New Test Area with SC Solenoid at SLAC

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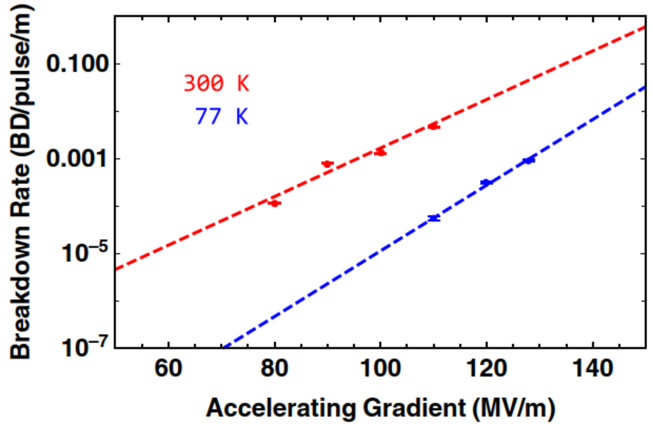
2nd USMCC Meeting, University of Chicago
August 8th, 2025

Why establish a new RF test stand?

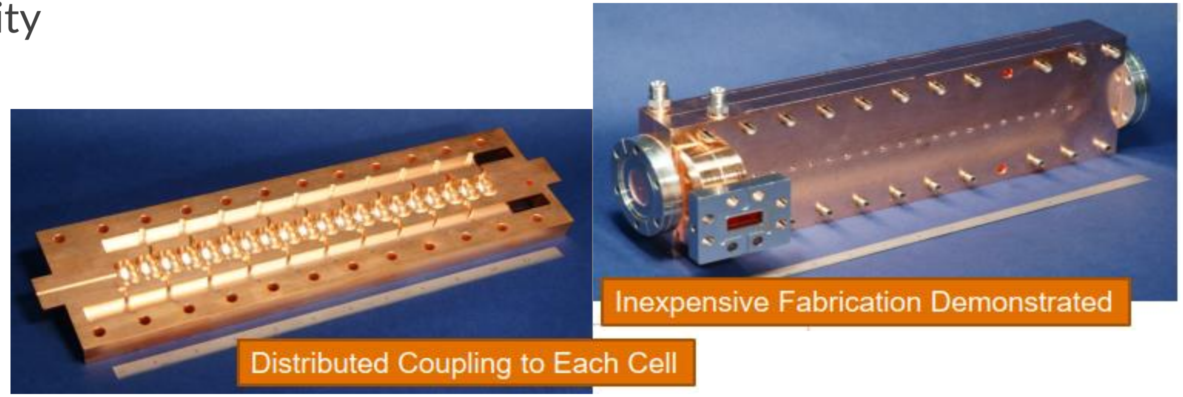
Efficient cooling remains one of the biggest technical hurdles for a muon collider

- Need enabling technology that can take us from the edge of "reasonable physical assumptions" to a viable path for ionization cooling
- Accelerator community needs a facility to validate these designs
- SLAC's General Accelerator R&D (GARD) program has made significant advances in normal conducting accelerator designs within the last decade to
    - Increase gradient
    - Increase power efficiency
    - Reduce breakdown rates
- Our new research thrust will investigate applying these techniques for operation within strong magnetic fields
- Siting this test area at SLAC's NLCTA Test Facility deliberately ensures this capability is readily accessible to the broader community

Breakdown rate reduced by 50x with cold copper



M. Nasr, et al. "Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature." *PRAB* 24.9 (2021): 093201.



RF cavity operation in external magnetic fields

Magnetic fields produce enhanced effects of field emission and multipacting

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 031002 (2009)

rf breakdown with external magnetic fields in 201 and 805 MHz cavities

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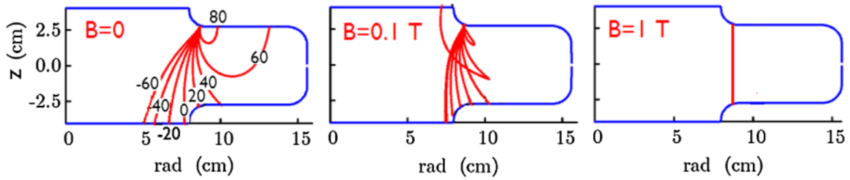

FIG. 7. (Color) Trajectories of electrons field emitted at different phases from the highest surface field location in an 805 MHz pillbox cavity with no external magnetic field (left), an axial field of 0.1 T (center), and an axial field of 1 T (right). The axial electric field is 25 MV/m. Phases are in degrees relative to the maximum.

Nuclear Instruments and Methods in Physics Research A 620 (2010) 147–154

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journal homepage: www.elsevier.com/locate/nima

Effects of external magnetic fields on the operation of high-gradient accelerating structures

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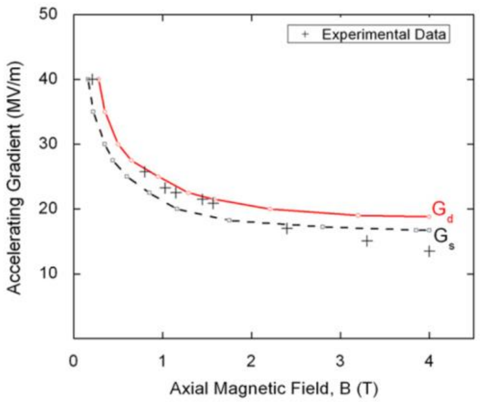

Fig. 8. Predictions of our model for the required accelerating gradients G_s, G_d for the 805 MHz cavity to reach the safe and surface-destruction temperature, ΔT_s and ΔT_d, respectively. Black crosses are measured breakdown data versus magnetic field from the PB experiment discussed in Ref. [6].

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23**, 072001 (2020)

Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration

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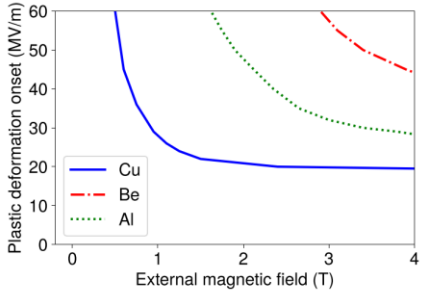
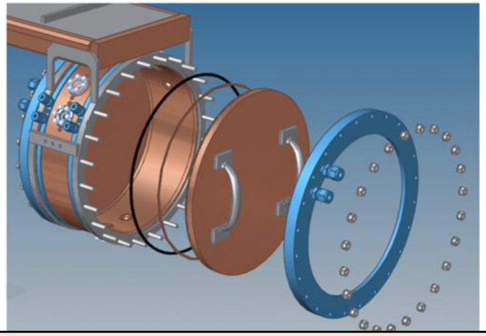


