Nb_3Sn for SRF applications

High efficiency cavities for future accelerators

Grigory Eremeev

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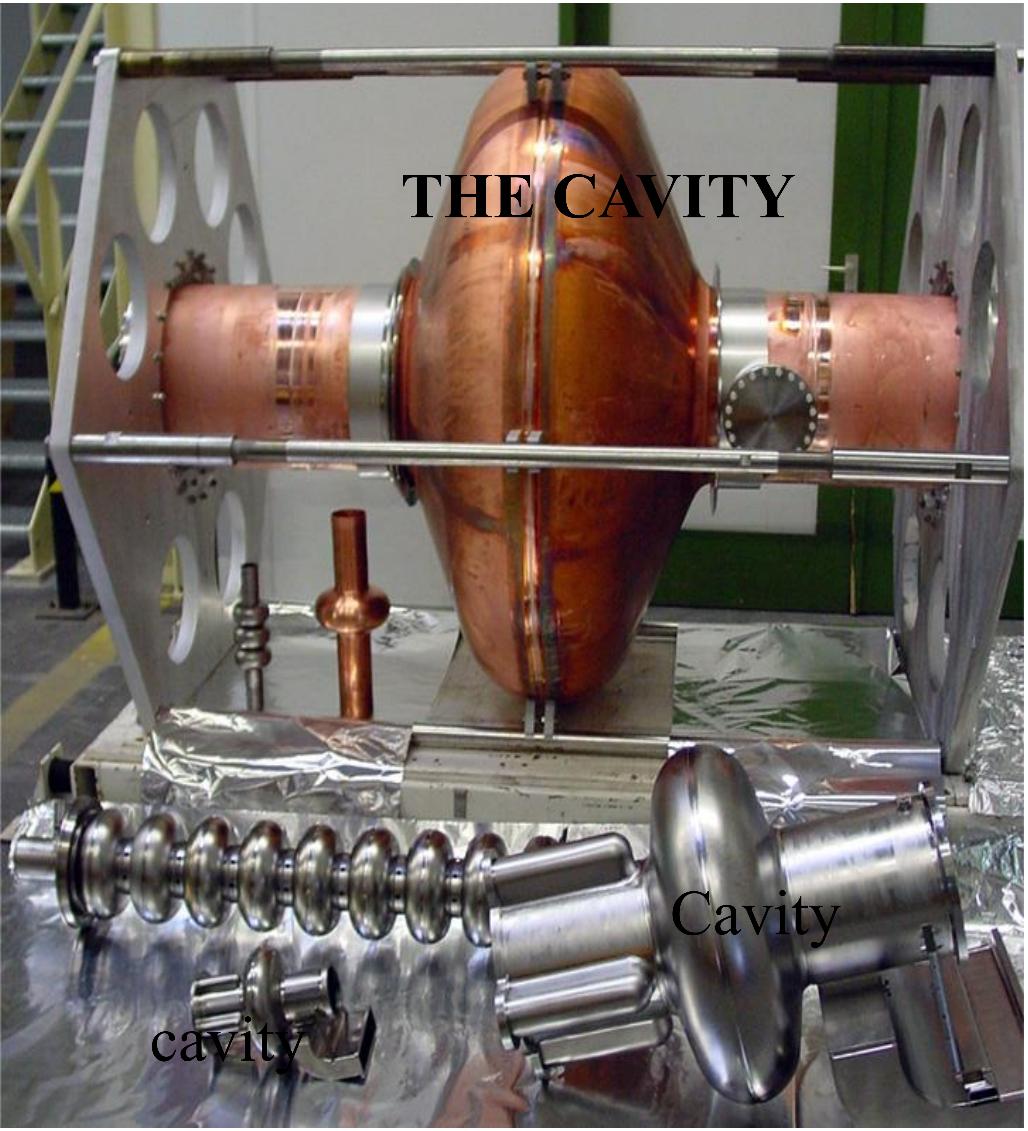
Acknowledgements

- ➢ Michael Kelley, Uttar Pudasaini, Jay Tuggle
- ➢ Hani Elsayed-Ali, Md. Nizam Sayeed, Jean Delayen, Jayendrika Tiskumara
- ➢ Gigi Ciovati, Charlie Reece, Bob Rimmer, Anne-Marie Valente-Feliciano, Larry Phillips, Peter Kneisel, John Mammosser
- ✓ N. Hasan, C. Mounts, K. Macha, W. Oren, A. Solopova, M. Wright, M. Drury, J. Grames, R. Kazimi, W. Crahen, M. Poelker, T. Powers, J. Preble, R. Suleiman, Y. Wang, M. Wright, A. Hutton, H. Areti et al.
- ✓ Matthias Liepe, Ryan Porter, Sam Posen, et al.
- ✓ JLab technical staff

Outline

- Motivation
- Background
- Current status
- Path forward

Niobium and its limitations



Niobium – best superconducting properties among all pure metals:

- T_c ~ 9.25 K;
- H_c ~ 2000 Oe;
- R_{bcs} ~ .00001 mΩ at 2 K

Nb : R_s ~ .00001 mΩ

Cu: Rs ~ 10 mΩ

↓

Q^{nb} ~ 10^{11} up to $E_{acc} = 50 \cdot 10^6$ Volts per meter

Niobium and its limitations

Limitation: Thermal breakdown; High field Q-reduction

Solution: High-purity Nb, sheet inspection, CBP, etc; Electropolishing, low temperature baking, …

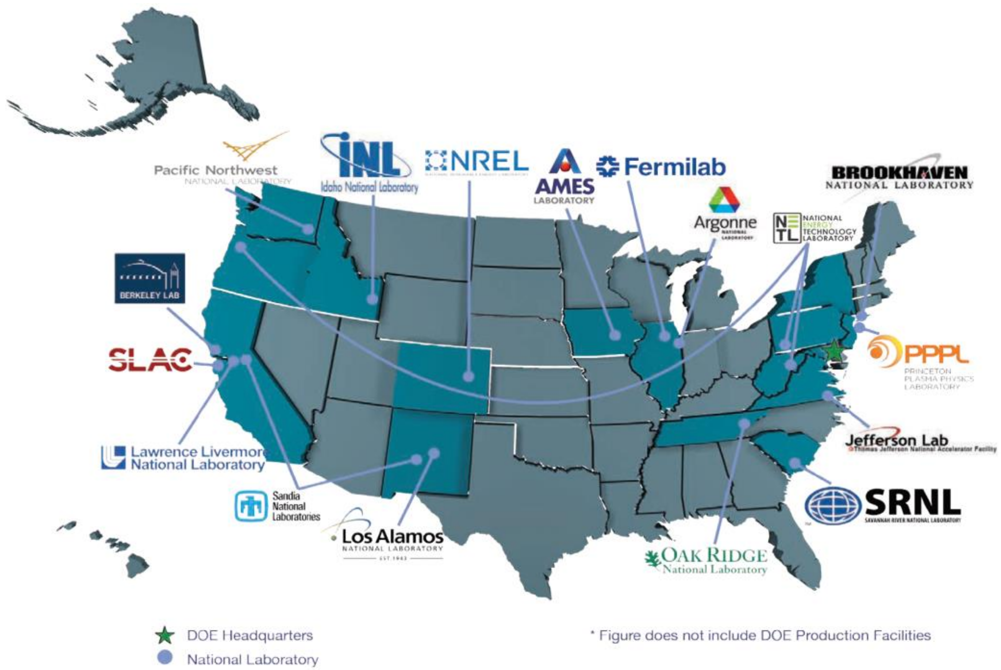
1975	1985	1990	1995	2000	2010
3 MV/m	6 MV/m	15 MV/m	25 MV/m	40 MV/m	50 MV/m

Limitation: Electron multiplication; Electron field emission; Quench

Solution: Improved cavity shape; High-pressure rinsing, cleanroom procedures; Further improved cavity shapes

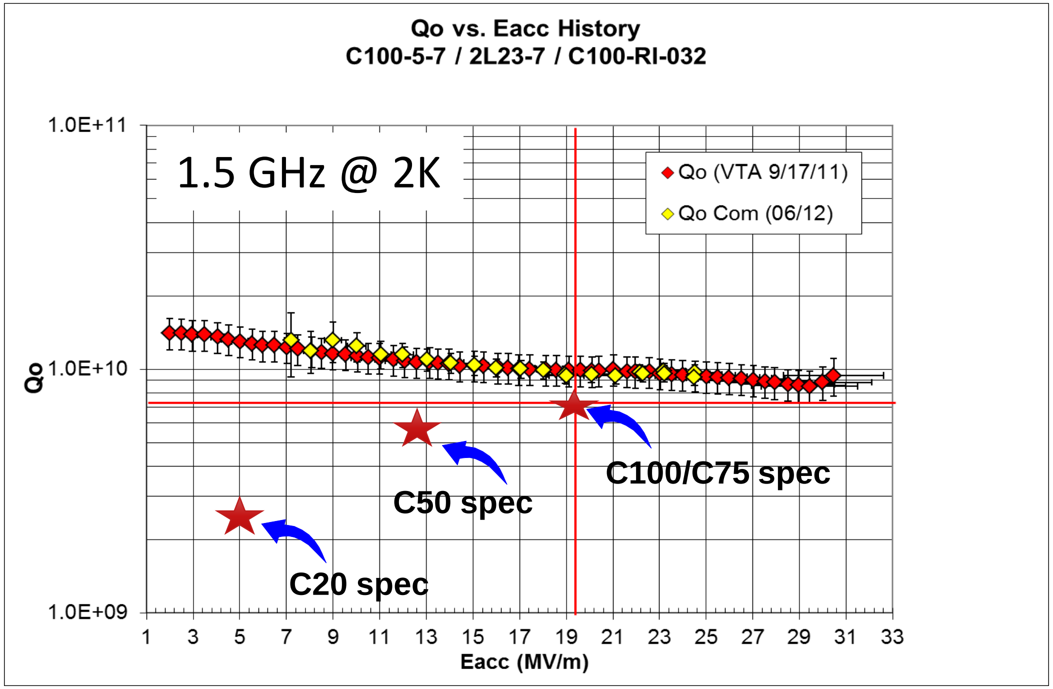
“Borrowed” from M. Liepe

Jefferson Lab Overview

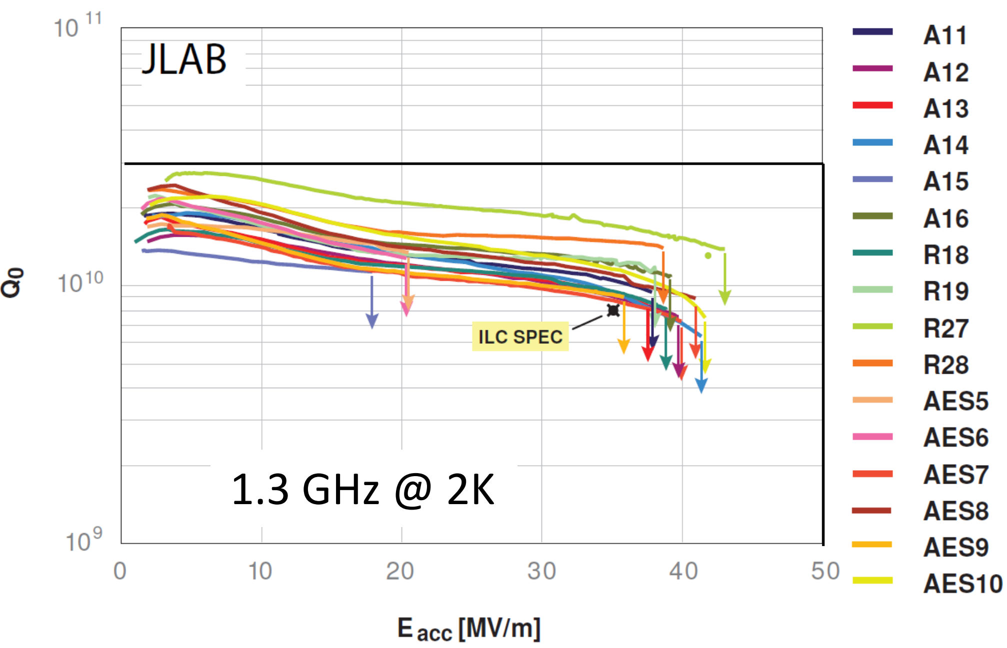


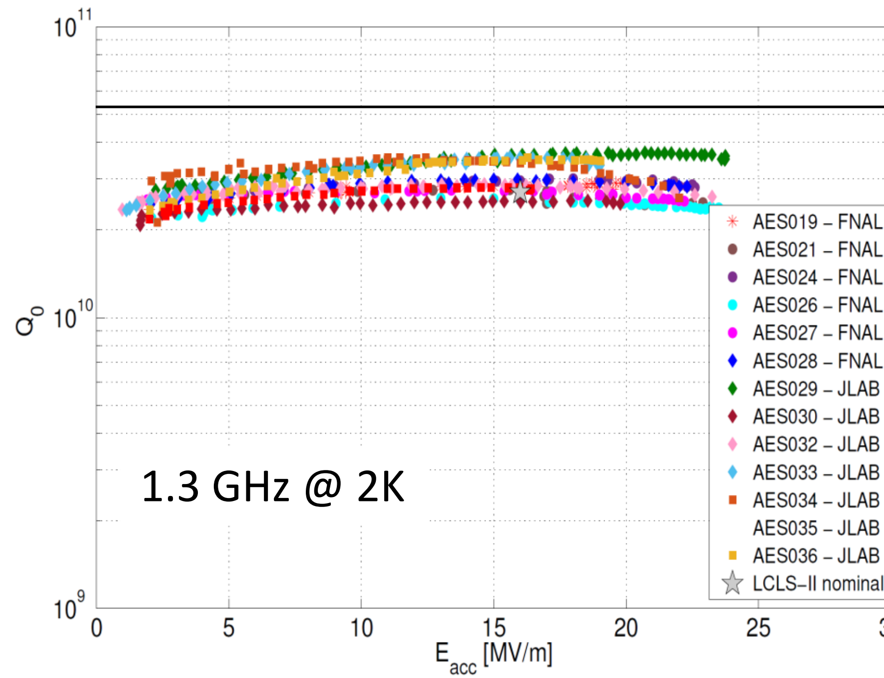
- **Core Competencies**
  - Accelerator Science and Technology
  - Large Scale User Facilities/Advanced Instrumentation
  - Nuclear Physics
- **Mission Unique Facilities**
  - Continuous Electron Beam Accelerator Facility

CEBAF SRF cavities



JLab SRF is a part of global efforts to improve SRF technology





THE INTERNATIONAL LINEAR COLLIDER
Technical Design Report | Volume 3.i: Accelerator R&D

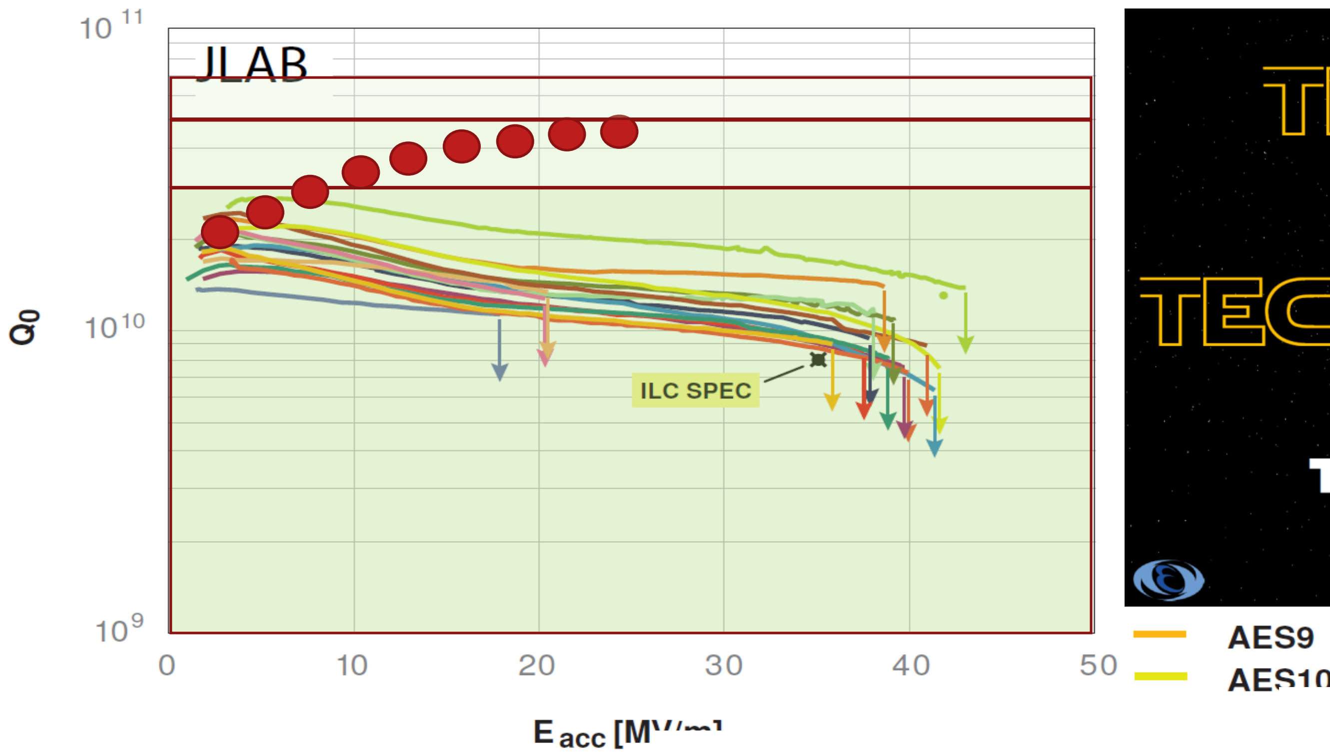
LCLS-II SRF CAVITY PROCESSING PROTOCOL DEVELOPMENT AND BASELINE CAVITY PERFORMANCE DEMONSTRATION, MOPB033, ***SRF'15***

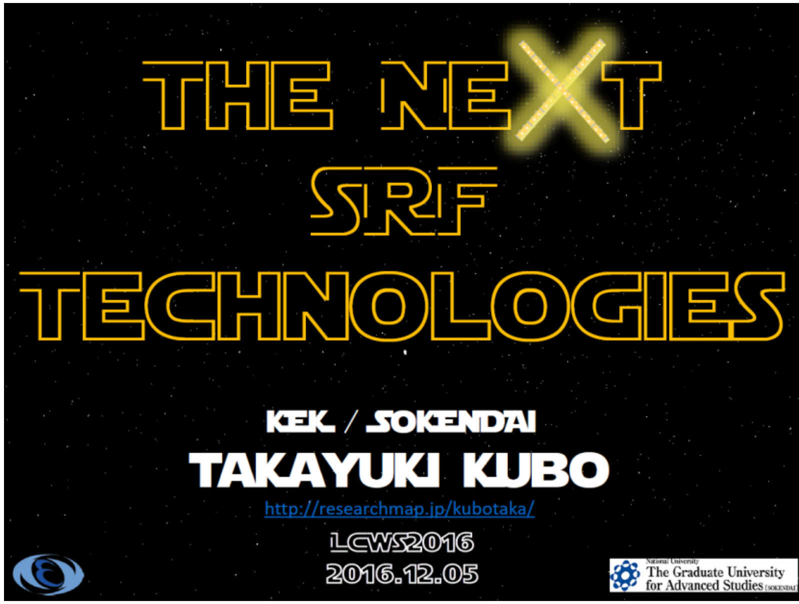
$$R_{BCS} \cong \frac{R_n}{\sqrt{2}}\left(\frac{\hbar\omega}{\pi\Delta}\right)^{\frac{3}{2}}\frac{\sigma_1}{\sigma_n} \cong A\sqrt{\rho_n}\; e^{-\frac{\Delta}{K_B T}}$$

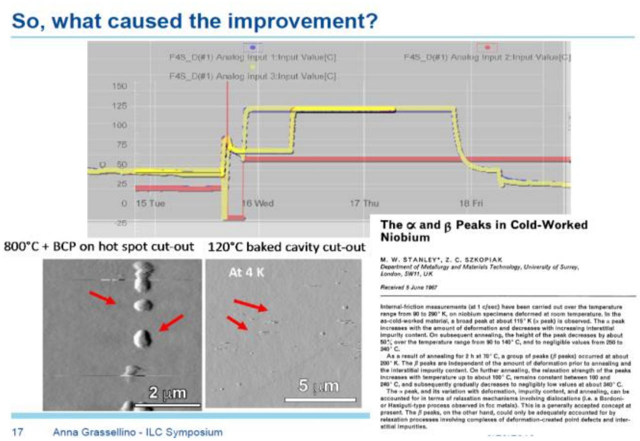
Δ = 1.45 meV ⇒ R_s ≥ 5 nΩ @ 2K @ ~ 1 GHz

H_c ~ 200 mT ⇒ H_{sh} ~ 240 mT ⇒ E_{acc} ~ 50 MV/m

Ideas for the future





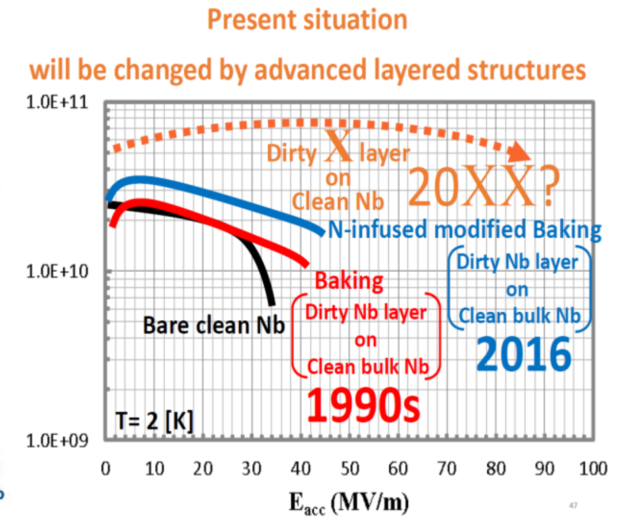


I suggest another key mechanism is at play

- In addition to surface barrier (superheating) there is a "time barrier"
  - There should be enough time for vortices to nucleate/dissipate
- Vortex nucleation is governed by the characteristic time scale of order parameter changes, so-called τ_Δ
  - If flux penetration/dissipation is happening or not depends on the relation between τ_Δ and RF period T_{rf}
    - $\tau_\Delta > T_{rf}$ => vortex-induced dissipation is delayed beyond Hsh
    - $\tau_\Delta < T_{rf}$ => Hc1 and superheating become more relevant – more DC-like
    - $\tau_\Delta >> T_{rf}$ => vortices don't matter as they never form
- $\tau_\Delta \sim \tau_{GL}$ << 1 ns is only relevant for gapless superconductors (which Nb is not) > was understood by e.g. Tinkham and Bezuglii in late 1980s
- For gapped superconductors at low T: $\tau_\Delta \sim \tau_E$ >~ 1 ns for Nb

