Cold Copper High Gradient Single-Cell Structure Tests

Emilio Nanni
LCWS 2024
7/10/2024

Acknowledgements

SLAC

Muhammad Shumail
Xueying Lu
Greg Le Sage
Mitchell Schneider
Emma Snively
Sami Tantawi
Valery Dolgashev
Zenghai Li
Dennis Palmer
Garrett Mathesen
Charlotte Wehner
Julian Merrick
Bradley Shirley
Mamdouh Nasr
Ankur Dhar

LANL

Evgenya Simakov
Muhammed Zuboraj
Ryan Fleming
Dmitry Gorelov
Mark Middendorf

CERN

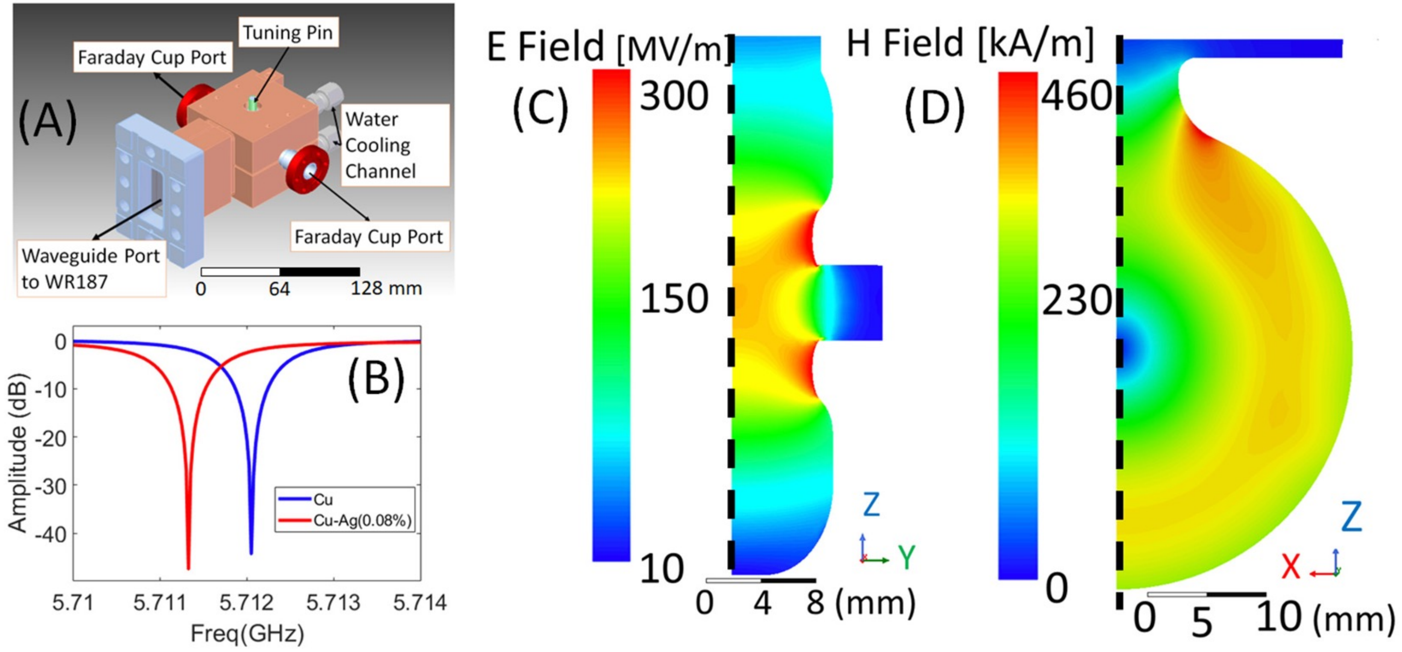
Victoria Madeleine Bjelland
Walter Wuensch

Radiabeam

Ronald Agustsson
Robert Berry
Amirari Diego
Alex Murokh
NG Matavalm
A Talignani
PR Carriere

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

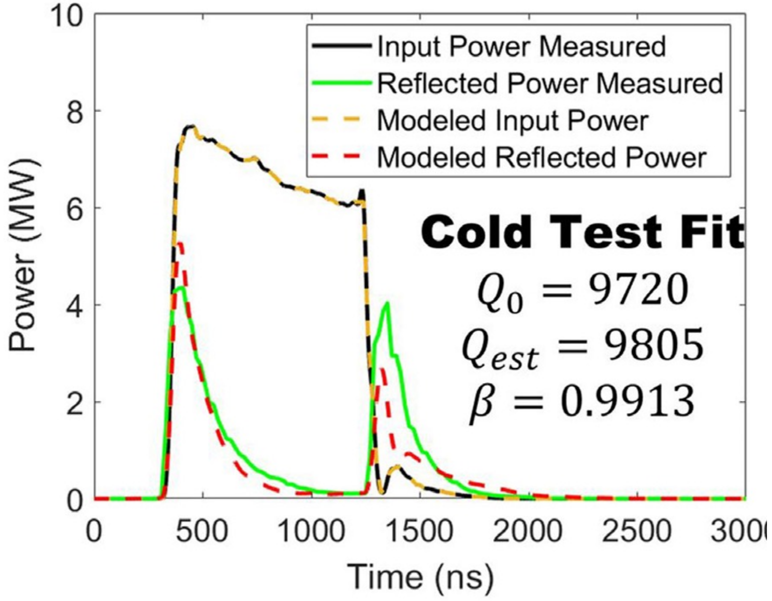


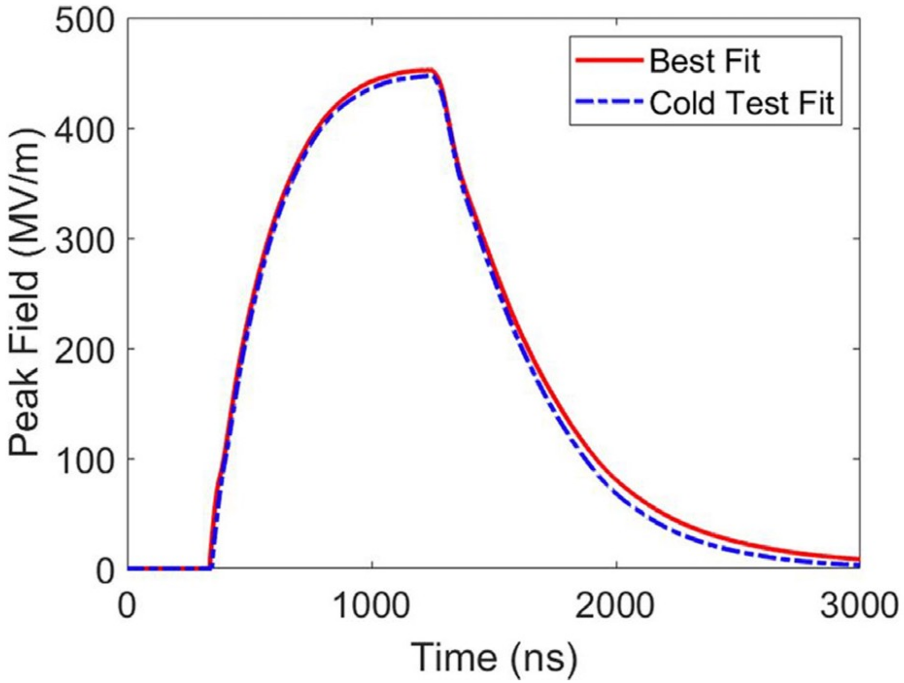
Parameter	Cu v = 0.5c Proton	Cu v = c Electron
Length	1.58 cm	
a/λ	0.0525	
Frequency	5.712 GHz	
σ	58 MS/m	
Q_0	9762	
Q_{ext}	10 165	
R_s	61.51 MΩ/m	115.8 MΩ/m
E_a	62 MeV/m $\times \sqrt{P\,[\mathrm{MW}]}$	81 MeV/m $\times \sqrt{P\,[\mathrm{MW}]}$
E_p/E_a	2.42	1.84
$H_p * Z_0/E_a$	1.40	1.07

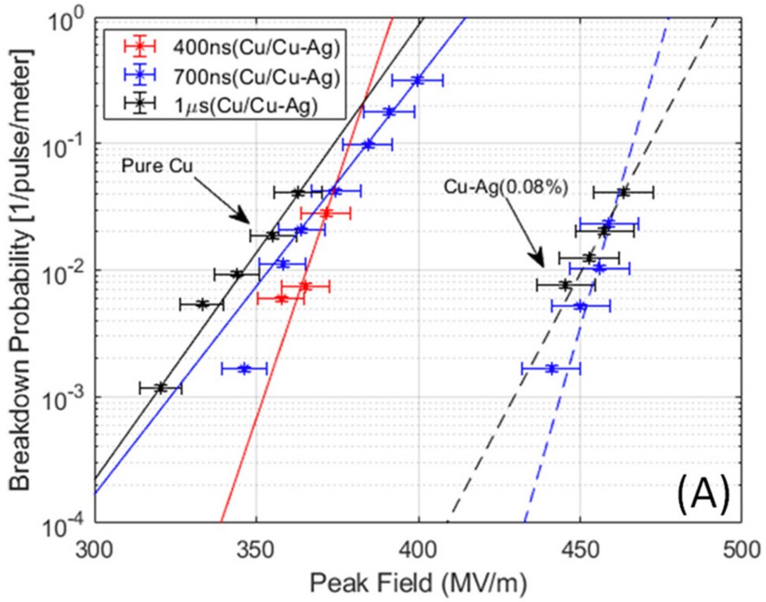
Schneider, Mitchell, et al. "High gradient off-axis coupled C-band Cu and CuAg accelerating structures." *Applied Physics Letters* 121.25 (2022).

High Gradient Performance of Cu and CuAg Cavities

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



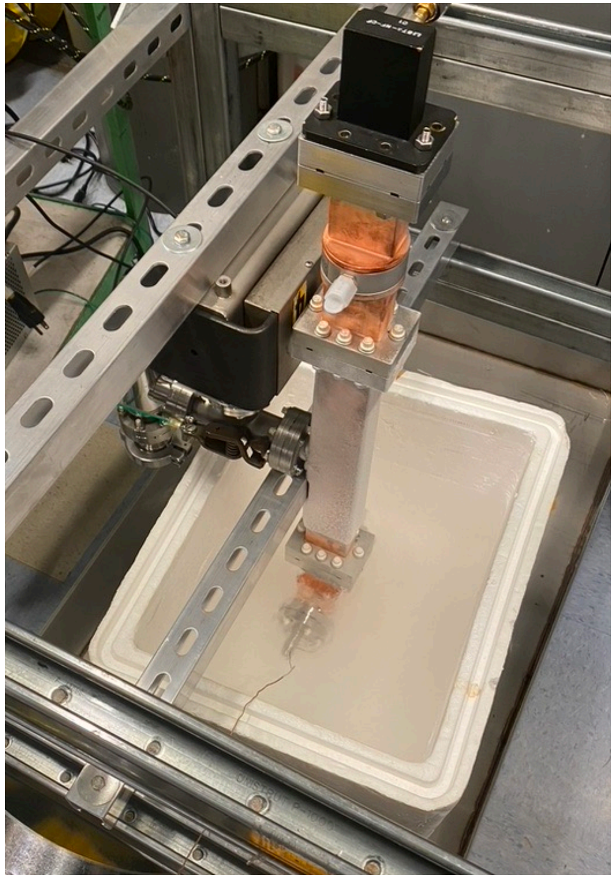


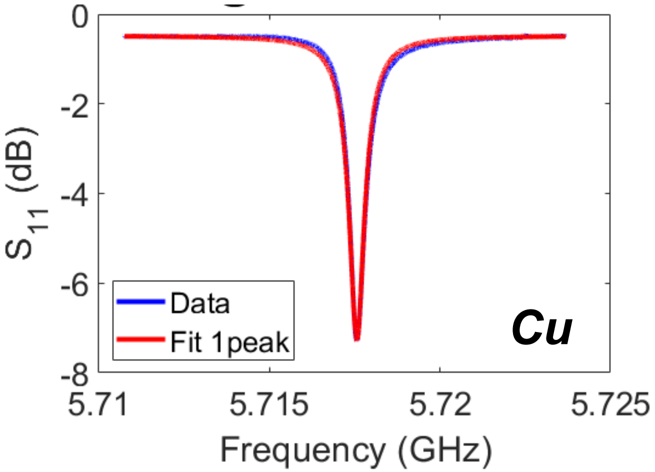


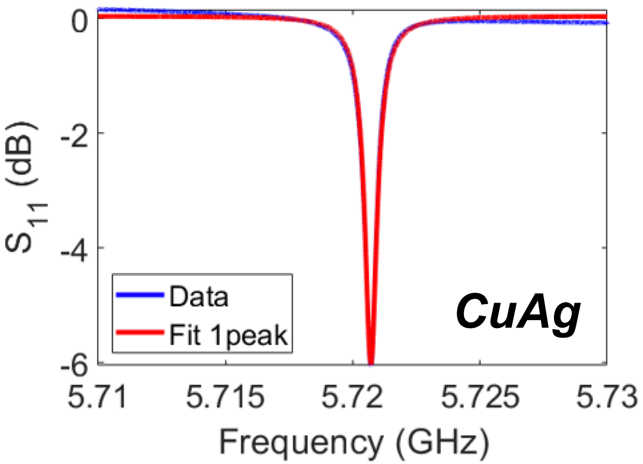
How does this behavior extend to cryogenic temperatures?

