Los Alamos NATIONAL LABORATORY

Update on the status of the C-band high gradient program at LANL

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Outline of this talk

- Introduction and LANL C-band project overview

- Experimental activities
  - ✓ CERF-NM: High gradient C-band test stand
  - ✓ High gradient C-band tests and resultsCARIE: new high gradient RF injector test facility

- Summary and near-term plans

Introduction: why Los Alamos

Achieving high-gradient performance (low breakdown rates, low field emission, new materials for HOM absorption, cathodes at high gradient etc.) is a *materials science* problem.

Los Alamos is, at core, a materials science laboratory with particular expertise and interest in metallurgy.

Los Alamos also considers itself the steward of accelerator science for the NNSA part of the DOE complex.

Thus, Los Alamos has both an institutional interest in, and capability to address, this problem space.

High gradient C-band work directly aligns with future NNSA and LANL missions.

LANL must develop accelerators for various national security needs

LANSCE accelerator upgrades:

Applications such as pRad desire higher proton beam energy
→ add a booster to current LANSCE linac to increase beam energy to 3-5 GeV

New capabilities: improve accessibility

Material science at LANL will benefit from powerful directional high repetition rate X-ray sources
43 keV photons can be produced with 42 MeV electron beam
43 keV photons are DMMSC relevant

Compact Accelerators: enabling feasibility

Achieving high gradient performance (low breakdown rates, low field emission, new materials for HOM absorption, etc.) is a material science problem.
LANL is, at core, a material science laboratory

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LANL High Gradient C-band research

The goals for LANL's high gradient project are

- To build a C-band (5.712 GHz) high gradient rf breakdown study facility (2019-2022).
- To build a C-band cryo-cooled photoinjector study facility (2022-2025).
- To conduct material studies.
- To develop C-band compact accelerator facility for X-ray production (future).

This work was funded by Los Alamos National Laboratory (LANL) Laboratory Directed Research and Development (LDRD) program and Technology Evaluation and Development (TED) funds.

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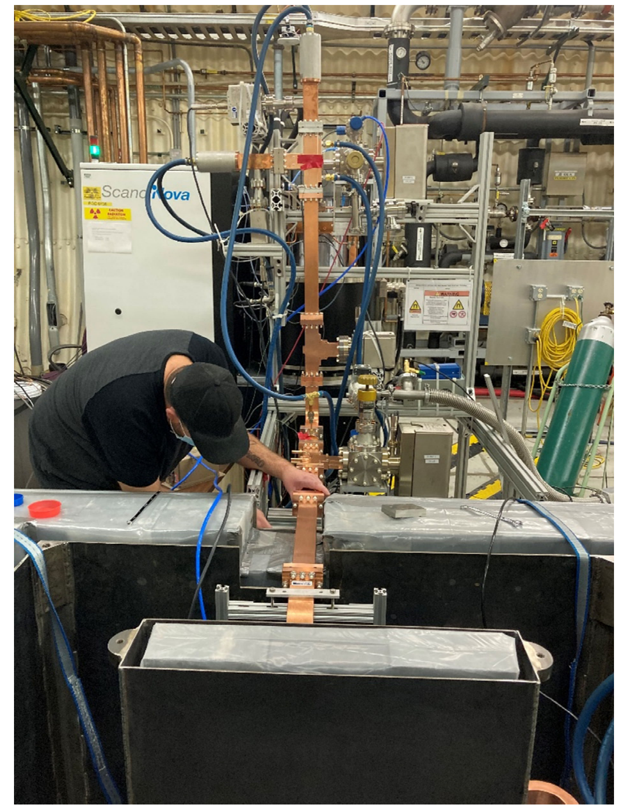
LANL C-band Engineering Research Facility (CERF-NM)

CERF-NM was built with $3M of LANL's internal infrastructure investment.

- Powered with a C-band Canon klystron
- Conditioned to 50 MW
- Frequency 5.712 GHz
- 300 ns – 1 μs pulse length
- Rep rate up to 200 Hz (typical 100 Hz)
- Nominal bandwidth 5.707-5.717 GHz



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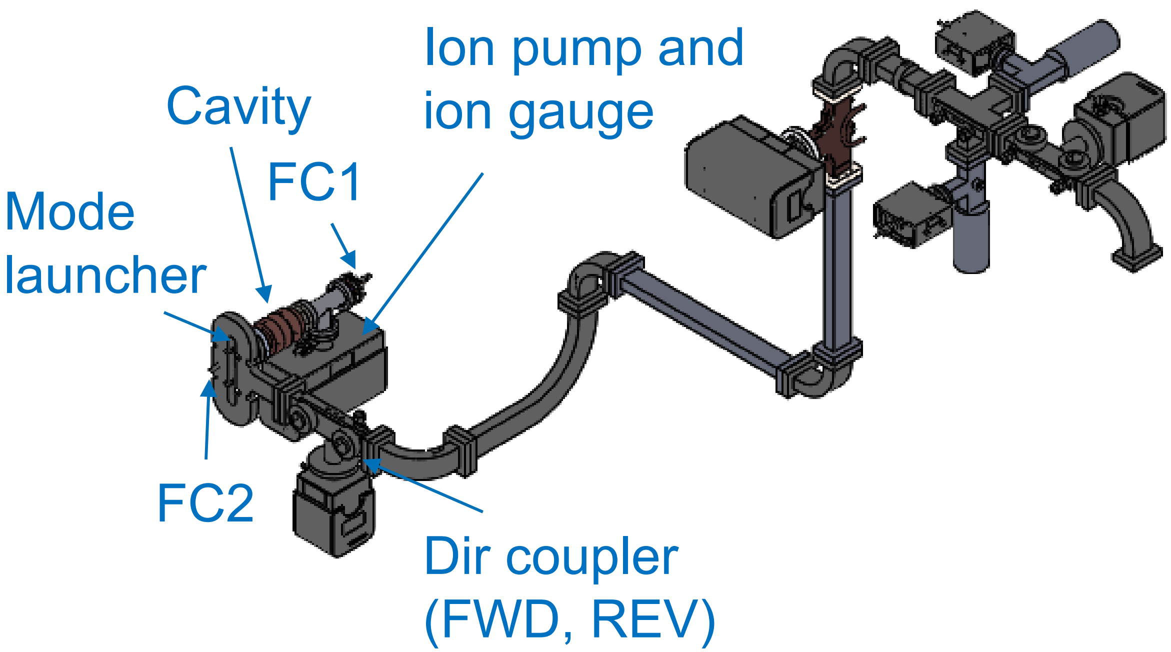
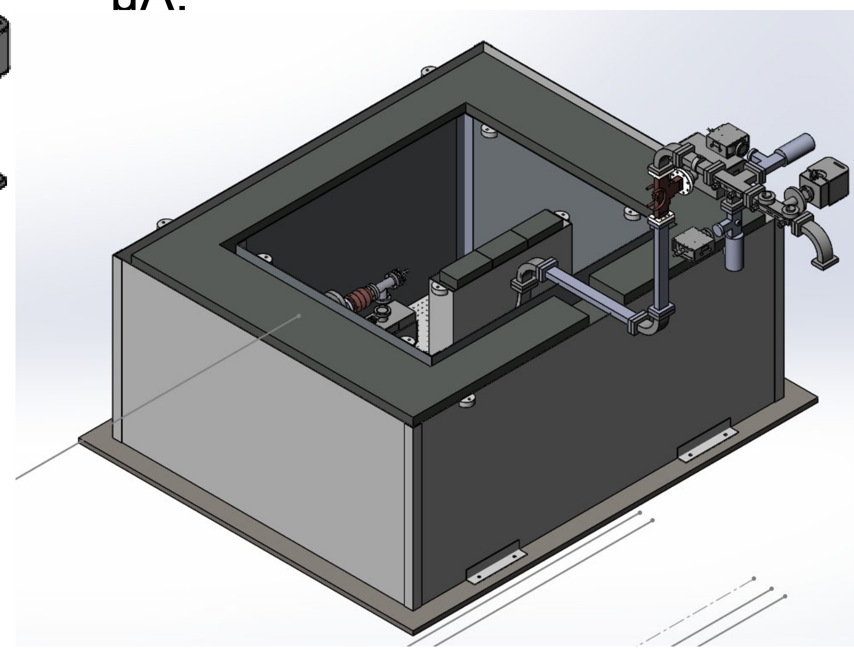
Schematic of the C-band test stand

