High Gradient Testing of a Meter-Scale Distributed-Coupling C^3 Accelerating Structures

2024 International Workshop on Future Linear Colliders

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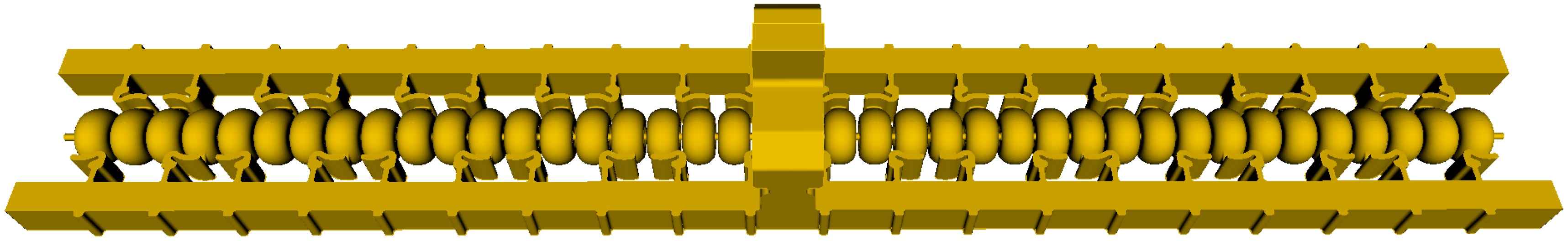
7/10/2024



SLAC NATIONAL ACCELERATOR LABORATORY

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What's the Optimal Frequency for High Charge Beams?

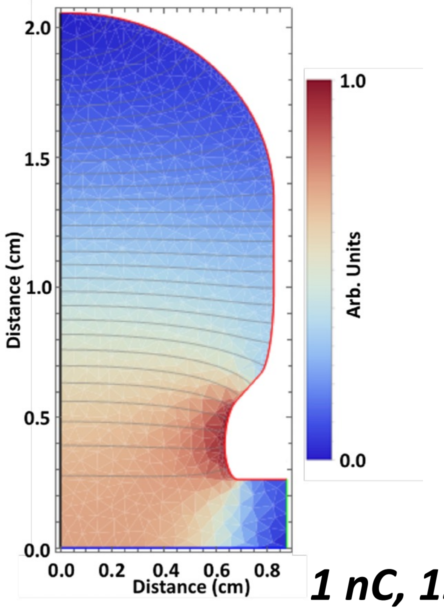
Linear collider: high beam power

→ 1 nC per bunch, 0.3 A during rf pulse

→ Most challenging design parameters

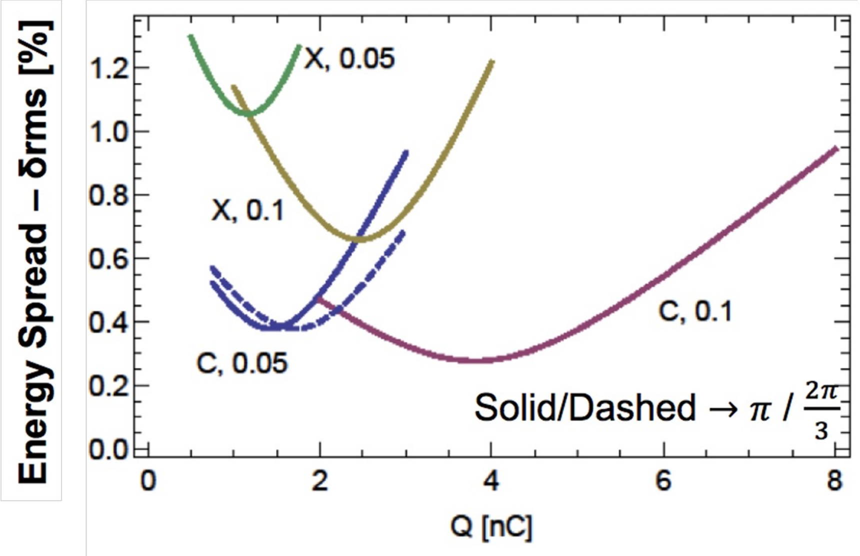
Pursue broad array of applications

→ 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)

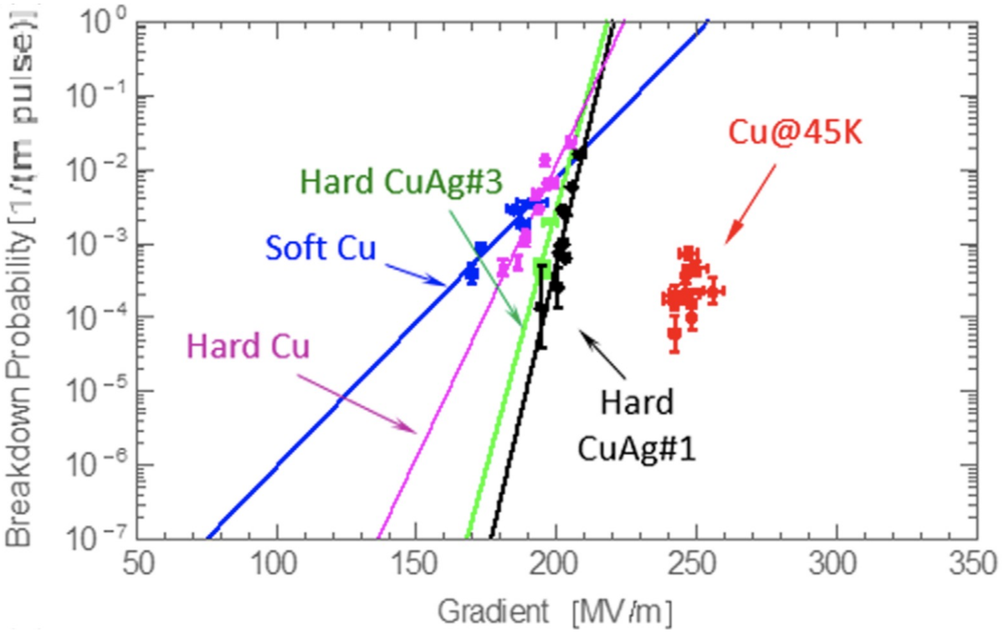
Cryo-Copper: Enabling Efficient High-Gradient Operation

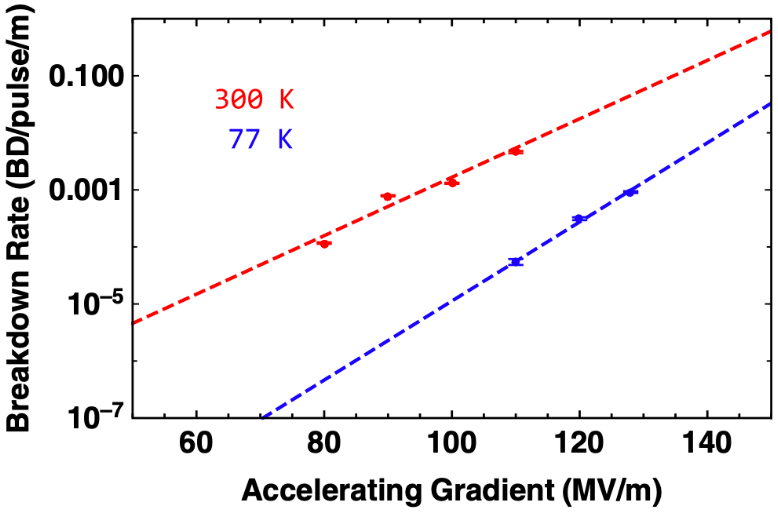
Cryogenic temperature elevates gradient

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

Operation at 77 K with liquid nitrogen

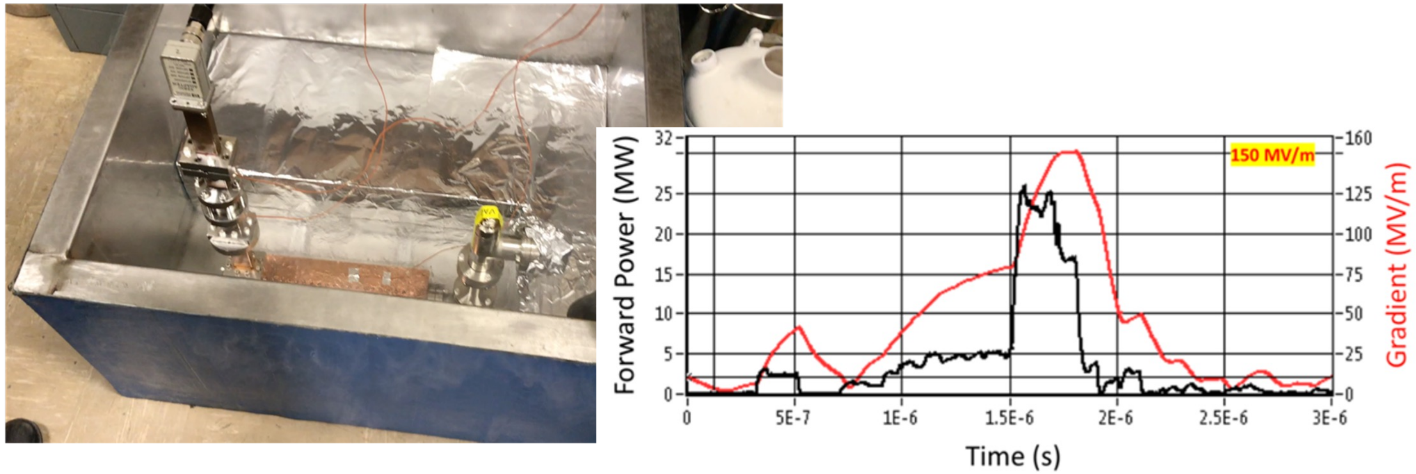
- Large heat capacity, simple handling
- Small impact on electrical efficiency





