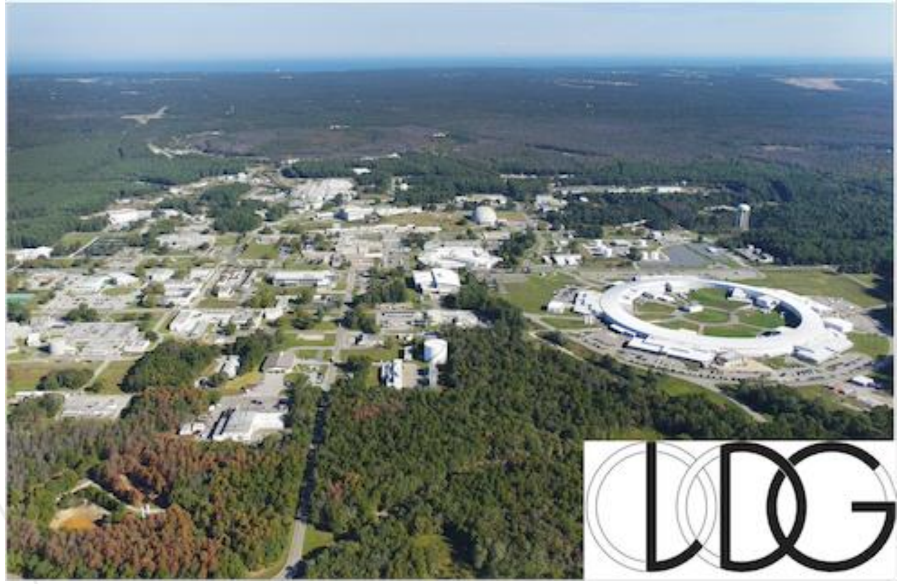
Progress on SRF accelerating cavities for future colliders



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Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Outline

- ❑ SRF bulk cavities for future colliders: ILC, EIC, CEPC, FCC, Helen…
  - Elliptical, Crab cavities,
- ❑ Nb/Cu Technology
- ❑ Beyond Nb
  - Nb_3Sn
  - SIS
- ❑ Summary

Disclaimer

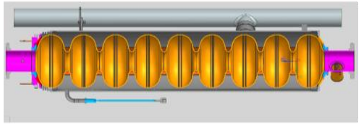
Non-exhaustive – Many other ongoing activities not presented

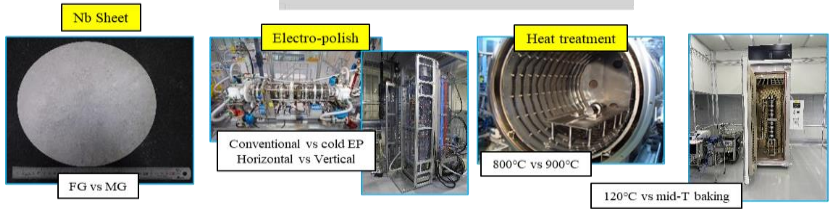
SRF Technology for the International Linear Collider

Matured technology based on TESLA, E-XFEL and LCLS-II experiences. R&D in Asia, Americas and EU geared towards higher performance with cost-effective production.

- ◆ Industrial-production readiness: 12 cavities produced in JP:
  - ◆ Evaluate the successful production yield
- ◆ Cavity performance expected: E_{acc} = <35 MV/m> (+/− 20%), $Q_0 = 1.0 \times 10^{10}$, Yield = ≥90%
- ◆ Globally common design applicable to High Pressure Gas Safety (HPGS) regulation in JP
  - ◆ Plug-compatible design
- ◆ Production process with higher performance/lower cost (i.e. cost-effective production)
  - ◆ Advanced Nb sheet production: Clean surface by direct slice + cost reduction
  - ◆ Advanced surface treatment: High-G and High-Q cavity
    - ◆ Optimization of best surface treatment

Cavity design based on TESLA/LCLS-II (globally common design)



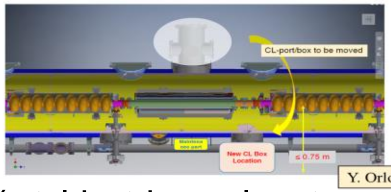


LCLS-II tuner has worked with high reliability, but there is no experience in pulsed mode operation. We need to check this with **first** CM.

LCLS II (HE)/FNAL's
N=320 units+ 180units

CM design is already completed, but we have to design outside components, that is, waveguide system, pumping system for power coupler, current lead box, etc. We need more detailed drawing.

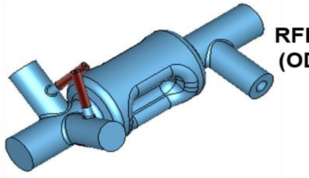
Proposal for the CL box to be moved to the Coupler Port Side



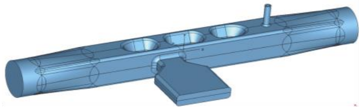
Y. Orlov

Performance yield (94 ± 6)% yield with accelerating gradients >28 MV/m and (75 ± 11)% for 35 MV/m.
Average gradient of 37.1 MV/m.
2 cryomodules (FNAL, KEK) tested with beams achieving ILC specifications.

- Several crab cavity designs have been proposed
- Down Selection Review on Crab Cavity Design – April 4-6, 2023 – KEK, Japan
  - Two crab cavity designs were down selected
- 2 Final Designs
  - RF-Dipole Cavity (RFD) [1.3 GHz] from ODU/JLab
  - Quasi-waveguide Multi-cell Resonator (QMiR) [2.6 GHz] from Fermilab
- 2 selected designs will go into prototype production in the 18-month Pre-Lab phase



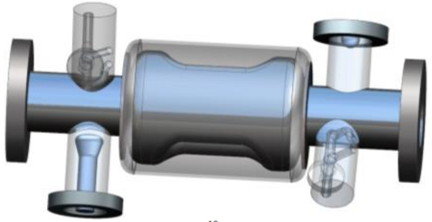
RFD 1.3 GHz (ODU/JLAB)

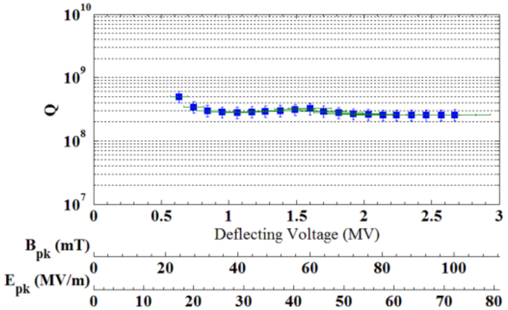


QMIR 2.6 GHz (FERMILAB)

RFD Design:

Basic design is completed next steps, to complete full engineering analysis
Develop detailed fabrication plan
Cu and RG Nb procurement on going





QMiR Design:

Basic design is completed next steps, to complete full engineering analysis
Cavity mechanical drawings are ready for manufacturing stage
Procurement of high-RRR Nb material is completed
Conceptual design of the frequency tuner completed

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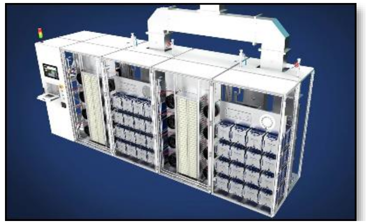
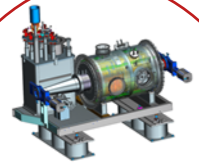
EIC RF systems



RF power and distribution
400kW×34 new SSAs for ESR 591MHz cavities, various power level for other cavities

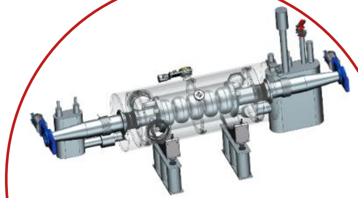
The ESR 591 MHz 1-cell and the HSR 197 MHz crab cavities being prototyped

CD3-A approved the ESR 591 MHz 1-cell first article cryomodule procurement

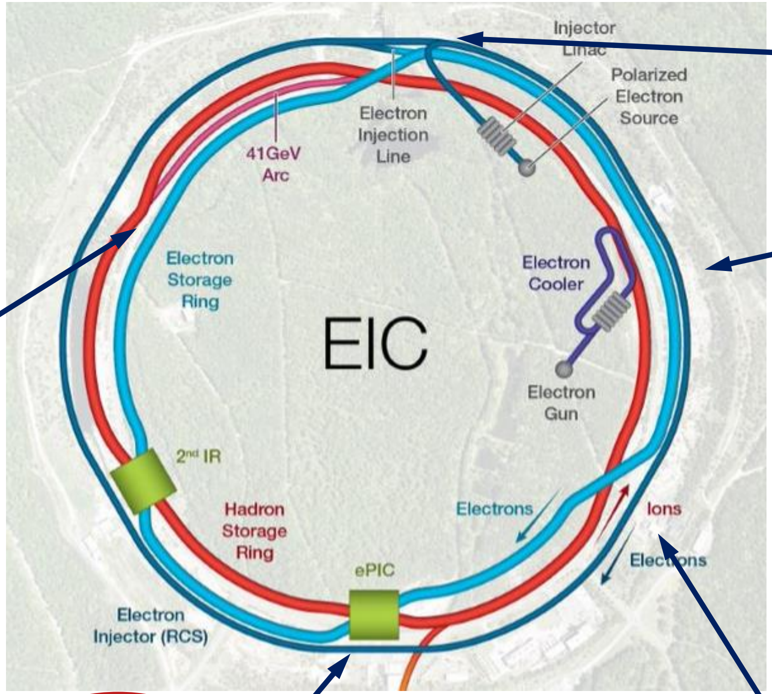


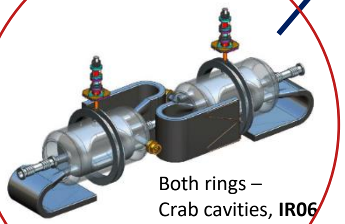
Hadron Storage Ring
591 MHz bunch compression cavity
5 CMs, IR10

Electron Storage Ring
591 MHz Single Cell Cavity Cryomodule
17 CMs, IR10



Rapid Cycling Synchrotron
591 MHz Five-Cell Acceleration Cavity Cryomodule
4 CMs, IR10

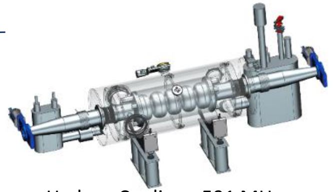




Both rings –
Crab cavities, **IR06**

Crab Cavities (per IR)	HSR (Cavities/CMs)	ESR (Cavities/CMs)
197 MHz	8/4	–
394 MHz	4/4	2/2

RCS injection harmonic RF kicker, **IR12**

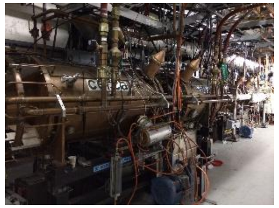


Hadron Cooling - 591 MHz acceleration cavity
10 CMs, Electron Cooler, IR02

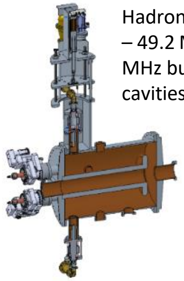
6 ea 197 QWR, 3 ea 591 SC Cavities (Not shown)
3 CMs, ERL Injector / Linac, IR02

1773 MHz 3rd Harmonic (4) Cavities (Not shown)
1 CM, Electron Cooler, IR02

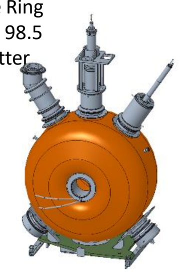
RCS – 148MHz and 296MHz bunch merger cavities **IR04**



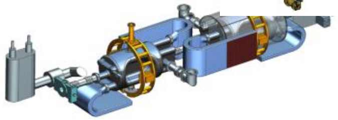
Hadron Storage Ring – 24.6 MHz acceleration cavity **IR04**



Hadron Storage Ring – 49.2 MHz and 98.5 MHz bunch splitter cavities **IR04**



Hadron Storage Ring - 197 MHz bunch compression cavity **IR04**



List of EIC RF/SRF cavities

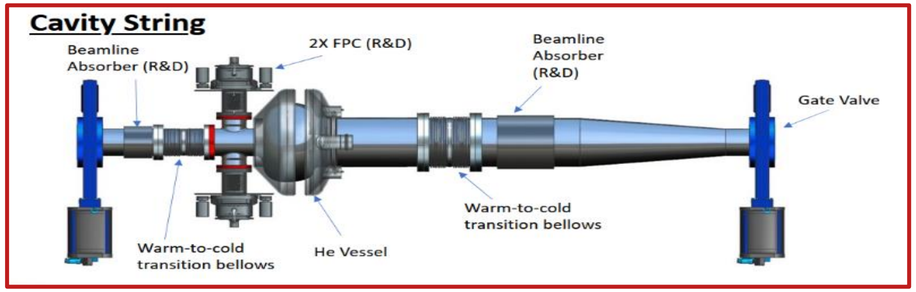
RF System	Sub System	Freq [MHz]	Type	Location	# Cavities	# FPC/cavity	FPC power (kW)
Electron Storage Ring	Accel / Store	591	SRF, 1-cell	IR-10	17	2	400
Rapid Cycling Synchrotron (RCS) The whole electron injection chain design under revision. The pre-injectors (linac and the potential booster) not included.	Accel / Store	591	SRF, 5-cell	IR-10	3	1	70
	Harmonic Kickers	295 148/443	NCRF, QWR, 1-mode NCRF, QWR, 2-mode	IR-2 or IR-12	1 1	1	1 5
	Bunch Merge 1	295	NCRF, Reentrant	IR-4	2	1	70
	Bunch Merge 2	148	NCRF, Reentrant	IR-4	1	1	70
Hadron Storage Ring	Capture / Accel	24.6	NCRF, QWR	IR-4	4	1	100
	Bunch Split 1	49.2	NCRF, QWR	IR-4	2	1	200
	Bunch Split 2	98.5	NCRF, QWR	IR-4	2	1	200
	Store 1	197	NCRF, Reentrant	IR-4	7	1	100
	Store 2	591	SRF, 1-cell	IR-10	5	1	60
Hadron Cooling ERL (combination of pre-cooler and strong hadron cooler) ERL design and requirements still evolving	ERL Injector	197 591	SRF, QWR SRF, 1-cell	IR-2	2 1	2 1	200 10
	ERL Low Energy Linac	197 591	SRF, QWR SRF, 1-cell	IR-2	4 2	2 1	200 10
	ERL Fundamental	591	SRF, 5-cell	IR-2	10	1	60
	ERL Third Harmonic	1773	SRF, 5-cell	IR-2	4 (1 CM)	1	5
Crab Cavities (2nd IR not included)	Hadron	197	SRF, RFD	IR-6	8 (4 CM)	1	70
	Hadron/Electron	394	SRF, RFD	IR-6	6	1	50

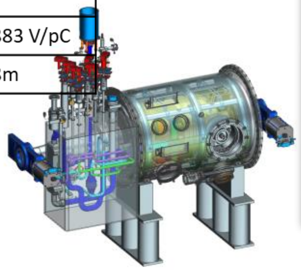
EIC electron storage ring 591 MHz elliptical SRF cavities

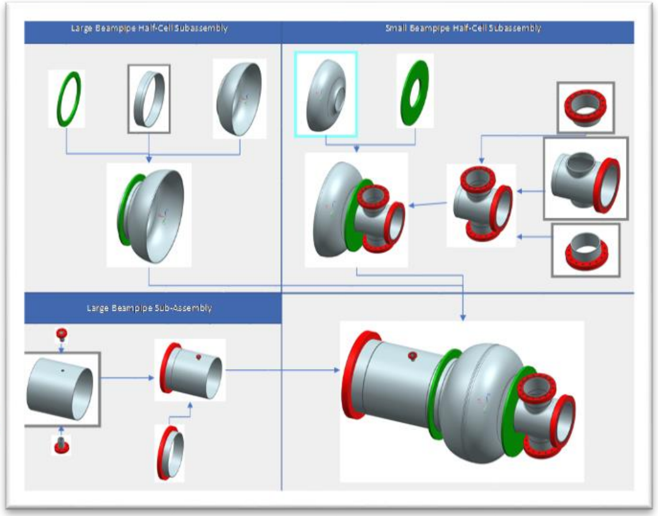
1-cell Cavity

- Designed for the ESR, may be used for the HSR too
- Strong HOM excitation from the high beam current and short bunches, damped by two BLAs
- Asymmetric design with R75mm beampipe on one side (matching the largest possible gatevalve fits the geometry constraints), R137mm on the other side to damp the lowest dipole HOM and lower the fundamental mode R/Q, but needs to be tapered to R75mm
- Intrinsic Qext set at 2E5, possible to tune down to 2.5E4 with external tuning network
- Single cavity cryomodule

