Nb_3Sn for SRF applications

High efficiency cavities for future accelerators

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Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Acknowledgements

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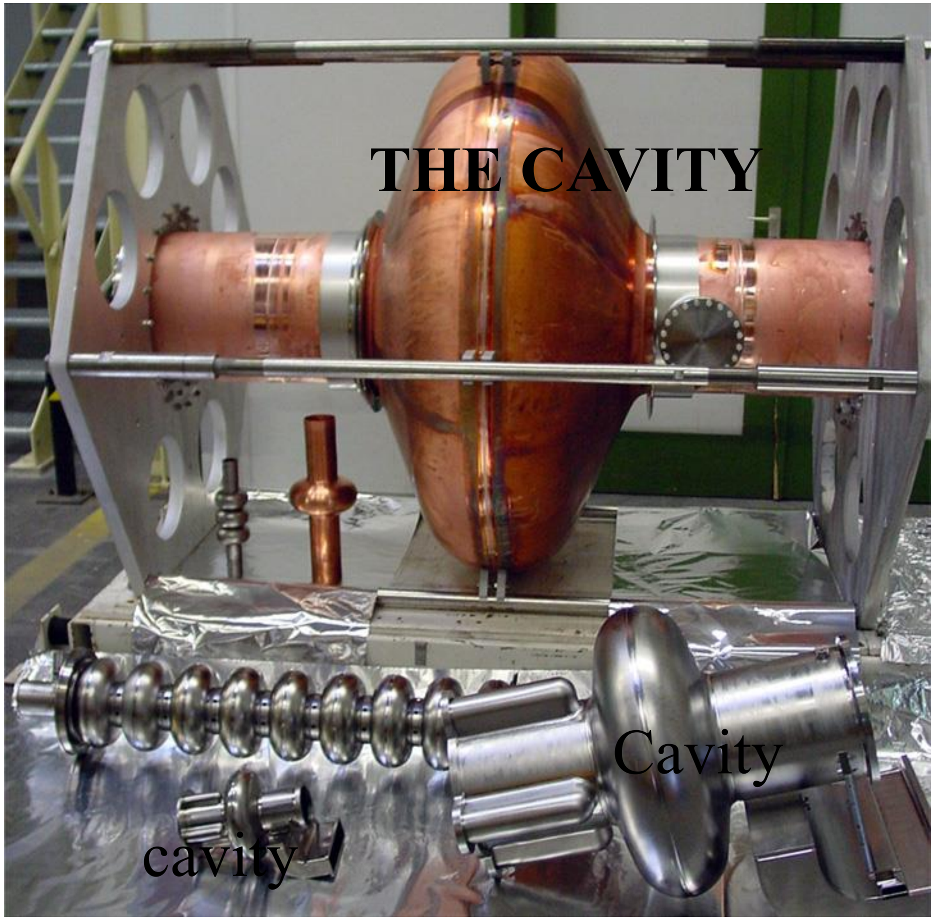
- ✓ Matthias Liepe, Ryan Porter, Sam Posen, et al.
- ✓ JLab technical staff

Outline

- Motivation
- Background
- Current status
- Path forward

Niobium and its limitations



Niobium – best superconducting properties among all pure metals:

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

Nb : $R_s \sim .00001$ mΩ
Cu: Rs ~ 10 mΩ

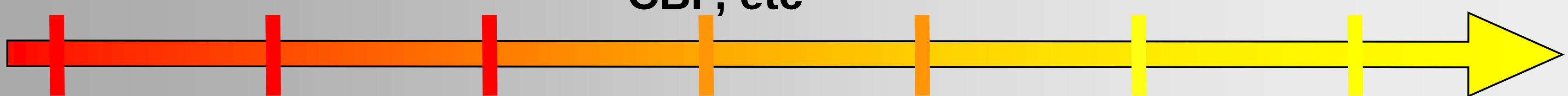
↓

$Q^{nb} \sim 10^{11}$ 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, …



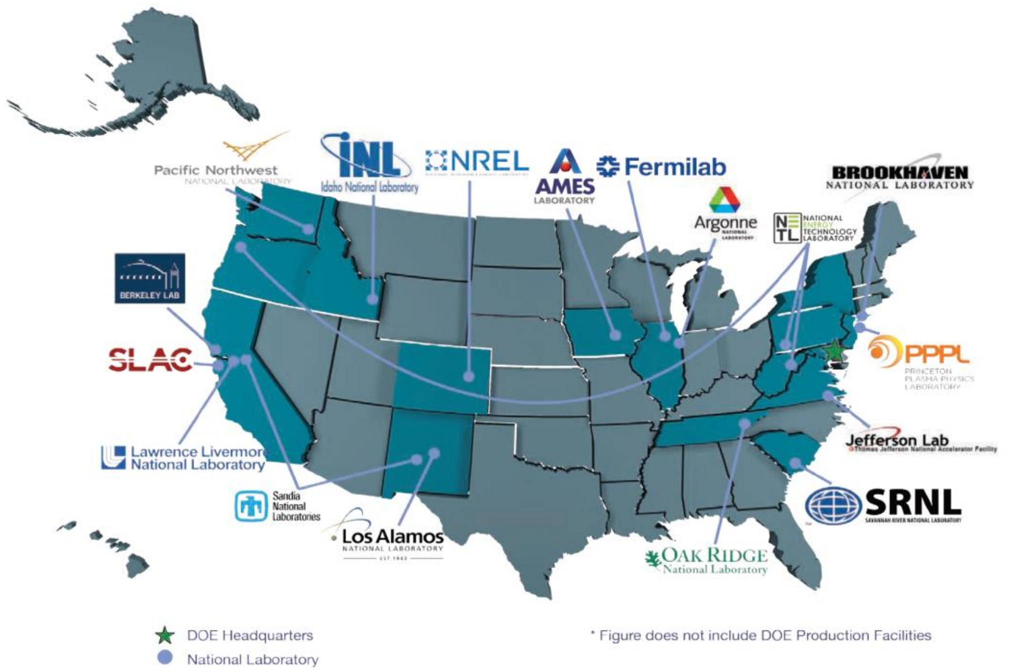
1975	1985	1990	1995	2000	2010
3 MV/m	6 MV/m	15 MV/m	25 MV/m	40 MV/m	50 MV/m

Limitation: Electron multiplication; Electron field emission; Quench

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

"Borrowed" from M. Liepe

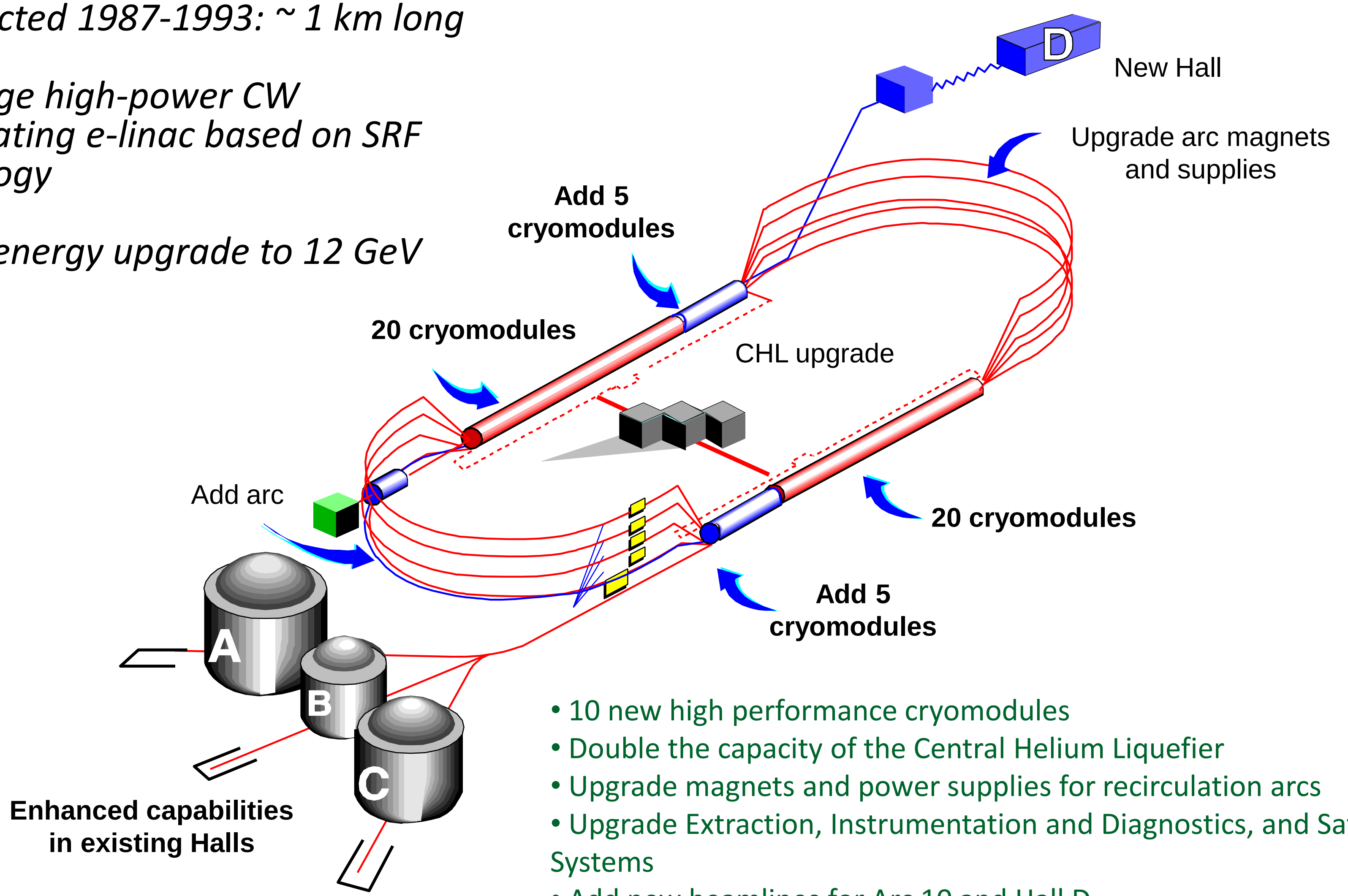
Jefferson Lab Overview



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

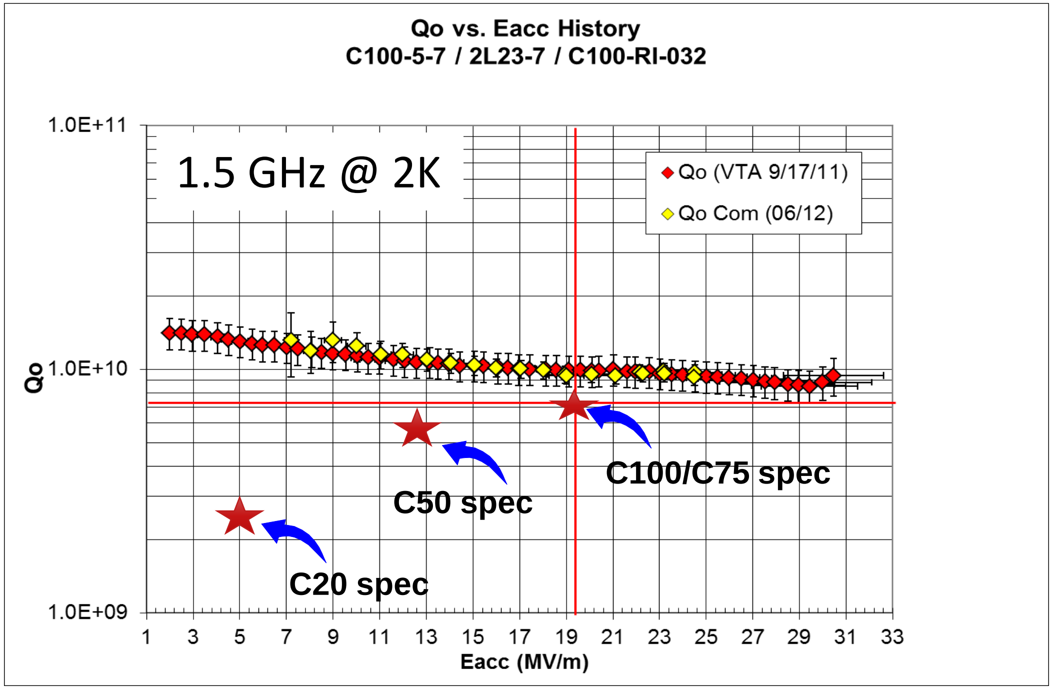
CEBAF @ 12 GeV

- *Constructed 1987-1993: ~ 1 km long*
- *First large high-power CW recirculating e-linac based on SRF technology*
- *Recent energy upgrade to 12 GeV*

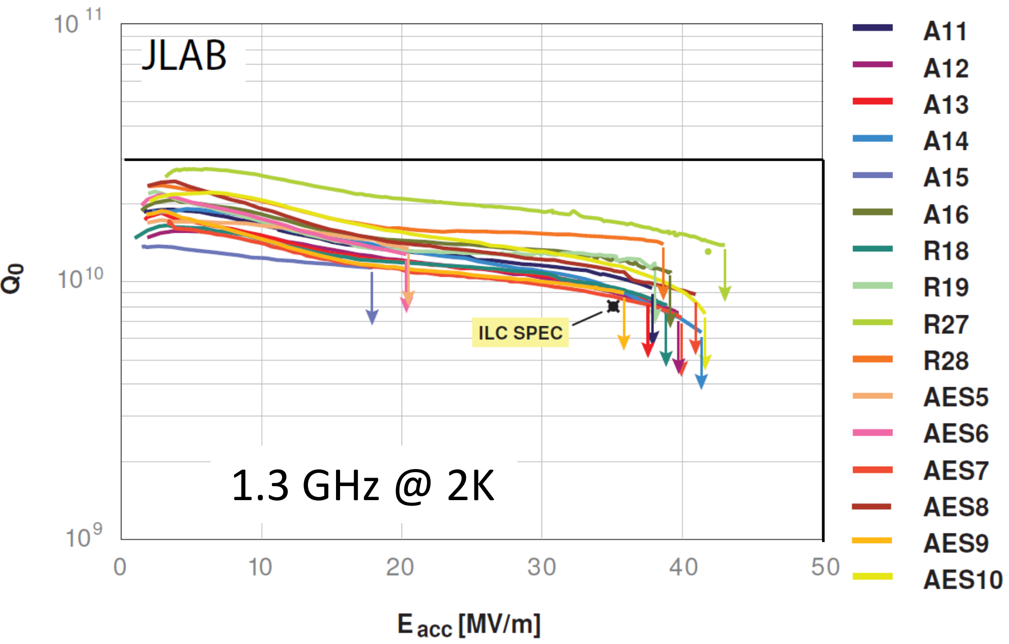


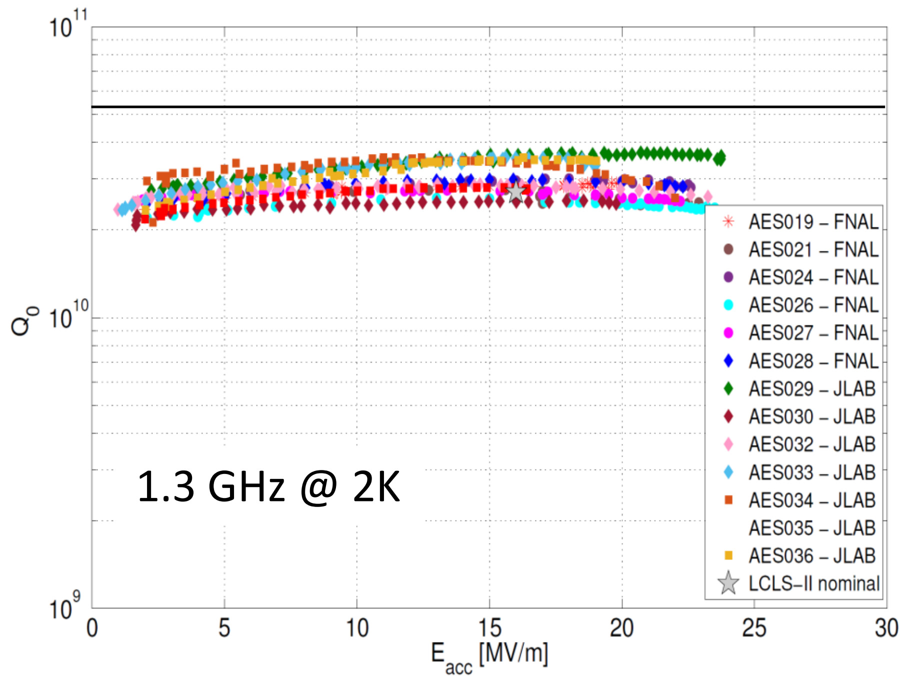
- 10 new high performance cryomodules
- Double the capacity of the Central Helium Liquefier
- Upgrade magnets and power supplies for recirculation arcs
- Upgrade Extraction, Instrumentation and Diagnostics, and Safety Systems
- Add new beamlines for Arc 10 and Hall D
- Add new experimental Hall D and upgrade existing Halls

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

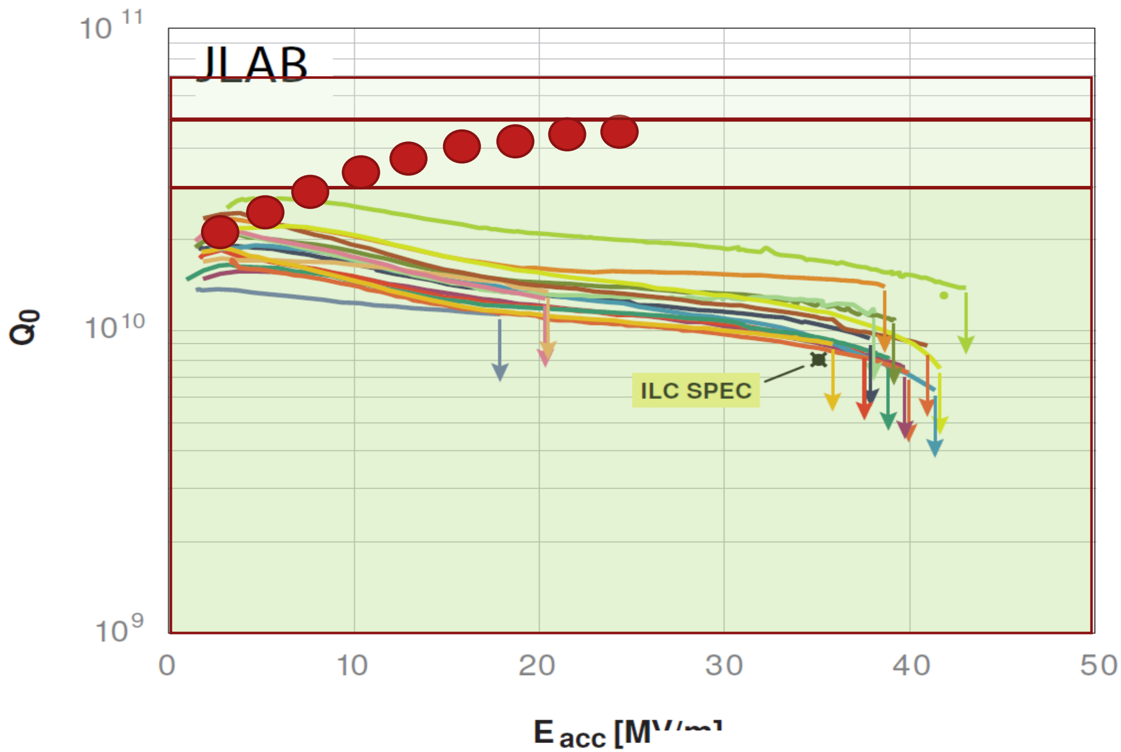
LCLS-II SRF CAVITY PROCESSING PROTOCOL DEVELOPMENT AND BASELINE CAVITY PERFORMANCE DEMONSTRATION, MOPB033, *SRF'15*

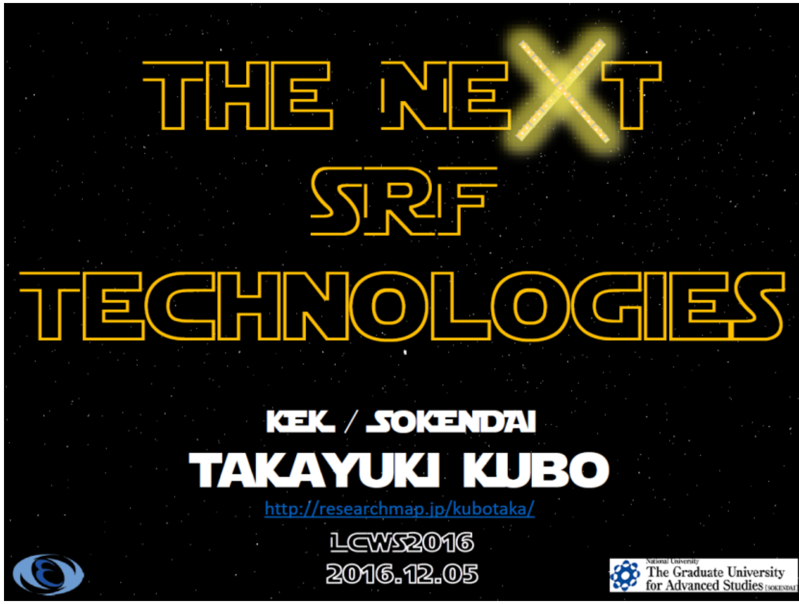
$$R_{BCS} \cong \frac{R_n}{\sqrt{2}}\left(\frac{\hbar\omega}{\pi\Delta}\right)^{\frac{3}{2}}\frac{\sigma_1}{\sigma_n} \cong A\sqrt{\rho_n}\; e^{-\frac{\Delta}{K_B T}}$$

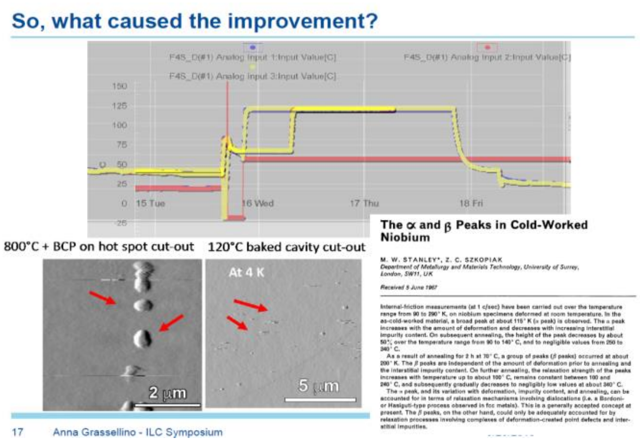
Δ = 1.45 meV ⇒ R_s ≥ 5 nΩ @ 2K @ ~ 1 GHz