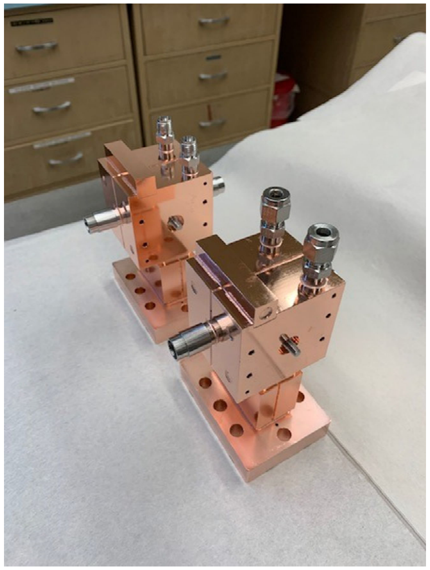


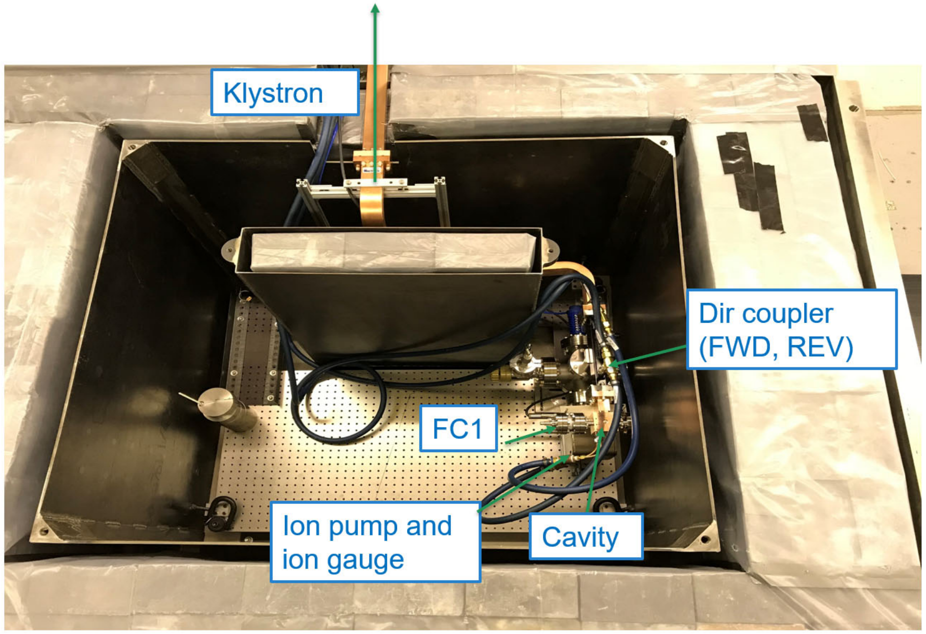
Radiologically certified for dark currents up to 5 MeV and 10 uA.

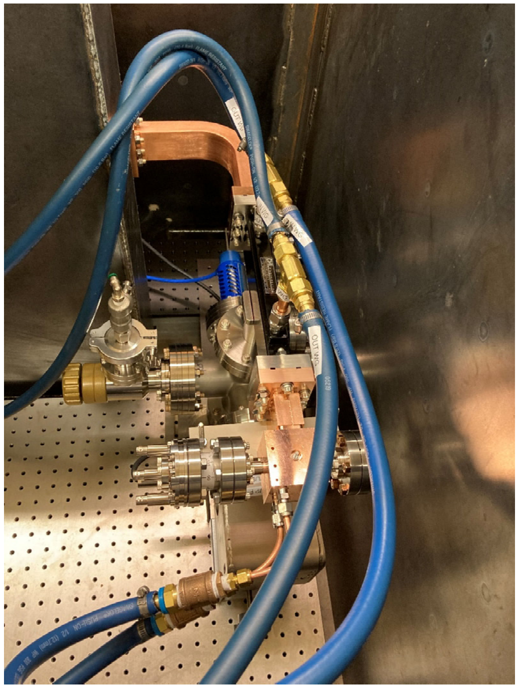


The first two high gradient cavities were tested at CERF-NM in FY21

This C-band high gradient test facility is nationally unique. The first cavities tested at CERF-NM were manufactured at SLAC.