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

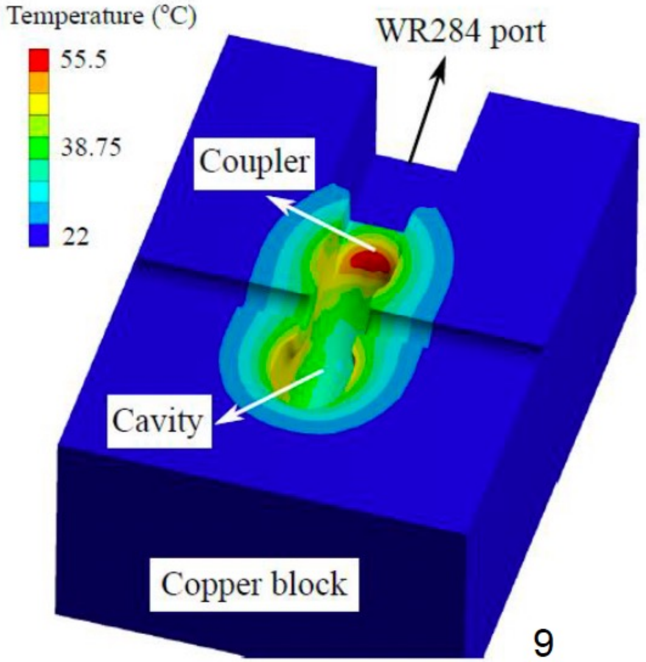
High Gradient Operation at 150 MV/m



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

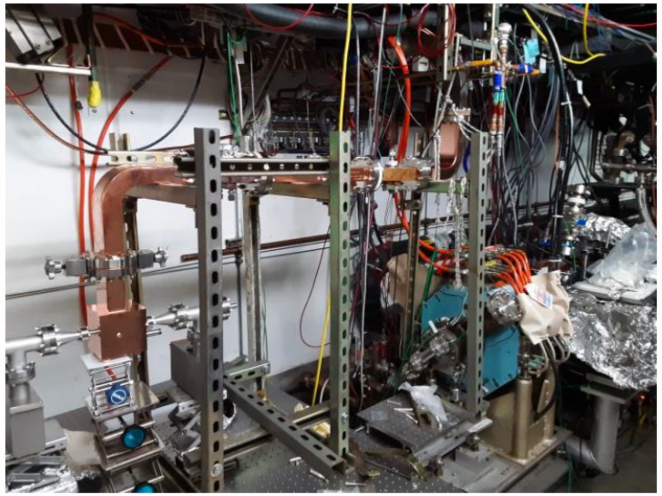
Time [s]

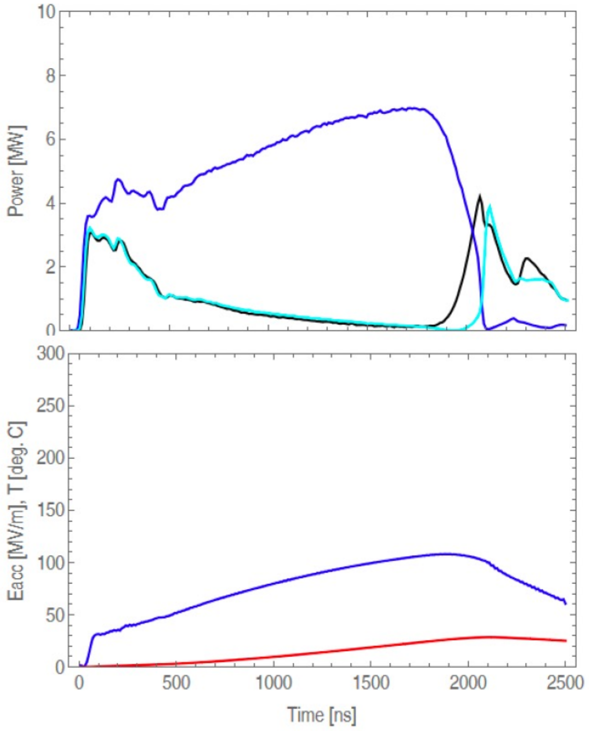


Single cell energy modulator prototype

-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.

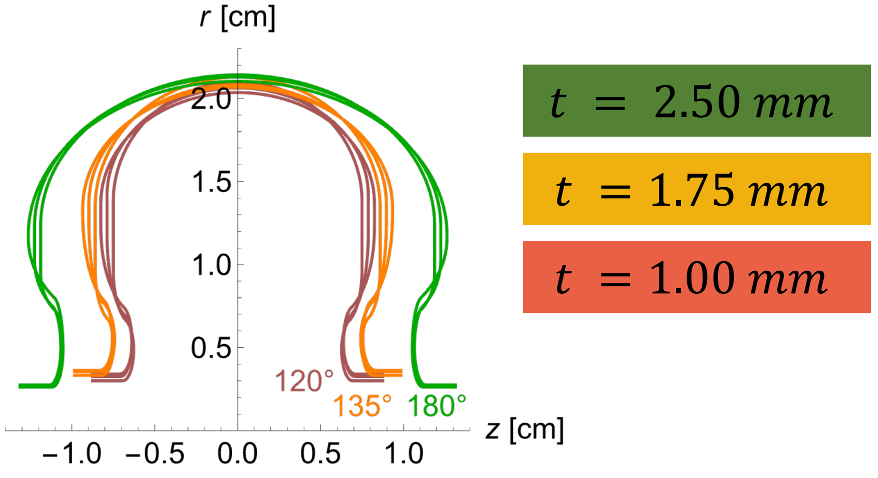
Calculated acceleration gradient and temperature rise

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

Meter-Scale Distributed-Coupling Structure

Cavity Geometry Optimized for Constant Aperture

Structure optimization at 5.712 GHz for phase advance of interest:
180°, 135°, and 120°.



[Shumail]

This work at 180°, in future 135°

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

RF Coupler Design

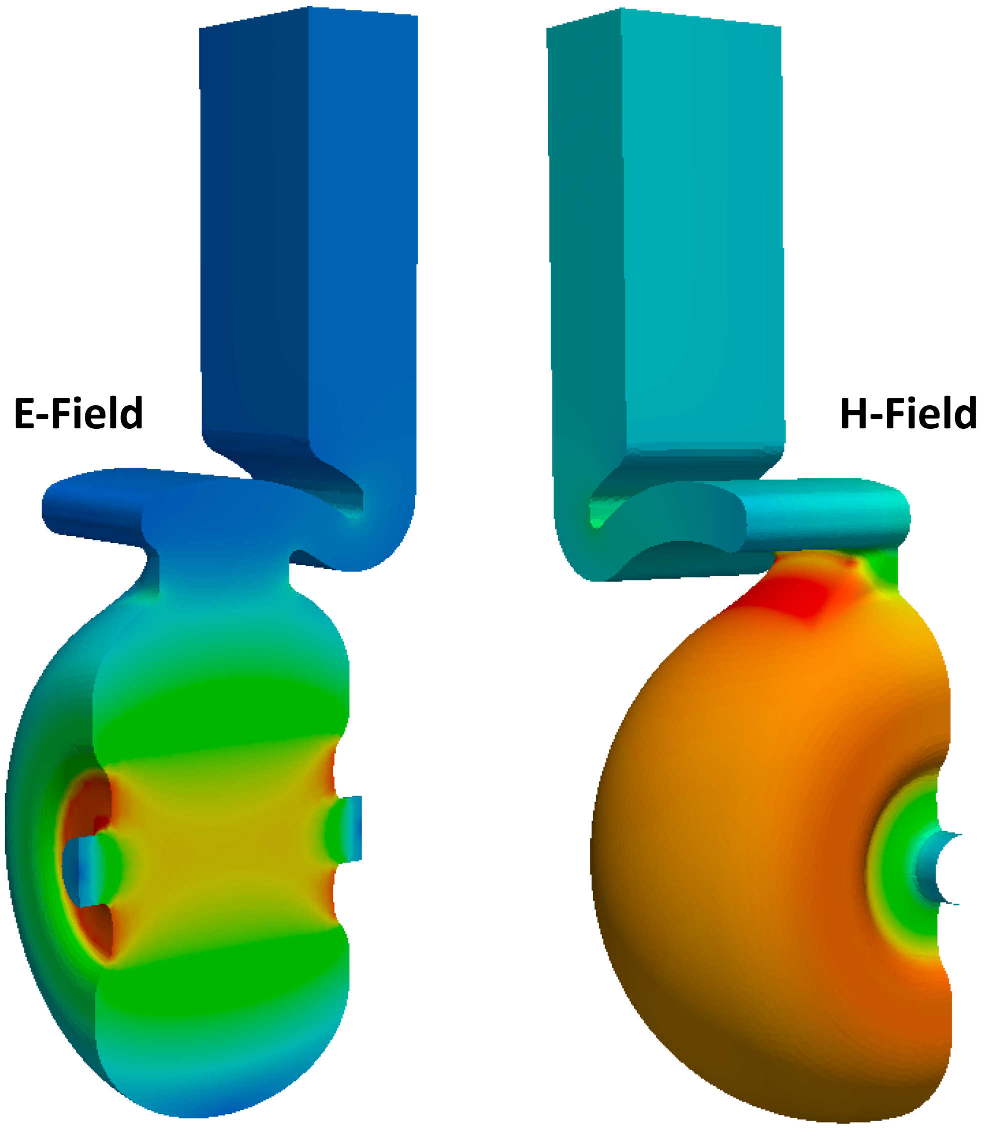
Structures are critically coupled at room temperature

