# RF studies at SLAC and application to cooling

## Muon Cooling Demonstrator Workshop

Emilio Nanni on Behalf of SLAC

**31st October 2024**

# Acknowledgements


**SLAC**

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# RF Studies for Muon Cooling Channel

Demonstrate cavity performance in strong magnetic fields

Test both strong longitudinal and transverse fields

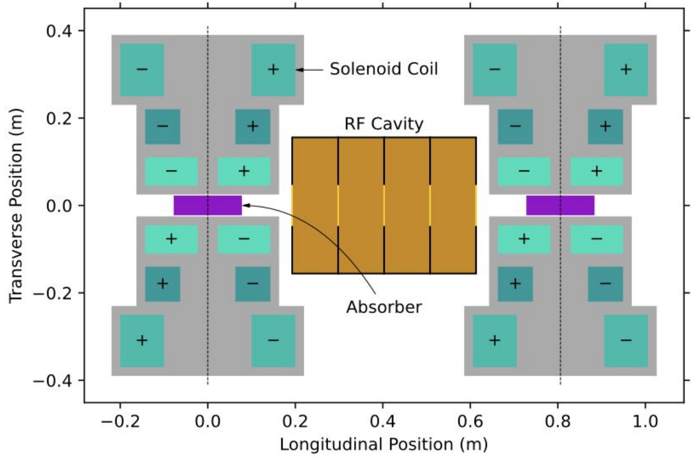
Perform frequency studies to understand scaling

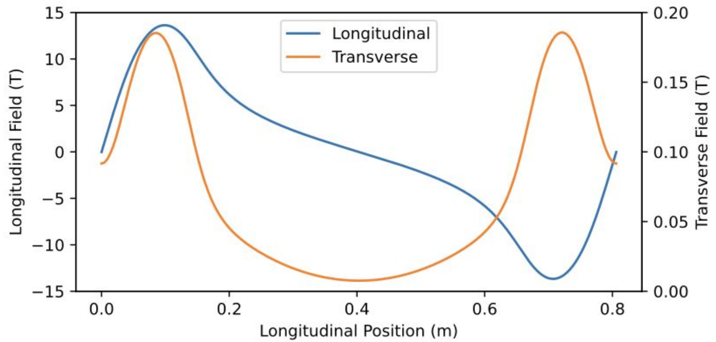
Benchmark against modeling tools

Investigate materials and temperature

Perform cavity designs and minimize rf power needed and thermal cooling needed

**Independent RF tests can provide early experimental validation and guidance for cooling demonstrator**




https://accelconf.web.cern.ch/ipac2024/pdf/WEPR34.pdf

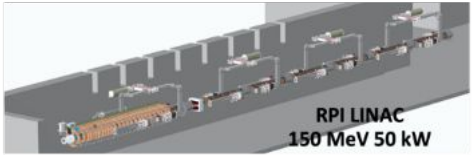
# RF Accelerator Research @ SLAC

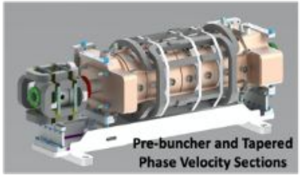
Design, fabrication and testing of accelerator structures, high-power RF sources and integrated systems

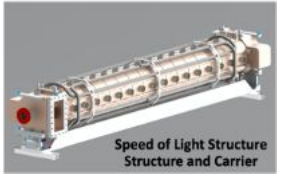
Multi-physics modeling & simulation of performance

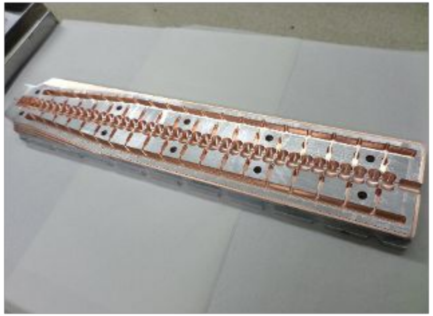
Integrated engineering capabilities

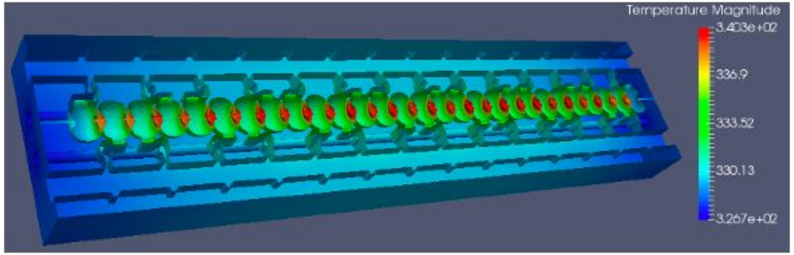
Expertise in S-band, X-band, C-band and THz



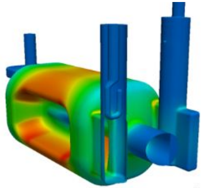
# ACE3P for Multi-Physics Accelerator Modeling

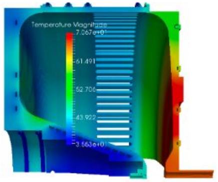
- **ACE3P**, developed at SLAC, is a comprehensive suite of *conformal, high-order, C++/MPI based parallel finite-element (FE) multi-physics codes* including electromagnetic (EM), thermal and mechanical capabilities.
  - Based on *curved high-order finite elements* for high-fidelity modeling
  - Implemented on *massively parallel computers* for increased memory (problem size) and speed

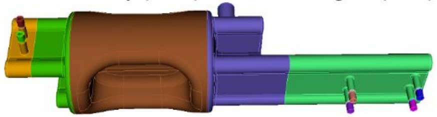
**ACE3P (Advanced Computational Electromagnetics 3P)**

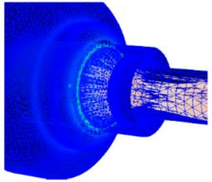
| | | |
|---|---|---|
| *Frequency Domain*: | **Omega3P** | **– Eigensolver (damping)** |
| | **S3P** | **– S-Parameter** |
| *Time Domain*: | **T3P** | **– Wakefields and Transients** |
| *Particle Tracking*: | **Track3P** | **– Multipacting and Dark Current** |
| *EM Particle-in-cell:* | **Pic3P** | **– RF guns & space charge effects** |
| *Multi-physics:* | **TEM3P** | **– EM, Thermal & Mechanical analysis** |
| *Static Particle-in-cell:* | **Gun3P** | **– DC guns & space charge effects** |

