The Center for BRIGHTBEAMS
A National Science Foundation Science & Technology Center

CrYogenic Brightness-Optimized Radiofrequency Gun (CYBORG) Beamline

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U.S. DEPARTMENT OF ENERGY

Outline of presentation

1. Motivations and background, relation to UCXFEL and CBB themes
2. RF and gun design
3. Cryogenics and phase 1 diagnostics
4. Phase 2 diagnostics
5. Status & future outlooks

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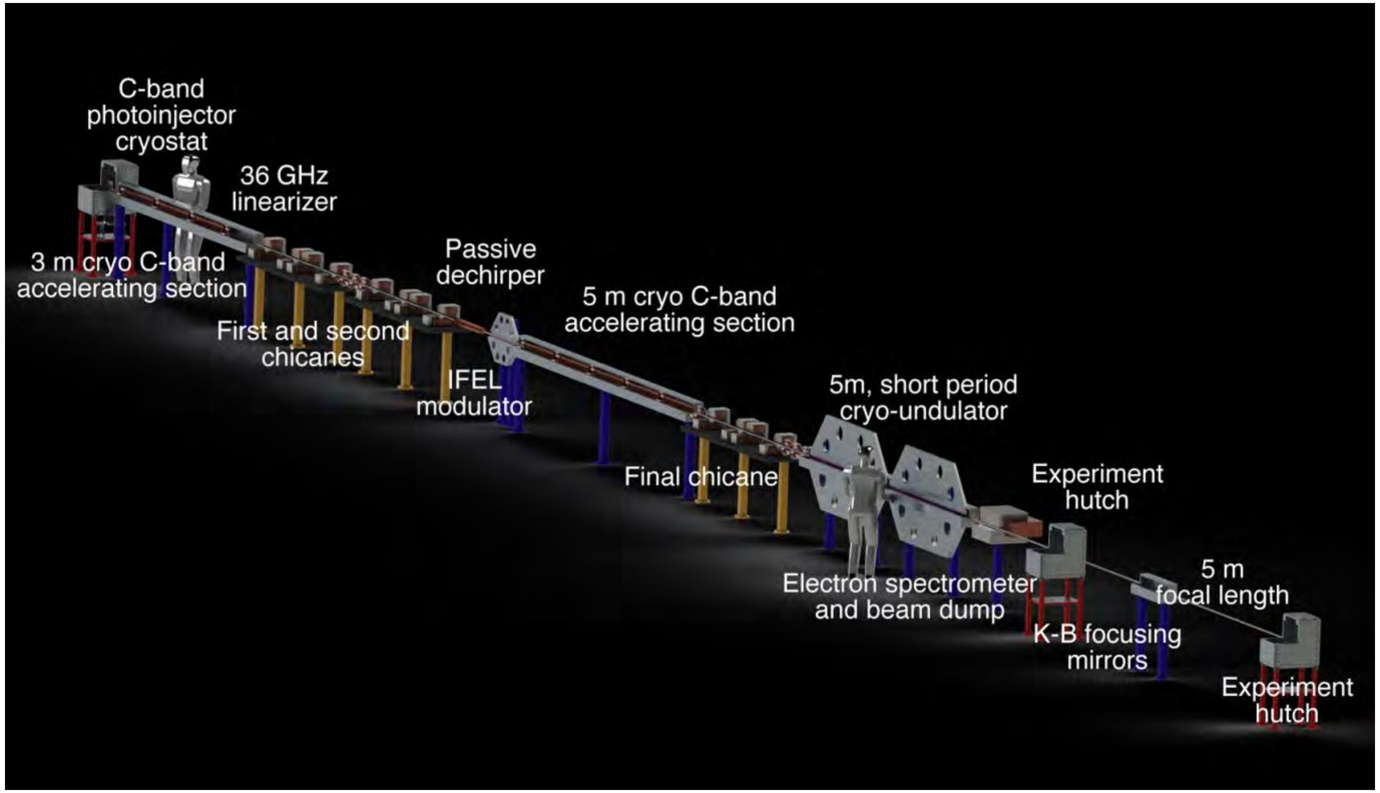
UC-XFEL Concept

