RadiaBeam

Cool Copper Collider Workshop
Buffalo Thunder, NM

High Gradient C-band Activities Report

Alex Murokh, *RadiaBeam Technologies, LLC.*

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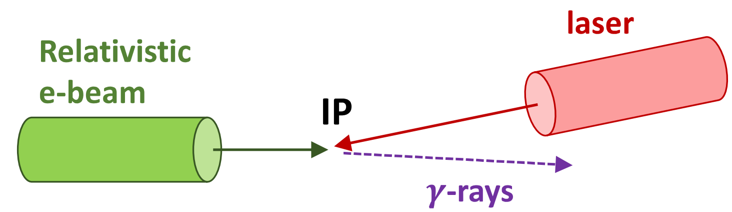
Outline

- DARPA GRIT program
- GRIT C-band sub-systems and infrastructure development
- Other relevant activities at RadiaBeam

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



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

$$\sigma_{th} = \frac{8\pi}{3} r_e^2 = 6.65 \times 10^{-25}\ \text{cm}^2$$

- 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 BAA

- High gradient brings us to either C-band or X-band NCRF linac solution
- High flux requirement favors C-band: long pulse trains and high r.r. can be supported by Cannon klystrons, and larger linac aperture can support longer pulse trains without a breakup.

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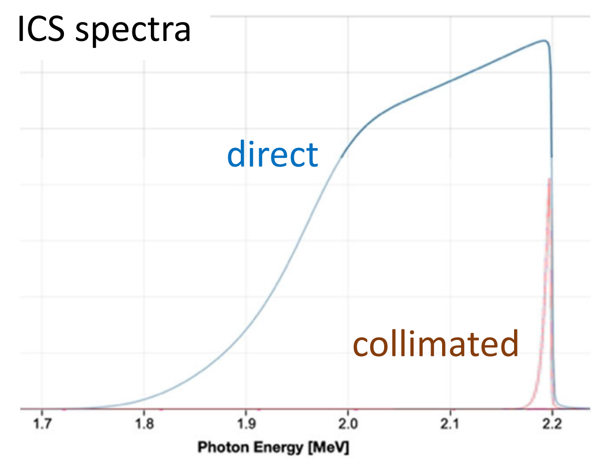
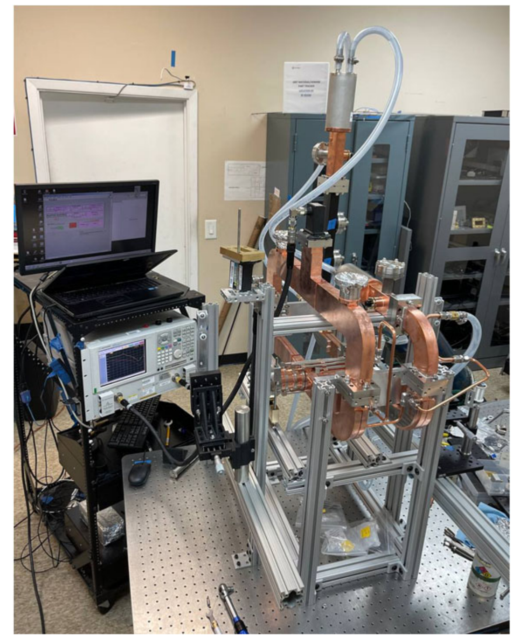
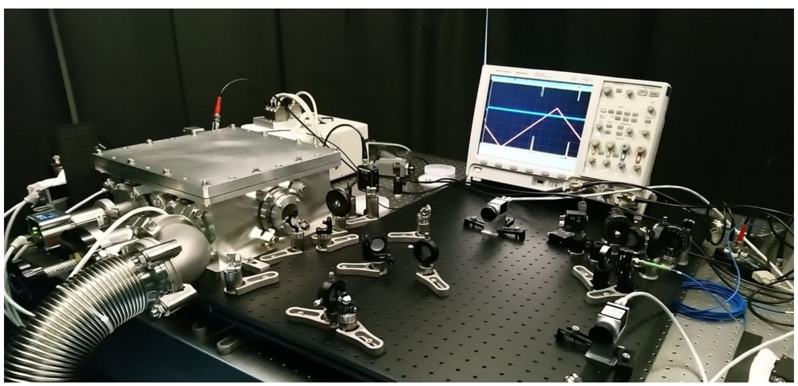


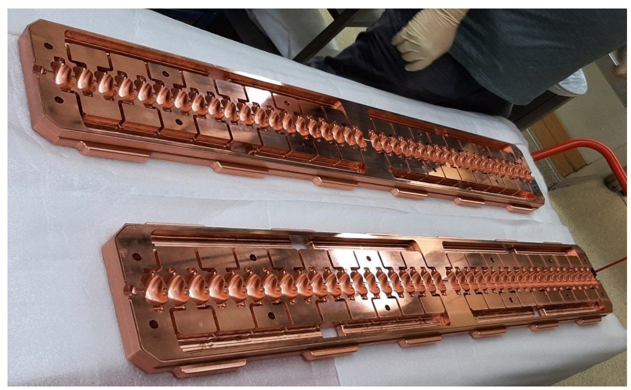
- **Still with the best RF power sources and laser drivers available we could not identify a path to achieve the desired flux and purity without going to cold RF (C^3), which was proposed**
- The contract was awarded in March 2020 for the Phase I scaled study, and eventually the flux and purity requirements were decoupled, enabling a room temperature solution.

