LA-UR-18-30015

Long-pulse, Ultra-high-gradient Radio-Frequency Accelerator Structures

Better Performance Through Smart Design, Manufacturing and Breakdown Suppression

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What we plan

Design, and prototyping of a ultra-high gradient C-band RF-structure for XFEL and compact accelerators

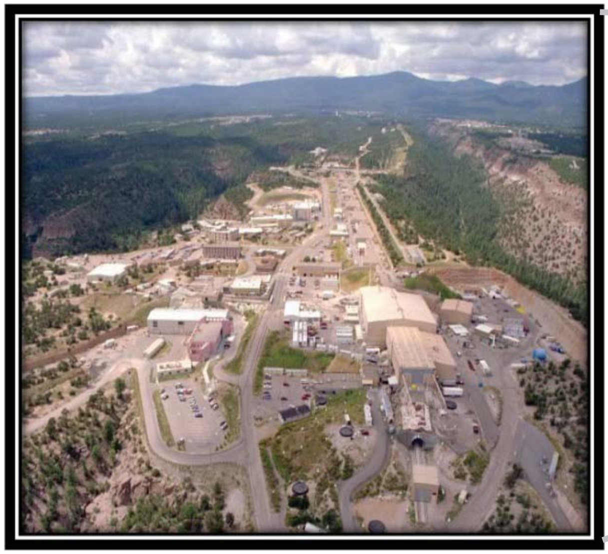
- Thrust areas
  - RF technology: Good resonator design for high gradient
  - Focus on long pulse operation: Cryo-cooled copper structure and dielectric insertions
  - Material Science: Explanation of breakdown mechanisms and development of beneficial copper alloys, and/or surface and bulk properties for breakdown suppression
  - Advanced manufacturing: Fabrication processes and joining techniques that create and preserve surface and bulk properties for breakdown suppression

What we want to achieve in 3-4 years

- High performance RF structure
- Contribution to high gradient collaboration
  - C-band test capability by establishing an electron test accelerator beamline
- S&T:
  - Enhanced Material Science modeling capability
  - Introduction of “designed” materials
  - Evaluation, if dielectrics can lead to performance improvements
  - Novel fabrication technologies for copper alloys
- Support for LANL Missions:
  - Technology solutions for MaRIE XFEL
  - Technology solutions for compact accelerators

Impact on MaRIE XFEL: Cost reduction and new performance regime

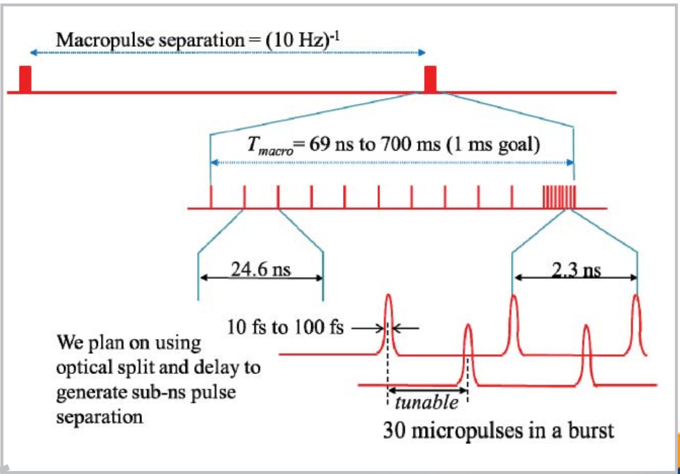
- It will reduce the cost of MaRIE by ~ $200M
- MaRIE will fit at TA-53 for higher beam energies



12 GeV @ 31.5 MV/m
➔ linac length ~750m

12 GeV @ 100 MV/m
➔ linac length ~170m

- Enable burst mode operation for high temporal resolution
  - S-band (slow rise-time)
  - X-band (stronger wakes)
  - C-band (overall good mix)