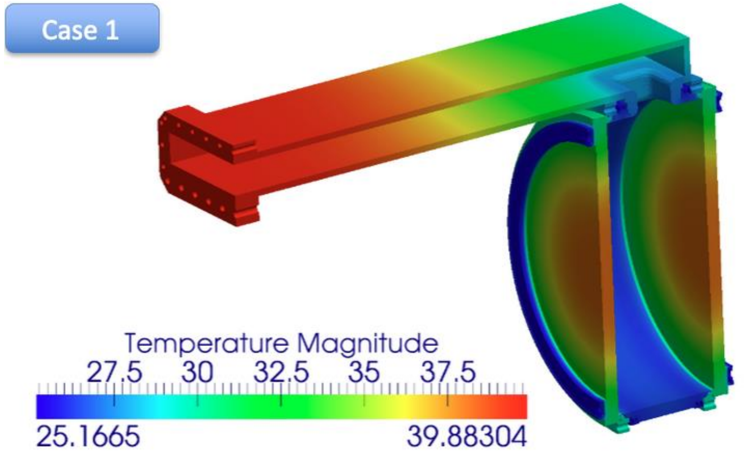
FIG. 3. Predicted cavity gradients vs external, solenoidal magnetic field strength, based on the beamlet pulsed heating model. Beryllium cavity walls should be less susceptible to fatigue from beamlet pulsed heating and should therefore operate at higher gradients relative to copper.



Reached a stable operating gradient of 50 MV/m in 805 MHz pillbox cavity with Be walls within 3 T solenoid field (0.2×10^{-5} breakdown probability, sparks per pulse) at Fermilab's MuCool Test Area

SLAC experience contributing to 805 MHz modular cavity

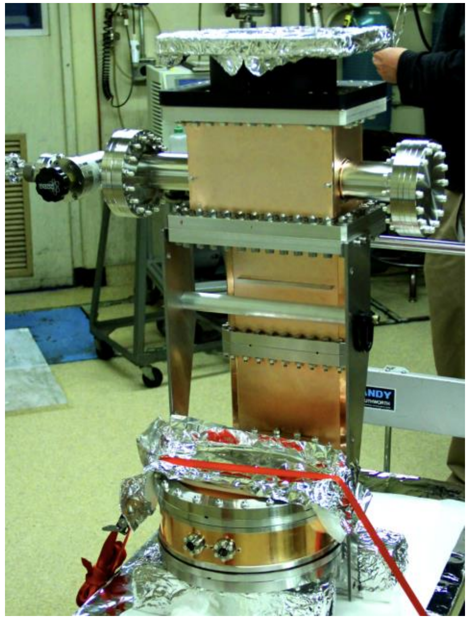
805 MHz Cavity Thermal Simulation



	E_{max}	σ for Beryllium	Duty Factor
Case 1	25 MV/m	2.33e7 S/m	0.001

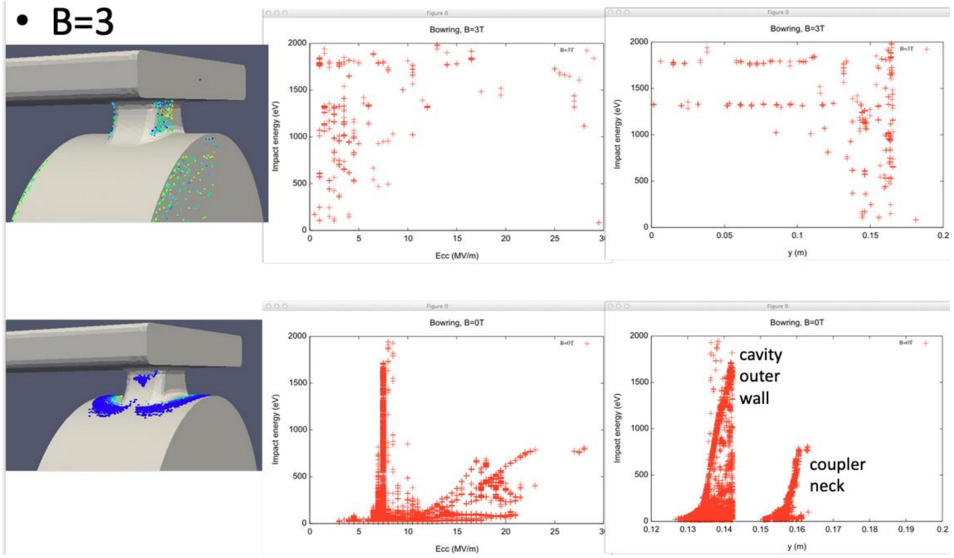
- RF field thermal load generated using Omega3P/S3P of ACE3P code suite
- thermal and mechanical stress analyzed using ACE3P multi-physics module TEM3P

Li, Zenghai, et al. "RF optimization and analysis of the 805-MHz cavity for the MuCool program using ACE3P." *AIP Conference Proceedings*. Vol. 1507. No. 1. American Institute of Physics, 2012.



Modeling emission for 805 MHz Cavity Multipacting, B = 3 T

- Impact of field emission and multipacting under high magnetic field analyzed using ACE3P codes suite
- RF field generated using Omega3P/S3P field solver
- External magnetic field applied for particle tracking study
- Multipacting bands and location identified using particle tracking module Track3P of ACE3P



Ge, Lixin, et al. "Multipacting simulation for muon collider cavity." *PAC09, WE5PFP020* (2012).

SLAC

See talk by Zenghai Li in today's earlier Accelerator session

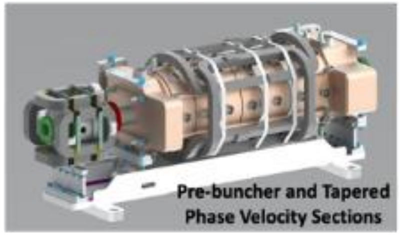
RF Accelerator Research @ SLAC

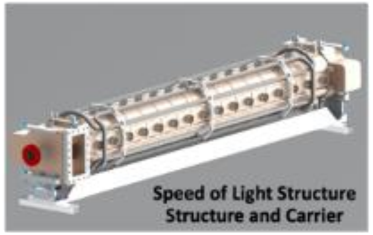
Design, fabrication and testing of accelerator structures, high-power RF sources and integrated systems

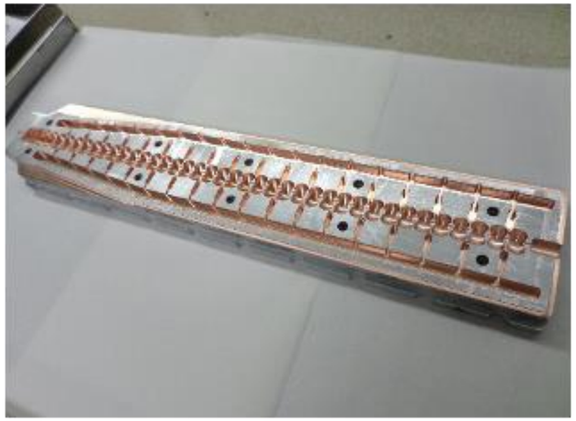
Multi-physics modeling & simulation of performance

