Radiabeam's high-gradient developments for accelerator applications

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RadiaBeam

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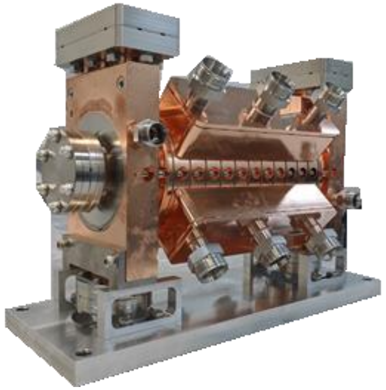
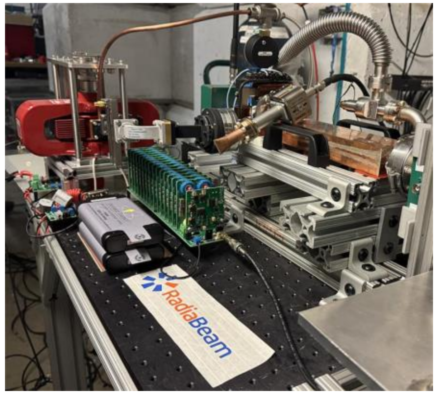
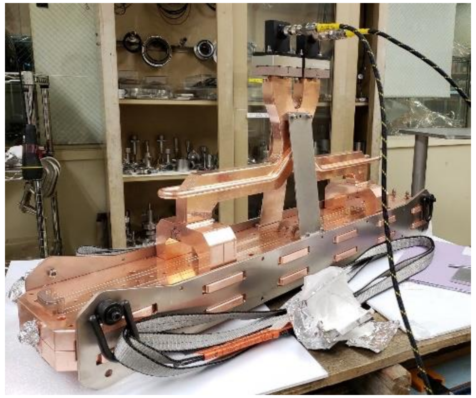
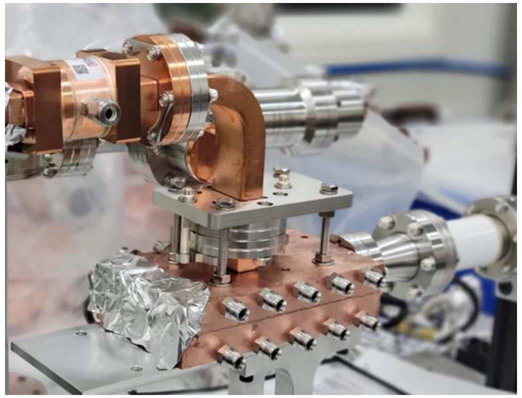
About RadiaBeam

- Spin-out of UCLA Physics Department: 2004
  - Santa Monica, California
  - Currently: ~50 employees, 30,000 ft^2
- Products: accelerator components (RF structures, magnets, diagnostics), medical/industrial accelerator systems, >MeV X-ray systems
- Core competencies
  - RF optimization, design, fabrication, and testing of linear accelerator structures, microwave sources, modulators, and power electronics
  - Custom instrumentation and beamline magnets
  - Cryogenic engineering
  - Teams: R&D, Engineering, Manufacturing, Integration & Testing



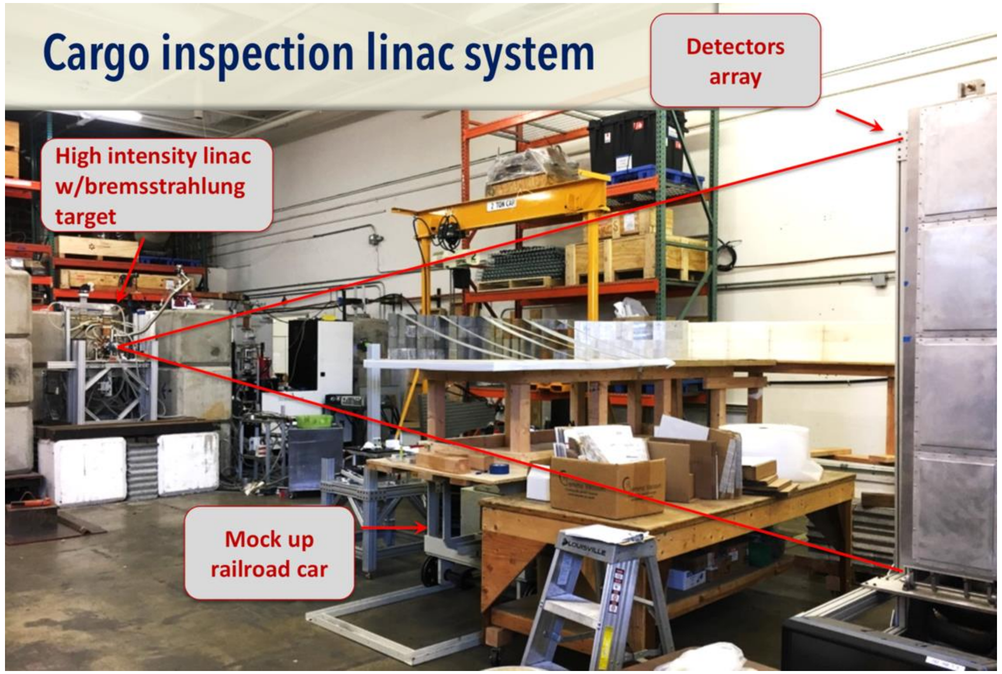


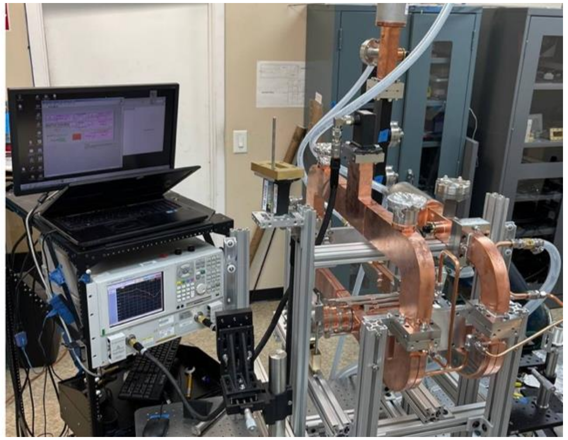




RadiaBeam's capabilities

- Clean, UHV-quality manufacturing focused on copper
  - In-house machining and chemical-cleaning capabilities
    - Vacuum brazing and electron beam welding: Toll vendors
  - Inspection & testing:
    - Metrology: CMM, conventional metrology
    - Metallography: digital microscope/polishing
    - Vacuum: Leak checkers, calibrated RGA pump cart
    - Magnetics: 3-axis field mapping, vibrating wire
    - RF: dedicated lab with multiple VNA's
- 8MeV X-ray CT scanning: Refractory AM parts & large assemblies
- High pulsed power klystrons S-band, C-band



