Cold Copper for VHEE

Emma Snively, SLAC National Accelerator Laboratory

VHEE’25

September 17th, 2025

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

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Supported by: **US DOE Accelerator Stewardship Program**

Improving radiation therapy with new accelerator technology

Medical Accelerator R&D Goals

- Increase therapeutic window
- Improve treatment efficiency
- Improve power efficiency
- Reduce size and cost
- Get to higher dose rate

VHEE

Normal Conducting Accelerator R&D

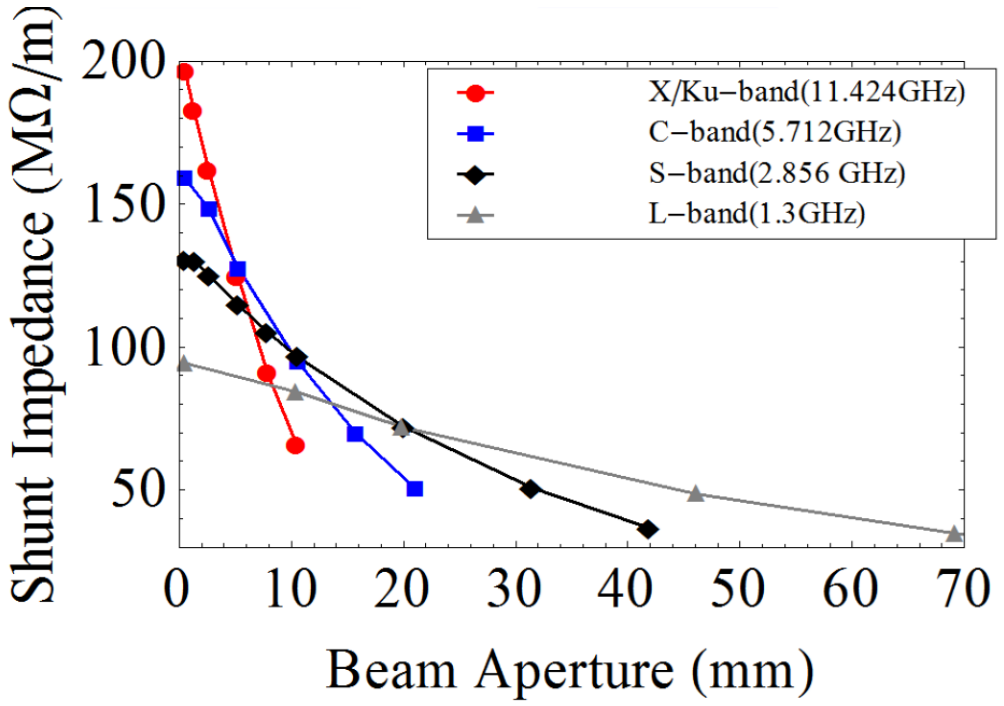
- Improve power efficiency, reduce breakdown rate, get to higher gradient
- Optimize RF frequency, pulse length, cavity geometry, power coupling, material and operating temperature
- Comprehensive multi-physics simulations

Operating frequency

- Empirical scaling of surface electric field limit

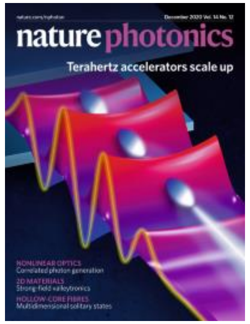
$$E_s \propto f^{1/2} / \tau^{1/4}$$

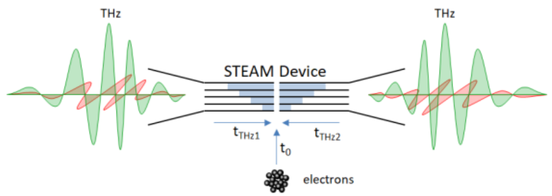
- High gradient due to higher breakdown thresholds at higher frequencies
- Reduced fill times which decrease pulsed heating and allow for higher repetition rates
- Increased shunt impedance and RF efficiency
- THz and mm-wave accelerators achieved peak surface field of 1.5 GV/m



High frequency accelerators have significant advantages if high rep rate, low instantaneous dose rate is suitable for observing FLASH effect

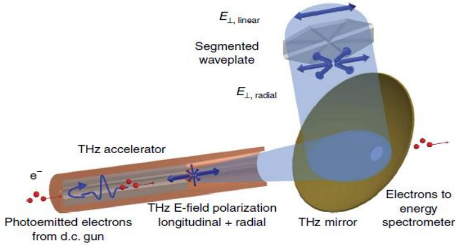
Hibberd, M. T., et al. "Acceleration of relativistic beams using laser-generated terahertz pulses." *Nature Photonics* 14.12 (2020): 755-759.



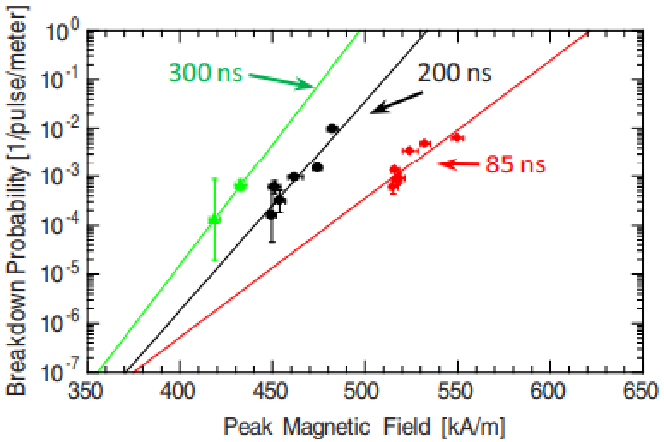


D. Zhang, et al. "Segmented terahertz electron accelerator and manipulator (STEAM)." *Nature Photonics* (2018): 1.

E. A. Nanni, et al. "Terahertz-driven linear electron acceleration." *Nature communications* 6 (2015): 8486.



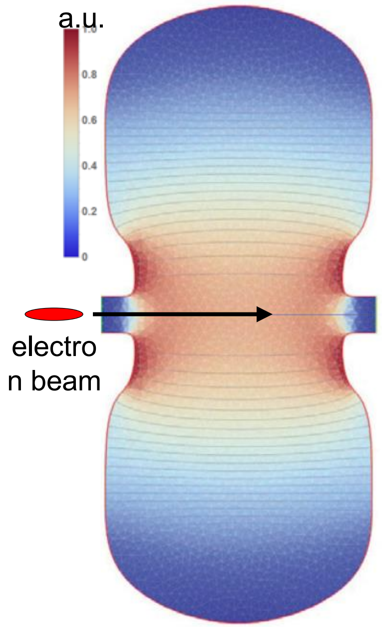
Cavity optimization

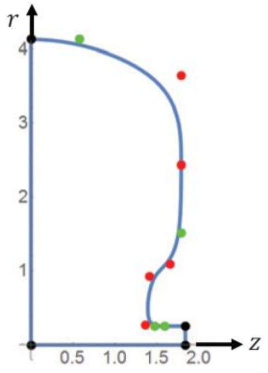


Dolgashev, Valery, et al. "Geometric dependence of radio-frequency breakdown in normal conducting accelerating structures." *Applied Physics Letters* 97.17 (2010).

Mitigating pulsed heating

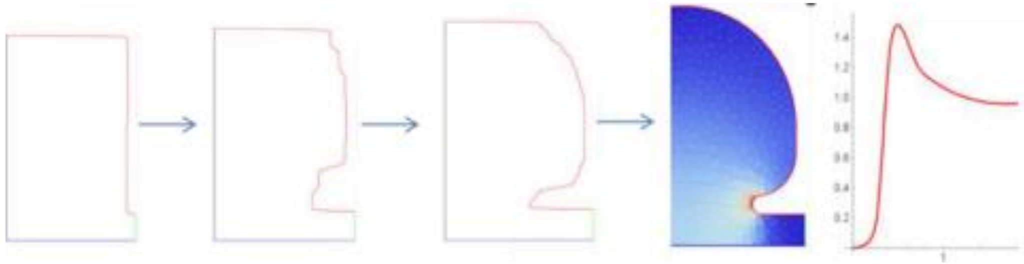
- RF breakdown correlation with surface pulsed heating caused by surface magnetic fields
- Results suggest increasing breakdown threshold by
  - Reducing RF pulse length
  - Using materials with high tolerance to surface fatigue due to pulsed heating
  - Cavity optimization constraining electric and magnetic fields on cavity surface

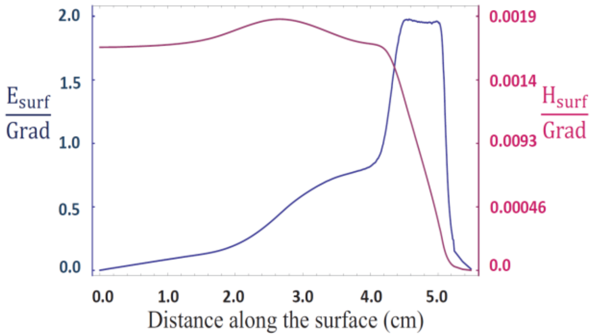




Nasr, M. H., and S. G. Tantawi. ***New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities' Performance***. No. thpmk049. IPAC, 2018.

Magnetic field distribution around the cell surface



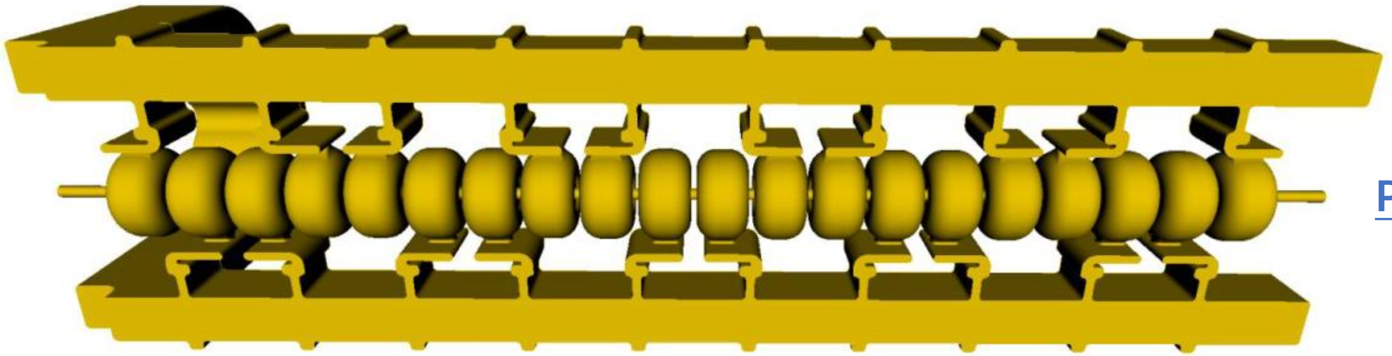


Maximizing efficiency

- Re-entrant nose cones increase accelerating gradient for on-axis beam
- Narrow iris aperture increases shunt impedance but introduces challenges with wakefields and power coupling

Power coupling

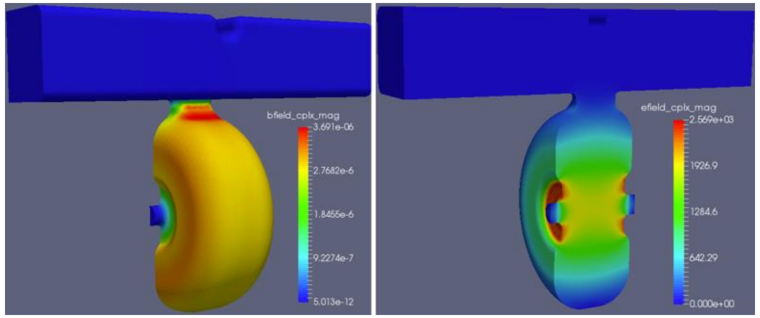
Tantawi, Sami, et al. "Design and demonstration of a distributed-coupling linear accelerator structure." *Physical Review Accelerators and Beams* 23.9 (2020): 092001.