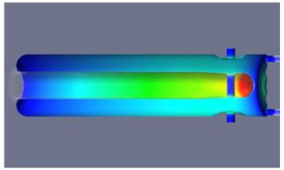
High-fidelity, high-accuracy simulation for virtual prototyping of accelerator components at large scale

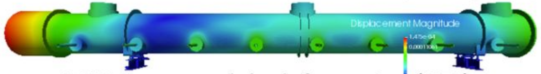

LHC-HL crab cavity (HEP)

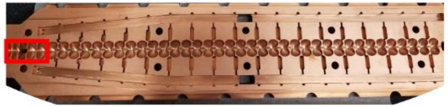

LCLS-II gun (BES)


EIC crab cavity (NP)


IOT gun emittance (HEP)


FRIB multipacting (NP)


LCLS-II cryomodule deformation (BES)


Betatron replacement prototype (NNSA)

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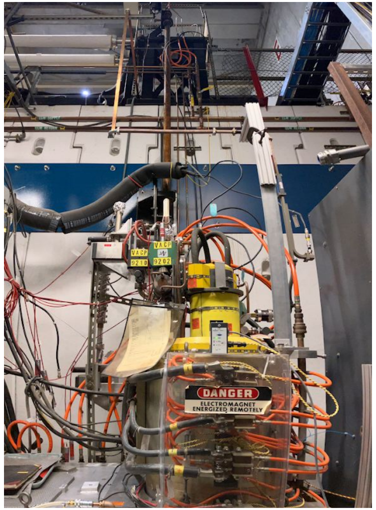
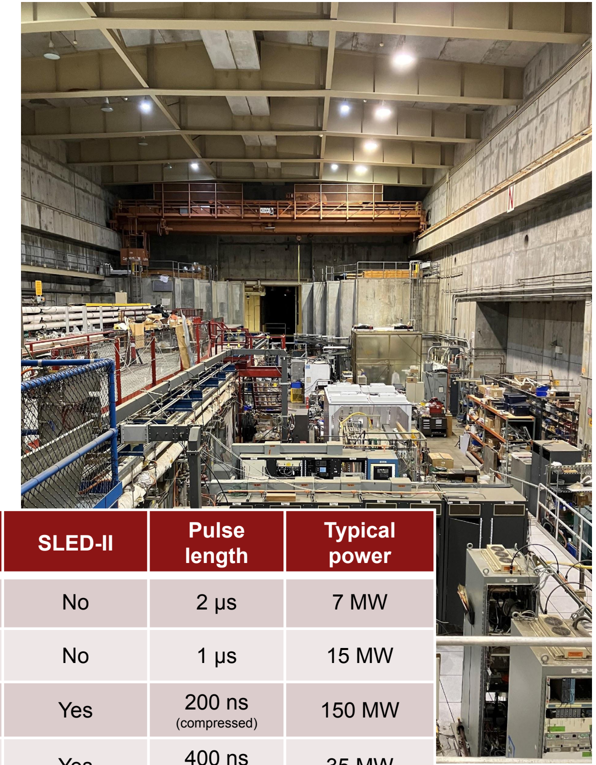
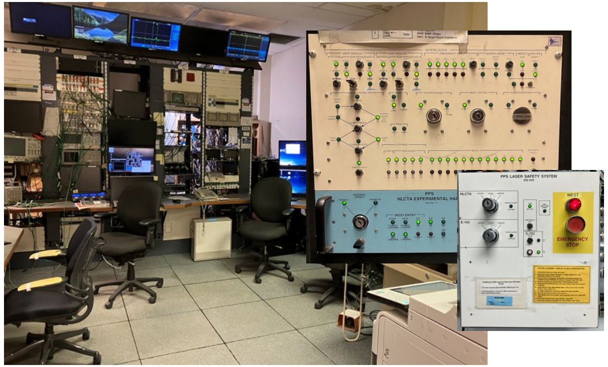
# NLCTA Facility Infrastructure

- Bunker was designed for a 1.066 GeV beam energy with 1.45 kW of beam power
- Multiple high power RF klystrons: 3 X-band, 1 S-band under current Accelerator Safety Envelope (ASE)
- Ti:Sapph laser system for XTA beamline
- Housed in the End Station B building with access to laser room, clean room, and machine shop, as well as experiment staging areas






| Test Stand | Klystron | Frequency (GHz) | SLED-II | Pulse length | Typical power |
|---|---|---|---|---|---|
| S | S-band 5045 | 2.856 | No | 2 µs | 7 MW |
| X0 | X-band XL-4 | 11.424 | No | 1 µs | 15 MW |
| X2 | X-band XL-4 | 11.424 | Yes | 200 ns (compressed) | 150 MW |
| X3 | X-band XL-4 | 11.424 | Yes | 400 ns (compressed) | 35 MW |

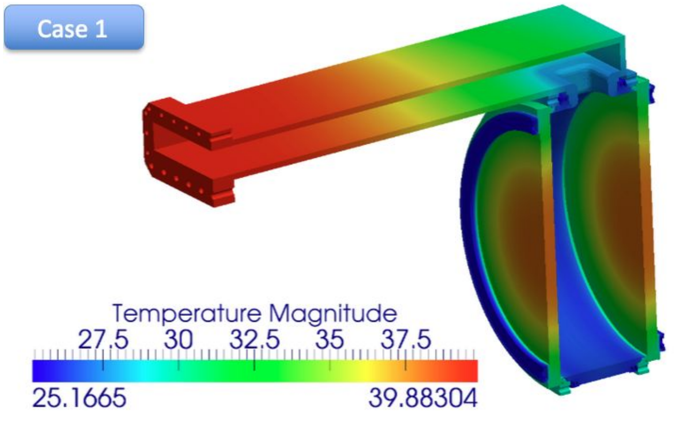
**High power L-band source (1.3 GHz) available but needs to be resurrected**

# Past Experience: Design, Fabrication and Low-Power Test of Cavities

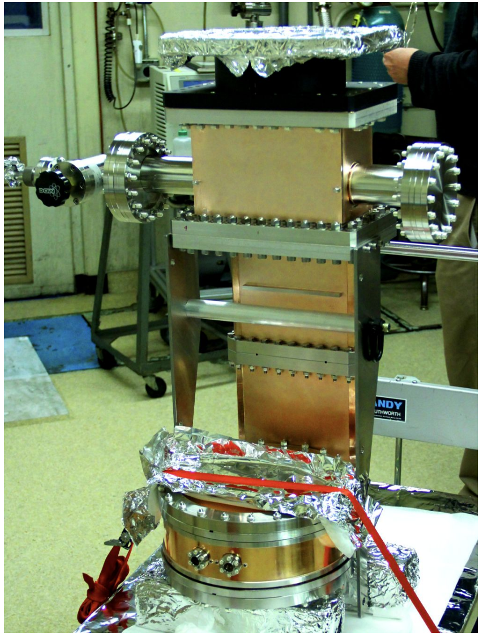
## 805 MHz Modular Cavity Thermal Simulation