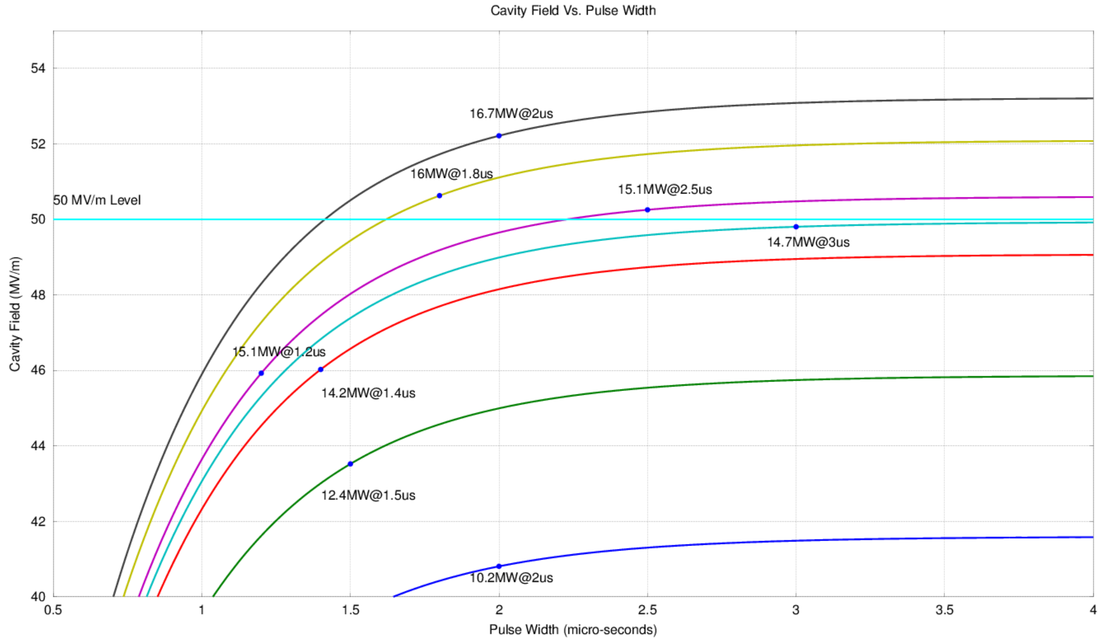


RF Testing

White room manufacturing of copper

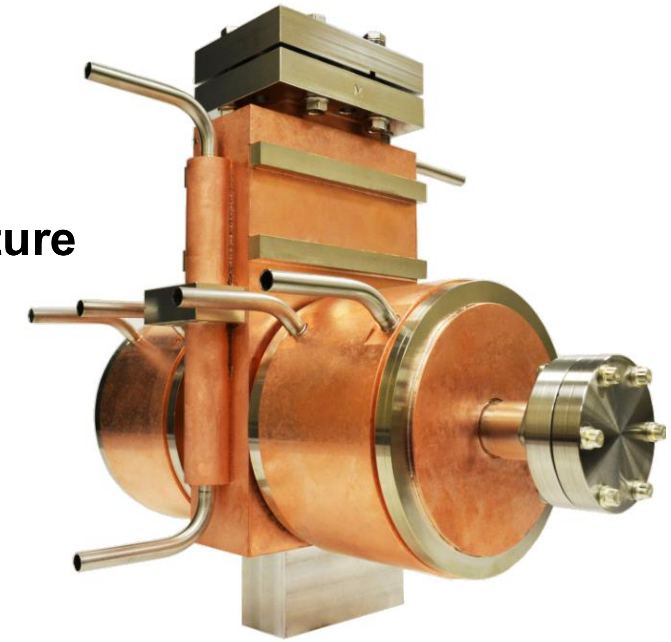
HG activities at RadiaBeam started +10 years ago

- 2013: We developed an X-band TW deflector cavity (XTD) operating at 11.424 GHz optimized for 100 MeV electron beam parameters at the BNL-Accelerator Test Facility. Peak deflecting voltage 38 MV/m at 20 MW.
- We designed, fabricated and high-power tested a high gradient S-Band accelerating structure (HGS) operating in the pi-mode at 2.856 GHz for beta=1
  - 2013: Initial high-power test at LLNL at 10Hz rep. rate, 1.3 μs, 16MW, and max field of 50MV/m
  - 2016: High power test at ANL at 30 Hz rep. rate, 2 μs, 16.7MW, and max field of 52.25 MV/m



X-band deflector

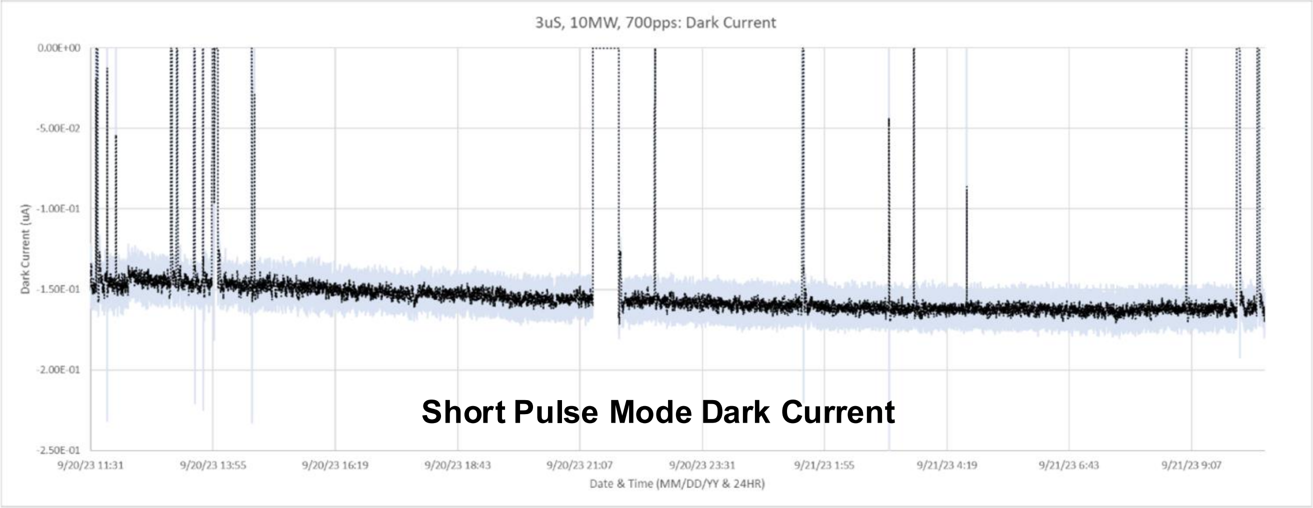
HGS structure



L-band accelerating structure for RPI

- RadiaBeam is fabricating a total of 8x 1300 MHz speed of light accelerating structures for the Gaerttner Linear Accelerator at Rensselaer Polytechnic Institute (RPI).
- The first structure was delivered in 2020 and high power testing was performed at RPI in 2023.
  - Test done at three different operational modes meeting the required performance criteria (~1.65E-8 BD rate). Additional conditioning of the structure was done up to 15 MW at 5μs.
- 3 structures to be delivered by the end of the month, and 4 more by the end of the year.