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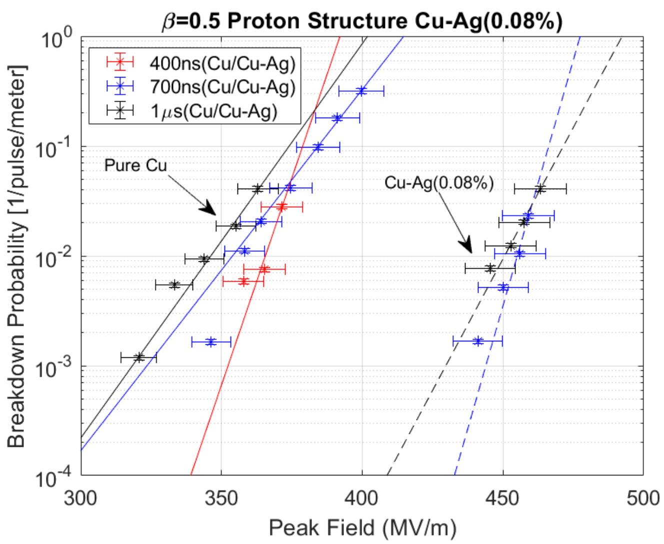
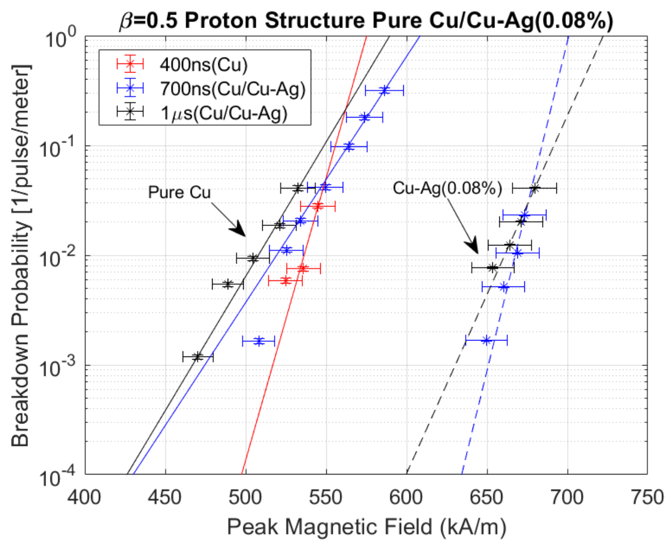
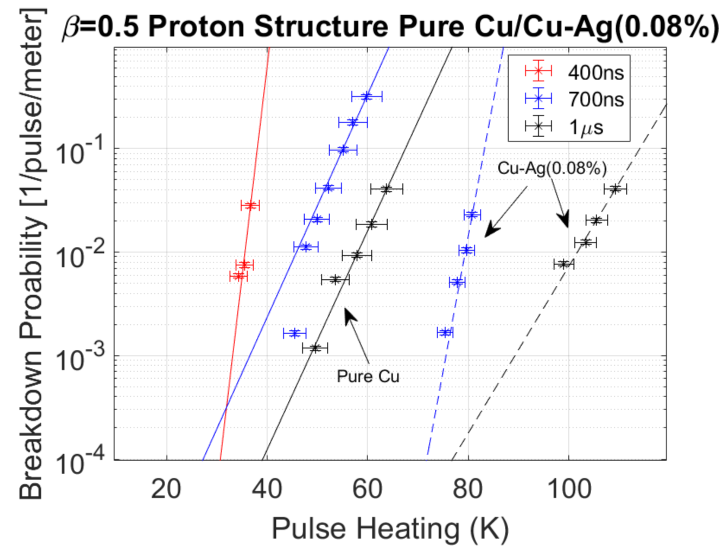
Peak surface electric fields in excess of 300 MV/m demonstrated in high gradient tests

Breakdown probabilities were recorded for three different pulse lengths for copper and copper-silver cavities.







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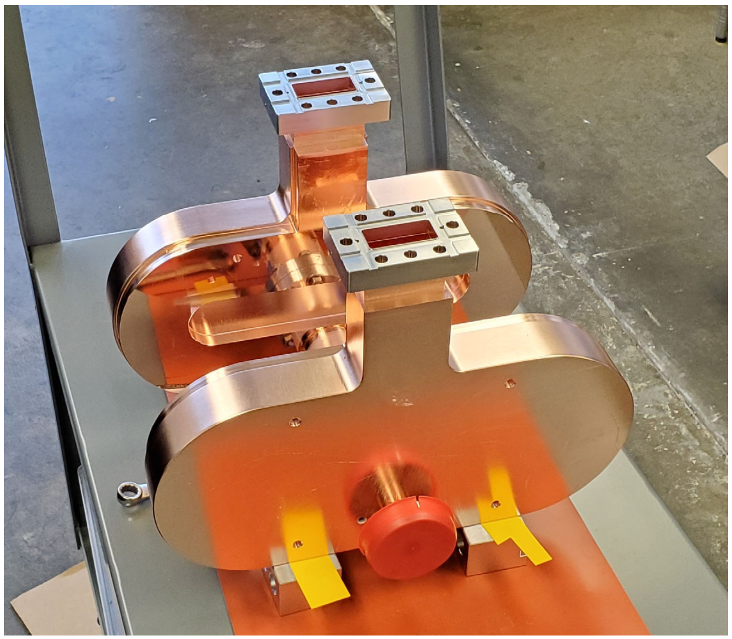
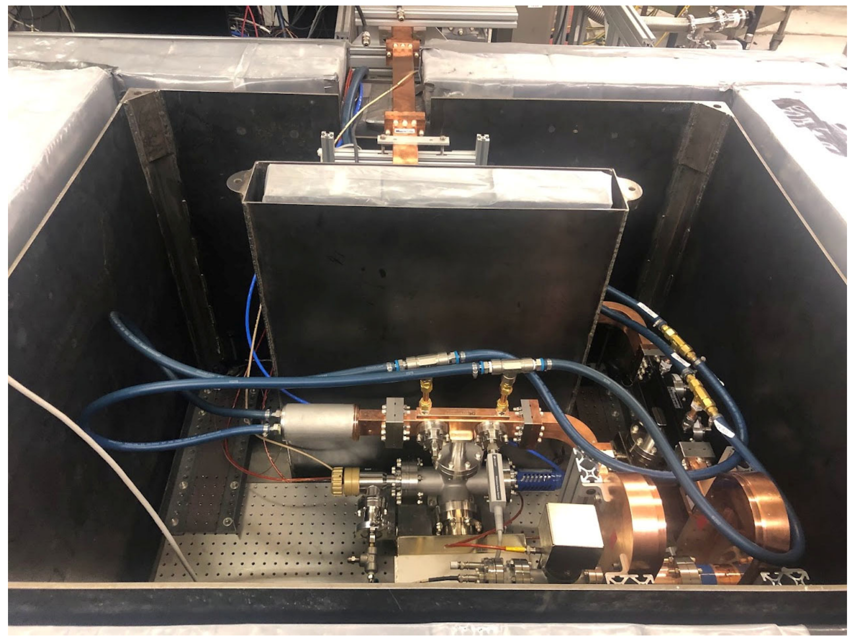
We fabricated and conditioned mode-launchers for on-axis coupling with decreased surface magnetic fields

The mode launchers are conditioned up to 20 MW of input power.





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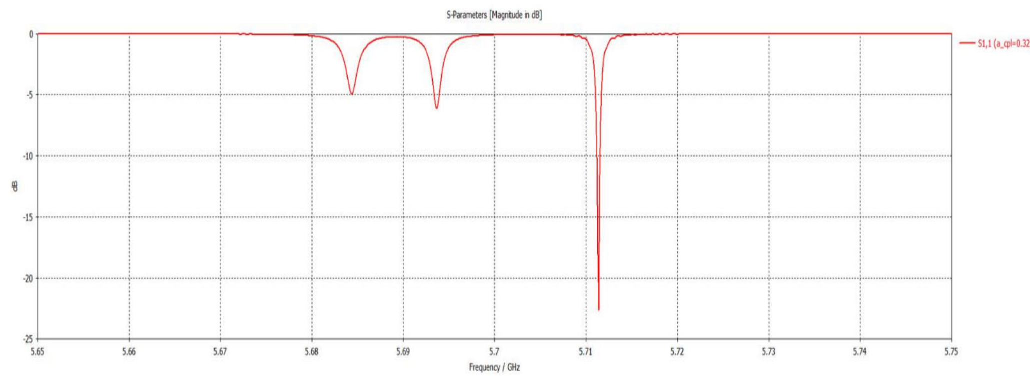
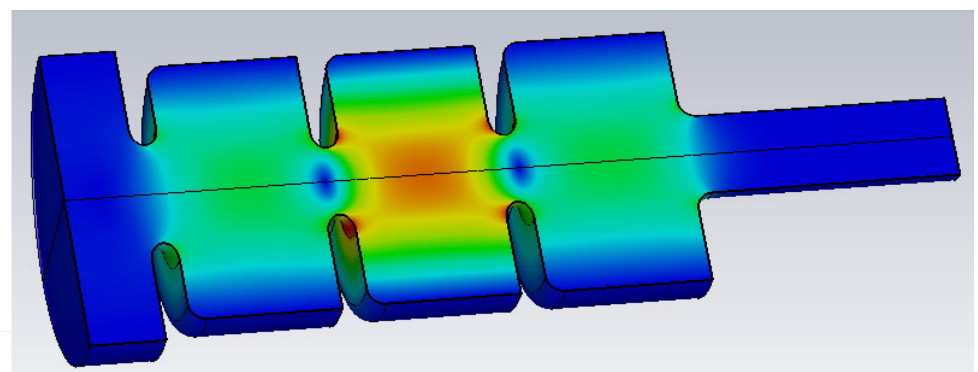
Tests of a benchmark cavity will allow us to establish gradient limitations at C-band as compared to other frequencies