- RF field thermal load generated using Omega3P/S3P of ACE3P code suite

- Thermal and mechanical stress analyzed using ACE3P multi-physics module TEM3P




| | $E_{max}$ | σ for Beryllium | Duty Factor |
|---|---|---|---|
| Case 1 | 25 MV/m | 2.33e7 S/m | 0.001 |



Li, Zenghai, et al. "RF optimization and analysis of the 805-MHz cavity for the MuCool program using ACE3P." *AIP Conference Proceedings*. Vol. 1507. No. 1. American Institute of Physics, 2012.

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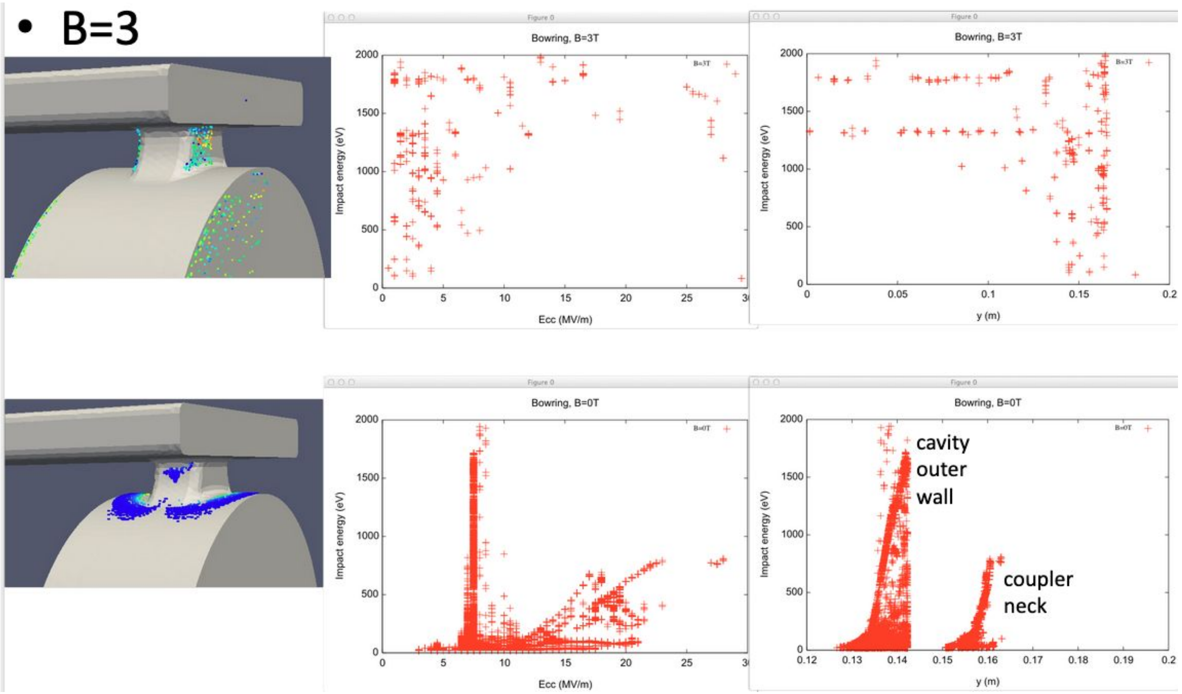
# Past Experience: Modeling of Emission

## 805 MHz Modular Cavity Multipacting , B = 3 T

- Impact of field emission and multipacting under high magnetic field analyzed using ACE3P codes suite
- RF field generated using Omega3P/S3P field solver
- External magnetic field applied for particle tracking study
- Multipacting bands and location identified using particle tracking module Track3P of ACE3P




Ge, Lixin, et al. "Multipacting simulation for muon collider cavity." *PAC09, WE5PFP020* (2012).

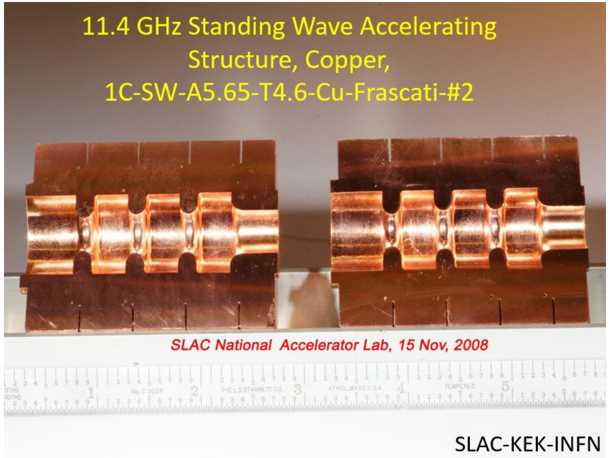
# Experience from the High Gradient Collaboration

## CERN, SLAC, INFN, KEK, LANL + many partner university and institutes

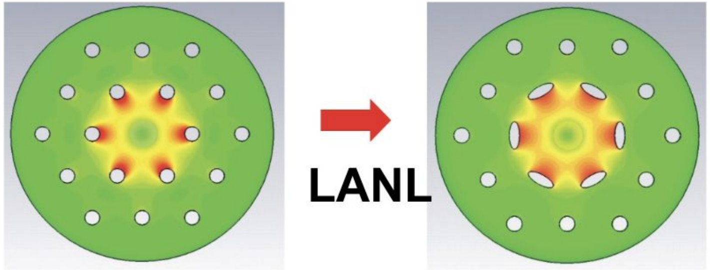
Robust experimental results with efforts focused towards:

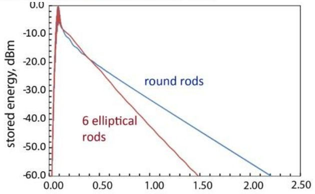
Material origin and purity, surface treatments, manufacturing technology

- Consistency and reproducibility of test results
- >50 structures tested at SLAC in ~10 years






