# Next-Generation Superconducting RF


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# Outline

- **Cornell SRF**
- **High Current Frontier:**
  - Cornell high current SRF R&D
- **Efficiency / Cost Frontier:**
  - Cornell $Nb_3Sn$ Program
  - Other Next-gen Material Research

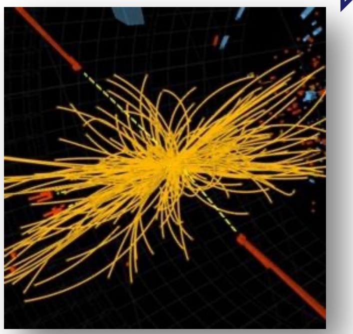
# Cornell SRF

# Accelerator Science

- **Research**
  - X ray sources and colliders for nuclear & particle physics
  - Electron microscopes

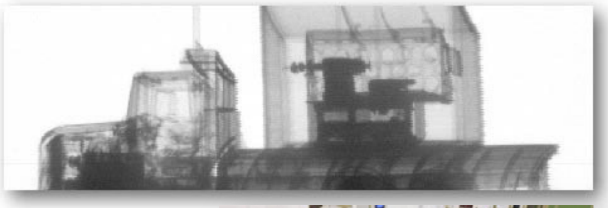
Since 1943, a Nobel Prize in **Physics** has been awarded to research benefiting from accelerators every 3 years.

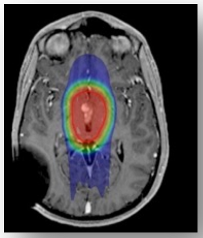
Since 1997, the same has been true of **Chemistry**.



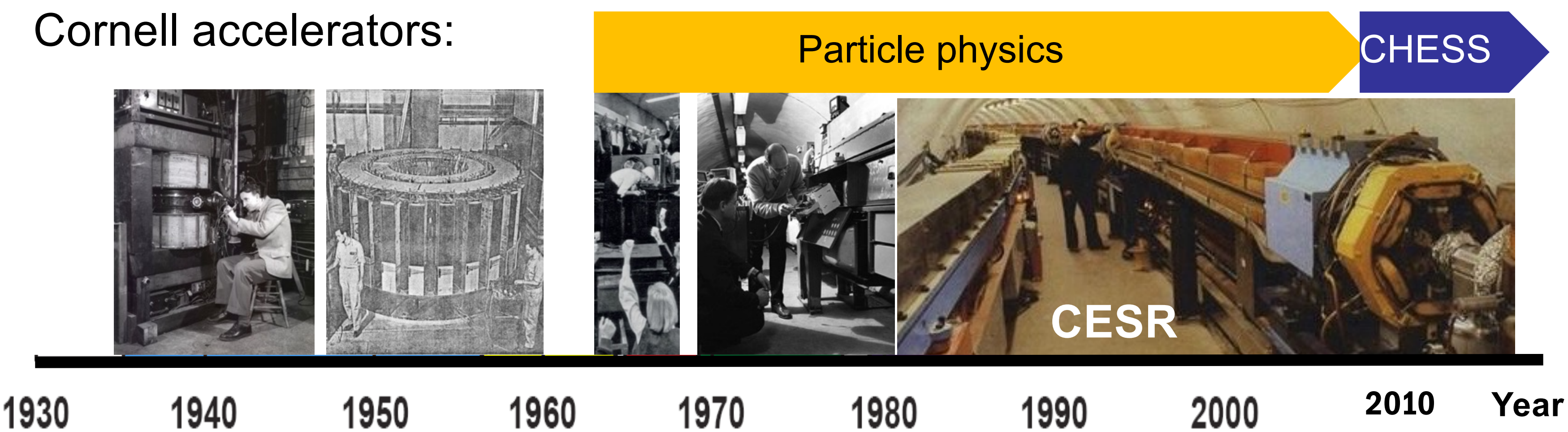
- **Industry**
  - Food & product safety
  - Contraband detection
  - Semiconductor fabrication
  - Bridge safety
- **Medicine**
  - Tumor detection and treatment

~30,000 industrial and medical accelerators are in use, with annual sales of $3.5 B and 10% growth per year.





# Cornell Accelerator R&D Program




**Cornell is a world leader in particle accelerators:**

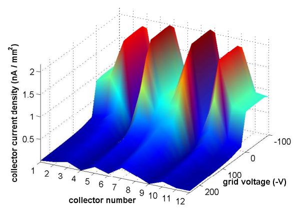
- CESR leads studies of **beam phenomena** in circular accelerators
- Cornell invented and advanced **high current Energy Recovery Linacs**
- Cornell's **high-brightness sources** and **superconducting RF programs**
  - Cornell pioneered and is a leading innovator in the **SRF acceleration systems**.
- Cornell's **graduate program** in accelerator science

# Cornell Accelerator R&D Program

## Fundamental Accelerator Research

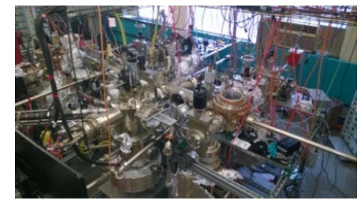
Center for
BRIGHT BEAMS
A National Science Foundation Science & Technology Center

- NSF Science and Technology Center led by Cornell with 10 universities, 3 national labs




- Storage ring beam dynamics R&D

- Superconducting RF R&D



- Photocathode / bright electron sources R&D

## On-Campus Accelerators

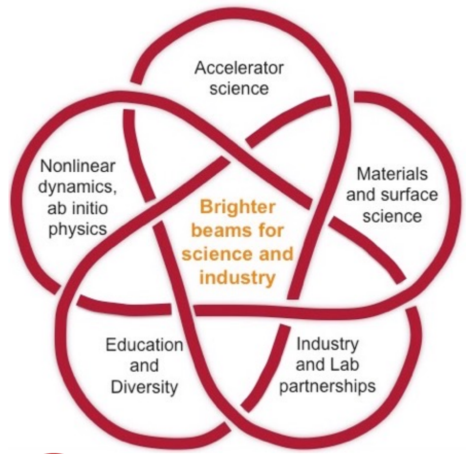


- CESR / CHESS
- CBETA / ERL prototype

# Center for Bright Beams (CBB)

*Center for Bright Beams (CBB)*

An NSF Science and Technology Center **led by Cornell** with **8 universities, 3 national labs** from the US and Canada, and industry partners.




## CBB Vision:

**Better particle beams** for applications ranging from giant colliders to tabletop electron microscopes enabling new opportunities for science and industry.

## CBB Mission:

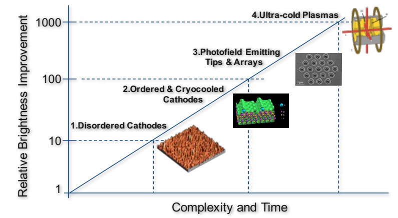
- **Transform the reach of electron beams** by increasing their **brightness x100** and **reducing the cost and size** of key enabling technologies.
- **Transfer** the best of these technologies to national labs and industry.

# Center for Bright Beams (CBB)

## Theme: Beam Production

**Goal:** Methods for x100 brighter electron beams through better photocathodes.

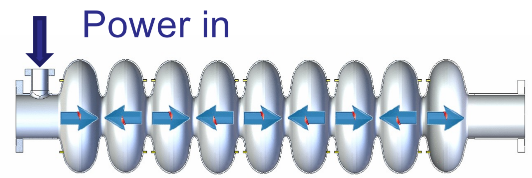
**Strategy:** Use **ab initio physics** and **surface chemistry** to identify promising materials and approaches, then fabricate, characterize and test them.




## Theme: Beam Acceleration

**Goal:** Methods for x10 lower power losses and x2 gradient.

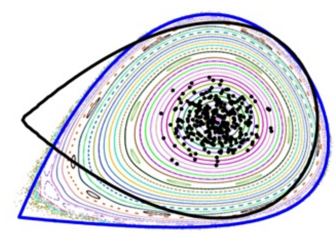
**Strategy:** Harness **condensed matter physics** and **surface chemistry** to understand RF superconductivity and learn to control the surfaces of niobium and compound superconductor cavities.




## Theme: Beam transport and storage

**Goal:** Methods for x10 brighter beams through mastery of the non-linear effects that reduce brightness, limit acceptance and induce instabilities.

**Strategy:** Use the tools of **nonlinear dynamics** to analyze dynamic aperture and test strategies they suggest for limiting emittance growth.



**Multidisciplinary approach ⇒ Brighter electron beams**

# Cornell Superconducting RF Group

## Cornell Superconducting RF Program

**Convergence research in accelerator physics, super-conductivity and materials science:** Transformative understanding of super-conductivity and superconductor growth

**Energy and environment:** Enabling sustainable science via energy efficiency

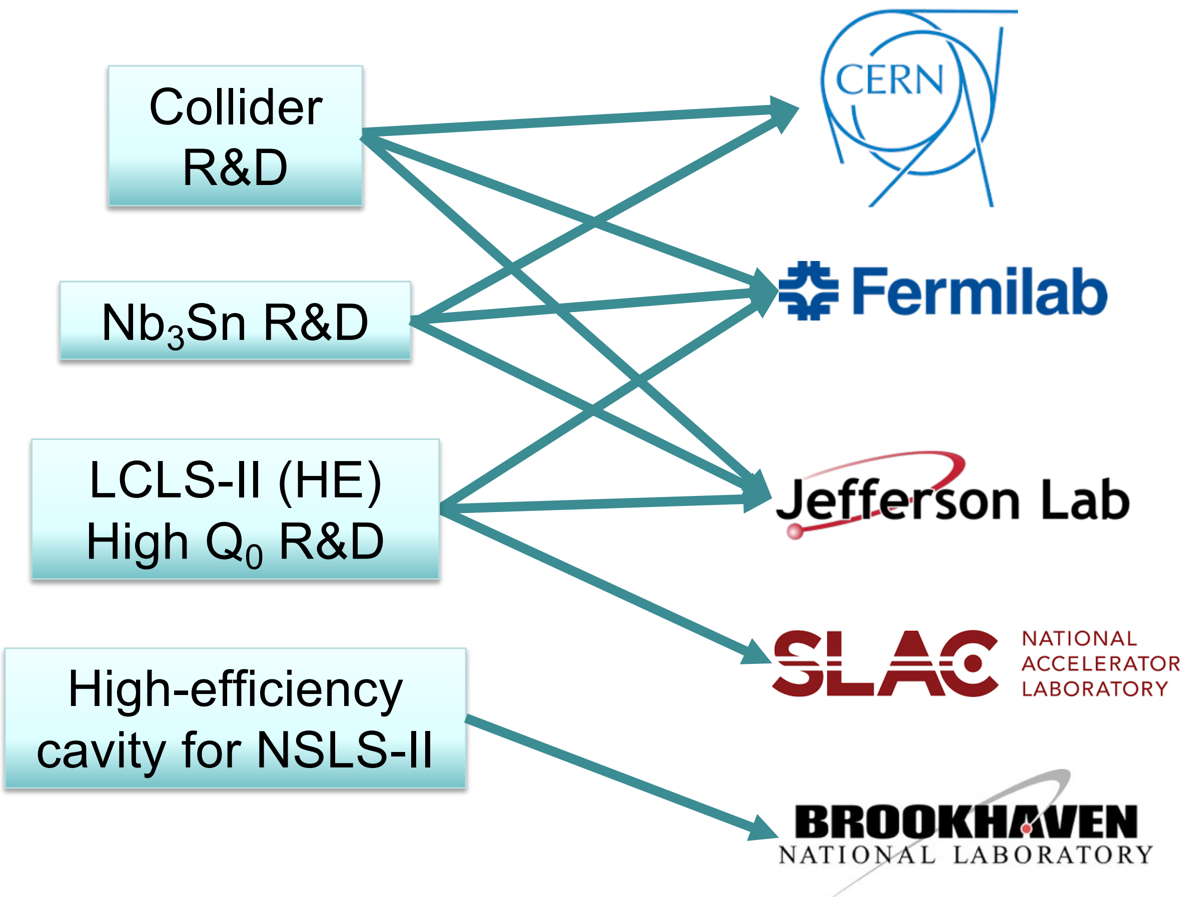
**Societal impact:** Accelerators for medicine, environment, industry…

**Workforce devolvement:** Scientists prepared to join the workforce in an area of critical need

**Quantum computing (3D qubits)**

**Dark matter detectors**

# Lab Connections




- FCC-ee SRF collaboratoin

- ILC cost reduction (high Q – high field)
- N-doping development
- US – Japan accelerator R&D
- Nb3Sn collaboration
- Widely tunable cavities

- US – Japan accelerator R&D
- N-doping development

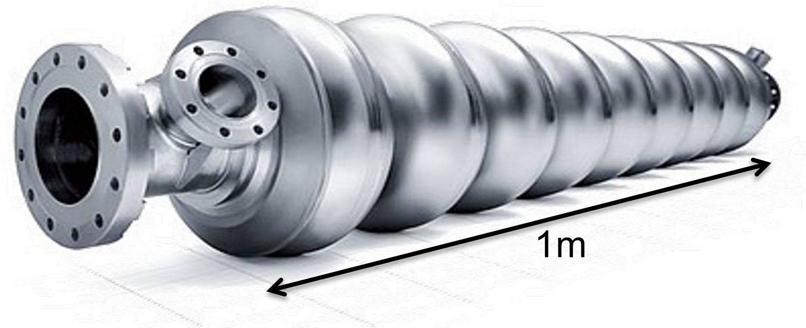
- First N-doped cavity in a cryomodule
- Discovered importance of minimizing trapped magnetic flux in N-doped cavities

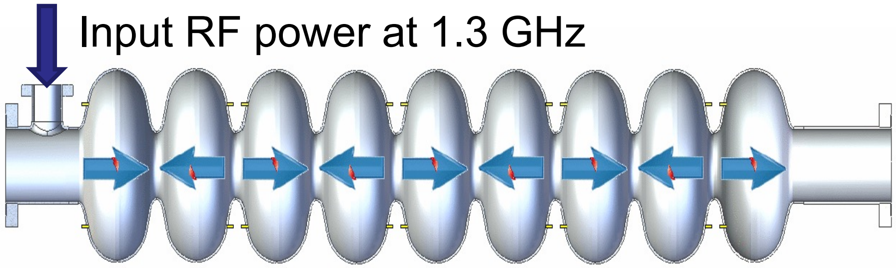
- First high-performance 500 MHz cavity for storage rings

# Superconducting RF Lab at Cornell

# Superconducting RF (SRF) Cavities

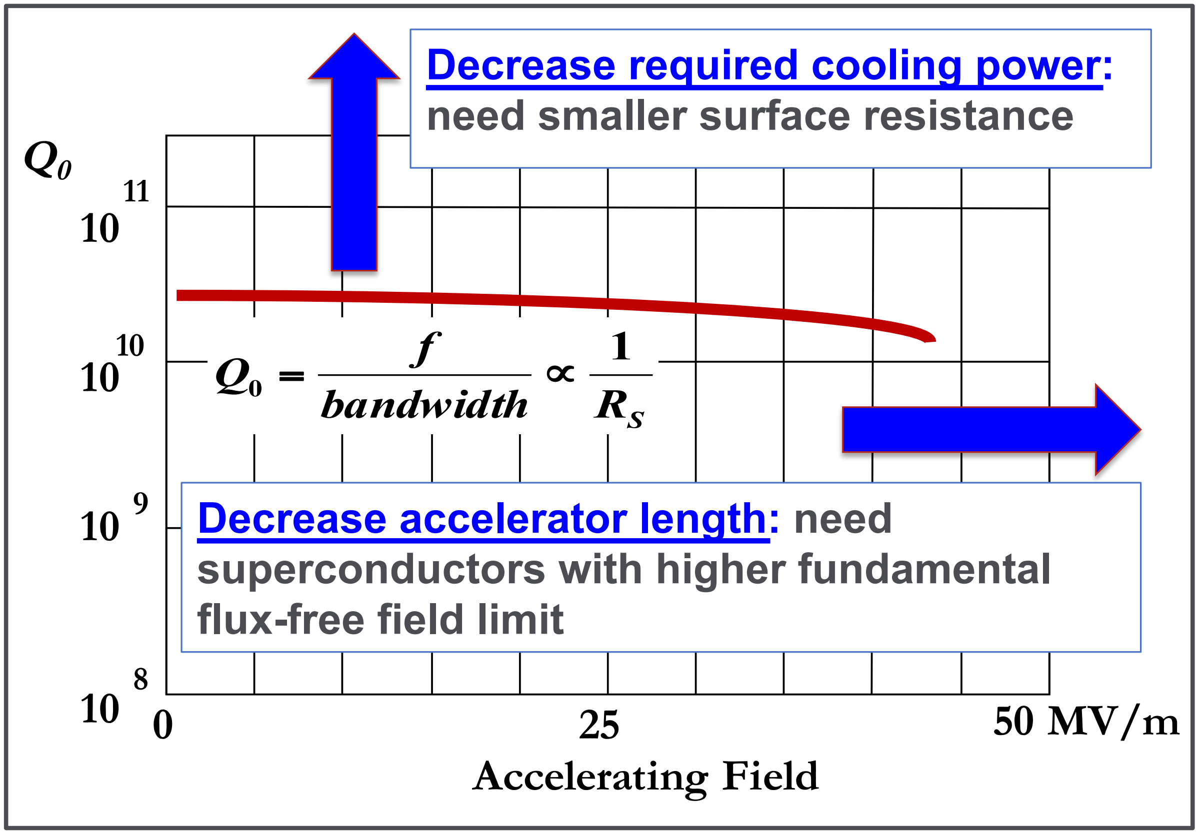
- SRF cavities accelerate charge particle beams very efficiently
  - Superconducting ⇨ Q>$10^{10}$
  - High Fields (~50 MV/m)
- "Gold-standard" for particle acceleration
- **Unique test vehicle to study superconducting response under extreme conditions (high fields and high frequency)**

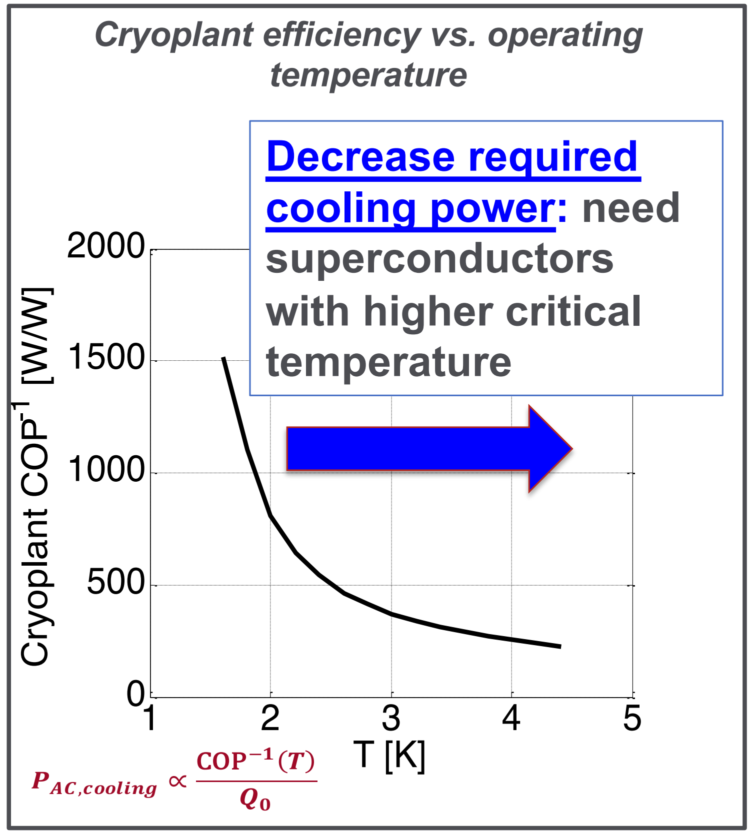


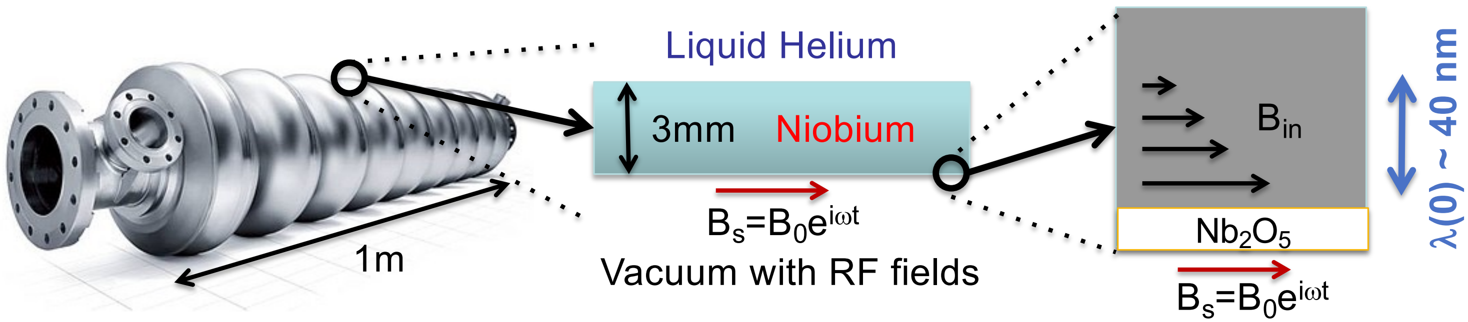

*Slowed down by factor of approximately 4x$10^9$*

# SRF Cavity Performance Figures of Merit

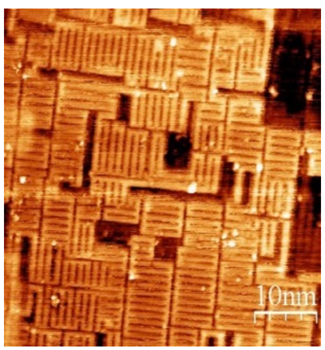


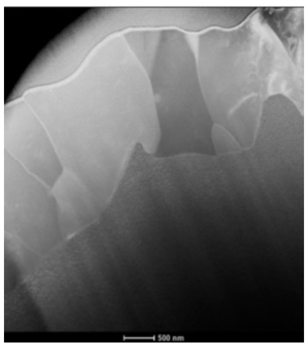
# Superconducting RF (SRF) Cavities



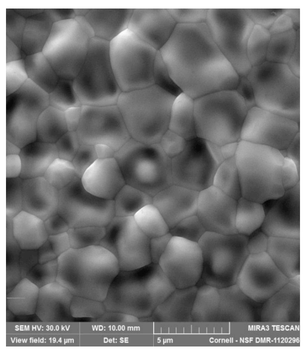

**Inner surface layer (few 100 nm) determines RF performance of the cavity!**



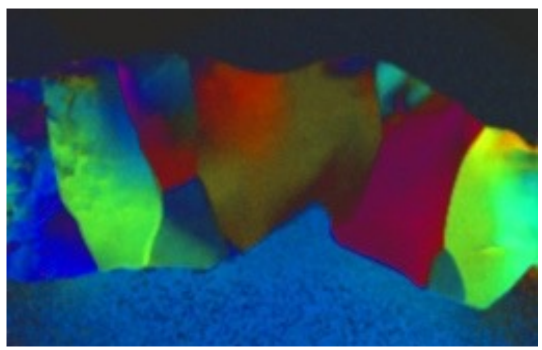

*NbO order on (100) Nb*



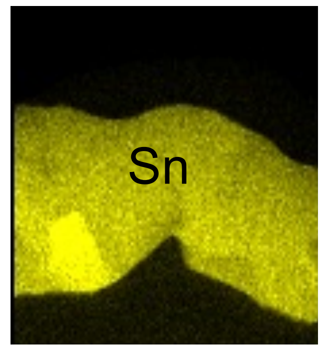
*TEM cross section*



*$Nb_3Sn$ grains*



*Grains Orientation in $Nb_3Sn$*




*Sn concentration*

**⇒ Optimization of RF performance by nm-scale *design* of this layer!**

# History of SRF (at Cornell)

Cornell accelerators:

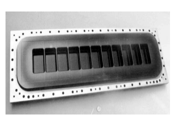
Particle physics

CHESS

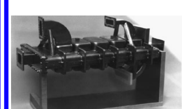

1930 1940 1950 1960 1970 1980 1990 2000 2010 Year

**Stanford, Cornell: R&D on s.c. cavities starts**

**Cornell Electron Synch.: First SRF cavity in a HEP accel.**

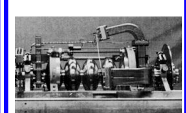


**CESR: First test of a SRF cavity in a HEP storage ring**



**Tristan, CESR, HERA, LEP, KEK-B, LHC,… : HEP accel. use SRF**

**CEBAF starts with 310 cavities. Cavity R&D by Cornell**



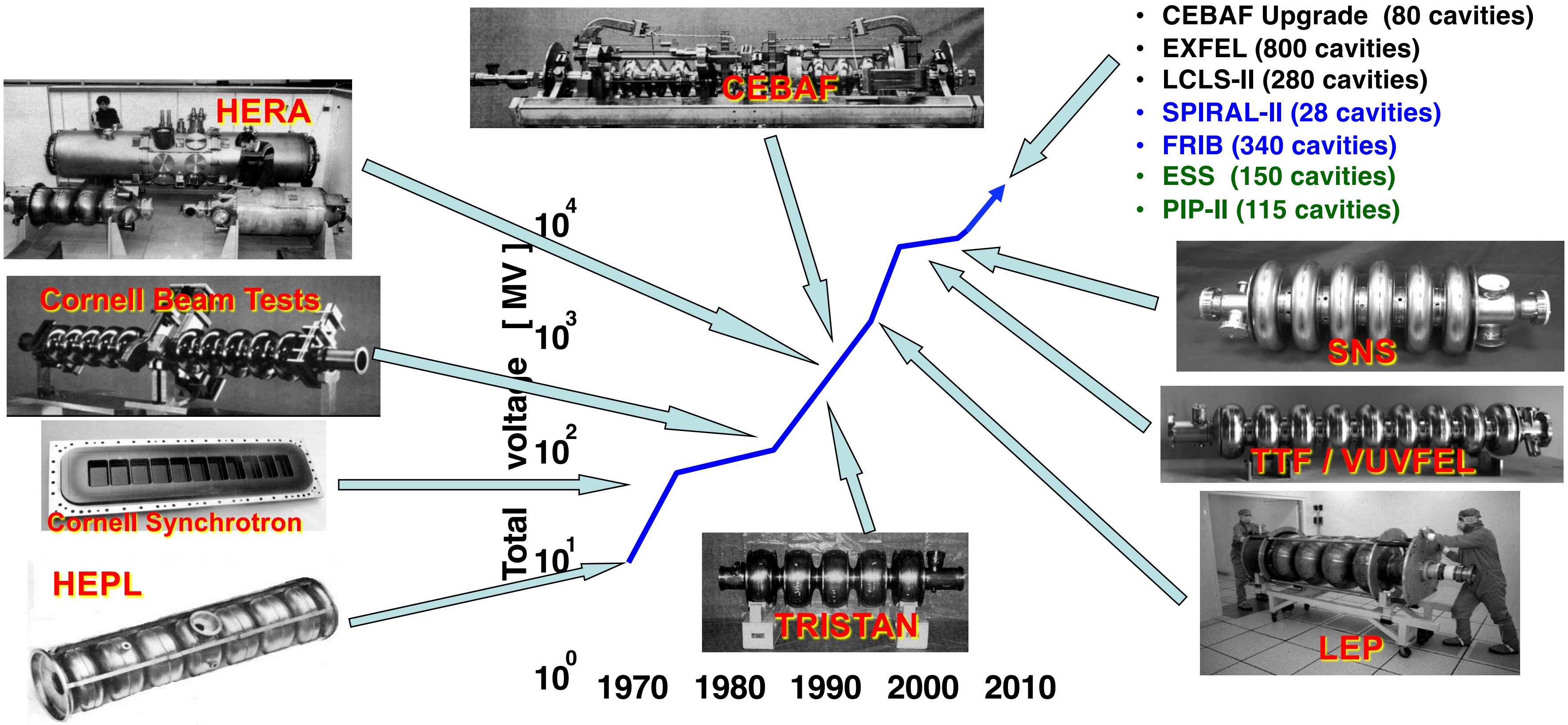
**CESR: First storage ring runs entirely on SRF cavities**