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)

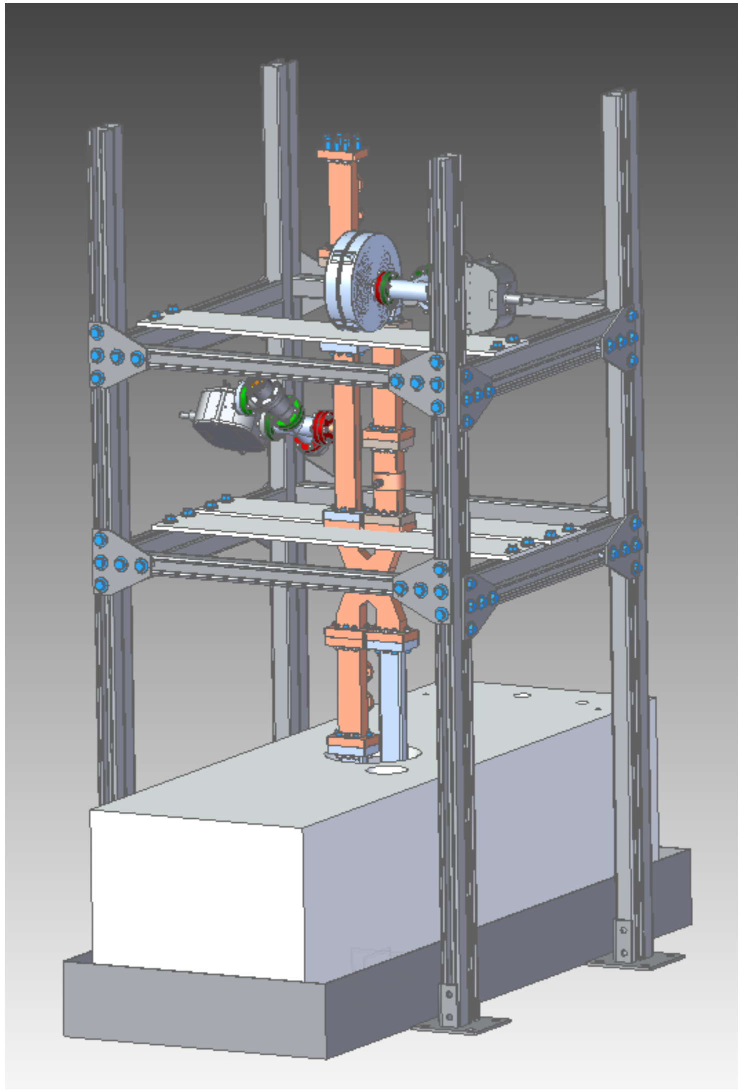


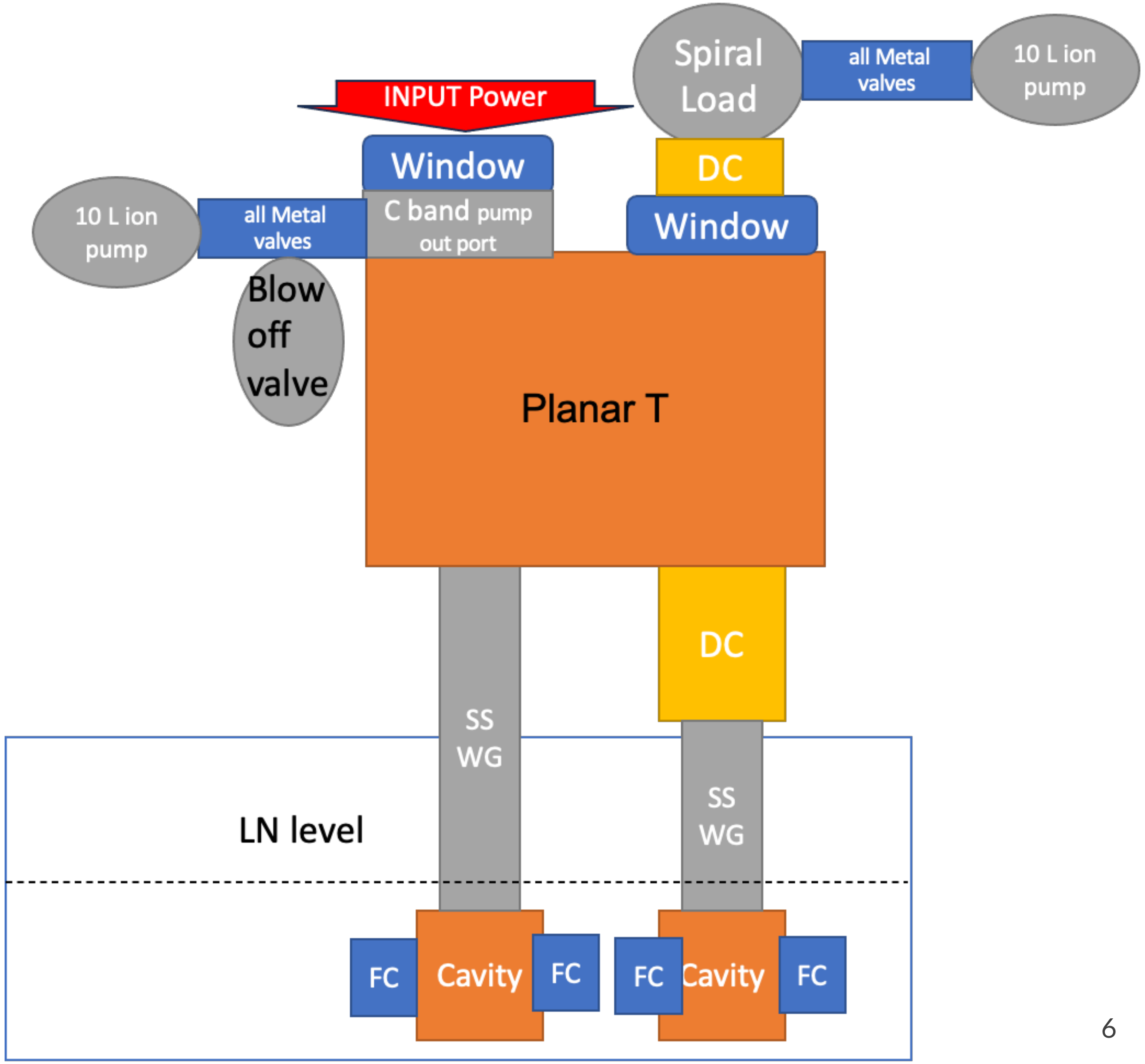




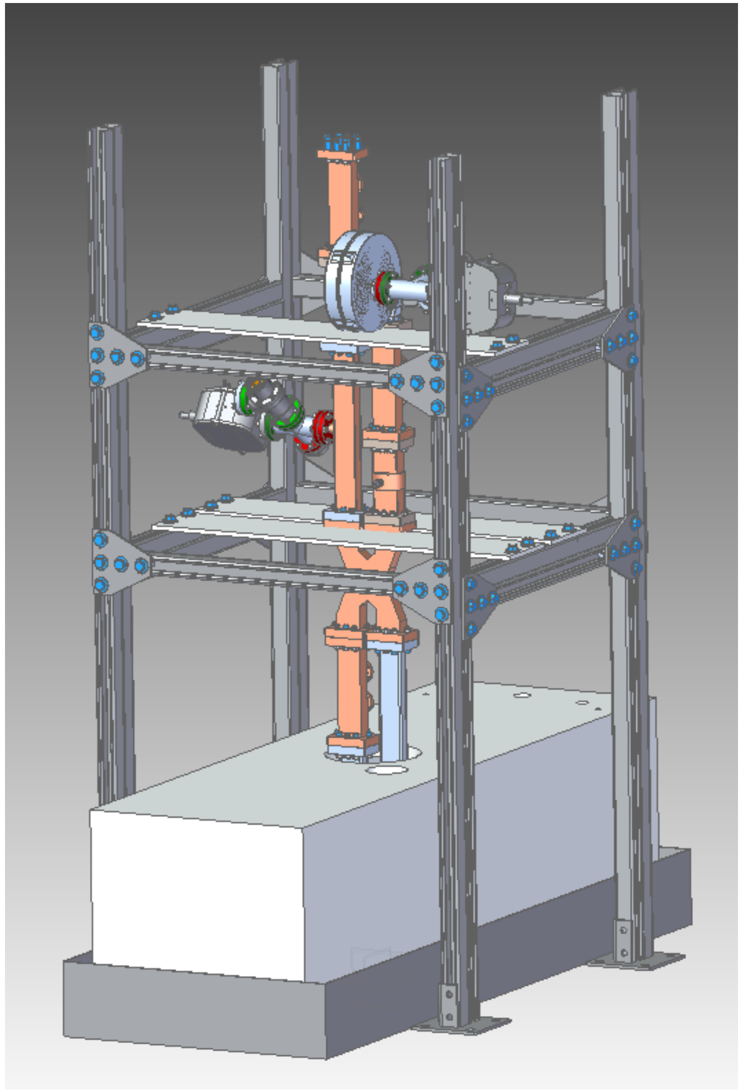
Parameter	CuAg	Cu
Temp	77K	
Frequency	5.71455 GHz	
Length	1.58 cm	
$\boldsymbol{\beta}$	2.97	2.683
$\mathbf{Q_0}$	29,695	25,697
Rs $(M\Omega/m)$	352	305
Ea MeV/m/$\sqrt{MW}$	141	131

