High gradient C-band research at Los Alamos

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ASD-APES Seminar, Michigan State University

26 March 2021

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

LA-UR-21-22923: unlimited release

Outline of This Talk

- Acknowledgements
- Project Overview
- Introduction to High Gradient Breakdown
- Experimental activities
    - High gradient C-band test stand
    - Test Cavities
    - Testing Plan
    - Collaborations
- Modeling and simulation
- Summary and near term plans

Acknowledgements and Thanks

- Frank Krawczyk – initial vision, project inception, strong leadership
- Leadership team (co-Pis and advisors): Dmitry Gorelov, Samantha Lawrence, Danny Perez, Evgenya Simakov, Tsuyoshi Tajima
- Project team members: Jon Acosta, Soumendu Bagchi, Amber Black, Ryan Fleming, Andrew Garmon, Tim Germann, Todd Jankowski, Mohammad Karim, Harbhajan Khalsa, Mark Middendorf, Paolo Pizzol, Adrian Romero, Bill Romero, Mitchell Schneider, Tsuyoshi Tajima, Gaoxue Wang,
- Facility support – klystron installation, lead work, etc.
- Nathan Moody, John Smedley, Stephen Milton, Toni Taylor – supportive and helpful line management
- Emeritus: Frank Krawczyk, Mark Kirshner

This work supported by the Los Alamos LDRD program

Project Overview

Our talk title begs three questions:

- Why high gradients?
- Why C-band, and
- Why Los Alamos?

Overview: Why high gradeints?

National-Scale Facilities: cost scales as size (length) of the accelerator.

$L \sim V_{beam}$ / Gradient

→ double the gradient, halve the cost

Capability Transition: improve accessibility

Higher gradients → same beam voltage in smaller space

Same voltage → similar output (e.g. X-ray energy)

Smaller space → enters range of accessibility for small institutions

More installations → more science enabled

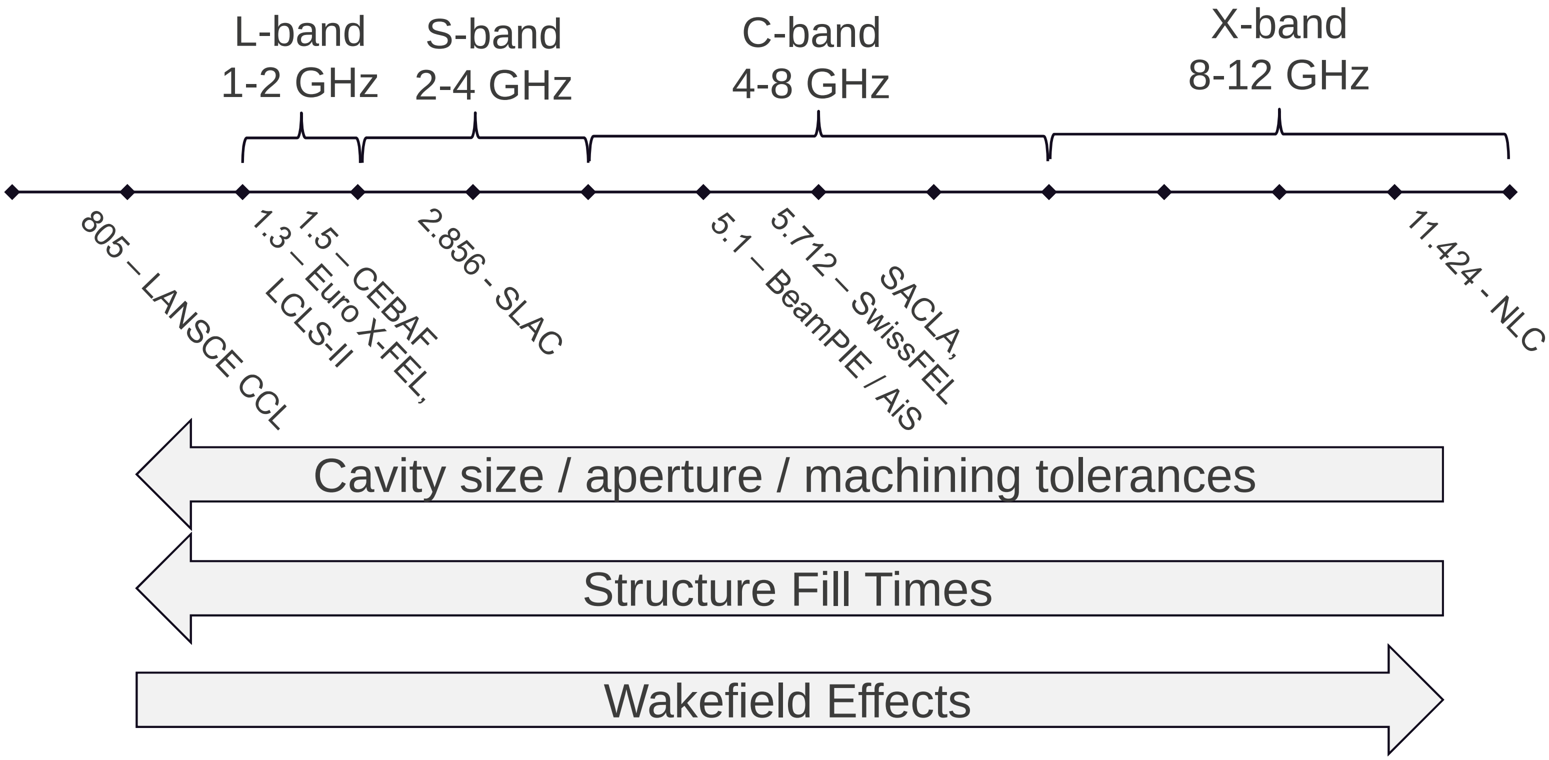
Compact Accelerators: enabling feasibility

Higher gradients → higher voltage in a given size

Higher gradients → target voltage with a smaller system

Impacts viability of concepts for cargo scanning, sterilization, etc.

Overview: Why C-band?


L-band
1-2 GHz

S-band
2-4 GHz

C-band
4-8 GHz

X-band
8-12 GHz

805 – LANSCE CCL

1.3 – Euro X-FEL,
LCLS-II

1.5 – CEBAF

2.856 - SLAC

5.1 – BeamPIE / AiS

SACLA,
5.712 – SwissFEL

11.424 - NLC

Cavity size / aperture / machining tolerances

Structure Fill Times

Wakefield Effects

C-band is *convenient*, for a number of metrics, for high-performance accelerators. In particular, a naturally “good fit” to hard X-ray FELs.

Overview: Why Los Alamos?

Posited: Achieving high-gradient performance (low breakdown rates, low field emission, etc.) is a *materials science* problem.

Los Alamos is, at core, a materials science laboratory with particular expertise and interest in metallurgy.

Los Alamos also considers itself the steward of accelerator science for the NNSA part of the DOE complex.

Thus, Los Alamos has both an institutional interest in, and capability to address, this problem space.

Project Overview in a single slide

To date, the resonant cavities of most operating RF accelerators have been made of either oxygen-free high-purity copper, or niobium.

Copper-based accelerators

- “Normal-conducting”
- Operate at room temp, or cryo temps (20 – 77 K)
- Scale well to high frequencies
- No fundamental physical limit to achievable gradient

Niobium-based accelerators

- “Superconducting”
- Operate at 2 – 4 K
- Do not scale well above ~ 1.5 GHz
- Fundamentally limited in gradient by quenching

This LDRD is focused on increasing the performance of copper-based accelerators, in particular addressing gradient limits and efficiency.

Introduction: high gradient breakdown

High gradient breakdown is the main phenomenon that limits the gradient in an rf linear accelerator.

- The rf breakdown abruptly and significantly changes the transmission and reflection of the rf power coupled into an accelerating structure.
- Breakdown is accompanied by a burst of X-rays and a bright flash of visible light.
- In TW structures the transmitted power drops to unmeasurable levels with a decay time of 20–200 ns.
- Up to 80% of the incident rf power is absorbed in the process.
- For the SW structures, most of the input rf power is reflected.
- RF breakdown often produces irreversible surface damage in structures, rf components, and rf sources.

The breakdown probability (number of breakdowns per total number of rf pulses) at a given gradient is one of the main quantitative parameters characterizing the high gradient performance of an accelerator structure.

Introduction: breakdown probability

Due to the statistical nature of the rf breakdown, the operational gradient is defined as a gradient at which the breakdown rate is below a certain acceptable value. At a given accelerating gradient, breakdown probability depends on:

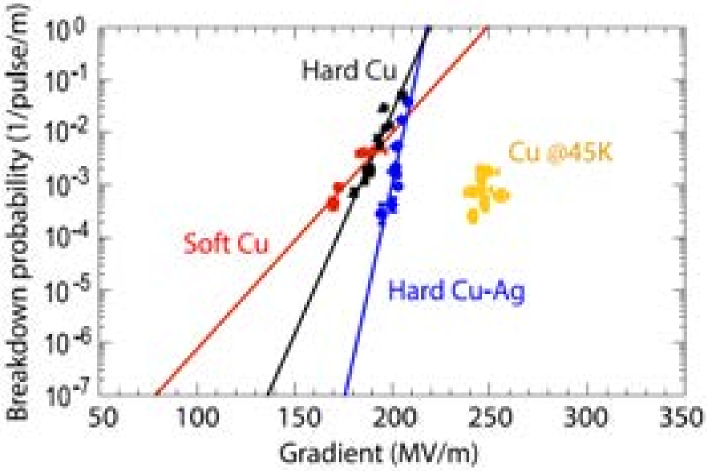
- Frequency of operation.
- Material of the structure.
- Operating temperature.
- Peak surface electric fields.
- Peak surface magnetic fields (pulse heating).
- Surface “modified Poynting vector” $Z' = \mathrm{Max}(|E \times H^*|)/\mathrm{Max}(|H^2|)$.

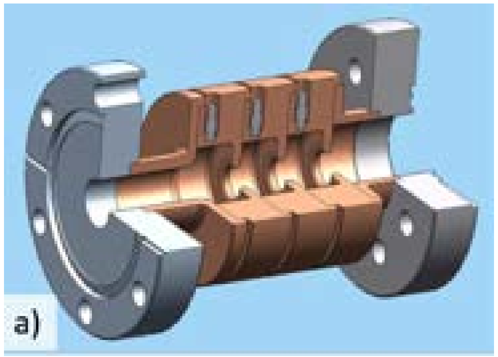
The goals for LANL’s high gradient project are

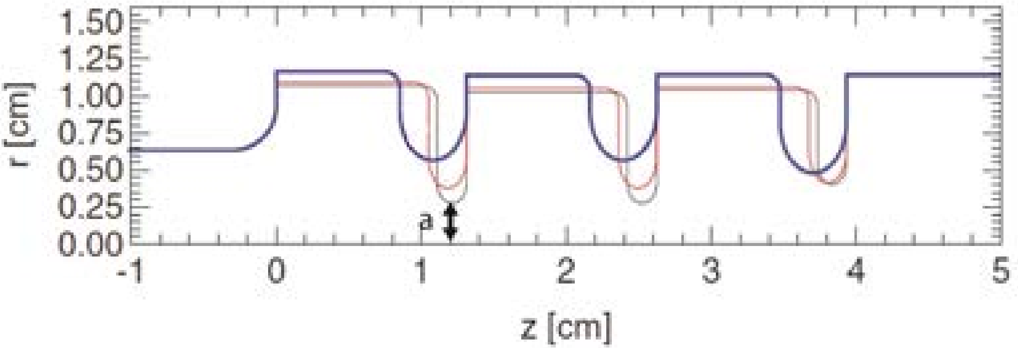
- To establish the benchmark point for the rf breakdown probability at C-band (5.712 GHz).
- To conduct material studies.