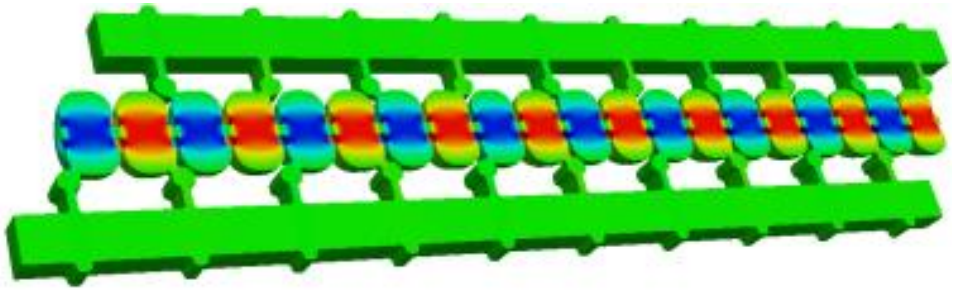
PRAB 21, 102002 (2018)

Distributed coupling to each cell

- Established a novel topology for achieving higher efficiency (2018)
- Enabled by modern virtual prototyping using high power computing
- Requires optimized coupling ports to limit local magnetic field enhancement



F=11.4241e9
Q0 = 21970
(factor 2.7 at 77 K)
Beta=1.8

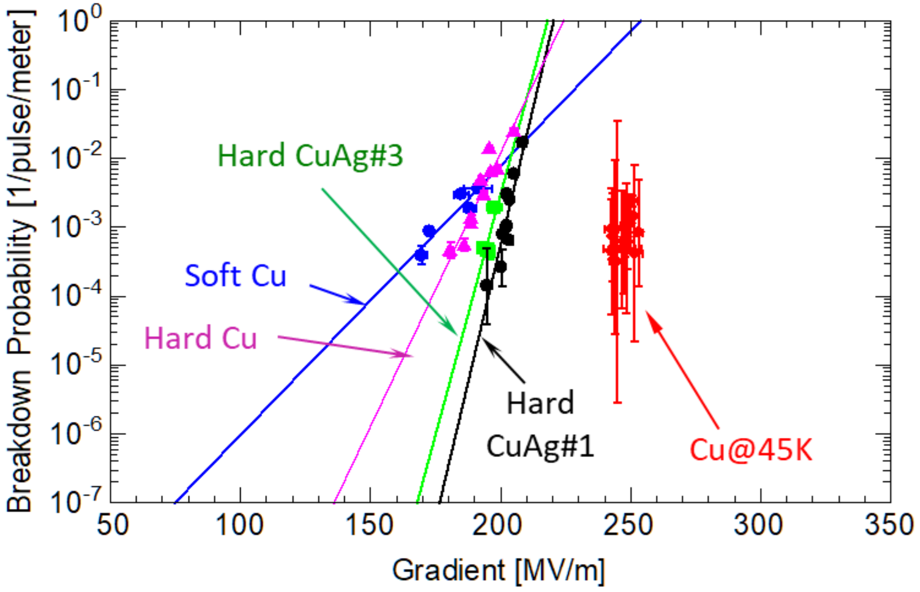


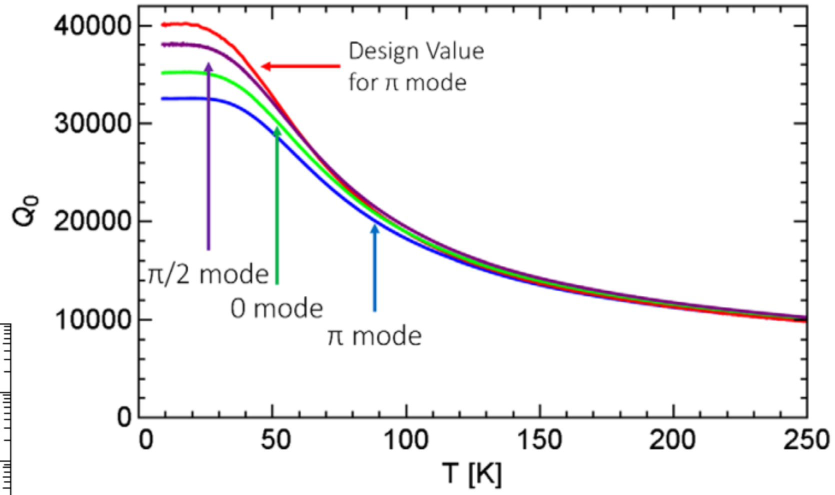
Cavity material and operating temperature

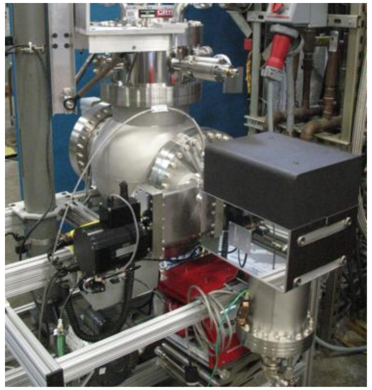
Cold-copper established as a pathway for achieving high gradients in single cavities

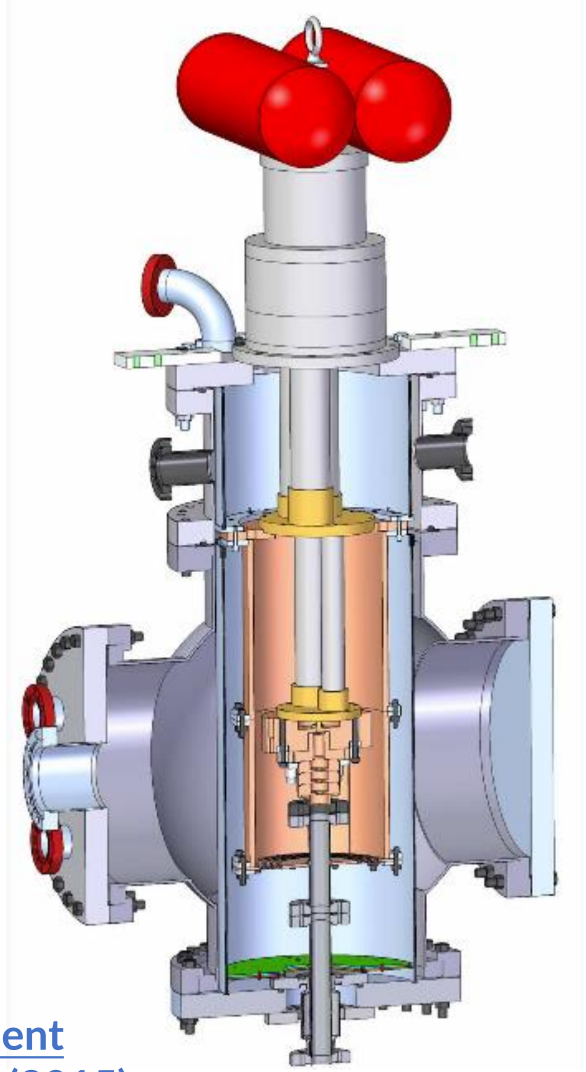
- Reduced material resistance
- Increased material hardness

Cahill, A. D., et al. "High gradient experiments with X-band cryogenic copper accelerating cavities." *Physical Review Accelerators and Beams* 21.10 (2018): 102002.









[High Gradient Workshop (2015)]

Cold copper RF accelerating structures

140 MeV/m measured in copper X-band linac at 77 K with beam tests at NLCTA

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

Breakdown limits primarily driven by high H-field regions within cell coupler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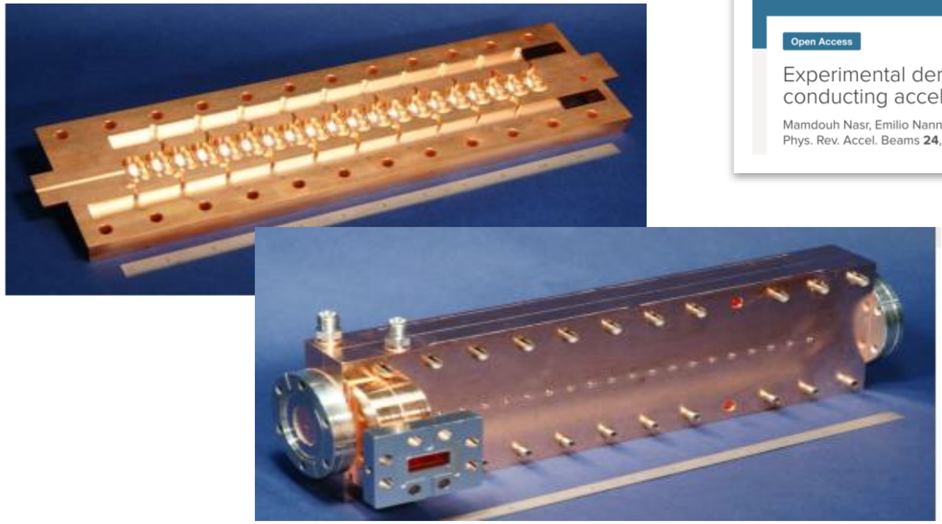
Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature

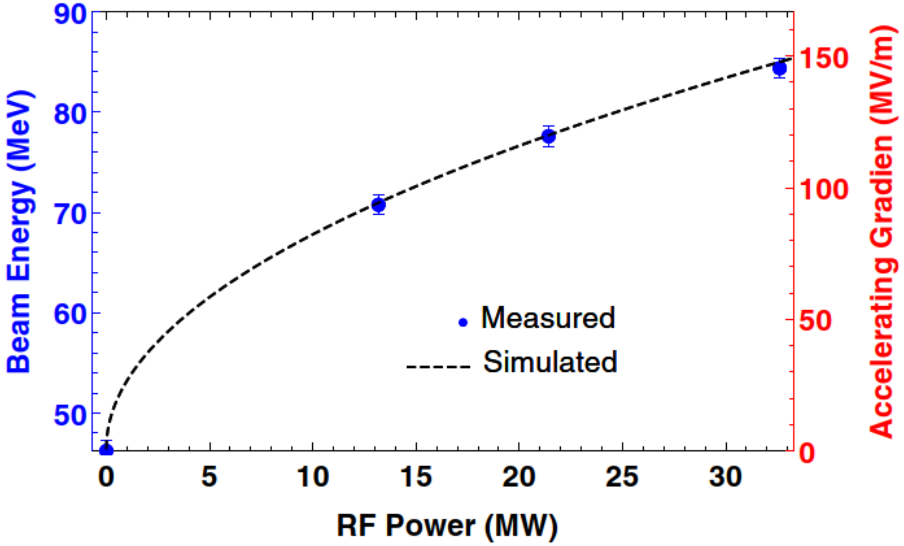
Mamdouh Nasr, Emilio Nanni, Martin Breidenbach, Stephen Weathersby, Marco Oriunno, and Sami Tantawi
Phys. Rev. Accel. Beams **24**, 093201 – Published 13 September 2021

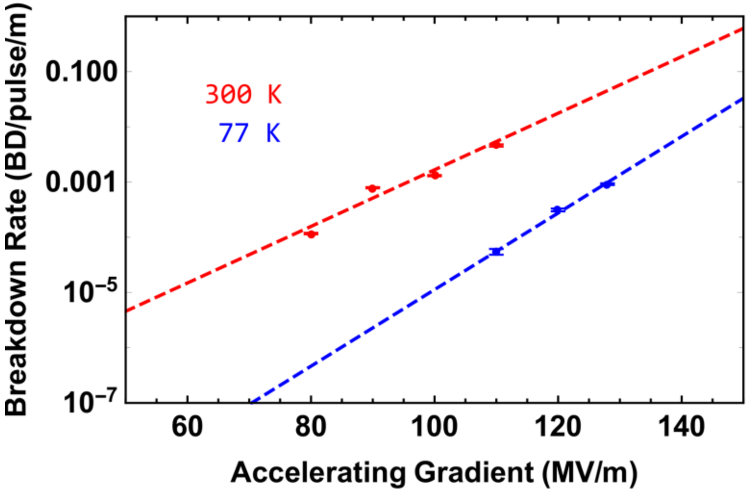
Ernest Courant Outstanding Paper Recognition



[PRAB 23, 092001 (2020)](#)

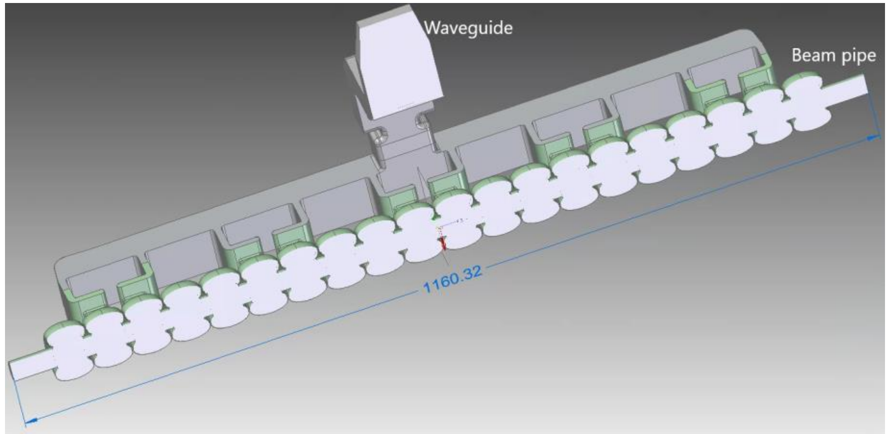
[PRAB 24, 093201 (2021)](#)

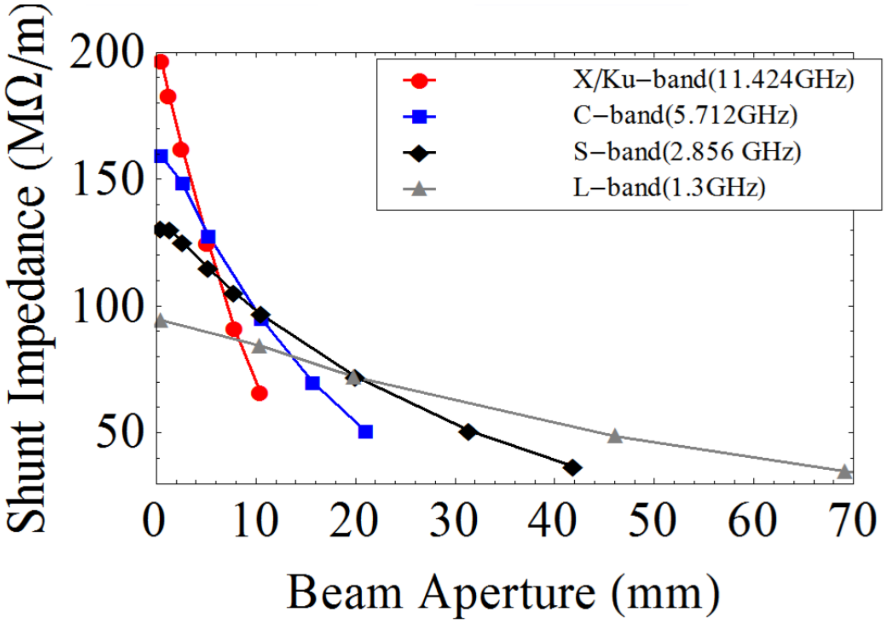




Accelerating high charge beams in distributed coupling linacs

- Damping/Detuning – Material testing, beam simulations, and RF design for bunch trains
- Beam Loading and Stability - Understanding beam dynamics, wakefields
- Need larger apertures to reduce wakefields
- Necessitates design at lower frequencies
- Opening up aperture between cavities results in cross-coupling need modeling in ACE3P to guide iterative cell tuning process to establish strong uniform coupling to pi-mode

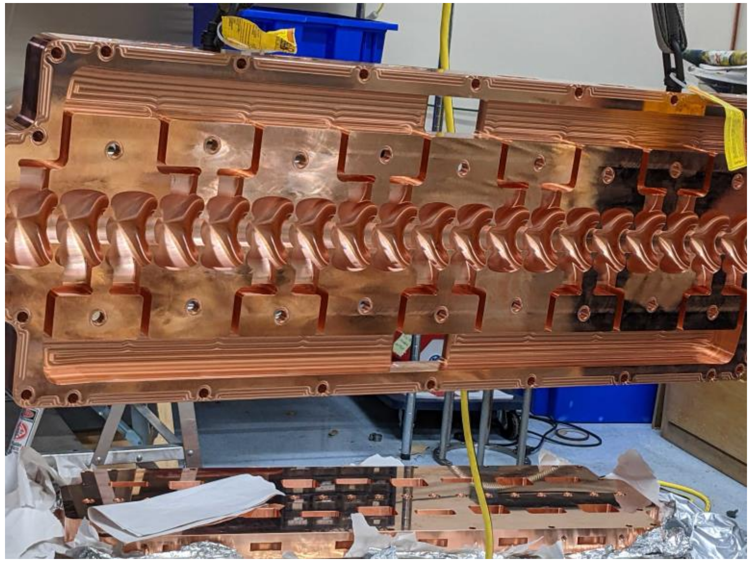




Potential cold copper applications for EIC and FCC

Injector linacs using cold copper

Preparations are underway to test this S-band structure at high power at Argonne National Laboratory (ANL), Advanced Photon Source (APS) using the Linac High-Power RF Test stand and the Linac Extension Area (LEA).



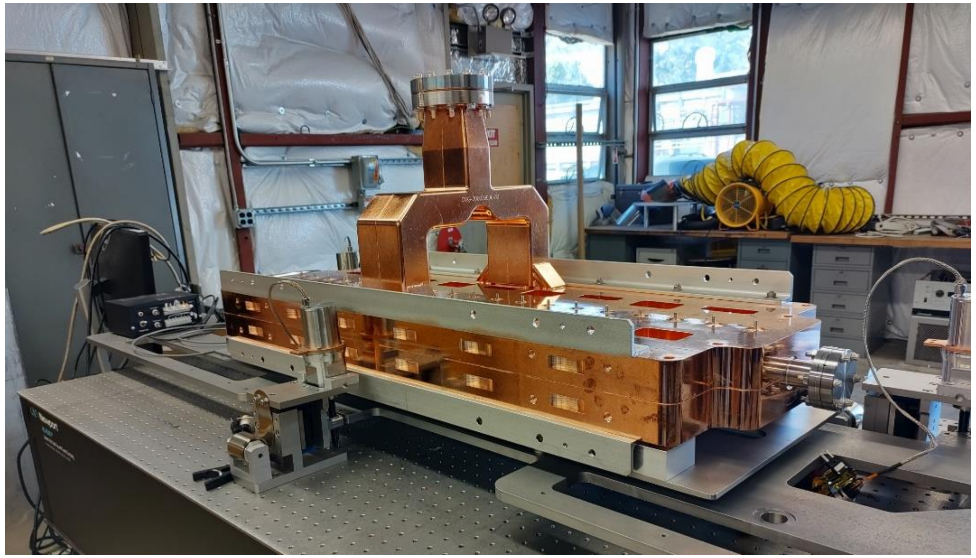
Dhar, Ankur, et al. "Distributed coupling linac for efficient acceleration of high charge electron bunches." *JACoW IPAC2024* (2024). https://epaper.kek.jp/linac2022/papers/thpojo14.pdf

Comparison of Injector Linac Structures for EIC

	Dist. Coupling	Travelling Wave
E_{acc}	16 MV/m	
T	77 K	300 K
R_s	145 MΩ/m	42 MΩ/m
P_{Diss}/L	1.8 MW/m	6.2 MW/m
RF Sources	3	8