Parameters	Value
Nominal voltage (MV)	3.9
Nominal gradient (MV/m)	17.3
R/Q (Linac Def) (Ω)	76
Epk/Eacc	2.01
Bpk/Eacc (mT/(MV/m))	4.87
G (Ω)	307
FPC tip penetration for Qext ~2E5 (mm)	9
Loss factor (with FPC, 2 BLAs, exc FM, 7mm bunch)	0.883 V/pC
Estimated total length (gate valve to gate valve)	2.8m







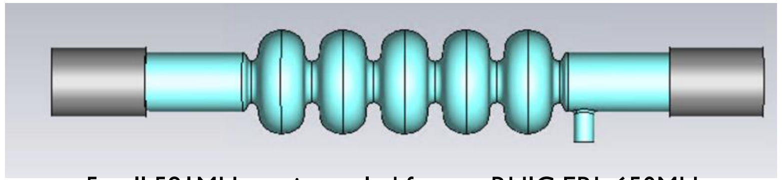
Under fabrication - EBW

5-cell Cavity

- Baseline : scaled BNL eRHIC 650MHz 5-cell with BLAs, which has been prototyped and meets the impedance requirements
- Possible to adapt the PERLE type coaxial HOM damper with smaller and shorter beampipes

Parameters	RCS (1GeV merging)	ERL
Nominal frequency (MHz)	591.1492	
Operation frequency range	± 120kHz	Small
Cavity voltage [MV]	20	
Number of cavities	3	10
Acceleration rate (MV/turn)	2.2	NA
Max. RF power [kW]	65	small
Longitudinal impedance threshold	~2MΩ (< 1GHz) ~2MΩ-GHz (>1GHz)	Not a concern
Transversal impedance threshold	12MΩ/m	1MΩ/m

EIC RCS/ERL 591MHz cavity requirements



5-cell 591MHz cavity scaled from e-RHIC ERL 650MHz

EIC electron storage ring 591 MHz elliptical SRF cavity

- Operating voltage per cavity: **8.5** MV for **197** MHz & 2.9 MV for 394 MHz.
- Designed specs: 11.5MV for 197MHz & 3.5MV for 394MHz, with E_{pk} 45MV/m & B_{pk} 80mT.
- Impedance budget (per cavity): For 197MHz **10kΩ** longitudinal **0.132MΩ/m** horizontal **0.66MΩ/m** vertical & for 394MHz **3.25kΩ-GHz** longitudinal **0.12MΩ/m** transverse (with two 394MHz for ESR per IP per side, considering two IPs).
- High HOM power per cavity, **a few kW** for hadron ring 197MHz and **>40kW** for electron ring 394MHz.

197 MHz Crab Cavity

S. De Silva

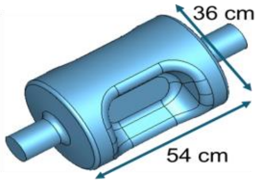
- Longer poles to provide higher crabbing voltage, elongated Double Quarter Wave (DQW) is not mechanically suitable, thus RFD is chosen.
- Electromagnetic design requires to achieve:
  - Cavity peak surface fields of E_p < 45 MV/m and B_p < 80 mT at 11.5 MV
    - At nominal voltage of 8.5 MV they will be lower
  - Bare cavity dimensions:
    - Cavity length ≤ 1.5 m
    - Cavity diameter (without couplers) ≤ 0.6 m

Dimension	Value
Cavity Length [mm] (iris-to-iris)	921.9
Cavity Length [mm] (flange-to-flange)	1435
Cavity Diameter [mm]	587.2
Pole Length [mm]	524
Angle [deg]	20

RF Property	Value	
V_t [MV]	8.5	11.5
E_p [MV/m]	32.3	43.7
B_p [mT]	58.1	78.6
Total V_t [MV]	34	
No. of cavities	4	3
Operating Temp. [K]	2.05	
Stored Energy [J]	50.3	92
R_s [Ω] (R_{BCS} = 0.4 nΩ)	15	
P_{diss} [W]	9.6	17.6
Q_0 (G = 97.2 Ω)	6.48×10^9	

394 MHz Crab Cavity

- 394 MHz cavities will be installed on both HSR and ESR
  - 197 MHz crabbing system is the primary crabbing system at HSR
  - Second harmonic crabbing system operating at 394 MHz will be installed at HSR to linearize the kick for the 6-7 cm long proton bunches
  - Beam aperture = 100 mm from HSR
  - Damping specs from ESR
  - HOM power handling from ESR
- Single cavity cryomodule to be similar for both HSR and ESR is the current plan
- Wide-Open-Waveguide (WOW) type produces >50% more HOM power comparing with on-cell damping design (next slide), thus is not preferred

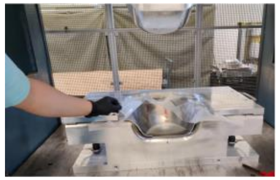


S. De Silva

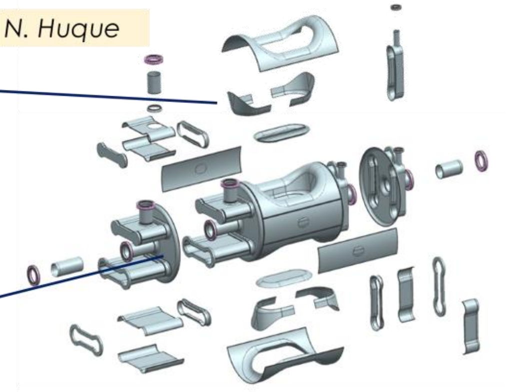
$^*E_t = V_t/(\lambda/2)$

Property	Value	
Operating frequency	394.0	
1st HOM [MHz]	537	
E_p/E_t^*	3.87	
B_p/E_t^* [mT/(MV/m)]	8.08	
B_p/E_p [mT/(MV/m)]	2.09	
G [Ω]	125.4	
R/Q [Ω]	308.6	
R_tR_s [Ω²]	3.9×10^4	
Max V_t [MV] per cavity	2.9	
E_p [MV/m]	29.5	
B_p [mT]	61.56	
Total V_t [MV]	2.9	4.75
No. of cavities	1	2

- Longer poles to provide higher crabbing voltage, elongated DQW is not mechanically suitable, thus RFD is chosen.
- On-cell waveguide ports to provide better damping
  - 197MHz: waveguide to coaxial design to avoid large waveguide damper; 2 cavities in 1 cryomodule to save longitudinal space.
  - 394MHz: waveguide damper (preliminary); WOW type causes higher HOM power thus is not preferred.
- Curved pole (machine from ingot Nb) for multipoles specs.
- High gain low delay loop → Amplifier on top of tunnel for low delay
- Noise control → Feedback with good pickup.



N. Huque



Under fabrication

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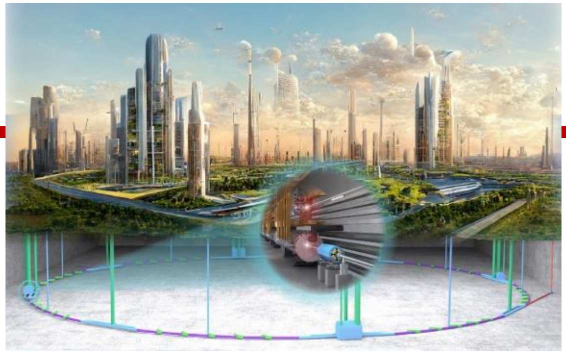
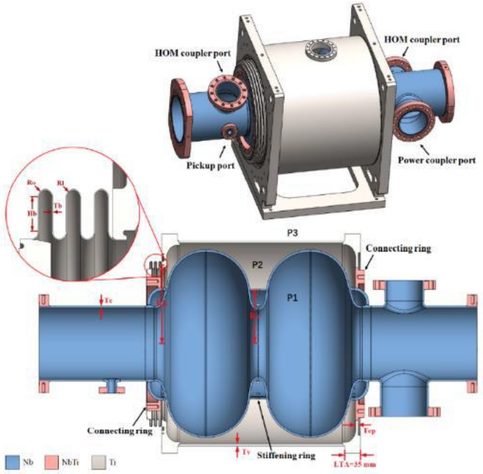
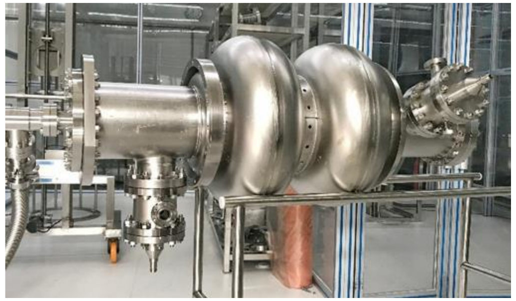
SRF for CEPC

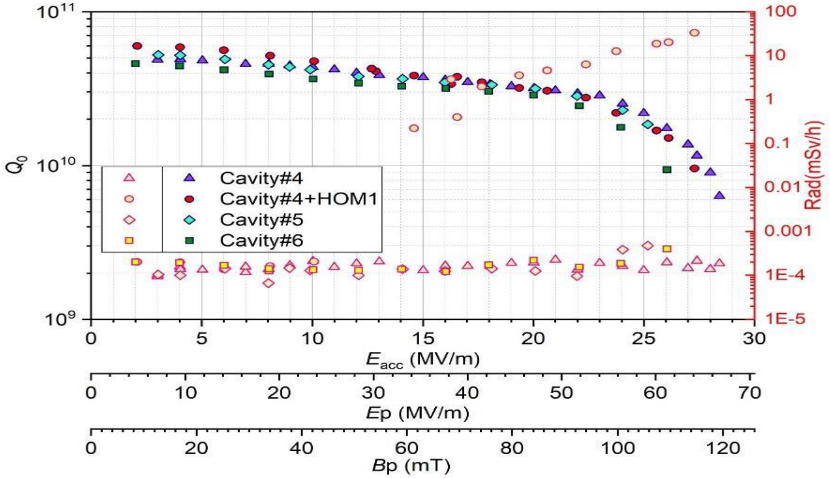


650MHz 2-cell and 1.3GHz 9-cell cavities R&D

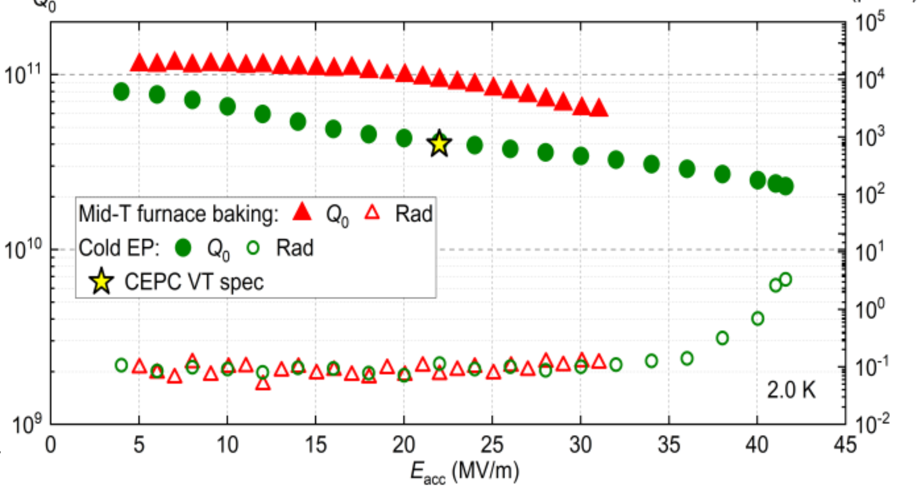




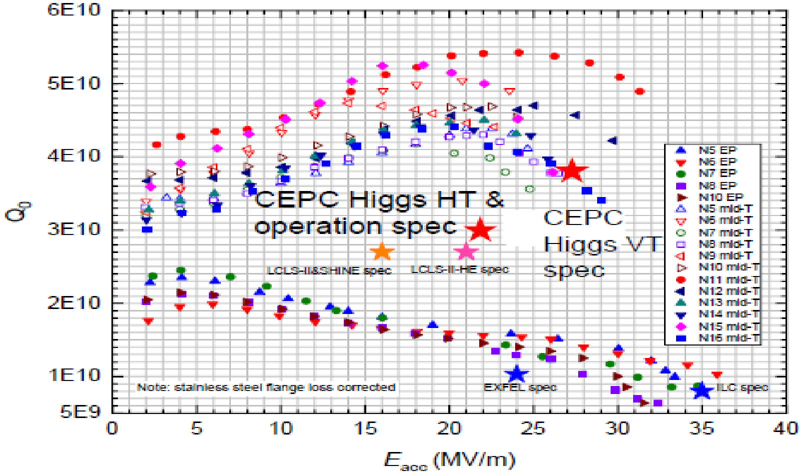
650 MHz 2-cell BCP



650 MHz 1-cell EP / mid-T bake



1.3 GHz 9-cell EP / mid-T



- 650 MHz 2-cell cavity: 3.8e[10] @ 25 MV/m, > 31MV/m (achieved in 1-cell) . Six cavities in the module.
- 1.3 GHz 9-cell cavity: 3.6e[10] @ 21.8 MV/m, > 27MV/m (increase gradient). 16 cavities in two modules

Jefferson Lab

800 MHz bulk Nb SRF Development for FCC

- High-efficiency 800 MHz RF power sources & modulators
- FCC-ee SRF cavities R&D goals

Phase 1: $Q_0 = 3 \times 10^{10}$ at $E_{acc} = 25$ MV/m for Booster up to Higgs operation (120 GeV per beam)

Phase 2: $Q_0 = 6 \times 10^{10}$ at $E_{acc} = 25$ for Booster and Main Ring for tt operation

In parallel: Cryomodule (CM) design optimization for 800 MHz cavities, possibly with integrated focusing

- 28 CMs for the booster up to the H energy
- 244 CMs for the tt energy

	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1280	0.080
W	80	135	1.05
H	120	26.7	2.1
ttb	182.5	5	11.3

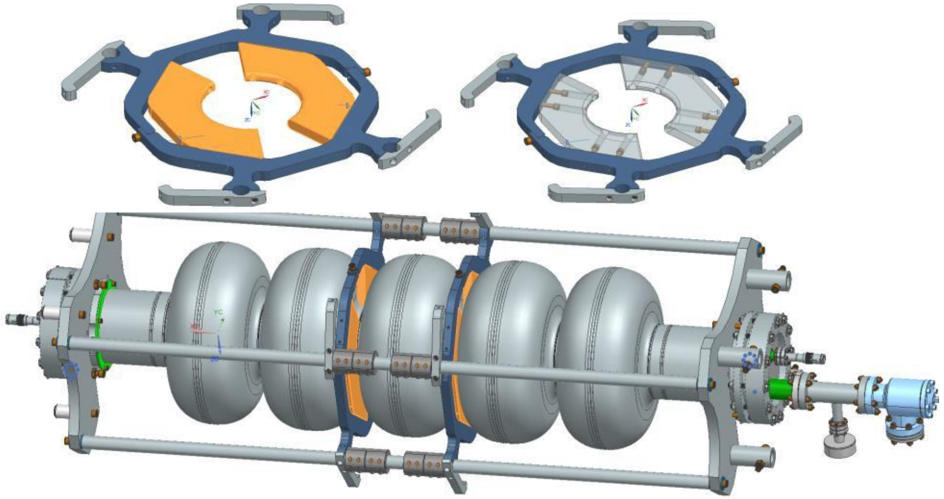
High current machine

High gradient machine

- Bulk Nb, High Q
- Desired performance
  - $E_{acc} = 20$ MV/m, $Q_0 = 3e^{10}$ in operation
  - $E_{acc} = 24.5$ MV/m, $Q_0 = 3.8e^{10}$ in vertical test

- Fabricated at JLab
- EP, last tested 2018
- High-power RF cold-test plan (Spring 2024) @ FNAL:
  1. Baseline cold-test
  2. First mid-T (300-350° C) baking treatment