**Decay of the energy stored in HOMs 14-18 GHz.**



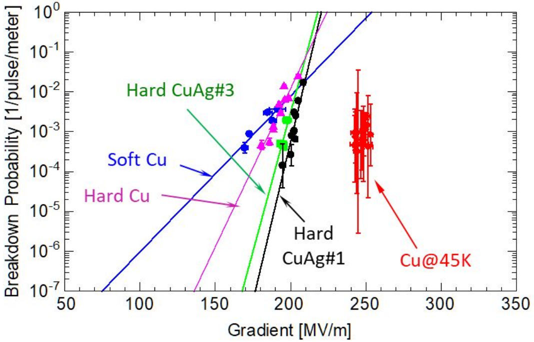
V. Dolgashev, B. Spataro, E. Simakov

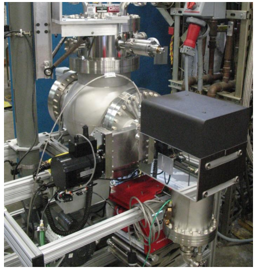
# Motivation for Developing Cold Copper RF Accelerators

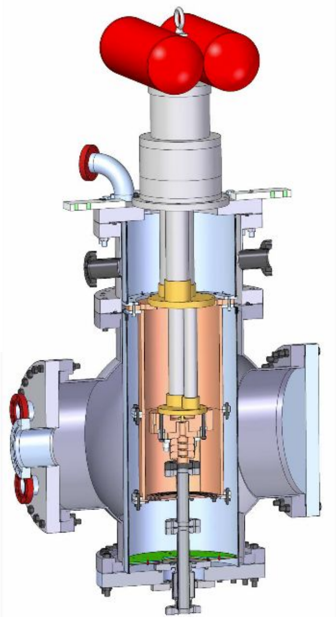
Cold-copper established as a pathway for achieving high gradients in single cavities (2015)

Distributed-coupling established a novel topology for achieving higher efficiency (2018)

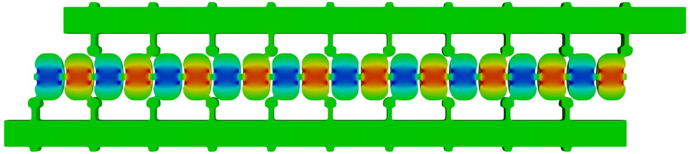
Cold-copper program has focused on understanding fundamental limits





- What gradients can we achieve?
- How efficient can we make these structures?
- How do we achieve and maintain precision alignment?
- Can we preserve beam quality with damping and detuning?
- Can we operate at higher beam powers?
- Is this concept scalable?



[High Gradient Workshop (2015)]
[PRAB 21, 102002 (2018)]

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# First Demonstration of Cold Copper Accelerating Structure

## 140 MeV/m measured with beam tests at NLCTA

Breakdown rate (BDR) reduction by 50x from room temperature operation

Breakdown limits primarily driven by high H-field regions within cell coupler

**Ernest Courant Outstanding Paper Recognition**


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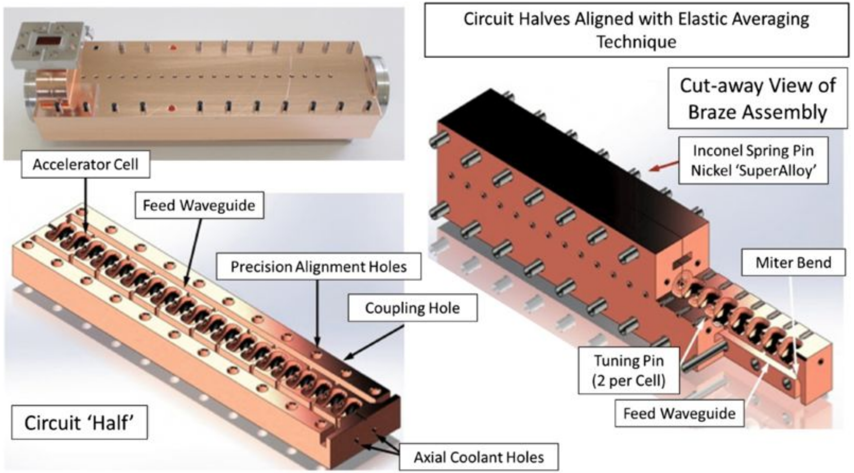
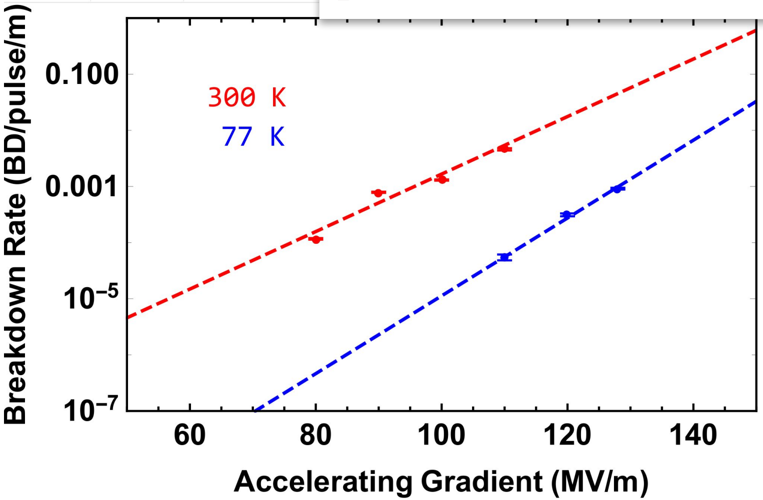
Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature

Mamdouh Nasr, Emilio Nanni, Martin Breidenbach, Stephen Weathersby, Marco Oriunno, and Sami Tantawi
Phys. Rev. Accel. Beams **24**, 093201 – Published 13 September 2021




PRAB 23, 092001 (2020)

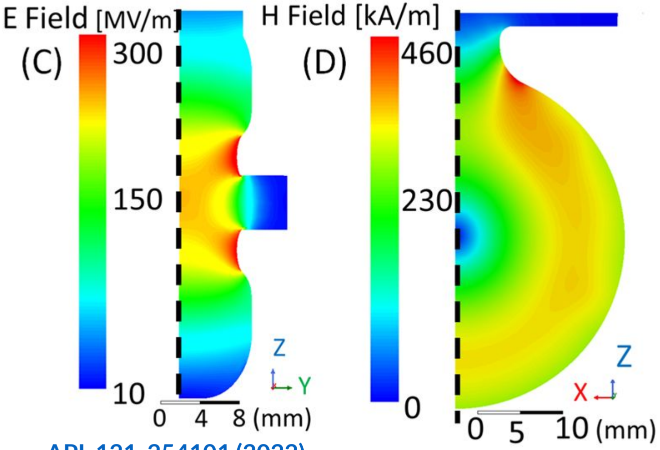
PRAB 24, 093201 (2021)