Introduction: a/λ=0.105 structure

Most of the RF breakdown studies at SLAC and elsewhere were done on an unoptimized 3-cell SW structure with a/λ=0.105.



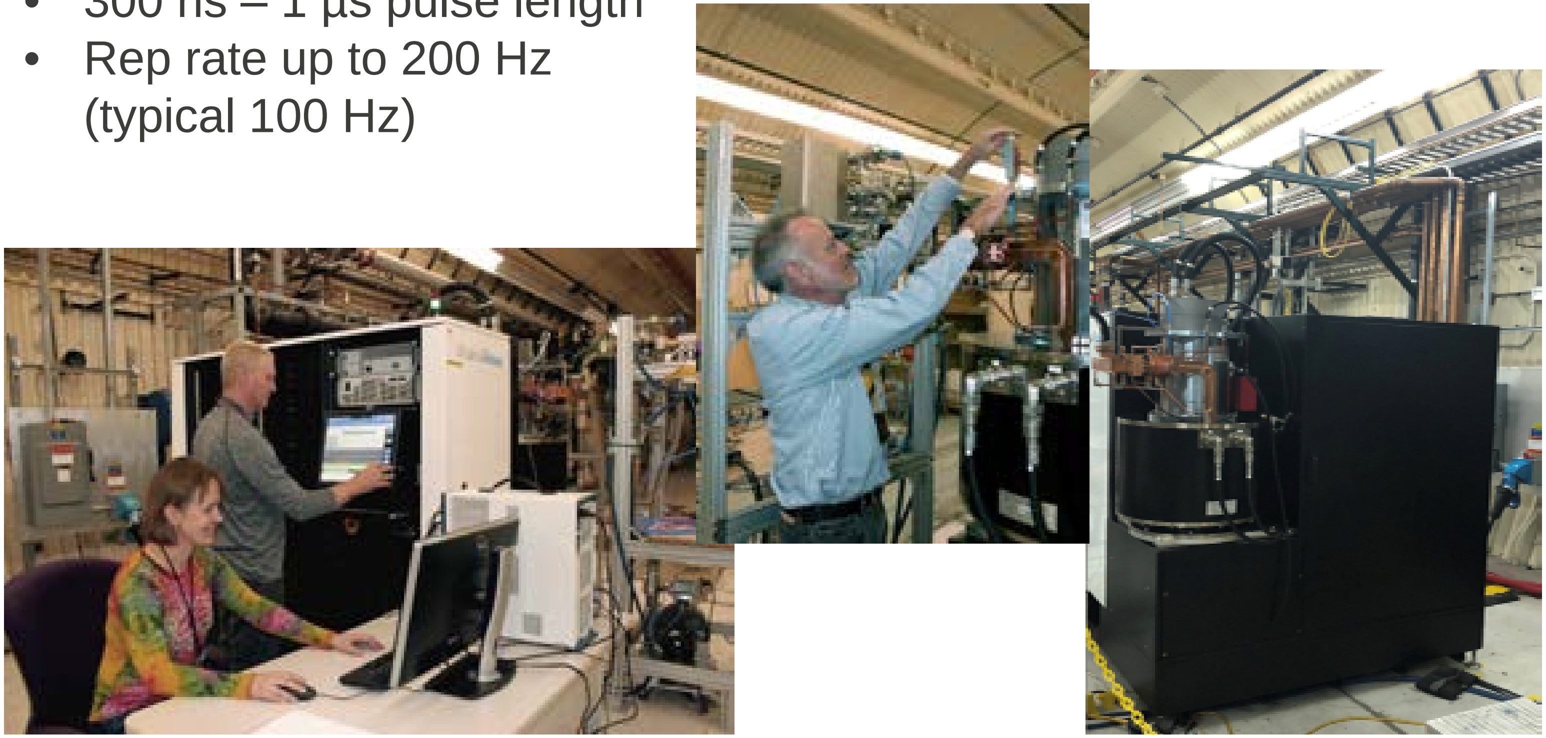




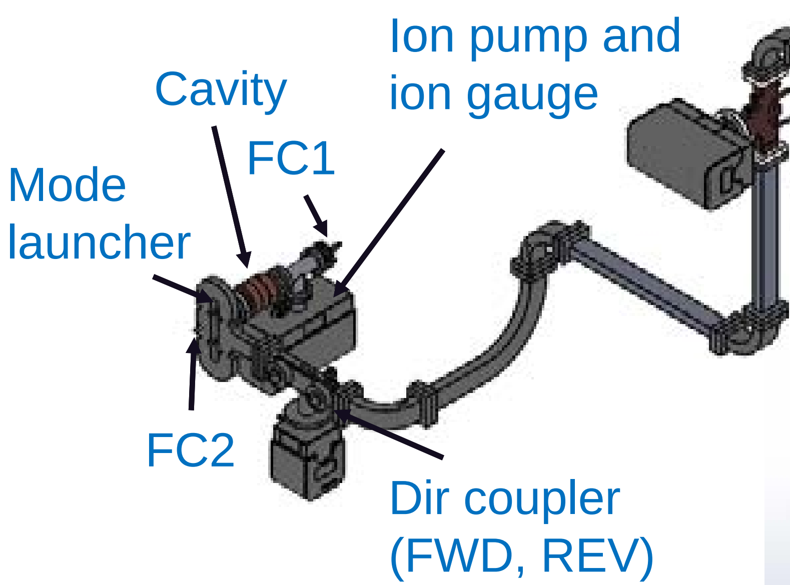
50 MW C-band klystron

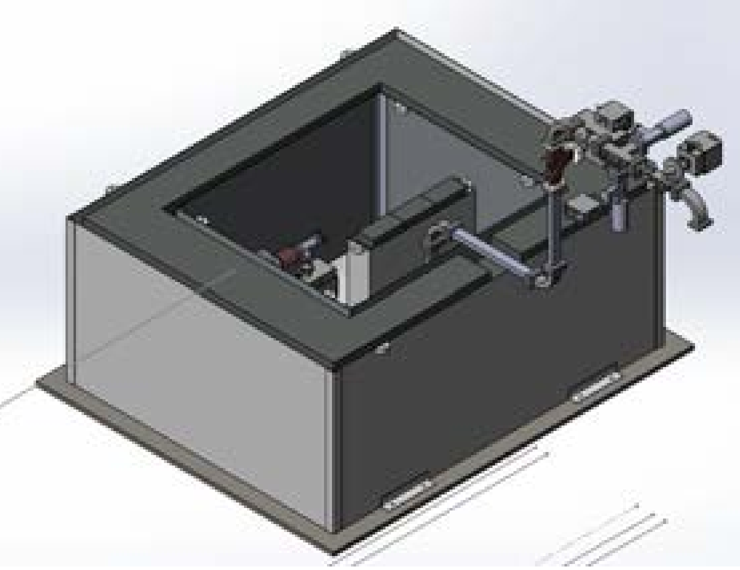
- Conditioned to 50 MW
- Frequency 5.712 GHz
- 300 ns – 1 µs pulse length
- Rep rate up to 200 Hz (typical 100 Hz)

- Nominal bandwidth 5.707-5.717 GHz



High gradient C-band test stand

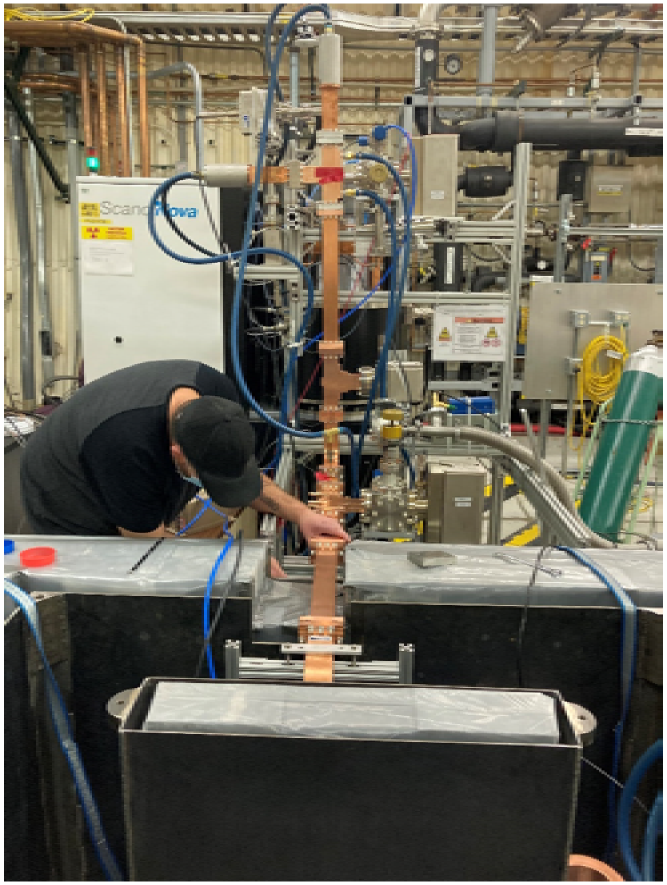


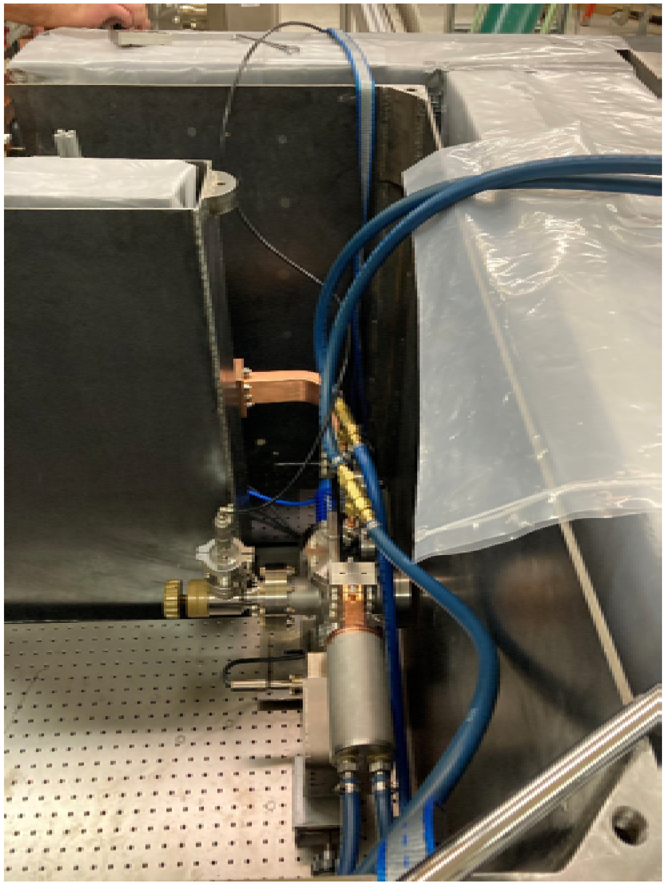


Radiologically certified for dark currents up to 5 MeV and 10 μA.

