Development of C-band RF infrastructure and initial experiments at RadiaBeam

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Outline

- About RadiaBeam
- DARPA GRIT program and C-band infrastructure development
- Initial results
- Outlook and conclusions

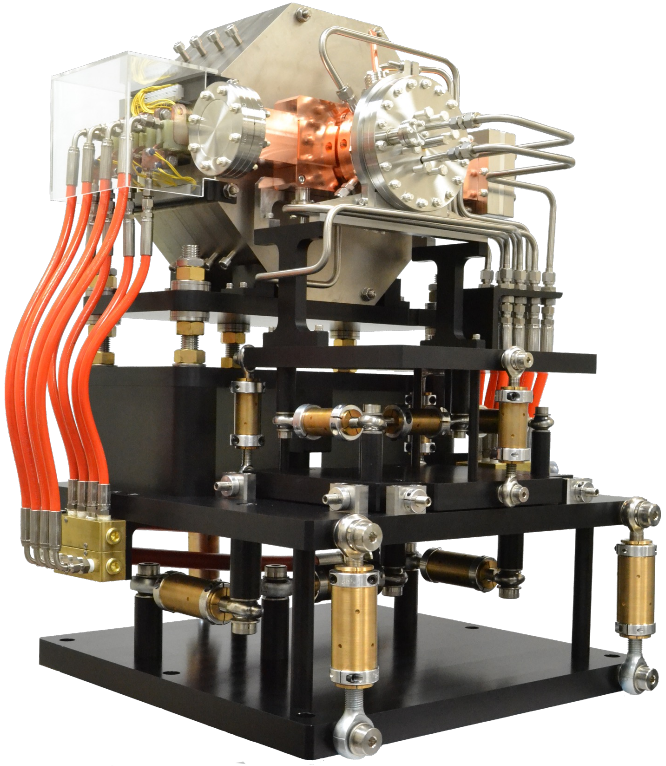
About RadiaBeam

- founded in 2004 (UCLA spin off), ~ 50 FTE, > 30,000 ft^2 facility
- Accelerator R&D, design, engineering, manufacturing and testing all under one roof
- Products: accelerator components (RF structures, magnets, diagnostics), medical/industrial accelerator systems, in-house testing services

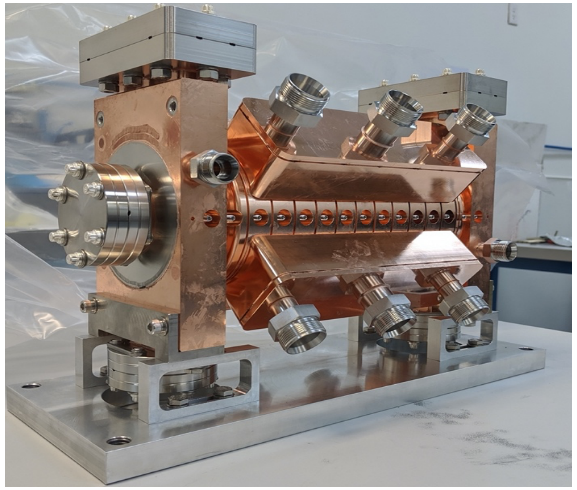
About RadiaBeam

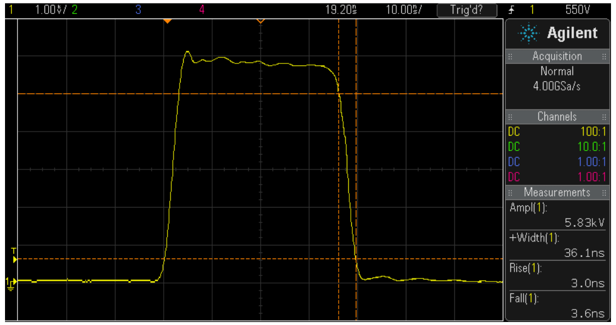
Wide range of capabilities and in-house expertise:

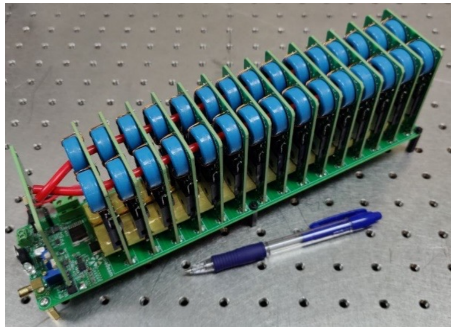
- **RF design and engineering, microwave sources, modulators and power electronics**
- Magnetic design, engineering, alignment, production and testing
- UHV systems, beamline instrumentation and diagnostics



1.6 cell S-band photoinjector (4 units sold)







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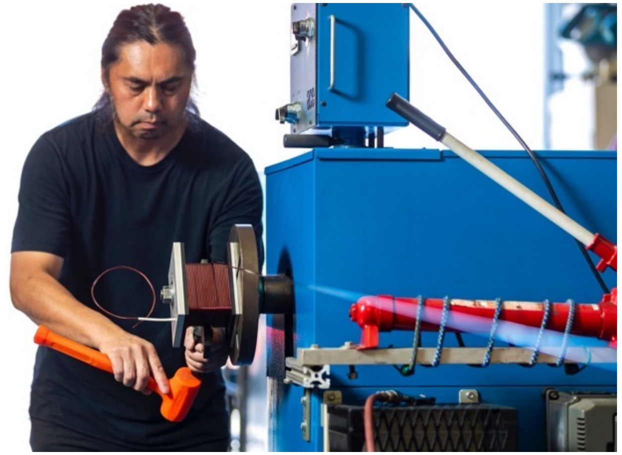
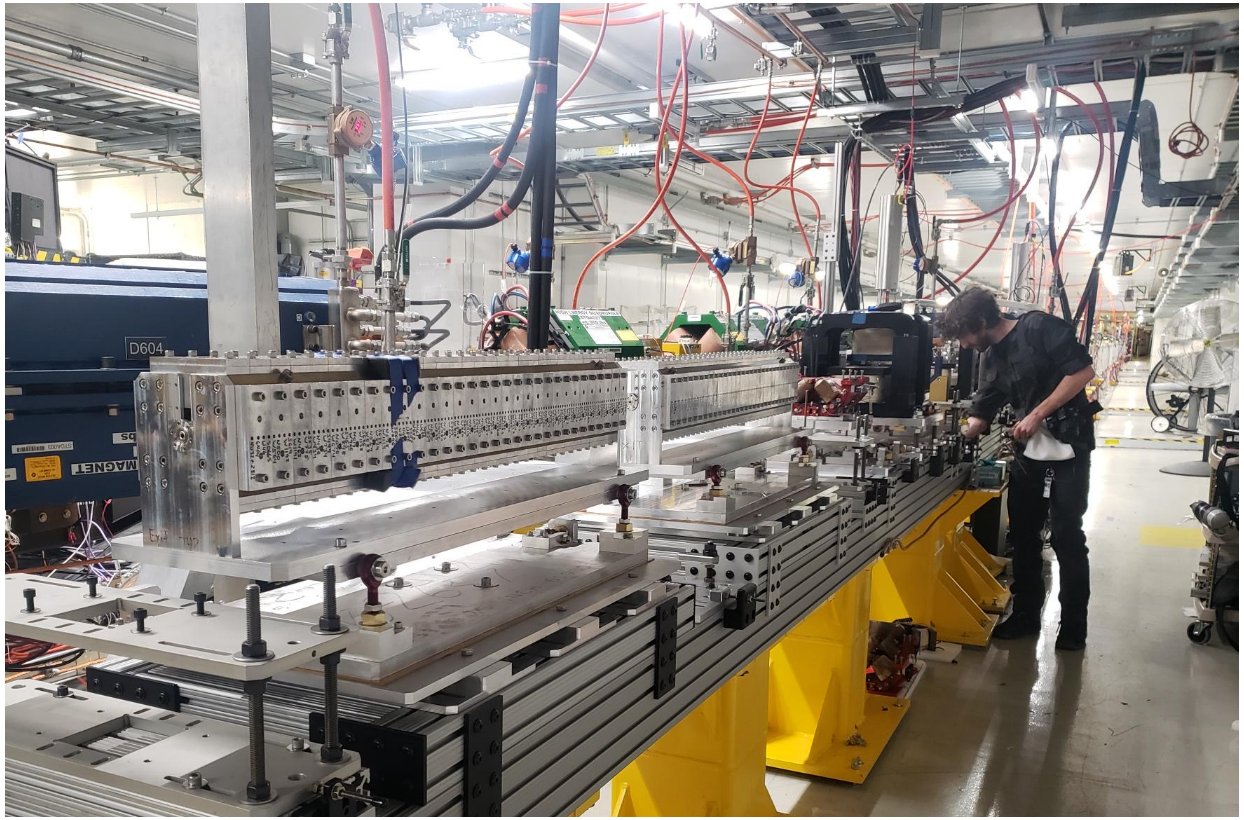