Fermilab

8 A. Romanenko | IPAC'2018 - Vancouver, Canada 5/2/18



Nb_3Sn

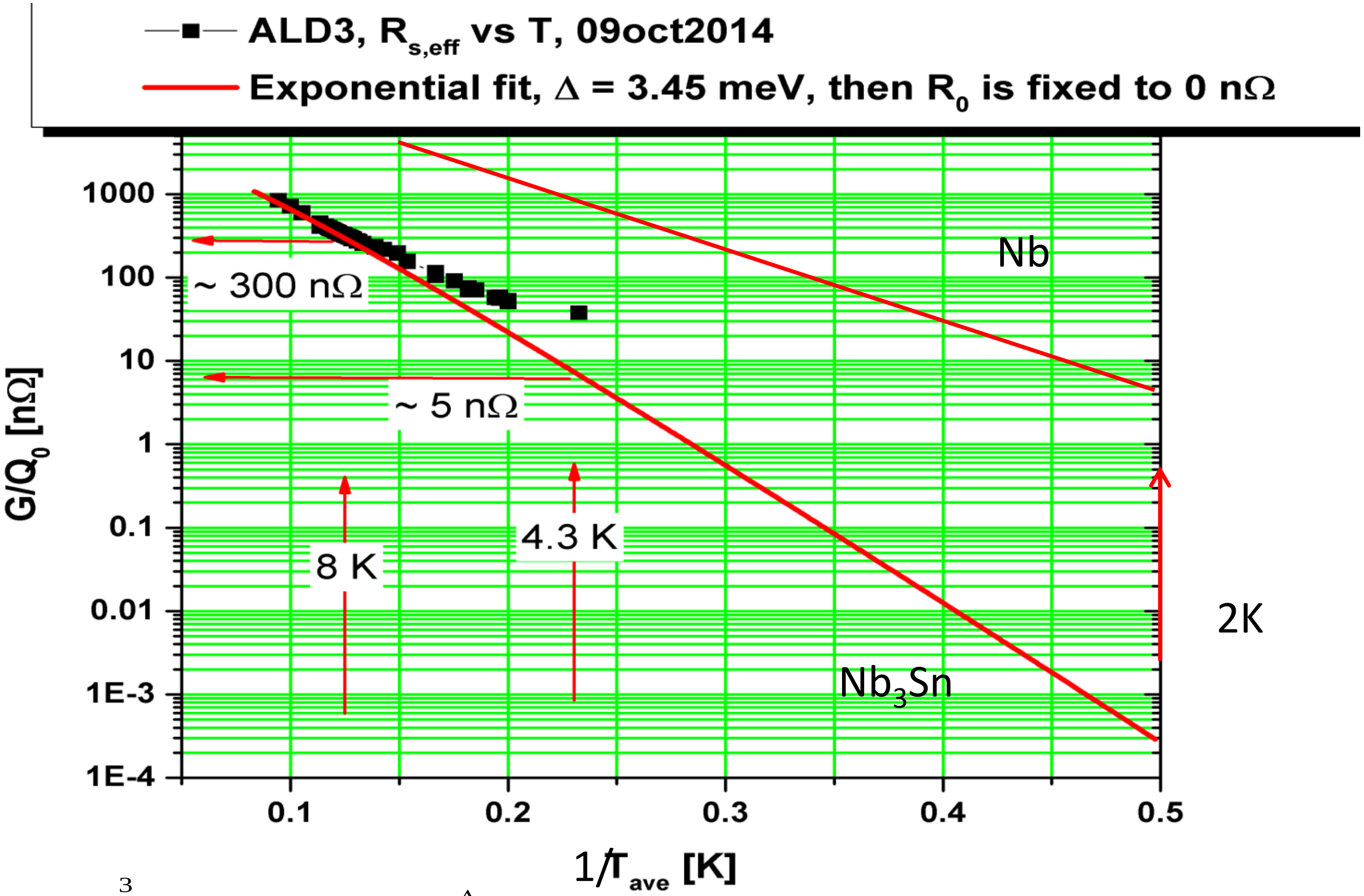
What are the better SRF Materials?

T_c [K]	ρ_n [µΩcm]	Δ [meV]	$H_c(0)$ [T]	$H_{sh}(0)$ [T]	$H_{c1}(0)$ [T]	λ(0) [nm]	Material
9.25	0.1	1.45	~ 0.2	~ 0.24	~ 0.17	40	Nb
17.2	70	2.6	~ 0.23	~ 0.19	~ 0.02	~ 200	NbN
17.5	35	3.0	~ 0.28	~ 0.24	~ 0.03	~ 151	NbTiN
18.3	5	3.1	~ 0.54	~ 0.45	~ 0.05	~ 85	Nb_3Sn
40	2	2.3/7.1	~ 0.43	~ 0.27	~ 0.03	~ 140	MgB_2

- s-wave superconductor
- large energy gap
- high H_{Sh}
- low normal-conducting resistivity

Material	Nb	Nb_3Sn
T_c [K]	9.25	18.3
ρ_n [µΩcm]	0.1	~ 5
$H_{sh}(0)$ [T]	0.24	~ 0.45
Δ [meV]	1.45	~ 3.1
Q^{BCS} @ 2K	~ $5\cdot10^{10}$	~ $5\cdot10^{14}$
Q^{BCS} @ 4K	~ $5\cdot10^{8}$	~ $5\cdot10^{10}$
E_{acc} [MV/m]	~ 50	~ 100

Nb3Sn properties and perspectives



$$R_{BCS} \cong \frac{R_n}{\sqrt{2}}\left(\frac{\hbar\omega}{\pi\Delta}\right)^{\frac{3}{2}}\frac{\sigma_1}{\sigma_n} \cong A\sqrt{\rho_n}\; e^{-\frac{\Delta}{K_B T}}$$

Δ ~ 3.1 meV ⇒ R_S ≥ 5 nΩ @ 4.3K @ ~ 1 GHz

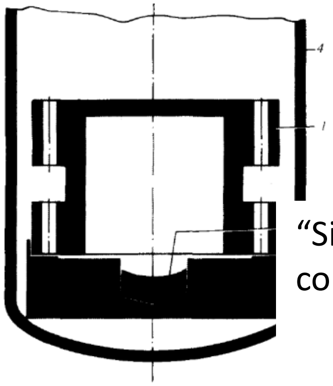
H_c ~ 540 mT ⇒ H_{sh} = 0.84·H_c ~ 450 mT ⇒ E_{acc} ~ 100 MV/m

Nb_3Sn: past and present

Nb_3Sn for SRF!! ... not exactly new

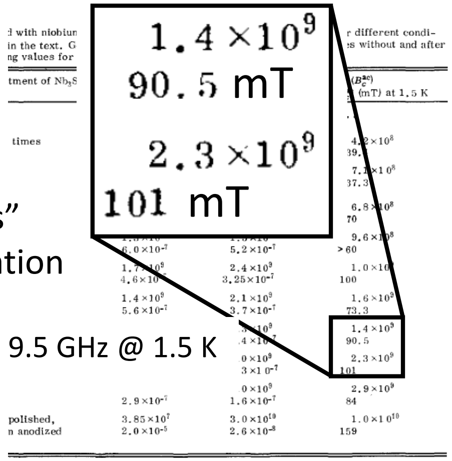
- 1953, discovered by B. Matthias et al.
- 1962, Saur and Wurm
- 1973, Siemens AG
- 1974, Karlsruhe
- 1974, Cornell University
- 1975, University of Wuppertal
- 1986, CERN
- …
- …
- …
- …
- 2009, Cornell University
- 2012, Jefferson Lab
- 2015, Fermilab

High Tc?



“Siemens” configuration

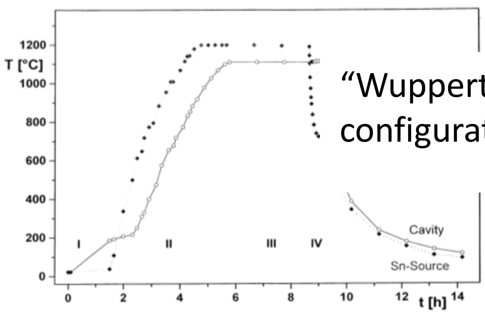
FIG. 1. All-niobium inner reaction room, consisting of the niobium cavity (1) and the niobium bottom plate (2) containing the tin source (3). The lower part of the quartz ampulla (4) is inserted into a resistance furnace.



9.5 GHz @ 1.5 K

B. Hillenbrand and H. Martens, J. Appl. Phys. 47, 4151 (1976)

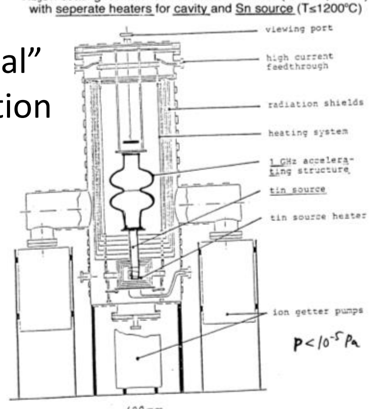
Typical temperature settings to grow Nb_3Sn by vapour diffusion



“Wuppertal” configuration

Fabrication of Nb_3Sn Layers on Bulk Nb Cavities by means of the Vapour Diffusion Technique

Nb_3Sn coating furnace for accelerator cavities (f≥1Ghz, L≤1m) with seperate heaters for cavity and Sn source (T≤1200°C)

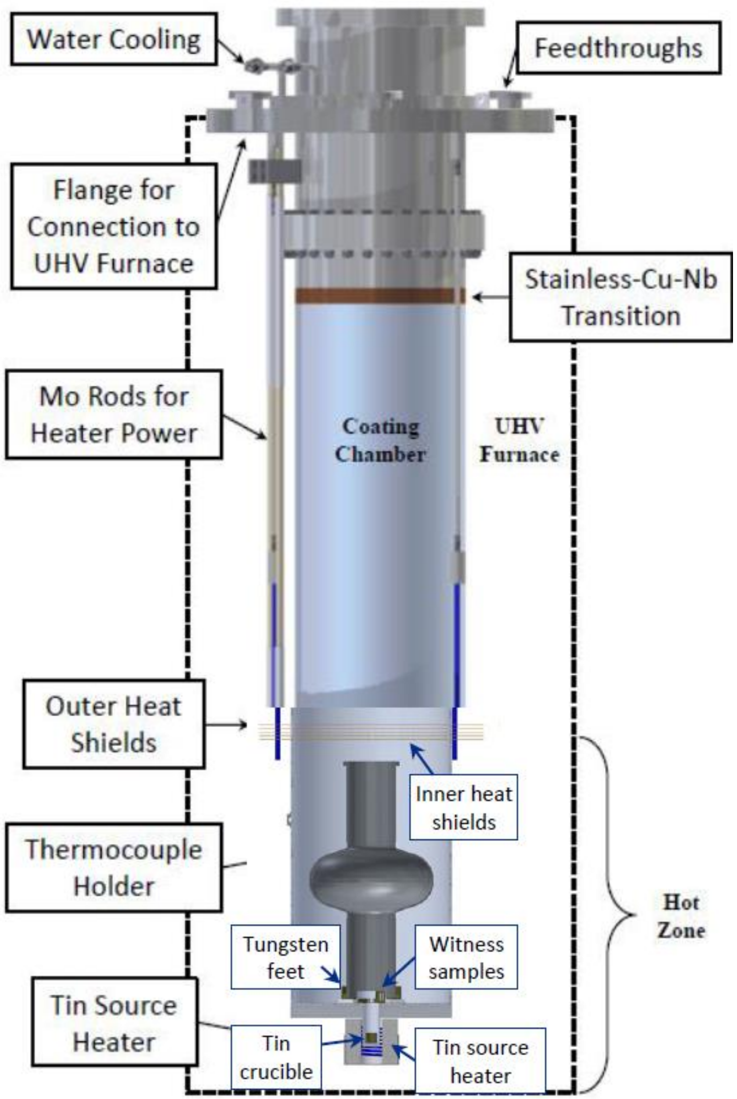


⇒ Improved nucleation of Nb_3Sn especially on high purity Nb by $SnCl_2$ (at T≥200°C) and oversaturated Sn pressure (1Pa)

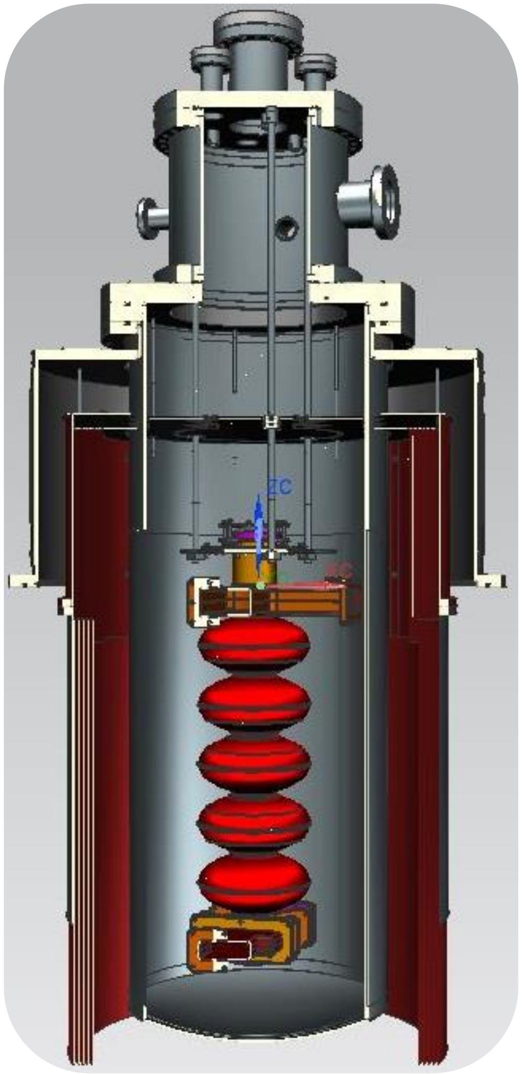
G. Mueller, TESLA 2000-15
G. Müller, P. Kneisel, D. Mansen, H.Piel, J. Pouryamout, R. W. Röth, EPAC’96

Jefferson Lab

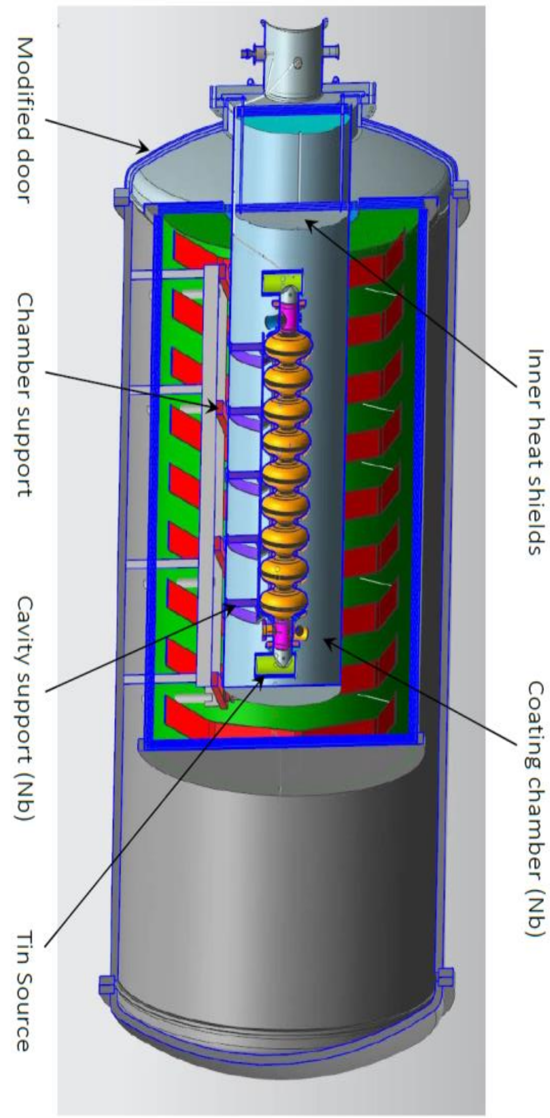
Nb_3Sn: Cornell, Jlab, and Fermilab



Cornell



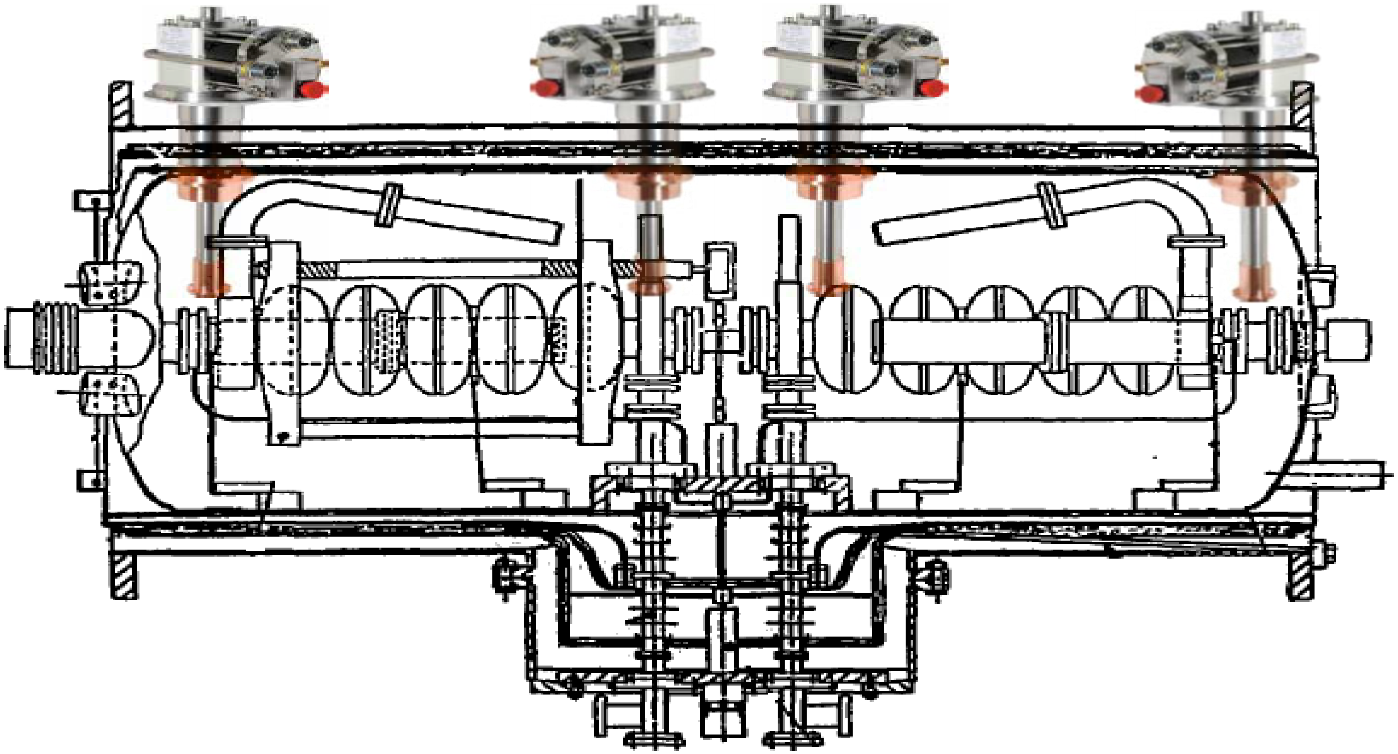
Jlab



Fermilab

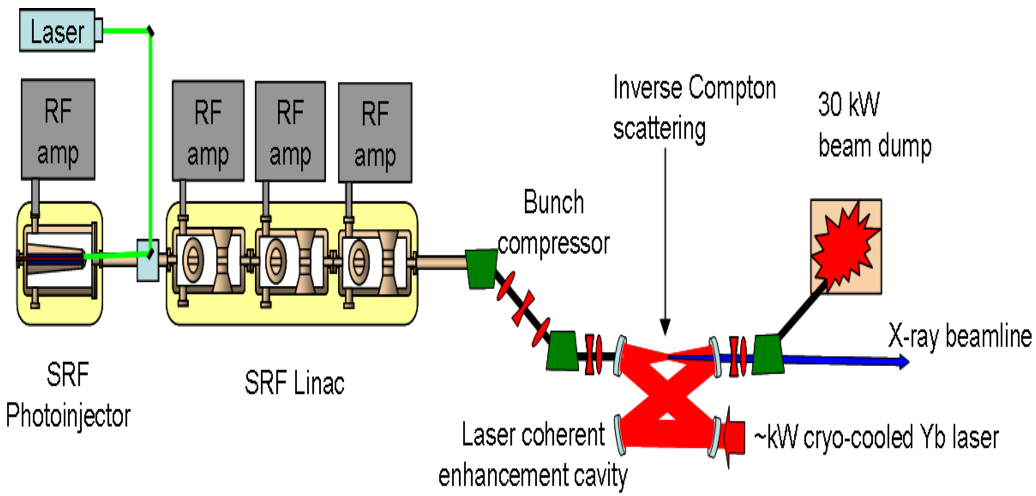
Nb_3Sn cavities cooled by cryocoolers

Cryocooler-cooled cryomodules?!

