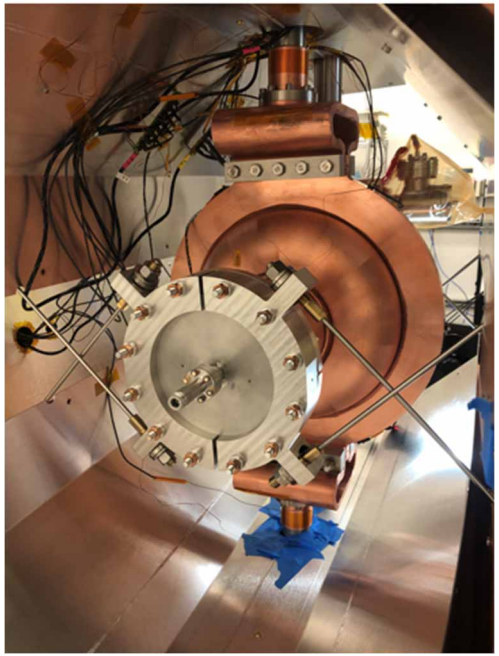
Development of a conduction-cooled SRF cavity for industrial accelerators

21st International Conference on Radio-Frequency Superconductivity

Grand Rapids, MI

25-30 June 2023



Gianluigi Ciovati

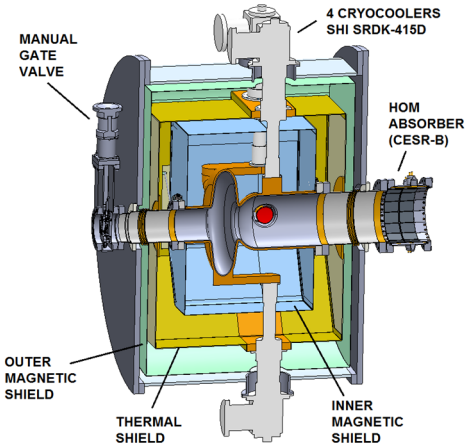
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Motivation

- The conceptual design and cost analysis for a 750 MHz, CW, 1 MeV, 1 MW SRF electron Linac for environmental remediation was published in 2018
  - Nb_3Sn/Nb/Cu, low-β, SRF elliptical cavity cooled by conduction with 4 cryocoolers



- RF power is a major capital and operating cost ➡ change frequency to 915 MHz, matching that of low-cost, commercial, high-power magnetrons for industrial heating
- Need an experimental proof-of-concept of an SRF cavity cooled by conduction by multiple cryocoolers in a horizontal cryostat

G. Ciovati et al., Design of a cw, low energy, high power superconducting linac for environmental applications, Phys. Rev. Accel. Beams ***21****, 091601 (2018)*

Prototype cavity to demonstrate performance with conduction cooling

- We used a 952.6 MHz Nb single-cell cavity developed as a prototype for JLEIC
- The cavity reached 184 mT (E_{acc} = 46 MV/m) in LHe at 2 K after electropolishing and baking at 120 °C/12 h *[Frank Marhauser]*

Prototype cavity to demonstrate performance with conduction cooling

- We used a 952.6 MHz Nb single-cell cavity developed as a prototype for JLEIC
- The cavity reached 184 mT (E_{acc} = 46 MV/m) in LHe at 2 K after electropolishing and baking at 120 °C/12 h *[Frank Marhauser]*

First step: Nb_3Sn coating

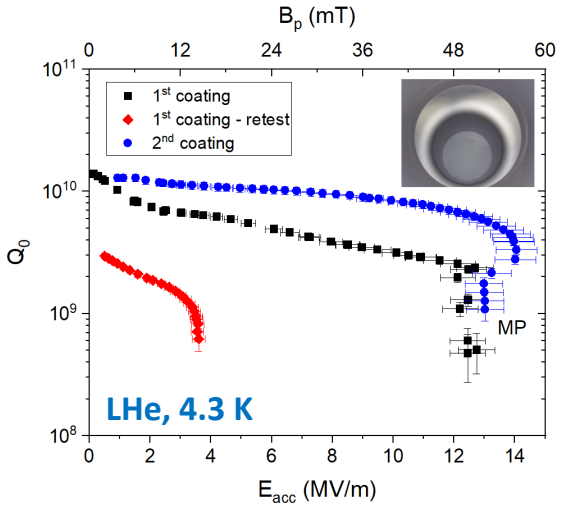
- ~3 μm thick film by vapor diffusion method: 500 °C/1 h followed by coating at 1200 °C/6 h *[Uttar Pudasaini]*

Prototype cavity to demonstrate performance with conduction cooling

- We used a 952.6 MHz Nb single-cell cavity developed as a prototype for JLEIC
- The cavity reached 184 mT (E_{acc} = 46 MV/m) in LHe at 2 K after electropolishing and baking at 120 °C/12 h *[Frank Marhauser]*

First step: Nb_3Sn coating

- ~3 μm thick film by vapor diffusion method: 500 °C/1 h followed by coating at 1200 °C/6 h *[Uttar Pudasaini]*

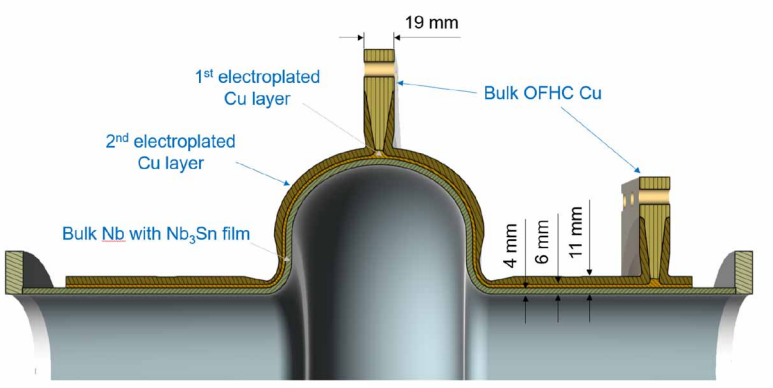


- *Creep while under vacuum for extended period of time lead to damage of the Nb_3Sn film*
- *2nd coating with additional crucibles with $Sn/SnCl_2$ for a more uniform coating*
- *Cavity performance limited by Multipacting at ~52 mT*