Overcoupled at cryogenic temperatures

- Reduces fill time
- Critically coupled with beam injection

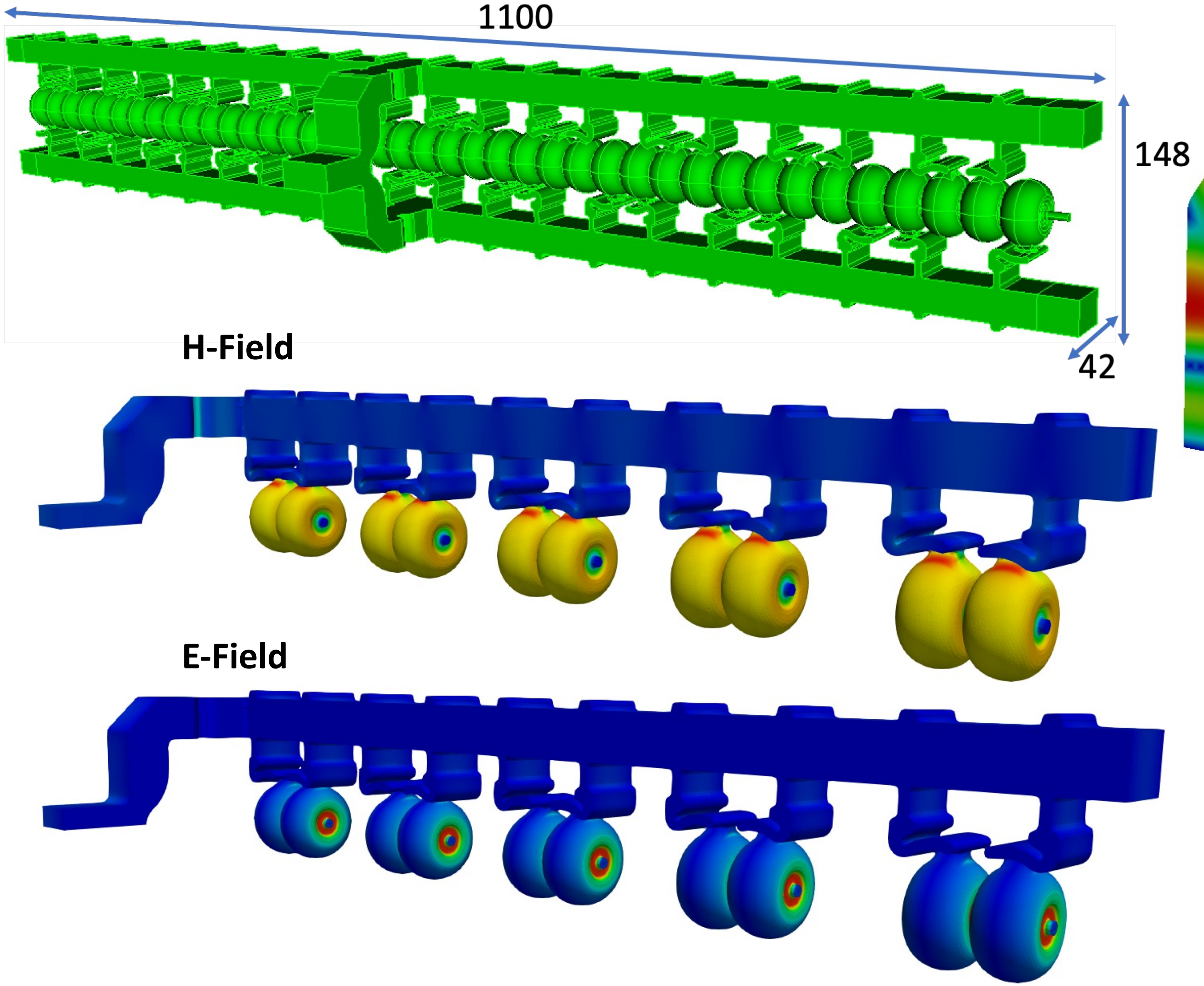
Coupler Impact – H-field enhancement 18.6%

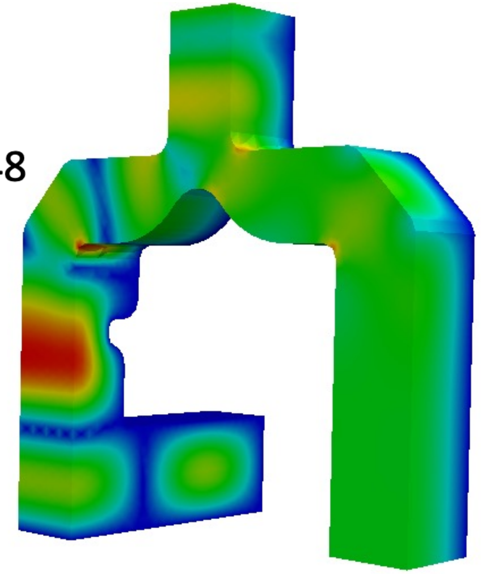
Peak surface E-field / Accelerating Gradient = 2.22