**Cold copper can dramatically reduce breakdown rates at high gradient**

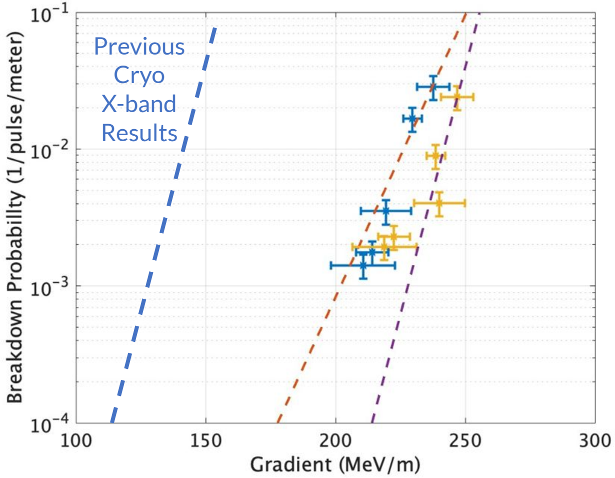
# Single Cell High Gradient Tests with Cu and CuAg Cavities

## High power tests at LANL (room temp) and Radiabeam (cryo) with up to 5 MW per cavity

- Improved coupler design significantly reduced breakdown probability
- **C-band cavities were able to reach gradients over 250 MeV/m in cryogenic tests**
  - C-band is a sweet spot for driving high power beams with high efficiency
- **~2.5X reduction in peak power required compared to 300K copper**

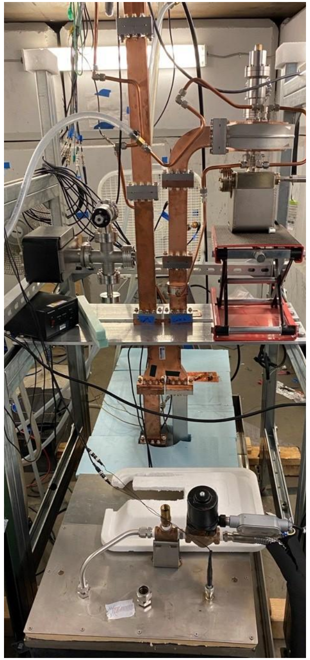



[APL 121, 254101 (2022)](#)
[IPAC2024 p. MOPR29](#)




**Improved RF design further enhances the achievable gradient**

Test at Radiabeam



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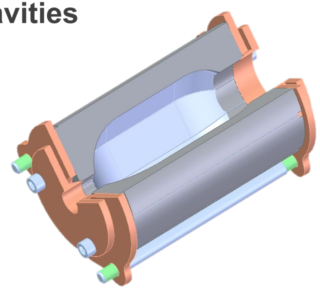
# RF Testing of High Temp Superconductors (HTS)

## Exploratory research to develop the basis for a HTS based RF cavity for pulse compression

Using the same cryostat that kicked off cold copper work, high power RF testing of HTS samples is underway

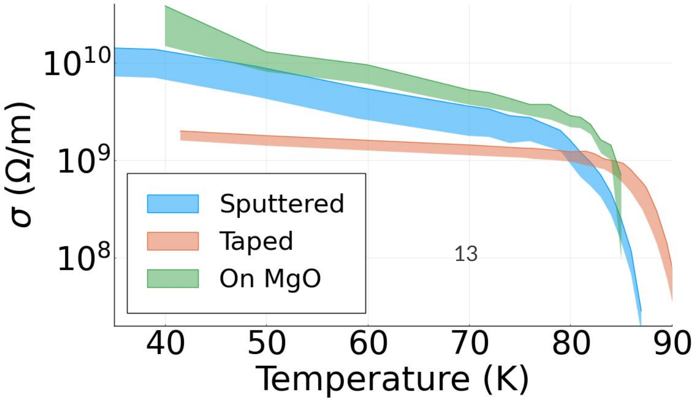
- Samples are deposited on copper and MgO as well as HTS tapes or compressed pucks
- **HTS coated samples can function in strong magnetic fields, potential candidate for muon cooling cavities**
- Estimated $Q_0$ for HTS cavity using the TM010 mode at 77 K is 150,000 (versus 22,500 for copper)
- **>10X reduction in peak power required compared to 300K copper**



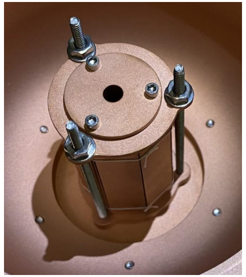
Cryostat


HTS Sample

Sample Conductivity with High Power




Prototype HTS Cavity



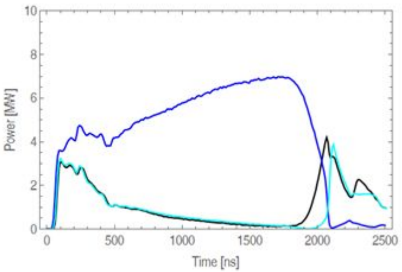
IPAC2024 p. WEPS37

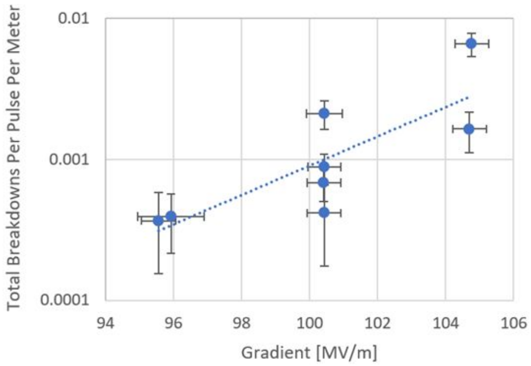
**HTS materials represent a new regime of SRF applications**