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

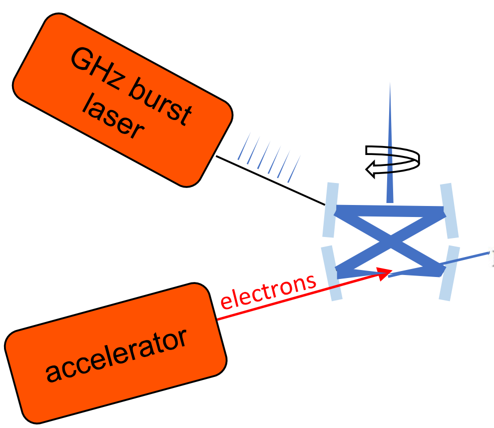
SLAC NATIONAL ACCELERATOR LABORATORY

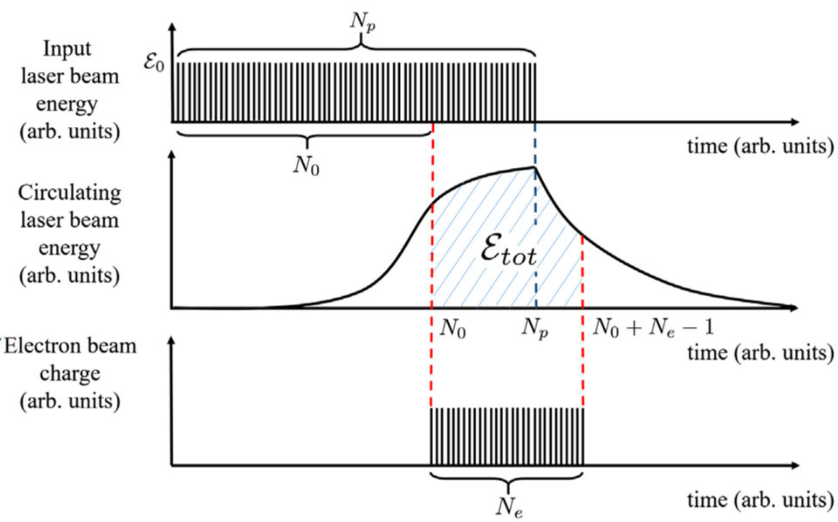
UNIVERSITY OF MICHIGAN

UCLA

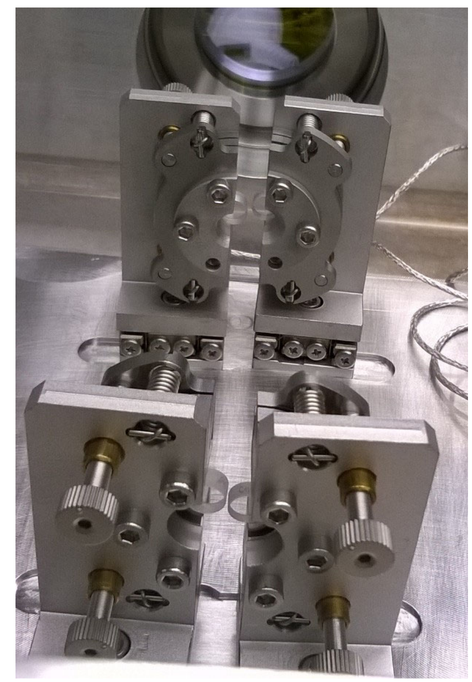
Fabry Perot Cavity (FPC)

- Burst mode pulse stacking cavity enables high finesse laser power amplification at the ICS interaction point in the burst mode (up to 1 kHz, 5 µs bursts)
- A prototype FPC is currently being developed at Amplitude, and will soon become available at RadiaBeam for pulse train ICS experimentation
- This technology is scalable to 10^5- 10^6 interactions/s

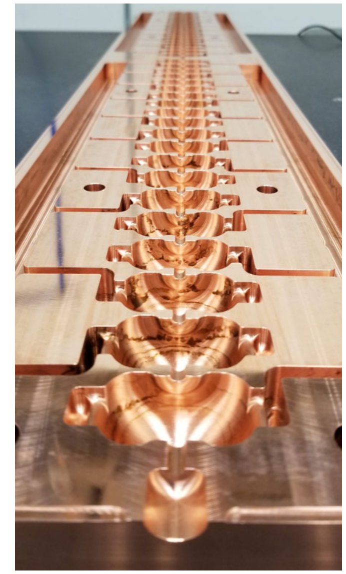




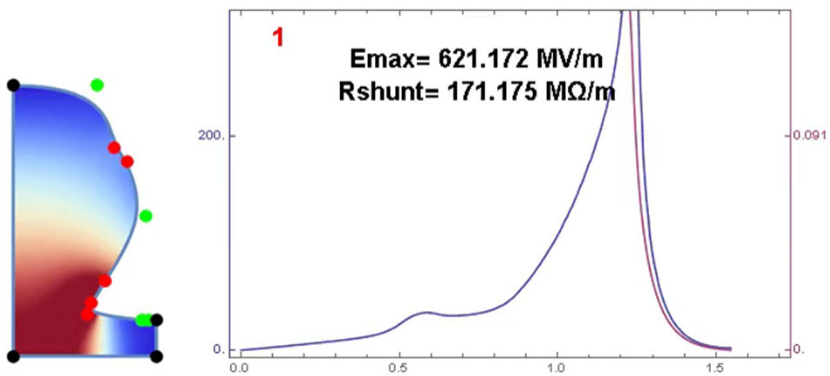
L. Amoudry et al. "Optimization of a Fabry-Perot cavity operated in burst mode for Compton scattering experiments," PR AB ***21****(12), 121601(2018).*



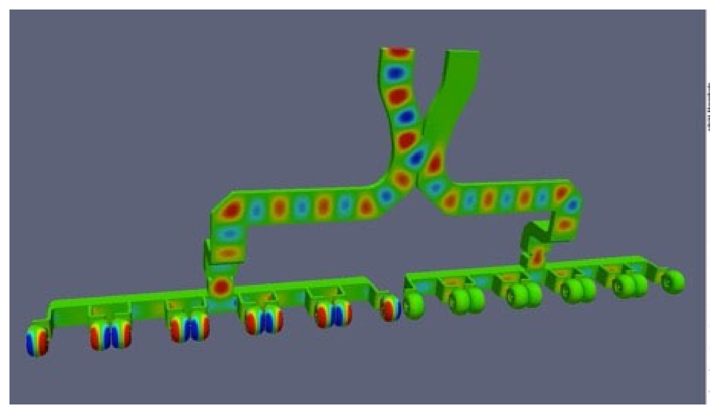
C-band high gradient linac



- *A split structure distributed coupling C-band linac* .
- The split structure geometry enables manufacturing the structure in two halves, which is less expensive process than a conventional cell by cell manufacturing.
- In addition, such open structure geometry enables unlimited freedom in optimizing the shape of the cells, thus optimizing the performance
- First 2–meter module is in fabrication

