

# C-band High-Gradient Photoinjectors at CARIE

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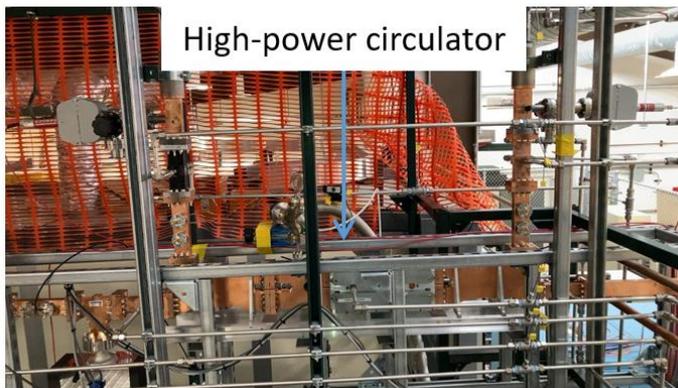
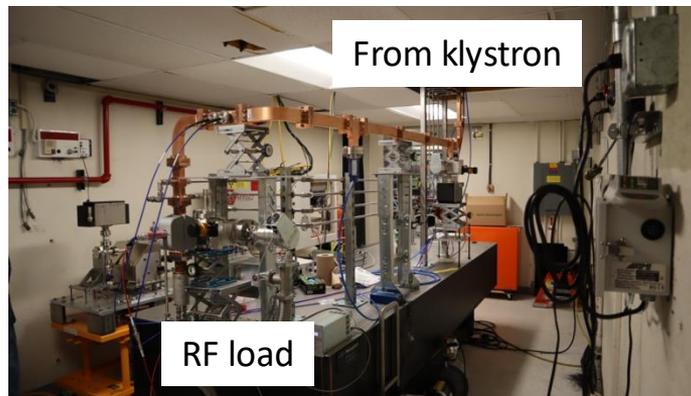
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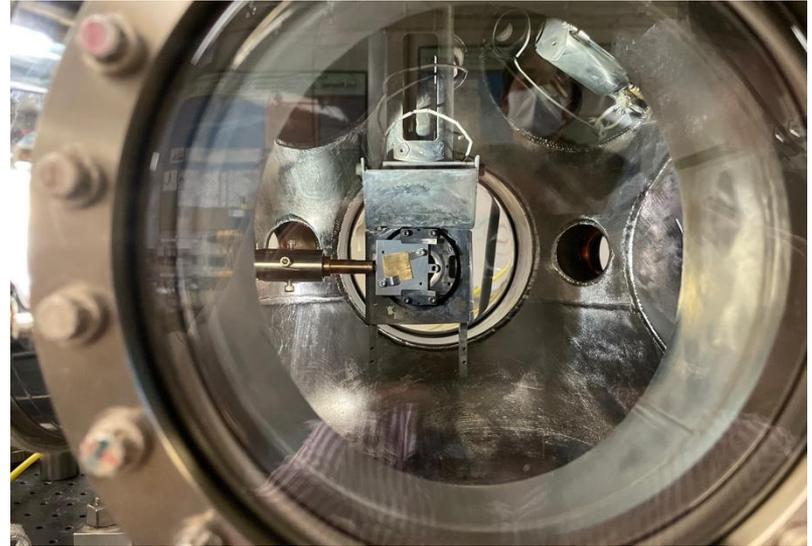
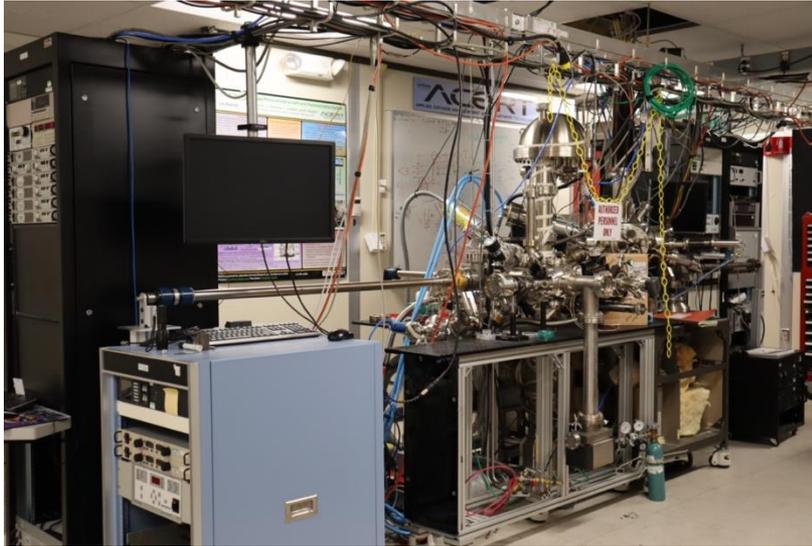
August 28<sup>th</sup>, 2025



# CARIE: Cathodes And Radiofrequency Interactions in Extremes

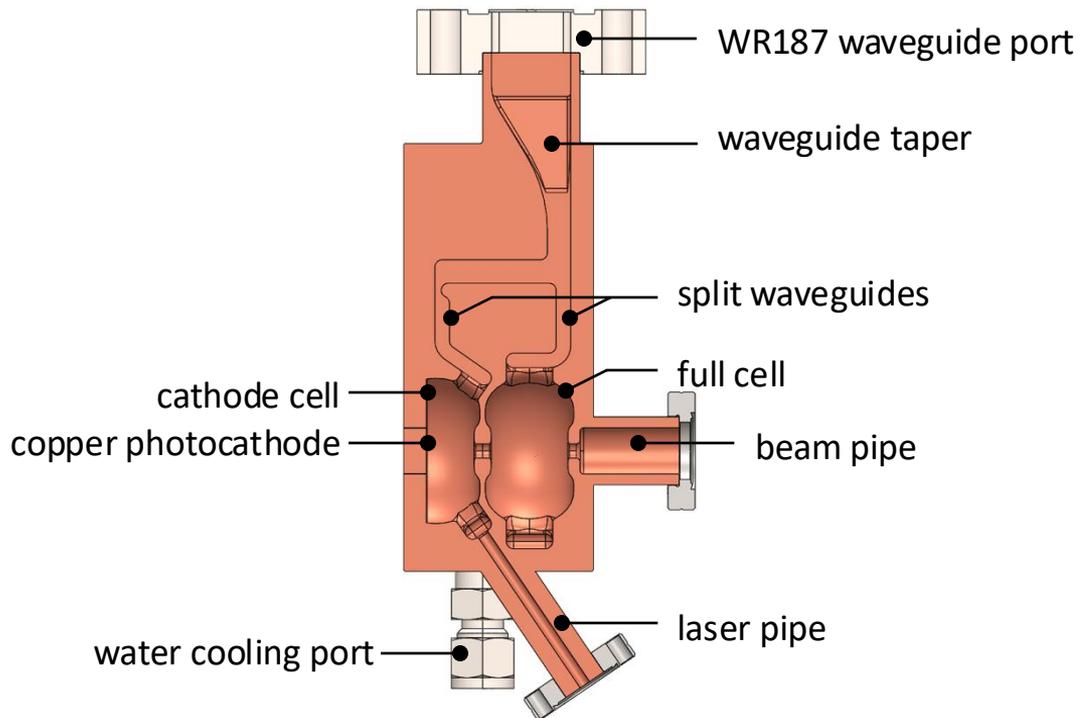
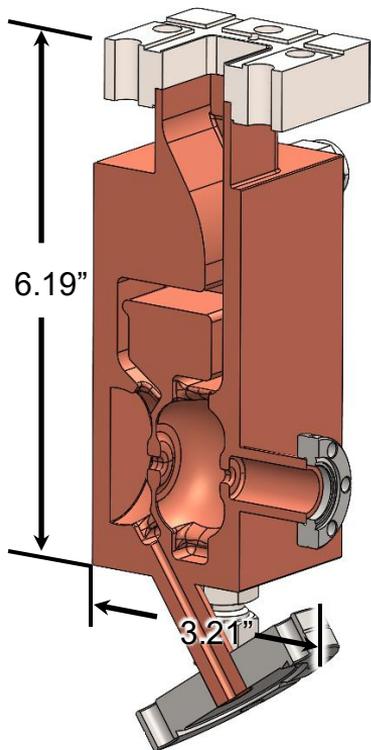


