High Gradient Testing of C-band Structures and Components

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Outline

- Motivation
- Related Experiments
- Safety Challenges at SLAC
- High Gradient Testing of C-band Structures and Components
  - Meter Scale C-band
  - Additive Load
  - Room Temp Single Cell Structures
  - Cryogenic Single Cell Structures

What's the Optimal Frequency for High Charge Beams?

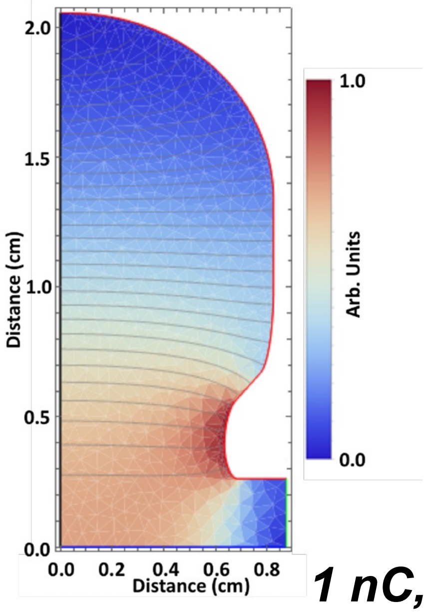
Linear collider: high beam power

→ 1 nC per bunch, 0.3 A during rf pulse

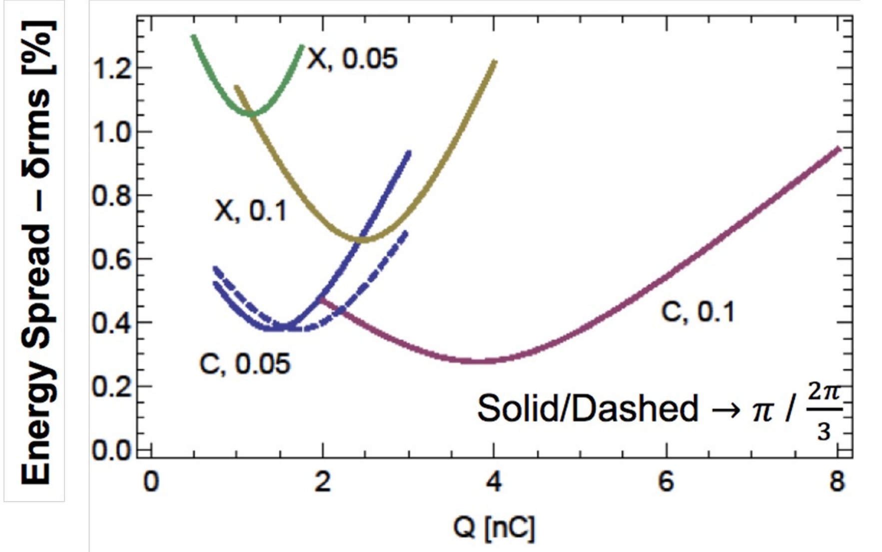
→ Most challenging design parameters

Pursue broad array of applications

→ Medical, x-ray sources, gamma-ray sources,….



1 nC, 150 micron, 25 deg.



Frequency	a/λ	Phase Advance	R_s (MΩ/m)
C-band (5.712 GHz)	0.05	π	121
C-band (5.712 GHz)	0.05	$2\pi/3$	133
C-band (5.712 GHz)	0.1	π	92
X-band (11.424 GHz)	0.05	π	176
X-band (11.424 GHz)	0.1	π	133

arXiv:1807.10195 (2018)

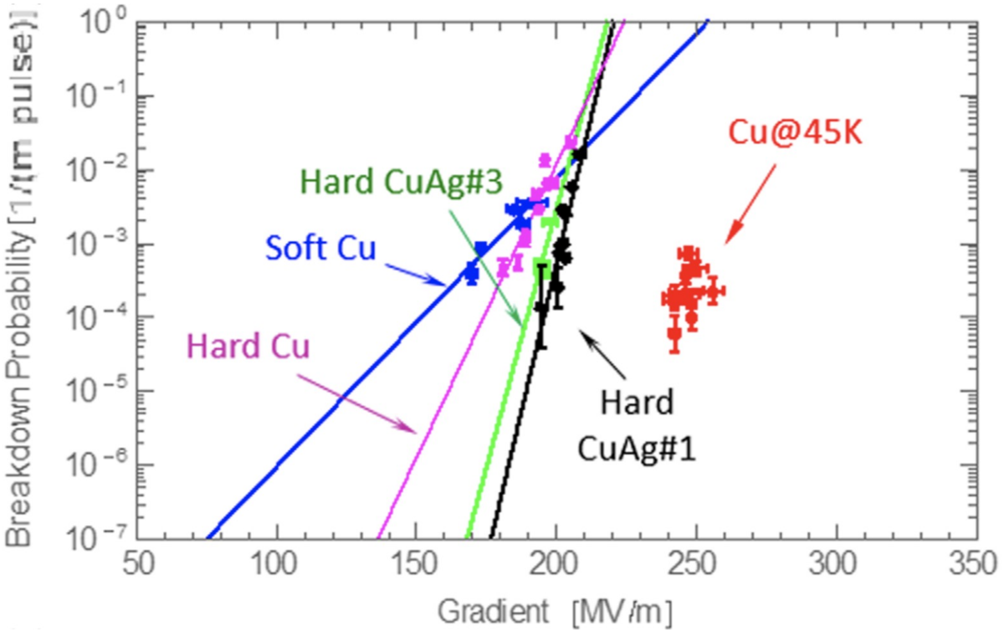
Cryo-Copper: Enabling Efficient High-Gradient Operation

Cryogenic temperature elevates gradient

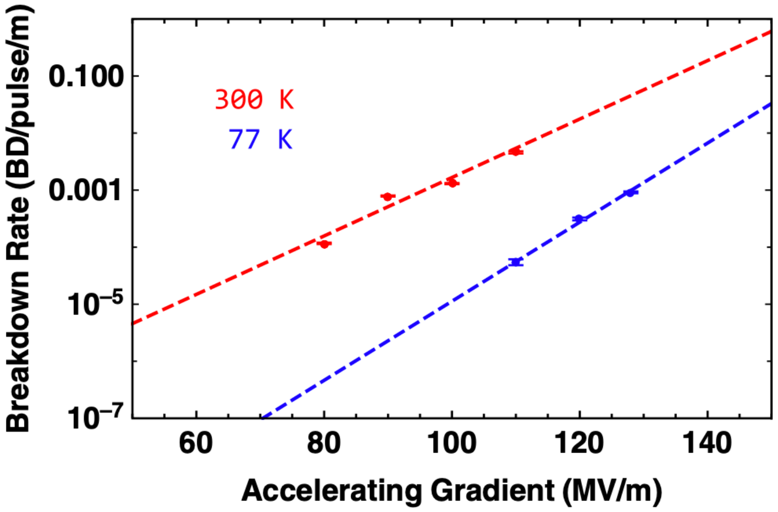
- Increased material strength is key factor
- Increase electrical conductivity reduces pulsed heating in the material

Operation at 77 K with liquid nitrogen

- Large heat capacity, simple handling
- Small impact on electrical efficiency

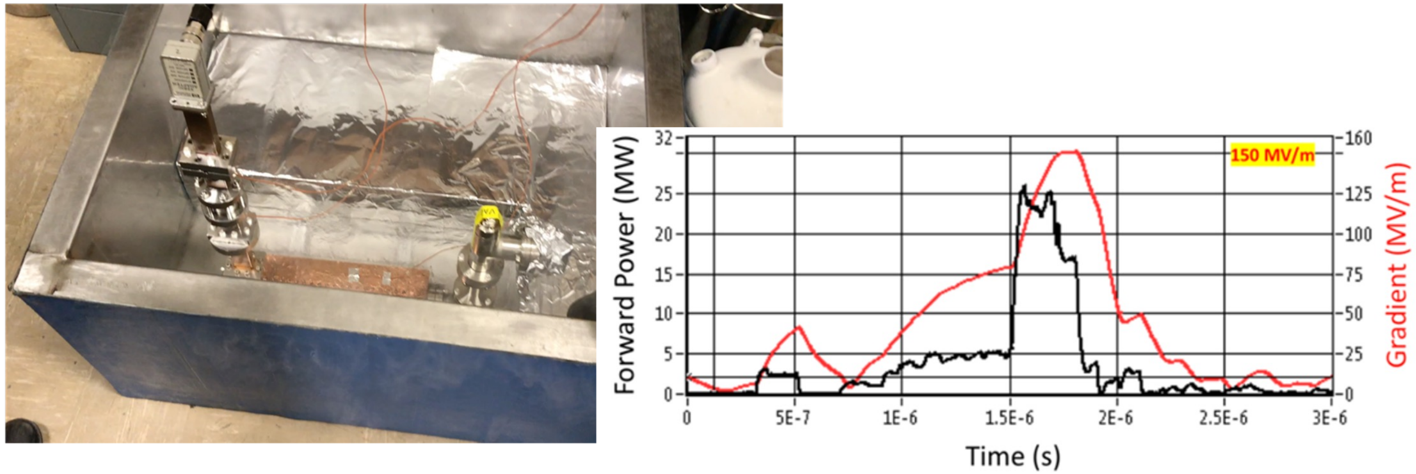


Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.



Nasr, et al. PRAB **24.9 (2021): 093201**

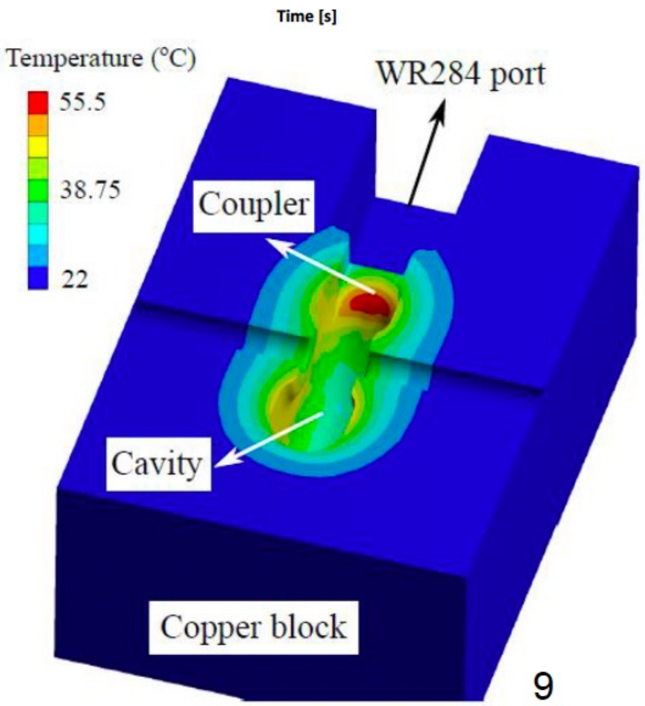
High Gradient Operation at 150 MV/m



Optimized RF Feed for Distributed Coupling Structure

- Energy modulator (and deflector) for rastering proton beams
- RF power coupled to each cell can lead to a local hot spot in H-field
- Tailoring coupler profile limits enhancement to 15-20% (vs. 230%)
- Built and tested on an S-band structure

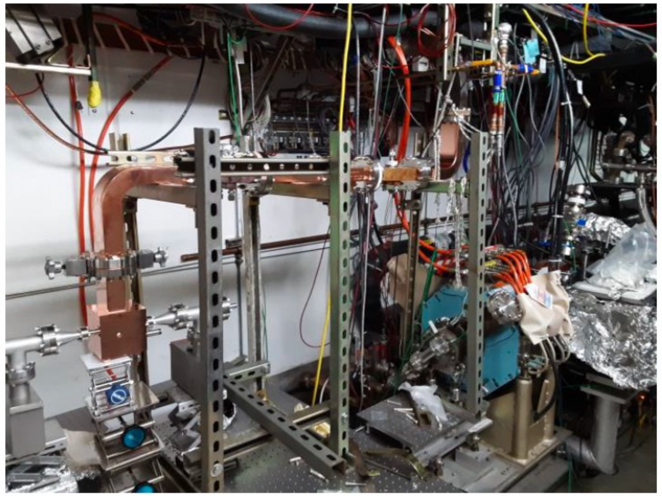
Lu, et al., *Review of Scientific Instruments* 92.2 (2021).