**Storage ring light sources are using the CESR SRF cryostat design**

**Cornell: First cavity passes 50 MV/m**

# A rapid Growth in SRF Application

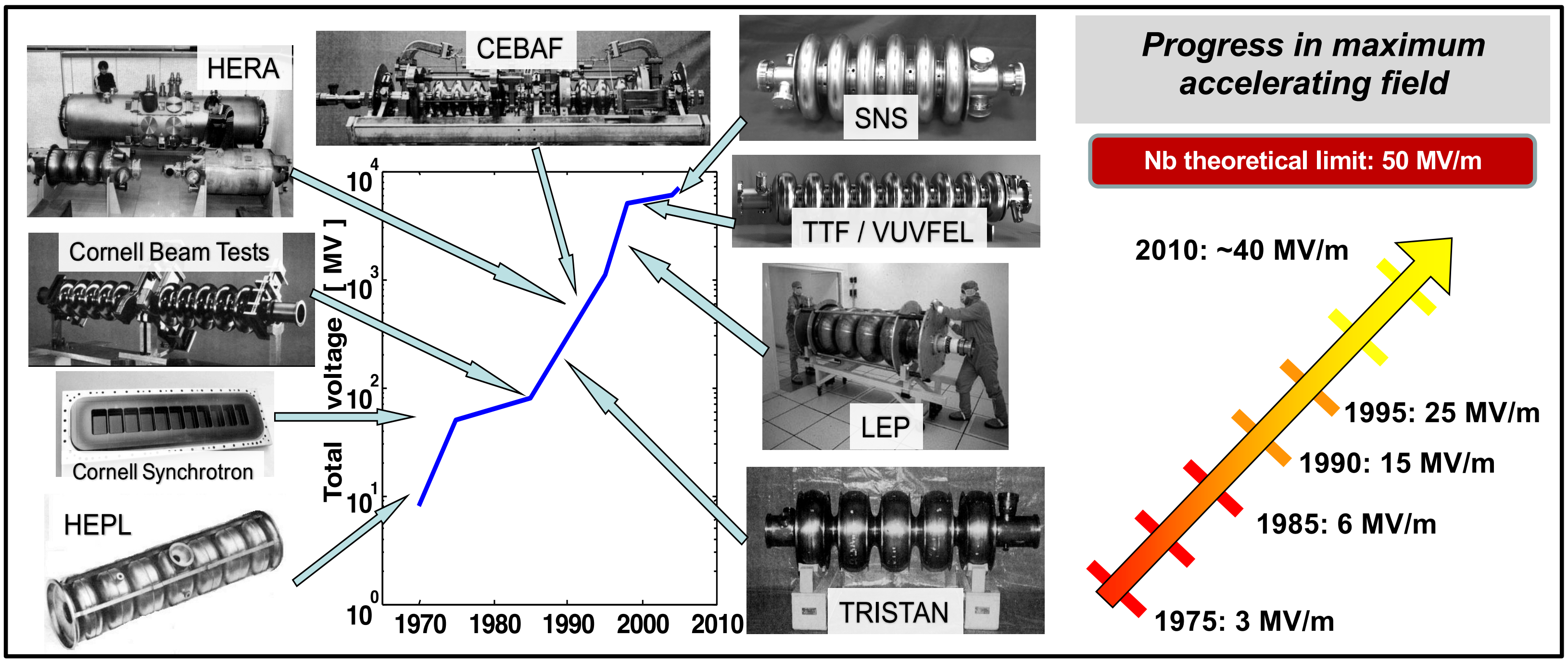
- CEBAF Upgrade  (80 cavities)
- EXFEL (800 cavities)
- LCLS-II (280 cavities)
- SPIRAL-II (28 cavities)
- FRIB (340 cavities)
- ESS  (150 cavities)
- PIP-II (115 cavities)




**Fundamental SRF and materials research, improved growth methods and preparation** ➡ ***Immediate* advances in energy reach of accelerators and/or beam intensity**

# SRF: Current State of the Art

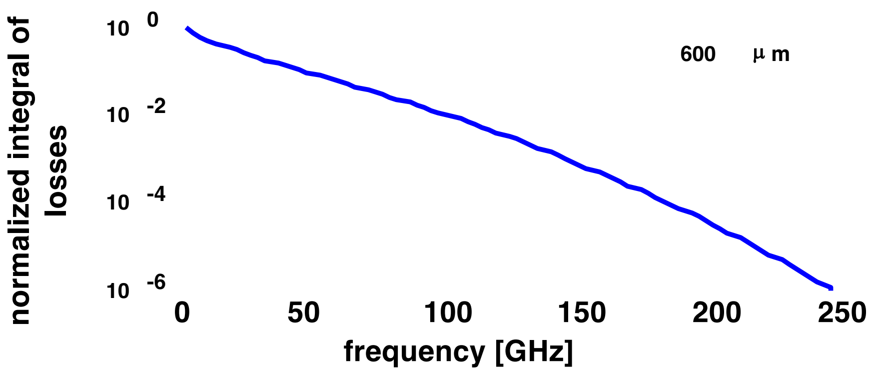
- **All SRF cavities currently in operation use Niobium as the superconducting material**
- Current generation of SRF cavities has **been transformational for accelerator driven sciences**, but **high cost and complexity limit current use in science and prevent small-scale university and industrial applications**

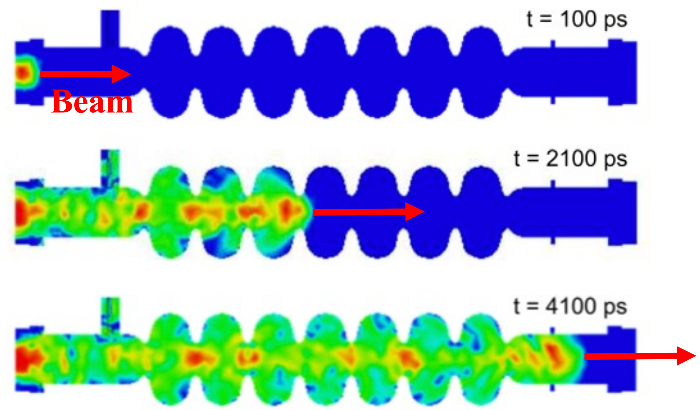


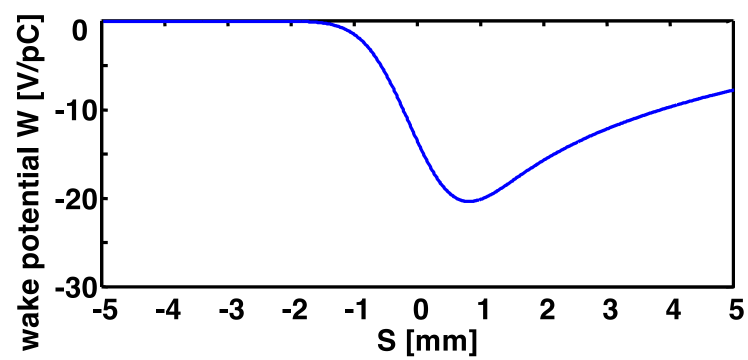
# High Current Frontier

Cornell high current SRF R&D

# High Beam Current and Higher-Order Modes



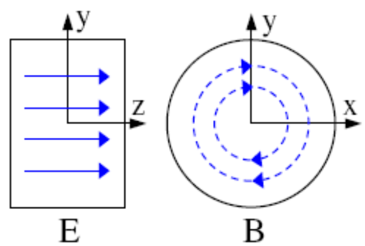




- **Bunch excites** EM cavity eigenmodes
- Short ps bunches will excite **1000s of HOMs up to *f* >100 GHz**.
- High current -> **high average HOM power per cavity**
- **Challenge: intercept HOM power and suppress excitation of HOMs**

# High Beam Current: The Challenge

## Resonant **Monopole Mode** Excitation if $f_{HOM}=N\cdot f_{bunch}$




$$P_{HOM} \propto Q_{HOM} I_{beam}^2$$

To increase beam current by factor 10 to 100:

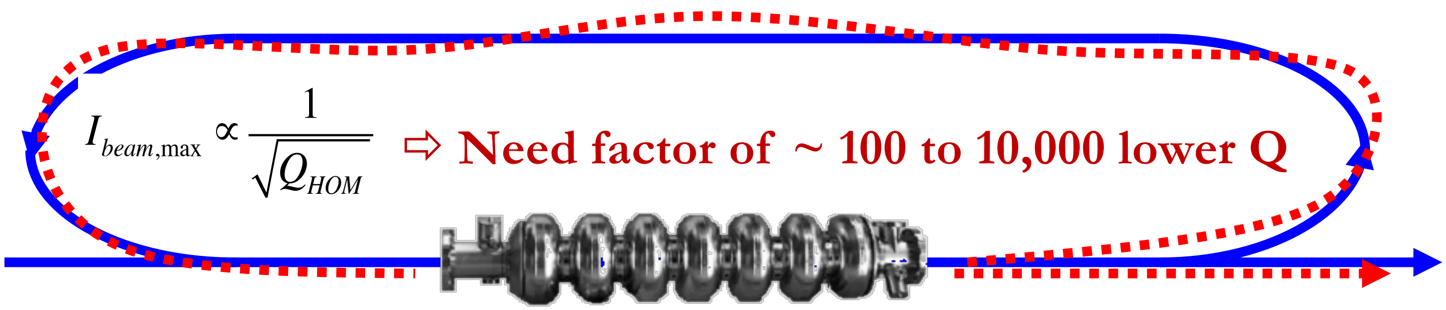
⇨ Need to increase HOM damping (further lower Q) by factor 100 to 10,000!

⇨ While keeping Q of accelerating mode at $>10^{10}$

## **Dipole Modes:** Beam instability at high currents

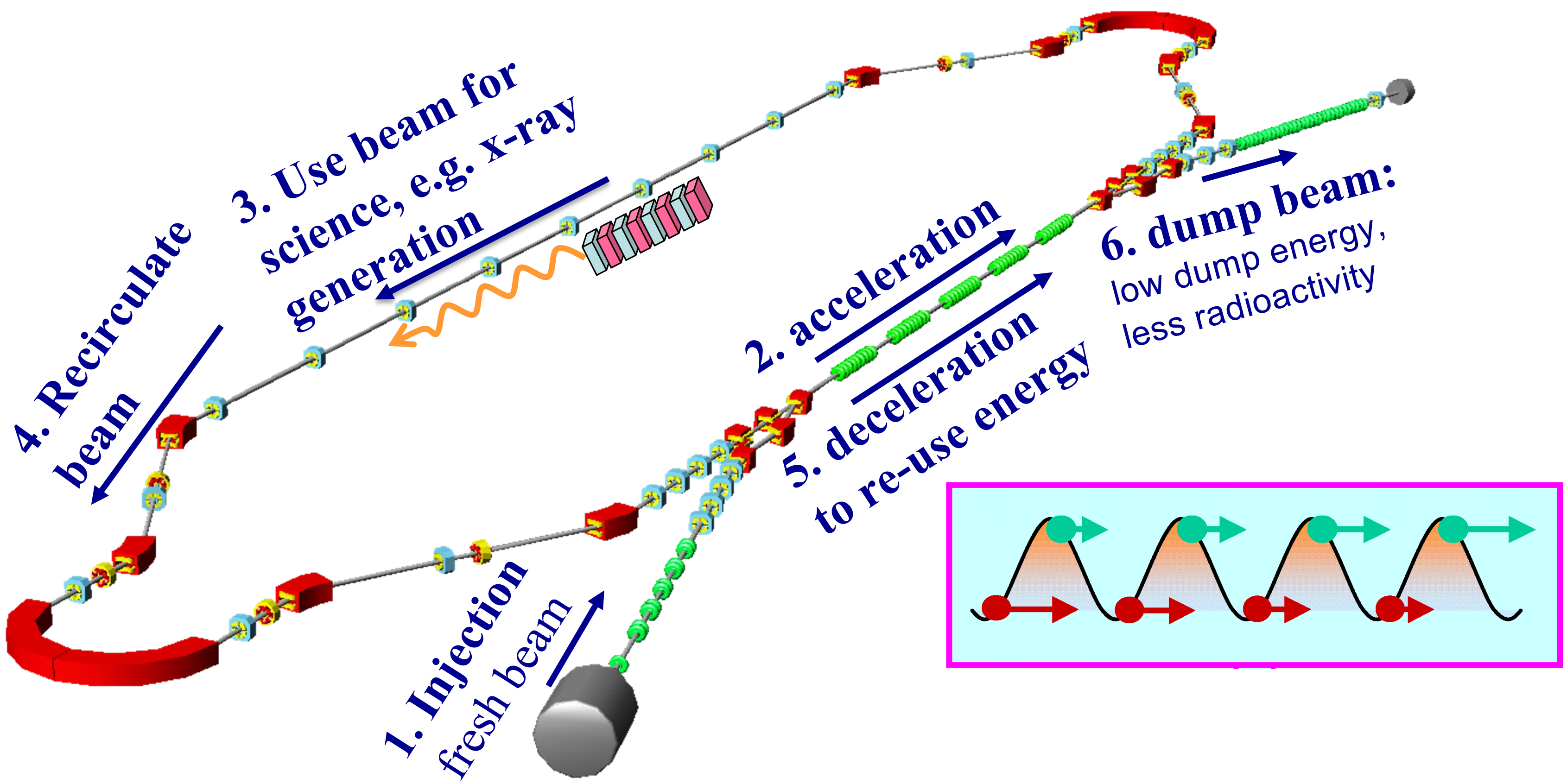
$$I_{beam,\max} \propto \frac{1}{\sqrt{Q_{HOM}}}$$

⇨ Need factor of ~ 100 to 10,000 lower Q

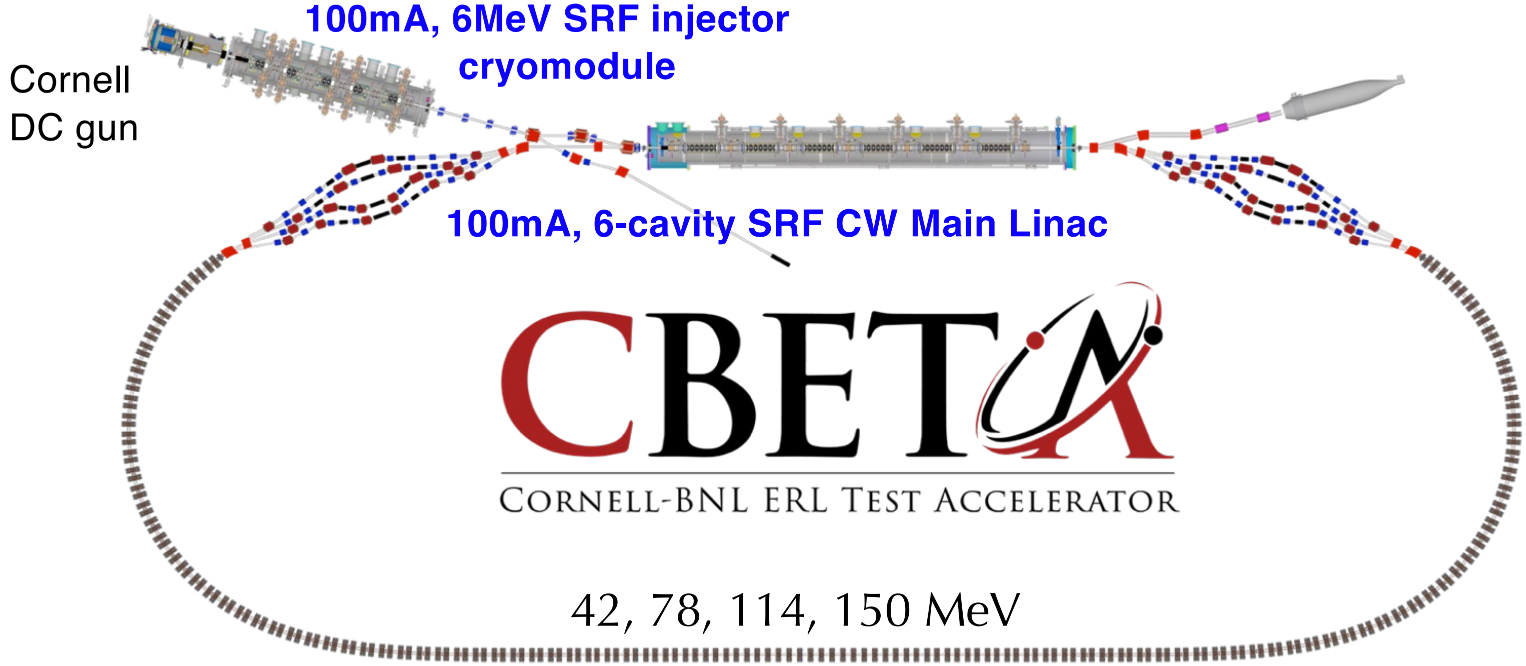


Cavities with dipole higher-order mode

# Example: Energy-Recovery-Linacs R&D

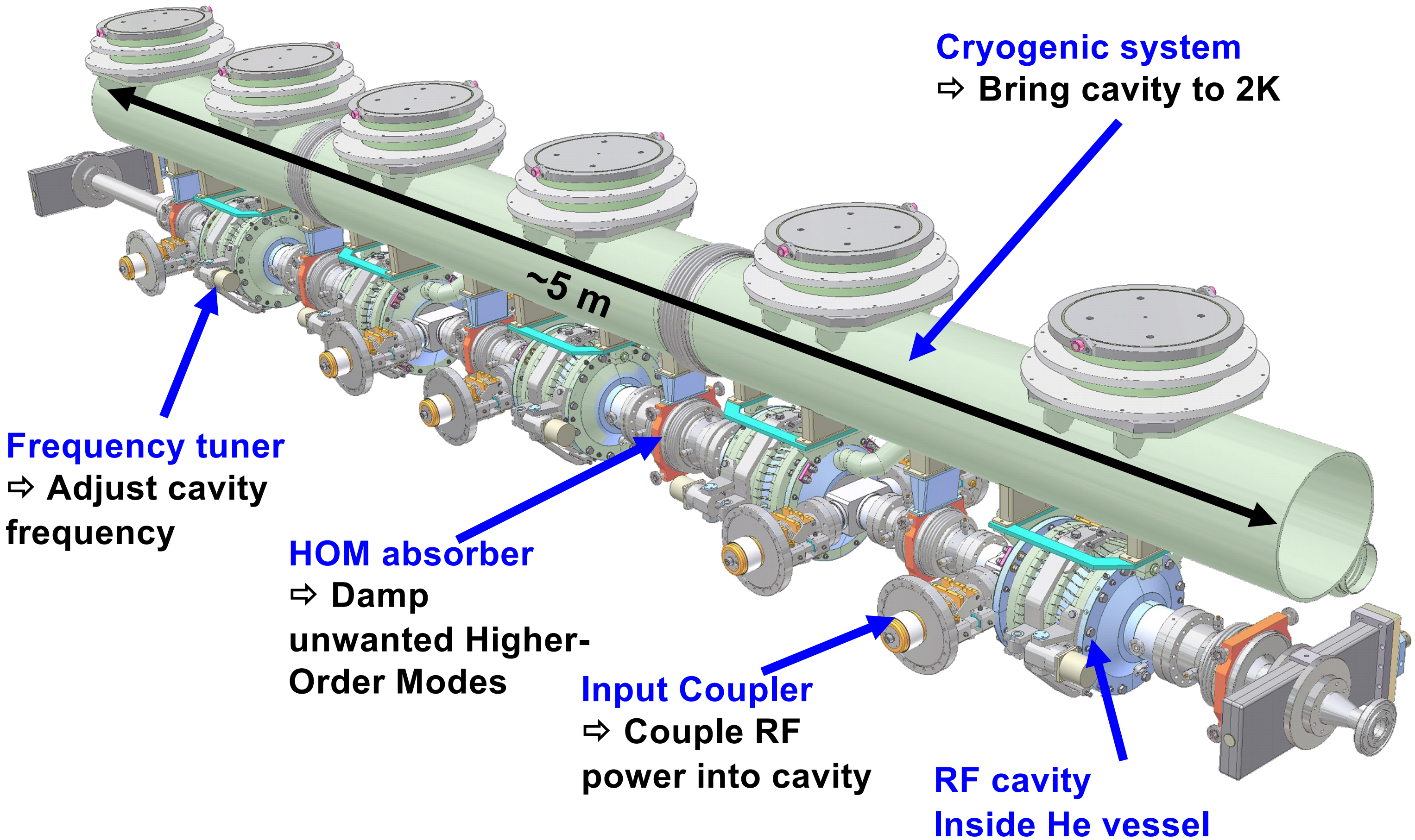


# Fixed-Field Alternating Gradient Accelerator (FFAG) ERL Prototype under construction at Cornell

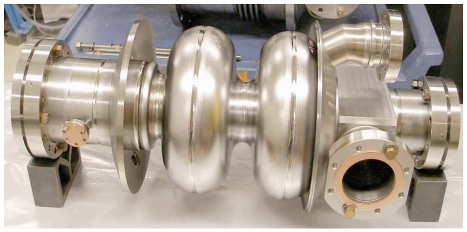



- **First SRF multi-turn (4 turn) ERL**
- **First ERL using FFAG recirculating arcs**
- **Prototyping of essential ERL components**

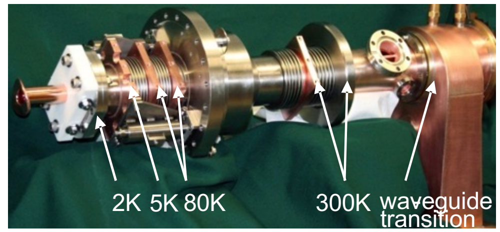
# Cornell ERL Injector Cryomodule



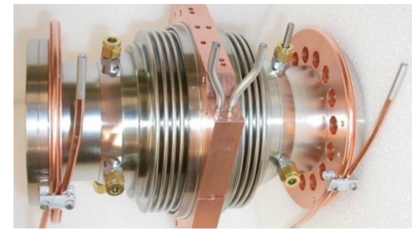
# Pushing the Envelope in Many Ways



**SRF cavity:** **design for high beam current**

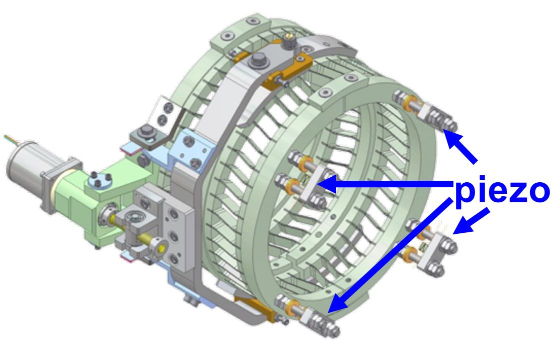



**RF input coupler:**
**design for high power**

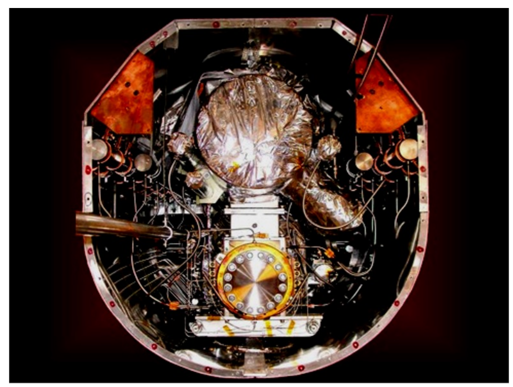


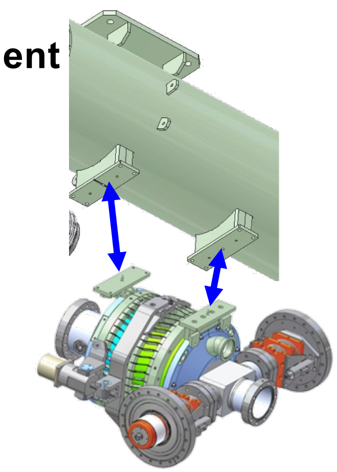
**HOM damper:** **design for strong HOM suppression**