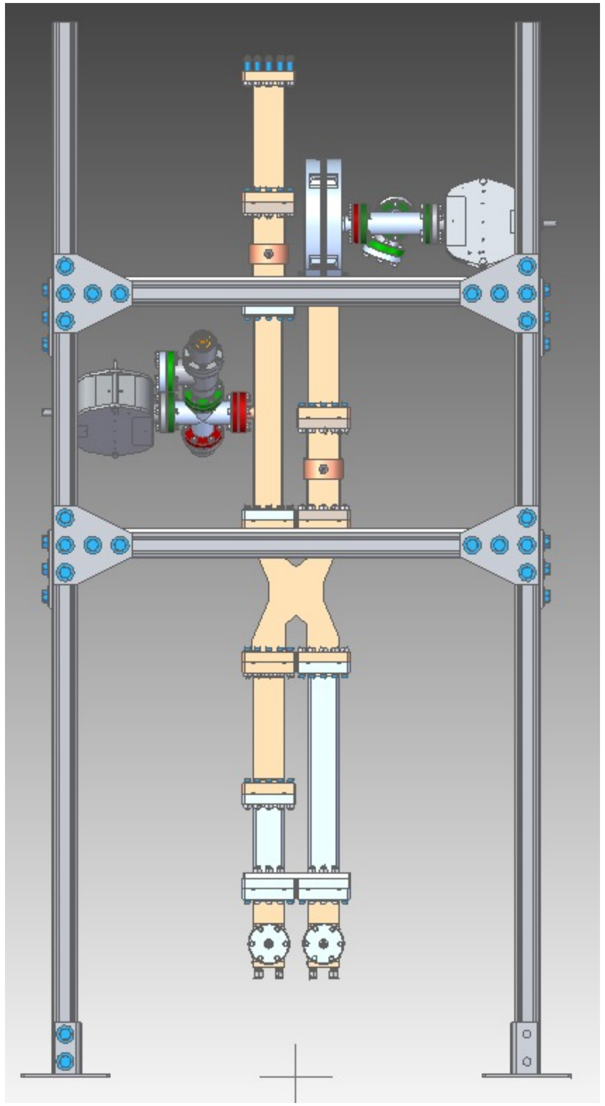
Two Cell Assembly for High Power Test



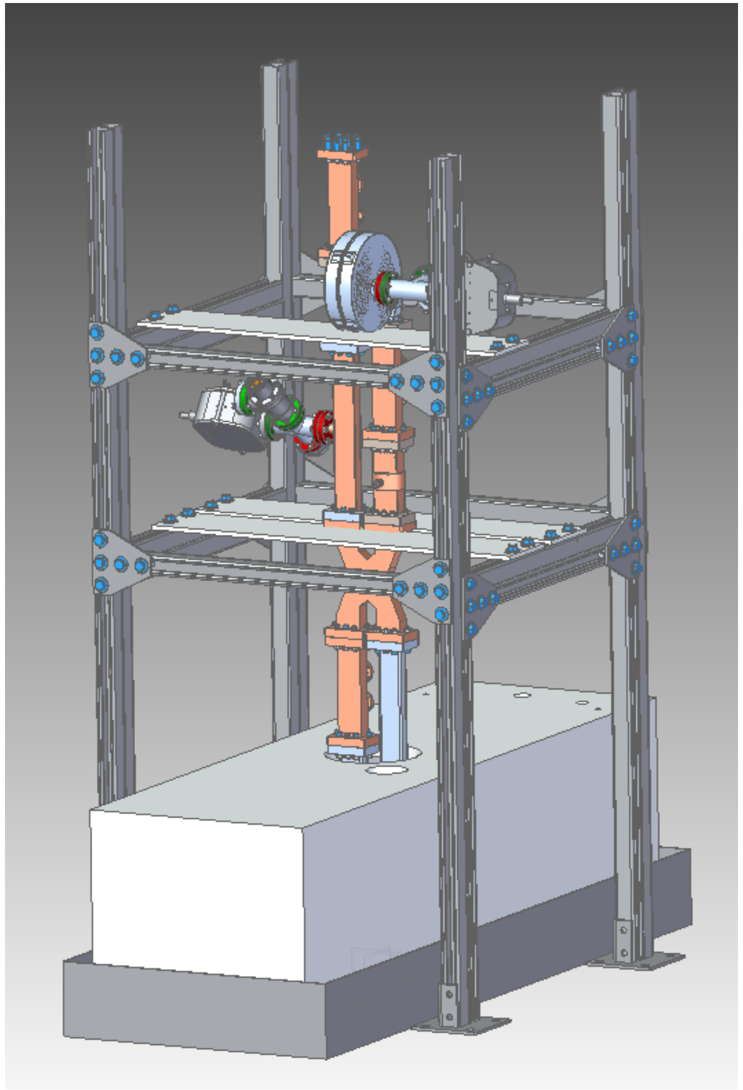


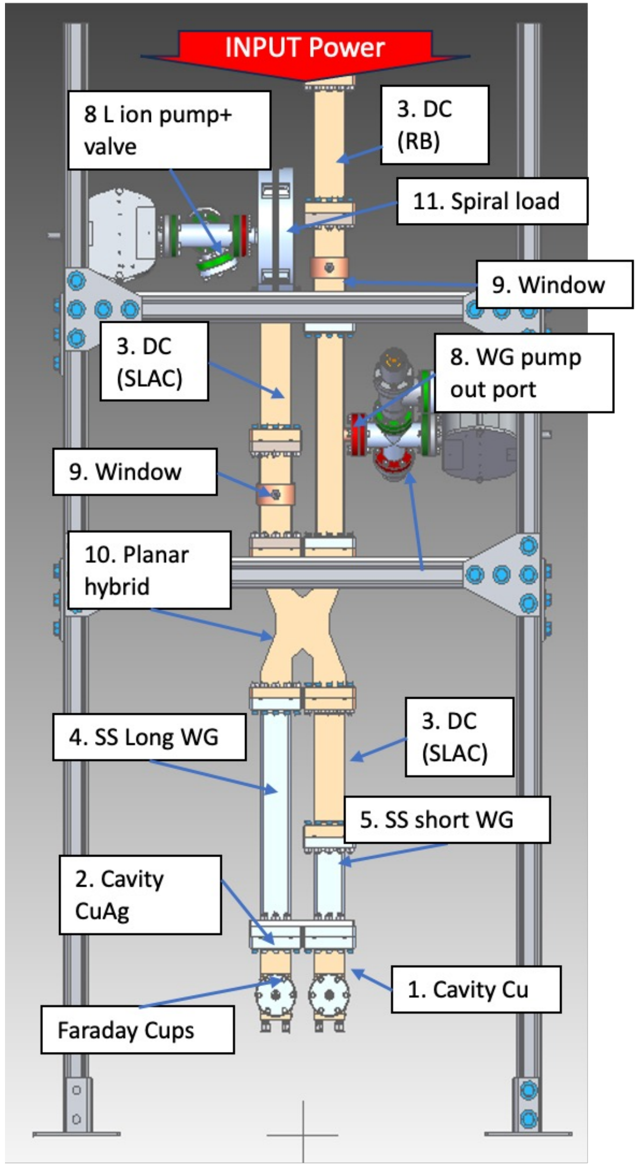
Two Cell Assembly for High Power Test





Two Cell Assembly for High Power Test

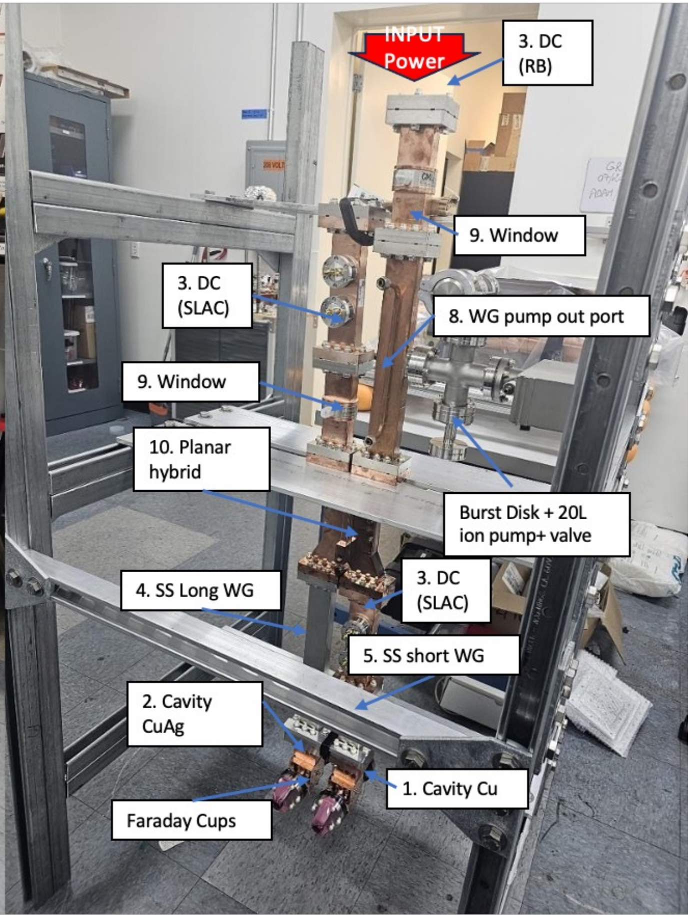


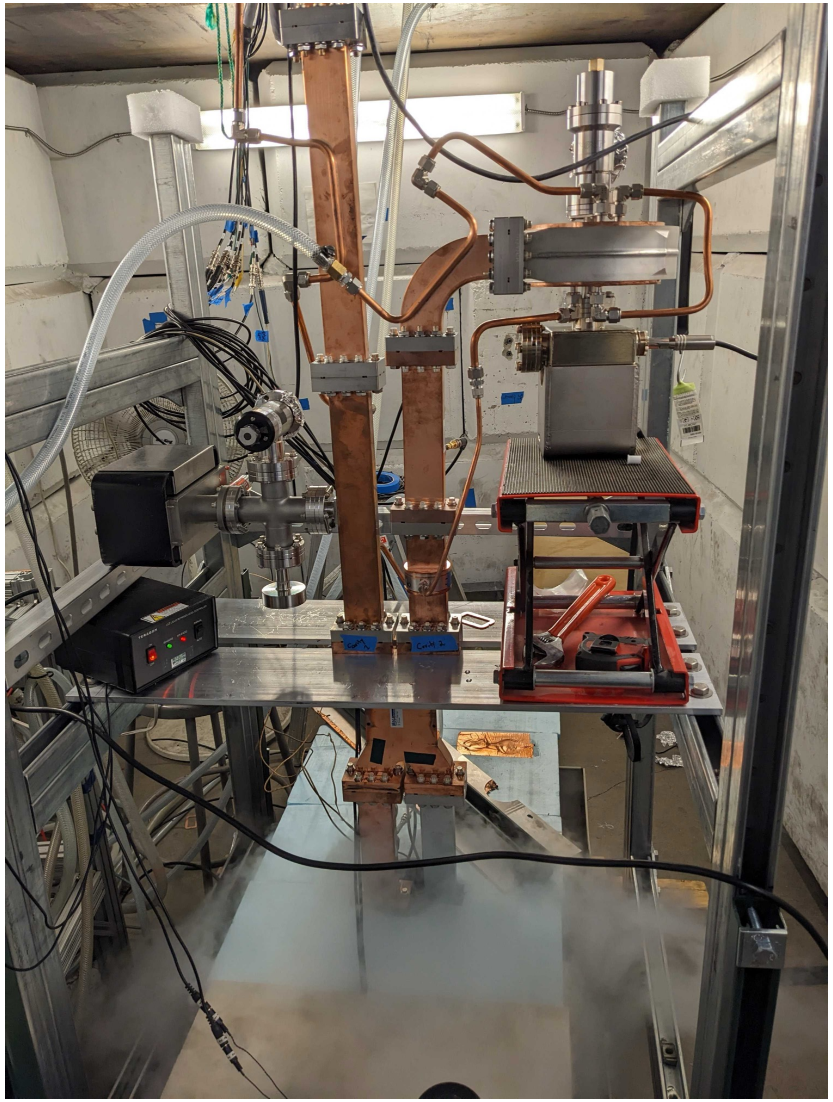


Two Cell Assembly for High Power Test

SLAC

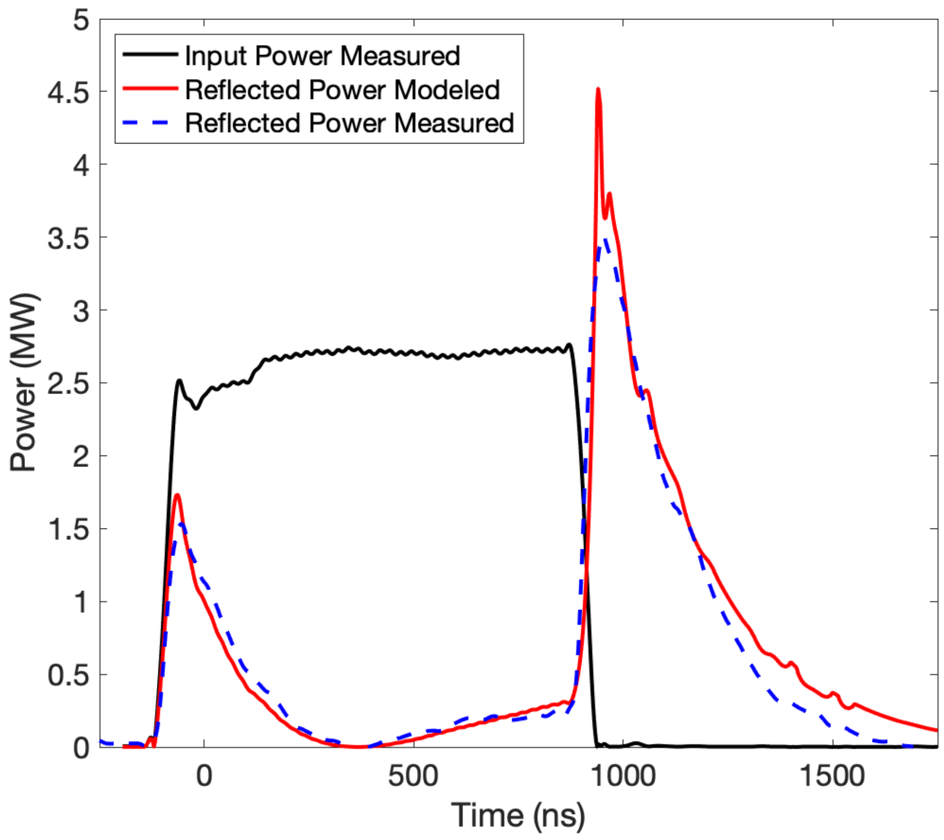
Radiabeam

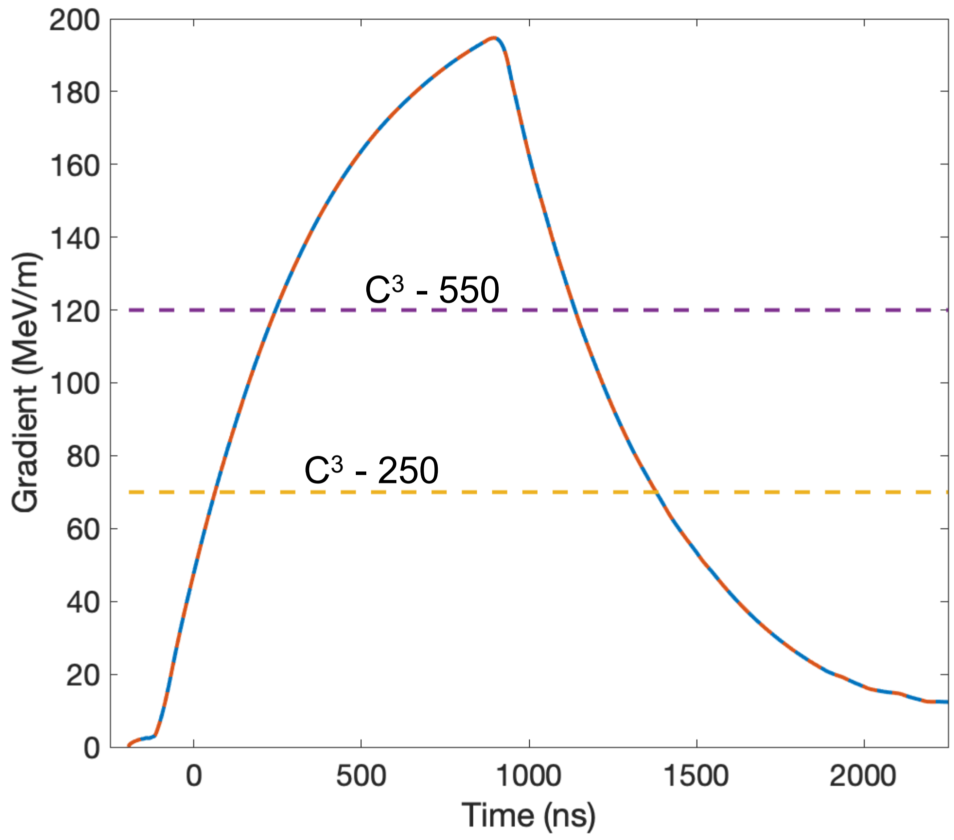




Typical Performance

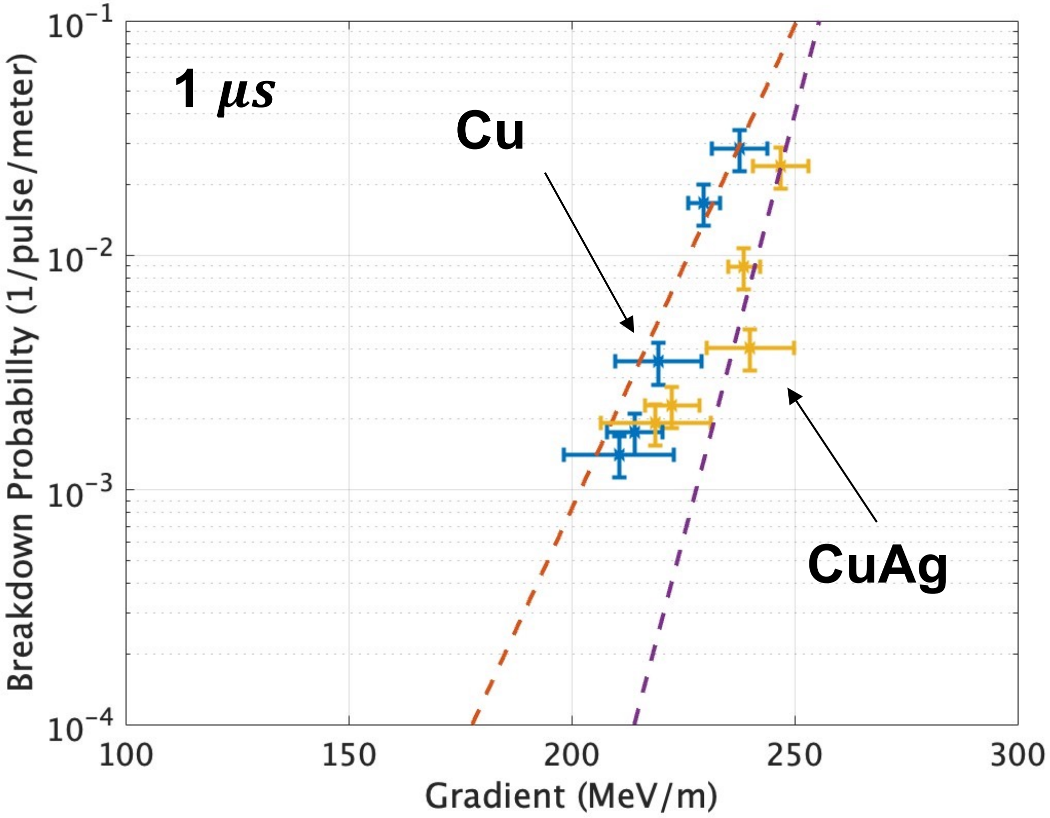
- Measured and modeled response for CuAg Cavity