Jefferson Lab

Copper outer layer

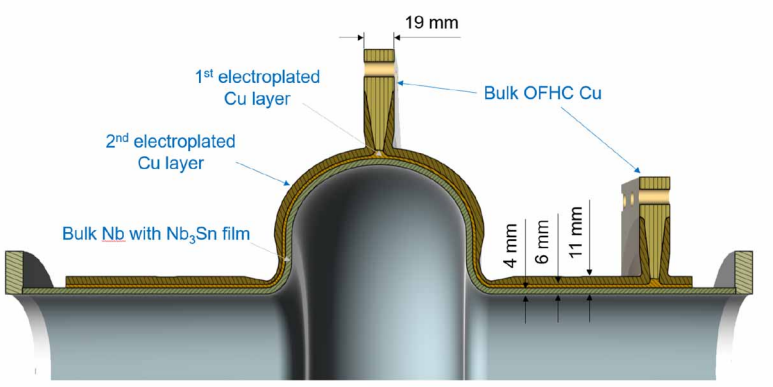
Second step: thick Cu outer layer



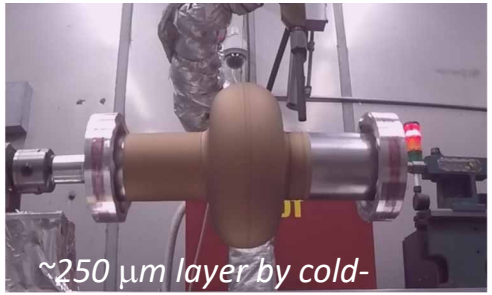
Jefferson Lab

Copper outer layer

Second step: thick Cu outer layer

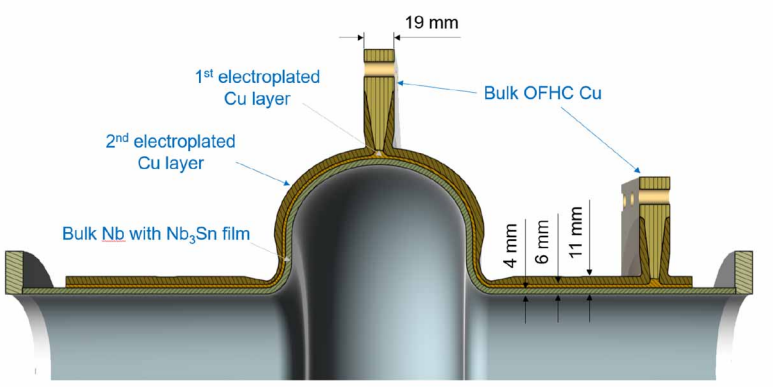


CTC Concurrent Technologies Corporation

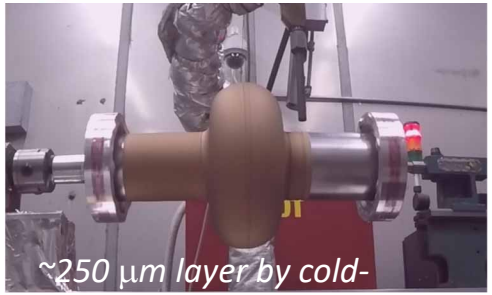


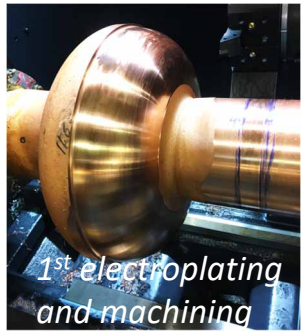
Copper outer layer

Second step: thick Cu outer layer



CTC Concurrent Technologies Corporation

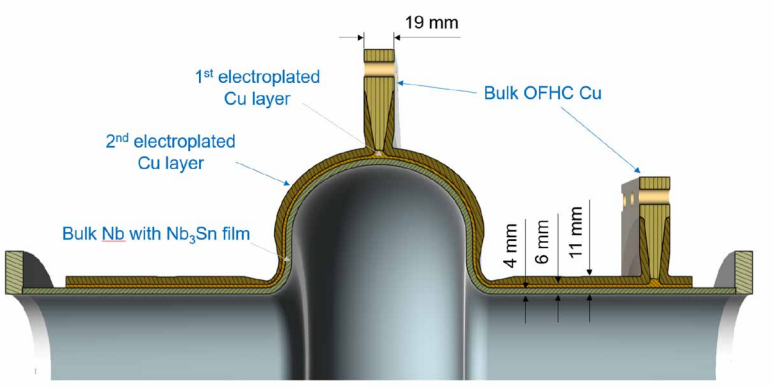


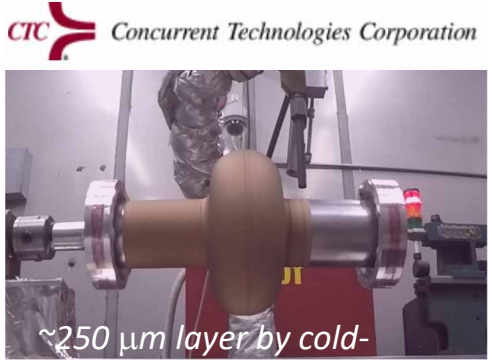


Jefferson Lab

Copper outer layer

Second step: thick Cu outer layer

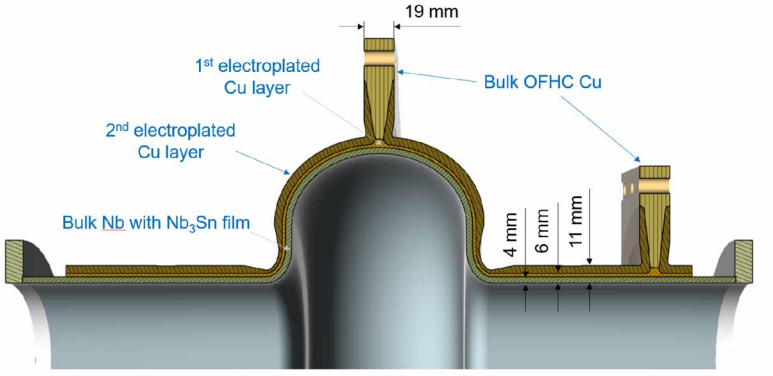


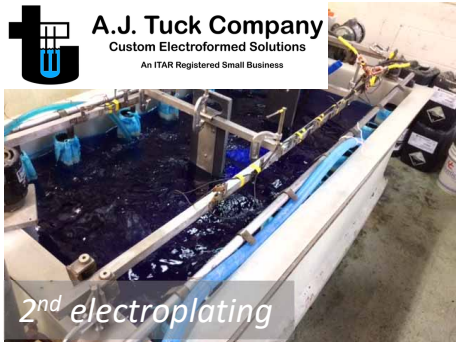


Jefferson Lab

Copper outer layer

Second step: thick Cu outer layer

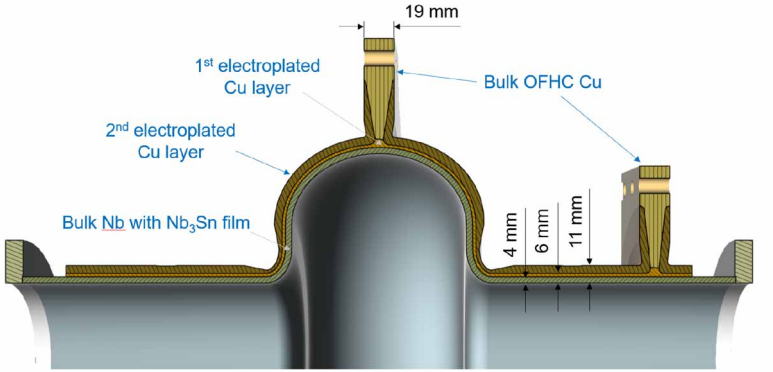


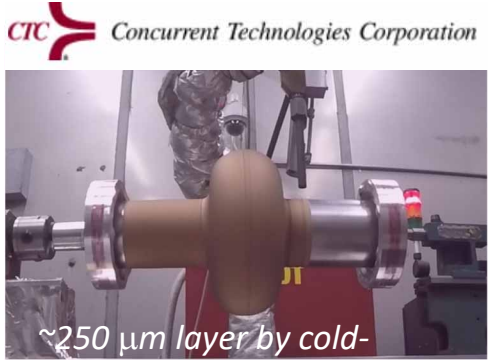


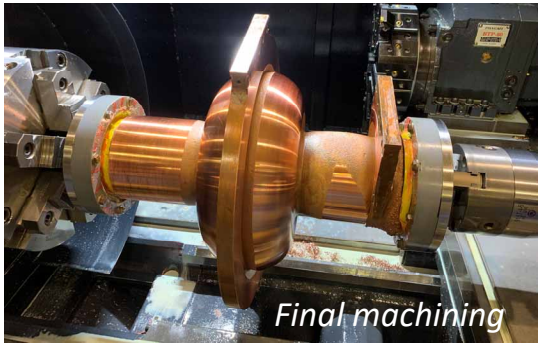
Jefferson Lab

Copper outer layer

Second step: thick Cu outer layer







Jefferson Lab

952.6 MHz Nb_3Sn/Nb/Cu cavity RF performance in LHe

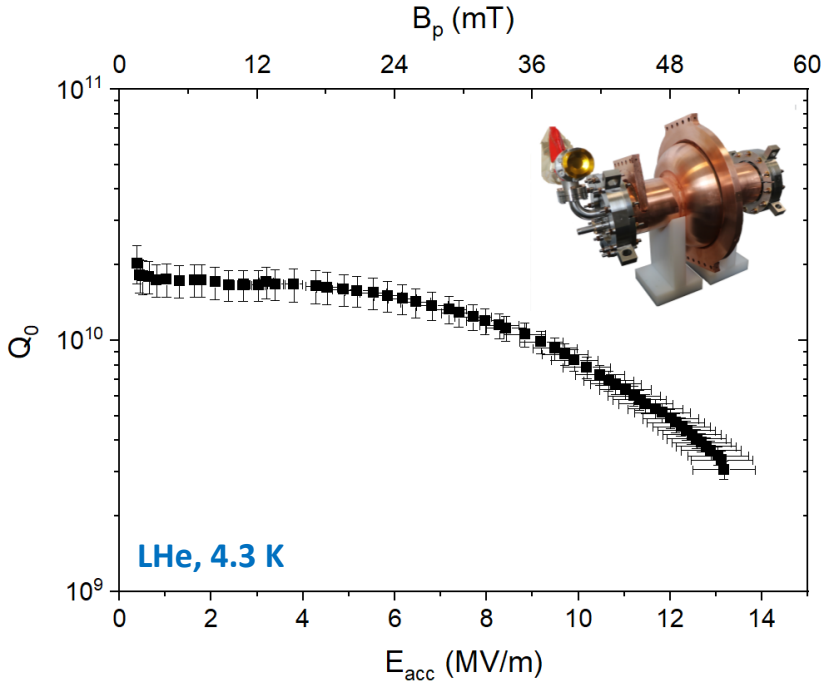
- The cavity was degreased and HPRed

- The cavity was assembled with right-angle valve and burst disk, evacuated and tested in vertical cryostat with LHe at 4.3 K

