High Gradient X-band Linac for Direct Electron Radiation Therapy

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SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

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Accelerator Stewardship Program

Outline

I. Motivation
II. Normal conducting accelerator R&D
III. VHEE linac

Improving radiation therapy with new accelerator technology

Advances in Medical Accelerator Design

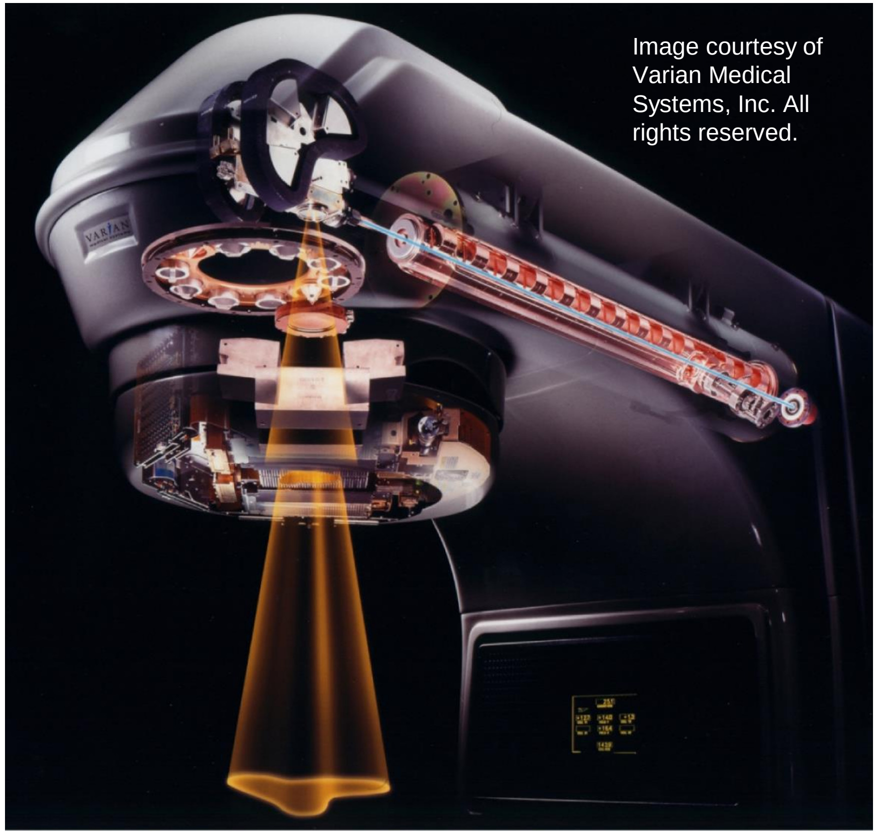
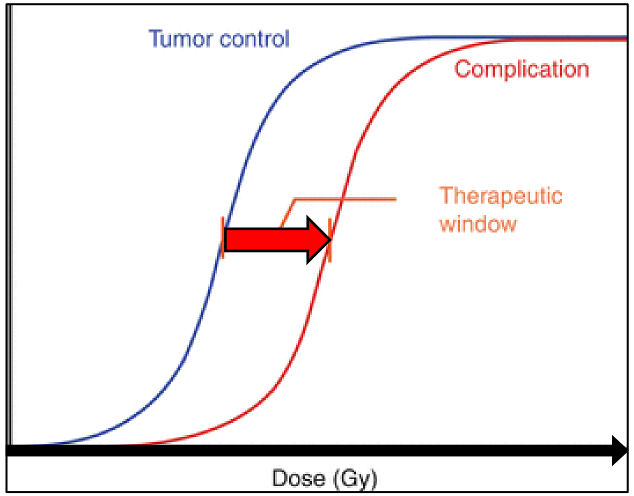


Image courtesy of Varian Medical Systems, Inc. All rights reserved.

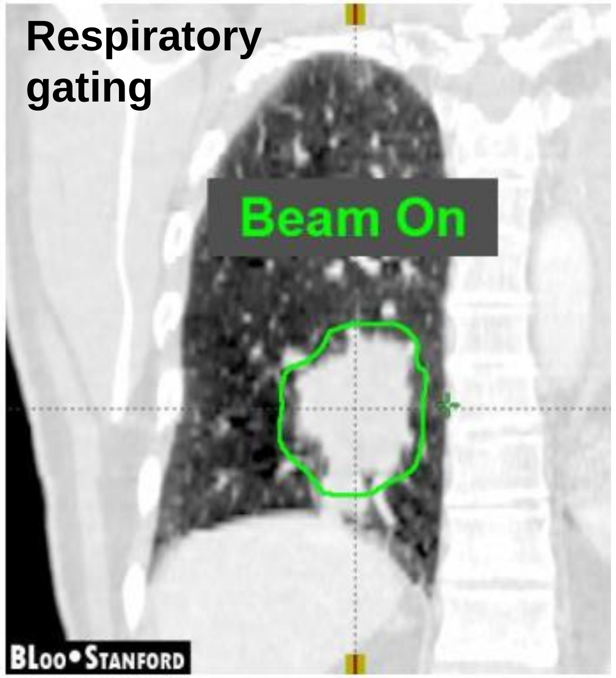
- Increase therapeutic window
- Improve treatment efficiency
- Improve power efficiency
- Reduce size and cost



Chang D.S., Lasley F.D., Das I.J., Mendonca M.S., Dynlacht J.R. (2014) Therapeutic Ratio. In: Basic Radiotherapy Physics and Biology.

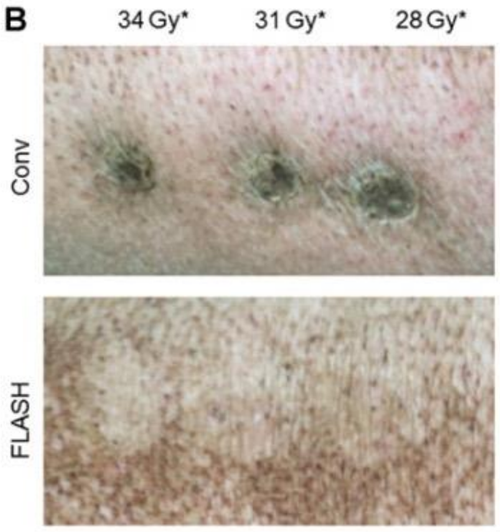
High Dose Rate Radiotherapy

Benefits of Speed



Motion Management

FLASH Therapy



Vozenin, M.C., et al. "The advantage of FLASH radiotherapy confirmed in mini-pig and cat-cancer patients." *Clinical Cancer Research* 25.1 (2019): 35-42.

- Sub-second treatment time appears to improve healthy tissue sparing with comparable tumor control
- Demonstrated in preclinical setting with photons, electrons, and protons
- Requires high dose rate >50 Gy/L/s

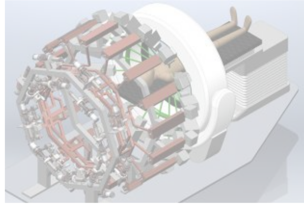
Bourhis, Jean, et al. "Treatment of a first patient with FLASH-radiotherapy." *Radiotherapy and oncology* 139 (2019).

Synergy with HEP Accelerator Development

- Cutting edge research in radiation therapy drives demand for innovations in accelerator technology
- Sustain and grow the expertise needed for breakthroughs in accelerator technology and beam delivery systems
- Engage with the private sector for commercialization and drive public-private partnerships

More compact structures
Higher rep rate, higher current

Medical Accelerator Projects at SLAC



PHASER

Pluridirectional High-energy Agile Scanning Electronic Radiotherapy

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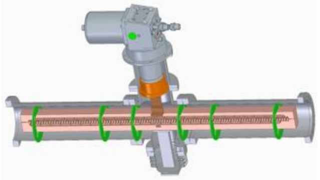
High Energy Compact Cryogenically Cooled Linac System for Very-High-Energy-Electron Radiation Therapy



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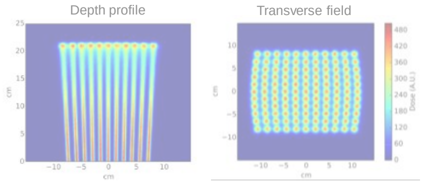
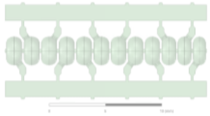
3D High Speed RF Beam Scanner for Hadron Therapy of Cancer



SLAC
LDRD

High Gradient mm-Wave Linac for Very High Energy Electron Therapy



Very High Energy Electron (VHEE) Therapy

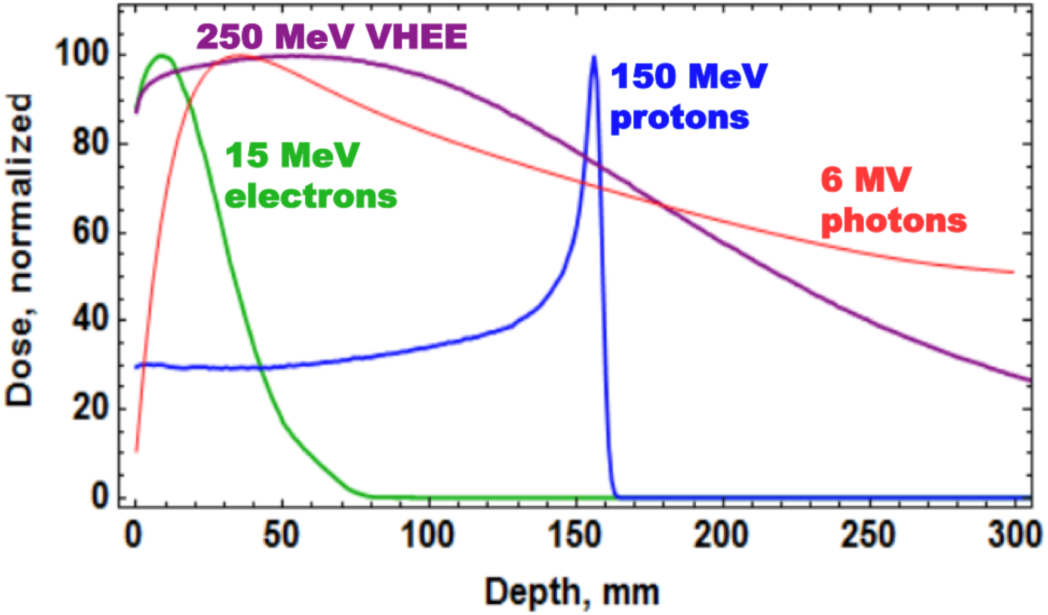
Why VHEE?