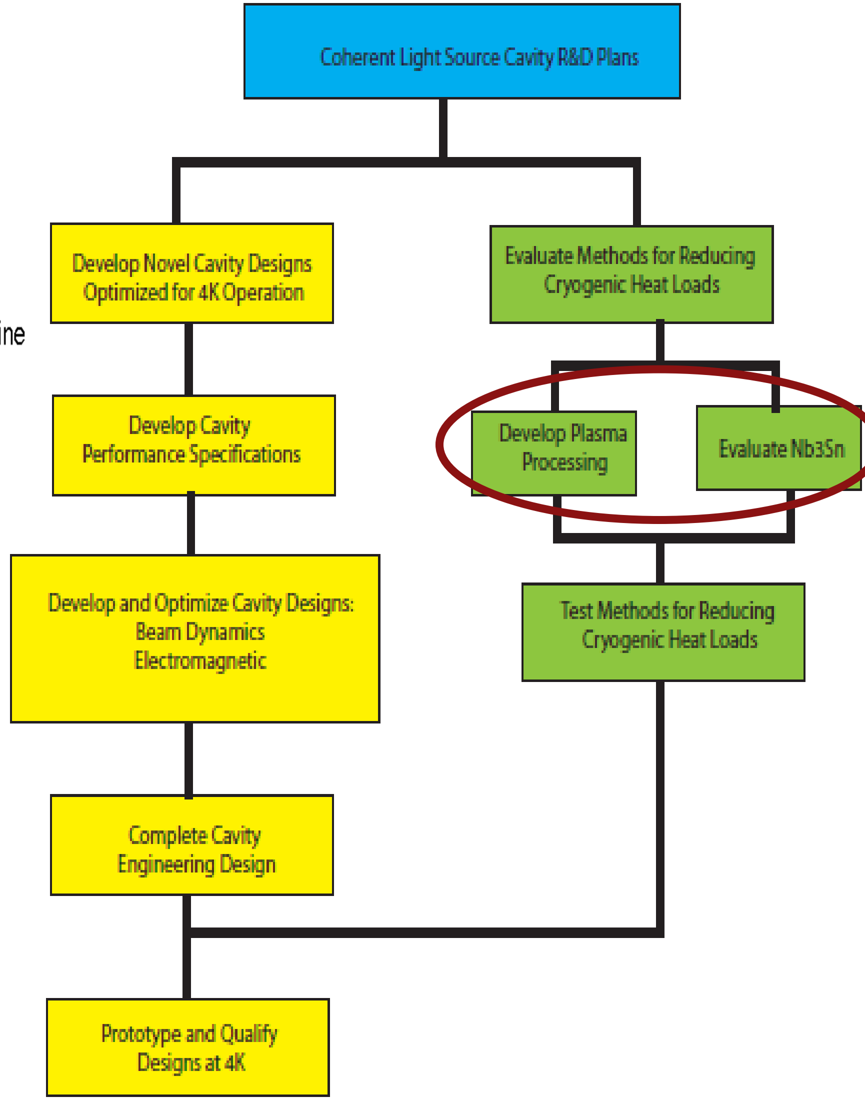


http://www.shicryogenics.com//wp-content/uploads/2012/11/Cryocooler-Product-Catalogue.pdf

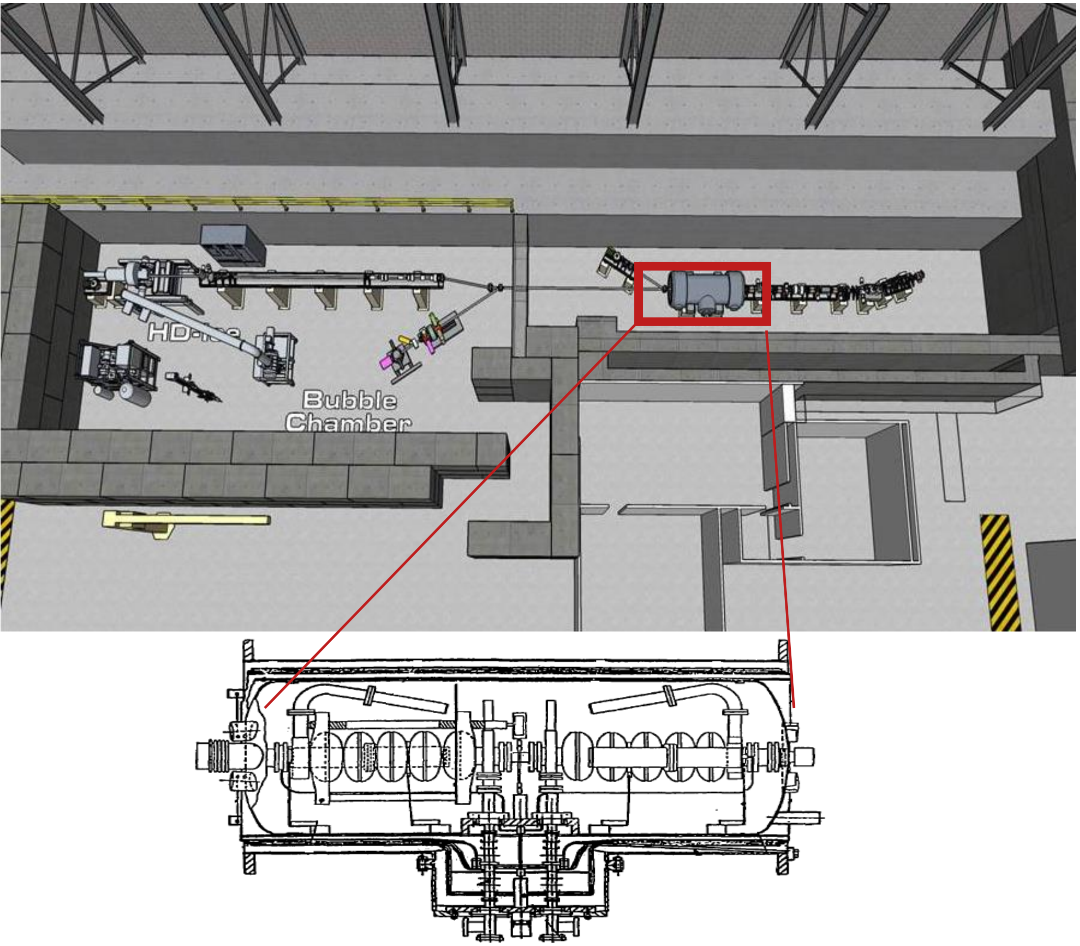
Nb_3Sn cavities for compact light sources

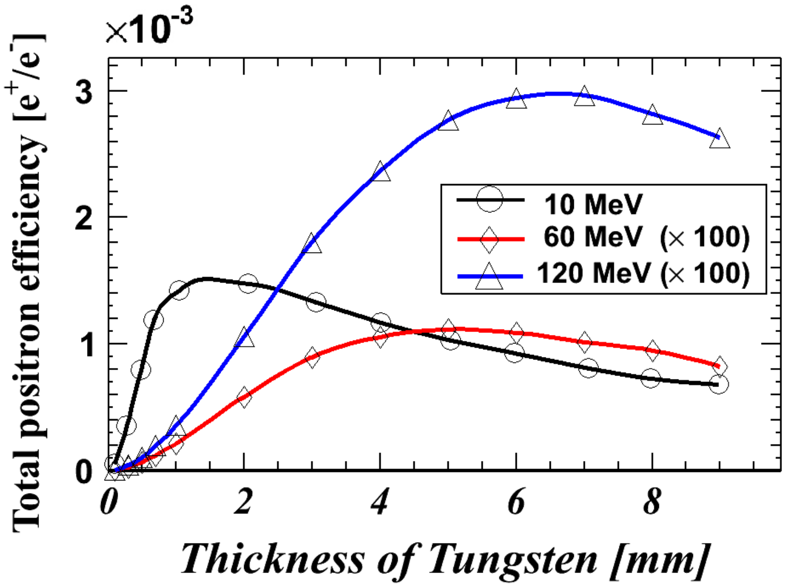


Injector Gain	4	MeV
Accelerator Cryomodule Gain	20-25	MeV
Number of Cryomodules	1	
Number of Cavities	2-4	
Frequency	352	MHz
Operating Temperature	4.5	K
RF Amplitude Stability	0.1?	%
RF Phase Stability	50?	fs
Cavity Type	Spoke or Elliptical	



Nb_3Sn cavities for Upgraded Injector Test Facility (UITF) @ Jlab





D. Abbott et al. , Phys. Rev. Lett. 116, 214801
B. DiGiovine et al., Proc. AIP Conf. 1563, 239 (2013)
http://wiki.jlab.org/ciswiki/index.php/Main_Page

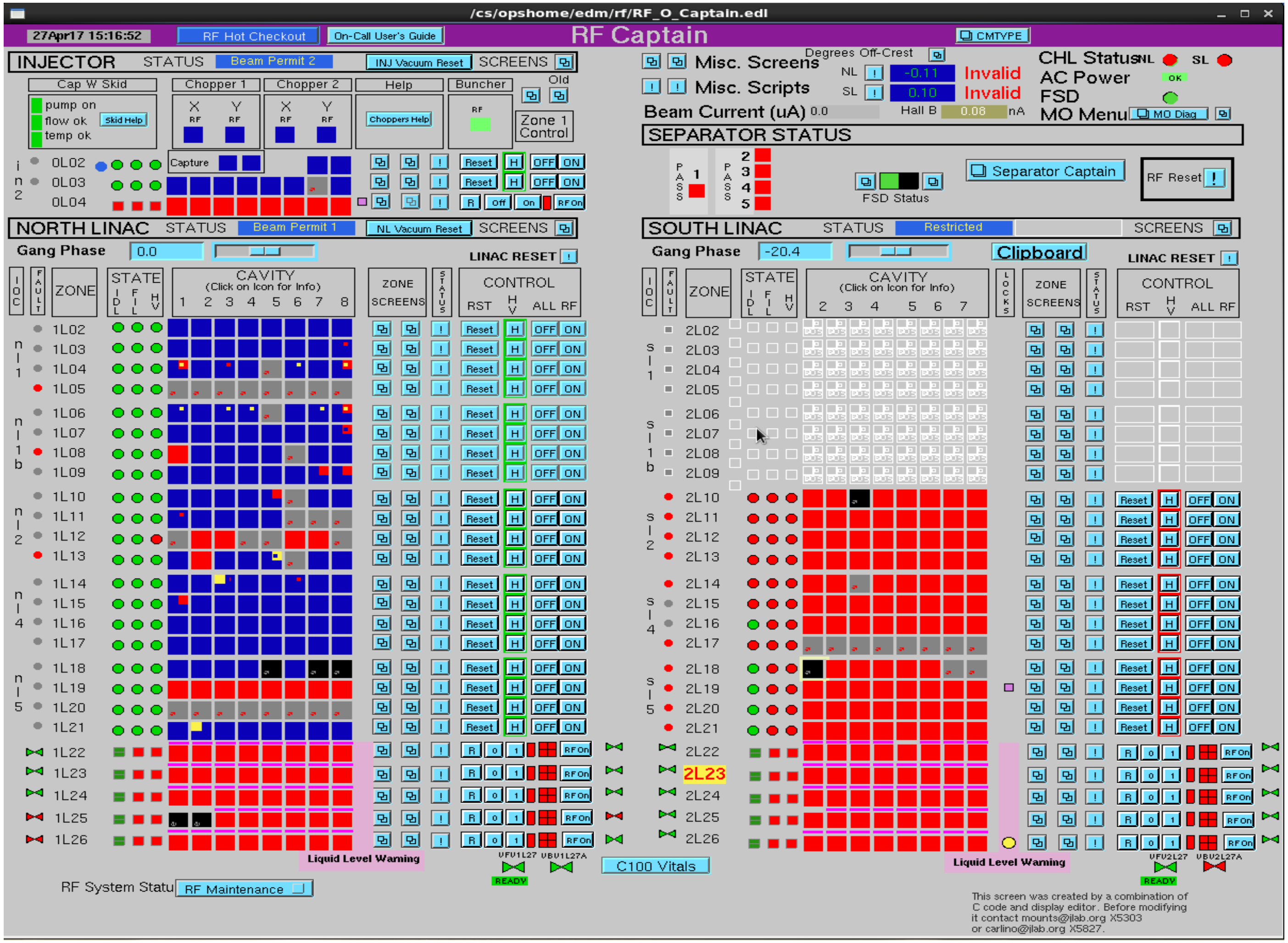
Fig. 12. Schematic of the proposed experiment.

The photon yield that hits the bubble chamber is shown in figure 14. Here the electron beam has a kinetic energy of 8.5 MeV and is irradiating the 0.02 mm Cu radiator. Since the $^{16}O(\gamma,\alpha)^{12}C$ cross section is very steep, only photons next to the end point will produce events from this reaction.

4K vs 2K beam quality

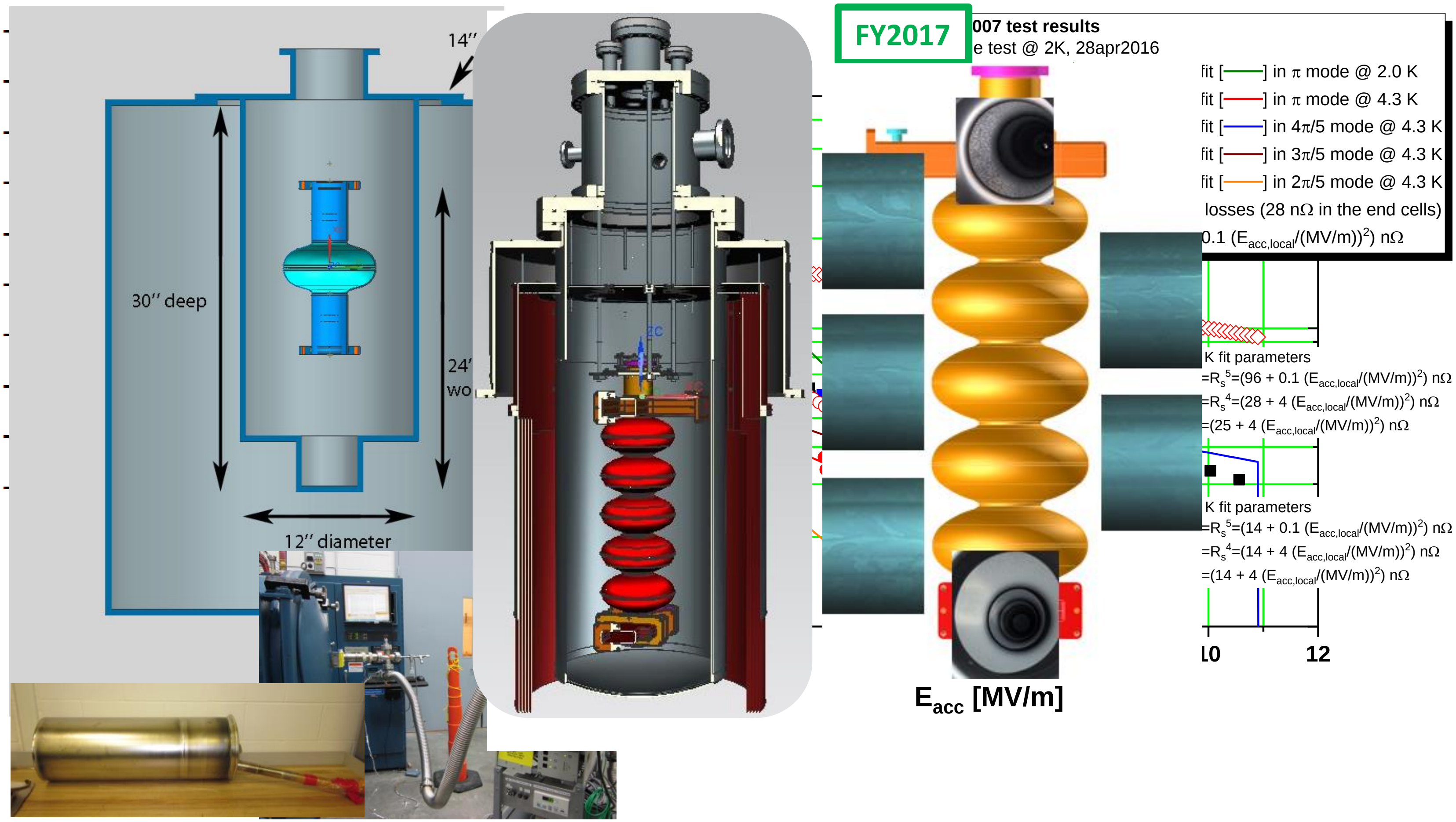
Parameter	Unit	March 23, 2016	June 17, 2016
CHL Condition	K	[redacted]	
Cavities	#	0L02-7,8	0L02-7,8
Gradient	MV/m	5.00, 5.32	5.00, 5.32
PSET (Crest)	deg	164.8, 83.2	-168.4, 123.6
Momentum	MeV/c	6.34	6.47
Laser Used	Hall	A	A
Max Intensity (IBC0L02)	µA	80	60
Horizontal Normalized Emittance (MQJ0L02)	mm-mrad	0.38 ± 0.01	0.44 ± 0.01
Horizontal Beta (MQJ0L02)	m	5.21 ± 0.08	9.55 ± 0.12
Horizontal Alpha (MQJ0L02)	rad	-1.01 ± 0.01	-3.03 ± 0.04
Vertical Normalized Emittance (MQJ0L02)	mm-mrad	0.34 ± 0.01	0.54 ± 0.01
Vertical Beta (MQJ0L02)	m	2.53 ± 0.06	15.8 ± 0.1
Vertical Alpha (MQJ0L02)	rad	-0.42 ± 0.01	-4.39 ± 0.02
Horizontal Profile Scan (IHA2D00)	mm	2.35 ± 0.02	1.46 ± 0.02
Momentum Spread (dp/p)	%	0.22%	0.14%
Energy Spread (dE/E)	keV	14	9

4K CEBAF test



N. Hasan, C. Mounts, W. Oren, A. Solopova, M. Wright, M. Drury, J. Grames, R. Kazimi, M. Poelker, T. Powers, J. Preble, R. Suleiman, Y. Wang, M. Wright, A. Hutton, H. Areti et al.

Jlab Nb_3Sn development timeline

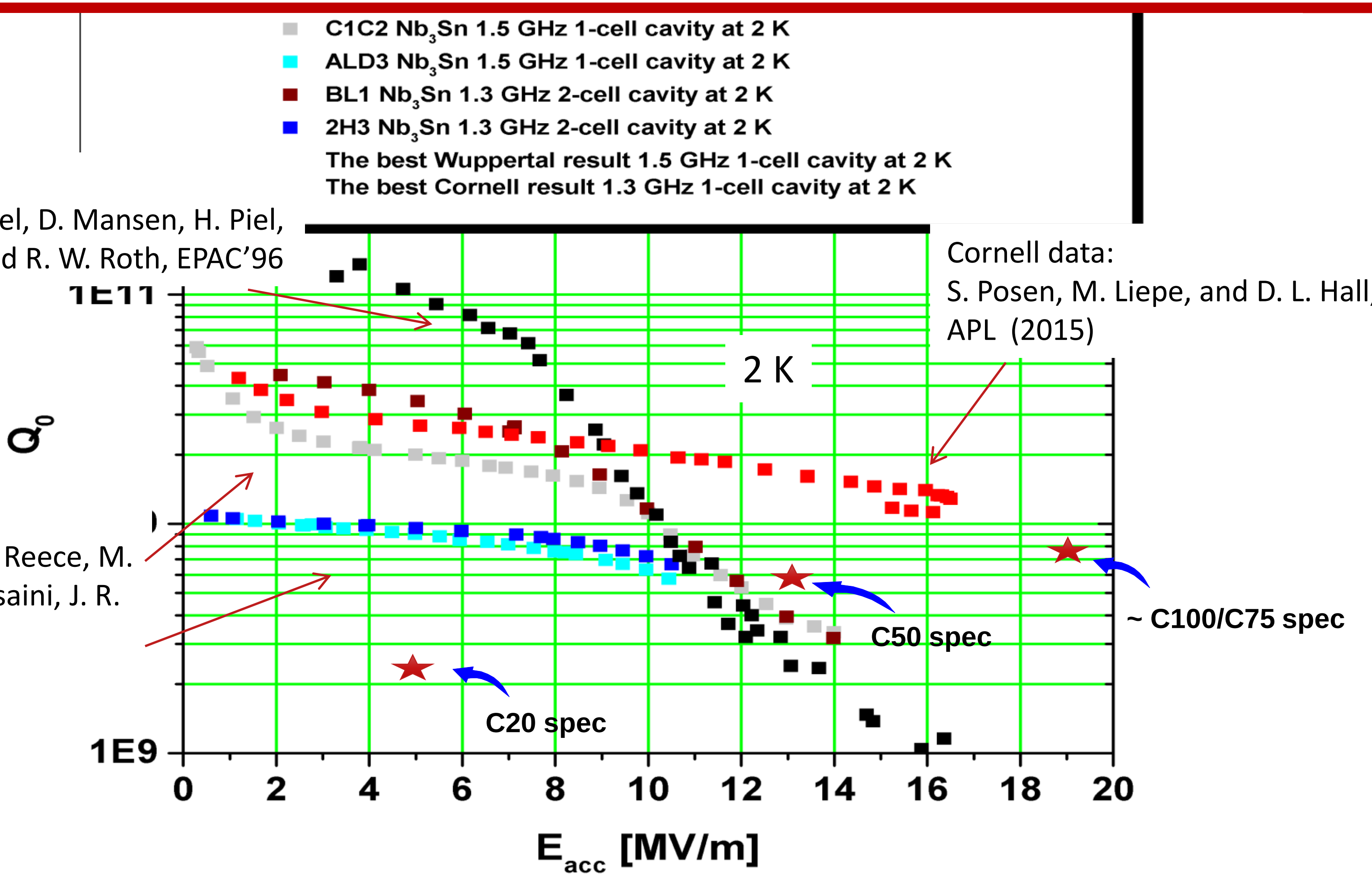


Present single-cell work

Wuppertal data:
G. Müller, P. Kneisel, D. Mansen, H. Piel, J. Pouryamout, and R. W. Roth, EPAC'96

Cornell data:
S. Posen, M. Liepe, and D. L. Hall, APL (2015)

JLab data:
G. Eremeev, C. E. Reece, M. J. Kelley, U. Pudasaini, J. R. Tuggle, SRF'15

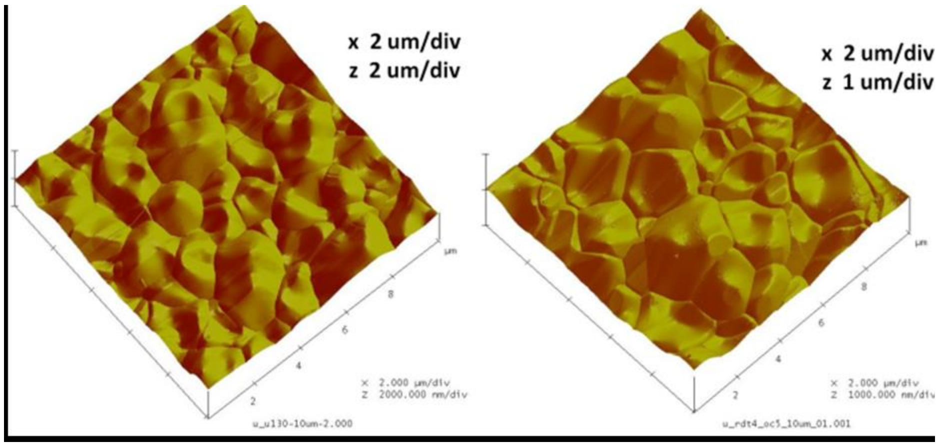


05.03.16

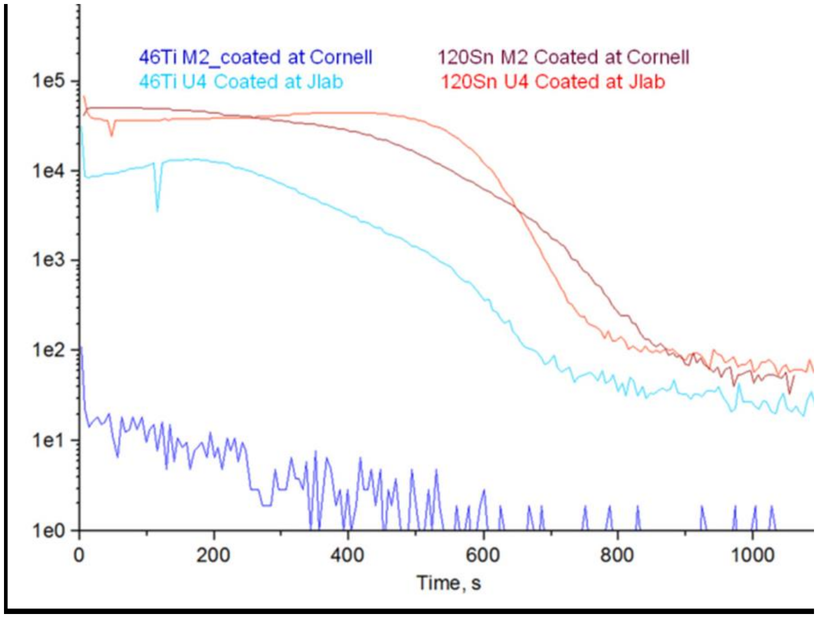
DOE's Office of Science Selects 49 Scientists to Receive Early Career Research Program Funding

Eremeev, Grigory V., Thomas Jefferson National Accelerator Facility, Newport News, VA, "Formation of Superconducting Nb_3Sn Phase for Superconducting Radio Frequency (SRF) Cavities," selected by the Office of Nuclear Physics.