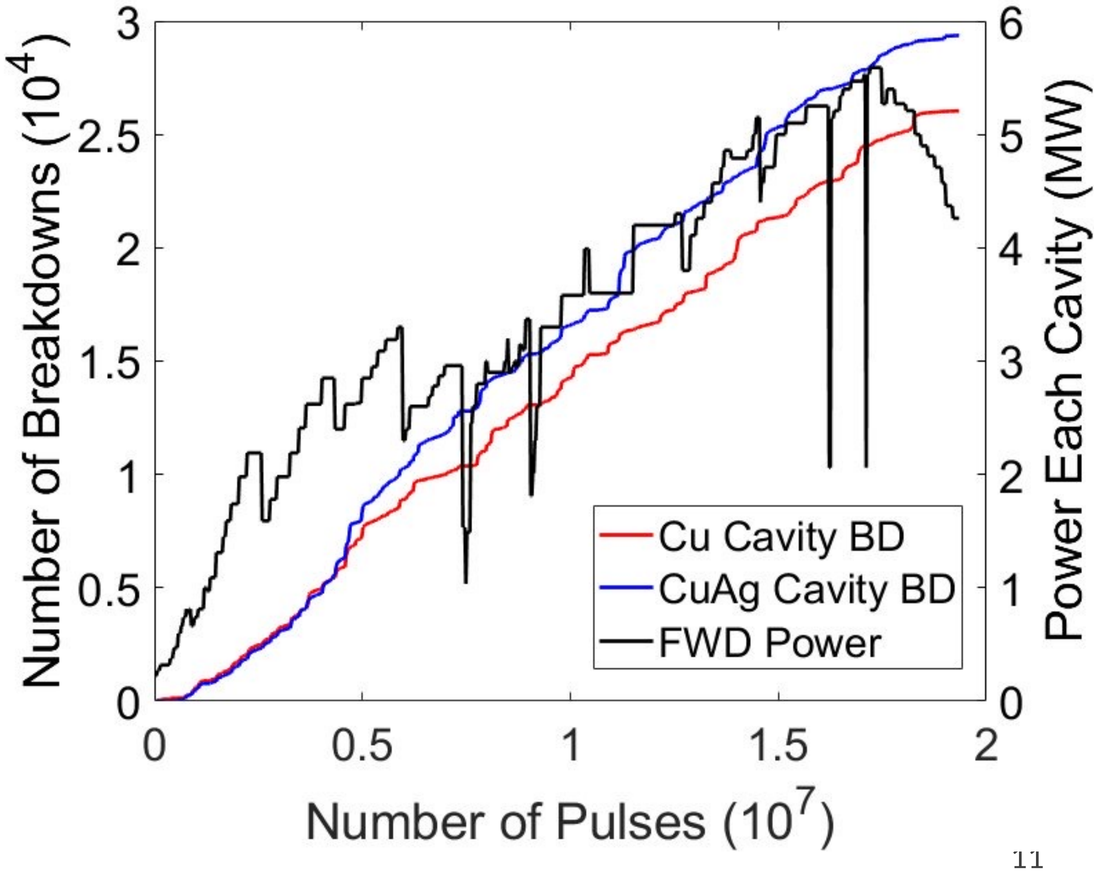




Structure Processing

- ~20M Pulses (two weeks)
- Increased pulse length – 400 ns, 700 ns, 1 microsecond

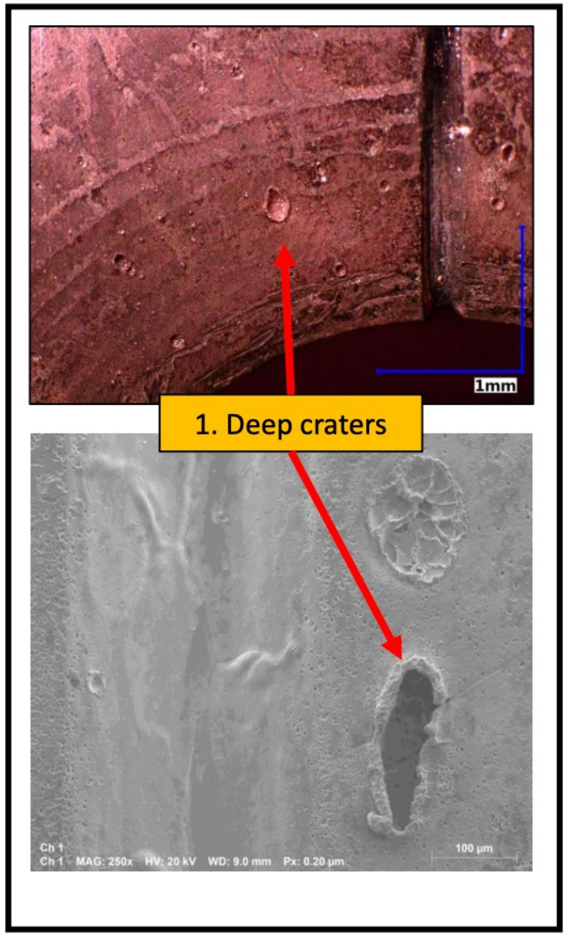


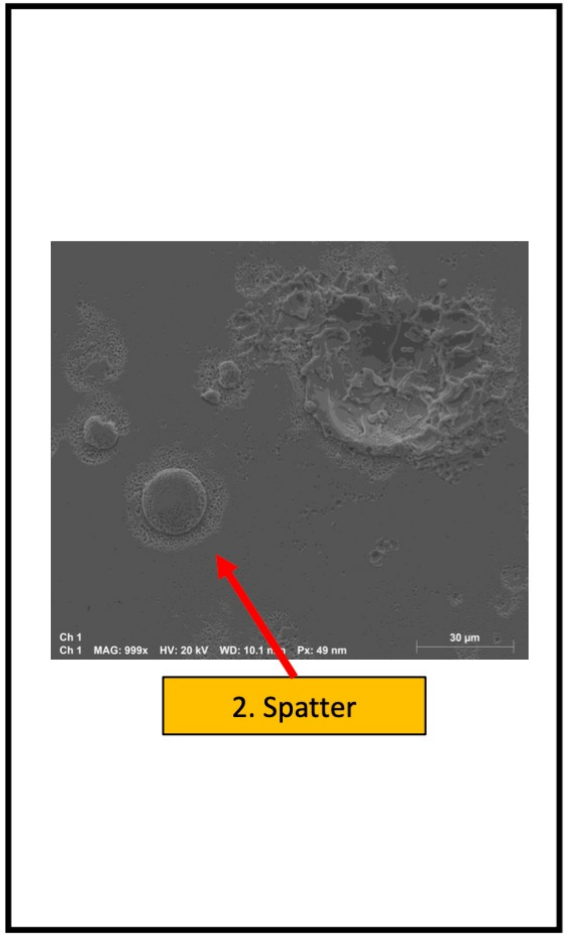


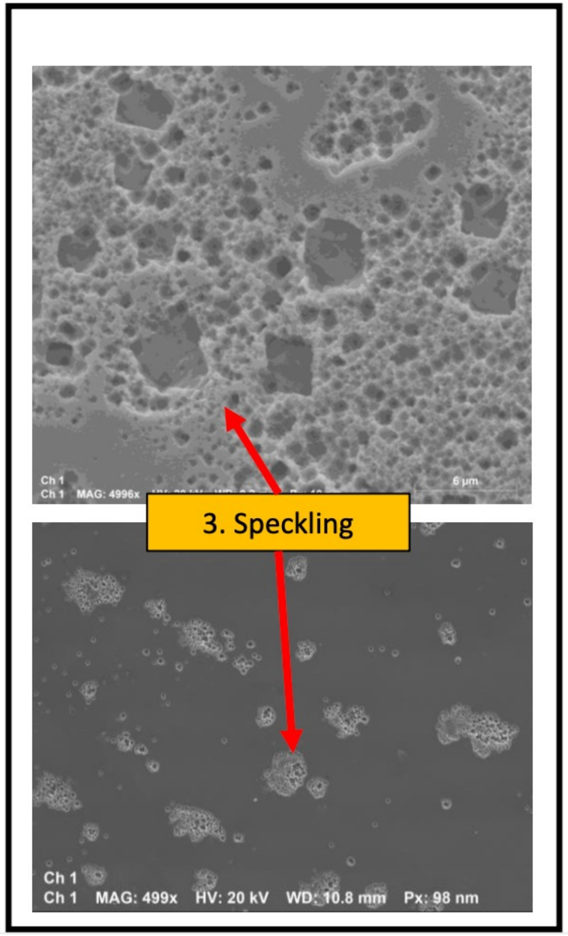
A. Diego, M. Schneider, M. Boyce and A. Dhar

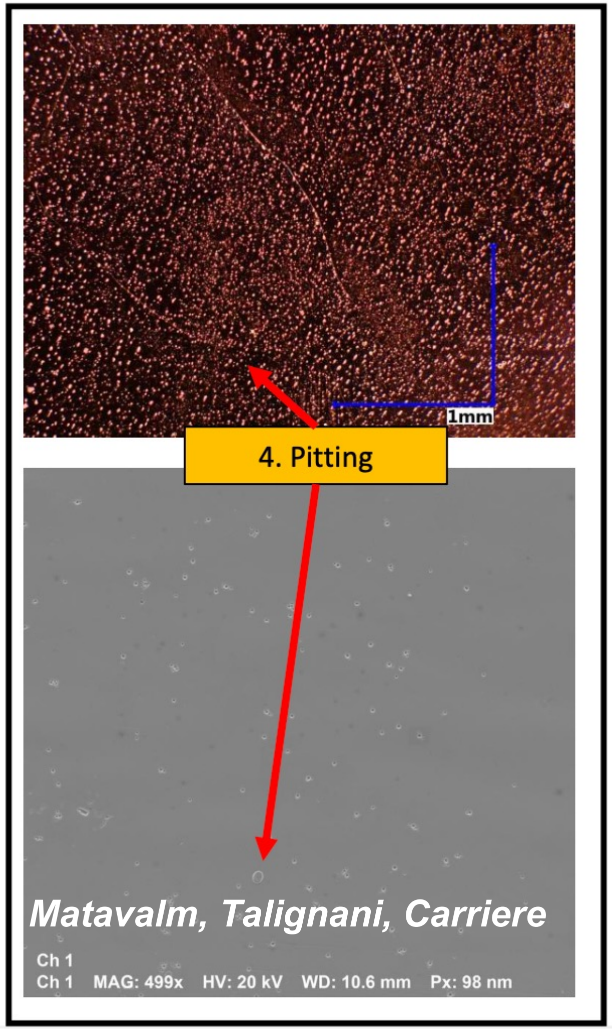
E-field Defect types classification

1. Deep craters(observed only in **Hi-E** regions)
2. Spatter (observed in **Hi-E** but not significantly on **Low-E** regions)
3. Speckling (Observed in **Low-E** regions only)
4. Pitting (Observed in **Hi-E** & **Low-E** regions)