Mode	RF pulse width (μs)	Peak Power (MW)	Rep. Rate (Hz)	Breakdown rate
Short pulse	3	10	700	<1.65E-8
High Avg. Power	7	10	250	1.65E-8
Low Energy	3	5	800	<1.65E-8

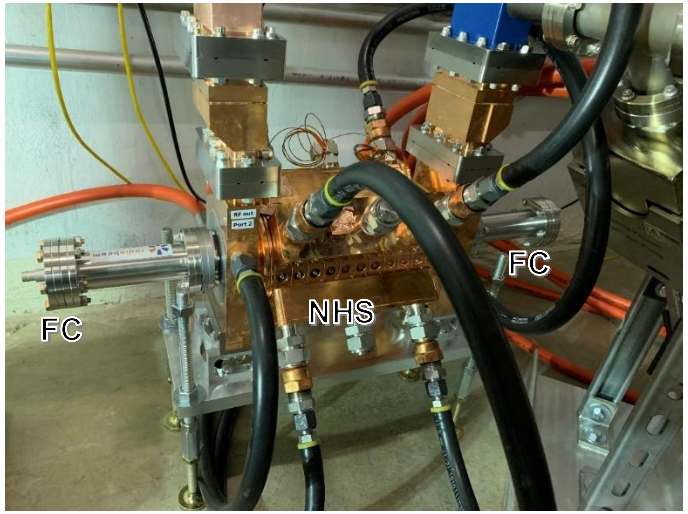


Short Pulse Mode Dark Current

S-band Advanced Compact Carbon Ion Linac

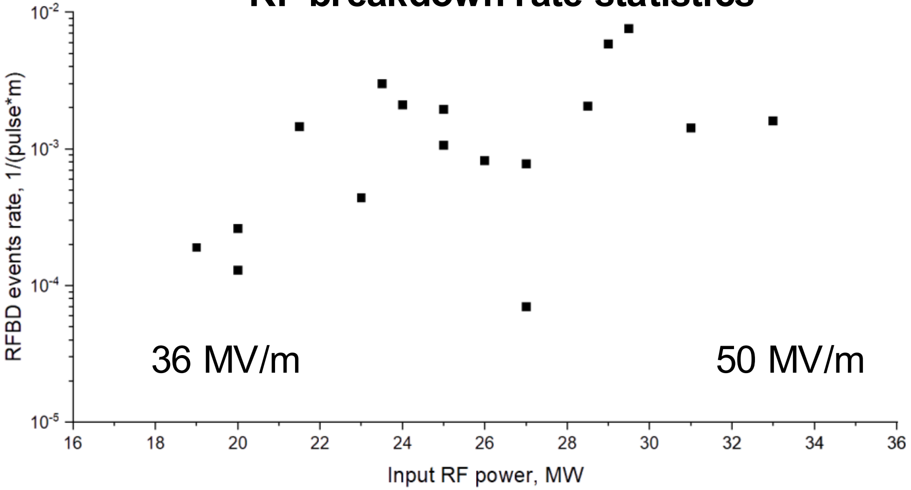
- 2016: Collaboration with ANL to develop an Advanced Compact Carbon Ion Linac (ACCIL) for hadron therapy. Deliver 450 MeV/u in a 45m footprint, required 50 MV/m structures for β=0.3-0.7
- 2021: We designed, fabricated, and tested a 15-cell Negative Harmonic Structure (NHS) for β=0.3 operating at 2856 MHz
  - High-power test at ANL with 30 Hz rep. rate, 700 ns, achieving 50 MV/m with 33 MW
- 2022: Upgraded NHS design for 1000 Hz rep. rate, 40 MV/m gradient with 20 MW

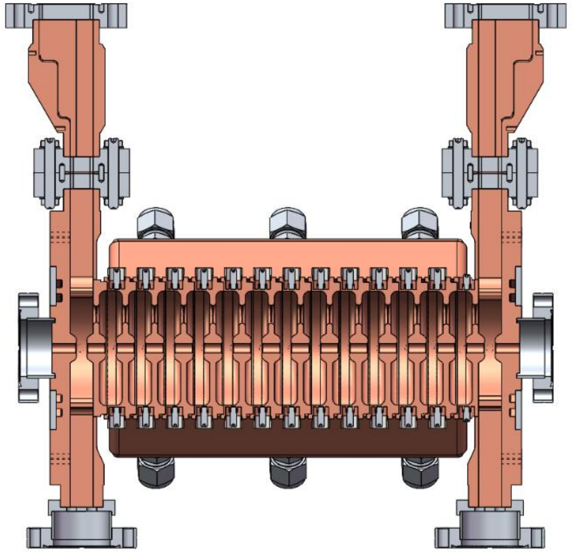
Parameter	Initial (built)	Flash design
$f_{m=-1}$	2856 MHz	
Rep. rate	120 Hz	1000 Hz
Group velocity	0.12-0.335 %c	0.23-0.43%
Filling time	450 ns	287 ns
Shunt impedance	32 MΩ/m	47 MΩ/m
Peak RF Power	33.8 MW	20 MW
Average RF losses	3.9 kW	5.6 kW
Accelerating gradient	50 MV/m	40 MV/m
Peak electric fields	160 MV/m	180 MV/m
Pulse Heating	28 K	12 K