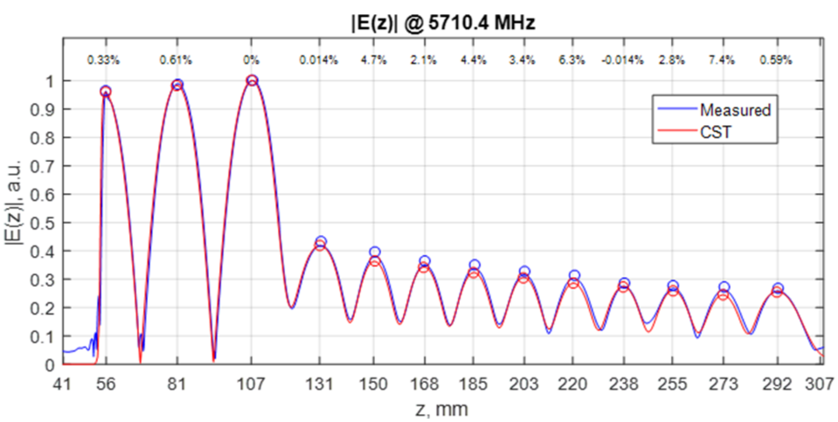


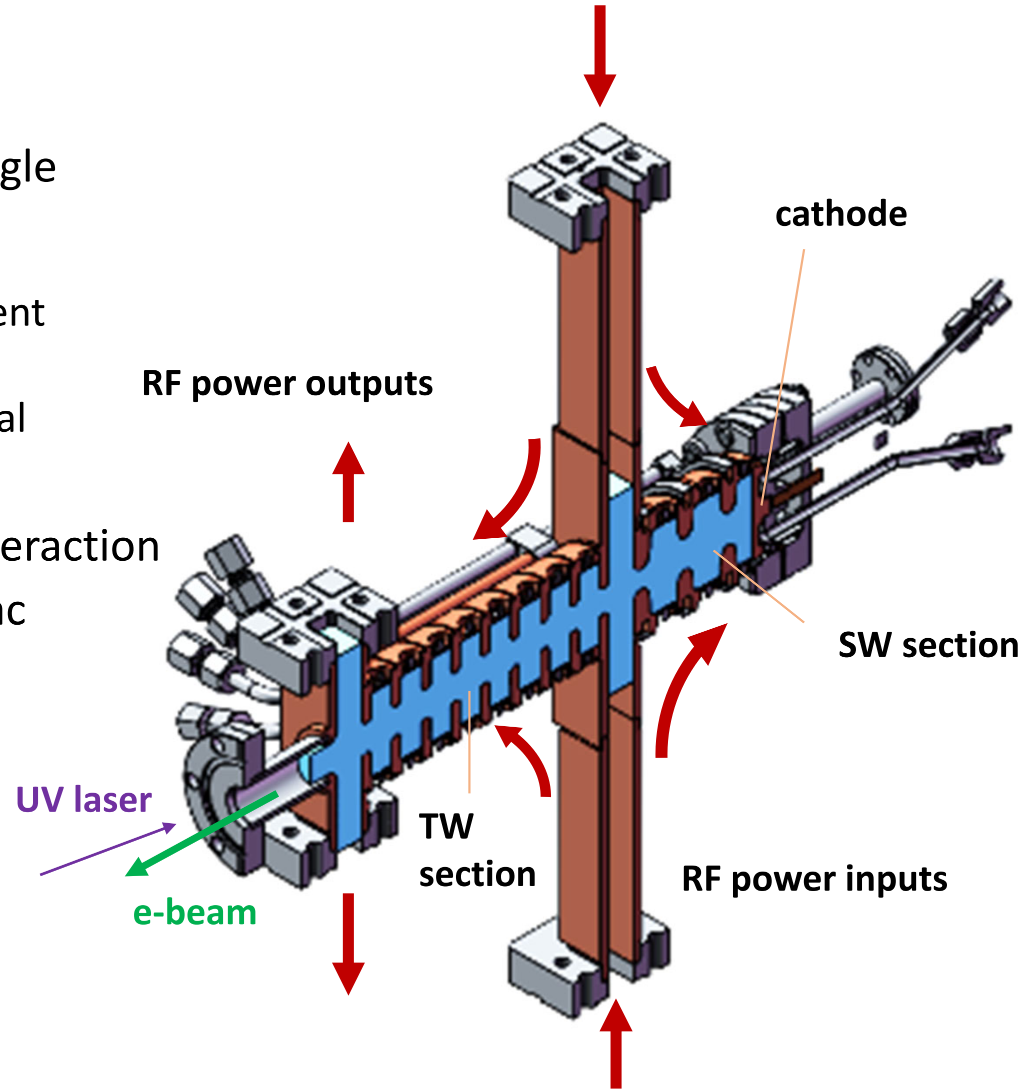
M. Nasr et al. New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities' Performance, IPAC'18



Hybrid photoinjector

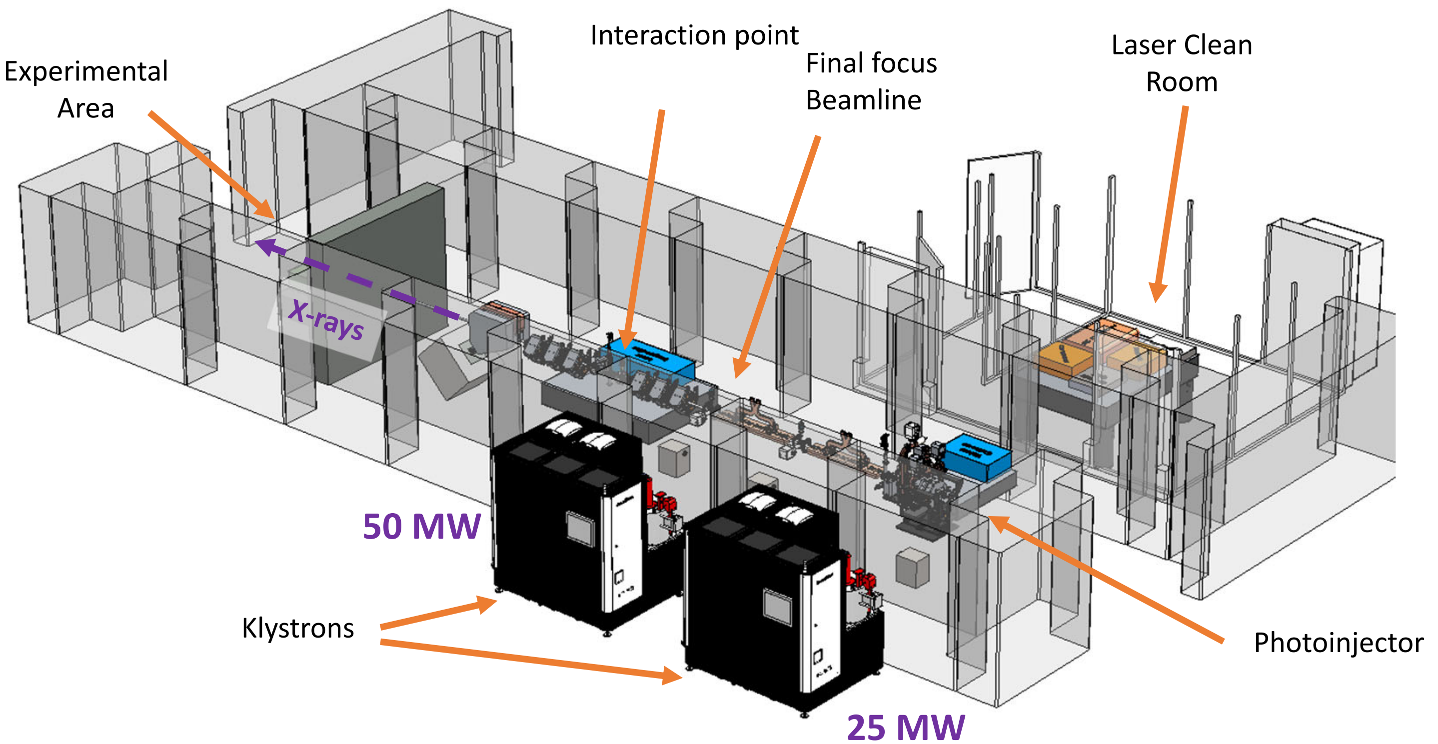
- Hybrid incorporate two C-band RF cavities in a single device:
  - Standing Wave (**SW**) RF cavity provides high gradient acceleration (120 MV/m at cathode)
  - Traveling Wave (**TW**) RF cavity provides longitudinal compression up to 500 A
- Hybrid allows to reduce ICS footprint, increase interaction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