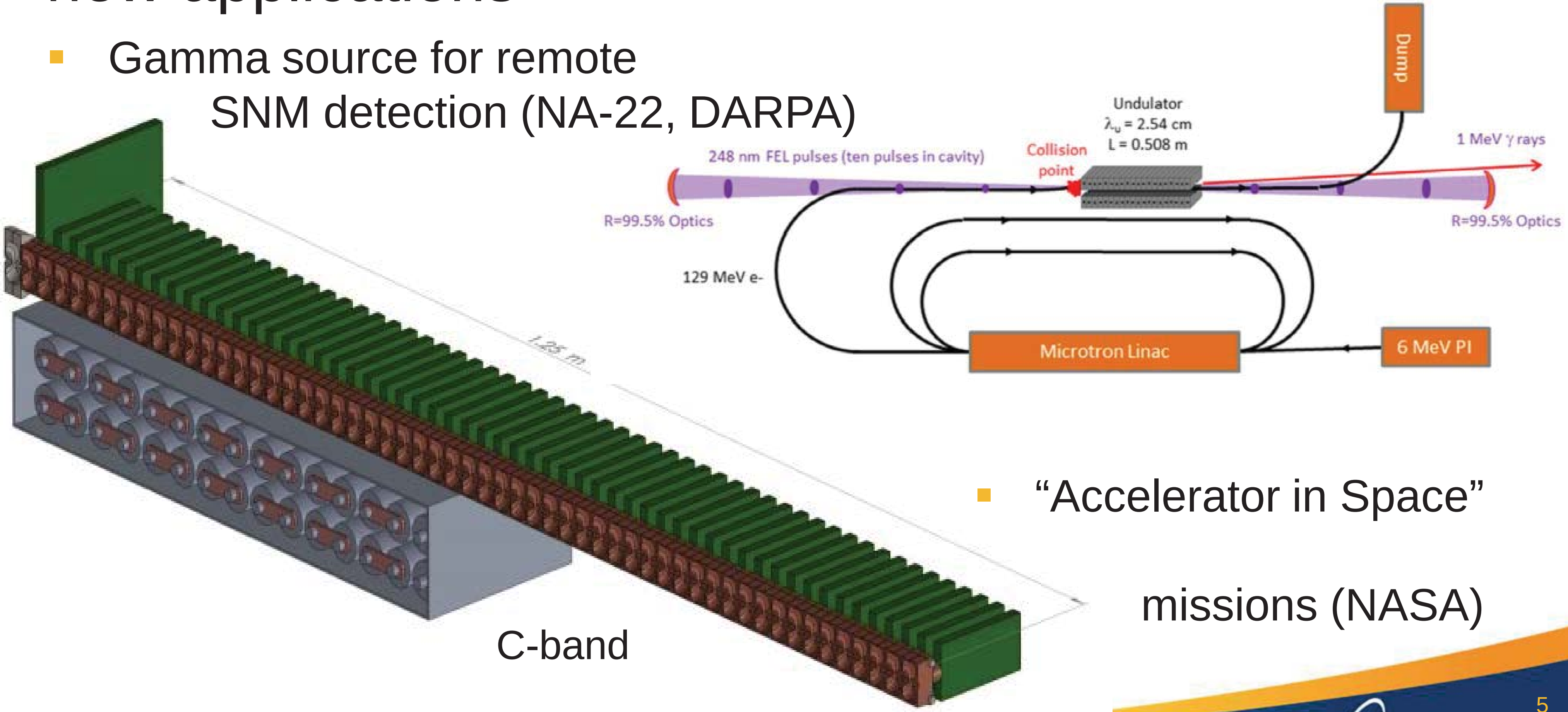


We plan on using optical split and delay to generate sub-ns pulse separation

Impact: Path to transportable accelerators for National Security applications

It will enable transportable accelerator systems for new applications

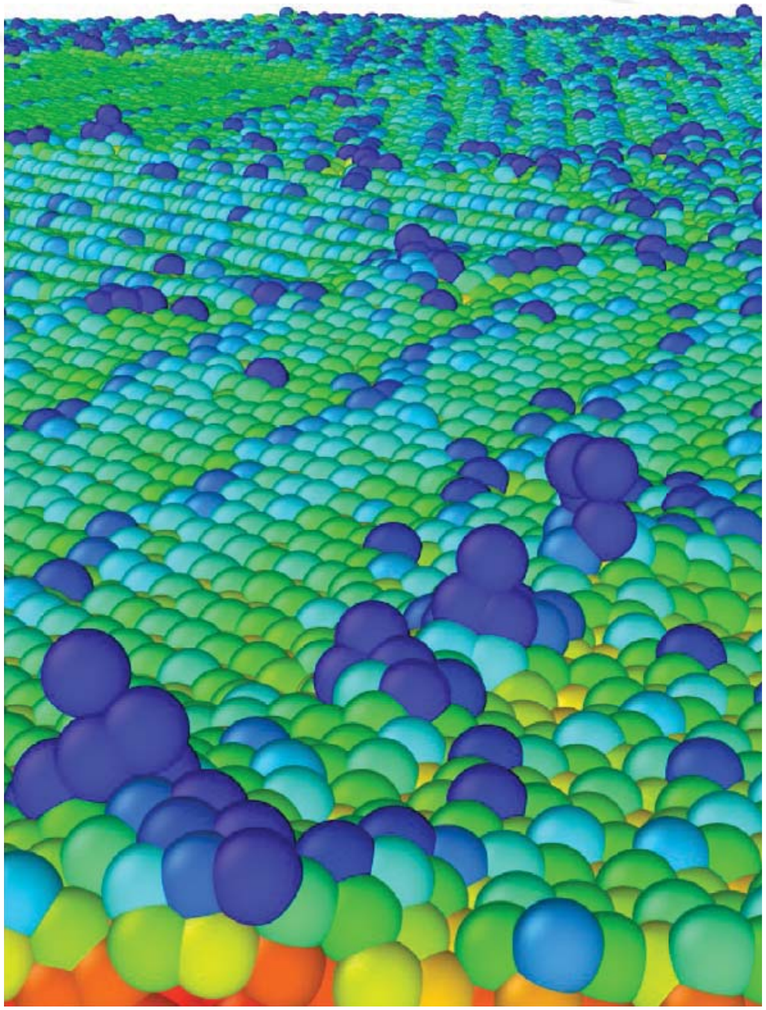
- Gamma source for remote SNM detection (NA-22, DARPA)



- “Accelerator in Space” missions (NASA)