Manifold Design

Each structure powered by a single feed split into two manifolds





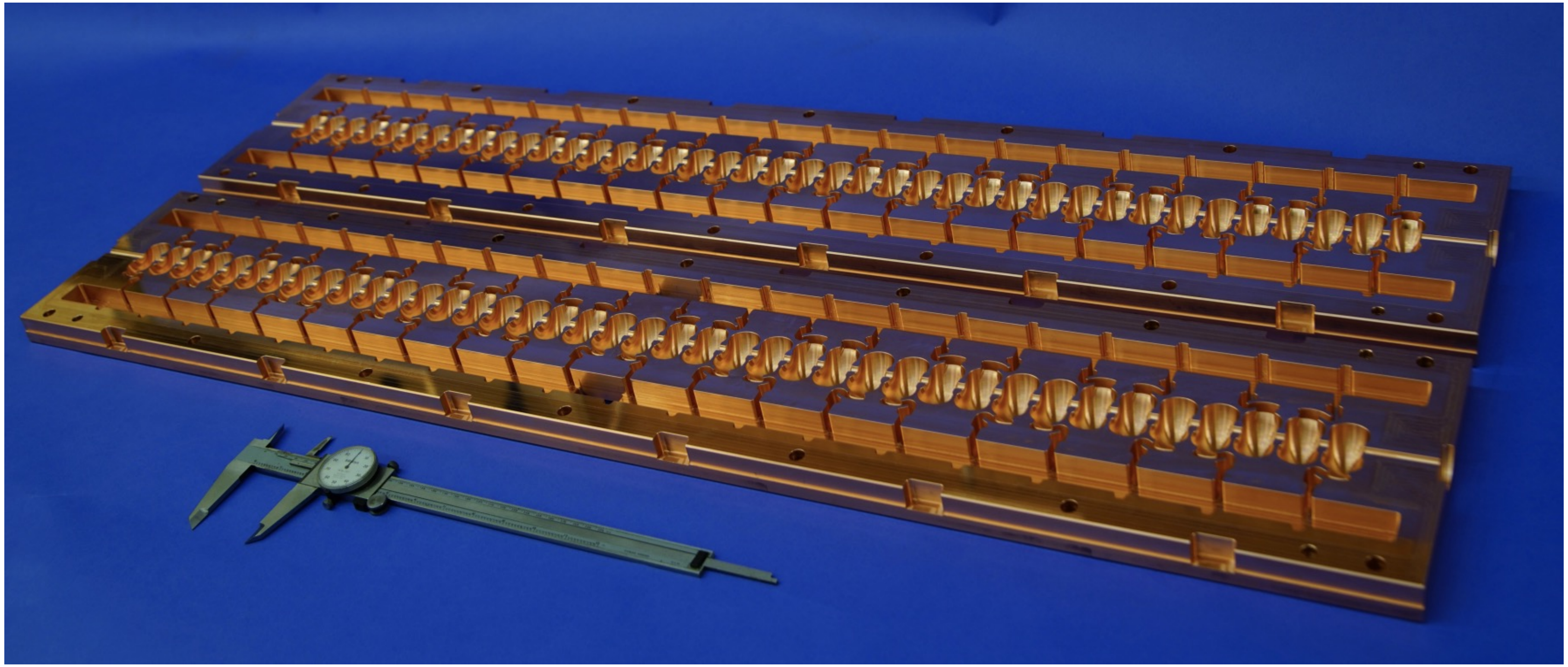
Power Splitter

Note: Pairs of structures fed by a hybrid to avoid reflections to klystron

Split Cell Manufacturing

One of the core innovations for C3 is distributed coupling, allowing RF power to be individually fed to each cavity with precise phasing

The engineering innovation that makes this possible is split cell manufacturing, where the cavities are machined in two halves and then joined via brazing or diffusion bonding

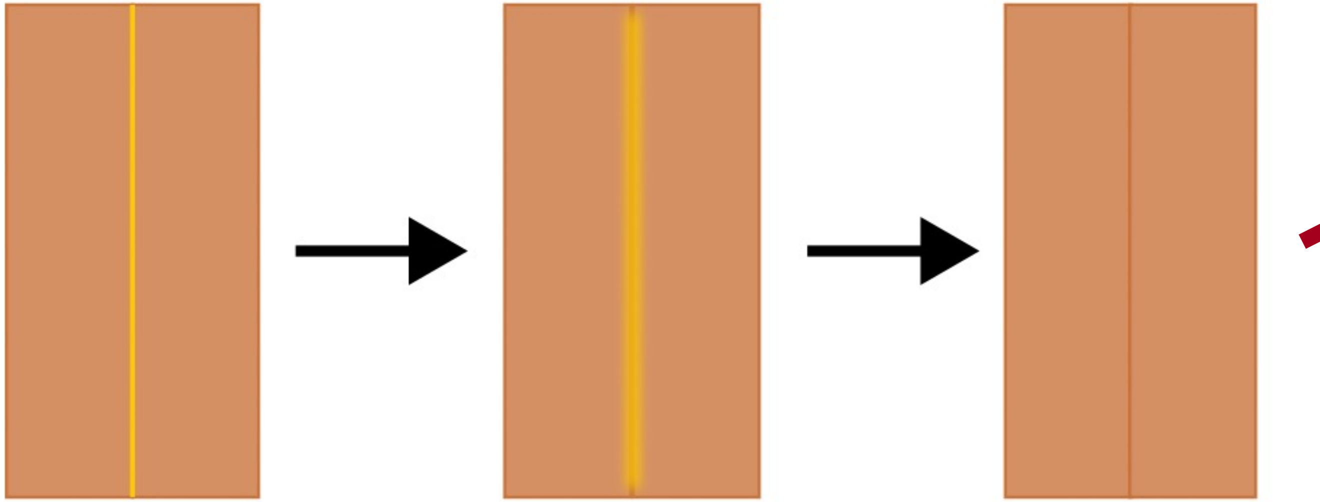


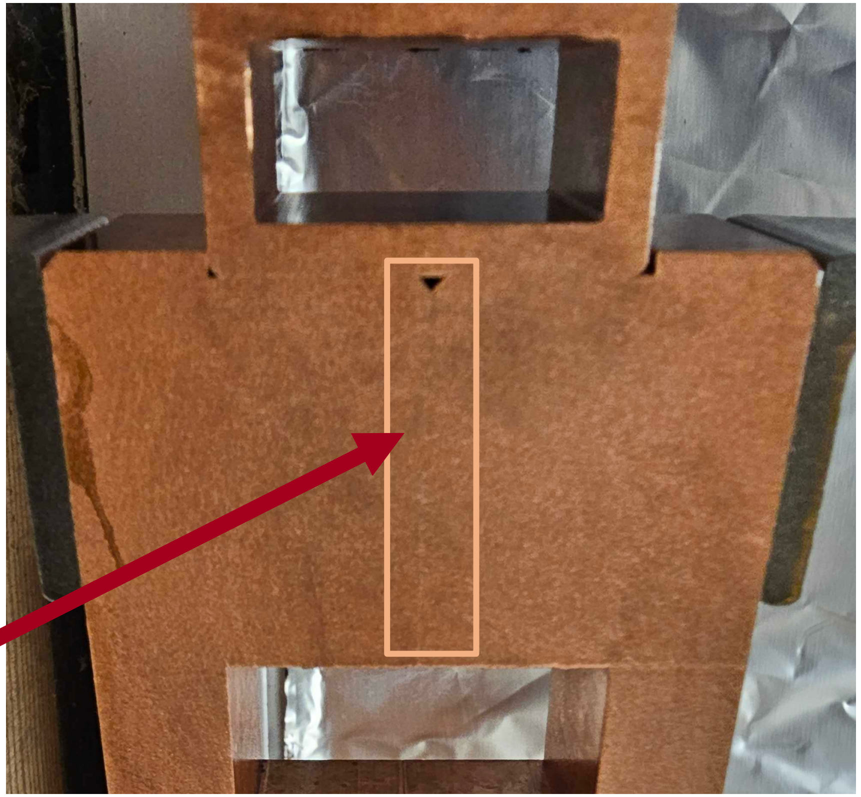
Brazing

Brazing is a process by which metals can be bonded by almost melting the interface between them and joining them with a filler metal with a lower melting point

In the case of RF structures, this is used for joining copper pieces together

- The filler metal in this case is typically an alloy of copper and gold, the exact proportion of each determining the melting point of the alloy
- Using split cell manufacturing greatly reduces the number of braze steps