TESSA helical tapered undulators installed at Fermilab FAST facility



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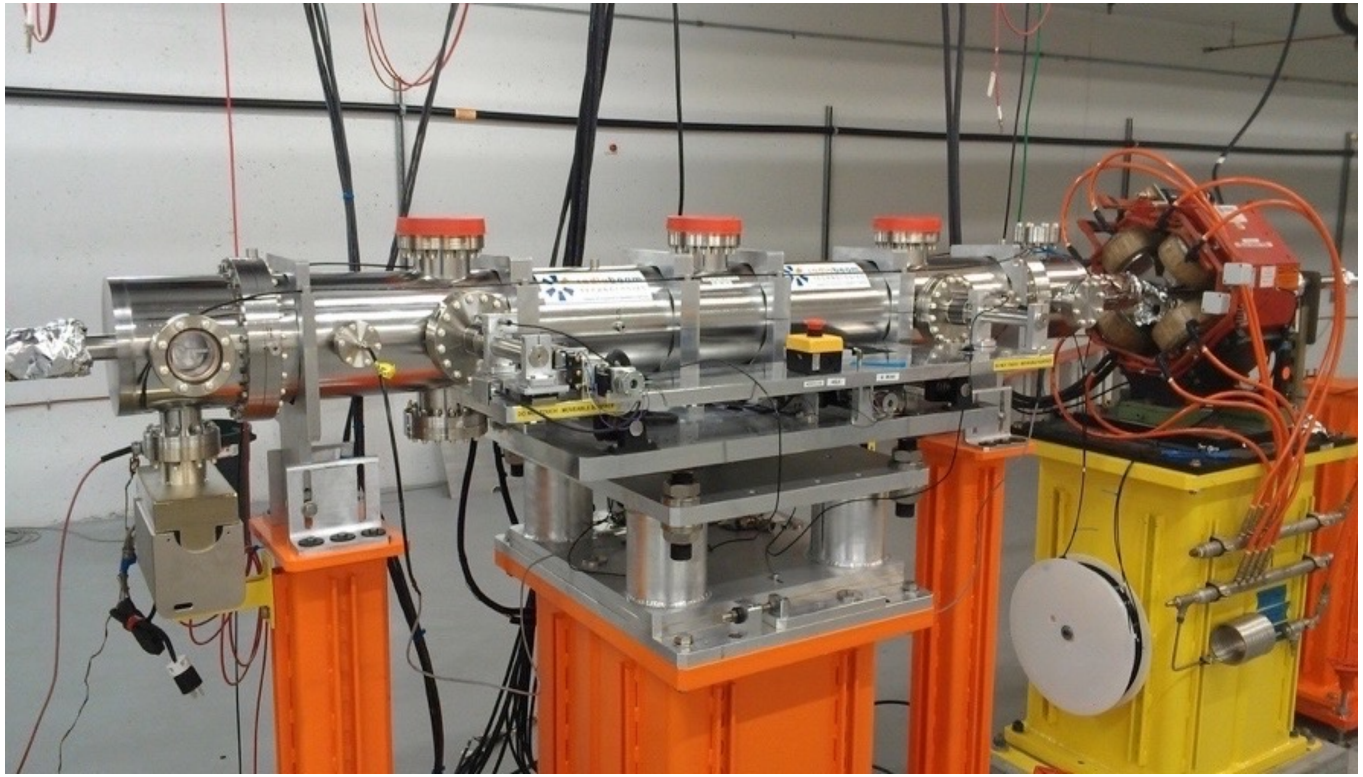
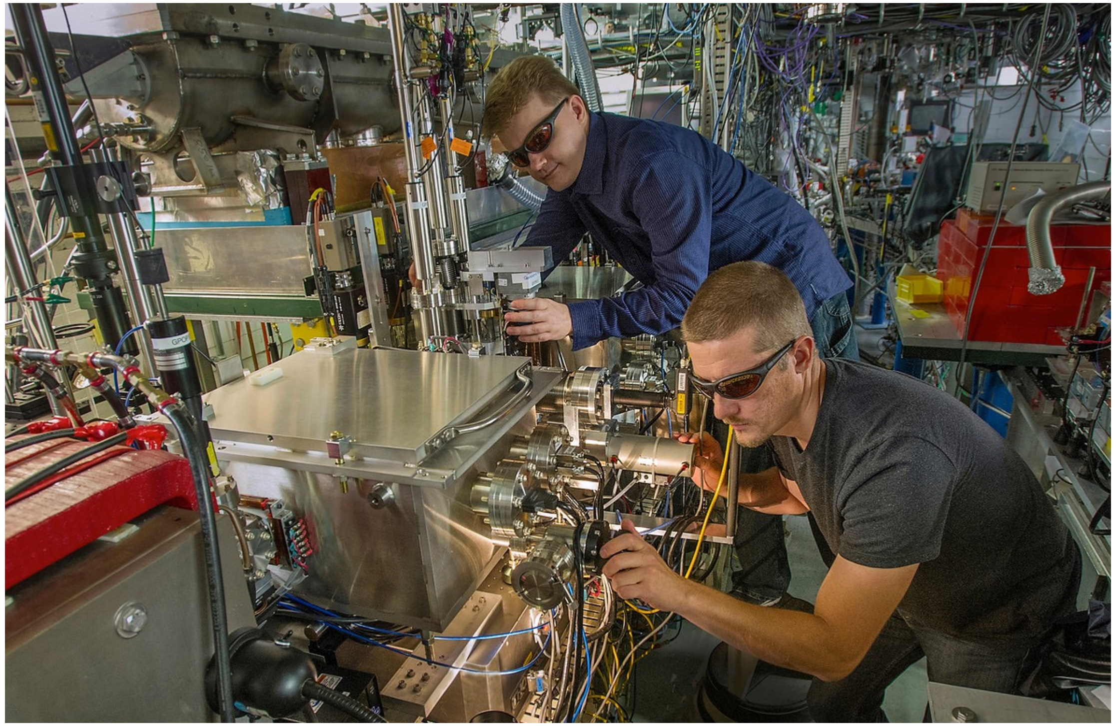


4-m long, adjustable gap corrugated pipe dechirper (has been operational at LCLS facility since 2016)