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

Ideas for the future





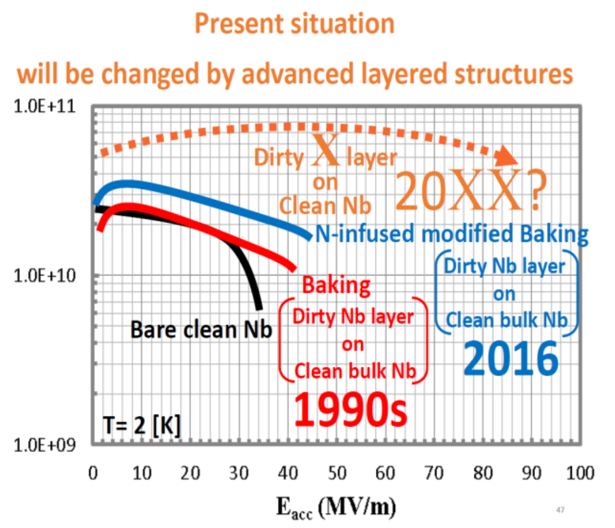


I suggest another key mechanism is at play

- 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

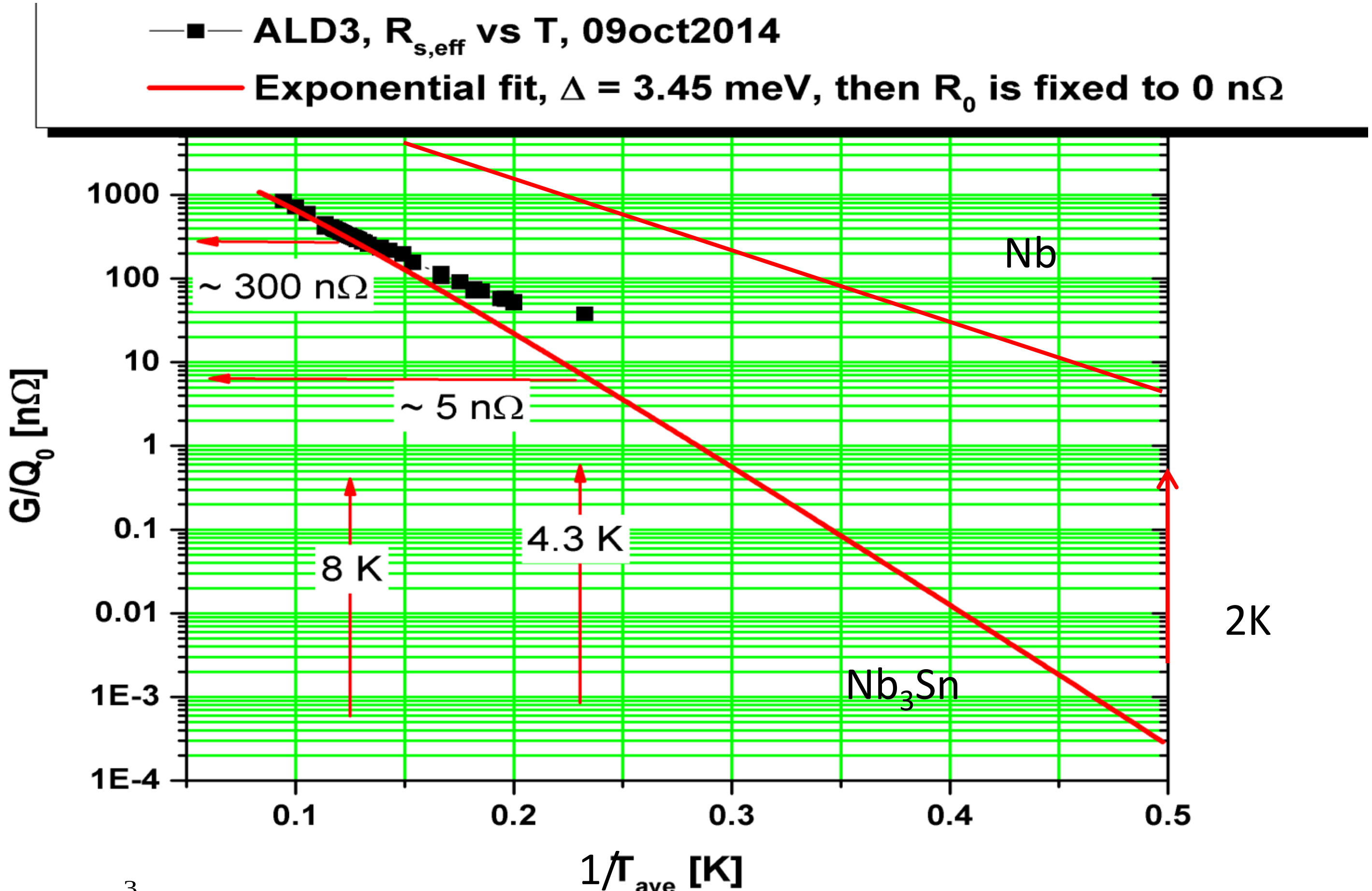
What are the better SRF Materials?

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 ⇒ $R_S \geq 5$ nΩ @ 4.3K @ ~ 1 GHz

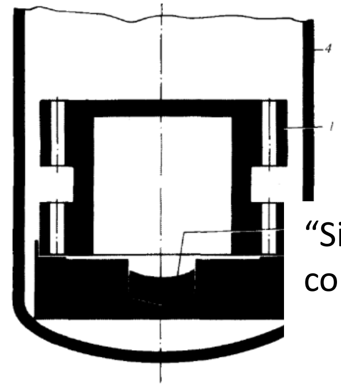
H_c ~ 540 mT ⇒ $H_{sh} = 0.84 \cdot H_c$ ~ 450 mT ⇒ E_{acc} ~ 100 MV/m

Nb_3Sn: past and present

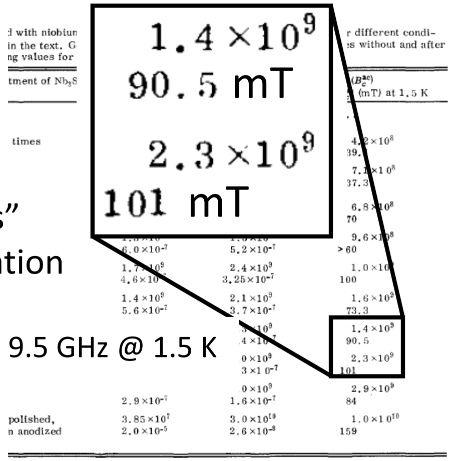
Nb_3Sn for SRF!! ... not exactly new

- 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

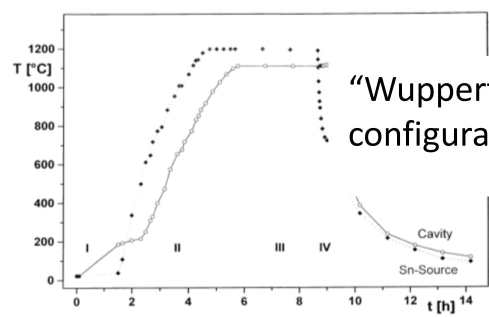


9.5 GHz @ 1.5 K

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.

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

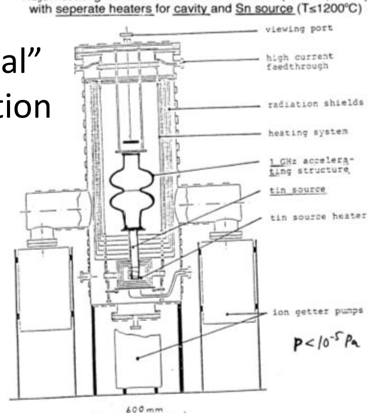
Typical temperature settings to grow Nb_3Sn by vapour diffusion



“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

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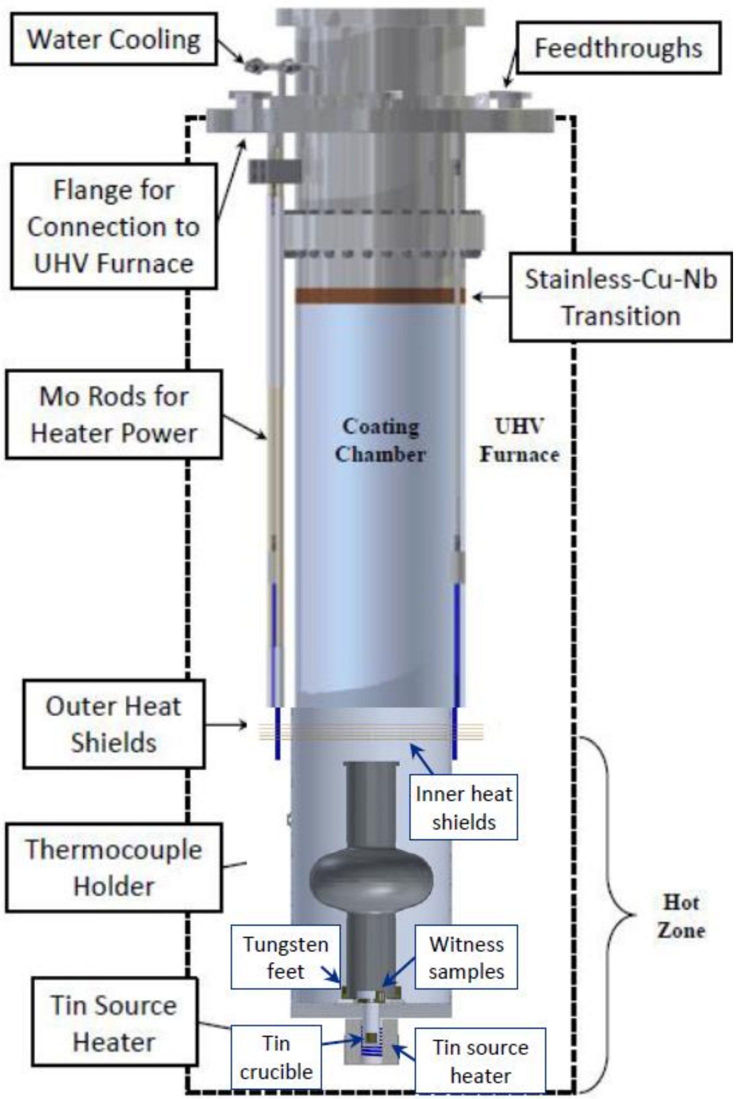
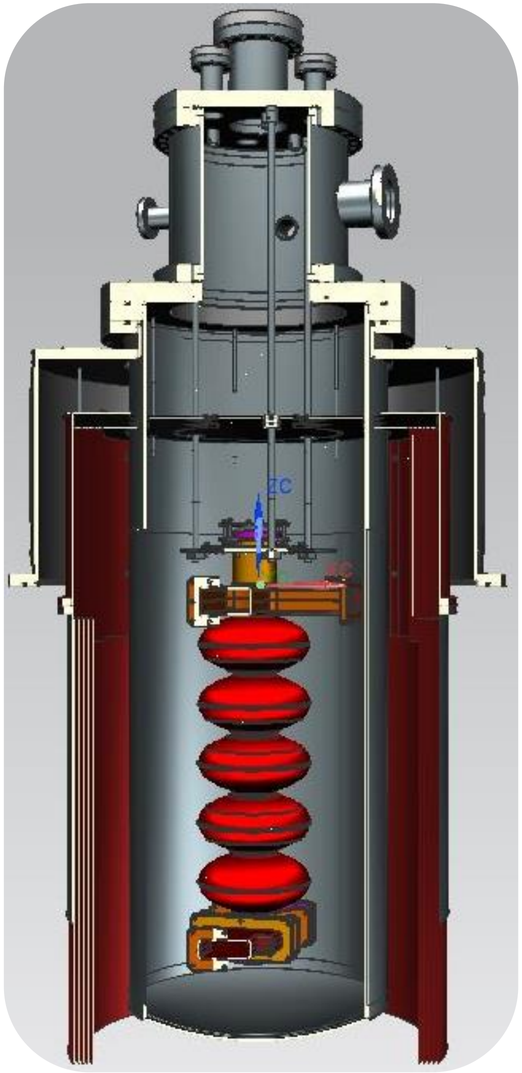
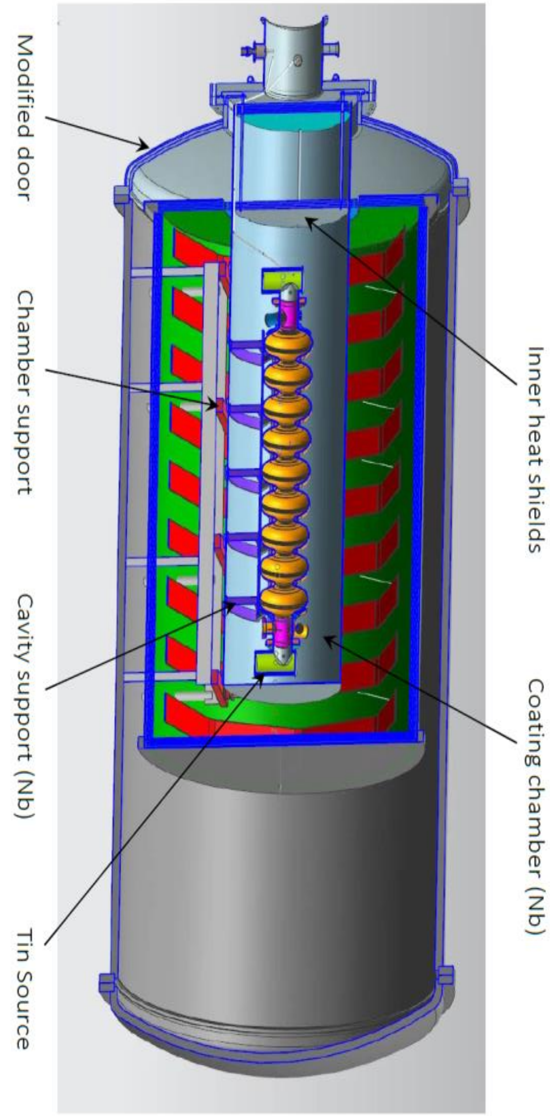
Nb3Sn: Cornell, Jlab, and Fermilab



Cornell



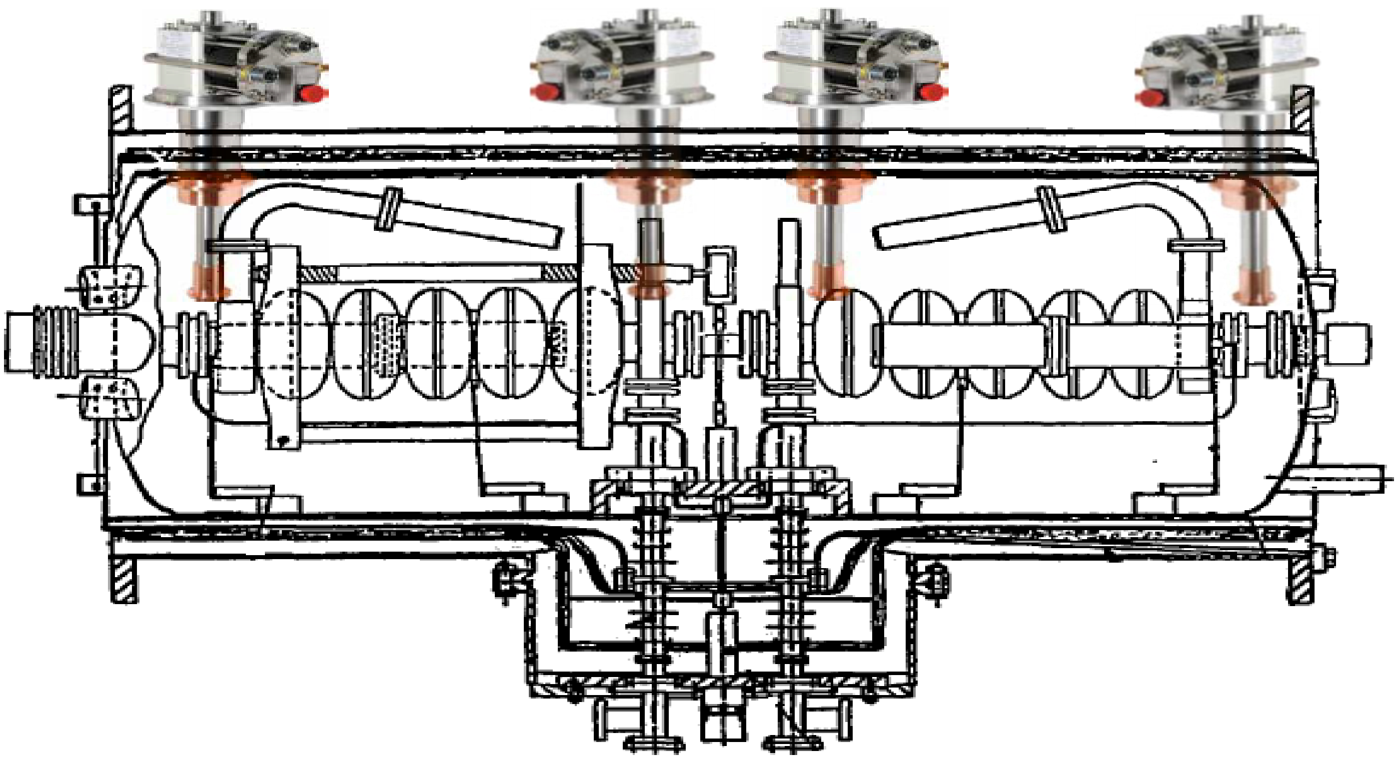
Jlab



Fermilab

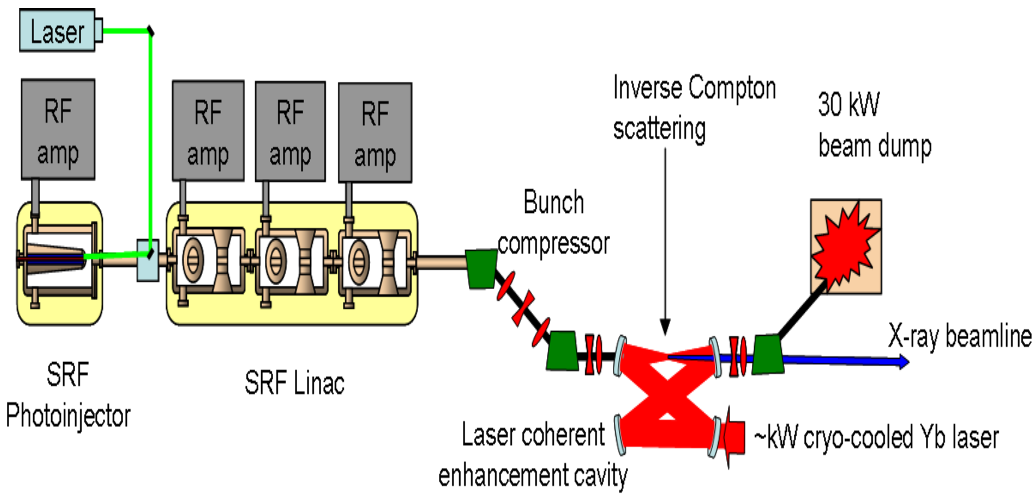
Nb_3Sn cavities cooled by cryocoolers

Cryocooler-cooled cryomodules?!

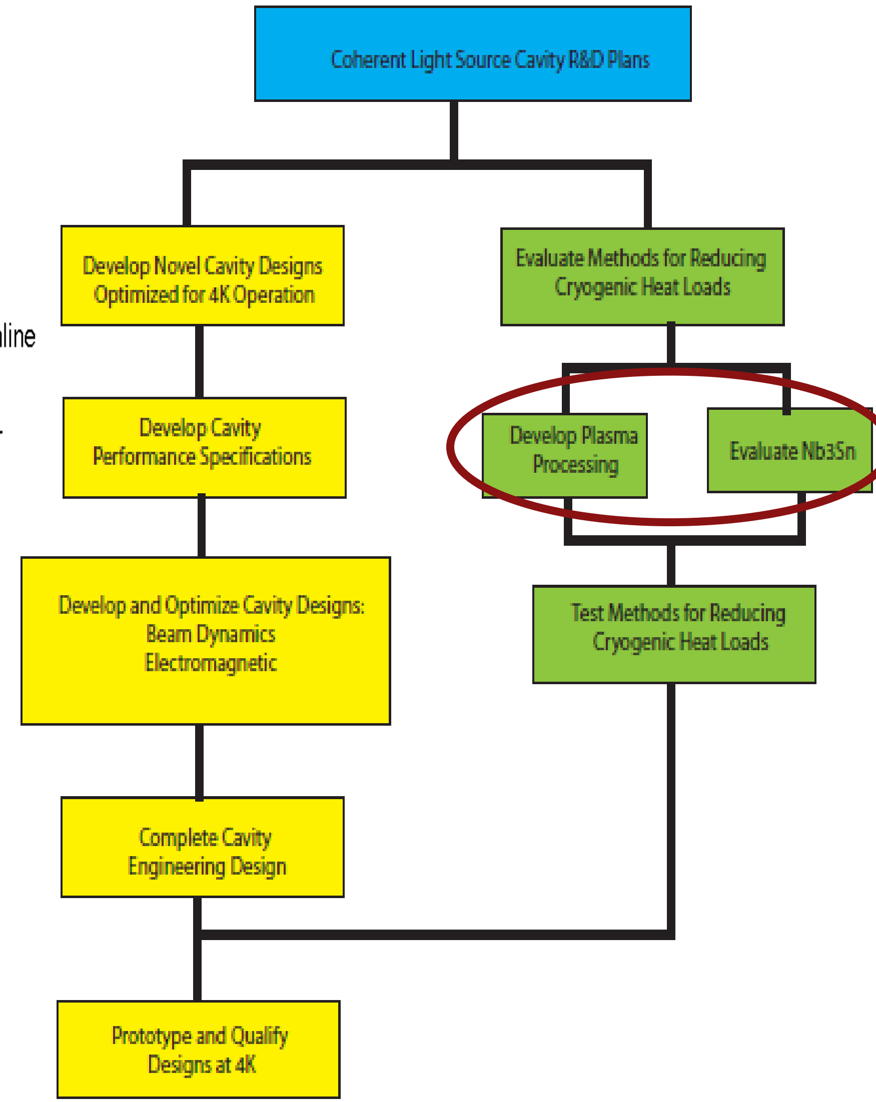


http://www.shicryogenics.com//wp-content/uploads/2012/11/Cryocooler-Product-Catalogue.pdf

