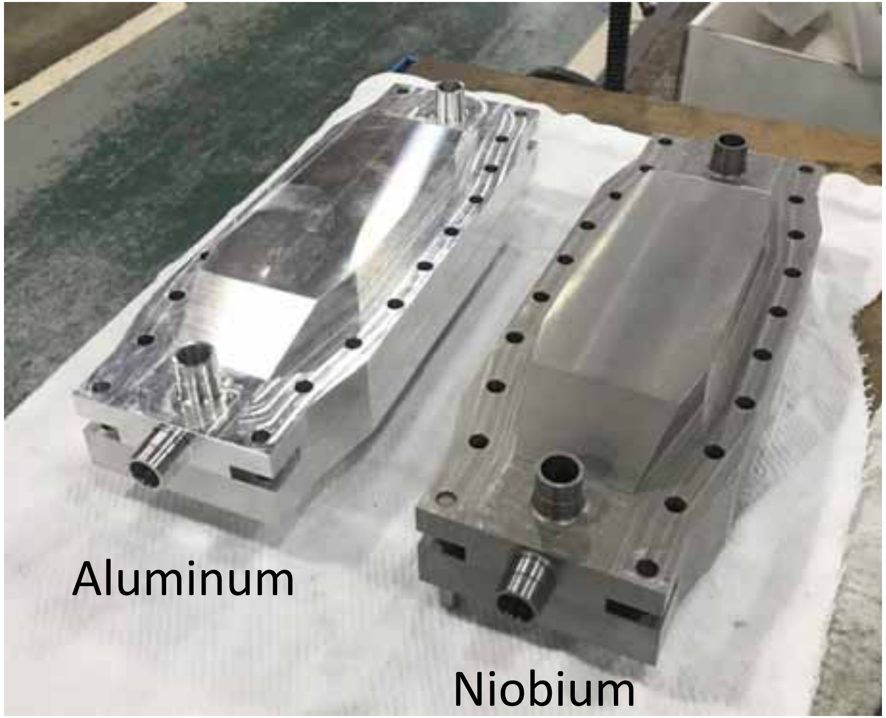


"Axion Axial" Geometry

Extrapolation beyond existing measurements – experiments can help improve theory

Cavity with Optimized Geometry

Designed to have surface currents highly parallel to applied field – minimize *JxB* term in Lorentz force



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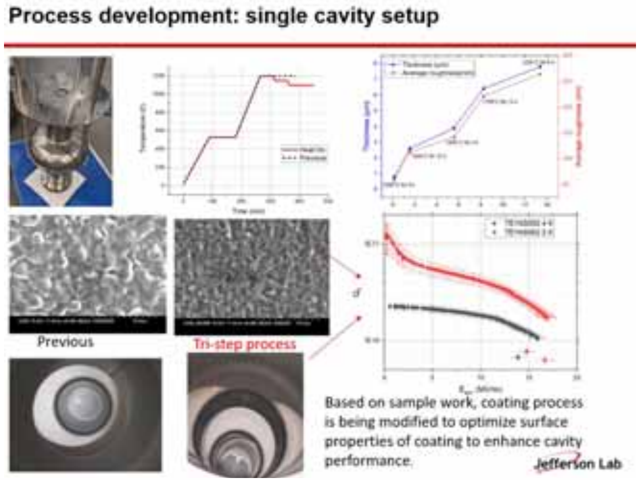
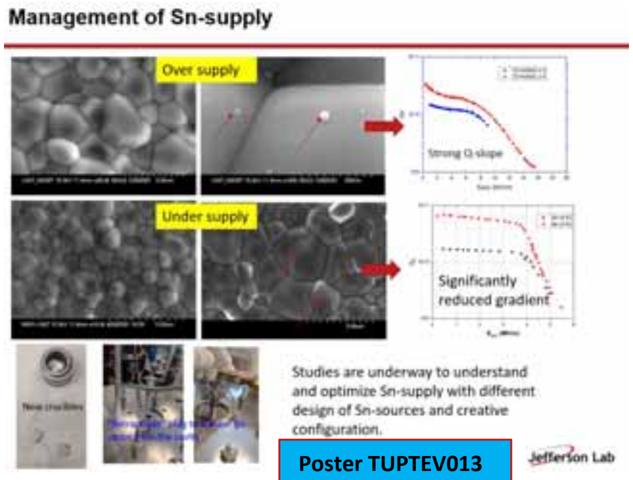
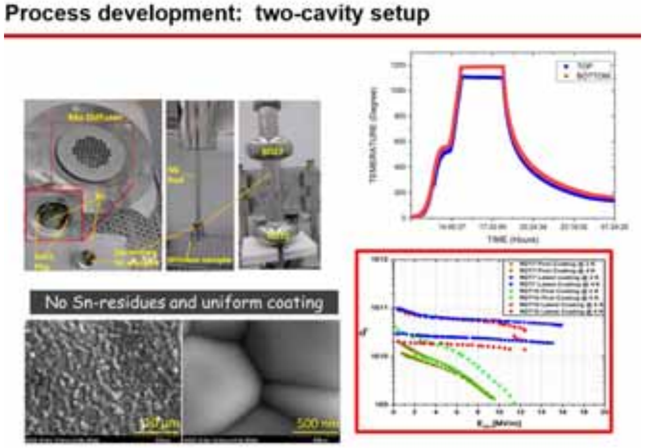
Nb_3Sn R&D work at Jefferson Lab