Types of radiotherapy currently available:

- 6-18 MV photons
- 5-20 MeV electrons
- 50-300 MeV hadrons (protons, Carbon-12)

Near future?

- 100-250 MeV "Very-High-Energy-Electrons" (VHEE)



Dose profiles for various particle beams in water (beam widths $r = 0.5$ cm)

Lawrence, *et al.*, in *Princ Pract Oncol*, DeVita, *et al.*, ed. 2008

VHEE Project Objective

Preclinical FLASH capability with 100 MeV electrons

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

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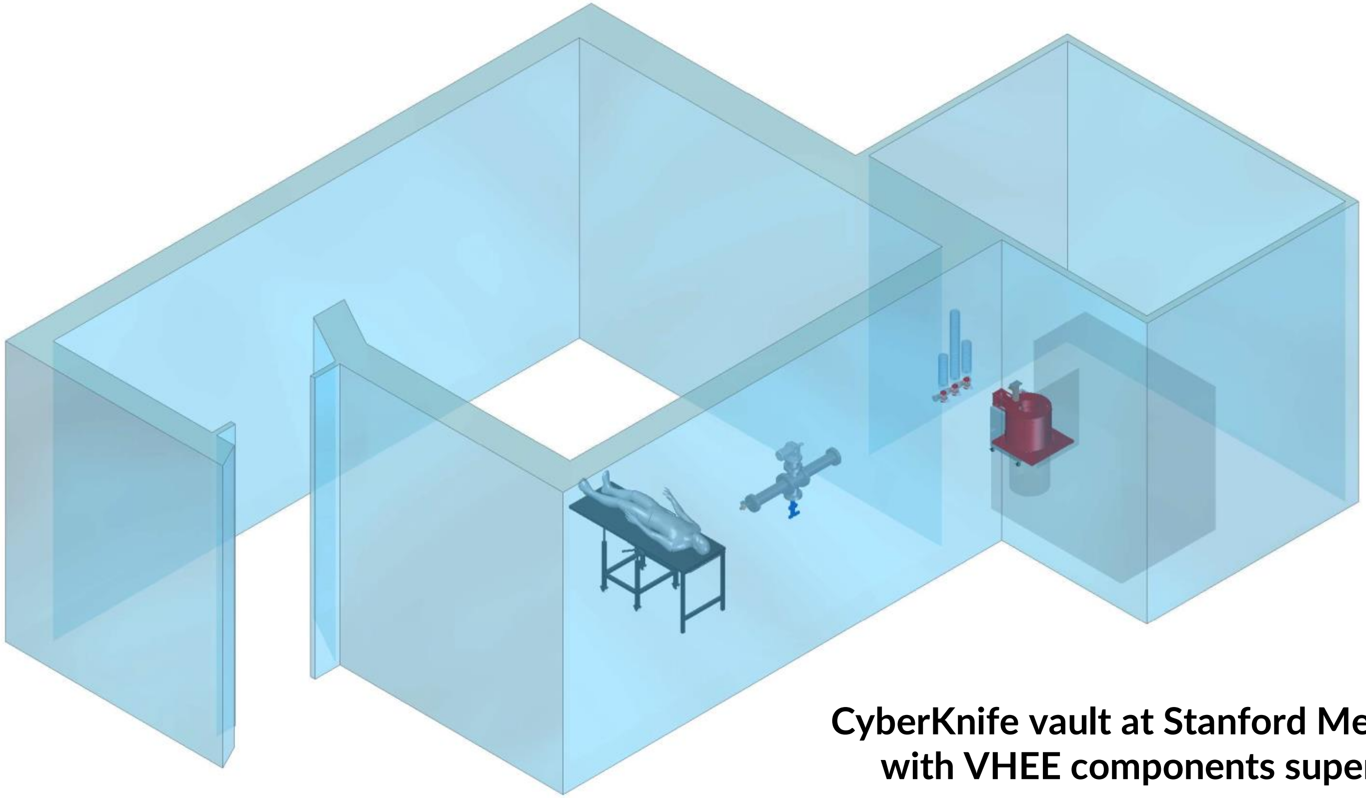
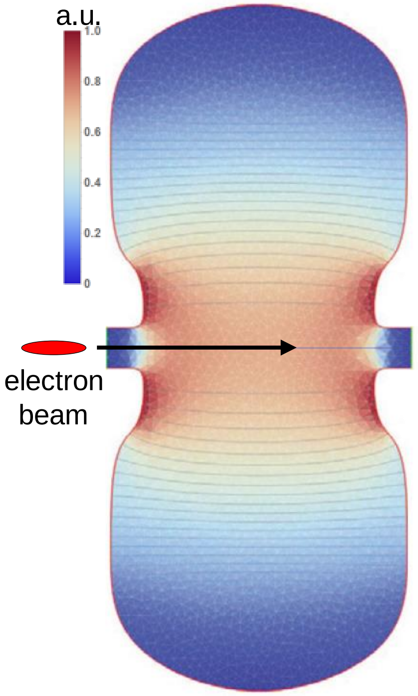
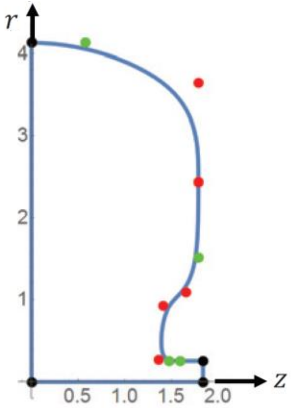


CyberKnife vault at Stanford Medical School with VHEE components superimposed

VHEE linac cavity optimization

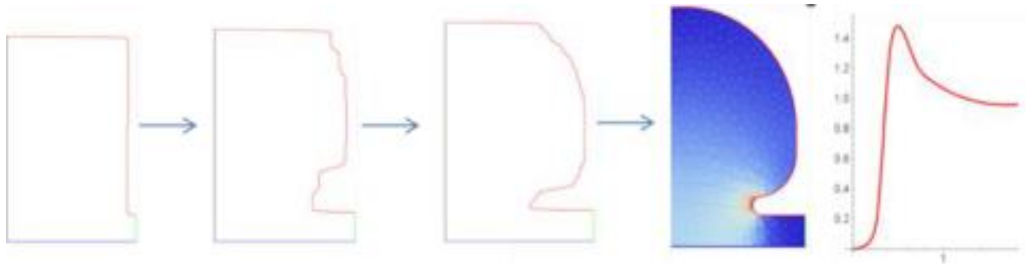


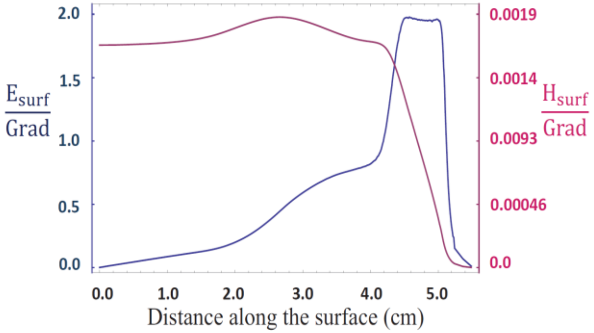


- Using a new geometric-optimization approach that minimizes both electric and magnetic fields on cavities' surfaces
- Reduced surface magnetic field enables a very high gradient structure
- Results in a very high shunt impedance, hence very efficient linac structure

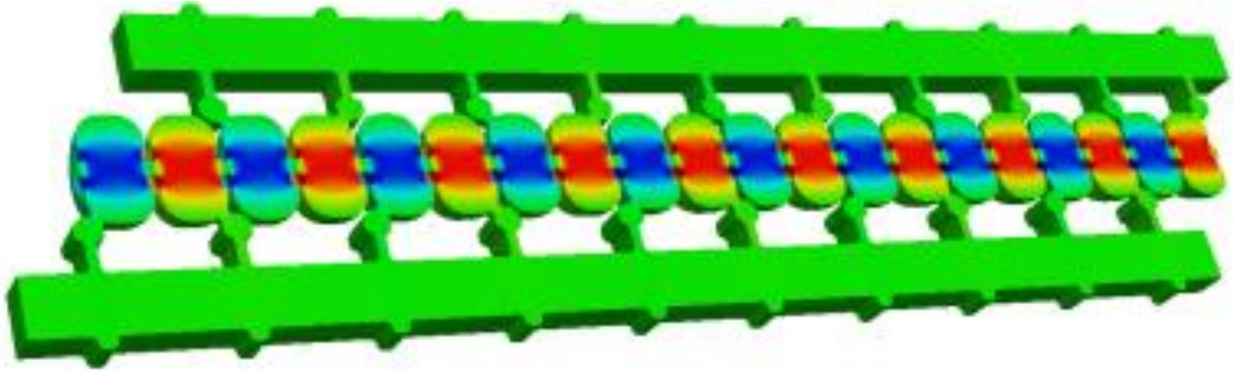
Nasr, M. H., and S. G. Tantawi. ***New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities' Performance***. No. thpmk049. IPAC, 2018.

Magnetic field distribution around the cell surface

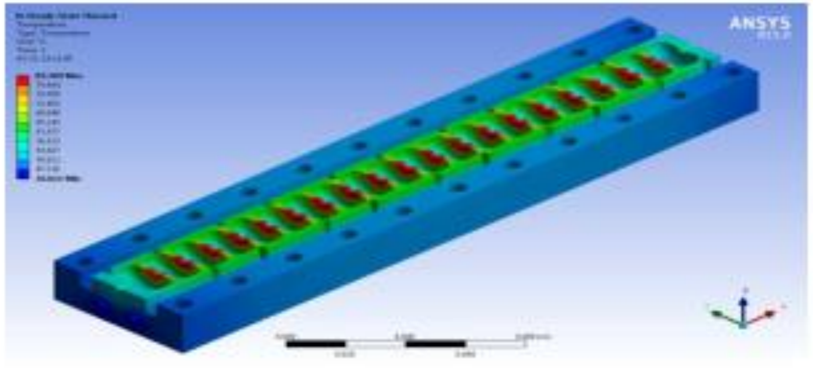




Distributed Coupling



Tantawi, Sami, et al. "Distributed coupling accelerator structures: A new paradigm for high gradient linacs." *arXiv:1811.09925* (2018).