**Frequency tuner:** **stabilize cavity length on nm scale**

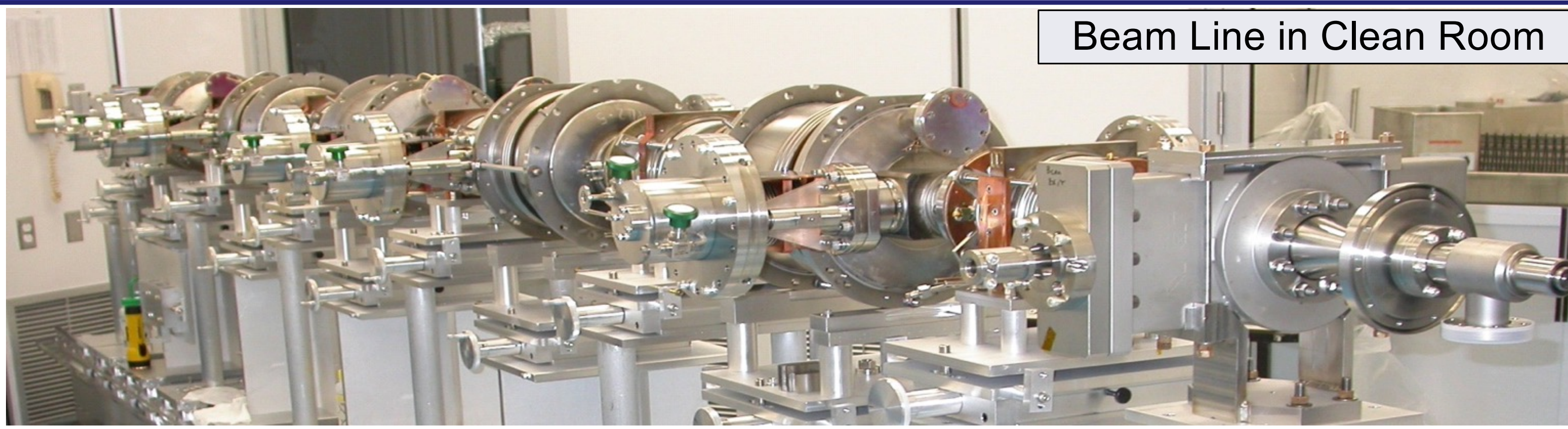


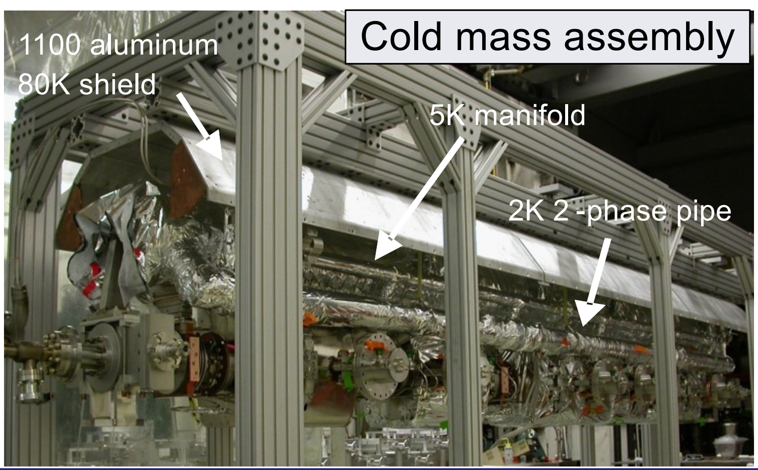

**Module design:** **support high cryo loads and provide excellent alignment**

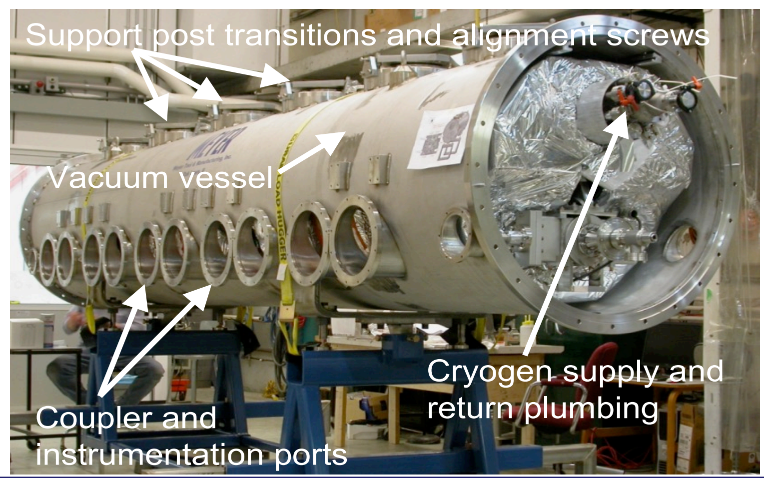




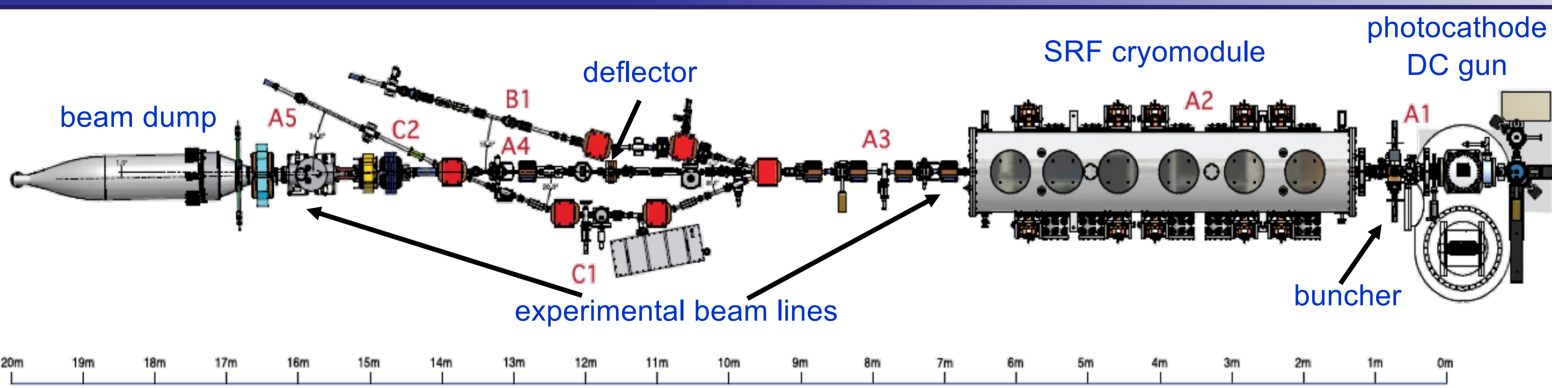
# Injector Module Assembly at Cornell

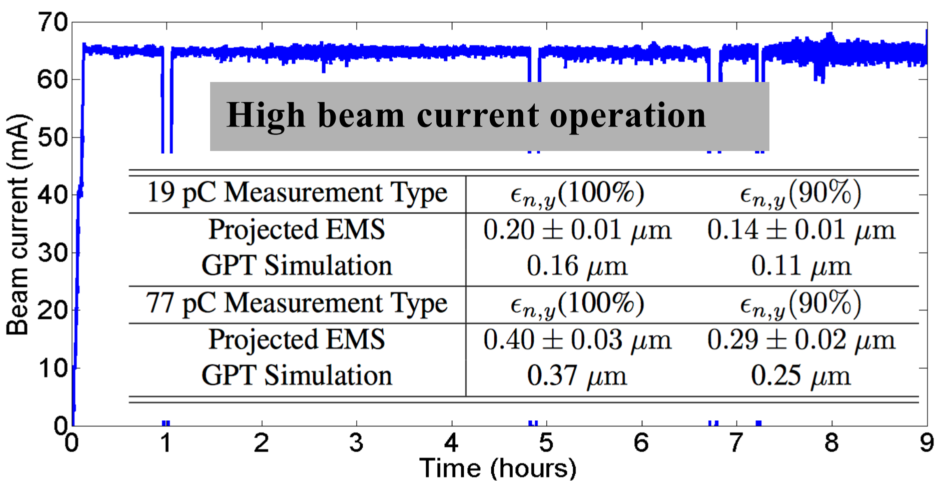


# Does it work? Cornell High Brightness Injector



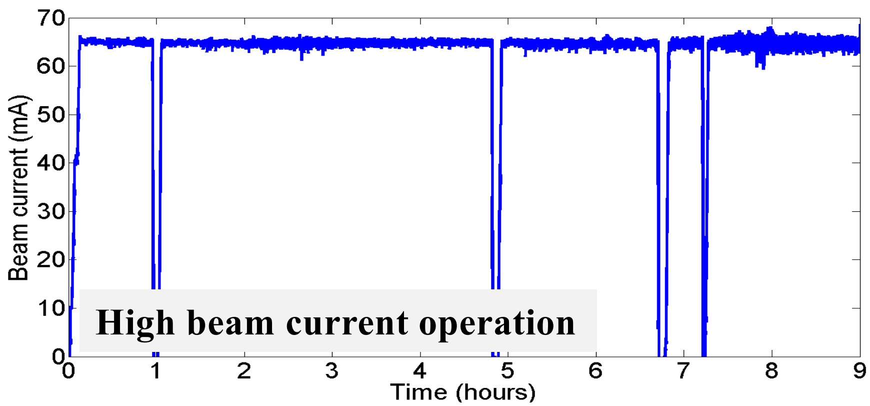



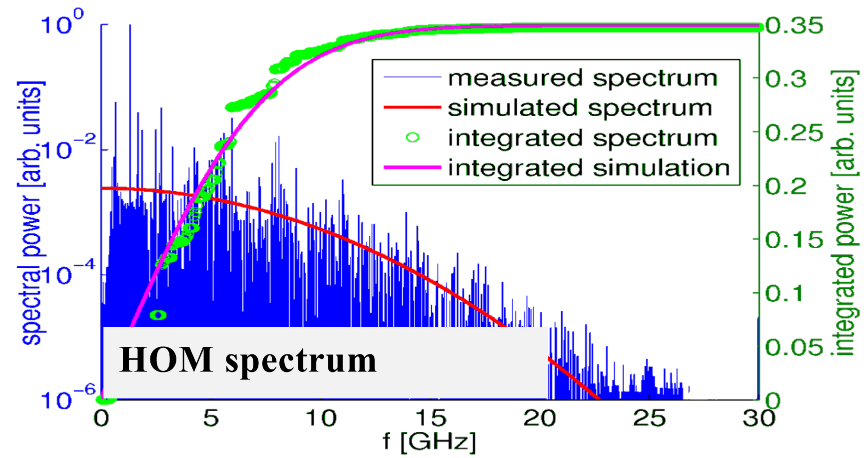

| 19 pC Measurement Type | $\epsilon_{n,y}(100\%)$ | $\epsilon_{n,y}(90\%)$ |
|---|---|---|
| Projected EMS | $0.20 \pm 0.01\ \mu m$ | $0.14 \pm 0.01\ \mu m$ |
| GPT Simulation | $0.16\ \mu m$ | $0.11\ \mu m$ |
| **77 pC Measurement Type** | $\epsilon_{n,y}(100\%)$ | $\epsilon_{n,y}(90\%)$ |
| Projected EMS | $0.40 \pm 0.03\ \mu m$ | $0.29 \pm 0.02\ \mu m$ |
| GPT Simulation | $0.37\ \mu m$ | $0.25\ \mu m$ |

- **75 mA <u>cw</u> beam** accelerated by 1.3 GHz SRF cavities **(7x previous record!)**
  - **~ 50% AC to beam power efficiency**
- Very small **beam emittance near theoretical photo-cathode limit**

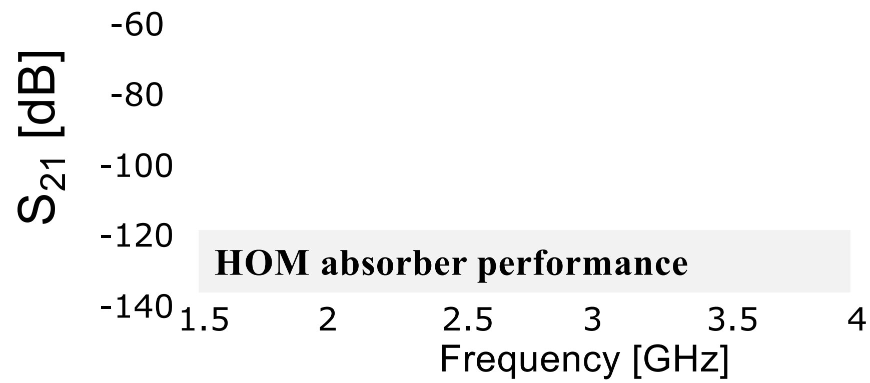
Appl. Phys. Lett. **102**, 034105 (2013); doi: 10.1063/1.4789395

# Results from the CBETA Injector SRF Module

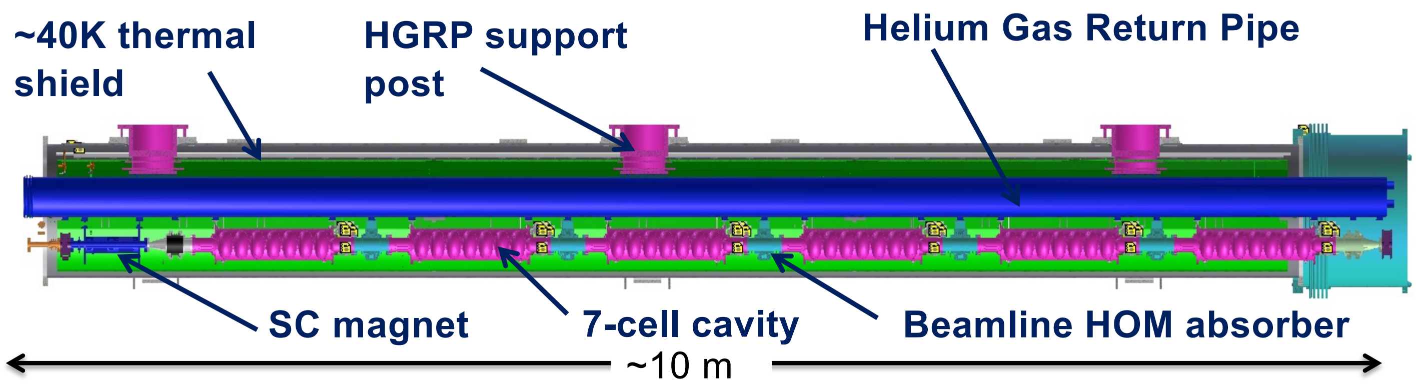


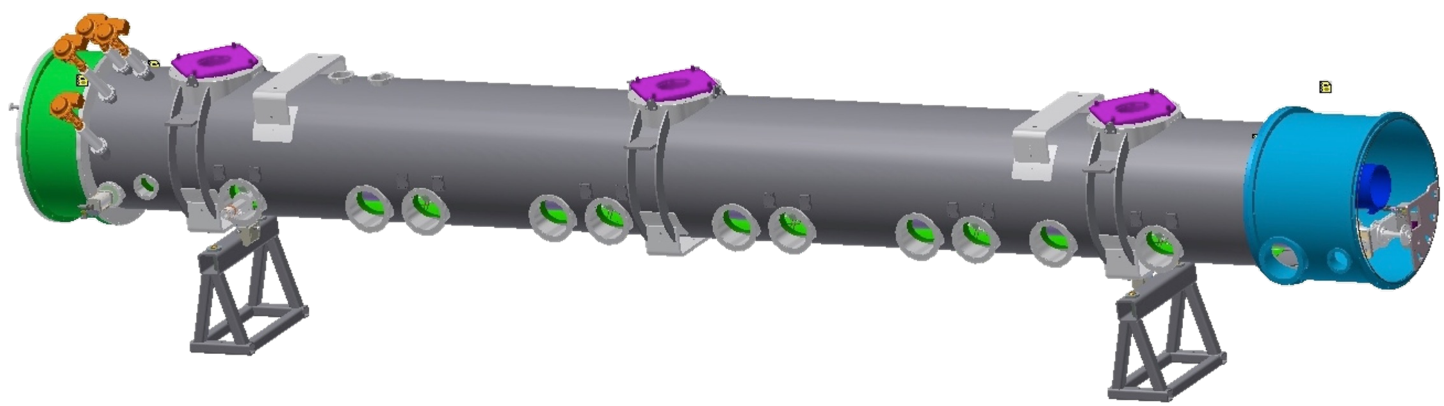




- ✓ **Accelerated beam currents of up to 75 mA over many hours**
- ✓ **No signs of beam instability or excessive heating by HOMs**
- ✓ **HOM spectrum in good agreement with simulation results**
- ✓ **Excellent HOM damping with typical Qs of a few 1000**



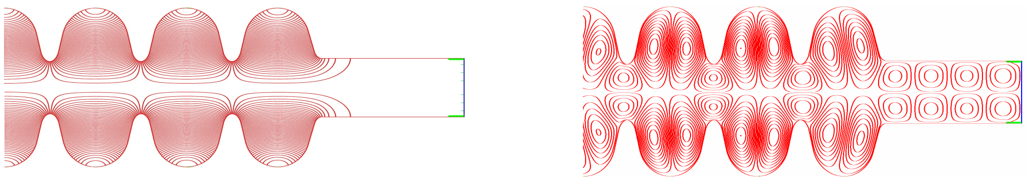
# CBETA ERL Main Linac Cryomodule



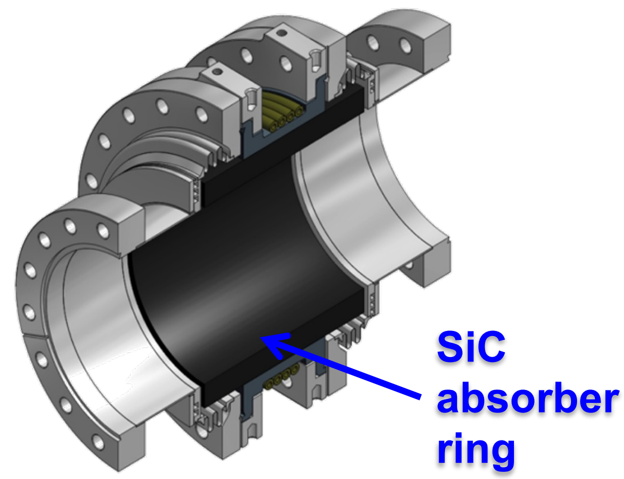



**First ever high-current, high efficiency (high $Q_0$) SRF linac module.**

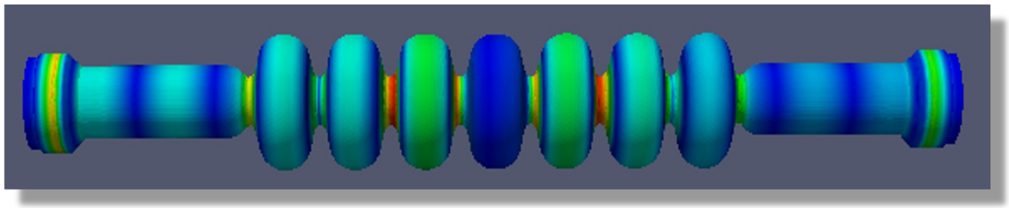
# CBETA ERL HOM Damping Solution

- Beam tube diameter optimized
  - to **trap** accelerating mode in cavity and
  - to **propagate** all HOMs
- **RF absorbers** in the beam pipes between the cavities
  - ✓ Simple HOM damping design
  - ✓ Broadband way of HOM damping

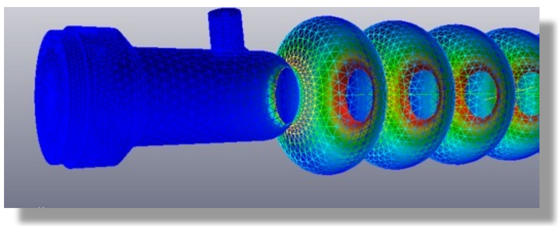


# Cavity Design for High Currents

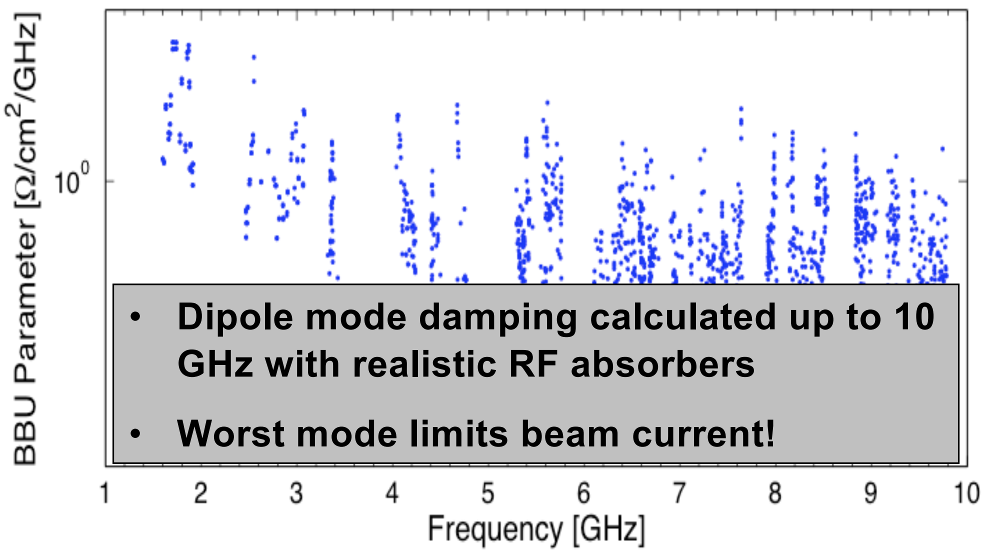


Cell shape optimization
- ~20 free parameters
- 1000’s of eigenmodes
- Impact of cell shape errors

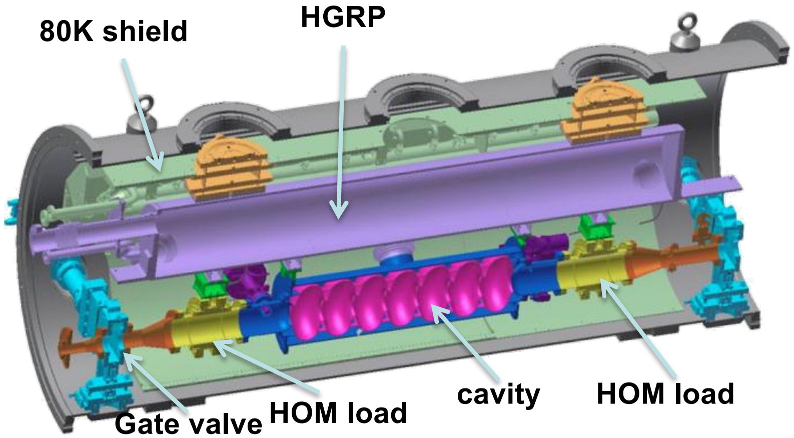
**Supports beam current >400 mA (previous record: 10 mA)**

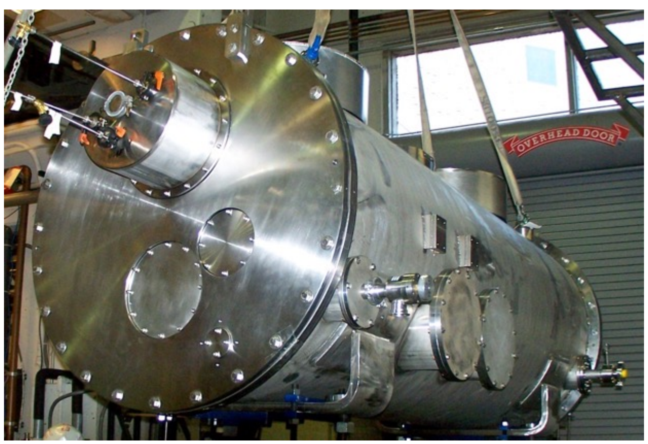


Franklin Cray XT4

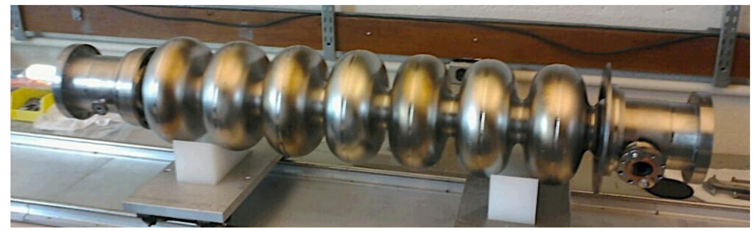



# ERL 1-Cavity Prototype Module

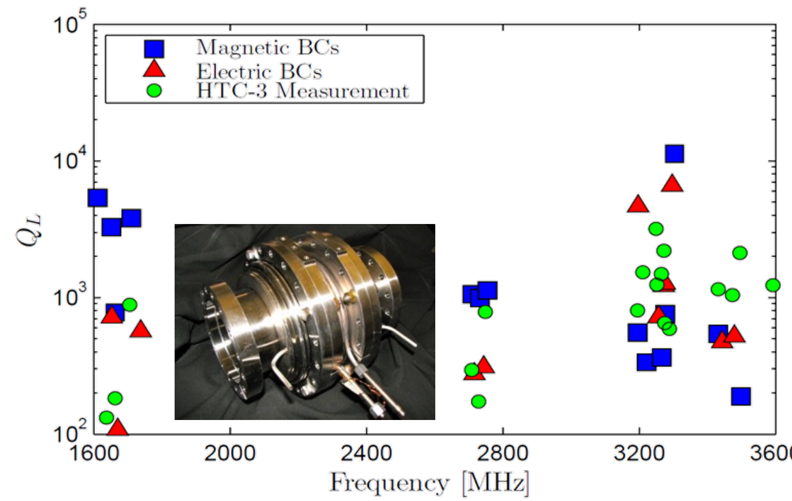


7-cell prototype 1.3 GHz cavity

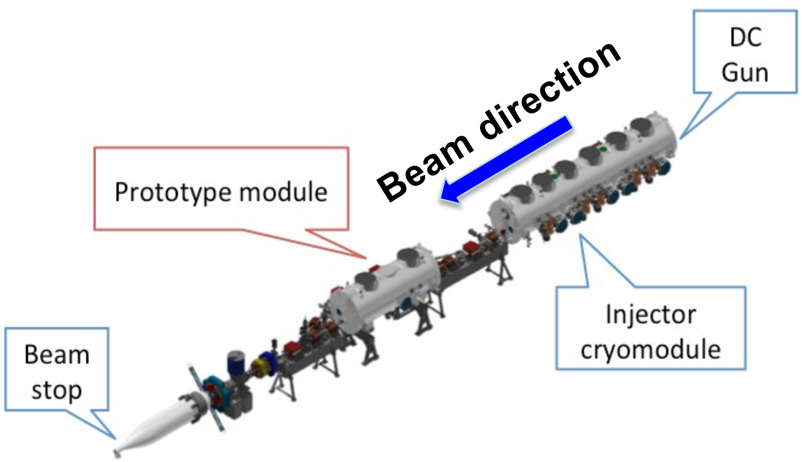


**Excellent HOM damping in agreement with simulations**



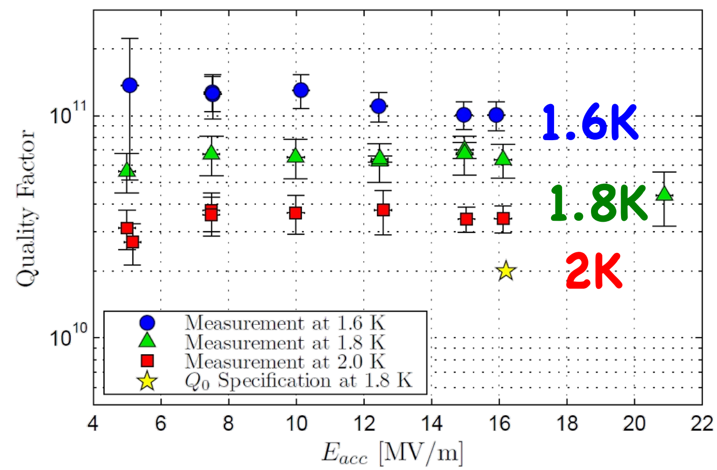
# Does it work? Results from the Prototype Module

## Record Beam Performance




- High CW currents >40 mA
- No significant heating from HOMs
- No sign of beam instability or weakly damped modes

## Record Cavity RF Performance




- Record (at that time) $Q_0$ for cavity accelerating mode:

  Q(2.0 K) = $3.5 \times 10^{10}$

  Q(1.8 K) = $6 \times 10^{10}$

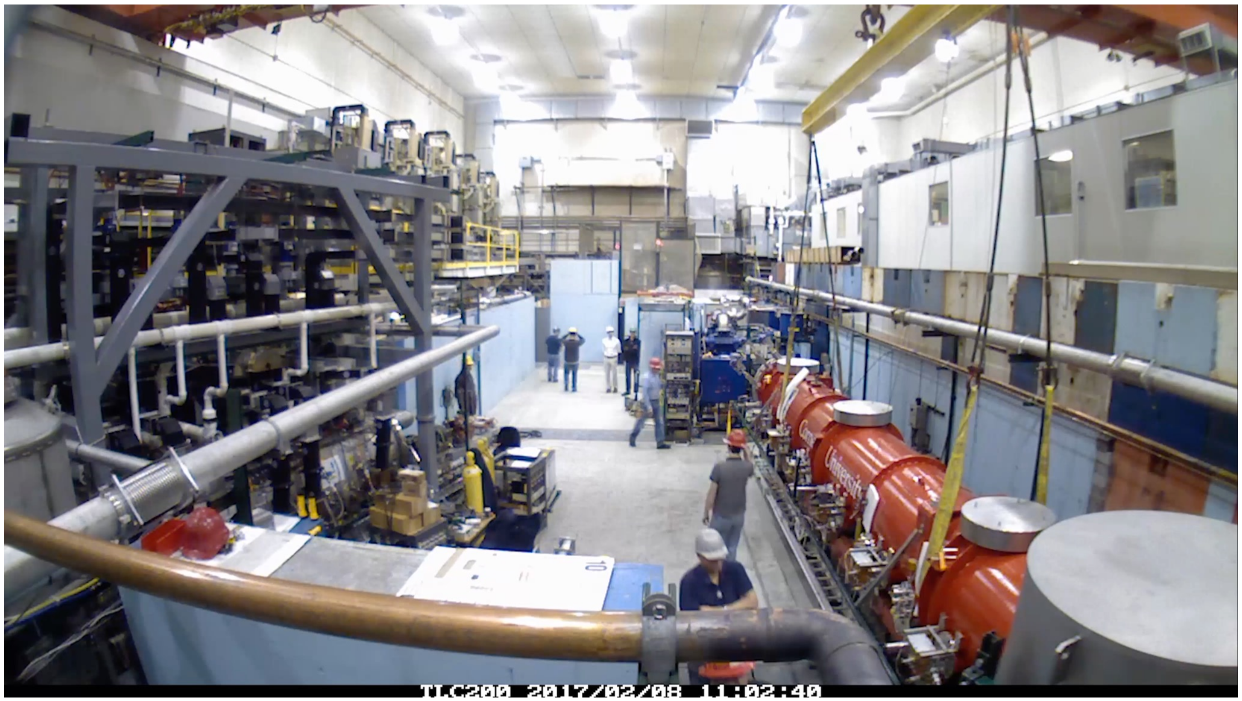
  Q(1.6 K) = $1 \times 10^{11}$

  Nuclear Instr. & Meth. in Physics Research A (2013)

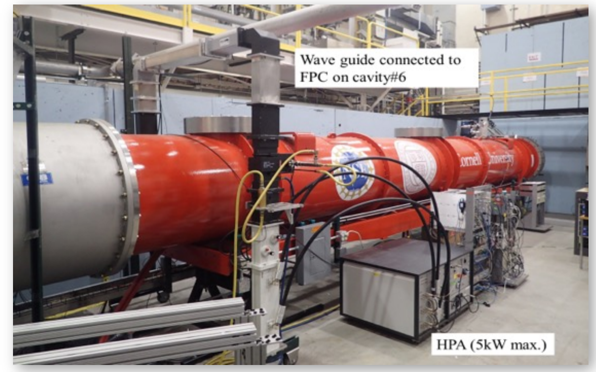
  http://dx.doi.org/10.1016/j.nima.2013.07.021

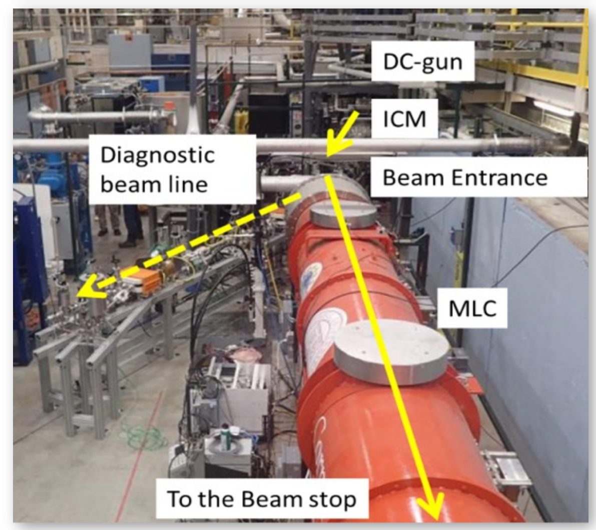
# Main Linac Module Assembly at Newman Lab

# Main Linac Module Installation at Wilson Lab

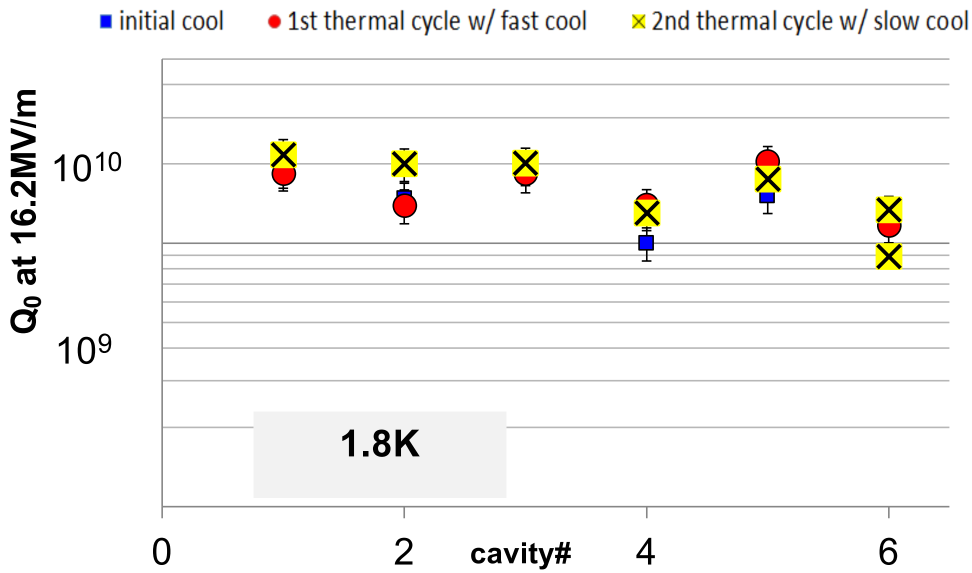


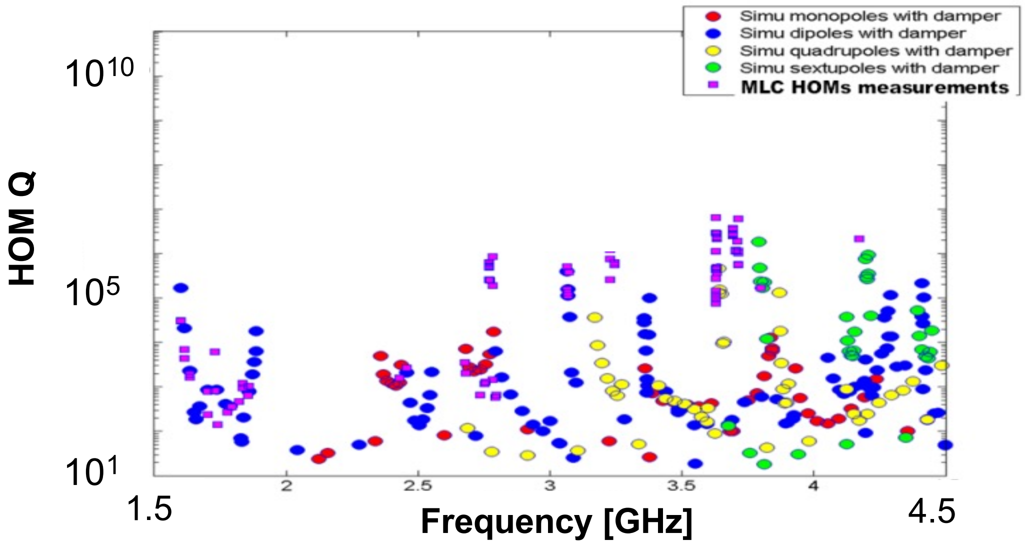

Video credit: Rick Ryan, CLASSE



# Does it work? Results from the Main Linac Module



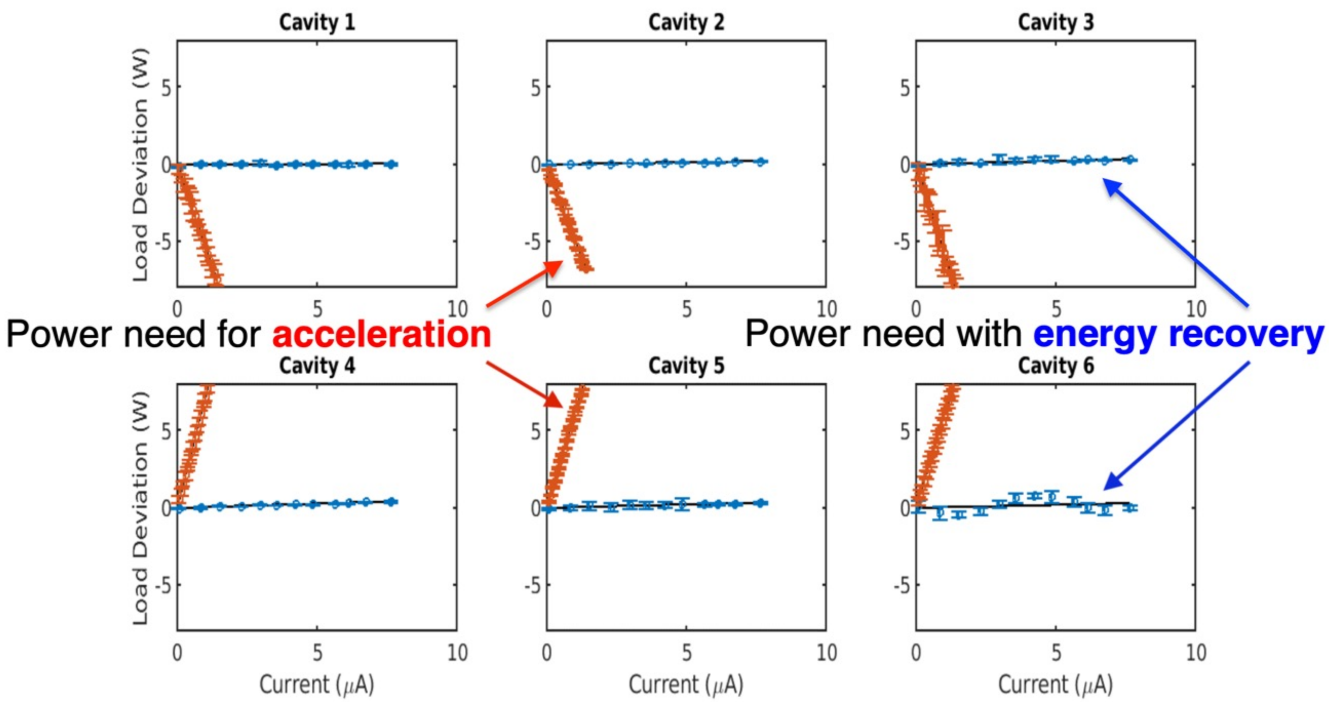




✓**Cavity performance meets specifications**

✓**Excellent HOM damping in agreement with simulations**

# CBETA

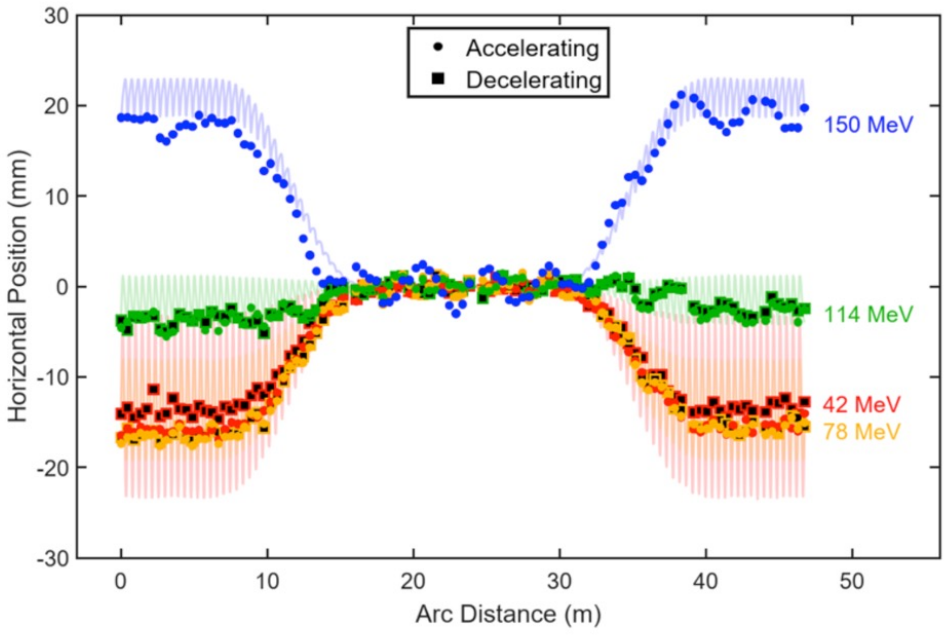
# 1-Turn ERL Operation



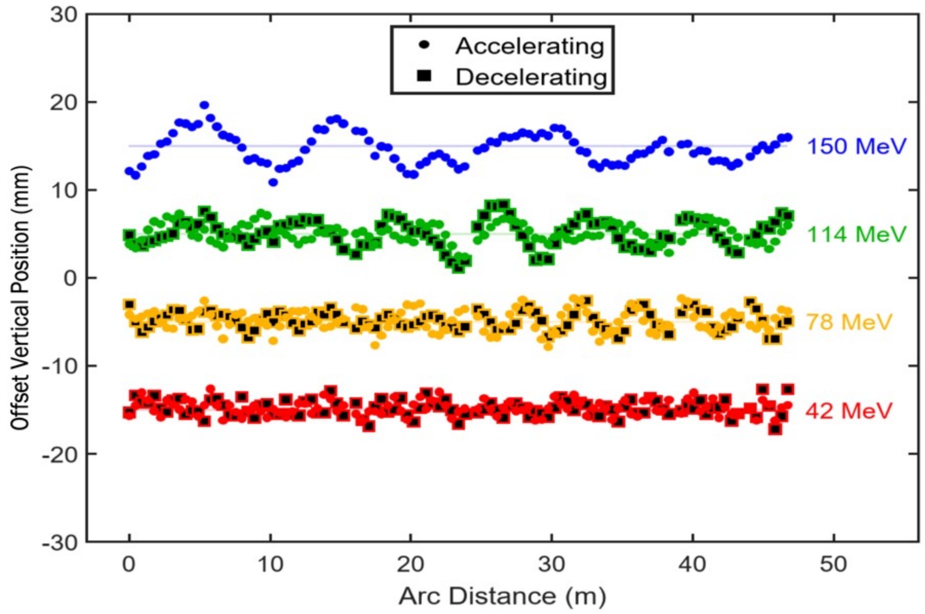

- Transmission 99.6 ± 0.1% ; energy recovery > 99.8%
- Measured up to 8 μA
- Each cavity accelerates beam **without** receiving **external power** for it.

# 4-Turn ERL Operation

## Horizontal Orbits




## Vertical orbits



# Efficiency / Cost Frontier:

Cornell $Nb_3Sn$ Program

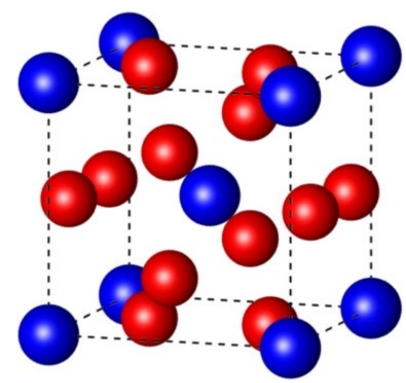
# A15 Superconductors

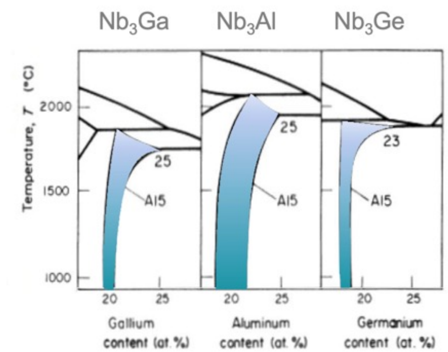
| Compound | $T_c$ | Compound | $T_c$ | Compound | $T_c$ |
|---|---|---|---|---|---|
| $Ti_3Ir$ | 4.6 | $Nb_3Os$ | 0.94 | $Mo_3Ir$ | 8.1 |
| $Ti_3Pt$ | 0.49 | $Nb_3Rh$ | 2.5 | $Mo_3Pt$ | 4.56 |
| $Ti_3Sb$ | 5.8 | $Nb_3Ir$ | 1.76 | $Mo_3A1$ | 0.58 |
| $Zr_3Au$ | 0.92 | $Nb_3Pt$ | 10 | $Mo_3Ga$ | 0.76 |
| $Zr_4Sn$ | 0.92 | $Nb_3Au$ | 11 | $Mo_3Si$ | 1.3 |
| $Zr_3Pb$ | 0.76 | $Nb_3Ai$ | 18.9 | $Mo_3Ge$ | 1.4 |
| $V_3Os$ | 5.15 | $Nb_3Ga$ | 20.3 | $Mo_2Tc_3$ | 13.5 |
| $V_3Rh$ | 0.38 | $Nb_3In$ | 8 | $Mo_3Re$ | 15 |
| $V_3Ir$ | 1.39 | $Nb_3Ge$ | 23 | | |
| $V_3Ni$ | 0.57 | $Nb_3Sn$ | 18.3 | | |
| $V_3Pd$ | 0.08 | $Nb_3Bi$ | 2.25 | | |
| $V_3Pb$ | 3.7 | $Ta_{4.3}Au$ | 0.58 | | |
| $V_3Au$ | 3.2 | $Ta_3Ge$ | 8 | | |
| $V_3A1$ | 9.6 | $Ta_3Sn$ | 6.4 | | |
| $V_3Ga$ | 15.4 | $Ta_3Sb$ | 0.72 | | |
| $V_3In$ | 13.9 | $Cr_3Ru$ | 3.43 | | |
| $V_3Si$ | 17.1 | $Cr_3Os$ | 4.03 | | |
| $V_3Ge$ | 7 | $Cr_3Rh$ | 0.07 | | |
| $V_3Sn$ | 4.3 | $Cr_3Ir$ | 0.17 | | |
| $V_3Sb$ | 0.8 | $Mo_3Os$ | 11.68 | | |

Table adapted from
https://doi.org/10.1016/0011-2275(75)90019-3

- **Several A15 superconductors hold promise for SRF with critical T of 15 – 23 K**
- **Many of these are not stable in bulk and/or at lower temperature**
  - **Need non-equilibrium growth processes**
- **$Nb_3Sn$ is stable and currently the most developed A15 material for SRF**

$A_3B$





# $Nb_3Sn$: A Potential Gamechanger

## Increased Accelerating Field

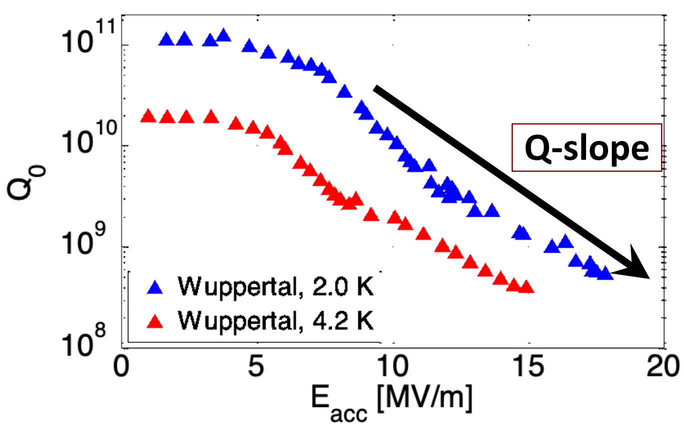
| | Niobium | $Nb_3Sn$ |
|---|---|---|
| Superheating field | 240 mT | 420 mT |
| Max. $E_{acc}$ (theoretical limit) | 55 MV/m | **100 MV/m** |

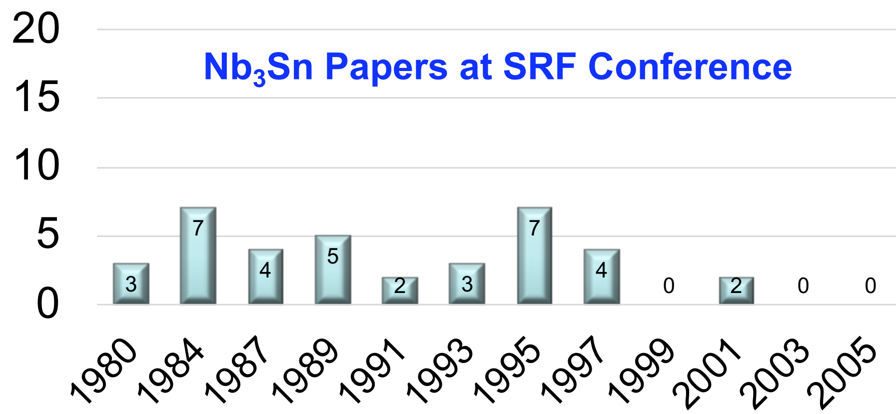
## Lower Cooling Cost and Complexity

| | Niobium | $Nb_3Sn$ |
|---|---|---|
| Critical Temperature $T_c$ | 9 K | 18 K |
| $Q_0$ at **4.2 K** | $6 \times 10^8$ | **$6 \times 10^{10}$** |

*$Q_0$ given for 1.3 GHz ILC-shape cavities*

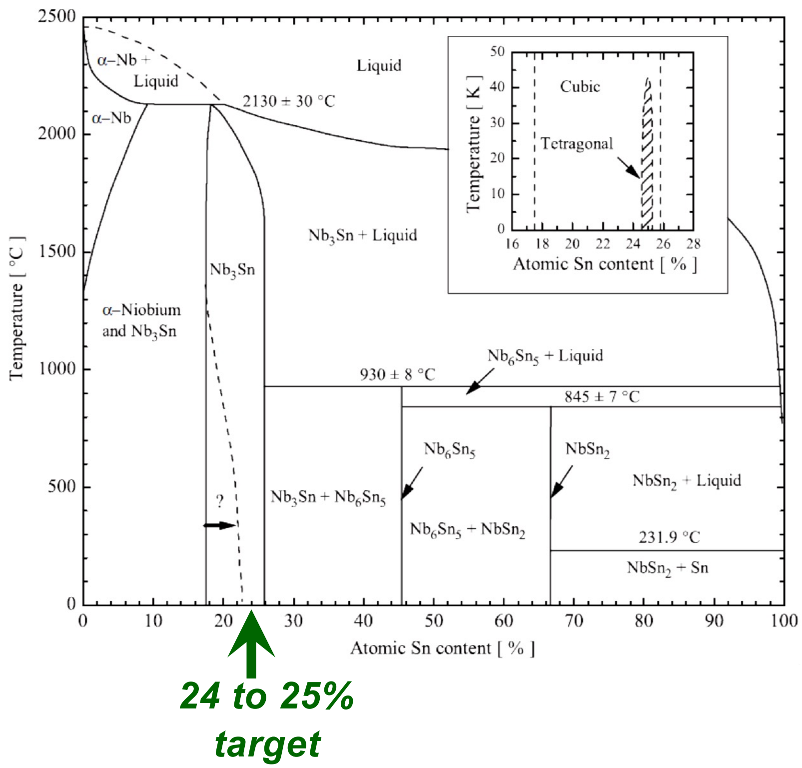
## Huge potential, but no success (prior to Cornell's $Nb_3Sn$ work)



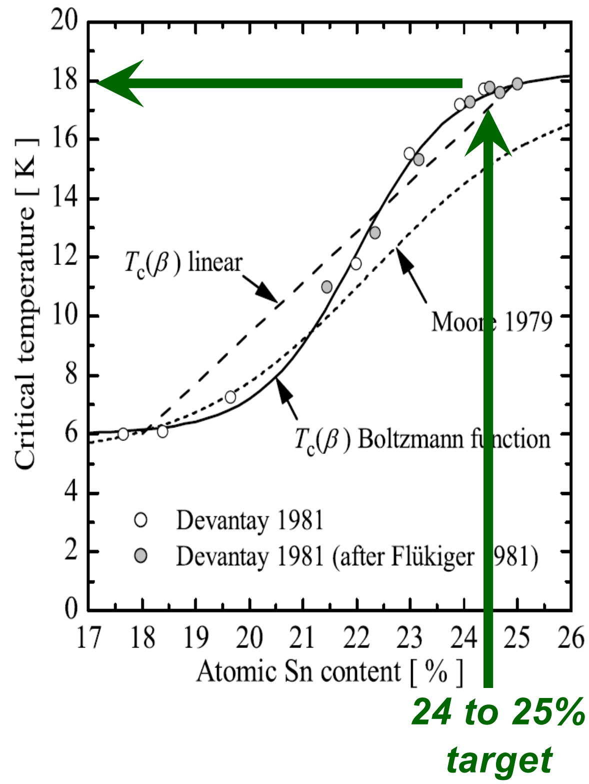



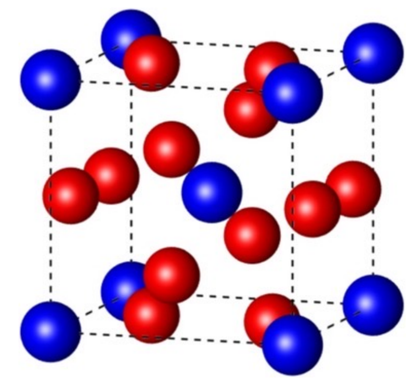
# $Nb_3Sn$ Challenge: Stoichiometry and $T_c$