Comparison of Injector Linac Structures for FCC

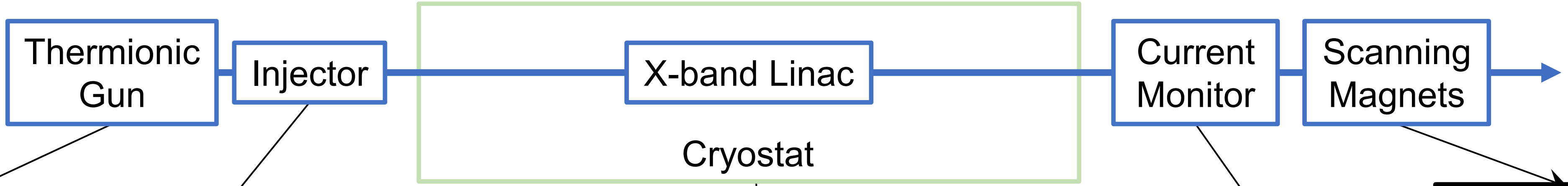
	Dist. Coupling	Travelling Wave
a/λ	0.125	0.095-0.135
f_0	2.8 GHz	
E_{acc}	20 MV/m	
T	77 K	300 K
R_s	145 MΩ/m	42 MΩ/m
P_{Diss}/L	3 MW/m	9.8 MW/m
RF Sources	54	168

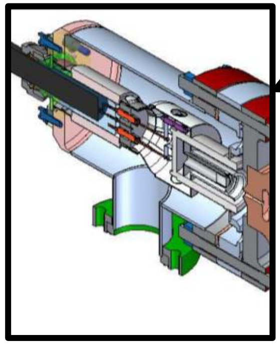


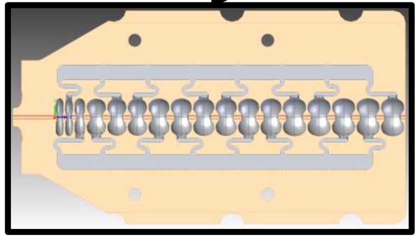
Cryogenic VHEE accelerator

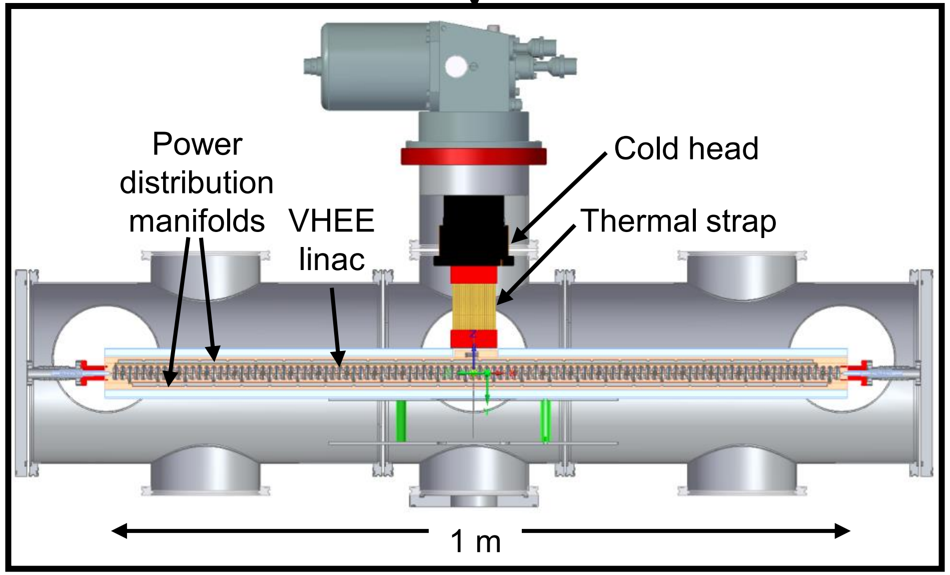
D.O.E. Accelerator Stewardship Program

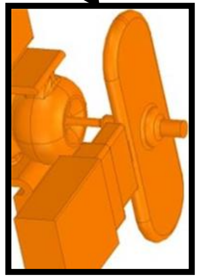
Objective: Deliver a 100 MeV electron beam from a 1 m linac at a dose rate of ≥40 Gy/s using an accelerator design and power supply that is compatible with existing clinical infrastructure

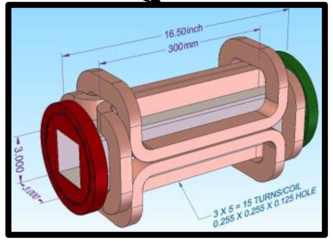












- 1 meter linac operating at 77 K
- Requires 11.424 GHz RF pulse with 20 MW peak power in ~200 ns flat top

- Bunch train with ~3000 electron bunches per pulse with ~1.7 pC per bunch
- Single linac operating at 20 Hz provides about 40 Gy/s in a $4\ cm^2$ area

135° phase advanced distributed coupling structure

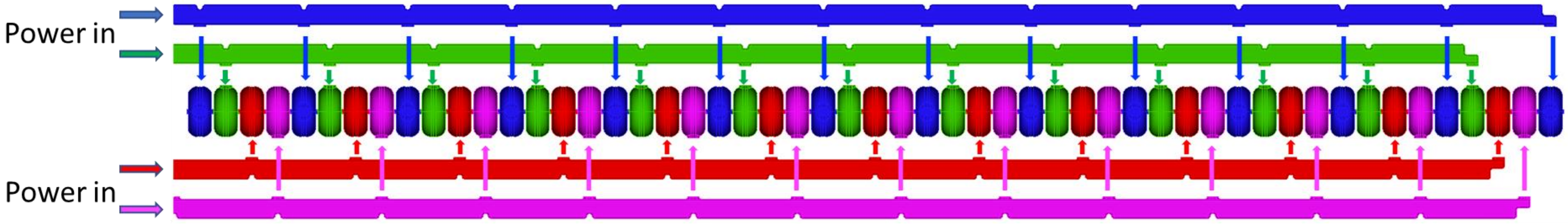
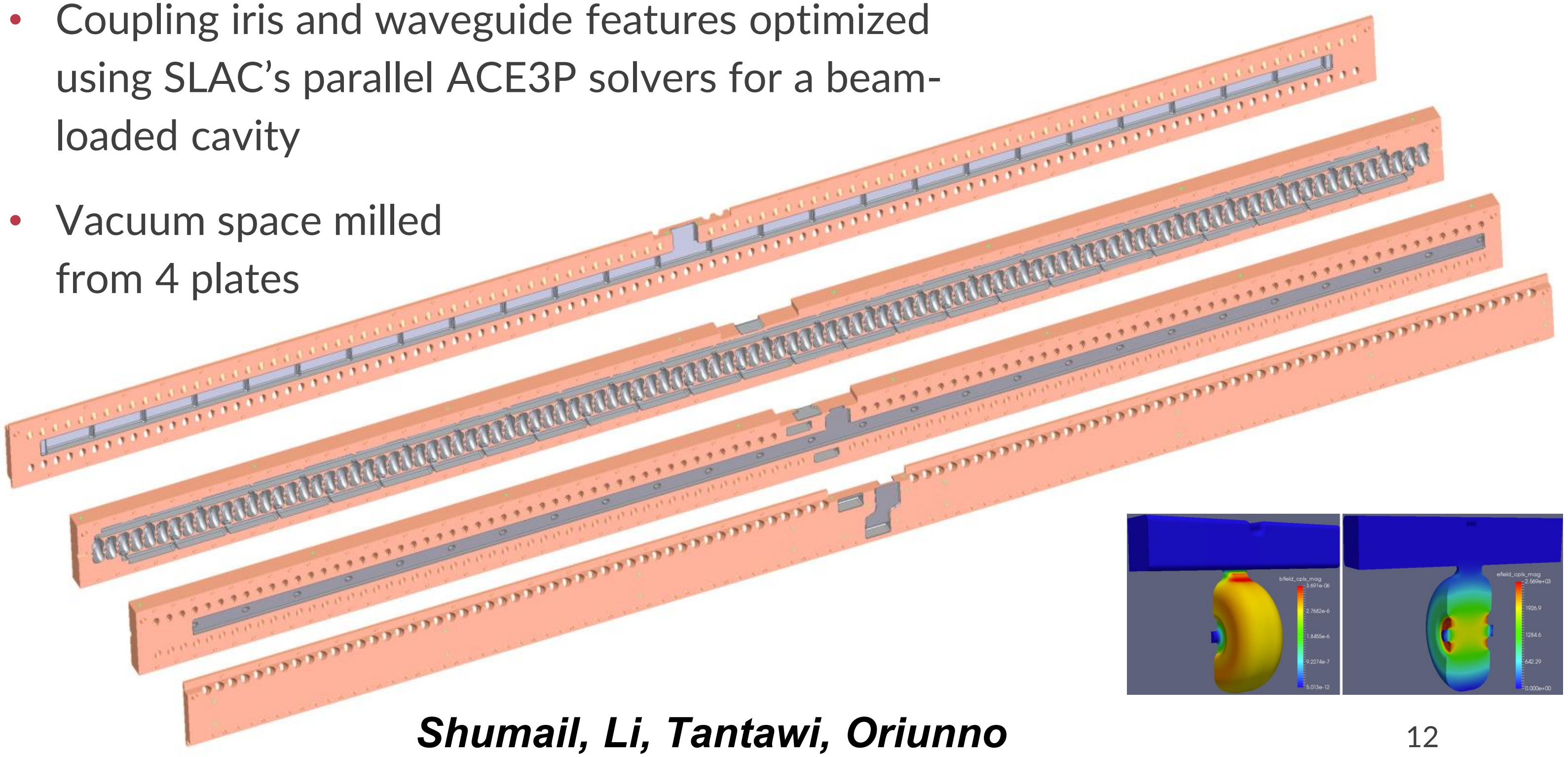


Table 1 Parameters of 135-degree phase advance cell	
f (GHz)	11.424
Cell-cell iris radius (mm)	1.0
Disk thickness (mm)	1.0
Cell length (mm)	9.841
Operating temperature (K)	77
Q0	22146
Shunt impedance R (MΩ/m)	526
Es/Ea	2.0
Hs/Ea (kA/m/(MV/m))	2.06
Coupling beta	1.8

- Coupling iris and waveguide features optimized using SLAC's parallel ACE3P solvers for a beam-loaded cavity
- Vacuum space milled from 4 plates