# CARIE: Cathodes And Radiofrequency Interactions in Extremes



Applied Cathode Enhancement and Robustness Technologies (ACERT) facility

# CARIE photoinjector I – concept validation



Ready for high-power test

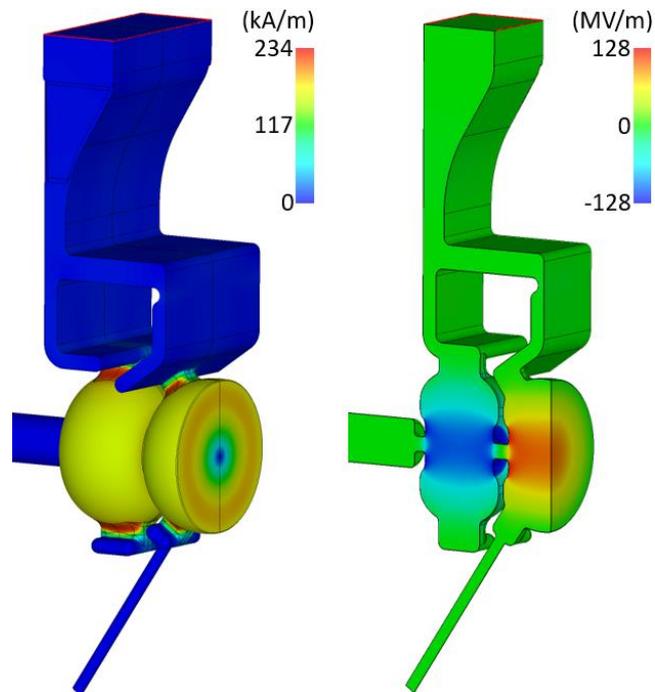
# CARIE photoinjector I – RF simulation

- RF operating specifications

Parameter (room temperature)	Value
Operating frequency $f_0$	5.7120 GHz
Cathode center electric field magnitude $E_{cath}$	100 – 240 MV/m
RF power required (without beam)	1.4 – 8.0 MW
RF pulse length	Up to 1 $\mu$ s
RF pulse repetition rate	Up to 100 Hz

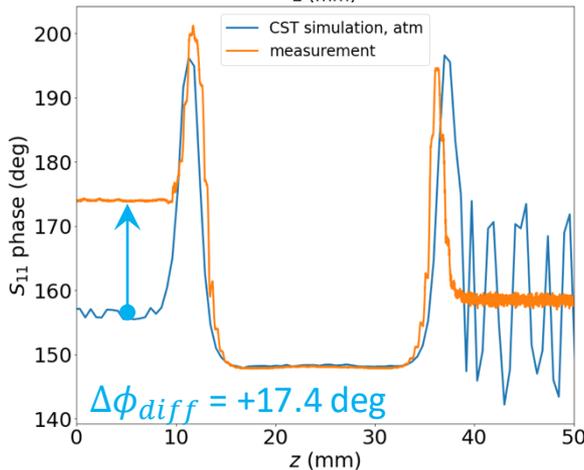
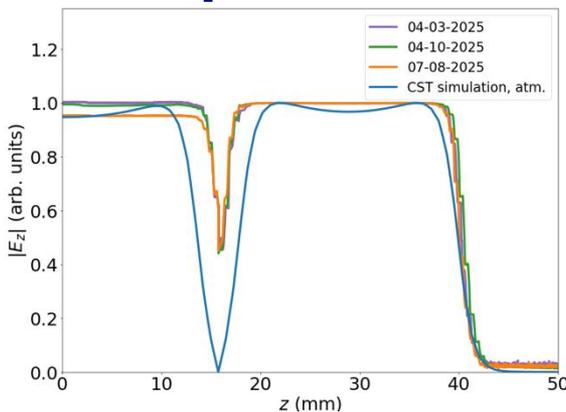
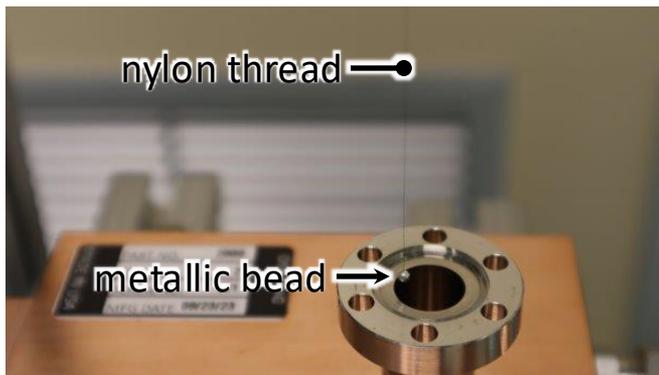
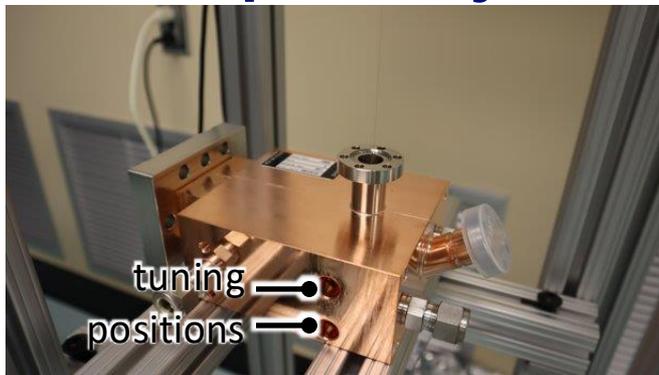
- CST High Frequency Solver results

Parameter (room temperature)	Value
Resonant frequency $f_0$	5.7121 GHz
Coupling factor $\beta$	0.965
Unloaded quality factor $Q_0$	11934
External quality factor $Q_e$	12370
Loaded quality factor $Q_l$	6074