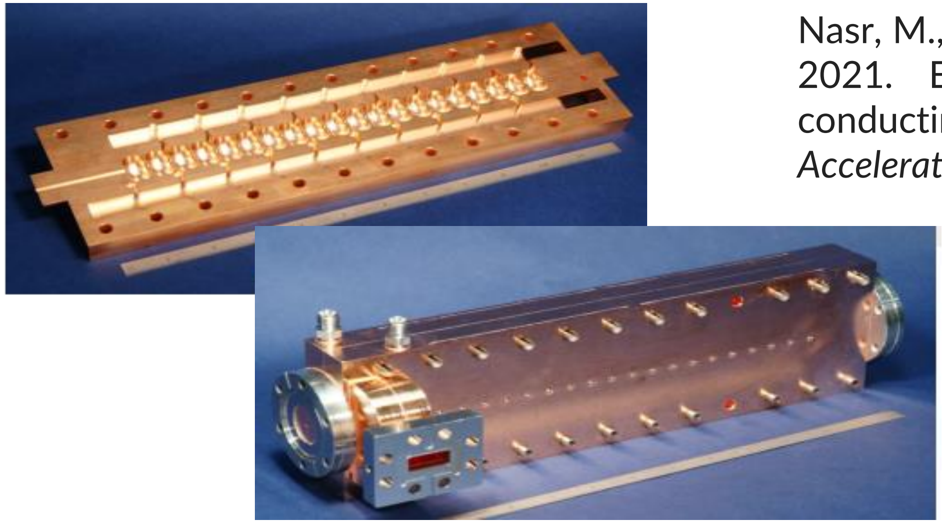


Split-block manufacturing

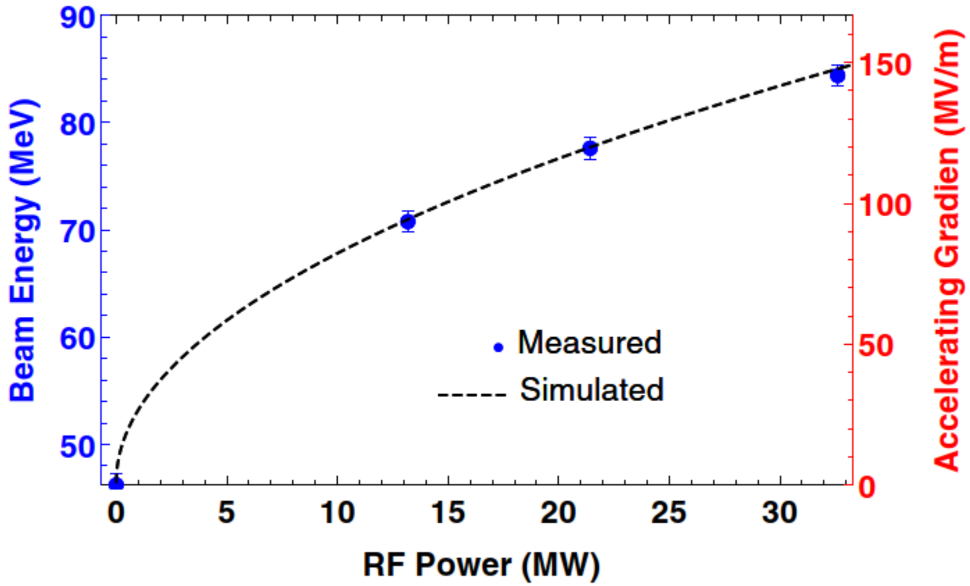
Novel distributed coupling to each cell

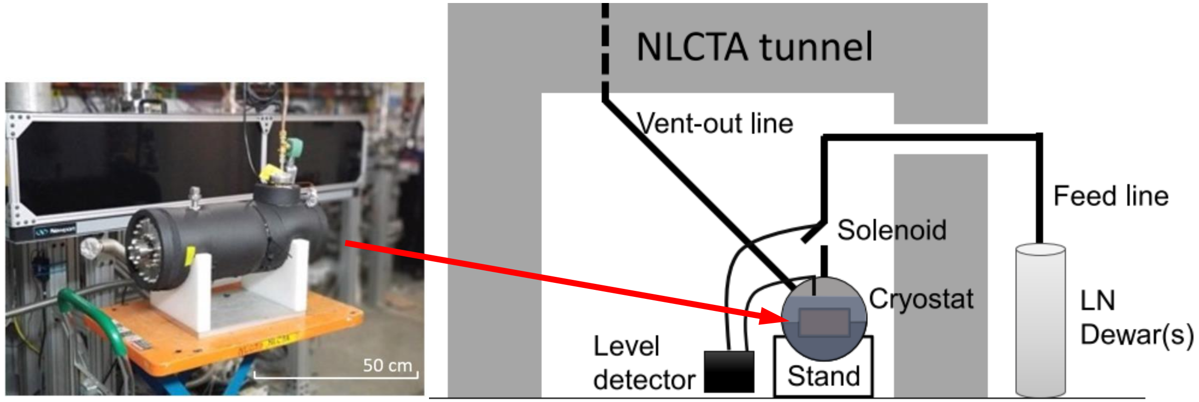
- *Doubling* RF to beam efficiency and ultra-high-gradient operation!
- Enabled by modern virtual prototyping using high power computing

Cryogenic accelerator tests at X-band

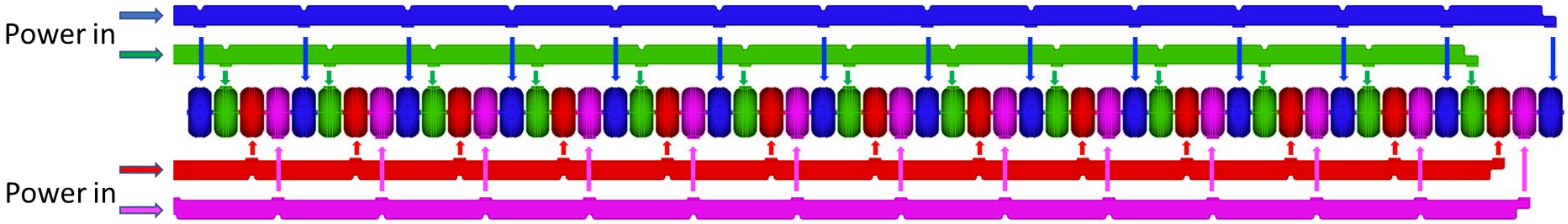


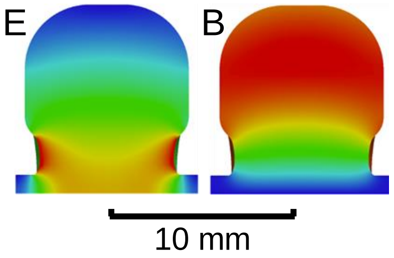
Nasr, M., Nanni, E., Breidenbach, M., Weathersby, S., Oriunno, M. and Tantawi, S., 2021. Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature. *Physical Review Accelerators and Beams*, *24*(9), p.093201.



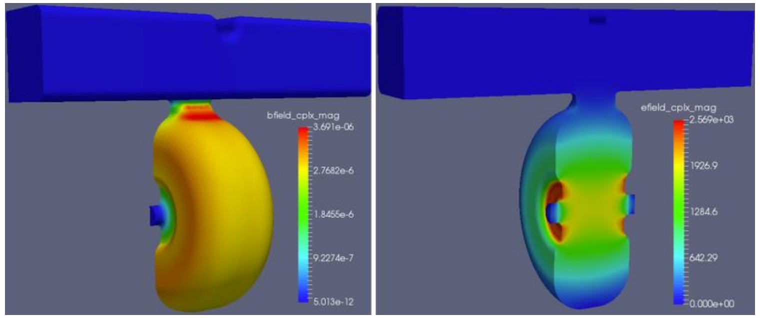


135° phase advanced distributed coupling structure





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



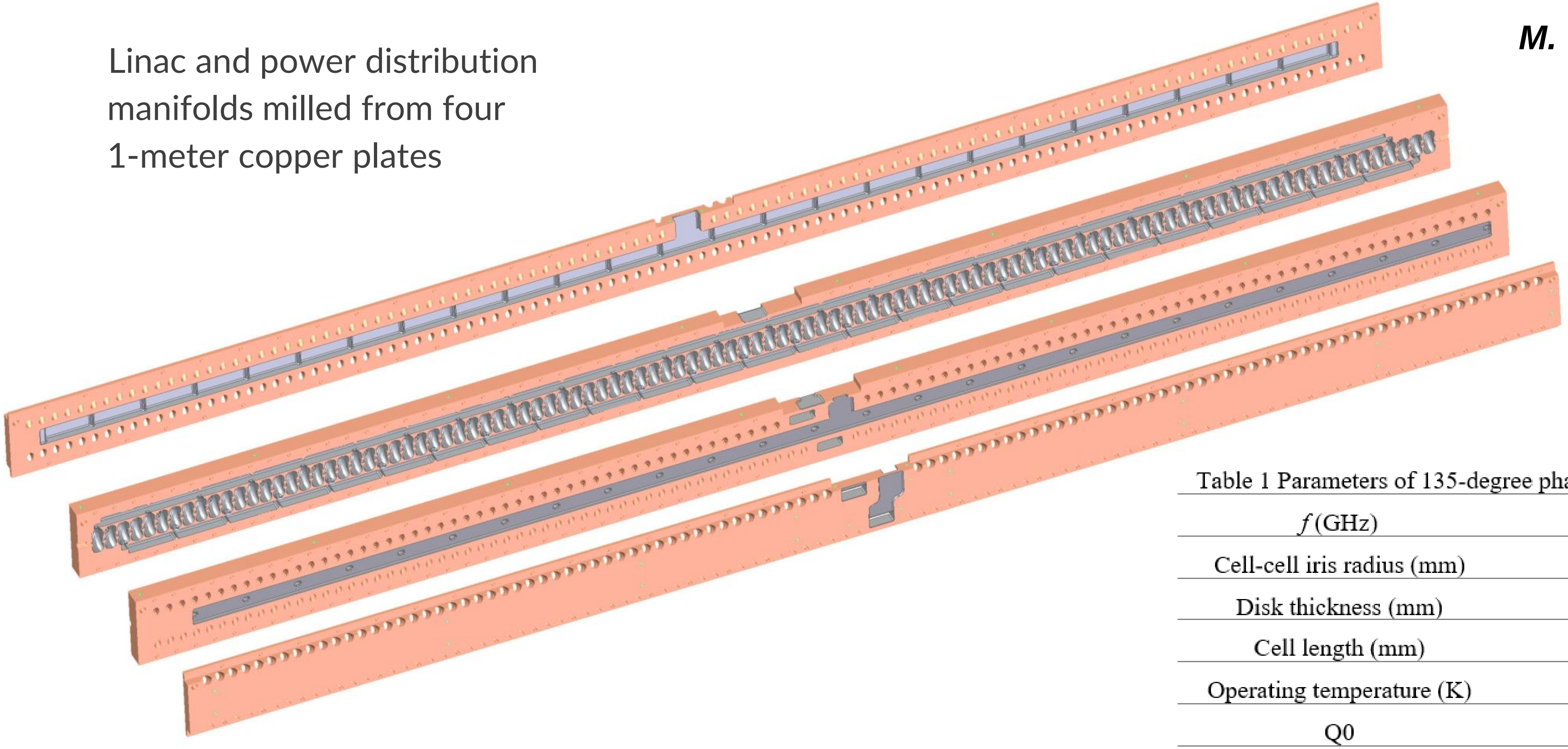
- With the cell period optimized for minimal surface magnetic field, the phase advance is ~132°
- Using a 135° phase advance, every 4^{th} cavity has a π phase shift
- Coupling iris and waveguide features optimized using SLAC's parallel ACE3P solvers for a beam-loaded cavity