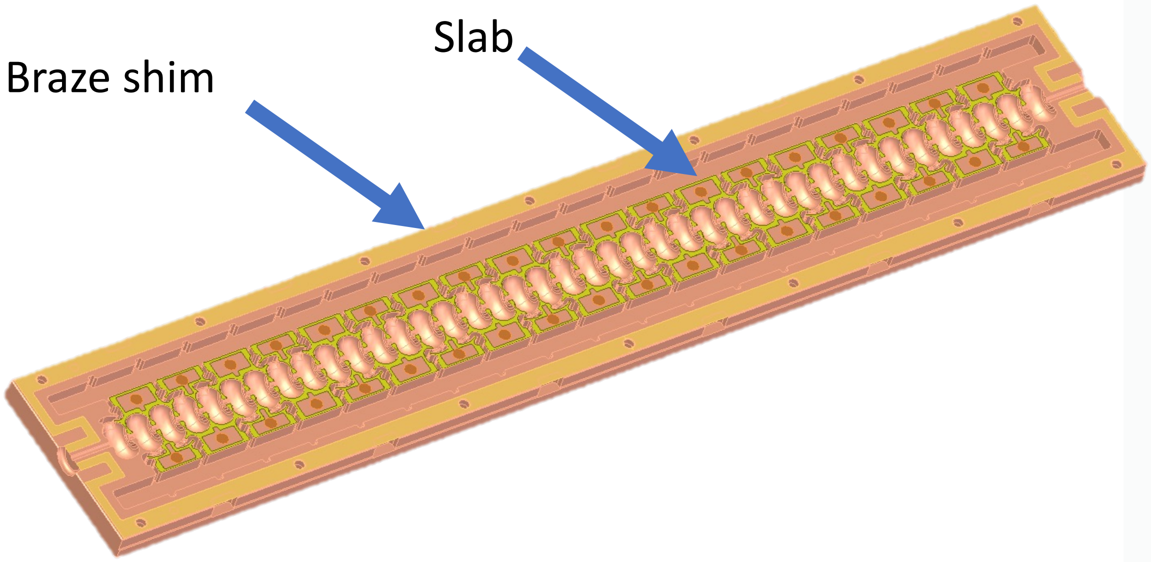


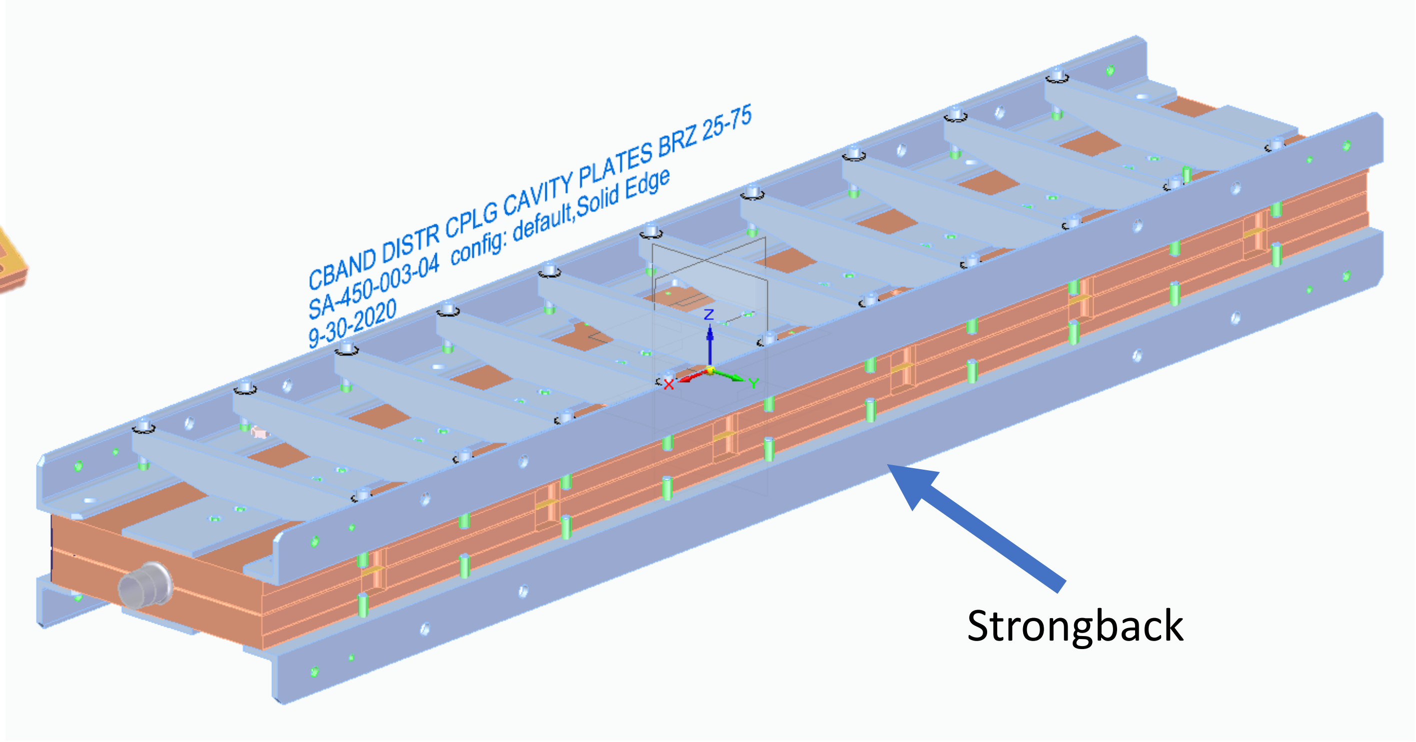
Brazing Assembly

Typical tolerances for bonding require surface flatness to within 0.001”

Braze filler metal is typically cut from sheet stock that is 0.001” to 0.002” thick

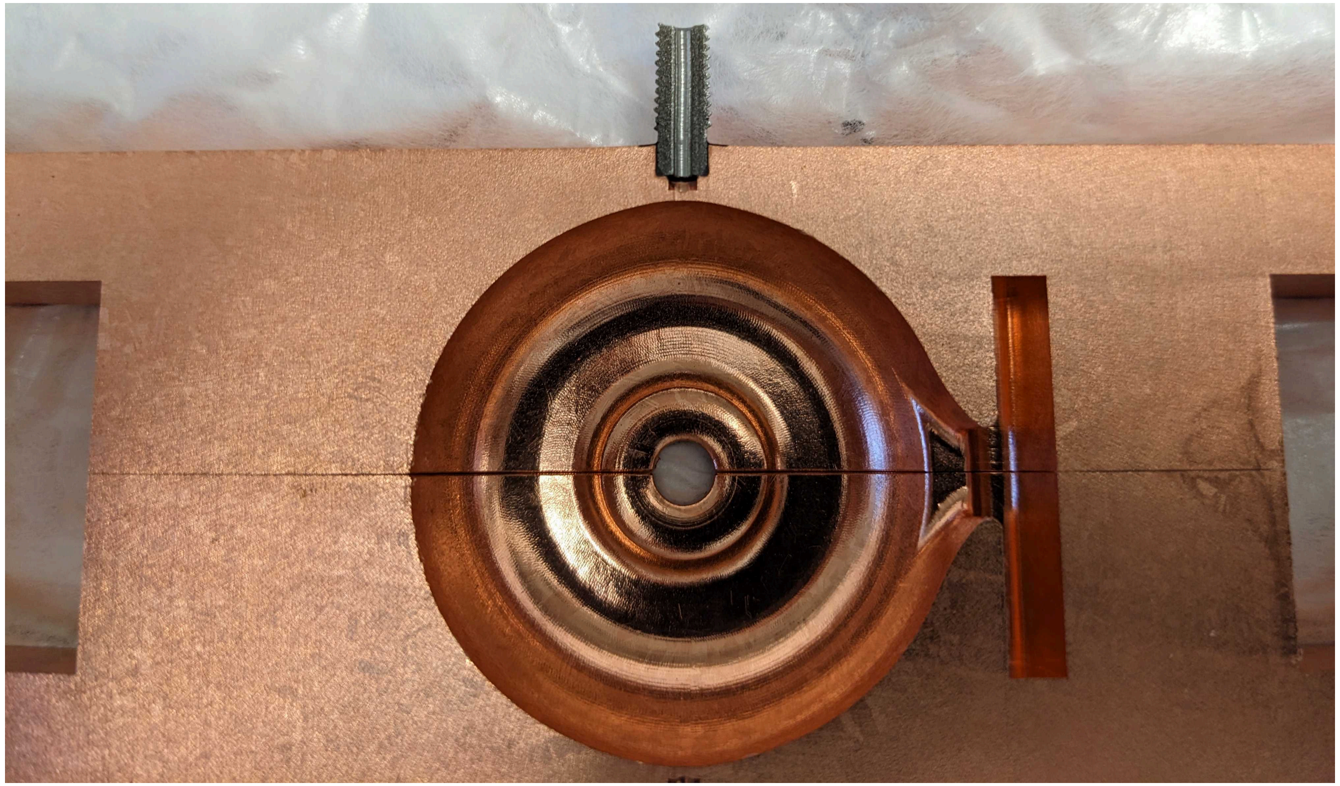
To ensure contact between bonding surfaces, strongback braces can be used

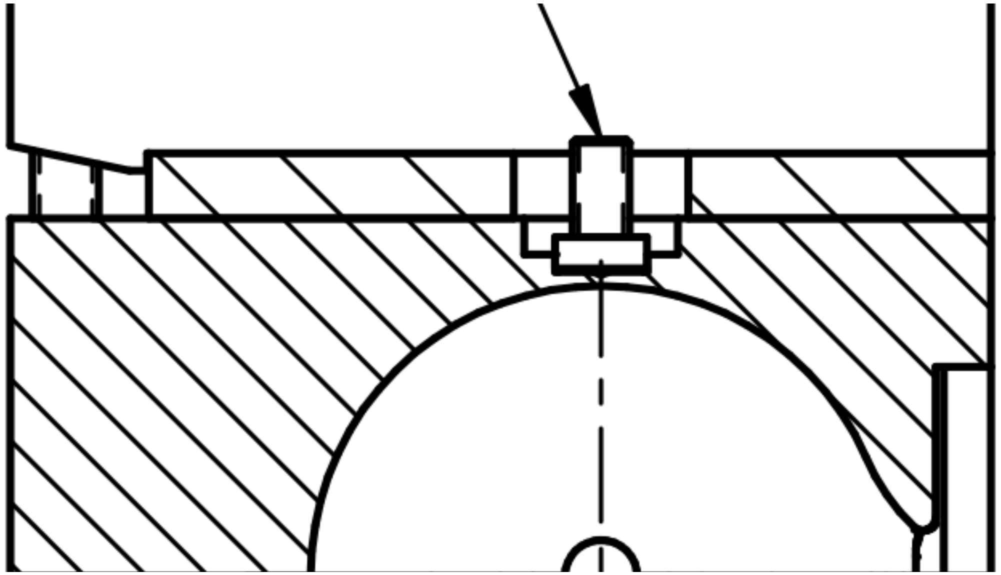




Frequency Tuner for Cavities

After the two slabs are bonded, extra features *e.g.* power splitter / tuning pins are brazed in