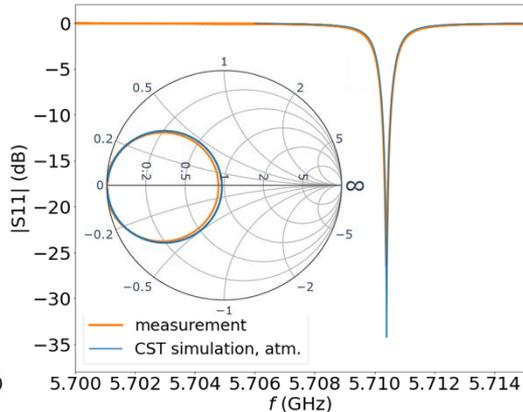


Cathode-center field 100 MV/m

# CARIE photoinjector I – low-power test

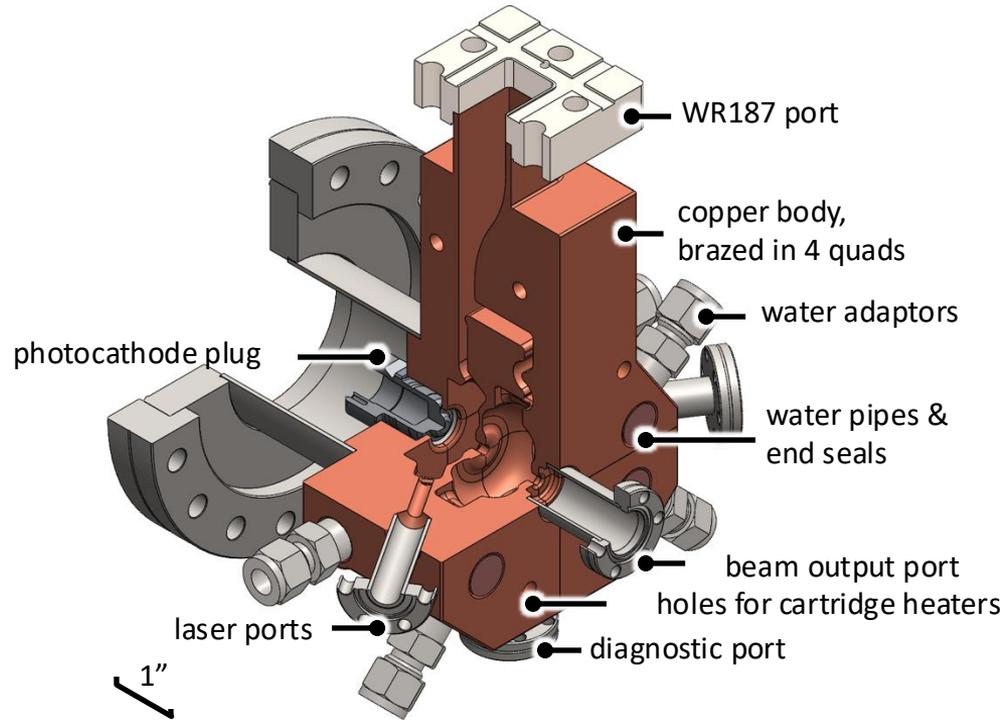


Low-power test: frequency, field balance, phase advance.



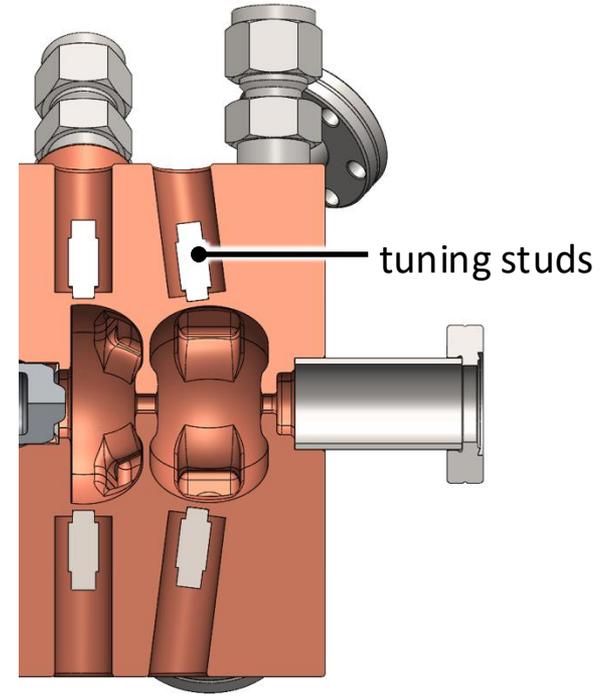
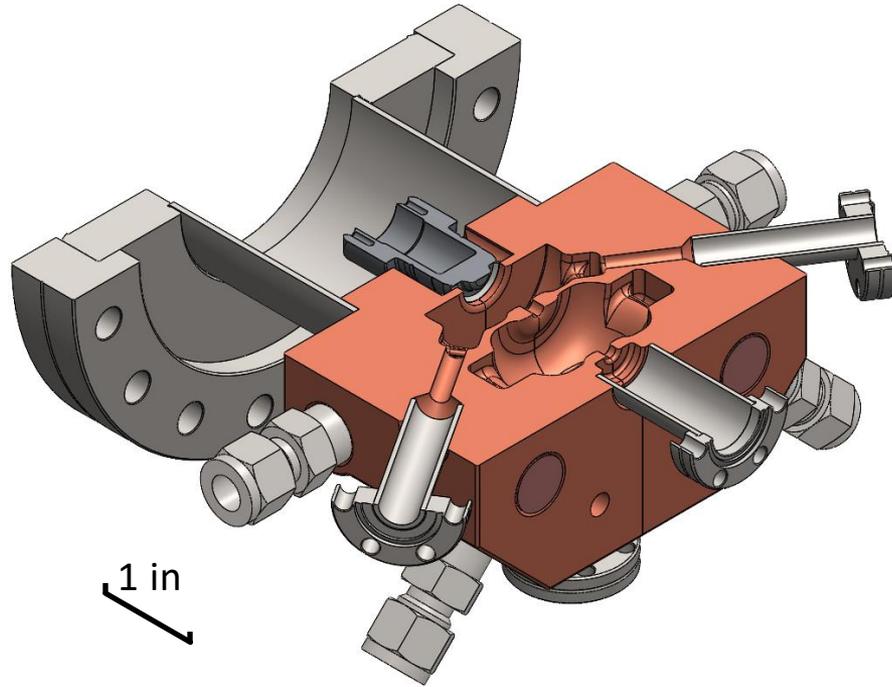
	In atm.	CST	Measured
$f_0$ (MHz)		5710.40	5710.39
$Q_0$		11936	12657
$Q_I$		6081	6722
coupl. fac $\beta$		0.963	0.883
norm. $E_{cath}$		0.989	0.957
$\Delta\phi$ (deg)		180.0	171.3