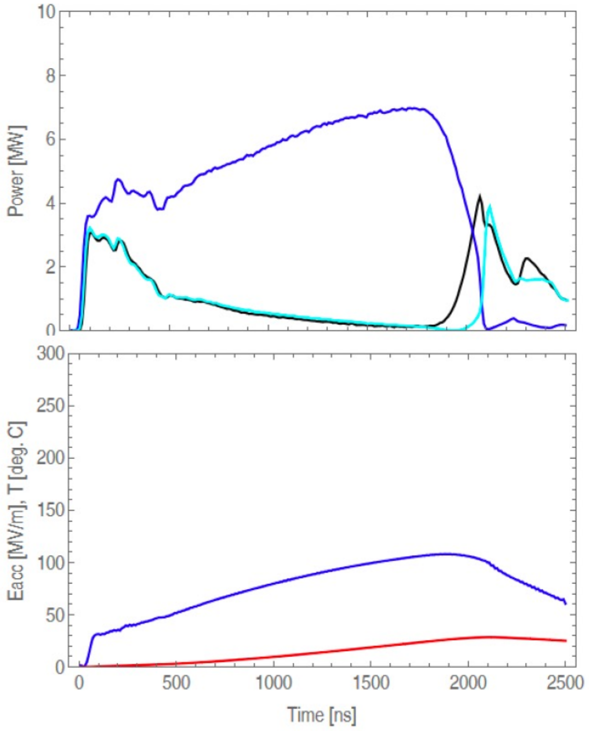


Single cell energy modulator prototype

-nominal input 400 kW, 30 MV/m

- Achieved 1 MW, 50 MV/m before observing breakdowns, now testing up to 6 MW





Measured forward and reflected power. Estimate of reflected power.

Calculated acceleration gradient and temperature rise

High Gradient Testing of C-band Structures and Components

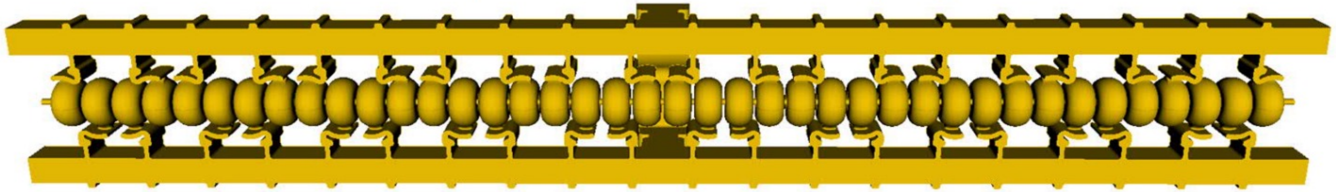
40 Cell Pi-Mode Distributed Coupling Structure

Incorporate the two key technical advances: Distributed Coupling and Cryo-Copper RF

Main linac utilizes meter-scale accelerating structures, technology demonstration underway

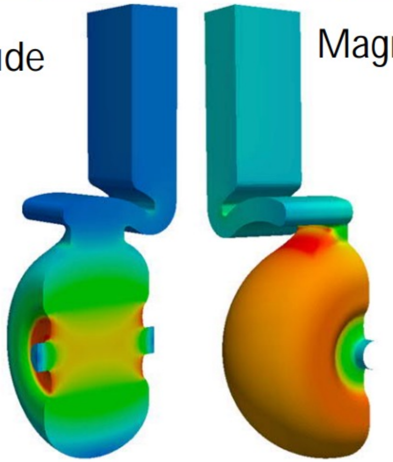
Implement optimized rf cavity designs to control peak surface fields

Vacuum Space for Distributed Coupling Linac



Electric Field Magnitude

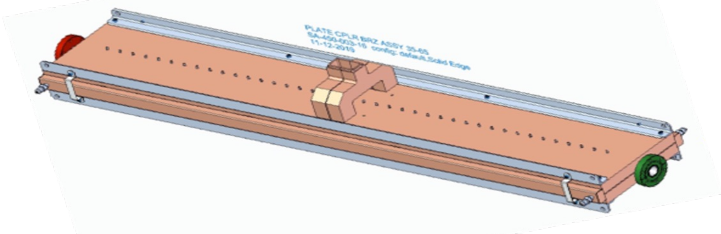
Magnetic Field Magnitude

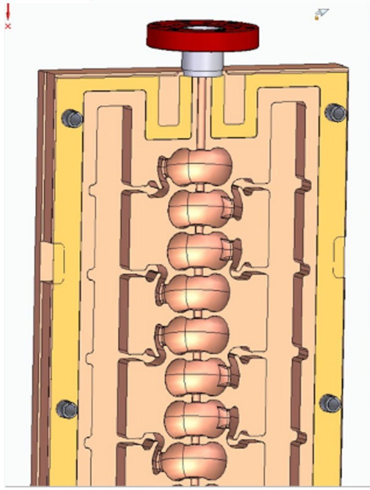


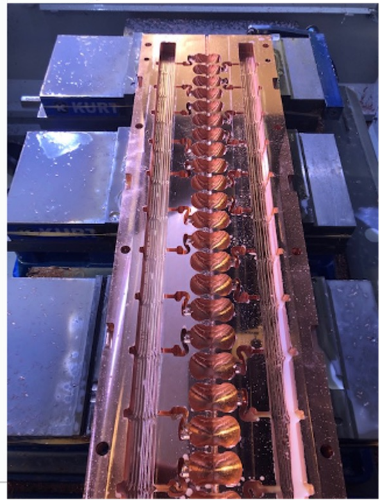
$$\frac{H_{peak}}{H_{unperturbed}} = 1.2$$

$$\frac{E_{peak}}{E_{acc}} = 2.22$$

Scaling fabrication techniques in length and including controlled gap

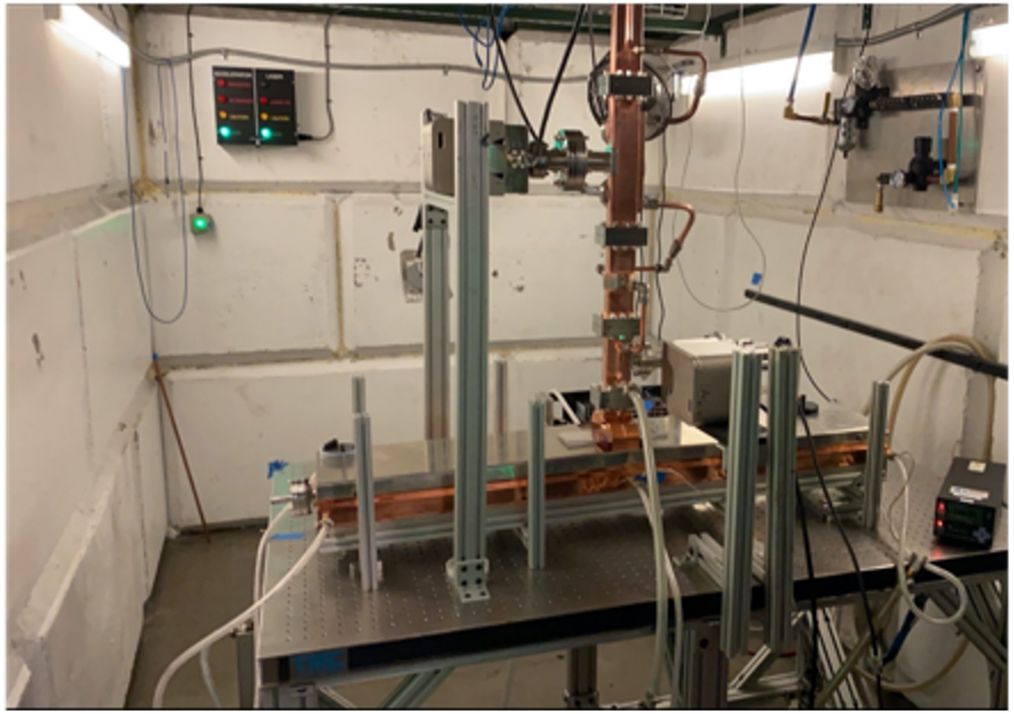


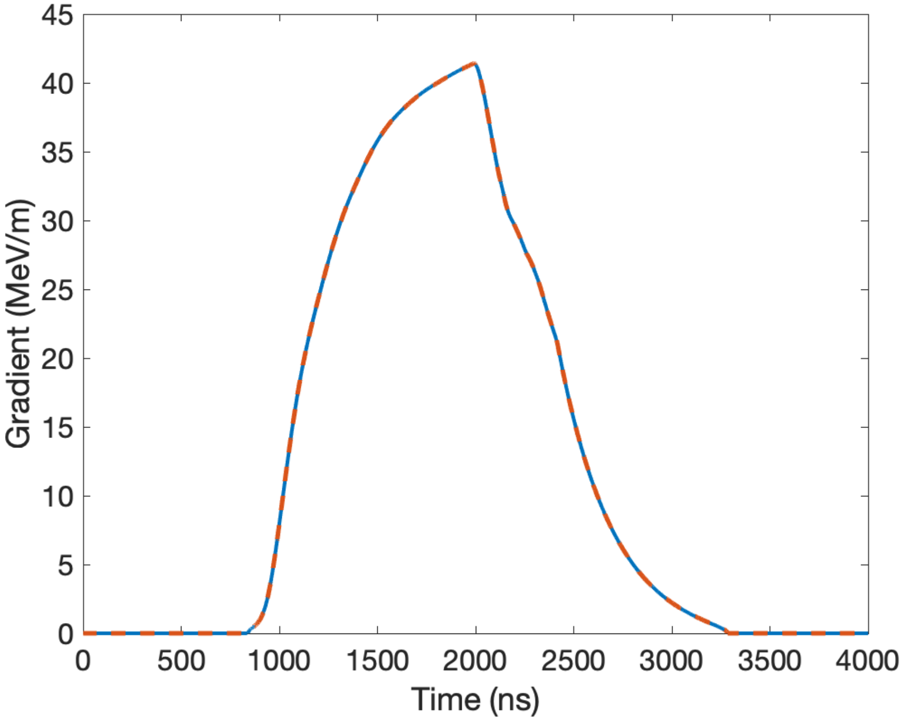




High Power Test of Meter-Scale Distributed Coupling Structure

- Tested at Radiabeam
- Up to 15 MW, 1 microsecond delivered to structure, no measurable breakdowns after reaching max power