- Ultra-compact xray free electron laser (UCXFEL) concept, 40 m
- Multiple sections dependent on cryogenic operation
- Photoinjector and associated cryostat most relevant for now



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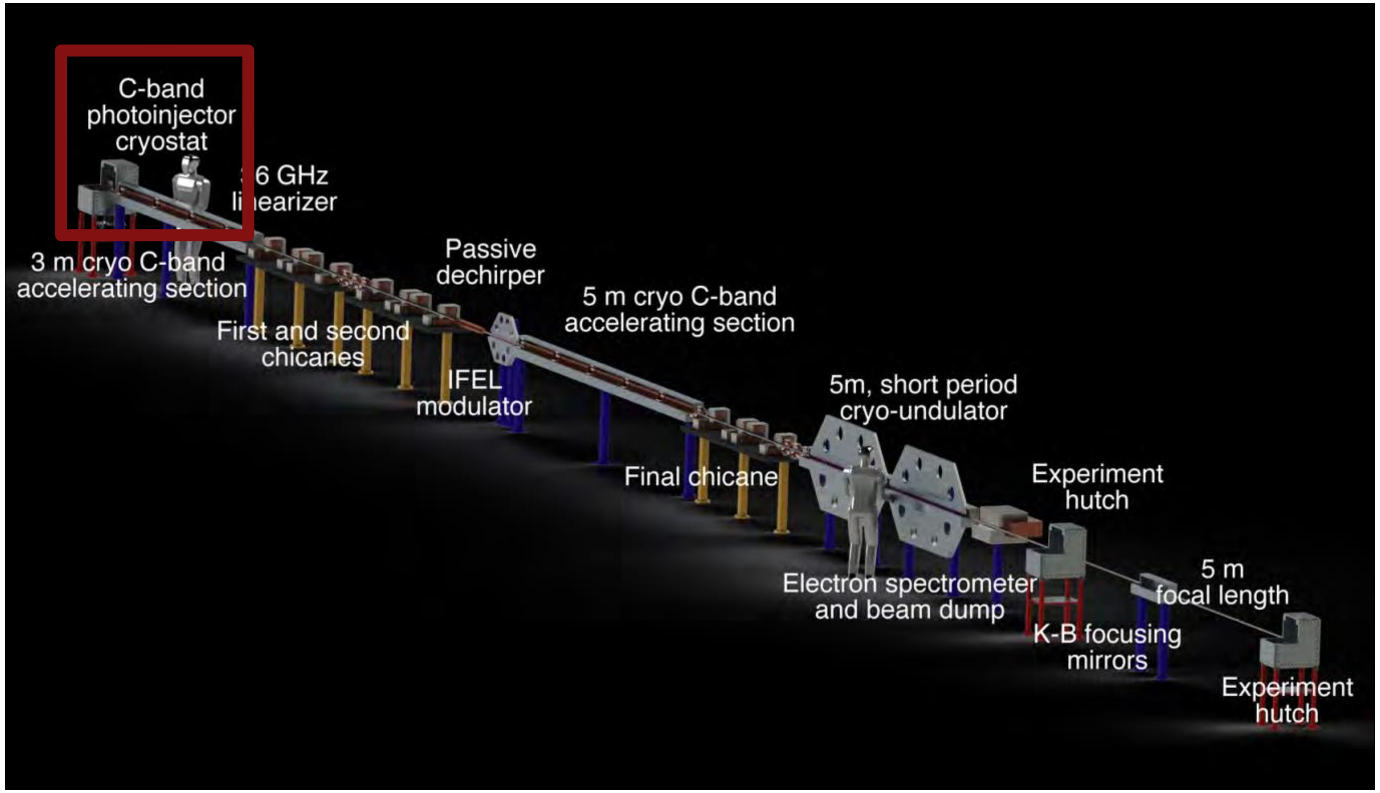
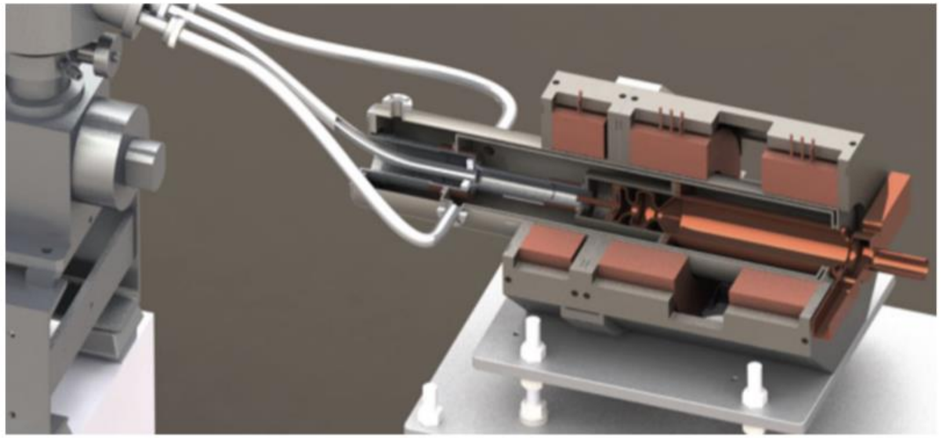
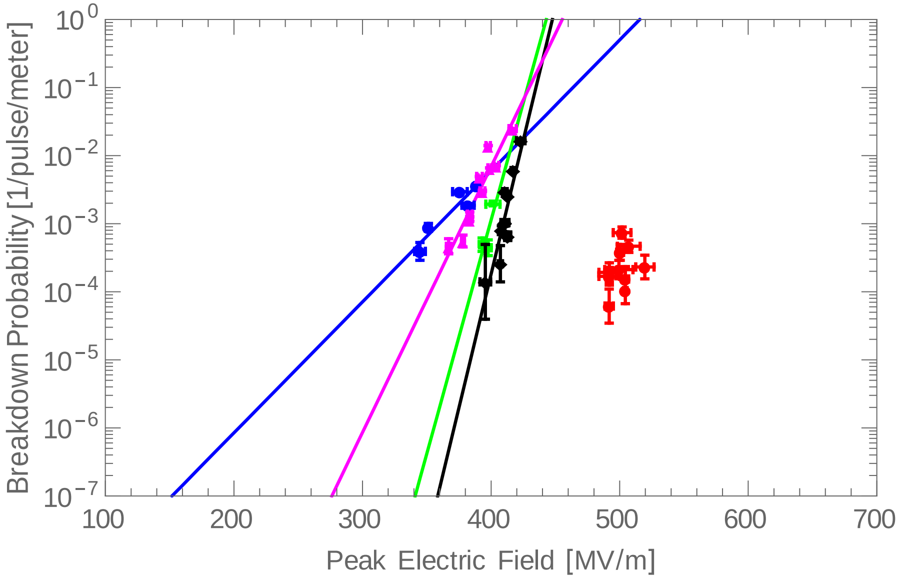
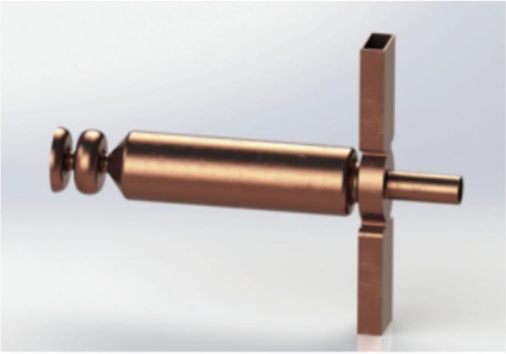