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	



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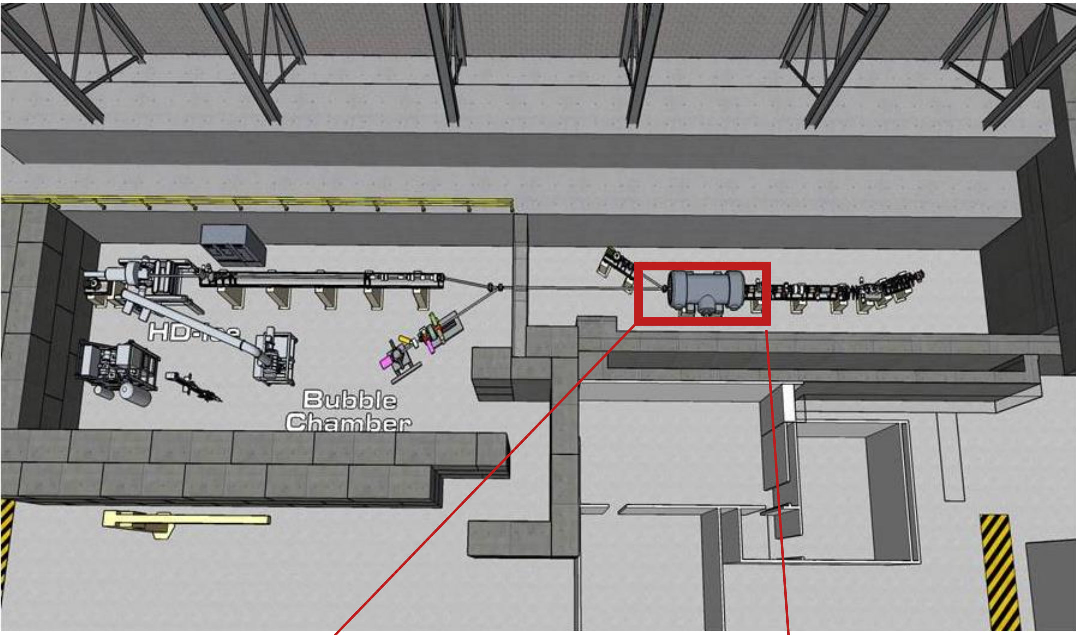
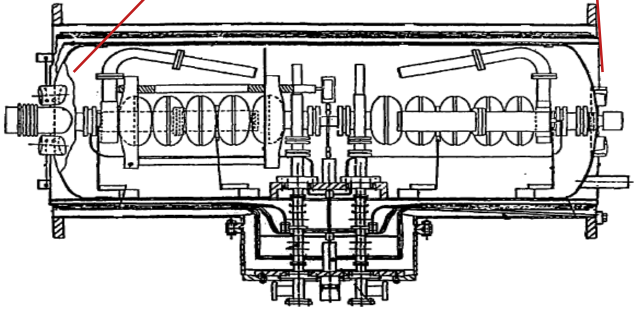
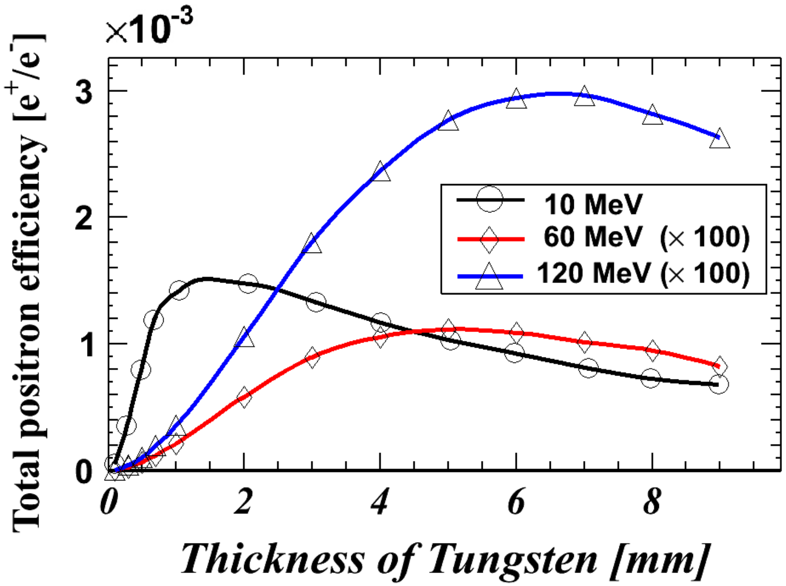
Nb_3Sn cavities for Upgraded Injector Test Facility (UITF) @ Jlab







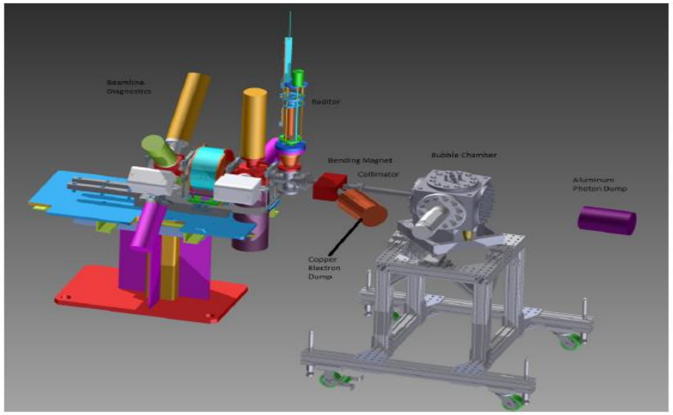
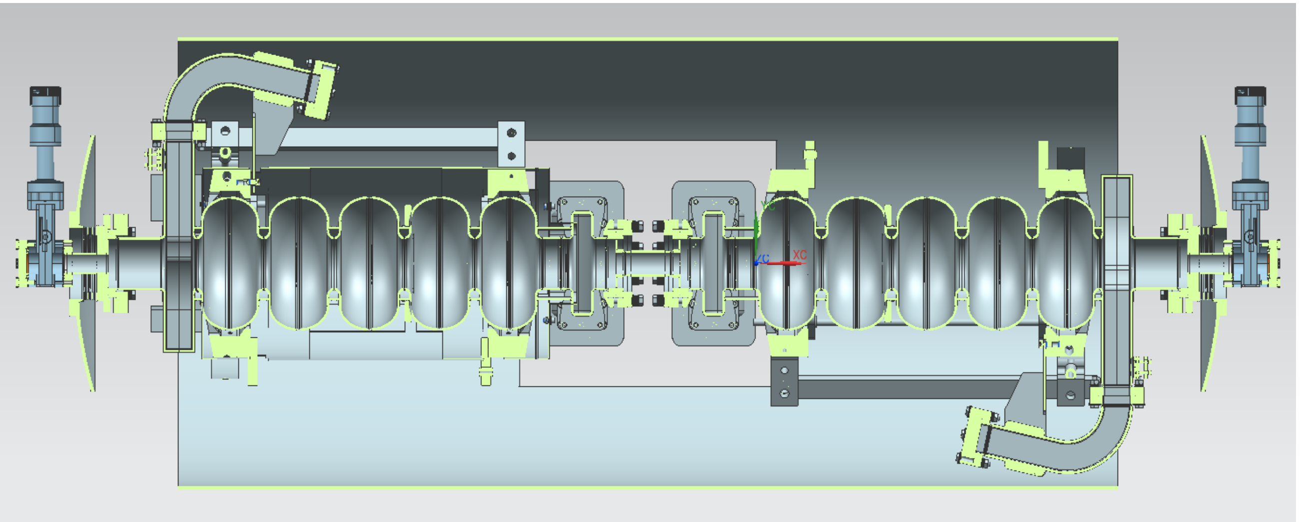


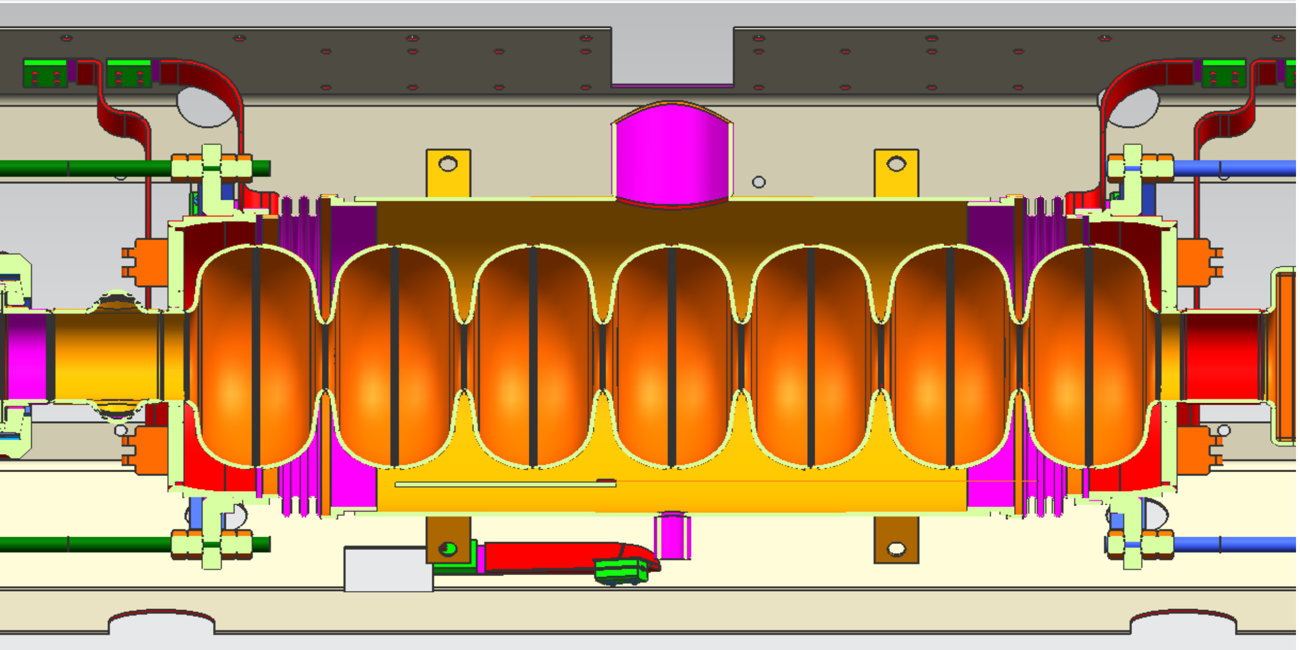
Fig. 12. Schematic of the proposed experiment.

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.

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

Jlab cavities : C20/C50/C75 vs C100





C20/C50/C75:

- OC/HC shape
- Waveguide HOM coupler/load inside helium vessel
- Worm/Wheel Gear
- Nb flanges/In seals

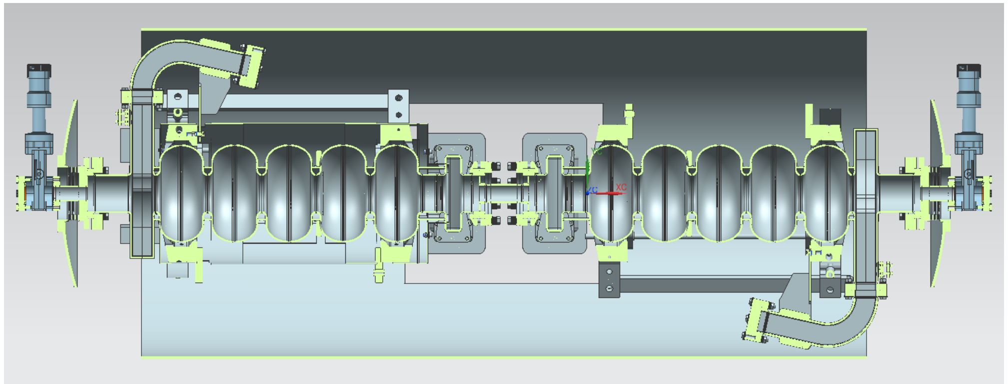
C100:

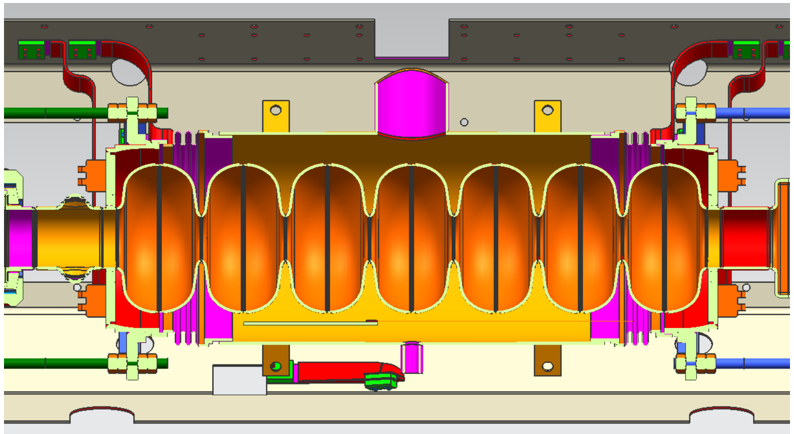
- LL shape
- Coax HOM coupler
- Cavity magnetic shielding
- “scissor-jack” tuner
- Supply/return cryogenic circuits
- NbTi flanges/AlMg gaskets

0L03 & 0L04 @ 4K

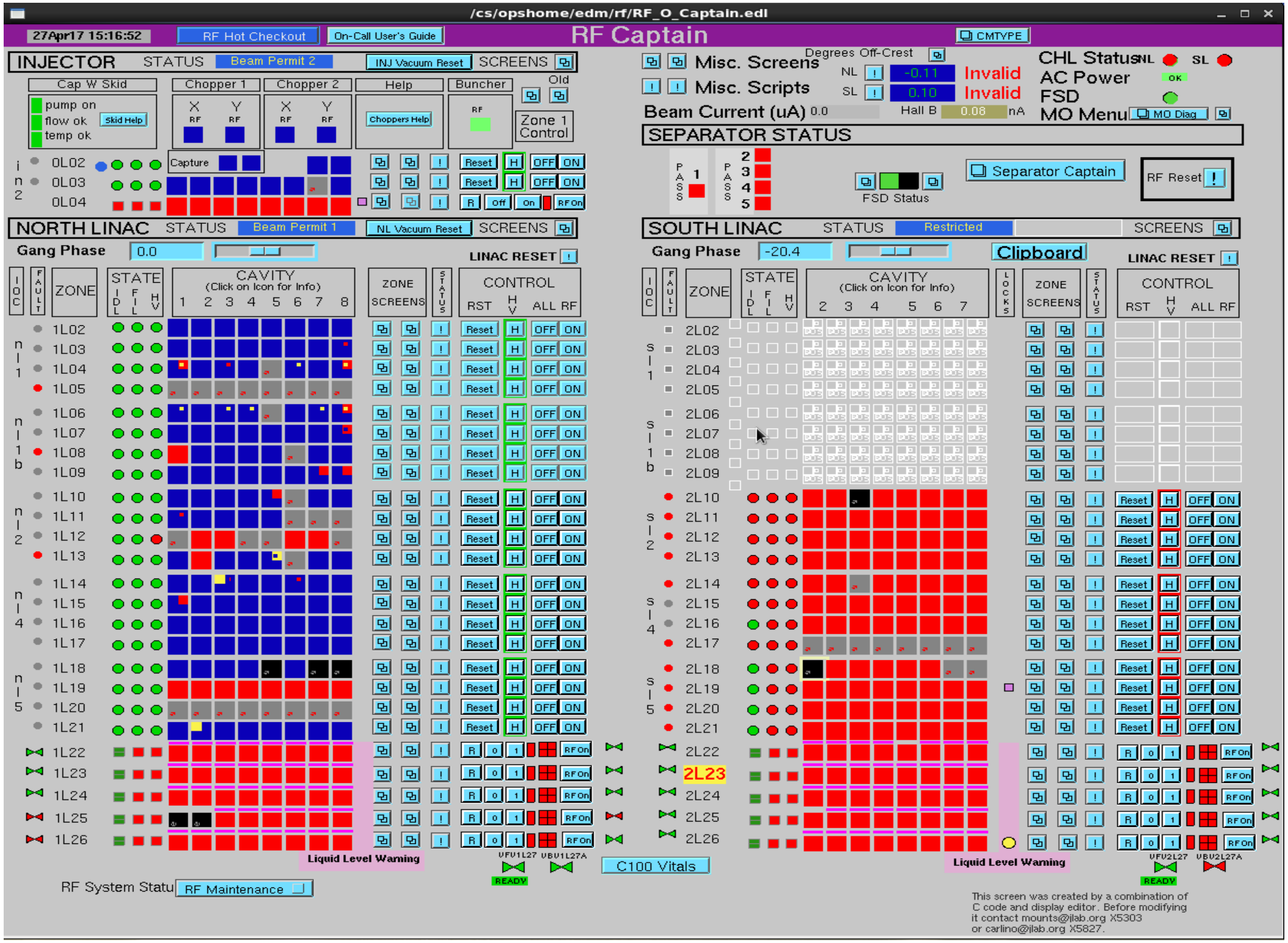
Cavity #	E_{max} [MV/m]	JT @ E_{max}
1	8.7	75%
2	(6.0)	59%
3	9.9	75%
4	8.4	70%
5	3.5	54%
6	3.4	53%
7	10.0	71%
8	6.9	72%

Cavity #	E_{max} [MV/m]	JT @ E_{max}
1	3	85%
2		
3		
4		
5		
6		
7		
8		





4K quarter cryomodule and CEBAF test

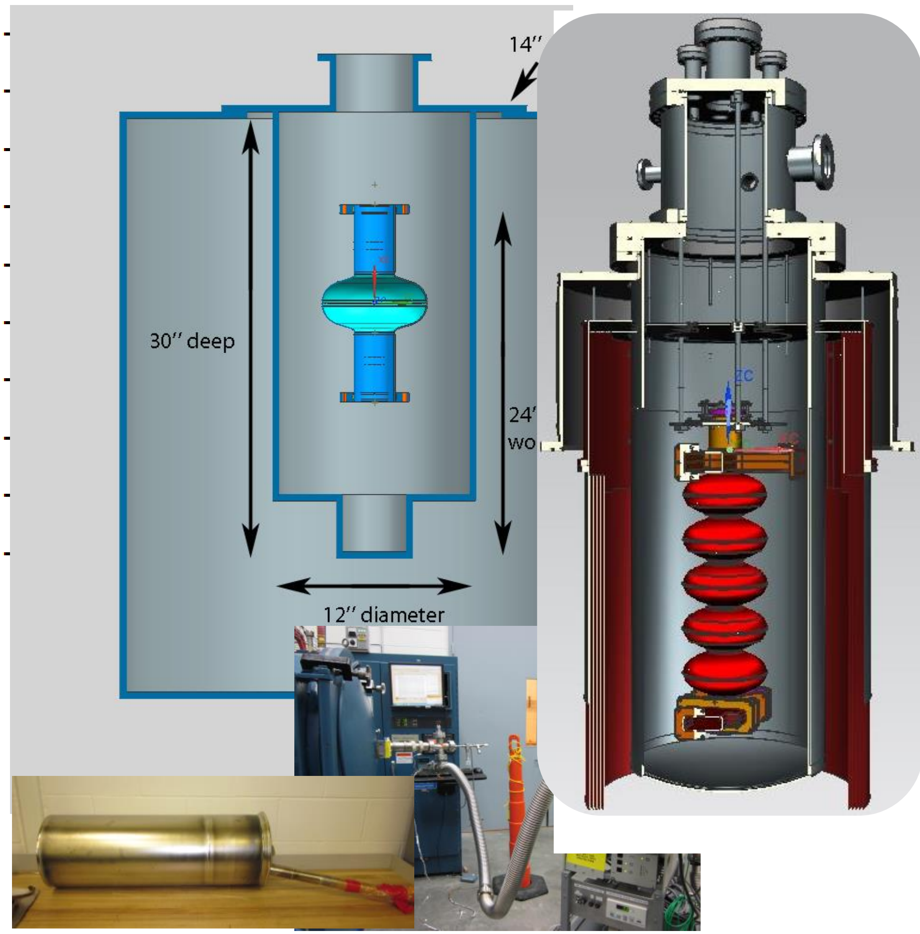


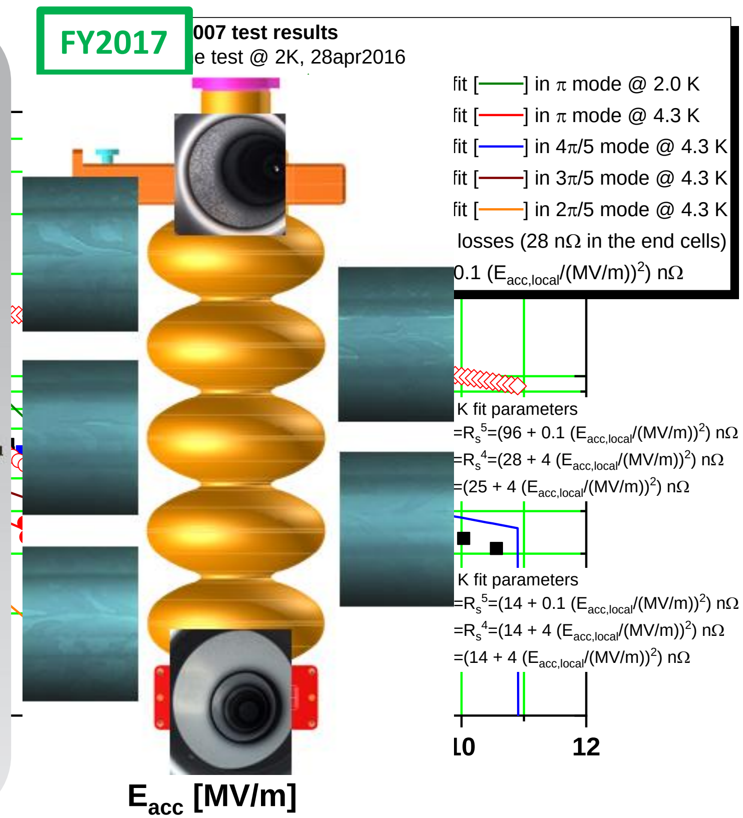
N. Hasan, C. Mounts, W. Oren, A. Solopova, M. Wright, M. Drury, J. Grames, R. Kazimi, M. Poelker, T. Powers, J. Preble, R. Suleiman, Y. Wang, M. Wright, A. Hutton, H. Areti et al.