Phase I System Overview

- The goal was to demonstrate ICS system integration and key components of the Phase II system in a scaled experimental configuration
- Single pulse system includes hybrid gun and 100 MeV linac, but the FPC is demonstrated separately



Repetition rate	100 Hz
Laser wavelength	1030 nm
Laser pulsed energy	23 mJ
Laser pulse length, FWHM	1.8 ps
E-beam charge	250 pC
Normalized emittance	0.5 µm
Spot size at IP, RMS	9 µm
Peak current	500 A
RF pulse length	< 1 µs
E-beam peak energy	105 MeV
Linac length	2 m
Accelerating gradient	50 MeV/m
RF power per linac	25 MW
Signal losses budget	60 %
Photon flux	10^9 ph/s
On-axis BW	0.65 %

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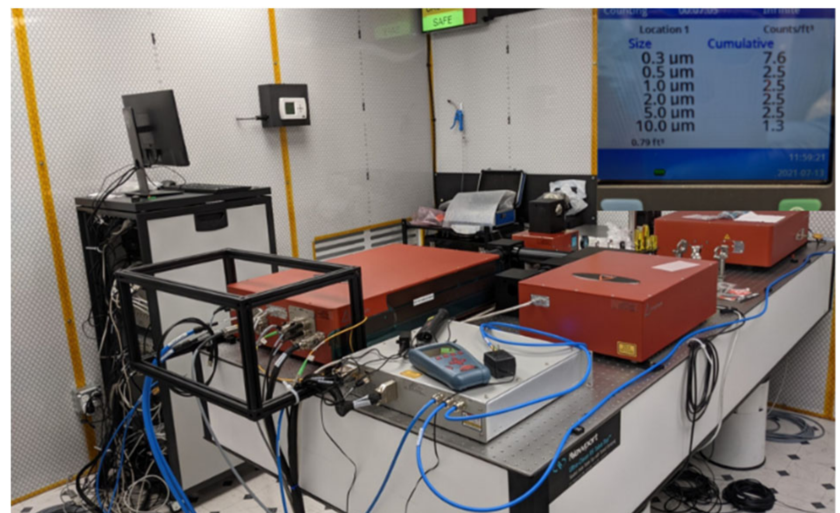
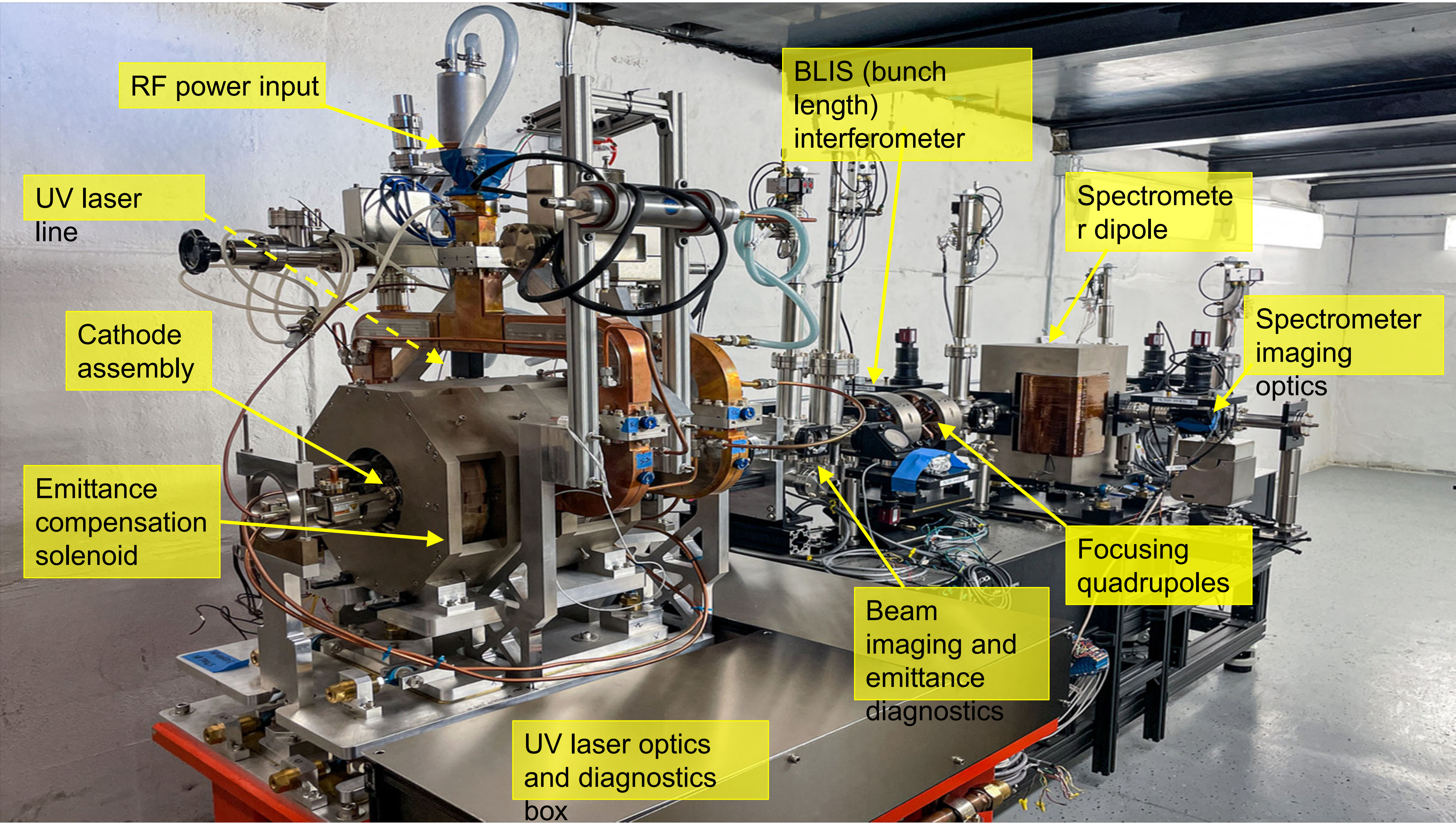
Phase I Timeline