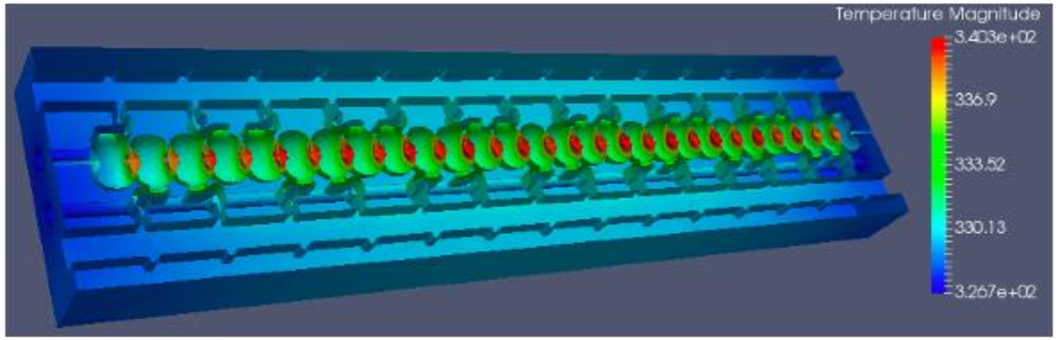
Integrated engineering capabilities

Expertise in S-band, X-band, C-band and THz







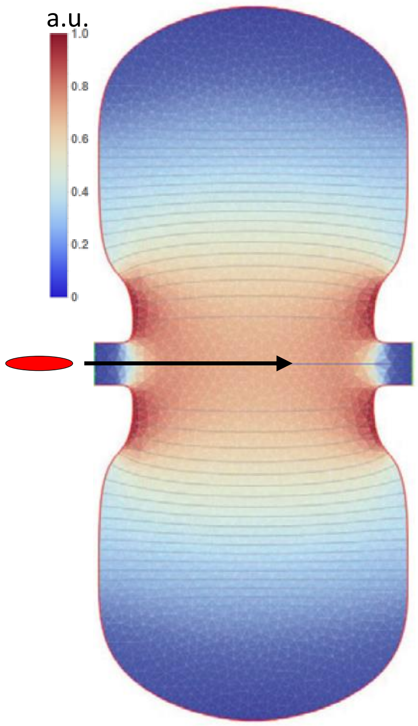


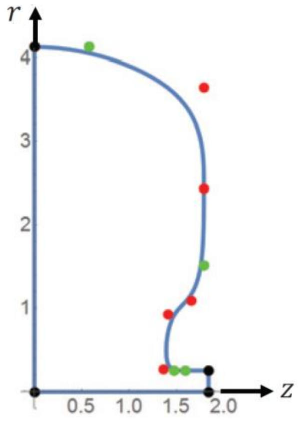
Normal Conducting RF Accelerator Design at SLAC

Improving cavity efficiency and cost-effective fabrication

Re-entrant nose cone design reduces surface magnetic field to enable a higher gradient and very high shunt impedance, hence very efficient linac structure

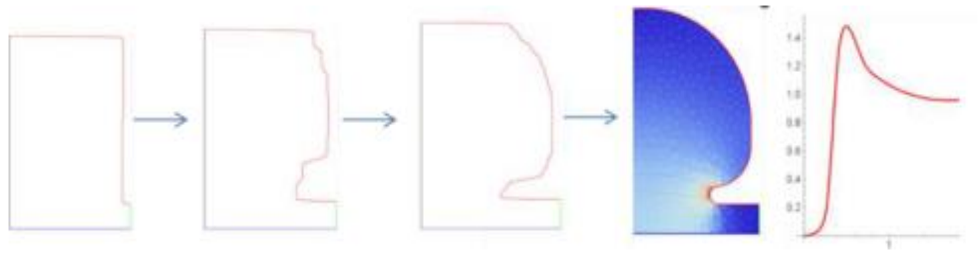
Maximize cavity shunt impedance with narrow iris apertures and distributed coupling of power



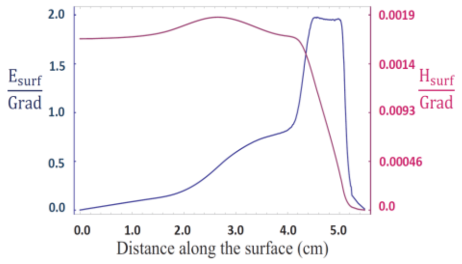


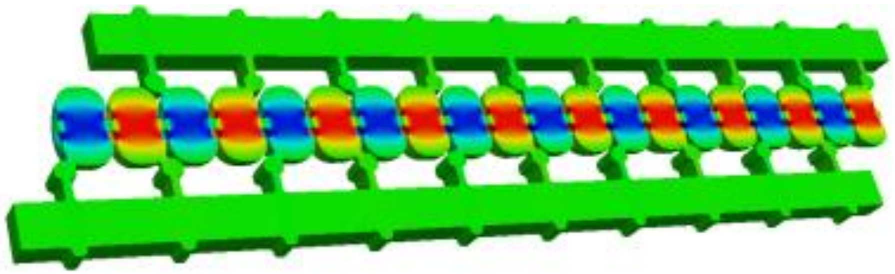
We can employ this optimization approach but with new design constraints determined by ionization cooling requirements

Magnetic field distribution around the cell surface



Nasr, M. H., and S. G. Tantawi. ***New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities' Performance***. No. thpmk049. IPAC, 2018.