800 MHz 1- & 5-cell Prototypes



F. Marhauser et al. *802 MHz ERL Cavity Design and Development (cern.ch)* *IPAC 2018* **THPAL146**

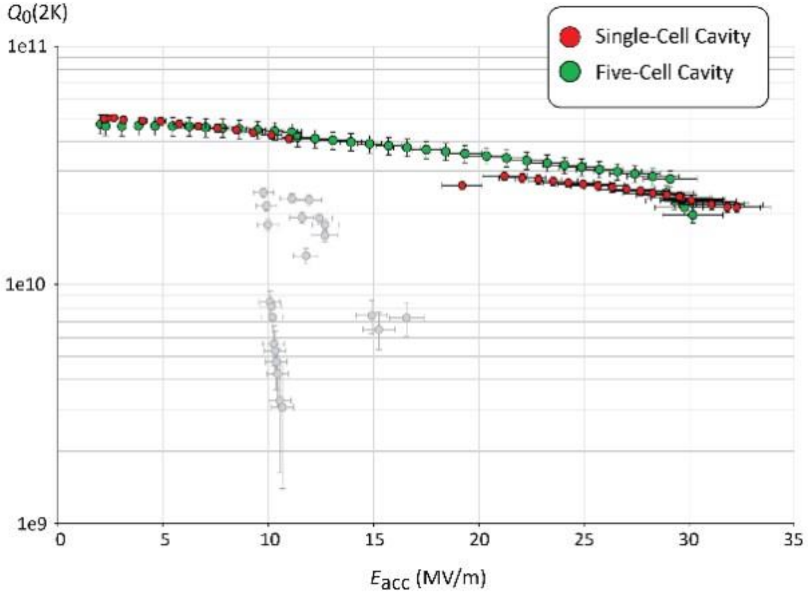
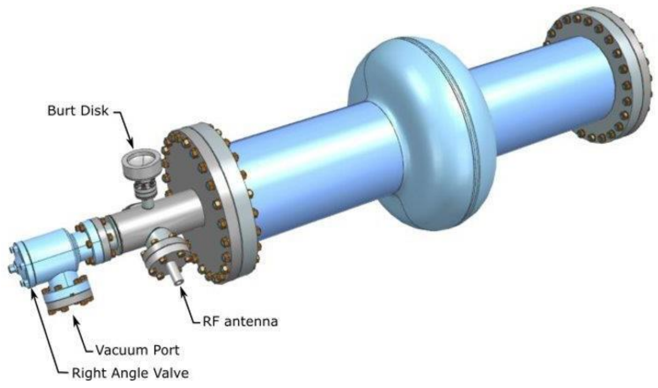


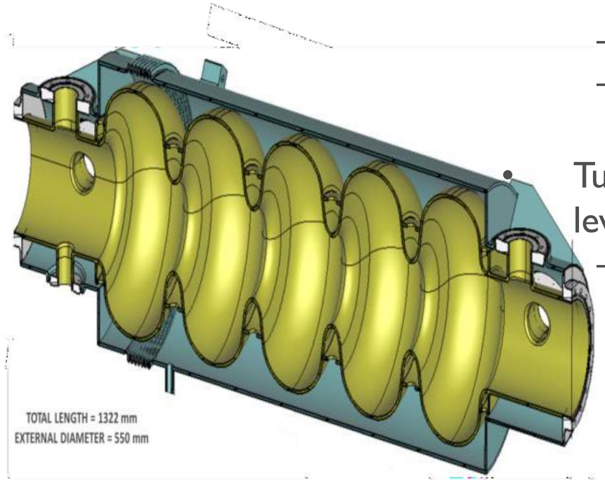
Figure 4: Combined VTA results for the five-cell and single-cell cavity as measured at 2 Kelvin.

800 MHz bulk Nb SRF Development for FCC

1-cell 800 MHz design

- FNAL mechanical design based on CERN RF design (end- cells)
- Compatible with high-temp; Nb_3Sn cavity R&D
- CERN to fabricate 3 in-house, send to FNAL for bulk surface processing, and RF testing

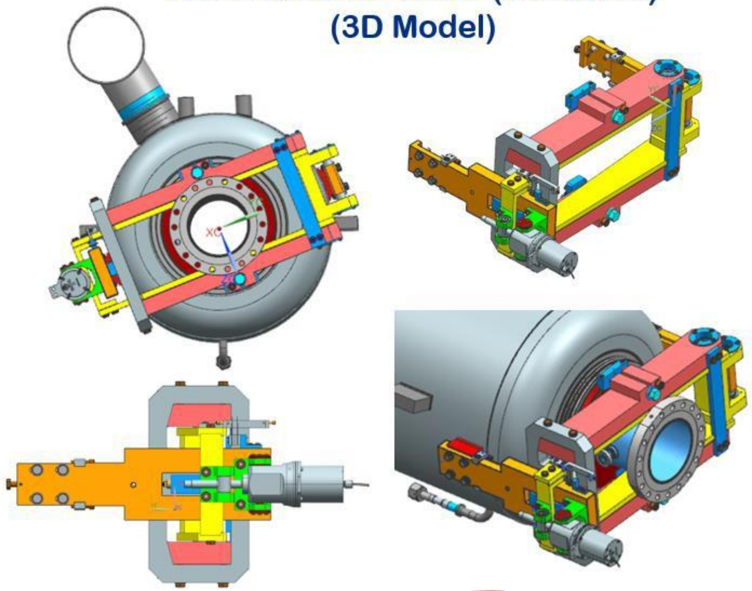




Integrated jacketed cavity + tuner design

- Initial design proposed by CERN
- FNAL contributing changes based on PIP-II,LCLS-II, e.g:
  - Redesign with smaller bellows
  - Integrated He jacket and tuner design so loads/stiffness managed efficiently
- Tuner design to be based on modified FNAL 650 MHz double-lever tuner
  - FNAL has unique experience manufacturing/QA testing these in production quantities

FNAL 650MHz Tuner (Version II) (3D Model)

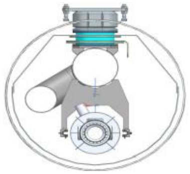


Cryomodule design

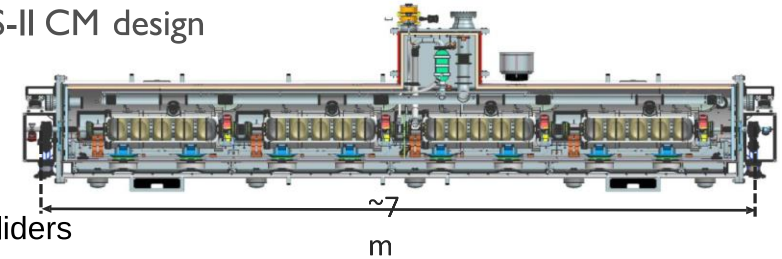
Preliminary design work for segmented, continuous, and hybrid cryomodule concepts

- Fine-segmented design draws heavily on PIP-II design, which also benefits from PIP-II international shipping studies, etc.
- Continuous design concept in early stages, based on LCLS-II CM design

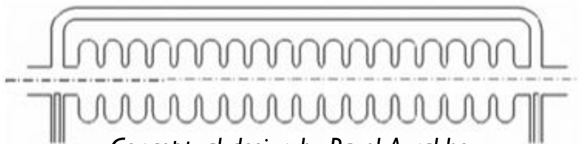
Continuous design



Segmented design, with 800 MHz cavities



TRAVELING WAVE SRF LINEAR COLLIDER HIGGS FACTORY - HELEN

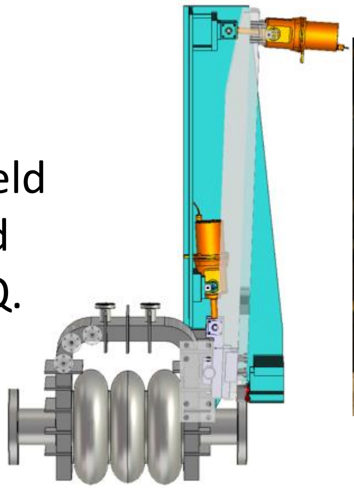


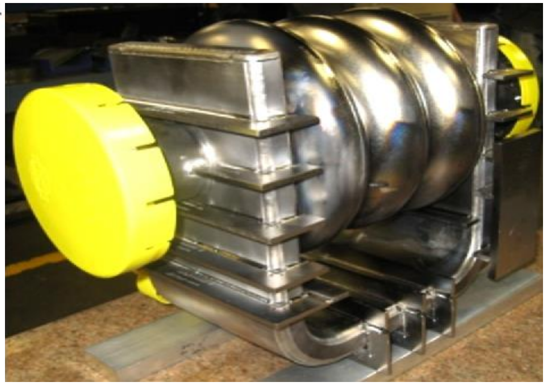
Conceptual design by Pavel Avrakhov

- Cost reductions per TW regime rely on mature, industry-standard practices.
- Well-developed TW technology brings a range of exciting high-energy compact linear collider concepts within the realm of possibility.
- An example, the proposed TW-based linear collider HELEN [2] can achieve a 250 GeV center-of-mass energy in only 7.5 km, in stark contrast to the 30-km scale of the SW ILC structure.

Advantages compared to standing wave cavities :

- lower peak magnetic field
- lower peak electric field
- substantially higher R/Q.





✓ **Conceptual design**

Superconducting Traveling-Wave accelerating structure with feedback waveguide to circulating RF power from the structure output to the structure input.

✓ **Feasibility study**

a single-cell cavity w/ feedback waveguide to demonstrate high gradient operation and conduct RF field measurements.

A proof-of-principle

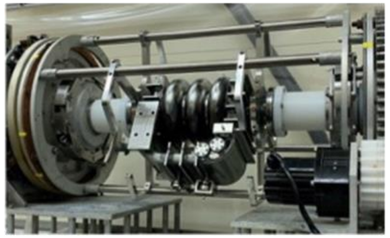
✓ 3-cell TW cavity and a special tuner fabricated

✓ Demonstrated TW excitation at room temp.

In progress

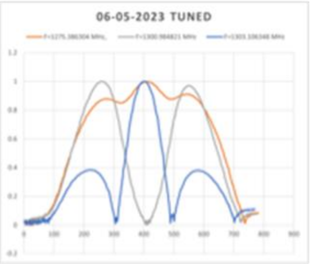
- The 1st cold test to demonstrate TW resonance excitation in 2K liquid is ongoing at IB1 VTS.

TW 3-cell VTS preparations

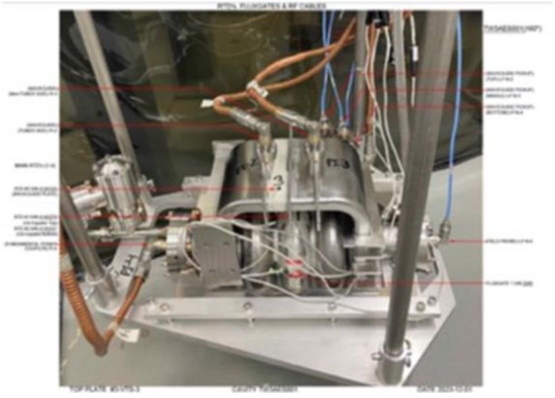


BCP at ANL

HPR at IB4, FNAL

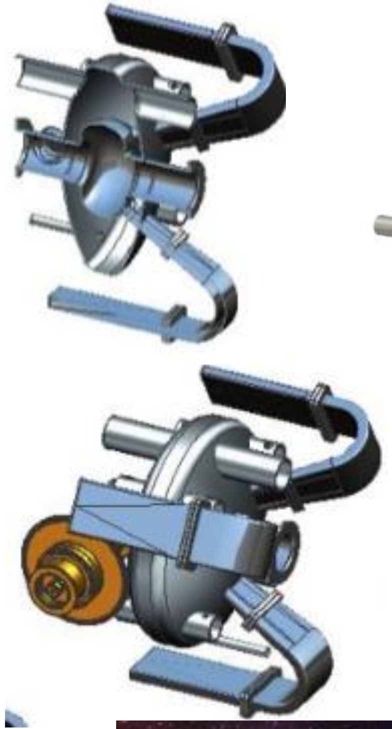


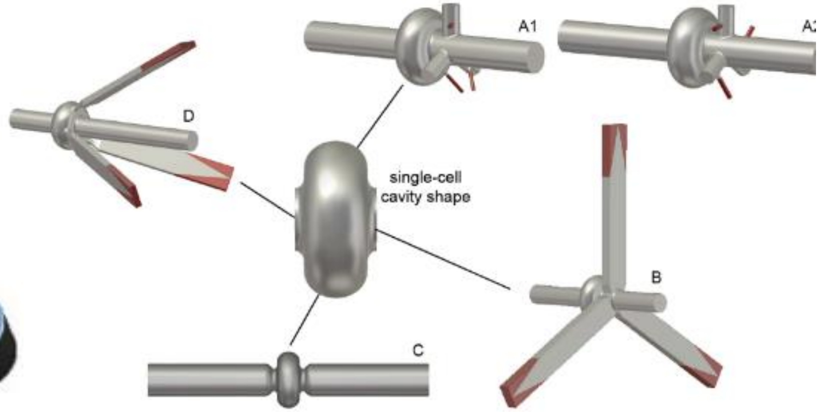
Tuning hardware on the 3-cell and the field profiles (SW mode) post tuning.



VTS instrumentations

Higher-Order Mode Damped SRF Cavities for Circular Colliders

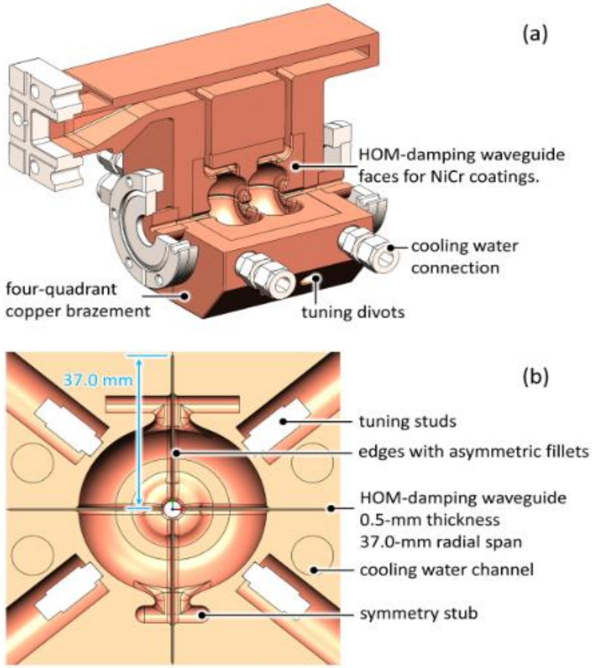




F. Marhauser. Next generation HOM damping. Superconducting Science and Technology Topical Review 30 (2017) 063002, 30(6):38, 2017

- Fabricated in house
- Cavity prepared with BCP
- 1^{st} RF test end of May 24 - preliminary

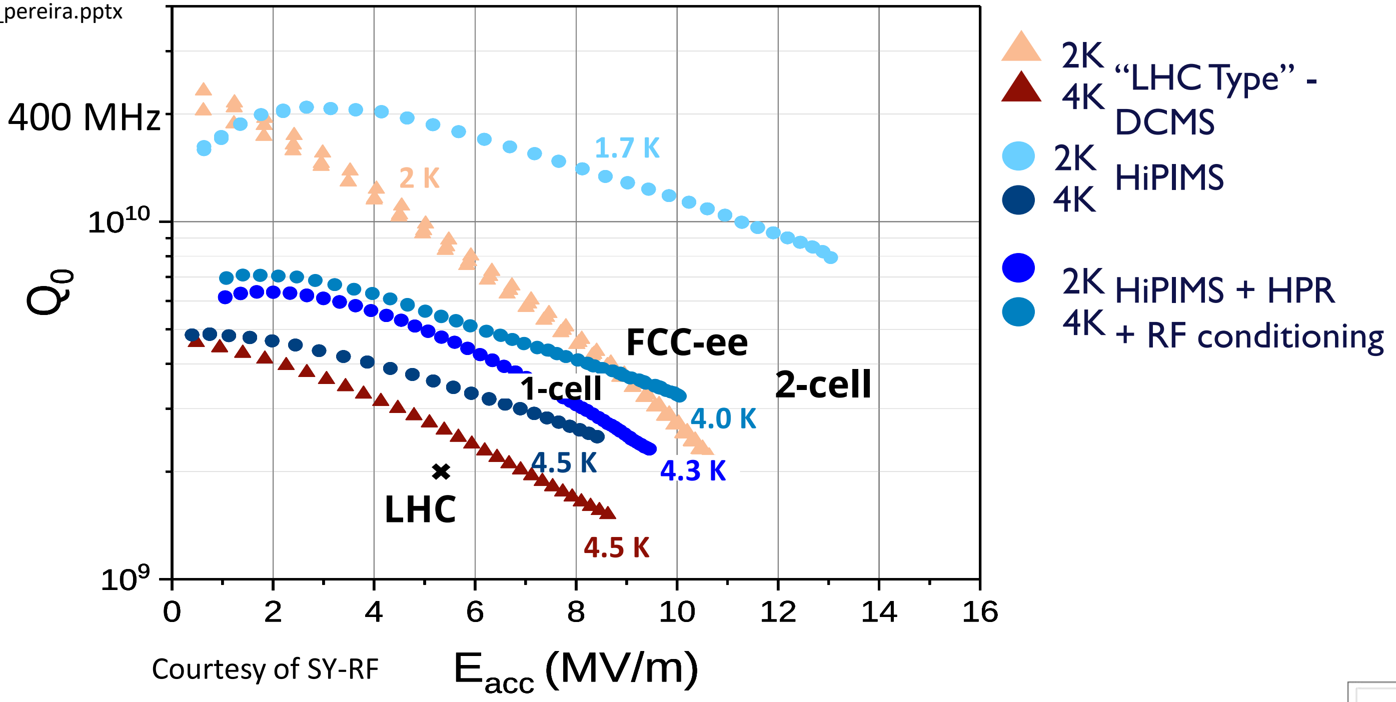
C-band cavity with distributed coupling & thin HOM- damping waveguides oriented in the radial direction
Proposed with NiCr coating deposited on the inner surface of thin waveguides to increase the
surface resistivity & damp the HOMs.