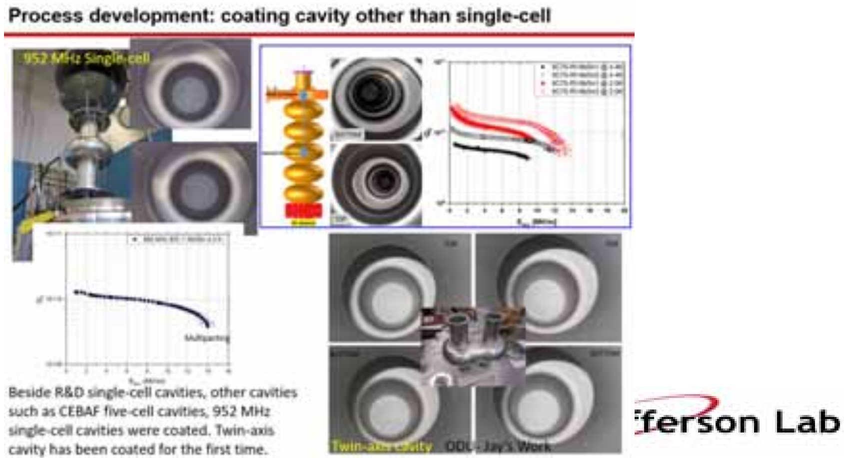




Poster TUPTEV013

Courtesy Uttar Pudasaini, Jefferson Lab





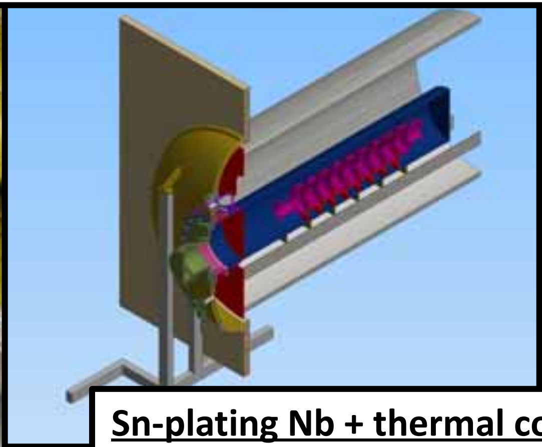
Cornell Nb_3Sn Program Overview

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Single-cell Sn vapour deposition

Courtesy Ryan Porter, Cornell University

Building multi-cell coating chamber

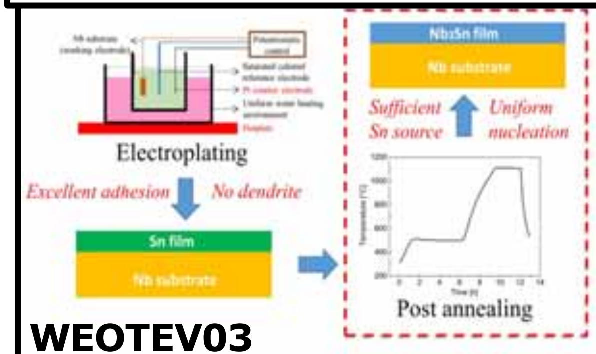


Chemical Vapour Deposition Nb_3Sn

- Collaborating with Ultramet to test their CVD Nb_3Sn process
- Setting up own CVD reactor