Cold Copper RF Accelerating Structures

140 MeV/m measured with beam tests at NLCTA

Ernest Courant Outstanding Paper Recognition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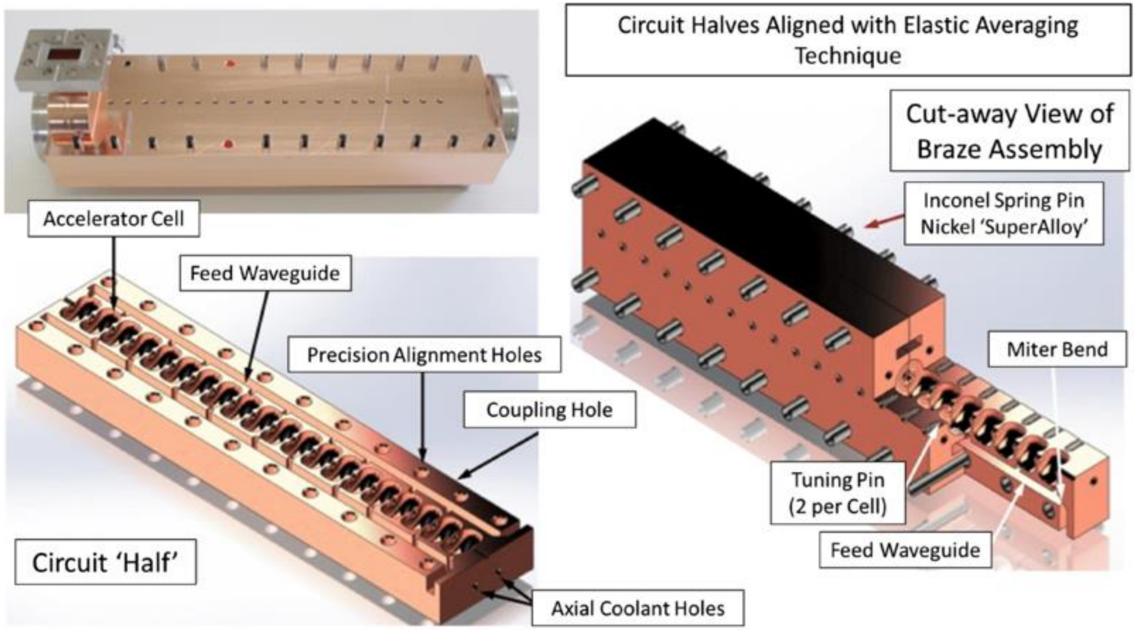
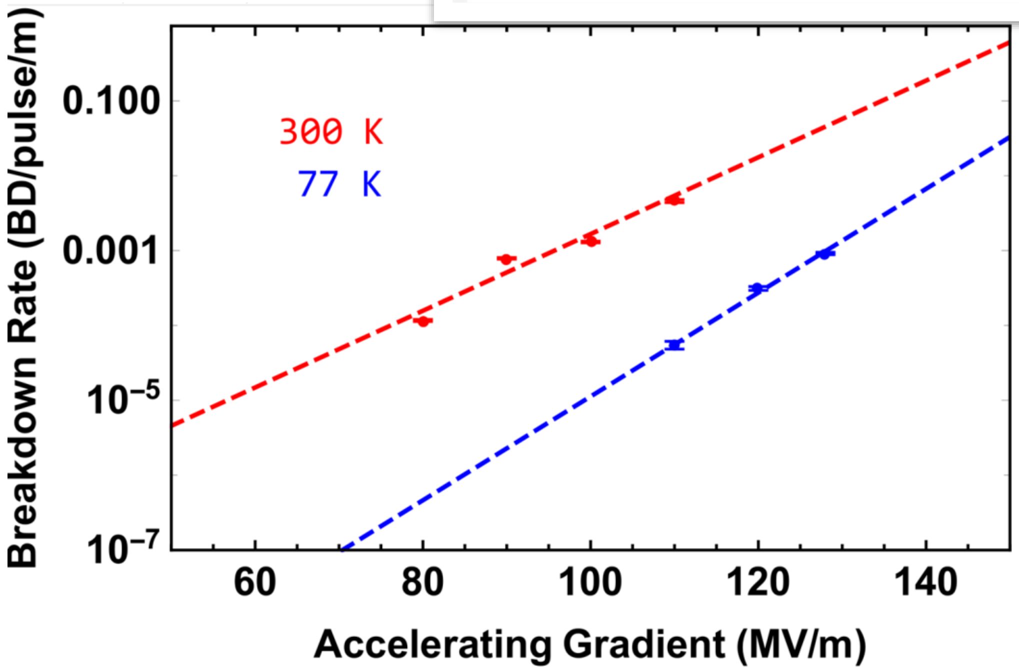
Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature

Mamdouh Nasr, Emilio Nanni, Martin Breidenbach, Stephen Weathersby, Marco Oriunno, and Sami Tantawi
Phys. Rev. Accel. Beams **24**, 093201 – Published 13 September 2021

Breakdown rate (BDR) reduction by 50x from room temperature operation

Breakdown limits primarily driven by high H-field regions within cell coupler





PRAB 23, 092001 (2020)

PRAB 24, 093201 (2021)

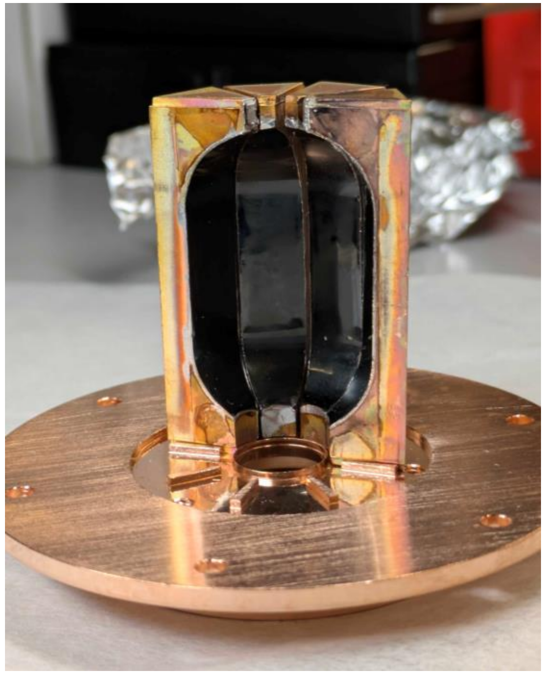
Cold copper can dramatically reduce breakdown rates at high gradient

Applying High Temp Superconductors to RF design

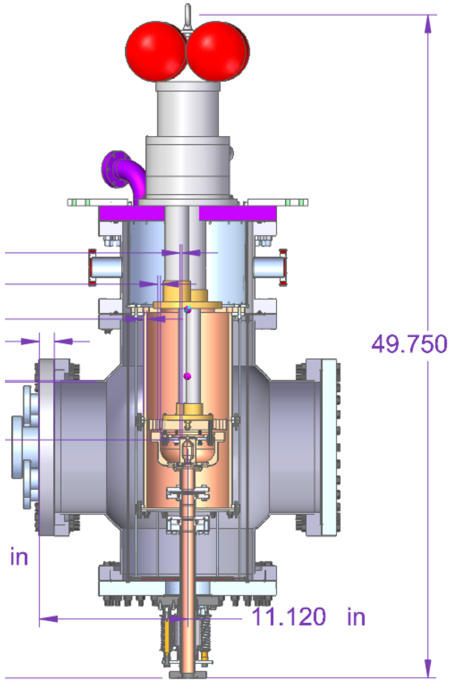
As a first approach, a pulse compressor cavity utilizing the TM010 mode is being built

Cavity is built from 8 facets coated with HTS tapes, with surface current to run longitudinally