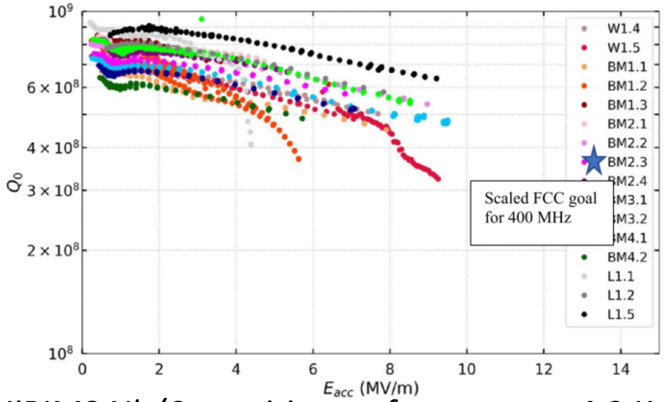
H. Xu et al., https://www.jacow.org/ipac2024/doi/jacow-ipac2024-tupc02/index.html

Nb/Cu SRF Technology

https://indico.cern.ch/event/1202105/contributions/5391683/attachments/2662106/4612074/HIPIMS%20Nb%20coatings_FCCweek_2023_carlota_pereira.pptx



Courtesy of SY-RF



1.3 GHz HiPIMS Nb/Cu cavities performance at 4.2 K

400 MHz 2-cell cavities Nb/Cu, 4.5 K for FCC

Moderate accelerating gradient and HOM damping requirements.

500 kW RF per cavity allowing the re-use of the 1 MW klystrons already installed for the Z machine.

Best ever produced 400MHz Nb/Cu

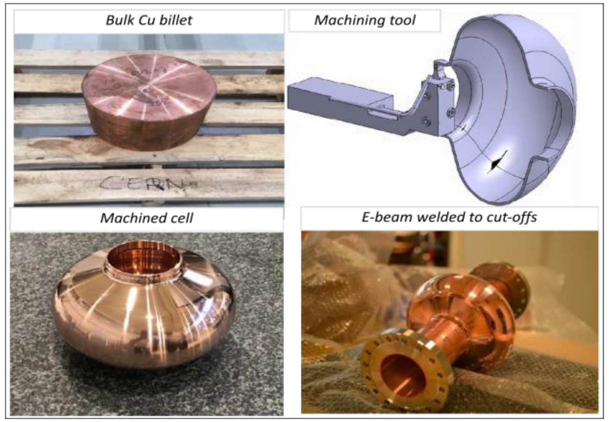
FCC 1-cell specs reached

- Chemistry : SUBU
- EP commissioned and ready for 2024

HiPIMS Technique

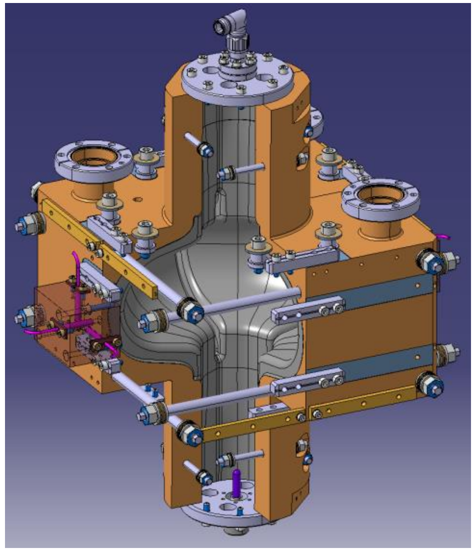
New Cu substrate: bulk machined

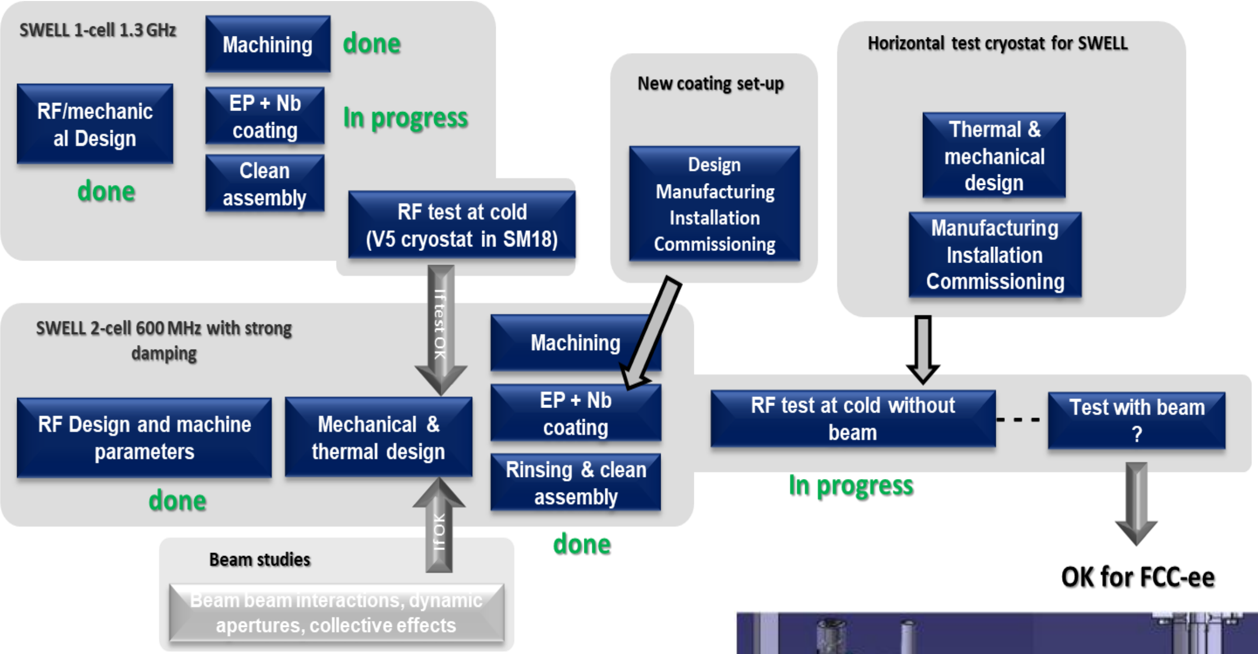
Next target: FCC 2-cell specs

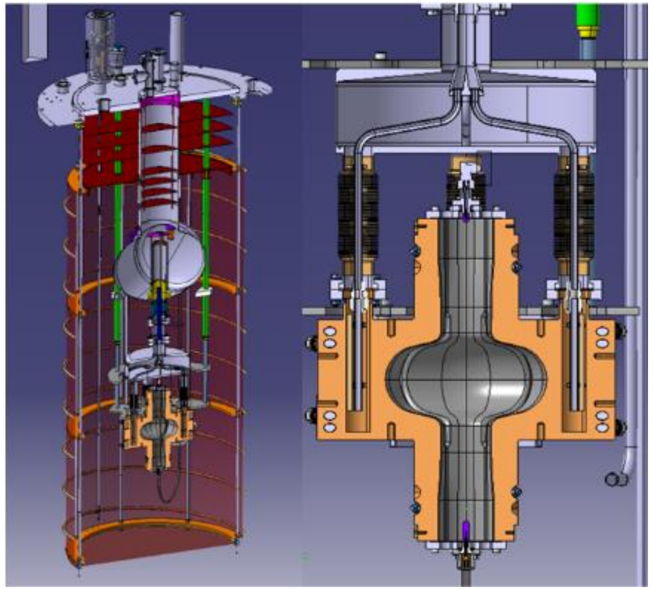


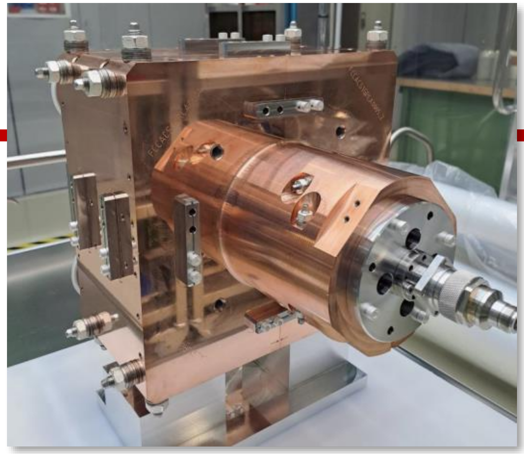
Nb/Cu SWELL

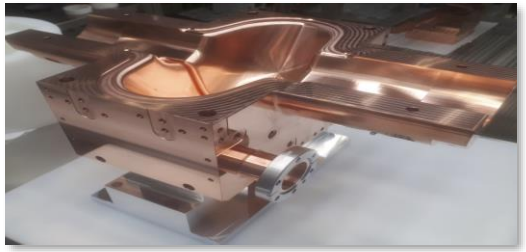
Feasibility study
&
development plan

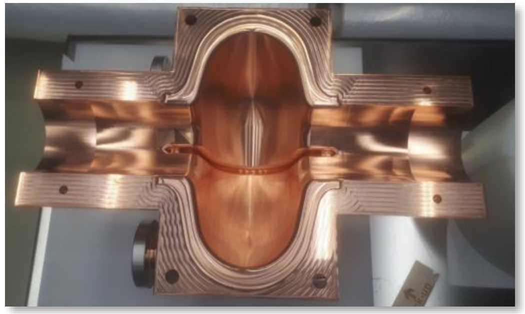


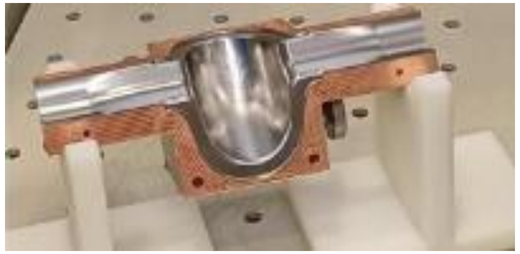










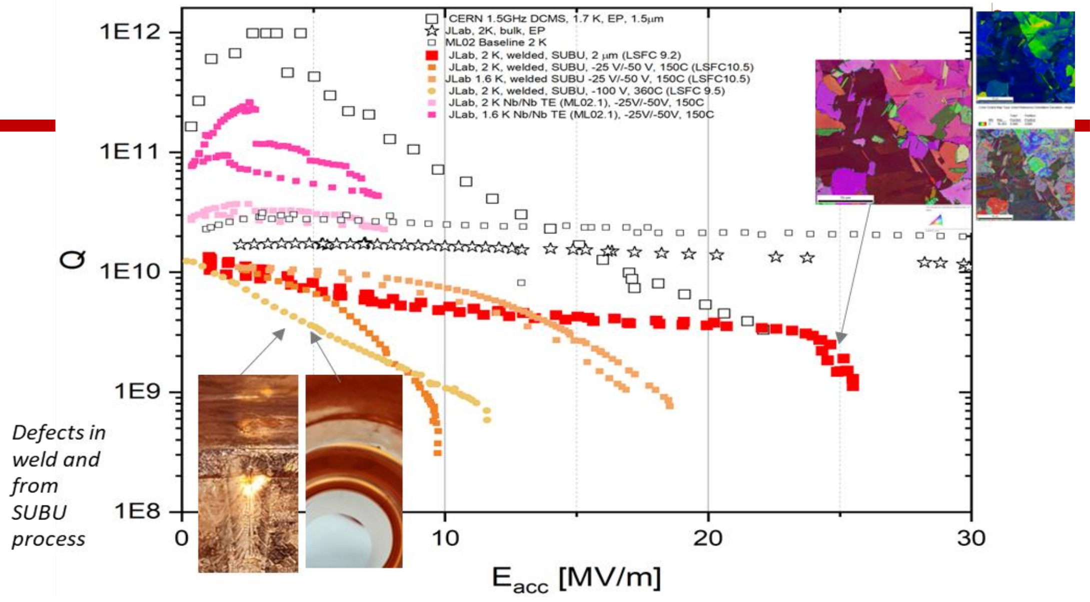


Demonstration with 1.3 GHz cavity

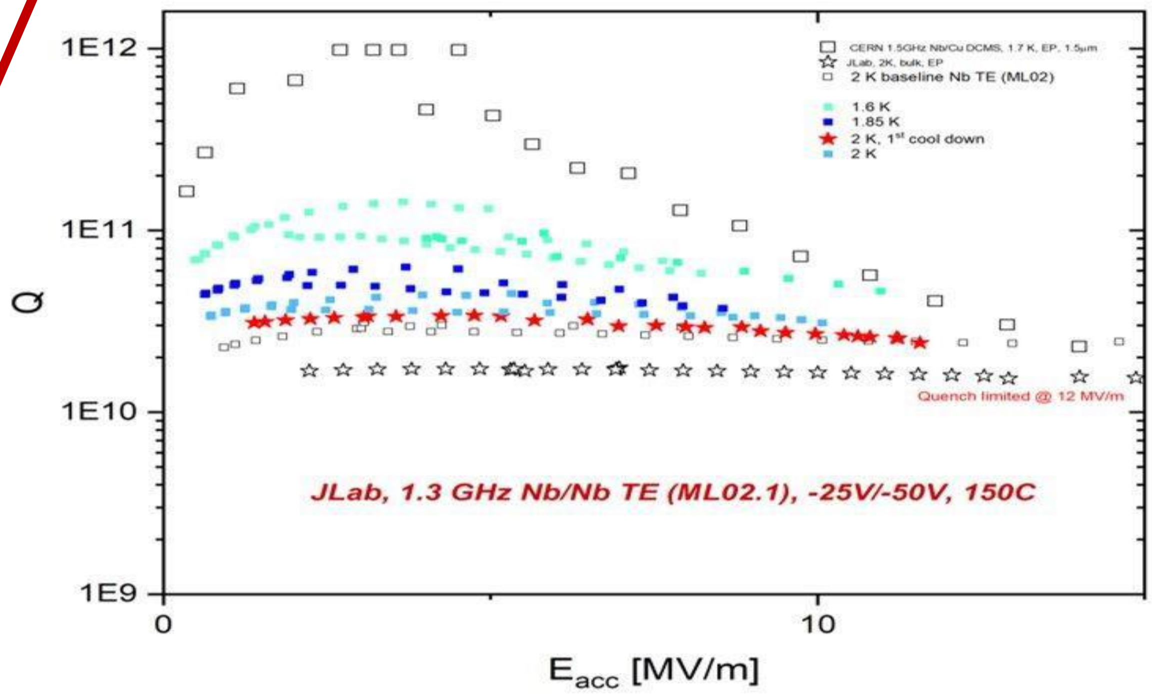
- Deposited 1 quadrant at a time with bi-polar HiPIMS
- Assembled
- Ready for RF testing – Summer 24

Nb/Cu SRF Technology

- ❑ Aim: Enable 4 K operation
- ❑ HiPIMS & ECR @ JLAB
  - – 1.3 GHz Nb/Nb demonstration
  - – lower frequency cavity deposition: 952.6 & 800 MHz, substrates on hand
  - – Ideal substrates development
    - – Machining (CERN), hydroforming (KEK)



HiPIMS Nb/Nb 1.3 GHz TE cavity



Machined cell

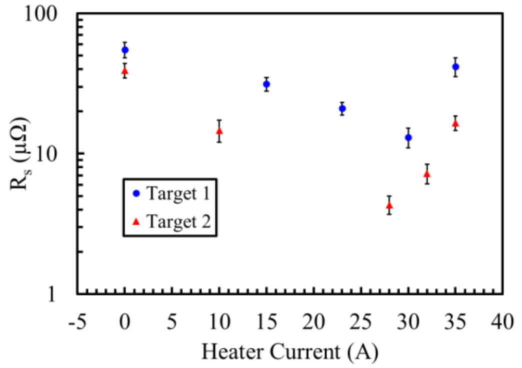
E-beam welded to cut-offs

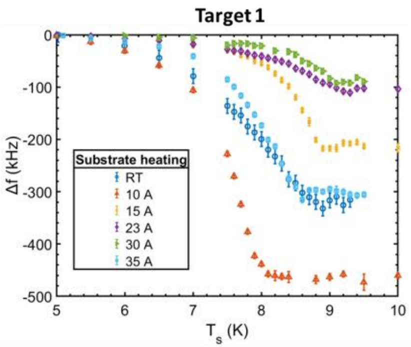
Courtesy: G. Rosaz, K. Scibor - CERN

Nb/Cu SRF Technology

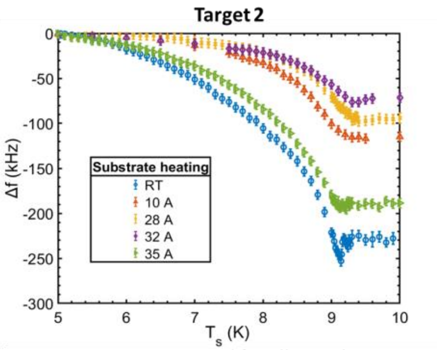
Science and Technology Facilities Council