Several cavities will be tested in FY22:

- Copper + brazed (fabricated)
- Copper + welded (in fabrication)
- Copper-silver, 0.085% silver (in fabrication)
- Copper-silver, 2% silver (in fabrication)

Frequency	5.712 GHz
Cell length	1.034 in
a/λ	0.105
Iris radius	0.217 in
Q(copper, RT)	12700
Power for 200 MV/m surface field	5.3 MW





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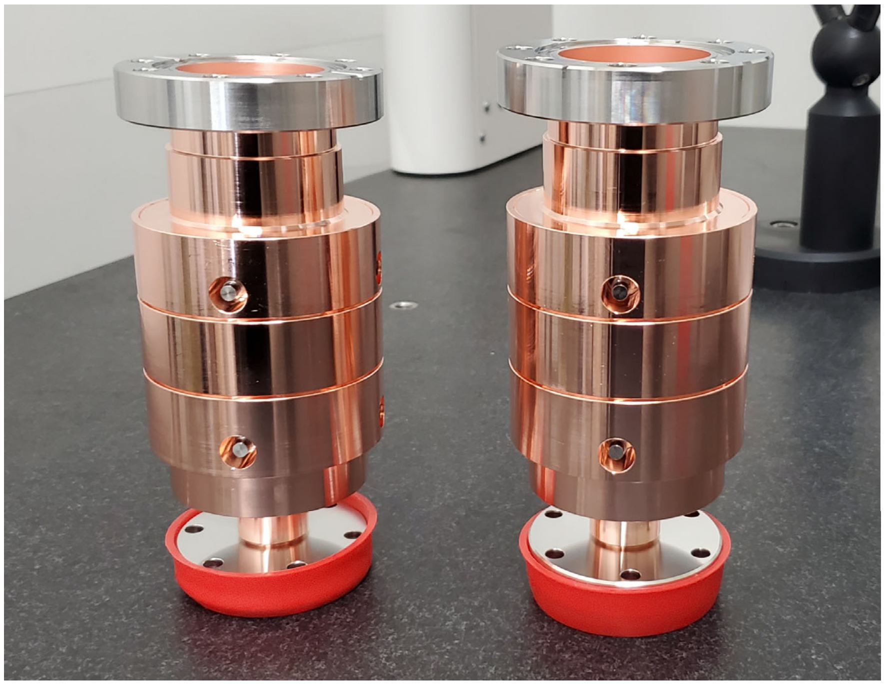
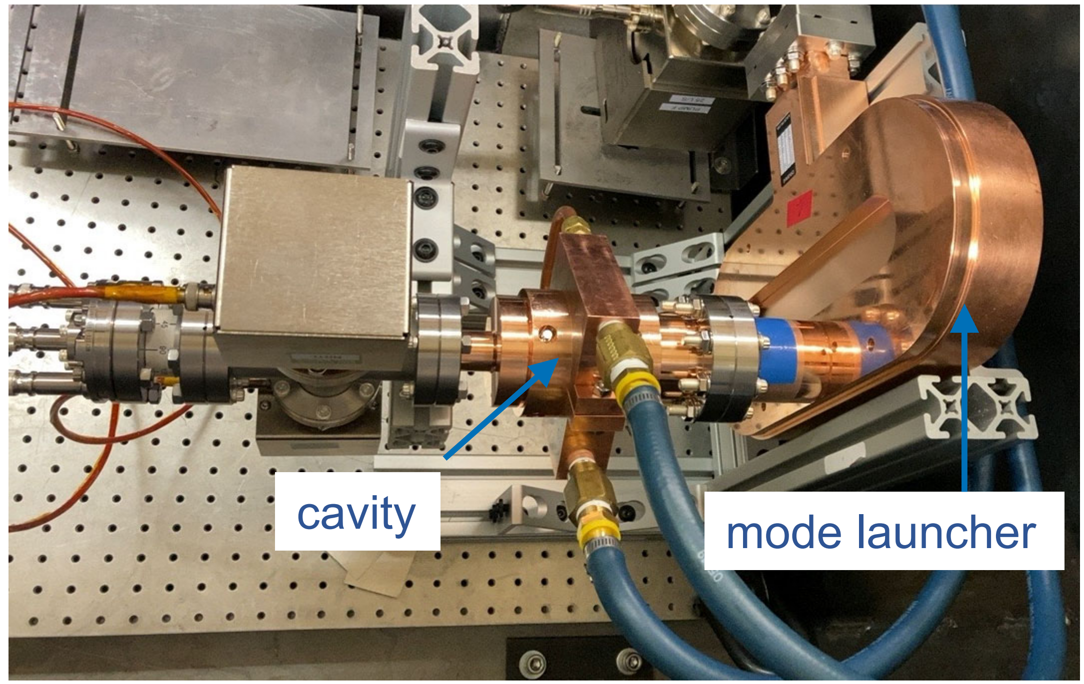
Two a/λ=0.105 cavities were fabricated and tested at high gradients





The cavities were conditioned up to the maximum available power at the test stand

The cavities were conditioned at 1 μs pulse length.

Cavity #1:

Maximum coupled power: 14 MW.

Peak surface electric field: 255 MV/m.

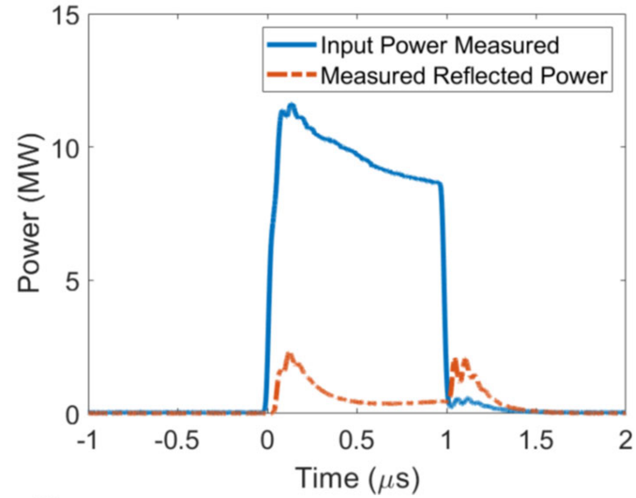
Peak surface magnetic field: 373 kA/m.