## $Nb_3Sn$ Phase Diagram




## $T_c$ vs. Tin Content



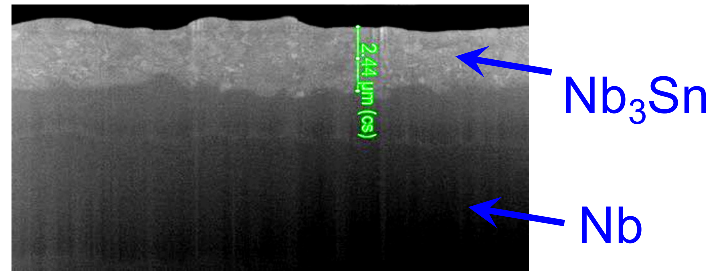
**Blue**: tin
**Red**: niobium

*A. Godeke, Supercond. Sci. Tech, 2006*

# More $Nb_3Sn$ Challenges

- Material is brittle
- Low thermal conductivity

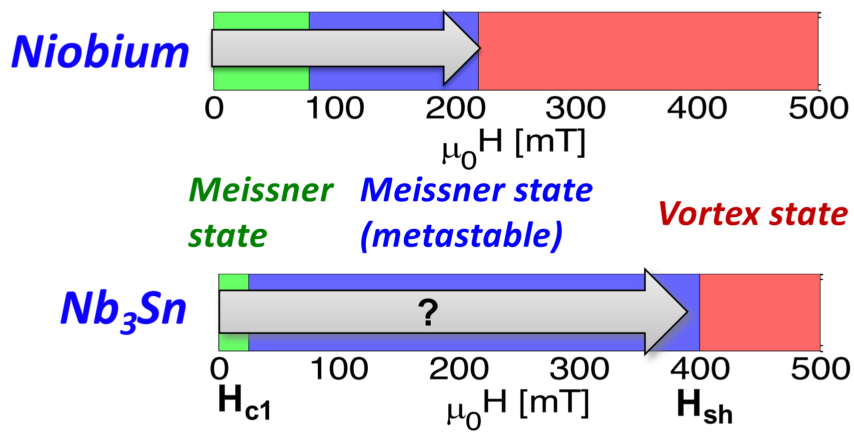
} *Thin films avoid/reduce these*



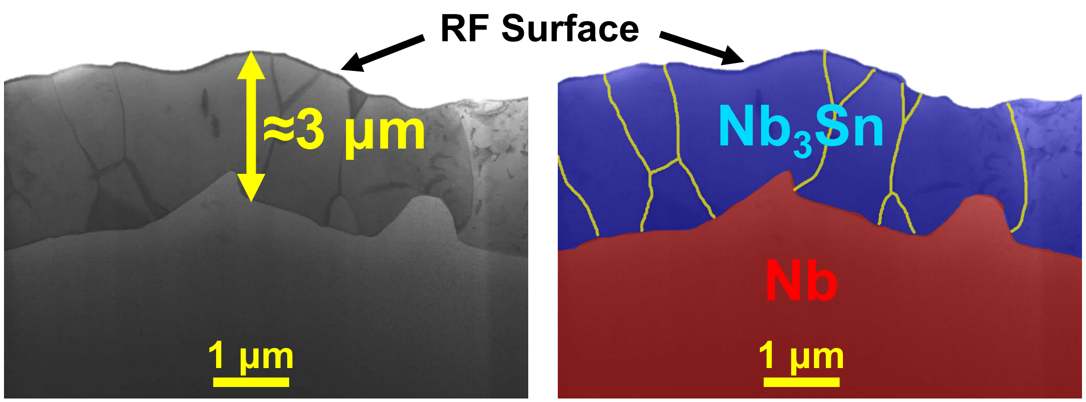

- **Small coherence length ξ ~ 3 - 4 nm**
  - **Sensitive to small defects**
  - **Small first critical field $H_{c1}$**

    ⇒ Need to operate in the flux free metastable Meissner state

⇒ **Need high quality $Nb_3Sn$ films!**

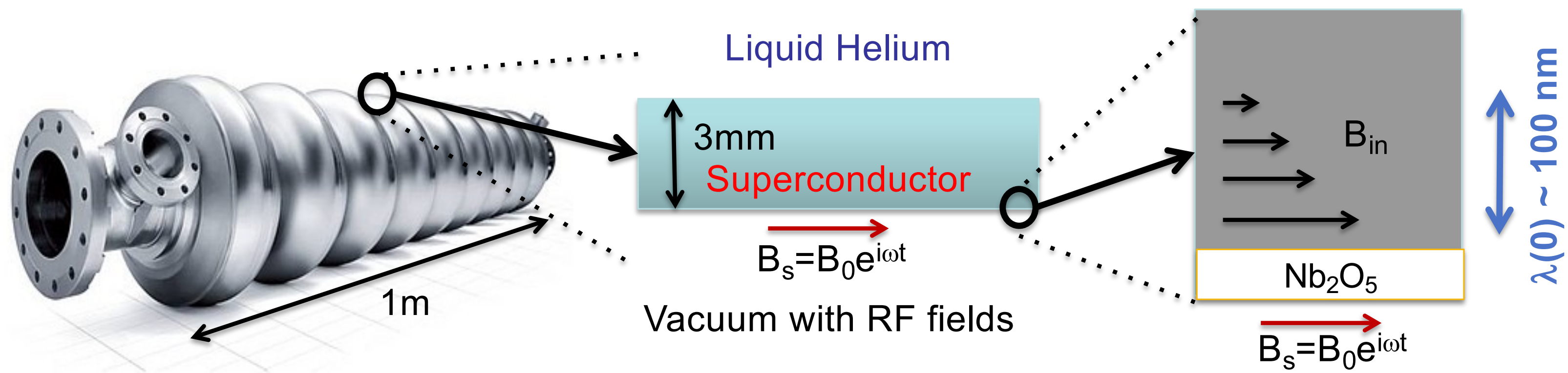


# Penetration Layer… Only Thin Films Needed

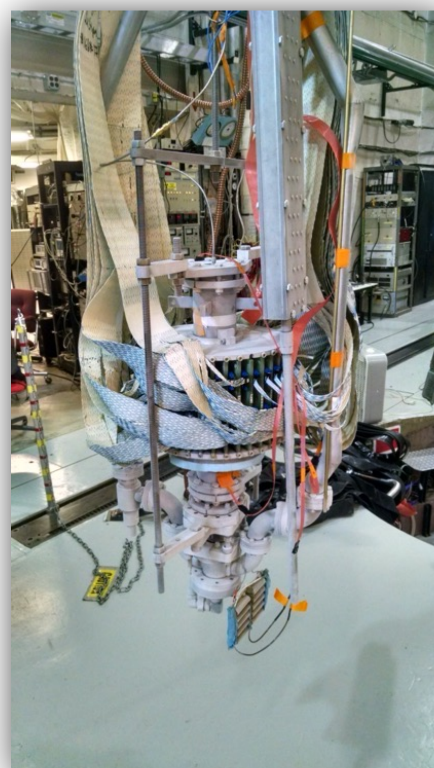



**$Nb_3Sn$ is brittle and has poor thermal conductivity**

- **Only films possible for SRF**
- **OK since RF field only penetrates ~100 nm, but more complex fabrication required**

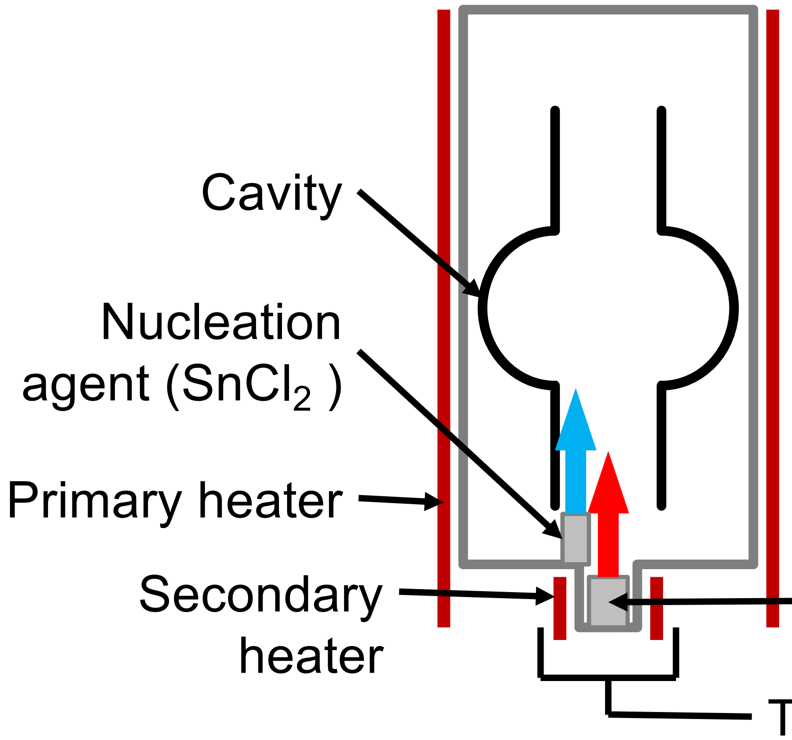


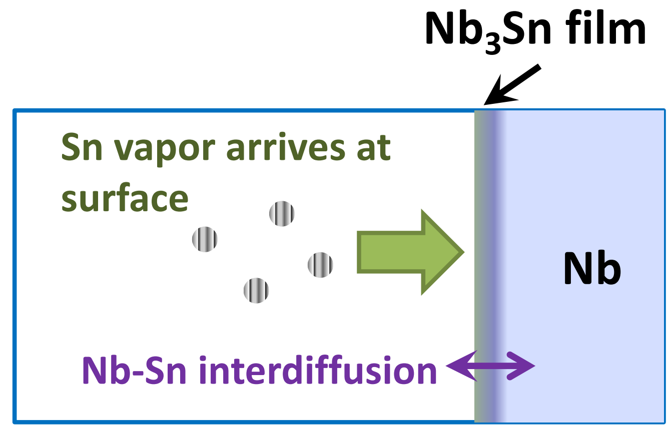
# Cornell $Nb_3Sn$ Program



**Started 2011, funded by DOE.**

# Tin Vapor Diffusion Growth of $Nb_3Sn$

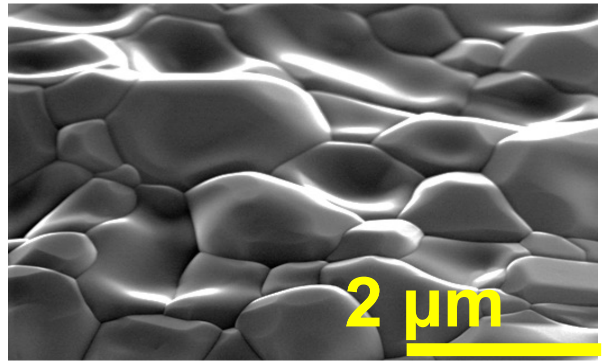




<u>"Wuppertal" configuration</u>, i.e., with secondary heater for the tin source
Optimized nucleation and temperature profile

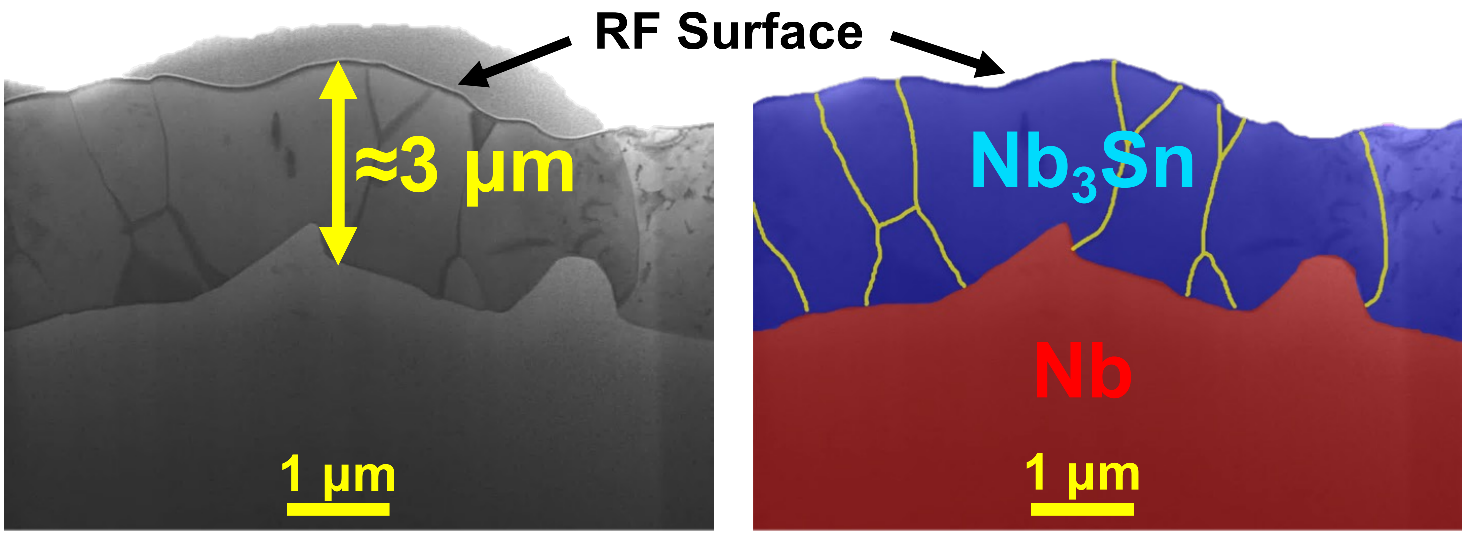
S. Posen and M. Liepe, Phys. Rev. ST Accel. Beams 15, 112001 (2014).

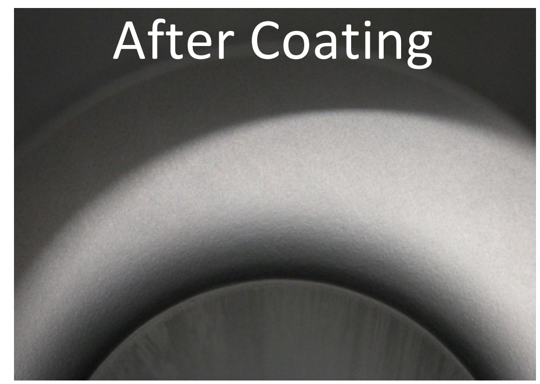
# $Nb_3Sn$ Coatings

**$Nb_3Sn$ forms a polycrystalline layer on the surface of the niobium**

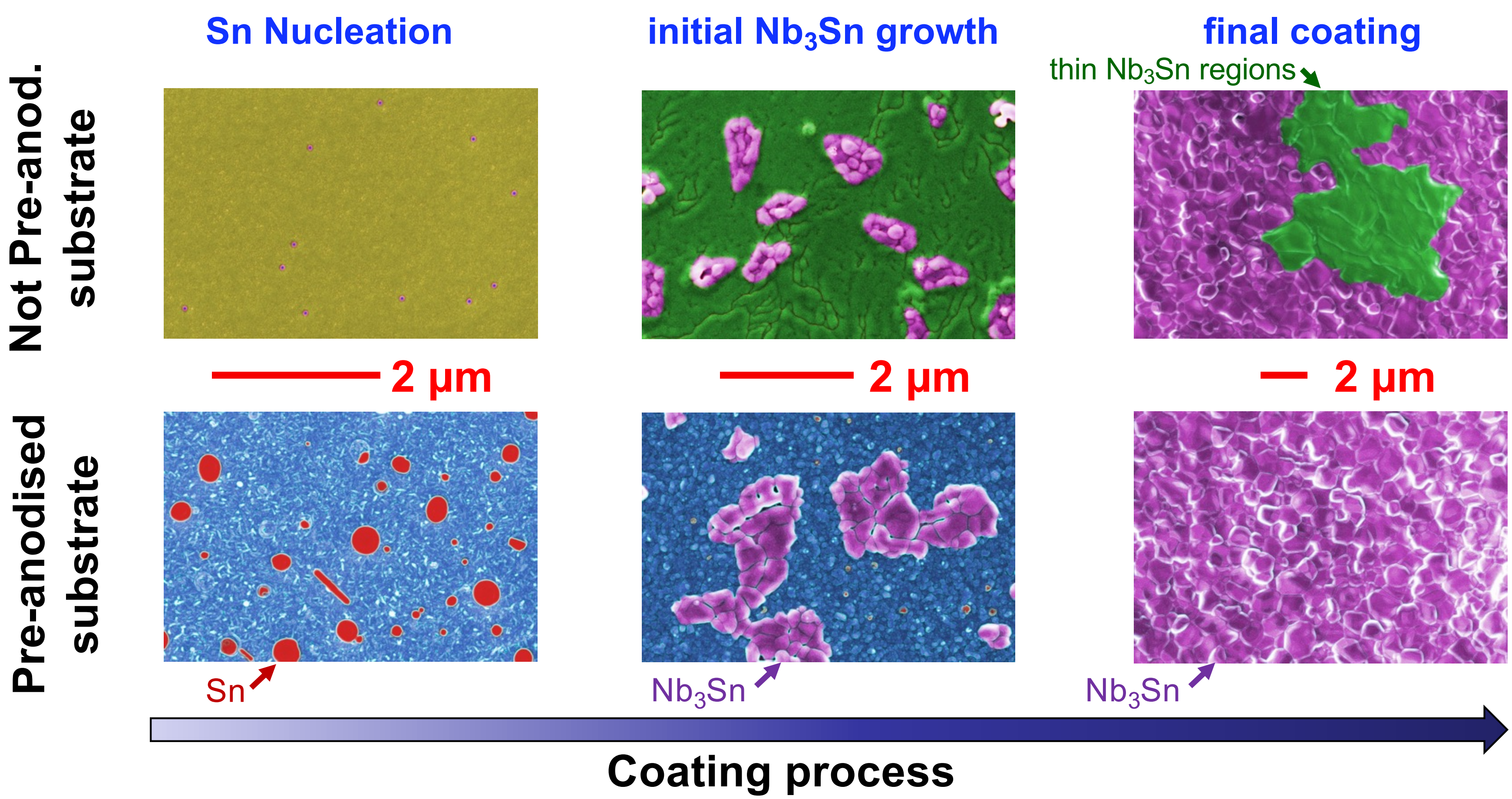




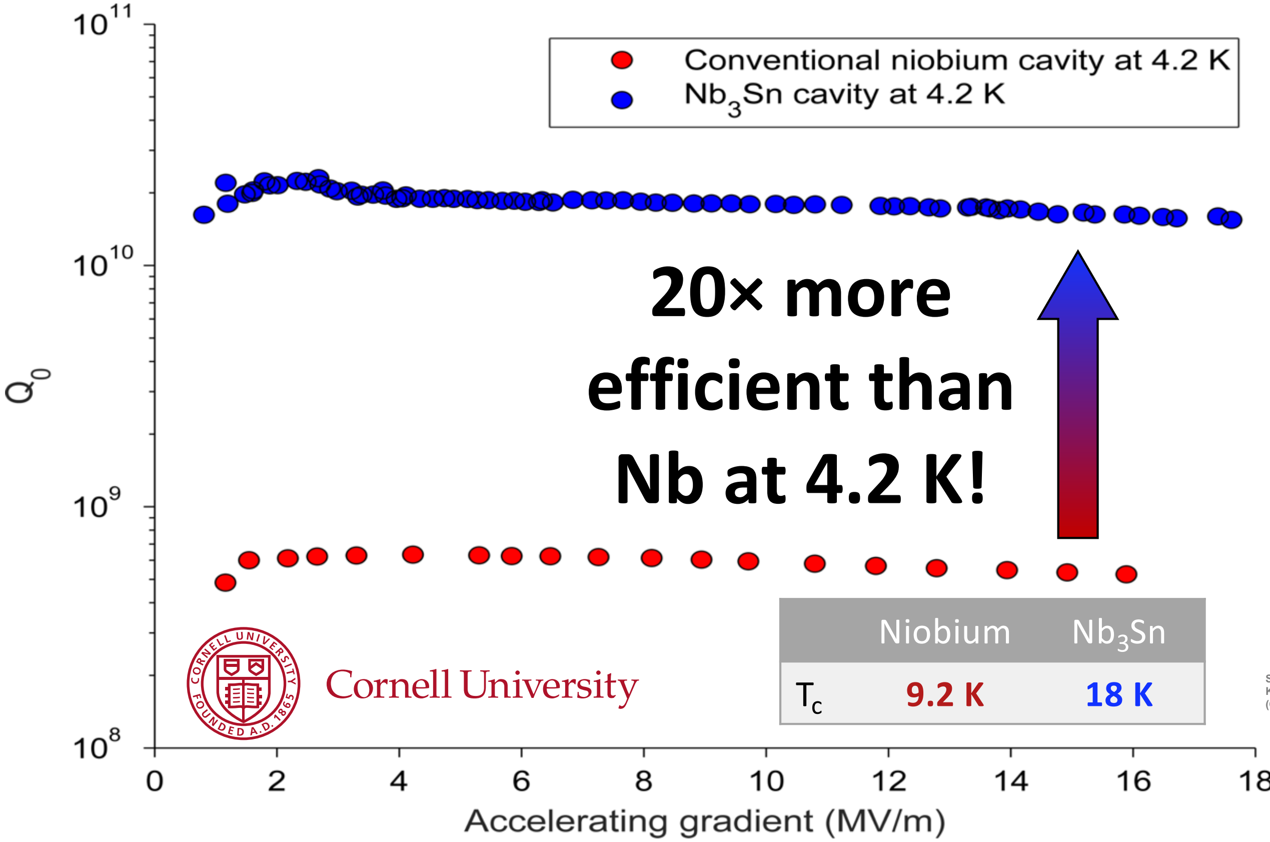


# $Nb_3Sn$ Film Growth Study

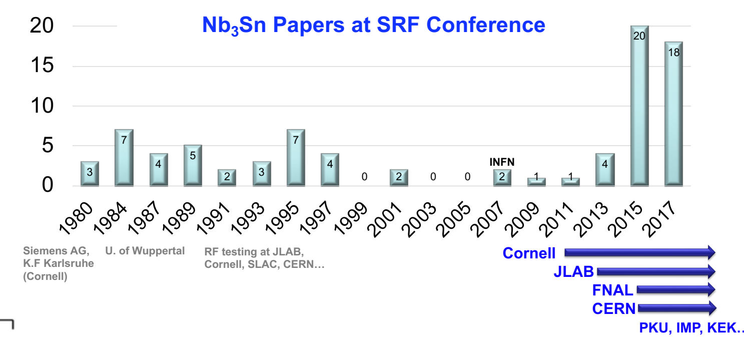


# Cornell 1.3 GHz $Nb_3Sn$ Cavity Breakthrough 4.2K Performance



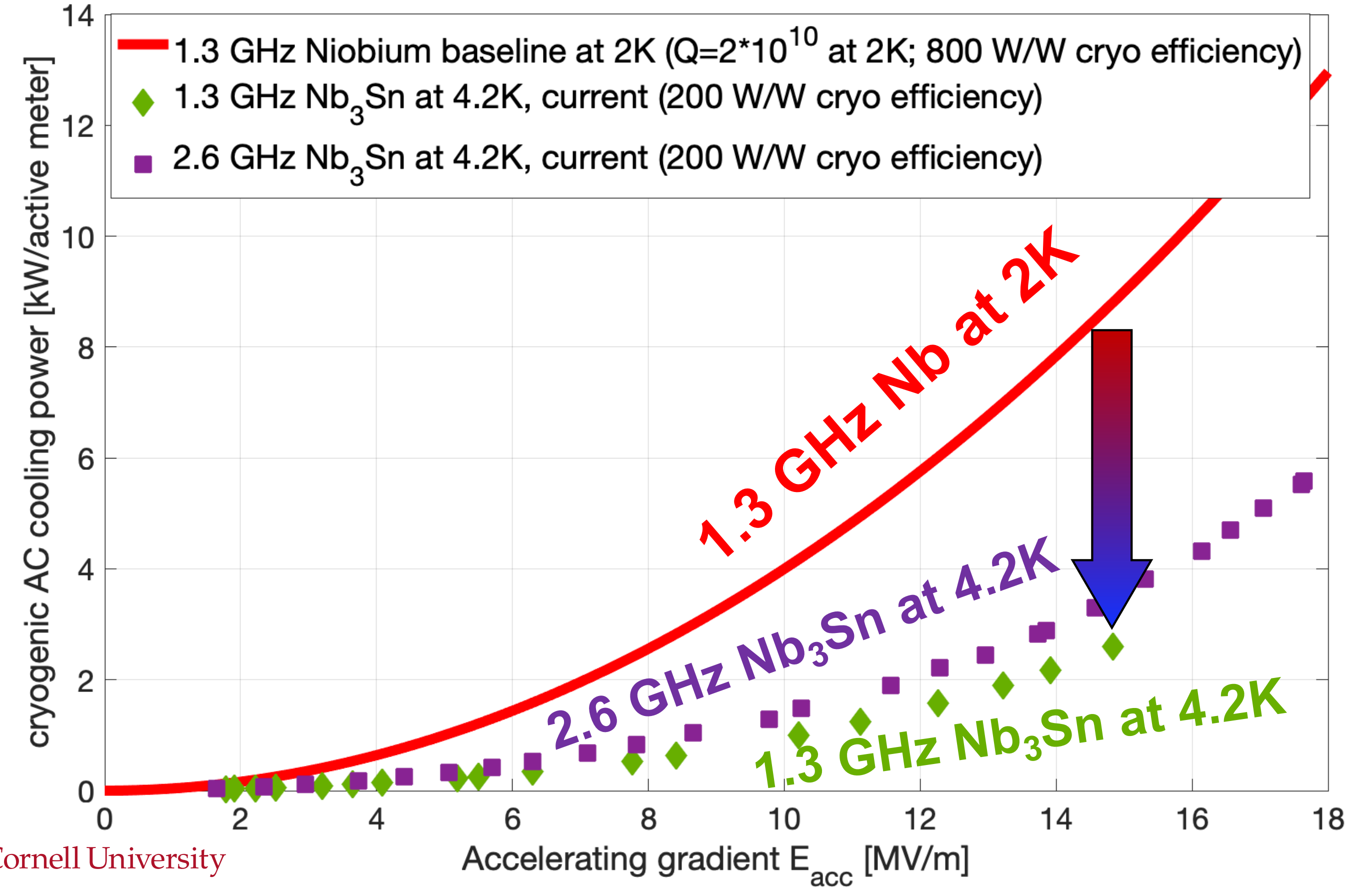

| | Niobium | $Nb_3Sn$ |
|---|---|---|
| $T_c$ | 9.2 K | 18 K |

**First non-Nb accelerator SRF cavities *ever* that outperformed Nb at usable gradients!**




S. Posen and M. Liepe, Phys. Rev. ST Accel. Beams 15, 112001 (2014).

# Drastic Reduction in Cryogenic Losses

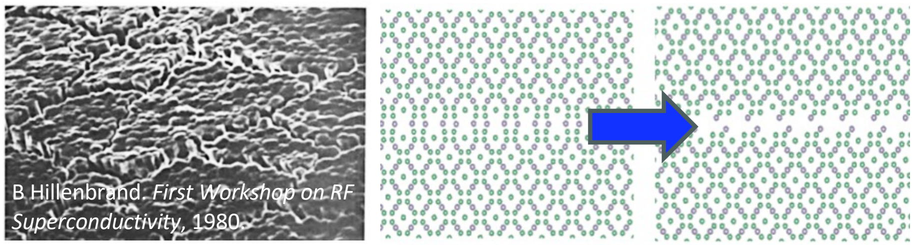



- **>60% reduction in AC cooling power**
- **Simplified cryo system (4.2K vs 2K operation)**