Titanium hypothesis



- 20 -



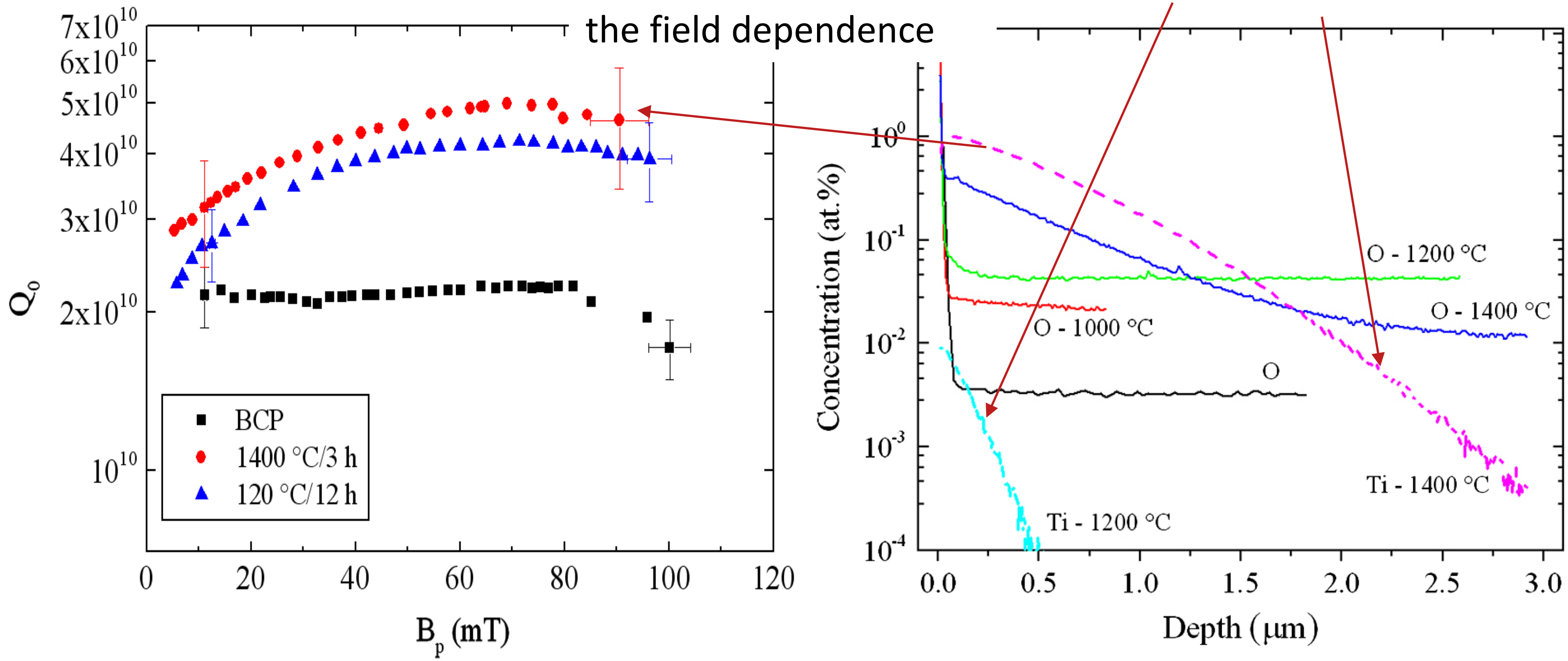
Zum anderen wurde zur Reduktion des Sauerstoffpartialdrucks im Ofeninneren der Resonator außen mit einer 0.5 mm dicken Titanfolie ummantelt. Dies führte während der Nb_3Sn-Beschichtung zu einer Titanbeschichtung der Resonatoraußenfläche. Eine geringe Verunreinigung (Low contamination) der innen aufwachsenden Nb_3Sn-Schicht durch hineindiffundieren- des Titan wird man praktisch kaum vermeiden können (siehe Kap. II.3). Dieser Effekt wird aber als unkritisch angesehen, da nach Ref. 71 Titananteile von 5 % nur zu einer T_c- Reduktion von weniger als 0.2 K führen. Zur Vermeidung von Keimbildungsproblemen

M. Peiniger, dissertation, 1989

Titanium hypothesis

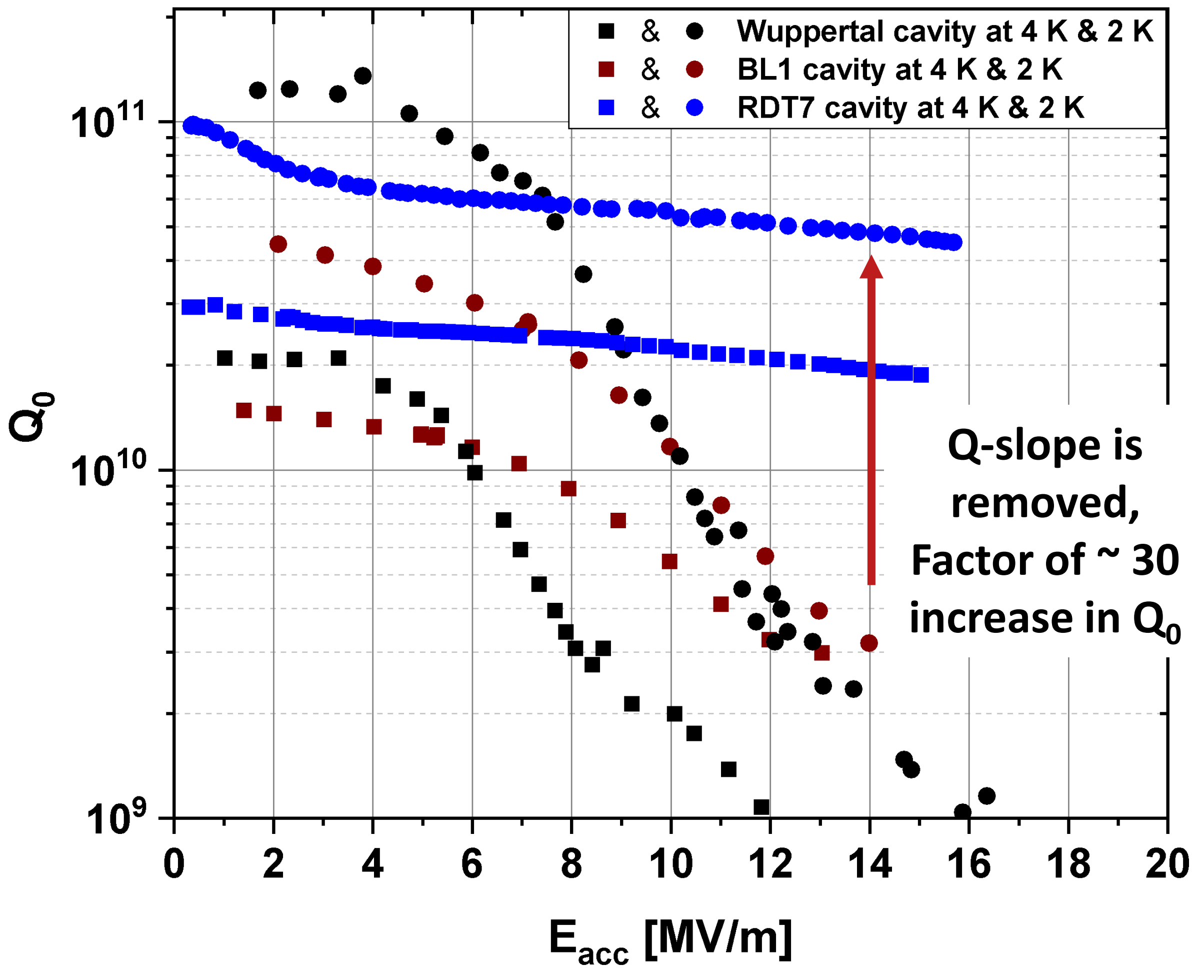
Surface Ti was linked to the field dependence

Ti from NbTi flanges



Effect of high temperature heat treatments on the quality factor of a large-grain superconducting radio-frequency niobium cavity, P. Dhakal et al., Phys. Rev. ST Accel. Beams 16, 042001, 2013

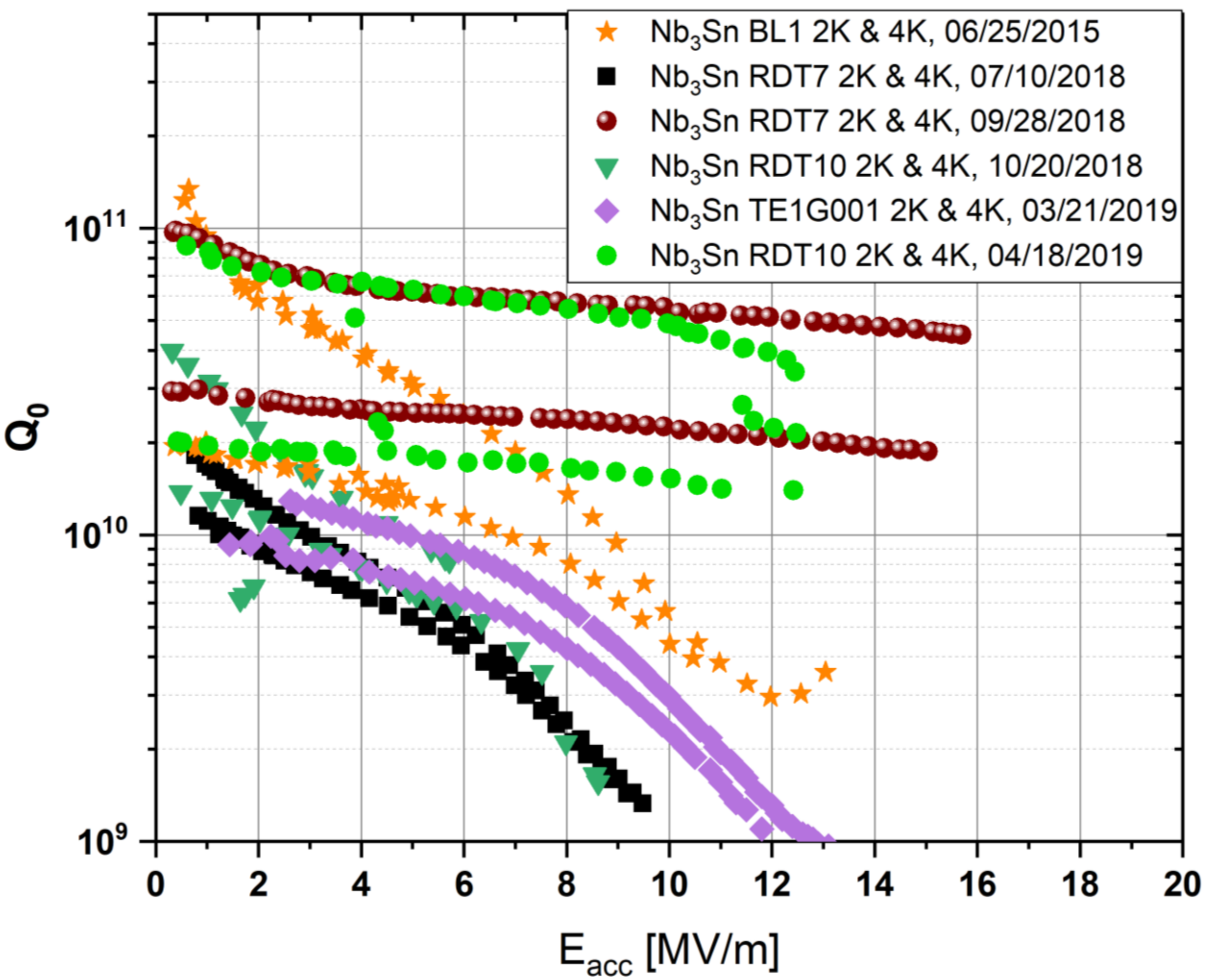
Recent data after the coating system upgrade



G. Ciovati, I. Parajuli, U. Pudasaini

- Following system upgrade, Q-slope free Nb_3Sn-coated cavity were observed
- Q_0 improved at all fields
- At low fields, Q_0 reached 10^{11}
- $Q_0 \sim 5 \cdot 10^{10}$ @ E_{acc} = 15 MV/m
- Cavities are still coated in "Siemens" configuration, i.e., no secondary heater for the tin source
- The cavity had NbTi flanges replaced with Nb flanges

Current data

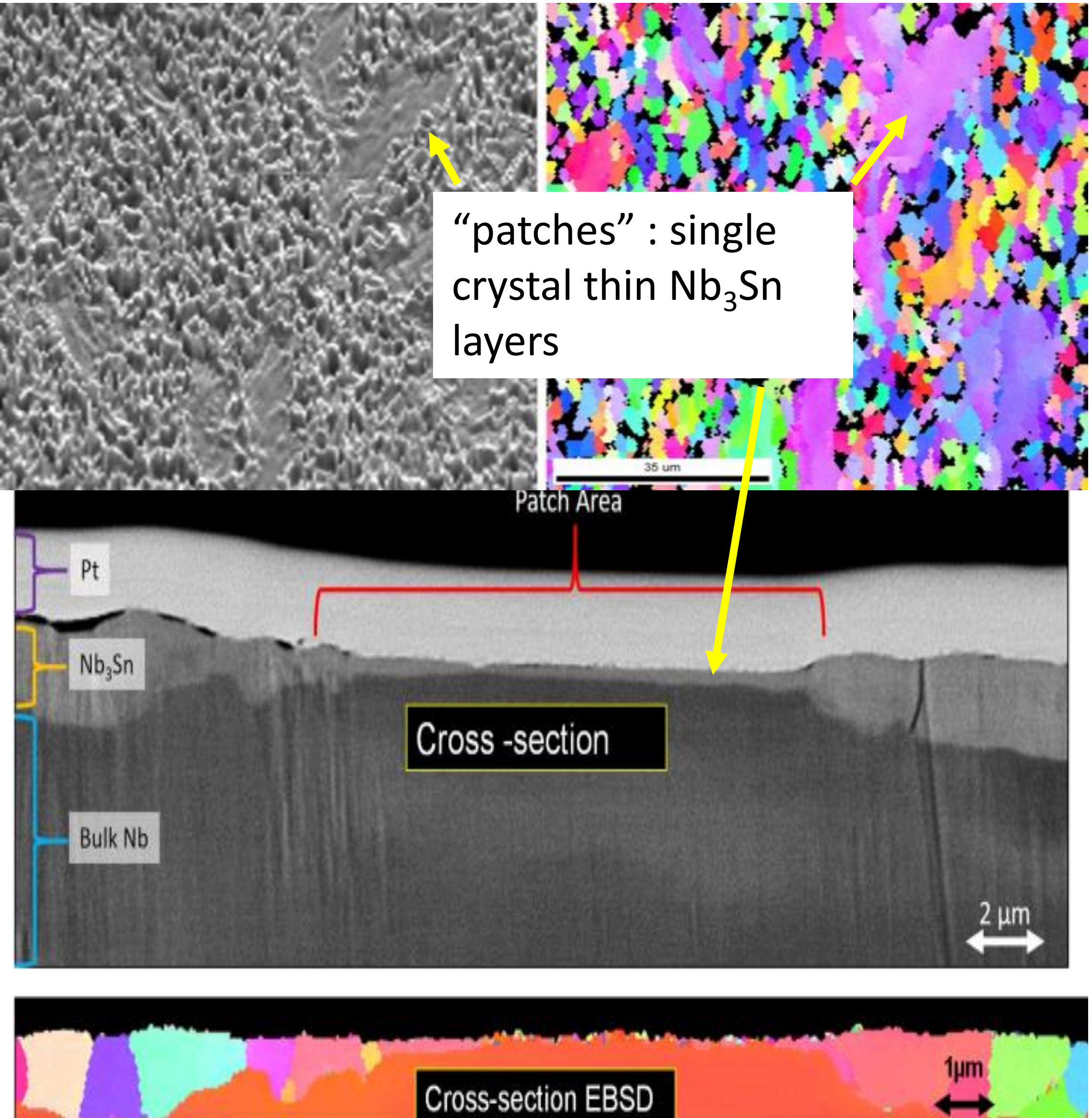


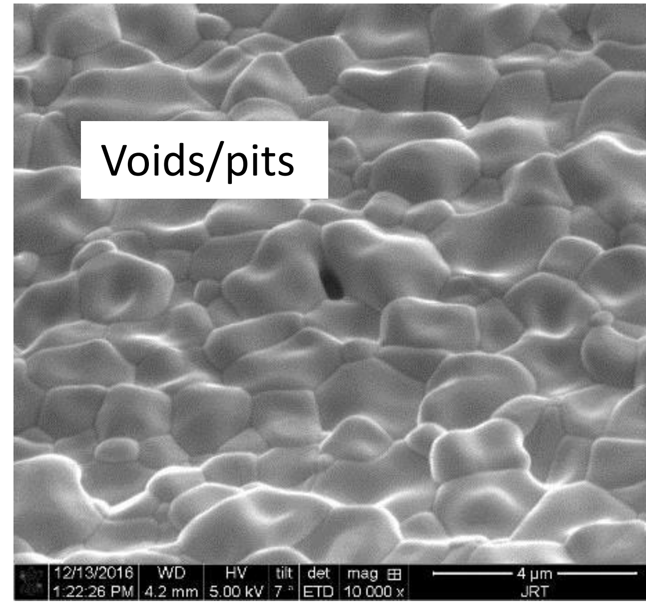
- Q-slope free Nb_3Sn-coated cavity was reproduced on another cavity
- Consistent Q_0 between Q-slope free cavities
- Q-slope limited performance for some coatings was linked to variation in Sn source; studies are ongoing
- RDT7, RDT10 & TE1G001 had NbTi flanges replaced with Nb flanges