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

Jlab Nb_3Sn development timeline





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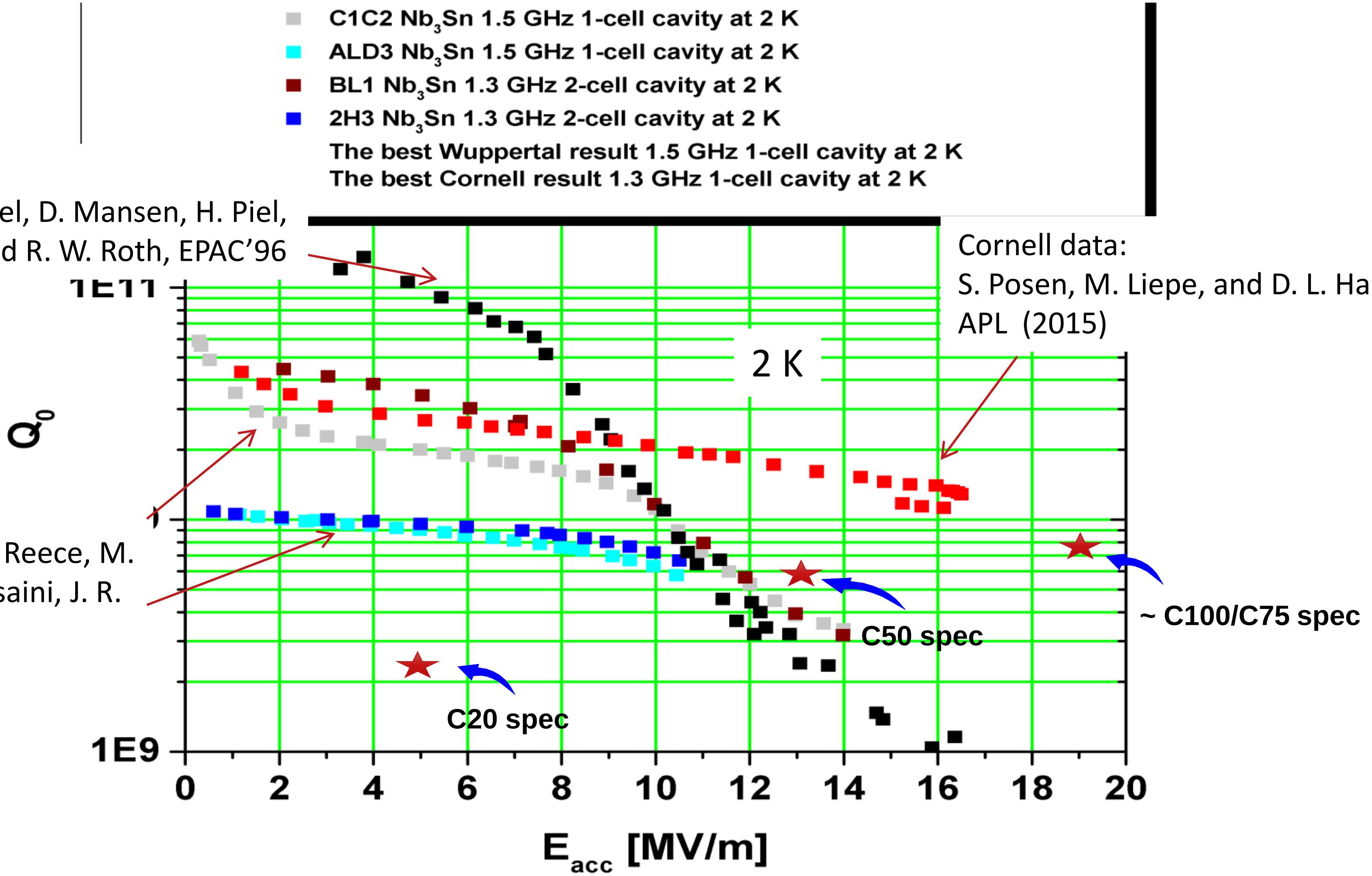
Present single-cell work

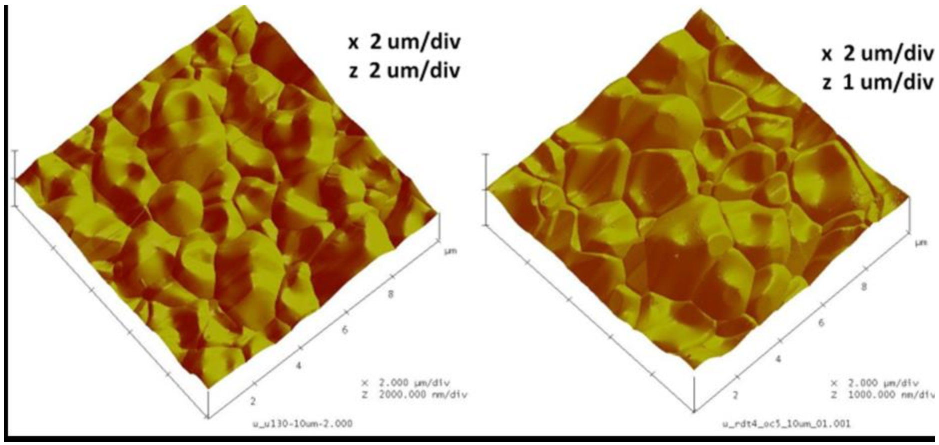
Wuppertal data:
G. Müller, P. Kneisel, D. Mansen, H. Piel, J. Pouryamout, and R. W. Roth, EPAC'96

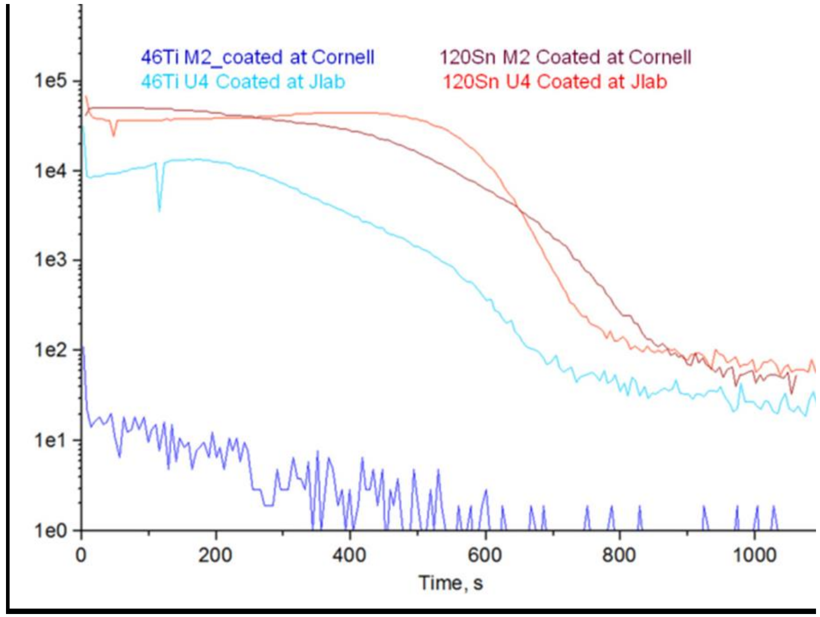
Cornell data:
S. Posen, M. Liepe, and D. L. Hall, APL (2015)

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



Titanium hypothesis



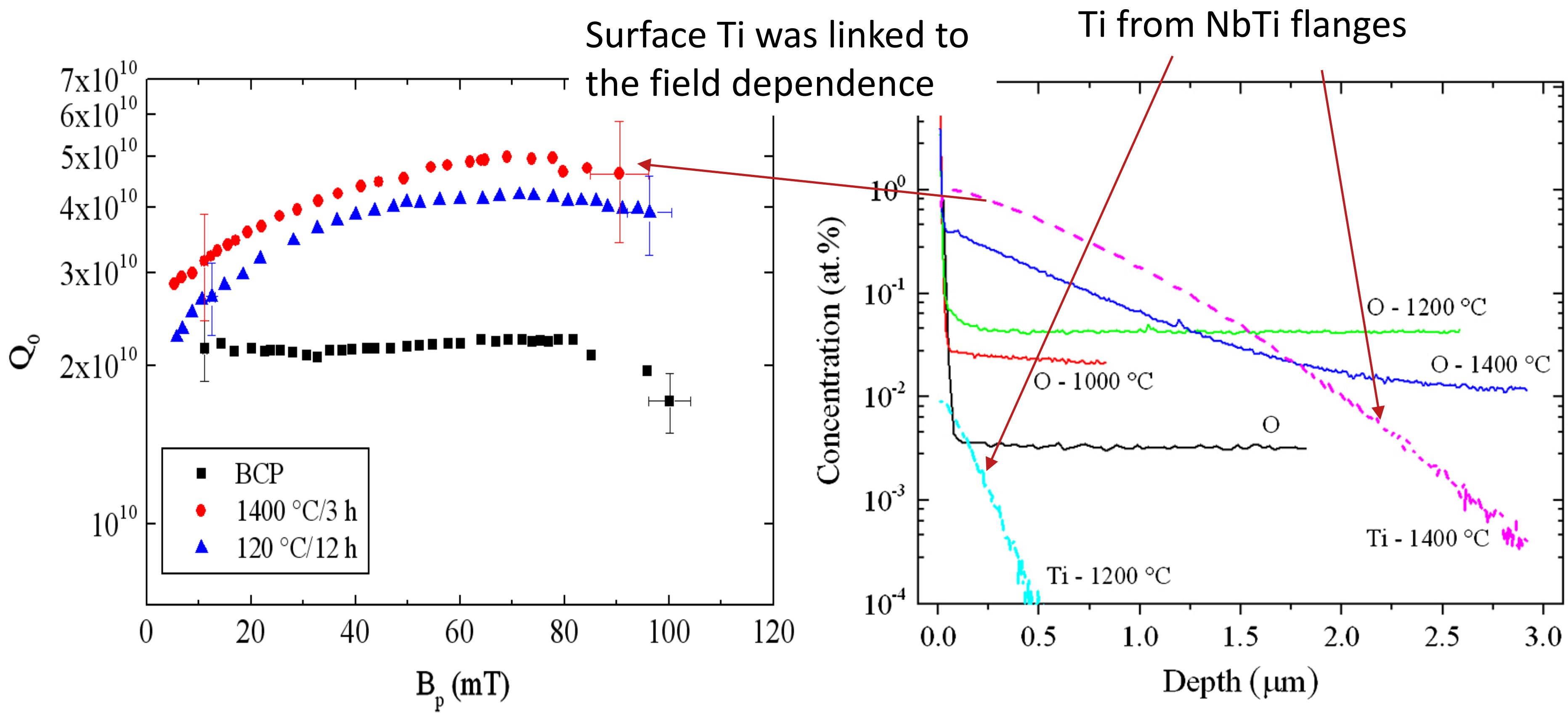


- 20 -

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

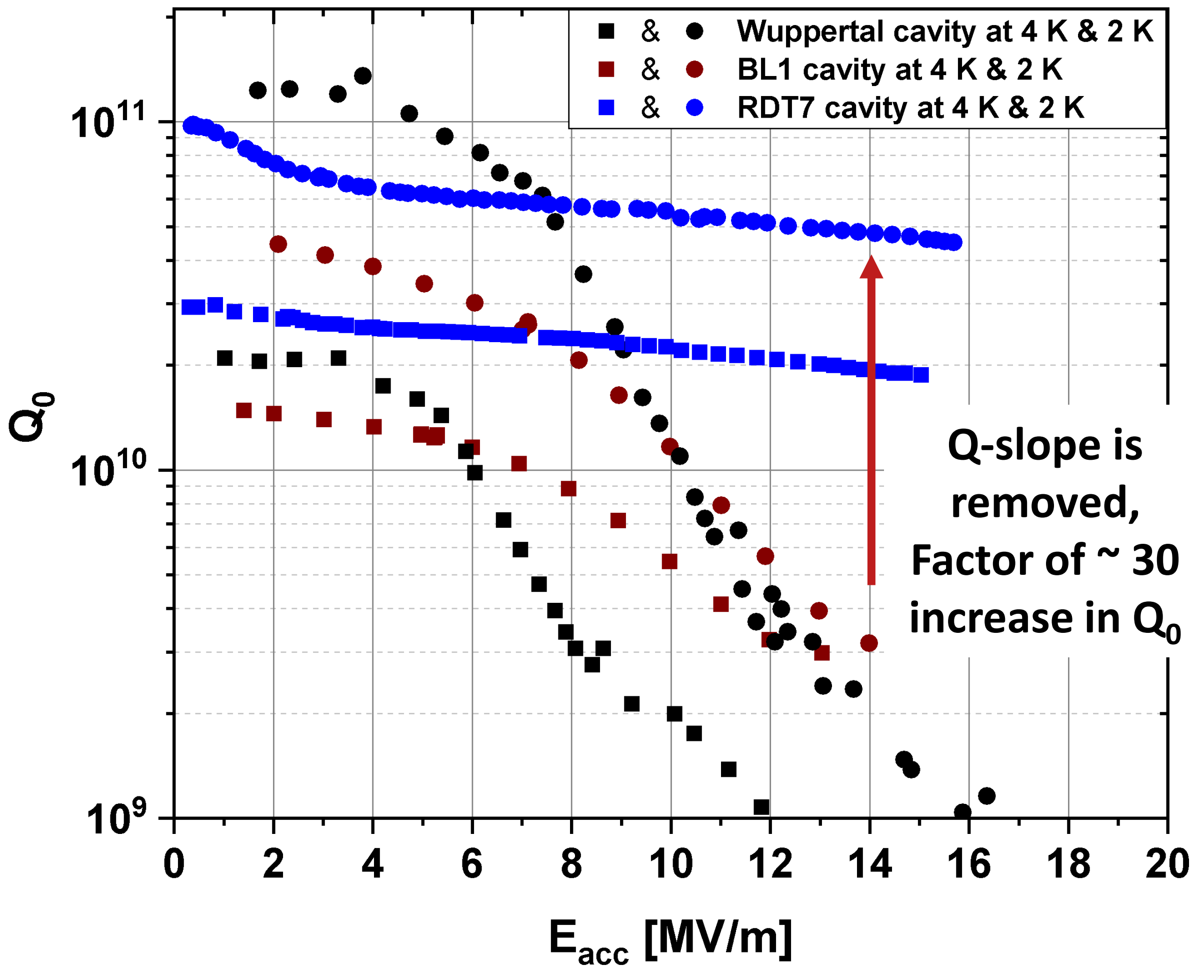
M. Peiniger, dissertation, 1989

Titanium hypothesis



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

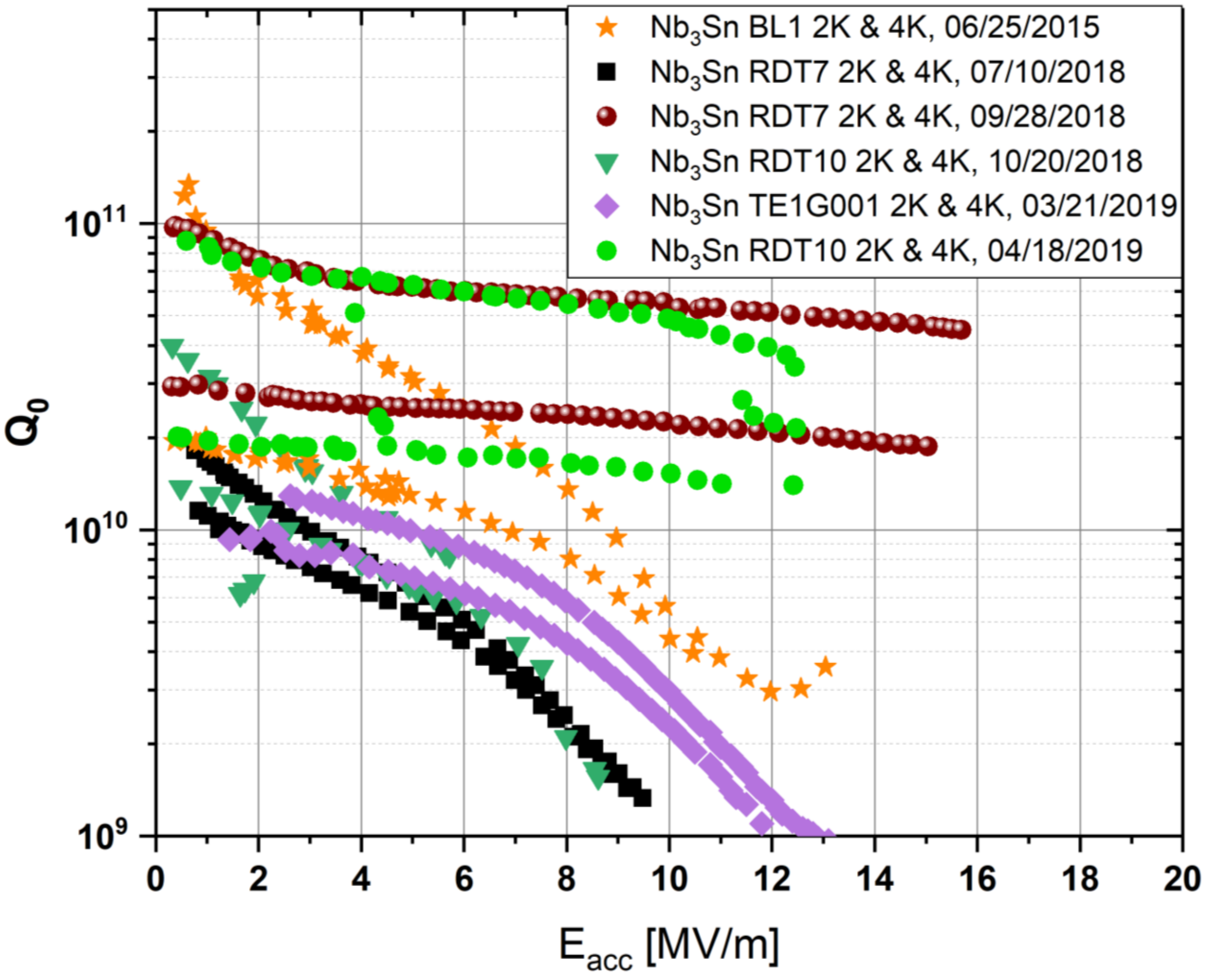
Recent data after the coating system upgrade



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}
- $Q_0 \sim 5\cdot10^{10}$ @ 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



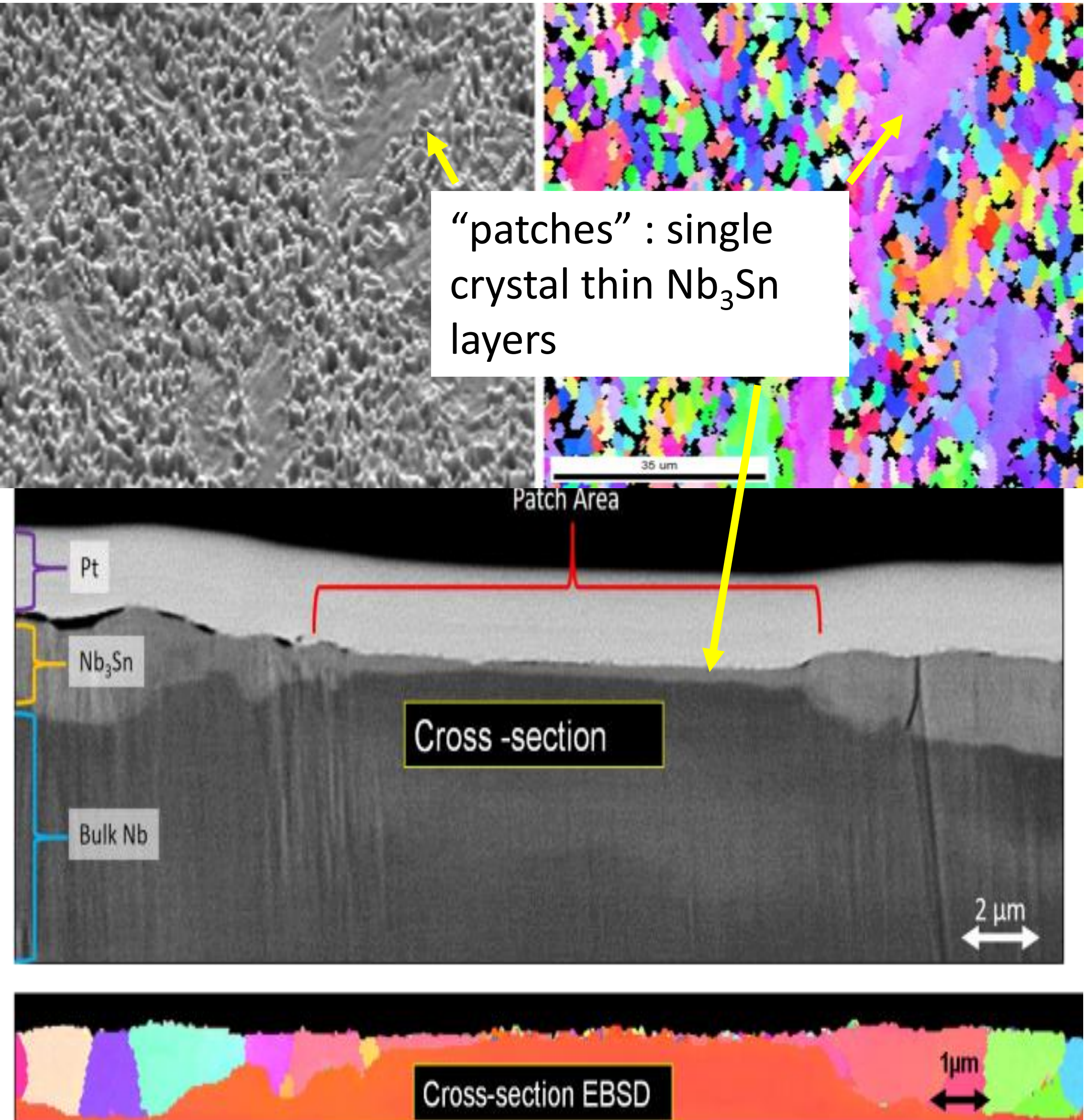
- Q-slope free Nb_3Sn-coated cavity was reproduced on another cavity
- Consistent Q_0 between Q-slope free cavities
- Q-slope limited performance for some coatings was linked to variation in Sn source; studies are ongoing
- RDT7, RDT10 & TE1G001 had NbTi flanges replaced with Nb flanges