Shumail, Li, Tantawi, Oriunno

VHEE linac fabrication and cold test

Upper distribution manifold

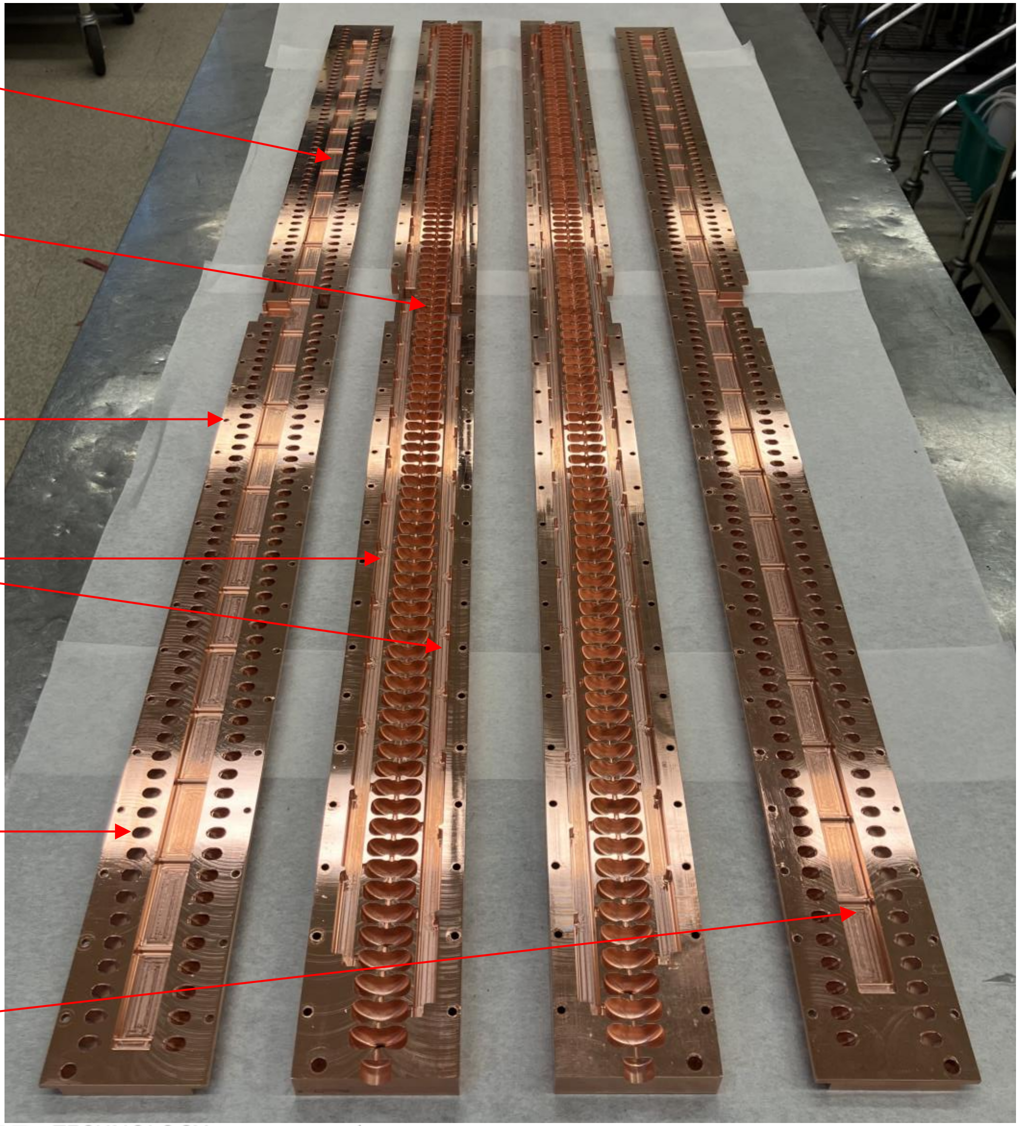
3π/4 cavities

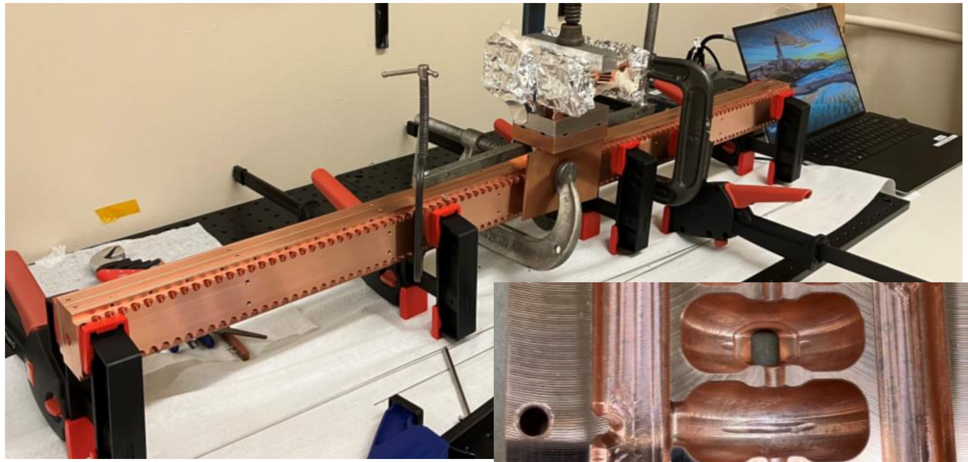
Alignment pin holes

Left and right distribution manifolds

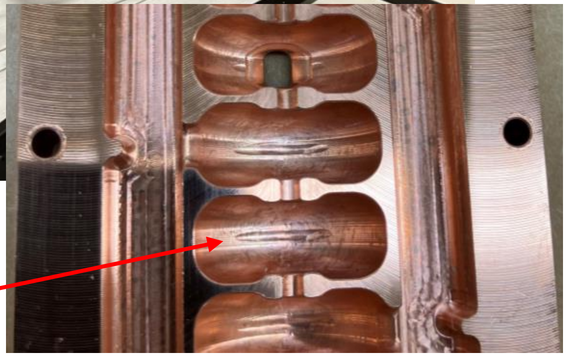
Tuning pin holes

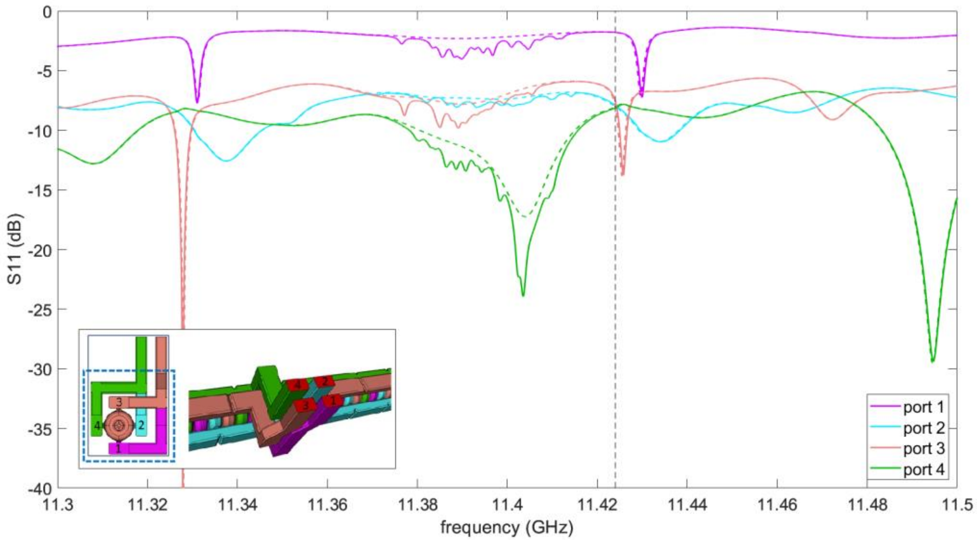
Lower distribution manifold





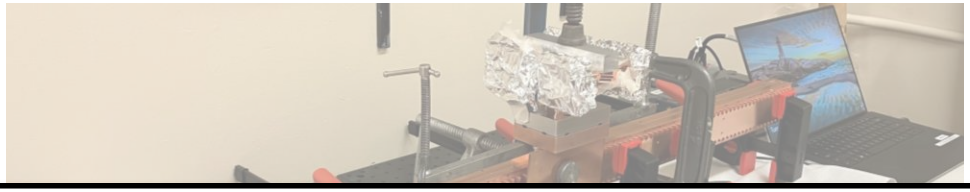
Machining defect repeated in each cell



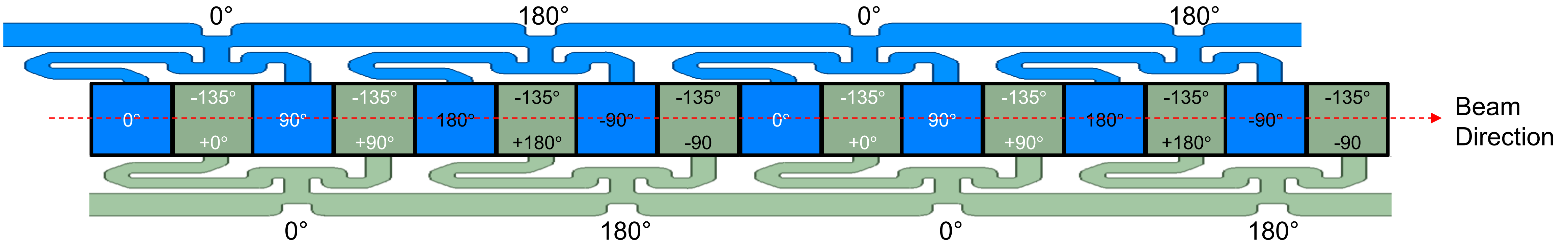


VHEE linac fabrication and cold test

Upper distribution manifold

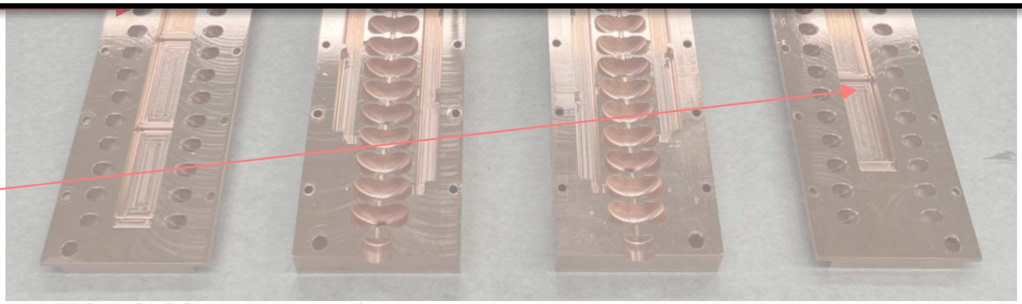


A Wakefield Resilient, High Shunt Impedance Accelerating Structure for Cold Copper Collider (C^3)
Muhammad Shumail, Zenghai Li, Emilio A. Nanni, LCWS'24