# CARIE photoinjector II – with photocathode plug insert

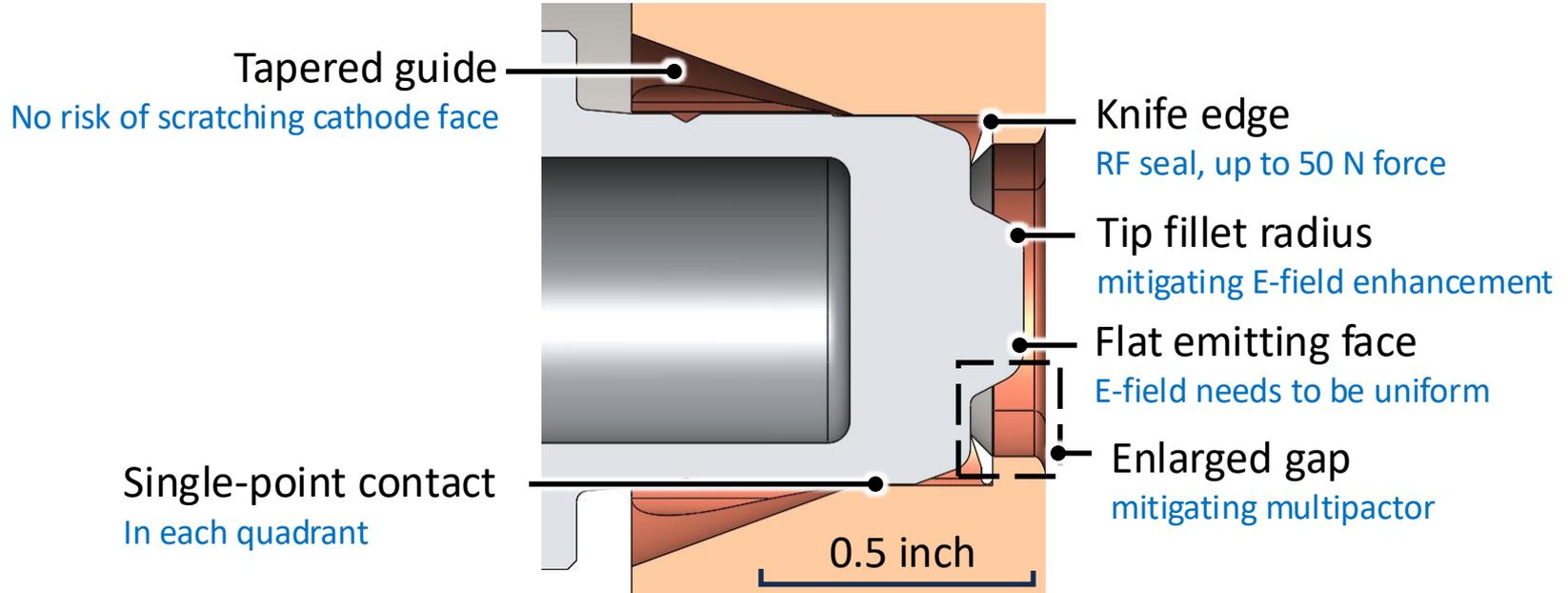


Initial low-power test performed, fine tuning required.

# CARIE photoinjector II – with photocathode plug insert

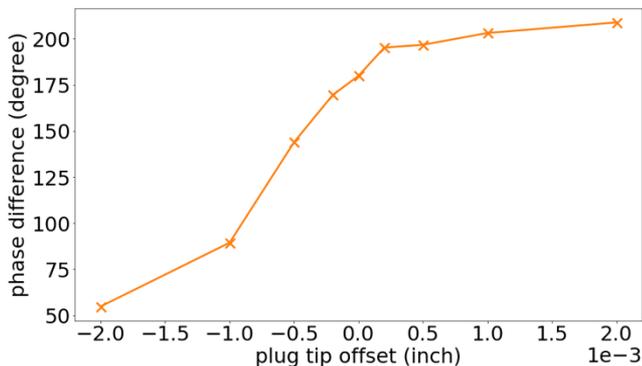
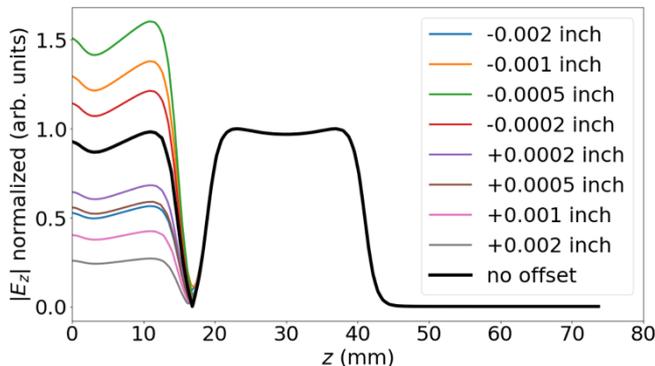


# CARIE photoinjector II – plug insert geometry

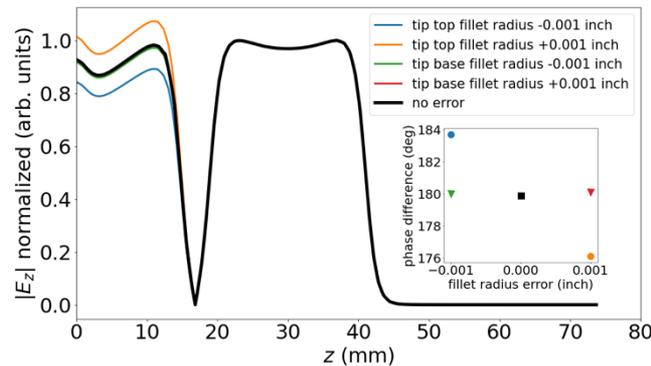


# CARIE photoinjector II – plug insert geometry

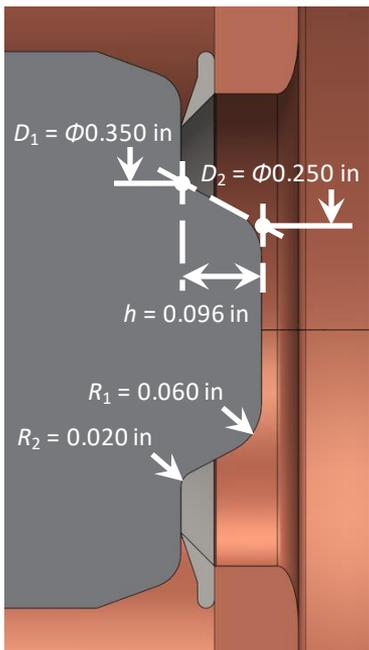
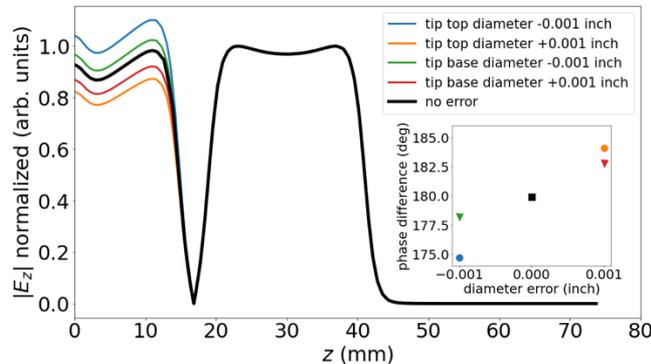
$h = 0.096$  in: plug tip step height



$R_1 = 0.060$  in,  $R_2 = 0.020$  in: plug tip fillets



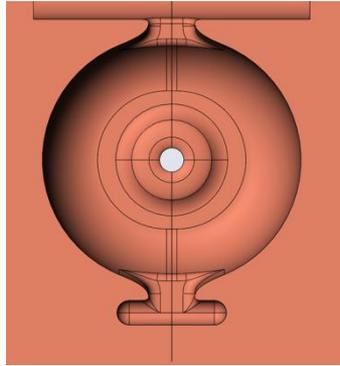
$D_1 = 0.350$  in,  $D_2 = 0.250$  in: plug tip diameters