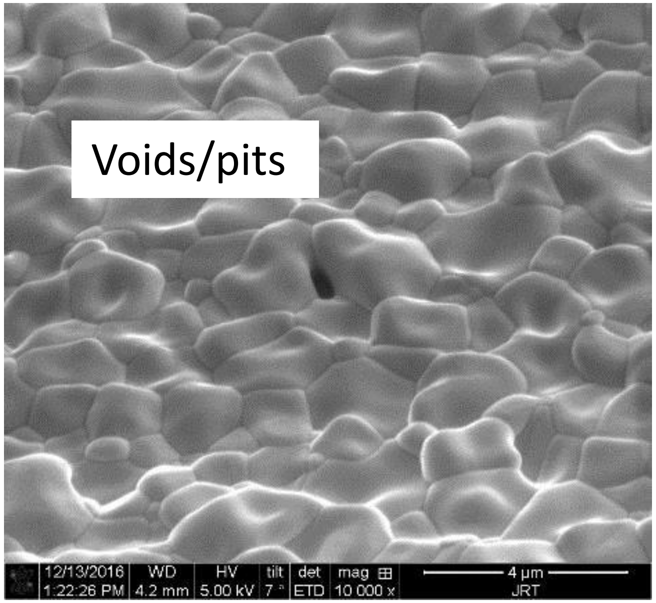
U. Pudasaini

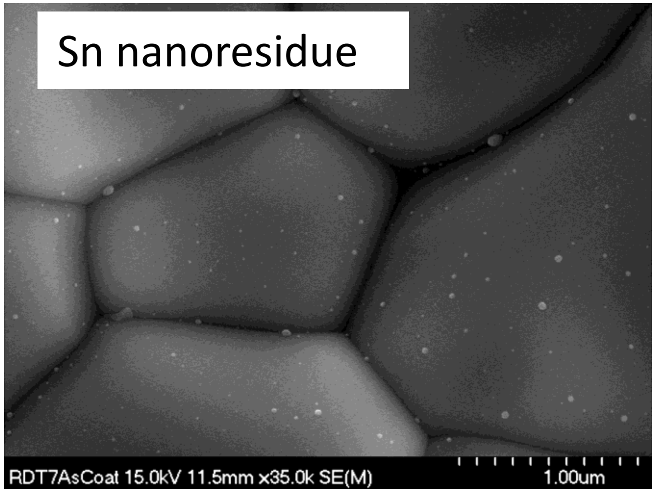
Jefferson Lab

Nb_3Sn growth and defects

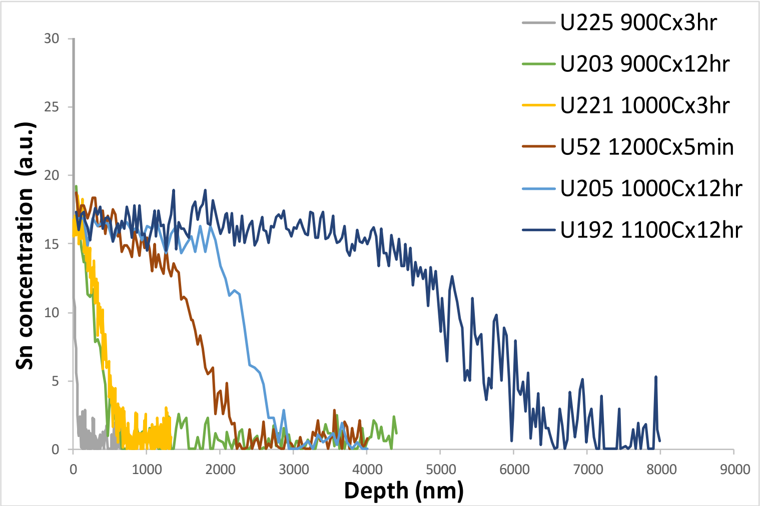
U. Pudasaini, J. Tuggle

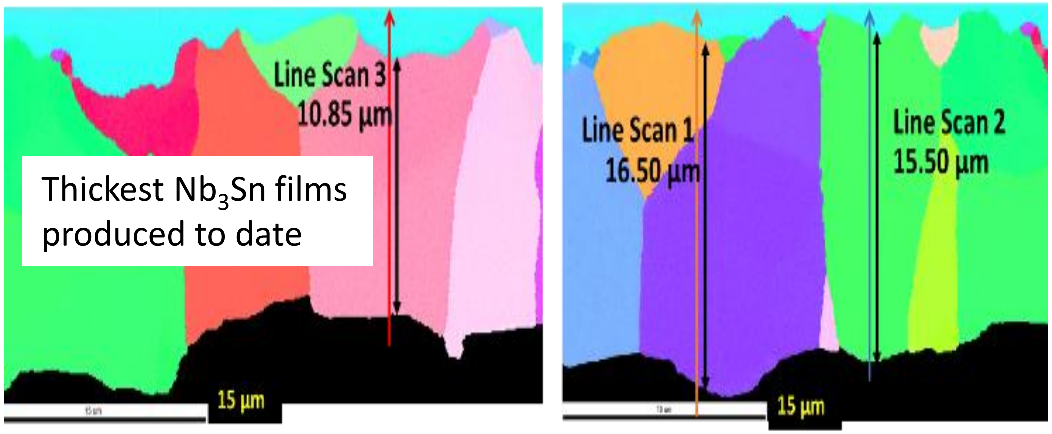






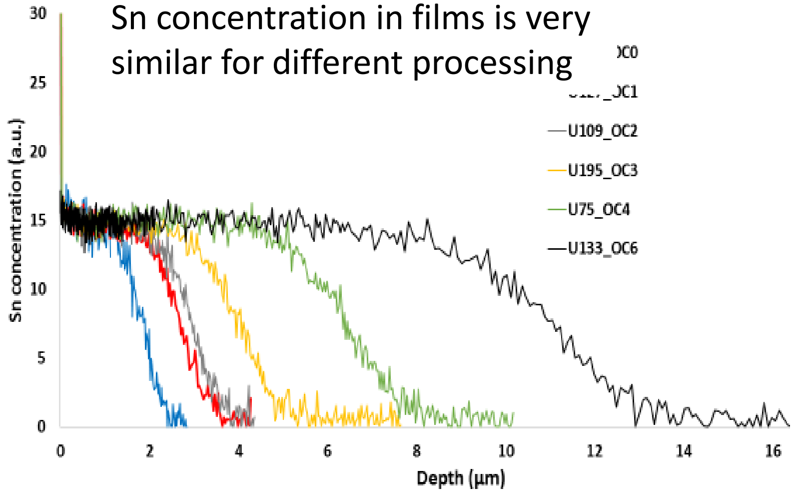
Concentration gradients

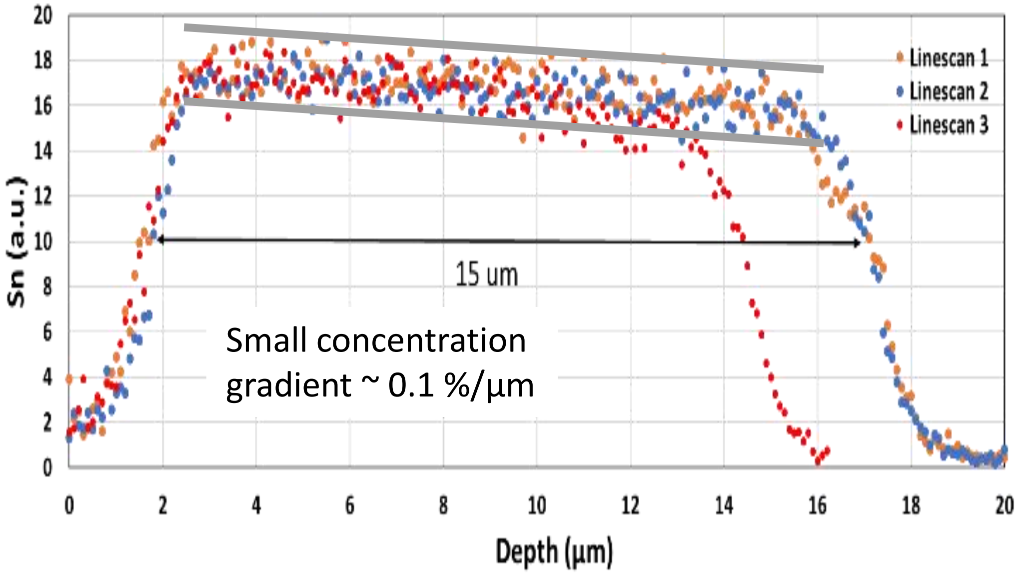




Thickest Nb_3Sn films produced to date

Sn concentration in films is very similar for different processing



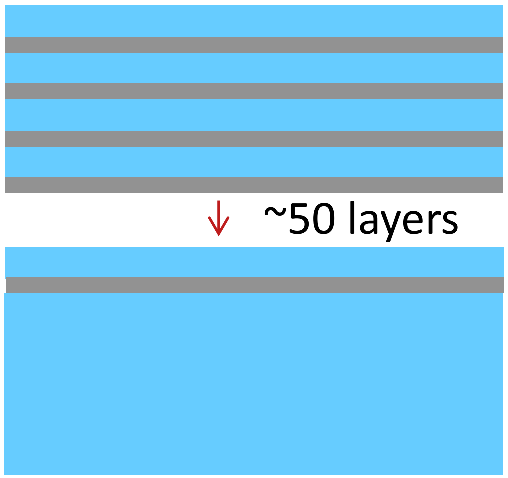


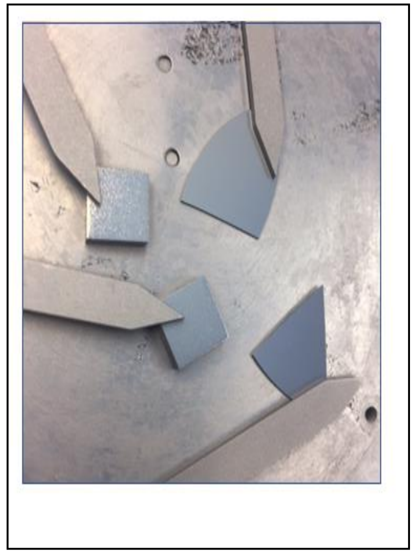
Small concentration gradient ~ 0.1 %/µm

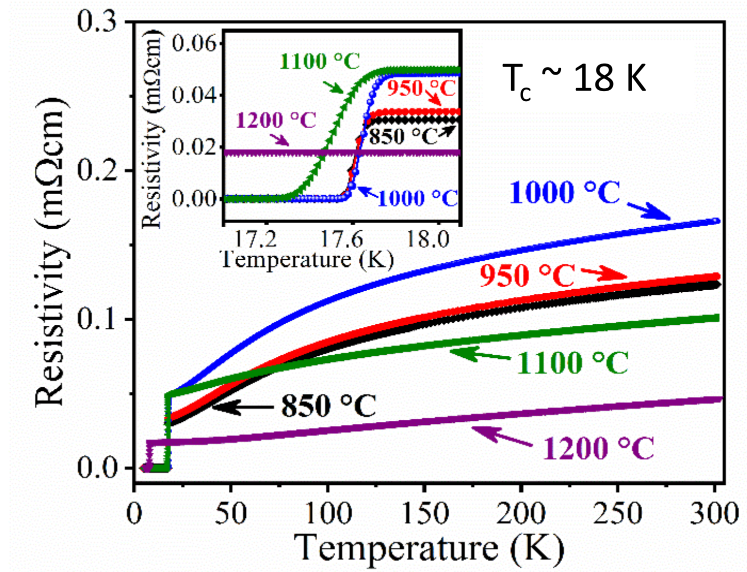
U. Pudasaini, J. Tuggle

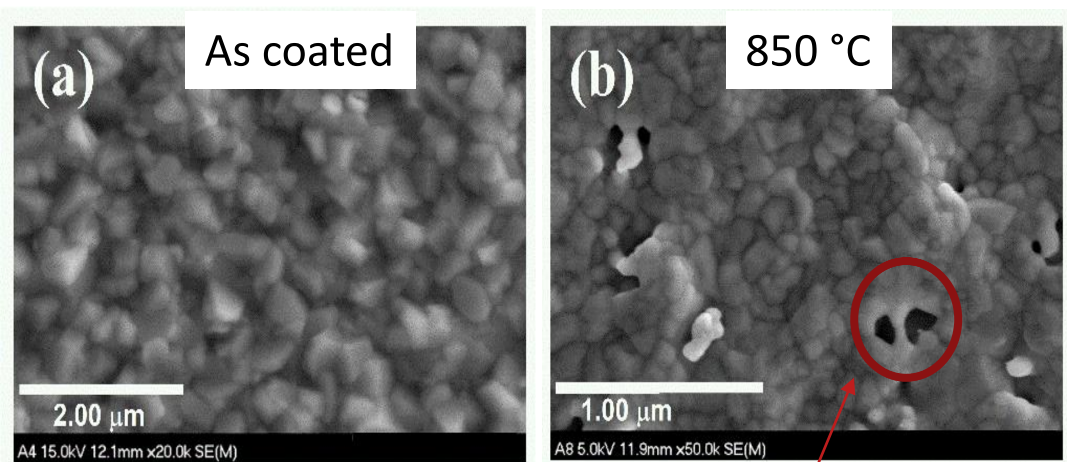
Concentration gradients, stoichiometry, and sputtering

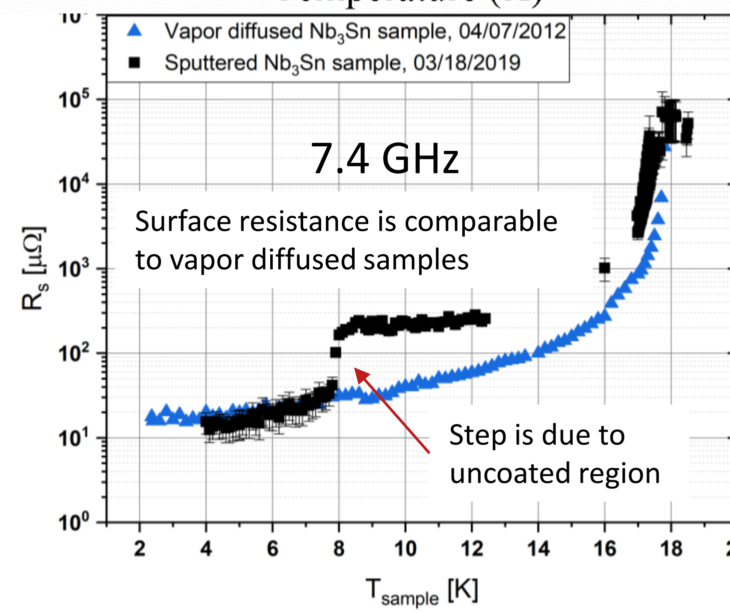
The goal : precise control of Sn content in Nb_3Sn films