952.6 MHz Nb_3Sn/Nb/Cu cavity RF performance in LHe

- The cavity was degreased and HPRed

- The cavity was assembled with right-angle valve and burst disk, evacuated and tested in vertical cryostat with LHe at 4.3 K



- The cavity performance was limited by multipacting at 53 mT and was shipped under static vacuum to General Atomics for assembly into the horizontal test cryostat

Jefferson Lab

Thermal Link Assembly

- A Cu thermal link was developed to:
  - Have sufficient flexibility to account for misalignments between cavity and cryocoolers' cold stage and thermal contraction
  - Have a thermal conductance of 17.5 W/K at 4 K and 39.7 W/K at 10 K, as determined by the thermal analysis of the 915 MHz cavity

Thermal Link Assembly

- A Cu thermal link was developed to:
  - Have sufficient flexibility to account for misalignments between cavity and cryocoolers' cold stage and thermal contraction
  - Have a thermal conductance of 17.5 W/K at 4 K and 39.7 W/K at 10 K, as determined by the thermal analysis of the 915 MHz cavity

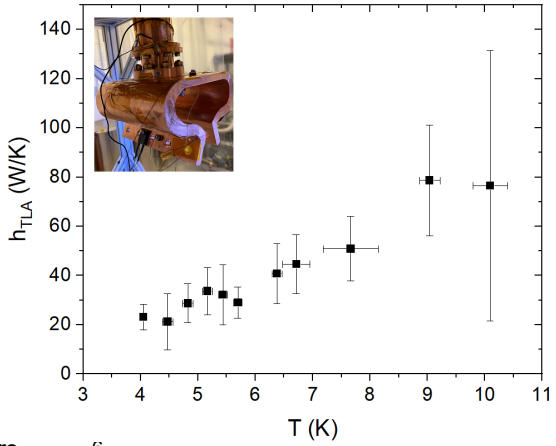
- Thermal links were made by stacking ~85, 100 μm thick Cu (C10300) foils, press-welding in Ar atmosphere and machining the interface regions (*Absolut System, France*)

Thermal Link Assembly

- A Cu thermal link was developed to:
  - Have sufficient flexibility to account for misalignments between cavity and cryocoolers' cold stage and thermal contraction
  - Have a thermal conductance of 17.5 W/K at 4 K and 39.7 W/K at 10 K, as determined by the thermal analysis of the 915 MHz cavity

- Thermal links were made by stacking ~85, 100 μm thick Cu (C10300) foils, press-welding in Ar atmosphere and machining the interface regions (*Absolut System, France*)

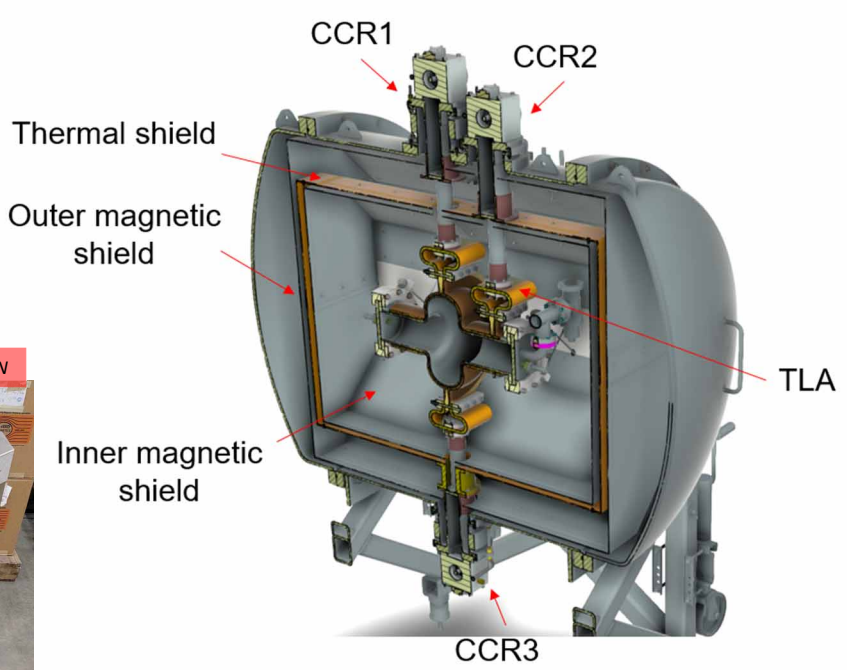
- The performance of one thermal link was measured with a cryocooler. The thermal conductance was 23 W/K at 4 K and 77 W/K at 10 K



Jefferson Lab

Horizontal Test Cryostat

- A horizontal test cryostat was designed and procured to test the 952.6 MHz Nb_3Sn/Nb/Cu cavity, cooled by 3 GM-type cryocoolers (*RDE418-D4, Sumitomo*)
- The cavity is suspended by 4 nitronic rods on each side



Master Machine & Tool, Newport News, VA

Vacuum vessel

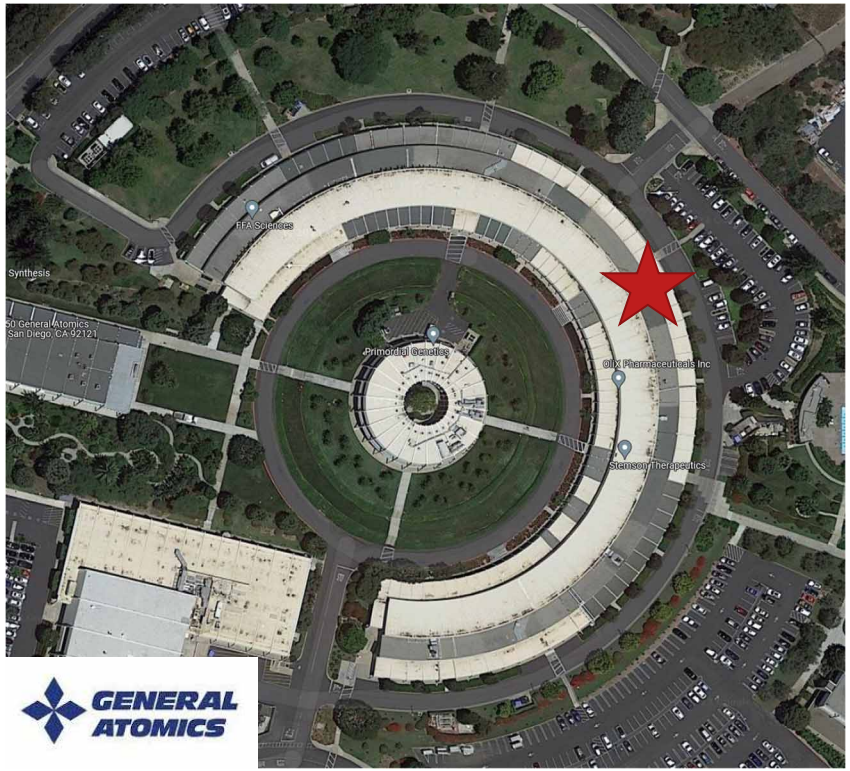
Thermal shield

Ad-Vance Magnetics, Rochester, IN

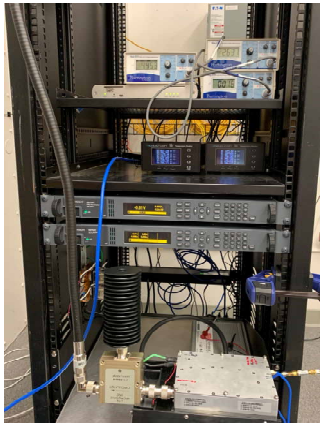
Inner magnetic shield

Jefferson Lab

“SRF Laboratory” at General Atomics



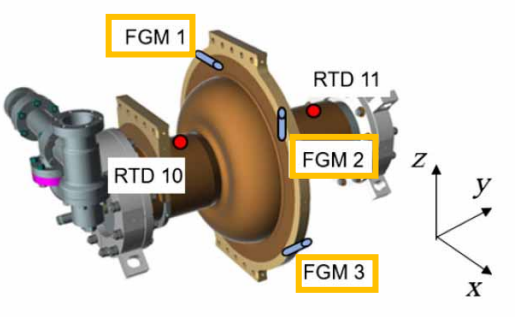
- *~50 m^2 laboratory space at GA’s flagship building in San Diego, CA*
- *Thick concrete-walls room with 5 x-ray area monitors*
- *Instrumentation and RF rack*
- *LLRF and data acquisition rack*
- *3 He compressors*