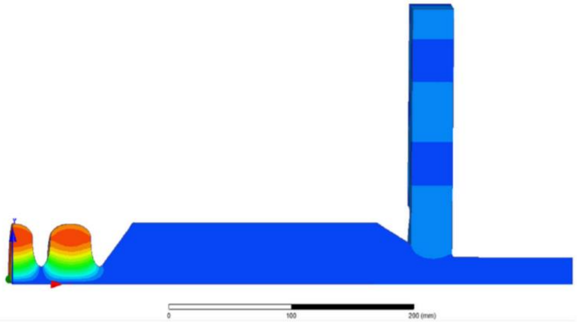
Historical Photoinjector Development

- TopGun previous development in Sband
- Based on normal conducting









Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources
JB Rosenzweig, A Cahill, V Dolgashev, C Emma… - Physical Review Accelerators and Beams, 2019

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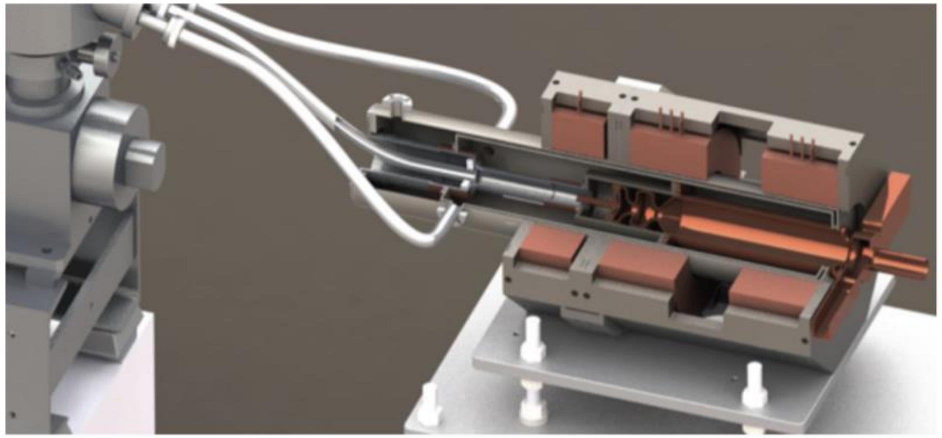

