LANL high gradient photoinjector and photocathode projects, technology, and plans

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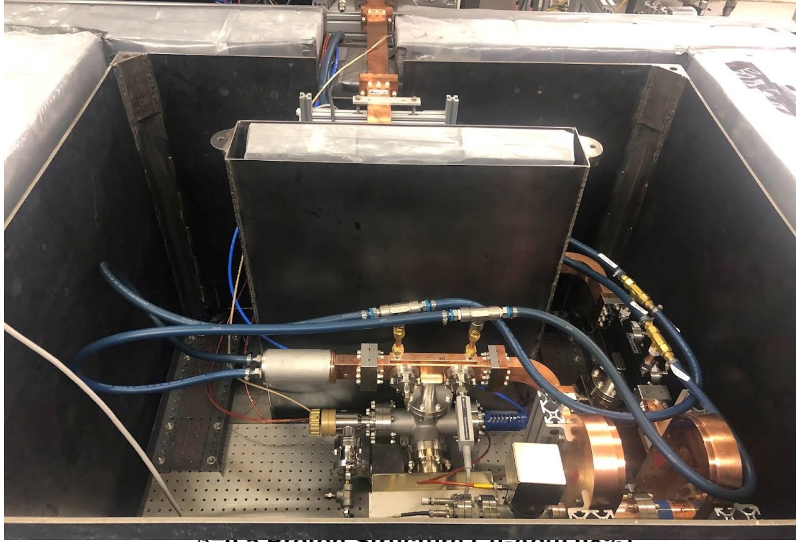
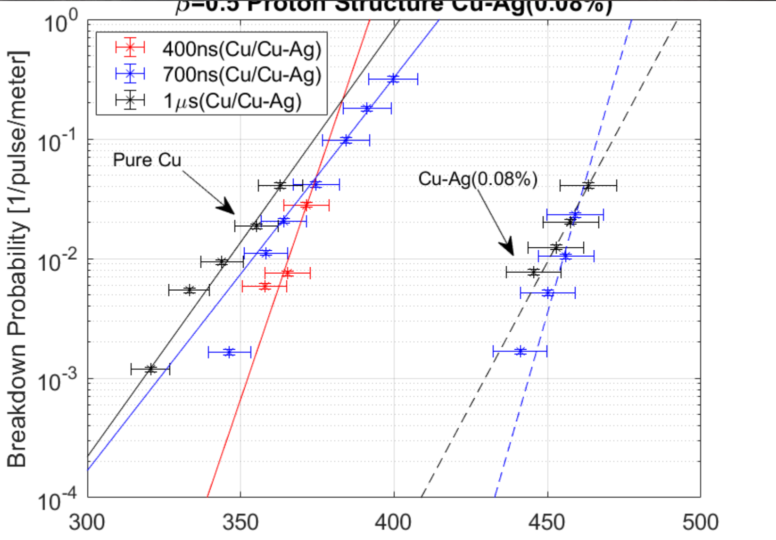
Carie: high gradient photoinjector capability

- Goal: demonstrate operation of high QE cathodes in a high-gradient RF injector

Why?

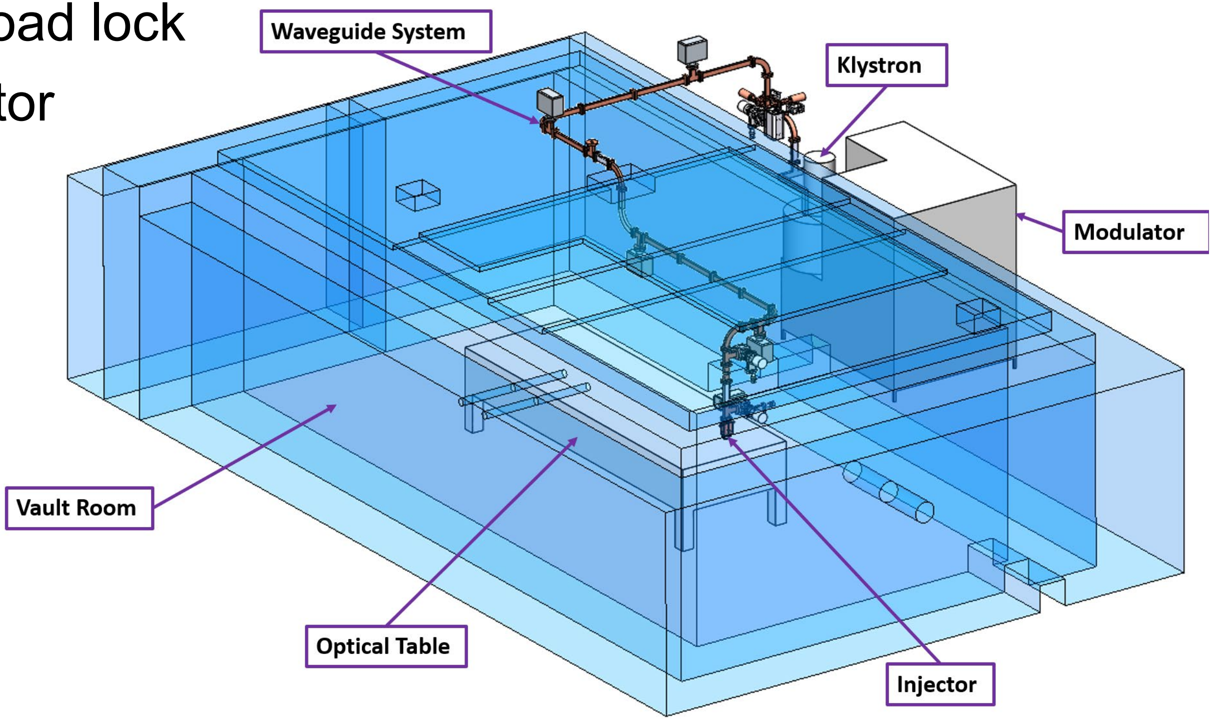
- ICS 44 keV xray source
- UED





Carie system design: components

- Photocathode plug+ load lock
- UHV 1.6 cell RF injector
- Solenoid
- Beam diagnostics



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Carie system design: infrastructure

- Photocathode fabrication and characterization
- 50 MW C band klystron
- Radiation shielded room
- Adjacent class IV laser lab
- Cryogen compatible