Jefferson Lab

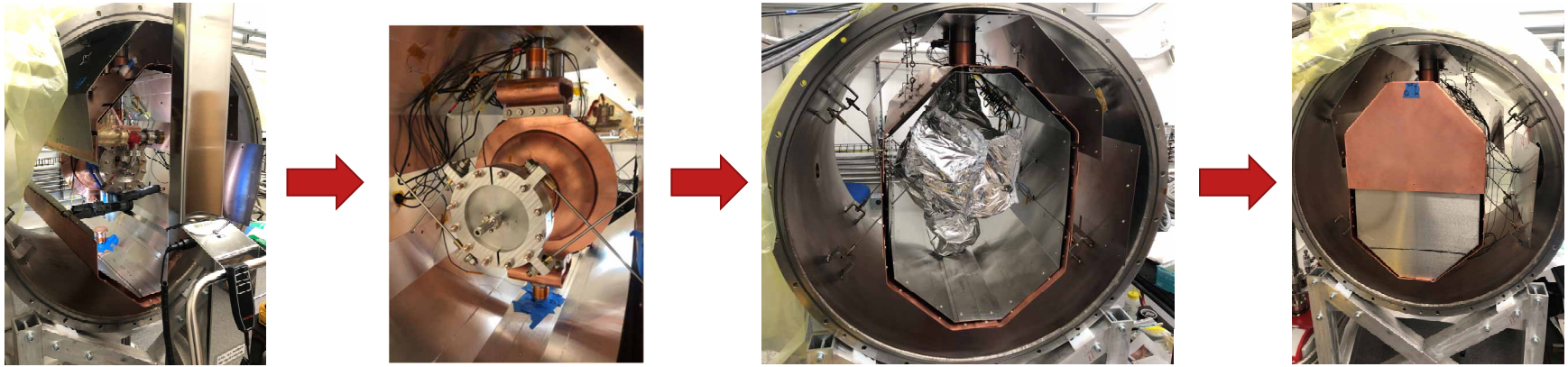
Horizontal test cryostat assembly

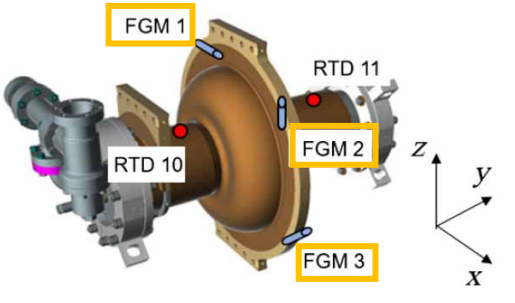
- Cavity is instrumented with 8 Cernox, 3 flux-gate magnetometers



Horizontal test cryostat assembly

- Cavity is instrumented with 8 Cernox, 3 flux-gate magnetometers



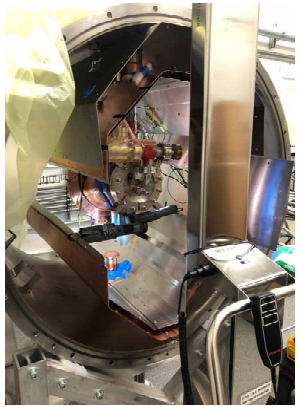


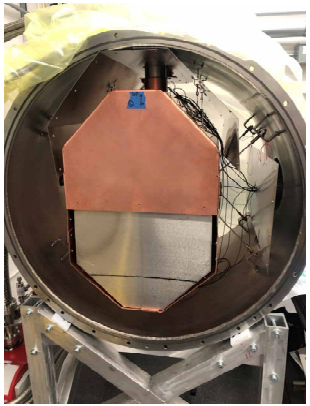
GENERAL ATOMICS

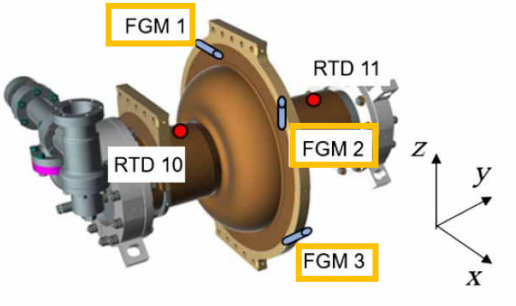
Jefferson Lab

Horizontal test cryostat assembly

- Cavity is instrumented with 8 Cernox, 3 flux-gate magnetometers







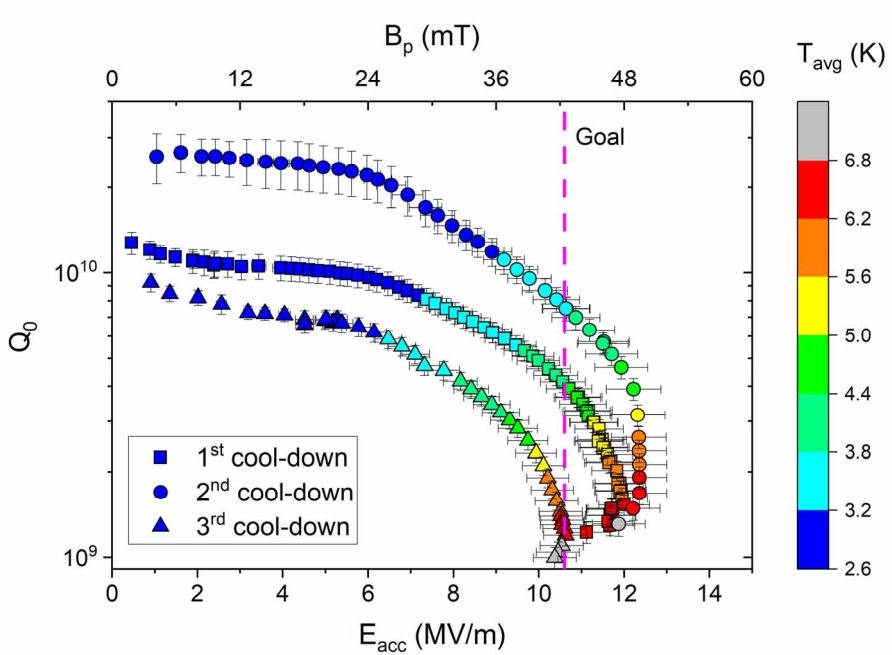
GENERAL ATOMICS

RF test of conduction-cooled cavity in HTC

- Local magnetic field at 300 K < 0.5 μT
- Total static heat load on cold stages ~ 1 W

RF test of conduction-cooled cavity in HTC

- Local magnetic field at 300 K < 0.5 μT
- Total static heat load on cold stages ~ 1 W