NHS built for 120 Hz

RF breakdown rate statistics

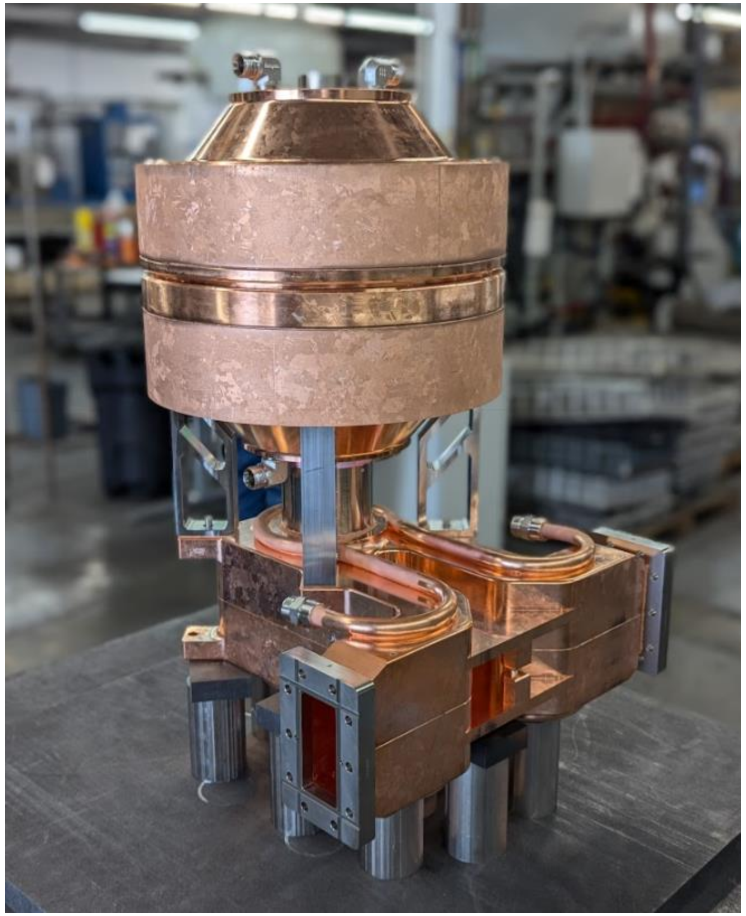


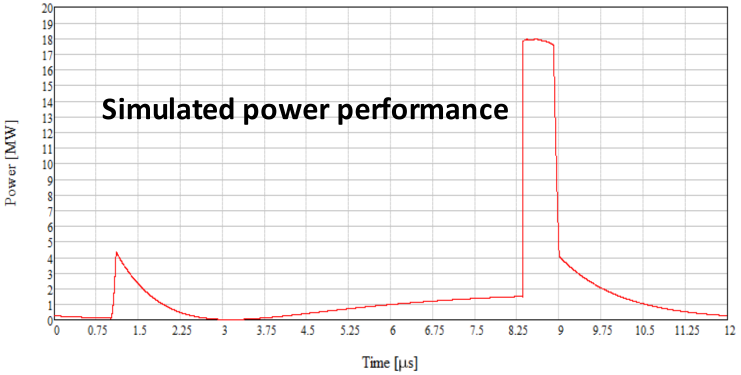

NHS upgraded design for 1kHz rep. rate

S-band RF pulse compressor (SLED)

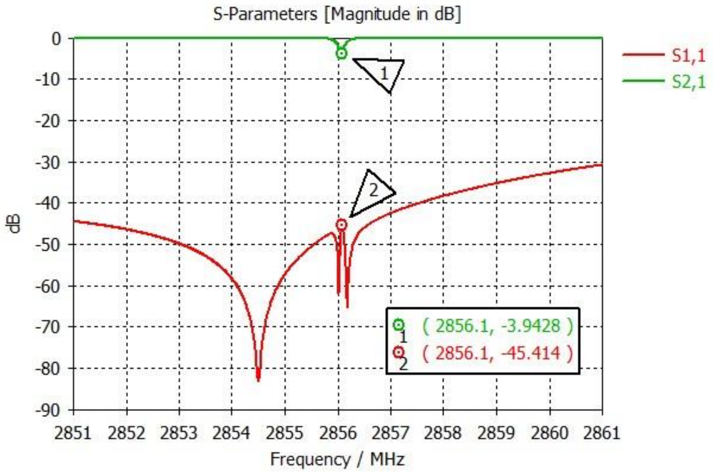
- RadiaBeam developed a 2856 MHz RF pulse compressor to produce multimegawatt peak power using a medical klystron
  - RF design based on a E-plane polarizer and a spherical cavity with $Q=1\times10^5$
  - Expected to generate a flat 18 MW 600 ns flat-top RF pulse with a 7 μs 5MW pulse, 62% efficiency
  - RF cold testing has been performed

Parameter	Value
Frequency	2856 MHz
Input power	5 MW
Pulse length	7 μs
Repetition rate	500 Hz
Duty factor	0.4 %
Opt. Temperature	30ºC