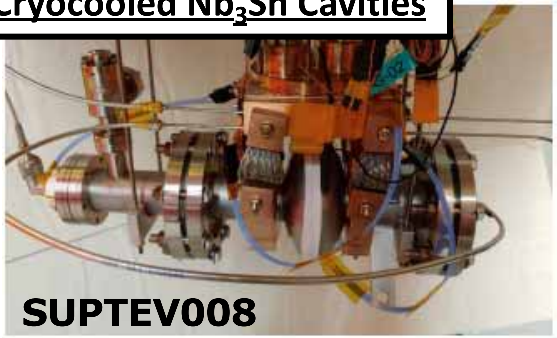
SUPTEV007

Sn-plating Nb + thermal conversion



WEOTEV03

Cryocooled Nb_3Sn Cavities



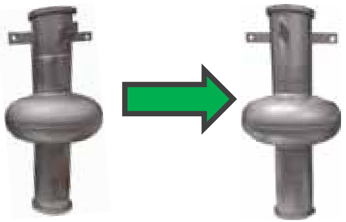
SUPTEV008

Cornell Nb_3Sn—Recent Developments/Highlights

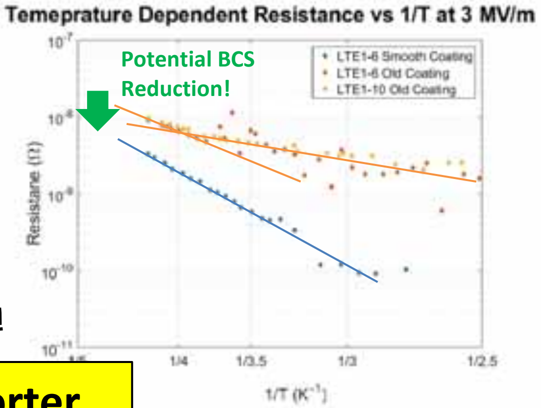
Improved Nb_3Sn vapour coatings:

- Reduced ‘double gap’
- Decreased resistance at 4.2 K
  - 4.5 nΩ BCS at 4.2 K

Smoother!



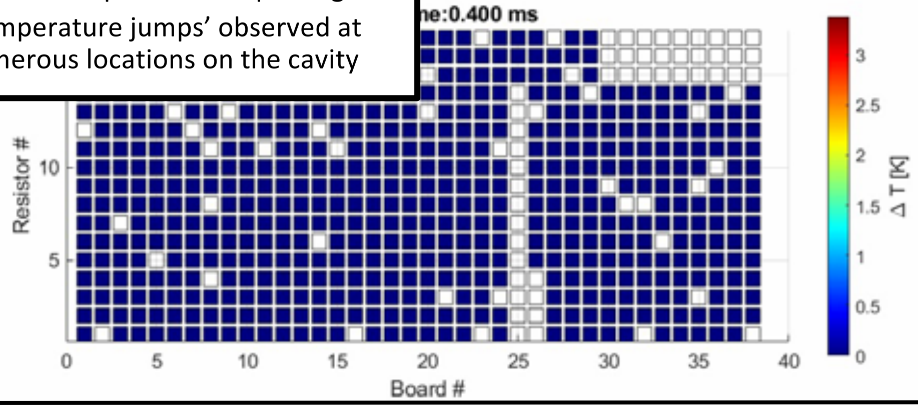
Lower resistance!!