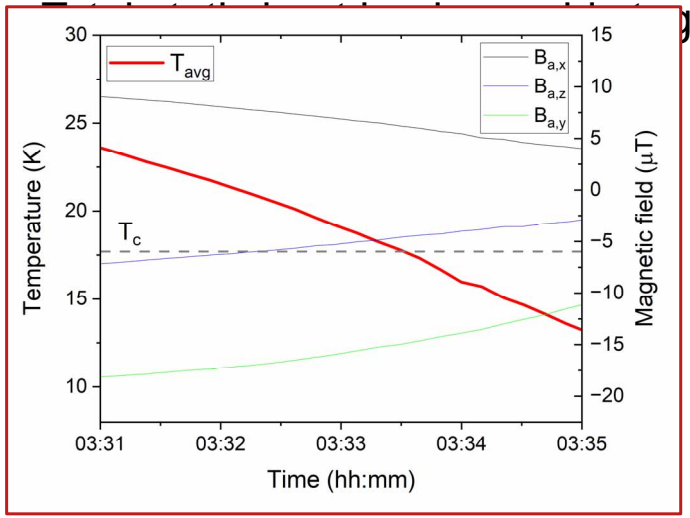


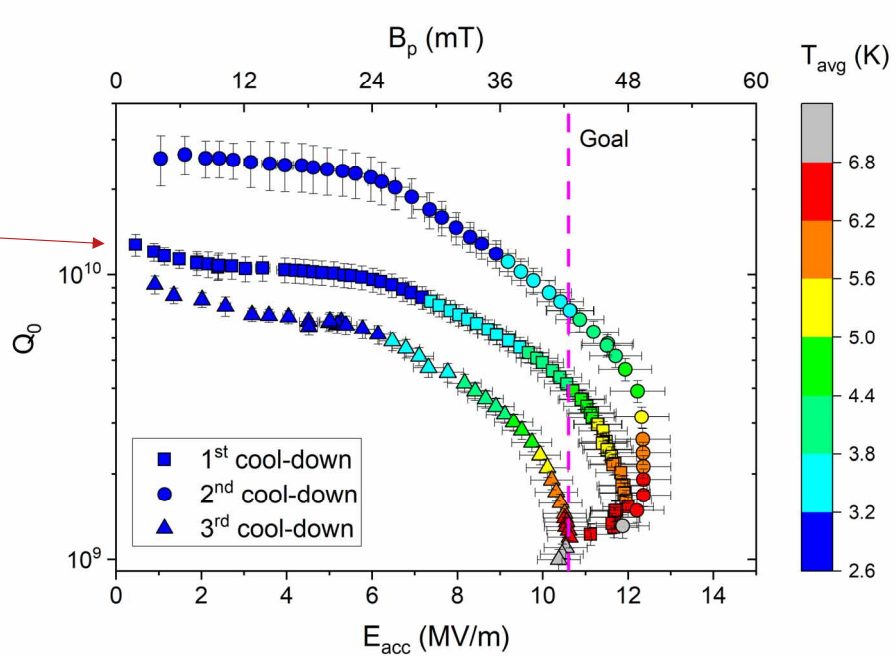
T_{avg} is the average cavity temperature, cooled by cryocoolers

GENERAL ATOMICS Jefferson Lab

RF test of conduction-cooled cavity in HTC

- Local magnetic field at 300 K < 0.5 μT
- ges ~ 1 W



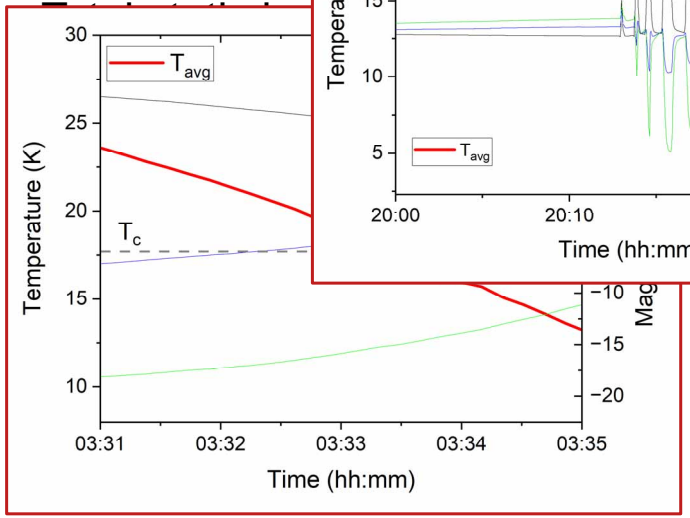


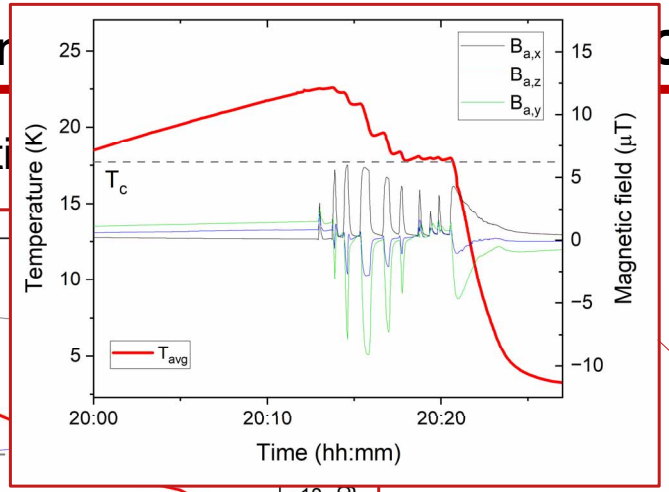
T_{avg} is the average cavity temperature, cooled by cryocoolers

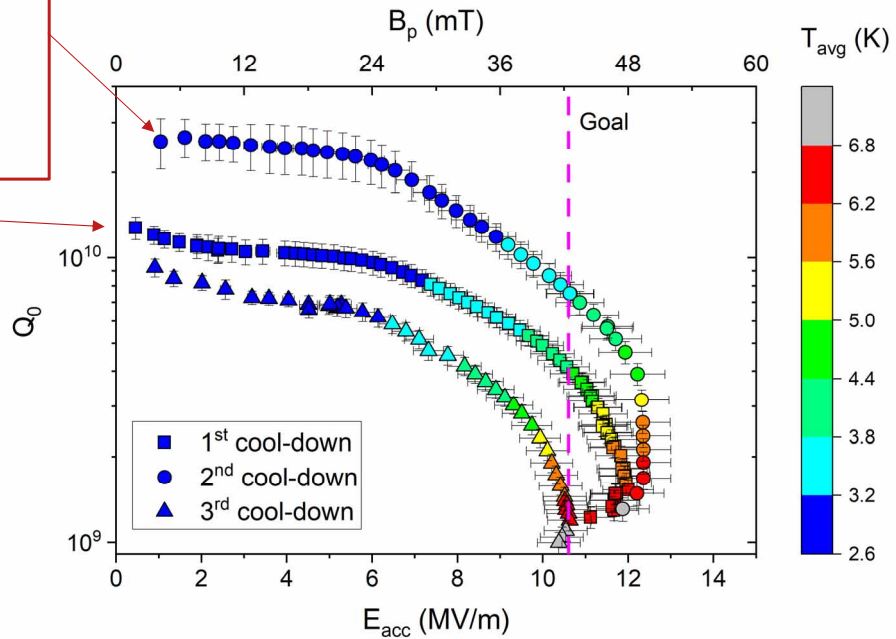
GENERAL ATOMICS Jefferson Lab

RF test of cor C

- Local magneti





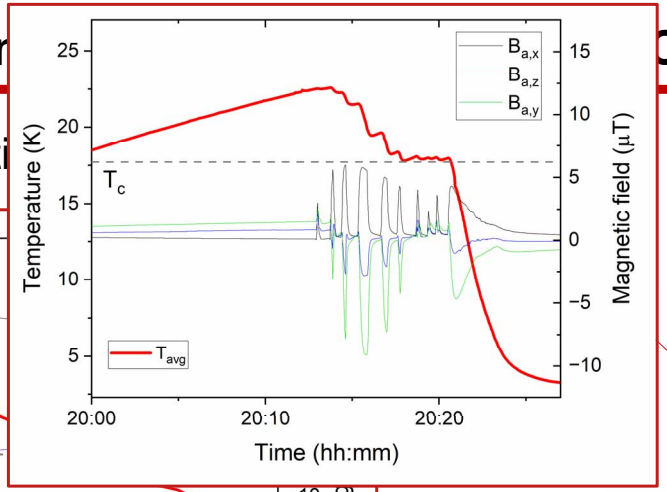


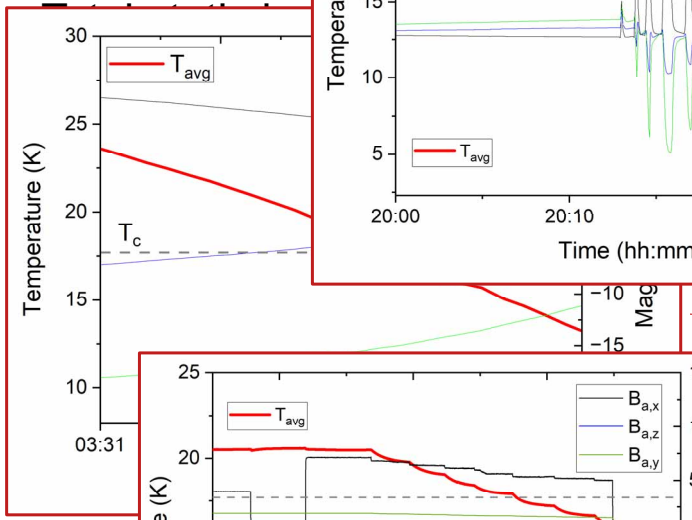
T_{avg} is the average cavity temperature, cooled by cryocoolers