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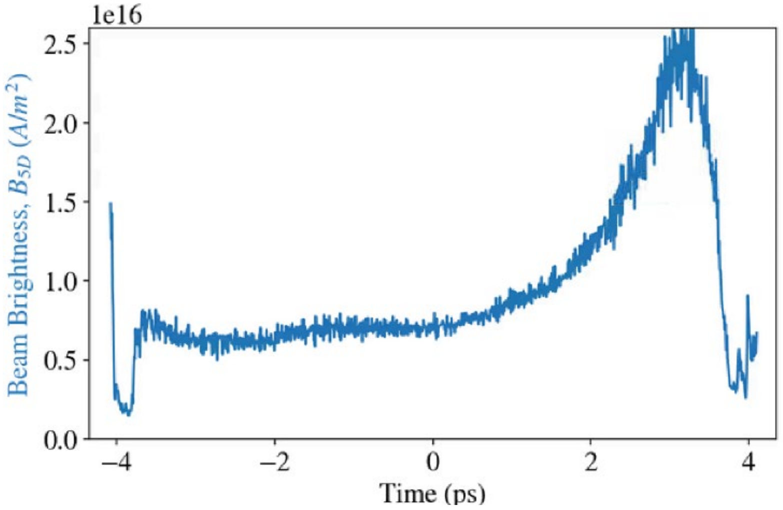
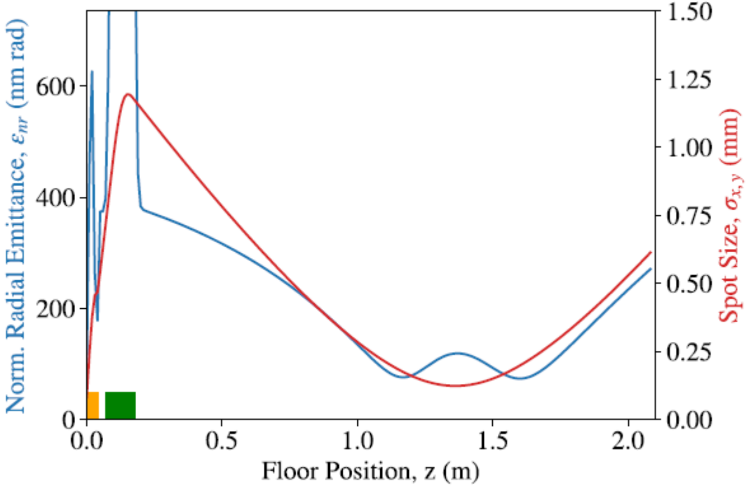
Injector overview

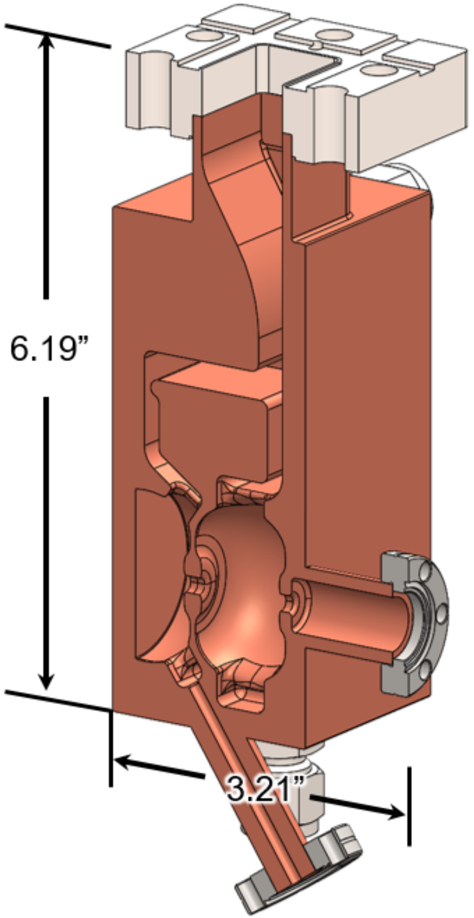
- 8 MeV
- 240 MV/m peak field on cathode
- 250 pC bunch charge
- 0.1 μm*rad emittance target
- $B_{5D} = 10^{16}$ A/m^2





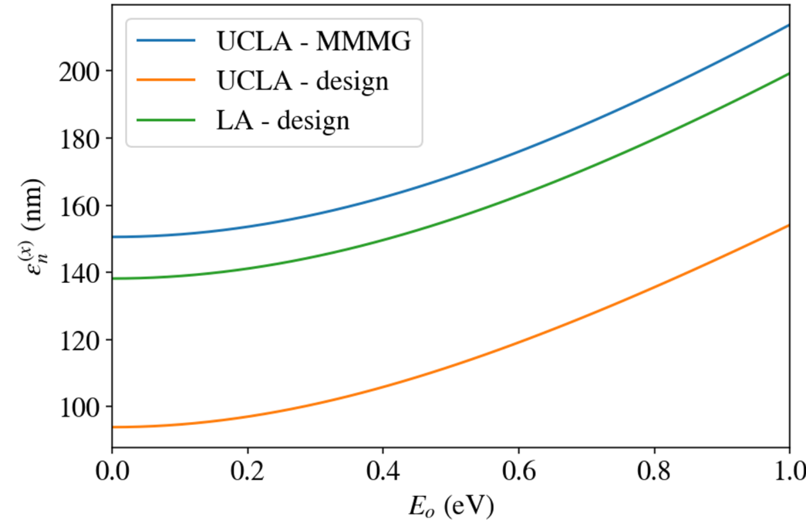
RF design parameters

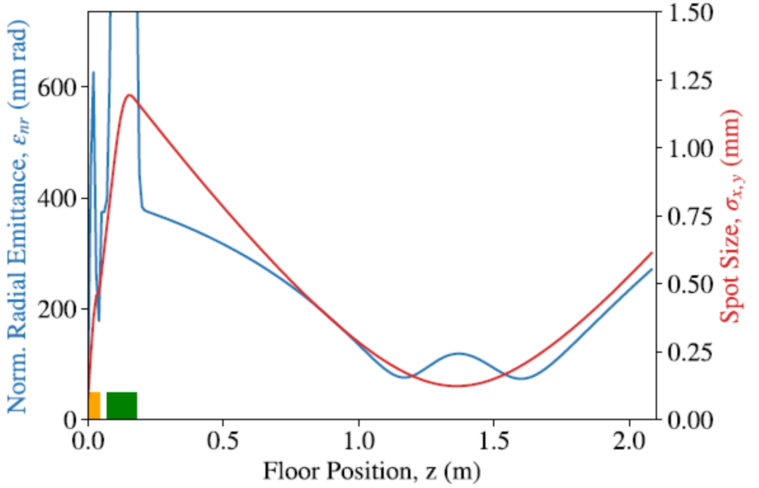
Design parameters	
Operating frequency f_0	5.712 GHz
Full cell shunt impedance R_{sh} (r_{sh})	3.09 MΩ (118 MΩ/m)
quality factor $Q_{0,cath}$	13603-14695
Cavity coupling factor β	1.00
RF power for 100-MV/m cathode field	1.4 MW
RF power for 240-MV/m cathode field	8.0 MW



Emittance sources: space charge, RF and intrinsic

- solenoid provides emittance compensation at a specific location
- RF emittance dominates if MTE < 100 meV
- Missing contribution: geometric emittance