Dynamic temperature mapping

- Shows first quench multipacting
- ‘Temperature jumps’ observed at numerous locations on the cavity

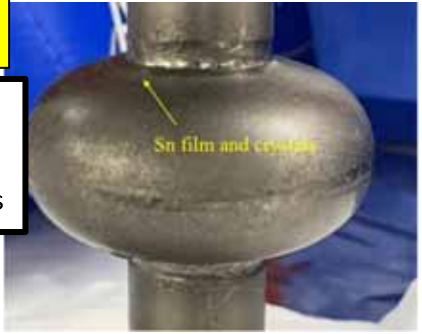
SUPCAV003



Courtesy Ryan Porter, Cornell University

Sn plating cavities

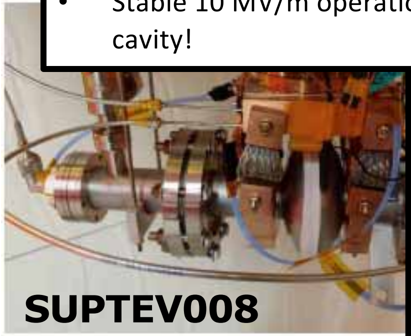
- Good results on samples
- Started Sn-plating 3.9 GHz cavities



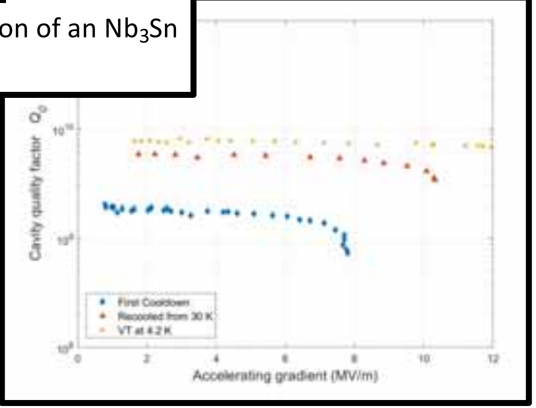
WEOTEV03

Cryocooler Performance

- Stable 10 MV/m operation of an Nb_3Sn cavity!



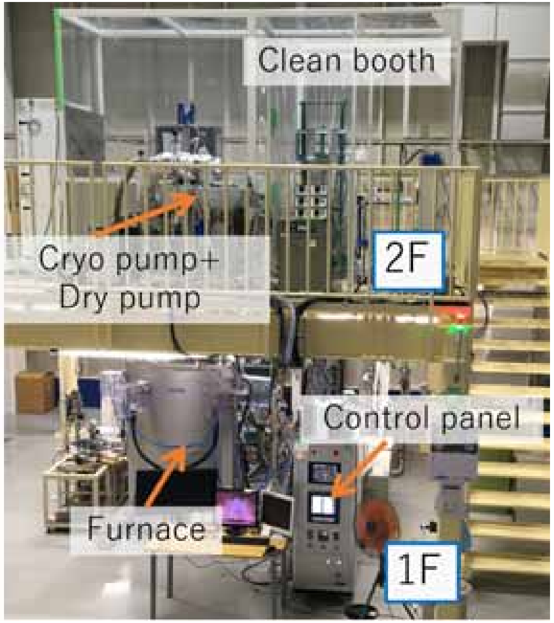
SUPTEV008



Nb3Sn Cavity R&D at KEK

- Nb3Sn coating system was constructed
  - Vertical type
  - Maximum size of coating : 1.3GHz 3 cell cavity
- Detail of the system :
  "Design and Construction of Nb3Sn Vapor Diffusion Coating System at KEK(SUPCAV008)"