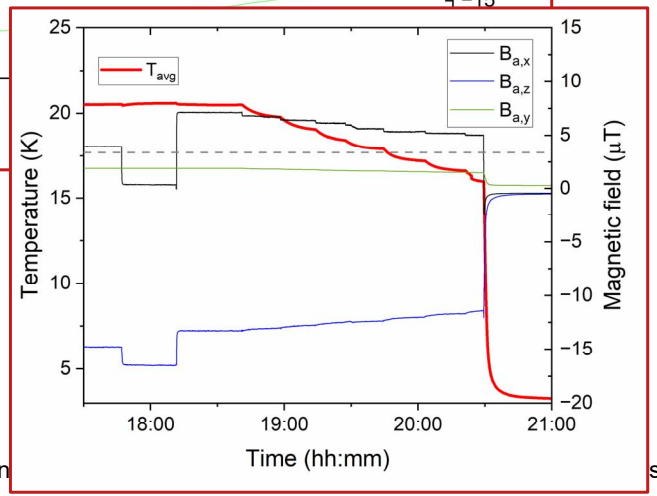
GENERAL ATOMICS Jefferson Lab

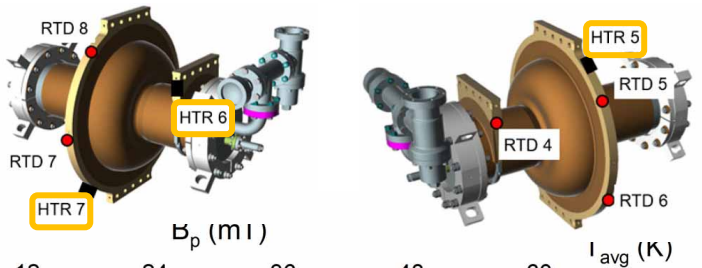
RF test of cor C

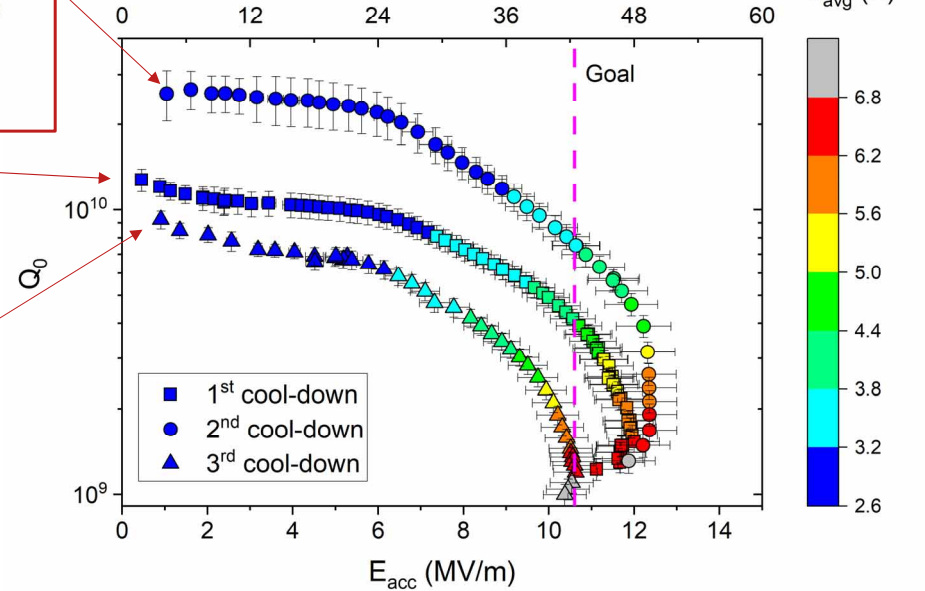
- Local magneti









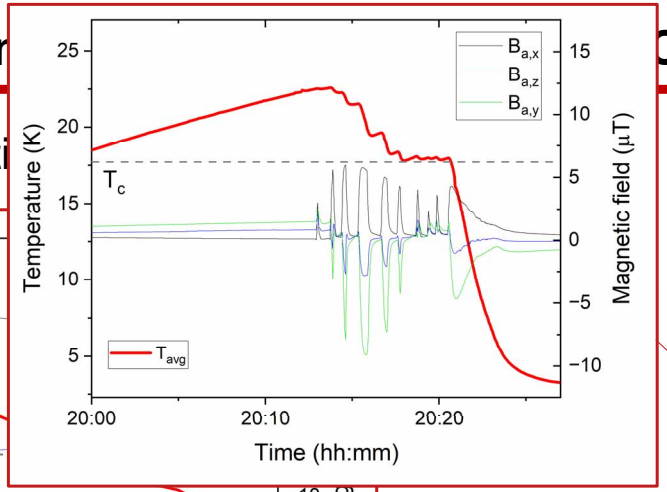


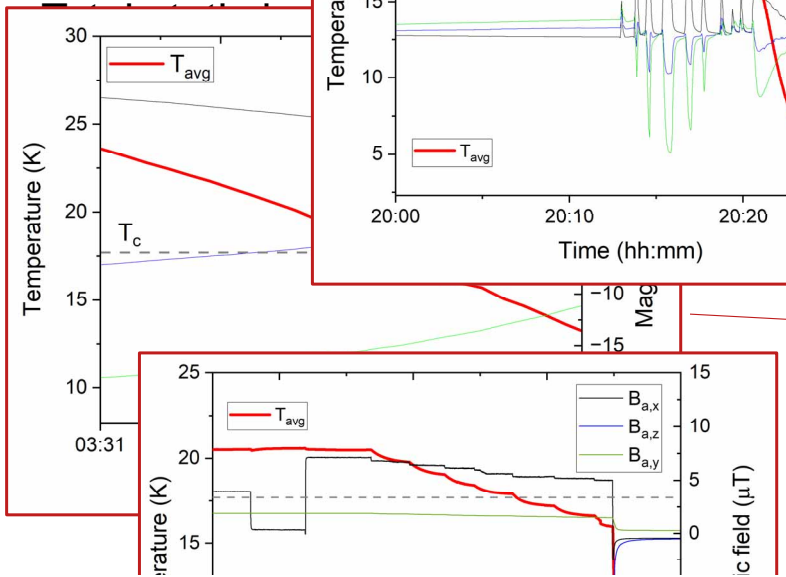
T_{avg} is the average cavity temperature, cooled by cryocoolers