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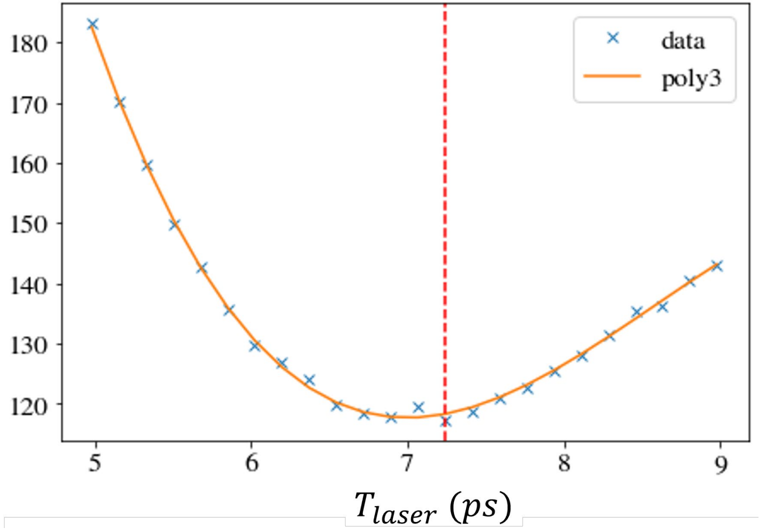
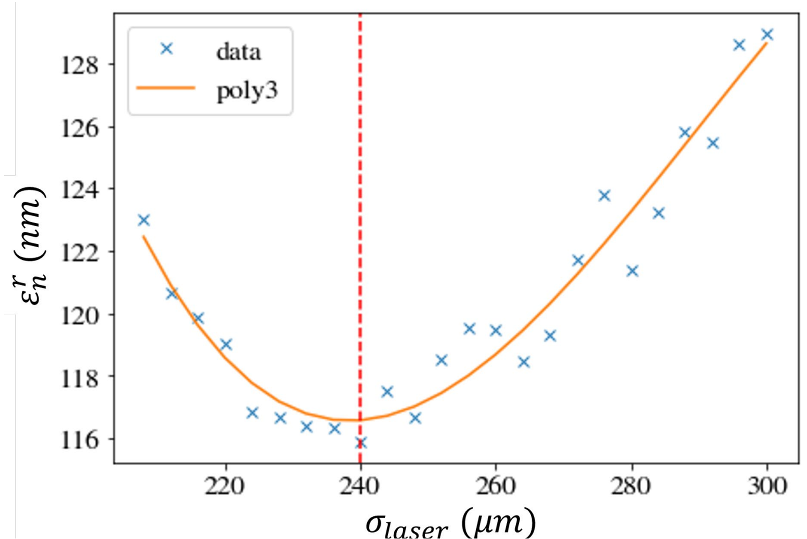
Implications of imperfect emittance compensation

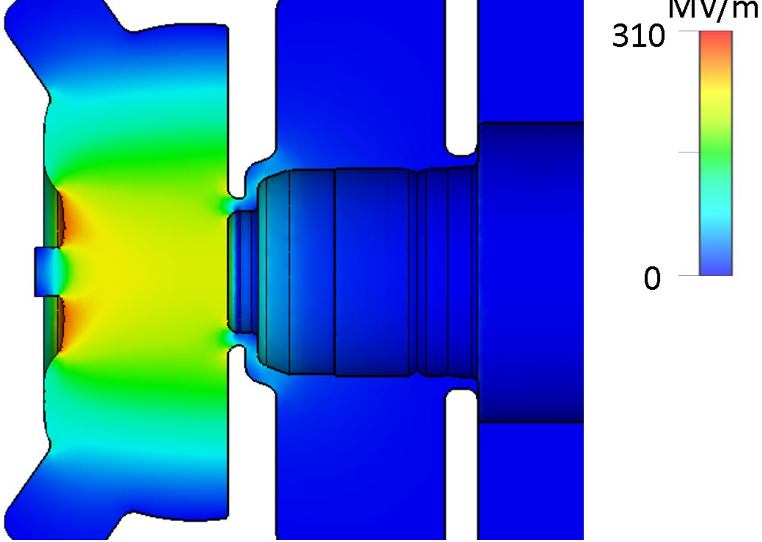
- Cathode on time < 7 ps
- Spot size: ~300 um

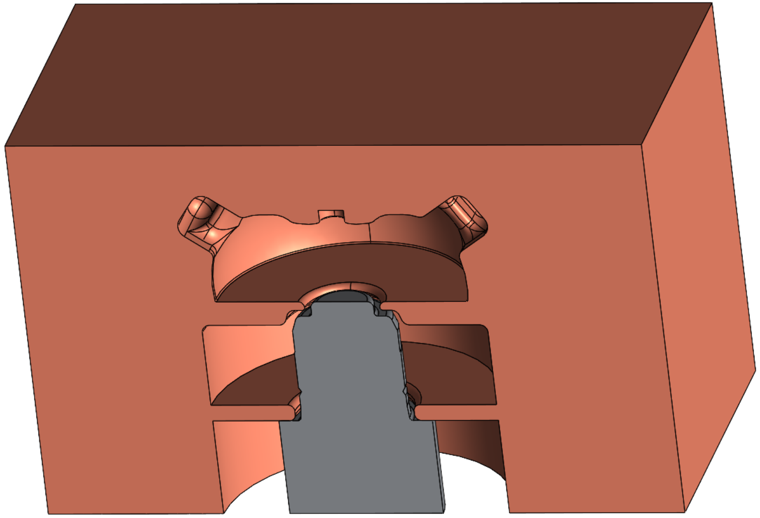




Cathode-gun-plug integration

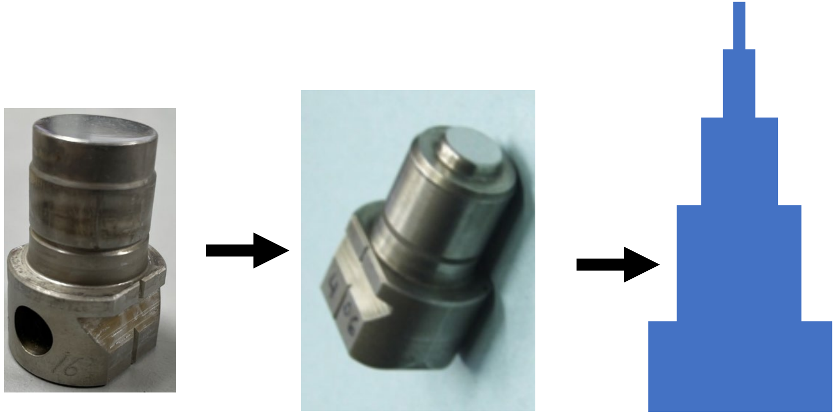
- EM Choke enables spring free design without RF seal
- Held in place using an arm: no locking mechanism
- Multipactoring and thermal simulations in progress

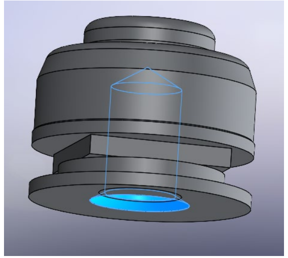




Cathode plug design

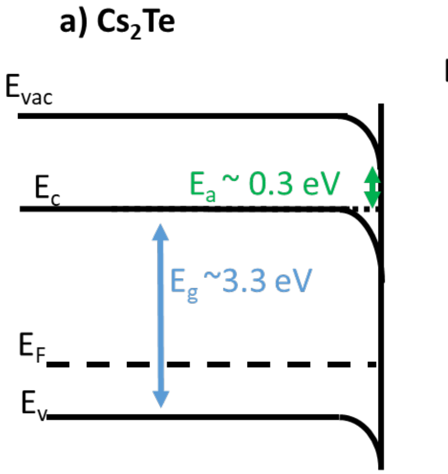
- System will be compatible with INFN plug
- Compatible with smaller plug for integration with material characterization capabilities