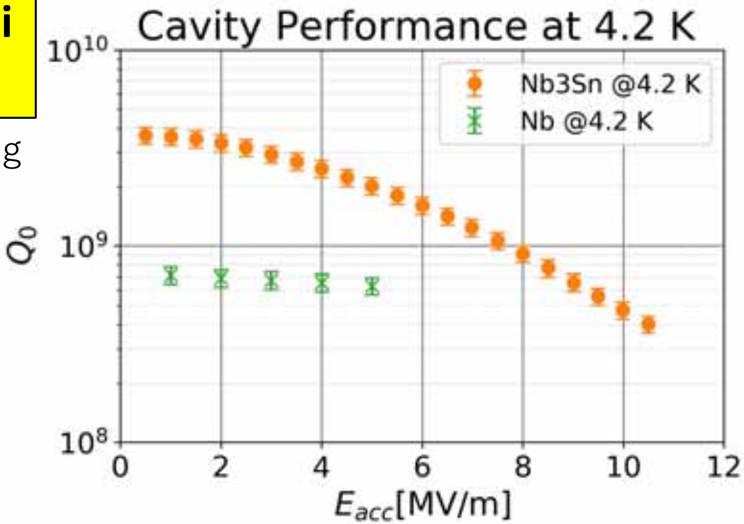
Coating system at KEK



- First Nb3Sn coating was performed for single cell cavity.
- Cavity surface was Nb3Sn, but cavity performance was not good.
  - Tc of the cavity was around 18 K.
  - Q0 was 3.9×10^9 at low field, and maximum Eacc was around 11 MV/m
- Detail of the cavity performance result :
  "First Nb3Sn Coating and Cavity Performance Result at KEK" (SUPCAV009)

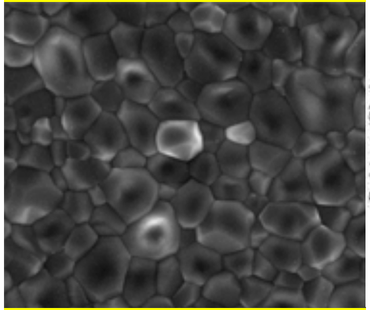
Courtesy Kotaro Takahashi & Kensei Umemori, KEK

Cavity surface after coating

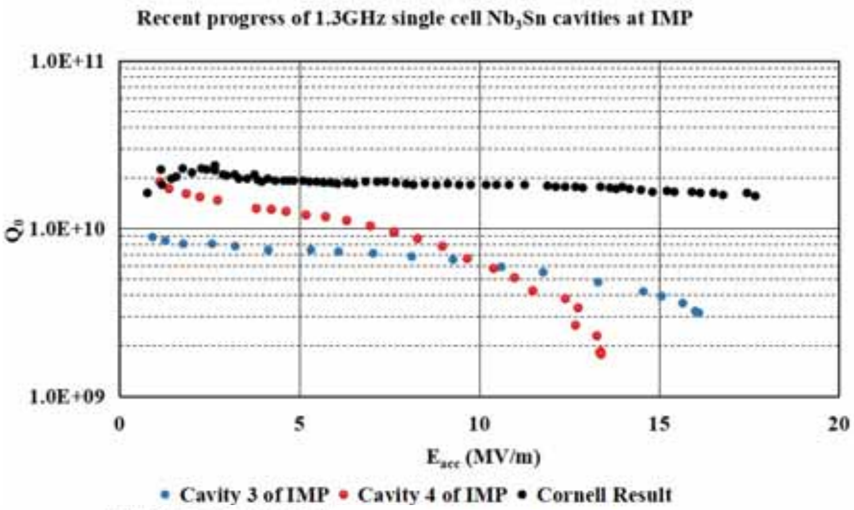


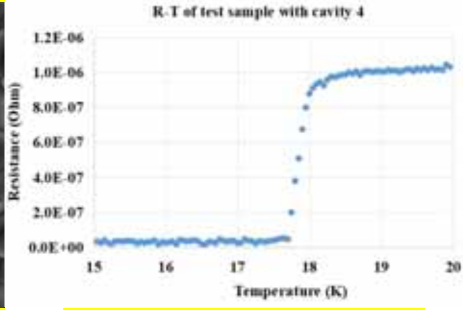
Vapor diffusion coated Nb_3Sn at IMP

Coatings after upgradation



C contamination eliminated





T_c=18.05K, ΔT_c=0.35K

Cavity No.	Low fild Q_0	High field Q_0	Max. E_{acc}
3	8.8e9	3.2e9	16.1
4	1.9e10	1.8e9	13.4

Further optimization underway

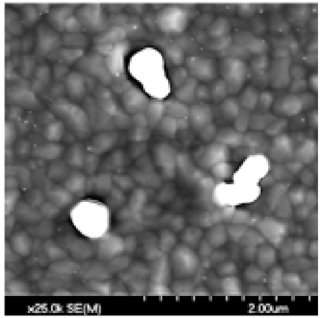
Courtesy Ziqin Yang, IMP CAS

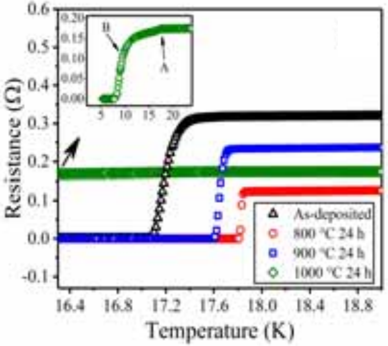
Fabrication of Nb_3Sn by magnetron sputtering