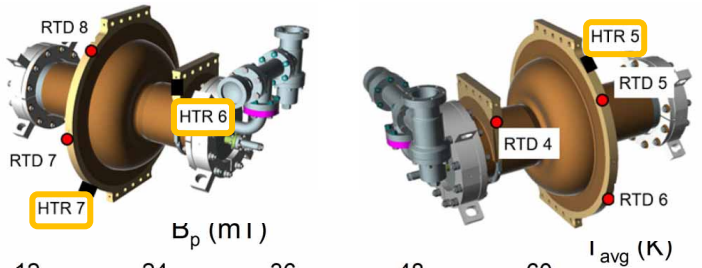
GENERAL ATOMICS Jefferson Lab

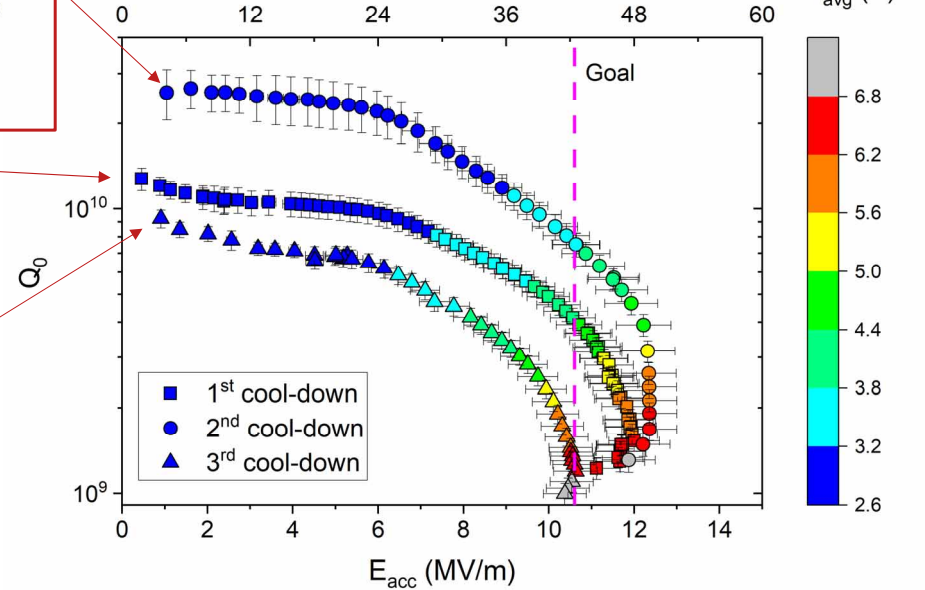
RF test of cor C

- Local magneti









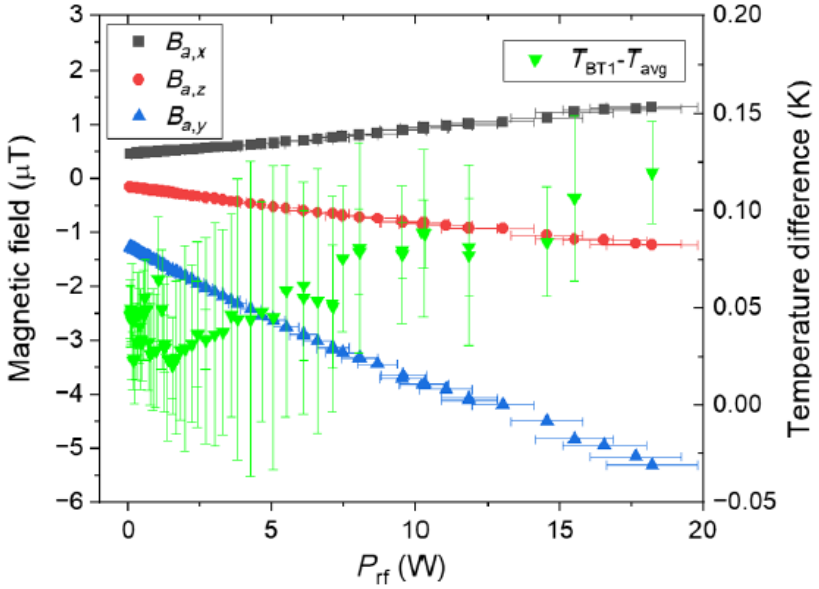
- The cavity achieved B_p = **50 mT**
- The cavity was operated stably for 1 h with a power dissipation of up to **18.5 W**

T_{avg} is the average cavity temperature, cooled by cryocoolers

GENERAL ATOMICS Jefferson Lab

RF test of conduction-cooled cavity in HTC

- Local magnetic field at the cavity equator increased linearly with increasing cavity dissipated power → thermoelectric currents

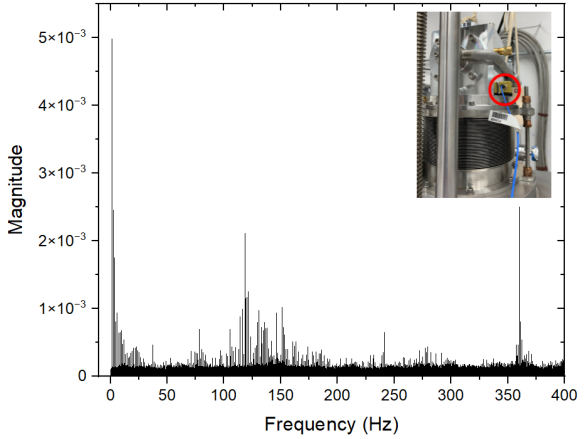


- The total thermal conductance across the interfaces between the cavity and TLA and between the TLA and cryocooler's cold stage was ~4 W/K at 4 K

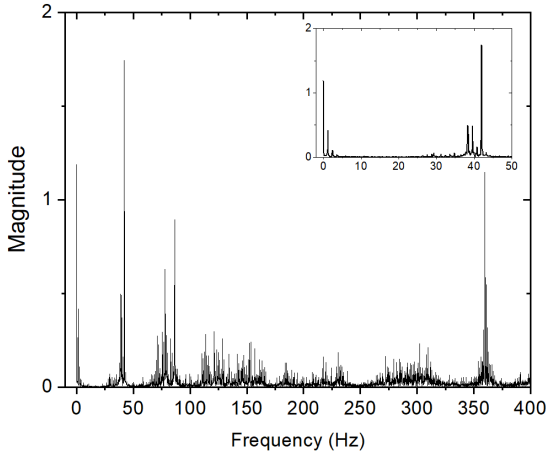
GENERAL ATOMICS Jefferson Lab

Microphonics measurements

- Frequency shift due to microphonics were measured at low rf field. The peak excursion was **23 Hz**.
- A tri-axial accelerometer was placed at different locations of the HTC.
- The spectra show peaks at 1.2 Hz (*frequency of the displacer inside the cryocooler*) and ~40 Hz, ~120 Hz and ~360 Hz (*He compressors*)



FFT of vertical component of acceleration

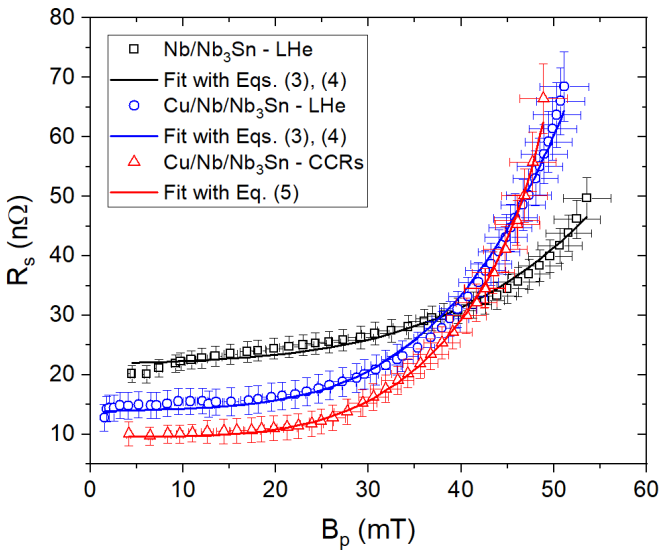


FFT of cavity frequency shift

Analysis of field dependence of surface resistance

- ANSYS simulations with the measured thermal conductance resulted in a maximum cavity dissipated power and temperature consisted with the measurements
- A simple 1D thermal feedback model provides a good description of $R_s(B_p)$ measured in LHe before and after Cu layer deposition and for the test with cryocoolers with the following:

$$R_s(T_m, B_p) = R_{BCS}(T_m) + R_{res}\left[1 + \gamma\left(\frac{B_p}{B_c}\right)^2 + \delta\left(\frac{B_p}{B_c}\right)^4\right]$$



Jefferson Lab

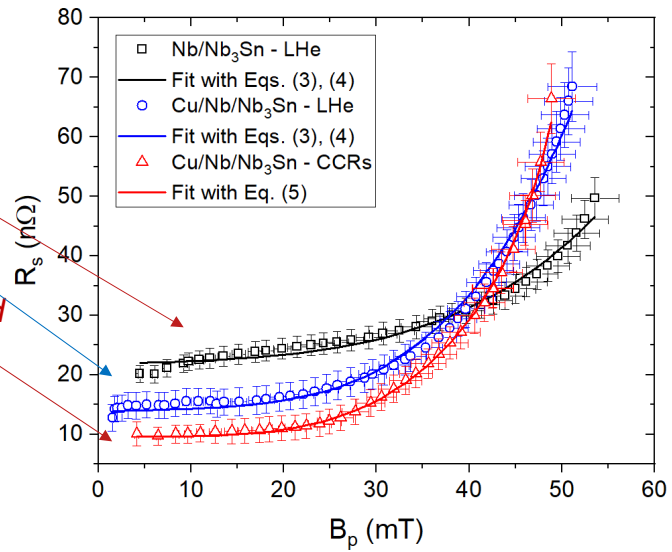
Analysis of field dependence of surface resistance

- ANSYS simulations with the measured thermal conductance resulted in a maximum cavity dissipated power and temperature consisted with the measurements
- A simple 1D thermal feedback model provides a good description of $R_s(B_p)$ measured in LHe before and after Cu layer deposition and for the test with cryocoolers with the following:

$$R_s(T_m, B_p) = R_{BCS}(T_m) + R_{res}\left[1 + \gamma\left(\frac{B_p}{B_c}\right)^2 + \delta\left(\frac{B_p}{B_c}\right)^4\right]$$

	R_{res} (nΩ)	γ	δ
LHe, no Cu	*20.5*	*24*	*6.6×10^3*
LHe, with Cu	*8.9*	*~0*	*4.8×10^4*
CCR, with Cu	*9.6*	*~0*	*4.8×10^4*