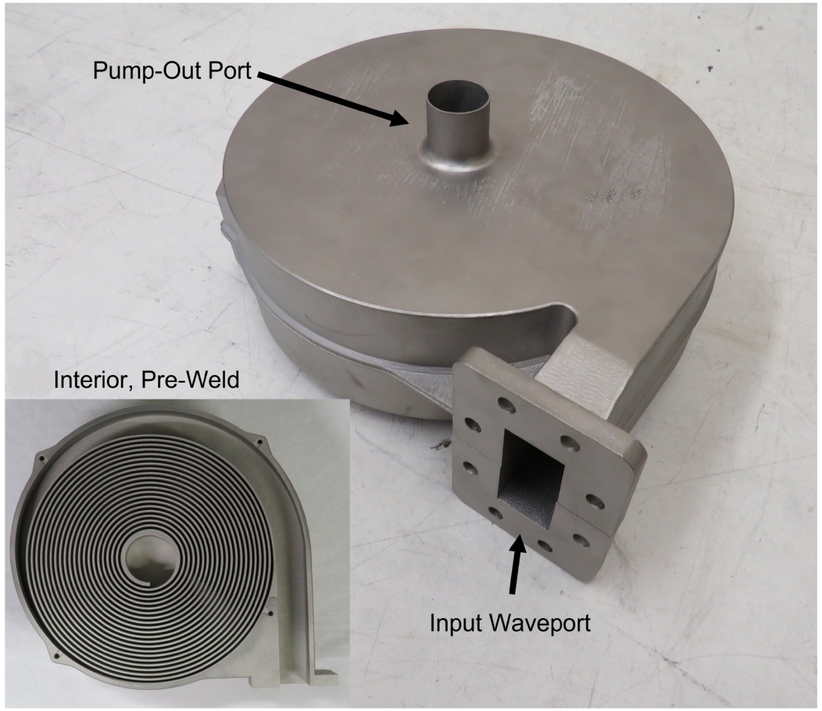


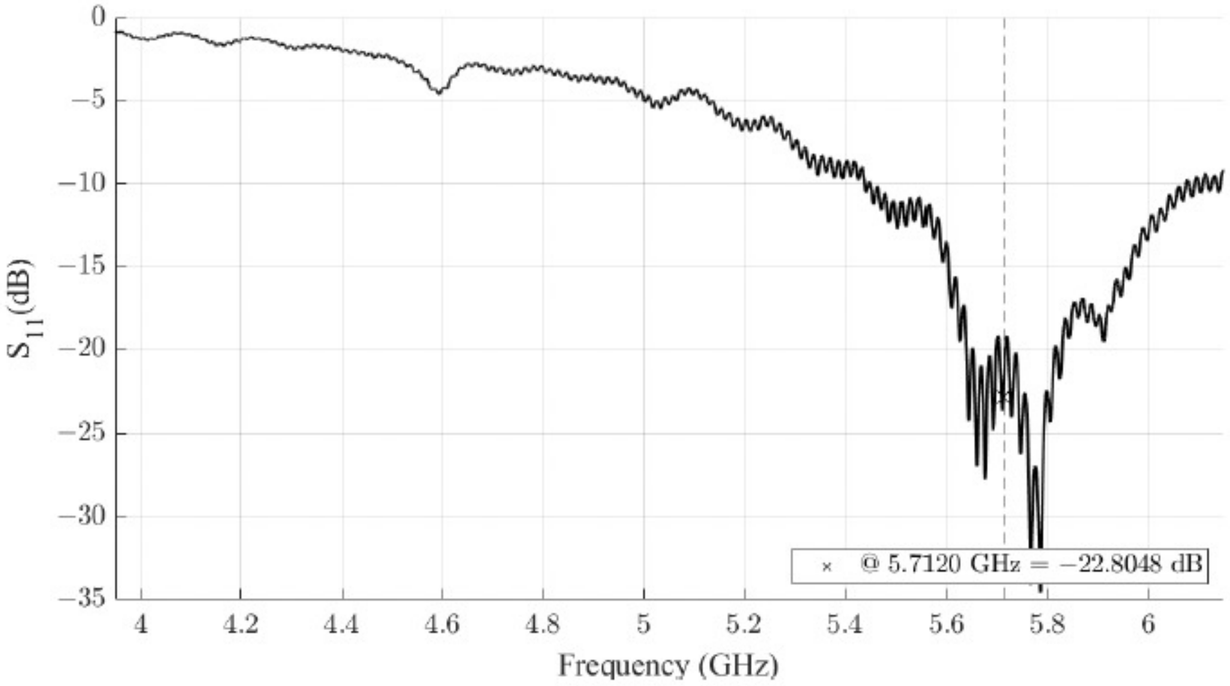


Structure Destroyed in Tuning Attempt for Cryogenic Operation
Structure for Cryogenic Operation in Production

Additively Manufactured Spiral Load

- Tested at Radiabeam
- 3D printed in stainless steel (inspired by CERN)
- First version is only air cooled

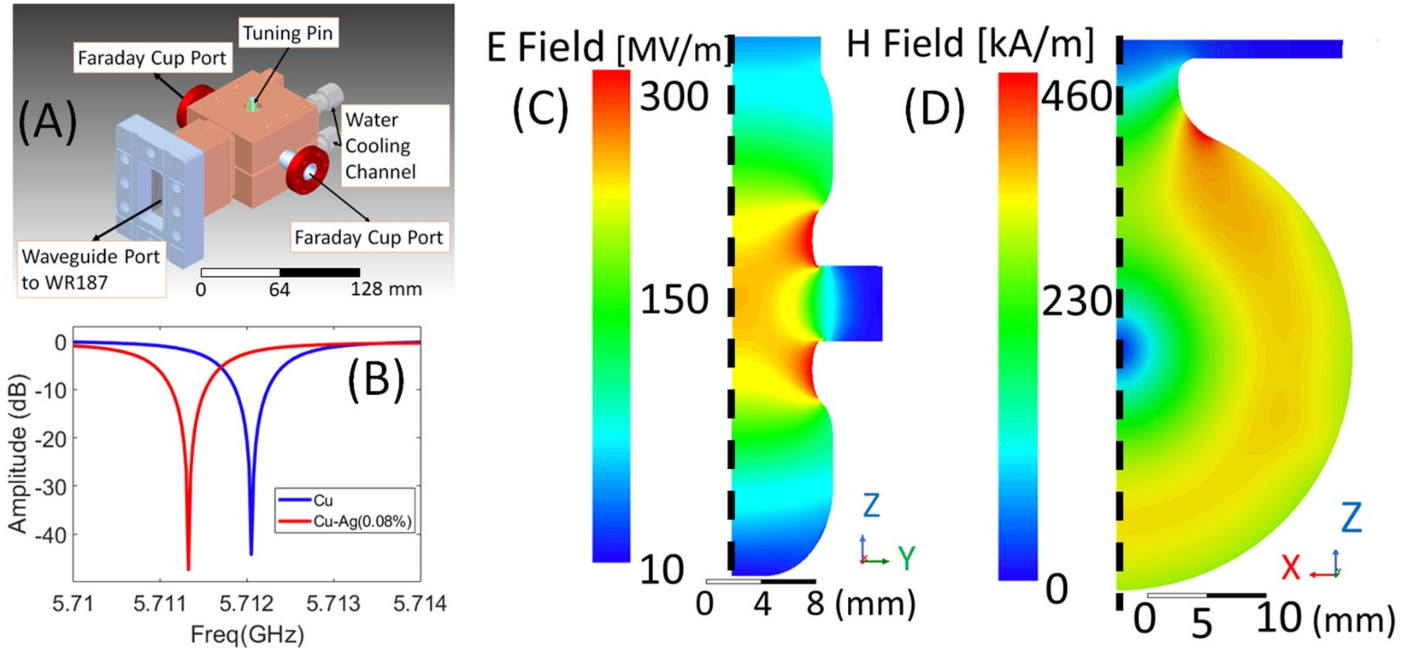




Tested to 8 MW, 20Hz, 700ns
Water Cooled Design for V2 (now in use)

Scaled Design of Low-Beta or Reduced Phase Adv. Struc.

- Original design was for low-beta protons – efficient with relativistic electrons and appropriate cell to cell phase advance

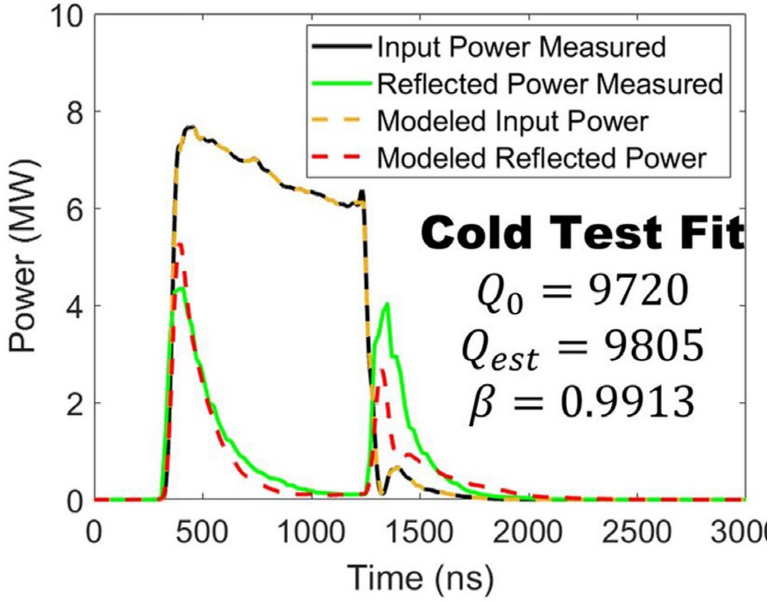


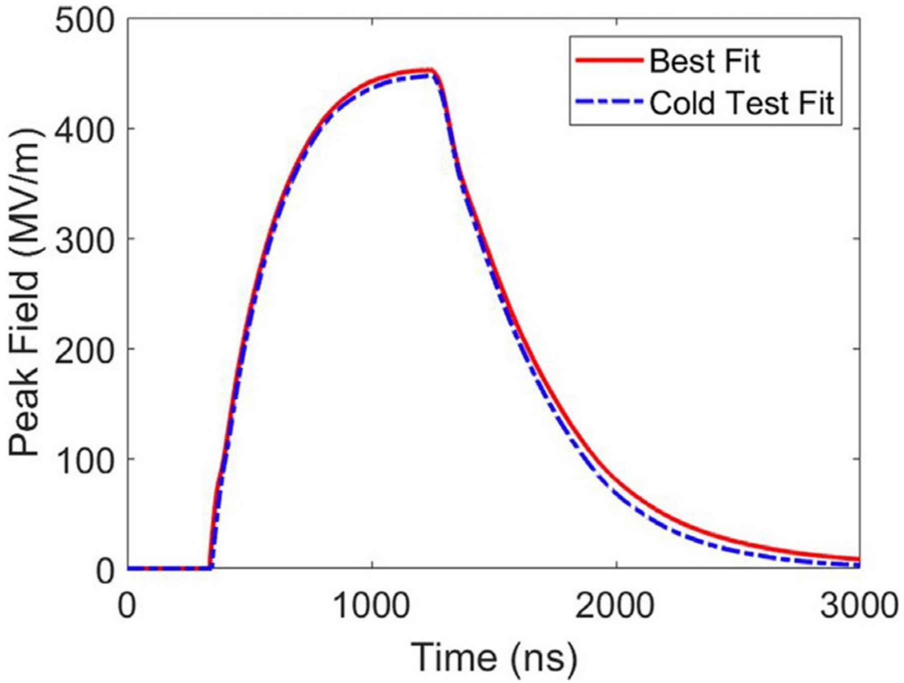
Parameter	Cu v = 0.5c Proton	Cu v = c Electron
Length	1.58 cm	
a/λ	0.0525	
Frequency	5.712 GHz	
σ	58 MS/m	
Q_0	9762	
Q_{ext}	10 165	
R_s	61.51 MΩ/m	115.8 MΩ/m
E_a	$62\ \mathrm{MeV/m} \times \sqrt{P\,[\mathrm{MW}]}$	$81\ \mathrm{MeV/m} \times \sqrt{P\,[\mathrm{MW}]}$
E_p/E_a	2.42	1.84
$H_p * Z_0/E_a$	1.40	1.07