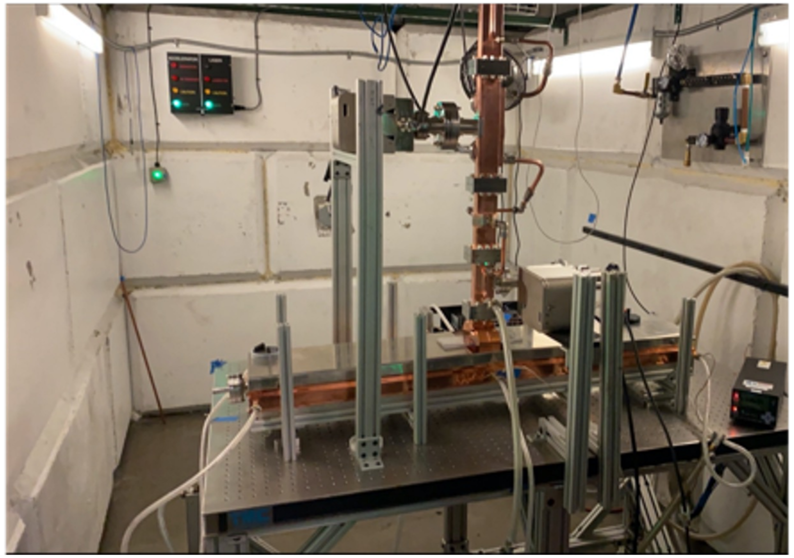
3rd C^3 Meter-Scale Prototype Completed Spring '24

Previous structures tested warm at high power

- Max power 15 MW into structure – klystron limited

Braze process and fixturing was improved iteratively

Third structure for cold operation



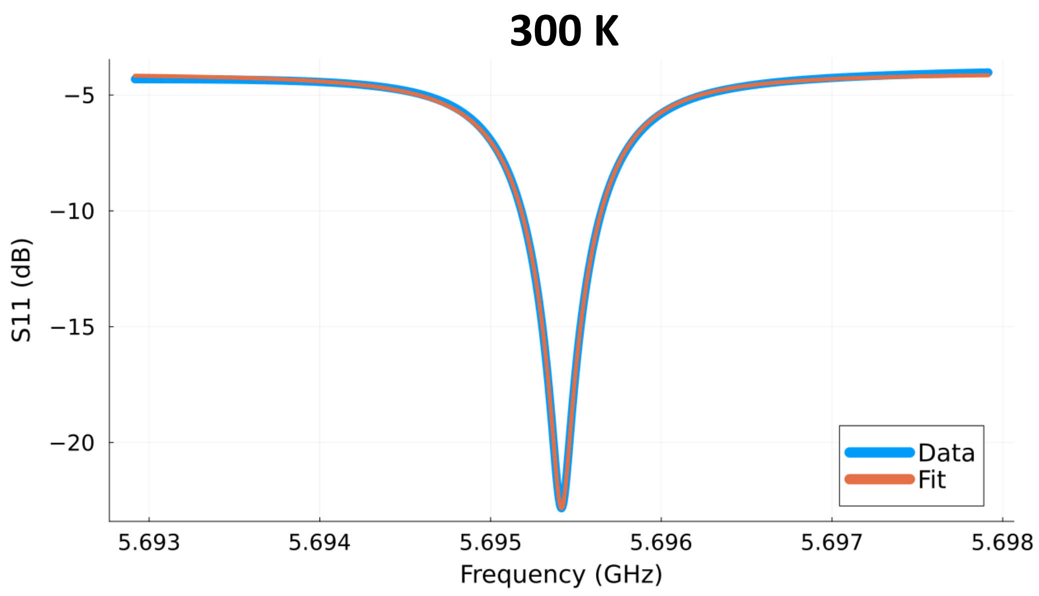
Low Power Structure Performance

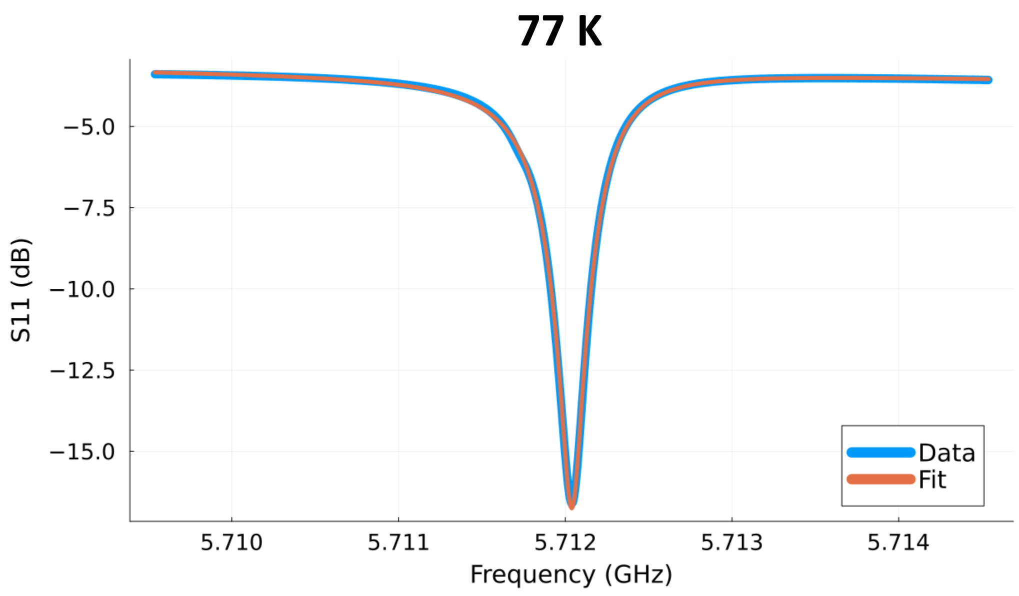
Structure Tuned at 300 K with N2 Purge

Frequency shift during cooldown predictable and repeatable

Each cell tuned while others are detuned by a rod

Parameter	Unit
Qo Design Warm - 300 K	13,800
Qo Warm - 300 K	12,300
Qo Cold - 77 K	28,700
Enhancement	2.34





Measurement of RF Signals and Breakdowns

Structure was processed over 10 days – power limit to structure from klystron 21 MW