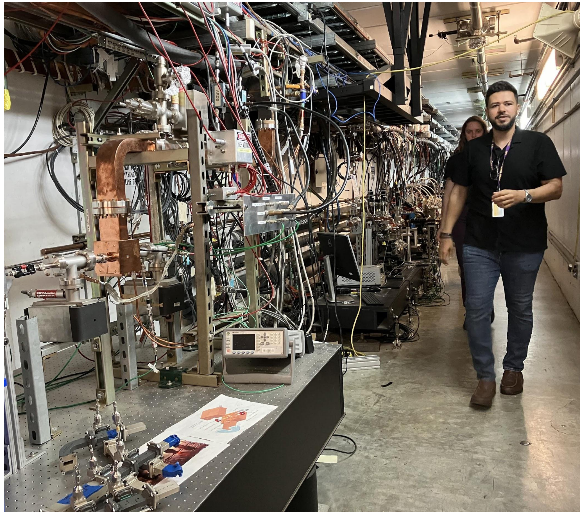
# High-Gradient Testing at S-band

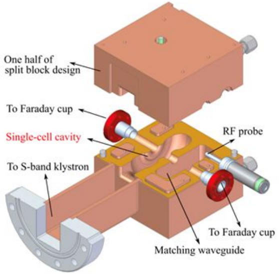
- High gradient testing of new accelerator designs
- Cavities optimized to reduce surface fields while maximizing gradient
- Comparative studies at different frequencies
- Current installation is a single cell S-band prototype fabricated for Accelerator Stewardship project
- Nominal input 400 kW, 30 MV/m
- Achieved 1 MW, 50 MV/m before observing breakdowns, now testing up to 6.7 MW
- Target application: energy scanning for proton therapy

Measured forward and reflected power at NLCTA with estimate of reflected power.






| | Desig n | Cold Test |
|---|---|---|
| *f* (GHz) | 2.856 | 2.853 Cu-Ag, 2.854 Cu |
| Q0 | 11936 | 12014 Cu-Ag, 12197 Cu |
| Coupling β | 1.0021 | 1.04 (both) |

# Possible Option for Magnet

## Target 5 T (7 T?) on axis, full immersion for 1.3 GHz cavity (or higher)

Preparing to place requisition

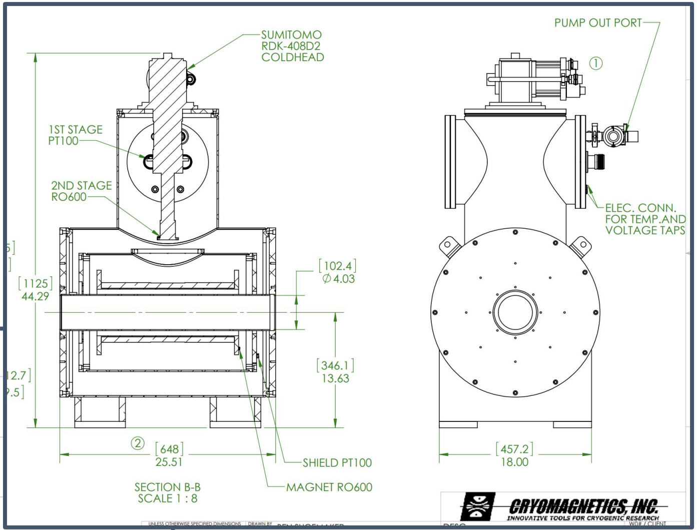
Will target 9.5” warm bore

+/- 1% field variation >10 cm

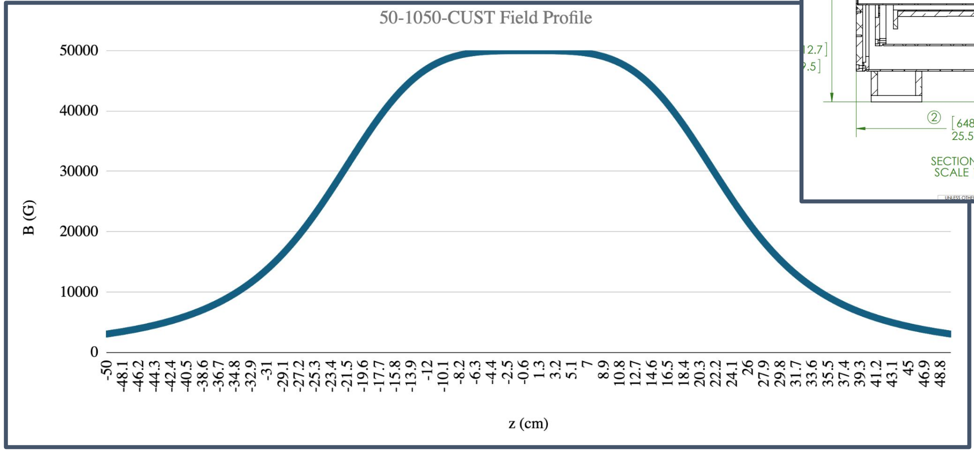
Cryogen-free magnet

Engaging Cryomagnetics for preliminary design and budgetary estimates

Comparable Magnet Cryostat




Longitudinal Field Profile

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# Possible RF Studies for Discussion

| | Leverages Existing Facilities | | Multiple Scenarios/Pathways Possible Should Optimized Across Collaboration | | |
|---|---|---|---|---|---|
| | 2025 | 2026 | 2027 | 2028 | 2029 |
| **Test Stand** | Install 5 T (7 T?) Magnet at NLCTA | Commission with S-band Cu Cavity Tests | Add X-band Capability | Revive L-Band Source | Transfer Magnet to 476 MHz Bunker |
| **Physics Studies** | | Normal Conducting Cavities | Cold Copper and/or Different Materials, Geometries | High Temperature Superconductors | Multi-Cell Cavities |
| **Design Studies** | | Benchmarking | Frequency Scaling | Cooling Cavity Designs | Multi-Physics Analysis |

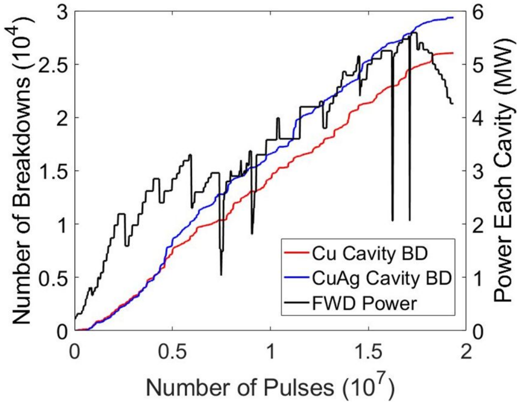
**Opportunities to collaborate in defining path, structure design, testing cavities and analysis**

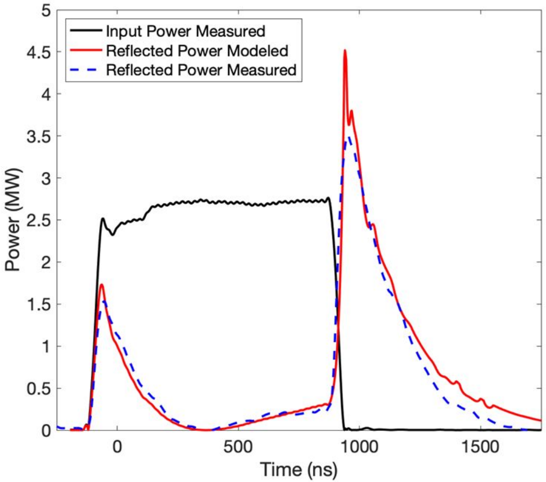
# Questions?