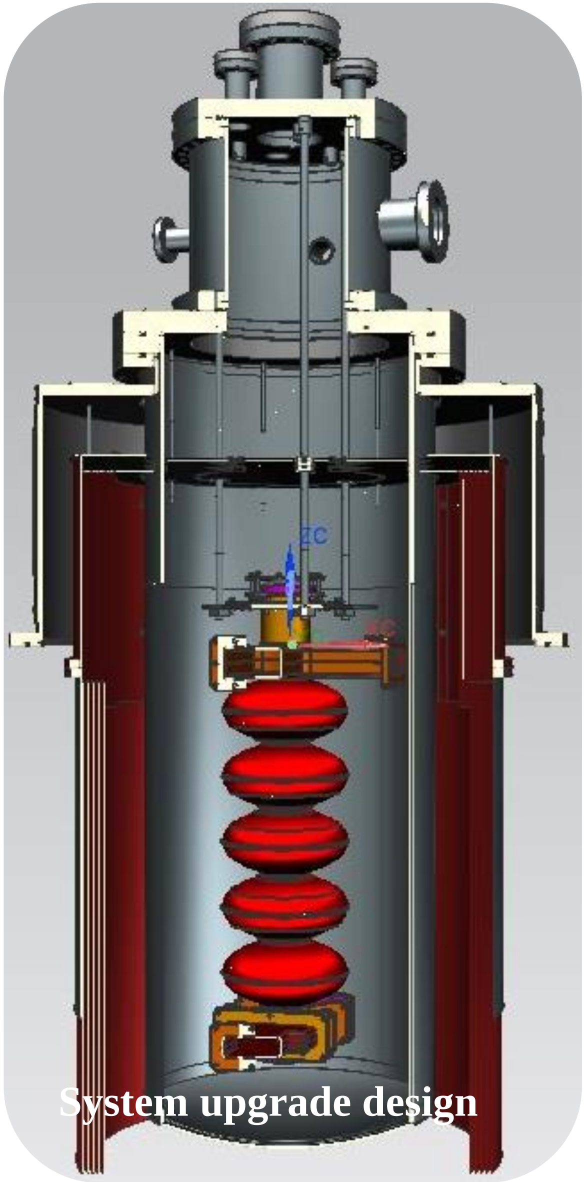






Needs to reduce/eliminate voids,
e.g., by adjust heat treatment

Application to 5-cell cavities



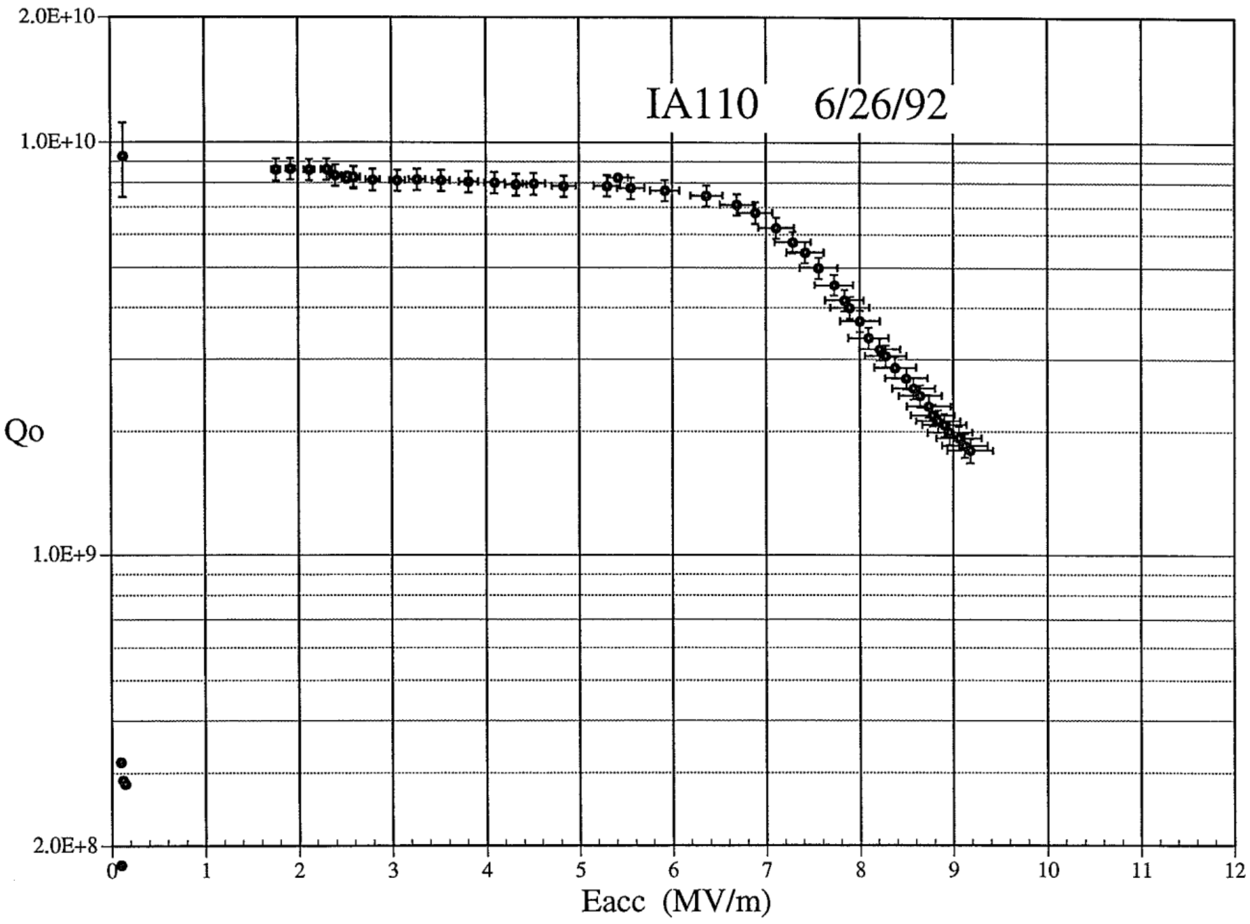
System upgrade design

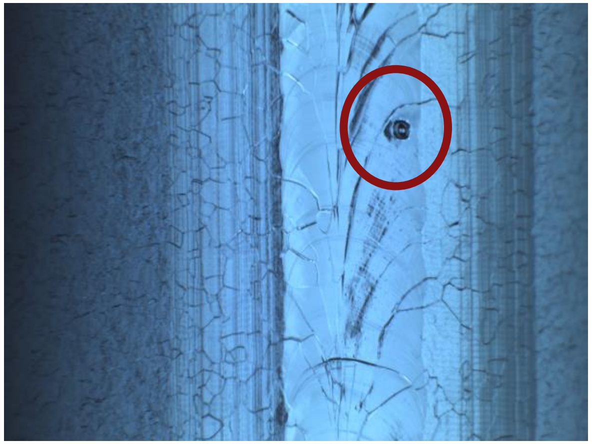
Upgrade commissioning

The new coating chamber

IA320 after coating

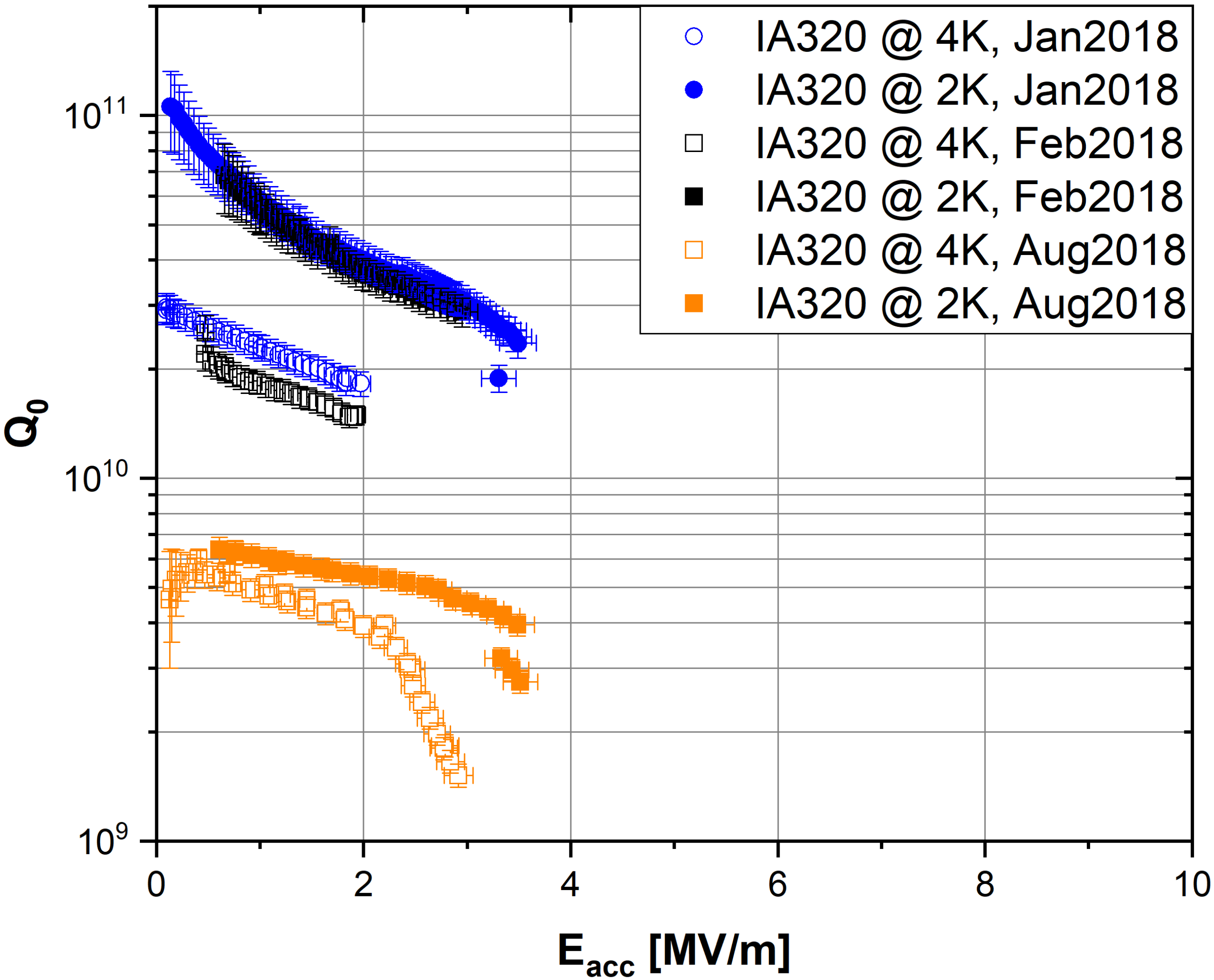
CEBAF 5-cell cavities





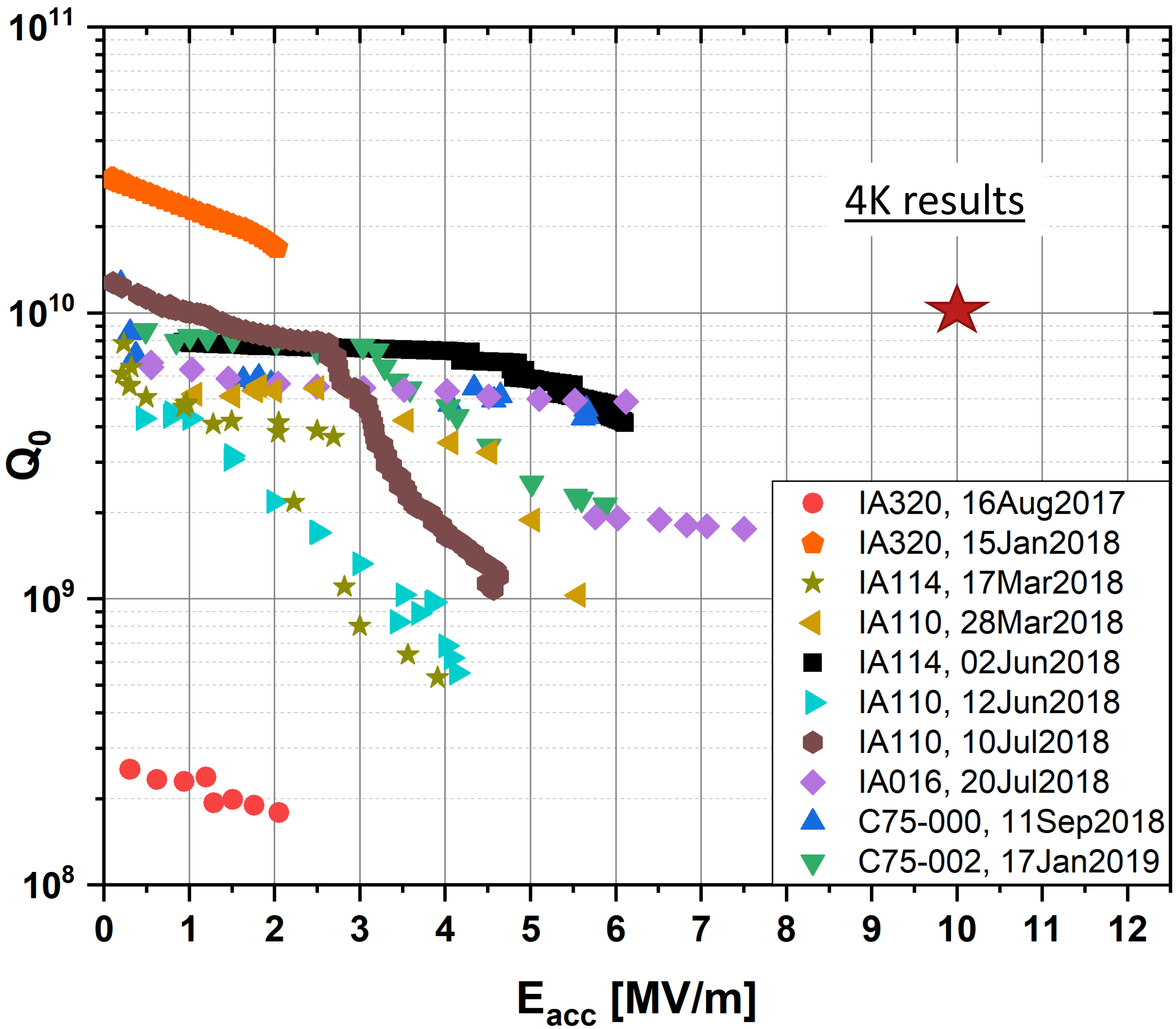
Tested by C. Reece!

5-cell cavity coating results

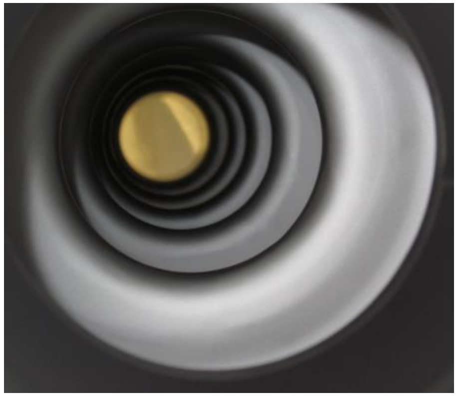


- **The first CEBAF cavity coated in the upgraded system**
- **The cavity limited at E_{acc} = 11 MV/m in the baseline test before coating**
- **Results are shown for the coating #8 done in Nov. 17**
- **Coated cavity had high Q_0(~ 10^{11}), but a strong Q-slope**
- **Re-tests after December 2017 to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

5-cell cavity coating results

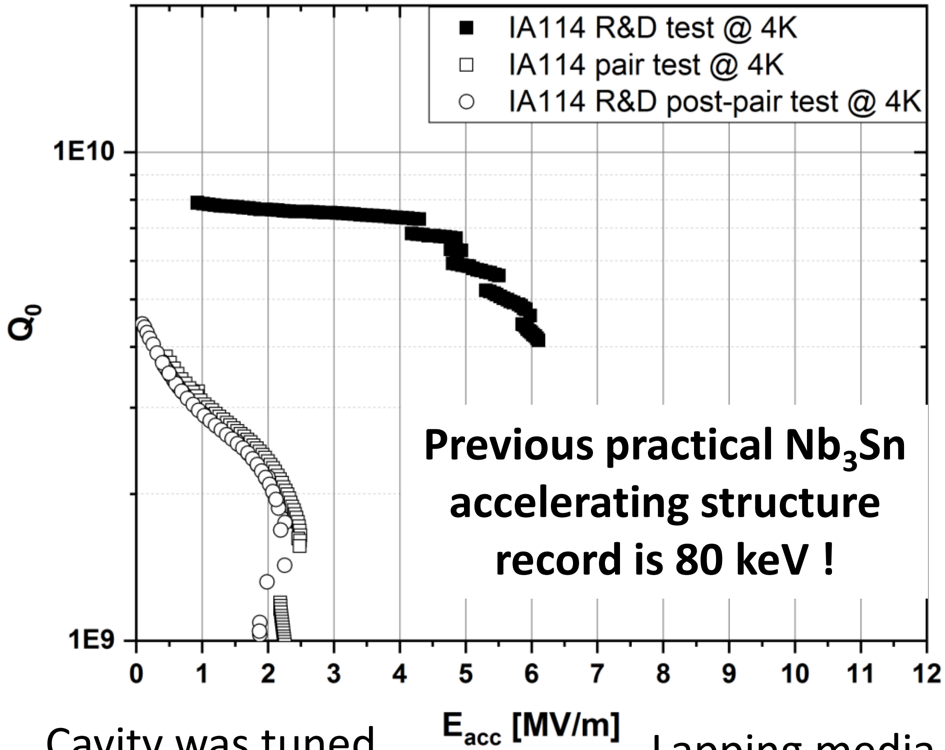


Uniform coating, no obvious asymmetry!



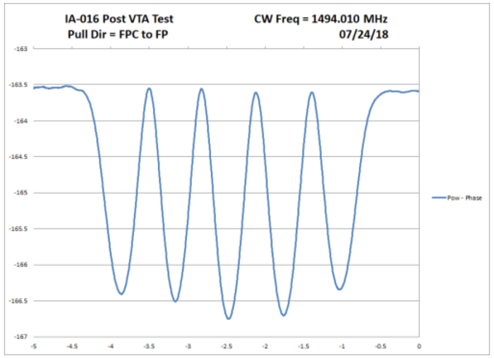
U. Pudasaini

Pair work and results

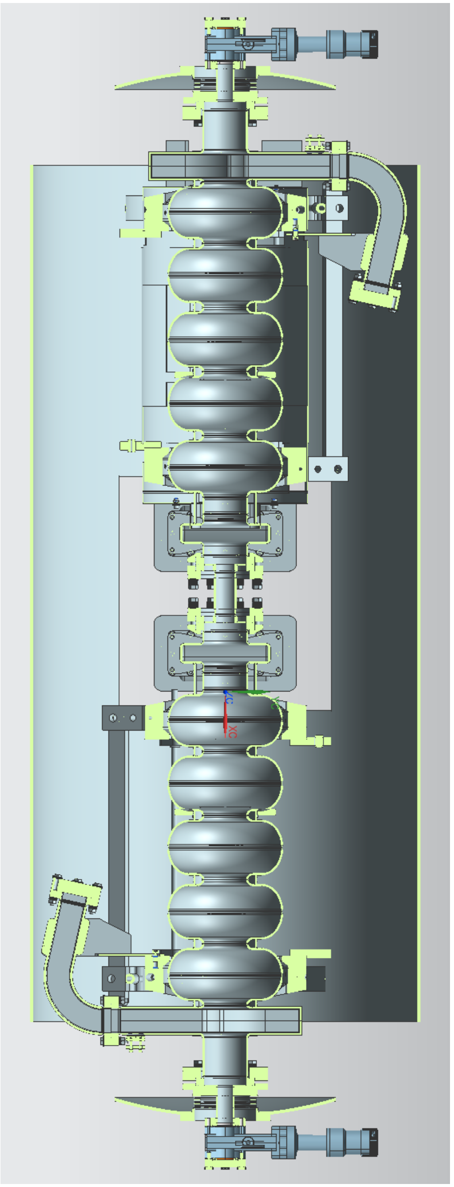


Previous practical Nb_3Sn accelerating structure record is 80 keV !

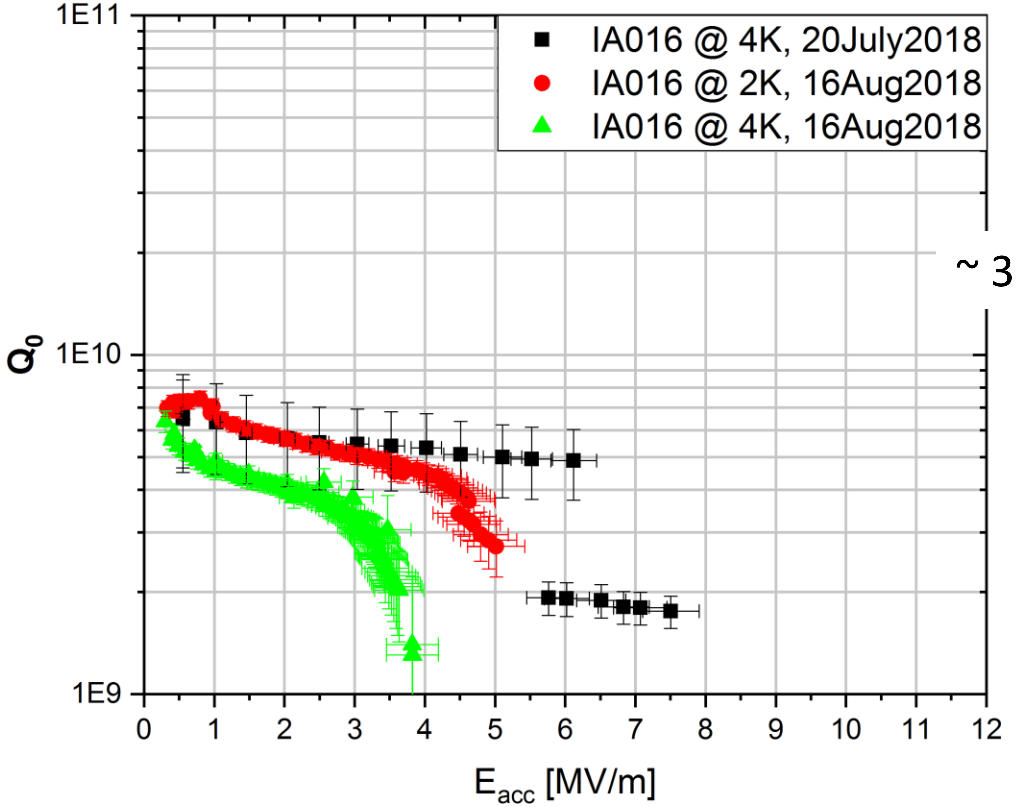
Cavity was tuned several times

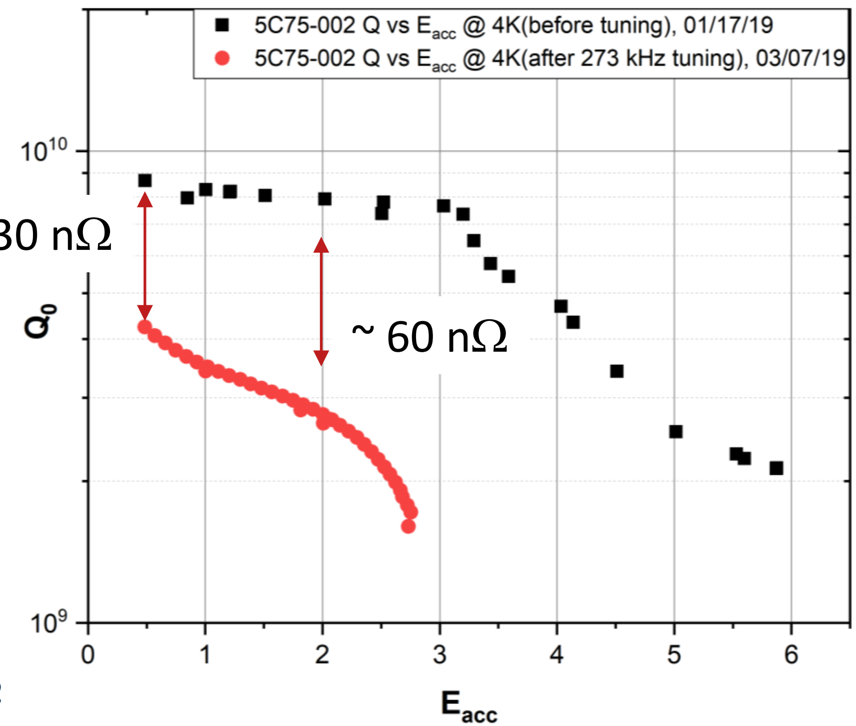


Lapping media after flange polish



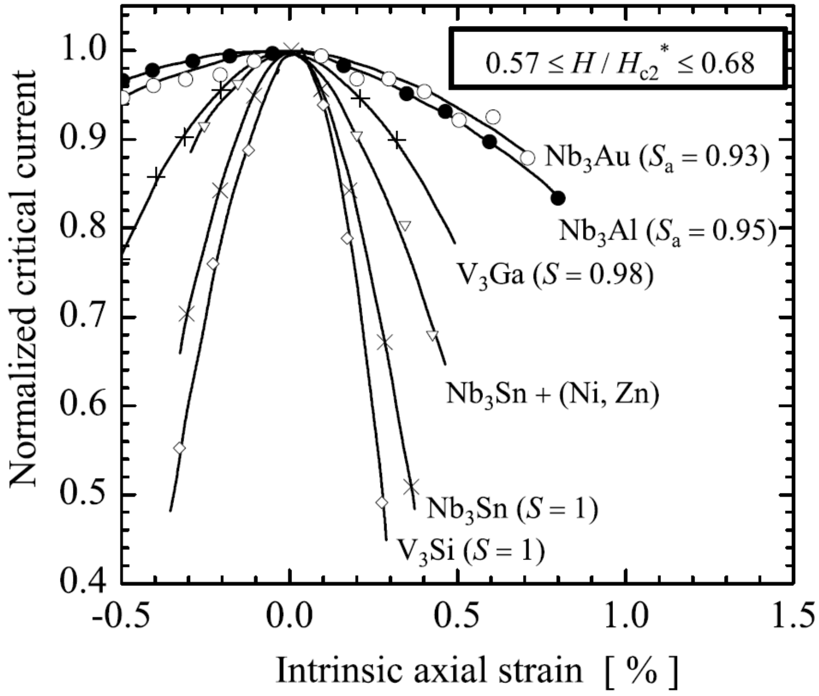
Pair work and results



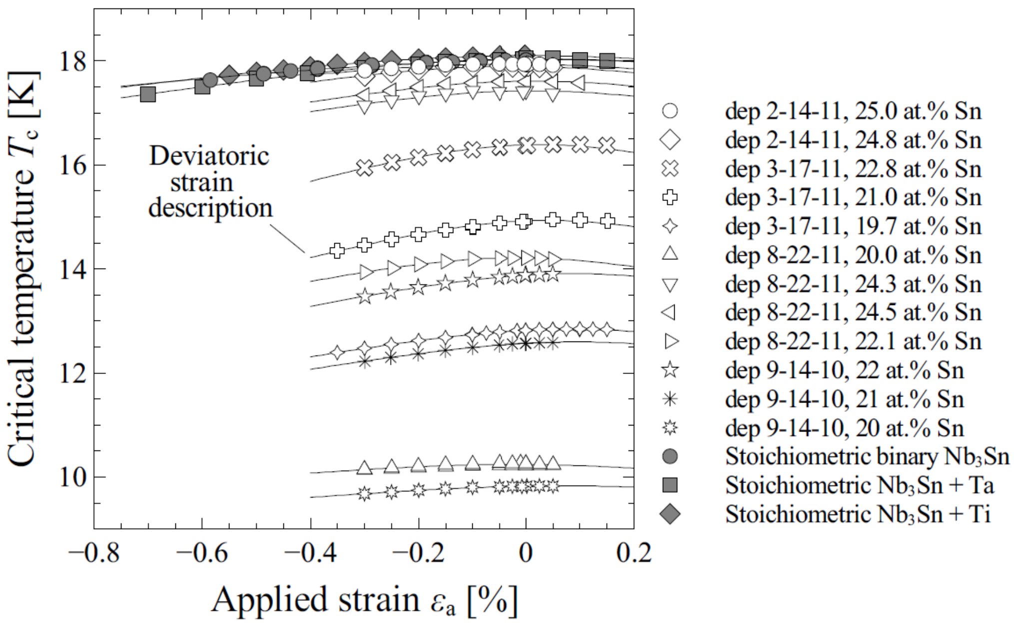


Quality factor and quench degraded after the cavity was tuned by about 200 kHz down. Tuning added field-dependent surface resistance, which increase by about 30 nΩ at low fields

Strain sensitivity



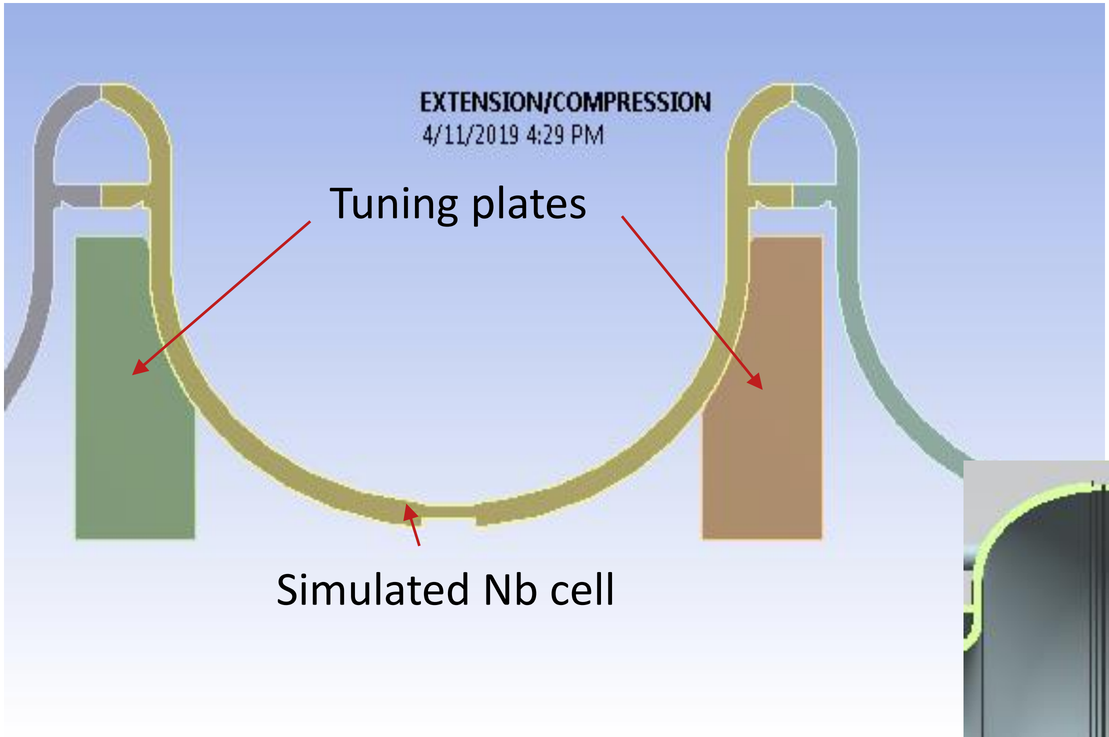
Degradation of critical current as a function of strain for some materials



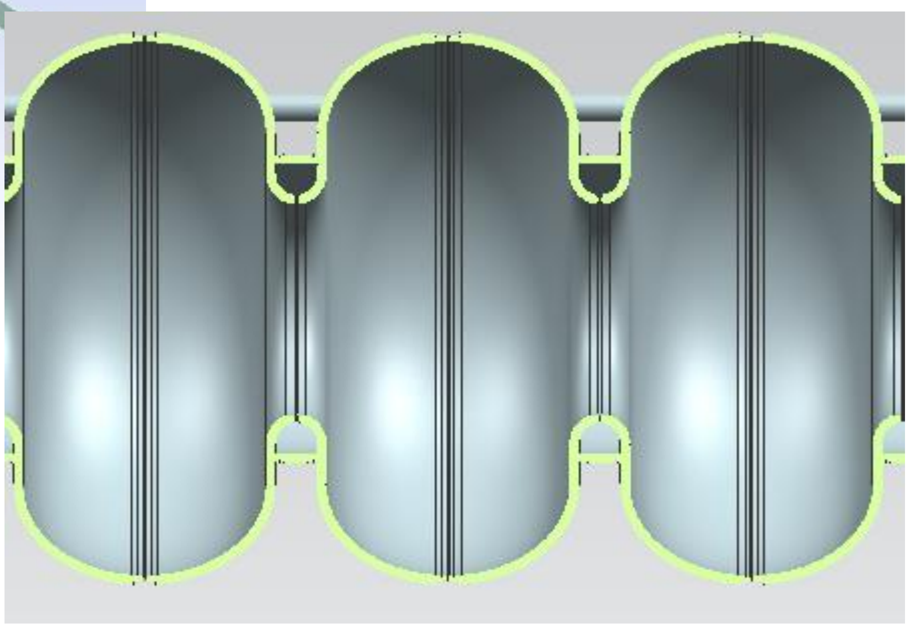
Dependence of the critical temperature on strain in Nb_3Sn

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

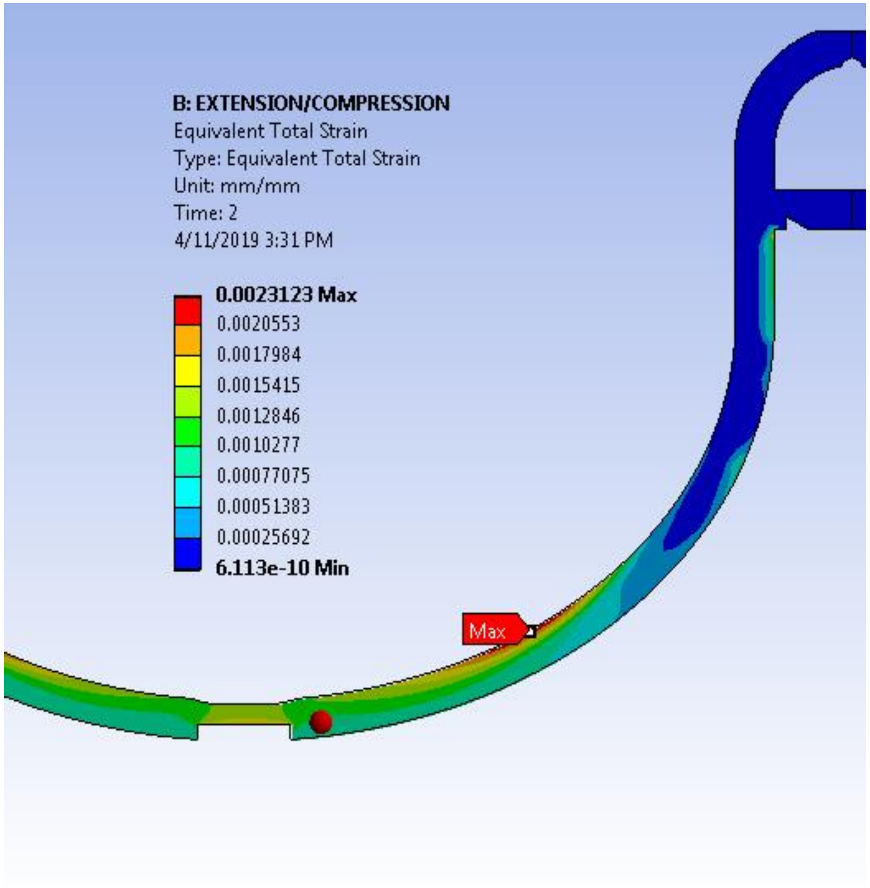


The goal was to simulate compression and extension of the center cell. The cavity needs to be squeezed/stretched beyond the desired frequency change in order to achieve the desired plastic deformation.