Cornell University

# $Nb_3Sn$ SRF: Technical Challenges

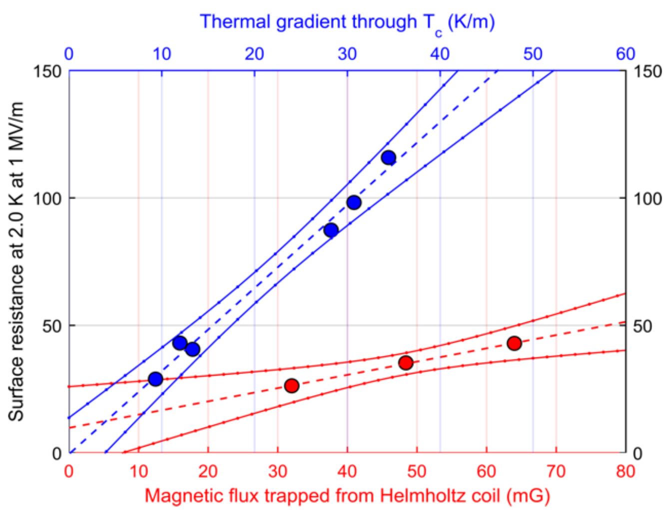
- **$Nb_3Sn$ is a brittle material**




⇒ Mechanical stress can result in cracks in $Nb_3Sn$ films

⇒ Need updated / improved handling and cavity tuning protocols

- **$Nb_3Sn$/Nb** ($Nb_3Sn$/Cu) **bimetallic**



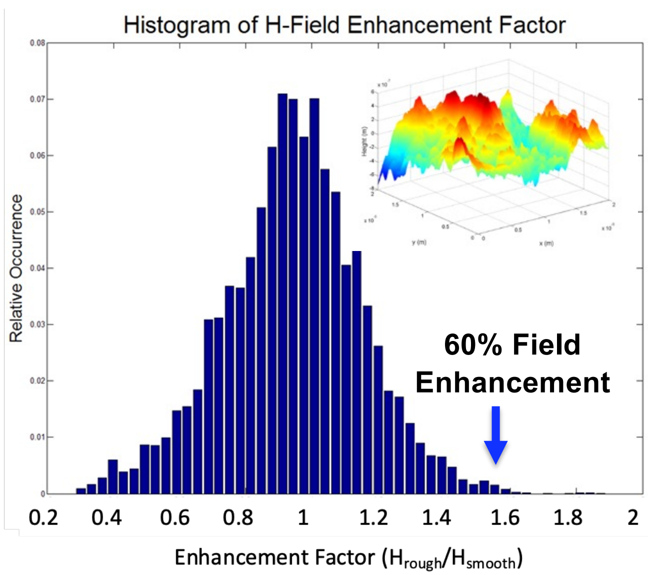

⇒ Thermoelectric currents can result in trapped magnetic flux and thus higher RF losses

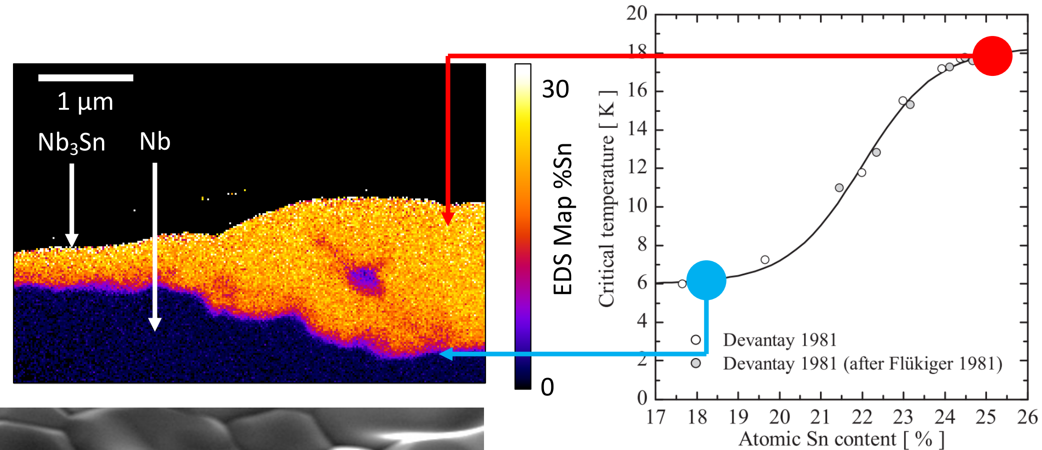
⇒ Need slow cool down with small spatial thermal gradients across cavity

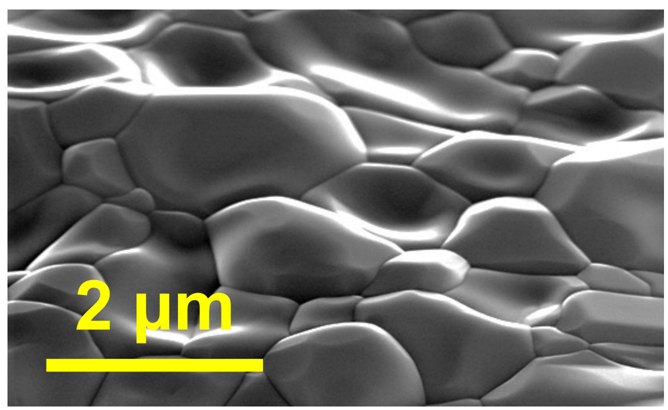
# $Nb_3Sn$ Film Growth Challenges

## Surface roughness

- Increases a local magnetic field
- Early flux entry / quench



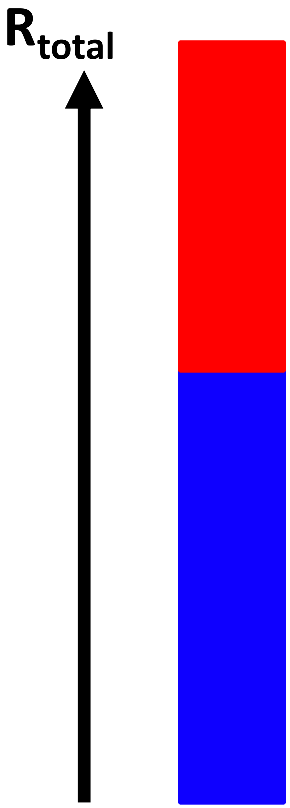




**$Nb_3Sn$ forms a polycrystalline layer on the surface of the niobium**

## Nonuniformity

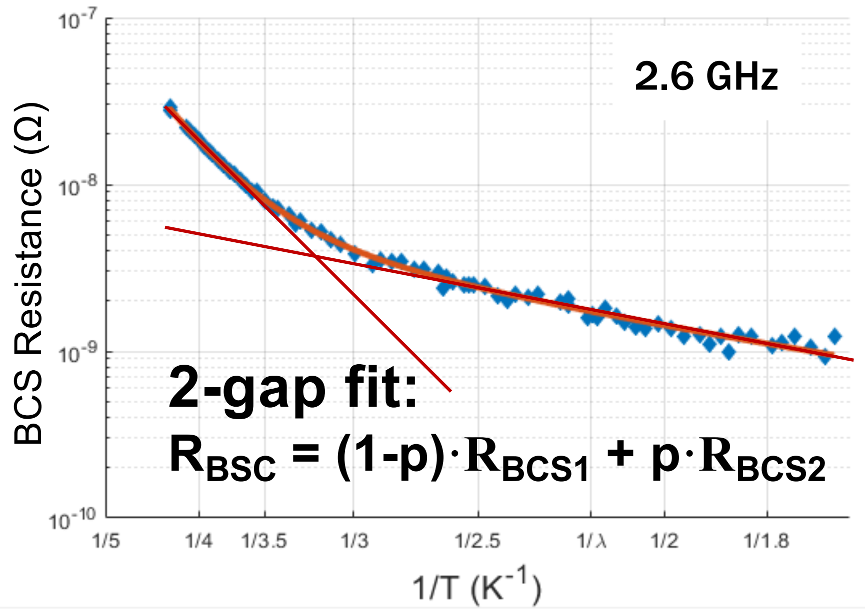
- Sn rich / poor areas have much lower Tc
- Variation in film thickness

# Sn Rich / Poor Areas




Two important contributions to surface resistance at 4.2K:

- $R_{res}$ from trapped flux
  => Improve magnetic shielding and cool down uniformity
- $R_{BCS}$ (T)

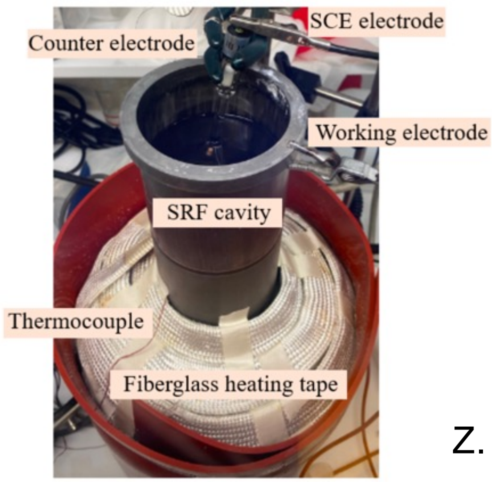


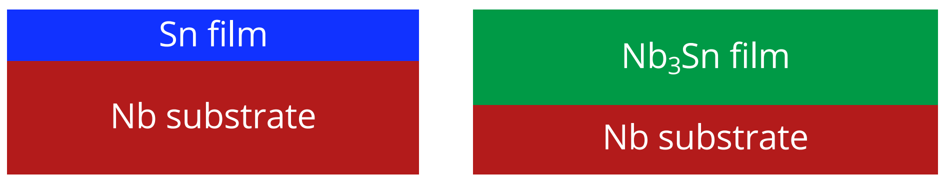

- At higher temperatures (≳4K): "normal" $Nb_3Sn$ gap dominates losses
- At lower temperatures (≲3K): second, small gap dominates losses
- Ratio $p \sim 10^{-5}$

# Cornell $Nb_3Sn$ Electroplating Achievement

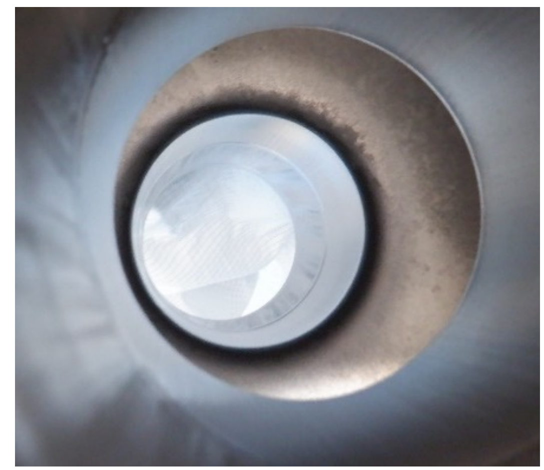
**Electroplating-based pre-deposition of Sn onto Nb**

**Thermal Conversion to stoichiometric $Nb_3Sn$**



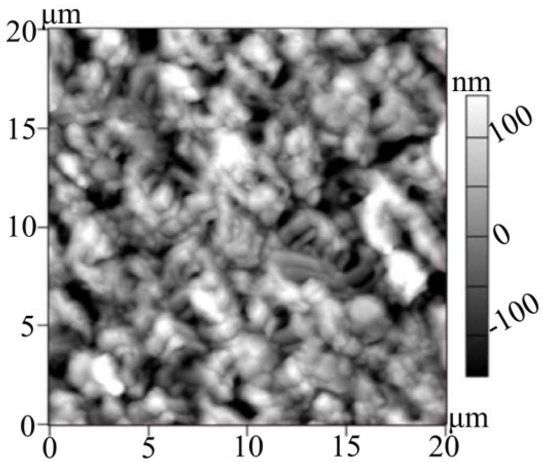

Z. Sun, et al., Supercond. Sci. Technol. 36 115003 (2023).

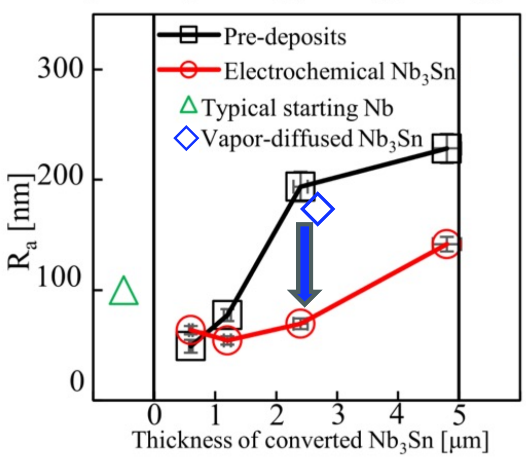


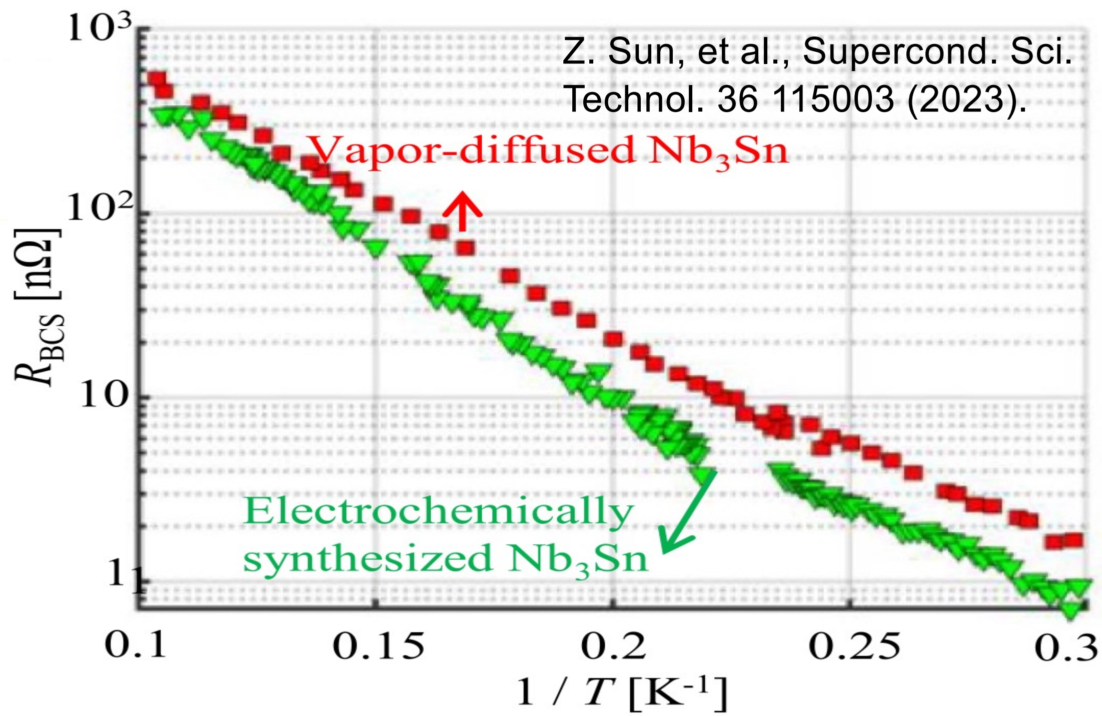
**Advantages:**

- Promotes **uniform** distribution of nucleation (reduced **surface roughness**)
- Provides **sufficient Sn supply** in critical times
- **Easy scale-up** to full accelerator cavity size

# Cornell $Nb_3Sn$ Electroplating $Nb_3Sn$ Growth: Performance



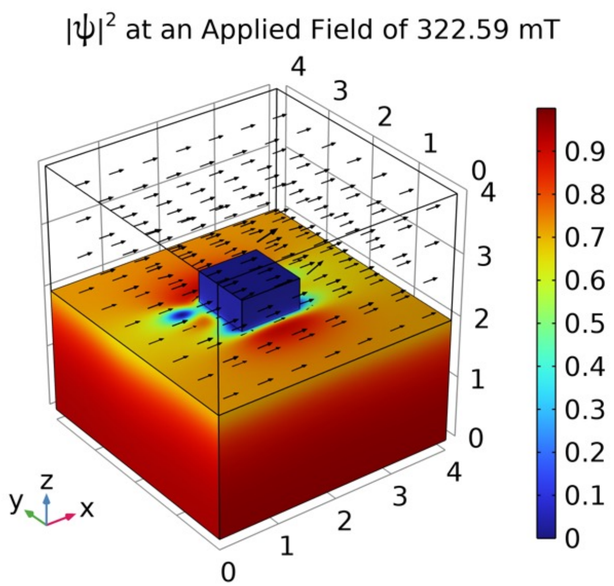



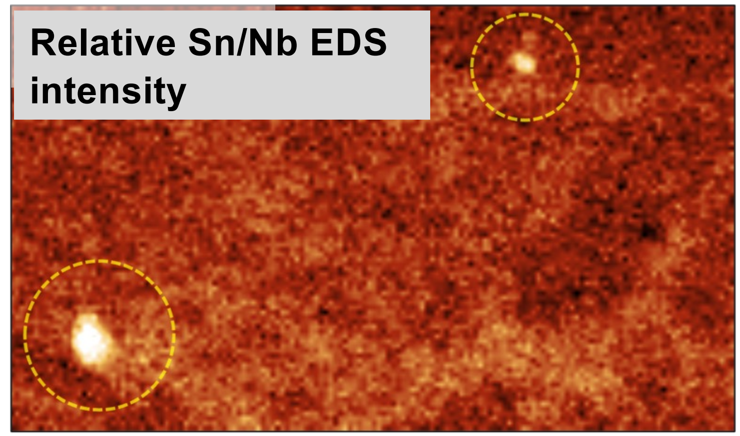




- **~2x lower surface roughness**
- **~2x lower BCS surface resistance**

# Impact of $Nb_3Sn$ Morphologies on SRF Performance

Example: **Impact of Sn-rich islands on vortex entry field**

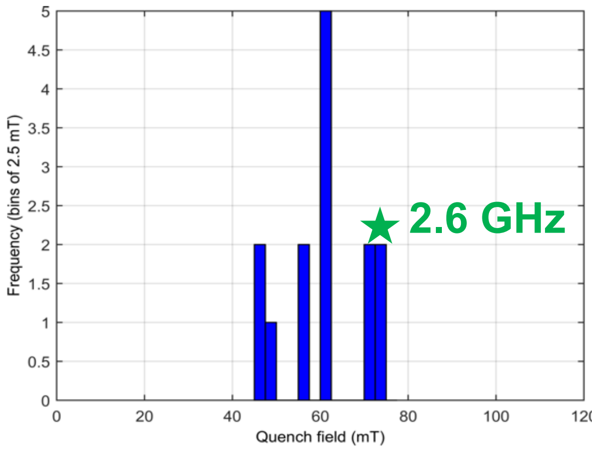


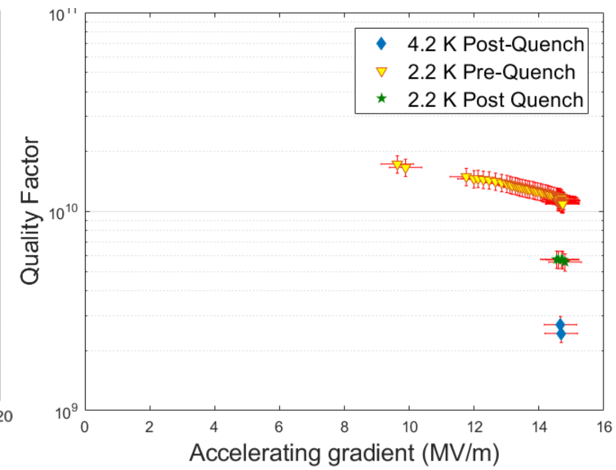



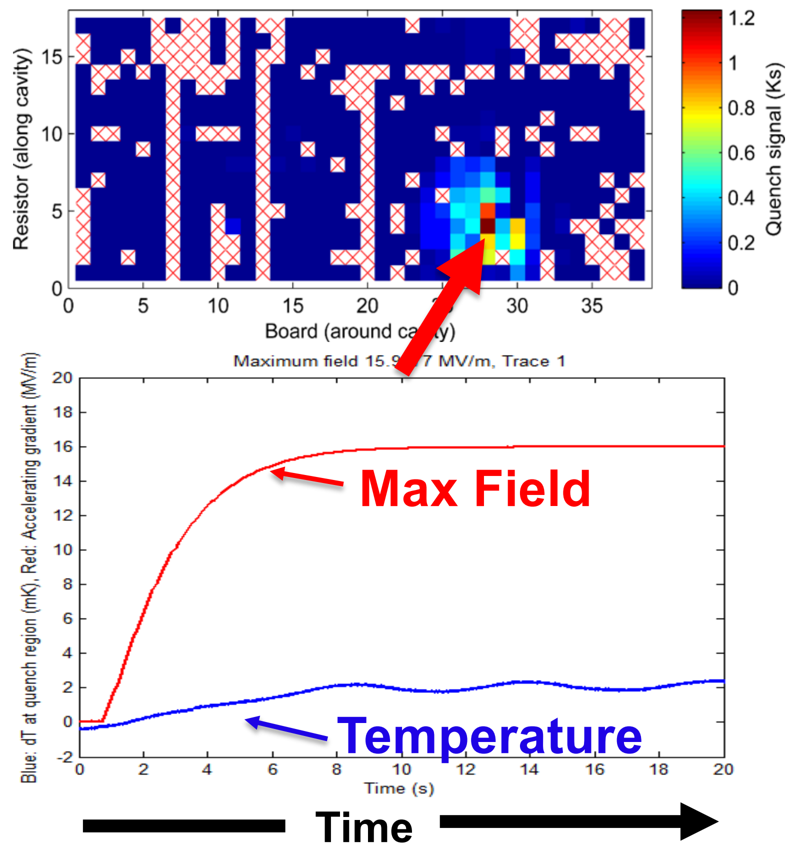

| | Partially Embedded Sn Island | | Fully Embedded Sn Island | |
|---|---|---|---|---|
| **Cubic Island Side Length (nm)** | $\mu_0 H_{vort}$ (mT) | % decrease from $H_{sh}$ | $\mu_0 H_{vort}$ (mT) | % decrease from $H_{sh}$ |
| **50** | 343.4 | **19.2%** | 313.65 | **26.2%** |
| **100** | 322.59 | **24.2%** | 274.55 | **35.4%** |
| **200** | 300.9 | **29.2%** | 228.65 | **46.2%** |

S.A. Willson, A. Harbick, *et al., PHYSICAL REVIEW RESEARCH 6, 043133 (2024)*

# Signature of Quench in $Nb_3Sn$



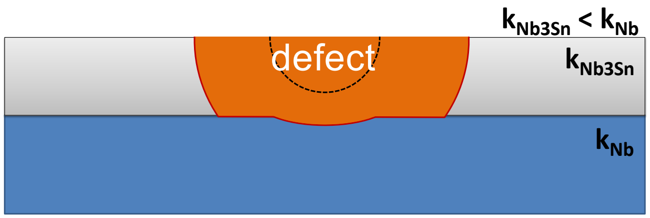



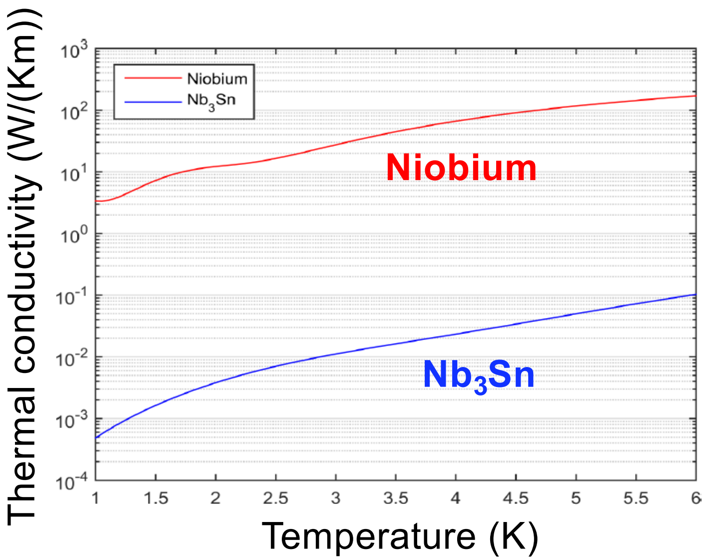




- **Weak dependence on RF frequency**
- **So significant change vs T** (1.7K to 4.2K)
- **$Nb_3Sn$ cavity field limited by localized defects**
- **Just below quench: Quantized jumps in losses**
  - **Vortex entry?**

# Thinner $Nb_3Sn$ Coatings

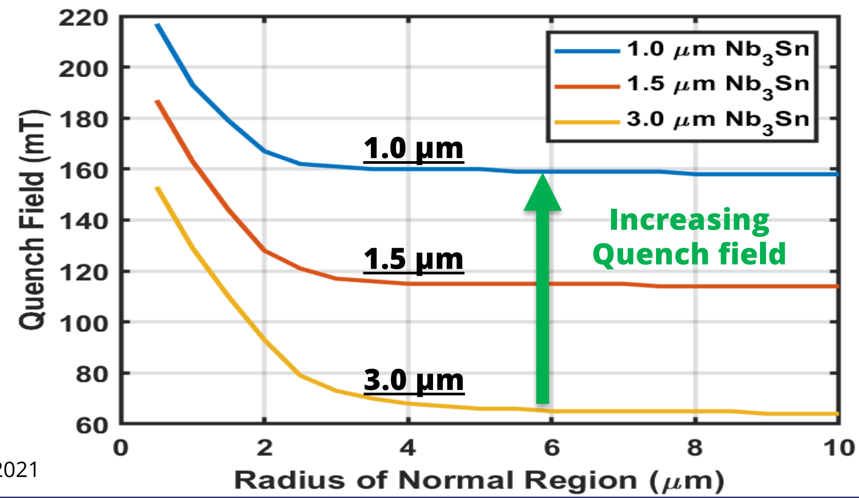
**Maximum $Nb_3Sn$ cavity fields currently limited by small, localized defects.**




R. D. Porter, Ph.D. thesis, Phys, Dept., Cornell University, Ithaca, United States, 2021

- **$Nb_3Sn$ has very poor thermal conductivity.**
  - ⇒ **Nb thermally stabilizes $Nb_3Sn$ and delays thermal runaway (quench)**
  - ⇒ **Thinner $Nb_3Sn$ layers lead to higher quench fields for same defect (but can't make them too thin)**
  - ⇒ **Challenge is to achieve uniform thin films**




**Copper substrate could improve thermal stability further.**

# Smale-Scale Applications of SRF Technology?

Applications for small-scale operations:

- **Energy and environment**
  - Sterilizing waste water, sludge, medical waste
  - Flue gas treatment
  - Remediation of contaminated soil
  - Asphalt treatments (durability)
- **Medicine**
  - Radioisotope production
- **Security & defense**
  - Cargo inspection
- **Industry**
  - Producing biofuel
  - Curing carbon fiber composites
- **… and many more!**

**Typical beam parameters**

- Moderate Energy: 1 – 10 MeV
- High Current: ≥ 100 mA
- High Avg. Power: ≥ 1 MW

→ High **average current & power** can be better obtained with **superconducting cavities**

→ **Continuous-wave (CW) operation** enables higher throughput

U.S. DOE Report, "Accelerators for America's Future"
U.S. DOE Report, "Workshop on Energy and Environmental Applications of Accelerators"