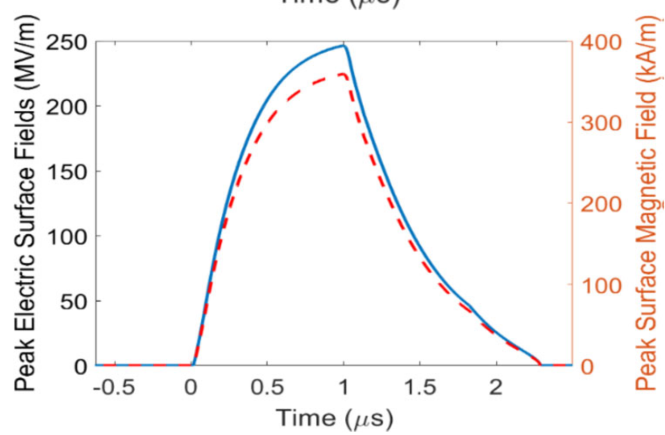
Cavity #2:

Maximum coupled power: 15 MW.

Peak surface electric field: 308 MV/m.

Peak surface magnetic field: 449 kA/m.





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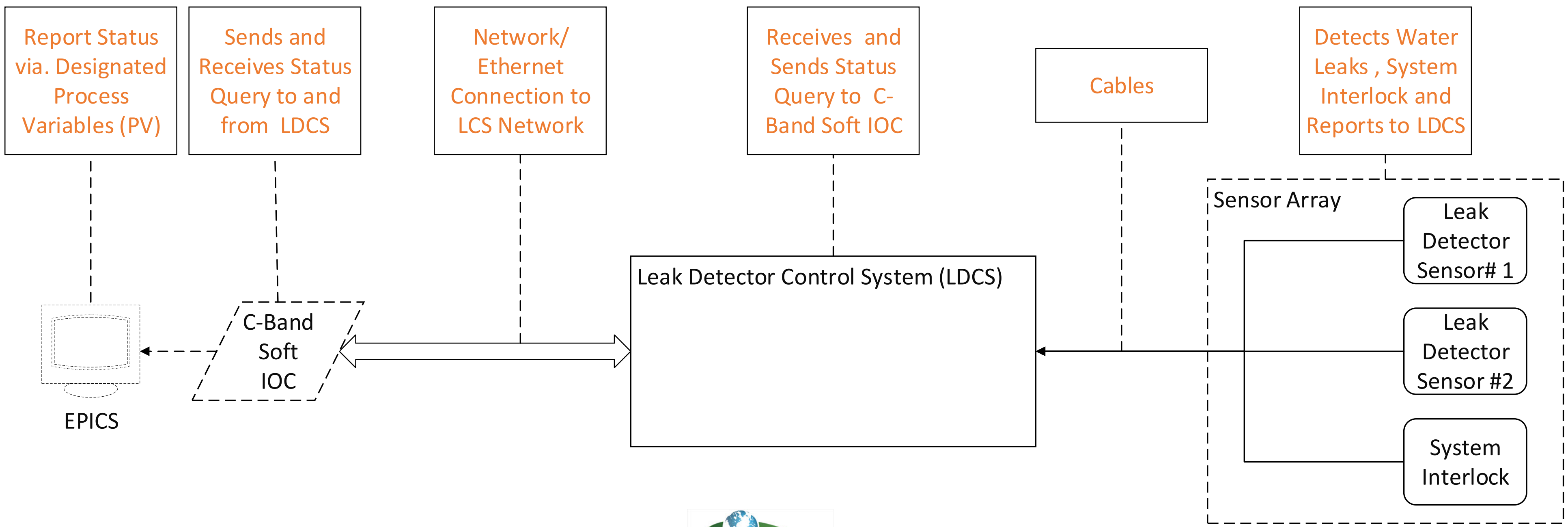
Remote operation of C-band

We are working to develop capability for round-the-clock operation of CERF-NM while being monitored from LANSCE Central Control Room (CCR).



Summary and test plans for CERF-NM

LANL C-band high gradient test stand is currently operational

- Testing of the SLAC copper beta=0.5 cavities is finished.
- We plan to test multiple $a/\lambda = 0.105$ cavities fabricated with different methods.
- In FY23 we will test the optimized proton booster cavity and ceramic-enhanced accelerator structures

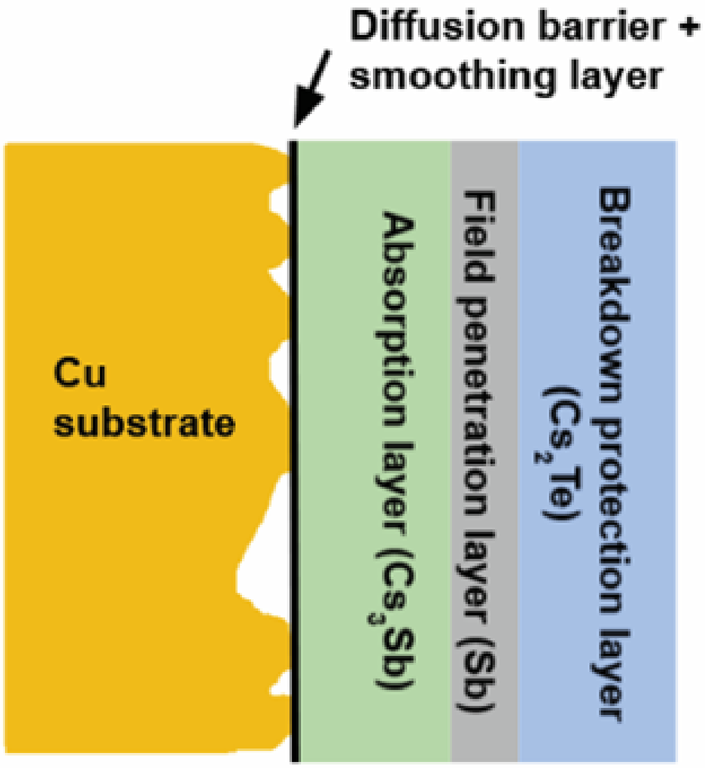
<u>The test stand is open to collaborators.</u>

We consider adding capability to cool cavities under test to cryogenic temperatures.

CARIE: Cathodes And Rf Interactions in Extremes

A new three-year project was funded at LANL to demonstrate operation of high-quantum-efficiency cathodes in a high-gradient RF injector.

- Project builds upon LANL's expertise in high-gradient C-band and high-QE photocathodes.
- The proposed heterostructured cathode will include multiple layers to ensure atomic flatness of the surface, high QE, and the ability to withstand high electric fields with no breakdown.
- Target beam parameters: 250 pC, 0.1 µm*rad, $B_{5D} = 10^{16}$ A/m^2.
- The project started in October of 2022.