Computational materials science effort

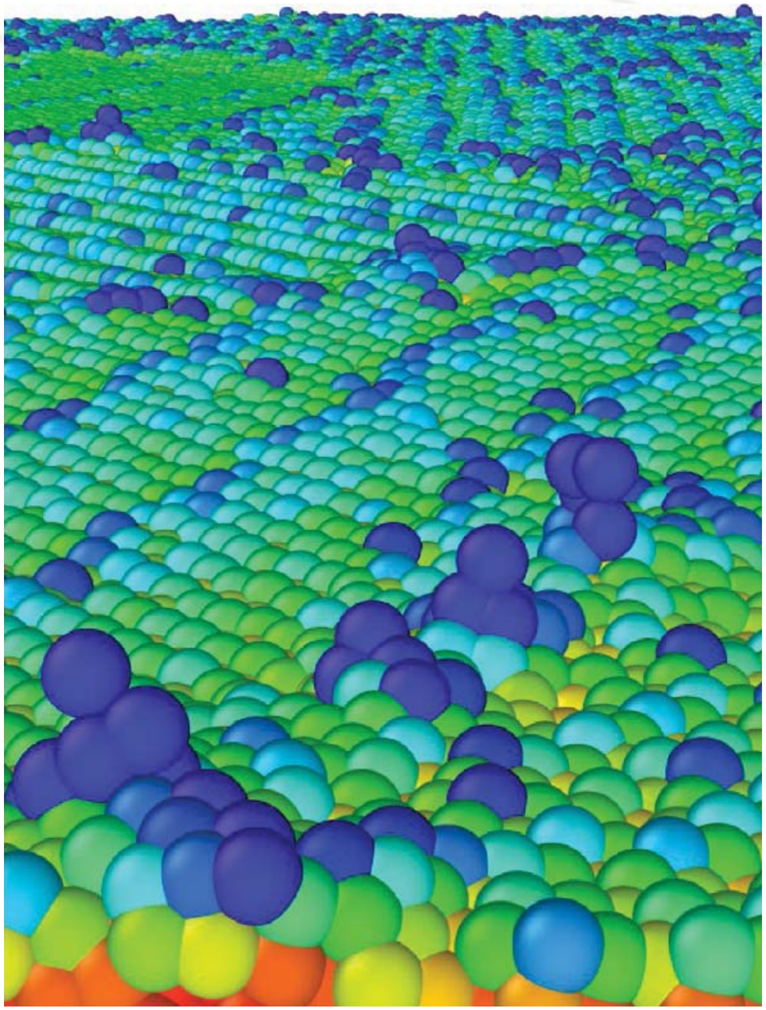
- Developed long-range charge equilibration solver under external field
- Charges are dynamically adjusted
- Unique massively-parallel simulation capability: Large-scale and accelerated molecular dynamics simulations:
  - MD: ~10^7 atoms for a few ns (large but short)
  - AMD: ~10^4 atoms for >tens of µs (small but long)