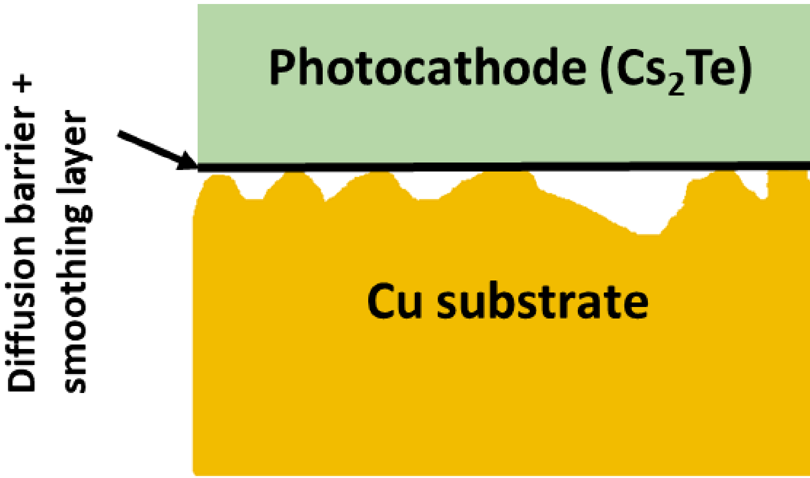




High gradient photocathode design:

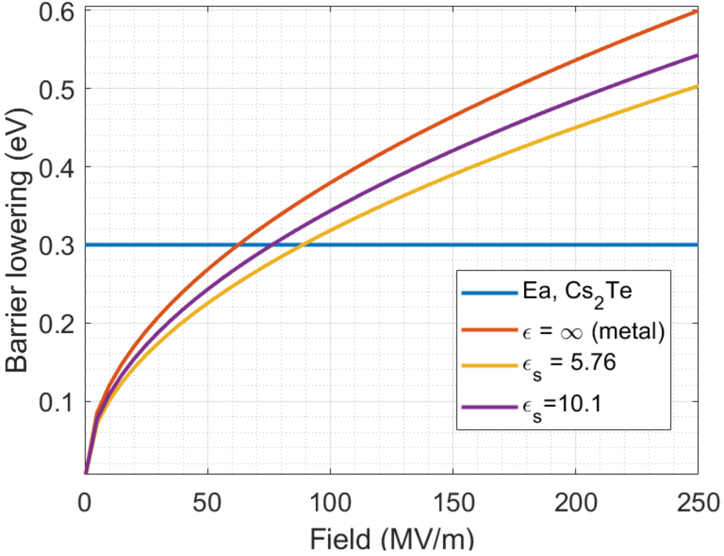
- High bandgap + high(er) Ea
- Ultrathin cathodes
- Heterostructures?
- Lossy/imperfect preferred?
- Does photoemission facilitate breakdown?
- What happens to the injector when photocathodes break down?



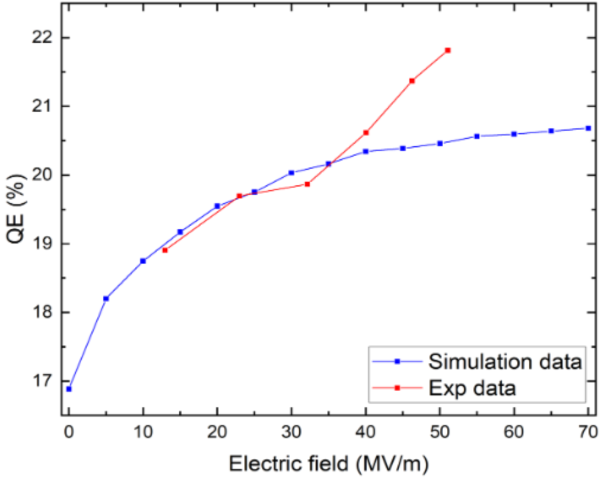


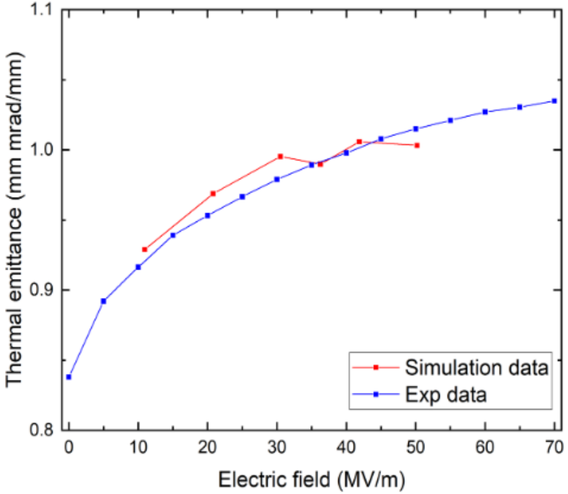
Cs2Te in high gradients

- Will we see NEA transition?



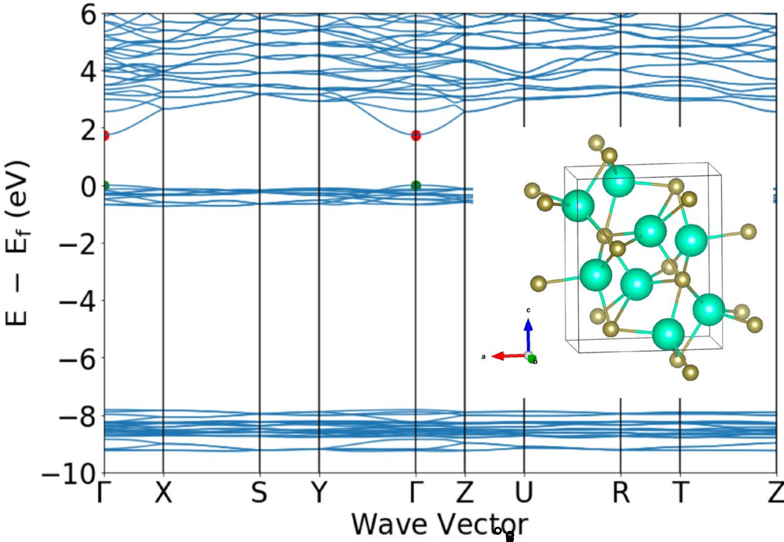
“Monte Carlo Simulation Study of Cs2Te”, Gowri Adhikari EWPAA 2022

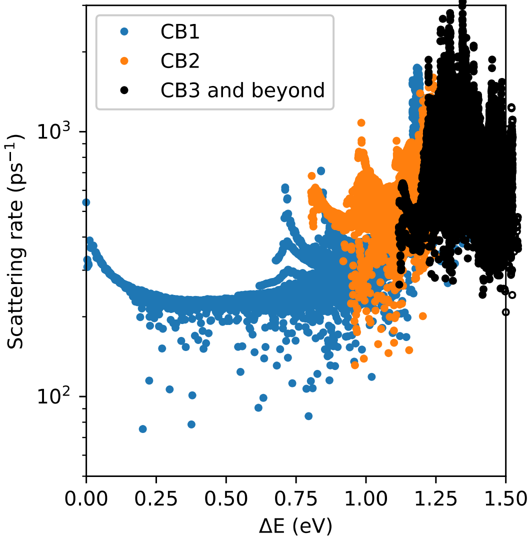




Theoretical models of Cs2Te

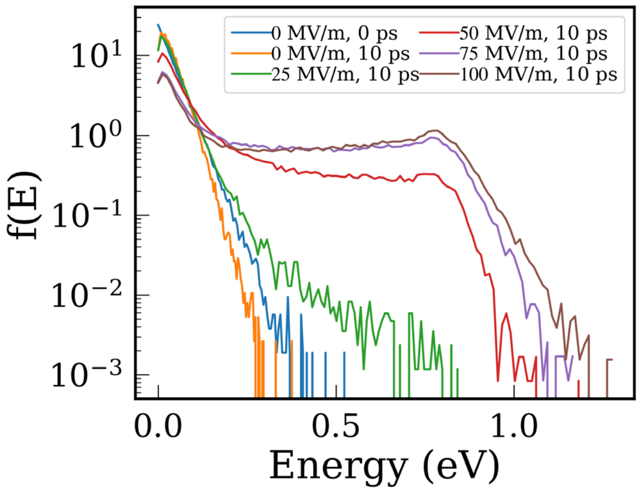
- Fully ab initio based initial model
- Optical constants, band structure, and phonon modes from DFT
- Monte carlo based transport model