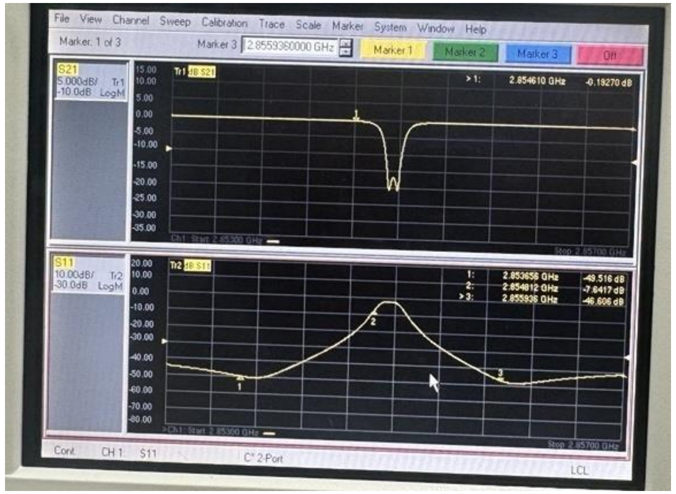




Simulation S-parameters

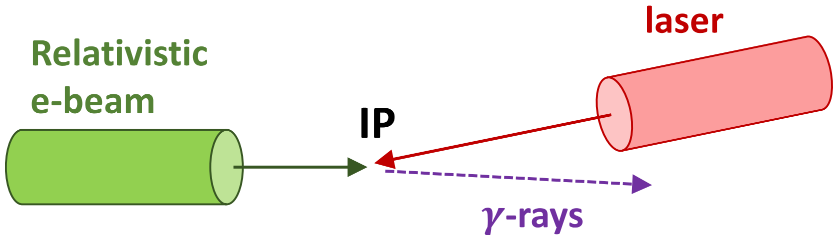


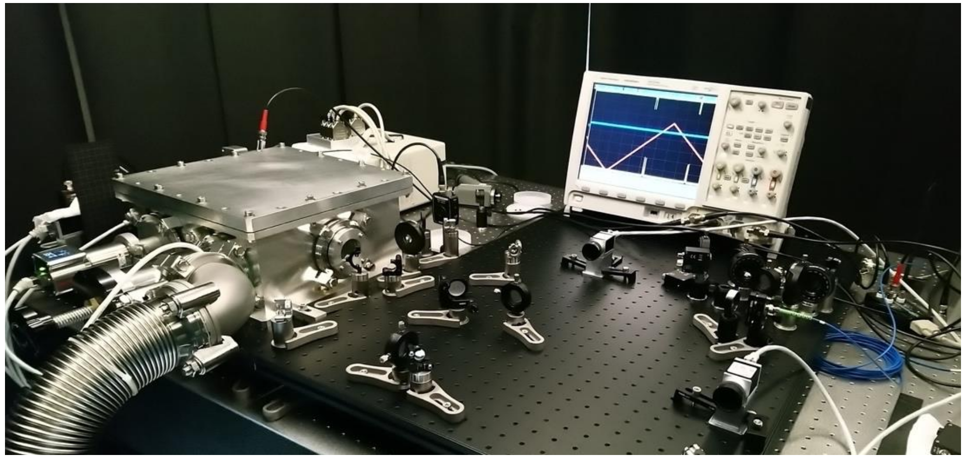
Measured S-parameters

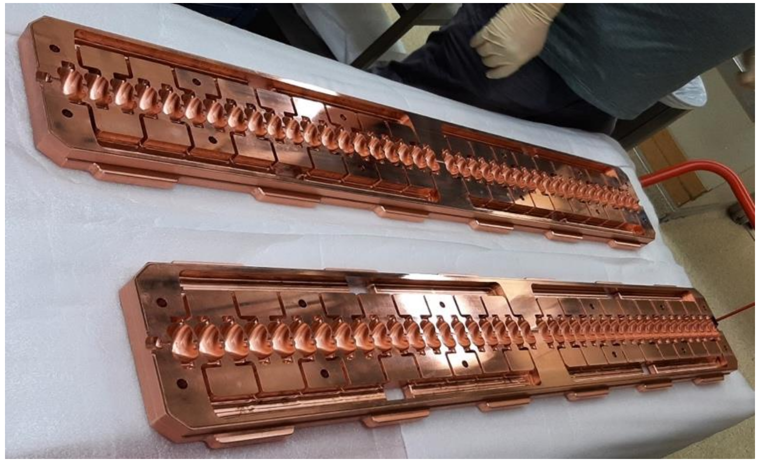


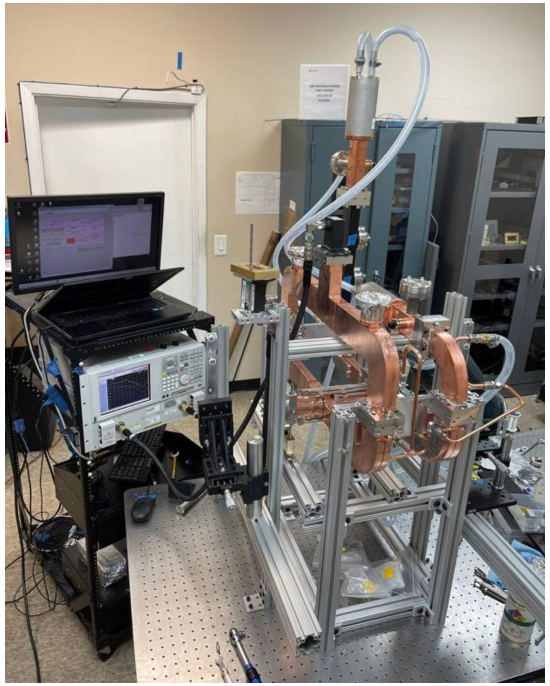
C-band RadiaBeam GRIT program

- The Gamma Ray Interrogation Technique (GRIT) program focused on the development high flux hard X-ray compact Inverse Compton Scattering (ICS) sources for medical and inspection applications
- The system's main components:
  - Magma 25 laser system (collaboration with Amplitude)
  - High gradient, 100 MeV, 5712 MHz linac (collaboration with SLAC)
  - Hybrid C-band photoinjector (collaboration with UCLA)







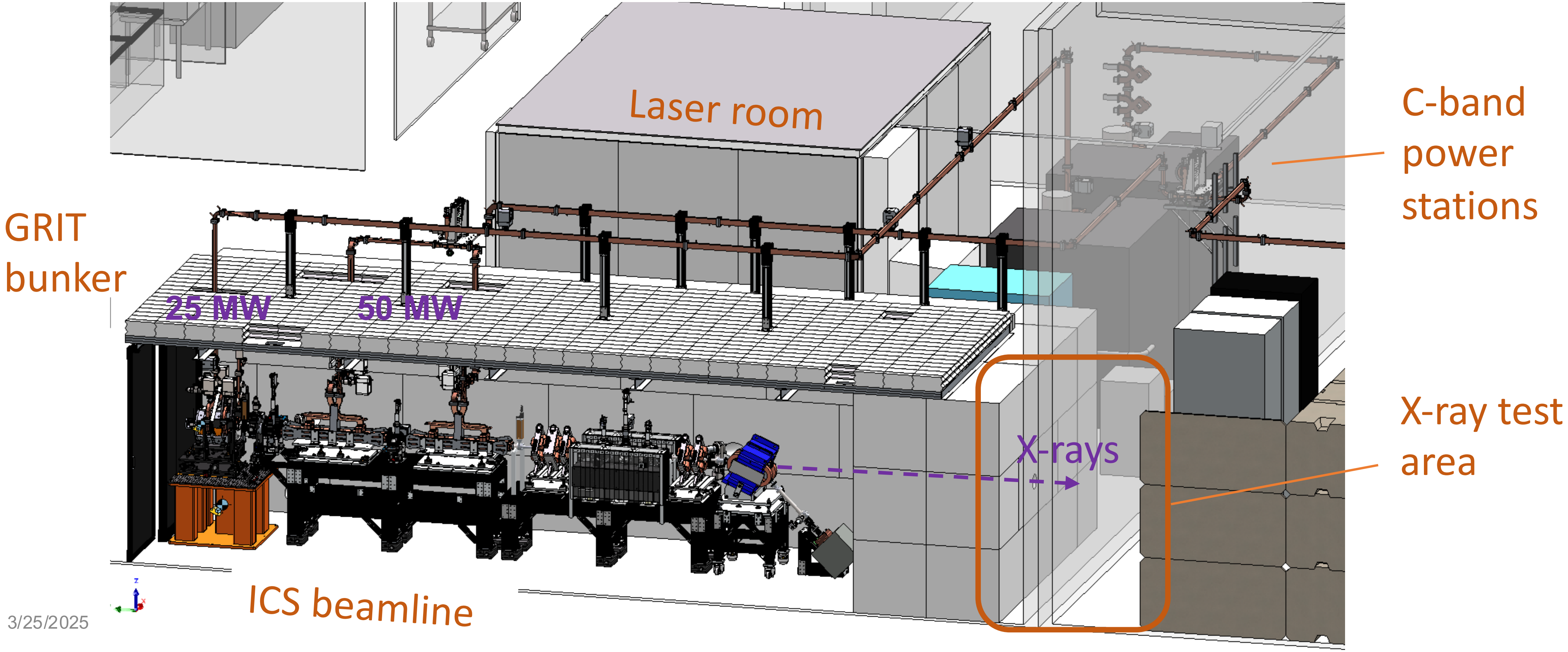


radiasoft Amplitude RadiaBeam SLAC NATIONAL ACCELERATOR LABORATORY UNIVERSITY OF MICHIGAN UCLA