Computational materials science effort

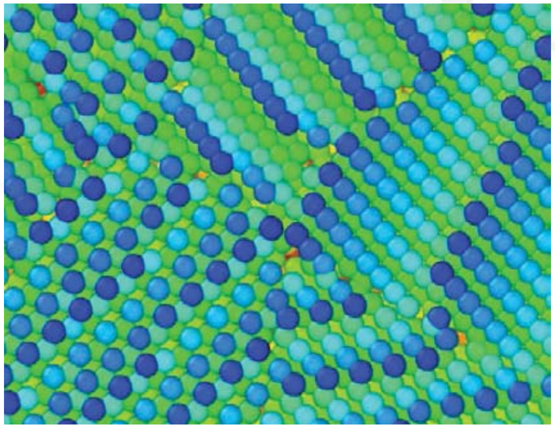
Strategy

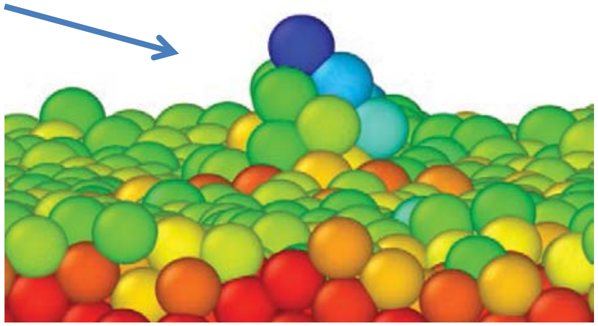
- Large scale MD:
  - Identify structures responsible for breakdown vs microstructure, defect content, and composition at high field and T
- Accelerated MD:
  - Quantify breakdown propensity of specific features at lower fields and temperatures
- Ab Initio calculations:
  - Parameterize/validate classical charge equilibration models using quantum calculations



Computational materials science effort

- **Proof of concept**
  - 10^{6}-atoms nanocrystalline Cu sample under a 10 GV/m surface field
  - Captures key field/material interactions:
    - Strong coupling between surface features and induced charge distribution
    - Spontaneous formation of nano-tips near grain junctions
    - Field-induced evaporation
    - Mechanical loading