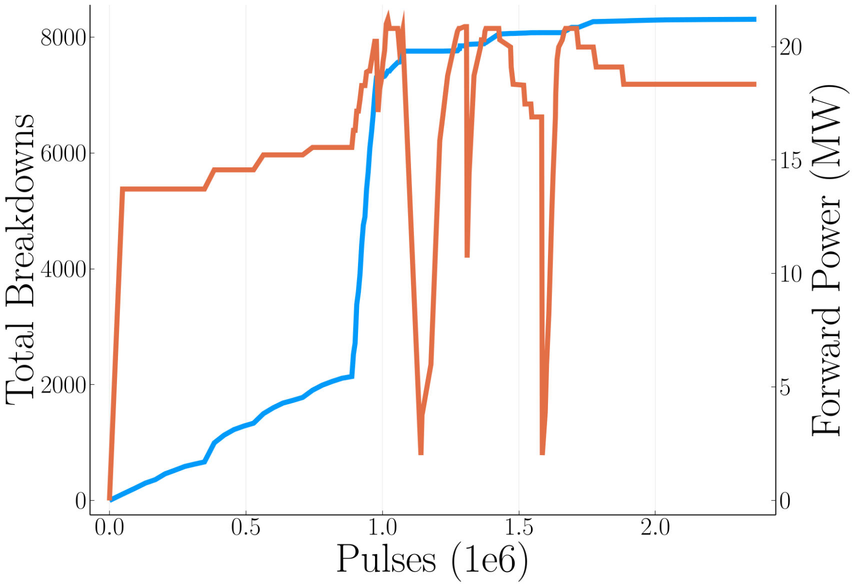
Processed at 400 ns, 700 ns and 1000 ns

First operation of RF network >5 MW

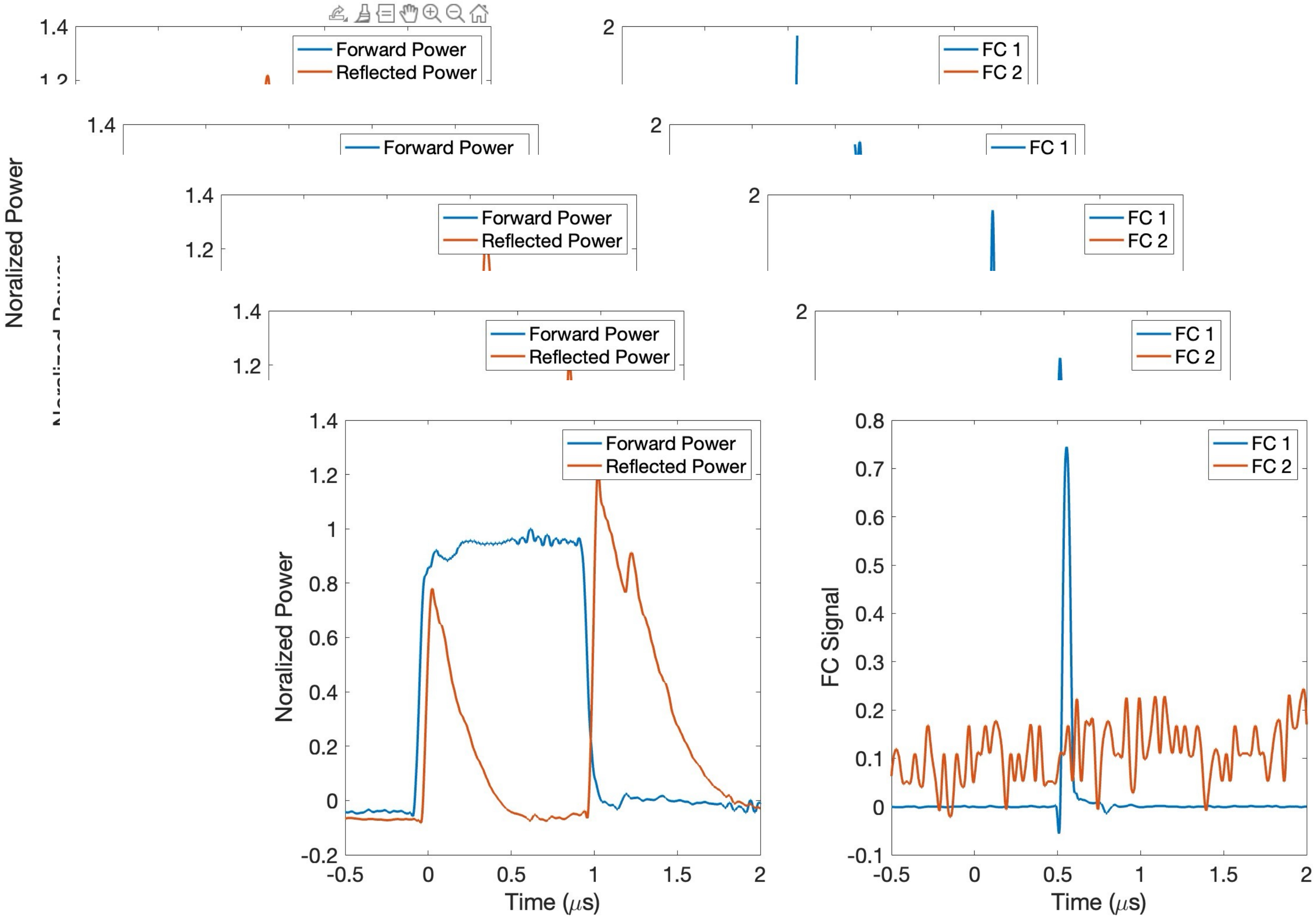
Rep rate was varied 10-80 Hz

50 MW Klystron into variable power splitter

Total Number of Pulses/Breakdowns



Example Breakdowns

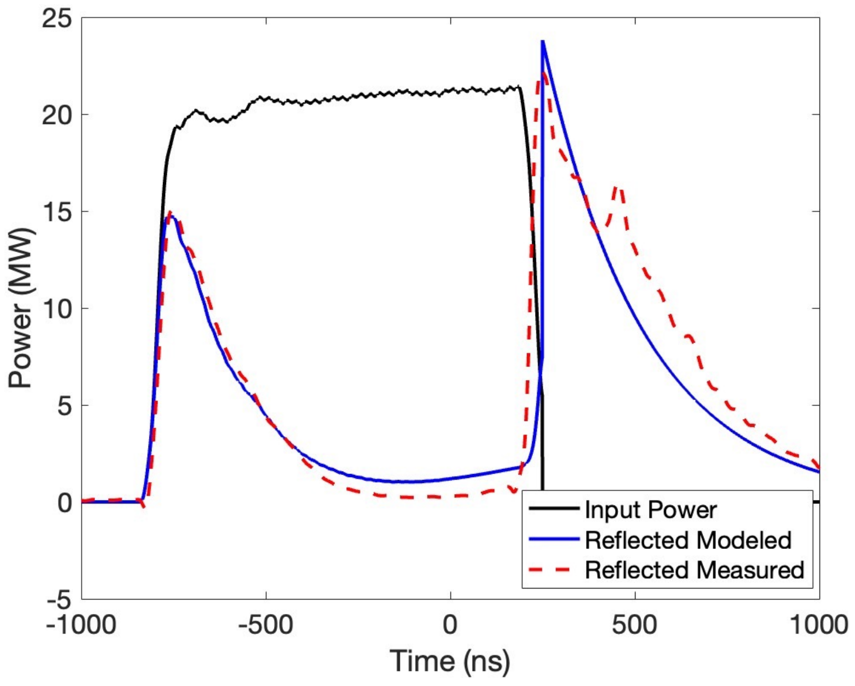


Achieved Accelerating Gradient

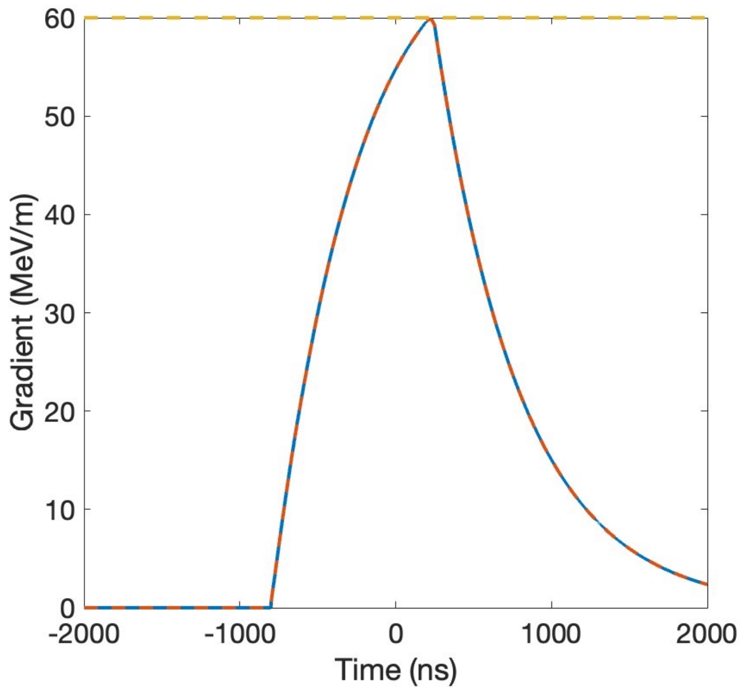
60 MeV/m for 21 MW (klystron/rf network limit) and 1 microsecond in just ~2M rf pulses!

At 50 MeV/m BDR was O(10^{-6}) /pulse/m

Measured and Modeled Reflected Power



Modeled Gradient

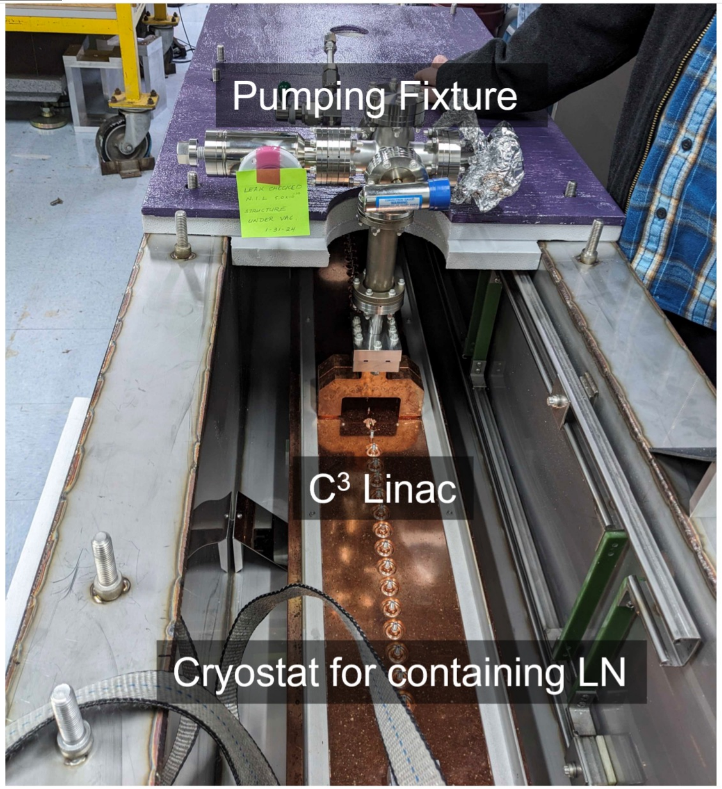


Moving Forward: Need longer pulse ~1.5μs, higher power ~35 MW, longer run time (over night, ~2 months)