C-band testing infrastructure overview

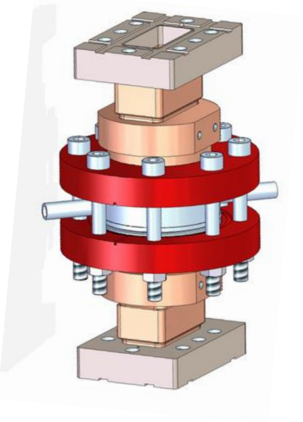
RadiaBeam

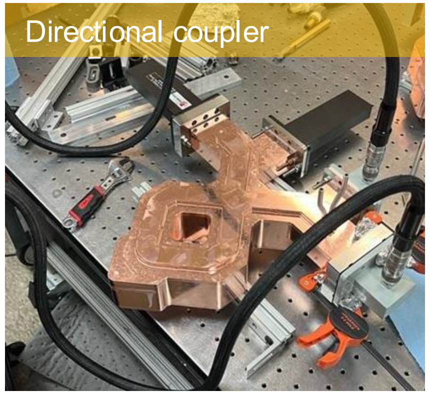
- 2 RF stations provide power 25 MW to hybrid gun and 50 MW to 100 MeV linac module
  - The current network supports parallel testing of an additional structure of up to 25 MW
- Laser system supports UV line for photoemission, and IR line for ICS
- Final focus and interaction system, beam dump/spectrometer beamline, and X-ray test station
- EPICS control system



C-band RF network components

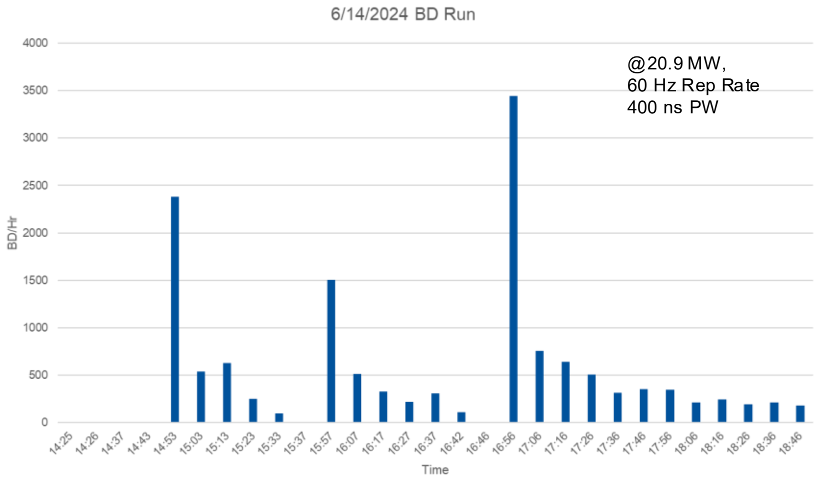
- RF network is rather complex
  - 2 Canon 5.712 GHz E37212 Klystrons driven by Scandinova K300 Modulators provide 25MW & 50MW to 100Hz, 1.2µs
  - 2 Phase Shifter Power Splitters (PS2) fully designed and manufactured by SLAC
  - 8x SLAC designed High Directivity Directional Couplers (6x manufactured by RadiaBeam)
  - 3D printed loads SLAC designed and manufactured by RadiaBeam
  - Variety of loads/windows from CML/Mega/Nihon Koshua/Custom
  - Multitude of WG components built in-house
  - WR187 straights/bends/pumps outs
- Tested multiple commercial components at high power for the first time. Many windows and loads failed, providing valuable feedback to vendors for improvements.
- Developed some components in-house (directional coupler, loads, windows, all SLAC designed)
- Very productive collaboration with SLAC on C-band high power components development