High gradient C-band test stand (photos)

High gradient C-band test stand (more photos)

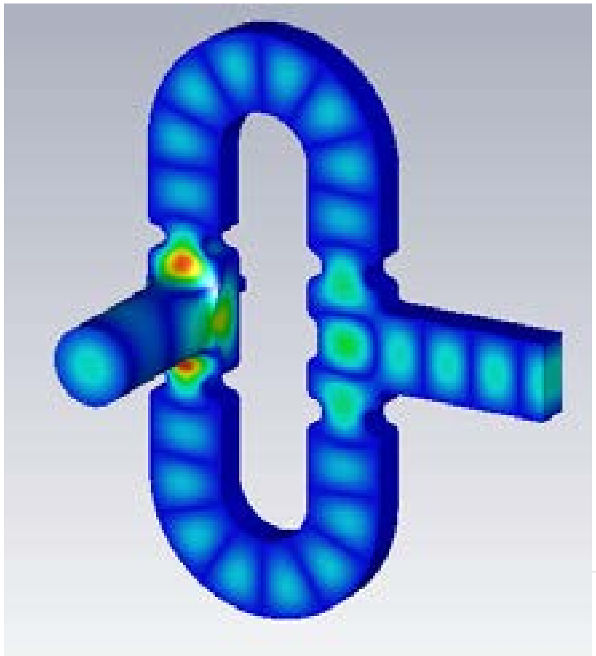


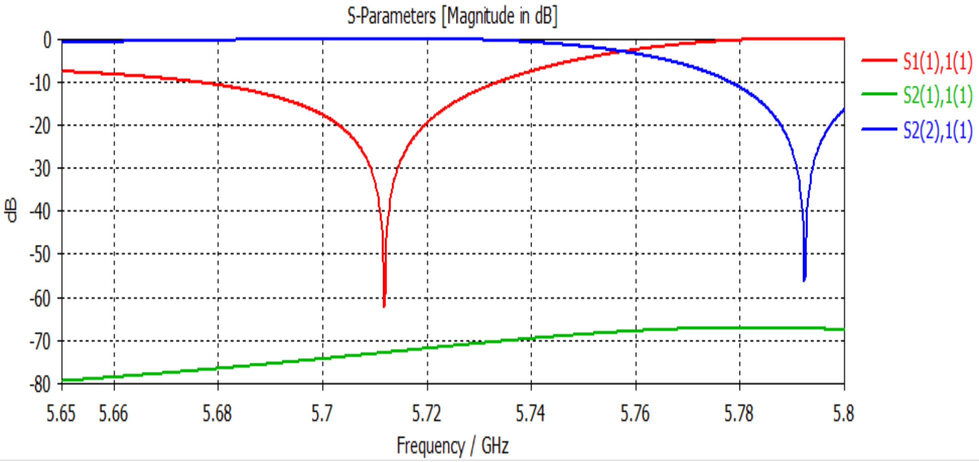


Mode launcher summary

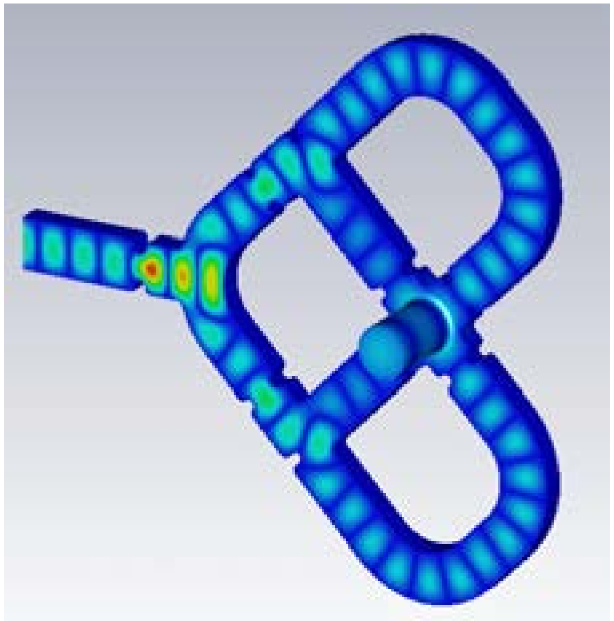
- The mode launcher converts the TE_{10} mode of the rectangular WR187 waveguide into the TM_{01} mode of the cylindrical on-axis coupler.
- Three designs of the mode launcher were considered: original LANL design, INFN-like design (scaled from X-band), and UCLA-like design (scaled from S-band).
- LANL design was chosen for fabrication due to the compromise between the bandwidth, peak fields and pulse heating, and the simplicity of fabrication.
- 4 mode launchers were fabricated with an outside vendor (Dymensco).