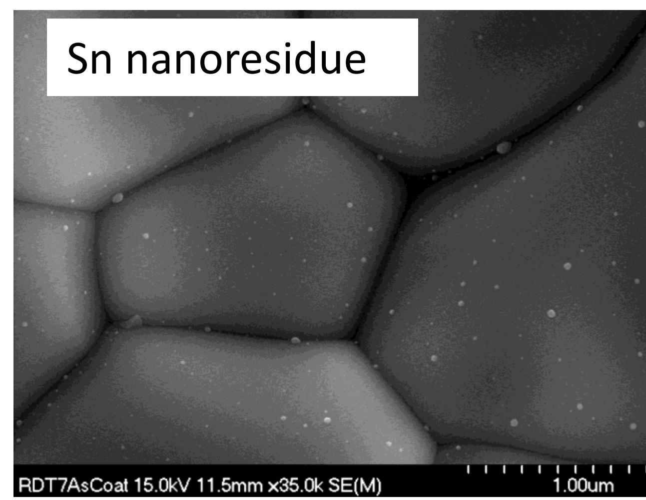
U. Pudasaini

U. Pudasaini, J. Tuggle

Nb_3Sn growth and defects

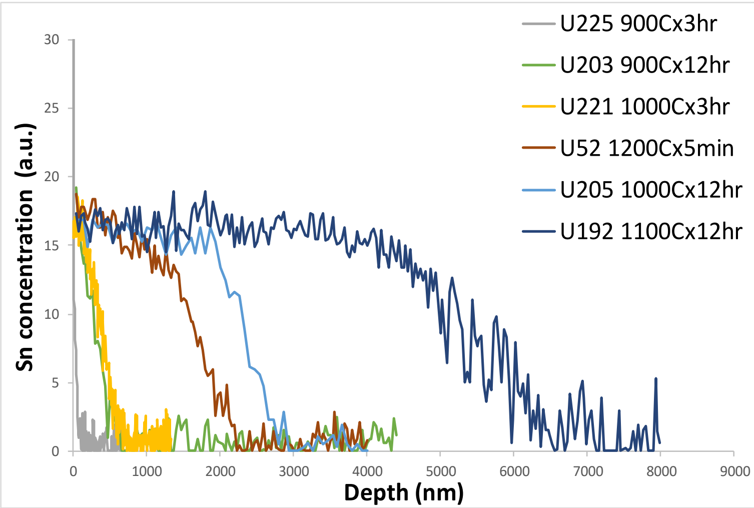


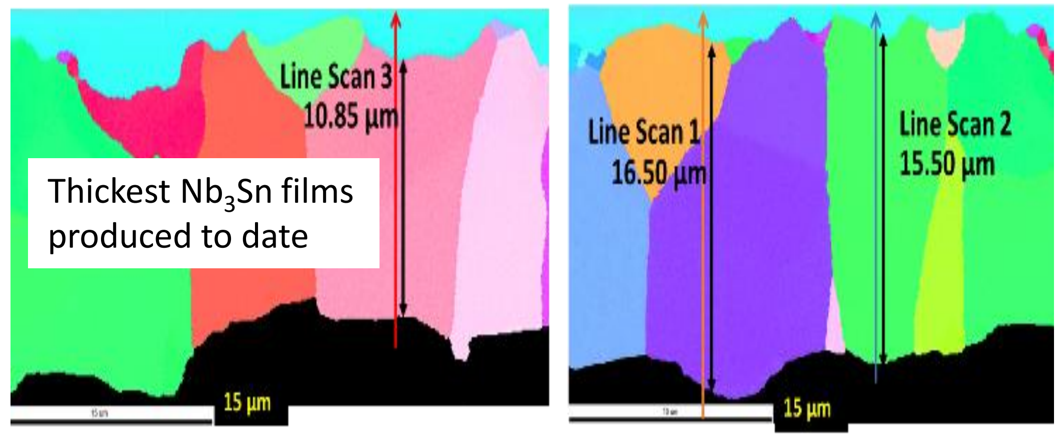




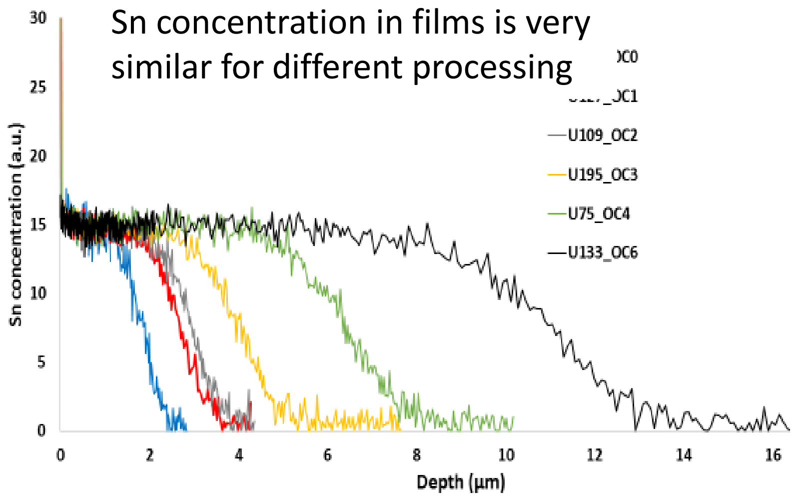
Concentration gradients

U. Pudasaini, J. Tuggle

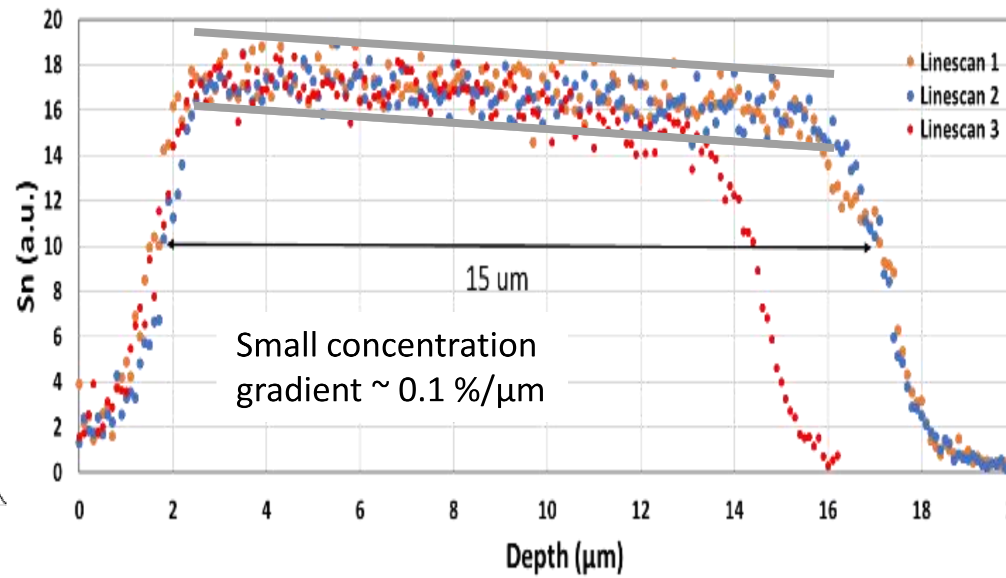




Thickest Nb_3Sn films produced to date



Sn concentration in films is very similar for different processing

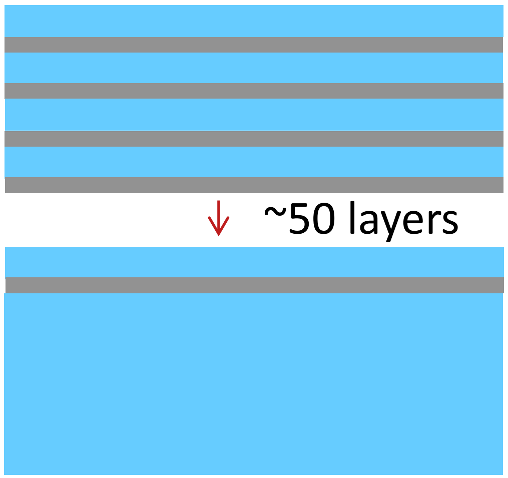


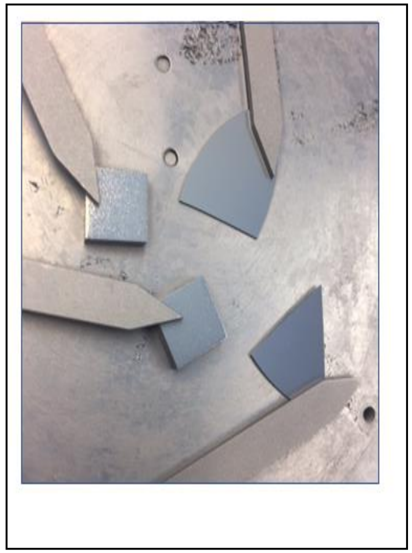
Small concentration gradient ~ 0.1 %/µm

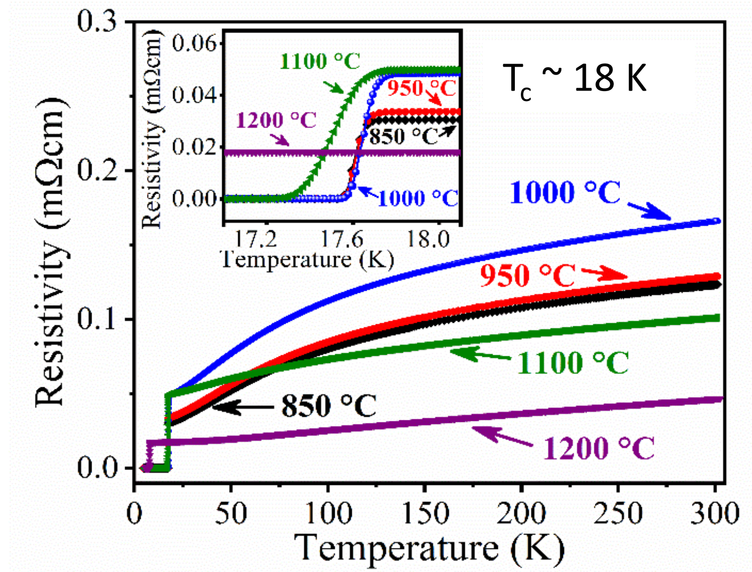
Md. N. Sayeed

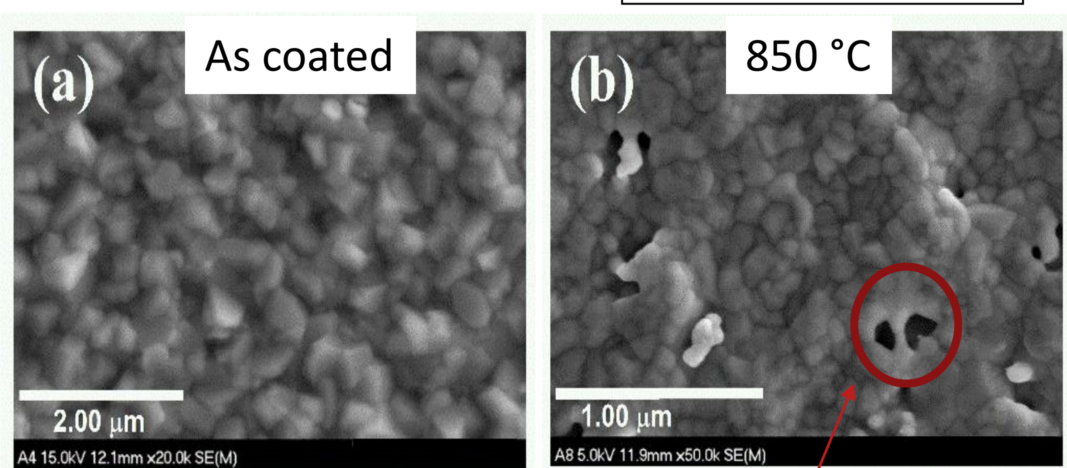
Concentration gradients, stoichiometry, and sputtering

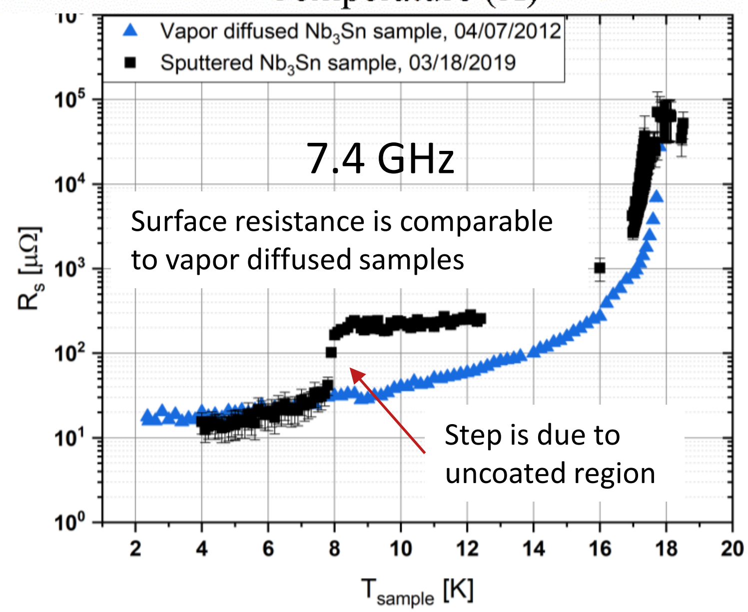
The goal : precise control of Sn content in Nb_3Sn films





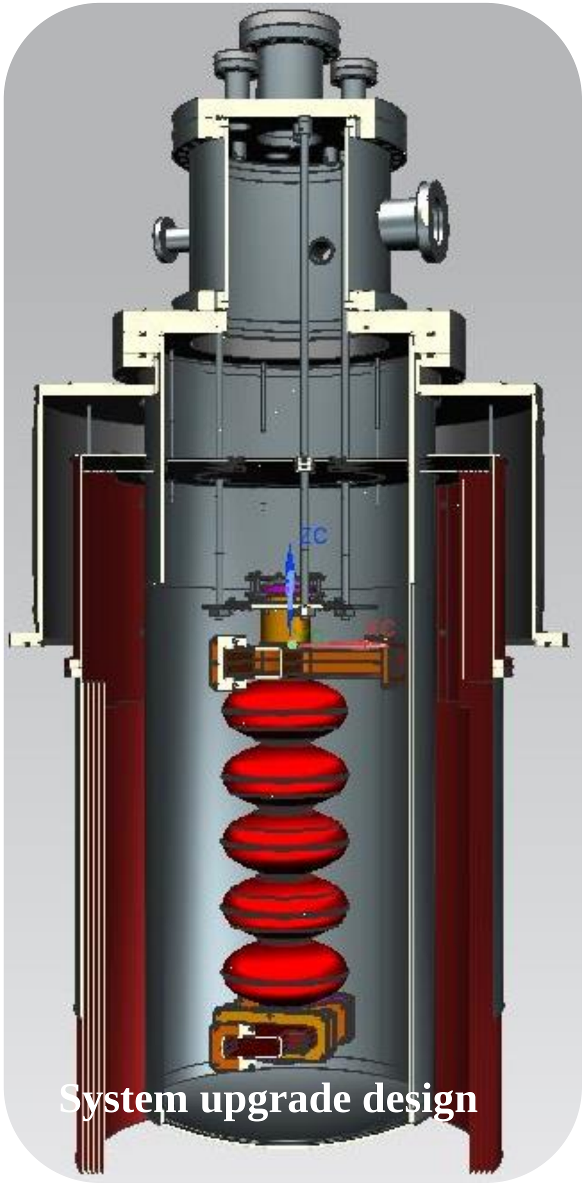






Needs to reduce/eliminate voids,
e.g., by adjust heat treatment

Application to 5-cell cavities

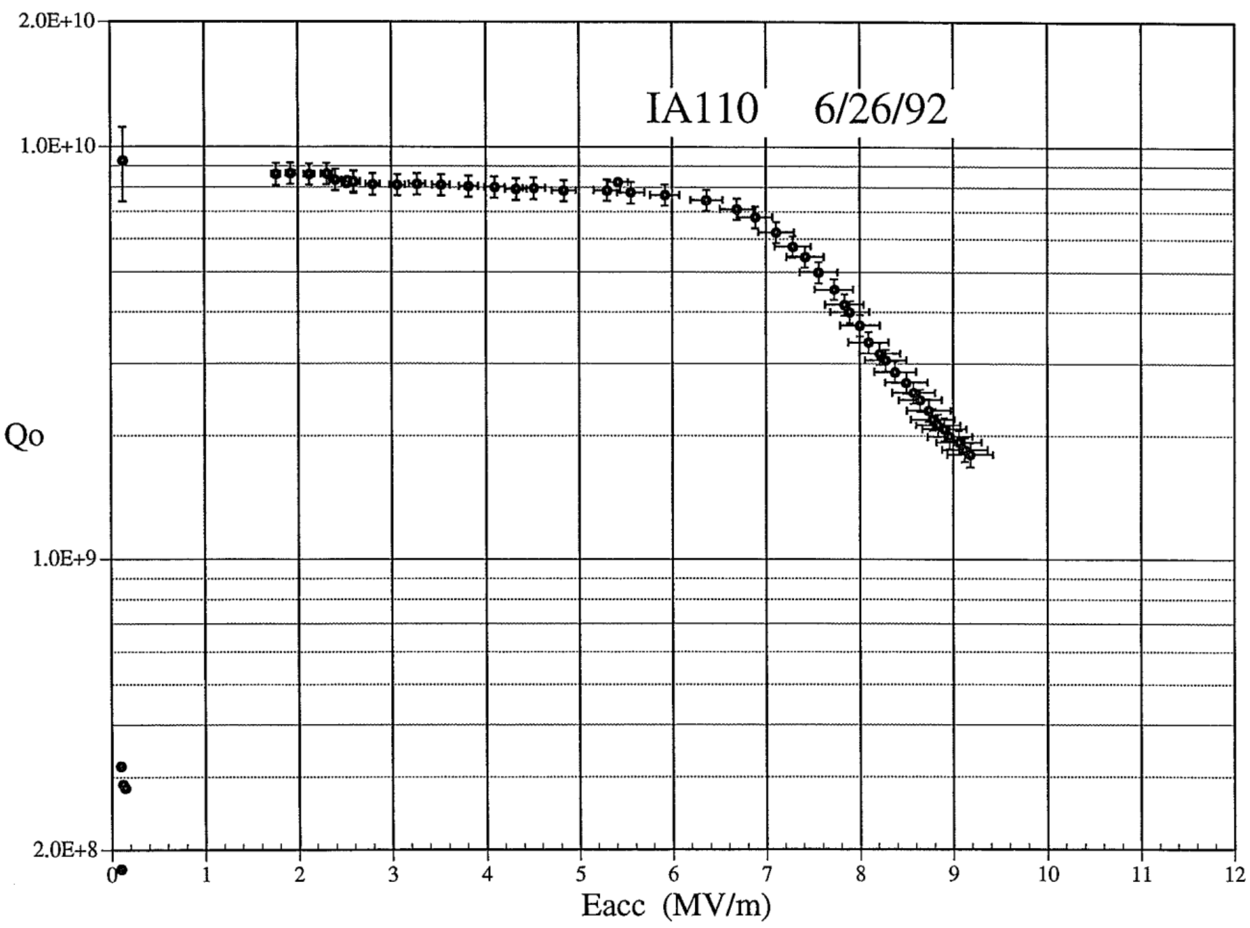

System upgrade design

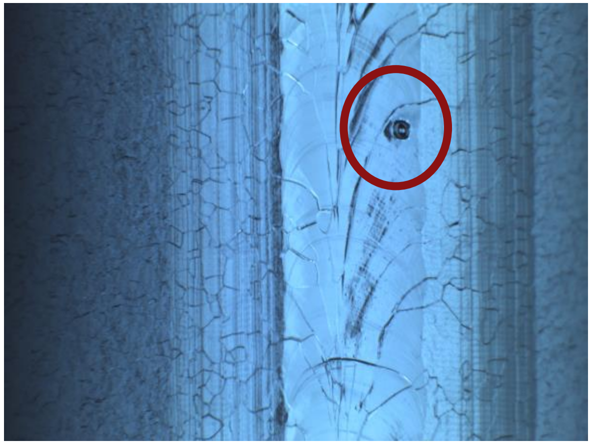

Upgrade commissioning


The new coating chamber


IA320 after coating

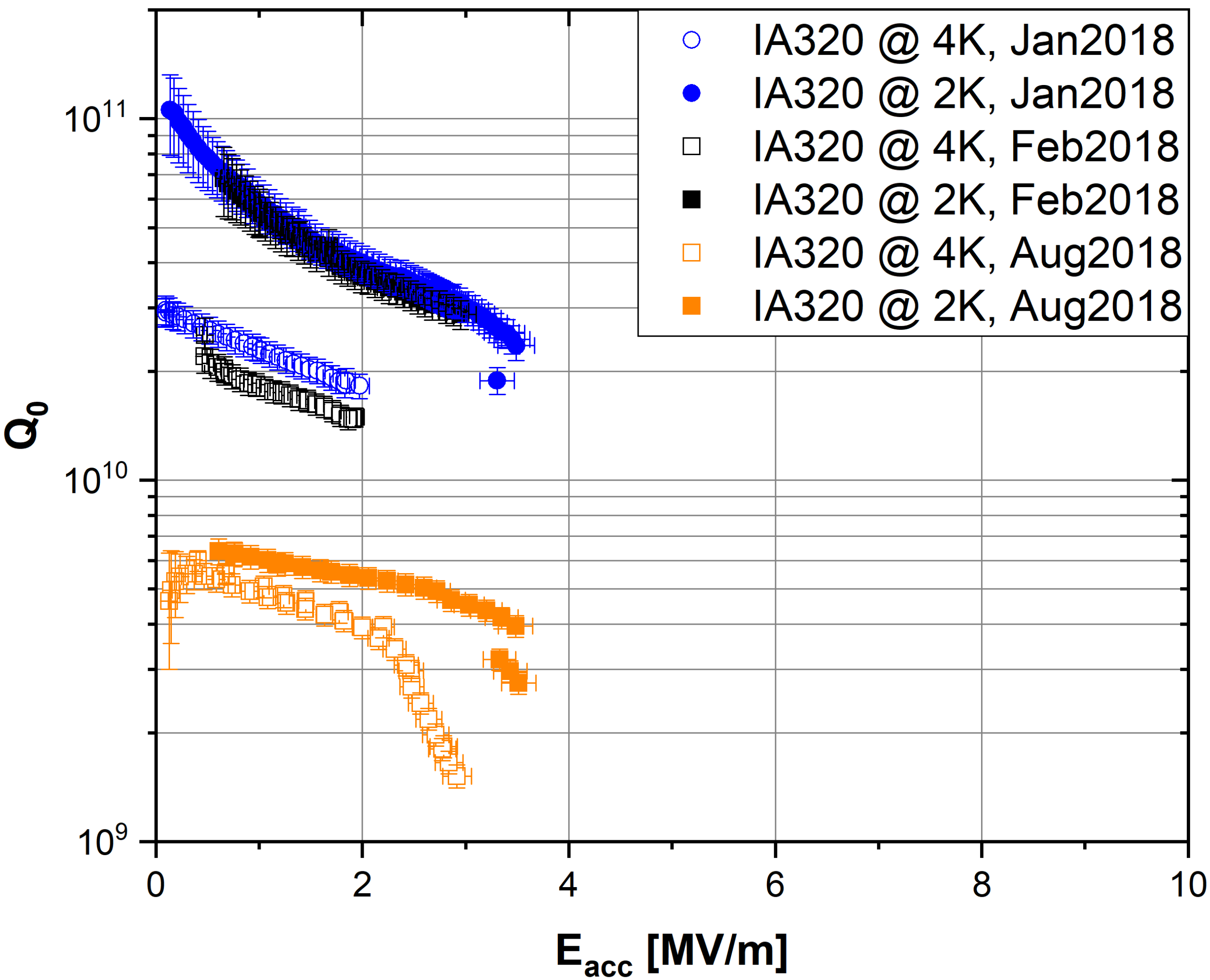
CEBAF 5-cell cavities





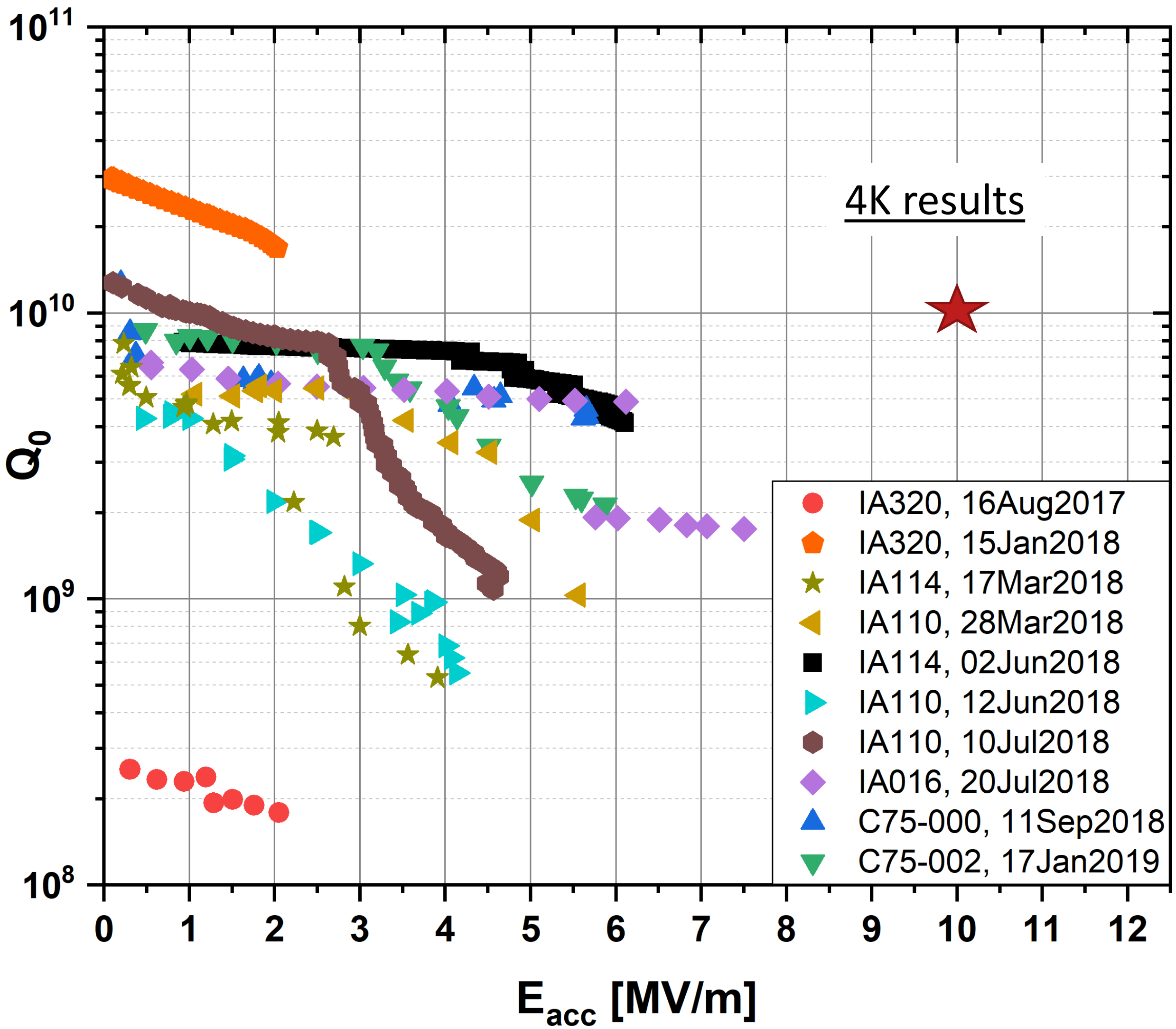
Tested by C. Reece!