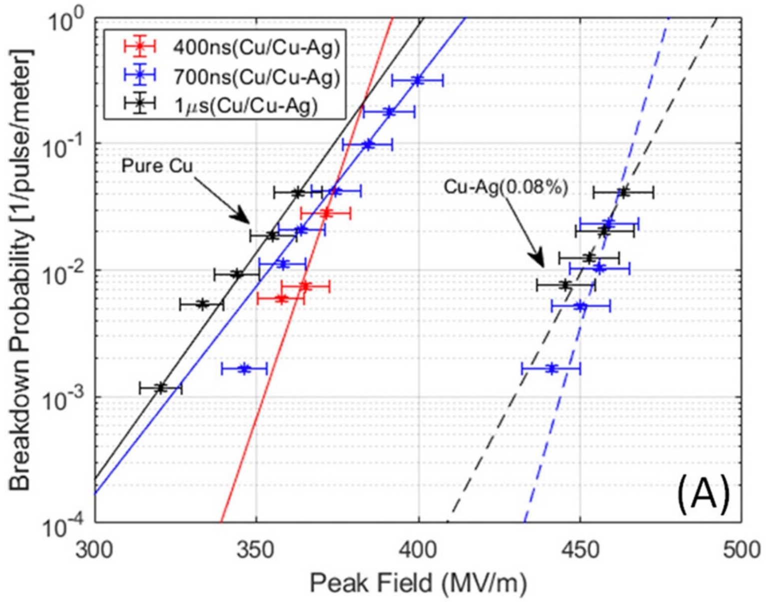
Schneider, Mitchell, et al. "High gradient off-axis coupled C-band Cu and CuAg accelerating structures." *Applied Physics Letters* 121.25 (2022).

High Gradient Performance of Cu and CuAg Cavities

- Utilized C-band test stand at LANL
- Each structure processed for O(100M) pulses



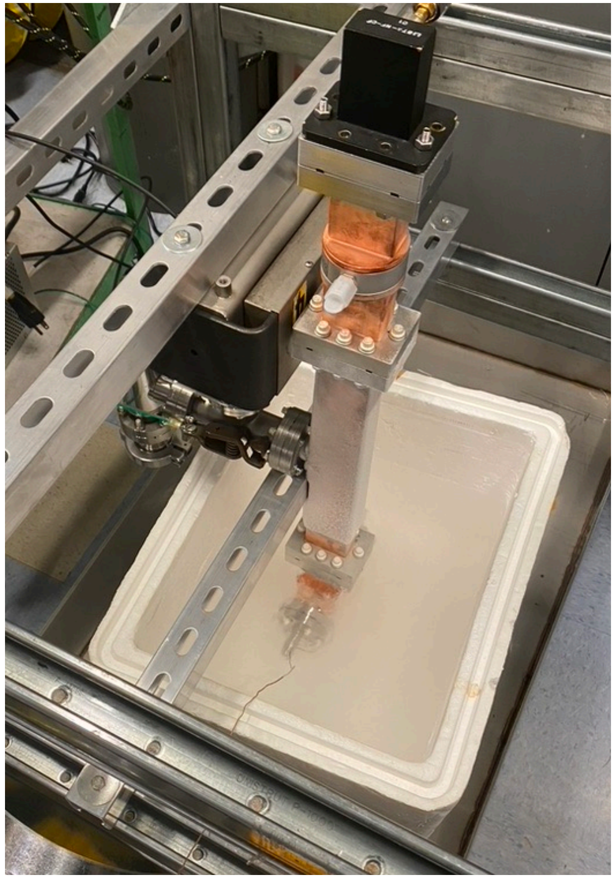


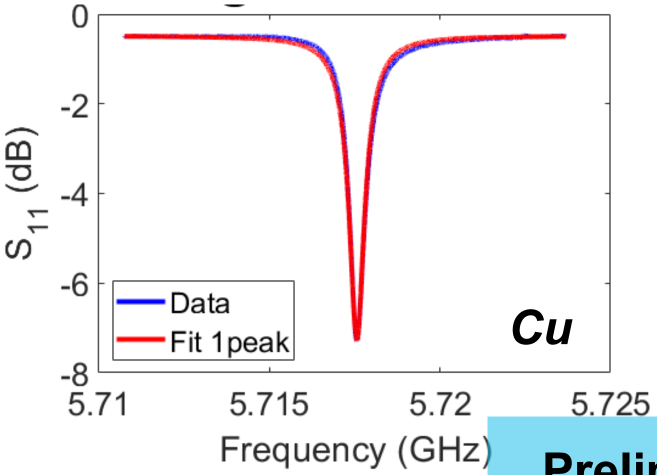


How does this behavior extend to cryogenic temperatures?

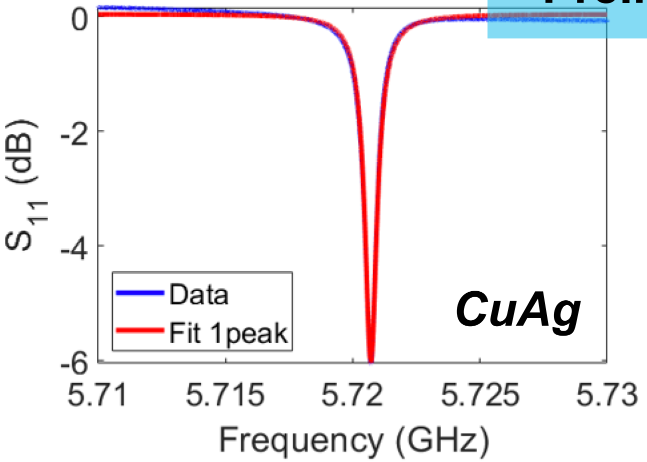
Characterization at 77K

- Improvement of 2.5 X for Cu and 2.9X for CuAg(!)
- 2.9 is consistent of Cu sample measurements at UCLA (may be material batch specific)