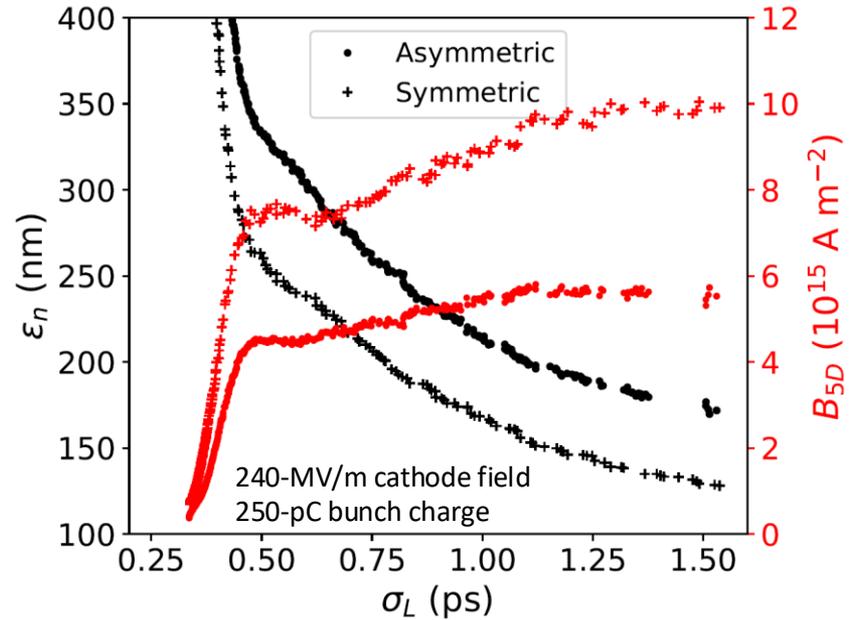
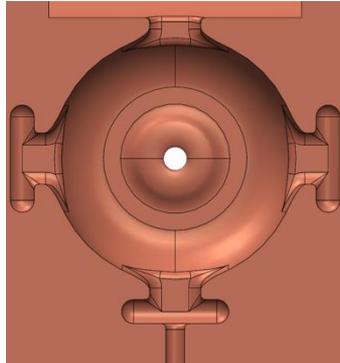
**Plug tip height tolerance  $\pm 5$  micron**

# CARIE photoinjector II – field symmetrization

Photoinjector I:  
race-track geometry  
(SLAC & UCLA)



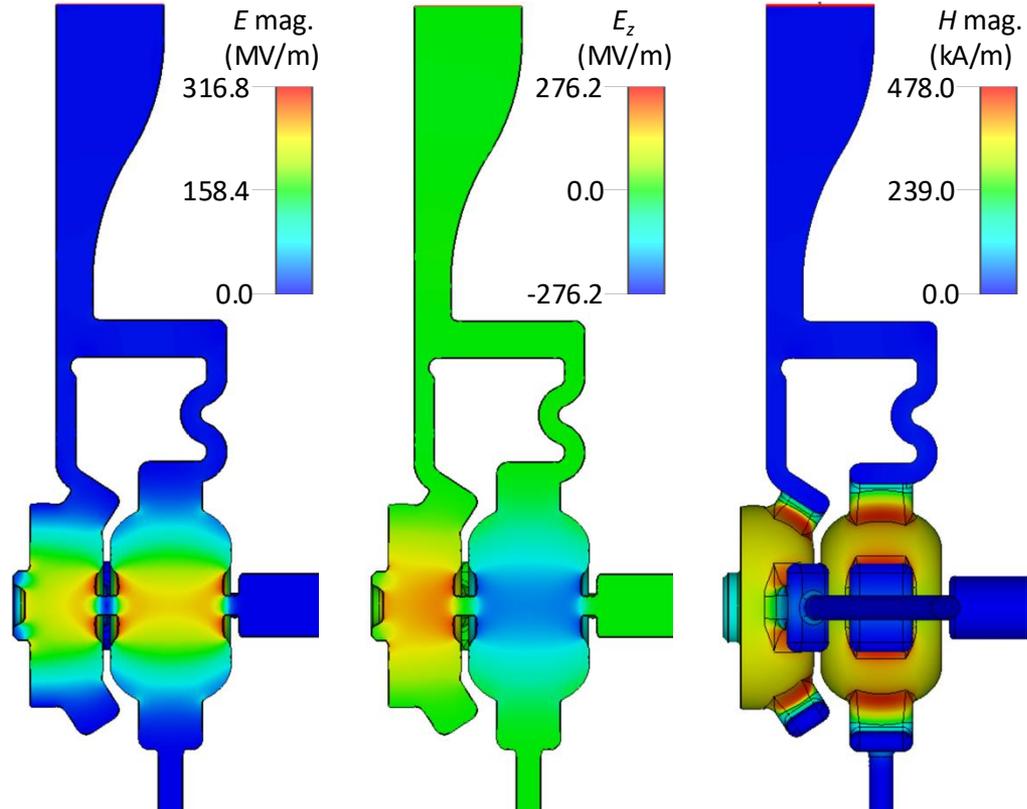
Photoinjector II:  
3X symmetry stubs



Three-symmetry-stub geometry is predicted to provide distinctly lower emittance and higher brightness.

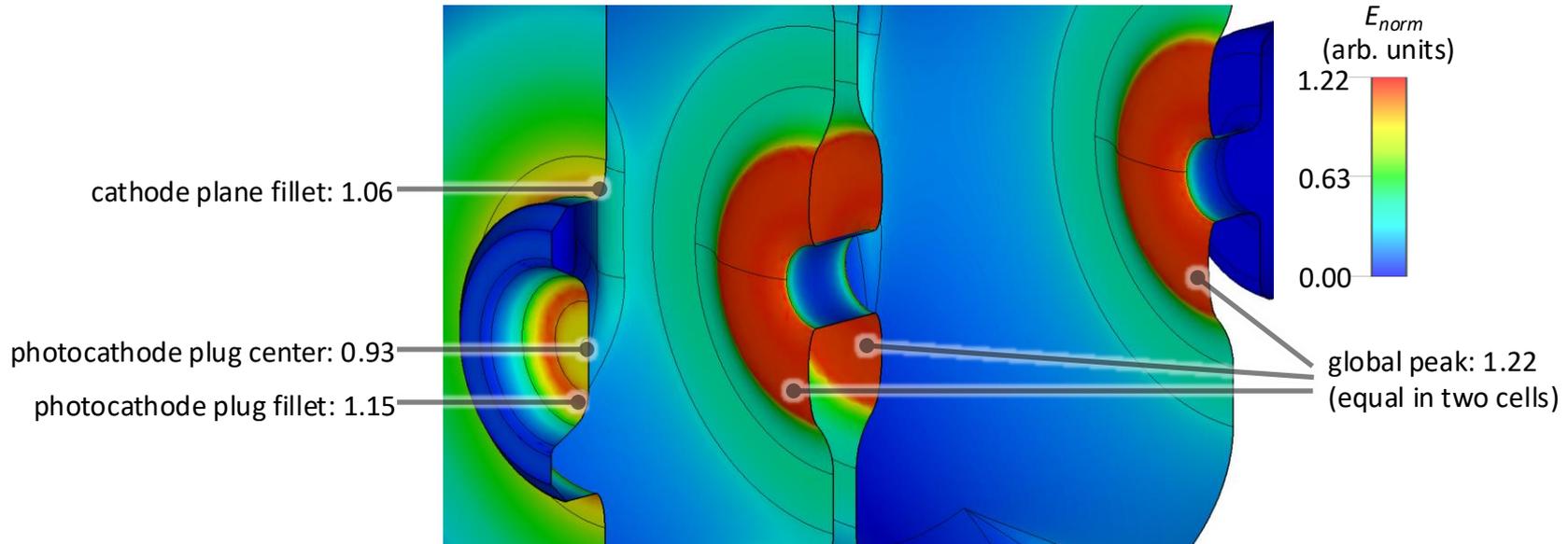
# CARIE photoinjector II – RF simulation