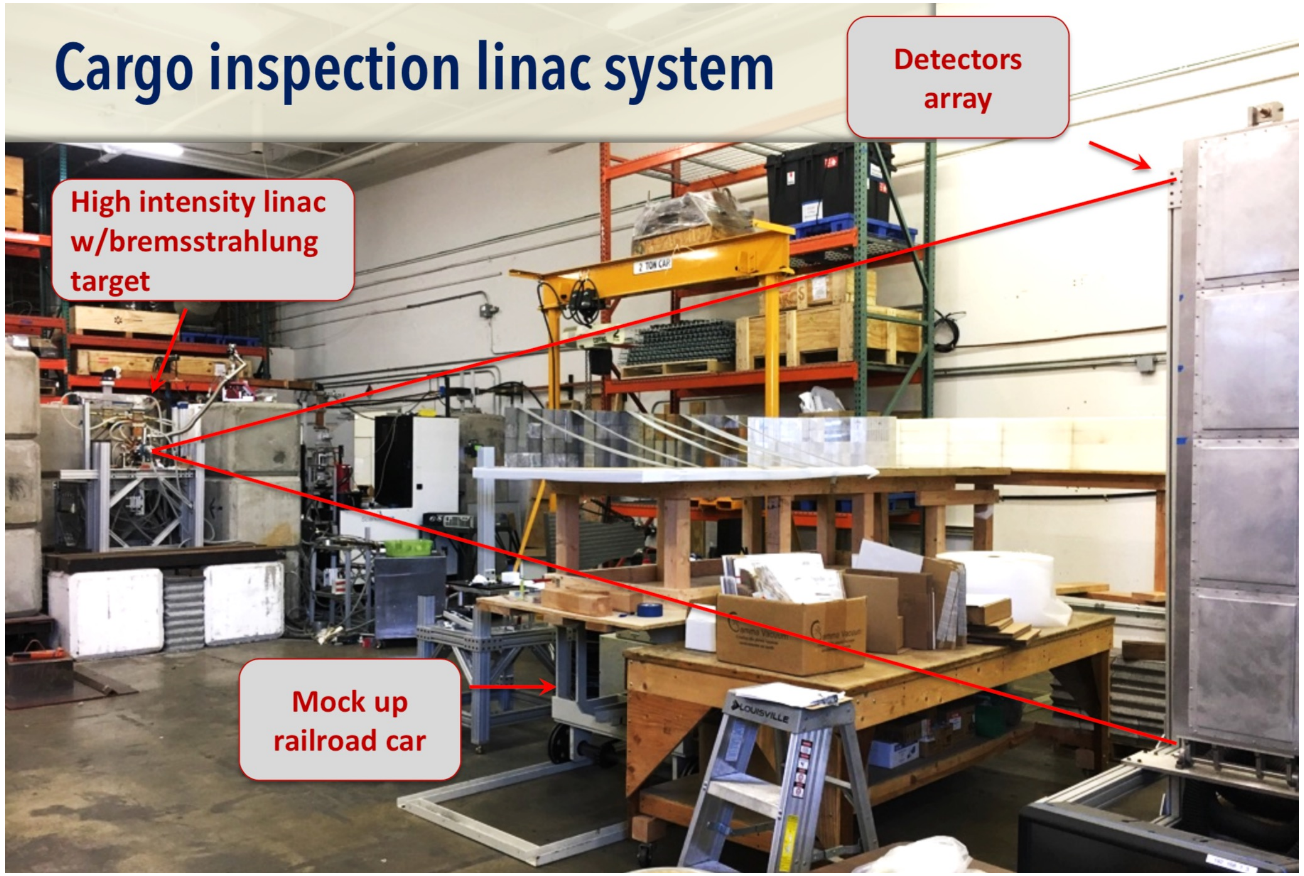


Pulse train beam-laser interaction chamber at ATF BNL

About RadiaBeam

Industrial linac, and irradiation systems pipeline

- OEM medical and industrial linacs
- Custom systems for specialized applications
- R&D pipeline, and in-house testing services



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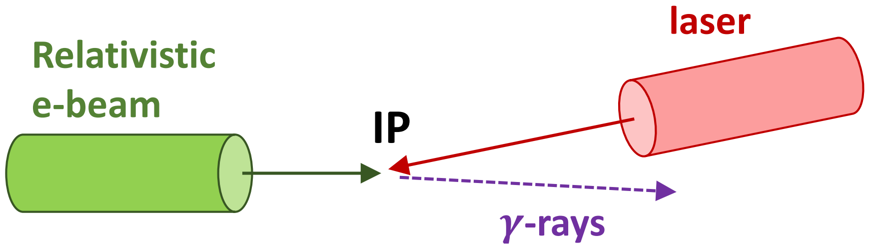
GRIT BAA requirements

- RadiaBeam has been working for years with UCLA and Amplitude on the Inverse Compton Scattering (ICS) X-ray source development, so we responded to the BAA
- In 2019 DARPA issued a call for a compact tunable gamma ray source (GRIT BAA)

Objectives	Parameter	TA 1 Phase 2
Intensity	Intensity (ph/s)	10^12
	Repetition Rate (kHz)	1
Tunability	Tunable Energy Range (MeV)	0.03 – 3
Purity	Bandwidth (dE/E)	< 0.1%
Compactness	Size (m) (40' Conex internal dim)	< 2.4 x 2.3 x 12.0
	Weight (kg)	< 16,000
	Power (kW)	< 300



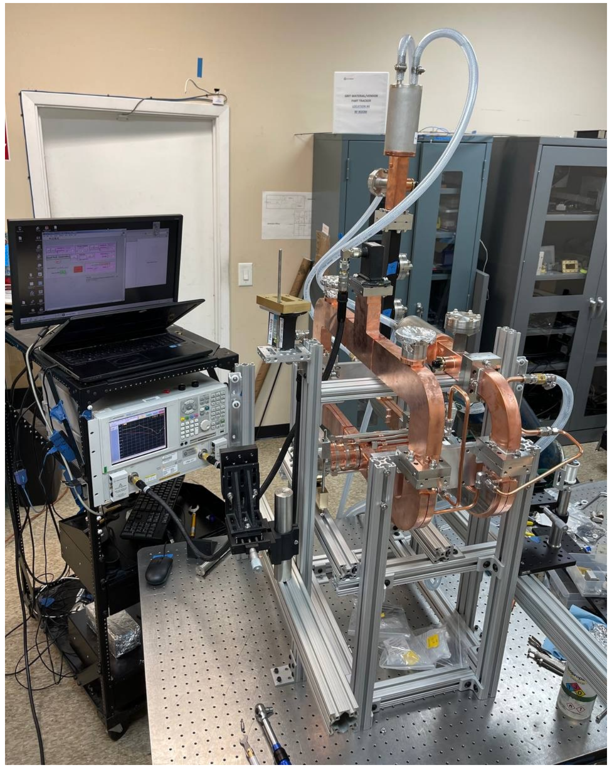
$$k_r \approx 4\gamma^2 k_L$$

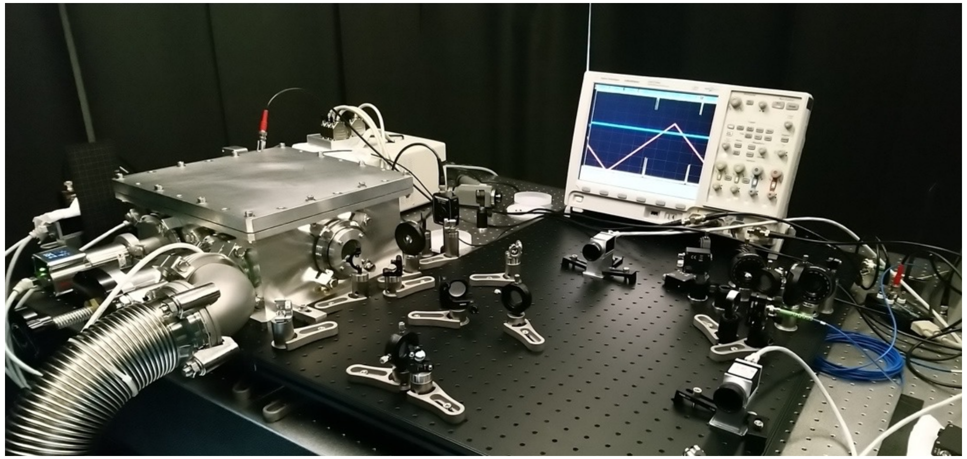
$$\sigma_{th} = \frac{8\pi}{3} r_e^2 = 6.65\times10^{-25}\ \text{cm}^2$$