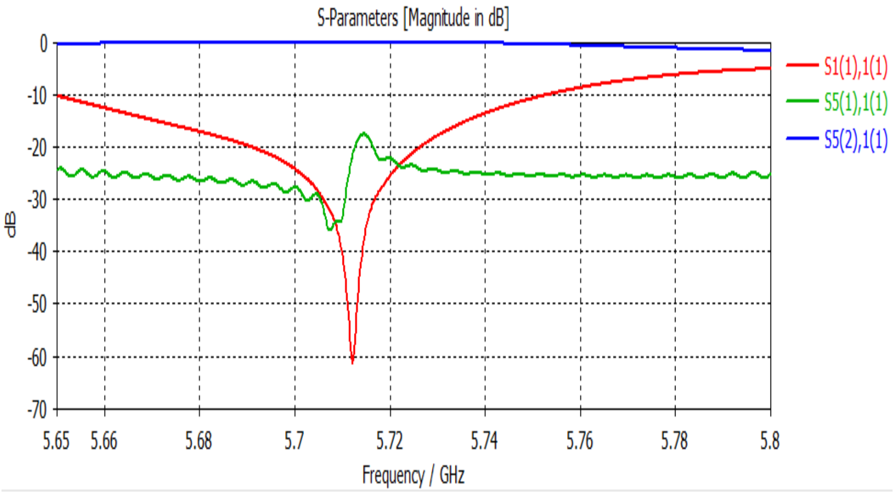
LANL Mode Launcher



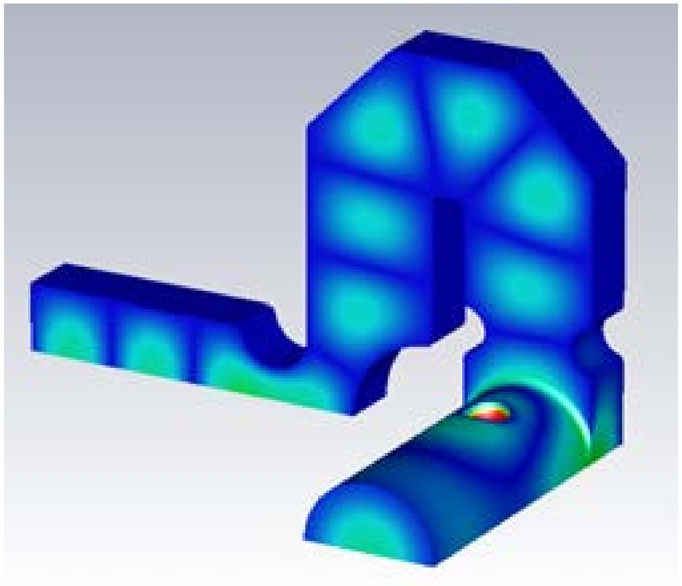


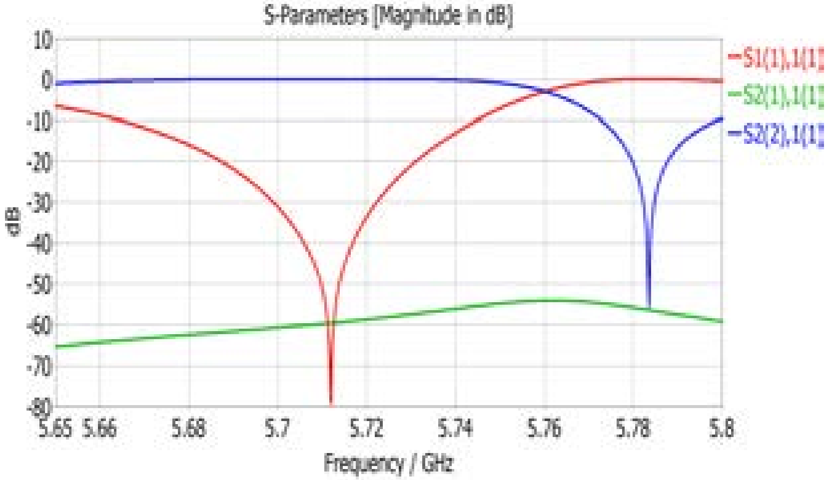
INFN Mode Launcher





UCLA Mode Launcher



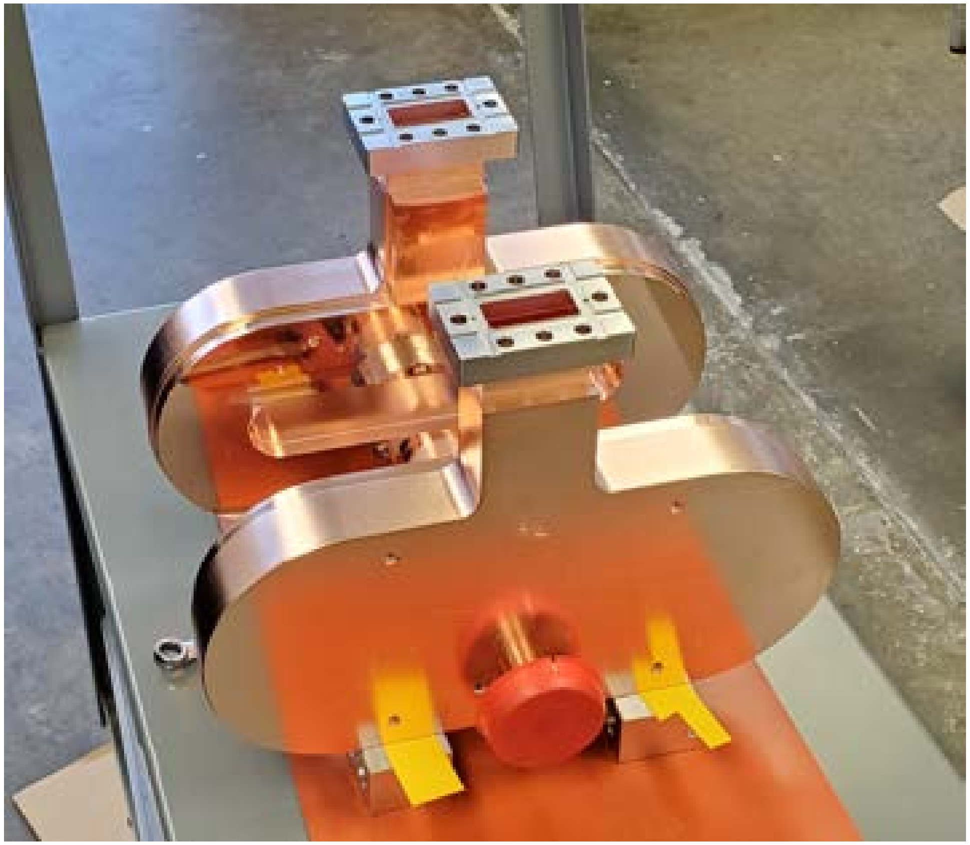


Mode launcher comparison

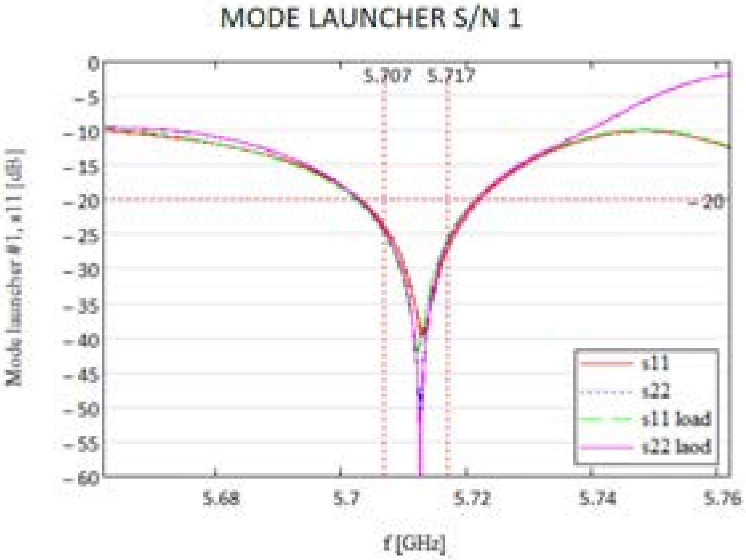
	LANL	INFN	UCLA
Bandwidth @-20 dB	17 MHz (5.703 to 5.720 GHz)	35 MHz (5.691 to 5.726 GHz)	44 MHz (5.687 to 5.731 GHz)
Emax for 25 MW power	15.34 MV/m	11.4 MV/m	29.41 MV/m
Hmax for 25 MW power	46.9 kA/m	41.7 kA/m	57.39 kA/m
Pulse heating for 1 µs pulse	0.67 ^{o}C	0.53 ^{o}C	1.00 ^{o}C

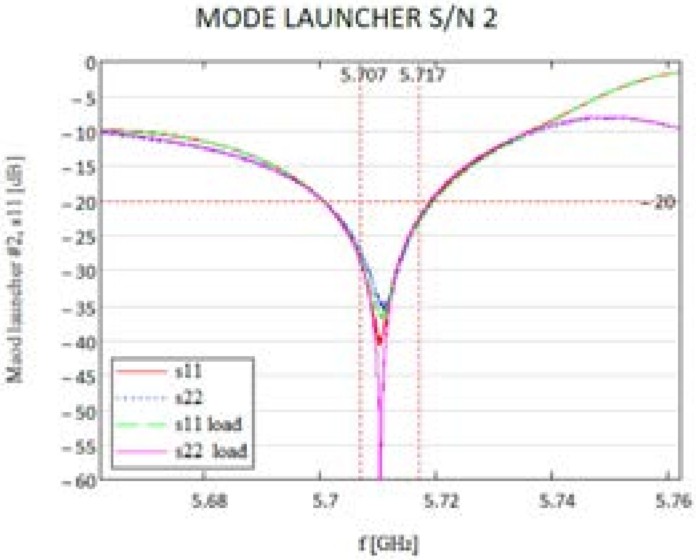
Fabricated mode launcher – photographs

Fabrication of 4 mode launchers was performed at Dymenso, Inc. in collaboration with Philipp Borchard.



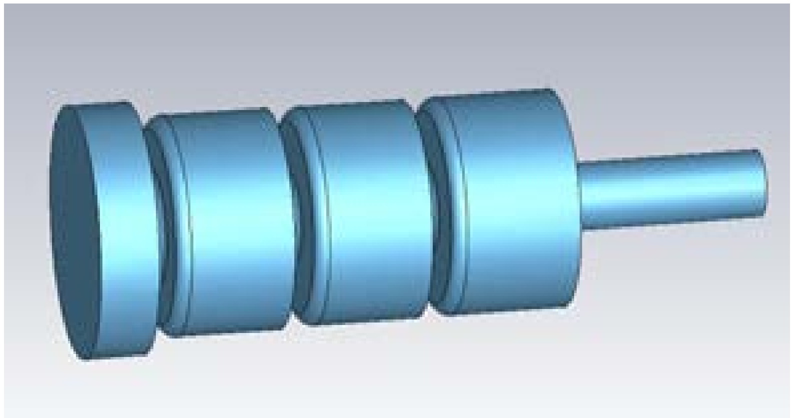
Fabricated mode launcher cold tests





C-band benchmark test cavity

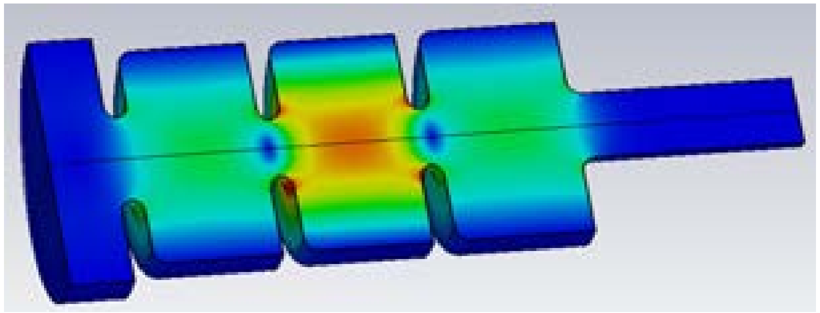
Frequency	5.712 GHz
Phase shift per cell	π
Cell length	1.034 in
a/λ	0.105
Iris radius	0.217 in

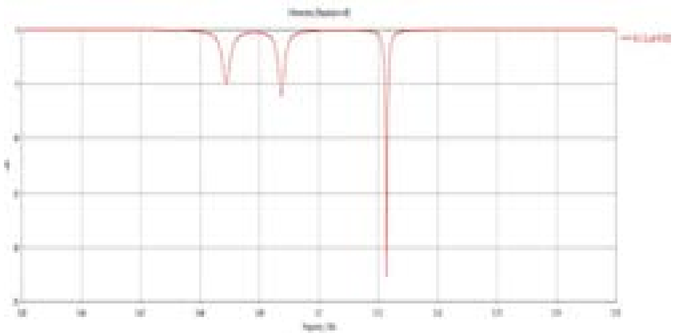


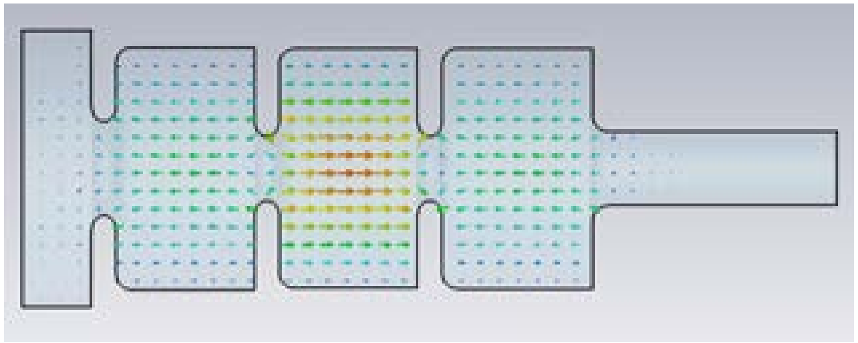
Benchmark test cavity characteristics

Q (room temperature copper) with coupler cells: 12682

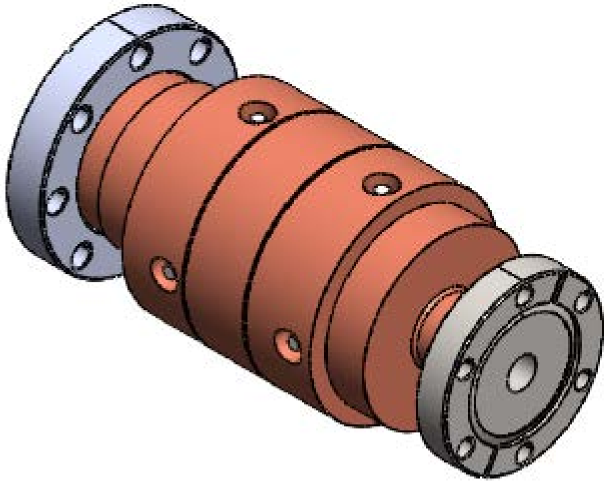
Peak power needed to achieve 200 MV/m peak surface field: 5.3 MW