- We received DARPA contract on March 19, 2020, 1 week after COVID shut down
- In some way the timing was fortunate to quickly settle on the Phase I system design
- 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
  - received many good advises from LANL C-band test stand group which were 6 months ahead of us on the infrastructure build up
- As a result, by the time serious COVID era supply shortages became an issue (Fall 2021), we had most of the critical subsystems in hand for the Phase I
- First beam from the photoinjector was obtained in April 2022
- Of course, some of the aftershocks significantly affected the schedule and the budget of the project, so we had to stop work and apply for additional funding
- The project restarted in October 2022, and we are back to the hybrid commissioning mode

Other sub-systems development

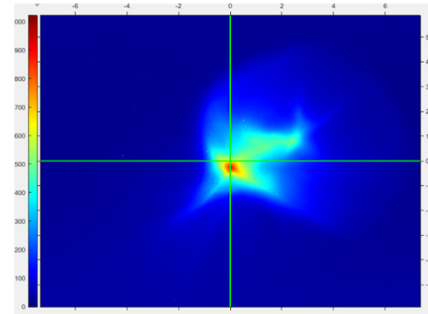
- C-band RF power stations and C-band infrastructure
- IR laser and photoinjector drive laser systems
- Radiation shielded bunker



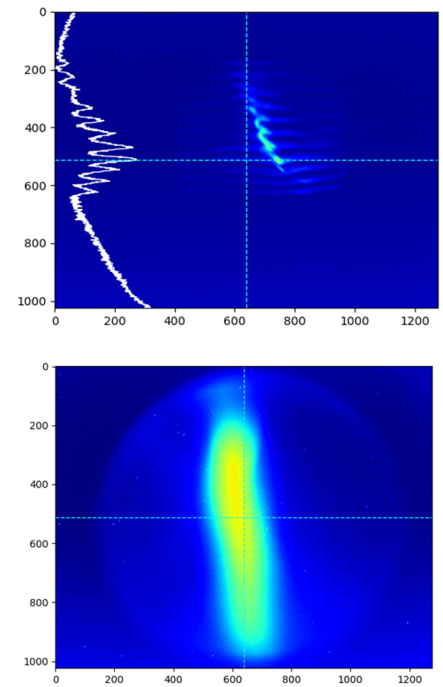

RF power input
UV laser line
Cathode assembly
Emittance compensation solenoid
BLIS (bunch length) interferometer
Spectrometer dipole
Spectrometer imaging optics
Focusing quadrupoles
Beam imaging and emittance diagnostics
UV laser optics and diagnostics box

Initial commissioning results

Parameter	Units	Design	Measured	Comments
Beam Energy	MeV	4.4	4.6 ± 0.2	There is a jitter obscuring more accurate measurements (before LLRF upgrade), also we are not convinced that TW section is at the zero-crossing
Energy spread, RMS	%	< 1%	ROM ~ 2%	Consistent with the non-optimal injection phase
Beam charge	pC	50-250	> 265	Over 400 pC measured by turbo-ICT, and 265 pC at Faraday cup, FC is more reliable
Bunch length, FWHM	ps	< 1	N/A	BLIS has not been commissioned yet
Emittance (normalized)	µm	< 0.8	N/A	Slits were tested but not properly commissioned