Nb/Cu: surface resistance at 4.2 K





- Variation in T_c due to Cu contamination

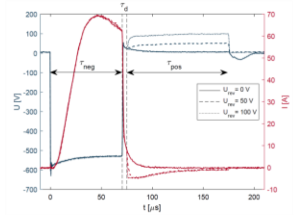


- T_c as expected for all samples

Plasma diagnostic study with Liverpool University

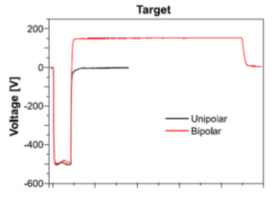
Bipolar HiPIMS discharge

Starfire Industries Impulse 2-2
Liverpool University



19/09/2022

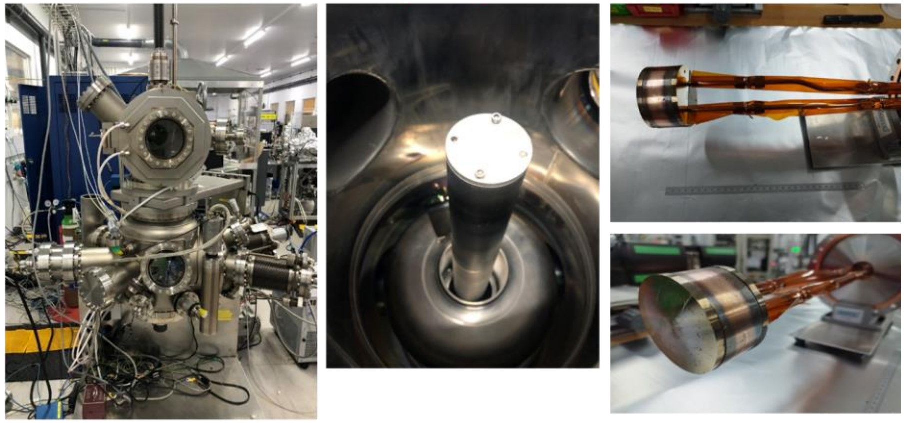
Ionautics HiPSTER Bipolar
Viloan et. al.*



* https://doi.org/10.1016/j.surfcoat.2021.127487

R. Valizadeh et al.

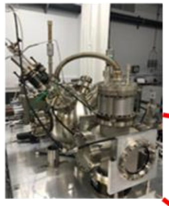
1.3 GHz Cavity deposition system



The system is equipped with load lock chamber, rotating arm that can turn and move up and down, the chamber wall is water cooled, fixed magnetron in the centre.
It will be positioned in an ISO 6 clean room with ISO 4 cabinet for final cavity preparation.

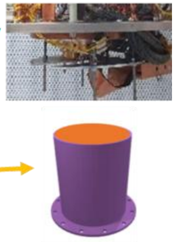
From planar samples to real cavities

Aim: Flat samples → split cavities → 1.3 GHz cavities



3 sets of samples:

1. Nb coated planar samples
   - Low power RF test with choke cavity
   - High power RF test with QPR
2. Split cavity deposited with planar magnetron & planar target
   - RF test
3. Split cavity deposited with cylindrical magnetron & tubular target
   - RF test

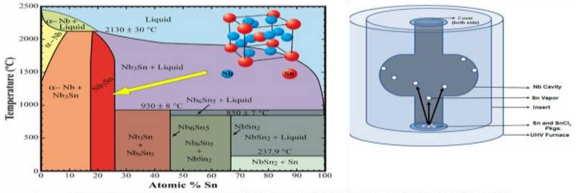


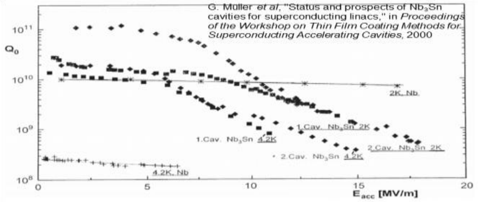
Jefferson Lab

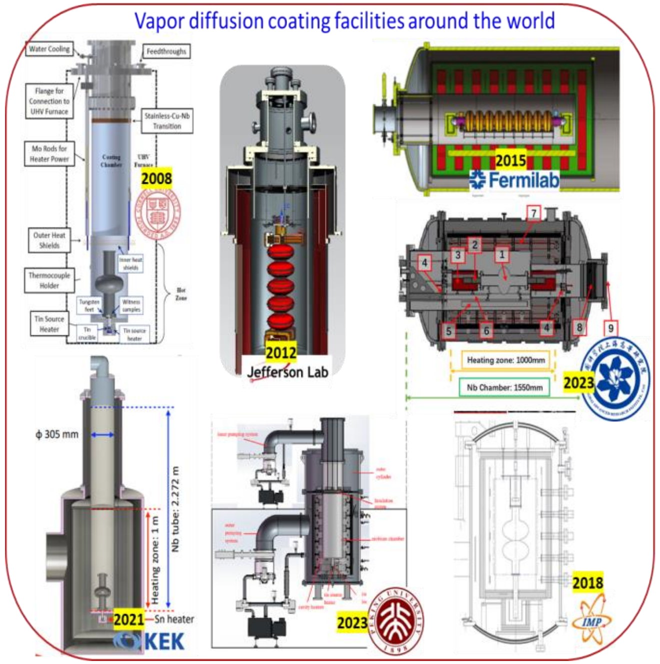
Beyond Nb : Vapor-diffused Nb_3Sn grown on Nb

Nb_3Sn by Vapor Diffusion

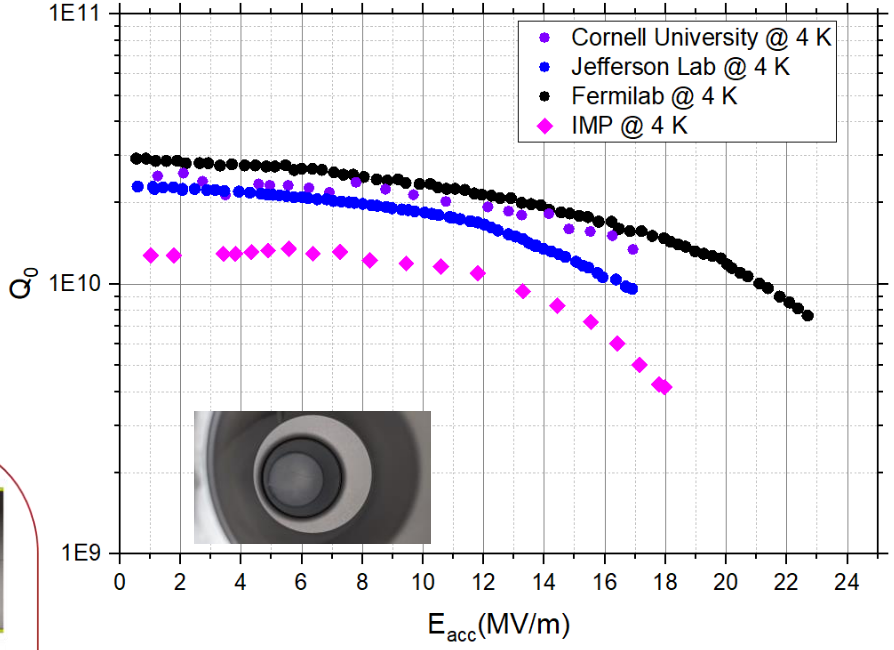
- since 1970s (*Siemens*)
- so far 'THE' technique producing practical Nb_3Sn cavities





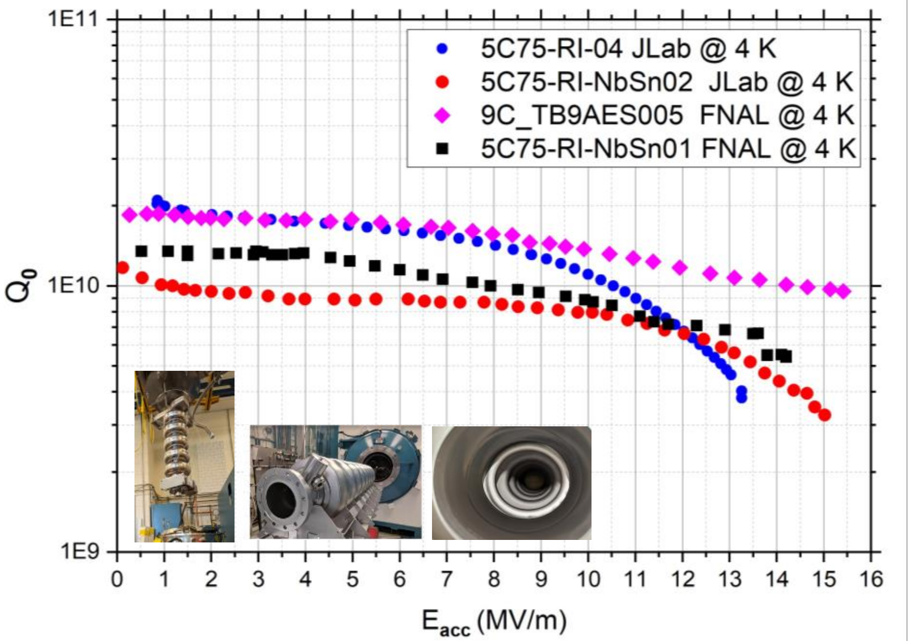


R&D 1.3/1.5 GHz single-cell cavity performance



- 1.3/1.5 GHz single-cell cavities attain an accelerating gradient over 20 MV/m with $Q\sim10^{10}$.
- Cavities of various frequencies (650 MHz, 952 MHz, 2.6 GHz, 3.6 GHz) coated at different facilities show comparable performance.

Multi-cell cavity performance



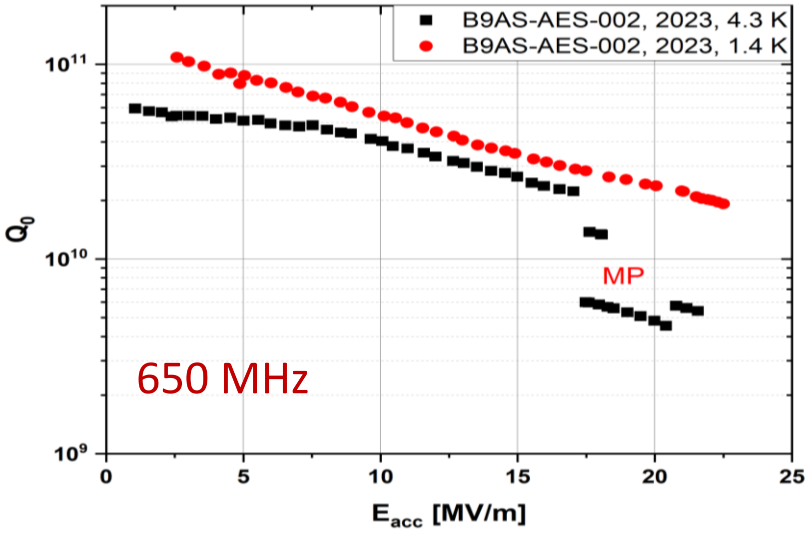
- 1.5 GHz five-cell and 1.3 GHz 9-cell cavities were demonstrated to reach $Q\sim10^{10}$ at 10 MV/m at 4.4 K.
- Maximum gradients achieved up to ~ 20 MV/m.

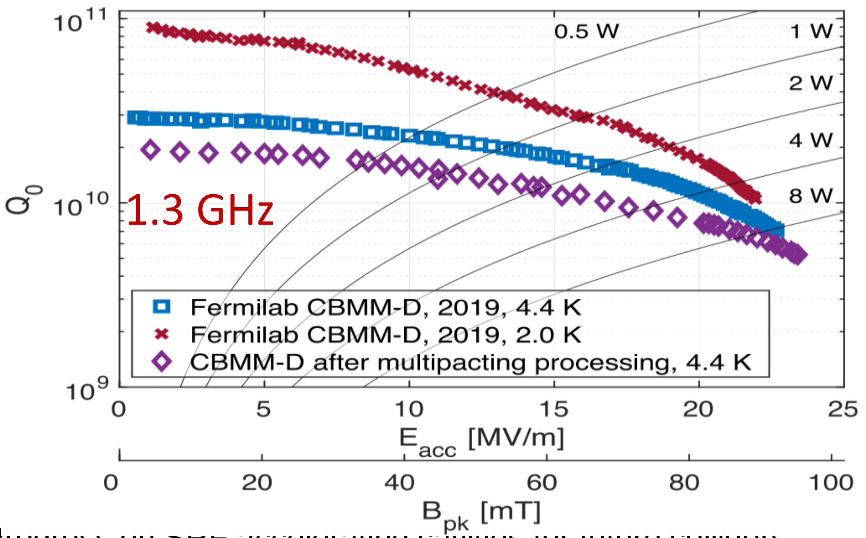
U.Pudasaini et al. "Managing Sn-Supply to Tune Surface Characteristics of Vapor-Diffusion Coating of Nb_3Sn", presented at the SRF'21, East Lansing, MI, USA, Jun.-Jul. 2021, doi:10.18429/JACoW-SRF2021-TUPTEV013.
S. Posen et al. "Advances in Nb_3Sn superconducting radiofrequency cavities towards first practical accelerator applications" Superconductor Science and Technology. 2021 Jan 11;34(2):025007.
D. Hall, "New Insights into the Limitations on the Efficiency and Achievable Gradients in Nb_3Sn SRF Cavities", PhD thesis, Cornell University (2017).
G. Jiang et al.. Understanding and optimization of the coating process of the radio-frequency Nb3Sn thin film superconducting cavities using tin vapor diffusion method. Applied Surface Science. 2024 Jan 15;643:158708.
G. Eremeev "Progress in Nb3Sn developments for CEBAF-style quarter cryomodule" TTC-2022,

Beyond Nb: Nb_3Sn

Single-cell cavity R&D

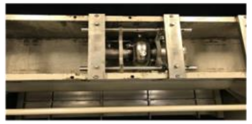
Demonstration of gradients > 20 MV/m on single-cell Nb_3Sn cavities

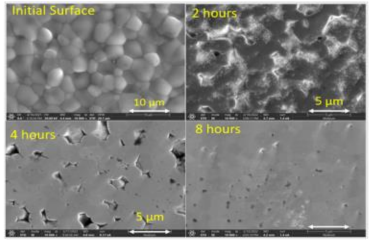




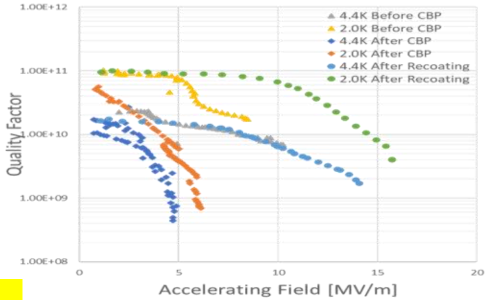
Roughness Reduction

- The Centrifugal Barrel Polishing method (CBP) used commonly to smooth Nb cavities has been adapted to smooth Nb_3Sn coated cavities
- Nanoparticle abrasive suspension (40 nm silicate or 50nm alumina particles) plus (0.25" wooden ball or 0.5" felt cube)
- 120 RPM in the barrel polishing machine





Cavity performance was improved after CBP followed by a short recoating procedure

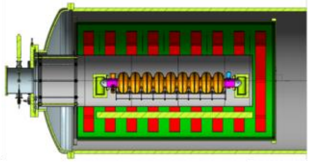


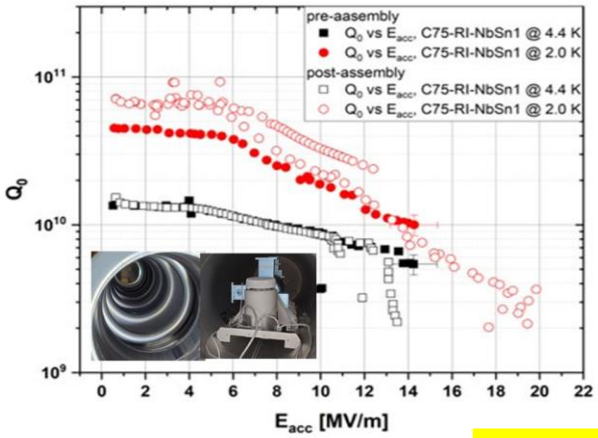
Viklund, Eric, David N. Seidman, David Burk, and Sam Posen. "Improving Nb3Sn cavity performance using centrifugal barrel polishing." *Superconductor Science and Technology* 37, no. 2 (2024): 025009.
Viklund, Eric, et al. "Healing Gradient Degradation in Nb3Sn SRF Cavities Using a Recoating Method." arXiv preprint arXiv:2405.00211 (2024).