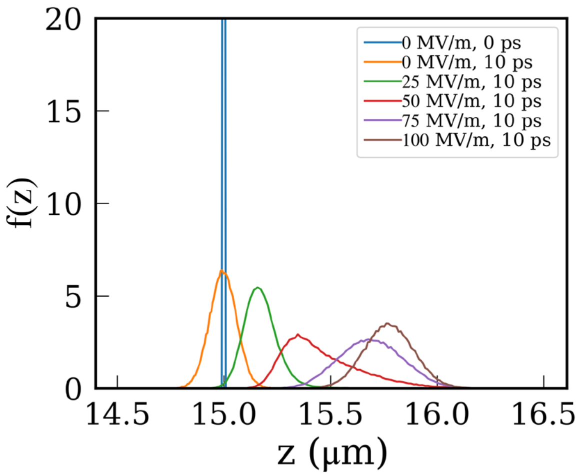




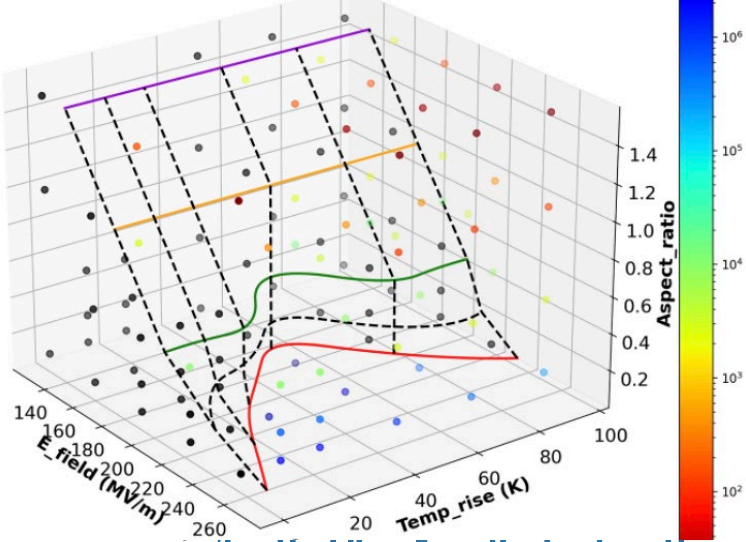
High gradient electron transport

- Clear increase in high energy tails (emittance increase?)
- Increased electron drift- potentially longer response time and emission of more deeply excited electrons





High gradient breakdown models



- Multiple breakdown models: which is most predictive?
  - Field induced curvature and field emission
  - Phonon-electron coupling
  - Additional scattering mechanisms
  - Time/thickness dependence

Energy gain rate:

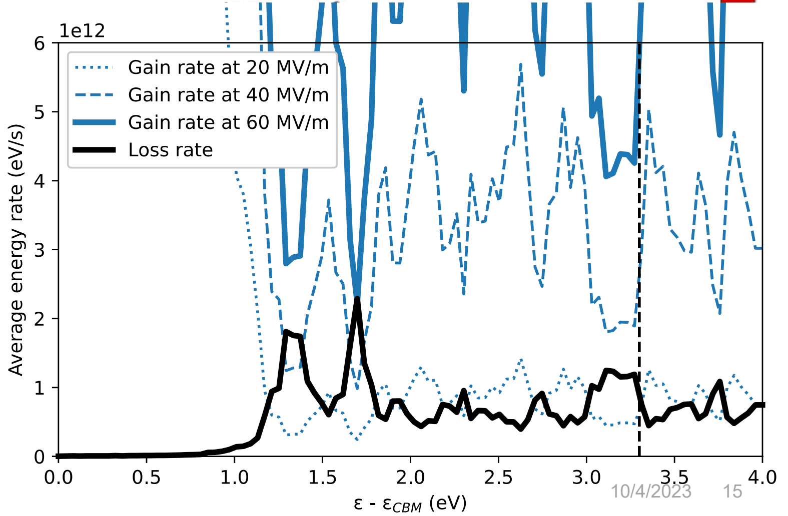
$$A(E,\varepsilon,T) = \frac{1}{3}\frac{e^2\tau(\varepsilon,T)}{m^*}E^2$$

Energy loss rate:

$$B(\varepsilon,T) = \frac{2\pi}{\hbar D(\varepsilon)}\sum_{nm\nu}\iint \frac{d^3k\,d^3q}{\Omega_{\mathrm{BZ}}^2}|g_{mn\nu}(\mathbf{k},\mathbf{q})|^2\delta(\varepsilon_{n\mathbf{k}}-\varepsilon) \times \hbar\omega_{\mathbf{q}\nu}[(n_{\mathbf{q}\nu}+1/2)\delta(\varepsilon_{n\mathbf{k}}-\varepsilon_{m\mathbf{k}+\mathbf{q}}+\hbar\omega_{\mathbf{q}\nu}) - n_{\mathbf{q}\nu}\delta(\varepsilon_{n\mathbf{k}}-\varepsilon_{m\mathbf{k}+\mathbf{q}}-\hbar\omega_{\mathbf{q}\nu})]$$

Breakdown criterion:

$$A(E,\varepsilon,T) > B(\varepsilon,T)$$



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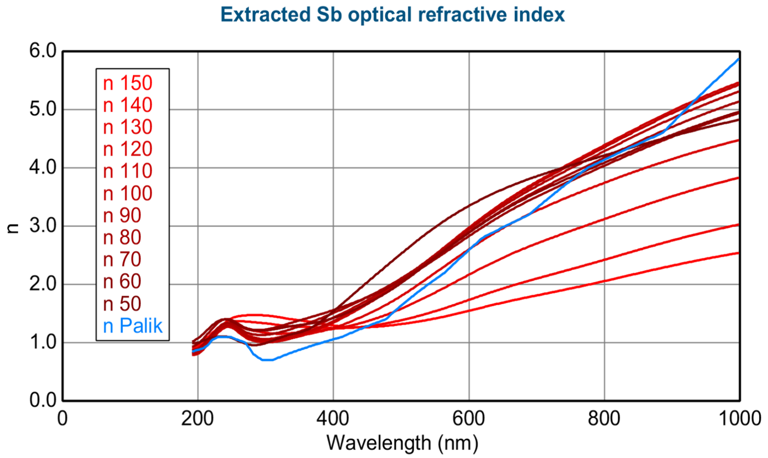
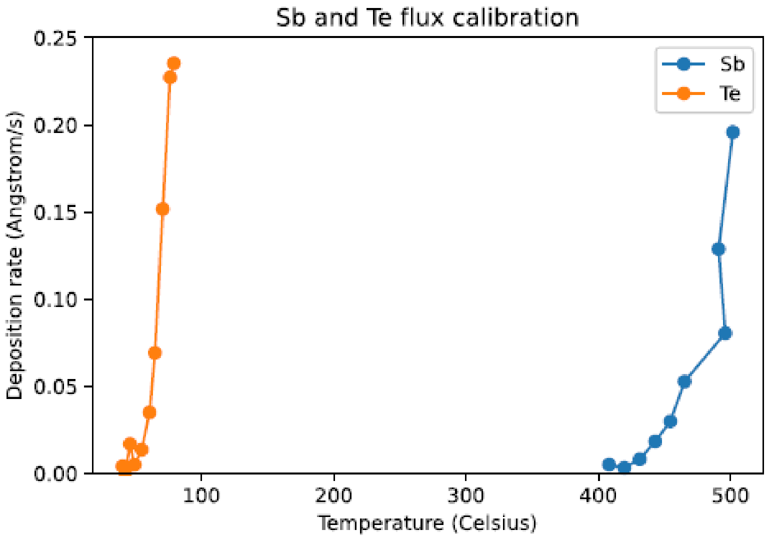
Where are we? ACERT upgrades

- Ultra precise alignment and motion
- In situ RHEED and ellipsometry
- Transition to temperature based evaporator control





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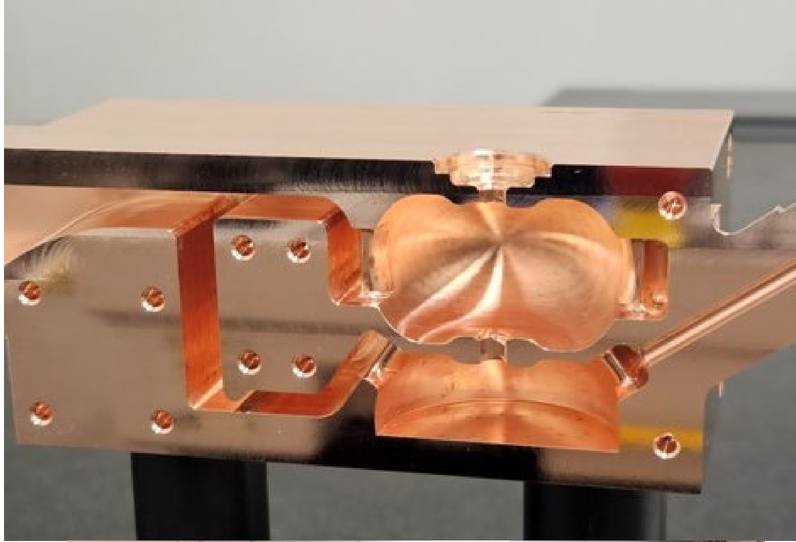
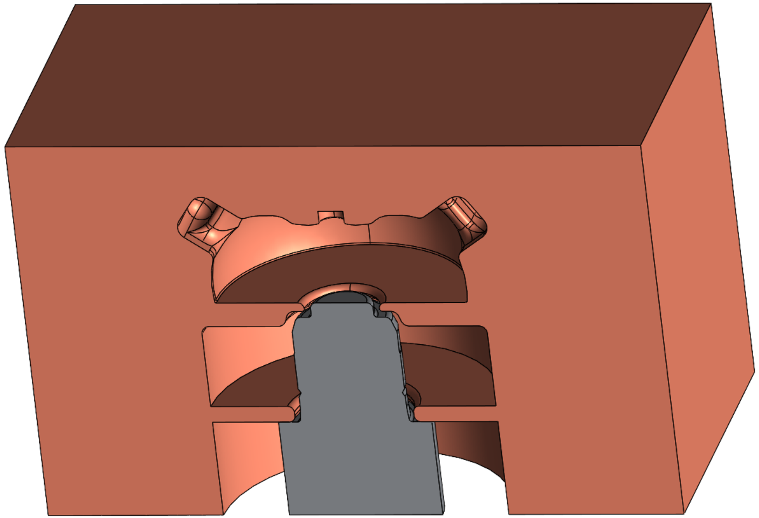
Future plans: plug free

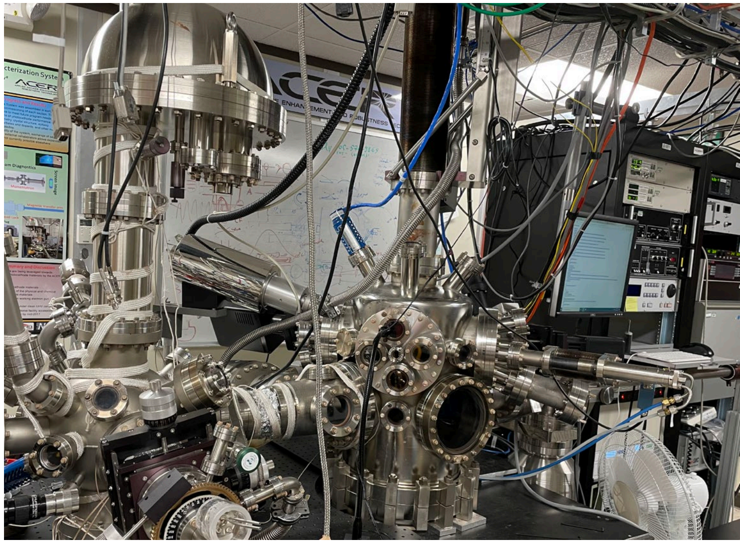
- All components have arrived
- Beamline being built now
- High gradient dark current tests mid 2024
- Tests with photocathode end of FY 2024



Future plans: injector with photocathode plug

- Gun and plug being finalized now
- Fabrication FY 2024
- Cu plug (dark current and photoemission) end of 2024
- Semiconductor photocathode (dark current and photoemission) early 2025



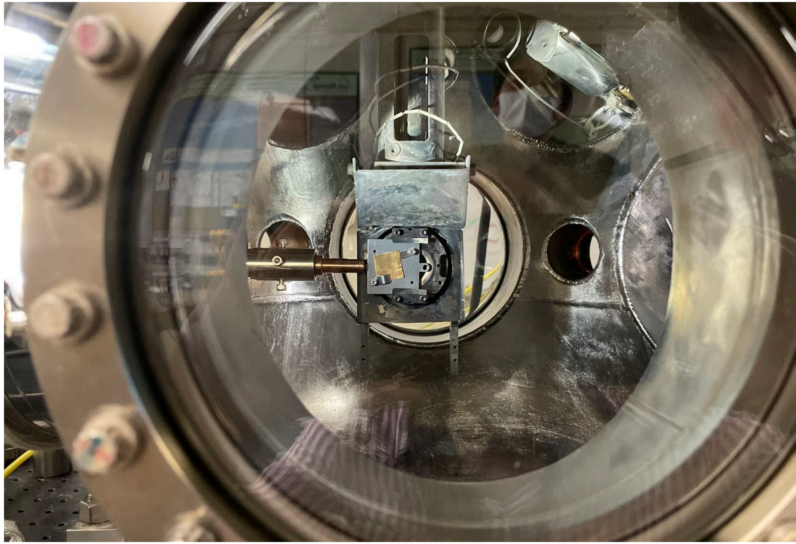


Questions?