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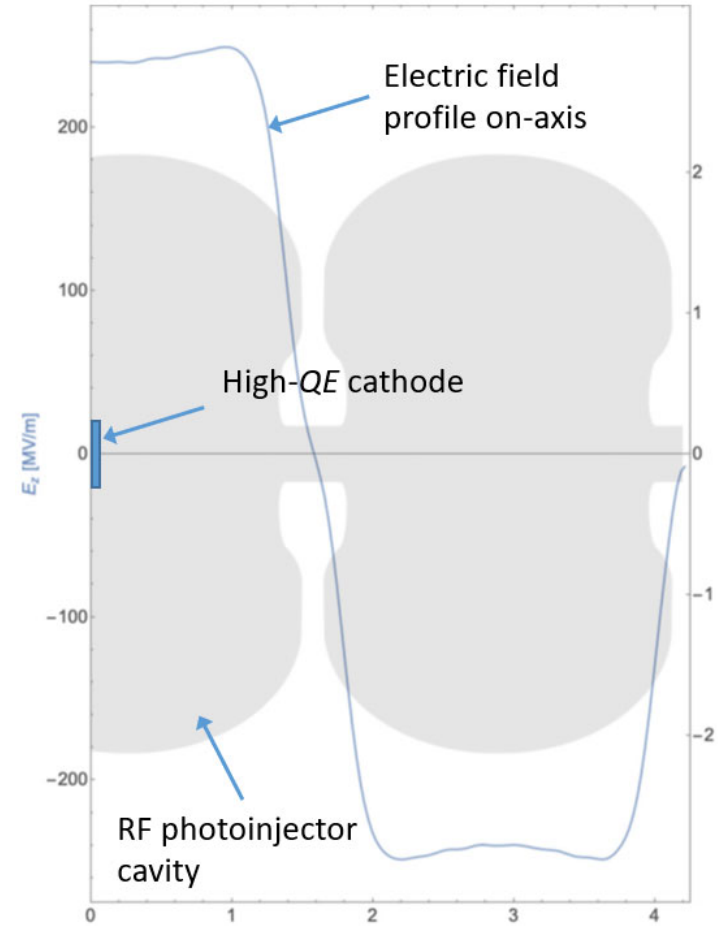
RF photoinjector considerations

We will fabricate 1.6 cell gun design by UCLA/SLAC.

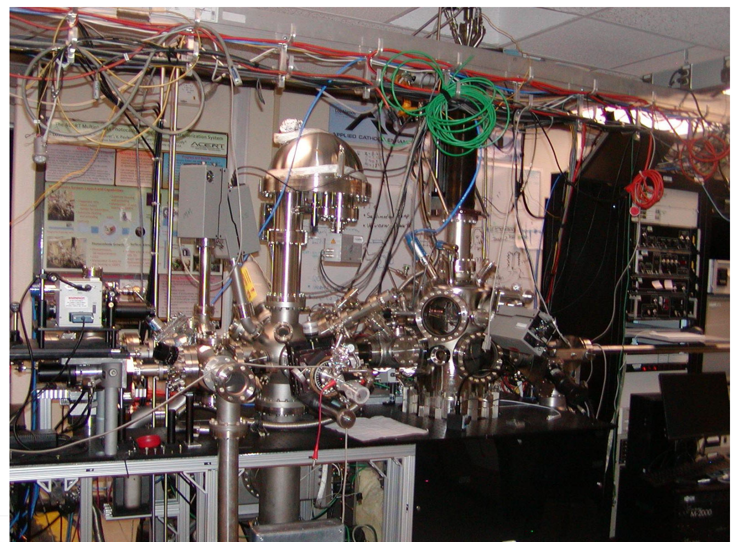
Questions we are trying to address:

- <u>The cathode</u>: there is an idea to grow the cathode straight on the copper wall. This is an engineering challenge. *Alternative:* INFN plug?
- <u>RF coupler design</u>: must take into account integration with the cryo-cooling and the solenoid.
- <u>Solenoid:</u> must take into account integration with the cryo-cooling.
- <u>Cryo-cooling:</u> cryo-cooler and low rep rate or liquid nitrogen?



CARIE vault

- A location was identified on LANSCE mesa that can accommodate a 20 kW electron beam.
- Co-located with a cathode fabrication and characterization facility (ACERT).
- The vault was cleaned for the new experiment.
- A modulator for the 50 MW C-band klystron is in procurement.



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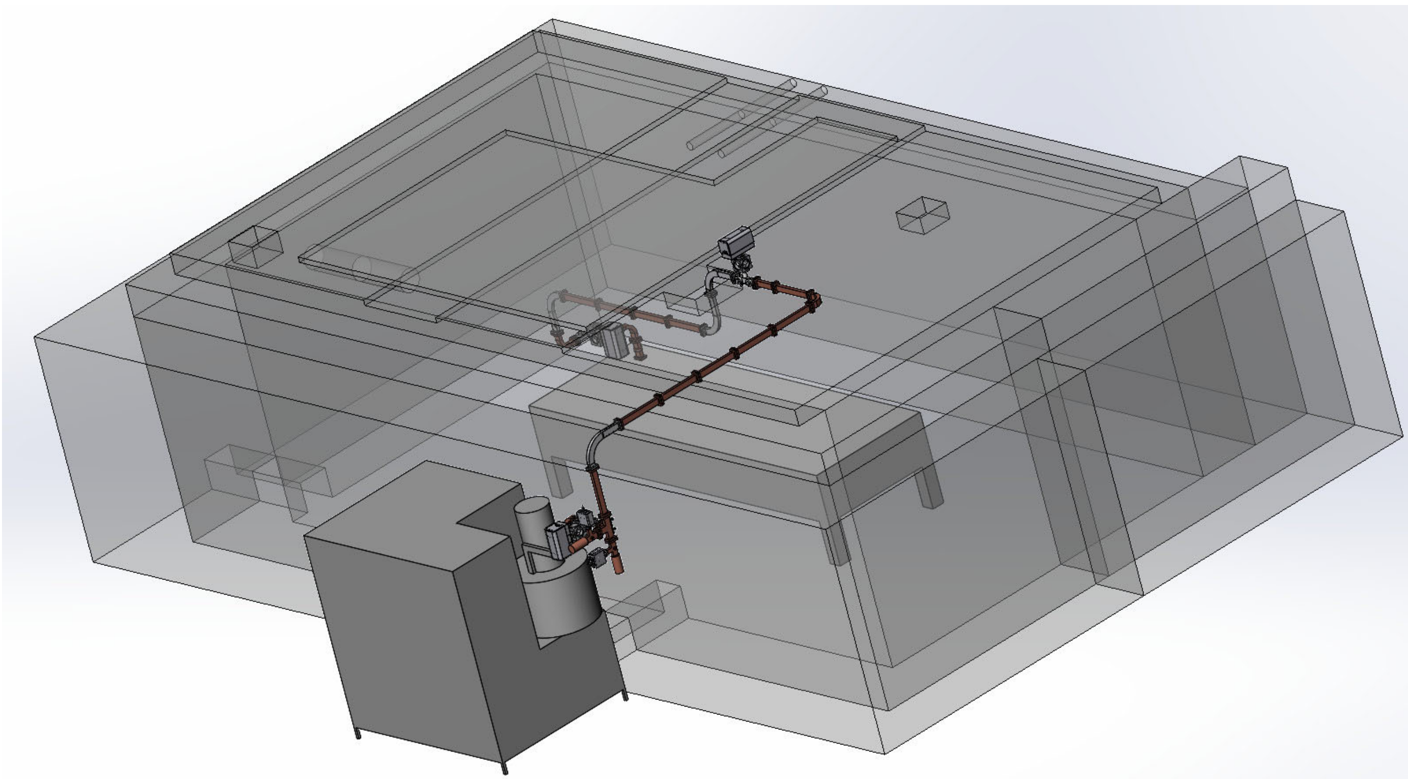
CARIE vault facility lineout