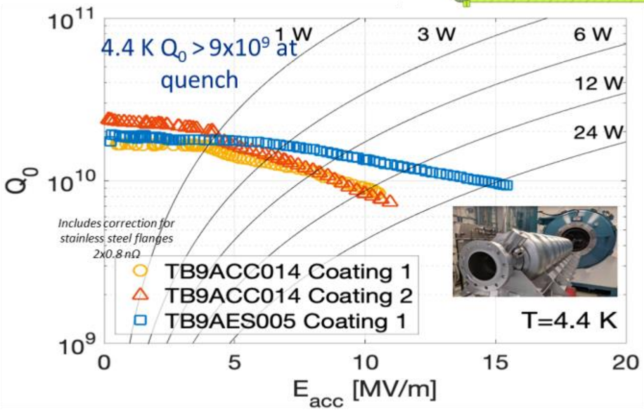
Courtesy of E. Viklund and S. Posen

Multi-cell Cavity Coating

- Coatings of multicell practical accelerator structures for various projects
- E_{acc} > 15 MV/m, Q ~ 1×10^{10} at 4.4 K





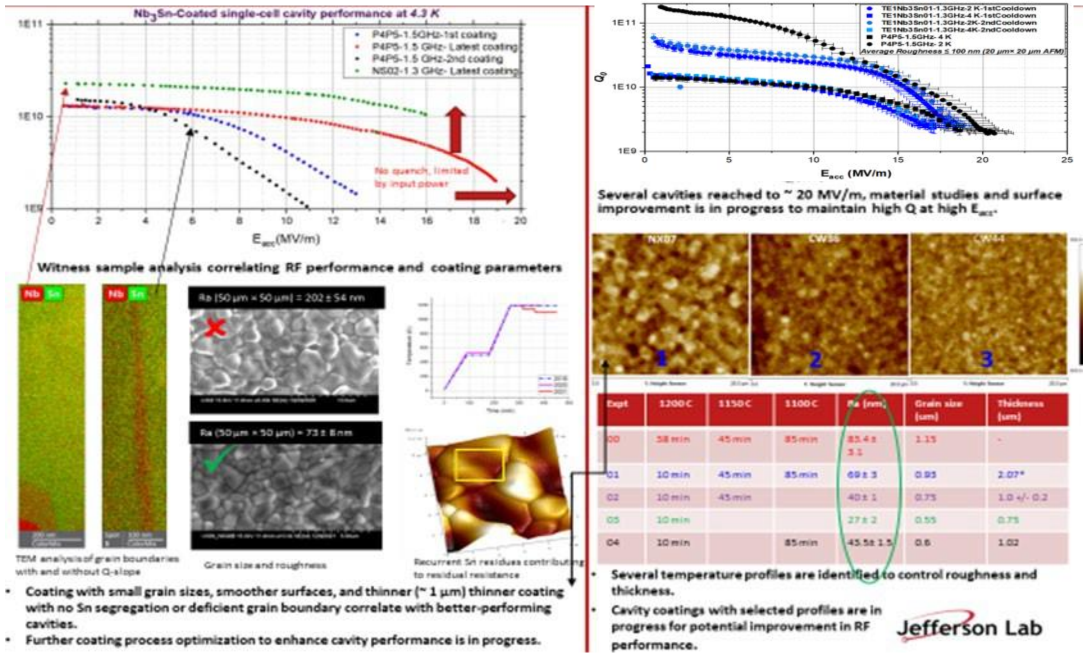


Courtesy of G. Eremeev and S. Posen

Beyond Nb: Nb_3Sn

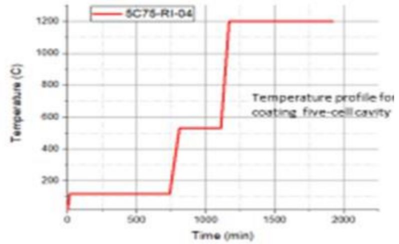
U. Pudasaini et al.

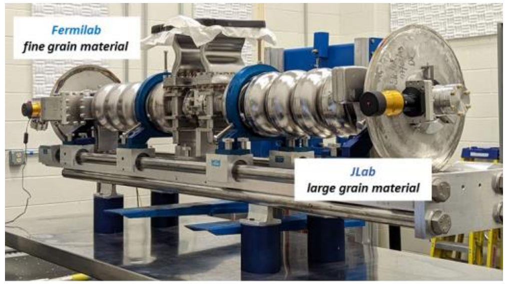
Material studies and development of Nb_3Sn-coated cavities



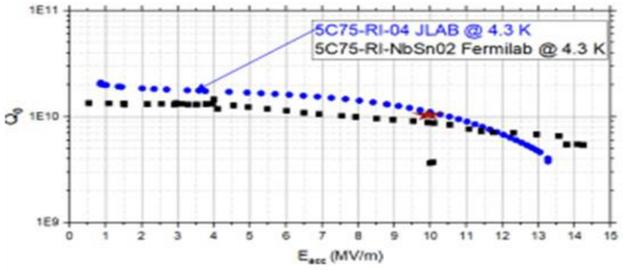
Process Developments towards Nb_3Sn cavities in operation

Specs: 1 e10 @10 MV/m

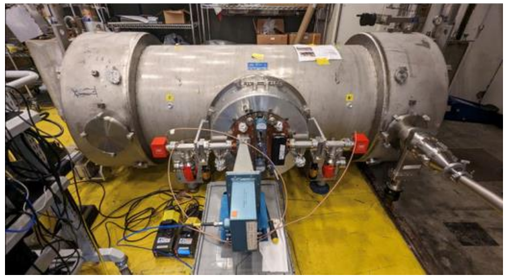


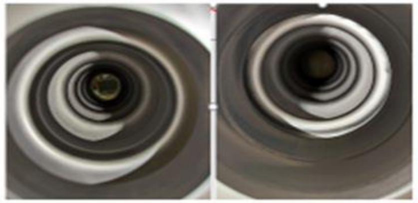


Based on G. Eremeev's ECA, Jlab cavity work supported by R&D fund.

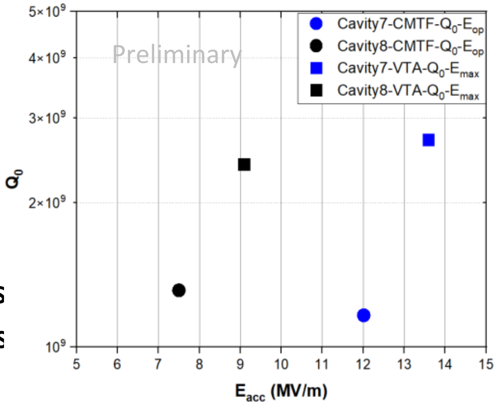


- Original C75 cavity made of ***large grain material***
- Limited by multipacting (no quench)



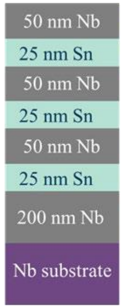


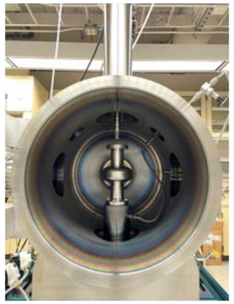
- One cavity was coated at Fermilab and another at Jlab..

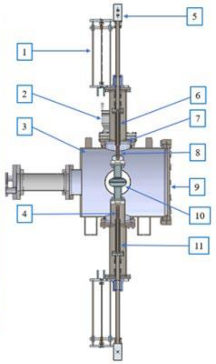


- accelerating gradients close to vertical tes
- frequency difference between two cavities ~150kHz
- installation at UITF next
- **beam test in October 2024.**

Alternate Techniques Development for Nb3Sn Deposition





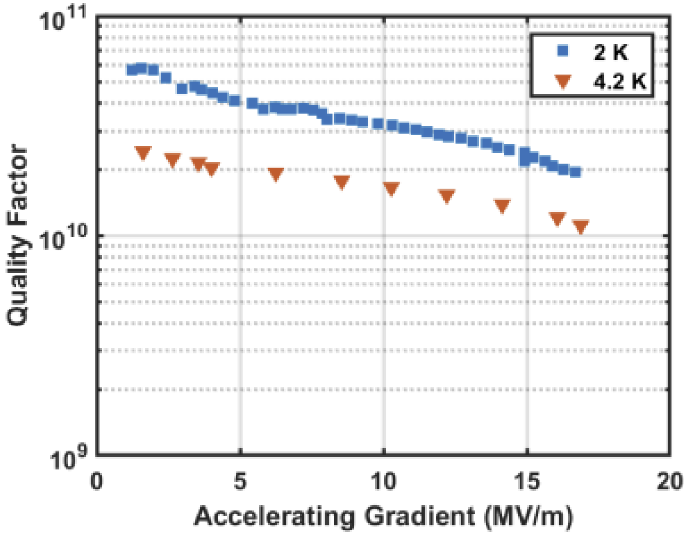


Compact Accelerators based on Nb_3Sn

Jefferson Lab

Beyond Nb: Nb_3Sn

Single-cell cavity performance



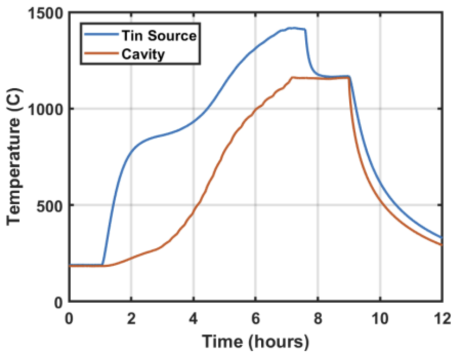
- $Q_0 > 10^{10}$ at accelerating gradient >15 MV/m in single-cell cavities prepared via vapor diffusion
- comparable performance demonstrated for 1.3 GHz, 2.6 GHz, and 3.9 GHz cavities

L. Shpani *et al.*, "Development of High-performance Niobium-3 Tin Cavities at Cornell University", in *Proc. 21th Int. Conf. RF Supercond. (SRF'23)*

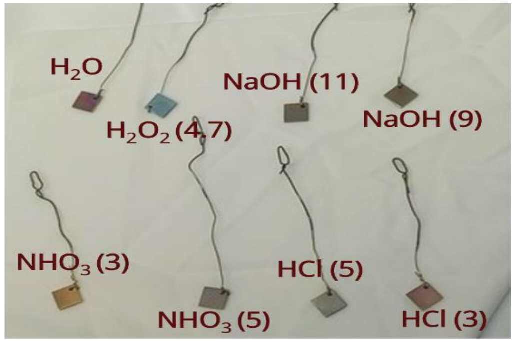
Z. Sun, Zeming, et al. "Smooth, homogeneous, high-purity Nb3Sn superconducting RF resonant cavity by seed-free electrochemical synthesis." Superconductor Science and Technology 36.11 (2023): 115003.

Thin Film Cavity

- new coating profile for smoother coating
  - low BCS resistance but higher residual resistance

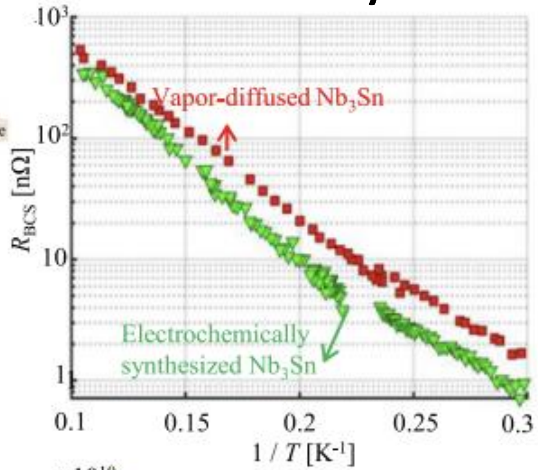


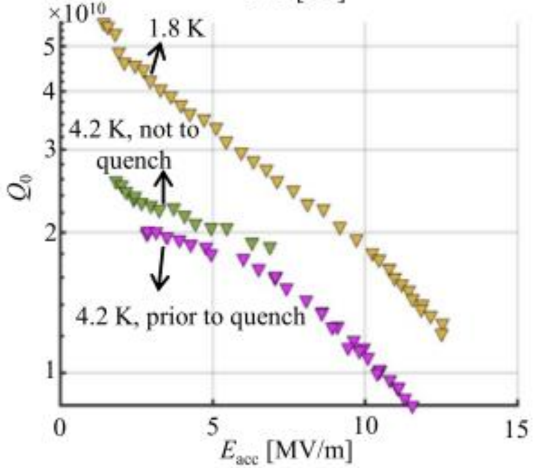
Nucleation Studies



- surface chemistry treatments to optimize nucleation for smoother films

Nb_3Sn via thermal diffusion of electrodeposited Sn on Nb cavity

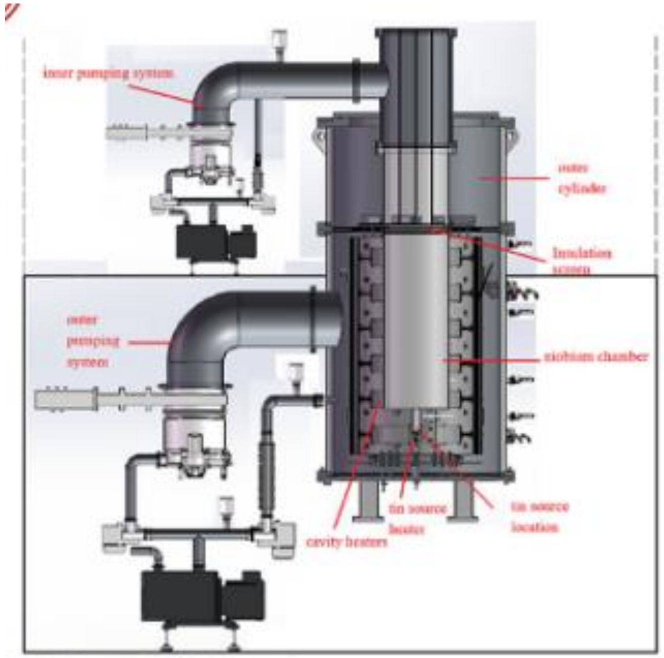




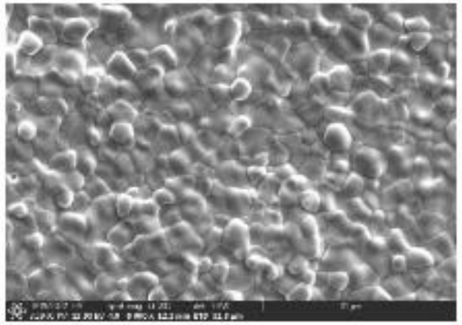
- smooth, homogeneous, high-purity Nb_3Sn