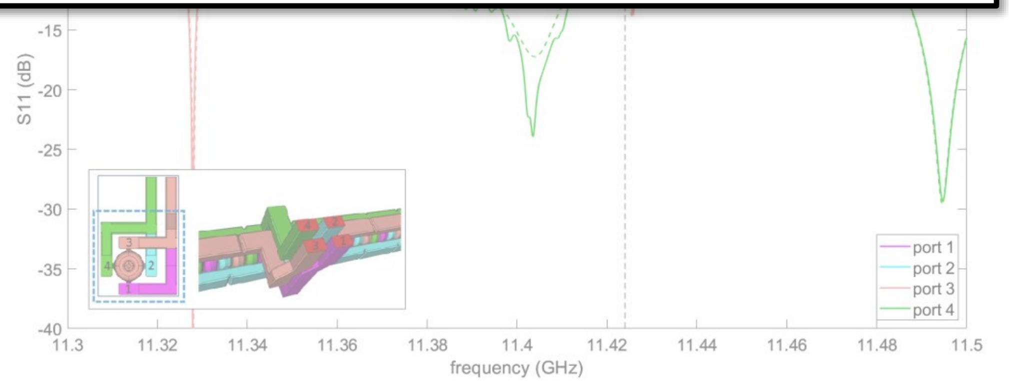


Equivalent phases and feeding scheme for of 135° structure with two manifolds

holes



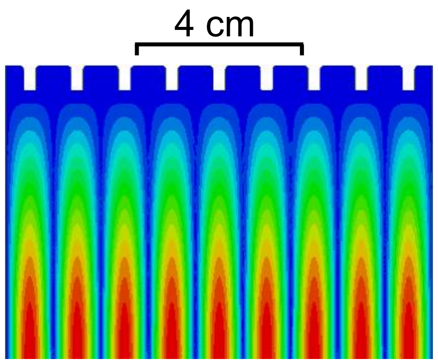
Lower distribution manifold



Compact RF pulse compression

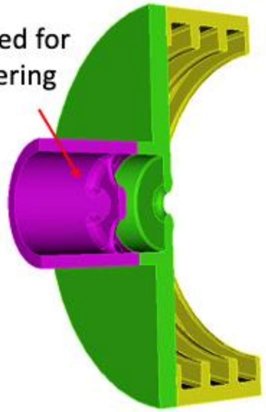
Key enabling technology for FLASH-VHEE linac

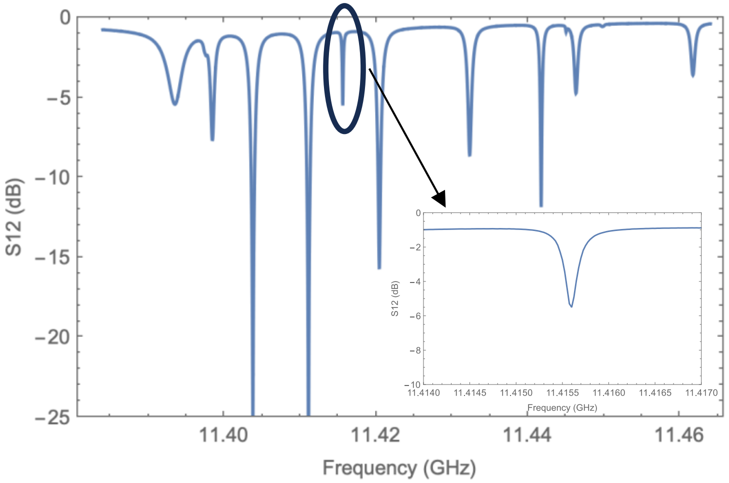
- Design specs chosen to exploit a 6 MW, 4 µs, 11.424 GHz pulse from a K200 ScandiNova Modulator and Canon Klystron
- HE_{11}-mode in the corrugated cylindrical cavity achieves a Q_0 of 405,000 with a cavity length of 0.87 m.
- Coupler designed with an intermediary low-Q TE_{11} cavity
  - small aperture to the compressor minimizes the perturbation to the HE_{11} mode
  - four irises into the low-Q cavity enhance the coupling factor
- 6 MW 4 µs input pulse reaches 19 MW peak in a 200 ns flattop

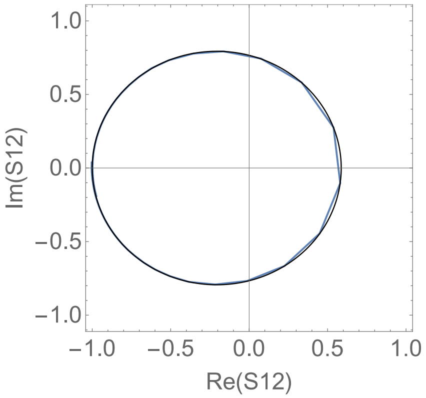


$$Q_0 = \frac{2391.448 a^3 f^{5/2} L}{a^3 f^2 + 121.126 L}$$

Nantista, Li, Tantawi







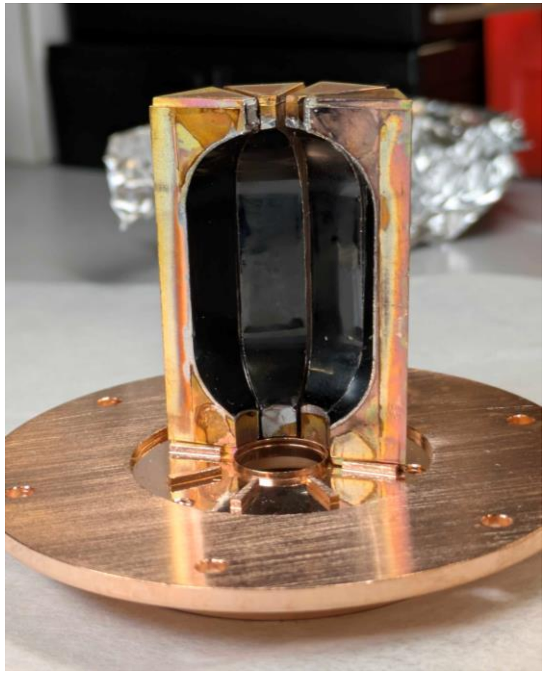
Q0=267729. $Copper \rightarrow$ 408283
Qe=69721
β=3.84. $Copper \rightarrow$ 5.85595

Applying high temp superconductors to RF design

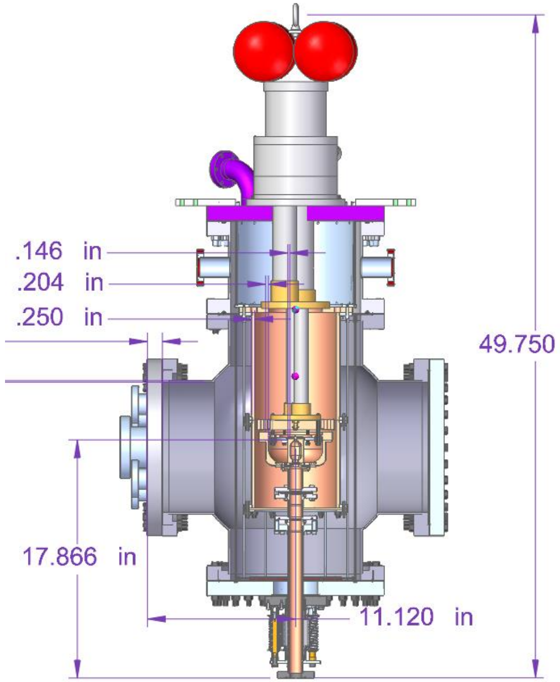
As a first approach, a pulse compressor cavity utilizing the TM010 mode is being built

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

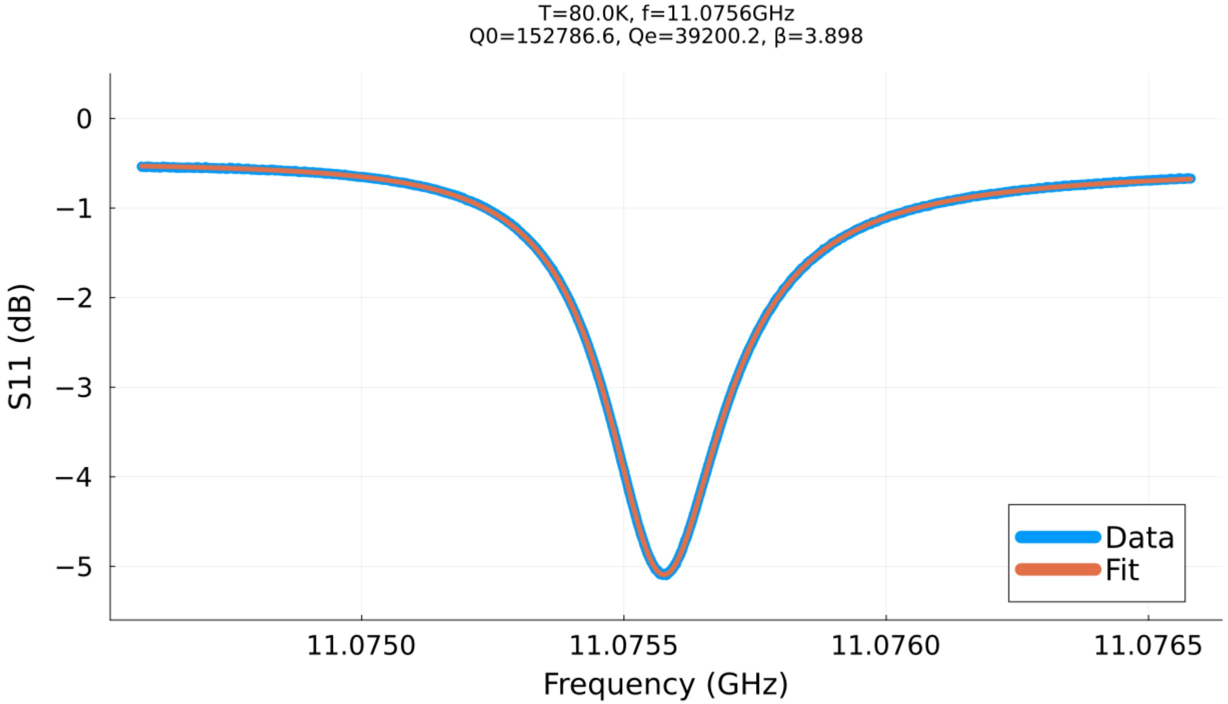
Q_e remains roughly constant around 39000, with Q_0 rising to over 150k at 80 K (3.5x Copper)