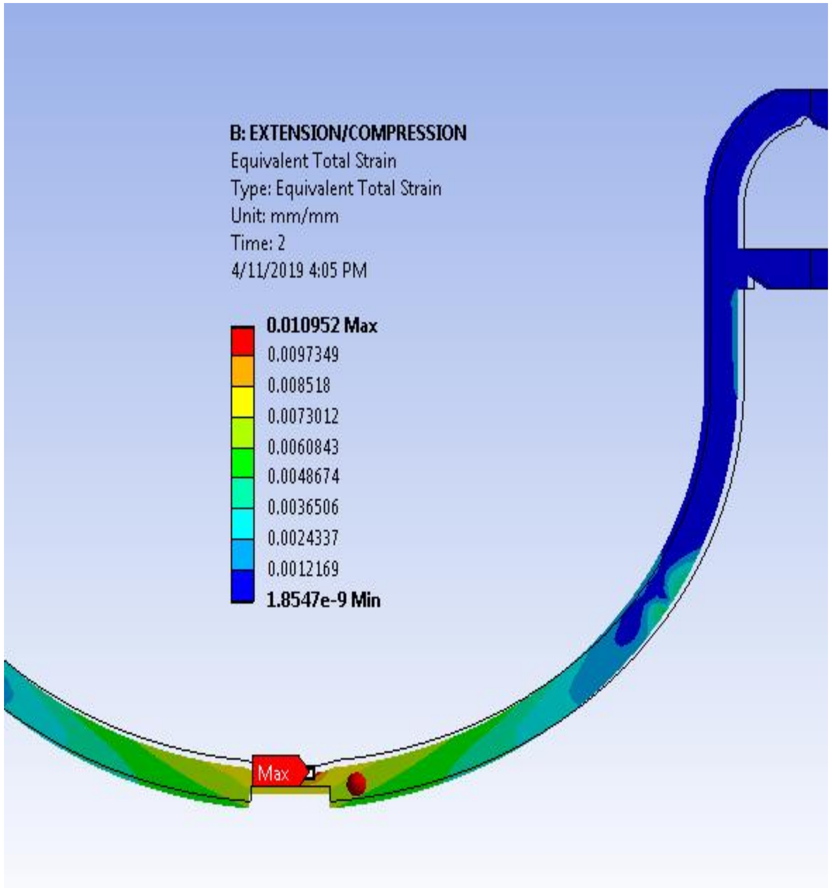
Simulation by W. Crahen

Tuning simulation

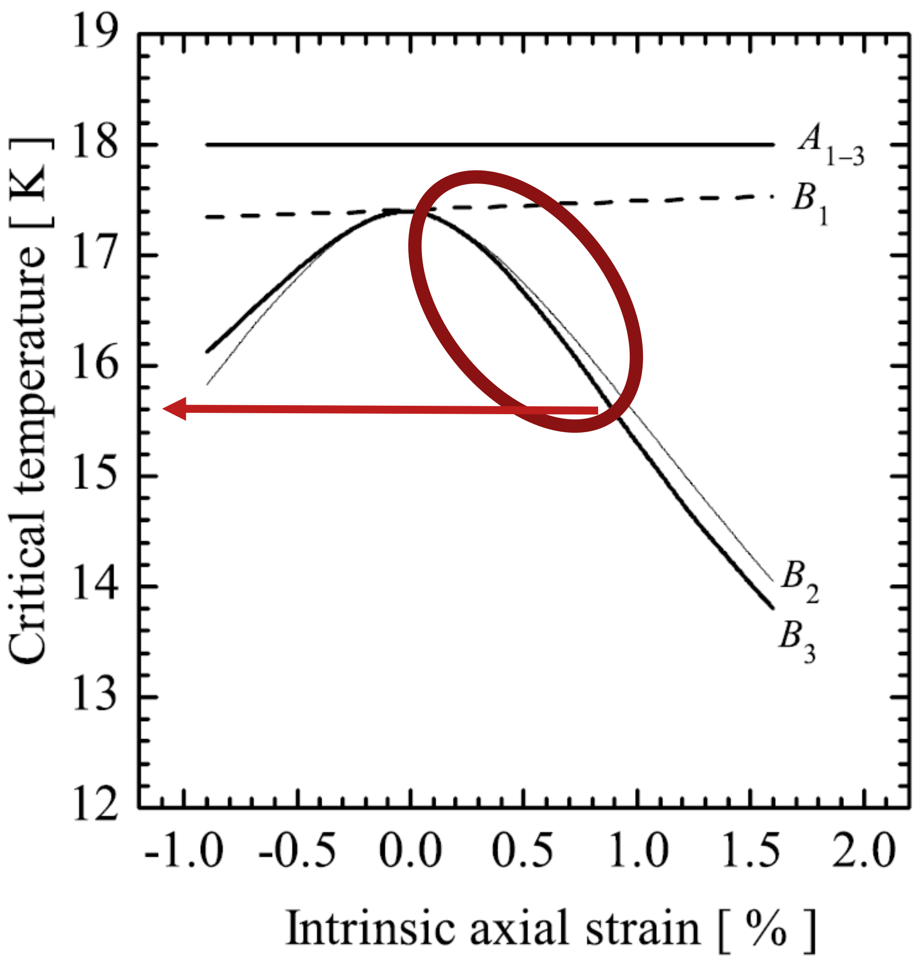
Equivalent Total Strain : 0.71 mm jaw compression yields 0.25 mm deformation



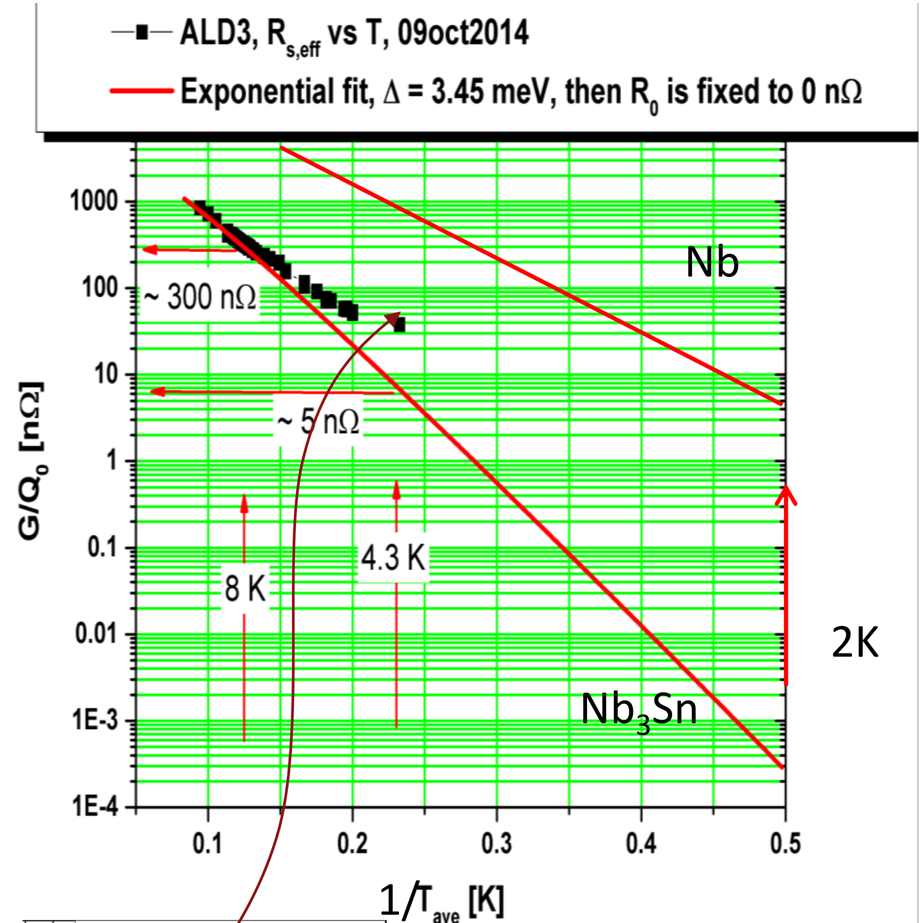
Equivalent Total Strain: -1.445 jaw compression yields 1 mm deformation

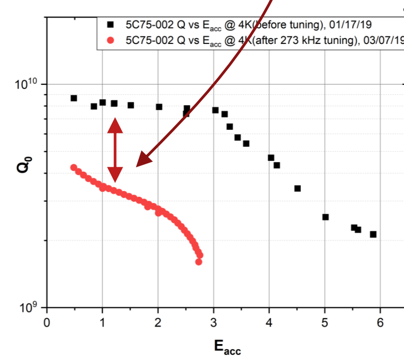


Tuning simulation



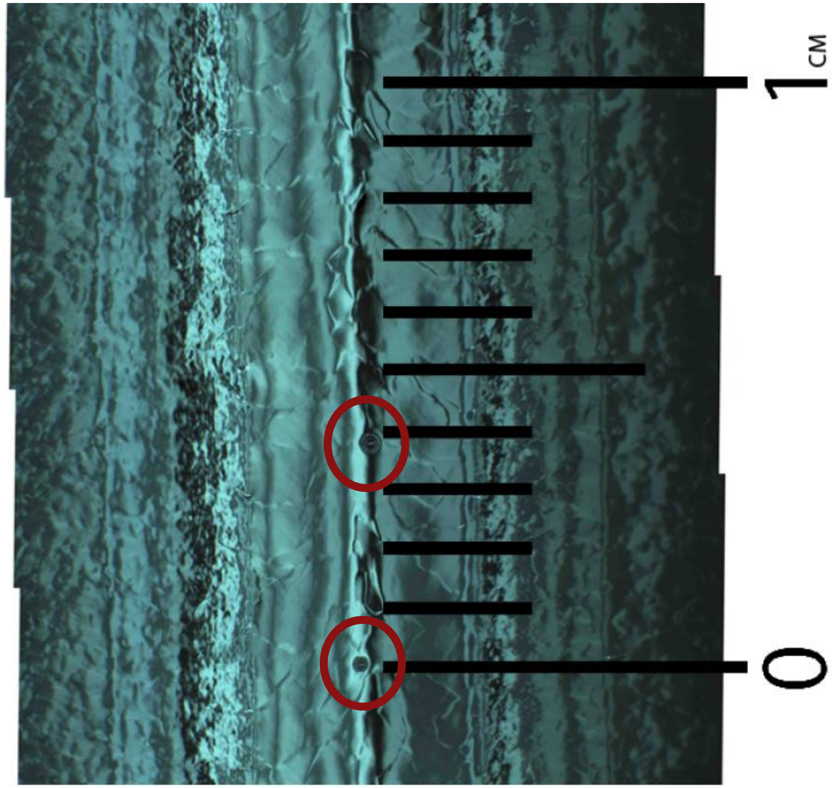
A. Godeke, Ph.D. dissertation

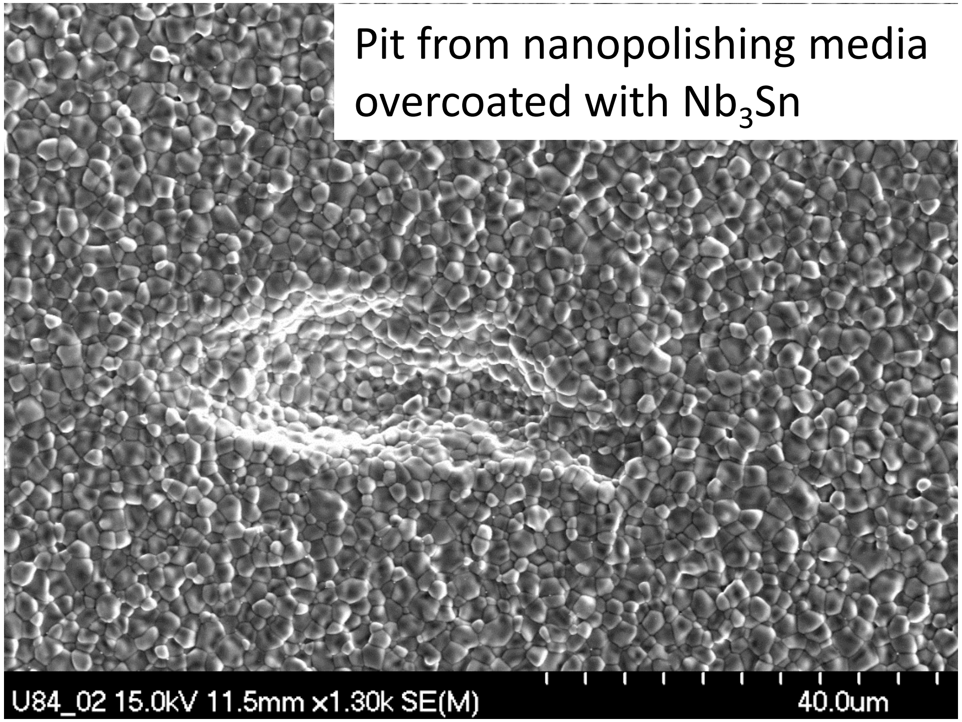




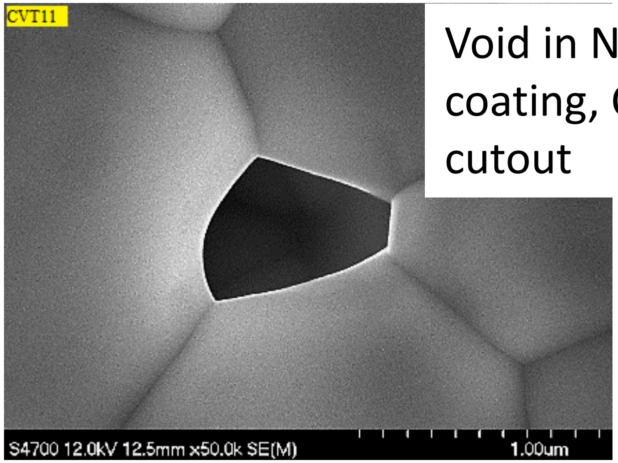
Expected degradation due to T_c reduction is not consistent with the measurement

Weak points?





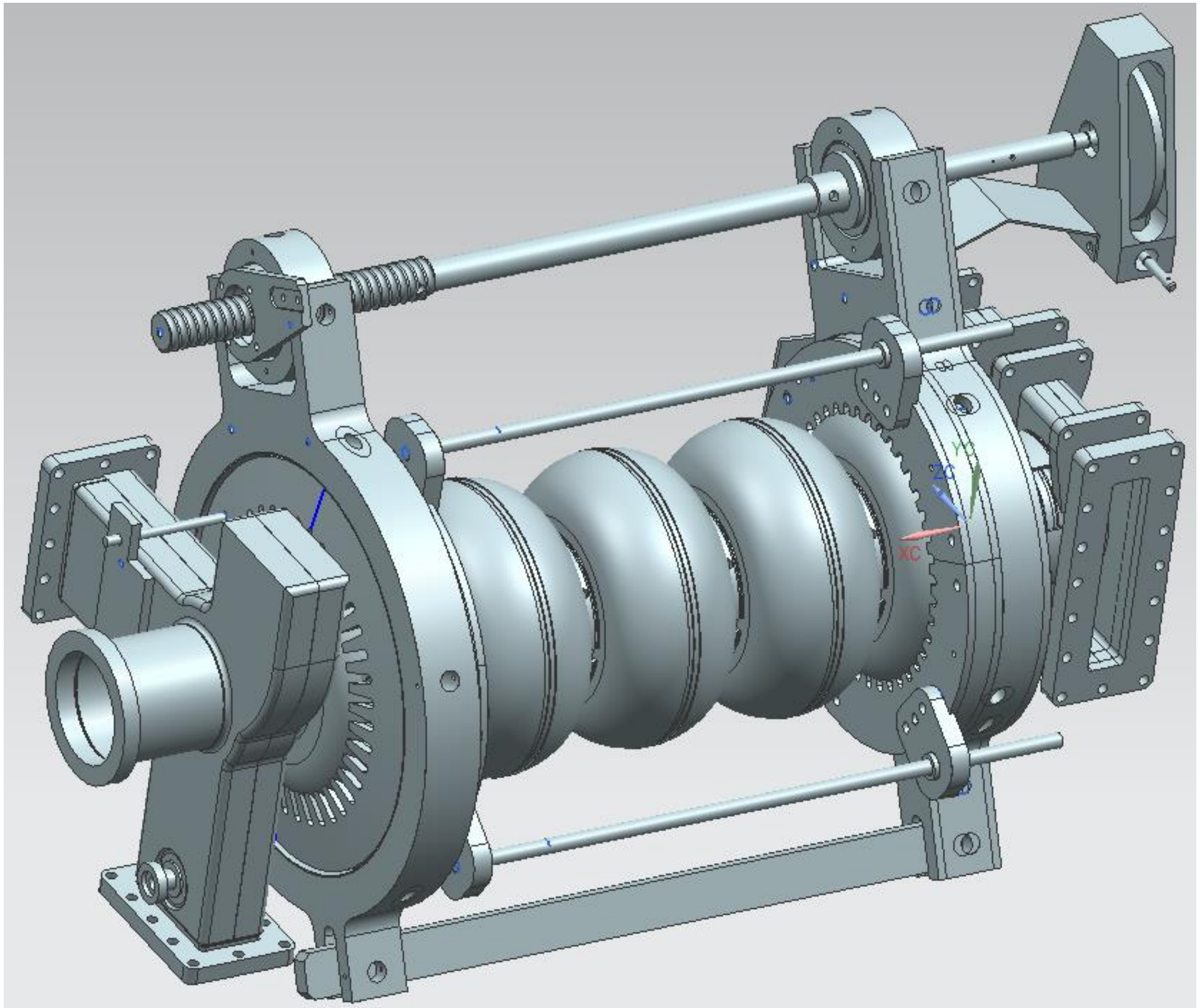
Pit from nanopolishing media overcoated with Nb_3Sn



Void in Nb_3Sn coating, C3C4 cutout

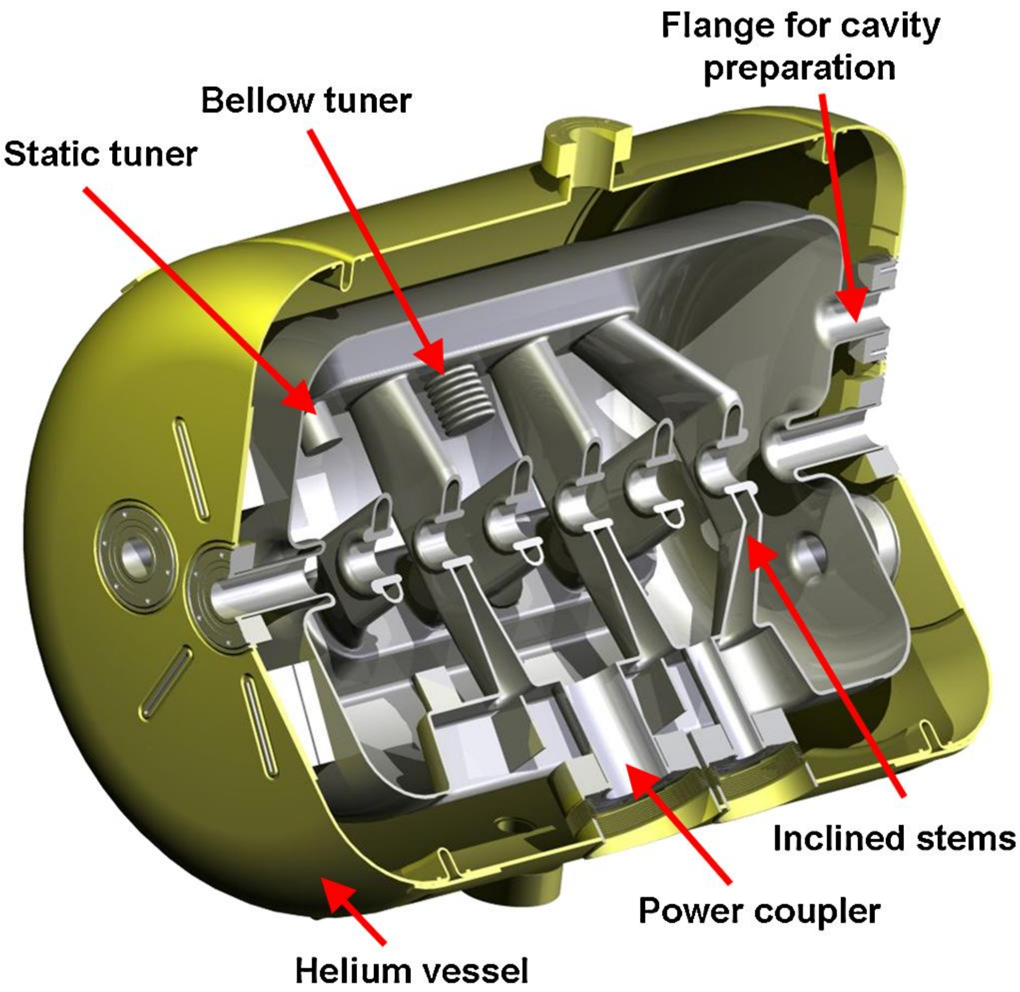
Surface imperfection are likely high stress points, where strain exceeds the average levels and significantly degrades surface resistance → smoothen the surface by centrifugal barrel polish