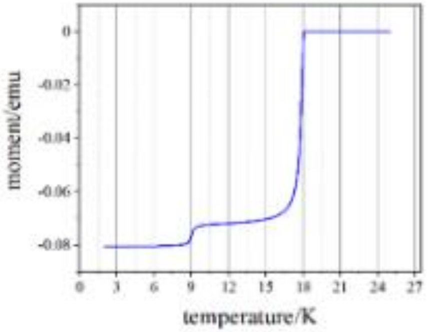
Beyond Nb: Nb_3Sn

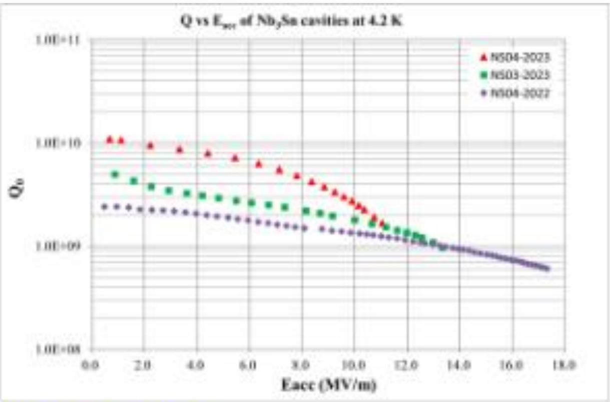
Courtesy of Jiankui Hao



3 tin sources

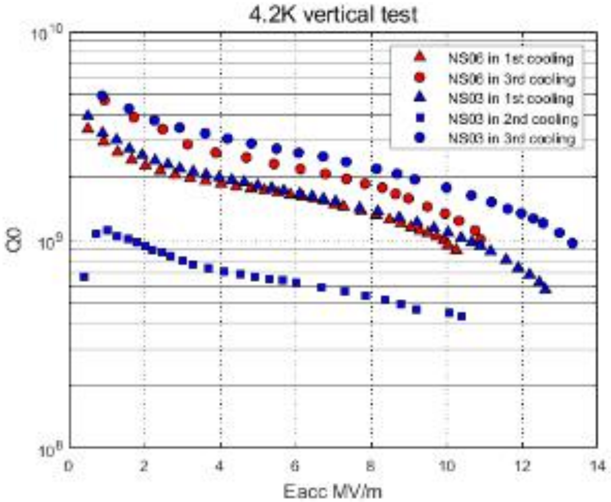






Coating: 1250°C, 120 min, Annealing: 1150 °C, 60 min

$Q_0 \sim 1.1 \times 10^{10}$ @4.2K @ low field, max. $E_{acc} \sim 17.3$MV/m



Vertical Tests (2023)	T grad., cooling rate	Q_0 @ ~1.0 MV/m
NS03(1st,Oct. 17)	15.7 K/m, ~6 min/K	3.3E9
NS06(1st,Oct. 17)	15.7 K/m	3.0E9
NS03(2nd,Oct. 18)	110	1.1E9
NS03(3rd,Oct. 23)	2.7 K/m, ~10 min/K	4.9E9
NS06(3rd,Oct. 23)	2.7	4.7E9

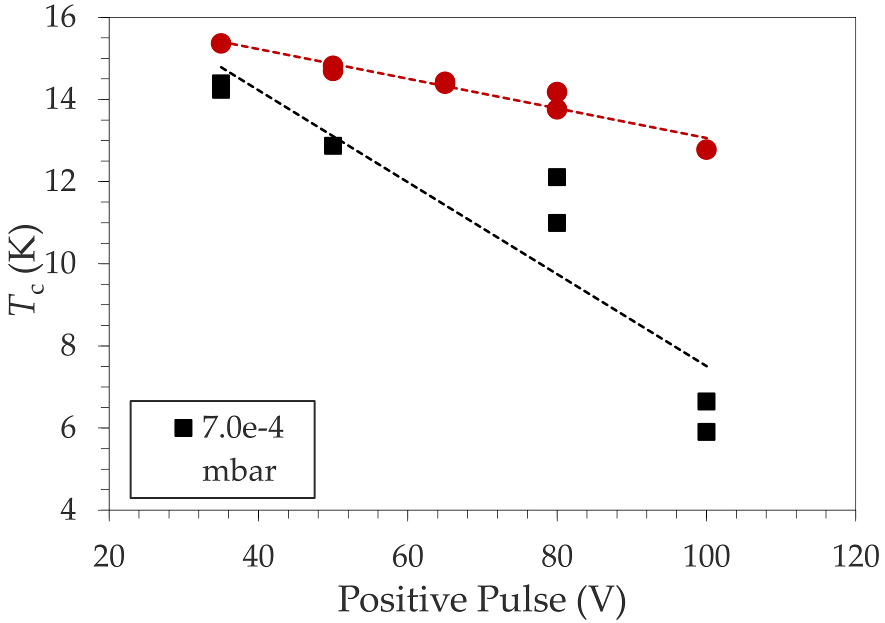
Vertical tests at different cooling rate

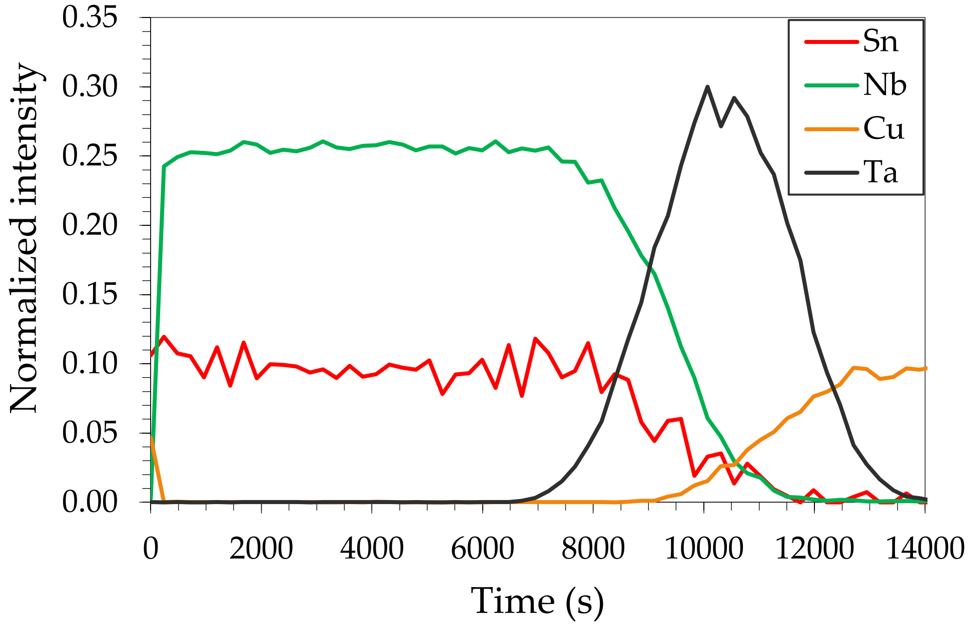
Beyond Nb: Nb_3Sn on Cu

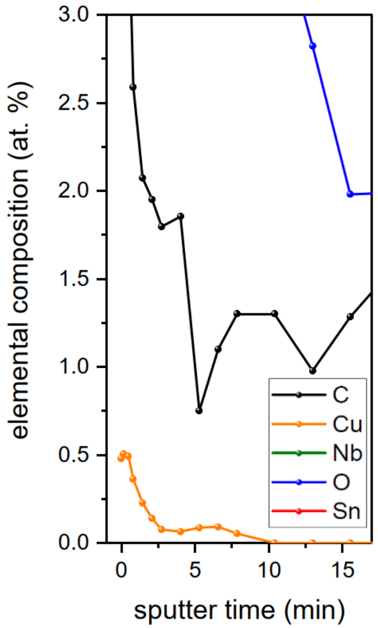
Courtesy of G. Rosaz

https://indico.jlab.org/event/535/contributions/10694/attachments/8476/12127/Recent%20advances%20with%20bipolar%20HiPIMS-deposited%20Nb3Sn%20films%20on%20Cu_S.%20Leith.pptx

Choice to move to Bi-polar HiPIMS
- Q-slope mitigation proven on Nb/Cu
- Detrimental to long range order parameter (bombardment energy)







Sn composition: OK
T_c: still lower than the theoretical value
Cu surface contamination is a key issue

Recent RF measurements of Nb_3Sn/Cu are very encouraging

QPR measurements at 4.5 K and at 400, 800 and 1200 MHz show a reduction by a factor 2 of the surface resistance compared to Nb/Cu

Communication under preparation

Beyond Nb: Nb_3Sn on Cu

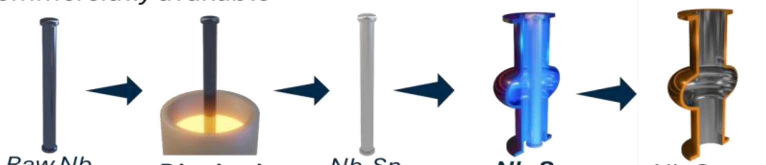
Courtesy of C. Pira

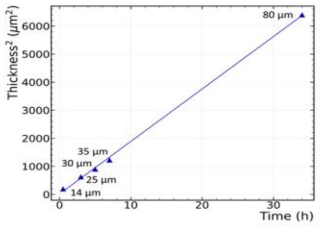
Nb_3Sn Coatings: Target Production

Single target configuration easiest to scale onto elliptical geometry

Nb_3Sn cylindrical target are not commercially available

LNL Strategy for Nb_3Sn cylindrical target production
(6 GHz cavities)





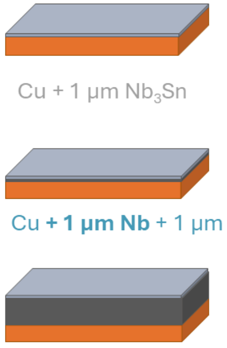
Nb_3Sn thickness related to dipping time

Possible tin content modulation

Proof of concept

Strategy to get the nominal Tc

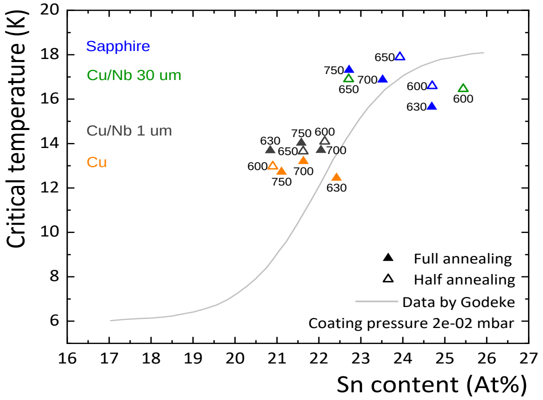
A very thick Nb barrier enhance dramatically Tc

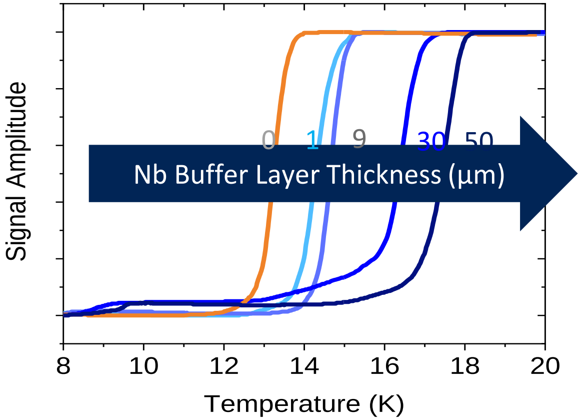


Cu + 1 μm Nb_3Sn

Cu + **1 μm Nb** + 1 μm Nb_3Sn

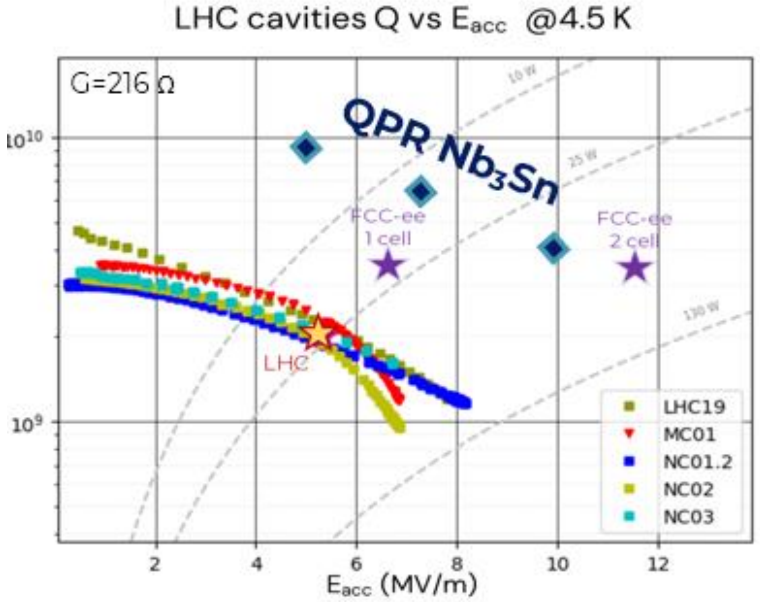
Cu + **50 μm Nb** + 1 μm Nb_3Sn





T_c = 17.33 ± 0.25 K on Cu + 50 μm Nb Buffer Layer at T_{dep} = 600 °C

PRELIMINARY RESULTS FROM Nb PLANAR RESONATOR



Nb_3Sn on bulk Nb to validate coating performances on 1.3 GHz Elliptical Cavities (2025)

C. Pira et al., "Progress in European Thin Film Activities", in Proc. 21th Int. Conf. RF Supercond. (SRF'23), Grand Rapids, MI, USA, Jun. 2023, pp. 607-614. doi:10.18429/JACoW-SRF2023-WECAA01

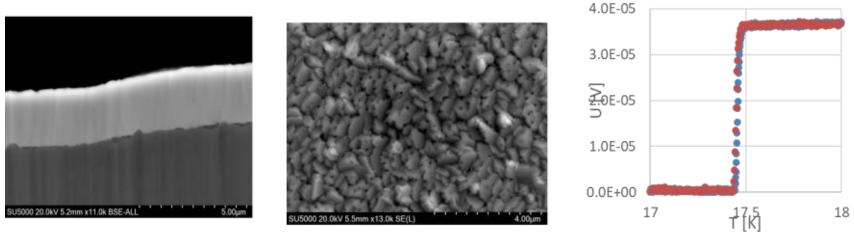
Beyond Nb: Nb_3Sn on Cu

Courtesy of R. Valizadeh

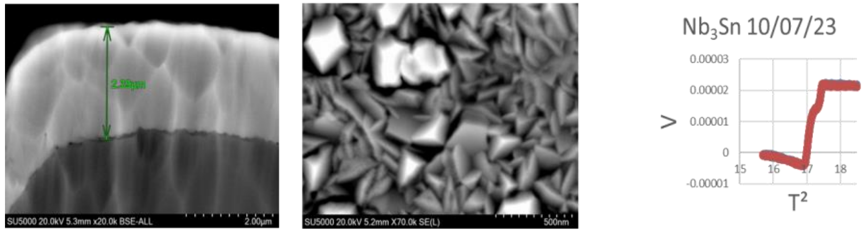
- 3 DCMS, 1 HiPIMS
- **Aim:** investigate effect of target power/deposition method
- **Substrate preparation:**
  - Diamond turned Cu disks – 10 cm diameter, 3 mm thick
  - Average roughness ~ 2-3 nm
- **Sample preparation:**

Parameter	DCMS	HiPIMS
Substrate heater current (A)	35 (~ 650 °C)	35 (~ 650 °C)
Target power (W)	200, 100, 50	100
Expected thickness (µm)	2.6	2.6

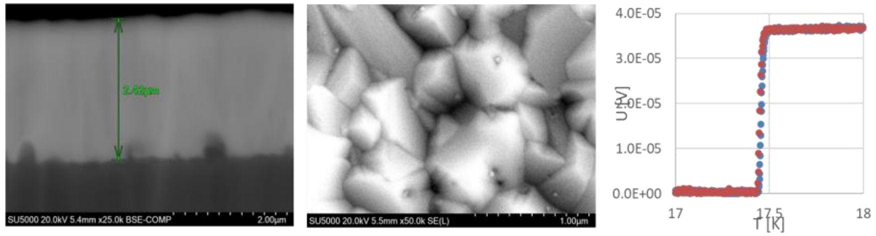
100 W DC Nb_3Sn on 50 and 100 mm diamond turned Cu



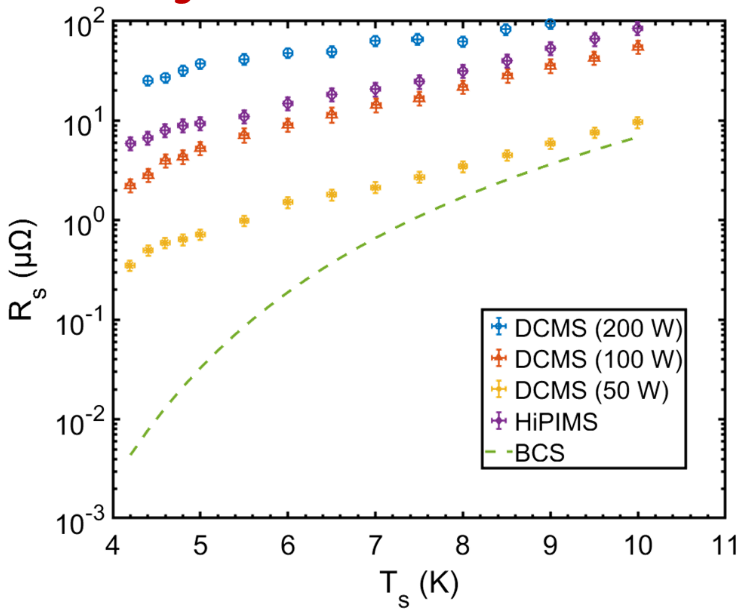
100 W HIPIMS Nb_3Sn on 50 and 100 mm diamond turned Cu