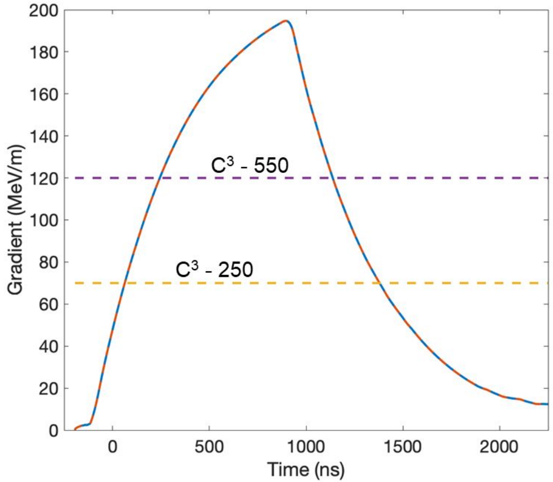
# Single Cell Cryogenic High Gradient Tests

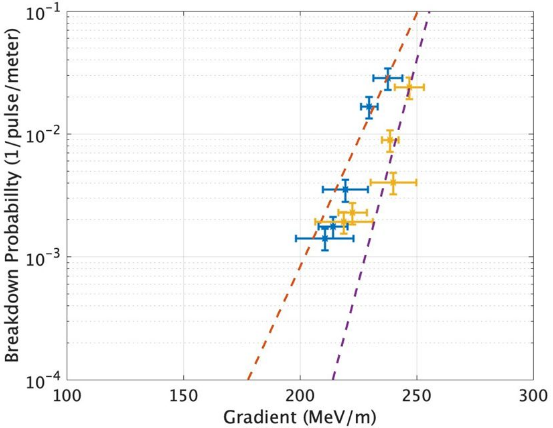
## First demonstration of high power tests up to 5 MW per cavity with Cu and CuAg

- Cavities were able to reach gradients over 250 MeV/m
- Demonstration of CuAg improvement over Cu at cryogenic temperatures



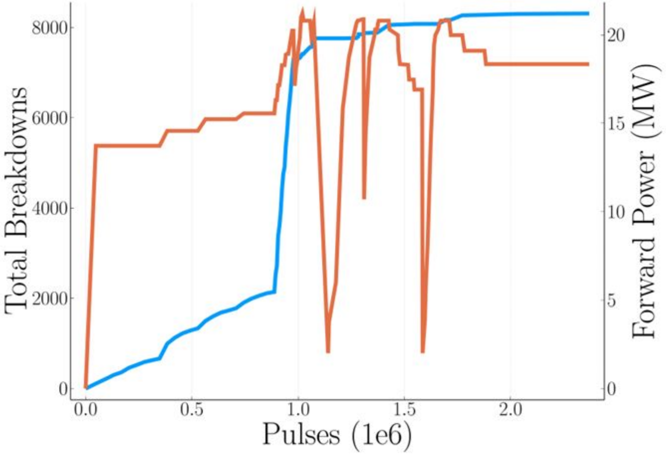



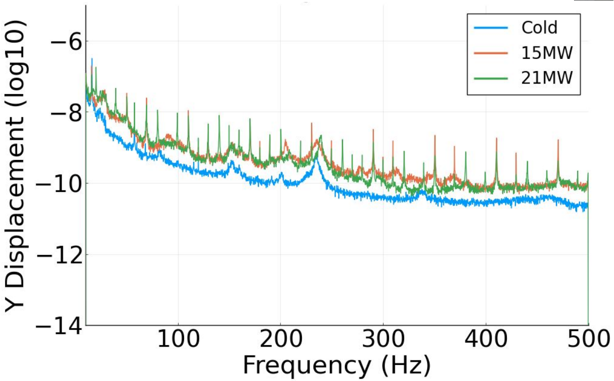

SLAC M. Schneider, et al. JACoW , Vol. IPAC2024 p. MOPR29.

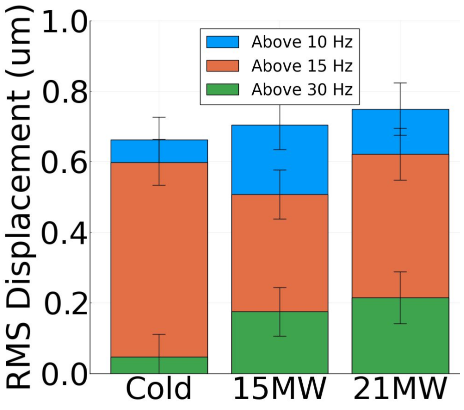
# Meter-long Linac Cryogenic High Gradient Tests

## Conditioned Linac at Radiabeam up to 21 MW, 60 Hz, and 1 μs

- Conditioning limited by klystron, not structure
- Reached 60 MeV/m for 21 MW
  - At 50 MeV/m BDR was O(10-6) /pulse/m after 2M pulses
  - Breakdown events remained localized within structure
- Vibration measurements showed displacements within 1 μm

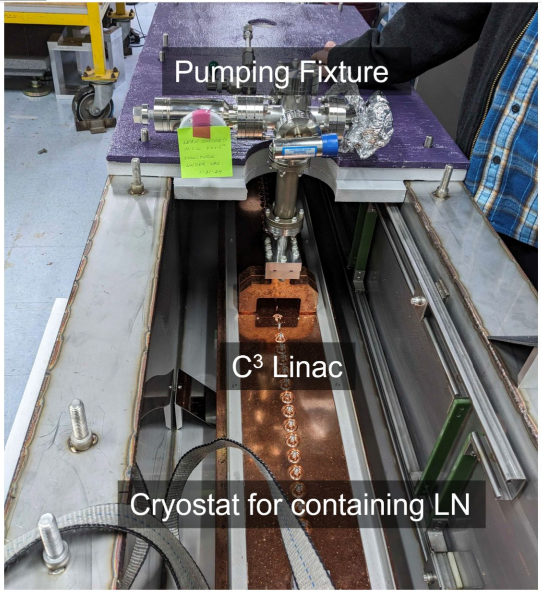



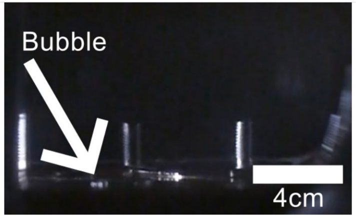
# Vibration Characterization of Liquid Nitrogen Bubbling