5-cell cavity coating results

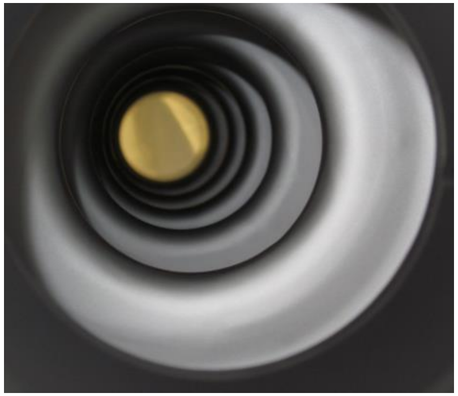


- **The first CEBAF cavity coated in the upgraded system**
- **The cavity limited at E_{acc} = 11 MV/m in the baseline test before coating**
- **Results are shown for the coating #8 done in Nov. 17**
- **Coated cavity had high Q_0(~ 10^{11}), but a strong Q-slope**
- **Re-tests after December 2017 to see if there is any degradation**
- **Clear degradation in August test…why?**

5-cell cavity coating results



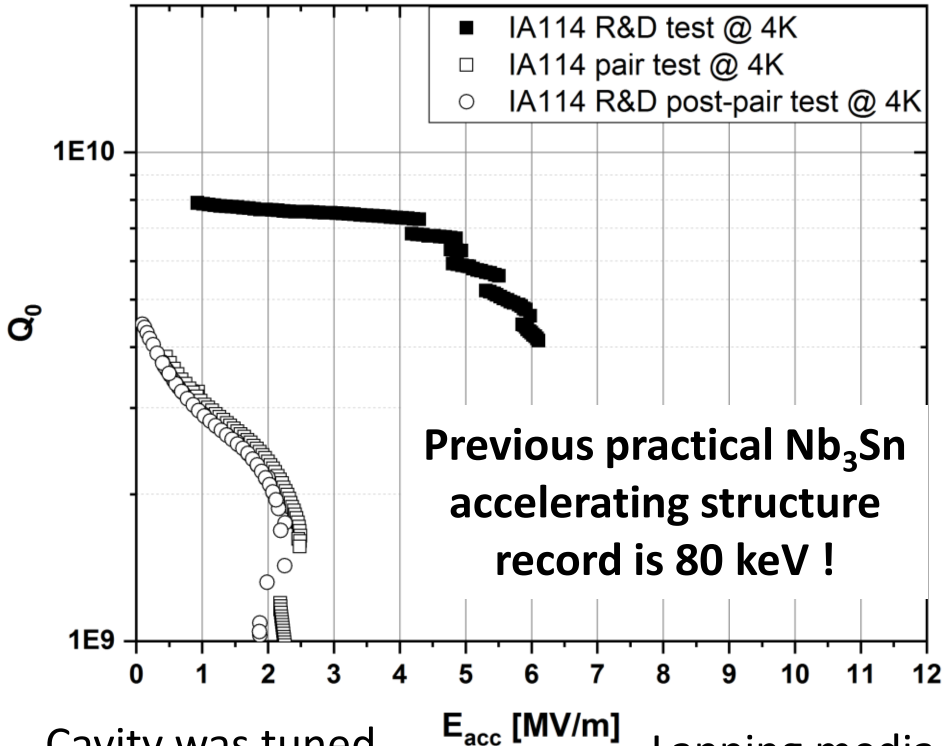
Uniform coating, no obvious asymmetry!



U. Pudasaini

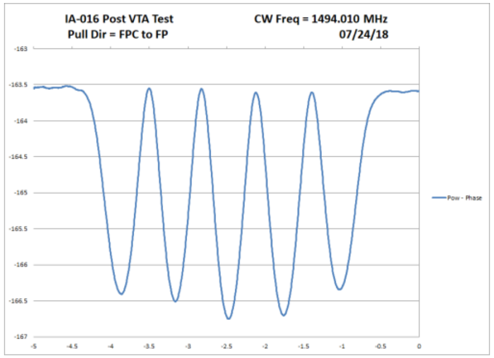
Jefferson Lab

Pair work and results

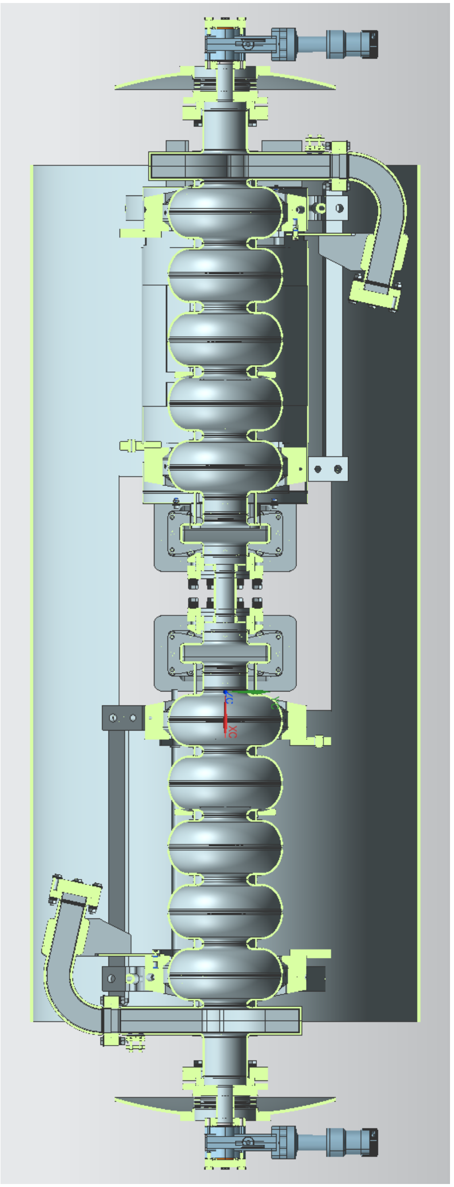


Previous practical Nb_3Sn accelerating structure record is 80 keV !

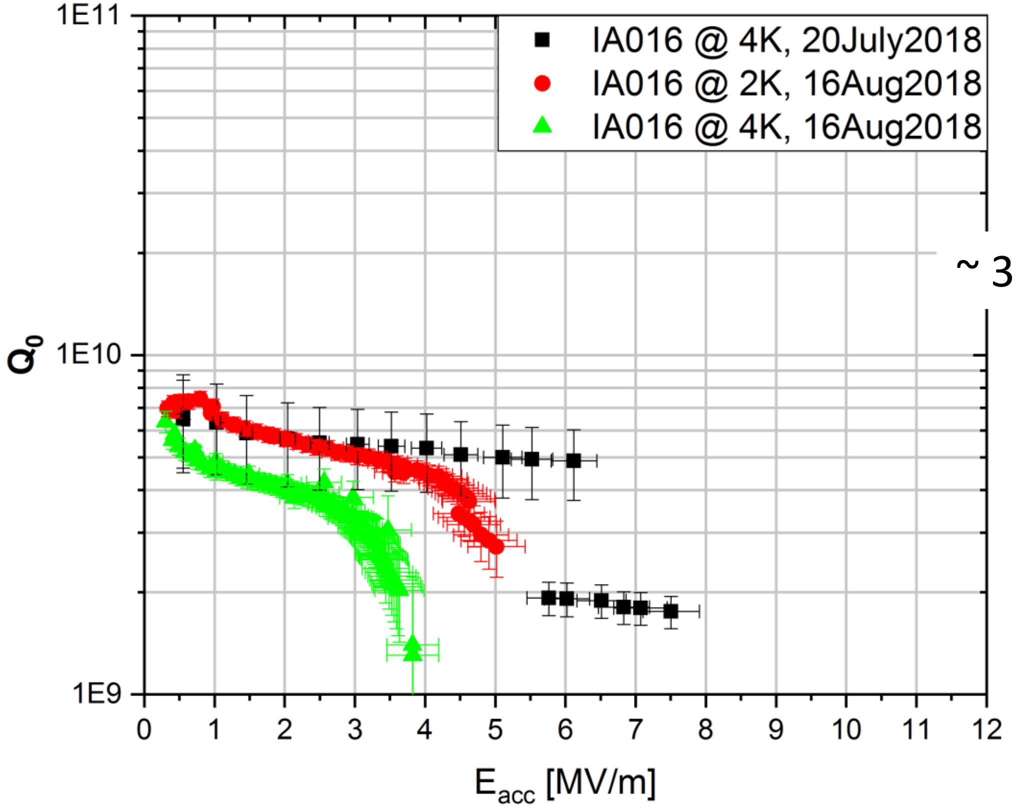
Cavity was tuned several times

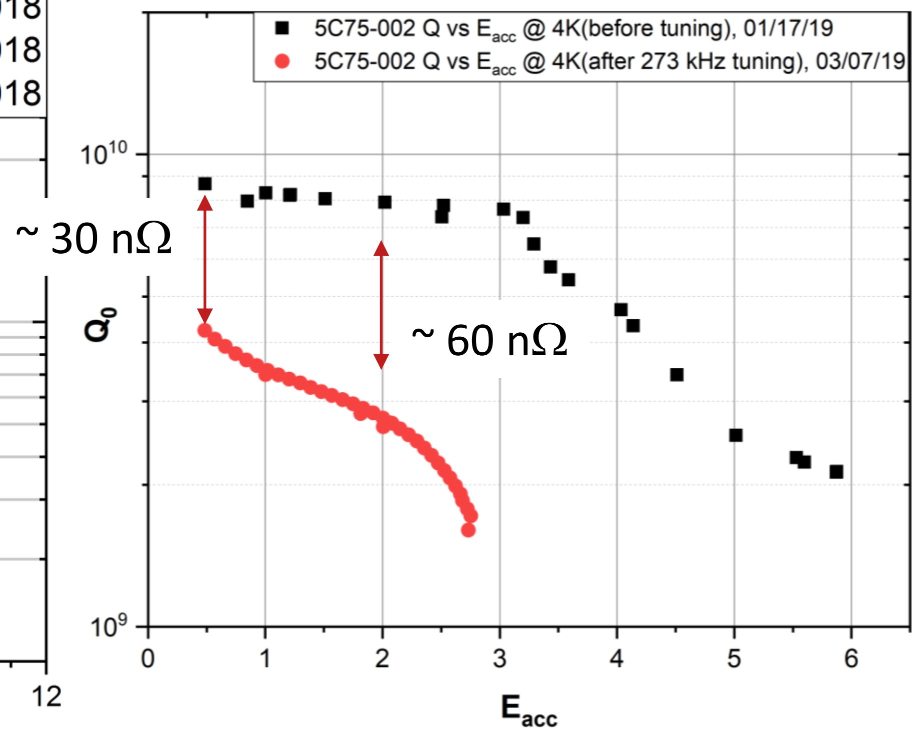


Lapping media after flange polish



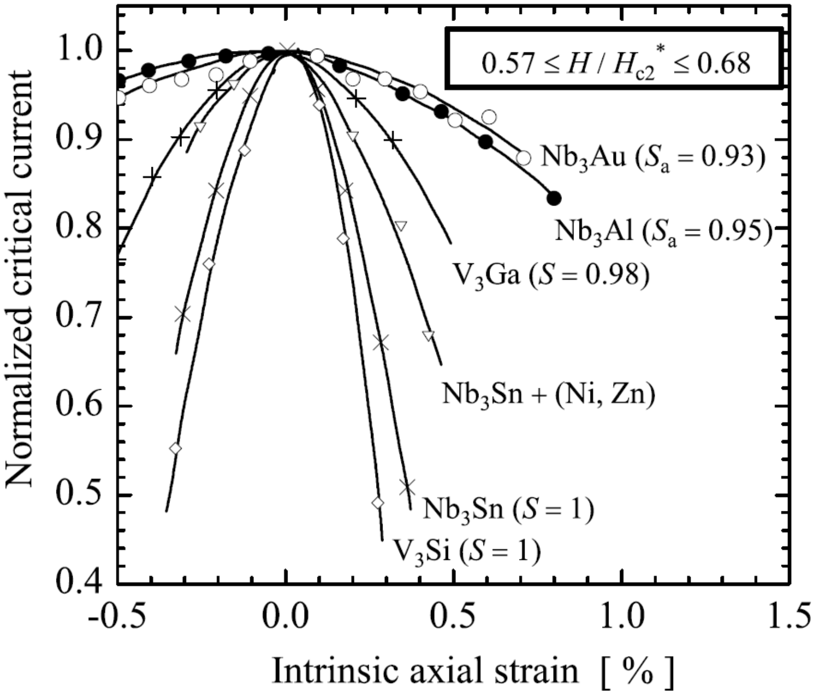
Pair work and results



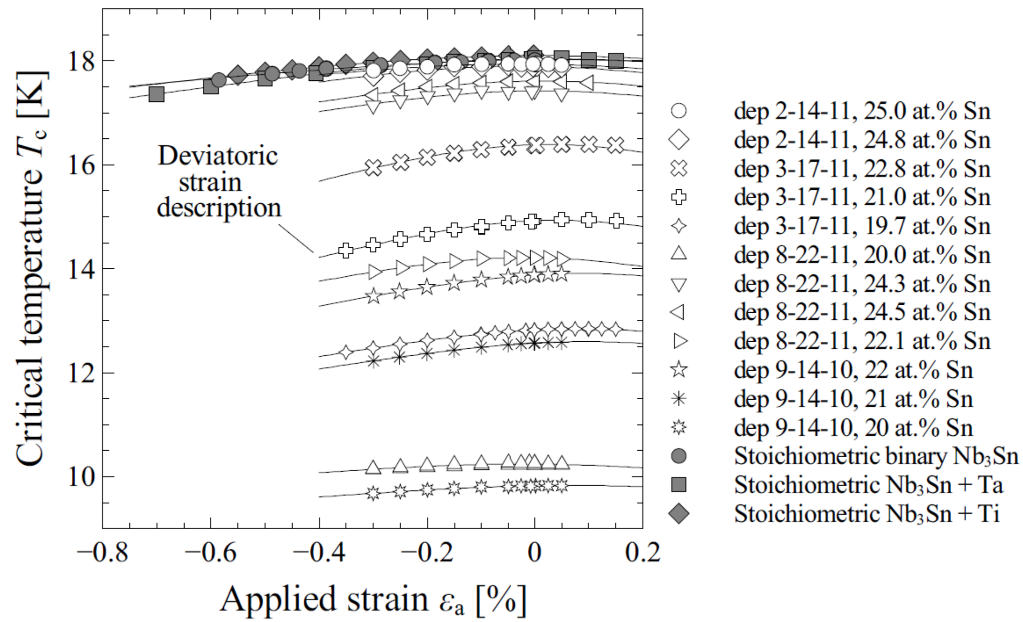


Quality factor and quench degraded after the cavity was tuned by about 200 kHz down. Tuning added field-dependent surface resistance, which increase by about 30 nΩ at low fields

Strain sensitivity



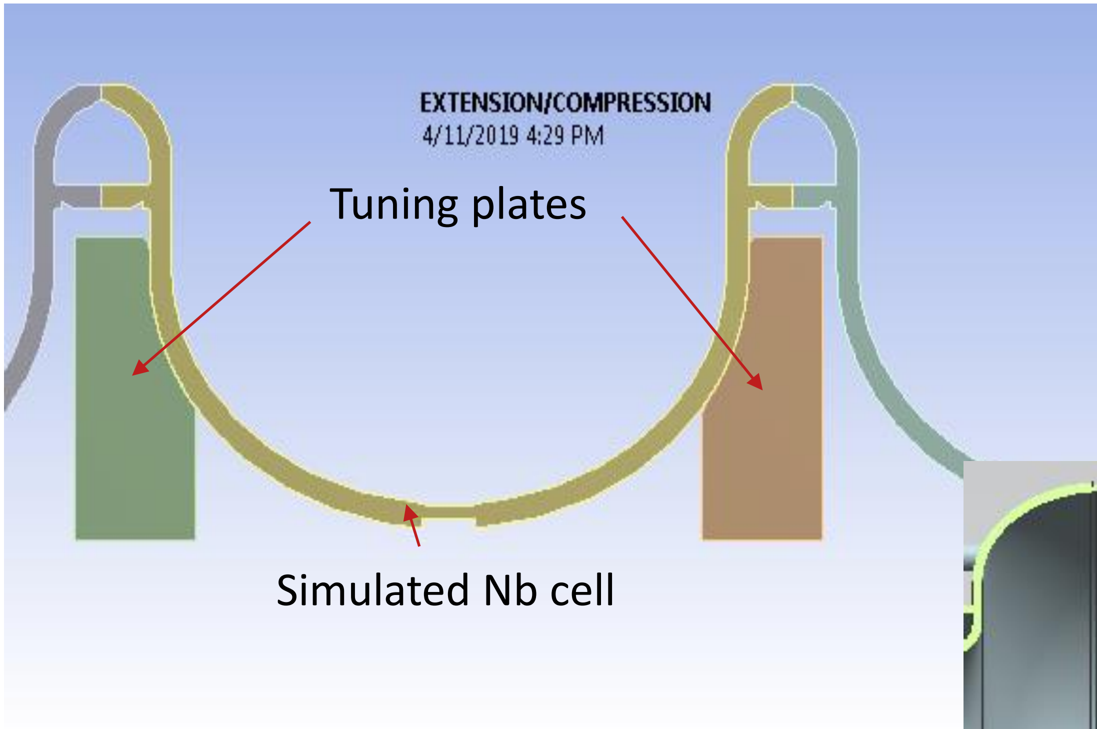
Degradation of critical current as a function of strain for some materials



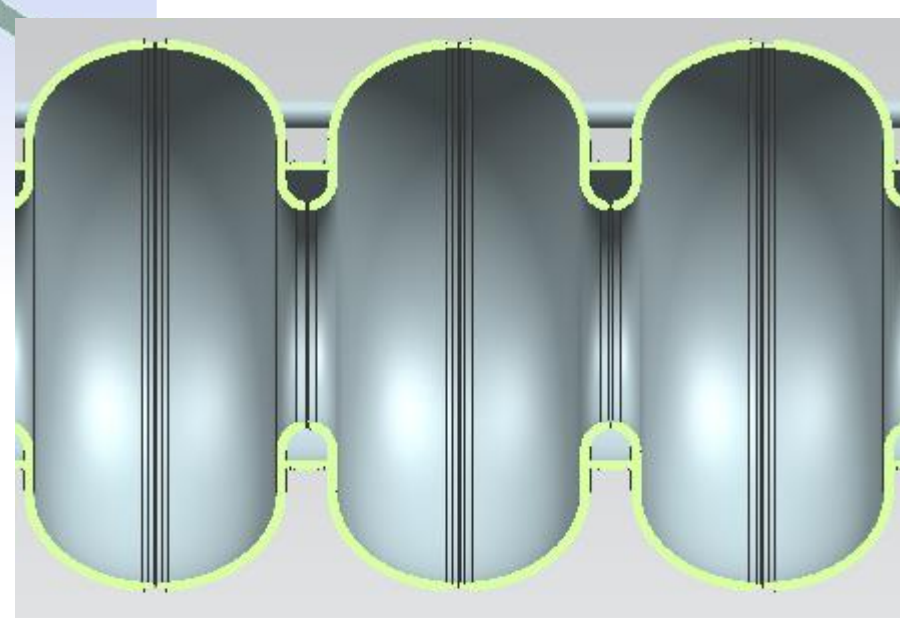
Dependence of the critical temperature on strain in Nb_3Sn

A. Godeke, Ph.D. dissertation
M. Mentink, Ph.D. dissertation

Tuning simulation



1 mm change in the cavity length corresponds to ~ 300 kHz of the frequency change

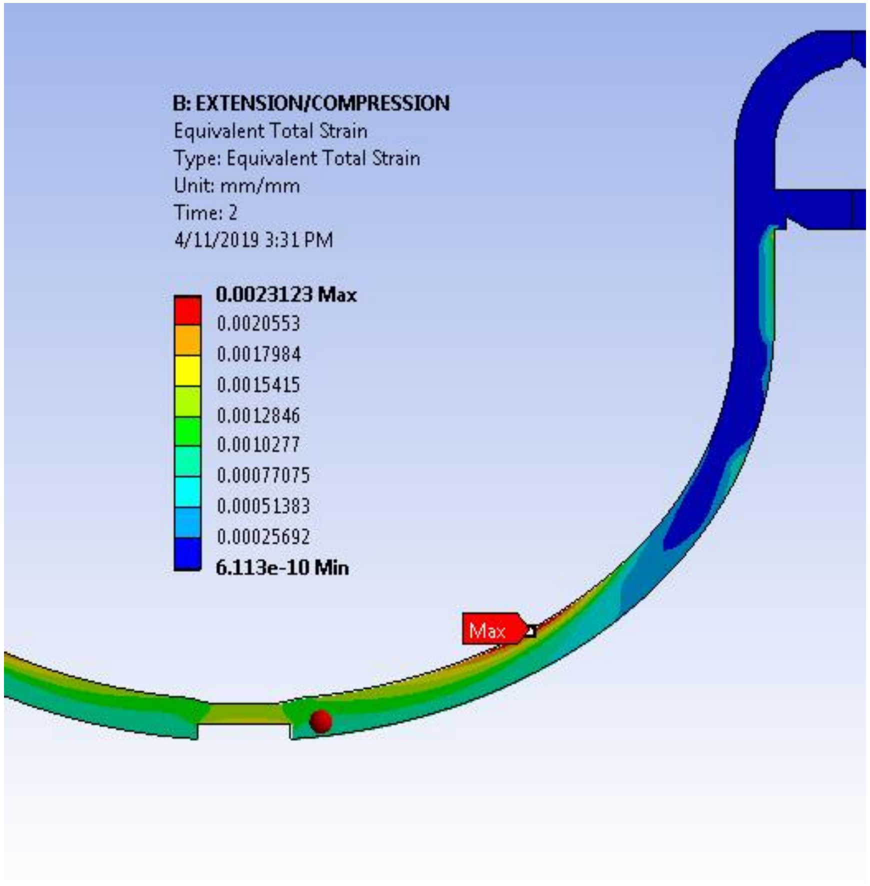


The goal was to simulate compression and extension of the center cell. The cavity needs to be squeezed/stretched beyond the desired frequency change in order to achieve the desired plastic deformation.