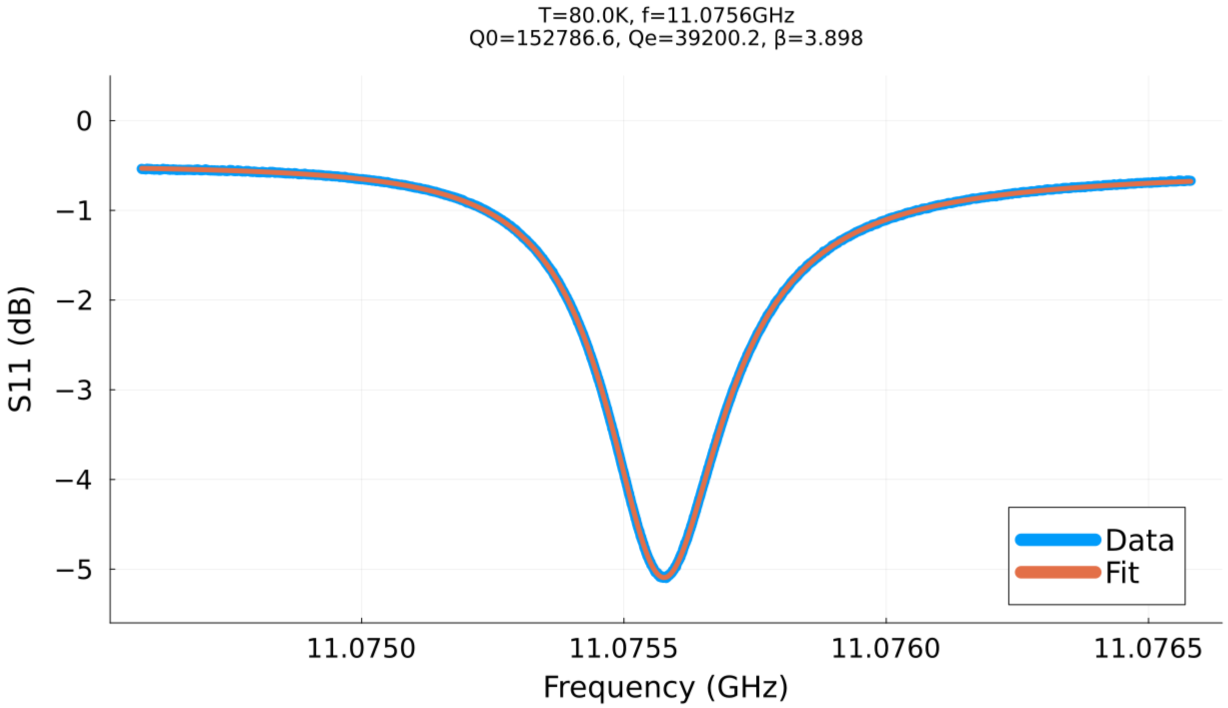
Q_e remains roughly constant around 39000, with Q_0 rising to over 150k at 80 K (3.5x Copper)



HTS Cavity



Cryostat for testing cavi

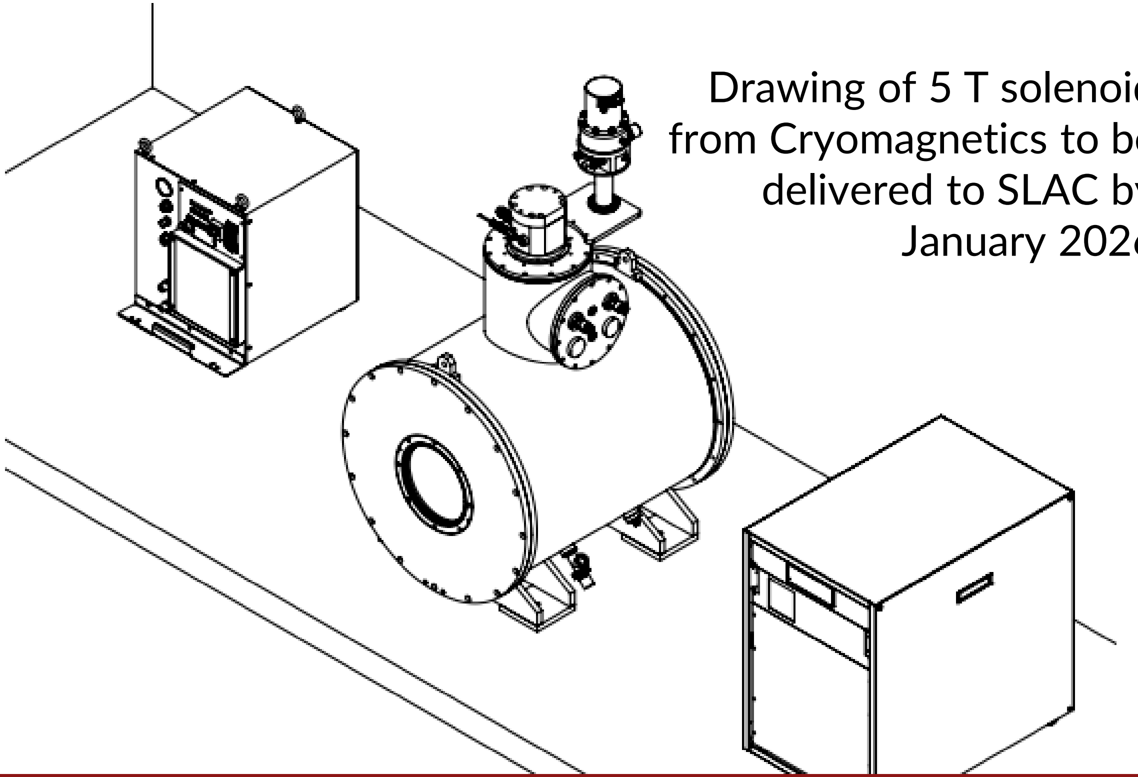


Testing with MW-scale power at NLCTA this fall

GARD Research at New Test Area

Determine gradient dependence on cavity geometry, material, pulse length, and operating temperature in high magnetic fields

- Test cavity geometries and materials relevant to muon cooling channel
- Benchmark high gradient results for frequency scaling with measurements at S-band and L-band available at NLCTA
- Measurements of the field emission and associated damage will be used to benchmark our simulated field emission in SLAC's ACE3P code suite.



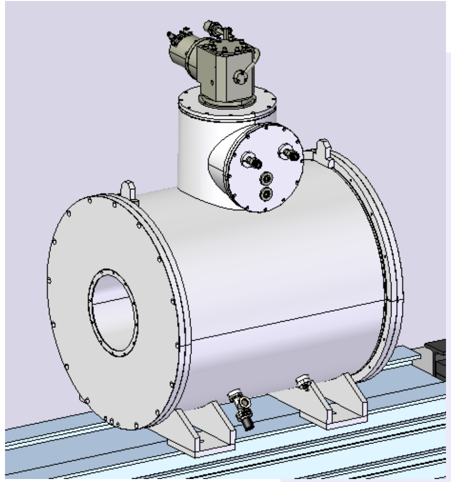
Drawing of 5 T solenoid from Cryomagnetics to be delivered to SLAC by January 2026

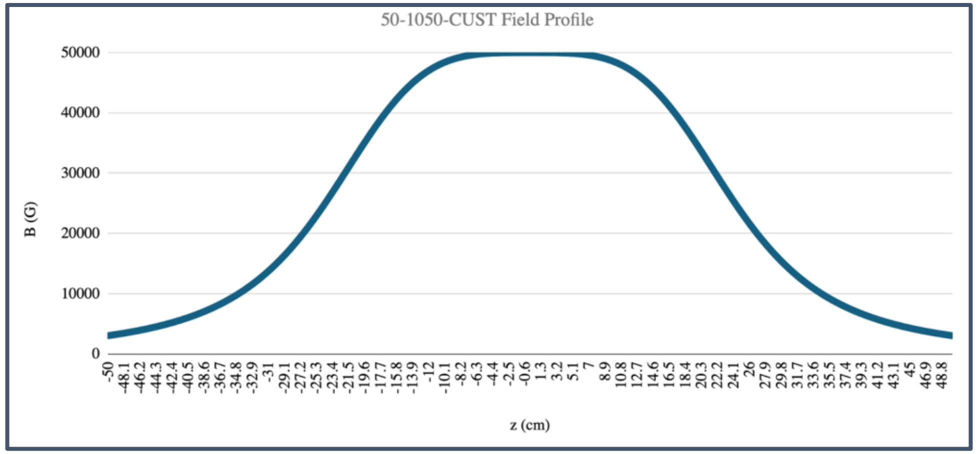
Additional SLAC LDRD proposal submitted to design normal conducting rf cavities specifically optimized for ionization cooling, scaled to S-band, and to test them with high power RF in the new 5 T solenoid.