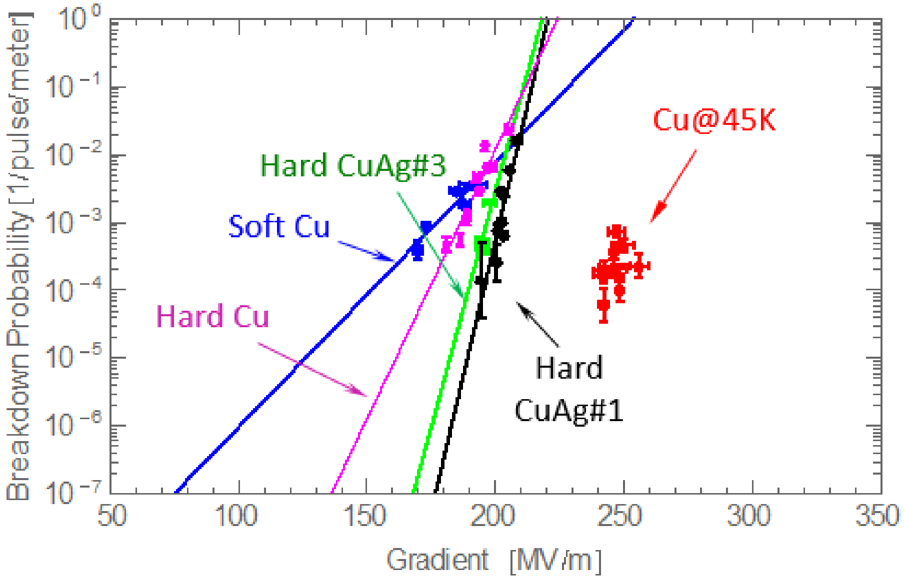

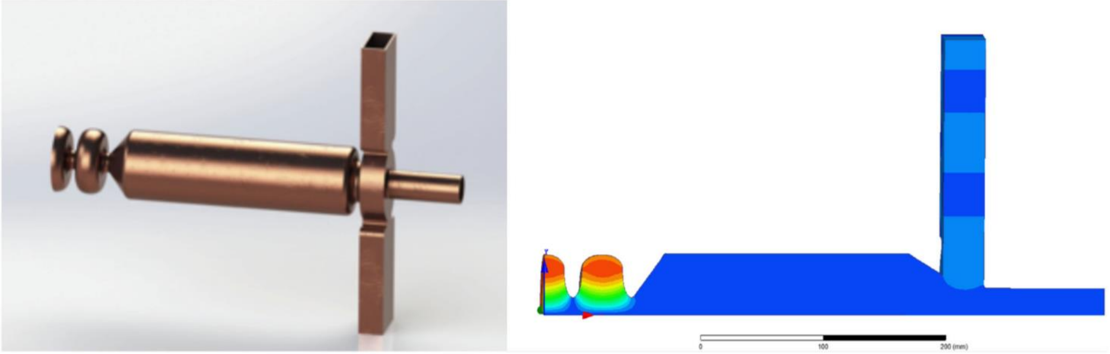

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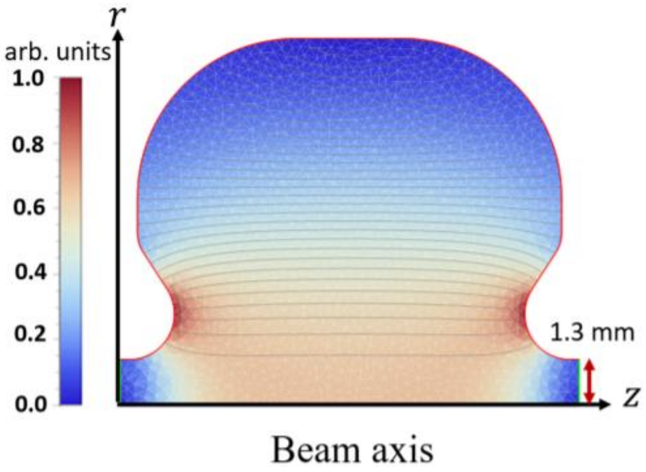
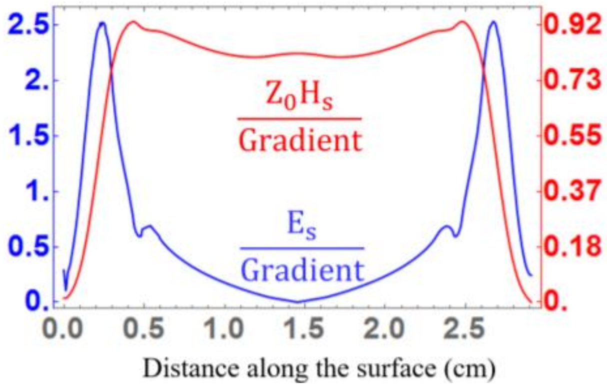
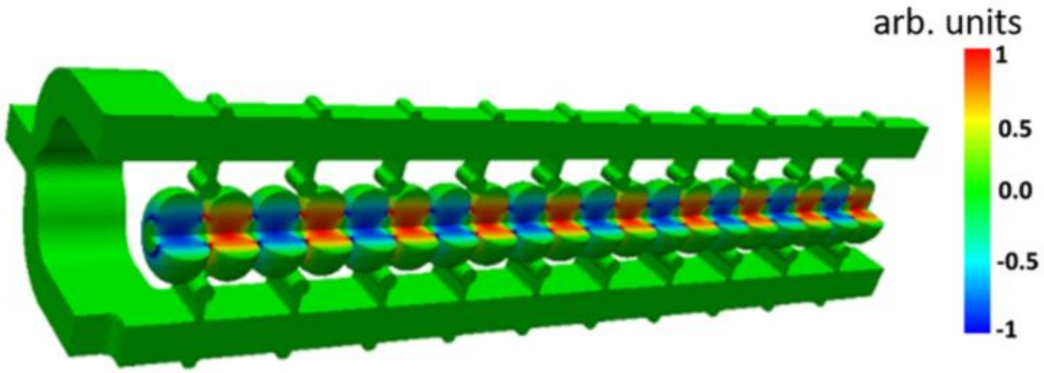
CYBORG Function 1: Cavity Structure Tests