Courtesy Nizam Sayeed, ODU

Nb_3Sn by sputtering from a single Nb_3Sn target:

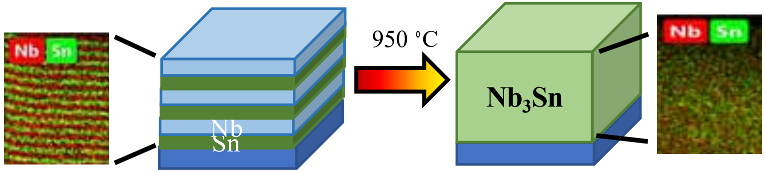
- ❖ Nb_3Sn films were sputtered from a single target on a Nb substrate at 800 °C.
- ❖ Film properties were modified by annealing at different temperatures and times.
- ❖ Highest observed T_c ~17.83 K.

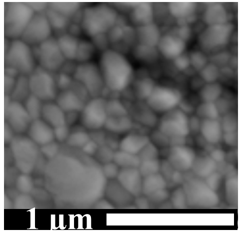


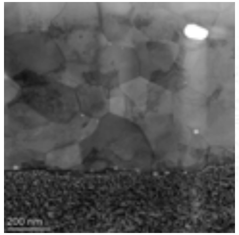


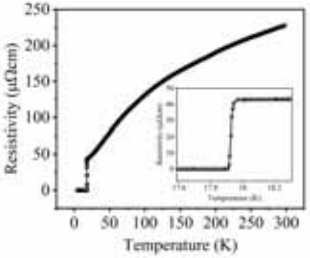
Nb_3Sn by multilayer sputtering:

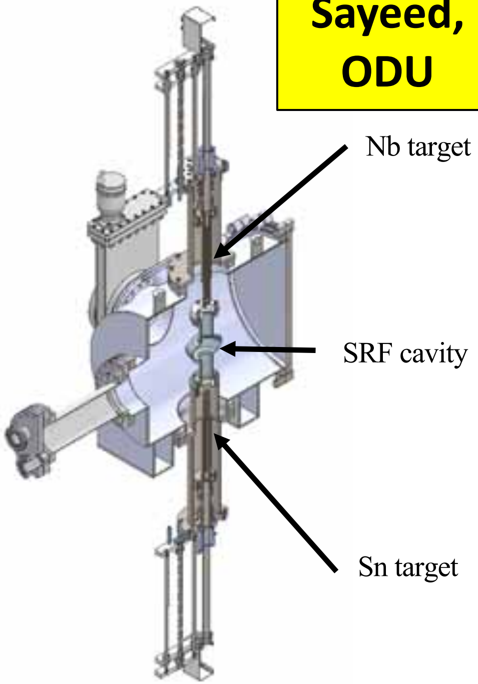
- ❖ Multilayers of Nb and Sn was deposited on Nb and annealed at 950 °C for 3 h.
- ❖ Parameters optimized: substrate temperature, multilayer thickness, annealing temperature.
- ❖ Highest observed T_c ~17.93 K.











SRF cavity sputtering system:

- ❖ A cylindrical sputtering system is designed with two identical cathodes of Nb and Sn to fabricate Nb-Sn multilayers inside the SRF cavities.
- ❖ The system will be commissioned this year.

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5. **Nb3SnSRF'20 – Recent Virtual Workshop on Nb_3Sn SRF**

indico.classe.cornell.edu/event/1806/

- For much more detail on the current state of the art in Nb_3Sn research, please see proceedings from the recent International Nb3SnSRF'20 Workshop
- 39 talks from all around the world in Fundamental Studies, Growth Studies, Performance, and Applications

Summary

- A lot of exciting work happening right now with Nb_3Sn SRF:
  - Improved understanding of materials science of Nb_3Sn
  - Continuing push to improve performance
  - Exploring new accelerator applications
  - Exploring new non-accelerator applications
  - New cavity coating facilities around the world

Fermilab

Acknowledgements

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