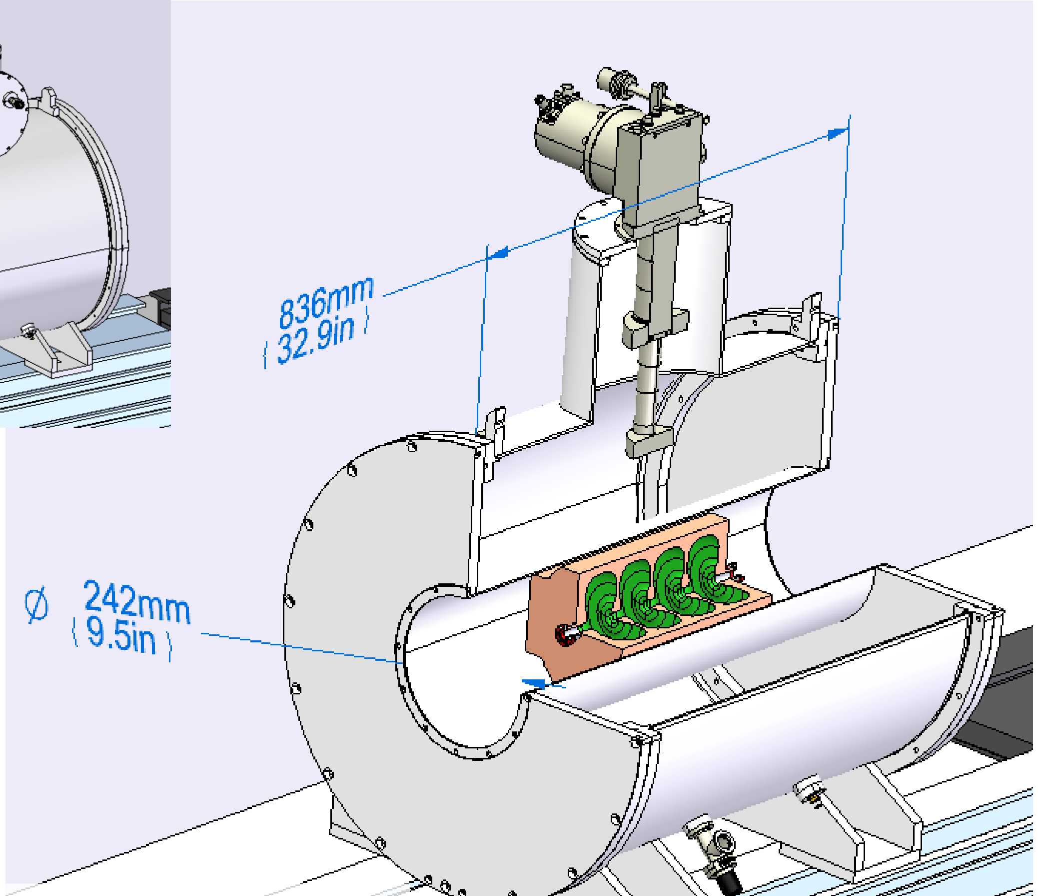
High Field Test Area with 5 T Solenoid

Superconducting solenoid from Cryomagnetics

- 5 T with +/-1% over >10 cm DSV Homogenous Region
- 9.5” diameter horizontal bore at room temperature







Cutaway view of solenoid with 4-cell copper L-band cavity

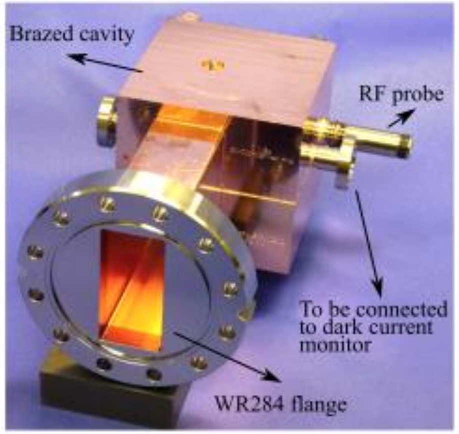
High-Power Testing at S-band for Initial Prototyping

Fabrication informed by existing SLAC structures at S-band and L-band

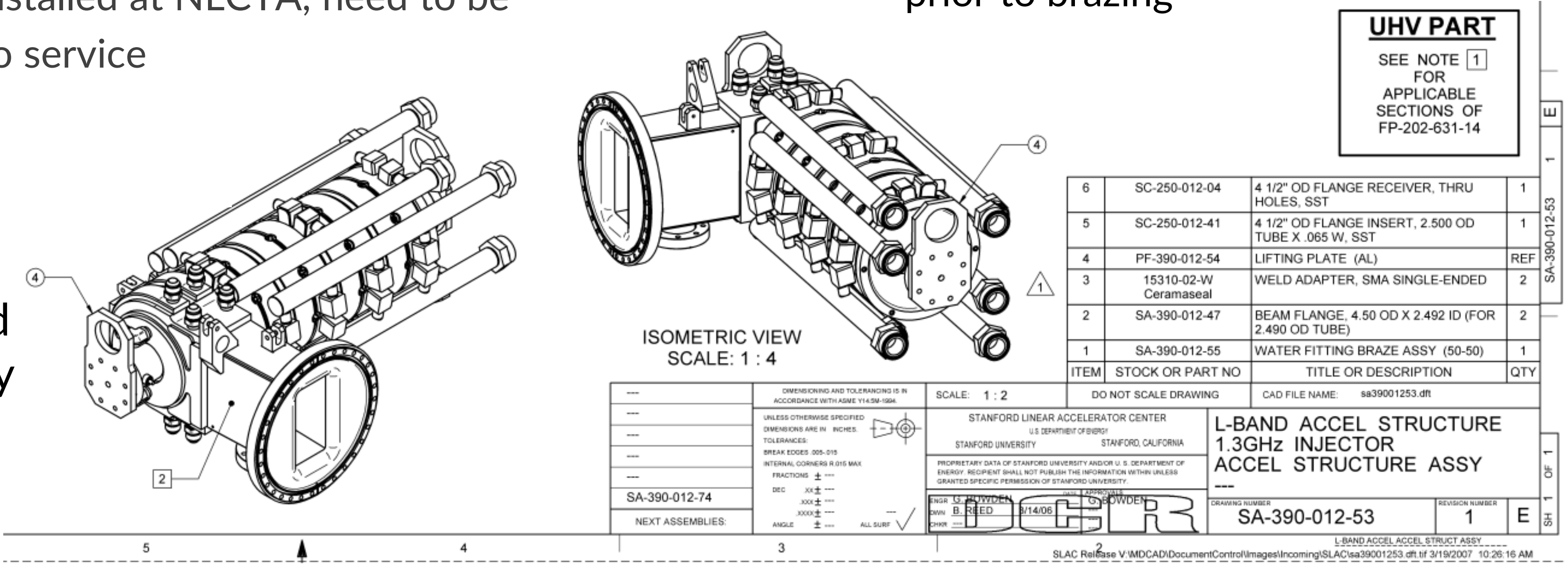
- Prototype cavities can be fabricated and tested cost effectively at S-band before scaling to the lower frequencies needed for ionization cooling
- Measurements at S-band will be used to benchmark frequency scaling
- L-band already installed at NLCTA, need to be brought back into service