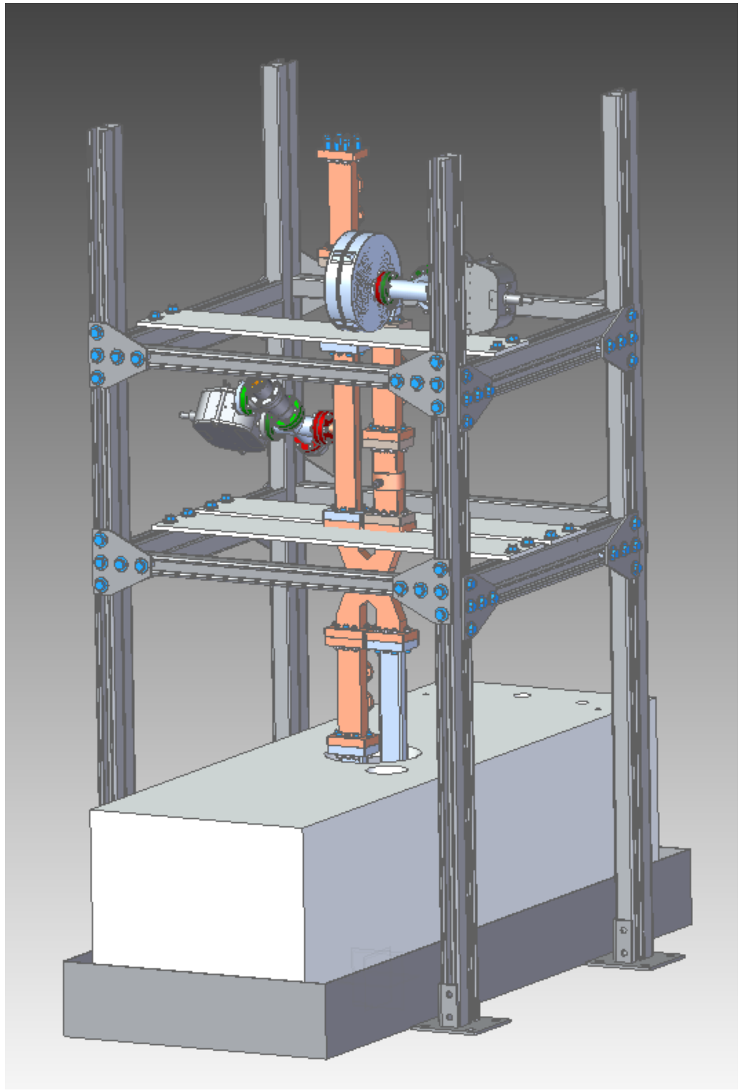


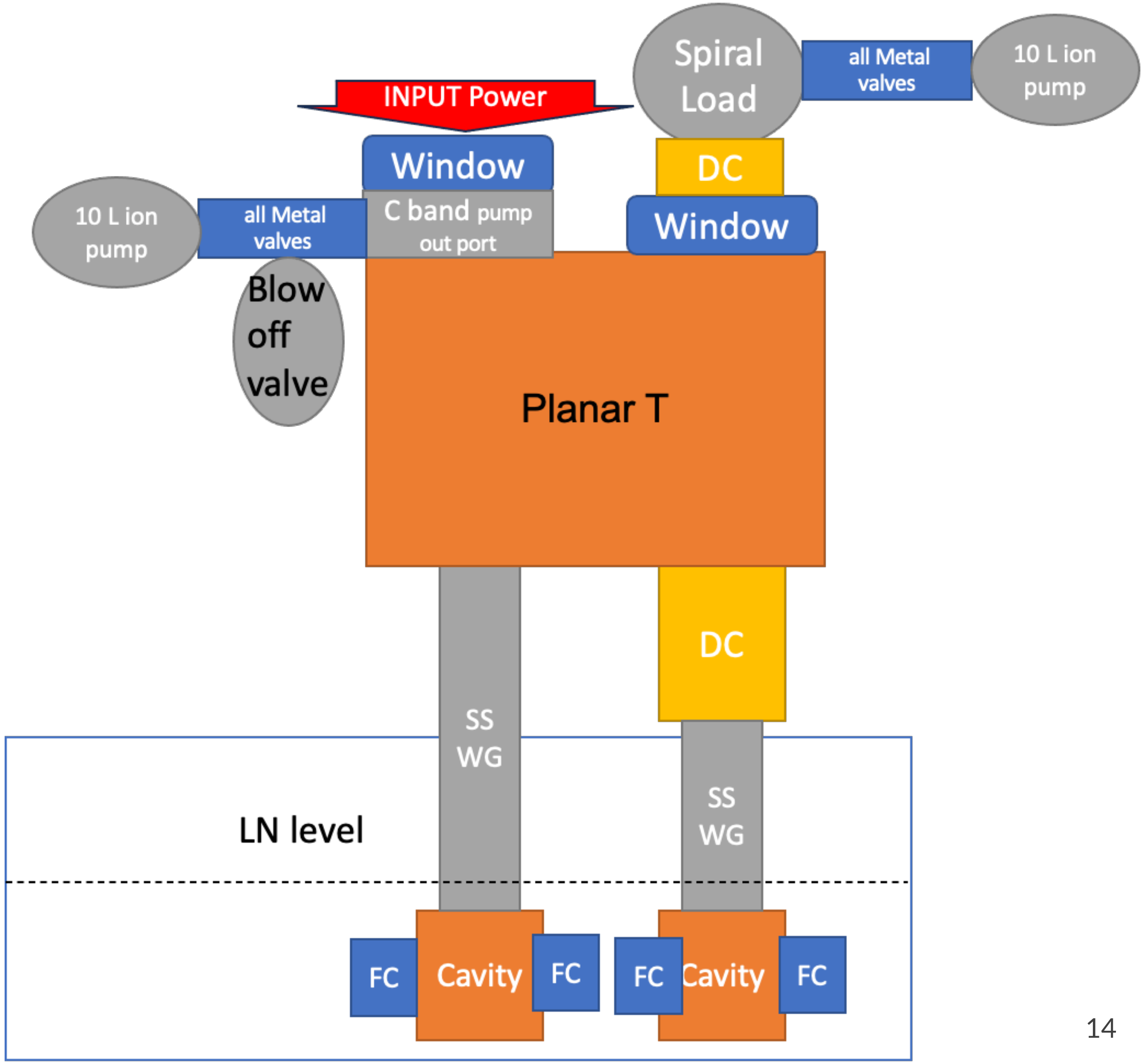
Preliminary



Parameter	CuAg	Cu
Temp	77K	
Frequency	5.71455 GHz	
Length	1.58 cm	
β	2.97	2.683
Q_0	29,695	25,697
Rs ($M\Omega/m$)	352	305
Ea MeV/m/$\sqrt{MW}$	141	131

Two Cell Assembly for High Power Test





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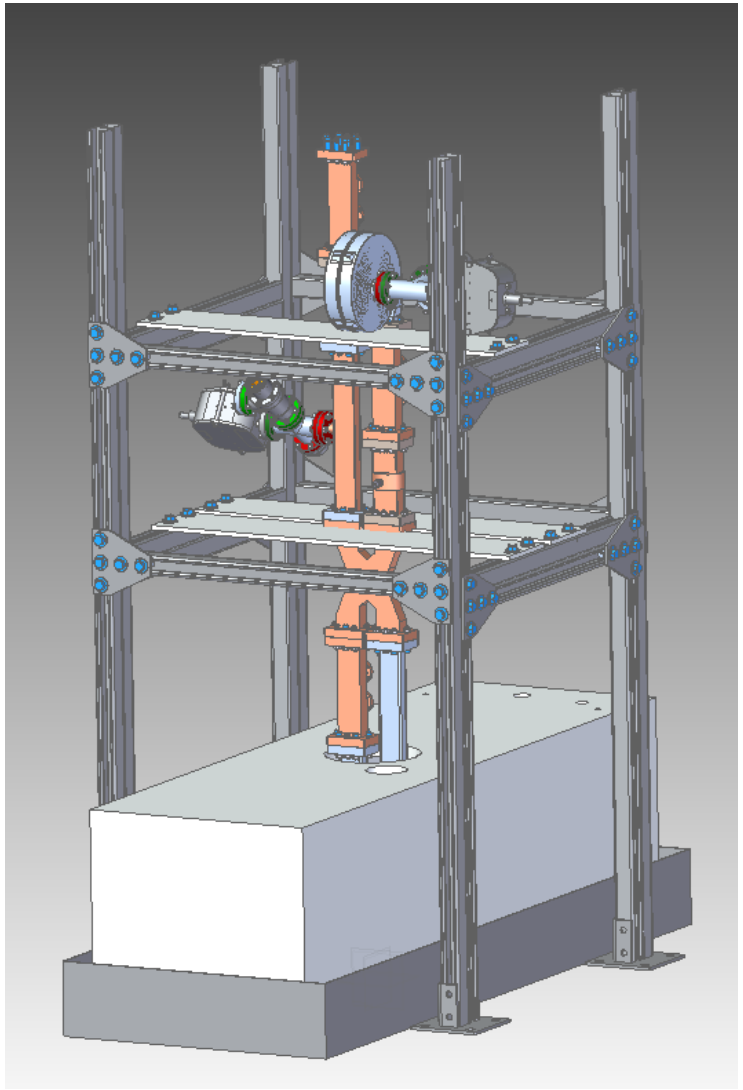
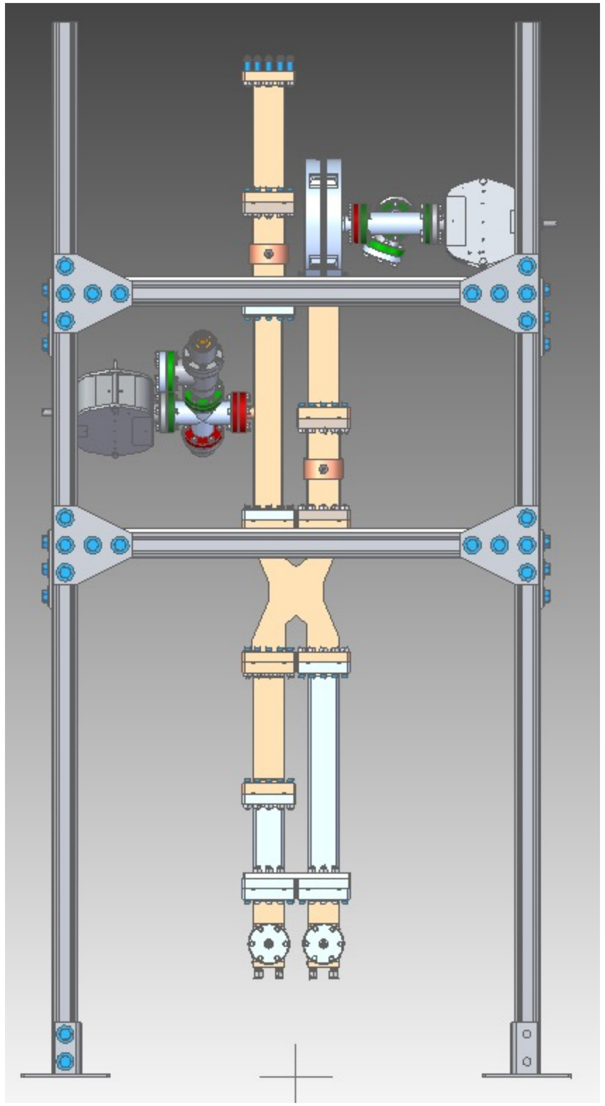
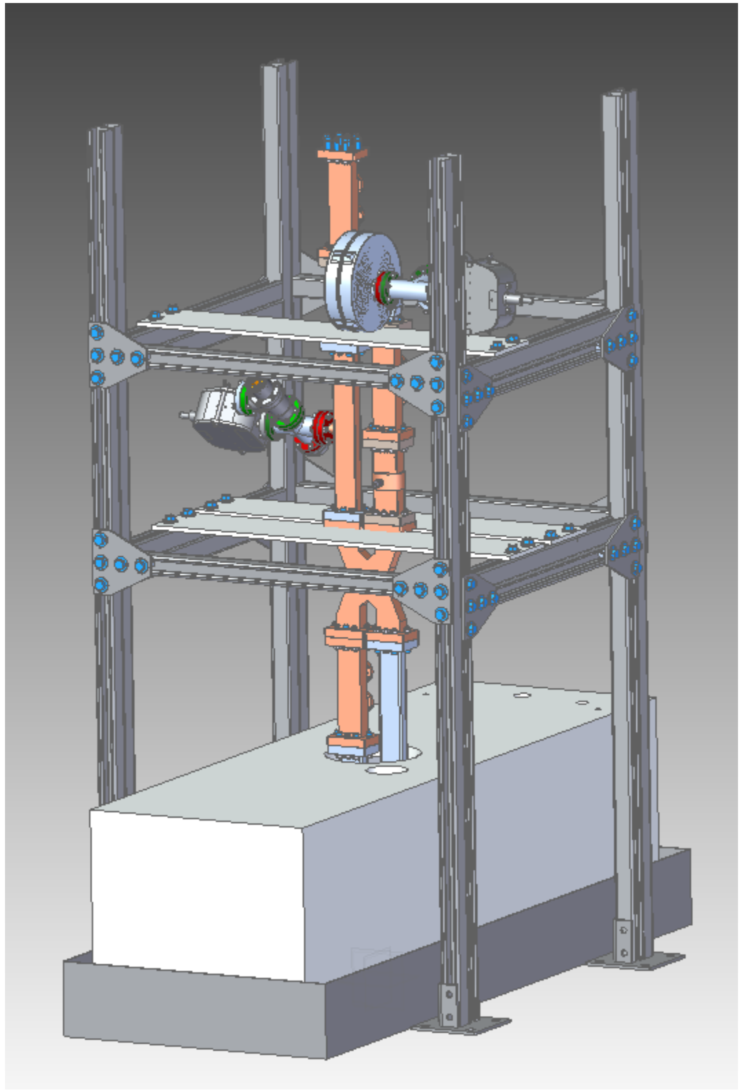
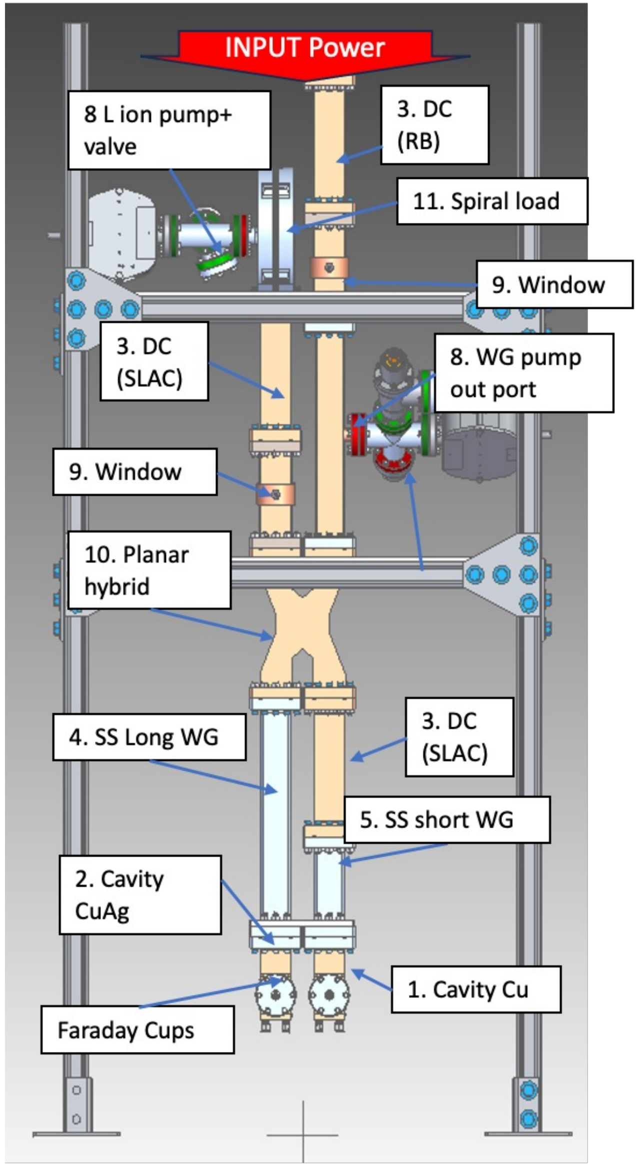