# But: Helium Requirements

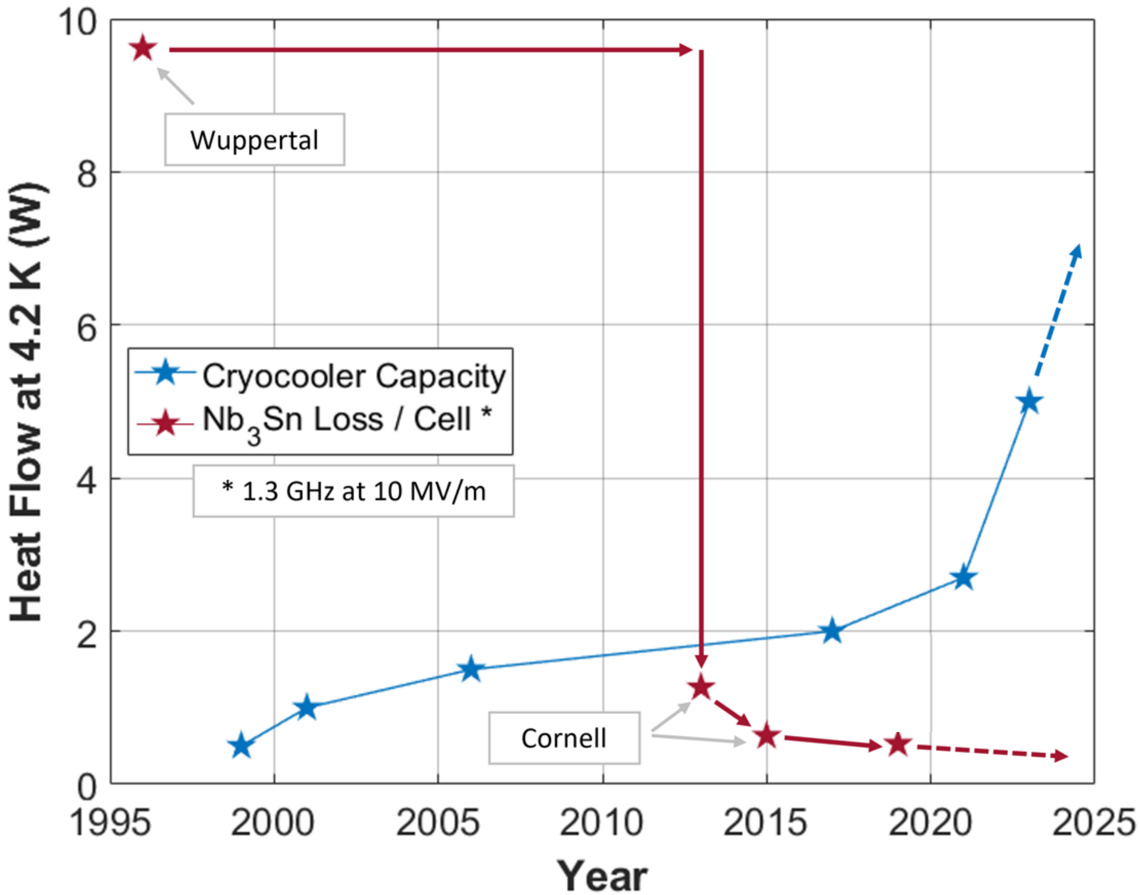
**Why hasn't this been done already?**

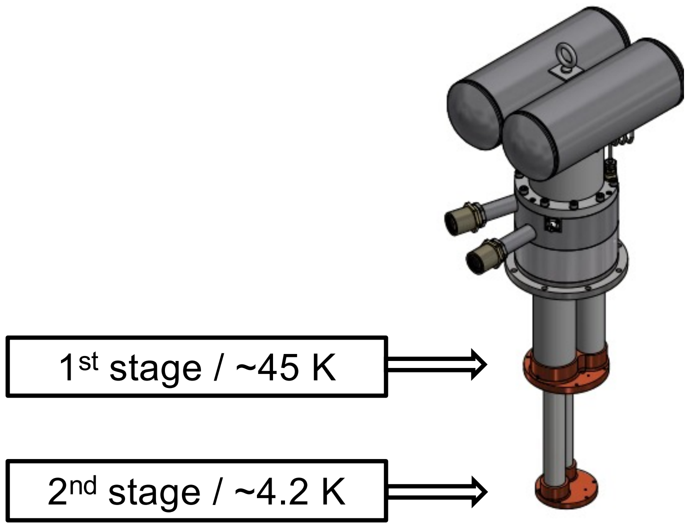
Current helium infrastructure requirements for 2K Nb of a single cavity (Cornell SRF Lab example):




Helium system requirements for operating small-scale SRF accelerators are **not feasible**!

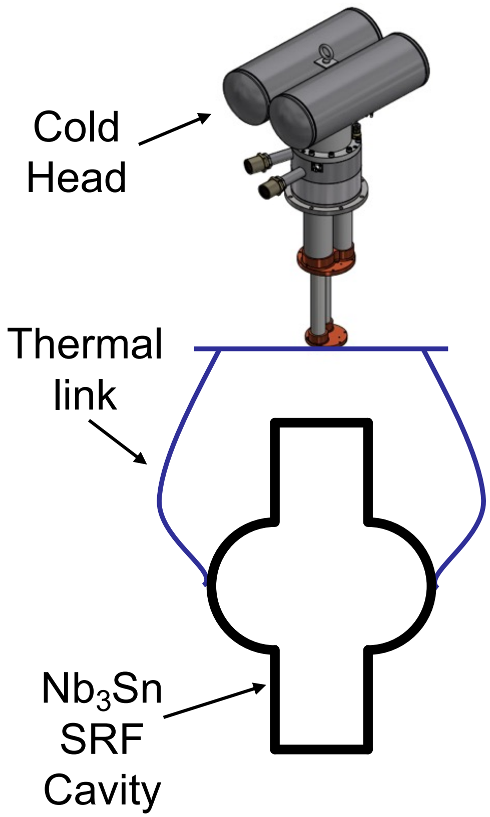
# 4K Cryocoolers Provide Sufficient Cooling for $Nb_3Sn$ SRF



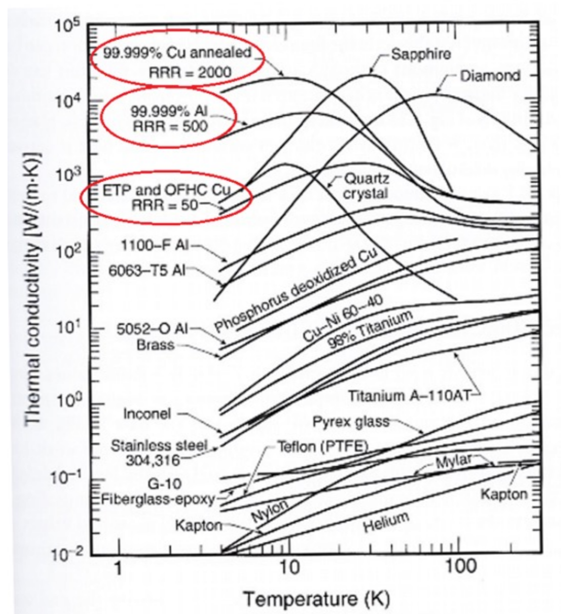




| | Niobium | $Nb_3Sn$ |
|---|---|---|
| 1-cell dissipated power (1.3 GHz, 4K, 10 MV/m) | ~20 W | <1 W |
| 9-cell dissipated power (1.3 GHz, 4K, 10 MV/m) | ~180 W | ~5 W |

# $Nb_3Sn$ Cavity 4K Operation in Conduction Cooling




**Challenge: Sufficient thermal link design, material choice, proper thermal contact**

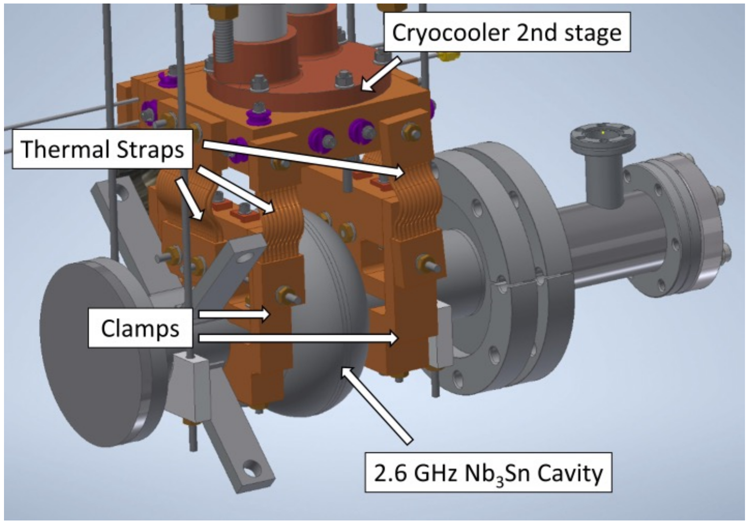


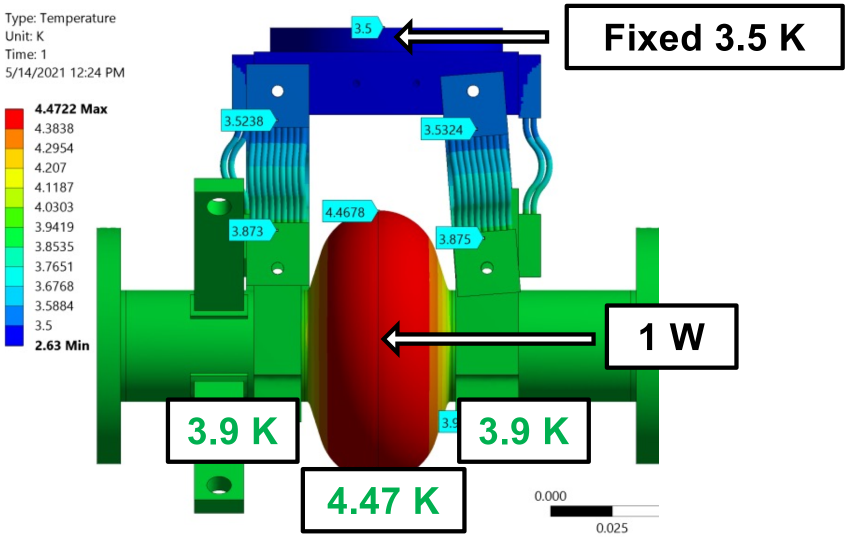

→ Ex: **1.5 W** heat load, **0.3 m** path length, target ΔT = **0.5 K**

| Material | k @ 4 K (W/(m*K)) | Required cross-section ($m^2$) |
|---|---|---|
| 316 SST | 0.3 | 3 |
| 1100 Al | 60 | 0.02 |
| OFHC Cu | 600 | 0.002 |

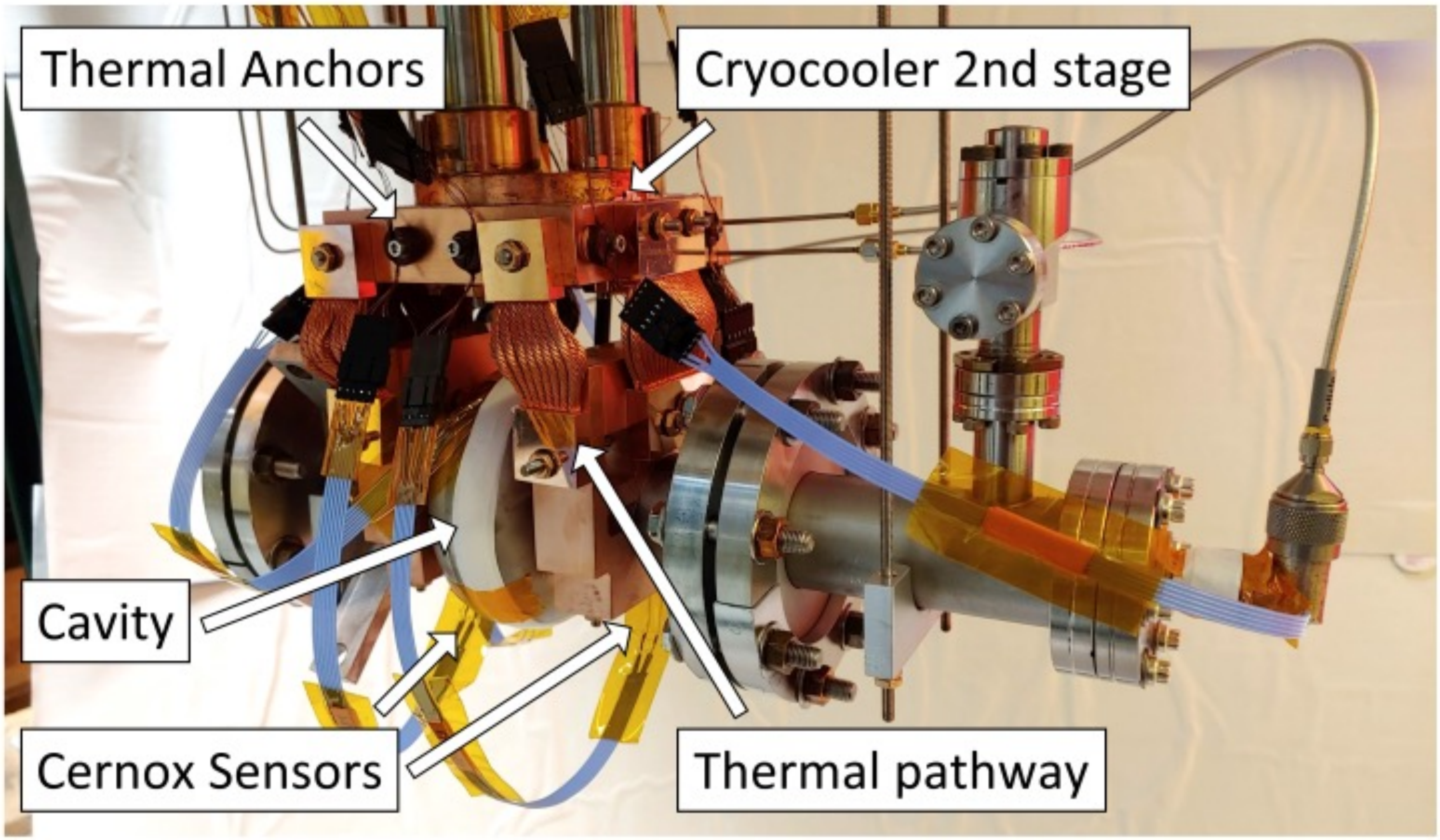
# Proof of Principle Setup: Design

- **Cavity**: 2.6 GHz $Nb_3Sn$ cavity **Cryocooler**: PT420-RM – 2.5W @ 4K
- **Thermal link design:**
  - High-purity copper clamps at beam tubes ⇒ Provides even cooling of cavity (critical for $Nb_3Sn$)
  - High-purity copper thermal straps ⇒ Provides flexibility and high thermal conductivity



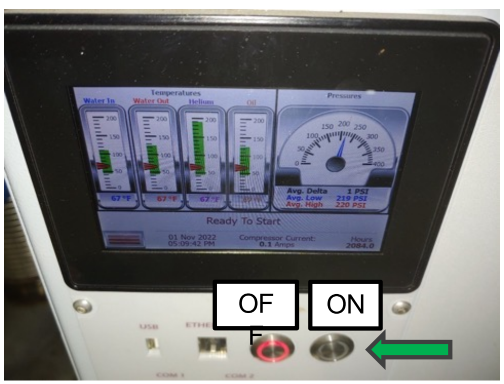
# Proof of Principle Setup: Assembly

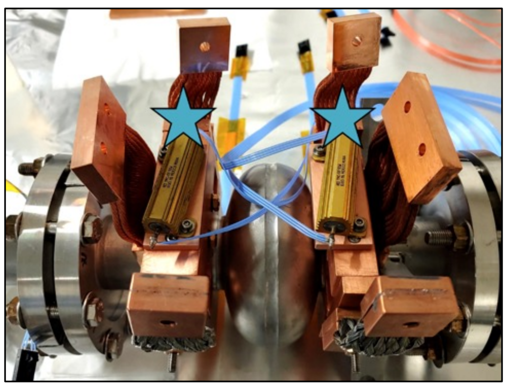


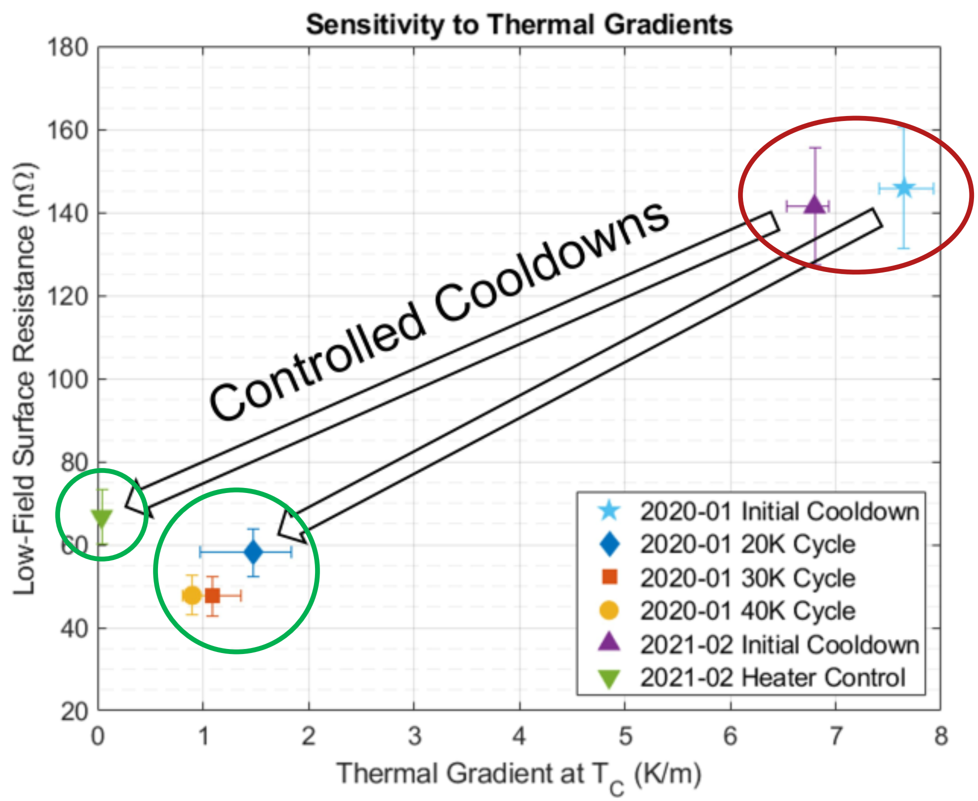

N. Stilin et al., 2023 Eng. Res. Express 5 025078 (2023).

# Proof of Principle Setup: Results (I)

- → Initial cooldowns were **completely uncontrolled**
  - → "Just press on" method
- → 20K/30K/40K cycles offer **intermediate control**
  - → Basic "off-on" method
- → Heaters offer **best control**
  - → Heaters located on copper clamps






N. Stilin et al., 2023 Eng. Res. Express 5 025078 (2023).

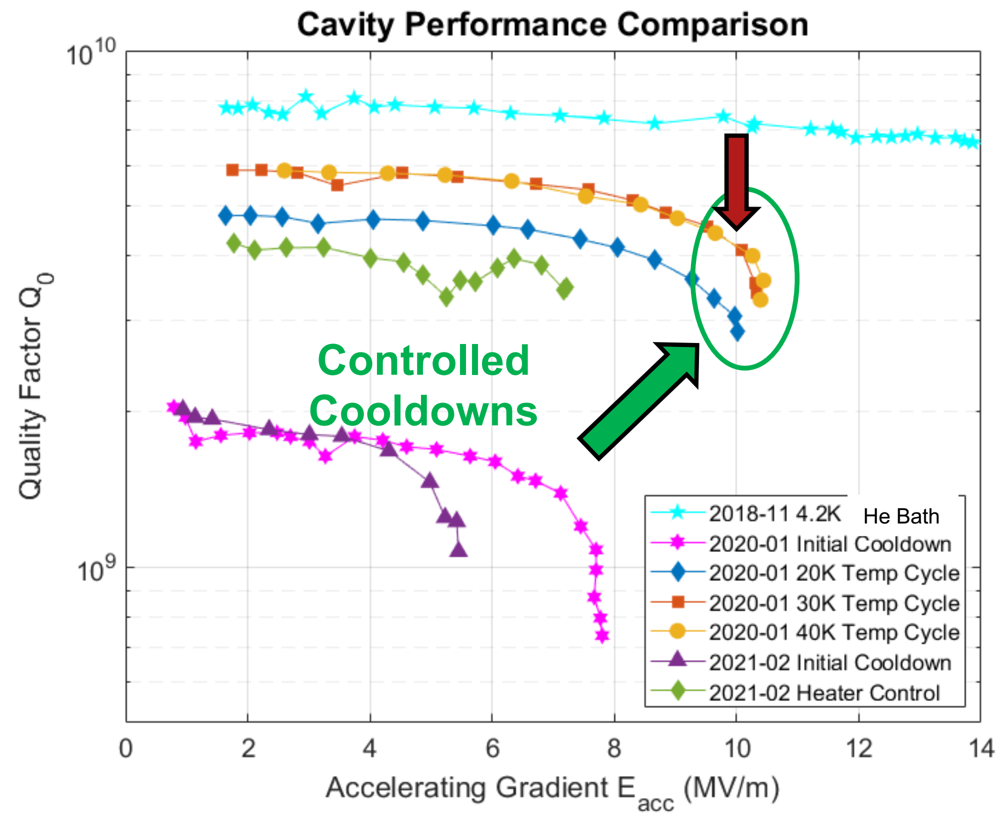
# Proof of Principle Setup: Results (II)

→ Stable RF operation at **10 MV/m**!

→ Best performance requires **controlled cooldown**

→ **Cavity $Q_0$** is **slightly reduced** compared to helium bath test

→ Likely due to higher ambient magnetic fields

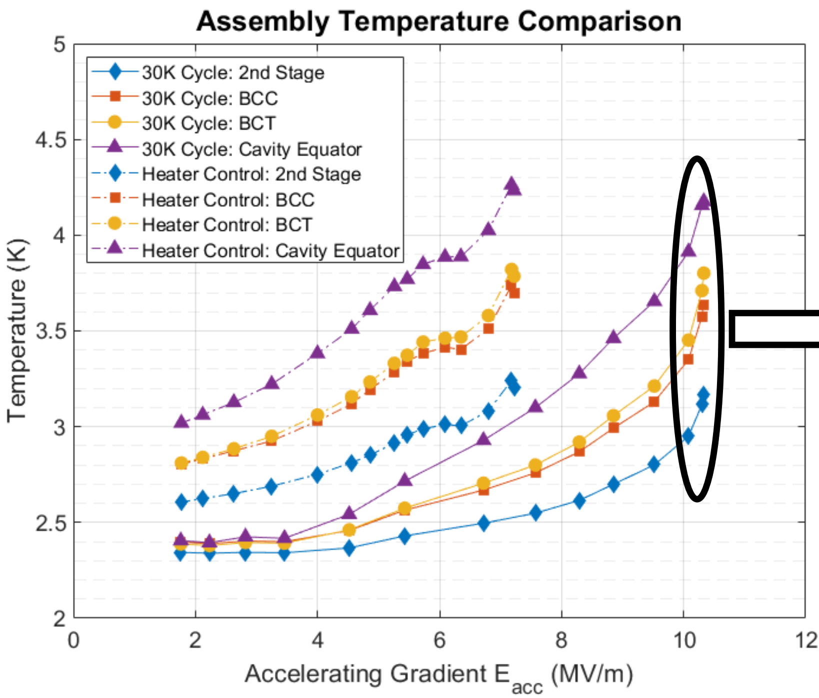


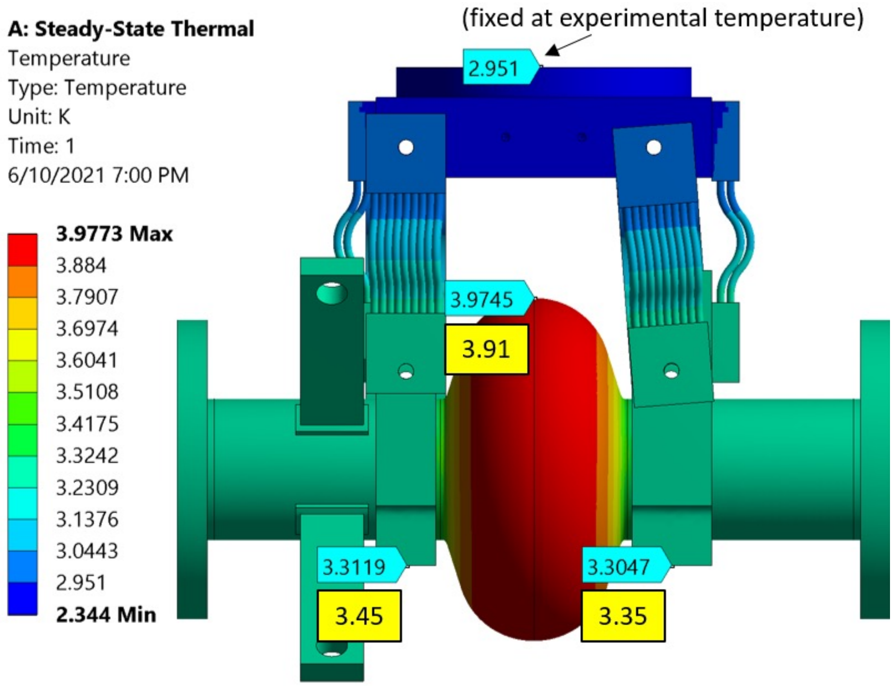

N. Stilin et al., 2023 Eng. Res. Express 5 025078 (2023).

# Proof of Principle Setup: Results (III)

→ Compare temperatures at **10 MV/m** to **simulation**

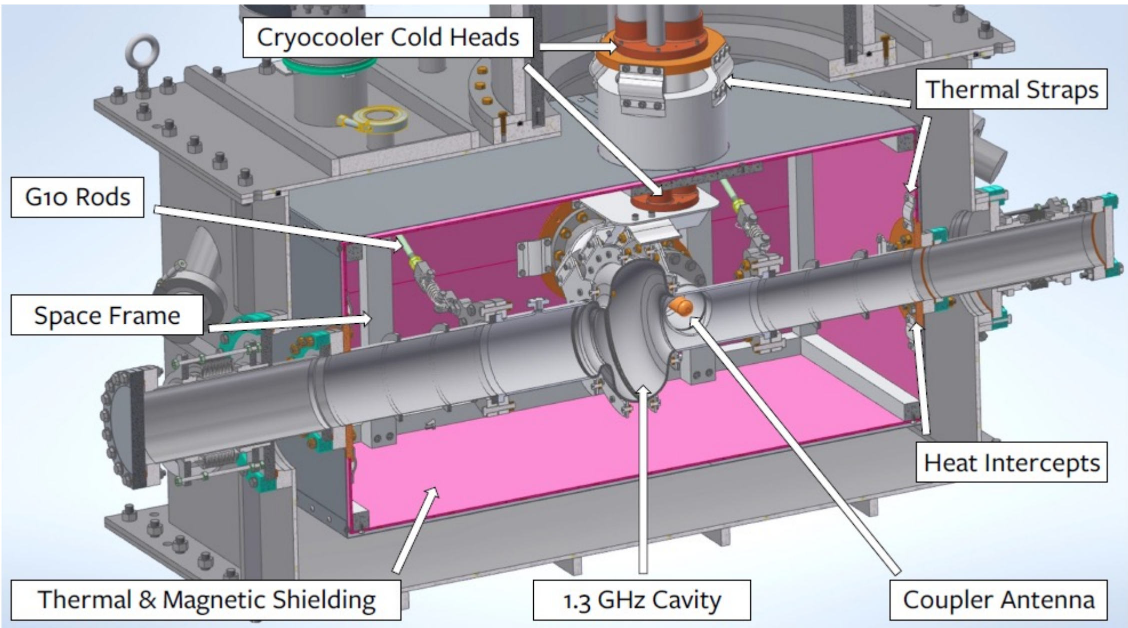
**Good agreement** between simulation and experiment!