Tuner in C20/C50/C75 cryomodules

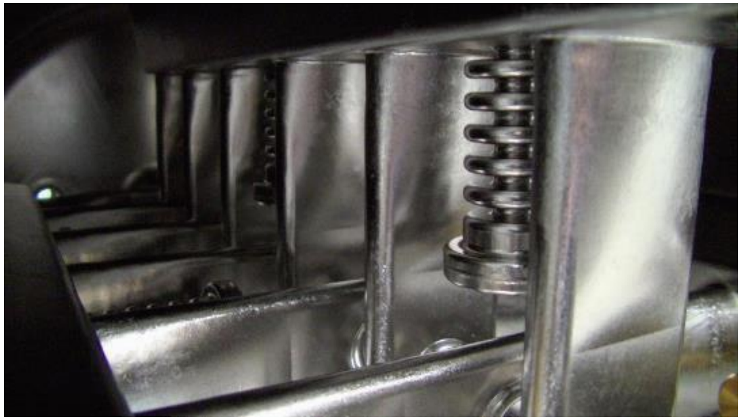


1. The cell holder are assembled "loose" (~ 0.02" "float")
2. Cavities are de-tuned by ~ 100 kHz before cooldown
3. Cavity pair is attached to the helium vessel by four mounts, which hold the cavities by the iris
4. Frequency shifts during cooldown

Alternative tuning solution: bellow tuner

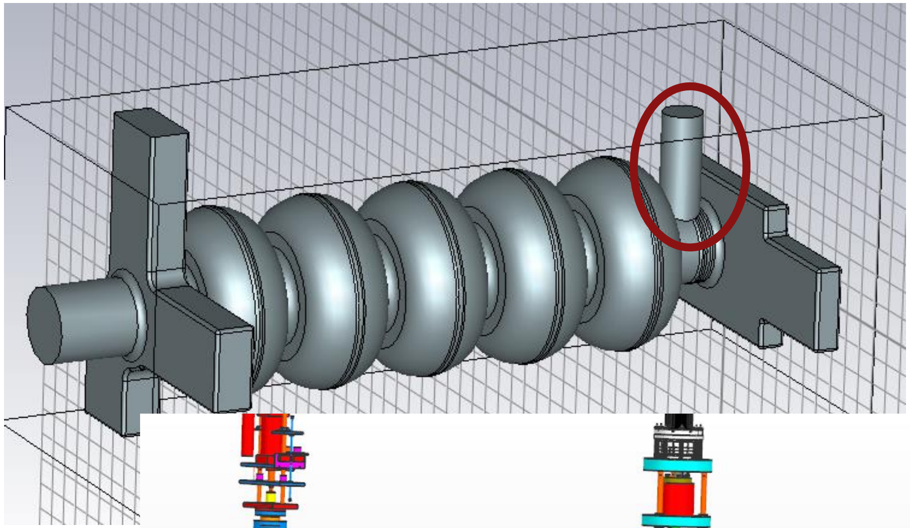


F.Dziuba et al., PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 041302 (2010)

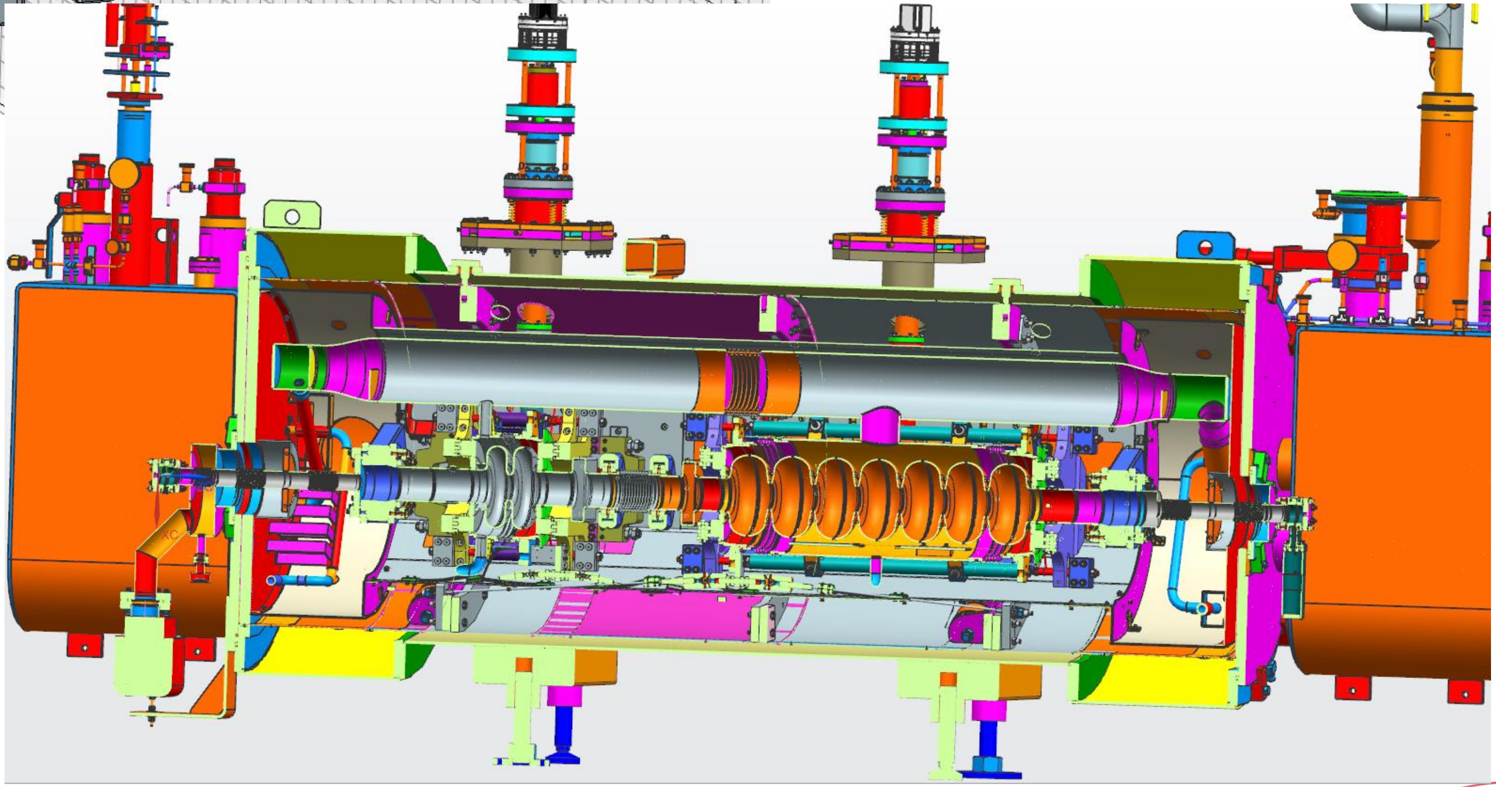


GSI, Helmholtz Institute Mainz, Goethe University Frankfurt

Plunger for CEBAF cavities and its challenges



Implementation of bellows tuner will likely require end group redesign, which will lead to the redesign of cryomodule ($$$).

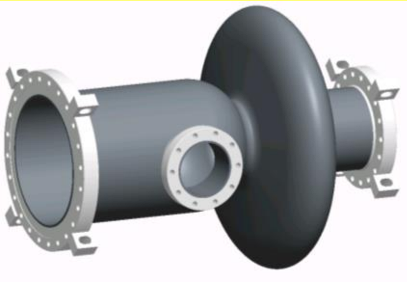


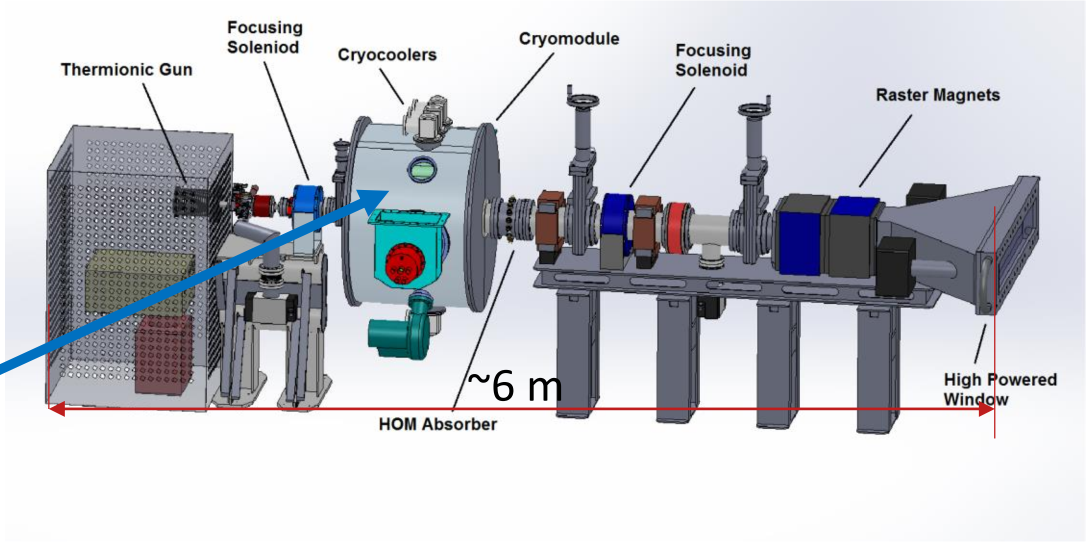
Strain sensitivity is not necessarily an issue for new designs

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

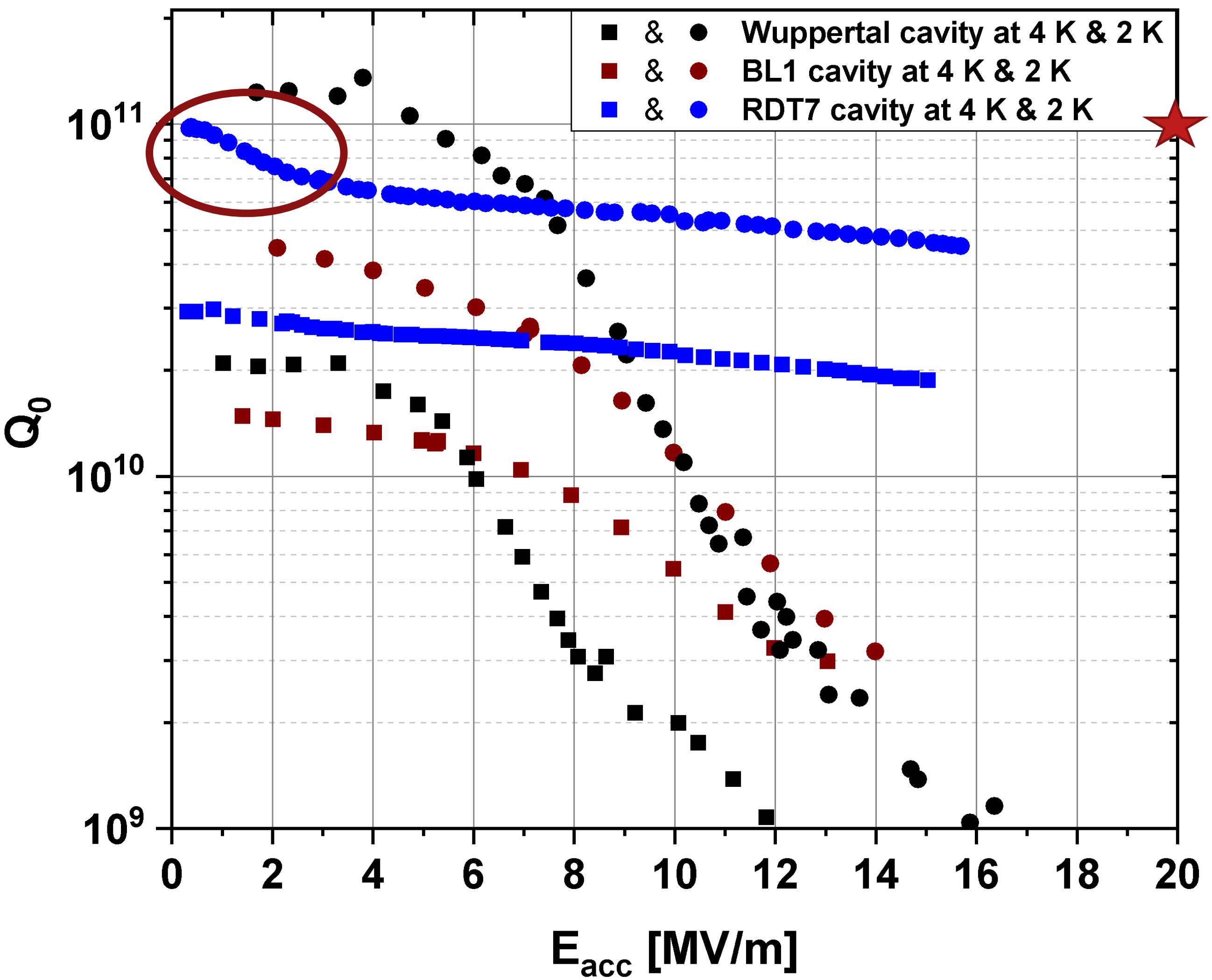
$Nb_3Sn/Nb/Cu$ β=0.5 single-cell cavity, conduction cooled with four 1.5 W cryocoolers





- Patent on Cryomodule design filed on 01/29/18
- Slide from G. Ciovati

Summary #1 : high-Q Nb_3Sn layers

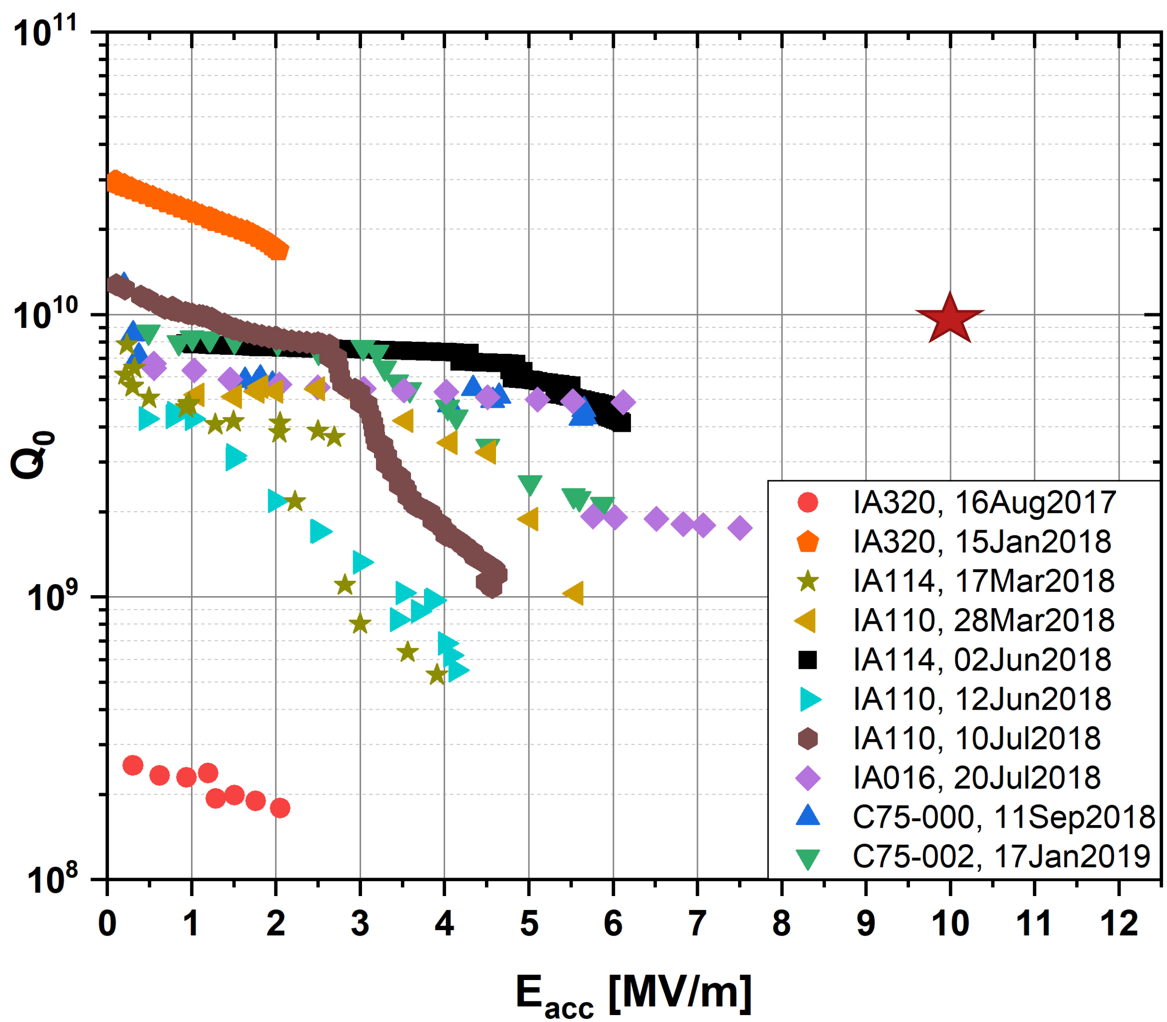


U. Pudasaini

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 <u>in "Siemens" configuration</u>
- 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.

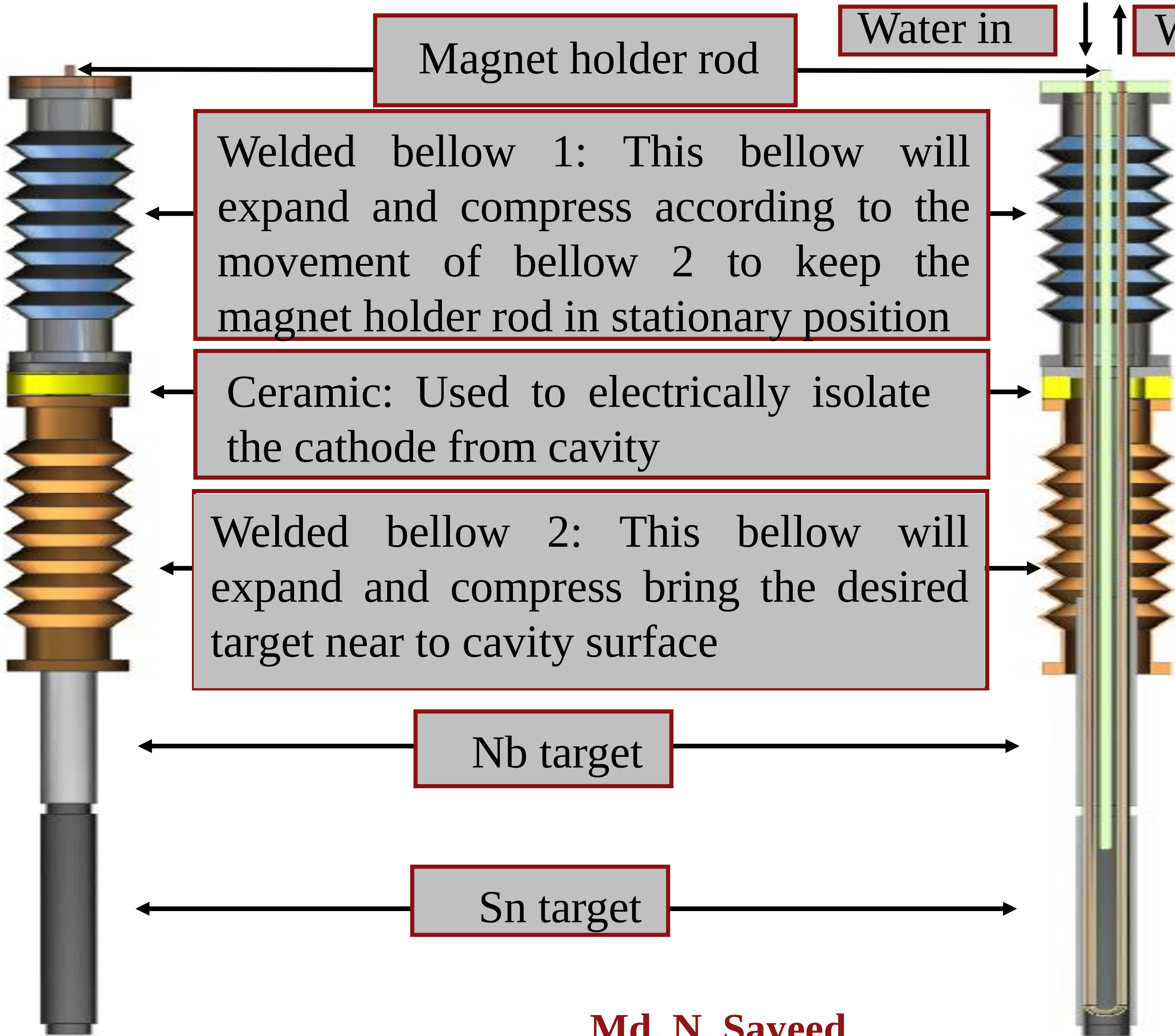
Summary #2 : Nb_3Sn for practical applications



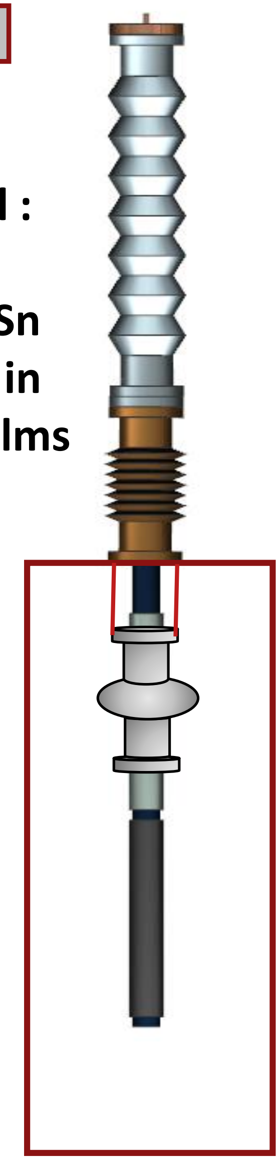
The goal is to study coating degradation by accelerating electron beams in a cryomodule with Q_0 of 10^{10} at E_{acc} = 10 MV/m at 4 K.

- Cavities are limited to below E_{acc} = 10 MV/m in VTA tests
- Possible substrate issues, expecting two new C75 cavities arrive to Jlab this month
- Discovered significant degradation after tuning
- Possible mitigations are surface smoothening and minimized tuning
- The best solution likely involves redesign of a quarter cryomodule

Summary #3 : optimum Nb_3Sn layers



The goal : precise control Sn content in Nb_3Sn films



Thank you for your attention!