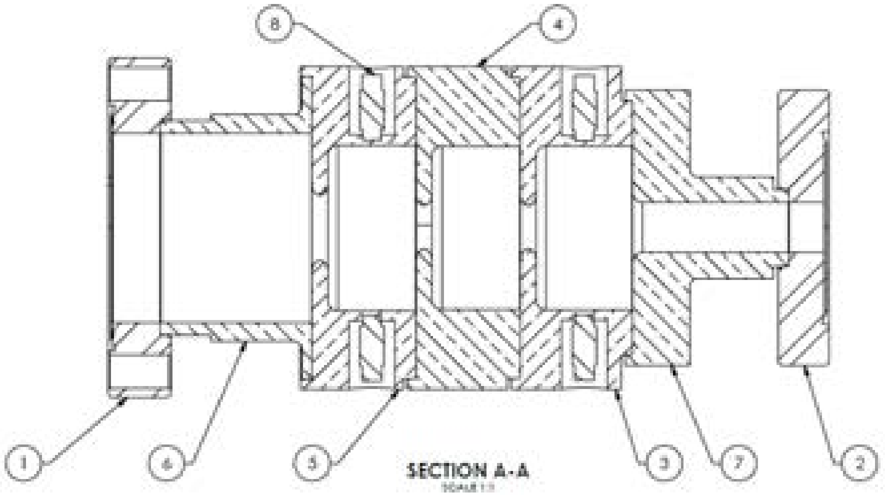




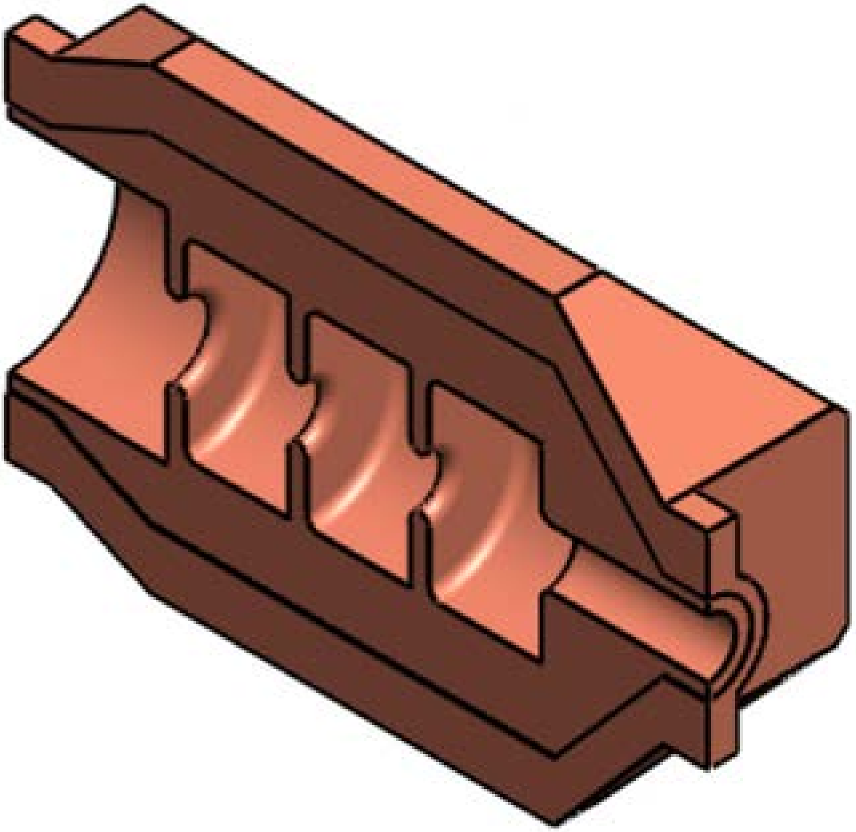


Test cavity fabrication - brazing





Test cavity fabrication – welding of the two clamshells



Cryo-cooling copper cavity

- 4-5 times higher Q-factor, 4-5 times lower rf power needs for high gradient.
- Higher achievable gradients.

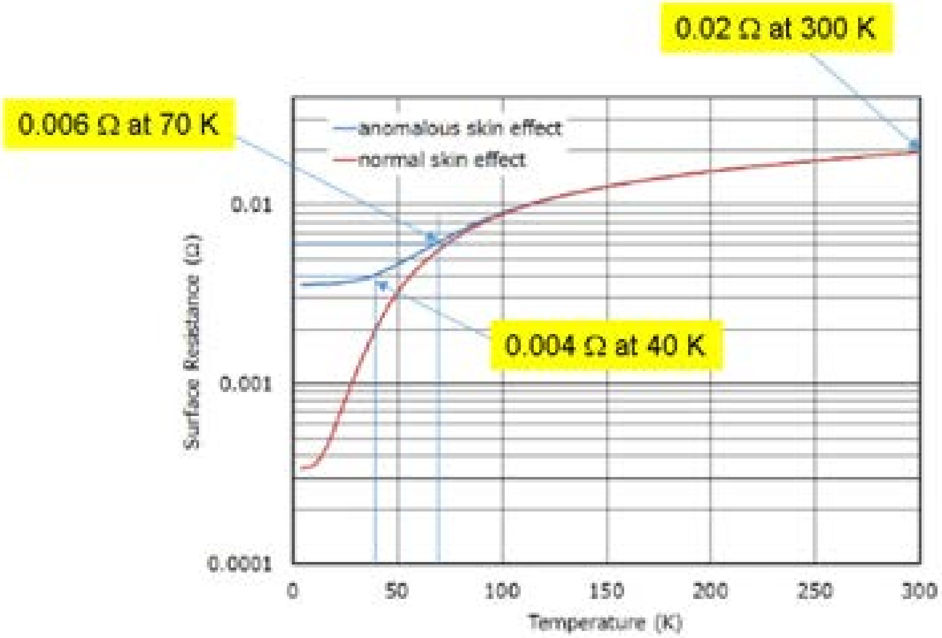


Figure 2: Temperature dependence of theoretical surface resistances of RRR = 3000 copper at 5712 MHz. Blue line: result of the anomalous skin effect, Red line: the normal skin effect.

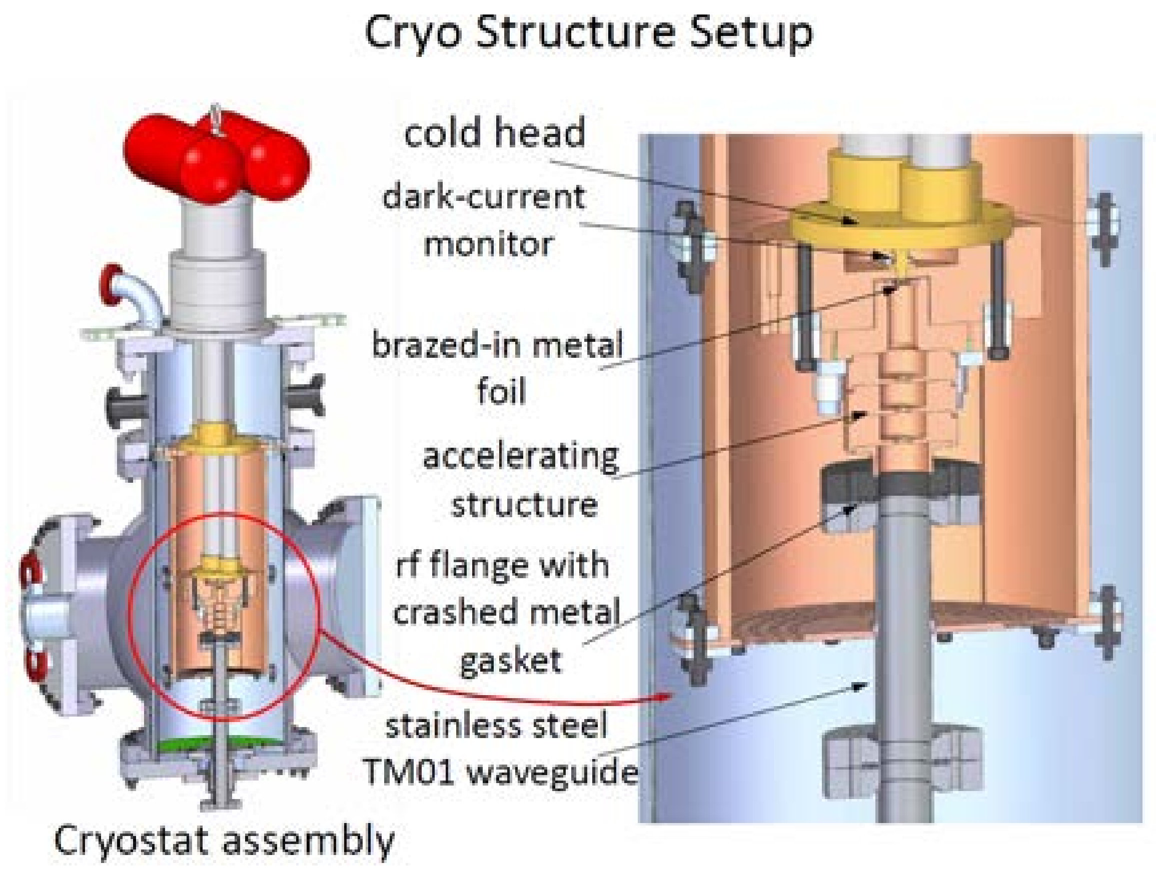
Cryo-cooled cavity testing

To establish the benchmark gradient point at cryo-cooled temperatures we plan to test the same a/λ=0.105 cavity at a cryogenic temperatures of 20-70K.

Q (70K) with coupler cells: ~50700

Cooling power needed for 300 ns pulse length, 100 Hz rep rate, 200 MV/m peak surface field - 40 W, 300 MV/m peak surface field – 90 W.

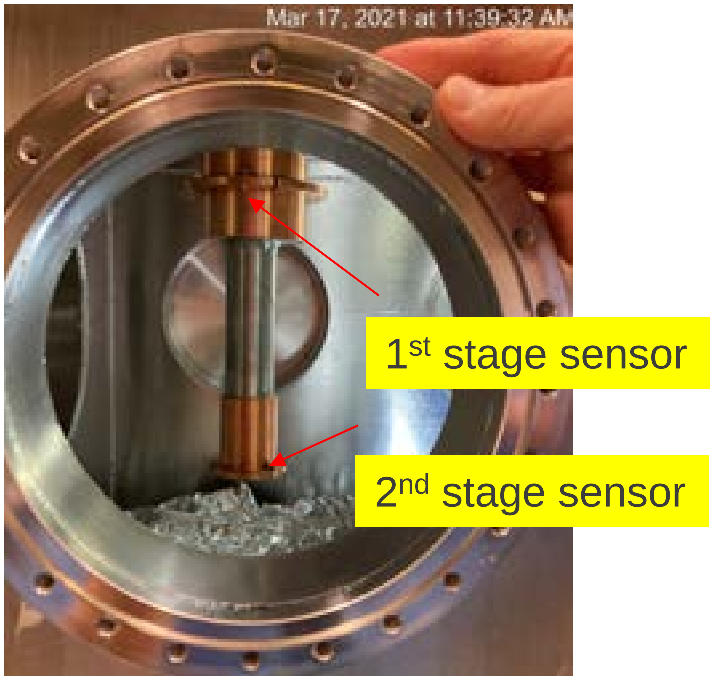
Cryostat design – will be copied after SLAC's



Sumitomo 4K cryocooler

Cold Head Model		RDK-415D
1st Stage Capacity	50 Hz	35 W @ 50 K
	60 Hz	45 W @ 50 K
2nd Stage Capacity	50 Hz	1.5 W @ 4.2 K
	60 Hz	1.5 W @ 4.2 K
Minimum Temperature[2]		<3.5 K
Cooldown Time[2]	50 Hz	<60
	60 Hz	<60
Weight		18.5 kg (40.8 lbs.)