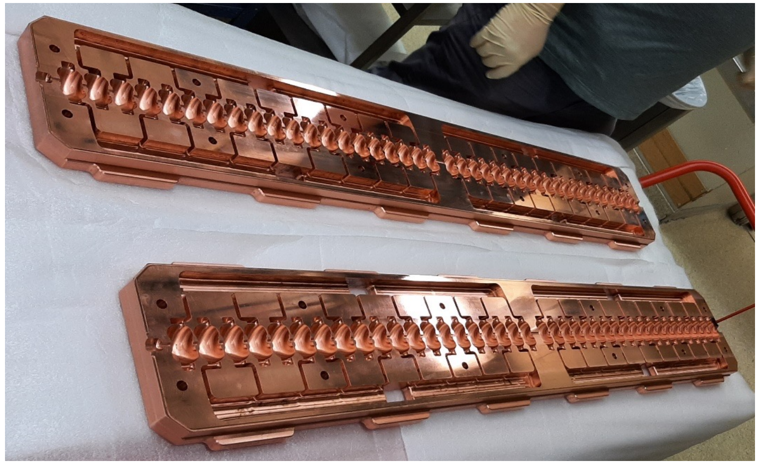
- ICS is the only path known to us to achieve the desired purity and tunability range
- To achieve flux requirements, we can not afford laser frequency conversion losses, and at 1 µm laser wavelength 3 MeV converts into the 400 MeV e-beam energy
- **Combined with the 12 m footprint, we need > 50 MeV/m acceleration**

GRIT collaboration

- The collaboration predated GRIT program with the focus on the high flux hard X-ray compact ICS sources for medical and inspection applications.
- The system combines 3 innovative components:
  - Fabry-Perot optical cavity and solid-state laser system (collaboration with Amplitude)
  - High gradient C-band linac (collaboration with SLAC)
  - Hybrid C-band photoinjector (collaboration with UCLA)