50 W DC Nb_3Sn on 50 and 100 mm diamond turned Cu



Nb_3Sn: surface resistance



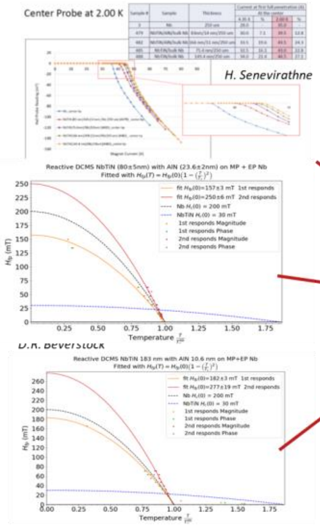
T_c ~ 16.5 – 17 K from frequency shift

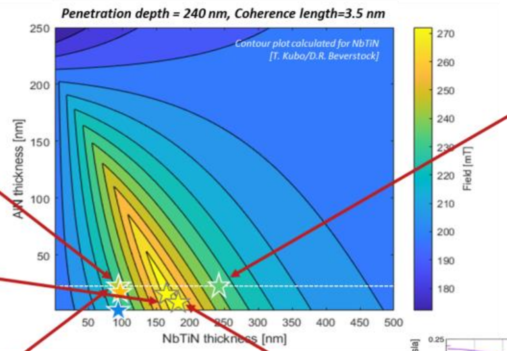
*BCS from SRIMP code (Parameters from: A-M Valente-Feliciano, *Superconducting RF materials other than bulk niobium: a review)*

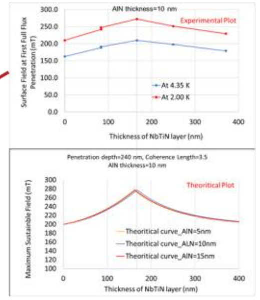
Beyond Nb: SIS Multilayer Structures

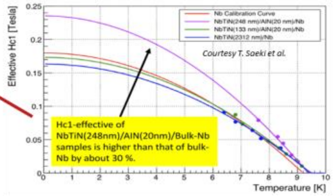
NbTiN/AlN

Measurement on NbTiN SIS structures on 1” & 2” Nb substrates



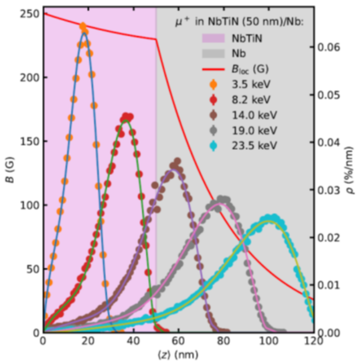






- *Deposited SIS structures fit the theoretical model*
- *3rd harmonic measurements show field enhancement up to 20-60% compared to base bulk Nb .*
- *Effect most sensitive to coherence length*

KEK, Old Dominion University, cea



LE-µSR measurements on NbTiN/Nb

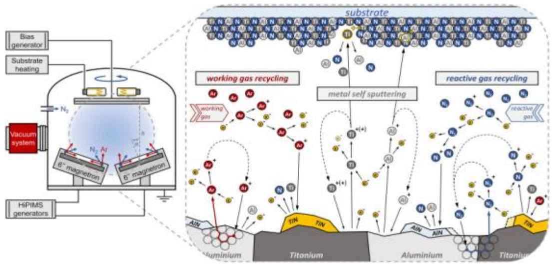
TRIUMF

- *µSR measurements demonstrate the requirement of the dielectric layer in the SIS model*
- *High quality SIS structures for thicknesses all the way down to the nm level (Stack of 32 bilayers NbTiN/AlN/NbTiN/MgO is fully crystalline*

TRIUMF, University of Victoria, PAUL SCHERRER INSTITUT PSI

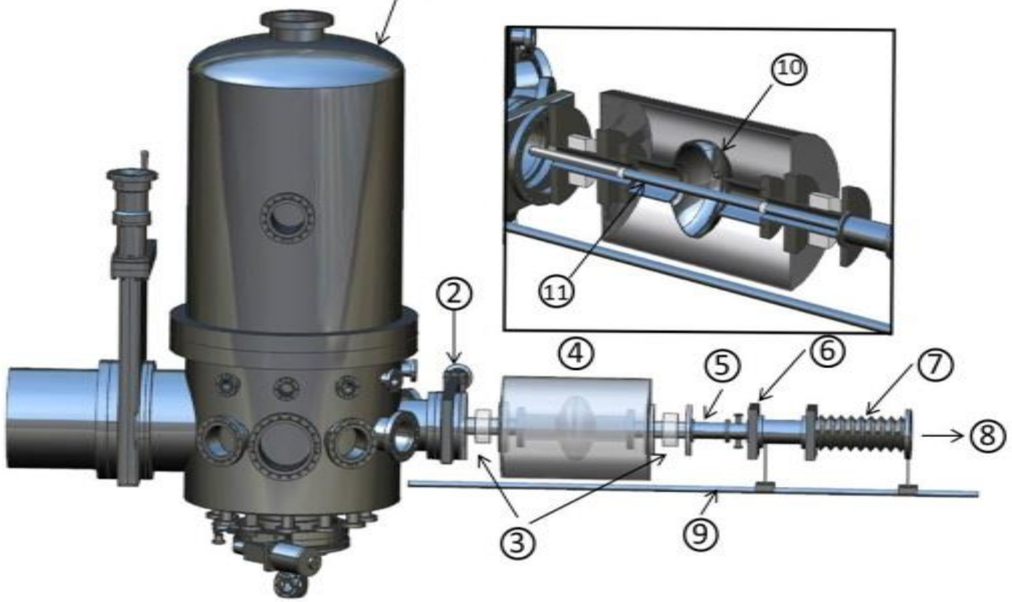
Re-HiPIMS

A-M Valente-Feliciano et al.



Refine deposition process for denser, more relaxed material in thin layers

Implementation on QPR samples & elliptical cavities for RF evaluation



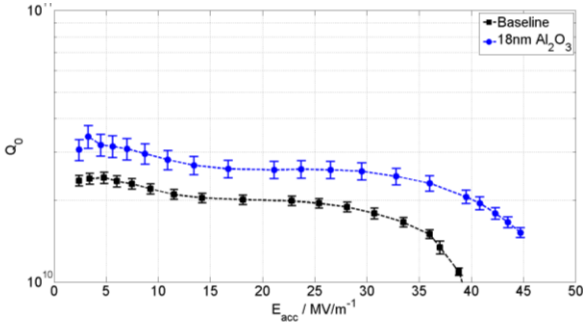
Development of Nb_3Sn Based SIS started

Beyond Nb: SIS Multilayer Structures

M. Wenskat et al.

Thermal ALD

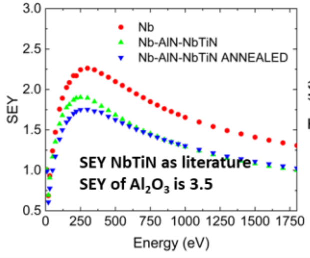
- Several coated cavities by ALD of Al_2O_3.
- No deterioration of performances.
- Maintaining E_{acc} above 40 MV/m
- for 2 out of 2 cavities.



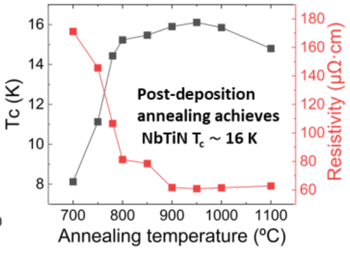
[Wenskat, M. *et al.*, Supercond. Sci. Technol. 36 015010 (2023)]

Plasma-enhanced ALD

- PEALD of AlN/NbTiN multilayers.
- Characterization methods: ETO, VSM, SEM/TEM, SEY, XPS, etc.

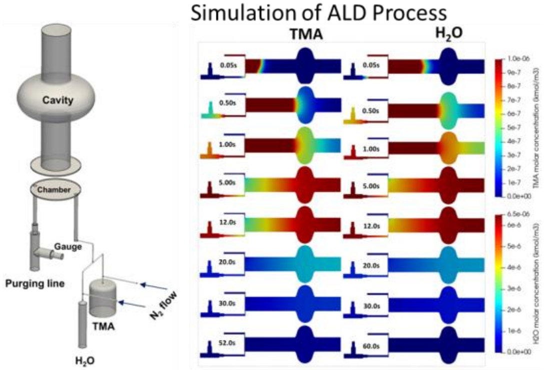


[Deneke, K. unpublished]



[González Díaz-Palacio, I. *et al.*, J. Appl. Phys. 134(3), 035301 (2023)]

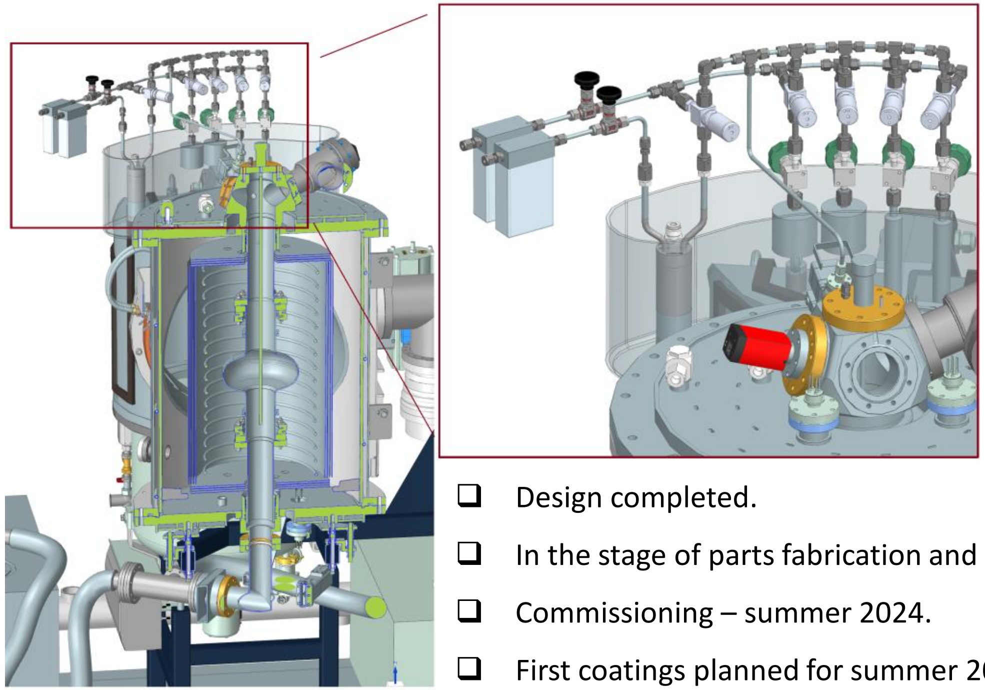
Thermal budget reduction of coating SRF cavities



[Deyu, G. *et al.*, Chemical&Fluid Simulations on CavityCoating – to be submitted]

Merge SIS sample results and cavity coating

Plasma-Enhanced – Atomic Layer Deposition setup for single-cell cavities



- ❑ Design completed.
- ❑ In the stage of parts fabrication and purchasing.
- ❑ Commissioning – summer 2024.
- ❑ First coatings planned for summer 2024.

Beyond Nb: SIS Multilayer Structures

Thin film R&D @ CEA

Y. Kalboussi, B. Delatte, C. Antoine, A. Four, F. Miserque, Y. Zheng, D. Hrabovsky, T. Junginger, N.Lochet , D.Bafia, L.Grasselino, T. Proslier

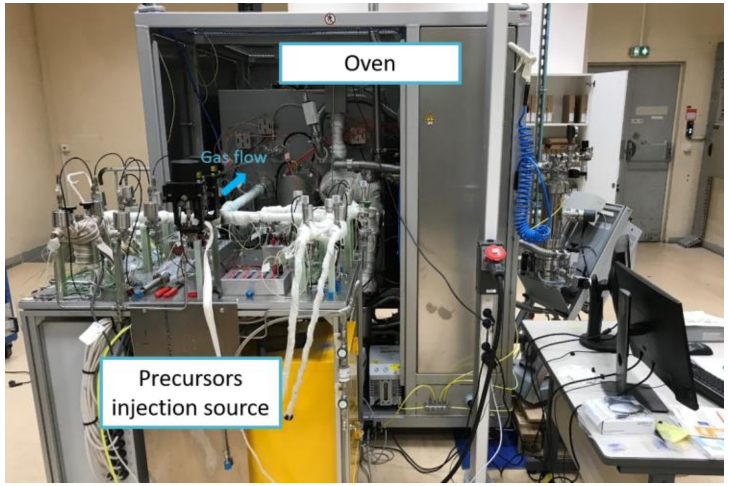
- New cooling techniques: 3D printing of 3.9 GHz cavities with closed loop cryocooler.
- Mitigating multipacting in SRF cavities by ALD and thermal treatments.
- Superconducting characterization of cavities and Qubits by tunneling spectroscopy.

✓Increased Q at low field for 3D superconducting resonators 1.3 GHz.

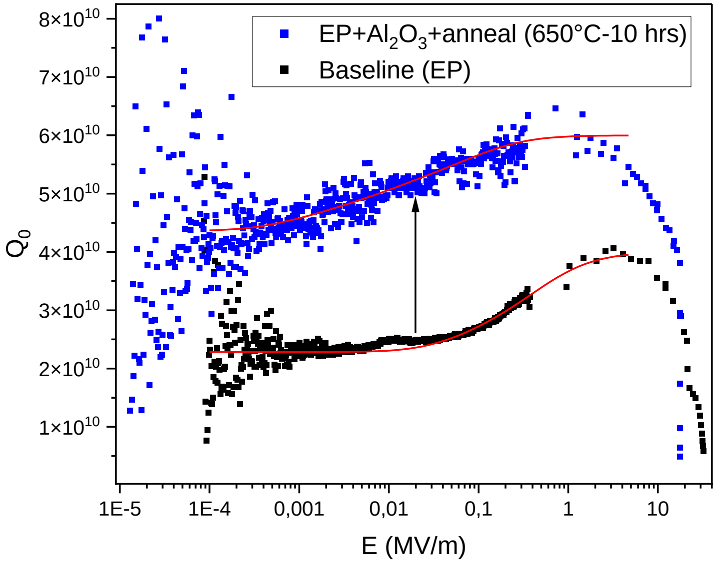
✓Increased penetration field on samples by 24%. First depositions of multilayers in 1.3 GHz cavities.

✓N doped cavity by ALD of NbN. Optimization underway. First depositions of multilayers in 1.3 GHz cavities.

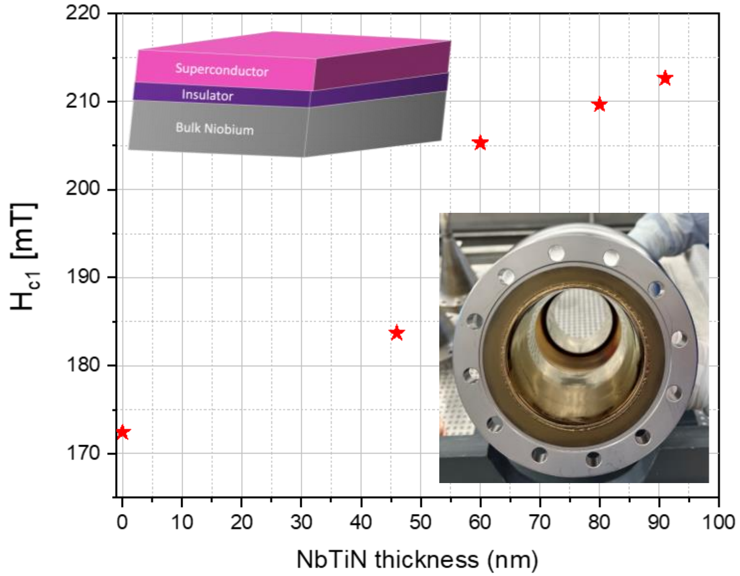
Home built Cavity deposition set up



High Q studies for Qubits and accelerators



High Gradient for accelerators increased penetration field.



Summary

❑ Bulk Nb

Active and rich developments for major & future projects

- 3 upcoming/future circular lepton or electron-ion colliders are all progressing quickly in the SRF systems development
- All projects need to develop a variety of SRF cavities for different subsystems and/or different operation cases, with different voltage and beam current/power requirements.
- There are plenty of interesting physics/engineering challenges in these SRF systems.
- Lot of synergy, especially in impedance control and high-power couplers.
- Many activities with mid-T bake, N_2 doping at frequencies of interest for Colliders (Muons, FCC, …)_
- Novel concepts with TW cavities, on-cell-damping…

❑ Beyond Nb

- Nb/Cu technology is making good progress with novel deposition techniques and cavity concepts
- Many exciting developments towards Nb_3Sn and multilayers – presented only selected work.

Other materials investigated such as V_3Si, MgB_2 and associated SIS structures