Testing the cryocooler - photos

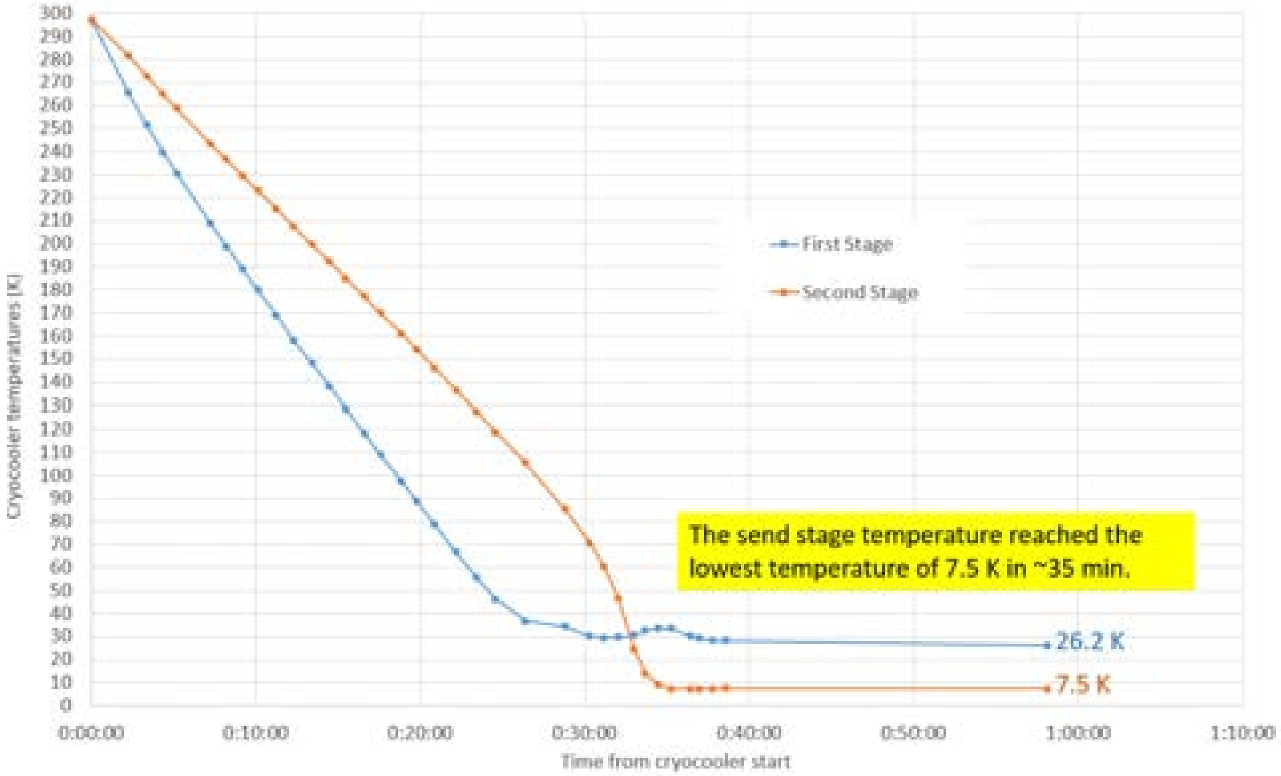


1st stage sensor

2nd stage sensor

Silicon diode temperature sensors were installed on 1st and 2nd stages

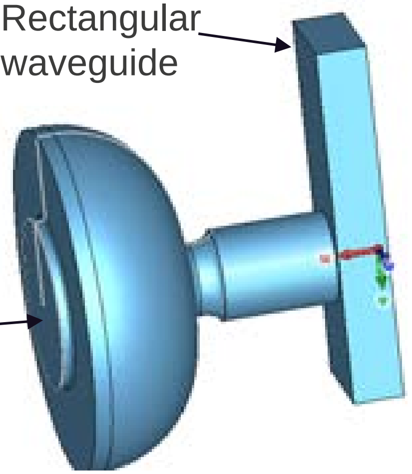
Testing the cryocooler



The send stage temperature reached the lowest temperature of 7.5 K in ~35 min.

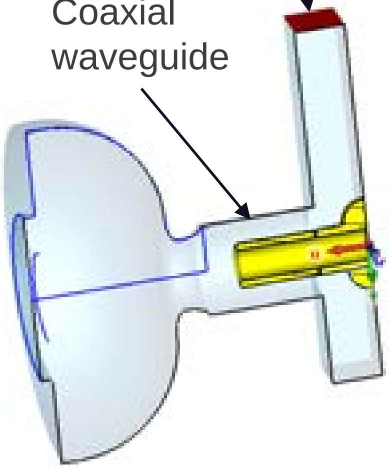
Materials coupon tester concept

- An overmoded resonator for RT/Cryo material testing
- Concept under development: coaxially coupled structure
- Design criteria:
  - Highest E, H surface fields on coupon surface
  - Maximize $E_{coupon}/E_{cavity,}$ H_{coupon}/H_{cavity}
  - Minimize fields at coupon/cavity joint



Rectangular waveguide

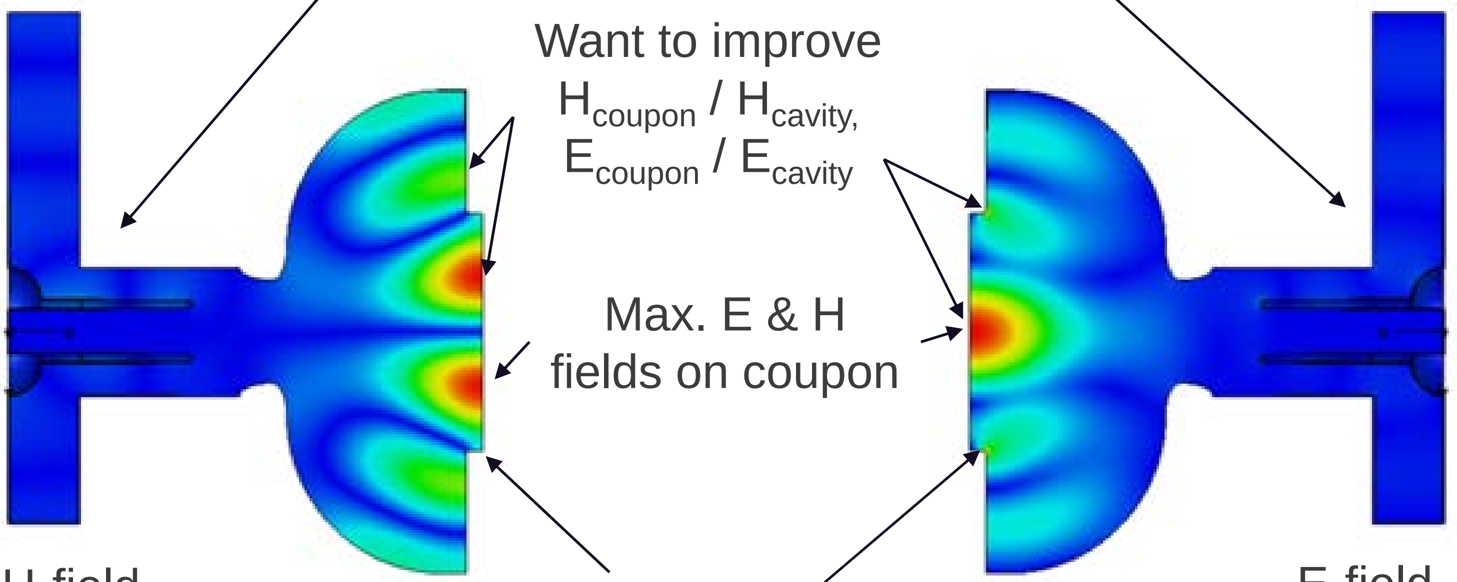
Coupon face



Coaxial waveguide

RF in

Materials coupon tester – design in progress



Low E, H fields in couplers

Want to improve
H_{coupon} / $H_{\text{cavity,}}$
E_{coupon} / E_{cavity}

Max. E & H
fields on coupon

H-field

E-field

Want to minimize fields at
coupon / cavity joint

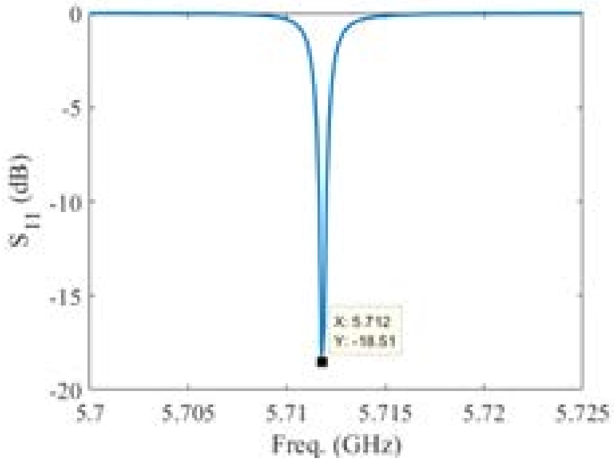
Working concept needs optimization, but is promising.

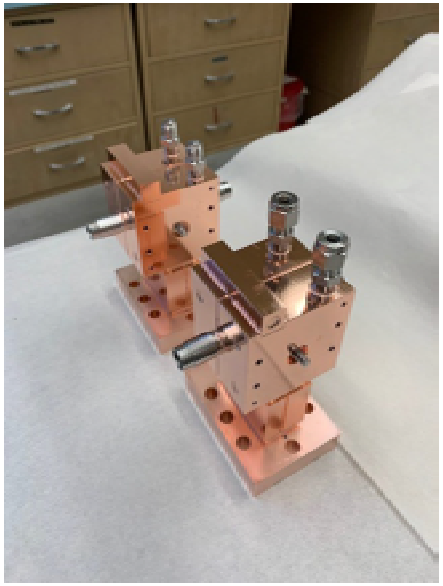
Plan for testing C-band cavities

1. Benchmark cavity
   - Fabricated by conventional machining.
   - Brazed in a hydrogen surface – soft copper.
2. Welded cavity
   - Fabricated by conventional machining in two halves.
   - Welded at LANL. LANL unique capability. Will result in a hard copper structure.
3. Same geometry with new materials
   - We plan to fabricate the same geometry of copper-silver with different contents of silver.
   - The structures will be welded.
   - The best content of silver will be evaluated in simulations.
4. Cryo-cooled cavity
   - The same geometries and materials will be tested at cryogenic temperatures.

Collaborations: SLAC C-band beta=0.5 cavities

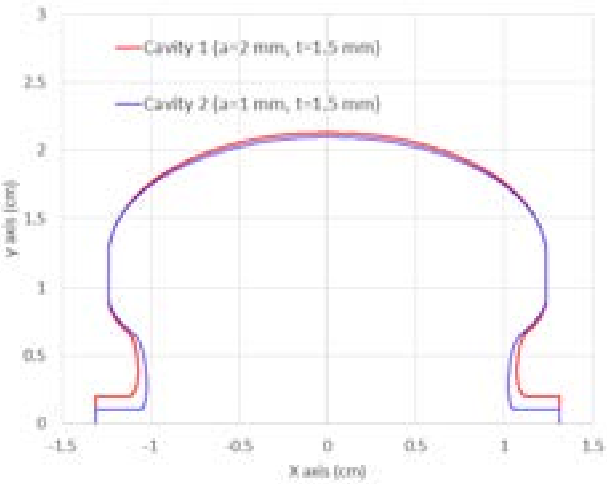
- LANL's high gradient C-band test facility is the only high gradient C-band test facilities in the US and is open to collaborators.
- LANL provided us with Technology Evaluation and Development (TED) funding to test SLAC's C-band beta=0.5 cavities at high gradient.
- First cavity to go for testing next week.