Shumail, Li, Tantawi

VHEE linac design

Linac and power distribution manifolds milled from four 1-meter copper plates

M. Oriunno



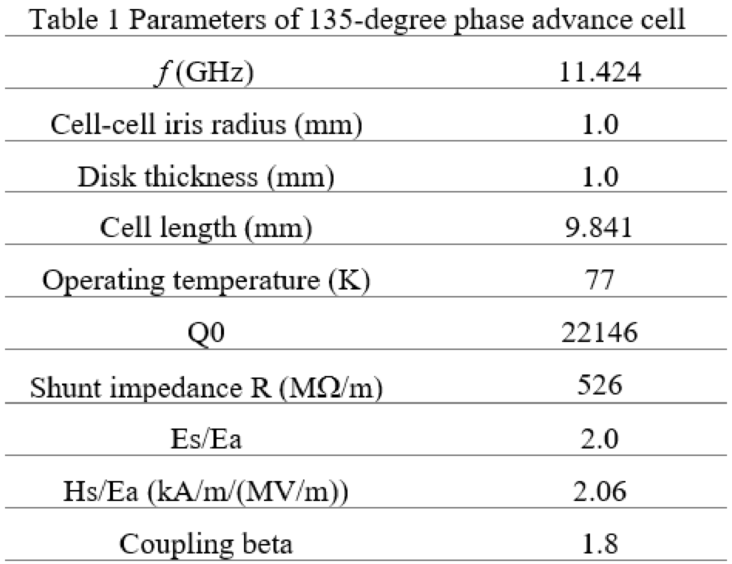
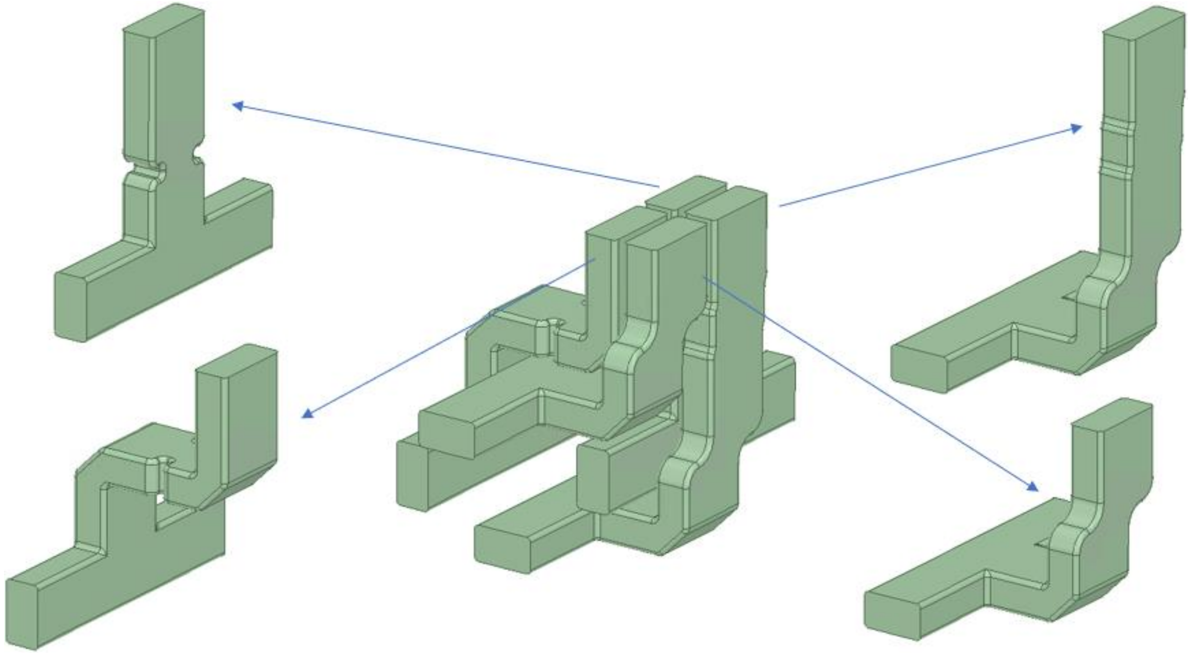
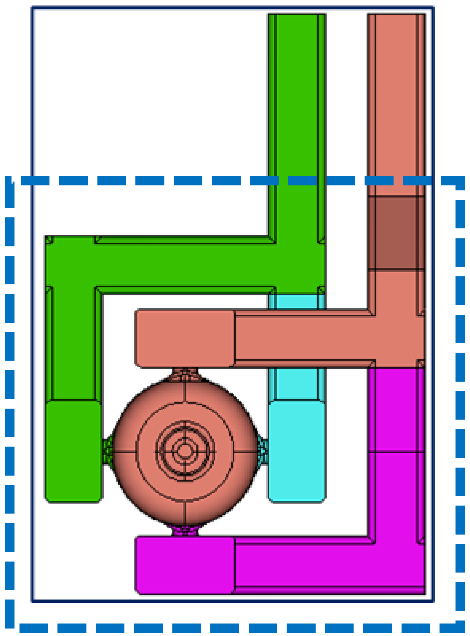


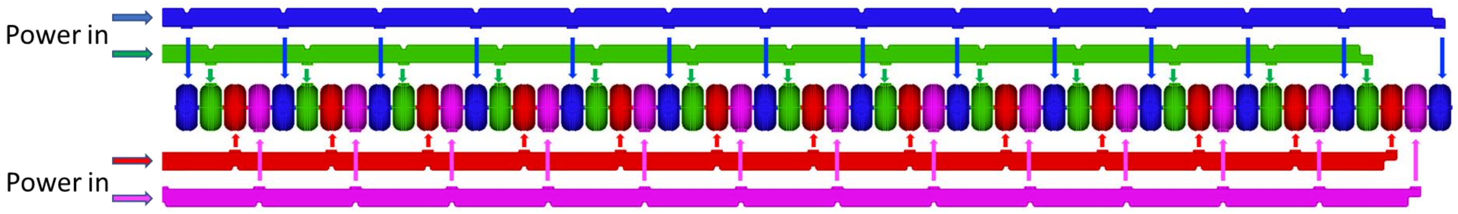
Table 1 Parameters of 135-degree phase advance cell

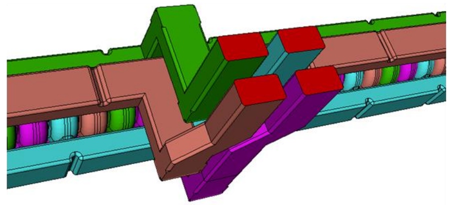
f (GHz)	11.424
Cell-cell iris radius (mm)	1.0
Disk thickness (mm)	1.0
Cell length (mm)	9.841
Operating temperature (K)	77
Q0	22146
Shunt impedance R (MΩ/m)	526
Es/Ea	2.0
Hs/Ea (kA/m/(MV/m))	2.06
Coupling beta	1.8