## Prototype C3 Linac with a resistive heater was used to test vibrations within LN up to 2 kW

- Maximum displacement induced by heating LN remained around micron-scale, within expected tolerances
- Next tests within quarter cryomodule to test displacements and alignment with  Rasnik system



(a)



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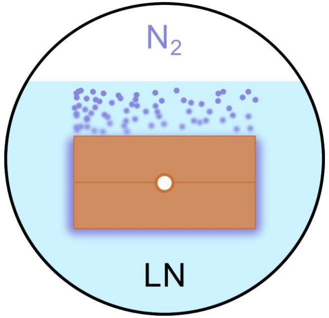

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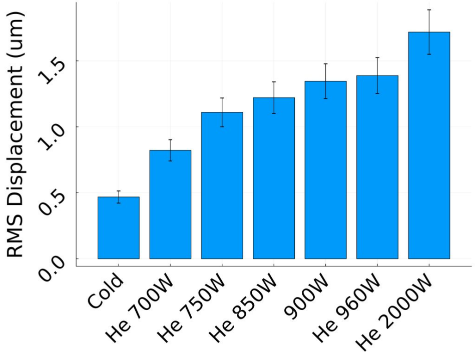
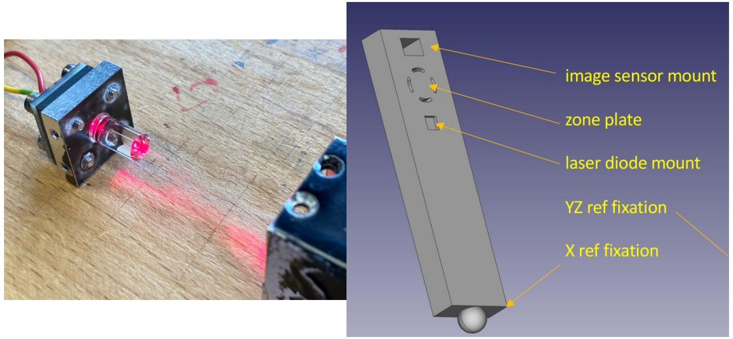


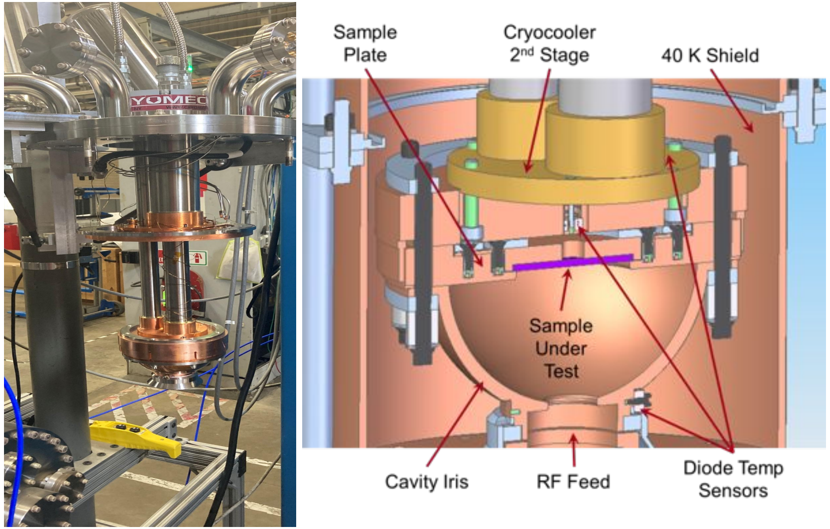


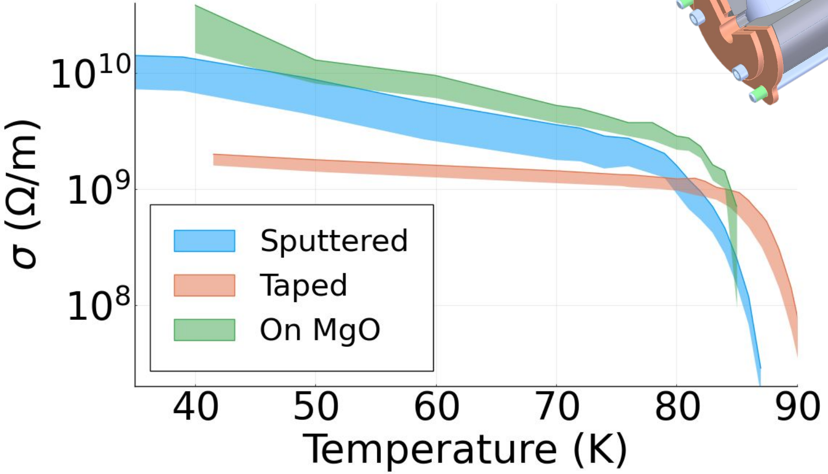

https://www.osti.gov/biblio/2371576

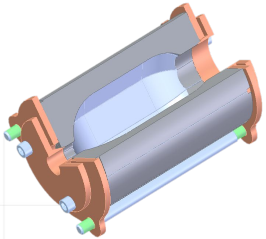
# RF Applications for High Temp Superconductors (HTS)

Using the same cryostat as in 2018, high power RF testing of YBCO deposited on Cu and MgO as well as YBCO tapes is underway

Exploratory research to develop the basis for a HTS based RF cavity for pulse compression



 A. Dhar, et al. JACoW , Vol. IPAC2024 p. WEPS37.

# Future Direction for Cold Copper R&D

Cold-Copper and Distributed Coupling -> demonstrated record gradients and record efficiency

- 6X reduction in RF Power
- 30% increase in gradient at the BDR needed for HEP applications

Key Scientific and Technical Questions

- Gradient – Understand impact of scaling to longer structures and different frequencies
- Vibrations / Alignment – Achieve and confirm sub-micron with cryogenic cooling
- Damping/Detuning – Material testing, beam simulations, and RF design for bunch trains
- Beam Loading and Stability - Understanding beam dynamics, wakefields,
- Scalability – Raft designs and integration

Quarter cryomodule will allow us to test these concepts at multiple frequencies and locations

- Demonstrate transformative impact of high gradient accelerators