Example S-band prototype cavity for proton accelerator for cancer therapy

Split-block cavity halves prior to brazing



Example L-band prototype cavity



SLAC National Accelerator Laboratory

BeamNetUS Facilities in Pilot Year (2025)

NLCTA in BeamNetUS

BeamNetUS is a network of test facilities with a common mission:

- Advance accelerator research and applications of accelerator technology
- Provide access to unique accelerator facilities and specialized equipment
- Foster collaboration to exchange ideas, skills and resources.

BeamNetUS offers a streamlined proposal process for gaining access to member facilities

- Awards cover beam time, expert support, travel and materials
- Expected timeline is 6 – 12 months from proposal submission to experimental run (1-3 weeks)

beamNetUS
accelerating beam-based research

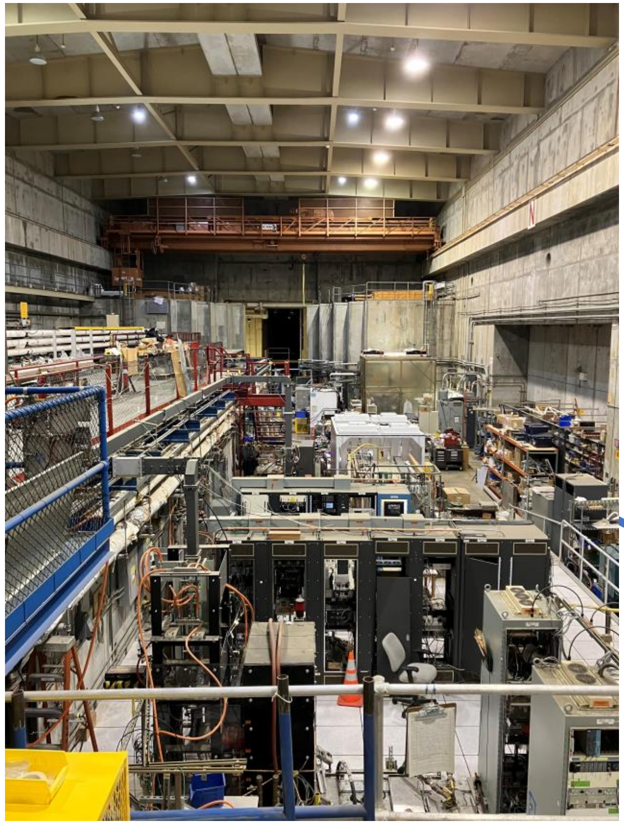
beamnetus.org

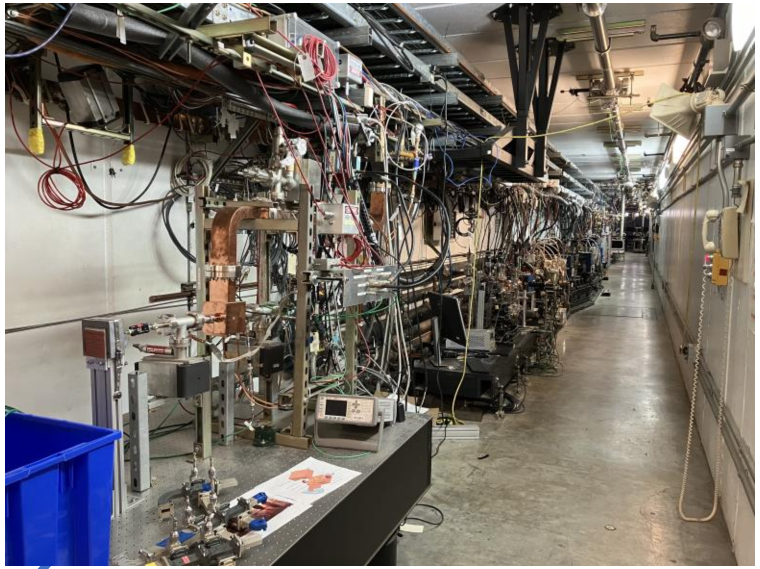
NLCTA test facility provides opportunities for early career scientist and engineers, and student mentoring with hands-on experience in an active accelerator research environment