Extra slides

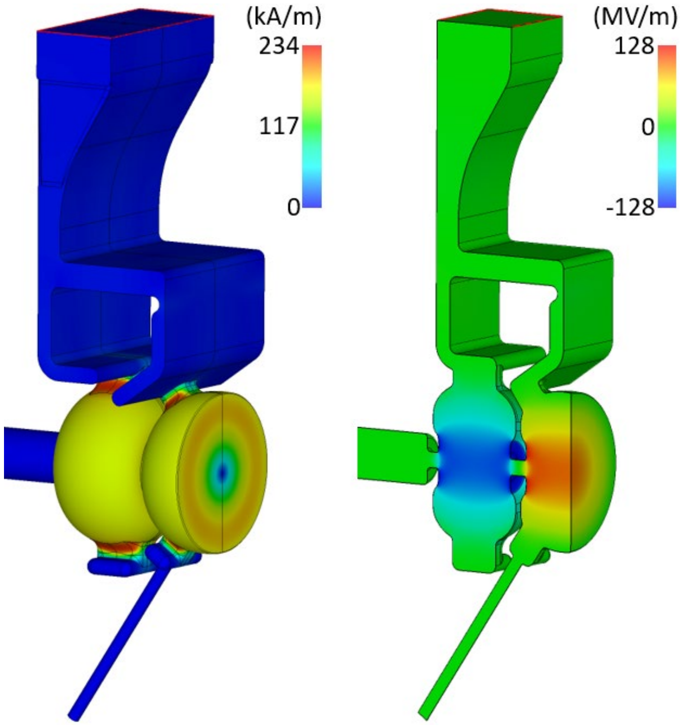
Cathode requirements:

- 250 pC charge → QE > .1%
- Emittance < .1 um
  - 7 ps total cathode on time
  - ~2ps response time
  - 300 um spot size
- Gun system:
  - Survive
  - Acceptable changes to dark current/break down rate

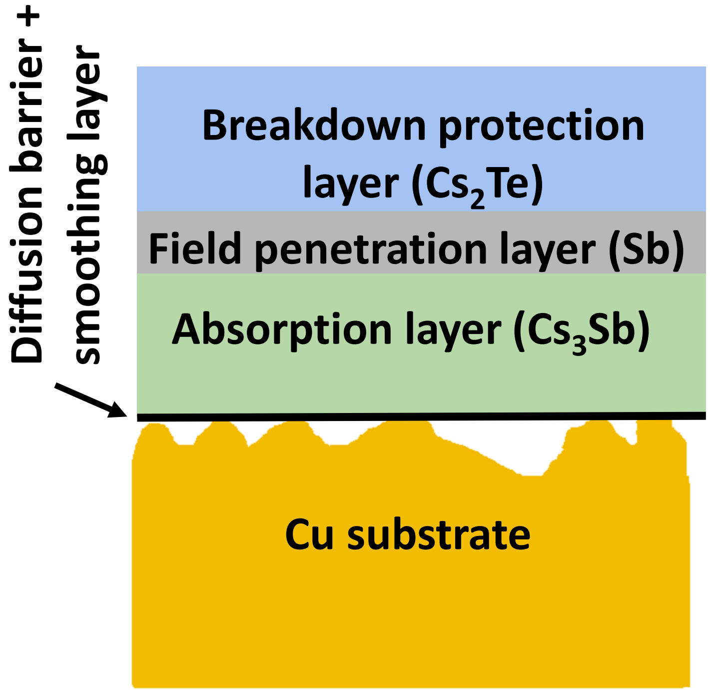


Key design considerations

- Design from UCLA
- Pi phase advance between cavities
- Isolated cavities
- Oversized beam pipe: accommodating the beam transverse dimension variation

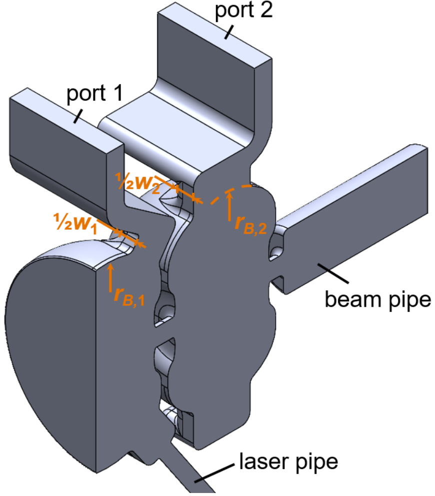


Heterostructures



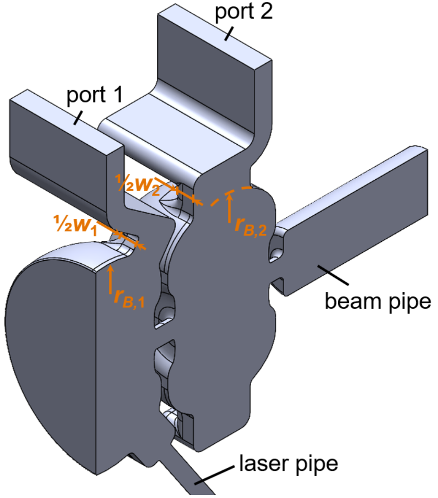
RF coupling

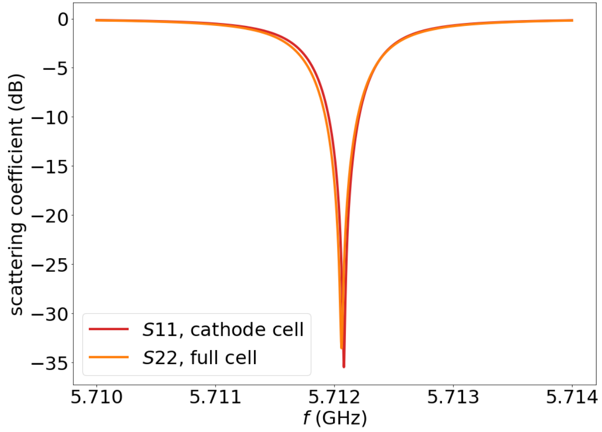
- Isolated cavities makes power coupling challenging, many requirements:
  - phase advance between cavities
  - Absolute field intensity in each cavitiy
  - Minimal reflections and losses in the waveguide
- Resonant frequency tuning by the elliptical cell profile minor radii ($r_{B,1}$ and $r_{B,2}$).
- On-resonance coupling tuning by the slot widths (w_1 and w_2).



Individual cells

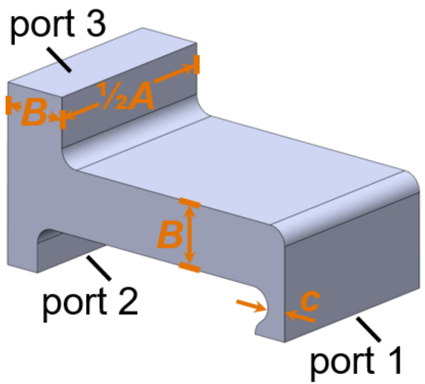
- Goal: both cells on critical coupling, at 5.712 GHz.
- Resonant frequency tuning by the elliptical cell profile minor radii ($r_{B,1}$ and $r_{B,2}$).
- On-resonance coupling tuning by the slot widths (w_1 and w_2).
- Oversized beam pipe: accommodating the beam transverse dimension variation.