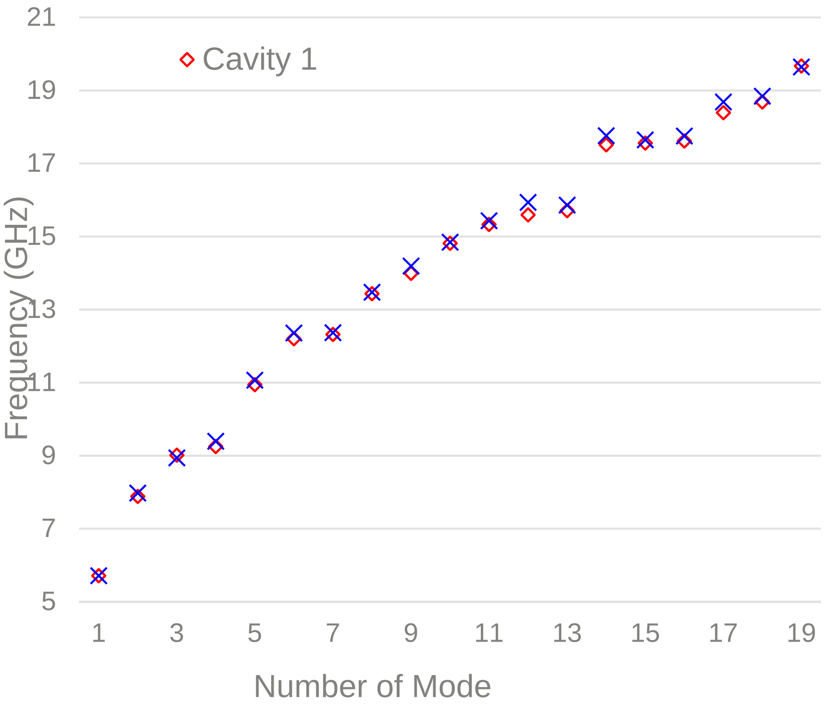




Collaborations: DOE HEP C-band project (collaboration with SLAC and UCLA)

- Evaluation of special cavity shapes to raise gradients and reduce wakefields.





Summary and near term test plans

- The high gradient test stand is finally coming online.
- FY21 outlook
  - Waveguide line is fully conditioned to 30 MW, 1 microsecond long pulses, 100 Hz repetition rate.
  - March - May, 2021: testing of SLAC’s beta = 0.5 cavities.
  - June-July, 2021: conditioning of the mode launchers.
  - August – September, 2021: testing room-temperature cavities.
- FY22 outlook
  - Cryogenic temperature testing.
  - Materials coupons testing.

Materials Modeling and Simulation – A Few Notes

A typical 100-pC bunch has ~ $6.2 \cdot 10^{8}$ electrons

In the past ~5 years, it has become somewhat routine to simulate as many “macro” particles as electrons in a bunch.

A typical copper C-band cavity is about 2 cm in radius, 2.6 cm long, and has a skin depth of around 0.86 μm.

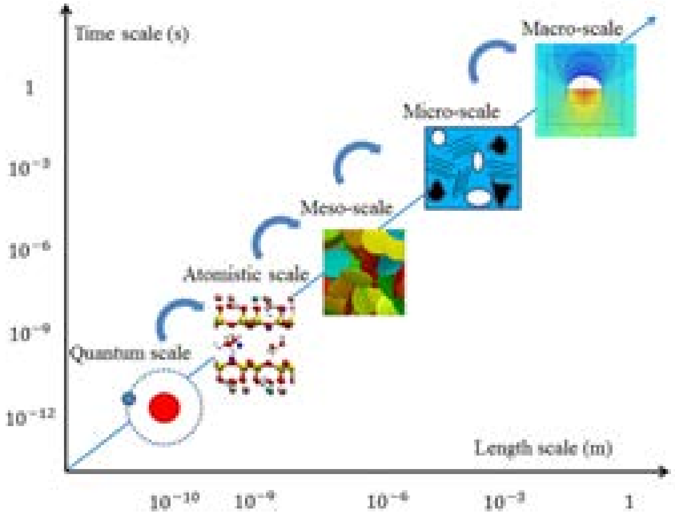
There are around $2.4 \cdot 10^{20}$ Cu atoms *in that skin depth alone*.

Levels of theory

- **Quantum:** approximate solution of Schrodinger equation. **Density Functional Theory (DFT)**

- **Atomistics:** simple empirical approximation to Schrodinger equation. **Molecular Dynamics (MD)**

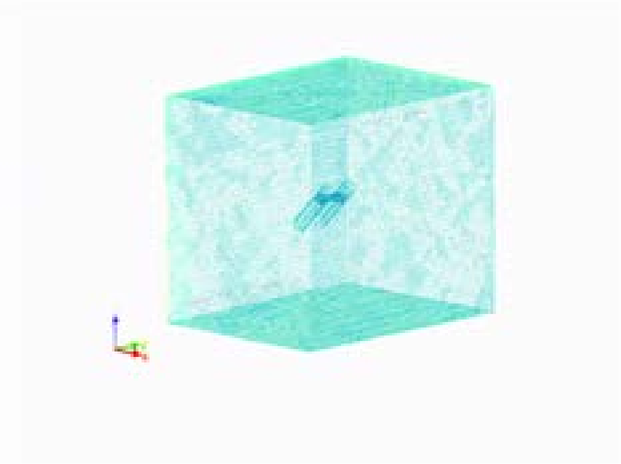
- **Mesoscale:** Microstructural evolution models, formulated at grain level. **Crystal Plasticity.**

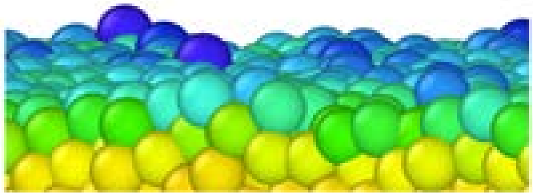


Courtesy Danny Perez & Gaoxue Wang

Research approach

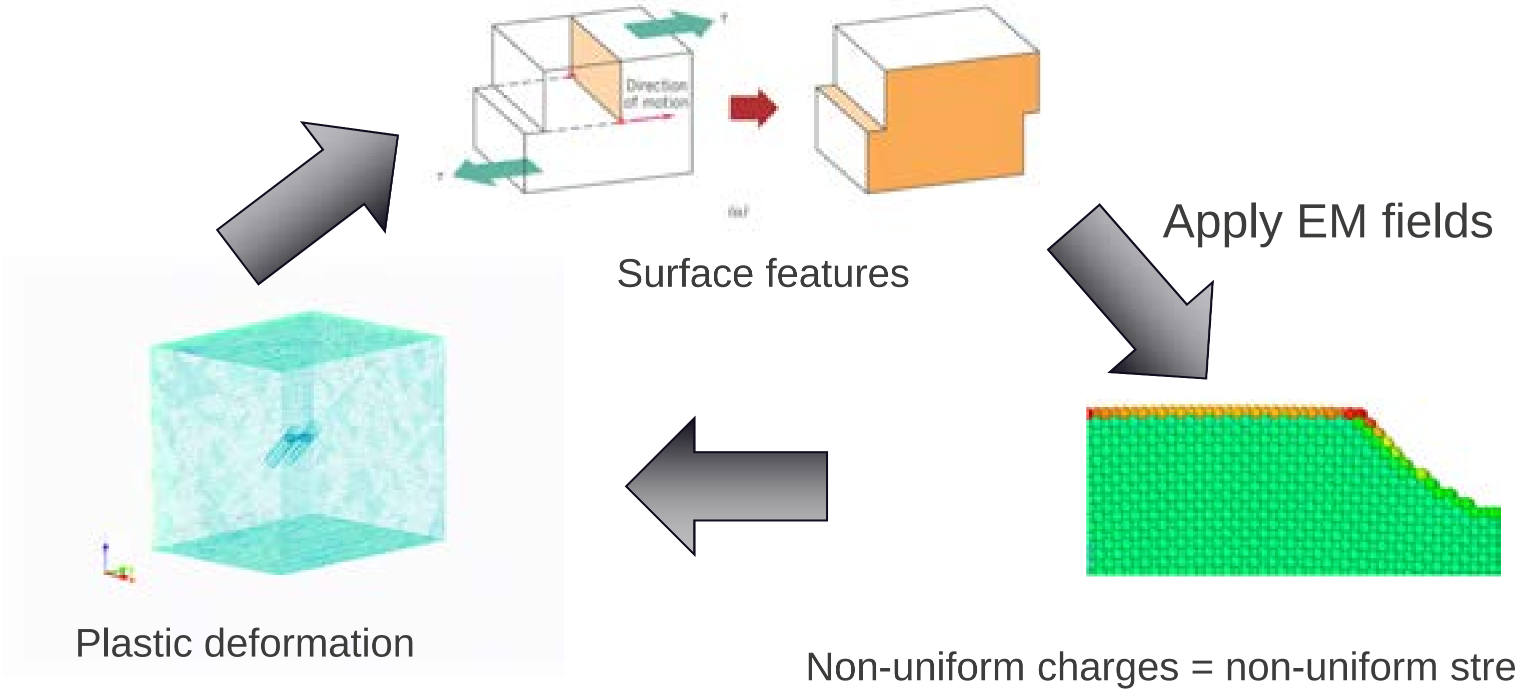
- How does bulk deformation drive surface evolution under thermal cycling?
  - – **Approach:** MD and mesoscale crystal plasticity
- What is the role of E?
  - – **Approach:** MD of surface evolution under E
- Can we systematically design breakdown-tolerant materials?
  - – **Approach:** High-throughput DFT alloy design





Courtesy Danny Perez & Gaoxue Wang

Research approach



Surface features

Apply EM fields

Non-uniform charges = non-uniform stress

Plastic deformation

Courtesy Danny Perez & Gaoxue Wang

Materials search: can we do better than OFE copper?

Considering dilute binary Cu alloys

Tradeoffs:

- **Good:** Adding solute atoms can improve strength: limit plastic deformation under thermal loading
- **Bad:** Adding solute atoms can increase RF dissipation and thermal stresses: increase driving force for plastic deformation

Figure of merit (FOM):

- (Critical stress to move dislocations) / (Thermal stress created by RF dissipation)

Other factors to consider:

- Compatible with the accelerator environment
- Can be made efficiently
- Amenable to fabrication (e.g. brazing, e-beam welding, etc.)