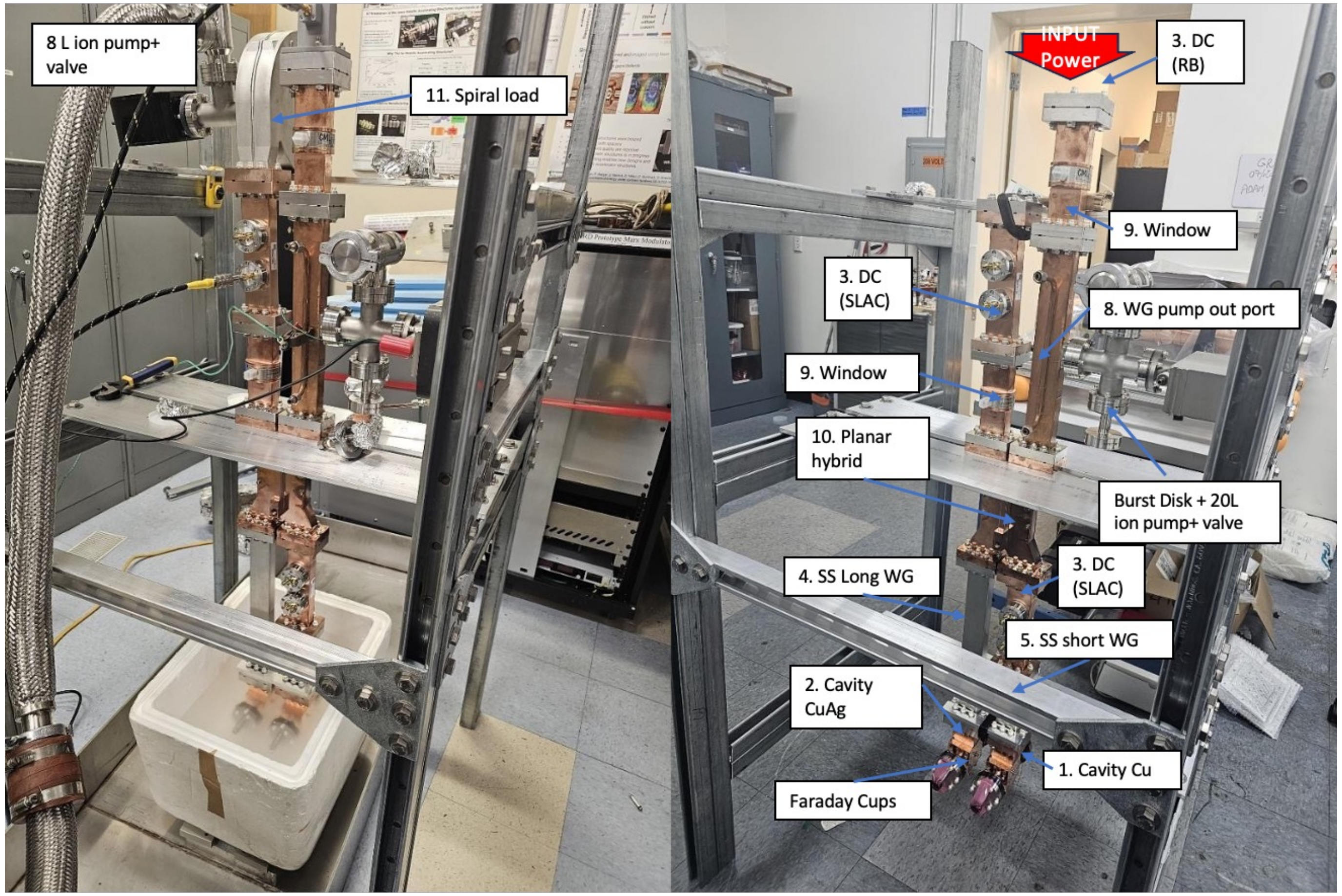
Two Cell Assembly for High Power Test

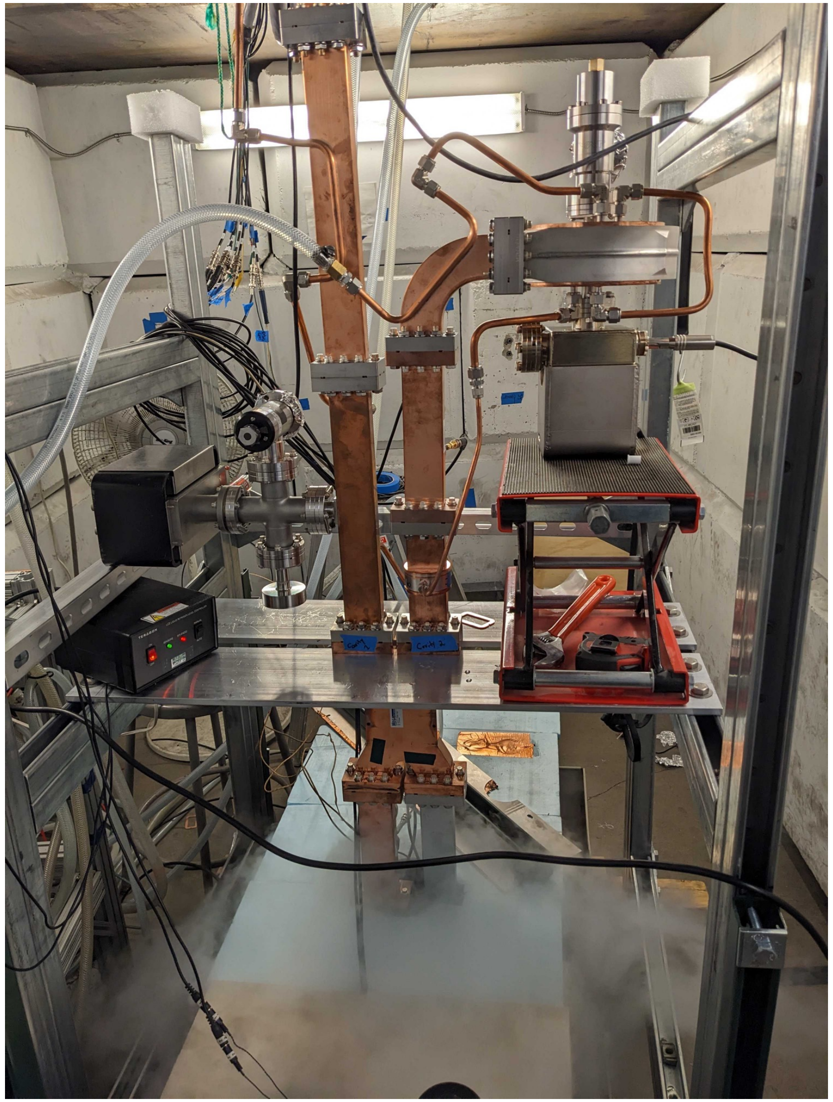




Two Cell Assembly for High Power Test

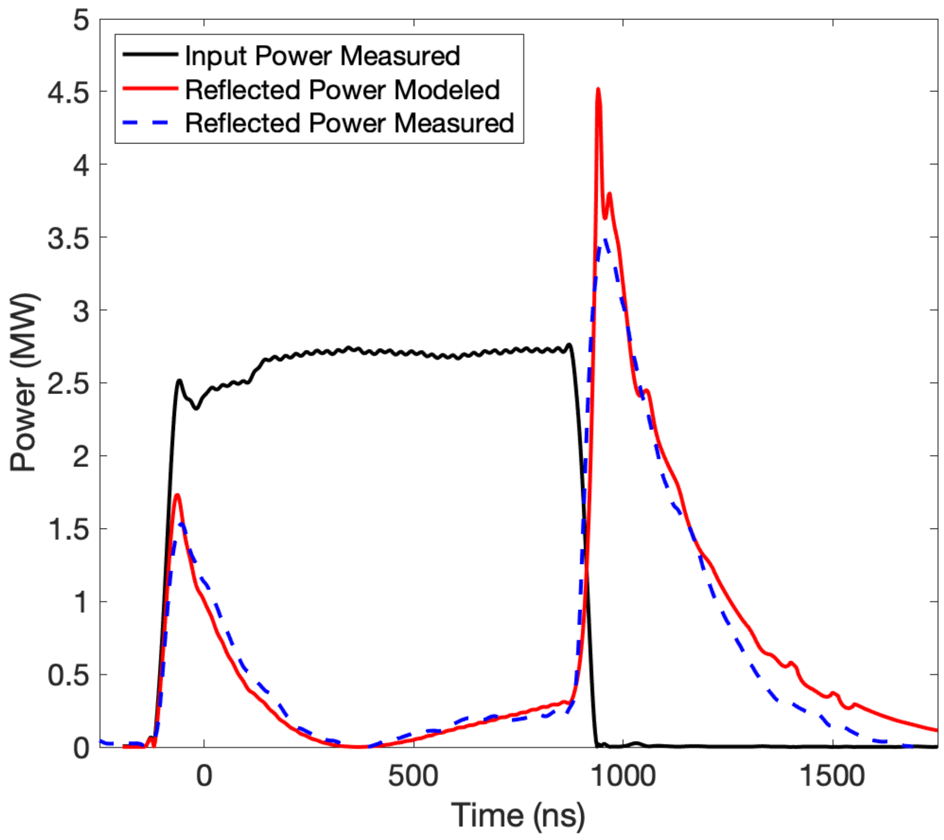
SLAC **Radiabeam**

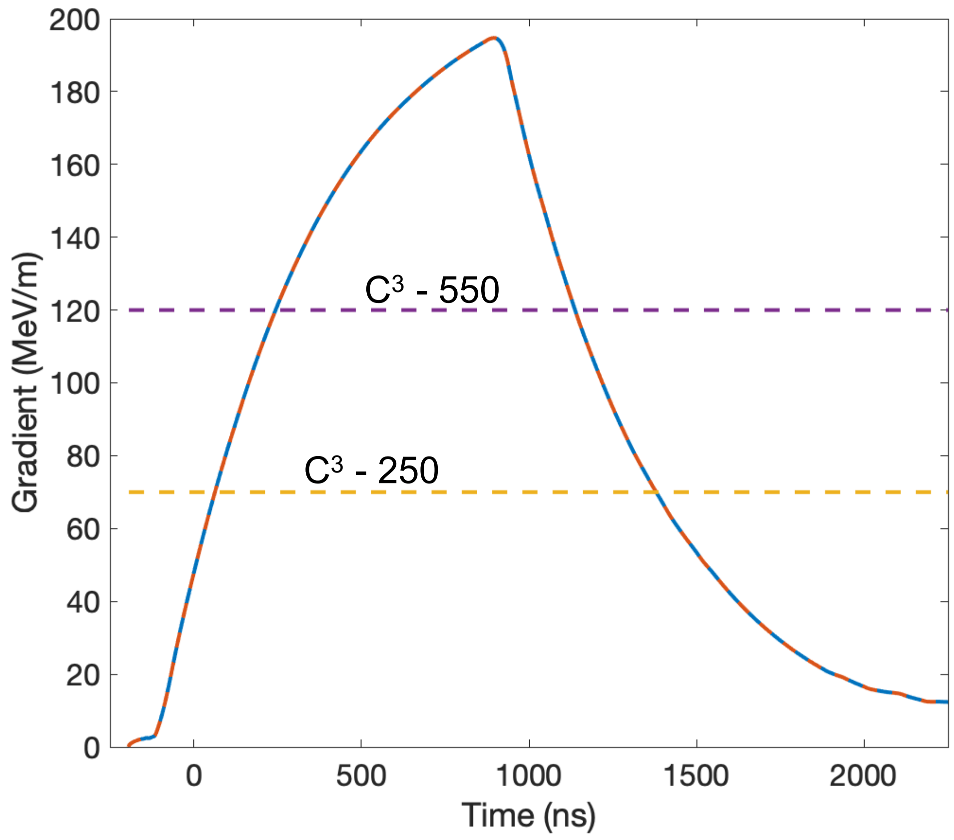




Typical (~~Highest Gradient~~) Performance

- Measured and modeled response for CuAg Cavity





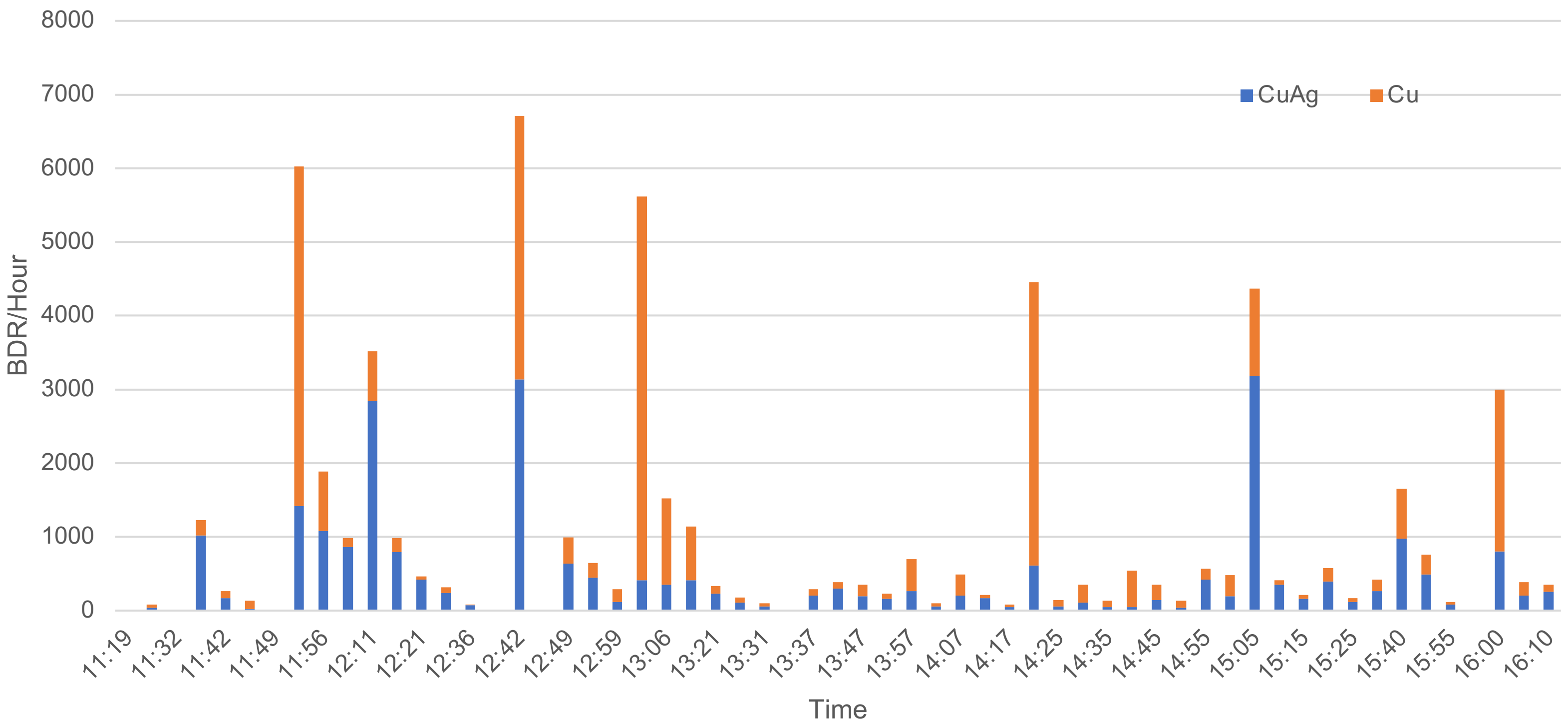
Structure Processing

- ~10M Pulses to Date
- Operating with human supervision

Max Power End of Day
Cavities: Max 3.37 MW into Cu Cavity
Pulse Width: 700 ns
Rep Rate: 80 Hz
Freq: 5714.3 MHz

Preliminary

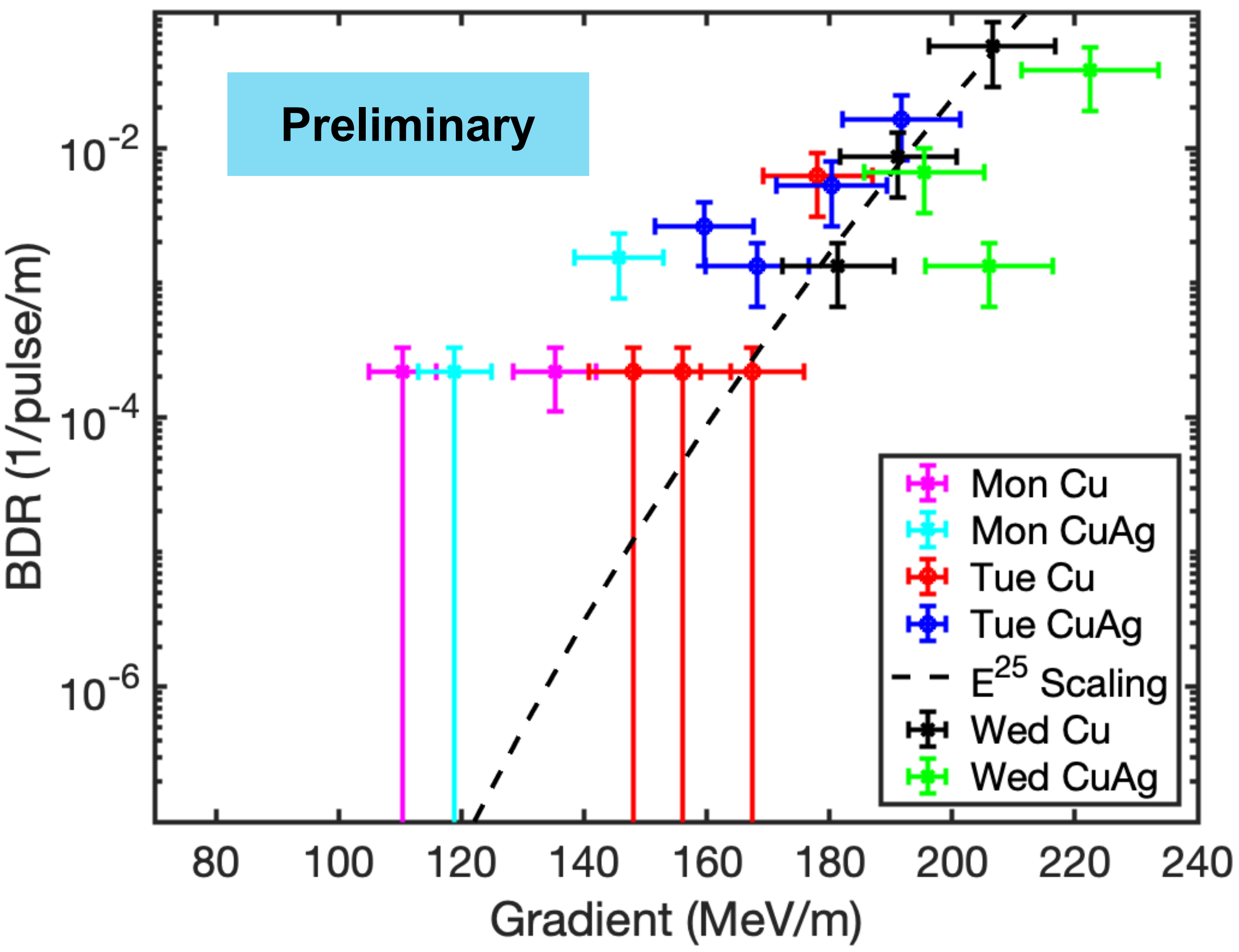