radiasoft

Amplitude

RadiaBeam

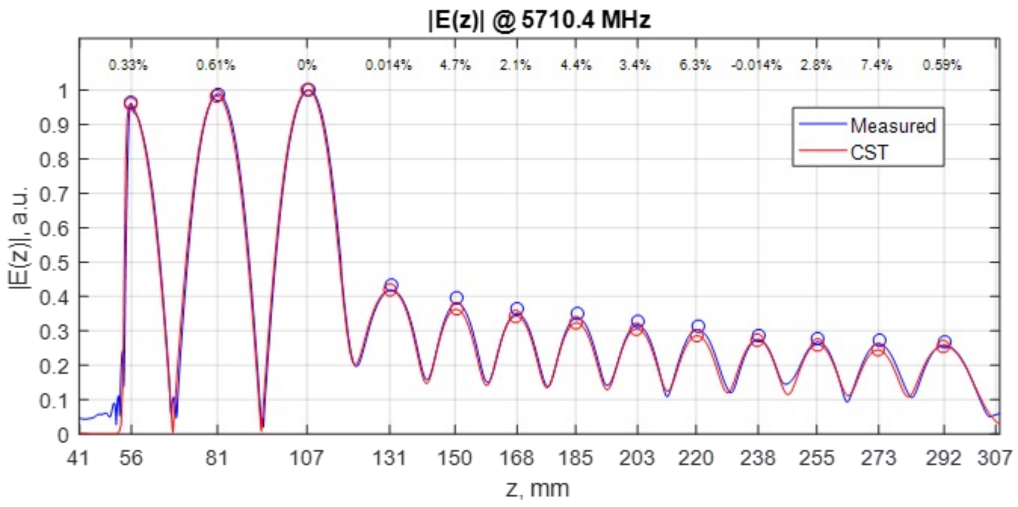
SLAC NATIONAL ACCELERATOR LABORATORY

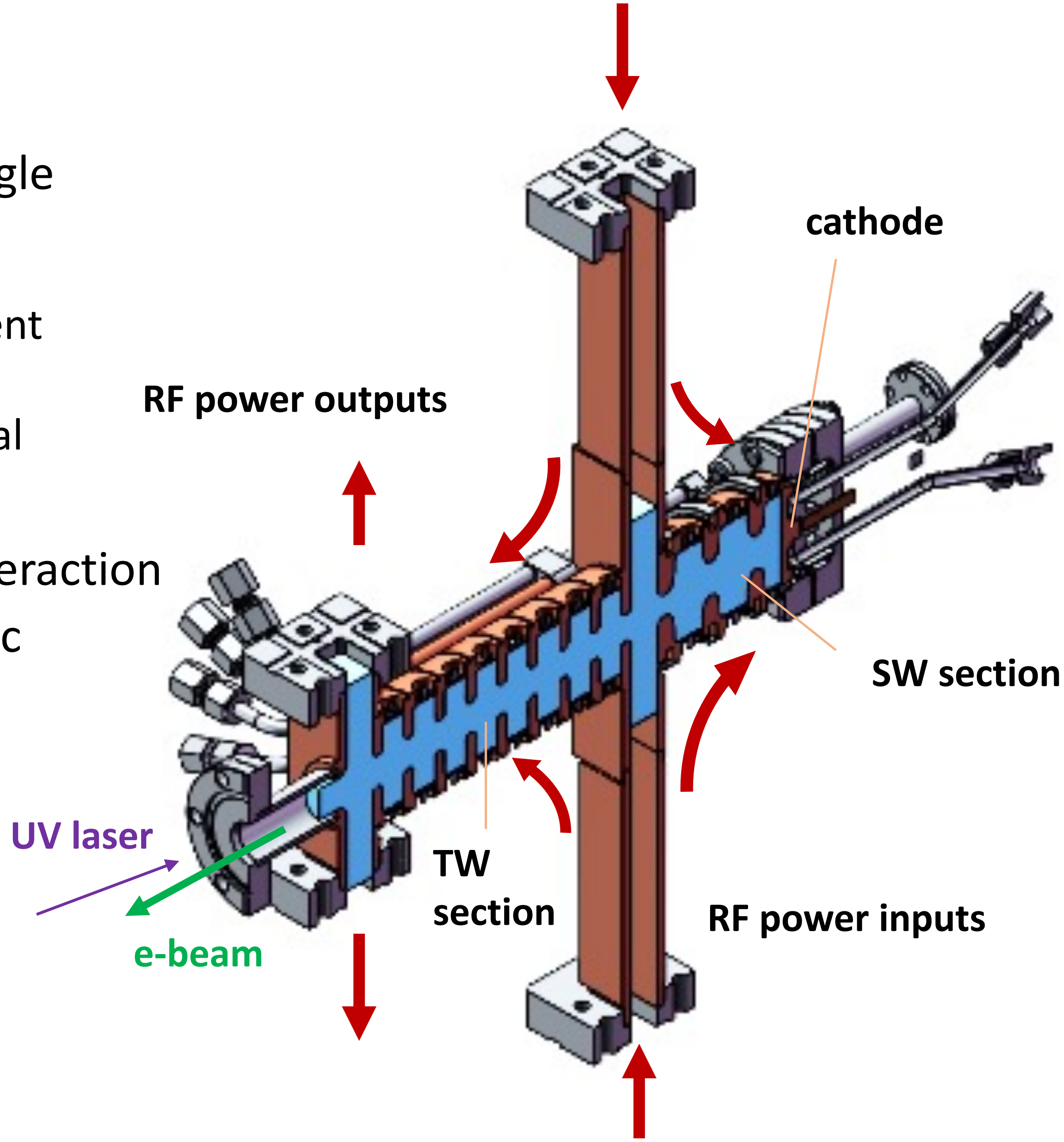
UNIVERSITY OF MICHIGAN

UCLA

Hybrid photoinjector

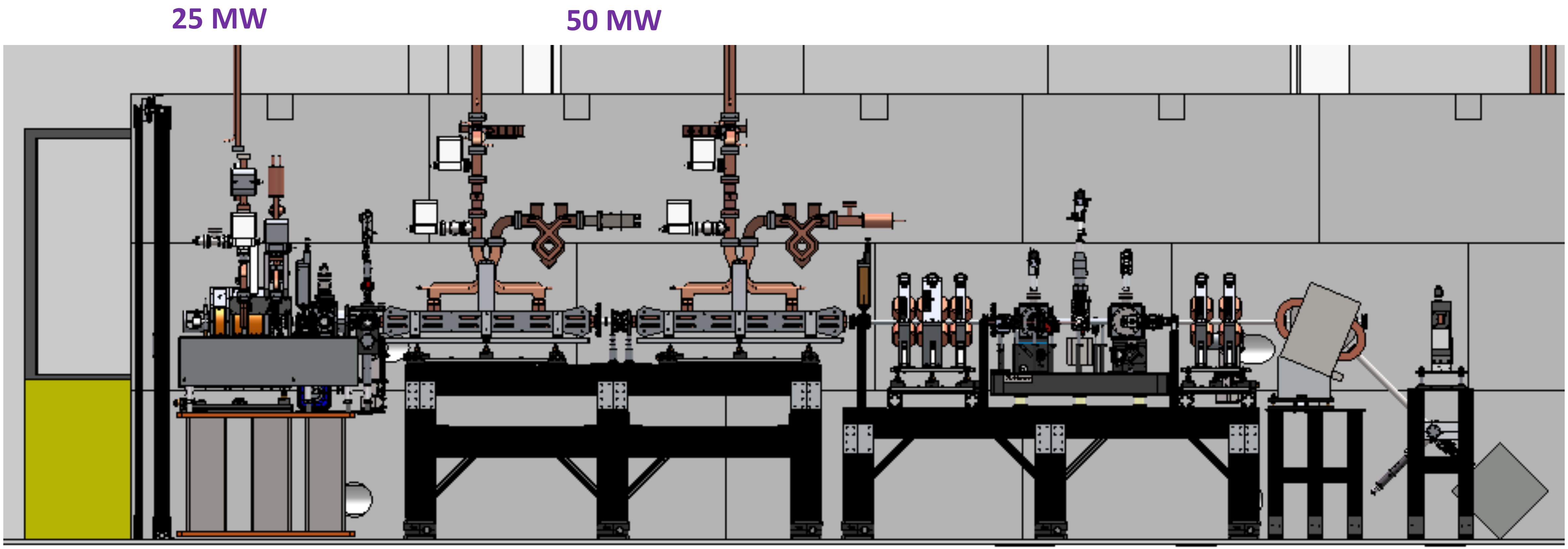
- Hybrid incorporate two C-band RF cavities in a single device:
  - Standing Wave (**SW**) RF cavity provides high gradient acceleration (120 MV/m at cathode)
  - Traveling Wave (**TW**) RF cavity provides longitudinal compression up to 500 A
- Hybrid allows to reduce ICS footprint, increase interaction efficiency, and improve beam dynamics in the linac





Beamline Overview

- 2 RF stations provide power to hybrid gun and 100 MeV linac module, respectively
- Magma 25 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