- Reentrant cavities
- High shunt impedance
- Lower RF pulse heating
- Tested to cryogenic (LN2) temperatures
- Independently coupled cells





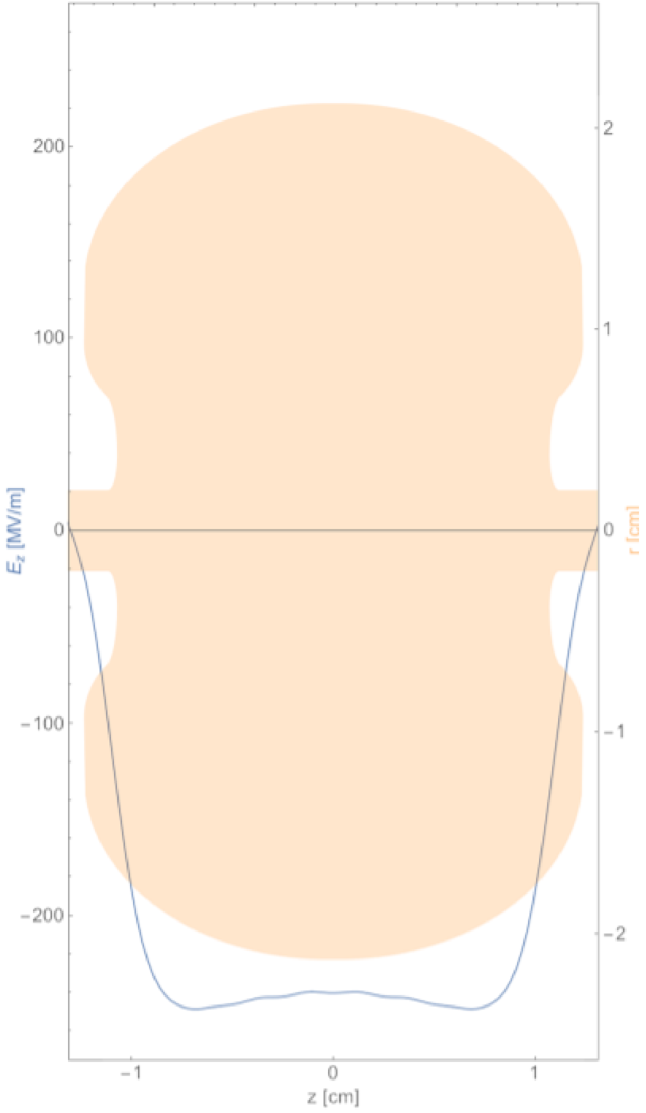


Design and demonstration of a distributed-coupling linear accelerator structure
S Tantawi, M Nasr, Z Li, C Limborg, P Borchard - Physical Review Accelerators and Beams, 2020

Reentrant Cavity Beam Dynamics

- Consideration of beam dynamics based on high spatial harmonic content
- introduction of strong second order focusing effects
- enhancing the emittance compensation by providing stronger focusing on the beam both as it leaves the cathode and as it is accelerated toward an emittance dominated state downstream
- 45 nm rad emittance at 100 pC and 20 A