C-Freeze Run 10/17/2023



Breakdown Statistics

- Challenging due to short structure length – most data points O(1 hr)
- BDR of Cu and CuAg remarkably similar (very different than room temp)
- Showing day to day improvement

- We will focus on statistics at end of the run

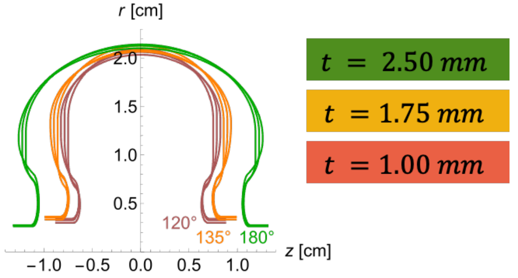


Special Thanks: A. Diego, M. Schneider, M. Boyce and A. Dhar

Conclusions

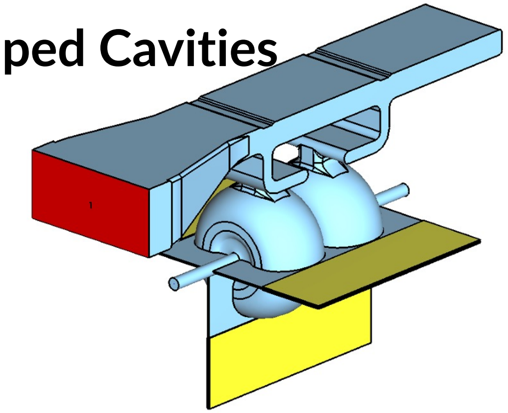
- Achievable gradient, breakdown rate and pulse length at C-band are promising
- How do we incorporate damping?
- How improve manufacturing of structures?
- How do meter scale structures perform?
- What is the optimal aperture and phase advance?