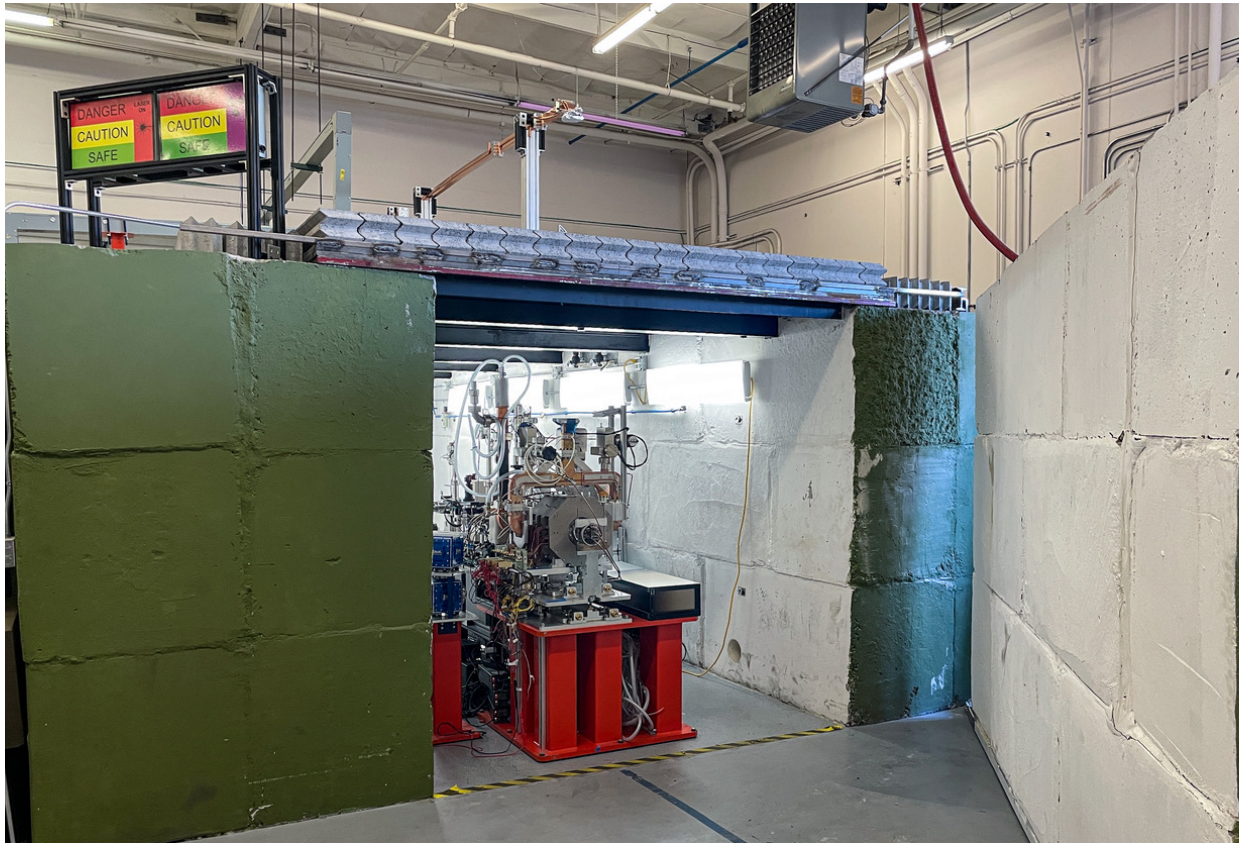


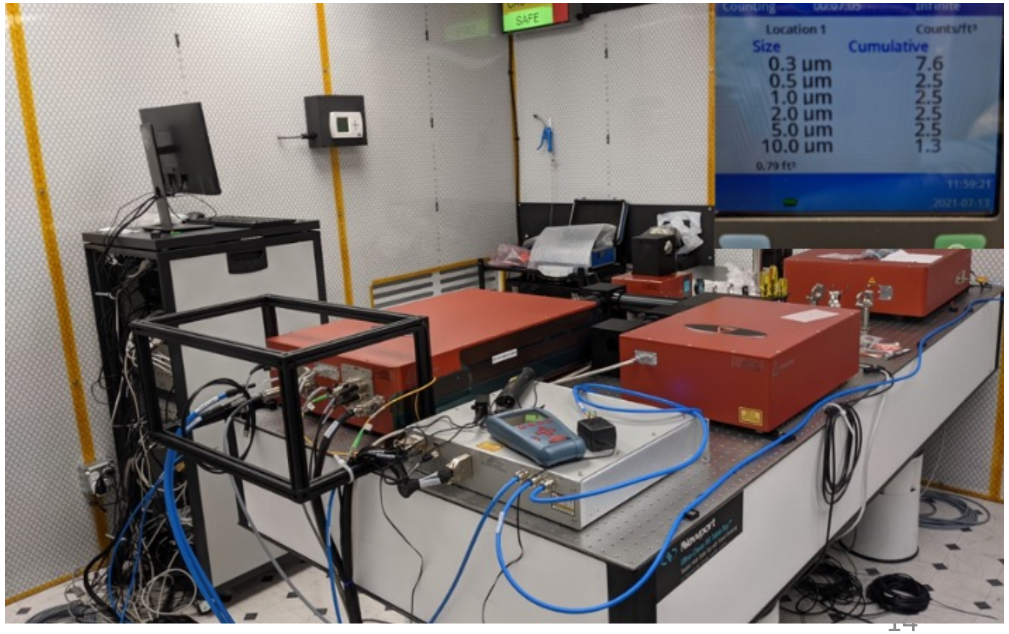
Phase I Timeline

- We received DARPA contract on March 19, 2020, 1 week after COVID shut down
- By June 2020 we were able to place critical purchase orders for C-band RF power stations, Magma 25 laser system from Amplitude, and most of the RF network and LLRF sub-components
- 2021: C-band hybrid engineering and fabrication, laser infrastructure development, RF systems assembly, commissioning and components testing, facility engineering
- First photocurrent was obtained in April 2022, in the industrial linac test cell
- Summer 2022, installed new 100 MeV bunker to host the complete 100 MeV system
- In October 2022, and we are back to the hybrid commissioning mode in the new bunker
- SLAC is planning to deliver linacs, and phase shifter system in Summer 2023
- The goal is to commission 100 MeV beam in Fall of 2023 and demonstrate first ICS photons before the end of CY2023.

Other sub-systems development

- C-band RF power stations and C-band infrastructure
- IR laser and photoinjector drive laser systems
- Radiation shielded bunker





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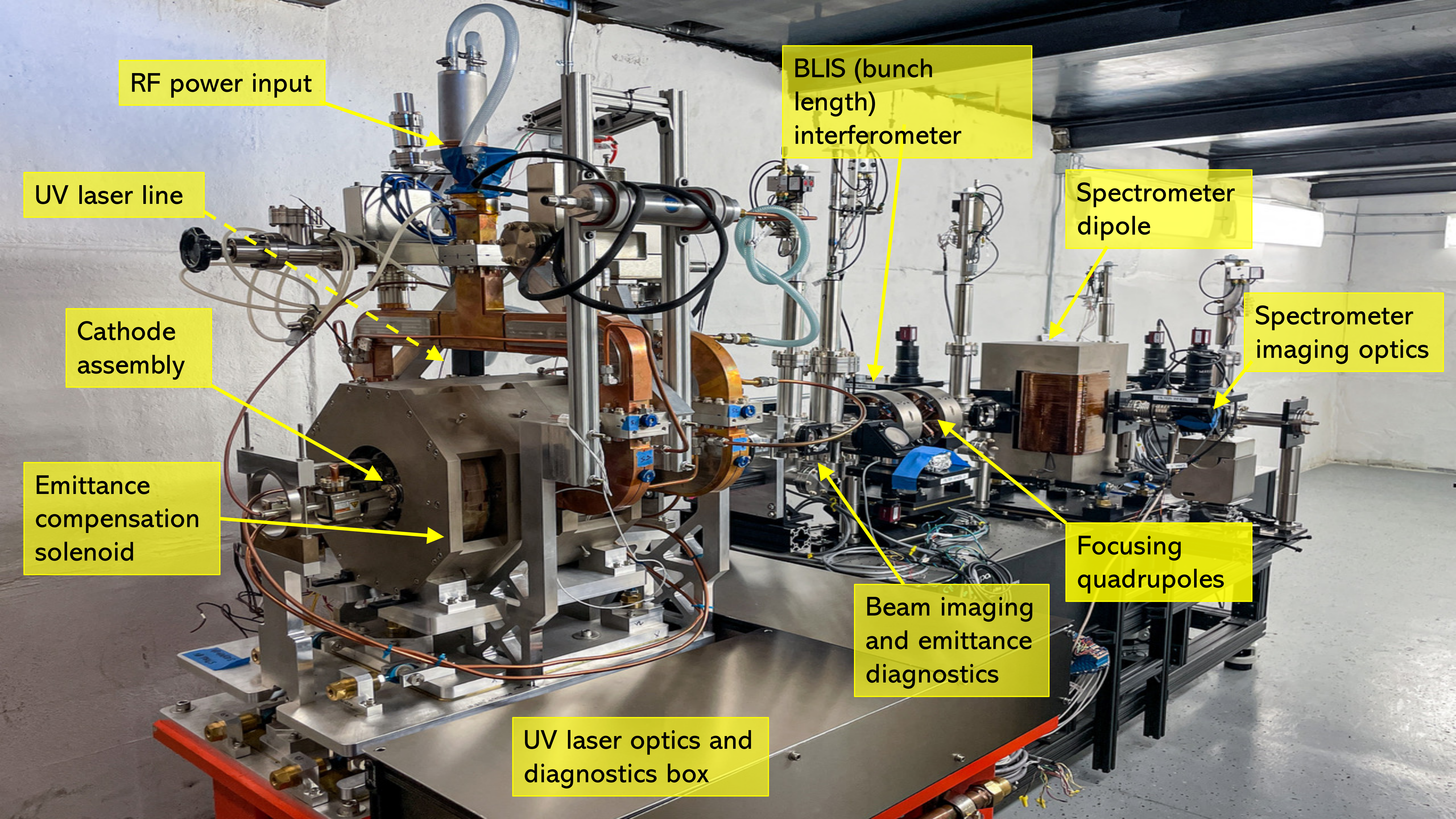
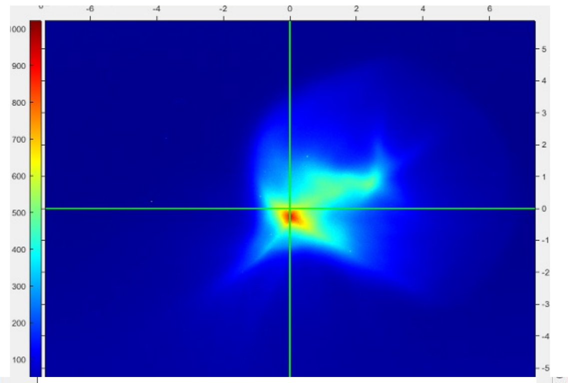
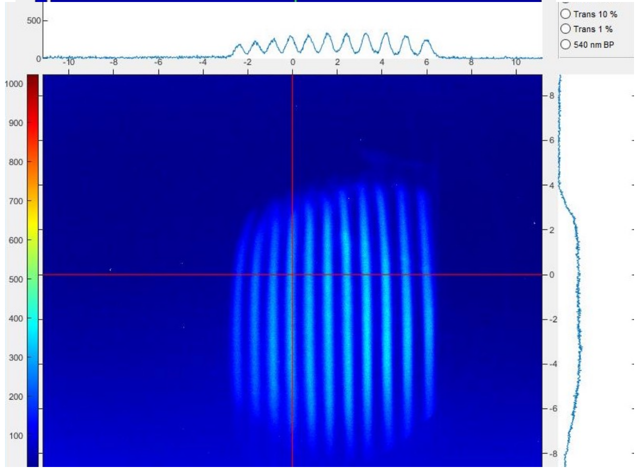