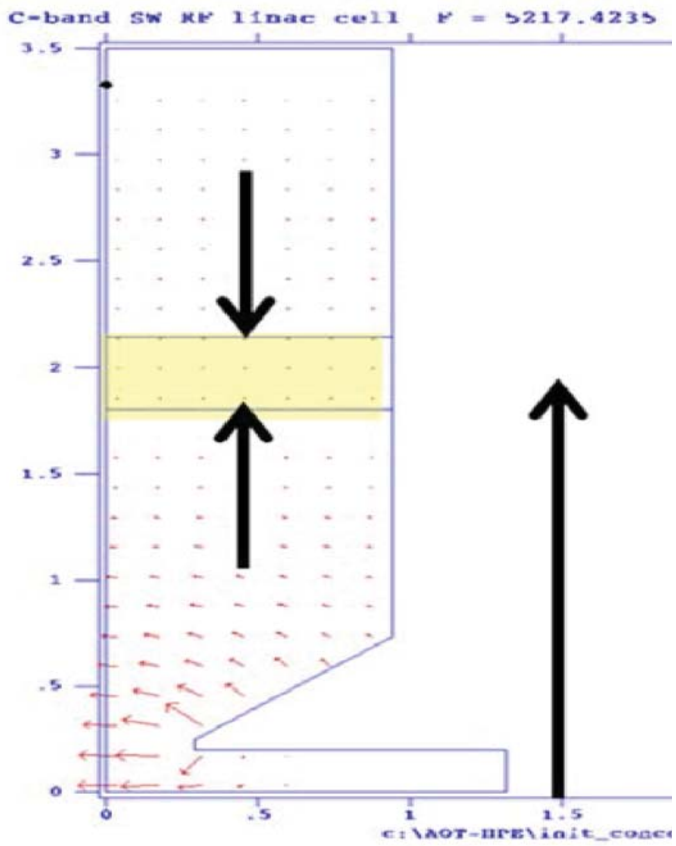


- Upcoming challenges: structures responsible for breakdown can be much larger and develop much slower at lower fields

Structure Design Details

- RF Design
  - SW vs TW decision
  - Geometry optimization based on best practices
  - Couplers, damping
  - Short range wakes for compact applications
  - Short range and long range wakes in context of XFEL type linac with a pair of bunch compressors
- Long-pulse improvements
  - Cryo-copper (efficiency, reduced rise in temperature)
  - Evaluate dielectric insertions (efficiency, but unknown high field properties)

What can dielectric insertions contribute?

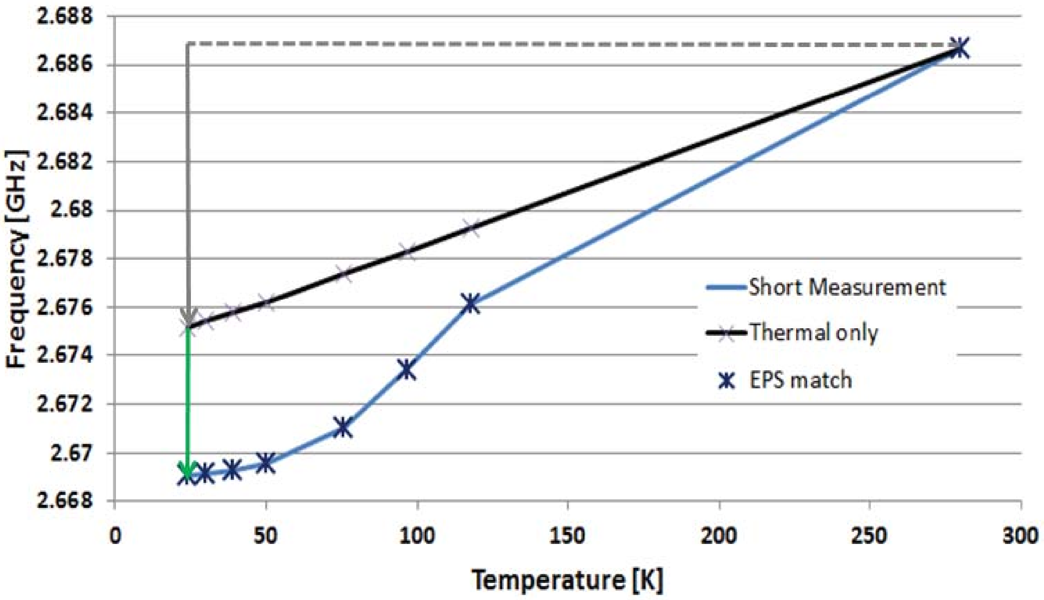


Re-entrant RF-structure with dielectric insert (yellow).