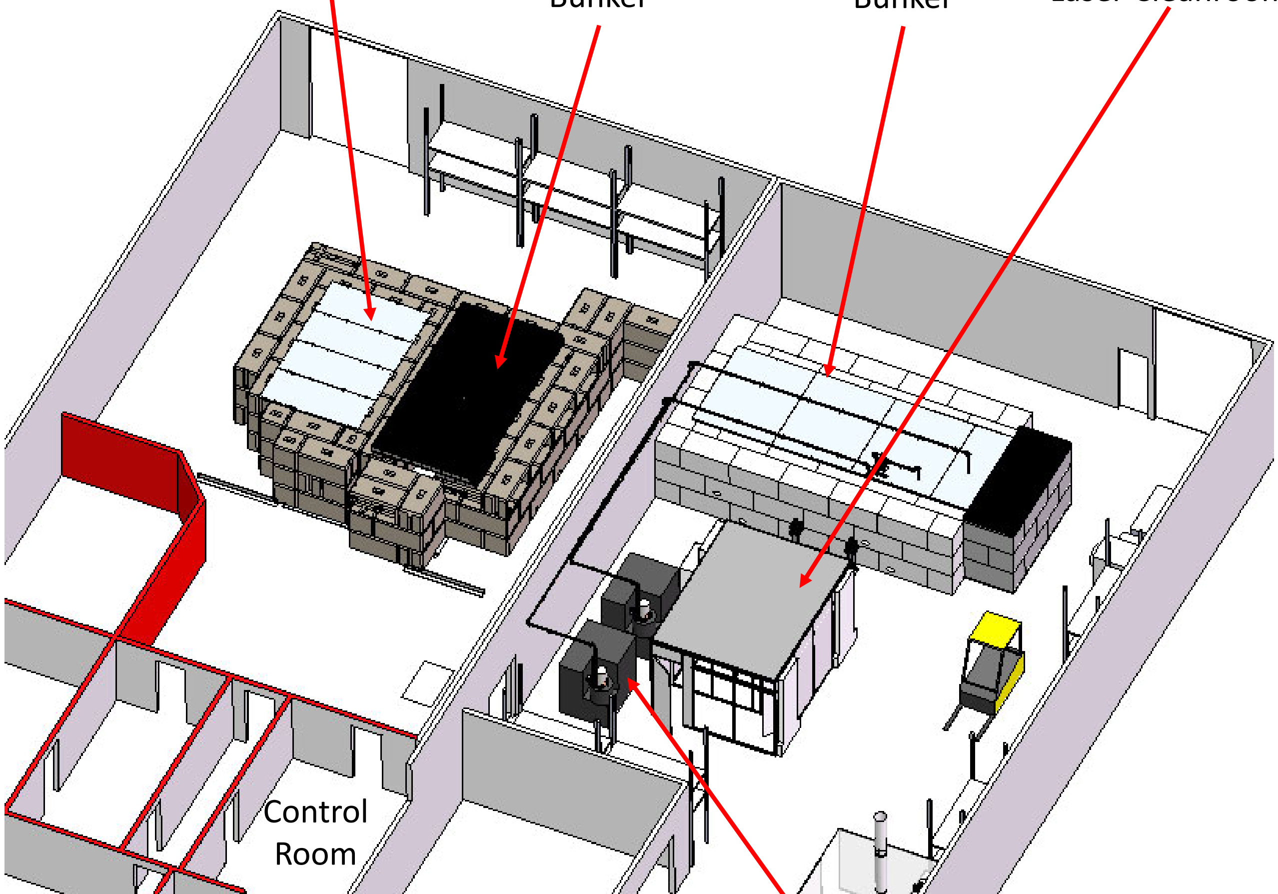
Slit Position YAG



Spectrometer Line YAG

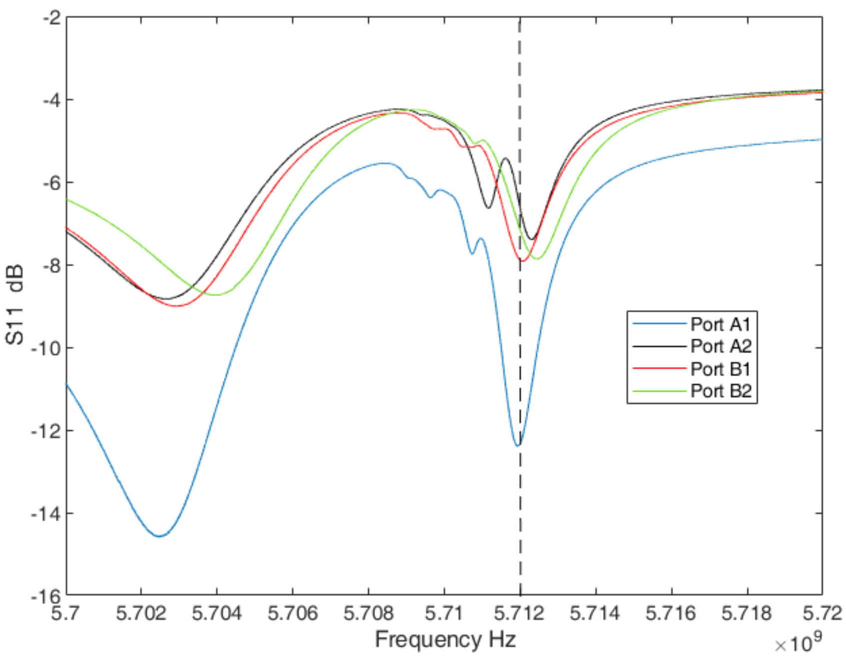
Hybrid gun recommissioning plans

- Over the break, the C-band hybrid gun was relocated to the GRIT bunker, realigned and reconditioned
- It took only 12 hours to get back to the full power (21 MW @ 1 μs pulse length)
- We generated the first photocurrent beam in the new bunker, but the actual commissioning will start later this week



Linac

- L1 bonding completed in December
- Initial cold test is promising
- We plan to assemble 100 MeV beamline in May-June 2023



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Available RF Power Test Sources

KLYSTRON

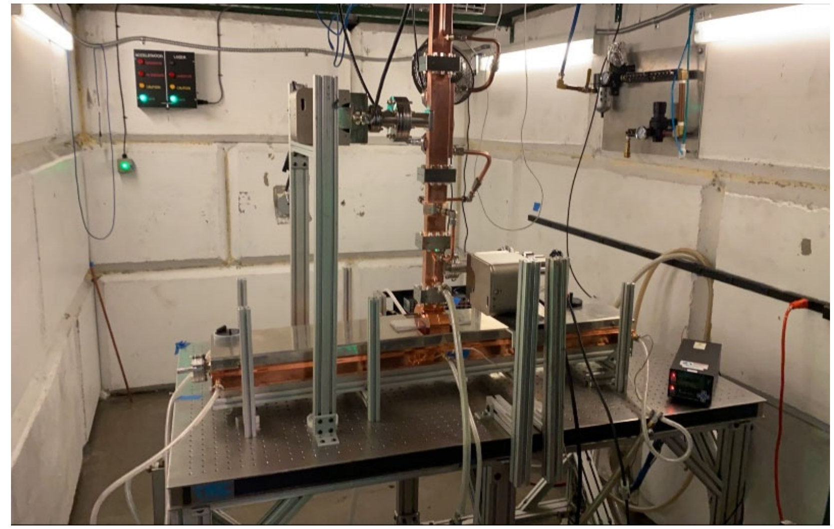
	C-Band RF Power Station #1	C-Band RF Power Station #2	S-Band RF Power Station #1	S-Band RF Power Station #2
Klystron	Canon: E37202	Canon: E37202	CPI: VKS-8262	Canon: 3772A
RF Peak Power	25 MW	50 MW	5 MW	7.5 MW
RF Average Power	2.5 kW	5 kW	16 kW	3 kW
Pulse Length (max)	1 µs	1 µs	16 µs	4 µs
PRF	100 Hz	100 Hz	200 Hz	100 Hz
Frequency	5712 ± 5 MHz	5712 ± 5 MHz	2856 ± 2 MHz	2856 ± 2 MHz