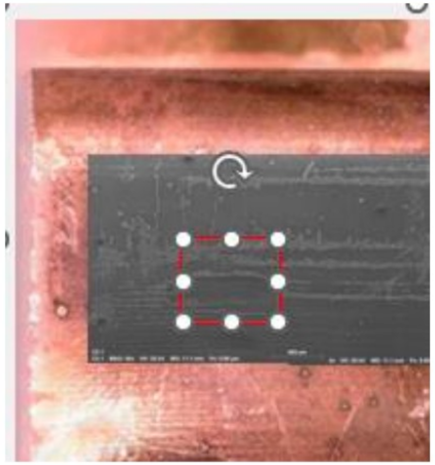


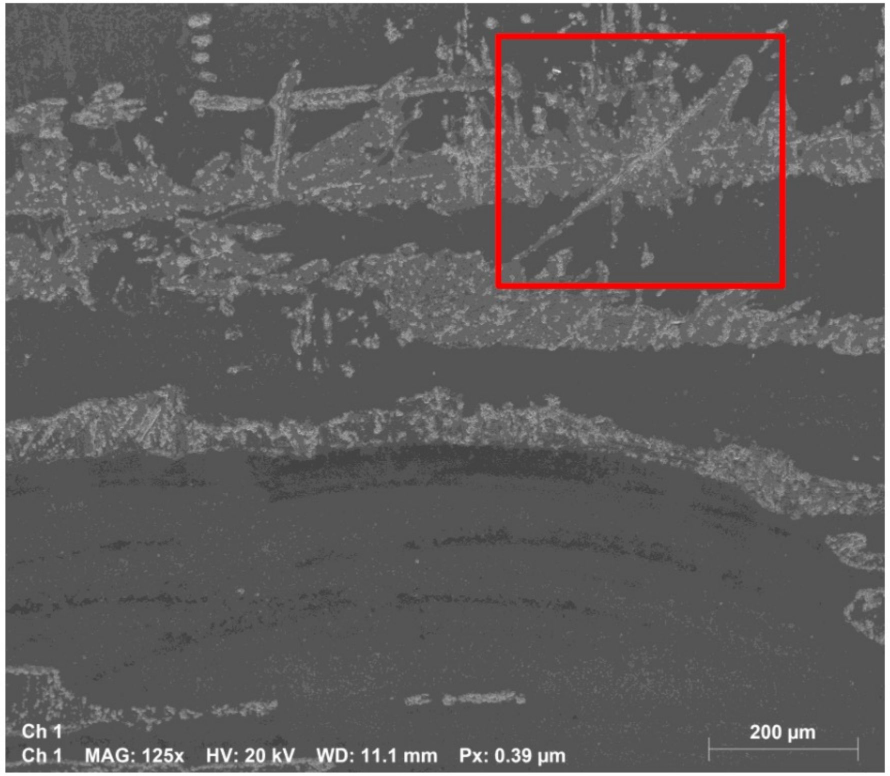


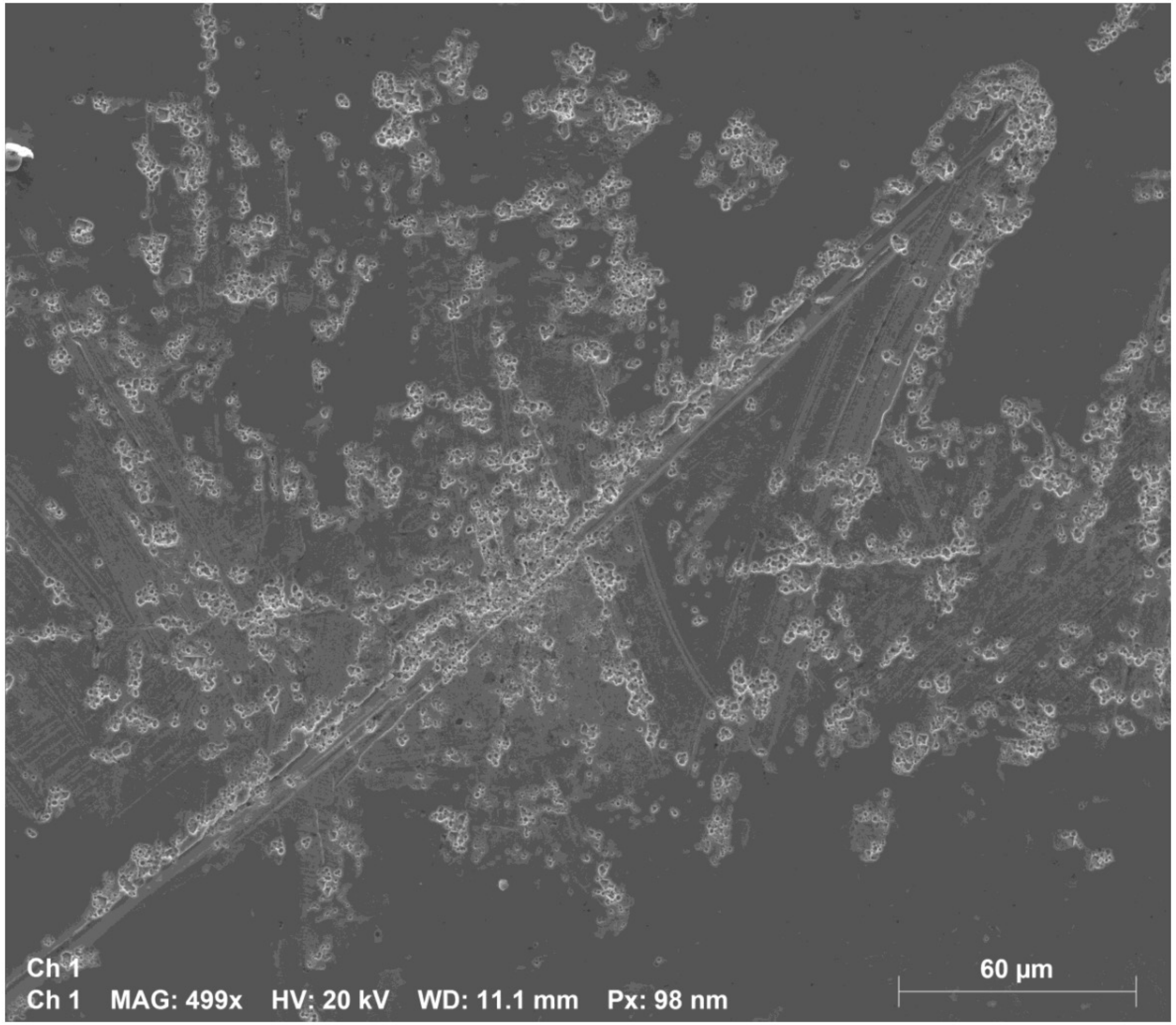




High B region - OFE





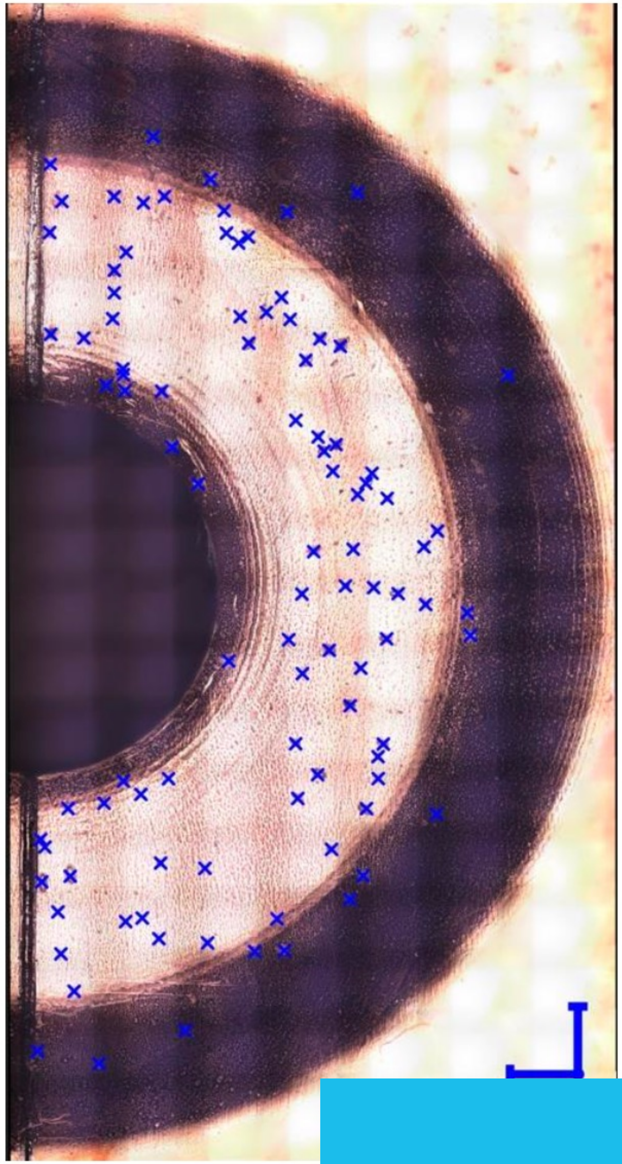


- Scratch from fabrication concentrates pits along scratch?

Matavalm, Talignani, Carriere

OFE High filed break down quantitative analysis

RadiaBeam

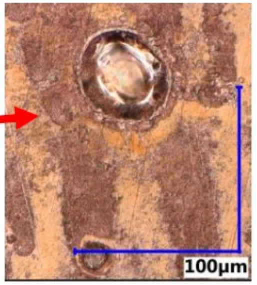


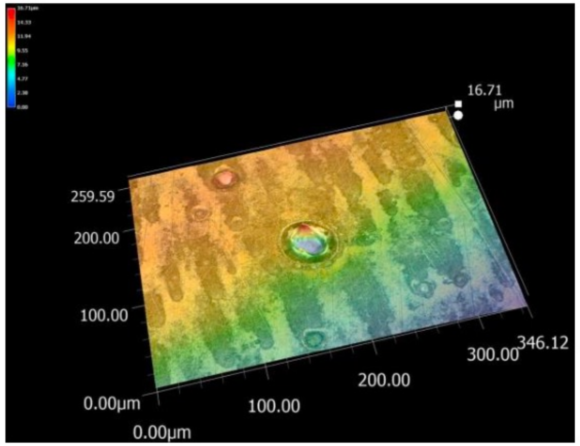
- Total number of break down events counted: 98 ± 10
- Surface area of high field: 94.12mm^2
- 1.04/mm^2 breakdown counts are observed at high field region (top 1.6% of electric field considered as high field)

CuAg cavity versus the Cu cavity 1.35 versus 1.04 BD/mm^2

Smallest crater considered for counting.

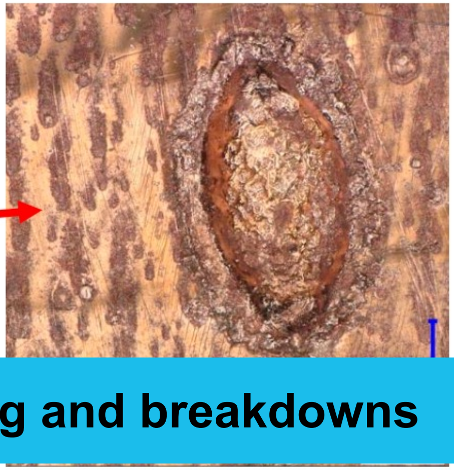
OD: 35um
Depth 16um

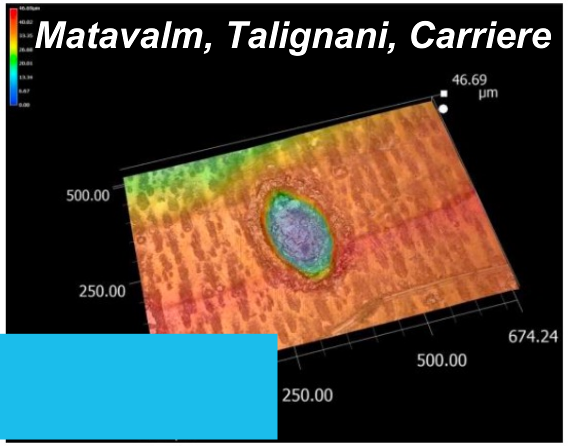




Largest crater considered for counting.

OD: 90um
Depth 47um





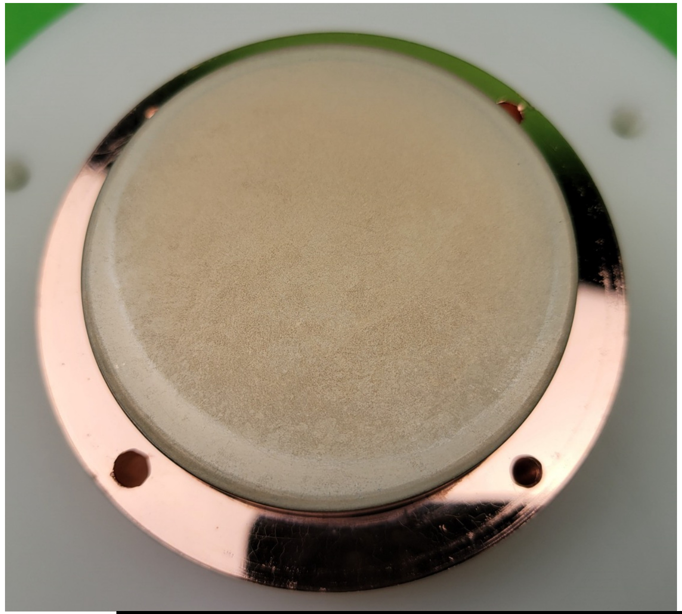
Matavalm, Talignani, Carriere

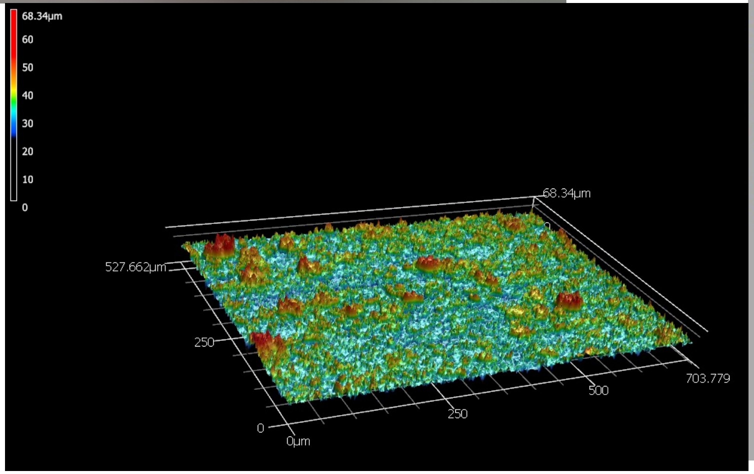
Resilient to damage from etching and breakdowns

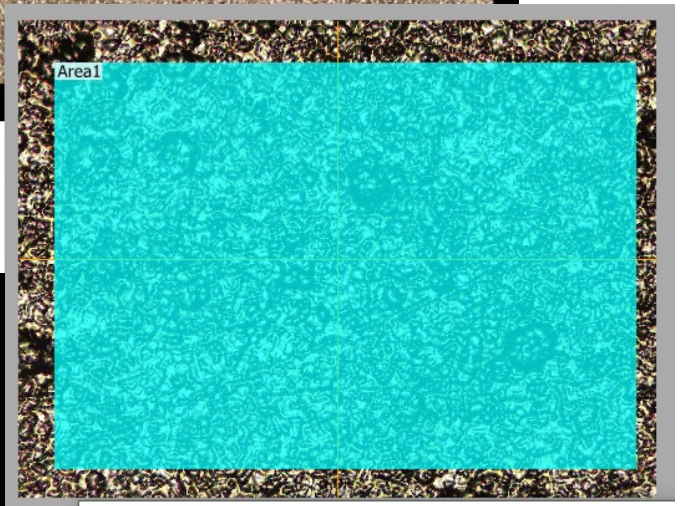
Next Steps

NiChrome Coating for Damping

- Formed with multi-layer electroplating
- Rough lossy conductor
- NiChrome (at 77K) coating conductivity 100X lower than copper at room temperature
- Conductivity confirmed at 77K with multi-layer coating with diffusion from high-temperature heat treatment







Measured values

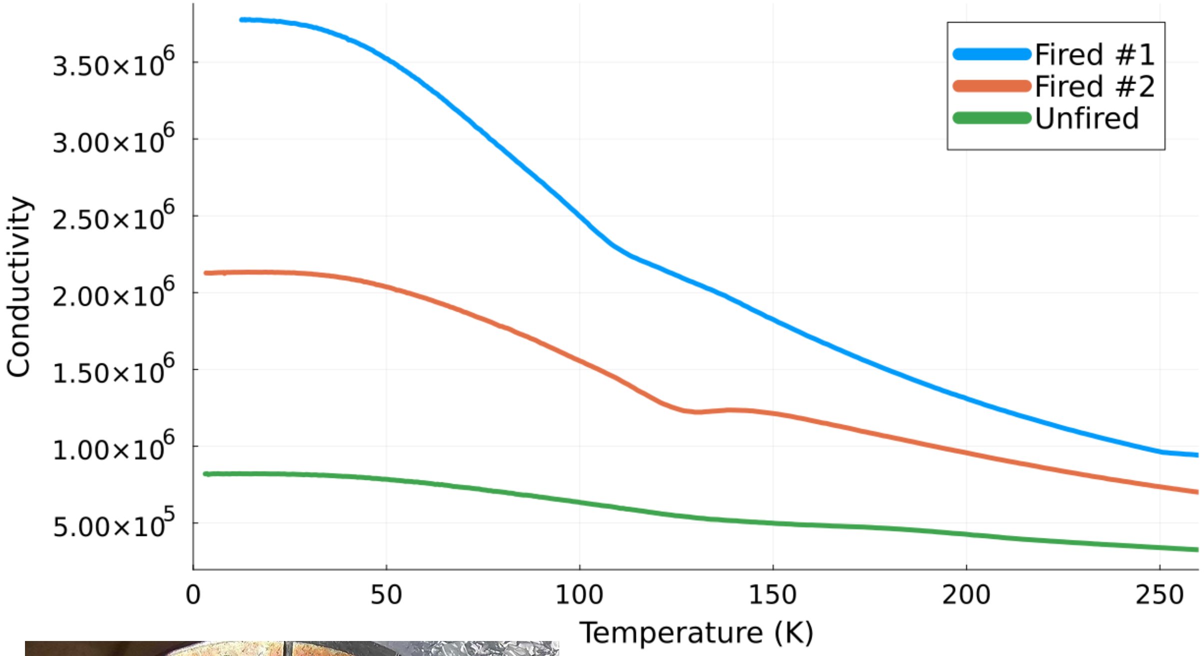
	Sa	Sz	Str	Spc	Sdr
	µm	µm		1/mm	
Max.	3.623	68.050	0.791	12083.811	8.135
Min.	3.623	68.050	0.791	12083.811	8.135
Ave.	3.623	68.050	0.791	12083.811	8.135
Std. DV	0.000	0.000	0.000	0.000	0.000000000
Area1	3.623	68.050	0.791	12083.811	8.135

NiChrome Conductivity After Hydrogen Braze

Unfired sample seemed to maintain low conductivity

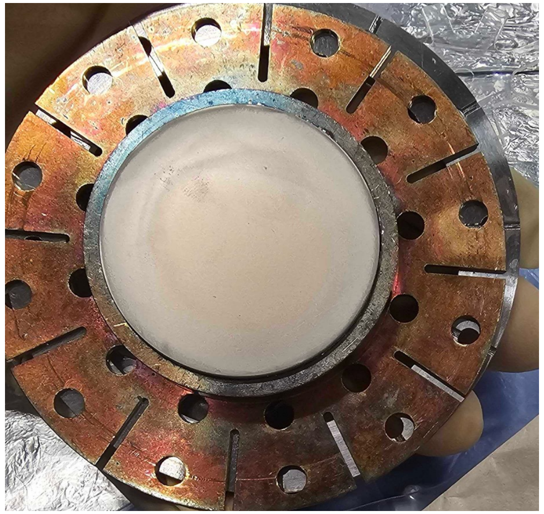
Fired samples started lossy, but approached Copper values as temperature rose