HTS Cavity



Cryostat for testing cavity

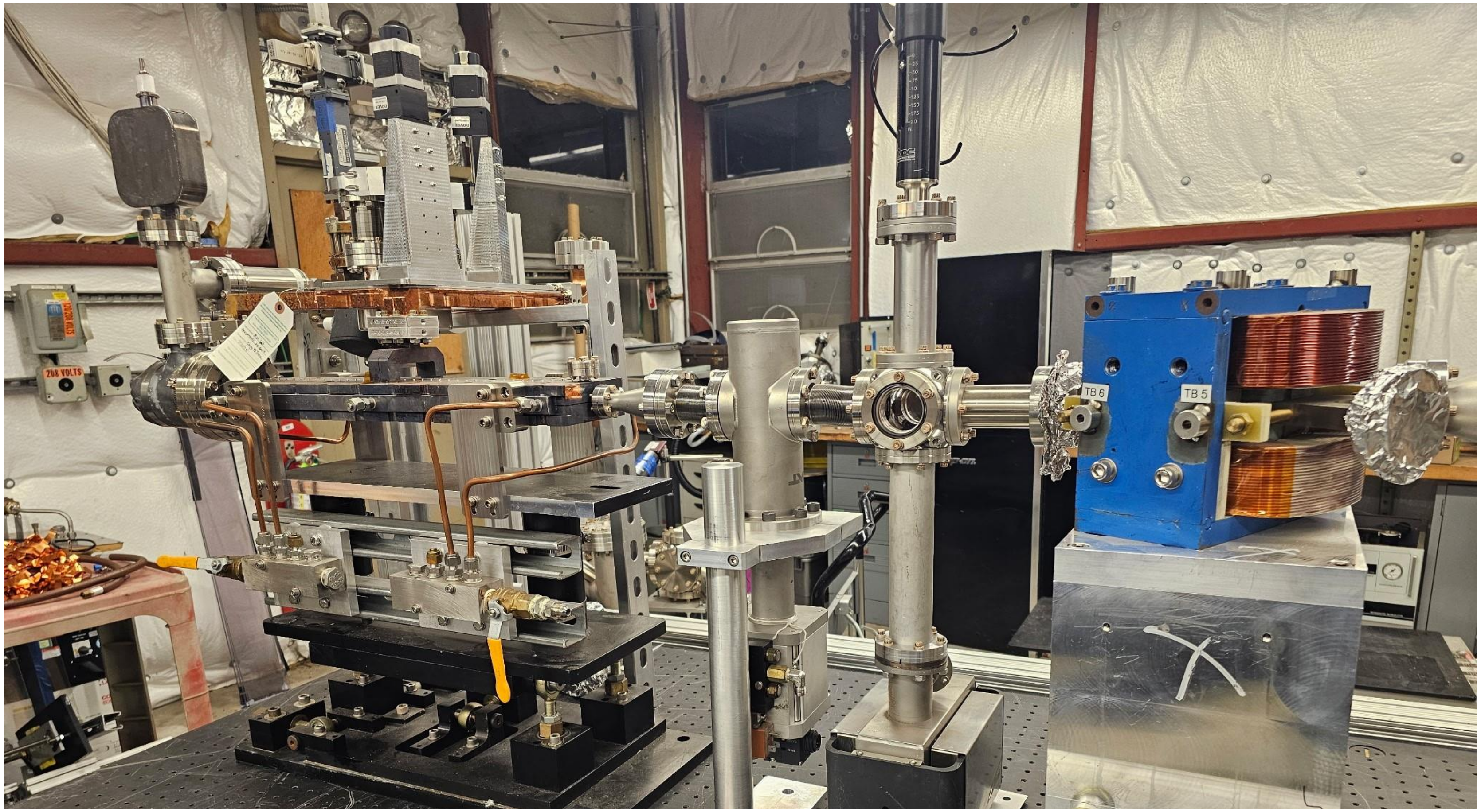


Testing with MW-scale power at NLCTA this fall

A. Dhar

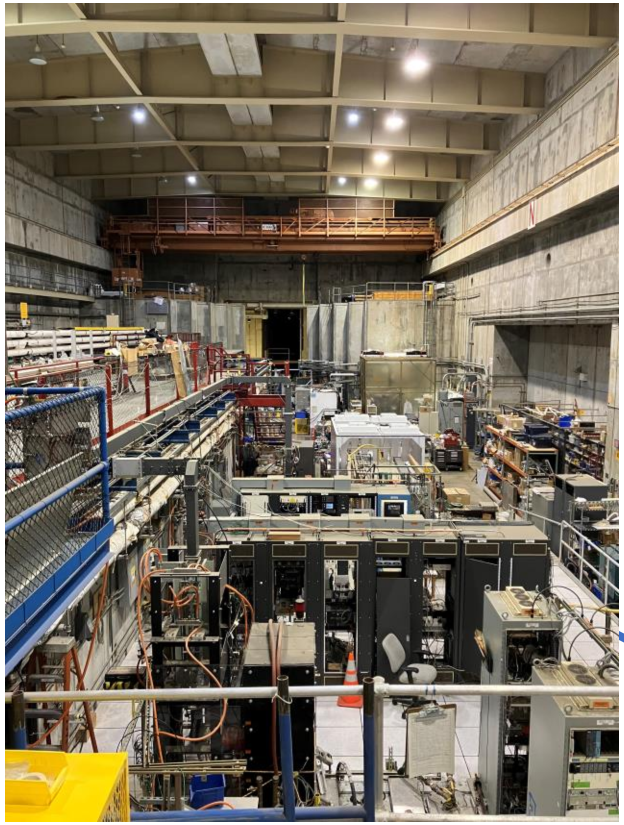
Commissioning compact X-band linac

Planned installation in Stanford's former CyberKnife vault



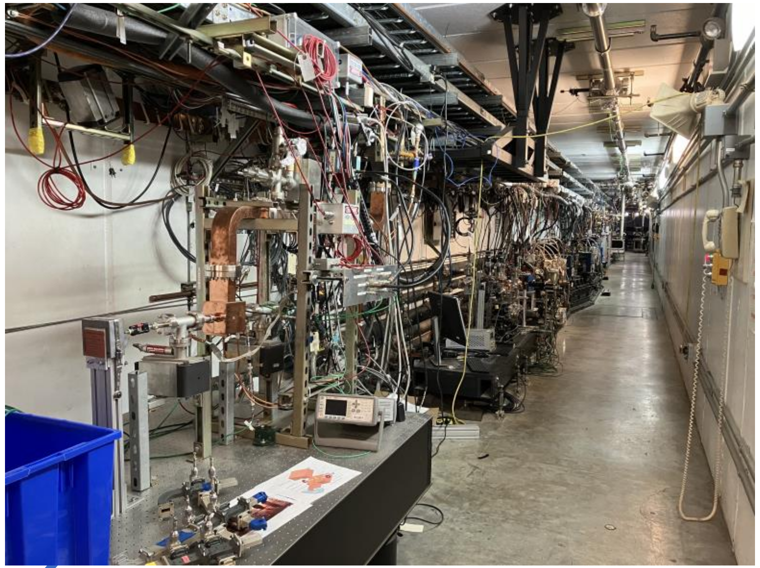
- Thermionic gun and distributed coupling linac already tested at NLCTA
- With 650 kW input power, produced a 6 MeV, 1 mA, 1 μs electron beam
- Portable beamline on a 1 m x 2 m optical table

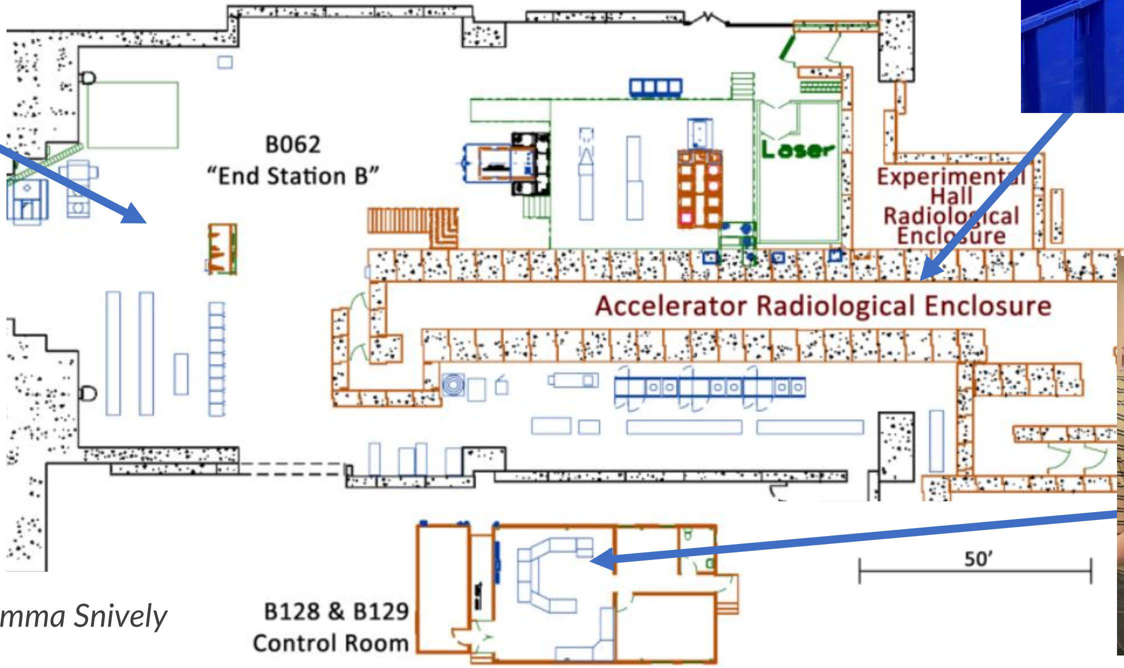
The NLCTA Test Facility at SLAC

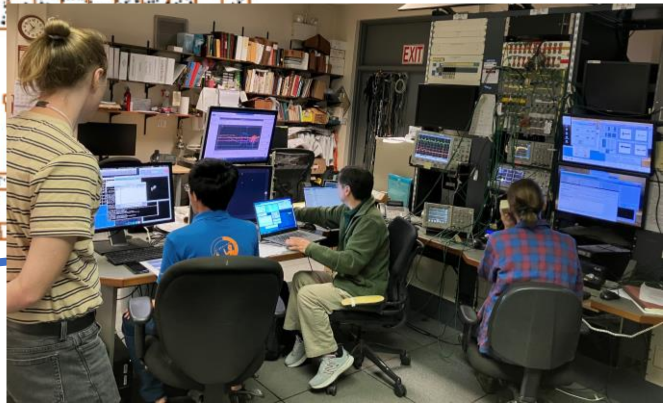


Next Linear Collider Test Accelerator (NLCTA)

- Stand alone XTA beamline
- High power RF test areas at X-band (11.424 GHz) and S-band (2.856 GHz)
- Dedicated laser room with Ti:Sapph system
- 4K Cryostats with high power RF at X-band
- 5 T solenoid with high power RF at S-band
- In-house clean room, machine shop, and experiment staging areas