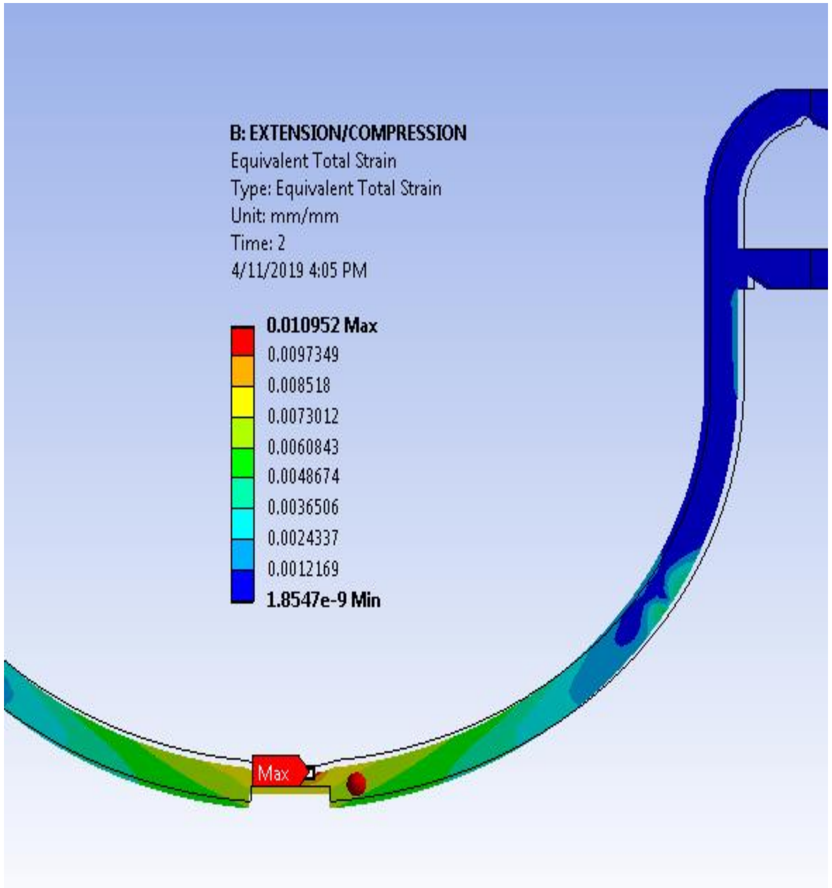
Simulation by W. Crahen

Tuning simulation

Equivalent Total Strain : 0.71 mm jaw compression yields 0.25 mm deformation

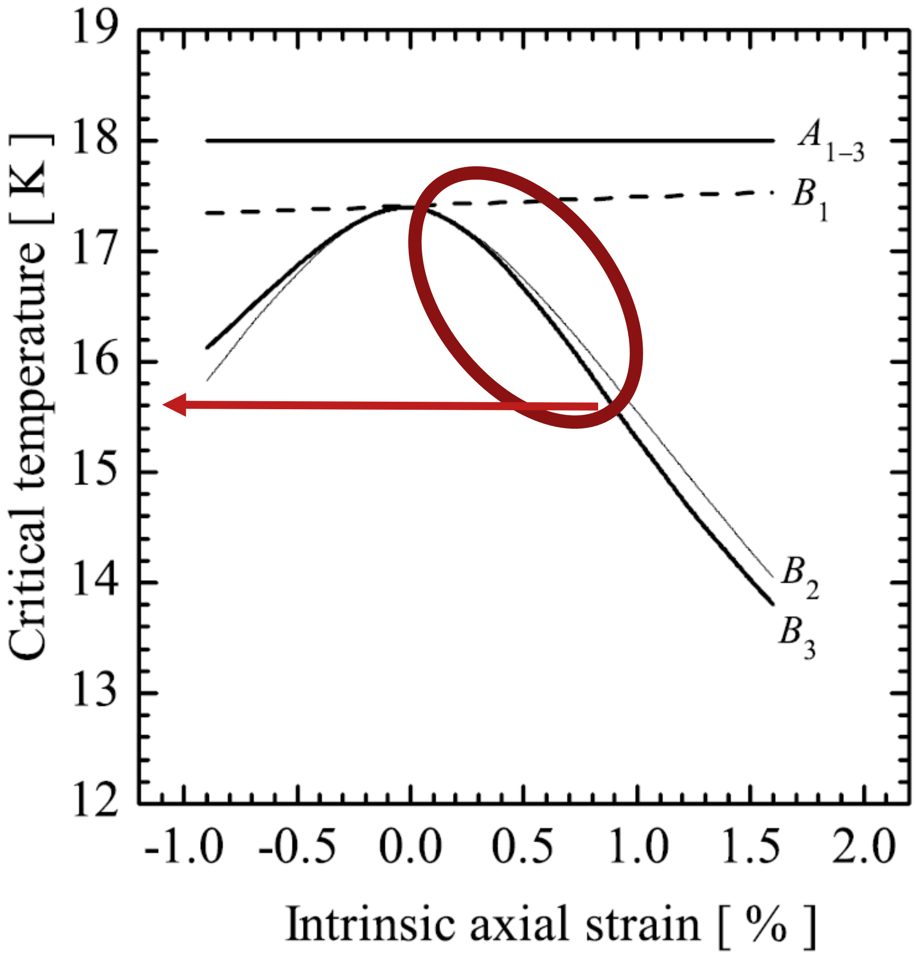


Equivalent Total Strain: -1.445 jaw compression yields 1 mm deformation

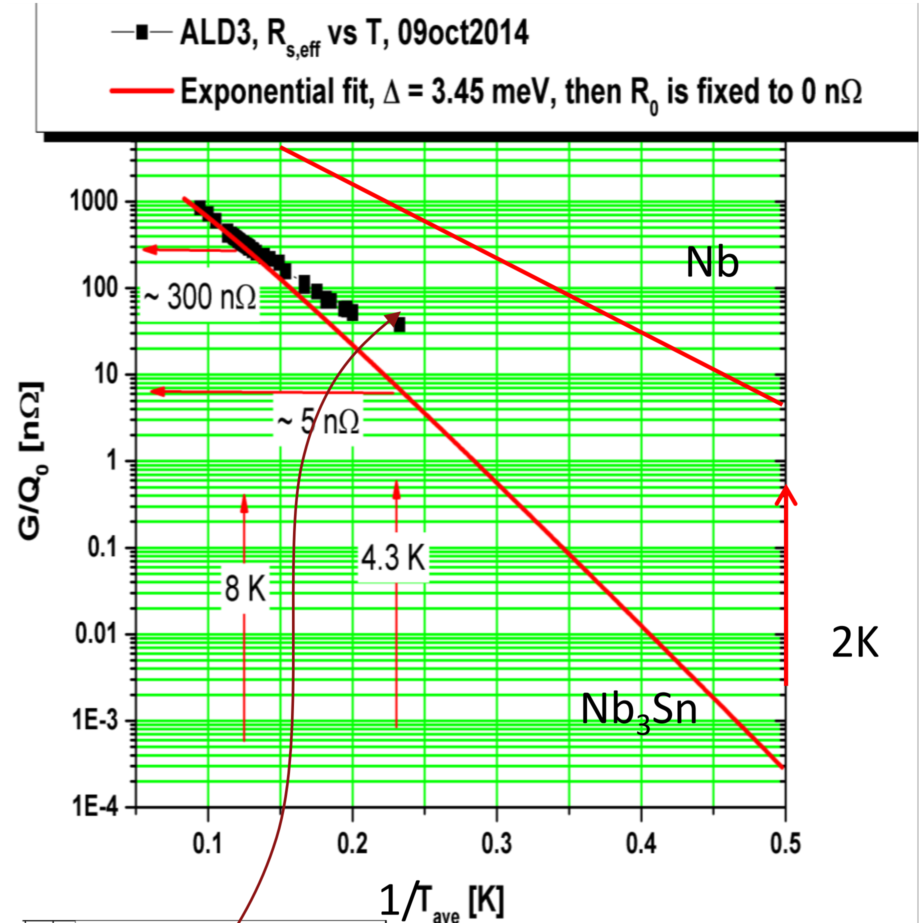


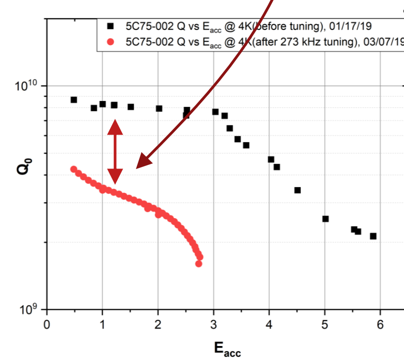
Simulation by W. Crahen

Tuning simulation



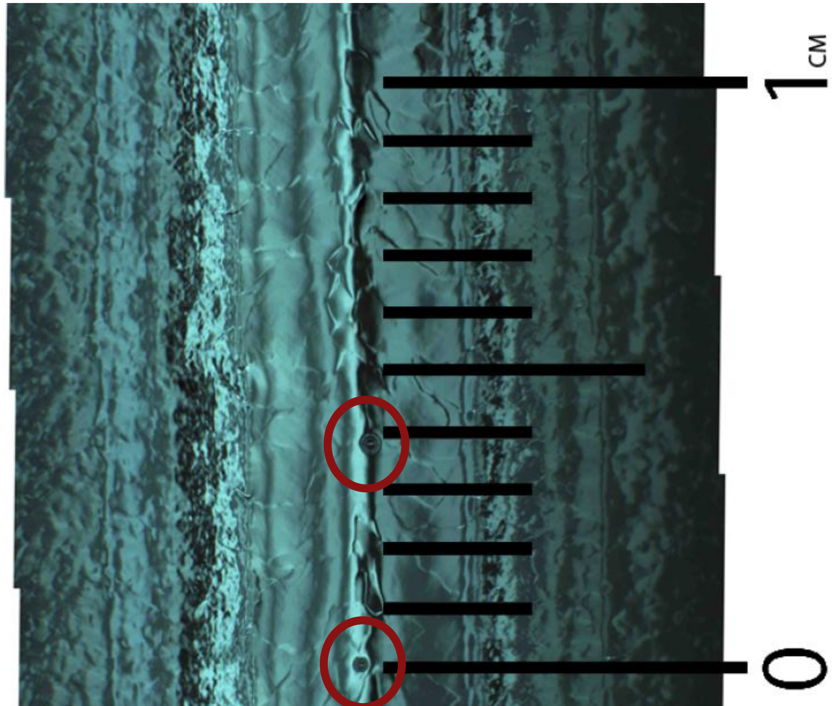
A. Godeke, Ph.D. dissertation

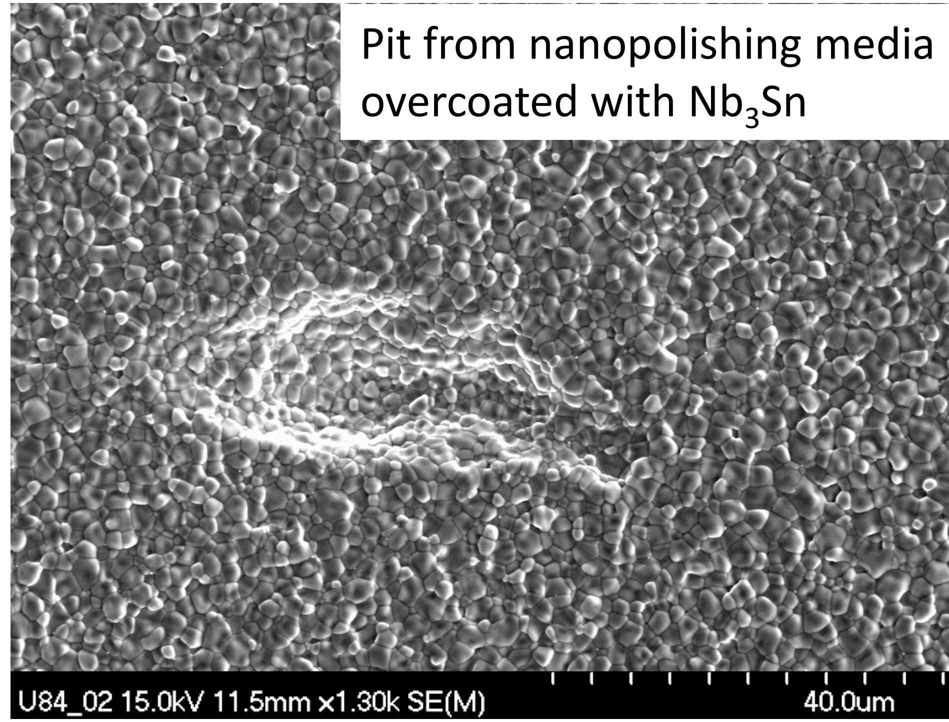




Expected degradation due to T_c reduction is not consistent with the measurement

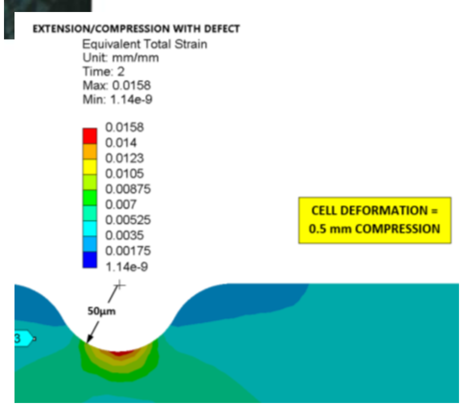
Weak points?

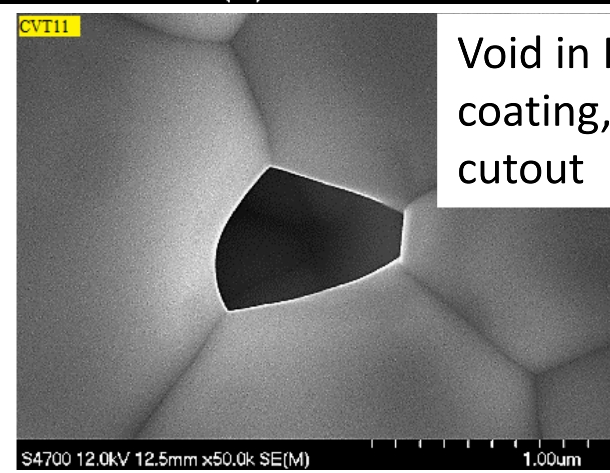




Pit from nanopolishing media overcoated with Nb_3Sn

Surface imperfection are likely high stress points, where strain exceeds the average levels and significantly degrades surface resistance → smoothen the surface by centrifugal barrel polish

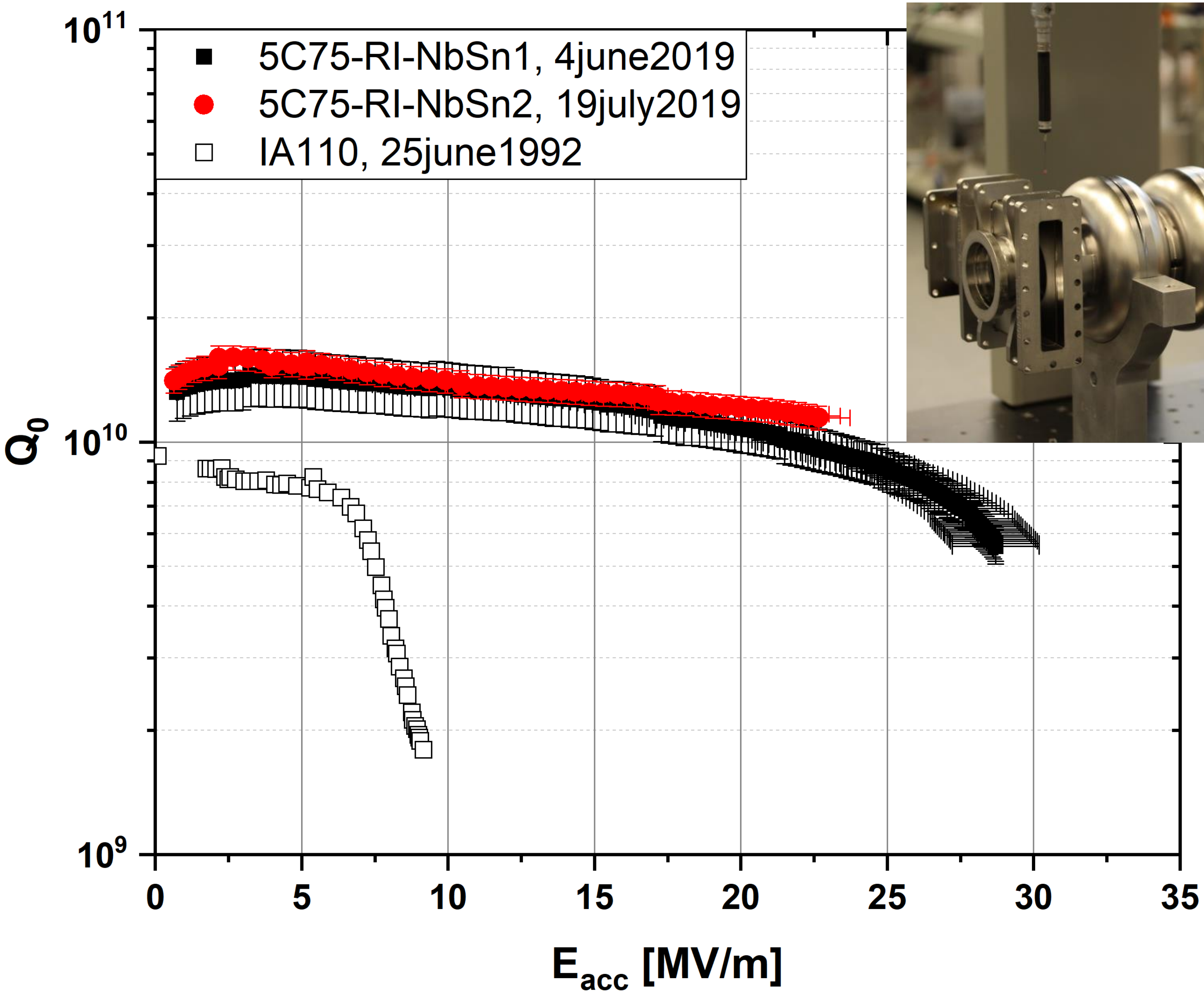


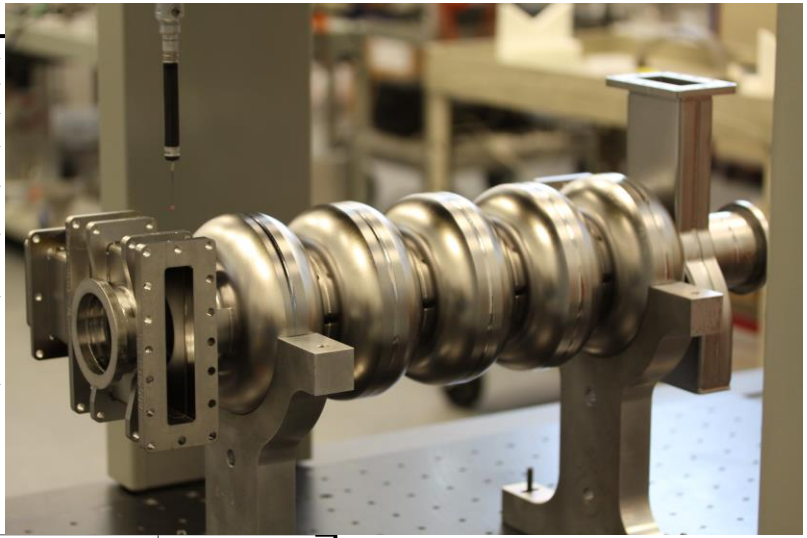


Void in Nb_3Sn coating, C3C4 cutout

The quality of the substrate could be important…

Baseline test of the new C75 cavities for Nb_3Sn project

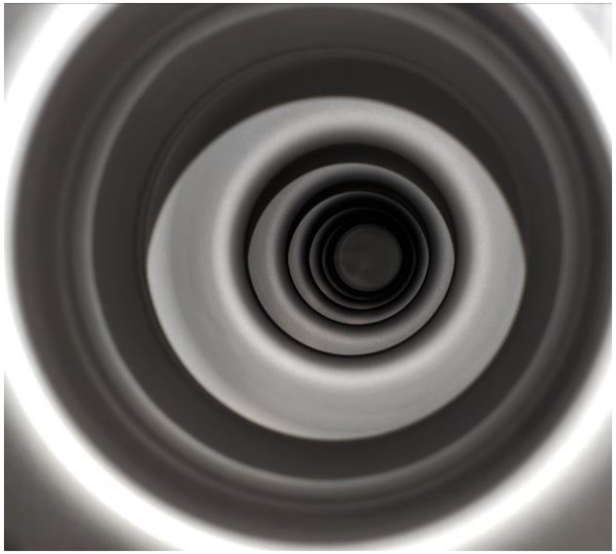




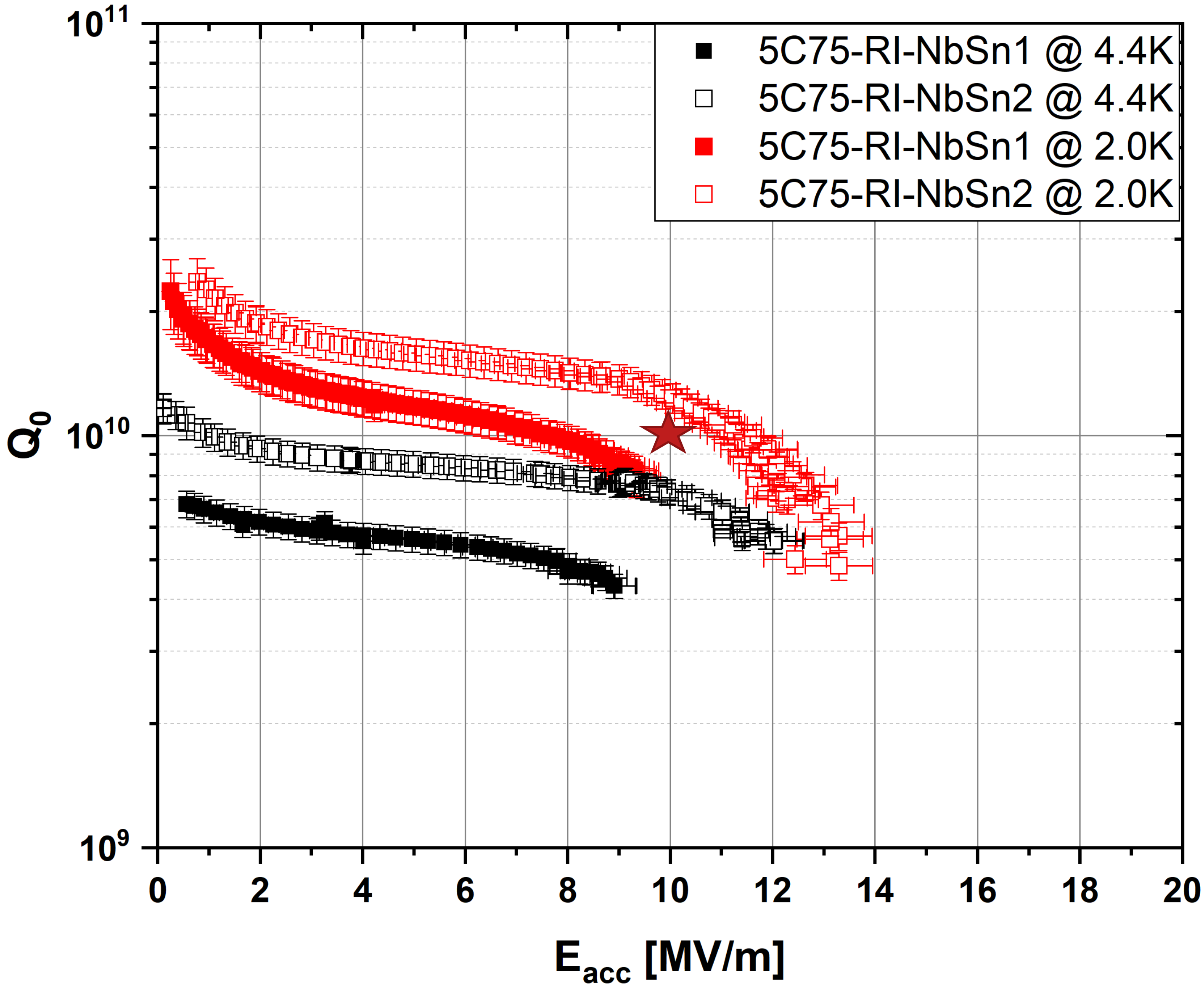
C75 cavity coating

U. Pudasaini

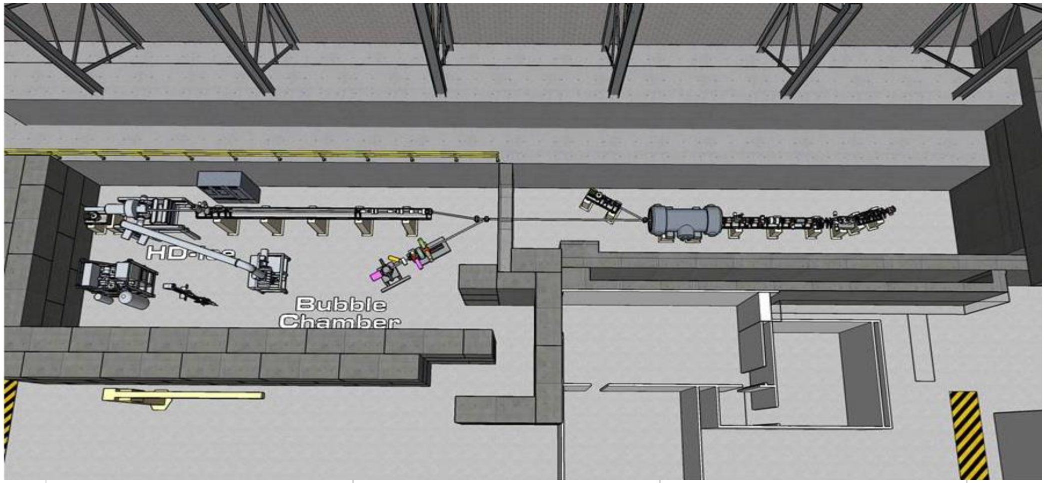
Uniform coating, no obvious asymmetry… in the second cavity!