Fixed



Jefferson Lab

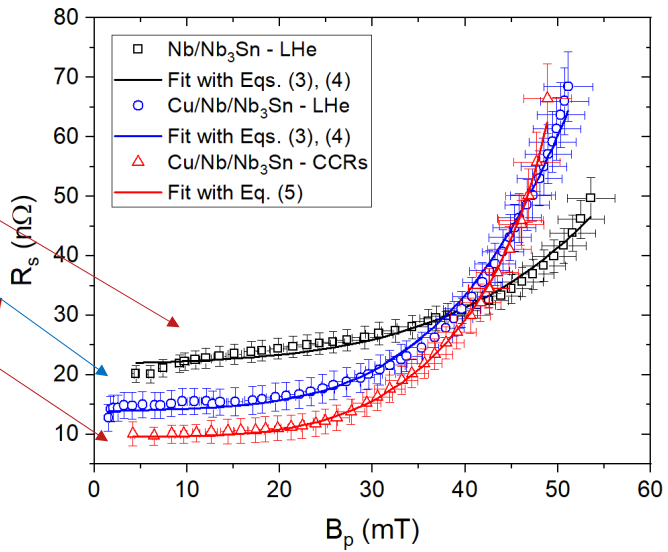
Analysis of field dependence of surface resistance

- ANSYS simulations with the measured thermal conductance resulted in a maximum cavity dissipated power and temperature consisted with the measurements
- A simple 1D thermal feedback model provides a good description of $R_s(B_p)$ measured in LHe before and after Cu layer deposition and for the test with cryocoolers with the following:

$$R_s(T_m, B_p) = R_{BCS}(T_m) + R_{res}\left[1 + \gamma\left(\frac{B_p}{B_c}\right)^2 + \delta\left(\frac{B_p}{B_c}\right)^4\right]$$

	R_{res} (nΩ)	γ	δ
LHe, no Cu	*20.5*	*24*	*6.6×10^3*
LHe, with Cu	*8.9*	*~0*	*4.8×10^4*
CCR, with Cu	*9.6*	*~0*	*4.8×10^4*

Fixed



- The increase of Q-slope after Cu layer deposition is due to increase of δ by a factor of ~7
  - This can be due to additional strain in the Nb_3Sn film because of differential thermal contraction between the Nb and the Cu

Jefferson Lab

Summary

- A 952.6 MHz Nb_3Sn/Nb/Cu prototype single-cell cavity was developed for demonstrating operation to an E_{acc} corresponding to 1 MeV energy gain
- The cavity cooled by 3 cryocoolers in a horizontal test cryostat achieved B_p=50 mT (E_{acc} = 12.4 MV/m), the highest achieved in a conduction-cooled cavity to date

Summary

- A 952.6 MHz Nb_3Sn/Nb/Cu prototype single-cell cavity was developed for demonstrating operation to an E_{acc} corresponding to 1 MeV energy gain
- The cavity cooled by 3 cryocoolers in a horizontal test cryostat achieved B_p=50 mT (E_{acc} = 12.4 MV/m), the highest achieved in a conduction-cooled cavity to date
- The conduction-cooled cavity system exhibited a remarkable thermal stability, up to 18.5 W of rf power dissipation

Summary

- A 952.6 MHz Nb_3Sn/Nb/Cu prototype single-cell cavity was developed for demonstrating operation to an E_{acc} corresponding to 1 MeV energy gain
- The cavity cooled by 3 cryocoolers in a horizontal test cryostat achieved B_p=50 mT (E_{acc} = 12.4 MV/m), the highest achieved in a conduction-cooled cavity to date
- The conduction-cooled cavity system exhibited a remarkable thermal stability, up to 18.5 W of rf power dissipation
- Impact of Cu outer layer:
  - increased the mechanical and thermal stability of the cavity
  - residual magnetic fields due to thermocurrents
  - strain in Nb_3Sn film due to differential CTE possibly causing increased rf losses

Summary

- A 952.6 MHz Nb_3Sn/Nb/Cu prototype single-cell cavity was developed for demonstrating operation to an E_{acc} corresponding to 1 MeV energy gain
- The cavity cooled by 3 cryocoolers in a horizontal test cryostat achieved B_p=50 mT (E_{acc} = 12.4 MV/m), the highest achieved in a conduction-cooled cavity to date
- The conduction-cooled cavity system exhibited a remarkable thermal stability, up to 18.5 W of rf power dissipation
- Impact of Cu outer layer:
  - increased the mechanical and thermal stability of the cavity
  - residual magnetic fields due to thermocurrents
  - strain in Nb_3Sn film due to differential CTE possibly causing increased rf losses
- The microphonics introduced by 3 GM-type cryocoolers are not an issue for SRF cavities operating with high beam power (low loaded-Q)

Summary

- A 952.6 MHz Nb_3Sn/Nb/Cu prototype single-cell cavity was developed for demonstrating operation to an E_{acc} corresponding to 1 MeV energy gain
- The cavity cooled by 3 cryocoolers in a horizontal test cryostat achieved B_p=50 mT (E_{acc} = 12.4 MV/m), the highest achieved in a conduction-cooled cavity to date
- The conduction-cooled cavity system exhibited a remarkable thermal stability, up to 18.5 W of rf power dissipation
- Impact of Cu outer layer:
  - increased the mechanical and thermal stability of the cavity
  - residual magnetic fields due to thermocurrents
  - strain in Nb_3Sn film due to differential CTE possibly causing increased rf losses
- The microphonics introduced by 3 GM-type cryocoolers are not an issue for SRF cavities operating with high beam power (low loaded-Q)
- Successful transfer of SRF technology to General Atomics

Summary

- A 952.6 MHz Nb_3Sn/Nb/Cu prototype single-cell cavity was developed for demonstrating operation to an E_{acc} corresponding to 1 MeV energy gain
- The cavity cooled by 3 cryocoolers in a horizontal test cryostat achieved B_p=50 mT (E_{acc} = 12.4 MV/m), the highest achieved in a conduction-cooled cavity to date
- The conduction-cooled cavity system exhibited a remarkable thermal stability, up to 18.5 W of rf power dissipation
- Impact of Cu outer layer:
  - increased the mechanical and thermal stability of the cavity
  - residual magnetic fields due to thermocurrents
  - strain in Nb_3Sn film due to differential CTE possibly causing increased rf losses
- The microphonics introduced by 3 GM-type cryocoolers are not an issue for SRF cavities operating with high beam power (low loaded-Q)
- Successful transfer of SRF technology to General Atomics
- Conceptual design for 10 MeV, 1 MW, CW linac is being developed (**Poster TUPTB033**)

For more information…

PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 044701 (2023)

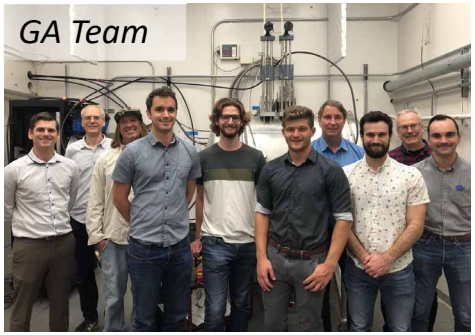
Development of a prototype superconducting radio-frequency cavity for conduction-cooled accelerators

G. Ciovati,[1,2,*] J. Anderson,[3] S. Balachandran,[1] G. Cheng,[1] B. Coriton,[3,†] E. Daly,[1] P. Dhakal,[1] A. Gurevich,[2] F. Hannon,[1,‡] K. Harding,[1] L. Holland,[3] F. Marhauser,[1,§] K. McLaughlin,[3] D. Packard,[3] T. Powers,[1] U. Pudasaini,[1] J. Rathke,[4] R. Rimmer,[1] T. Schultheiss,[5] H. Vennekate,[1] and D. Vollmer[3]

[1]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[2]*Center for Accelerator Science, Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA*
[3]*General Atomics, San Diego, California 92121, USA*
[4]*TECHSOURCE, Inc., Los Alamos, New Mexico 87544, USA*
[5]*TJS Technologies LLC, Commack, New York 11725, USA*

Acknowledgements

- JLab Team: S. Balachandran, G. Cheng, E. Daly, P. Dhakal, F. Hannon, K. Harding, F. Marhauser, T. Powers, U. Pudasaini, R. Rimmer, H. Vennekate, SRF Cavity Production Group
- Engineering consultants: J. Rathke, T. Schultheiss
- Collaborator: Prof. A. Gurevich (*ODU*)
- GA Team: D. Packard, J. Anderson, B. Coriton, L. Holland, K. McLaughlin, D. Vollmer



U.S. DEPARTMENT OF ENERGY | Office of Science

Accelerator R&D and Production (ARDAP)