Visual observation suggests some of the coating may have degraded in the firing



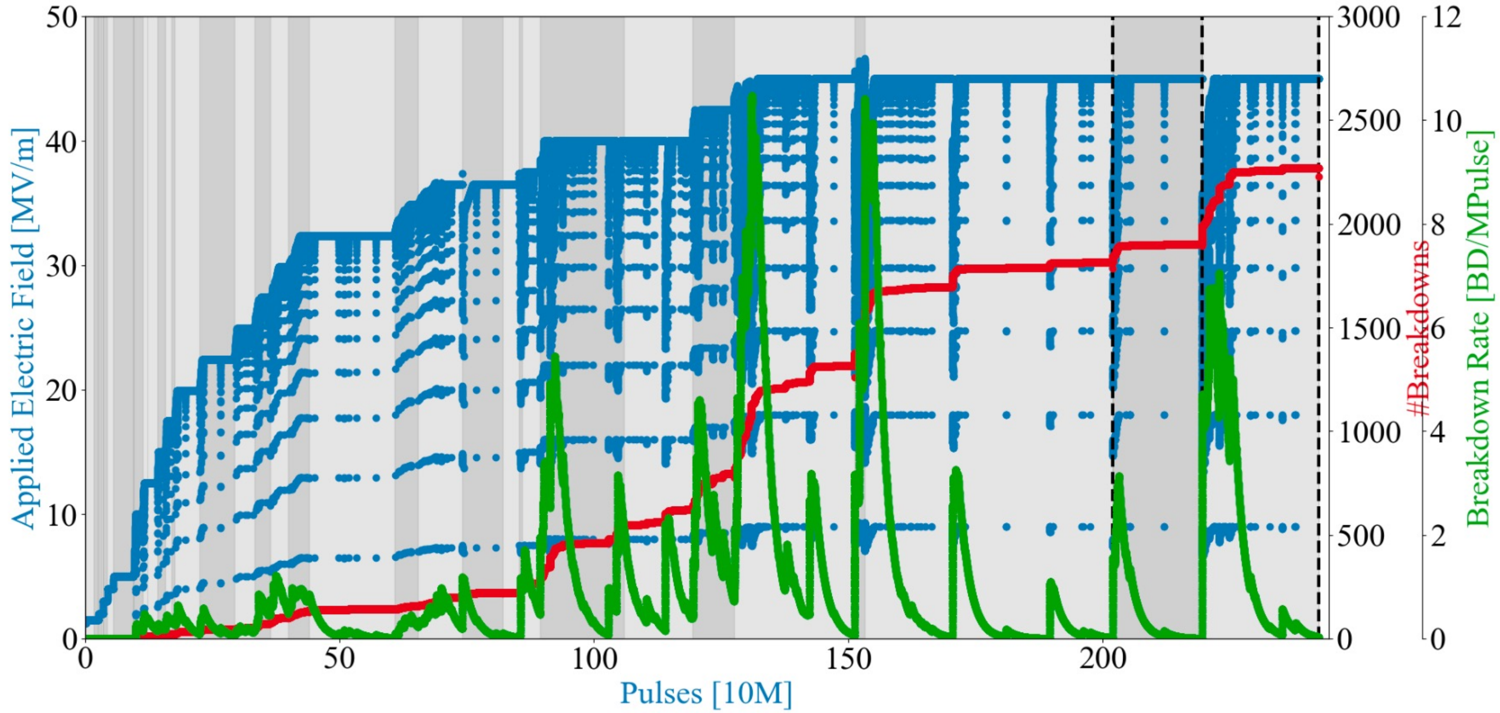
Sample @ 77K	Q0	Qe	β	Qs	σ
Fired #1	44826	214023	0.209	35092	3 MS/m
Fired #2	32783	206483	0.159	27252	1.8 MS/m
Unfired	19072	208524	0.09	17056	706 kS/m

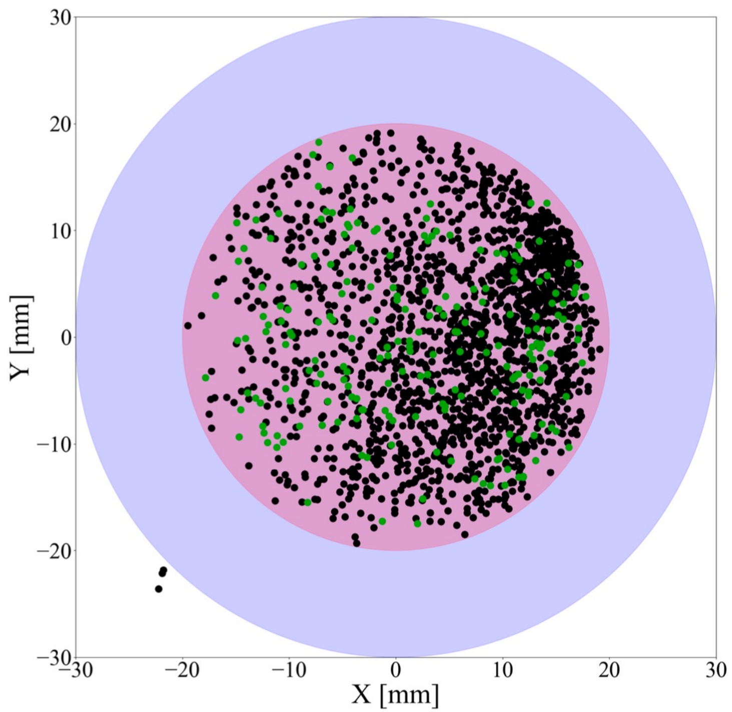
Cu (77 K) ~500 MS/m

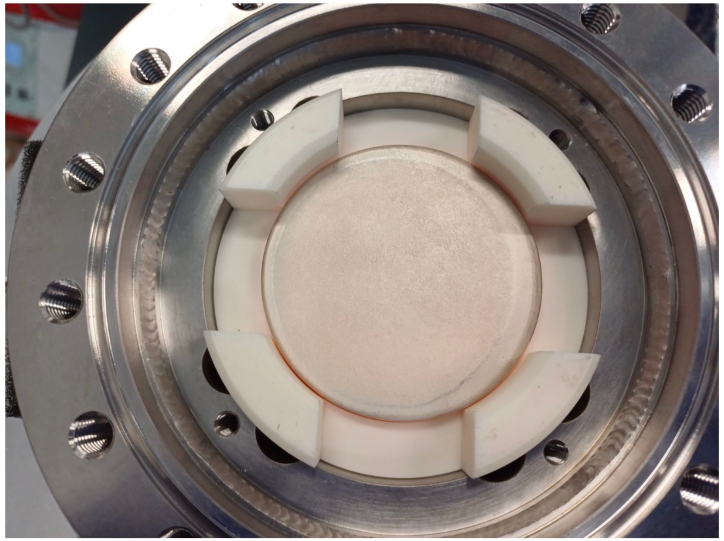


NiChrome High Voltage DC Testing

- Normal operation NiChrome only sees low fields
- Breakdowns can result in HOM coupling
- CERN to test with strong DC field on film to observe if film and vacuum preserved







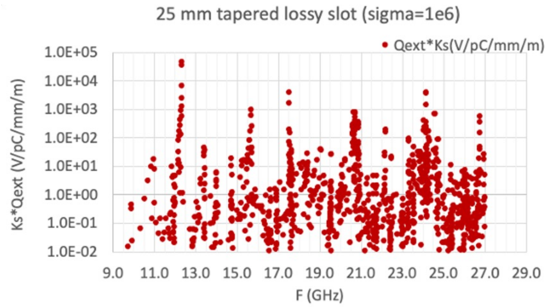
V. Bjelland, W. Wuensch

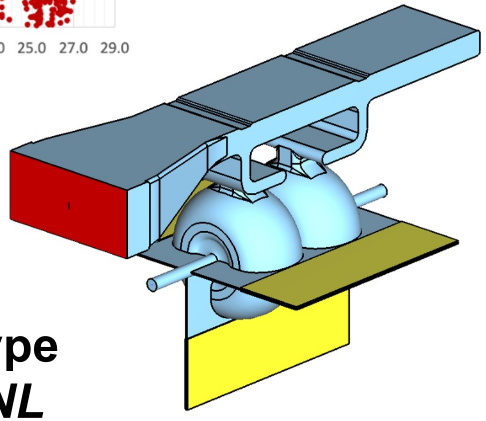
Implementation of Slot Damping

Need to extend to 40 GHz / Optimize coupling / Modes below 10^4 V/pC/mm/m

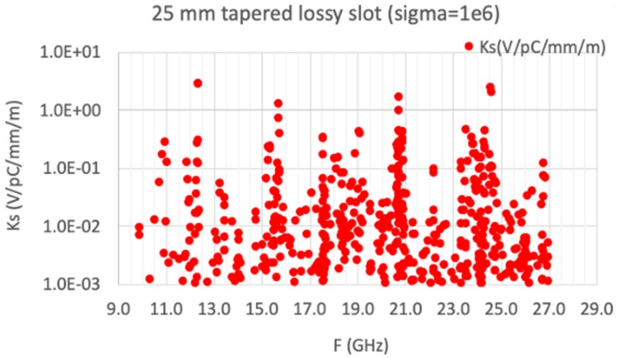
NiCr coated damping slots in development

Kick Factor * Q

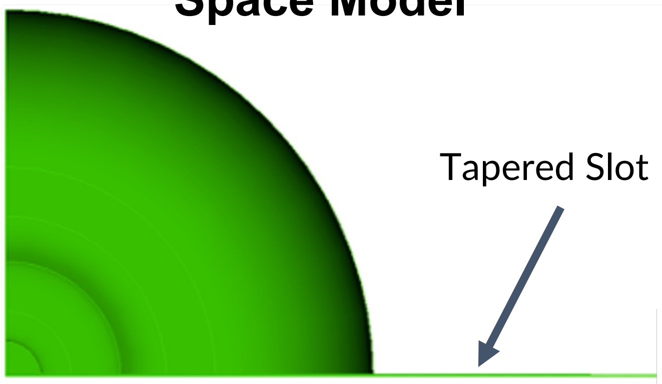




Kick Factor



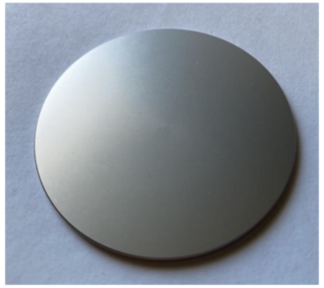
Vacuum Space Model

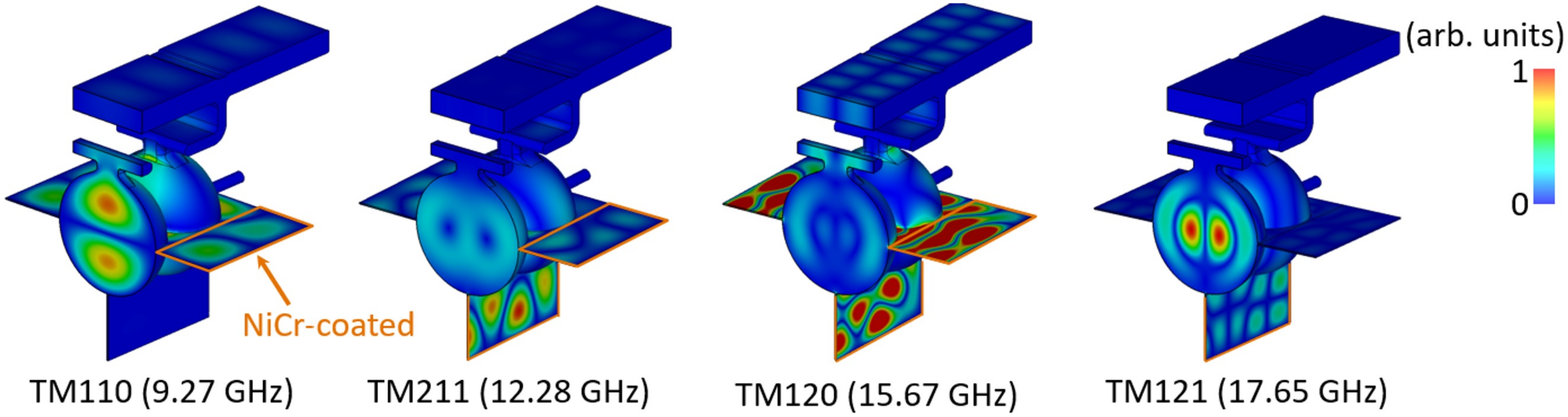


Two Cell Prototype

H. Xu, E. Simakov, LANL

NiCr Tested at 80K

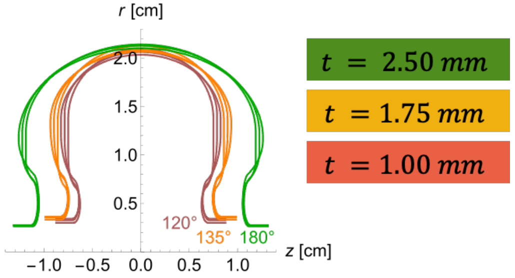




Conclusions

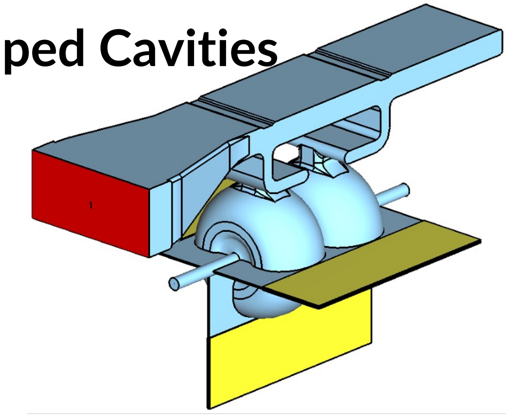
- Achievable gradient, breakdown rate and pulse length at C-band are promising
- How do we incorporate damping?
- How improve manufacturing of structures?
- How do meter scale structures perform?
- What is the optimal aperture and phase advance?

Wide-Aperture Reduced Phase Adv.