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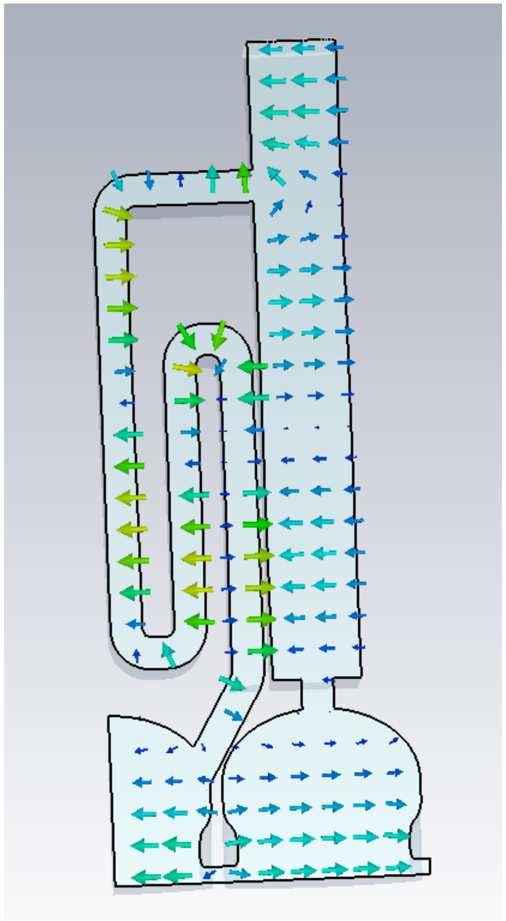
RF injector electromagnetic design

- 1.6 cell RF injector.
- Side coupling will be used to accommodate positioning the solenoid right after the injector and the cathode insertion mechanism upstream.
- Side coupling is also essential because of a very small iris.
- 180^0 phase advance is achieved by adjusting the length of the two waveguides.
- The electromagnetic design is being conducted to minimize surface fields.



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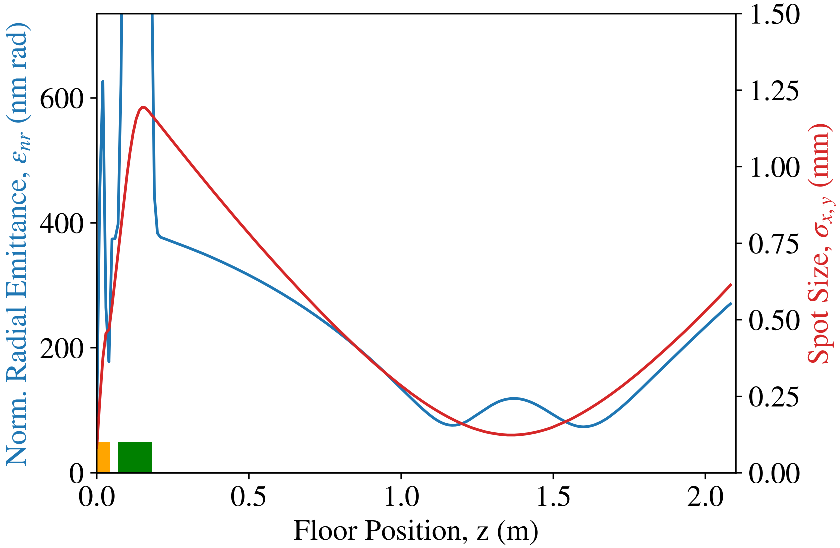
RF injector beamline design (and comparison to 100 pC case)

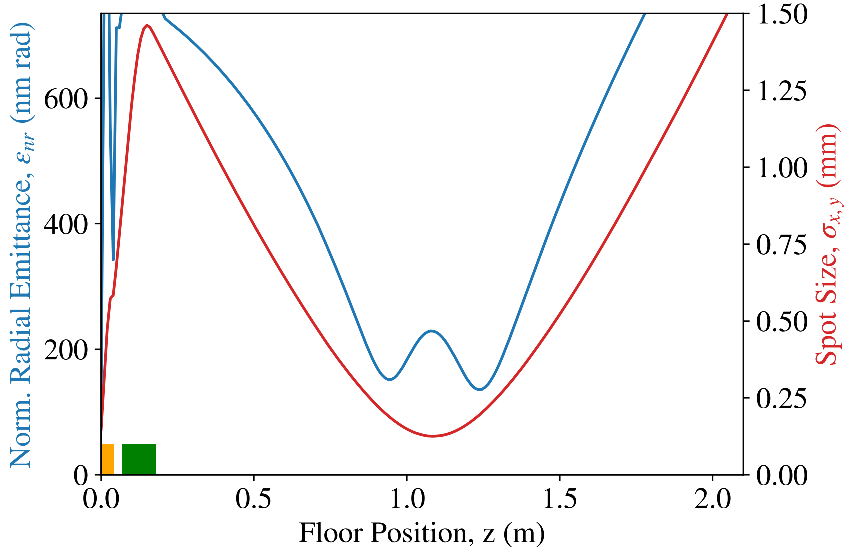
Parameter	Unit		
Charge	pC	100	250
Laser RMS spot size, σ	μm	129	233.5
Laser aperture size		1σ	1σ
Injection phase		$44°$	$43°$
Laser length	ps	5.62	6.075
Peak cathode field	MV/m	240	
Solenoid field	T	0.5665	0.5759
Solenoid FWHM	cm	7.4	
Solenoid center	cm	12.5	