VHEE linac power distribution





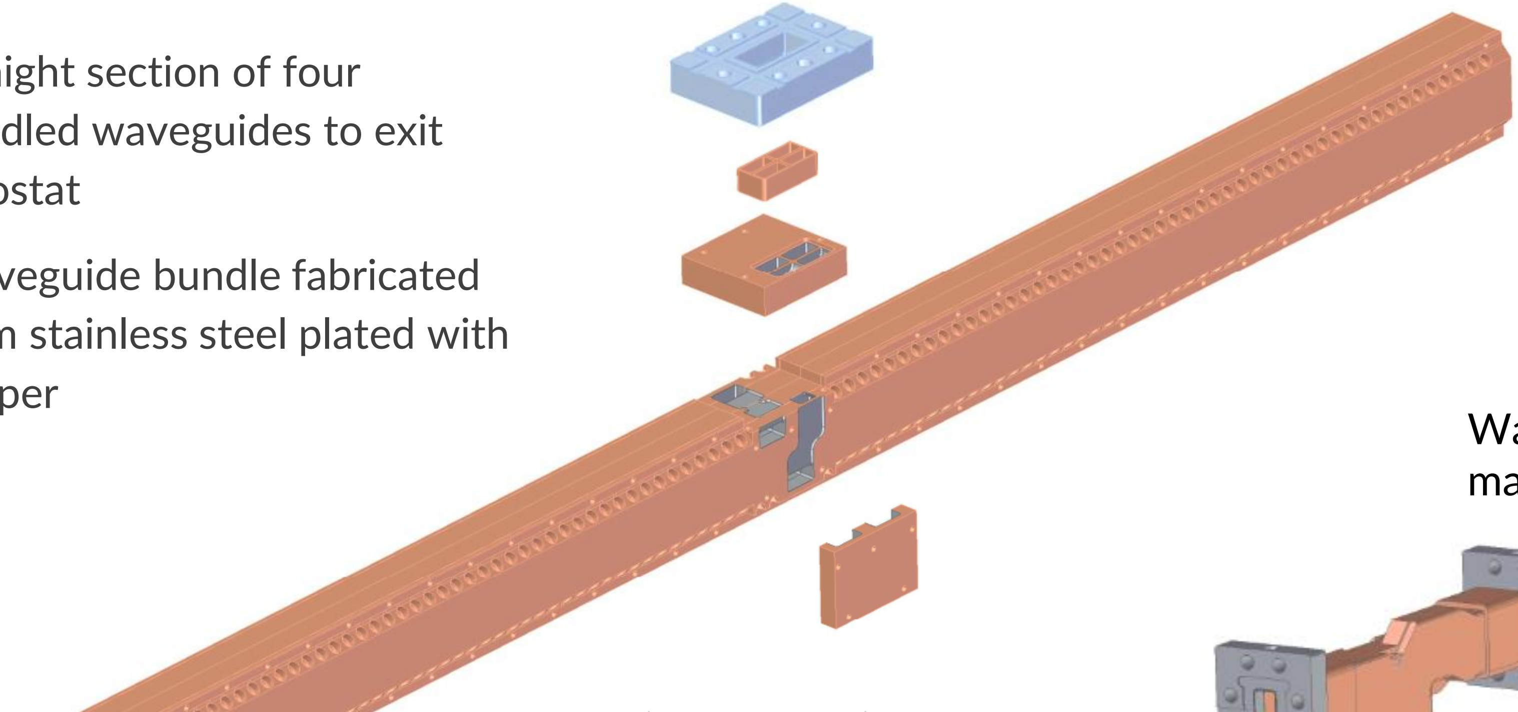


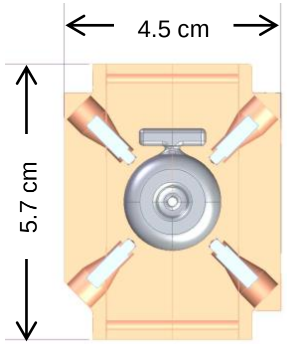


Nantista, Li, Tantawi

VHEE linac design

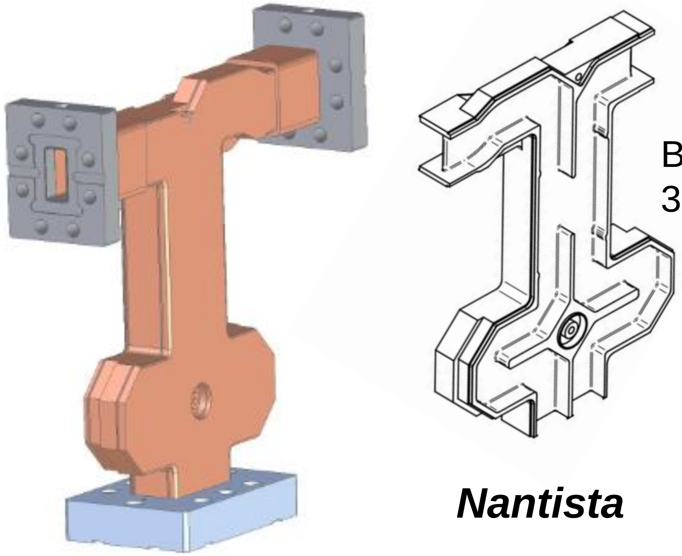
- Straight section of four bundled waveguides to exit cryostat
- Waveguide bundle fabricated from stainless steel plated with copper