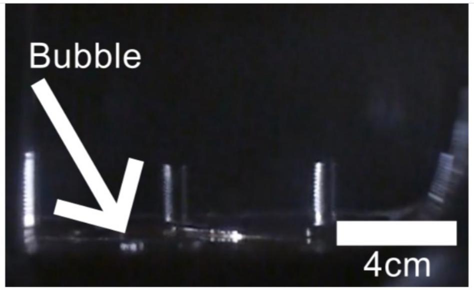
Vibration Measurements Resistive Heater in Beam Tunnel

For main linac structures vibration tolerance is ~10 μm

Prototype C3 Linac with a resistive heater was used to test vibration within LN up to 2 kW (thermal load of main linac)



(a)



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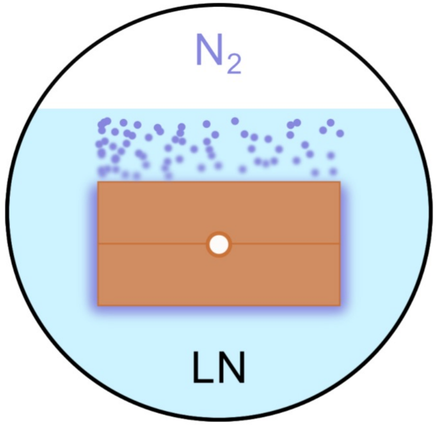

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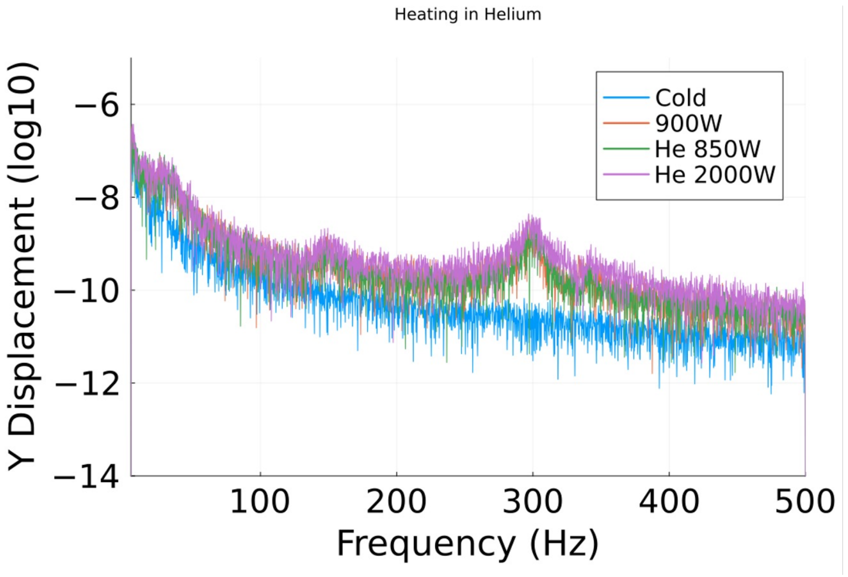
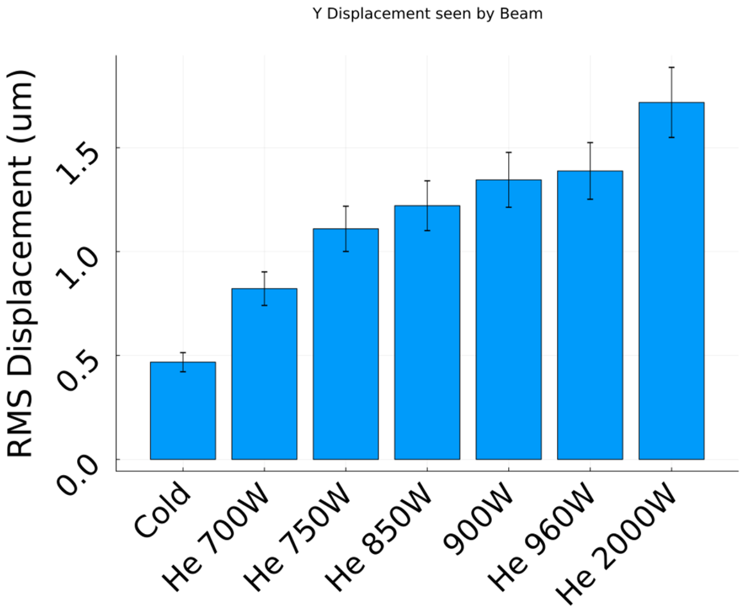


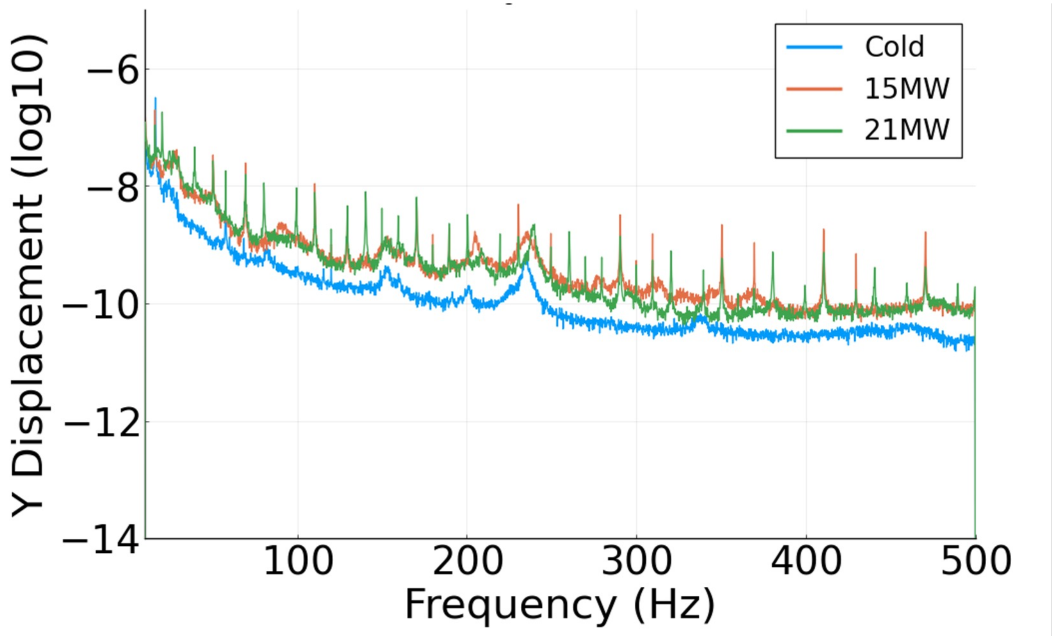


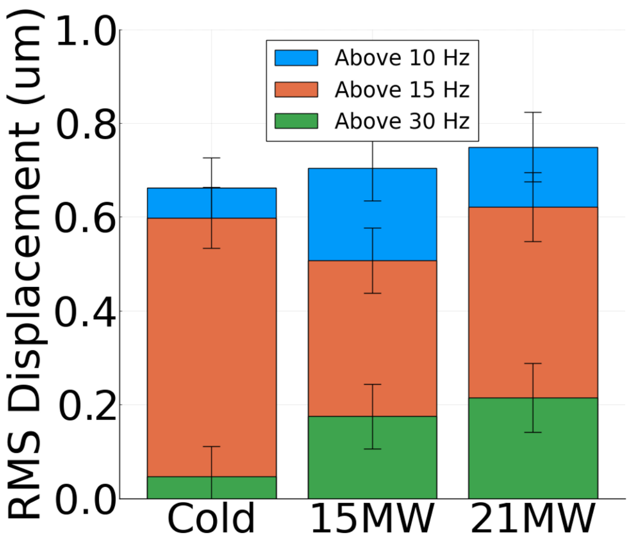
https://www.osti.gov/biblio/2371576

Vibration Measurements with RF Heating

Vibration Data Collected at 10 Hz and 1 μs

Accelerometer measurements at max power showed sub-micron displacements, even with mechanical propagation from outside the bunker





More Environmental Background – RF Heating RMS Displacement Consistent with Resistive Heating

Conclusions

RF tests for cold copper meter scale structures are underway

Structure tests should proceed with:

- Beam: Direct measurement of gradient, wakefield studies
- RF: Need longer pulse ~1.5 μs, higher power ~35 MW, longer run time (over night, ~2 months)

Future efforts to increase aperture, reduce phase advance and incorporate damping

Quarter CryoModule (QCM)