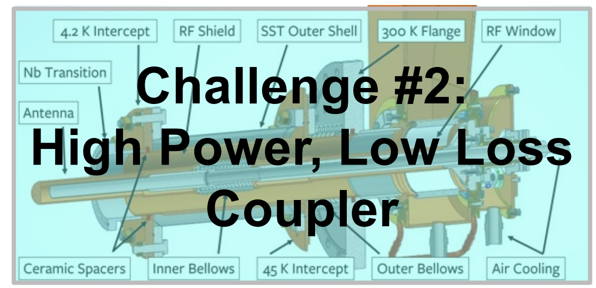



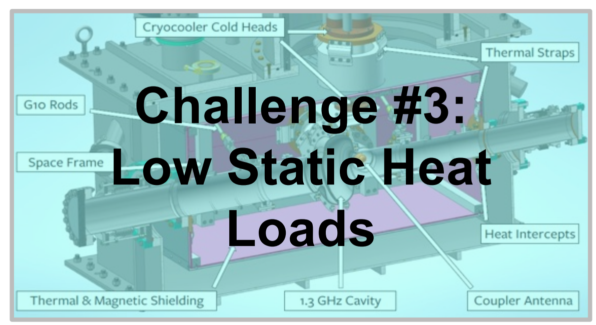

N. Stilin et al., 2023 Eng. Res. Express 5 025078 (2023).

# Cornell Conduction Cooled Cryomodule Prototype




| | |
|---|---|
| Energy Gain | 1 MeV |
| Beam Current | >100 mA |
| Average RF Power | >100 kW |

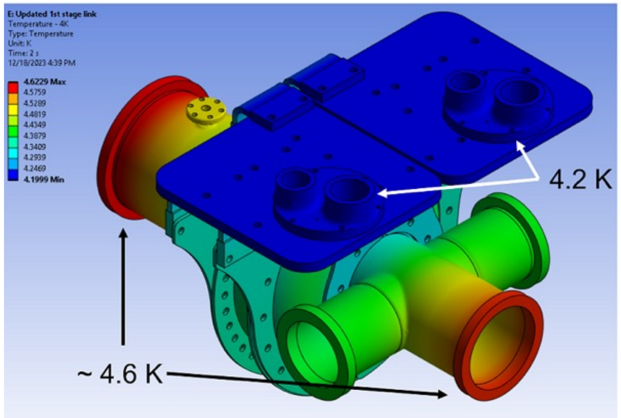



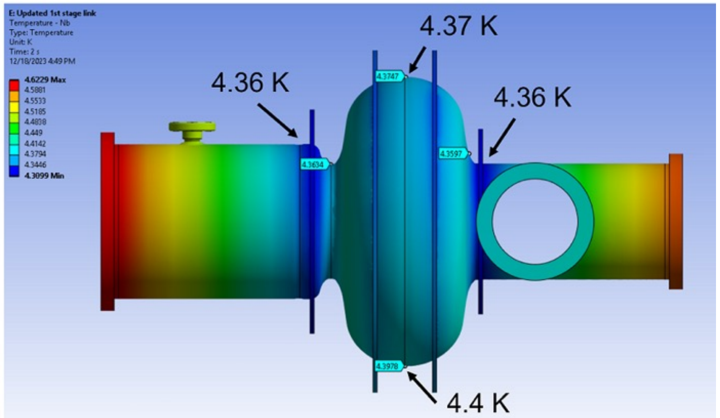



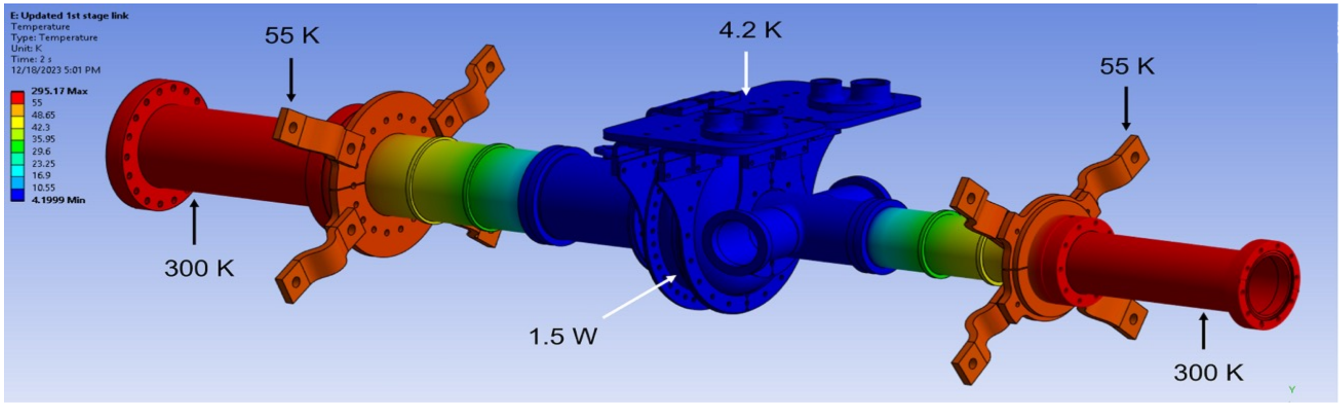
# Conduction Cooling Thermal Design

**Challenge: Effective conduction cooling**

- **4 heat intercept rings**
- **High purity Al, Cu**
- Thermal modeling (10 MV/m operation)
  - **Cryocooler 2nd stage to cavity: ΔT ≤ 0.2 K**
  - **Temperatures across cavity: ΔT < 0.05 K**



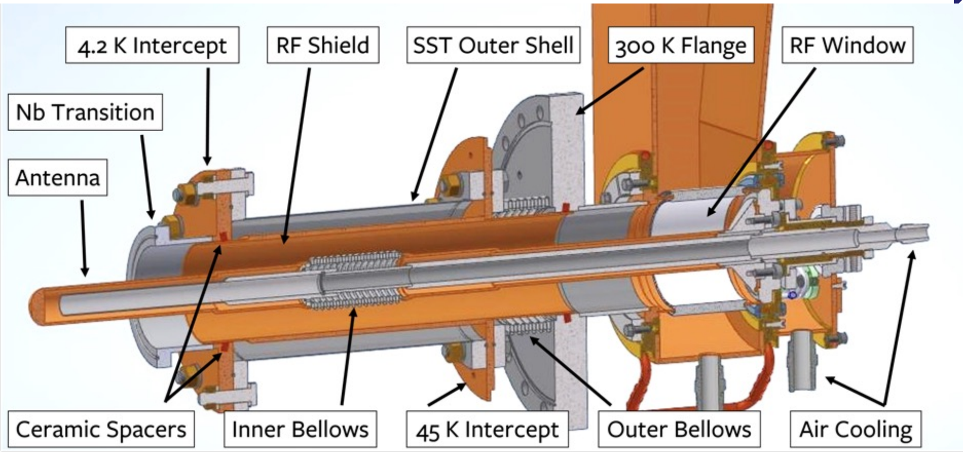



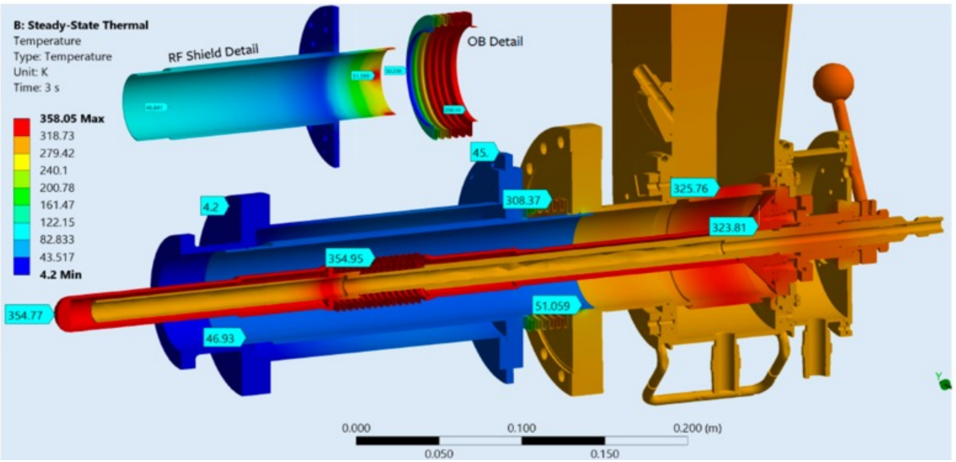



# High-Power Conduction-Cooled RF Coupler

**Challenge: High-power input coupler with low 4.2 K heat load**

- **100 kW** forward power with only ~ **1 W** lost at **4.2 K**
- **Quarter-wave transformer** to inner bellows optimizes RF behavior
- **RF shield** (inspired by Fermilab design) protects 4.2 K components from high RF fields
- Simulated heat loads for 100 kW:
  - **Total of 38 W at 45 K**
  - **Total of 1.1 W at 4.2 K**



# Conduction-Cooled Cryomodule Design

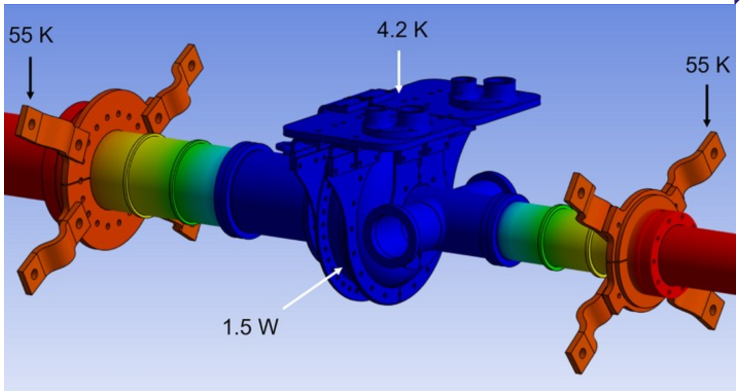
## Challenge: Minimize 4.2 K static heat load

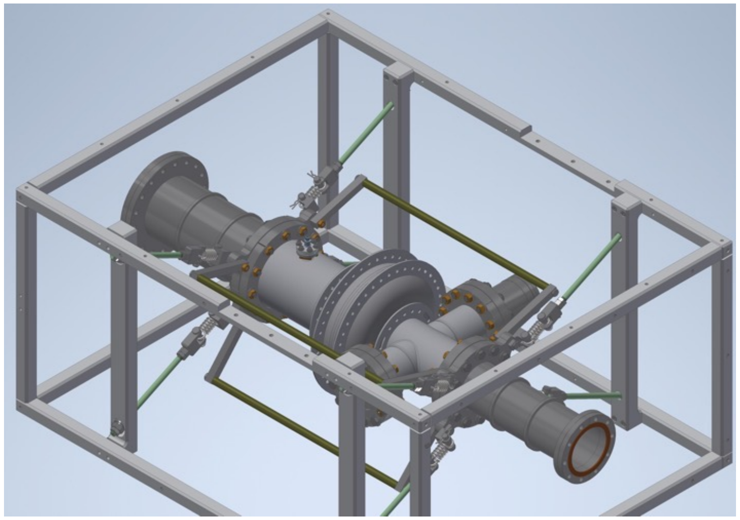
- **316 SST tubes** with 0.5 mm wall thickness
- **Space-frame** cavity support with G10 rods

**Heat Loads (W)**

| Source | 1st Stage | 2nd Stage |
|---|---|---|
| Cavity + Beam Tubes | 13.30 | 1.74 |
| Coupler* | 29.50 / 37.90 | 0.80 / 1.11 |
| G10 Support Rods | 0.34 | 0.02 |
| Thermal Radiation (est.) | 5.00 | 0.10 |
| All Sources (incl. 2x coupler) | 77.64 / **94.44** | 3.46 / **4.08** |
| Thermal Shield Model | 76.40 / **93.20** | |
| Cryocooler Limits | **110** | **4.15** |

* Coupler heat loads are for 50 kW / 100 kW operation.



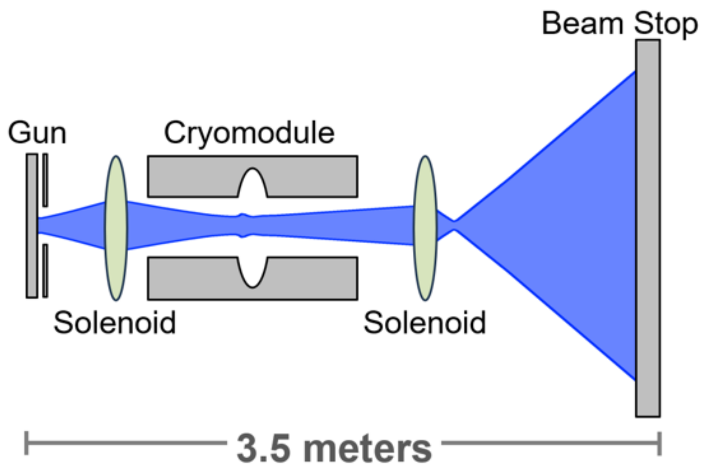



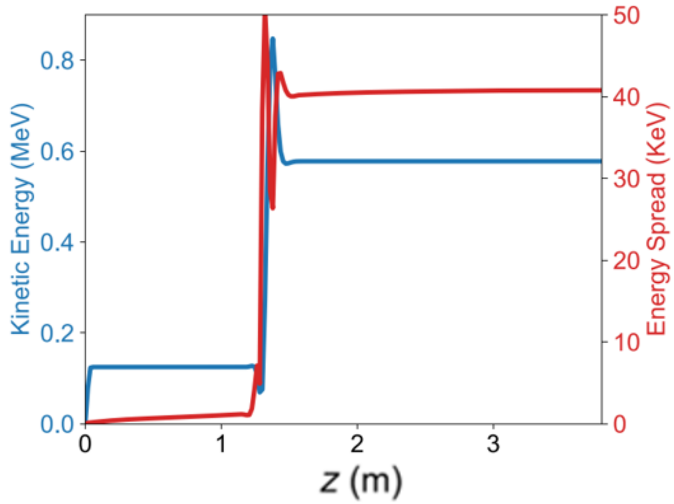
# Outlook: RF Testing and Beam Operation

**Next: SRF test of compact conduction cooled cryomodule**

**Soon: Installation in compact beam line for high-current testing**

- High current gun (>20 mA average beam current, cw operation)
- 20kW RF/beam power



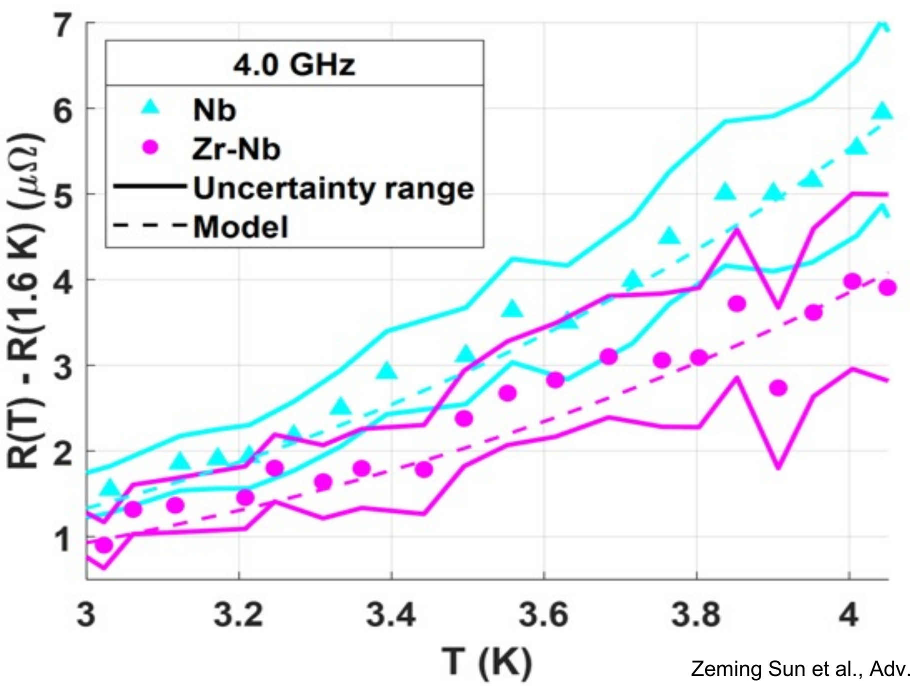

# Efficiency / Cost Frontier:

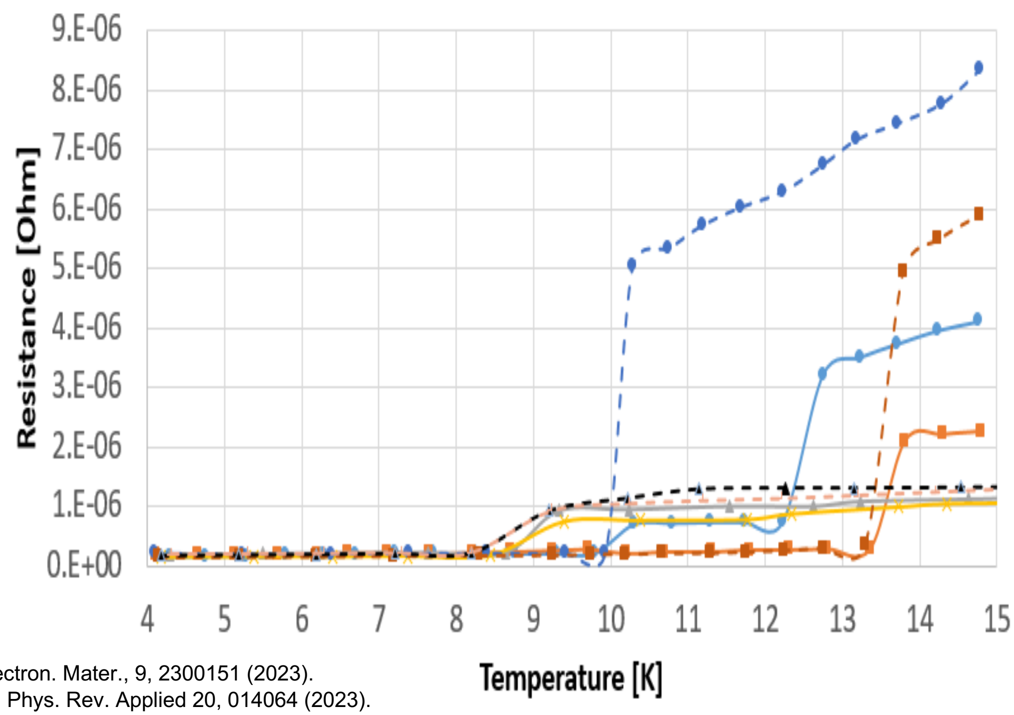
## Other Next-gen Materials

# Zirconium Alloying/Doping of Niobium

## Potential for $T_c$ and superheating field above Nb limits

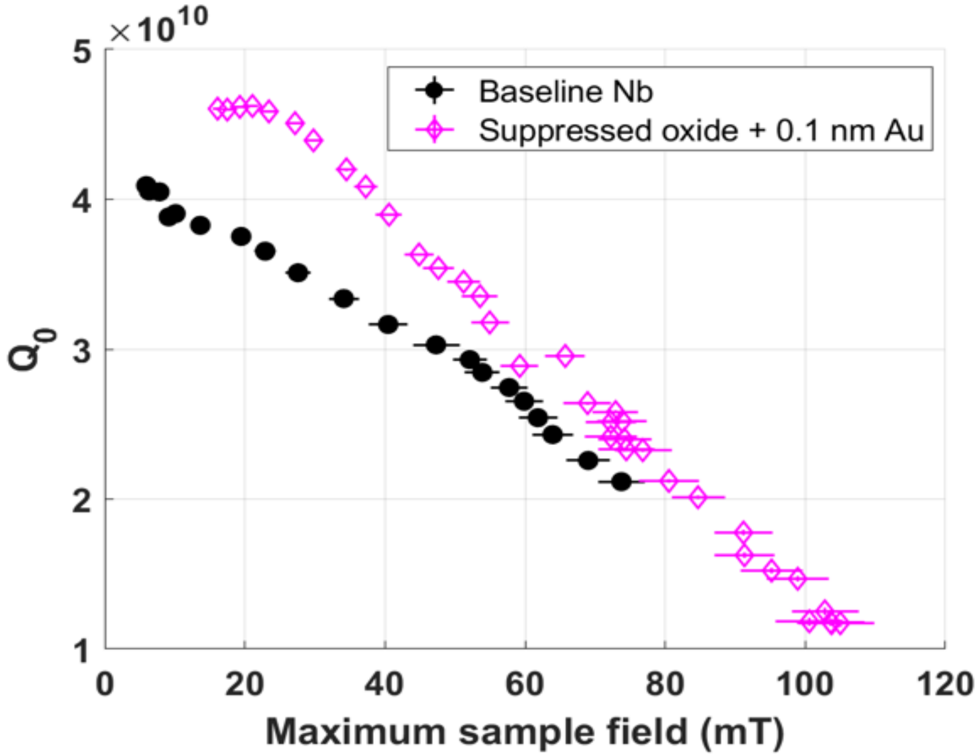
| | Niobium | Nb-Zr |
|---|---|---|
| Predicted critical Temperature $T_c$ | 9.2 K | 13 - 16 K |
| Predicted superheating field | 220 mT | >300 mT ? |




Zeming Sun et al., Adv. Electron. Mater., 9, 2300151 (2023).
Nathan S. Sitaraman et al., Phys. Rev. Applied 20, 014064 (2023).

# Thin Gold Caping Layer on Niobium

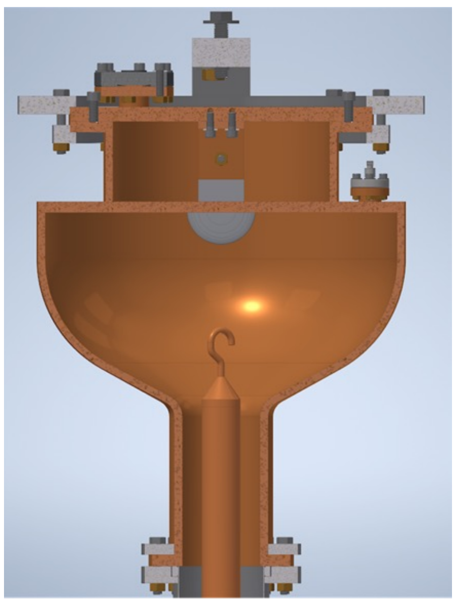



- Suppression of lossy surface oxide?
  - Of interest also for QIS
- Potential of optimized proximity-coupled surface layer to reduce total surface resistance?

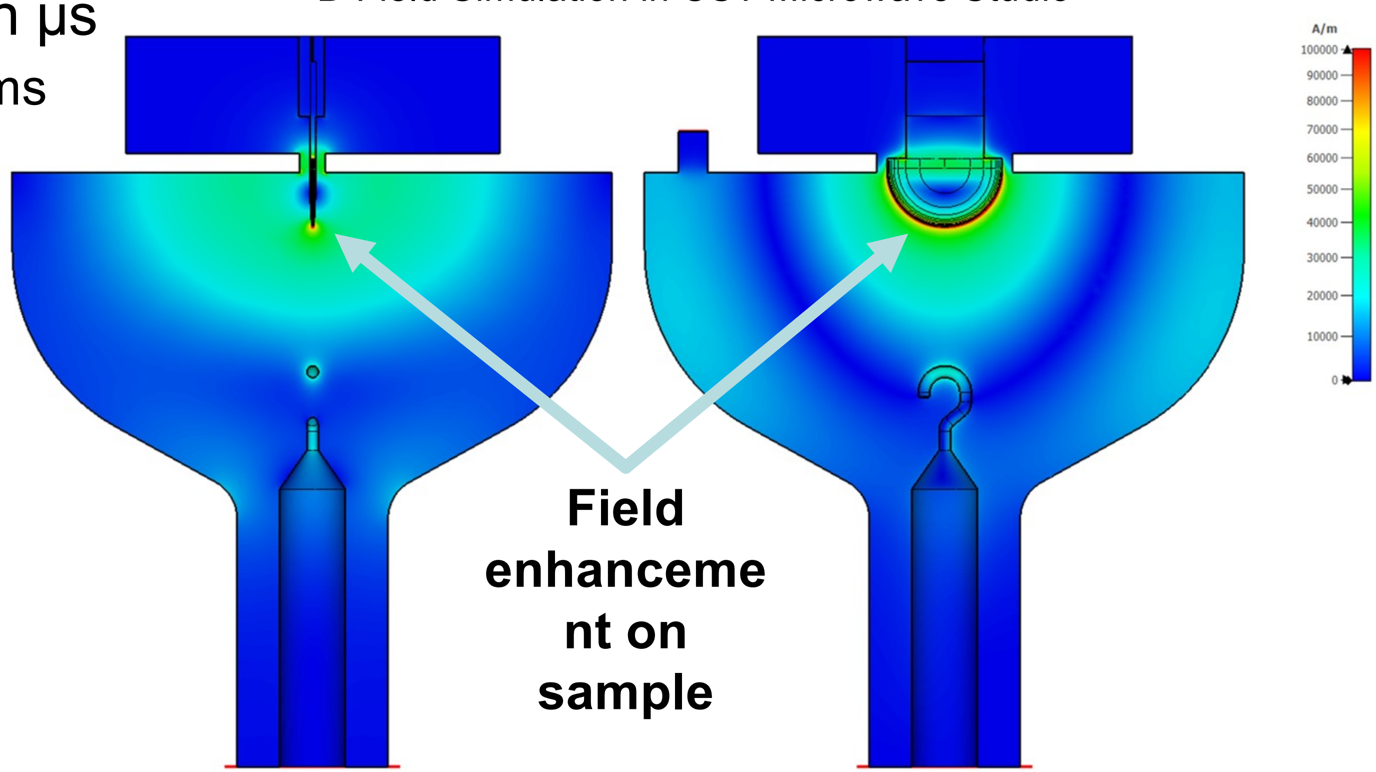
Thomas Oseroff et al., 2023 Supercond. Sci. Technol. 36 115009 (2023).
A Gurevich and T Kubo Phys. Rev. B 96 184515 and Phys. Rev. B 100 064522

# Cornell Pulsed Power Sample Host Cavity

- Maximum sample field of ~0.5 T
- Charge to quench in μs
  - Thermal effects ~ ms



B-Field Simulation in CST Microwave Studio



# That's all for now. Stay Tuned!