Epsilon	R_{cav}	Ceramic Width	Ceramic R frac	P_{cav}
	[cm]	[cm]	[cm]	[W]
1	4.64	N/A	N/A	134
3	4.00	0.65	0.59	89.5
5	3.80	0.544	0.56	78
6	3.78	0.494	0.56	76
8	3.65	0.426	0.56	72
10	3.62	0.360	0.54	70
15	3.56	0.312	0.56	66
20	3.59	0.268	0.52	64

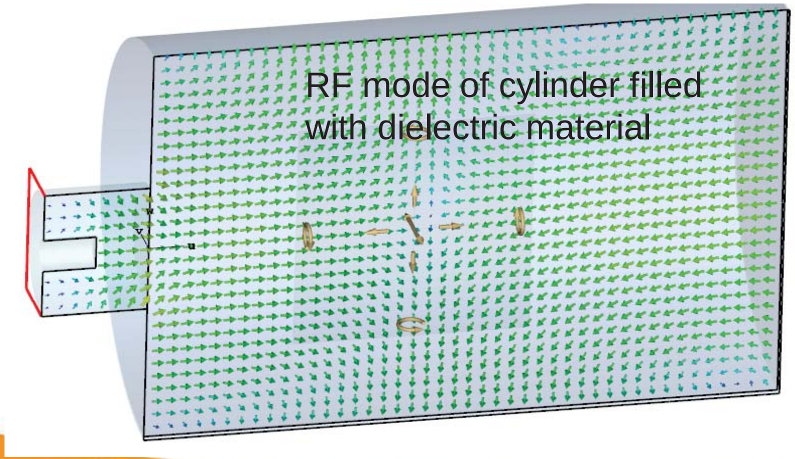
Structure gets smaller and more efficient