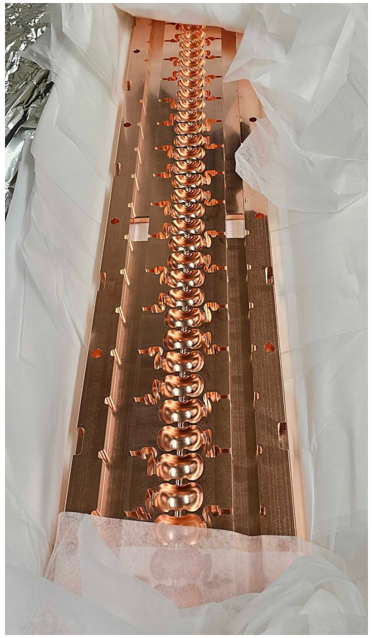
M. Shumail

Damped Cavities



H. Xu + LANL

Cryogenic Pi-Mode

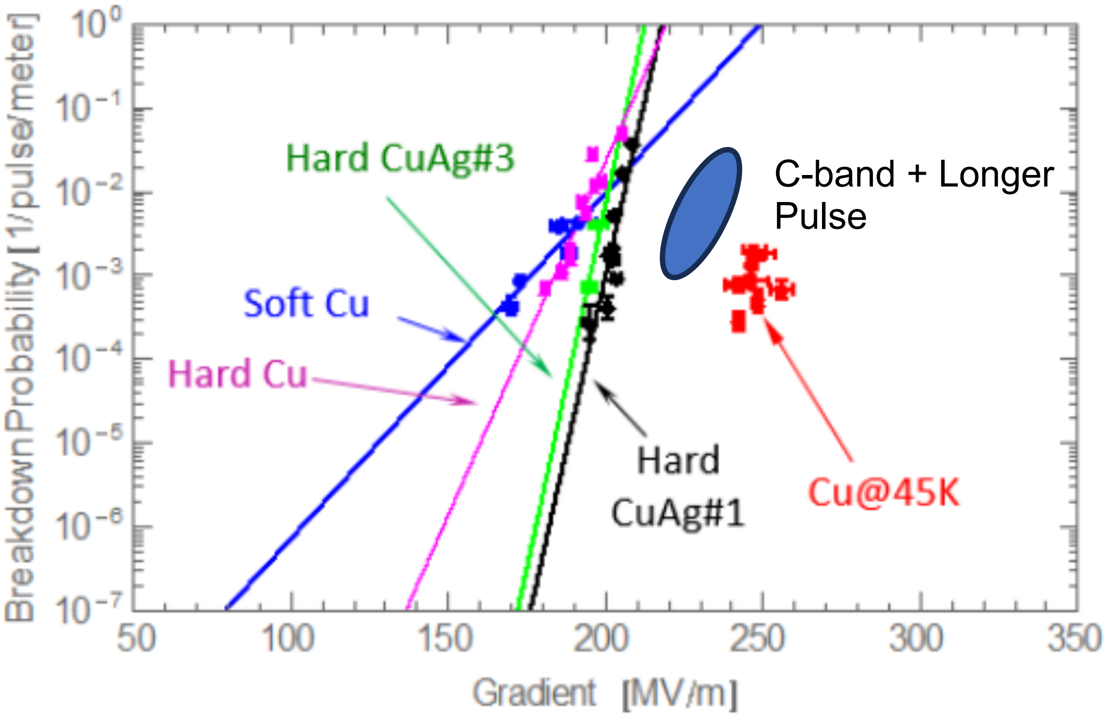


S-Band Large Aperture

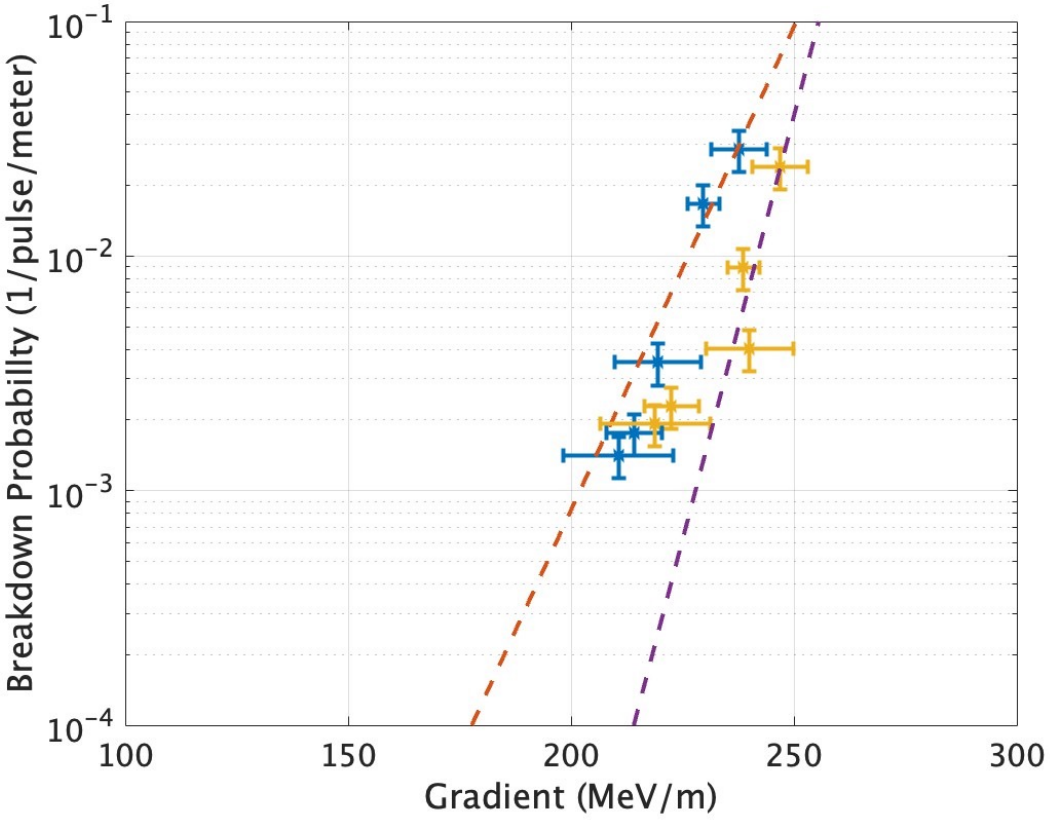
A. Dhar

Questions?

Additional Material



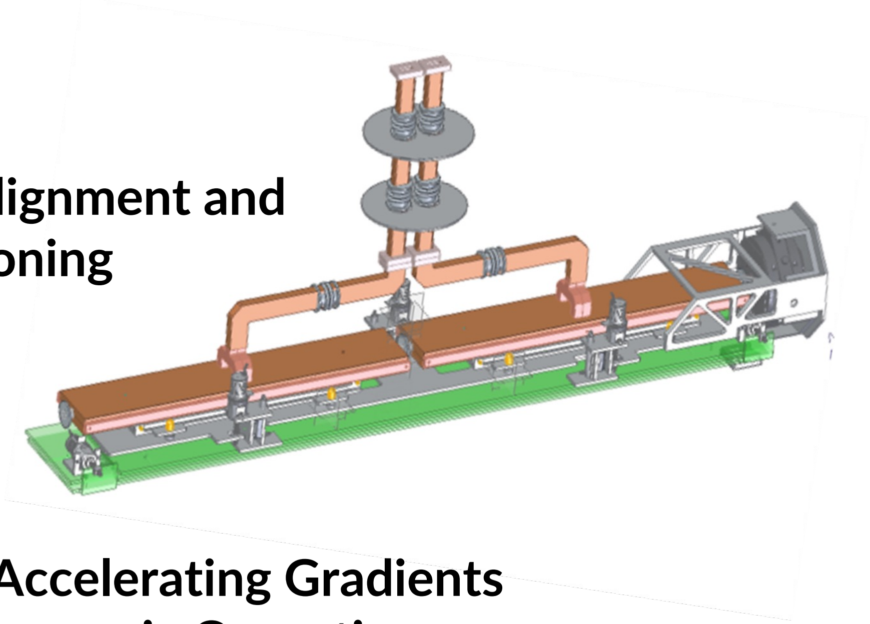
Breakdown Probability [1/pulse/meter]
Gradient [MV/m]
Hard CuAg#3
Soft Cu
Hard Cu
Hard CuAg#1
Cu@45K
C-band + Longer Pulse



Breakdown Probability (1/pulse/meter)
Gradient (MeV/m)

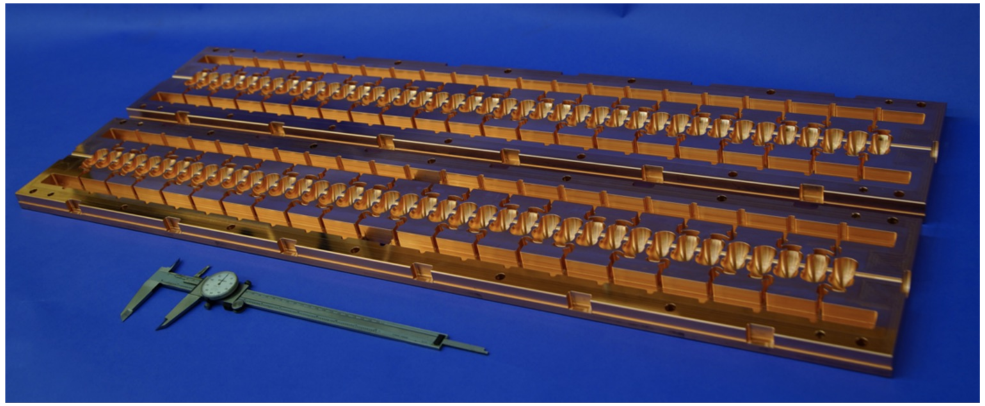
Ongoing Technological Development

Preliminary Alignment and Positioning



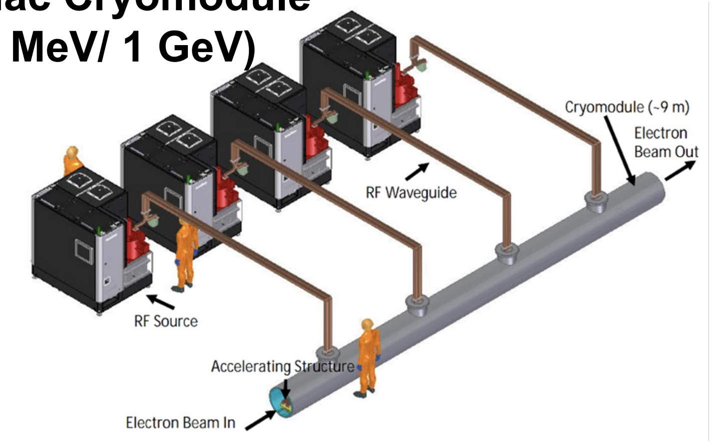
High Accelerating Gradients
Cryogenic Operation

Modern Manufacturing
Prototype One Meter Structure



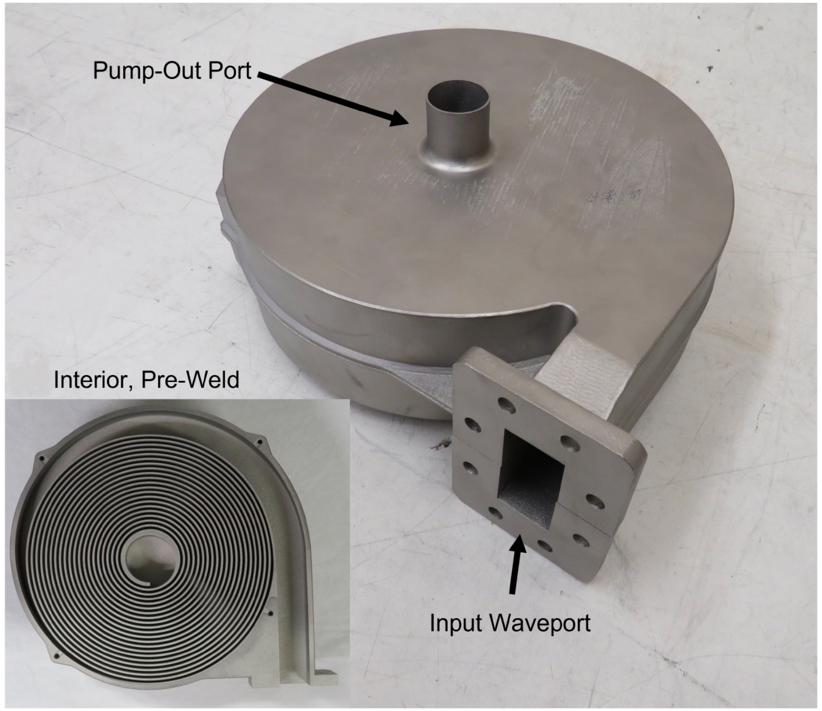
Integrated Damping with NiChrome Coating

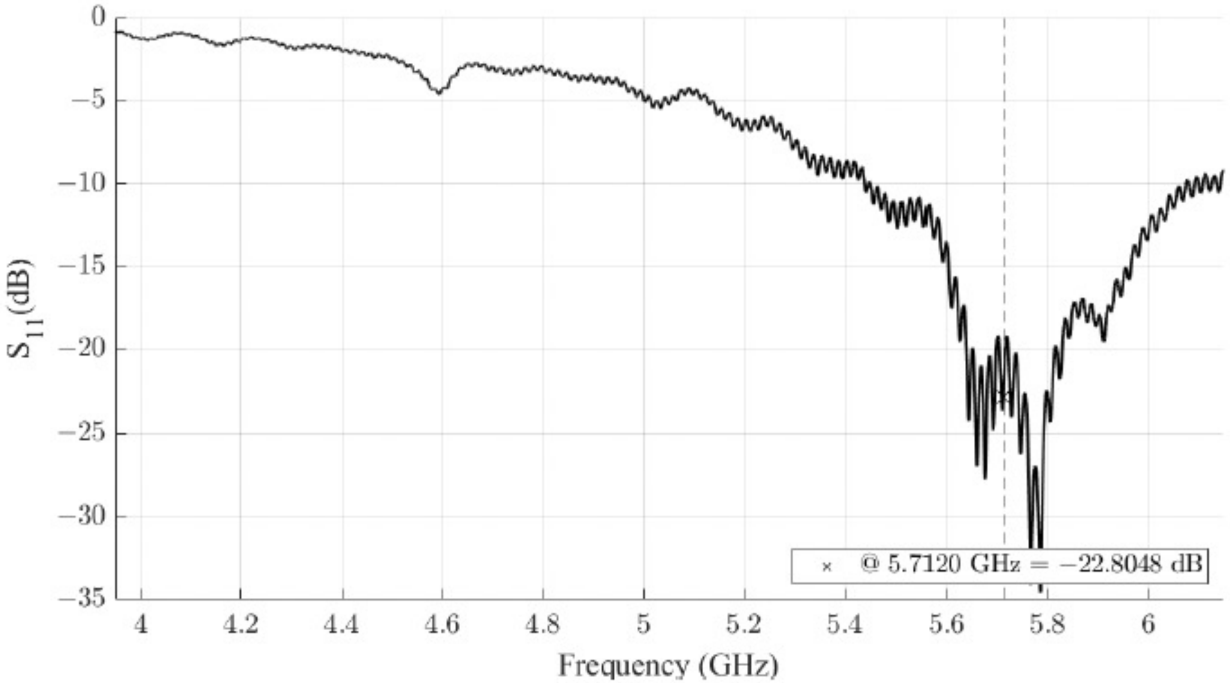
C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)



Additively Manufactured Spiral Load

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

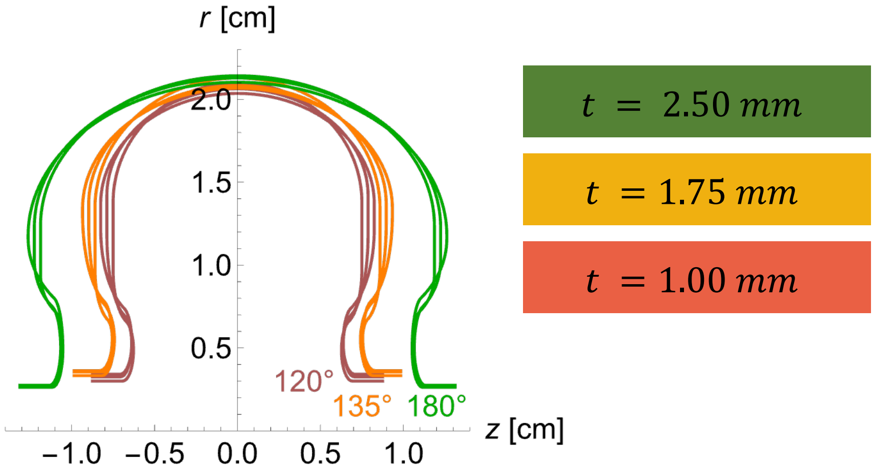




Tested to 8 MW, 20Hz, 700ns
Water Cooled Design for V2 (now in use)

Cell Optimization to Reduce Alignment Requirements

2) Structure of optimal phase advance
phase advance of interest:
180°, 135°, and 120°.