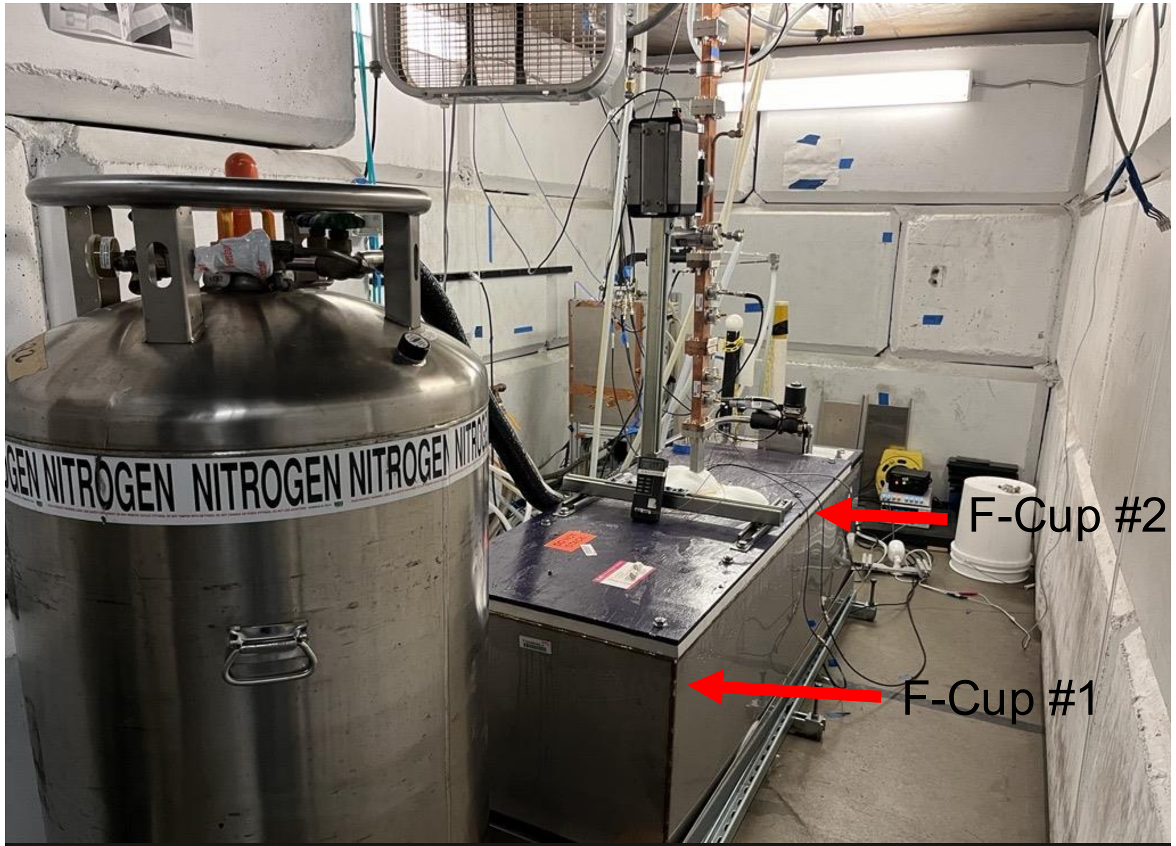




C3 Cryo-High Power Testing

- 25 MW C-band power station was used to test SLAC C3 5712 MHz linac structures
- Conditioned 3x structures while monitoring breakdown rate and vacuum. Breakdown rate declined over the conditioning period.
  - SN1: Conditioned up to 15 MW, 100 Hz, 1 μs pulse width at RT
  - SN3: Conditioned up to 10 MW, 100 Hz, 1 μs pulse width at 77 K. Failure of a vacuum window stopped progress.
  - SN2: Conditioned up to 20 MW, 20 Hz, 1 μs pulse width at 77 K. ~80 hours conditioning, more run time can improve BD rate.

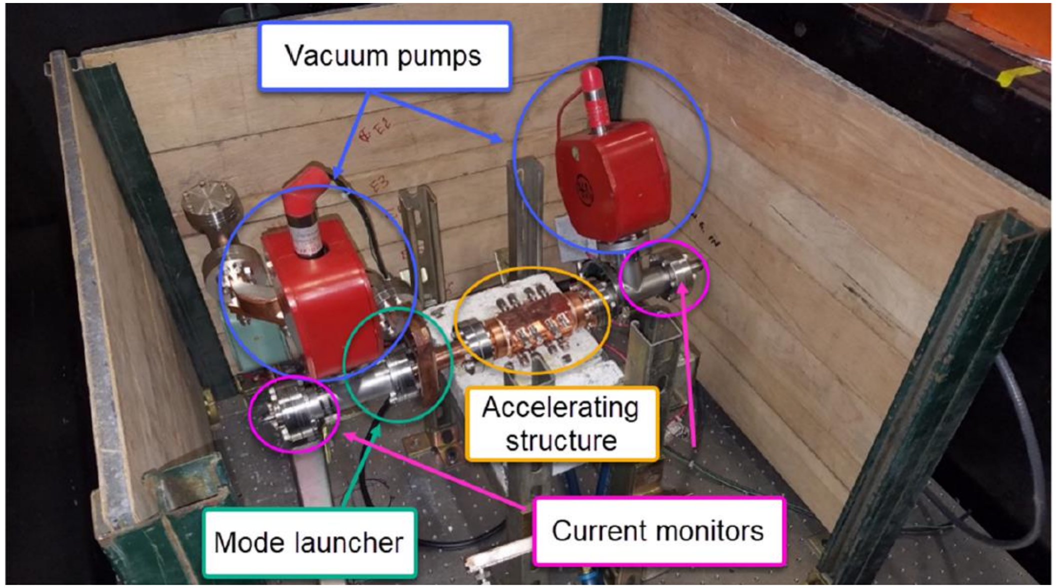


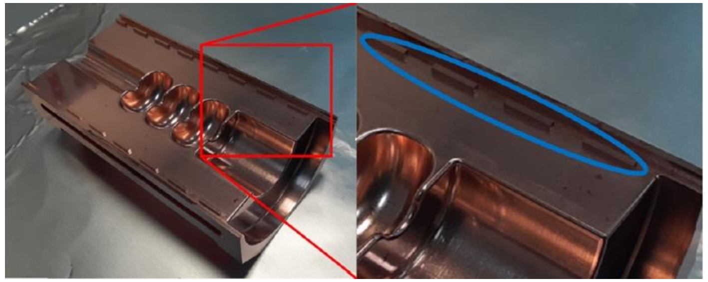


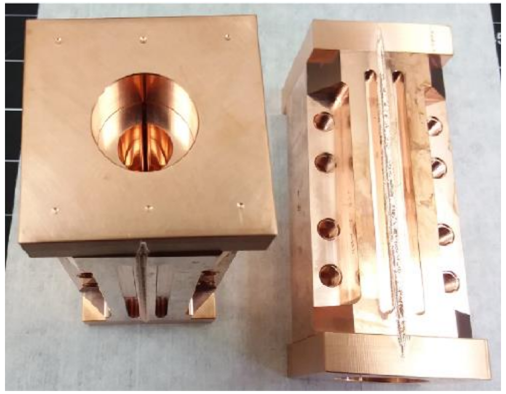
X-band EBW split accelerating structure

- We developed high-gradient X-band accelerating structure adapting the split approach and Electron Beam Welding (EBW)
  - SW 3-cell structure operating at 11.424 GHz
  - Utilized hard copper alloys to improve high-gradient performance over traditional annealed copper structures
- Test performed at SLAC with 600 ns, 60 Hz, up to 3.7 MW demonstrated 140 MV/m gradient with surface peak fields of 400 MV/m, BD rate 10^{-4}/pulse.m
- The split feature results in higher surface fields compared to conventional structures at the same breakdown rate, it provides a great potential for cost reduction of their fabrication