Courtesy Danny Perez & Gaoxue Wang

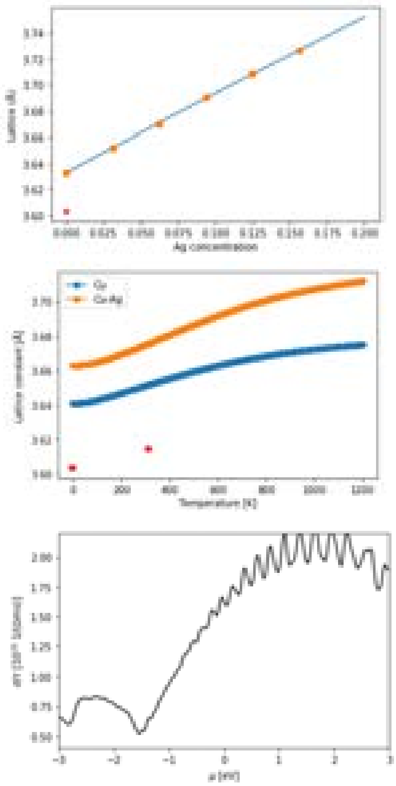
FOM

Estimating the FOM requires:

- Lattice constant: direct relaxation
- Elastic constants: finite distortion
- Thermal expansion coefficient: quasi-harmonic approximation
- Thermal conductivity: Boltzmann transport
- Electrical conductivity: Boltzmann transport

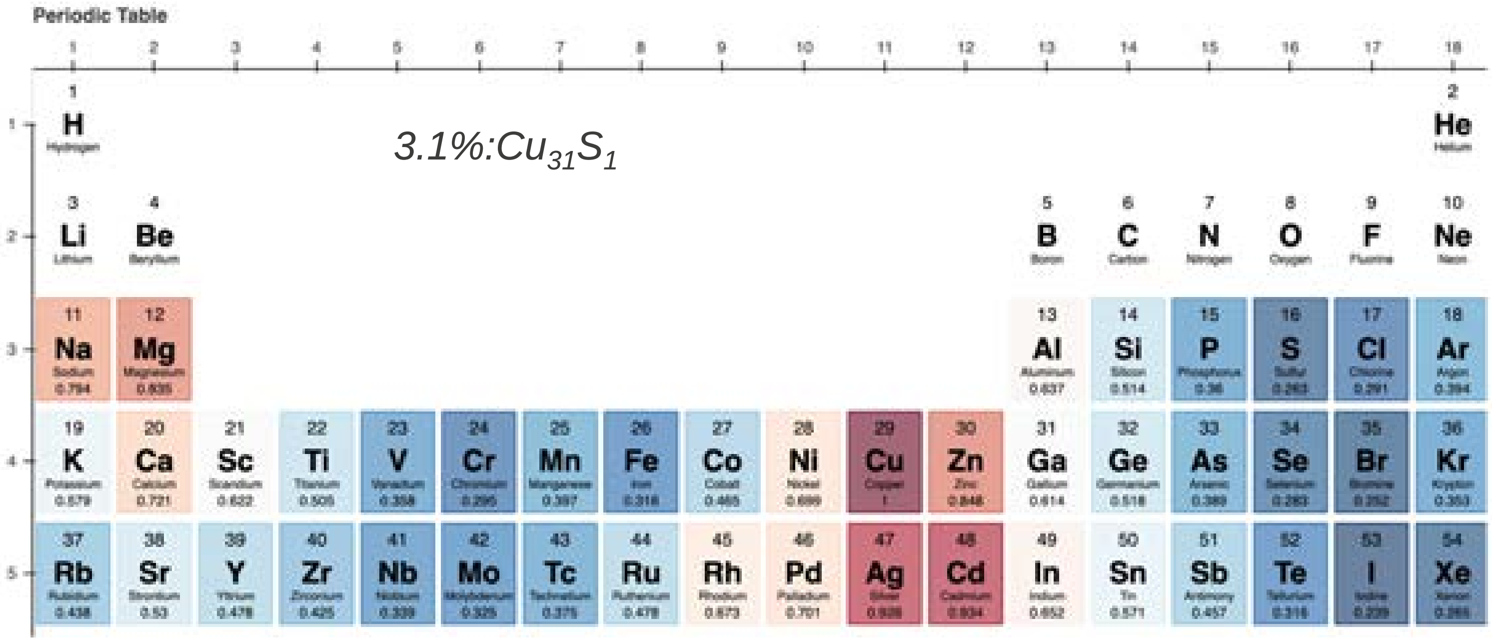
These quantities need to be computed vs solute concentration.

This requires tens of DFT calculations per solute per concentration (!)



Courtesy Danny Perez & Gaoxue Wang

Material search: electrical conductivity

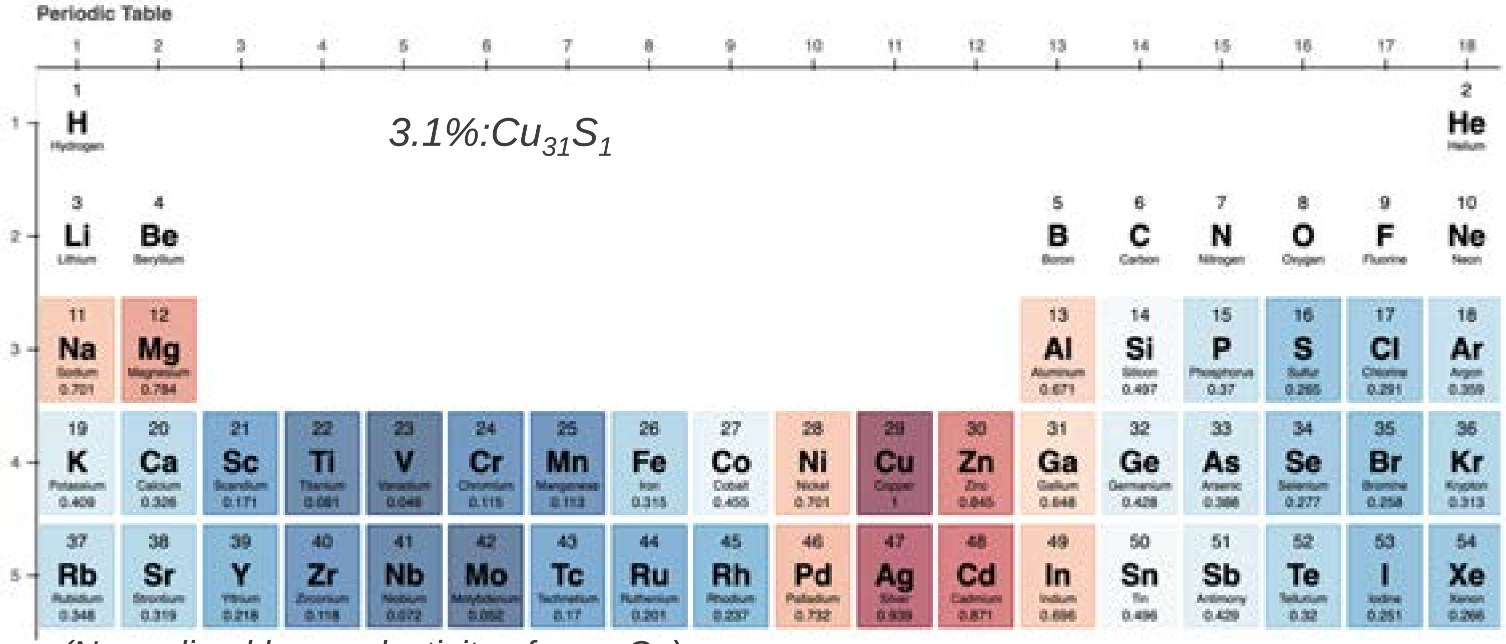


$3.1\%:Cu_{31}S_1$

(Normalized by conductivity of pure Cu)

Courtesy Danny Perez & Gaoxue Wang

Material search: thermal conductivity



Periodic Table

3.1%:$Cu_{31}S_1$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 **H** Hydrogen																	2 **He** Helium
2	3 **Li** Lithium	4 **Be** Beryllium											5 **B** Boron	6 **C** Carbon	7 **N** Nitrogen	8 **O** Oxygen	9 **F** Fluorine	10 **Ne** Neon
3	11 **Na** Sodium 0.701	12 **Mg** Magnesium 0.784											13 **Al** Aluminum 0.671	14 **Si** Silicon 0.497	15 **P** Phosphorus 0.37	16 **S** Sulfur 0.265	17 **Cl** Chlorine 0.291	18 **Ar** Argon 0.359
4	19 **K** Potassium 0.409	20 **Ca** Calcium 0.326	21 **Sc** Scandium 0.171	22 **Ti** Titanium 0.081	23 **V** Vanadium 0.046	24 **Cr** Chromium 0.115	25 **Mn** Manganese 0.113	26 **Fe** Iron 0.315	27 **Co** Cobalt 0.455	28 **Ni** Nickel 0.701	29 **Cu** Copper 1	30 **Zn** Zinc 0.845	31 **Ga** Gallium 0.648	32 **Ge** Germanium 0.428	33 **As** Arsenic 0.388	34 **Se** Selenium 0.277	35 **Br** Bromine 0.258	36 **Kr** Krypton 0.313
5	37 **Rb** Rubidium 0.348	38 **Sr** Strontium 0.319	39 **Y** Yttrium 0.218	40 **Zr** Zirconium 0.118	41 **Nb** Niobium 0.072	42 **Mo** Molybdenum 0.052	43 **Tc** Technetium 0.17	44 **Ru** Ruthenium 0.201	45 **Rh** Rhodium 0.237	46 **Pd** Palladium 0.732	47 **Ag** Silver 0.939	48 **Cd** Cadmium 0.871	49 **In** Indium 0.696	50 **Sn** Tin 0.496	51 **Sb** Antimony 0.429	52 **Te** Tellurium 0.32	53 **I** Iodine 0.251	54 **Xe** Xenon 0.266

(Normalized by conductivity of pure Cu)

Courtesy Danny Perez & Gaoxue Wang

Theory / Experiment Comparisons

Some of the theoretical work can be benchmarked against known alloys.

We are considering a series of tests specific to copper-silver alloys in a range of 0.1 – 3%:

- Make sample alloys via vacuum melting;
- Treat all samples via the same post-cast annealing cycle;
- Evaluate mechanical, electrical, thermal properties;
- Compare to theoretical predictions

We will also be doing these same characterizations on the copper alloys we use to make our cavities.

Conclusions

- The Los Alamos C-band Test stand (CERF-NM) is operational.

- We are about to start testing and fabricating cavities
  - Various materials
  - Various fabrication methods
  - Ours and collaborators' cavities

- Theory and modeling of the breakdown process
  - Multiscale physics required
  - Thermal stress driving Frank-Read sources for slip / dislocation – results in surface perturbations

- Materials search
  - Broad-scale modeling of dilute copper alloys for property optimization
  - Will prepare & characterize promising candidates, also characterize the materials we use to make cavities.