- 5.712 GHz (C-band), critical coupling
  - $Q_0 = 11510$
  - coupling factor  $\beta = 1.042$
  - 180-degree phase difference
- RF power vs. cathode-center E-field mag.
  - 1.83 MW: 100 MV/m
  - 10.52 MW: 240 MV/m



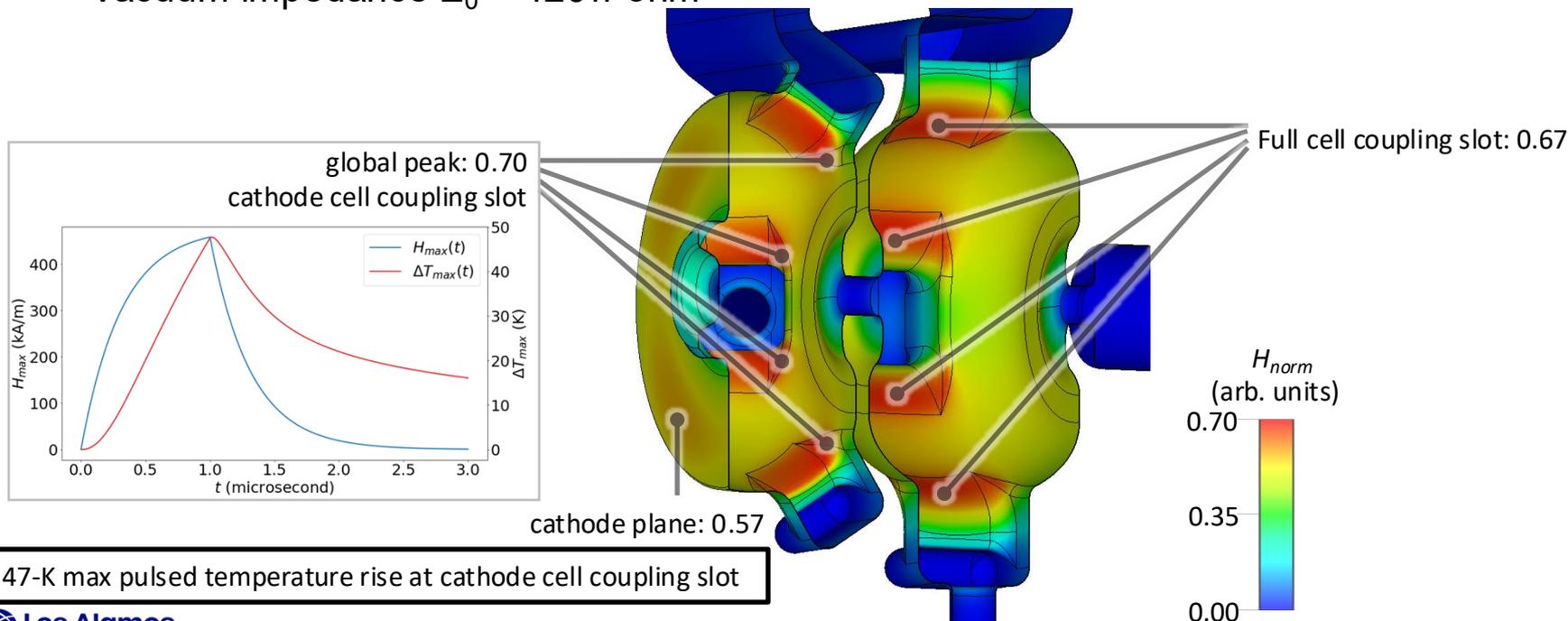
# CARIE photoinjector II – RF simulation

- E-field magnitudes normalized by  $E_m$  (beam-axis peak field), designated as  $E_{norm}$ .
  - When cathode-center E-field magnitude is 240 MV/m,  $E_m = 259.0$  MV/m.

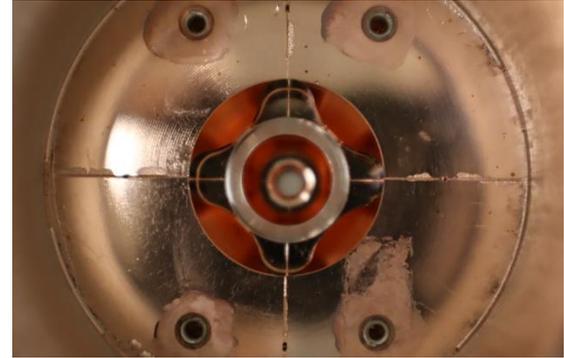
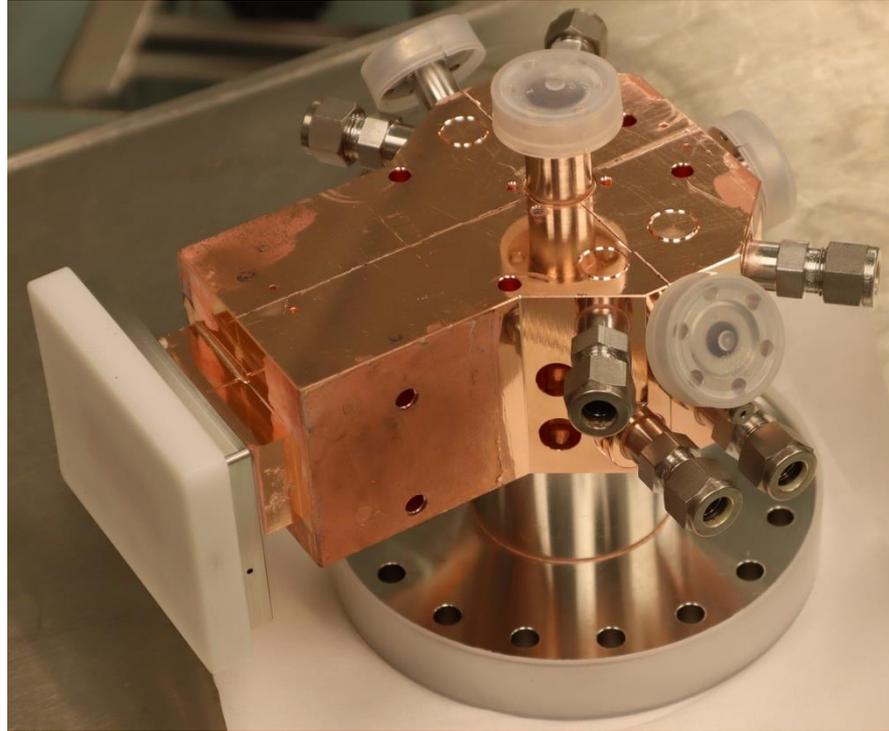