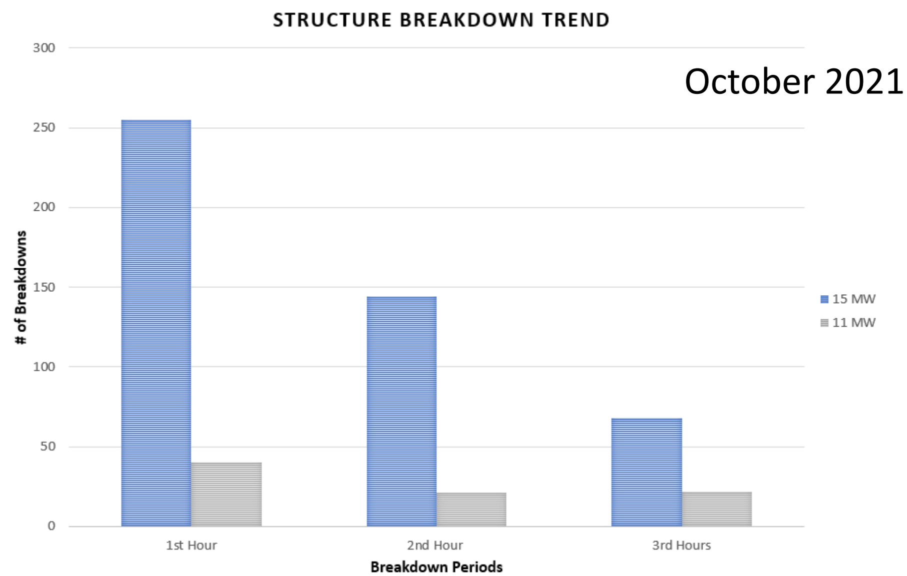
Magnetron

	S-Band RF Power Station #1	X-Band RF Power Station #2
Magnetron	E2v: MG7095	E37202
RF Peak Power	3.1 MW	2 MW
RF Average Power	3.1 kW	1.6 kW
Pulse Length (max)	5 µs	4 µs
PRF	200 Hz	200 Hz
Frequency	2998 ± 4 MHz	9295 ± 20 MHz

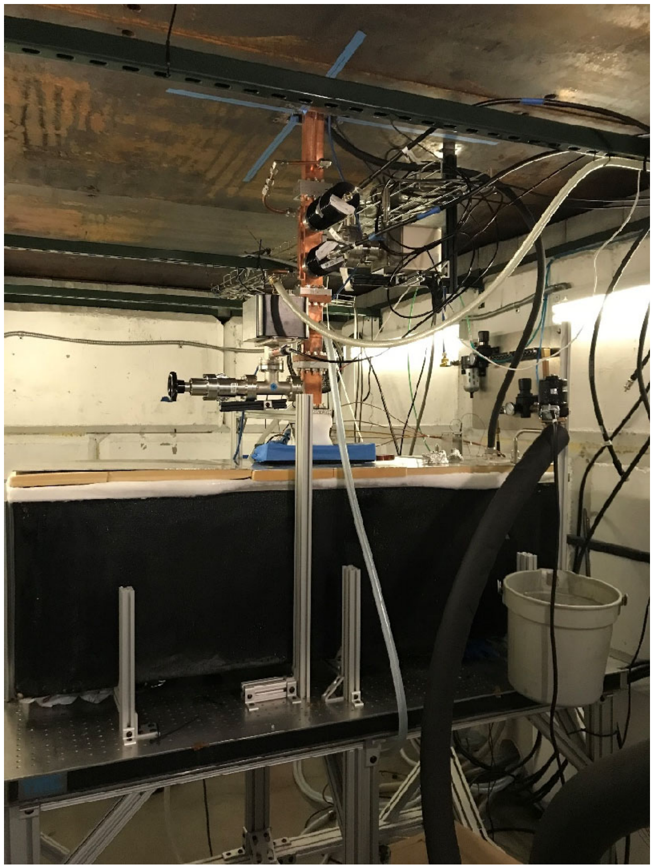
Testing C-band Structure

- 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 (de)tuned to be at 5716.8 MHz @ ≈50°C
- 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



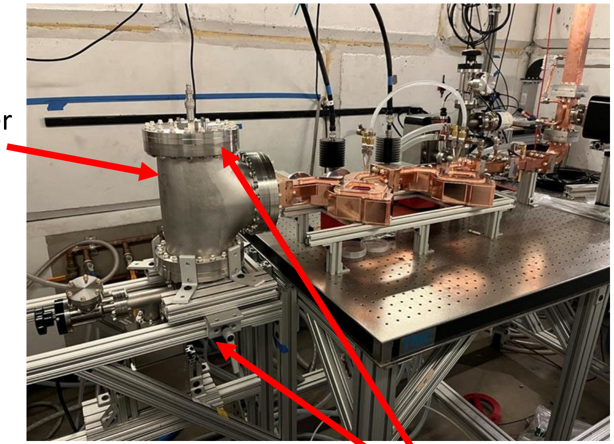
July 2022

- Repeated the test of the same structure, at LN2 temperature
- Baked the structure prior to testing
- Frequency scaling:
  - @26 °C = 5694.1 MHz
  - @-195 °C = 5712.4 MHz
- 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

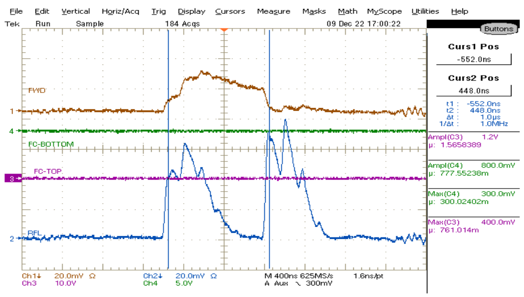
C-Band Single Cell Testing (ACCEL)

- ACCEL is another DARPA supported program, to develop a very compact, battery powered, high power linac
- SLAC leads the effort, RadiaBeam is a junior partner
- Utilized 50 MW C-band power station in December of 2022 to high power test two clamped single cell cavities designed to operate at ~ 500 kW Peak Power
- Cavities were placed inside cavity chamber, 8” vacuum tee
  - Cavity #1: Conditioned up to 2 MW, 10 Hz, 1 μs pulse width
  - Cavity #2: Conditioned up to .2 MW, 10 Hz, 1 μs pulse width
- Breakdown rate decreased as conditioned progressed