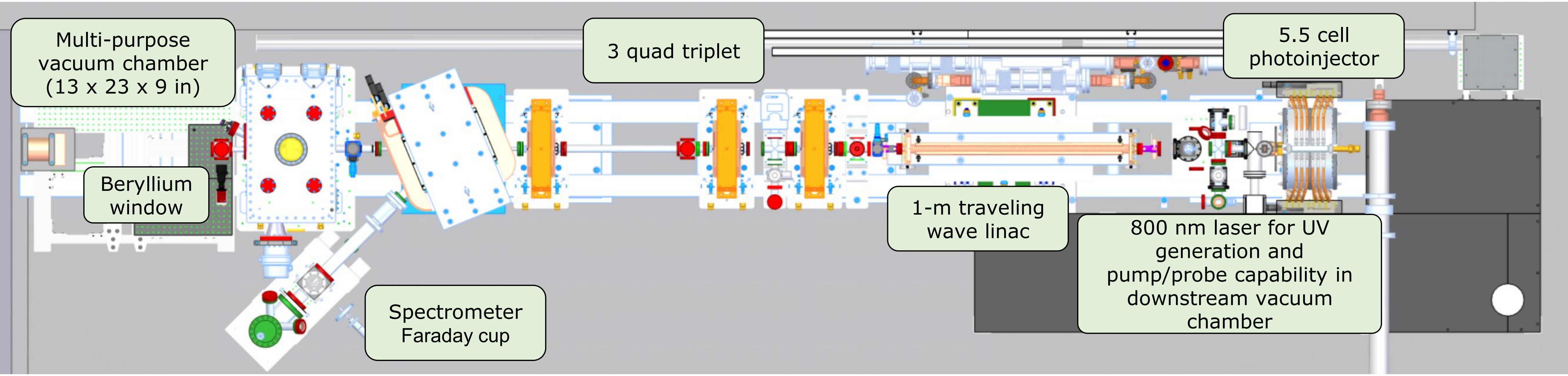






Link to Virtual Tour of NLCTA

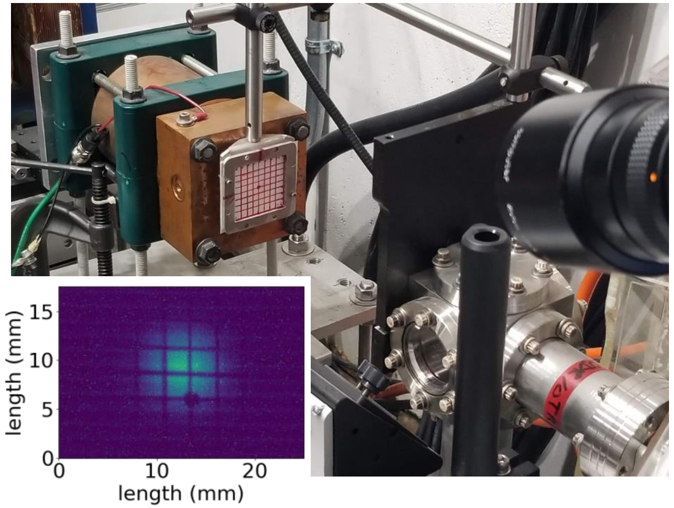
Irradiation on the X-band Test Accelerator (XTA) at NLCTA



XTA beam parameters:

Beam energy: 30 – 75 MeV
Repetition rate: 0.5 – 30 Hz
Bunch charge: 1 – 100 pC
Beam spot size: 2 – 4 mm rms
Energy spread: 0.5 – 20 %

XTA beam on scintillating screen in air



Recent irradiation experiment examples: defect engineering in SiC samples for quantum computing applications, effects testing on electronics and detector development

Submit new User proposals through BeamNetUS:

- Beam time is free
- Typically 1-3 week runs
- User travel expenses are covered
- Submission deadline: end of Nov. 2025

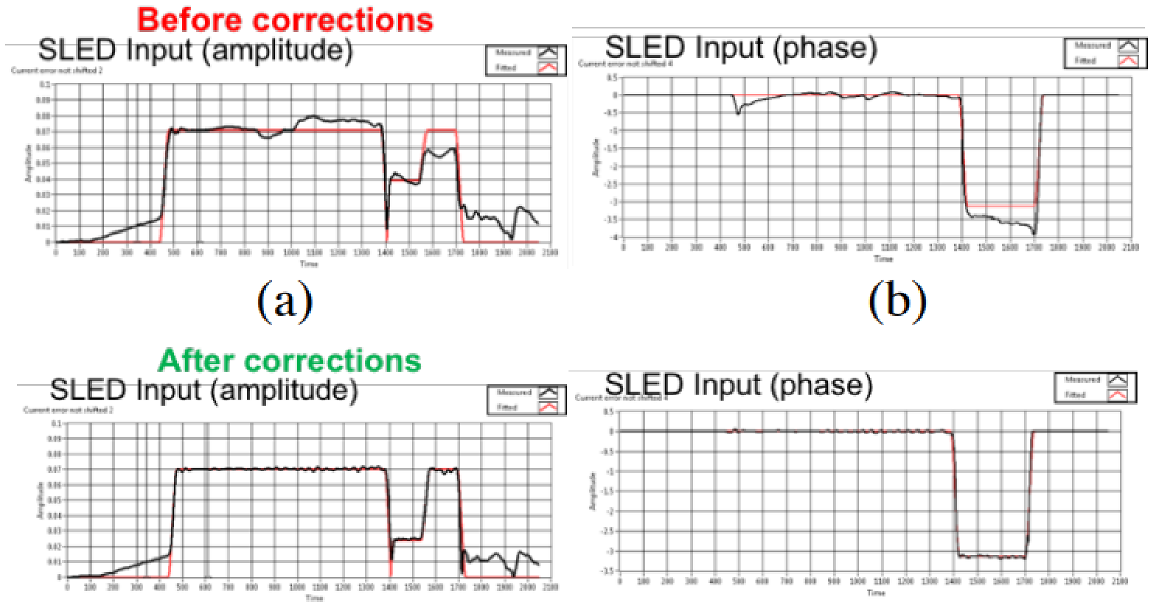
beamNetUS
accelerating beam-based research

beamnetus.org

SLAC

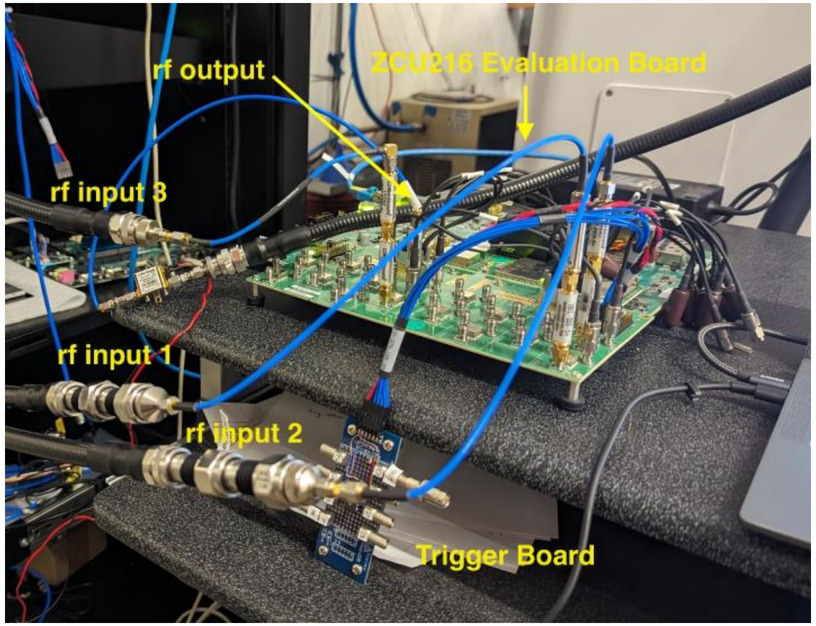
Active feedback for low level RF (LLRF)

- Pulse correction used on the SLED-II RF pulse compressor to power structures under test on the XTA beamline.
  - This active feedback was used in the testing of the cryo-copper linac
- Compensates for large reflected power from standing wave accelerators operating at ultra-high gradient



Klystron output is a 1.2 μs pulse with a phase flip for the last 400 ns

Nasr, Mamdouh H., and S. G. Tantawi. *Corrections of Klystron Output Pulse in SW Accelerator Testing*. In IPAC 2019 Proceedings.

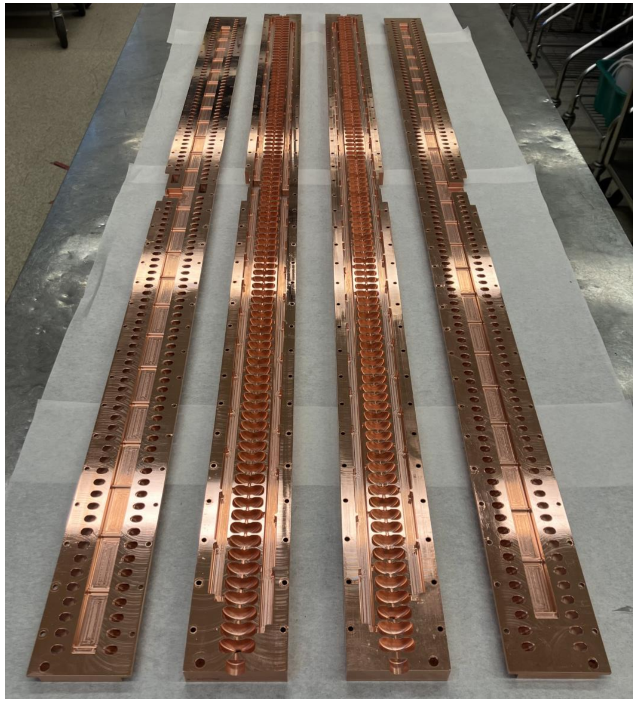


- Active experiment to test an RF System on a Chip (RFSoC) at S-band at NLCTA for a compact LLRF system with active feedback capability
- 8 RF input channels and 8 RF output channels
- Can record the full RF pulse with bandwidth up to 200MHz at a data rate around 250 MHz

Summary

- Optimized VHEE linac design with 526 MΩ/m shunt impedance at 77 K
  - Enables 100 MeV/m gradient in 1 meter linac with 20 MW input power
  - Target dose rate of 40 Gy/s in 4 cm^2 treatment field
- Active materials research, and RF pulse compression and accelerator design research to push the boundaries of RF efficiency and gradient
- NLCTA Test Facility supports accelerator testing and can deliver beam for VHEE studies on XTA
- Planned test of "portable" X-band beamline at Stanford

US DOE Accelerator Stewardship Program



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