# CARIE photoinjector II – RF simulation

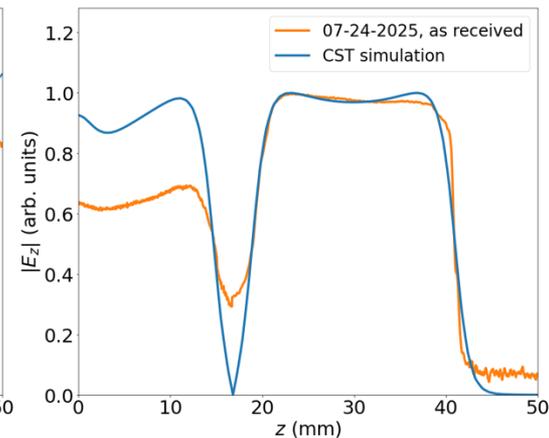
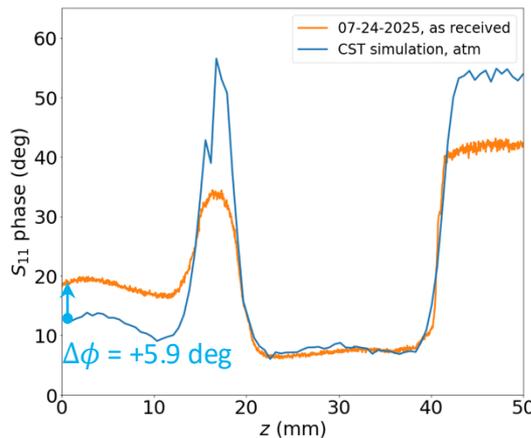
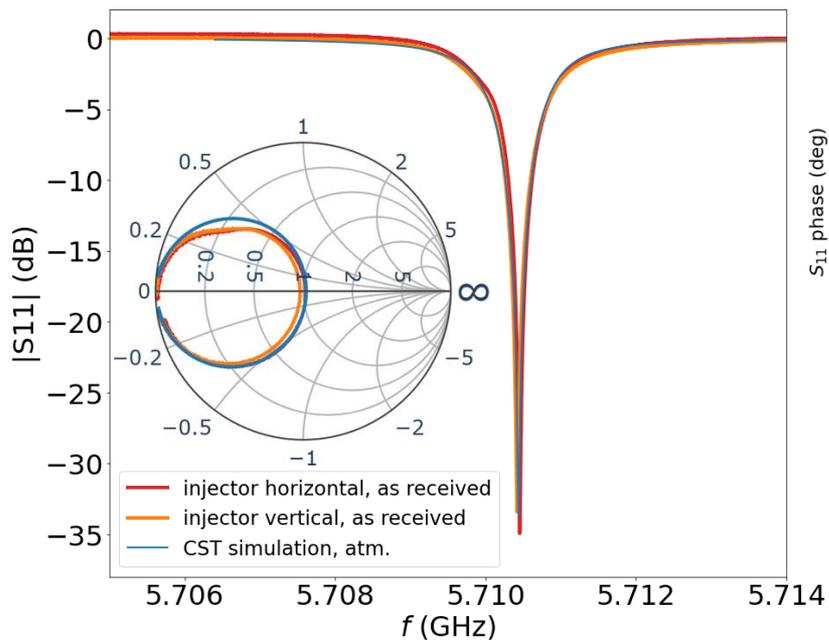
- H-field magnitudes normalized by  $( E_m / Z_0 )$ , designated as  $H_{norm}$ .
  - Vacuum impedance  $Z_0 = 120\pi$  ohm



# CARIE photoinjector II – low-power test



# CARIE photoinjector II – low-power test



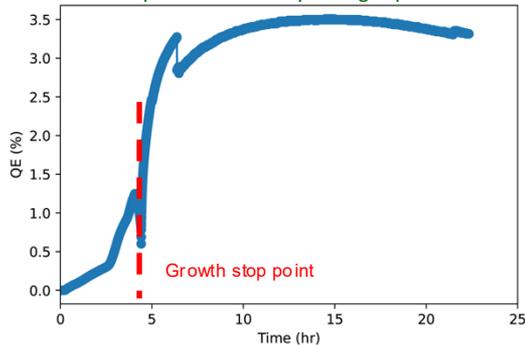
In atmosphere	CST	Meas. Hori.	Meas. Vert.
Resonant freq. (MHz)	5710.40	5710.46	5710.42
$Q_0$	11510	10292*	10576*
$Q_I$	5715	5062*	5399*
Coupl. fac $\beta$	1.014	1.033	0.959

As-received cavity already showed very good agreement with theory.

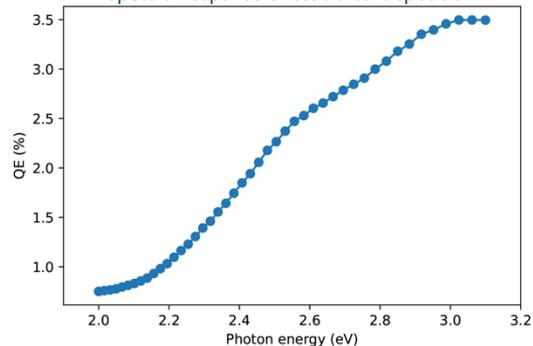
# CARIE photocathode development

## Sequential deposition: CsSb

CsSb quantum efficiency during deposition

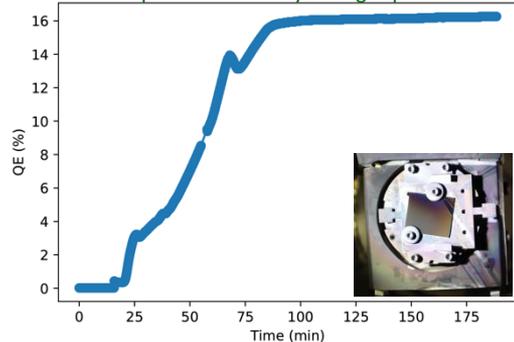


Spectral response of CsSb after deposition

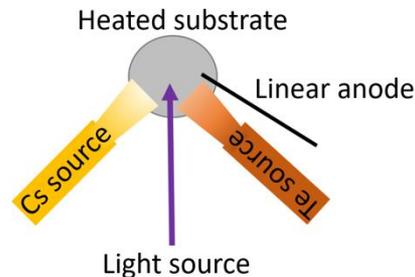
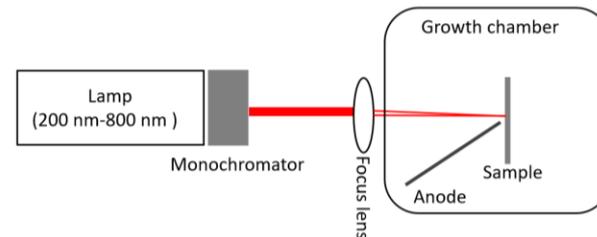
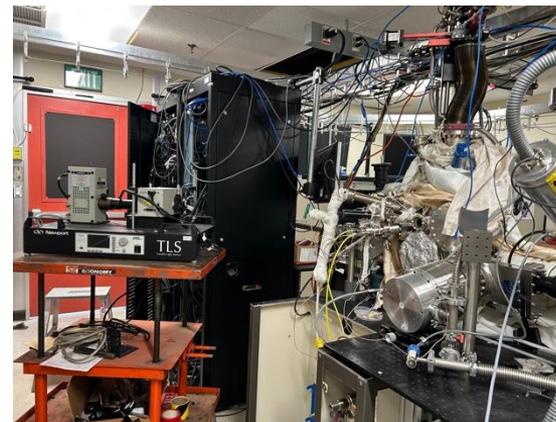
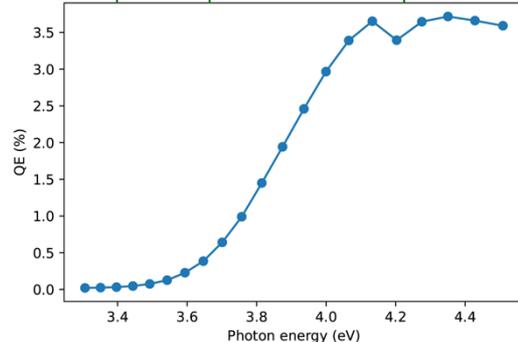