Four tuning pins per cell

Waveguide splitter to feed four manifolds from one input

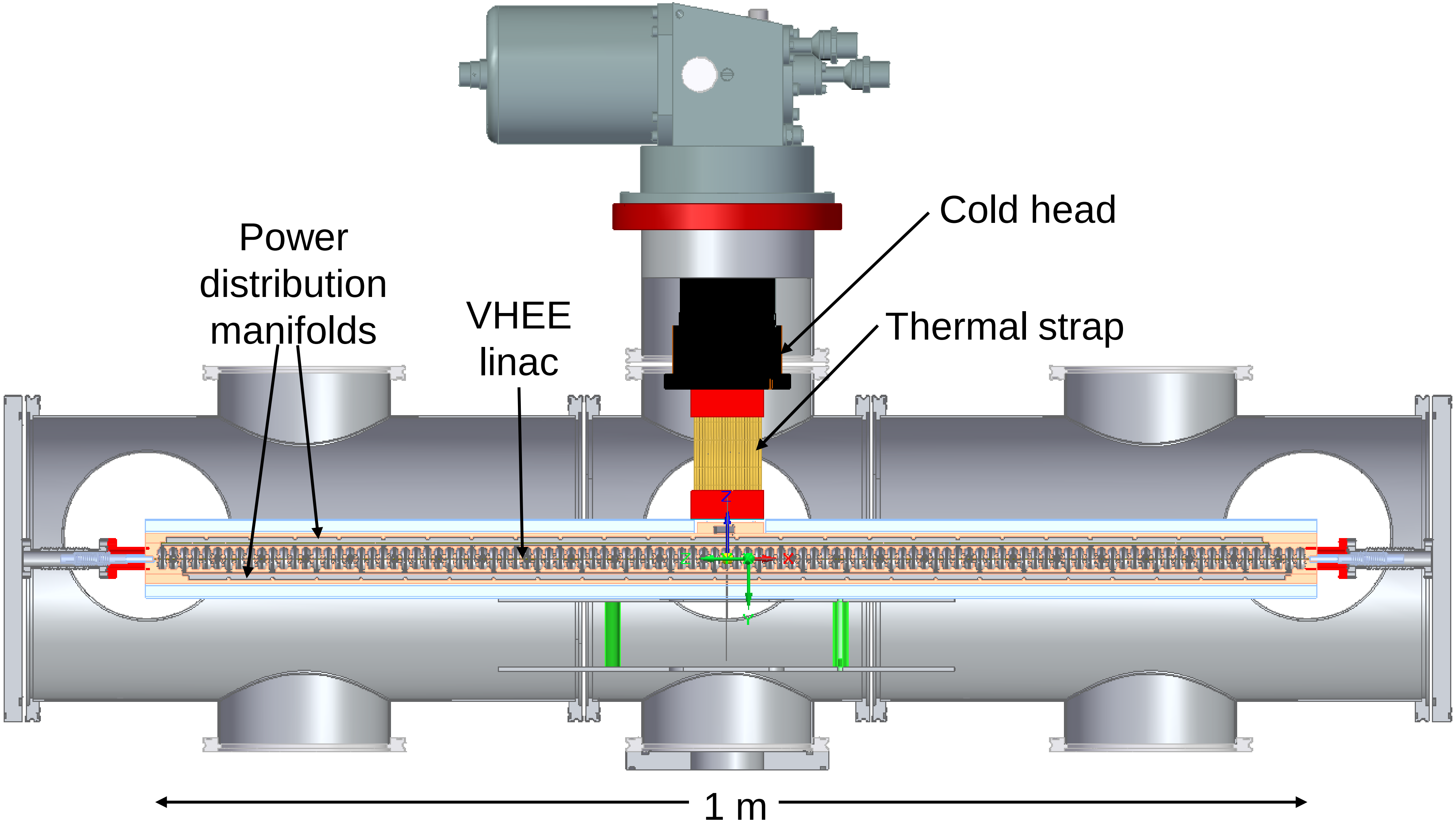


Back-to-back 3dB hybrids

Phase length equalizers

Nantista

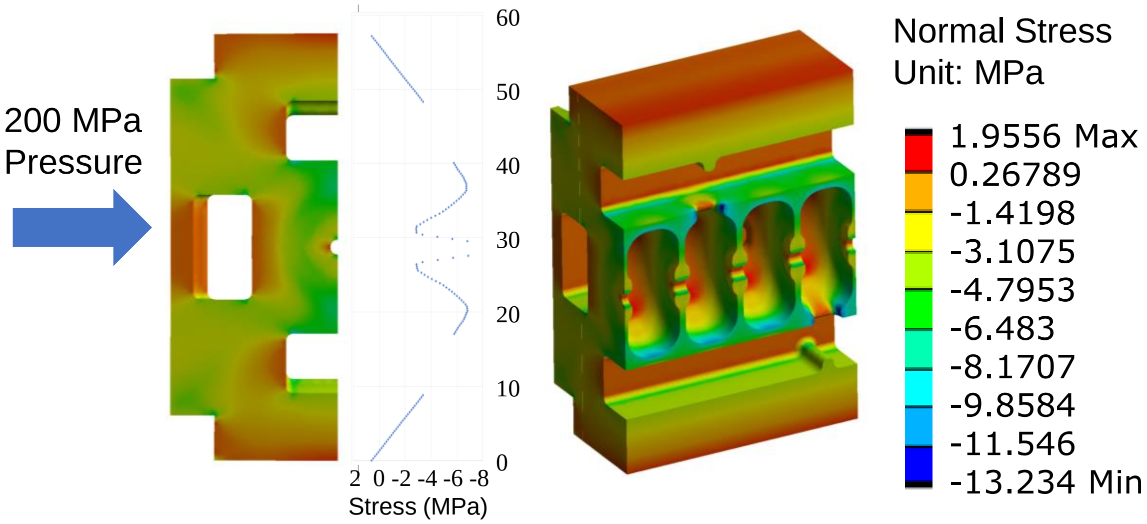
Cryogenic operation

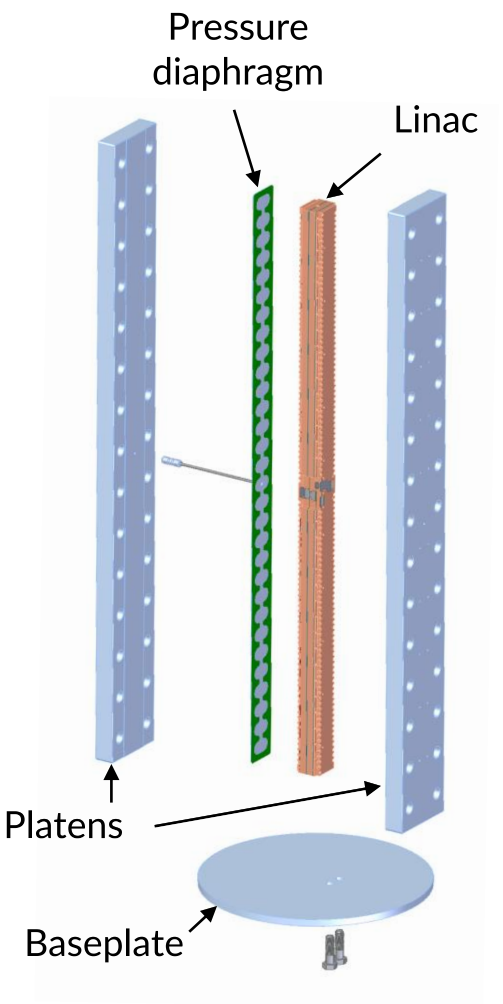


Mechanical design

Diffusion bonding

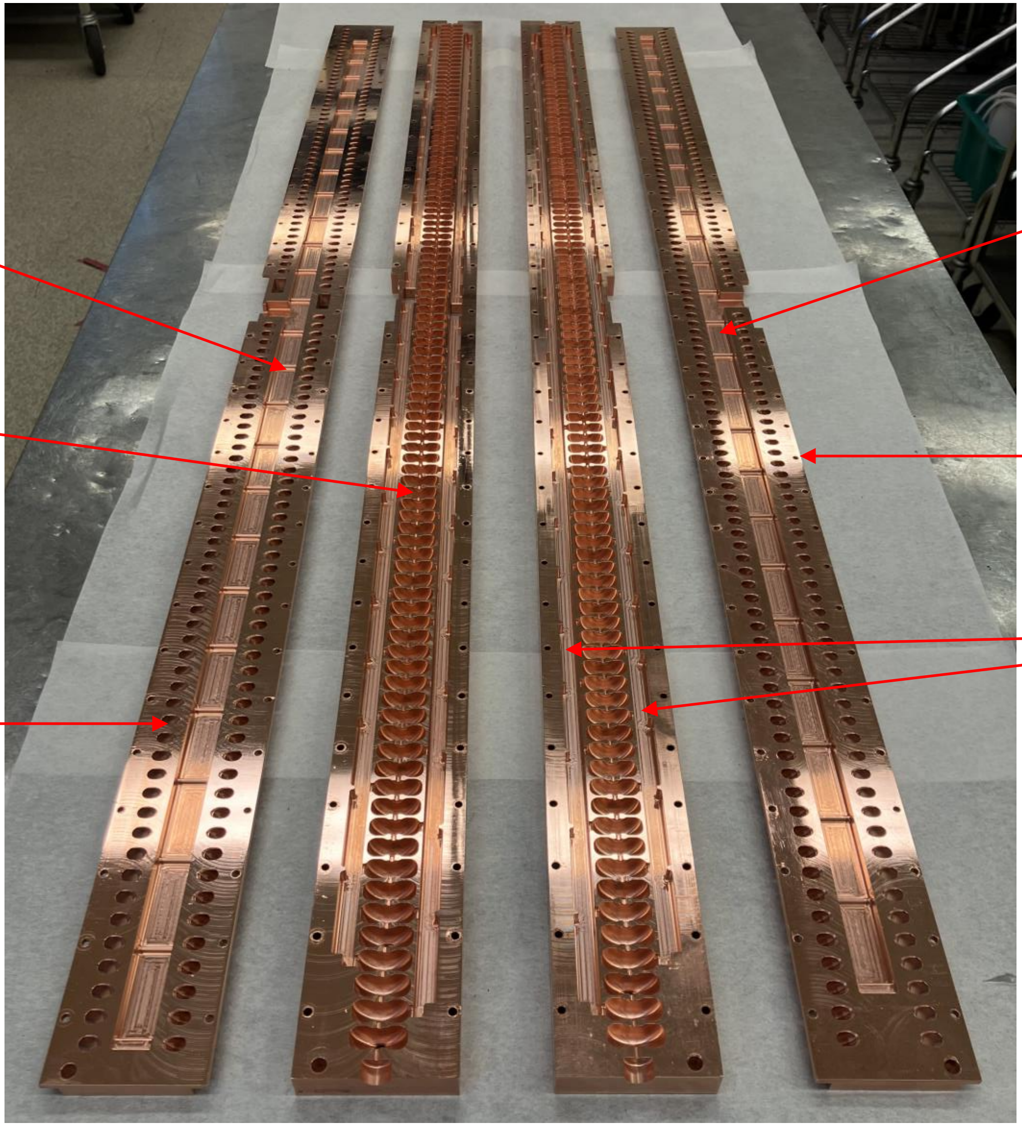
- Simulated stress distribution analysis (below) in one half of the VHEE linac during diffusion bonding
    - Variation in normal stress at the interface running through the center of the cavities covers a range up to 8 MPa
    - Within the expected tolerance for diffusion bonding
    - Primary risk is vacuum leaks