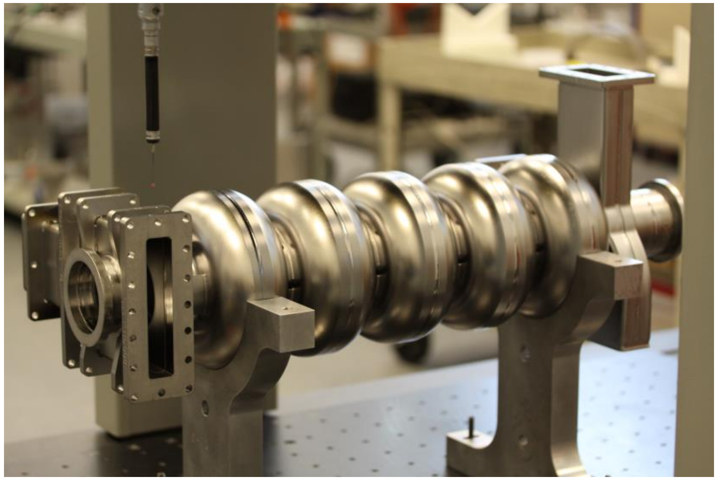


Nb_3Sn-coated C75 cavity test results



Installation of Nb_3Sn-coated C75 into UITF



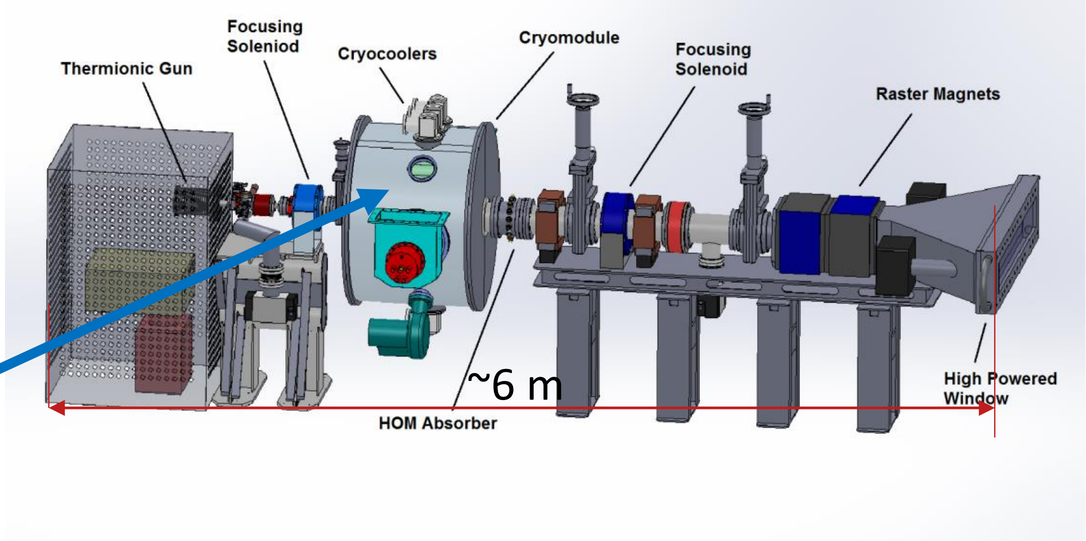


Application	Beam Energy	Beam Current	Experiment Duration	Notes	Presenter
Commission QCM for CEBAF	6 MeV, but prefer up to 10 MeV	up to 100 uA	three or four 1-week long tests	tests complete before long shutdown of 2020, when QCM to be installed at CEBAF	R. Kazimi
Commission HDIce for CEBAF	~ 8 MeV	up to 100 nA for tuning, 0.25 to 5 nA for production	four or five run periods, one-month long each	target provides transverse polarization required for 3 A-rated Hall B experiments	A. Sandorfi
Manufacturing polarized targets for CEBAF via DNP	1 - 10 MeV	1 to 10 uA	hours, days	likely some R&D to determine optimum polarizing conditions	C. Keith
Bubble Chamber astrophysics	4 - 10 MeV	0.01 to 100 uA	3 weeks, as often as possible	UITF better location than CEBAF injector, when CEBAF shutdowns are short	R. Suleiman
MeV parity violation experiment	10 MeV	milliamps preferred, will reduce experiment duration	months to years	requires polarized electron beam, transmission geometry offers advantages	R. Carlini
Testing Nb3Sn-coated cavities	determining the beam energy of test cavity is point of test	up to 100 uA	as many tests as possible	Nb3Sn cavities require only 4K Helium	G. Eremeev
Wastewater treatment	2- 10 MeV	100 uA	imagine week-long test durations over three years	together with local partners	G. Ciovati
Polarized positron source	5 - 10 MeV	up to 100 uA	staged tests, likely many required, 1-week long duration	requires polarized electron beam	J. Grames
EIC: fast kicker tests	5 - 10 MeV	up to 100 uA	two 1-week long tests	together with sbir-partner	H. Wang
EIC: testing high bunch charge	5 - 10 MeV	up to 100 uA	two 1-week long tests	requires polarized electron beam	J. Grames and J. Guo

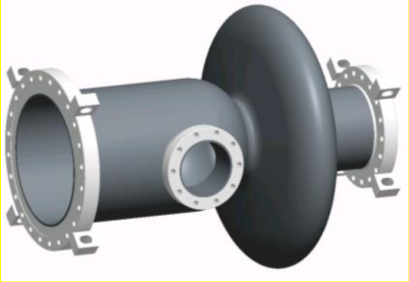
Strain sensitivity is not necessarily an issue for new designs

Compact high-power CW SRF accelerator for industrial application

- 1-year design collaboration among JLAB, AES, General Atomics
- Funded by DOE-HEP (Accelerator Stewardship)
- Use in wastewater and flue-gas treatment
- 1 MeV, 1 A electron beam

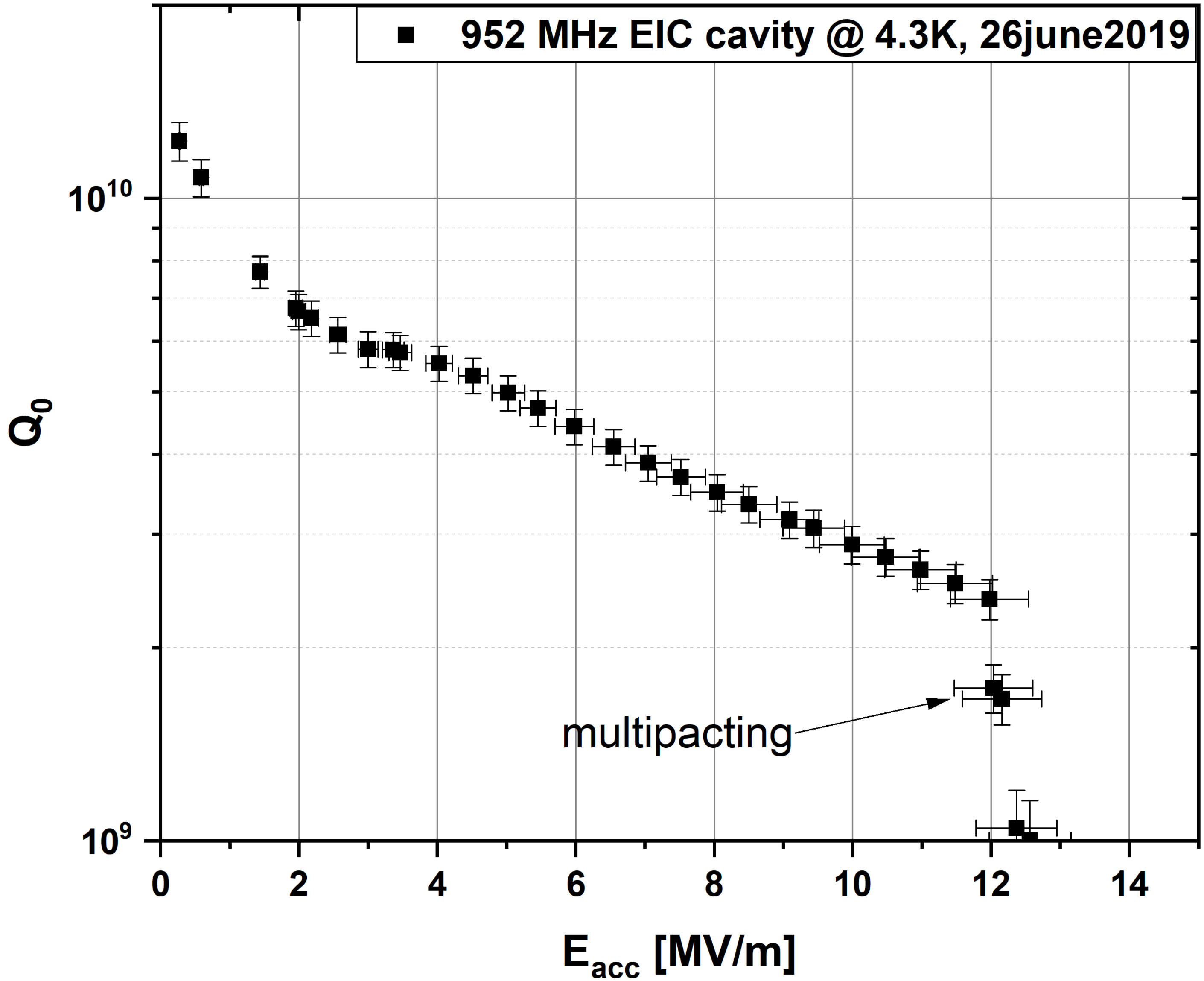


$Nb_3Sn/Nb/Cu$ β=0.5 single-cell cavity, conduction cooled with four 1.5 W cryocoolers

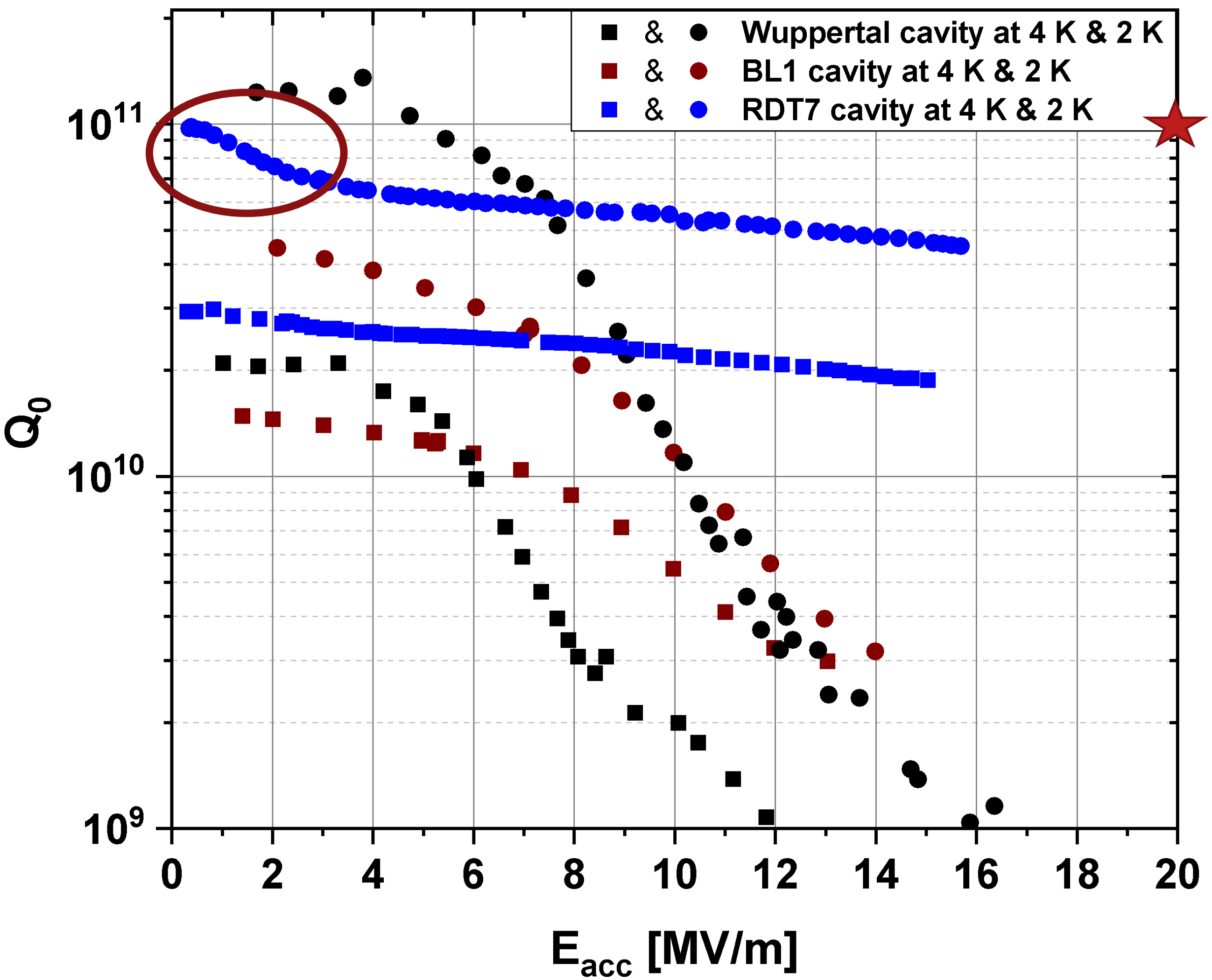


- Patent on Cryomodule design filed on 01/29/18

Nb_3Sn-coated 952 MHz cavity



Summary #1 : high-Q Nb_3Sn layers

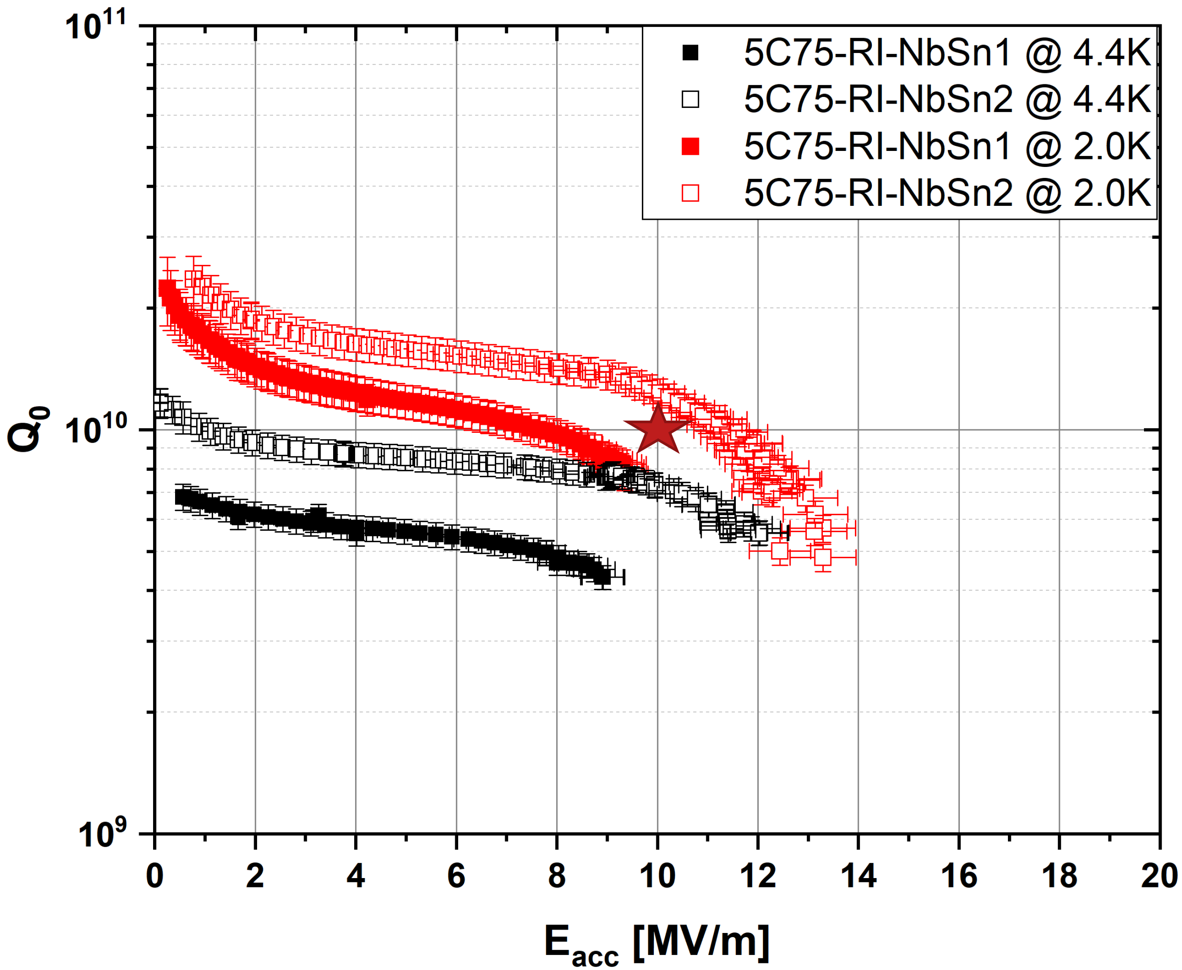


The goal is to optimize the coating process towards Q_0 of 10^{11} at E_{acc} = 20 MV/m at 2 K.

- Cavities w/o Q-slope were produced in "Siemens" configuration
- Q_0 of 10^{11} are measured at low fields
- Current focus is on low-field and medium field Q-slopes
- Temperature-controlled Sn source is being built
- It may be challenging to consistently reach E_{acc} = 20 MV/m w/o cleanroom around the coating system.

U. Pudasaini

Summary #2 : Nb_3Sn for practical applications

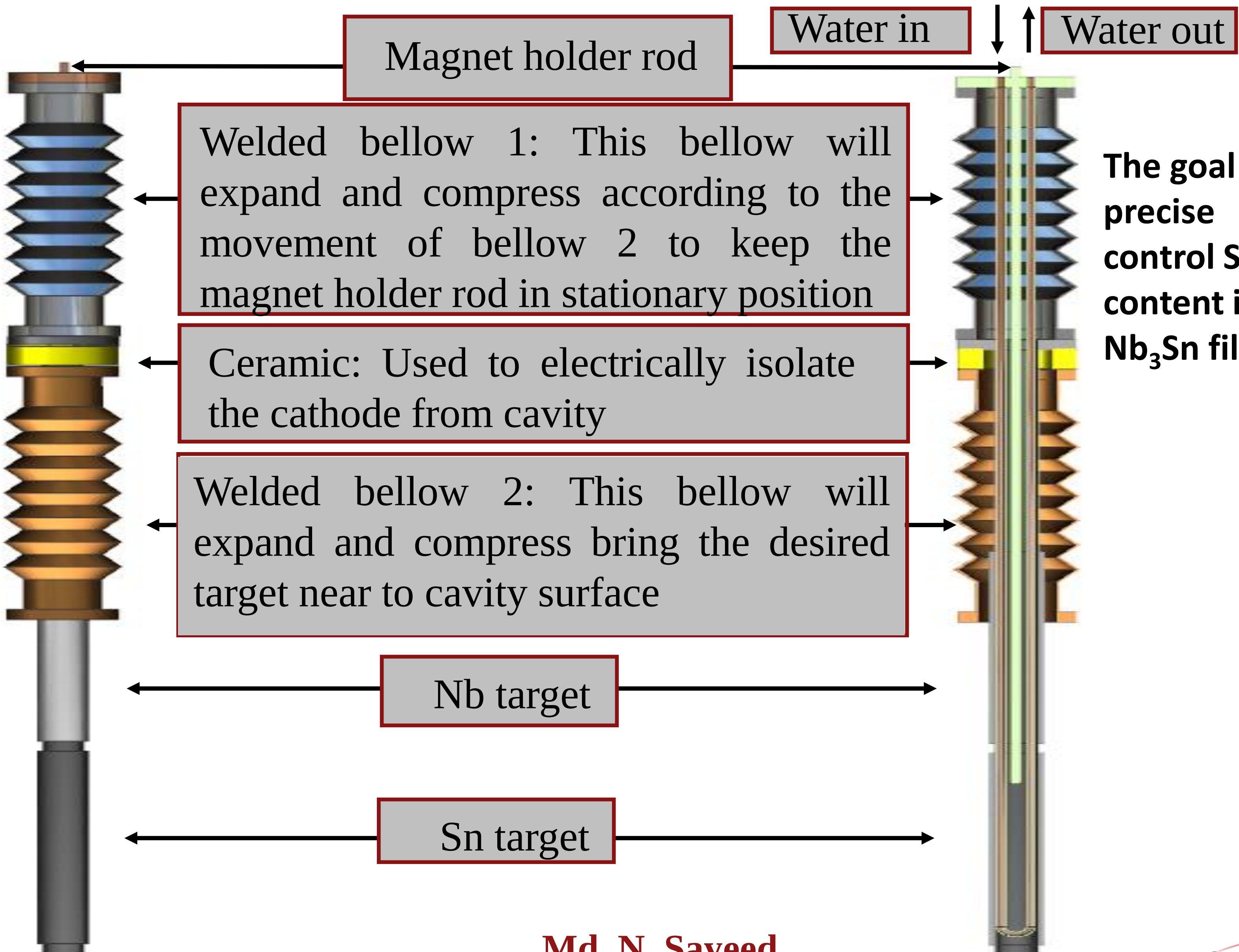


The goal is to study coating degradation by accelerating electron beams in a cryomodule with Q_0 of 10^{10} at E_{acc} = 10 MV/m at 4 K.

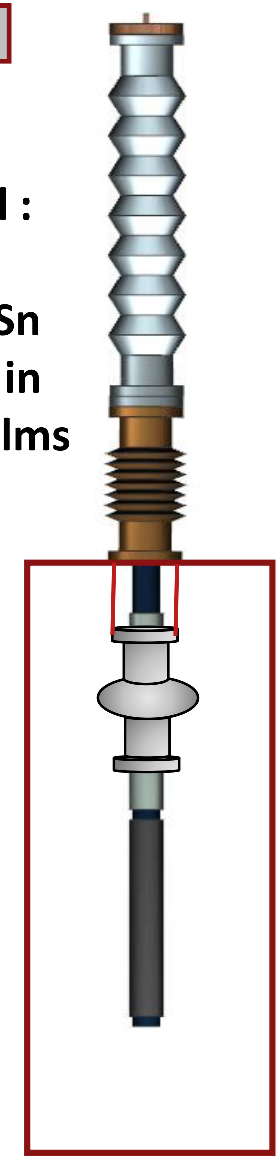
- Substrate issues were resolved with the two new C75 cavities
- Discovered significant degradation after tuning likely related to surface features
- Possible mitigations are smooth surface and minimized tuning
- The best solution may involve redesign of a quarter cryomodule

Jefferson Lab

Summary #3 : optimum Nb_3Sn layers



The goal : precise control Sn content in Nb_3Sn films



Thank you for your attention!