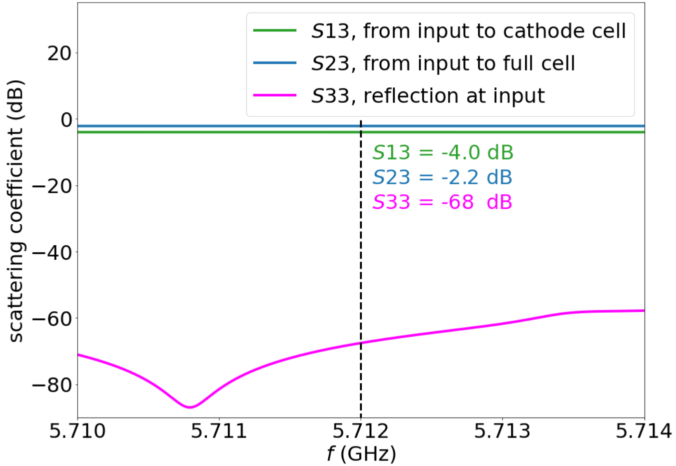




Waveguide splitter

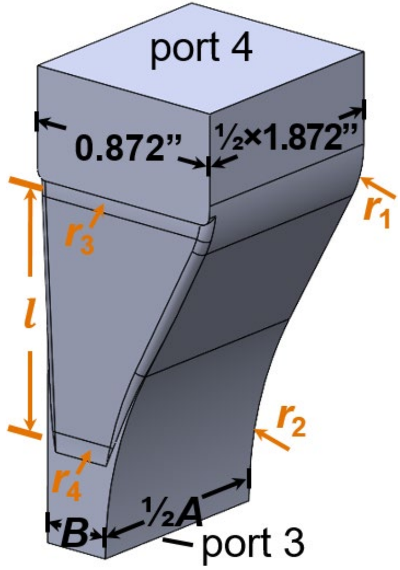
- Goals
  - To ensure that the peak electric fields in the individual cells are identical.
  - To minimize the power reflection at the input.
- Power split tuning by the choke size (*c*).
- Phase delay tuning by dimension *A*.
- Reflection tuning by dimension *A* and *B*.





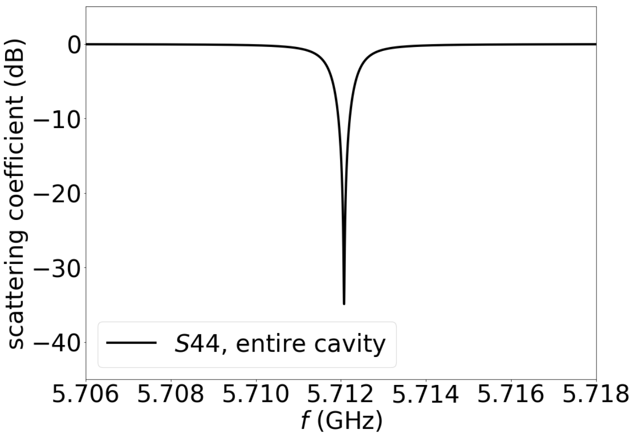
Waveguide horn taper

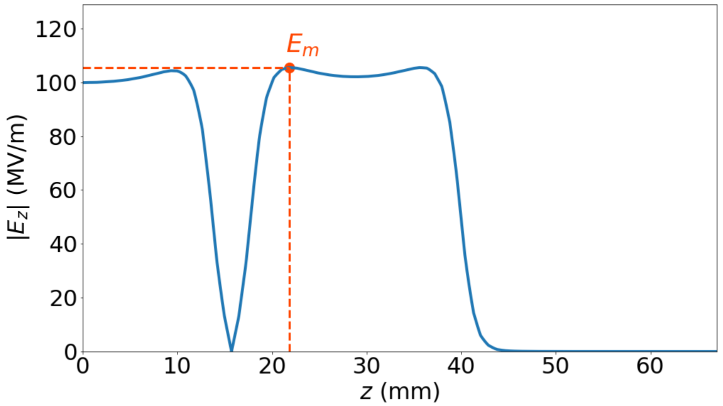
- Goals
  - To adapt the waveguide with dimensions A and B to the standard WR187 port.
  - To minimize reflection of input power, at 5.712 GHz.
- CST Frequency Domain Solver optimizer
  - 4X fillet radius.
  - Taper section length.
  - < -60 dB reflection attained.



Entire-cavity RF analysis

- Critical coupling at 5.712 GHz.
- Identical peak electric field magnitude in the individual cells.
- Peak accelerating field magnitude E_m.



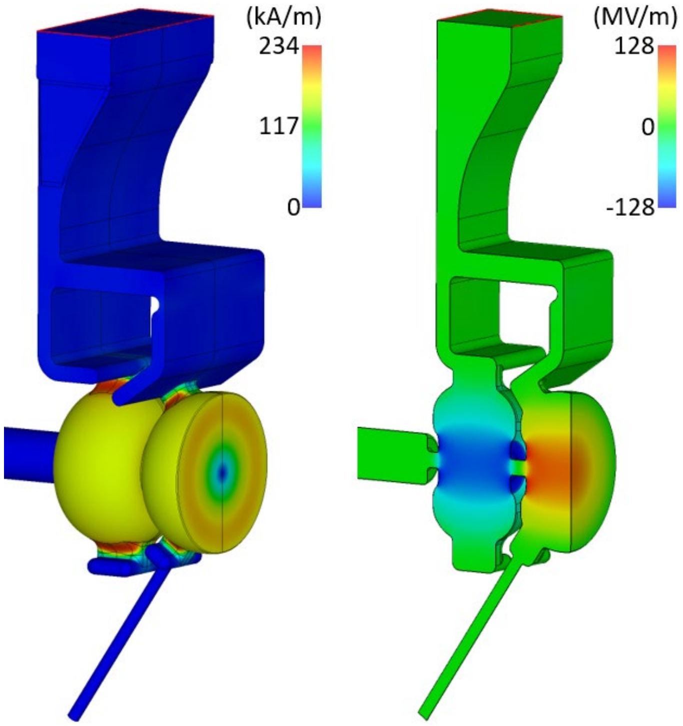


Entire-cavity RF analysis

- Local peak E-field normalized to E_m.
- Local peak H-field normalized to (E_m/Z_0).
  - Z_0 = 377 Ω.

Electric field local peak values	
Cathode cell overall	1.20
Cathode plane	0.94
Cathode cell coupling slot	0.48
Full cell overall	1.20
Full cell coupling slot	0.30
Choke	0.059

Magnetic field local peak values	
Cathode plane	0.55
Cathode cell coupling slot	0.69
Full cell coupling slot	0.66
Choke	0.035



100-MV/m cathode peak field

Fabrication and challenges

- OFHC copper cavity fabricated in halves, and then brazed together.
- One pair of tuners for each cell.
- Machining tolerance sensitivity.
  - 0.001-inch increase of the elliptical cell profile minor radius results in 5-MHz reduction in the cell resonant frequency.
  - 0.001-inch increase of the waveguide splitter choke size results in 1% increase in the peak electric field ratio in the cathode cell to that in the full cell.