RF power input
UV laser line
Cathode assembly
Emittance compensation solenoid
BLIS (bunch length) interferometer
Spectrometer dipole
Spectrometer imaging optics
Focusing quadrupoles
Beam imaging and emittance diagnostics
UV laser optics and diagnostics box

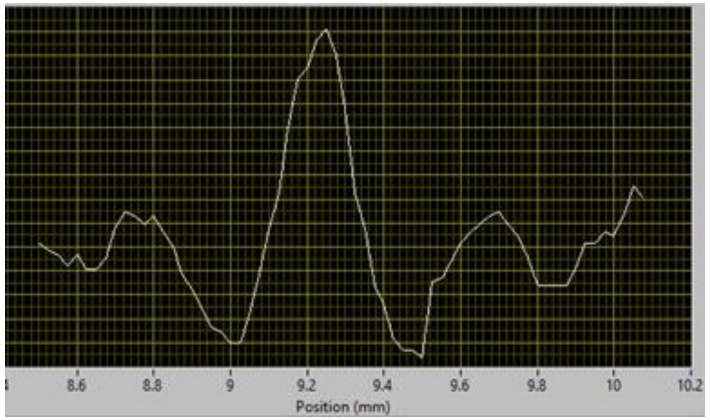
Hybrid commissioning results, so far

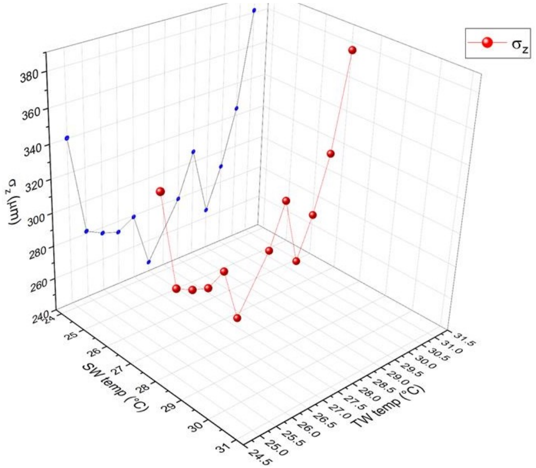
Parameter	Units	Design	Measured	Comments
Beam Energy	MeV	4.4	4.6 ± 1.0	Depends on the RF phase and temperature tuning of the TW section
Energy spread, RMS	%	< 1%	0.1%	Excluding the tails
Beam charge	pC	250	150 - 350	QE ~ 4 x 10^{-5}
Bunch length, FWHM	ps	< 1	1-2	Data are still to be analyzed, but it looks like we have > 200 A peak current
Emittance (normalized)	µm	< 0.8	< 3	Slits are in the wrong place on the beamline, so this is not an optimal value