Exploded view of diffusion bonding assembly

VHEE linac fabrication



Upper distribution manifold

3π/4 cavities

Tuning pin holes

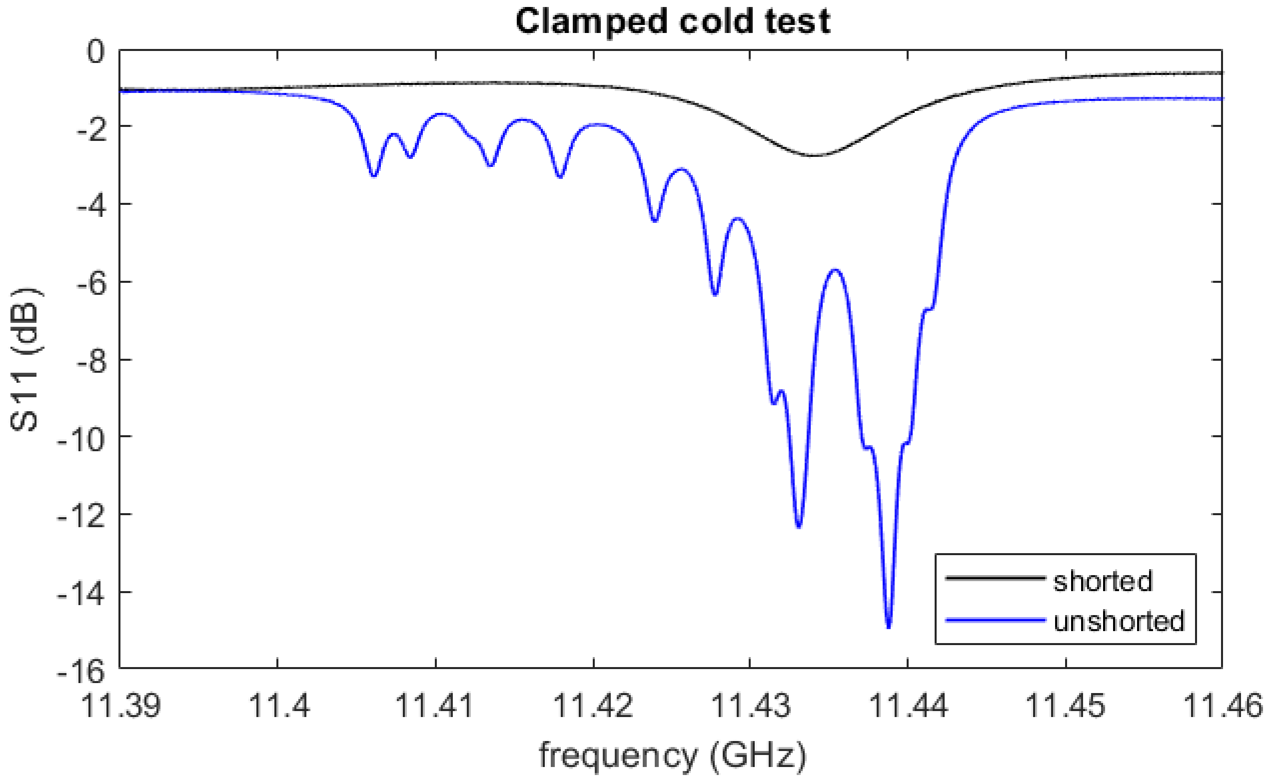
Lower distribution manifold

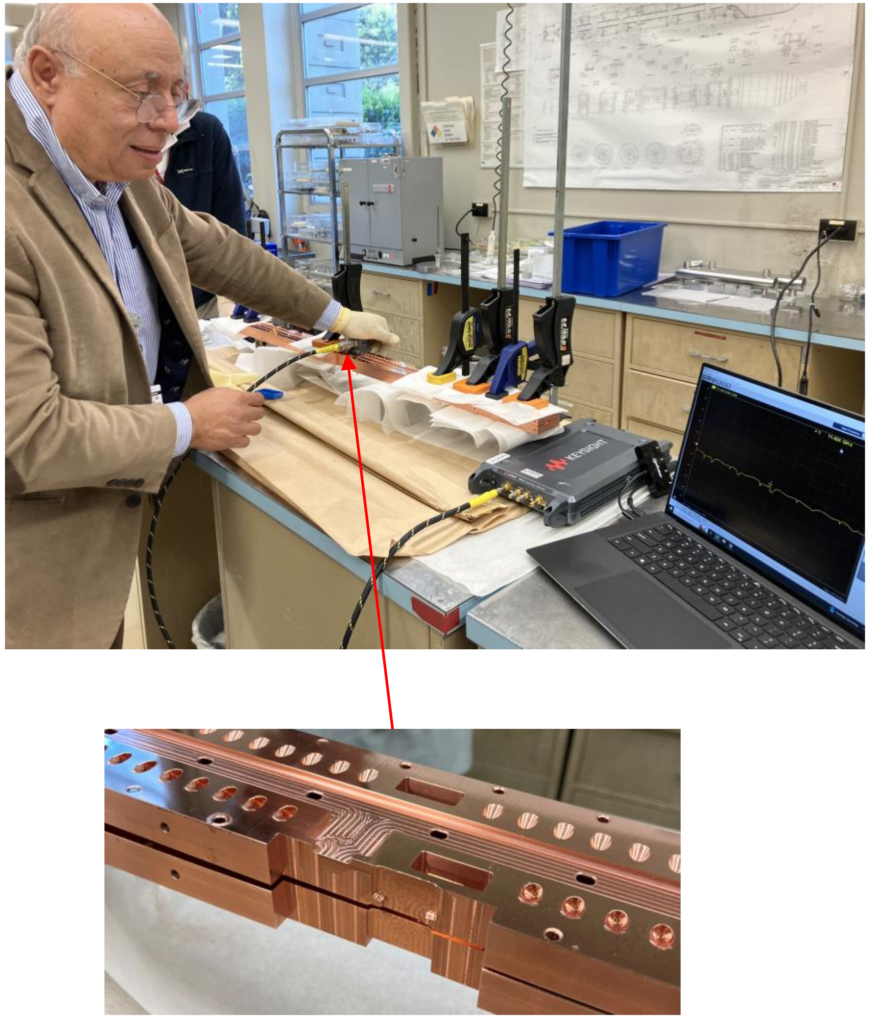
Alignment pin holes

Left and right distribution manifold

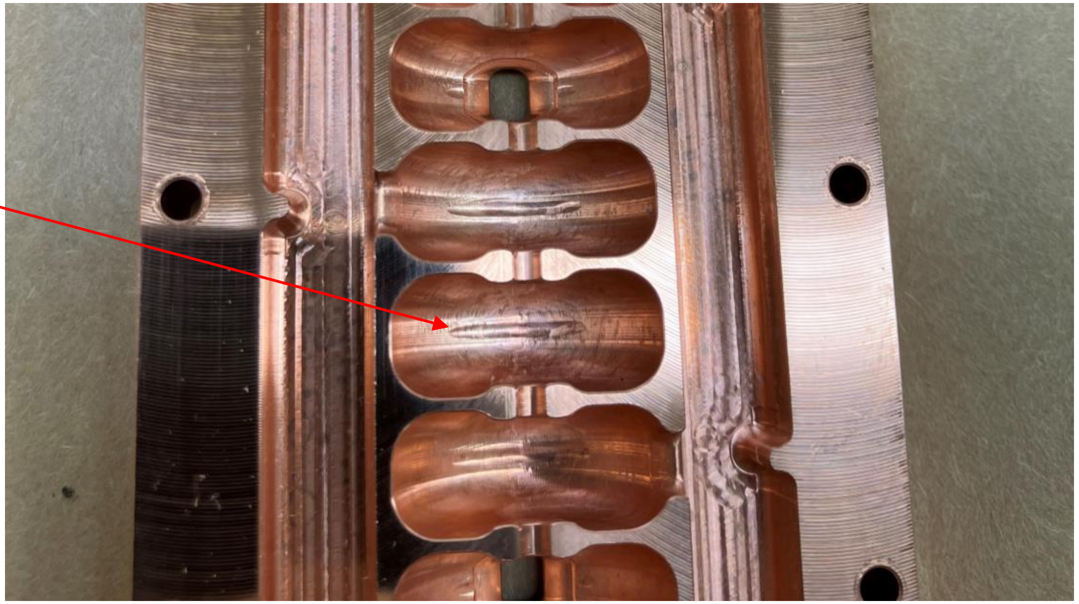
Clamped cold-test of VHEE linac

Inner two plates clamped together with two input feeds accessible

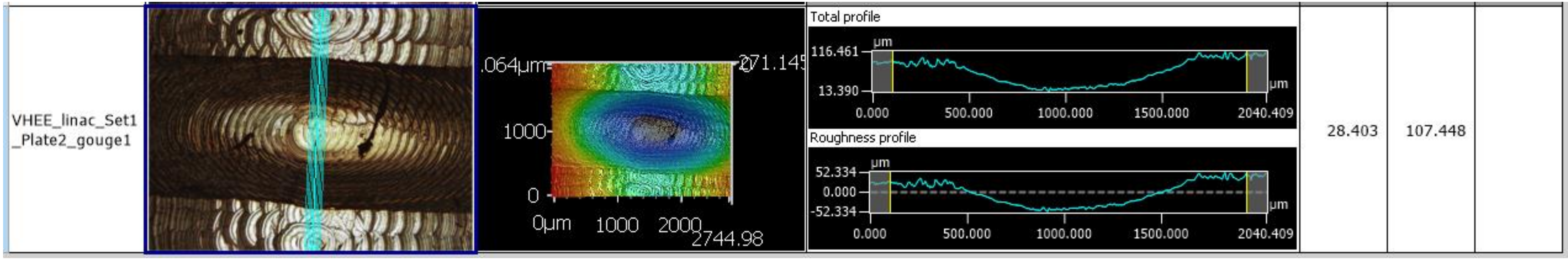




Machining defect in VHEE linac

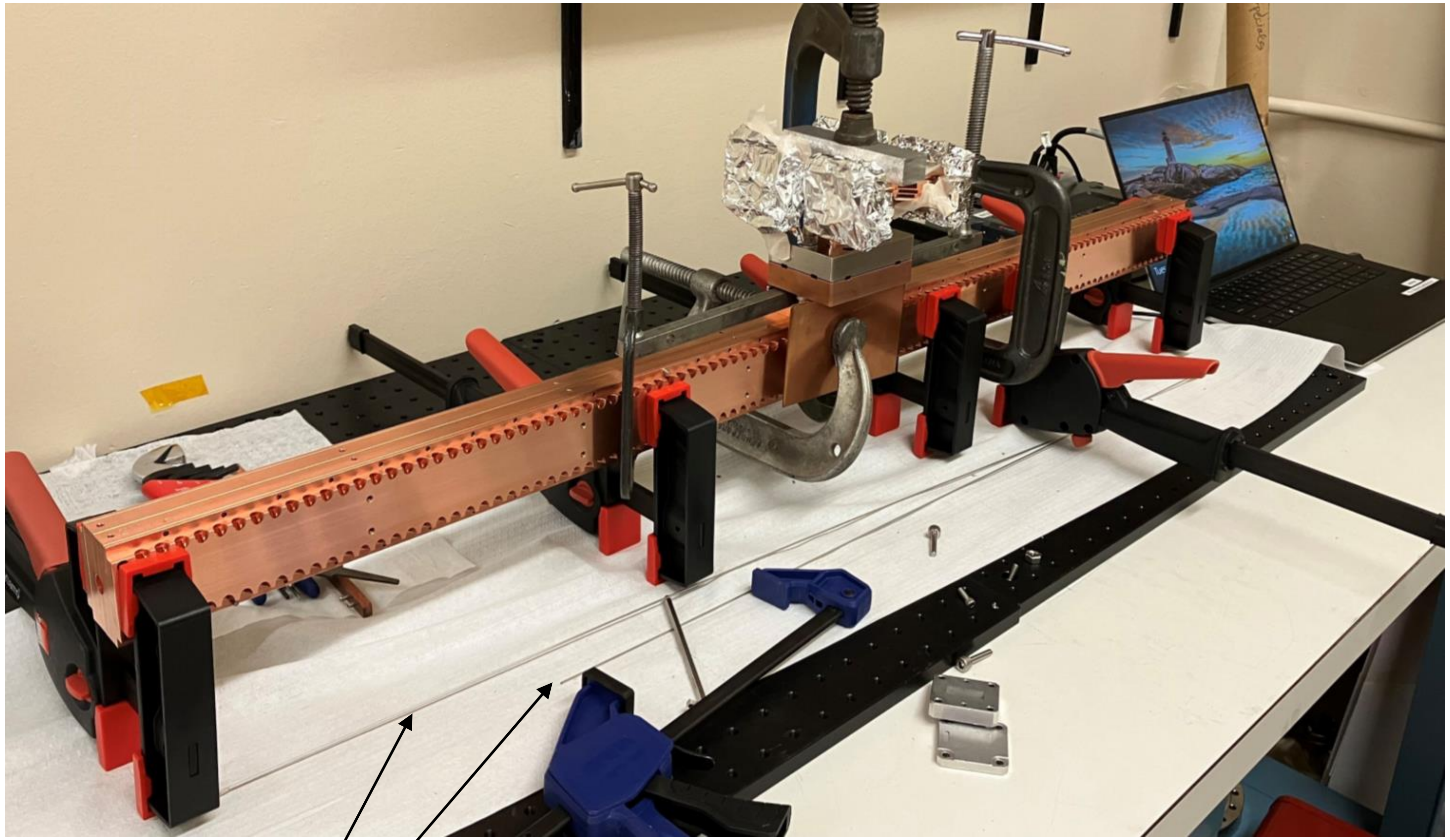


Defect repeats in each cell



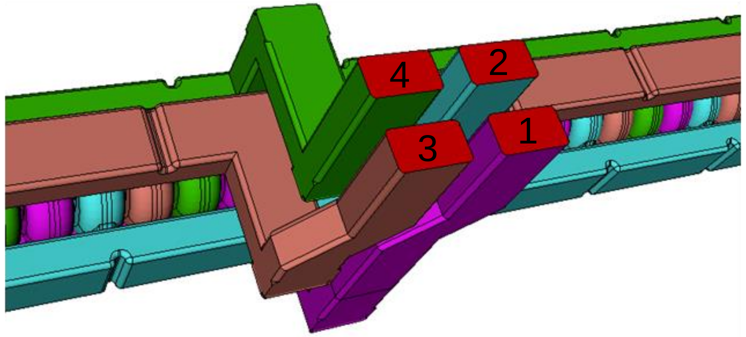
VHEE_linac_Set1_Plate2_gouge1				28.403	107.448	