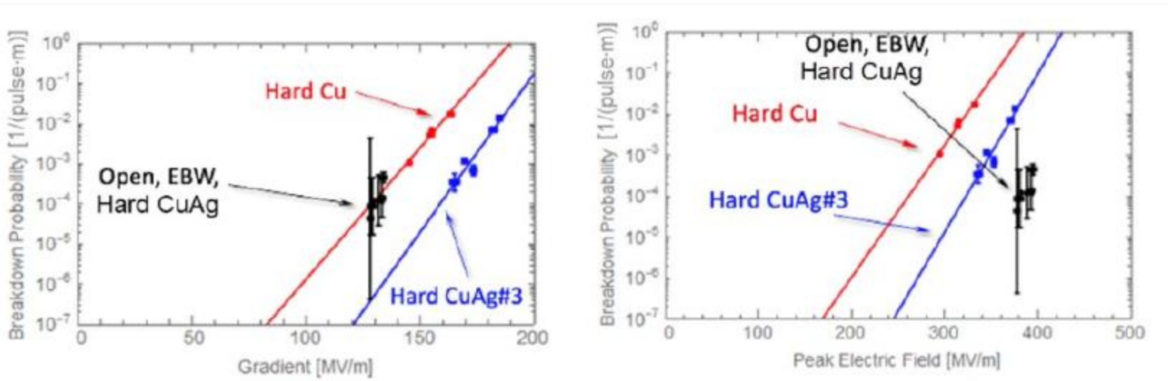
Test setup at SLAC







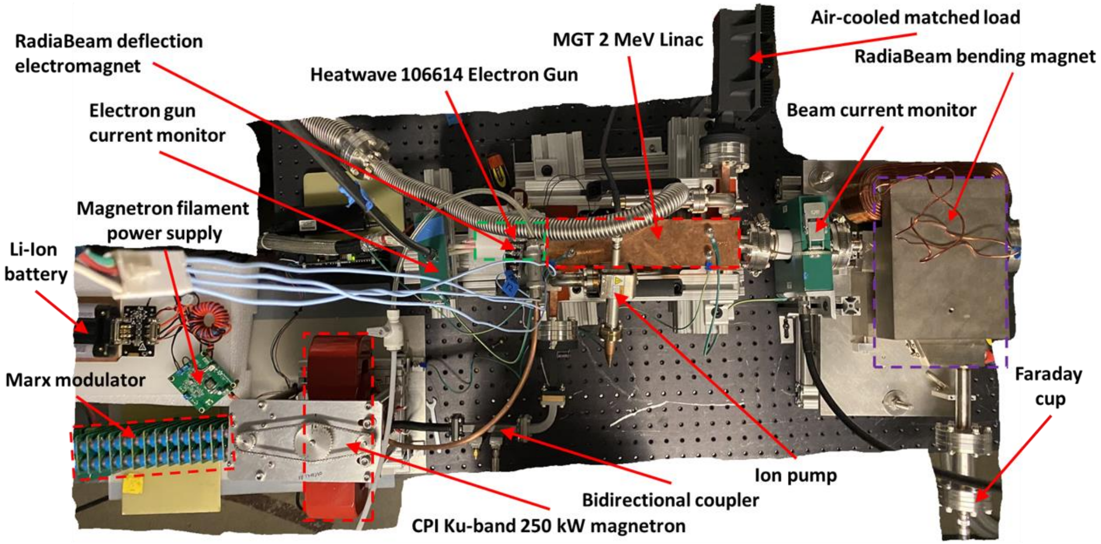
Comparison of EBW split structure with conventional multiple cell structure at 600 ns

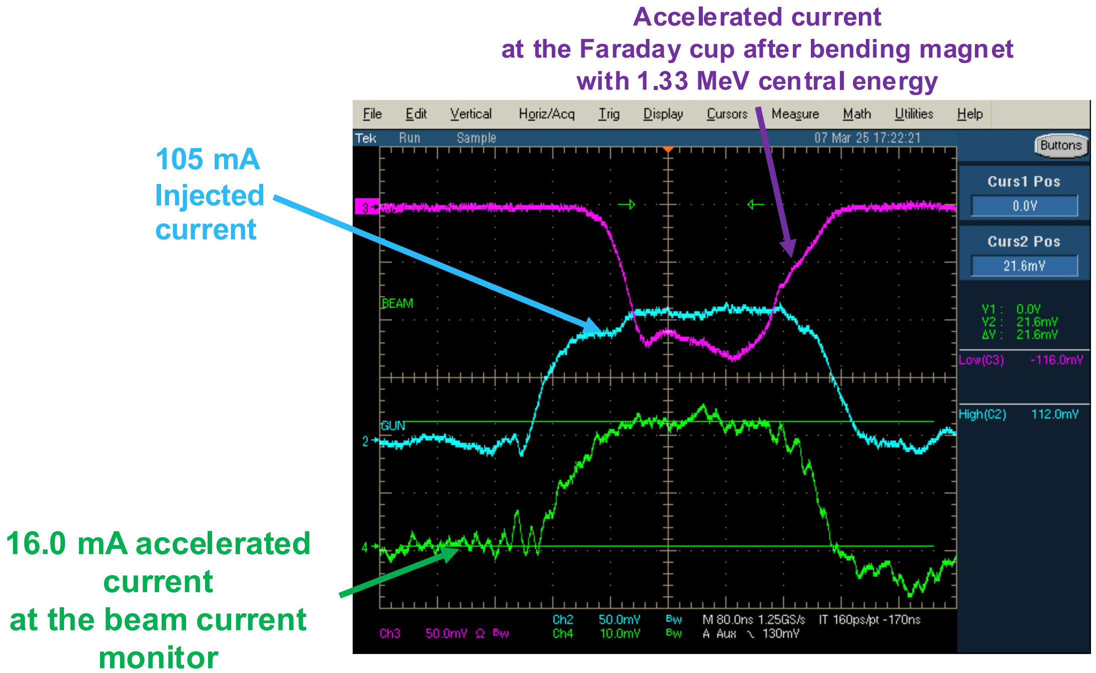


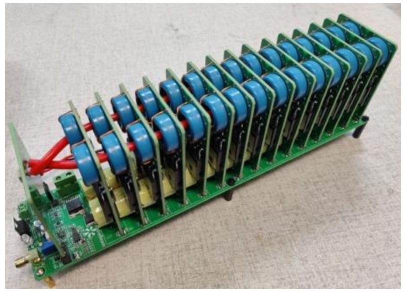
Ku-band Hand-Portable Linac

RadiaBeam

- RadiaBeam has developed a first-of-its-kind hand-portable TW Ku-band (15.1GHz) linac using a split structure approach
  - Up to 2 MeV electron energy to replace Co-57, Ir-192, Cs-137 and X-ray tubes for NDT and Nuclear Safeguard applications
  - ~ 23 kg, > 1 cGy/min @ 1 m
  - 24 kV solid-state Marx modulator ~1.5kg
  - Uses an air-cooled Ku-band magnetron
  - Can be operated from battery or small generator
- We have achieved 1.8MeV beam at 300 Hz rep. rate







Summary

- For over 15 years, RadiaBeam has been developing custom accelerator components from L-band to Ku-band for industrial, and medical applications. We offer comprehensive services encompassing design, manufacturing, high-power testing, and beamline testing.
- Our state-of-the-art C-band facility, capable of supporting up to 50MW, opens the door to a wide range of cutting-edge experiments and technology development programs.
- We’re open to new collaborations. Come explore the possibilities with us!