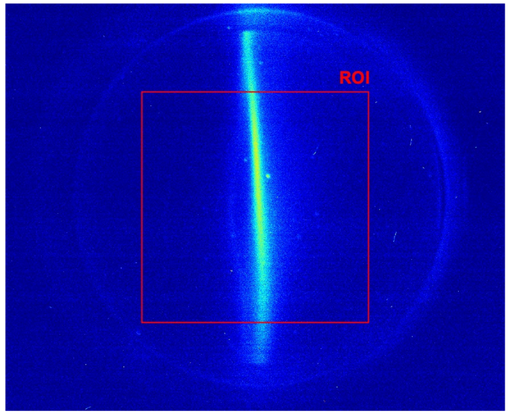




Slits image



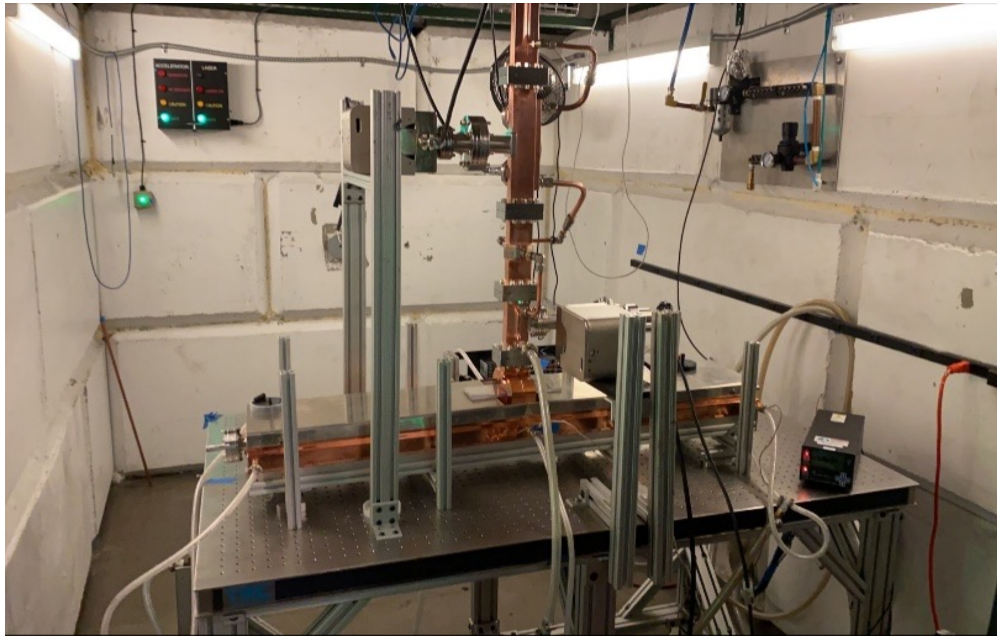


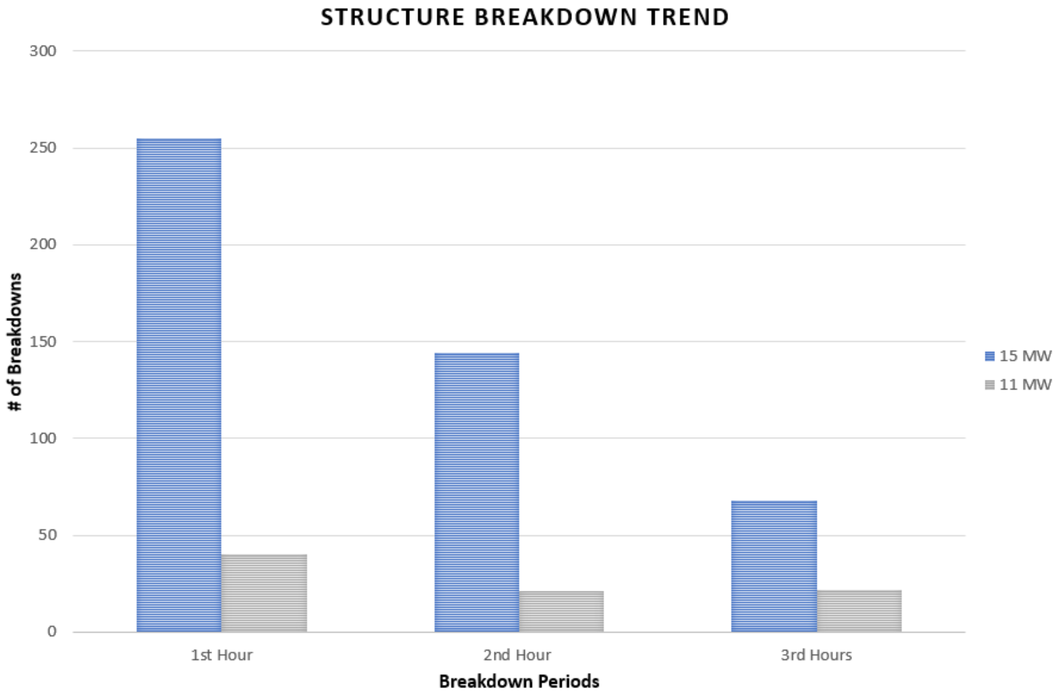


Spectrometer Line YAG

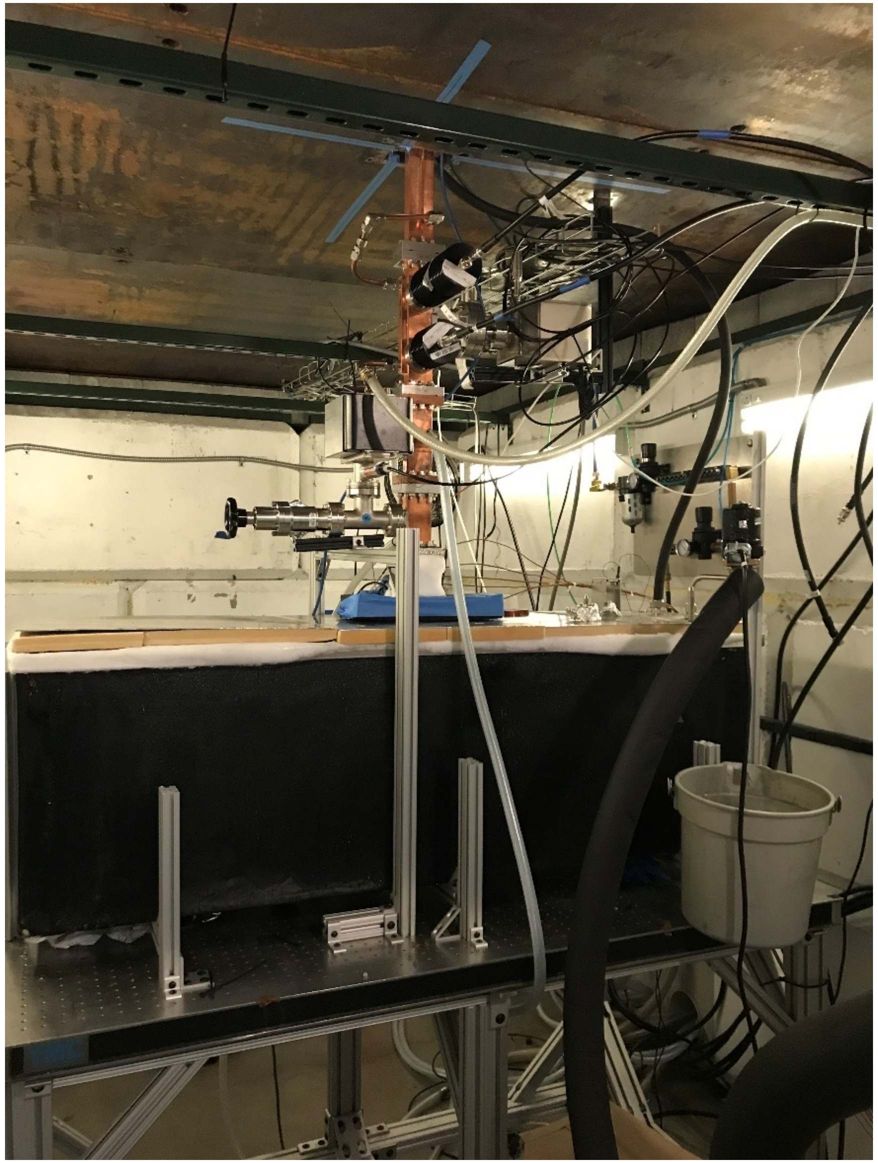
Other experiments: testing C-band Structure

- In support of the SLAC C^3 R&D program we conducted a number of hot tests, using the GRIT C-band infrastructure
- Utilized 25 MW C-band power station to test SLAC prototype linac structure
- Conditioned the structure while monitoring breakdown rate and vacuum
- Conditioned up to 15 MW, 100 Hz, 1 µs pulse width
- Saw expected breakdown rate decline over conditioning period

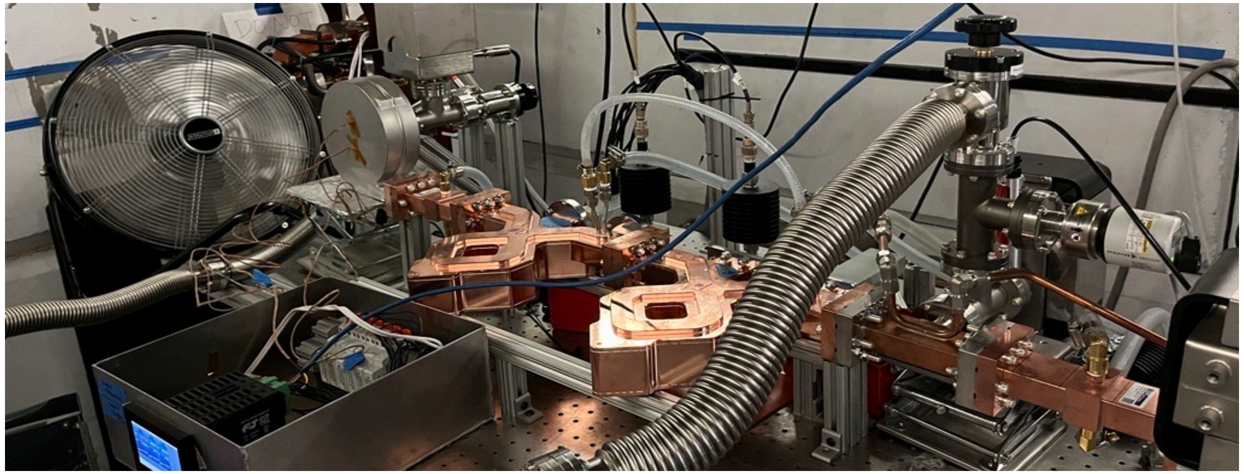




Testing: Cold C3 Structure



- Repeated the test of the same structure, at LN2 T
- Conditioned up to 10 MW, 100 Hz, 1 μs pulse width
  - Suspected ion pump failure halted progress
- There were no significant RF breakdown events
  - There was some breakdown in waveguide close to structure
- LN2 burn rate was 230 liters per day
  - Did not try to optimize setup
- *In addition, conducted tests of C-band RF components in support of SLAC program*.



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C-band facility outlook

- Thanks to DARPA GRIT program, we developed a C-band photoinjector facility, currently under commissioning; a 100 MeV upgrade is expected to be completed in 2023
- The facility is already producing useful results, and can serve accelerator community in many areas including C^3, AAC, and light source R&D, as well as RF components and beamline instrumentation development and testing
- There is no such concept as operational or development funds for businesses in DOE ecosystem (procurement and SBIR program are the only DOE sources of funding known).
- **In 2023 DOE introduced 50-70% cuts in the AT components of the SBIR program**
  - This was historically the critical DOE program to support R&D activities by small businesses
  - These cuts affect RadiaBeam and other companies in the field, and may result in a major loss of capabilities and trained personnel within 1 -2 years
  - Putting in question ability of the US small businesses to remain a part of the accelerator community
- We look for a community feedback, on the ideas how to support these new capabilities in this new environment, after DARPA program is completed

Conclusions

- RadiaBeam is a small business currently focused on the accelerator technology development for research and industrial facilities and applications
- Thanks to DARPA GRIT program, RadiaBeam has put together a C-band infrastructure and photoinjector laboratory, and have plans and funding for 100 MeV upgrade by the year end
- The C-band infrastructure (and trained personnel) developed for the GRIT program can be utilized for other projects, including C^3 R&D
- We are looking for new ideas on how to sustain and further develop GRIT facility once the DARPA program is completed

- Acknowledgement: GRIT program has been a fast paced, dynamic team effort, and there a long list of contributors to this talk at RadiaBeam, SLAC, UCLA, Amplitude, RadiaSoft and other participating institutions