[Shumail]

Plausible choice:
- 135 deg/cell, t=1.75 mm
- a=3.55 mm

Disk T=2.5mm	180°	135°	120°
Aperture radius (a)	$2.624\ mm$	$3.33\ mm$	$3.00\ mm$
Gap width (g)	$21.06\ mm$	$15.00\ mm$	$12.54\ mm$
Quality factor (Q_0)	13,846	11,625	10,624
Shunt impedance (R_s)	$114.2\ M\Omega/m$	$114.1\ M\Omega/m$	$114.1\ M\Omega/m$
max$(E_s/Gradient)$	2.00	2.00	1.98

Disk T=1.75	**180°**	**135°**	**120°**
Aperture radius (a)	$\mathbf{2.74\ mm}$	$\mathbf{3.55\ mm}$	$\mathbf{3.26\ mm}$
Gap width (g)	$21.32\ mm$	$\mathbf{14.84\ mm}$	$12.76\ mm$
Quality factor (Q_0)	13,883	**11,614**	10,773
Shunt impedance (R_s)	$114.3\ M\Omega/m$	$\mathbf{114.1\ M\Omega/m}$	$114.0\ M\Omega/m$
max$(E_s/Gradient)$	2.00	**2.01**	2.00

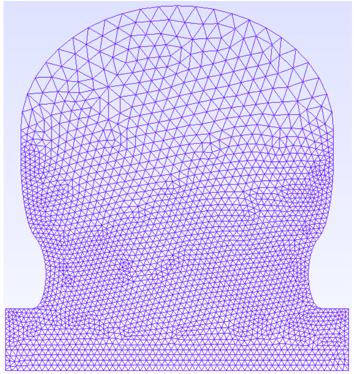
Disk T=1.0 mm	180°	135°	120°
Aperture radius (a)	$2.75\ mm$	$3.63\ mm$	$3.41\ mm$
Gap width (g)	$21.06\ mm$	$15.10\ mm$	$12.74\ mm$
Quality factor (Q_0)	13,621	11,674	10,795
Shunt impedance (R_s)	$114.1\ M\Omega/m$	$114.1\ M\Omega/m$	$114.2\ M\Omega/m$
max$(E_s/Gradient)$	2.00	2.00	1.99

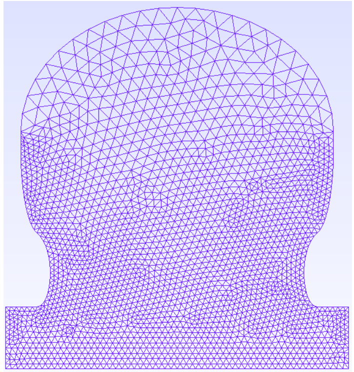
Cell Detuning

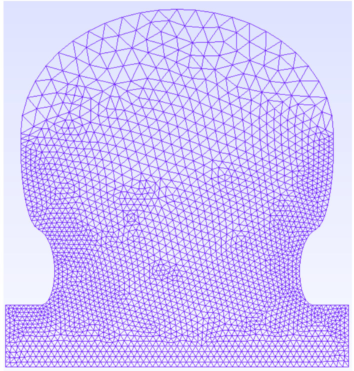
Cell-to-cell phase advance: 135 deg

- Cell length: 19.682 mm
- Detuning using iris “thickness”

Exceeds detuning bandwidth needed for dipole mode



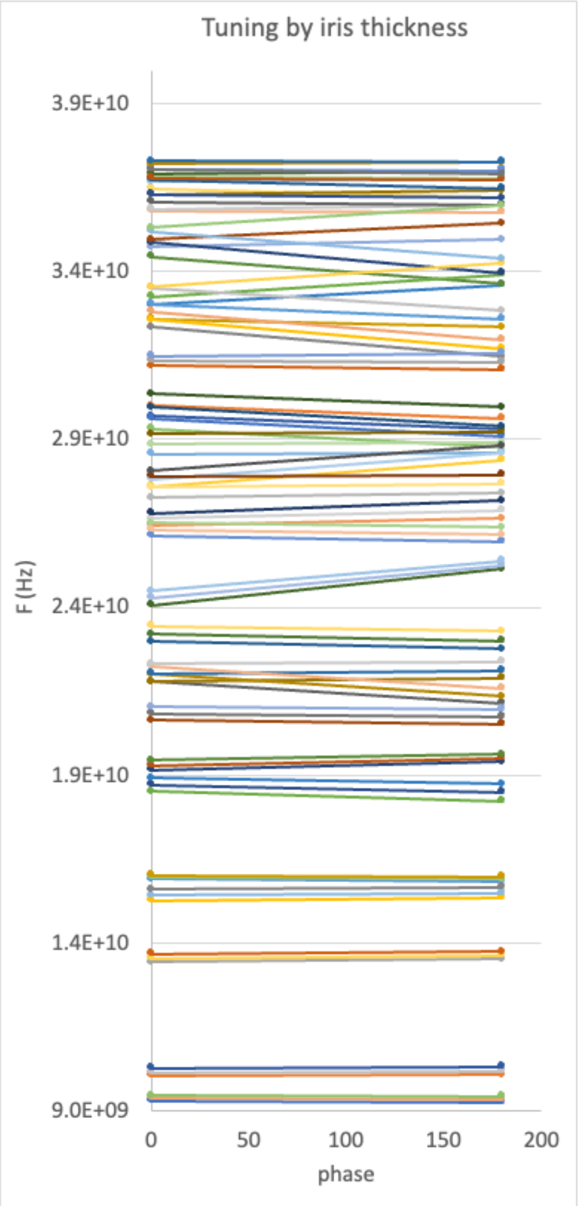


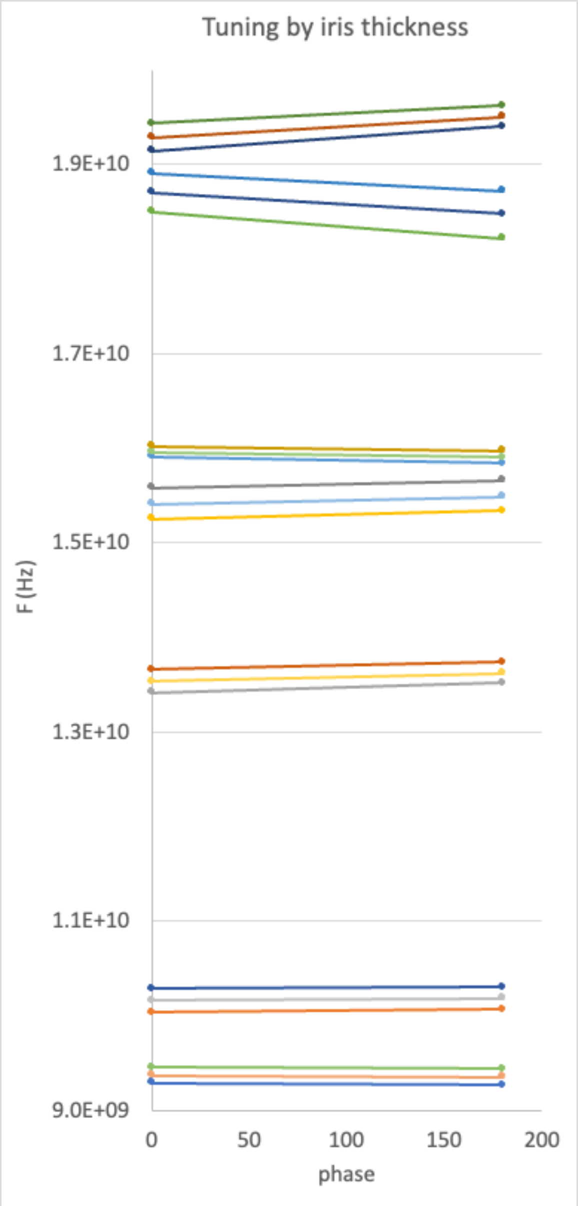


Gap1
R=113.67 Mohm/m

Gap1-0.5mm
R=114.32 Mohm/m

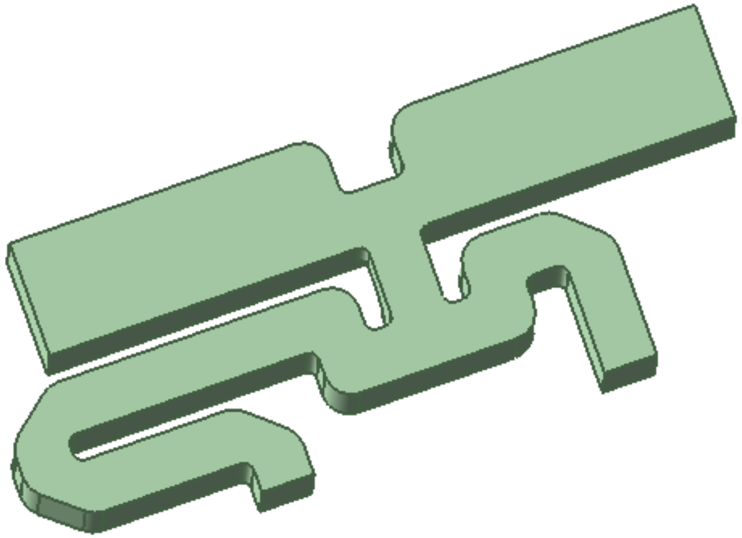
Gap1-1mm
R=114.38 Mohm/m

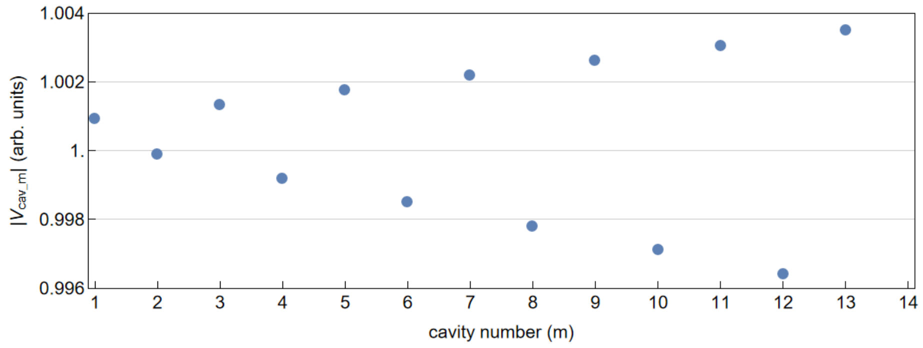


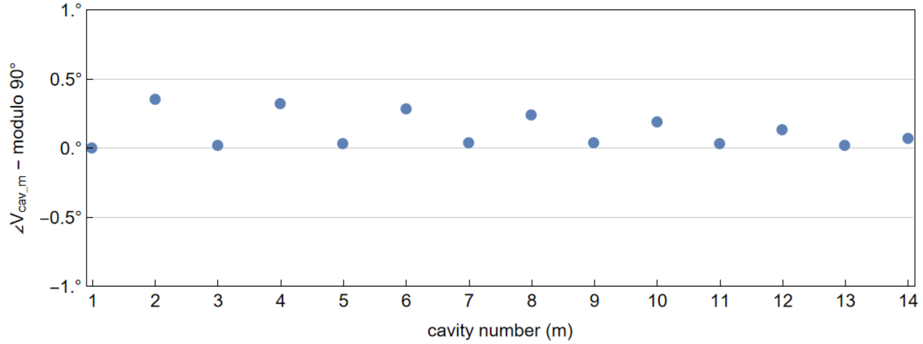


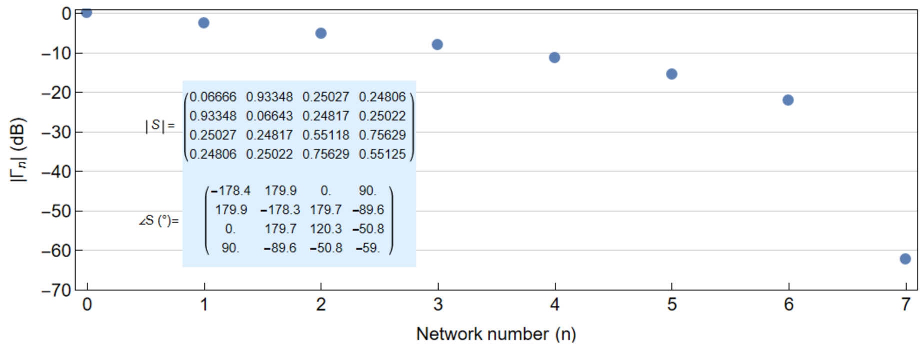
RF Network and Analytical Cascading

- Reduced phase advance structure has larger aperture but needs new manifold
- Two fold symmetry possible by bifurcating feed









- The analytical results show excellent uniformity in the amplitude and phase of the 14 cavities fed by a cascade of seven of these networks terminated with a short.
- The reflection coefficient at the entrance of the network (Γ_7) is less than -60 dB.