GPT simulations: beam emittance and spot size

100 pC case

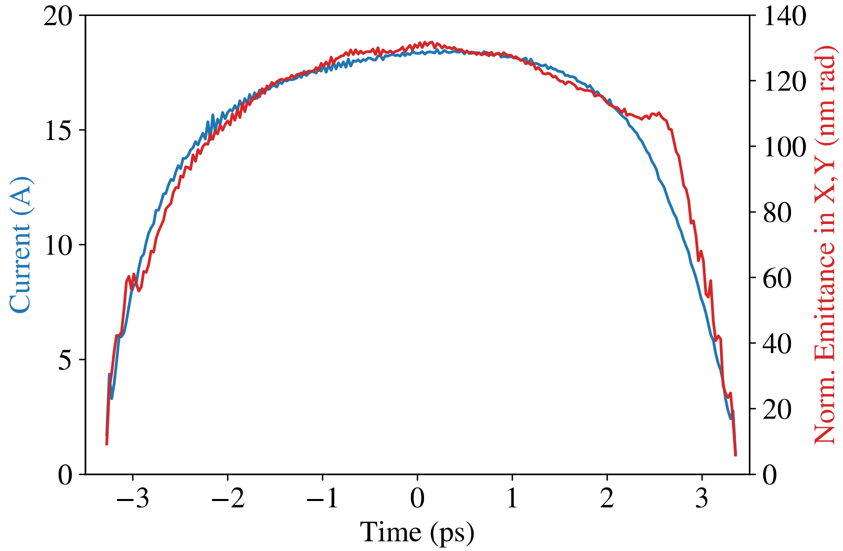


250 pC case

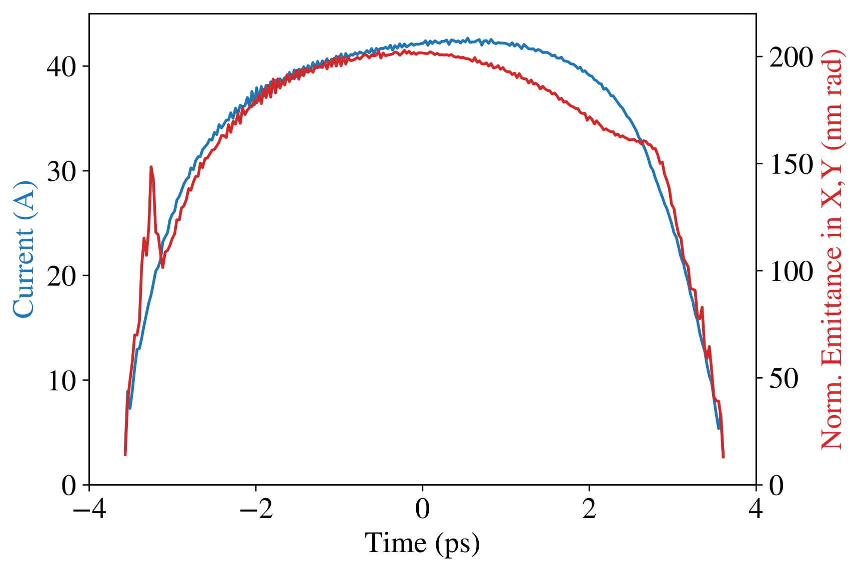


GPT simulations: beam current and slice emittance at beam waist

100 pC

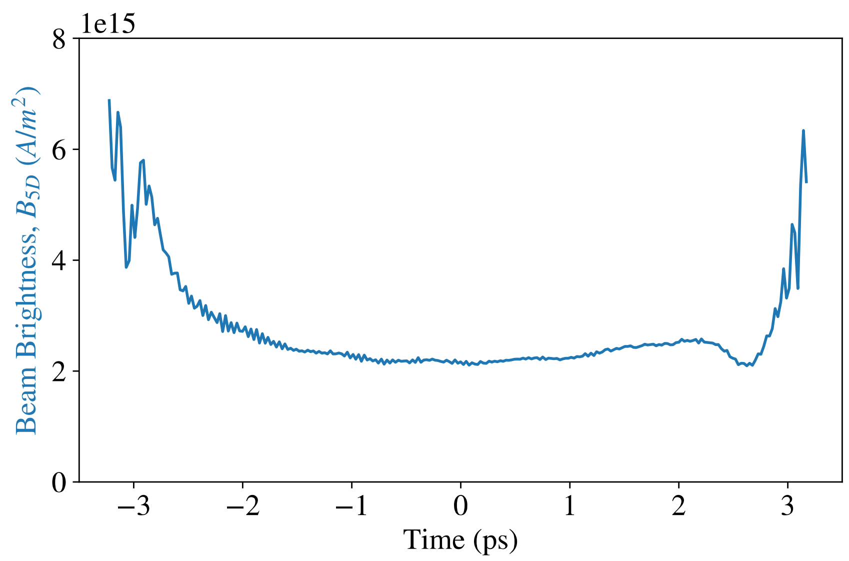


250 pC

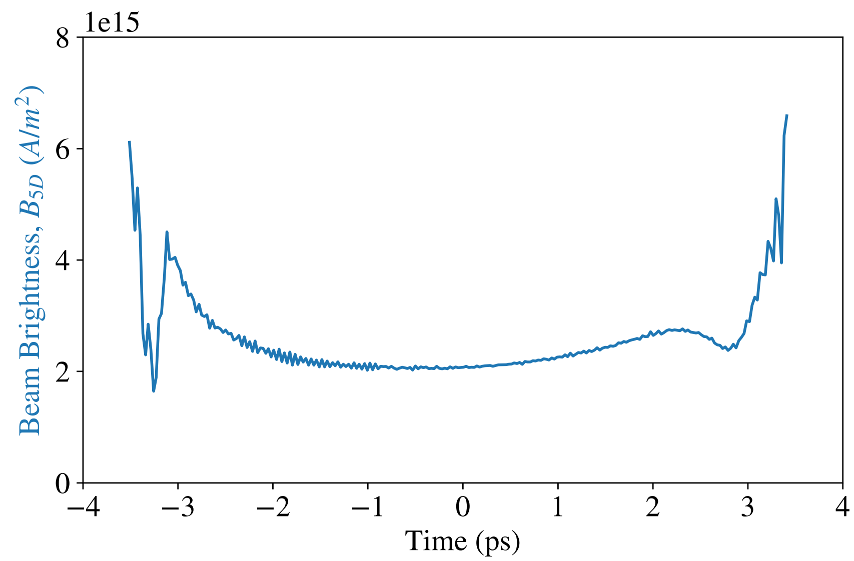


GPT simulations: beam brightness

100 pC

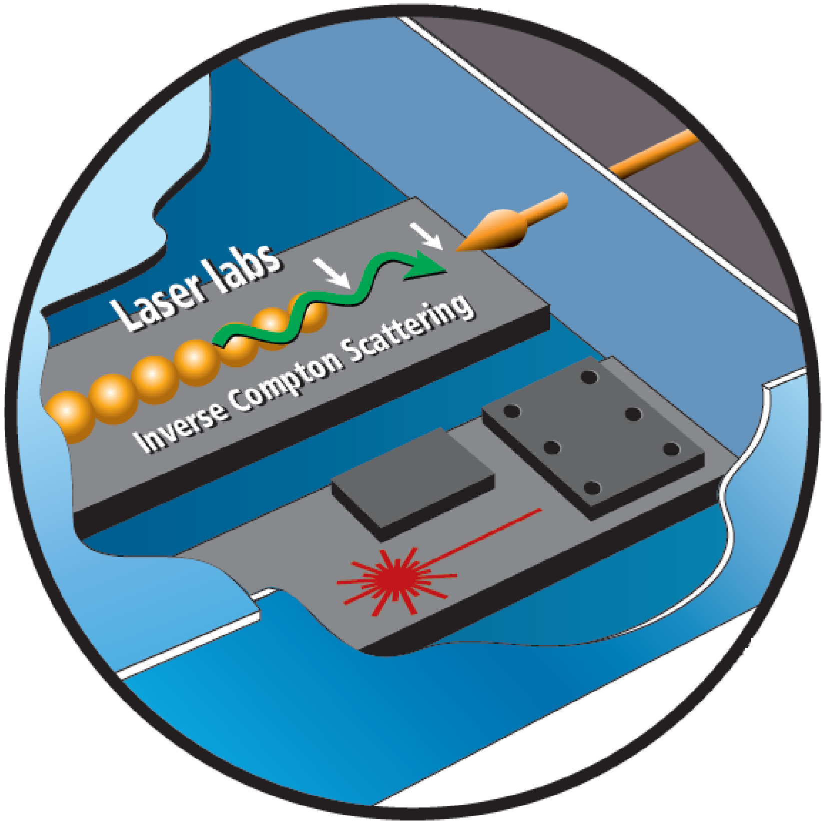


250 pC



LANL has plans for further developing its C-band accelerator capabilities

- Director Initiative money were allocated in FY22 to jump start this facility.
- 5-year goal: build operational C-band cryo-cooled copper accelerator.
- Ultimate goal: provide 43 keV and 100 keV photon bursts for material studies with ICS



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