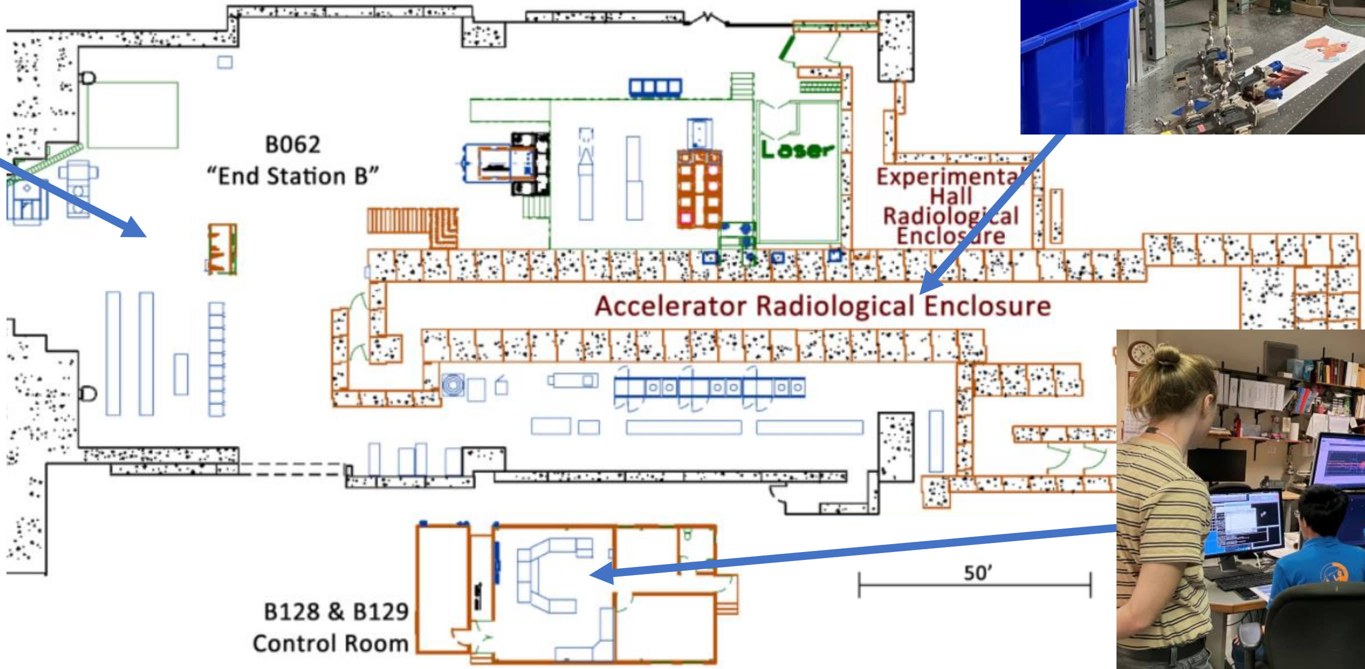
NLCTA Test Facility

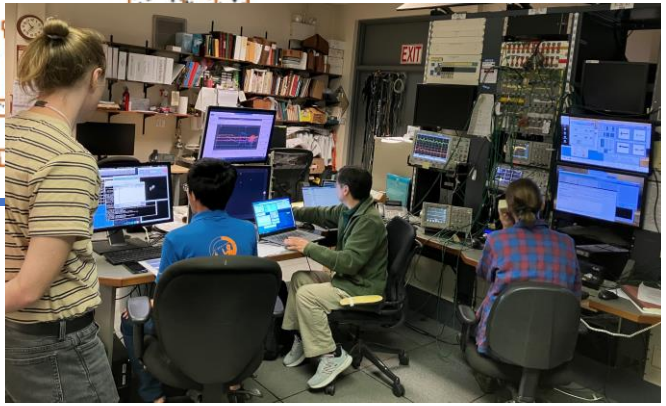
Next Linear Collider Test Accelerator (NLCTA)

- Radiation shielded bunker with accelerator hardware and multiple high power RF klystrons at X-band (11.424 GHz) and S-band (2.856 GHz)
- Dedicated laser room with Ti:Sapph laser system
- Cryostats reaching 4 K with high power RF at X-band
- In-house clean room, machine shop, and experiment staging areas









[Link to Virtual Tour of NLCTA]

SLAC

NLCTA Test Facility Capabilities

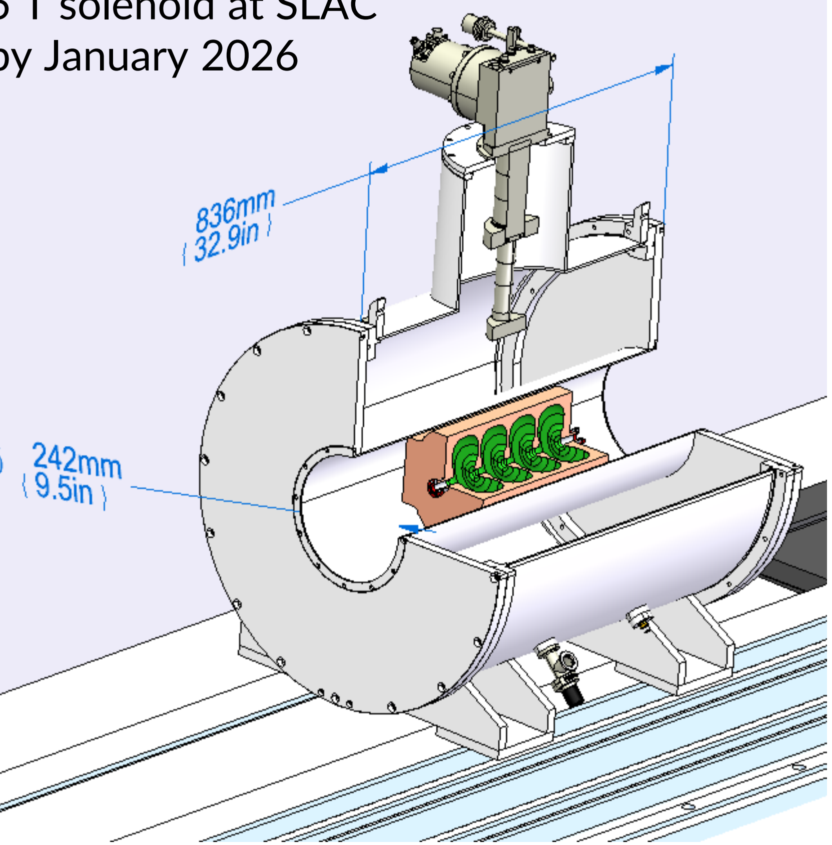
Test bed for accelerator technology R&D

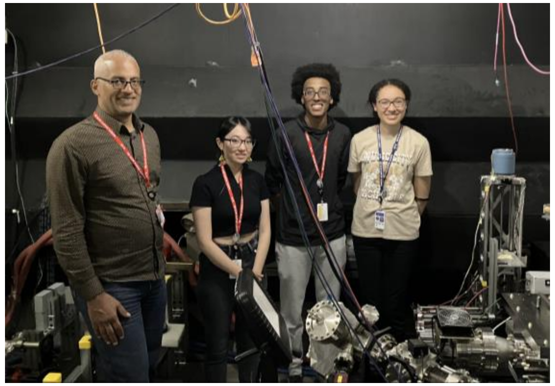
- Multiple distinct high-power test areas in a radiation shielded bunker, including the stand-alone high-power XTA beamline delivering beam up to 75 MeV
- High power RF available at X-band and S-band now, soon L-band too
- Accelerator housing is located inside of the End Station B building with access to the laser room (Ti:Sapph laser for XTA), clean room, and machine shop, as well as experiment staging areas

Examples of potential areas for proposals and collaboration:

- **Room temperature and cryogenic tests of high gradient RF structures and materials studies**
- **Detector testing and development on the XTA beamline**

5 T solenoid at SLAC by January 2026





NLCTA's first BeamNetUS Users were a team of undergrads from Harvey Mudd College completing a capstone engineering project.

DOE's Science Undergraduate Laboratory Internship (SULI) program
https://science.osti.gov/wdts/suli

NLCTA Point of Contact: Emma Snively, esnively@slac.stanford.edu

Outlook for High Field Test Area Capabilities and R&D Effort

Year 1 → Year 5

S-band room temperature → S-band at 77 K → L-band at room temperature → L-band at 77 K

RF Materials Studies:

- Normal Conducting Cavities
- Cold Copper and/or Different Materials, Geometries
- High Temperature Superconductors

Design Studies:

- Multi-Physics Analysis
- Benchmarking
- Frequency Scaling
- Cooling Cavity Designs
- Multi-Cell Cavities

Opportunities to collaborate in defining path, structure design, testing cavities and analysis

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SLAC

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Wei-Hou Tan
Sami Tantawi
Glen White
Cho-Kuen Ng
Juan Cruz
Annika Gabriel
Stephen Weathersby
Cristina Padilla Hernandez
Carsten Hast
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CERN

Victoria Bjelland
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Jessica Golm
Patrick Krkotic
Walter Wuensch

LANL

Evgenya Simakov

Arizona State University

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Radiabeam

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