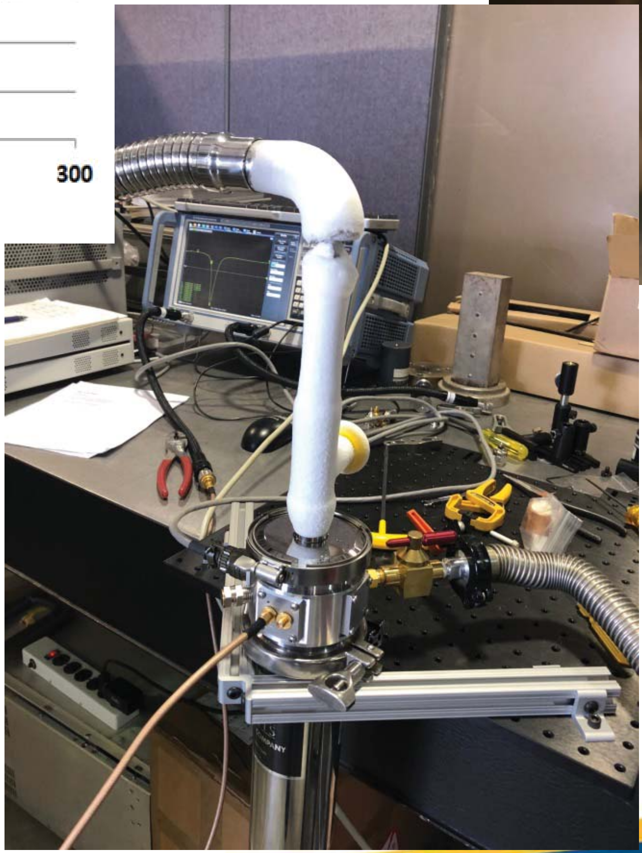
Dielectric in cryo environment



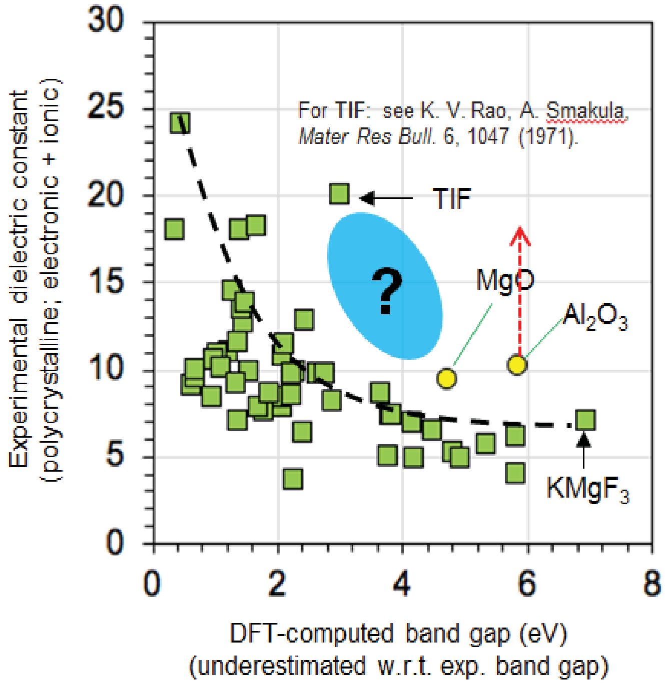
Measured frequency, as a function of temperature (blue) and the contribution from thermal contraction (black).

Alumina based dielectric compatible with cryo operation.