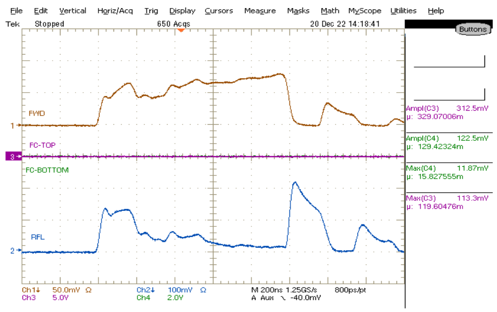
Cavity Chamber



Faraday Cup (2nd not seen)



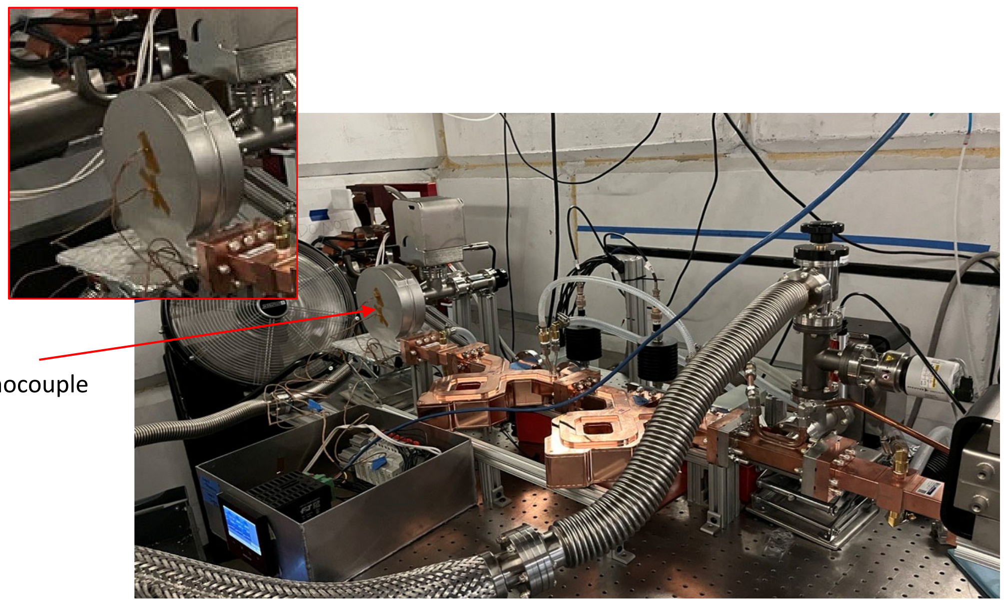
Cavity #1



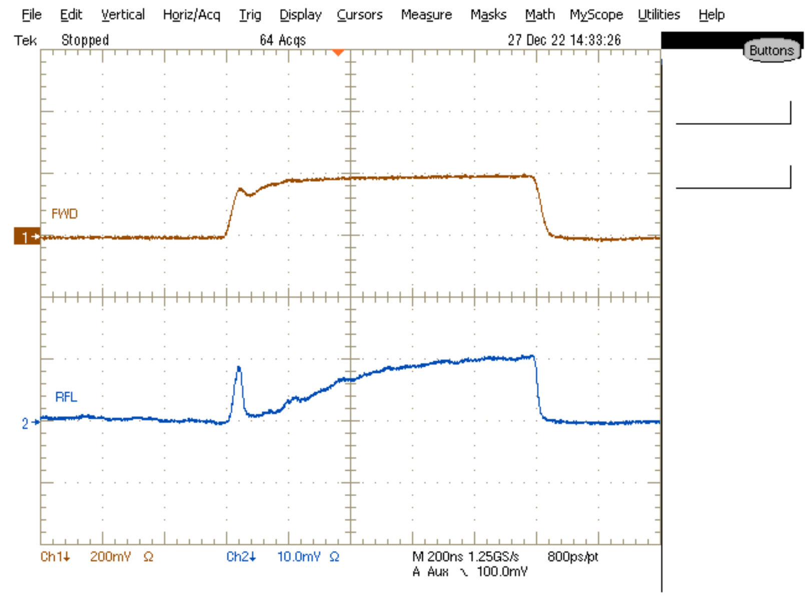
Cavity #2

C-Band Spiral Load Test

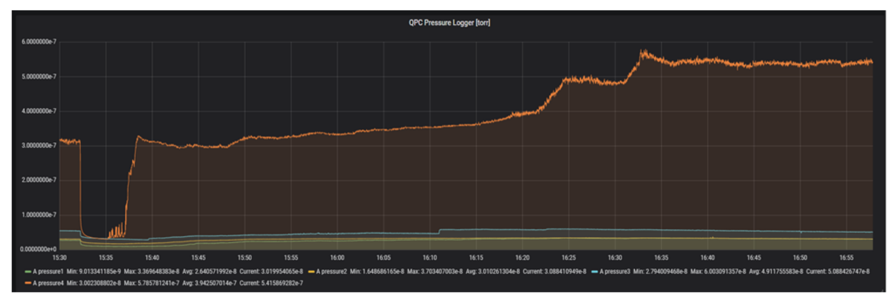
- High power tested SLAC Spiral Vacuum load (3D printed)
- Conditioned from up to 8.1 MW peak power, 1 µs pulse width, 20 Hz rep rate
  - About 9 hours of conditioning
  - Convection cooled load
  - Monitored temperature and vacuum



Thermocouple



December 2022



Future Test Plans

- Commissioning 50 MW C-Band Power Station
- Route to the general testing bunker and GRIT bunker
- Plans to test additional C-band components and test structures at lower power
- High power testing of C^3 structure in cryostat
- Potential for C^3 beam testing
- Plan to Install power splitter on 50 MW power station to enable low power tests concurrently with the accelerator operation

Conclusions

- DARPA is awesome!
- RadiaBeam and collaborators are developing high brightness 100 MeV C-band accelerator for GRIT ICS program, which should become operational in 2023
- The C-band infrastructure (and trained personnel) developed for the GRIT program can be utilized for other projects, including C^3 R&D
- The newly developed C-band capability has already been employed to provide support to SLAC C^3 R&D program, and we hope that this collaboration will expand further
- We also welcome a more general community interest in future uses of the GRIT accelerator system
- Acknowledgement: this program has been a fast paced, dynamic team effort externally and internally, and there is here is a long list of contributors to this talk at RadiaBeam, SLAC, UCLA, Amplitude and other institutions