## Co-deposition: CsTe

CsTe quantum efficiency during deposition



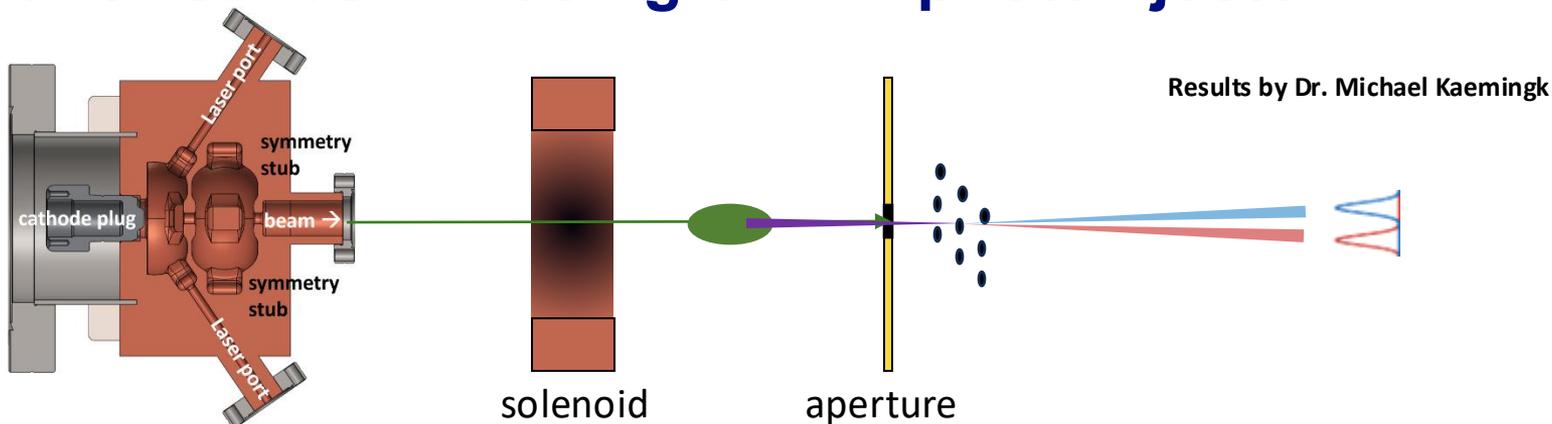
Spectral response of CsTe after deposition



## C-band for UED/UEM: balanced beam dynamics vs. RF frequency

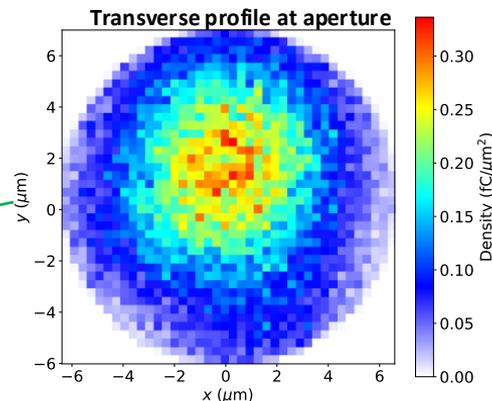
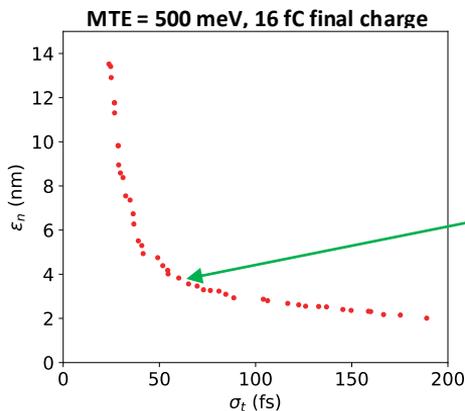
- Sufficiently high gradients expected
  - 240 MV/m cathode field
    - Faster acceleration allows better preservation of normalized emittance.
  - 7.2 MeV at gun exit
    - Covering the optimal energy range for thick samples\*.
- Reasonable dimensions and tolerances
  - Machining
  - Photocathode plug insert geometry
  - Cryo-RF operation

# C-band for UED/UEM: using CARIE photoinjector



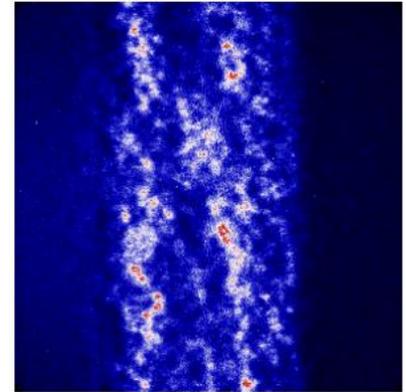
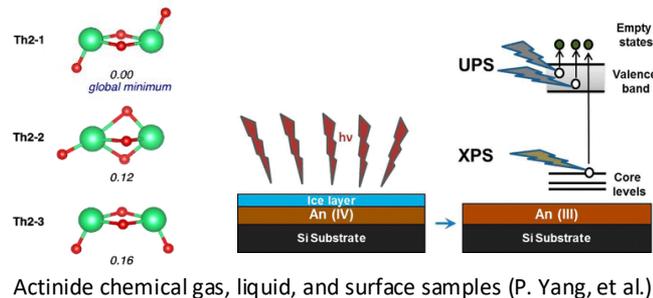
## Optimization parameter range

Parameter	Value	Unit
Bunch charge	16 - 80	fC
Laser spot rms x-/y-size	0.1 - 100	$\mu\text{m}$
Laser rms pulse length	0.025 - 5	ps
Gun phase	-40 - 90	deg

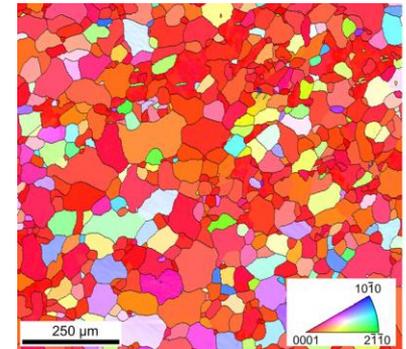


# UED/UEM potentials at LANL\*

- Greatest potential: in situ STEM
- ps-to-ms, variable time scale
- Stroboscopic mode
- Extreme conditions, miscellaneous pumping modalities\*\*
  - High strain rate, high stress loading
  - Extreme temperature
  - High pressure
  - Melting & solidification
  - Intense radiation



Void nucleating in magnesium due to spall damage (S. Fensin, et al.)



Metallic phase change due to shocks and extreme temperature (R. Pokharel, et al.)

# Conclusions

- Cathodes And Radiofrequency Interactions in Extremes (CARIE) facility high-power RF system is towards the end of commissioning.
- The photoinjector with planar copper cathode low-power test results agreed with theory. The 1.6-cell high-gradient photoinjector geometry was validated.
- Photoinjector using photocathode plug insert has been designed and fabricated. Initial low-power test has been performed and the results agreed with theory.
- After high-power test validation, the photoinjector using photocathode plug insert will be ready for photocathode research and exploring applications such as UED/UEM.

# Acknowledgment