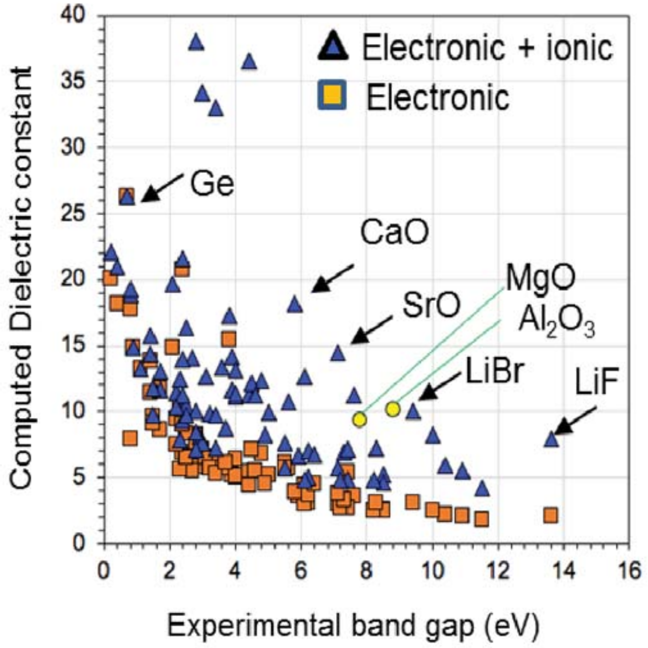

RF mode of cylinder filled with dielectric material



Theoretical study of dielectrics



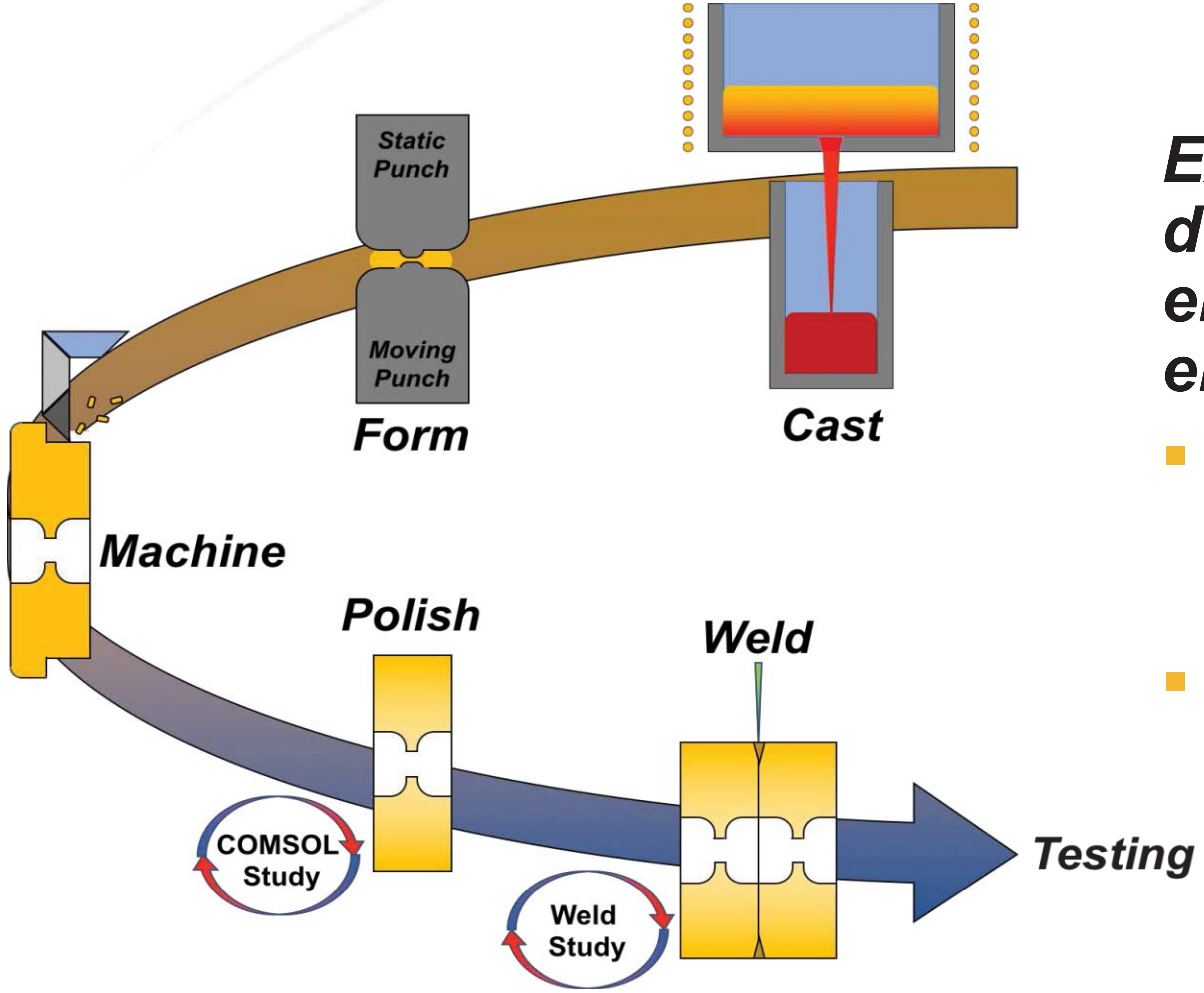
Dielectric constant versus bandgap (computed within DFT) plot for a set of polycrystalline ceramic materials previously reported in literature. Yellow circles identify materials that have been proposed as promising dielectrics for the hybrid cryogenic copper/ceramic accelerator. The arrow at the alumina dot shows the doping Euclidlabs did for our test dielectric.



Dielectric constant versus experimental bandgap plot for all binary octet AB-type compounds. Yellow circles identify materials that have been proposed as promising dielectrics for the hybrid cryogenic accelerator and other compounds with comparable performance are highlighted.

- High dielectric constant and large bandgap (low losses) are desirable
- Most materials have one or the other
- Can new materials be designs (like toe doped alumina)?
- Do compromise materials have good vacuum and/or breakdown properties?

LANL has the full cycle from alloys to finished machining, to integrate with predictive MD capability



Exercise expertise in alloy design, forging & forming, electron beam welding, and electrofinishing.

- Develop a near-net shape fabrication strategy for Cu alloy cavities
- No comparable expertise in metallurgy at other accelerator laboratories

Roadmap

- Funded in FY19
  - Verification of MD capability
  - Establish C-band advantages for our applications
  - RF-source concepts for higher peak power
  - Evaluation of dielectrics
- Application for LDRD funds based on FY19 results
  - Develop good copper alloy and structure
  - Optimize C-band cavity with or without dielectric
  - Build and verify prototype
  - Start test beamline with injector, C-band tank and commercial klystron – future programmatic extension