Wide-Aperture Reduced Phase Adv.



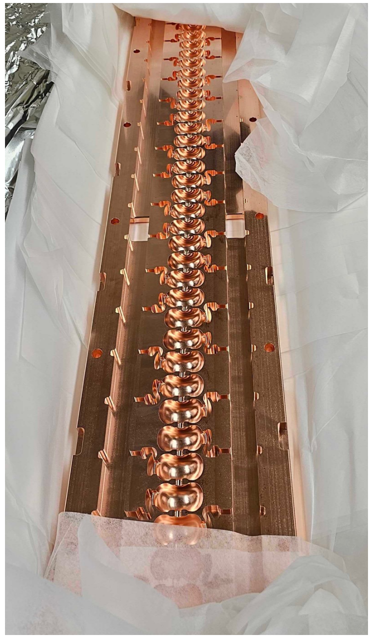
M. Shumail

Damped Cavities



H. Xu + LANL

Cryogenic Pi-Mode



S-Band
Huge Aperture

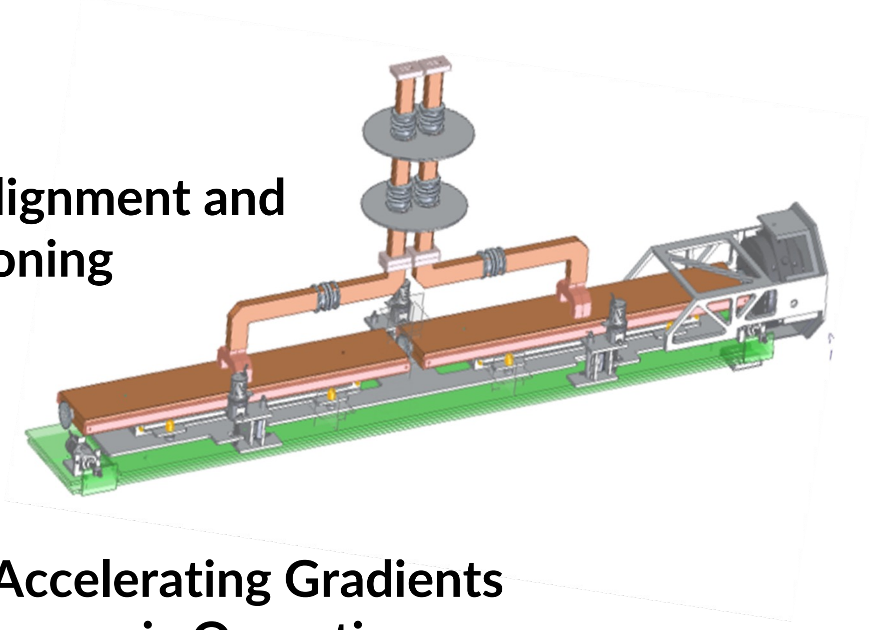
A. Dhar

Questions?

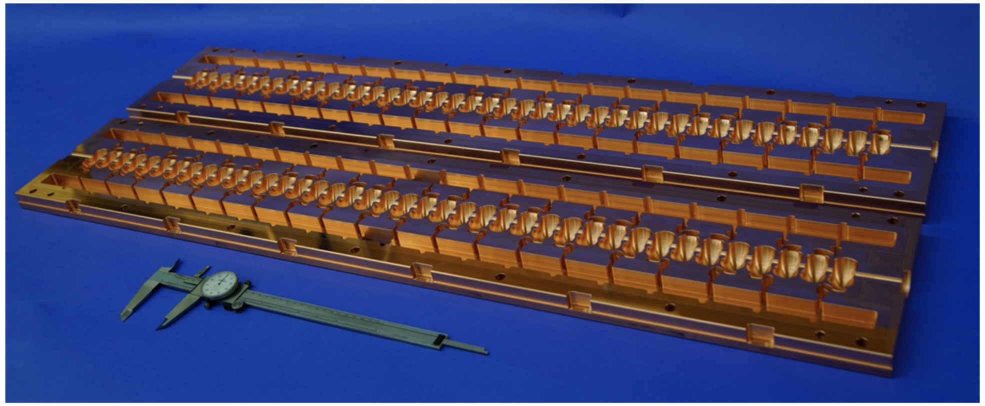
Additional Material

Ongoing Technological Development

Preliminary Alignment and Positioning



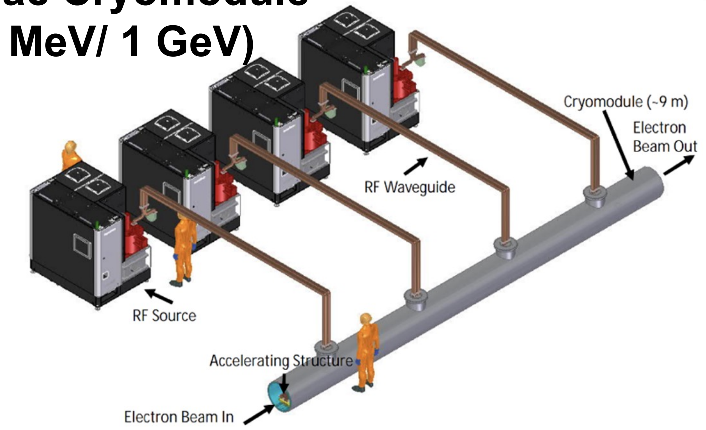
Modern Manufacturing
Prototype One Meter Structure



High Accelerating Gradients
Cryogenic Operation

Integrated Damping with NiChrome Coating

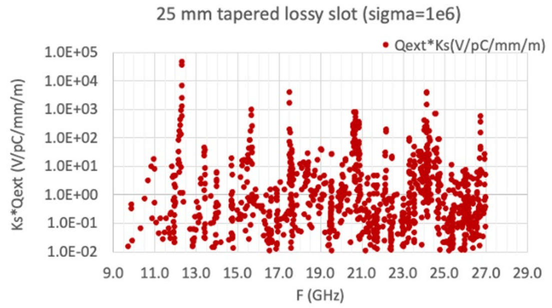
C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)

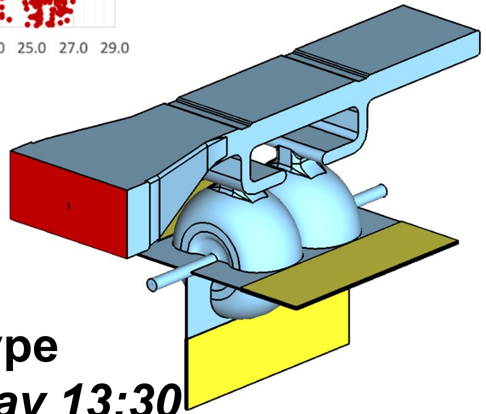


Implementation of Slot Damping

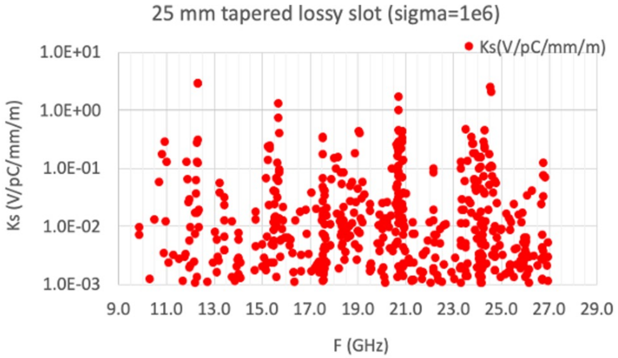
Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m
NiCr coated damping slots in development

Kick Factor * Q



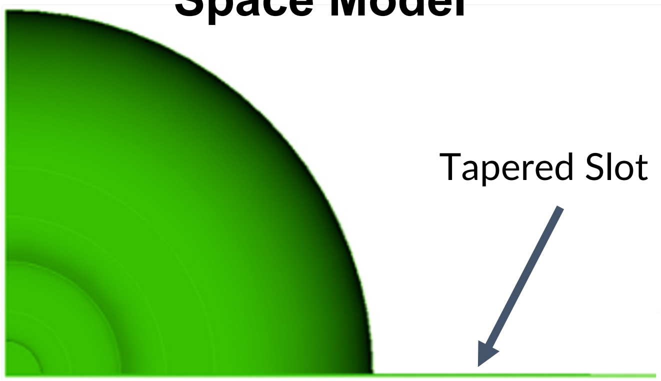


Kick Factor

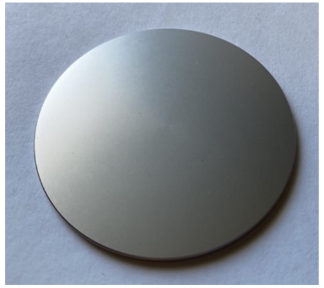


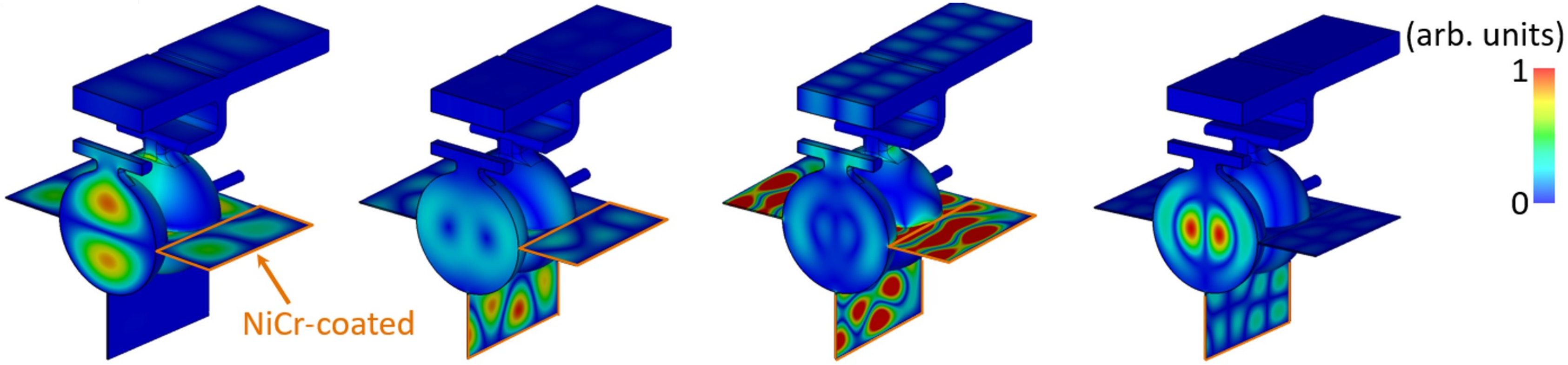
Two Cell Prototype
H. Xu, NCRF W 17th May 13:30

Vacuum Space Model



NiCr Tested at 80K





TM110 (9.27 GHz) TM211 (12.28 GHz) TM120 (15.67 GHz) TM121 (17.65 GHz)