Clamped cold-test of VHEE linac



Rods used to short cells from either end

Splitter designed for cold test measurements at each port



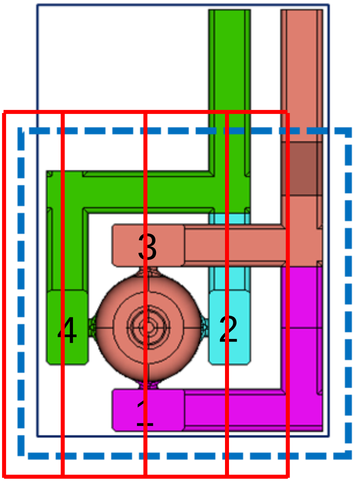
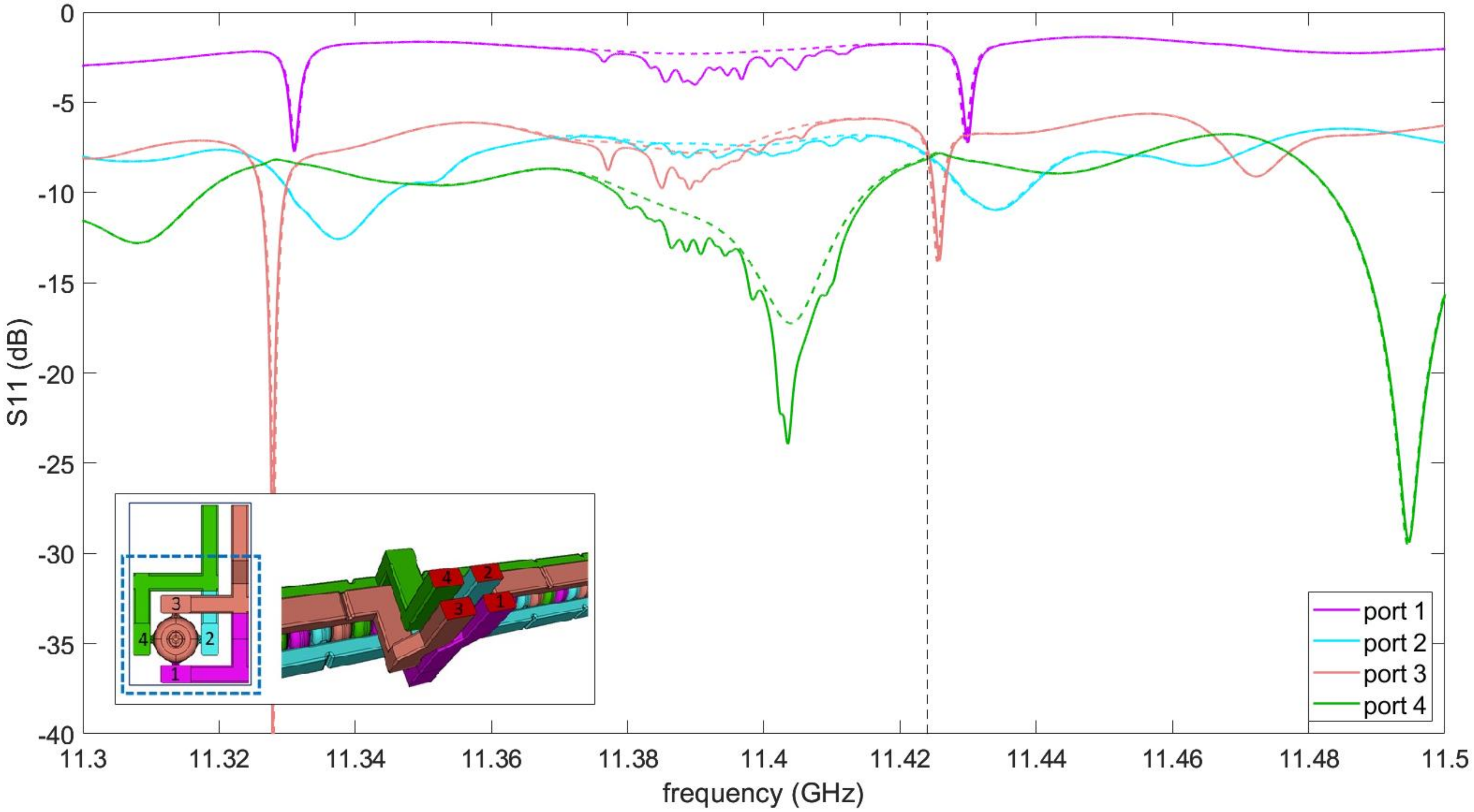
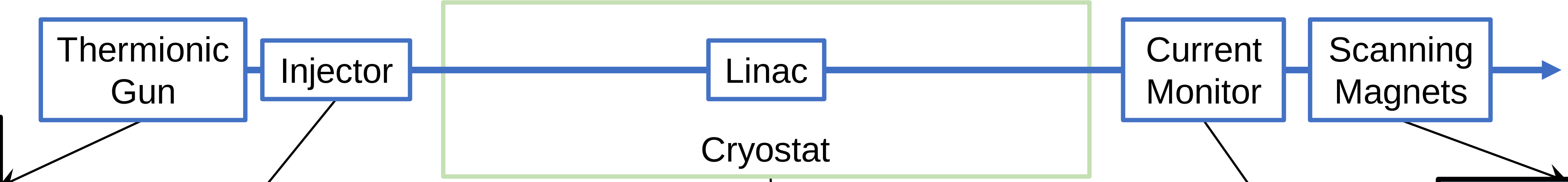


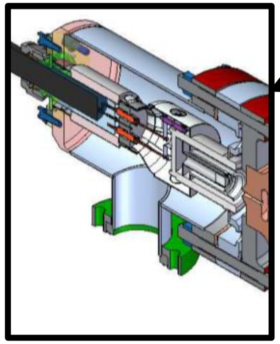
Plate boundaries

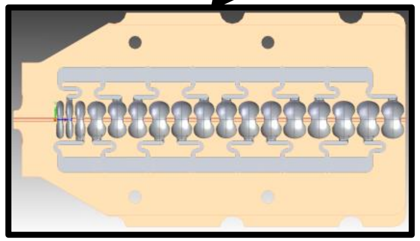
Clamped cold-test of VHEE linac re-machined

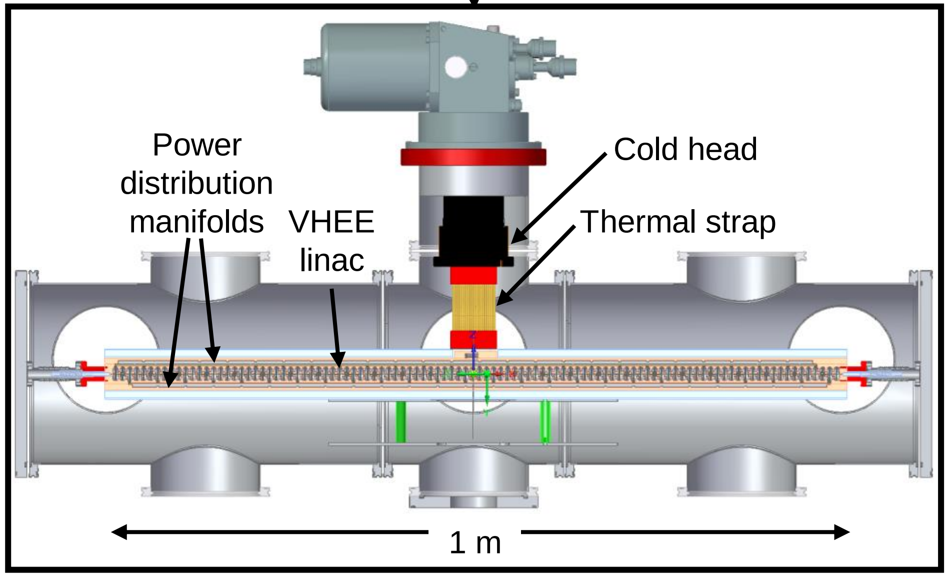


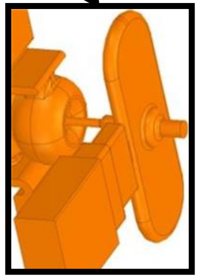
VHEE beamline

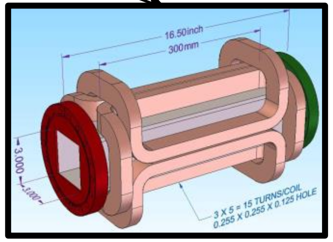












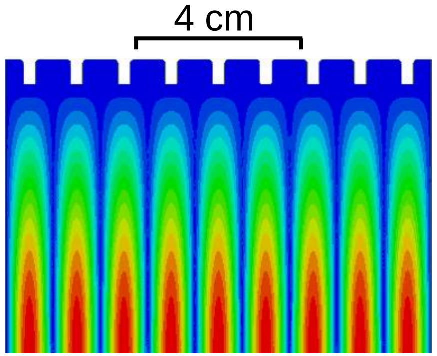
- Pulse compression to provide ~200 ns flat top pulses at 20 MW
- ~3000 electron bunches per pulse with ~1.7 pC per bunch

- Single linac operating at 20 Hz provides about 40 Gy/s in a 4 cm^2 area

Compact RF pulse compression

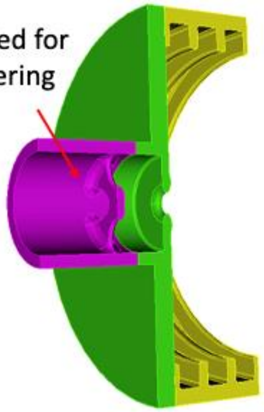
Powering the FLASH-VHEE linac

- 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



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

Improved for engineering design



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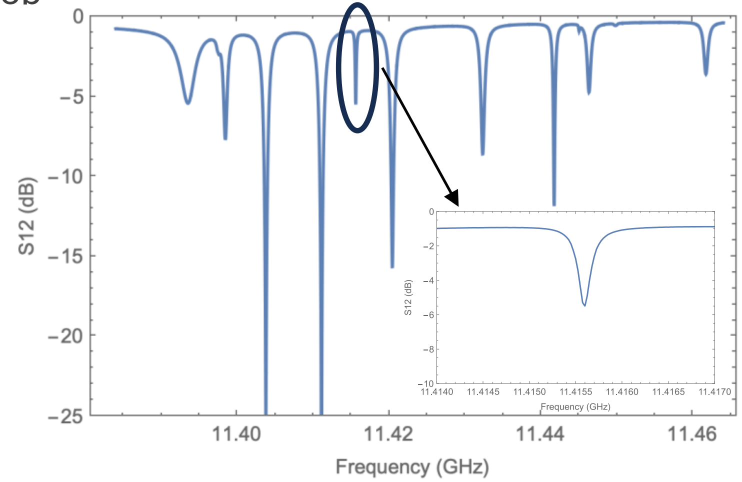

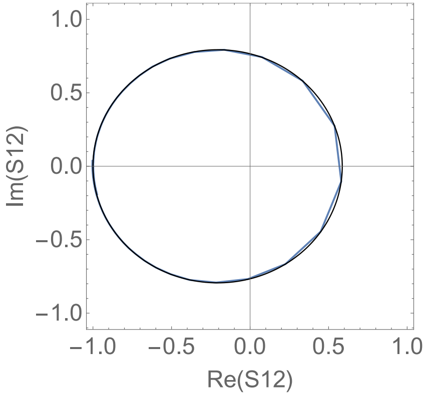

Q0=267729. $Copper \rightarrow$ 408283
Qe=69721
β=3.84. $Copper \rightarrow 5.85595$

Summary

VHEE linac designed for 100 MeV/m gradient with 526 MΩ/m shunt impedance operating at 77 K

- Medical accelerator R&D projects support and benefit from advances in accelerator technology for discovery-science facilities
  - Overlapping demand for more efficient, compact structures
  - Testbed for novel accelerator technology and beamline components
  - Successful transition to commercialization can help prepare the accelerator manufacturing sector to deliver on the large-scale discovery-science initiatives at the core of the HEP mission

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