RR Robles et al. *Physical Review Accelerators and Beams* 24 (6), 063401



Parameter	Unit	Value
Charge	pC	100
Laser spot size (precut)	μm	151
Laser spot size (post-cut)	μm	76
Injection phase	°	44
Laser length	ps	5.8
Peak cathode field	MV/m	240
Bucking solenoid field	T	0.58
Compensation solenoid field	T	0.48
Compensation solenoid FWHM	cm	7.4
Compensation solenoid center	cm	12.5
Booster gradient	MV/m	52
Booster entrance	m	1.6
Booster phase	°	90

CYBORG Function 2: Cryogenic cathode test

- Emission properties of photocathodes change @ cryogenic temperatures (<93K)
- Where hv ≫ ϕeff scaling as below

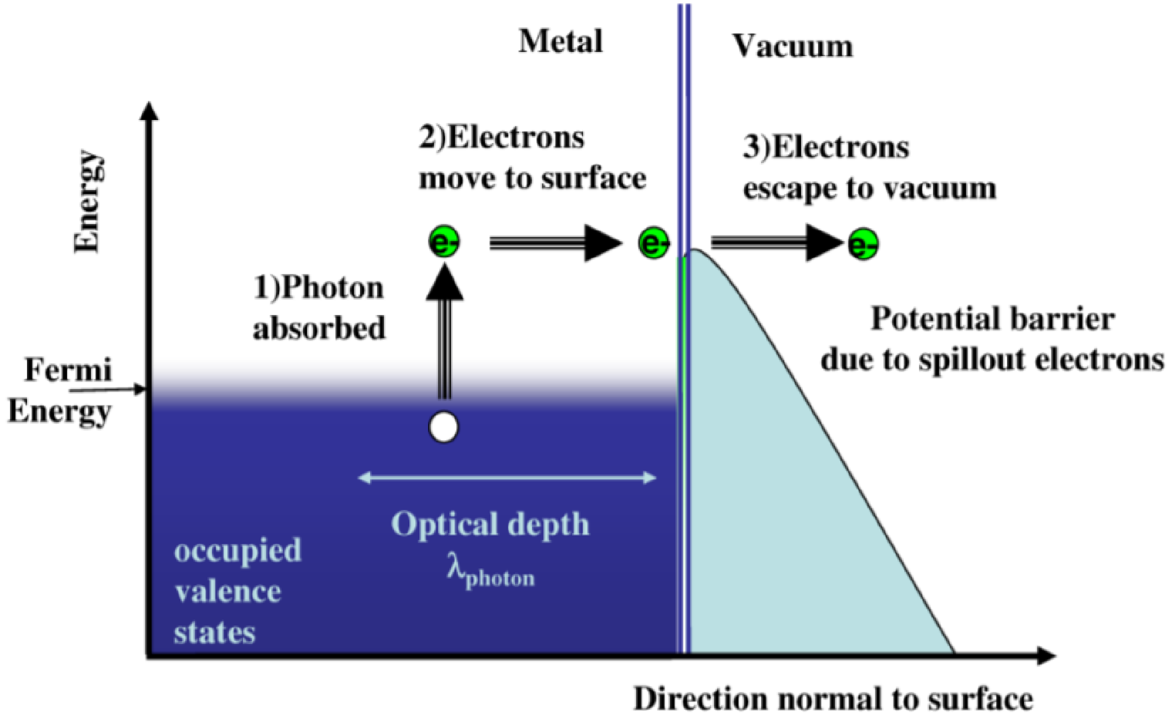
$$k_b T_c = (h\nu - \phi_{\text{eff}})/3$$

$$QE = N_{e-}/N_\gamma \propto (h\nu - \phi_{\text{eff}})^2$$

- Cu photocathodes emission temp ranges from ~100 meV to 1 eV depending on wavelength
- Brightness scaling (below)
- From UXFEL NJP, note 6D brightness importance

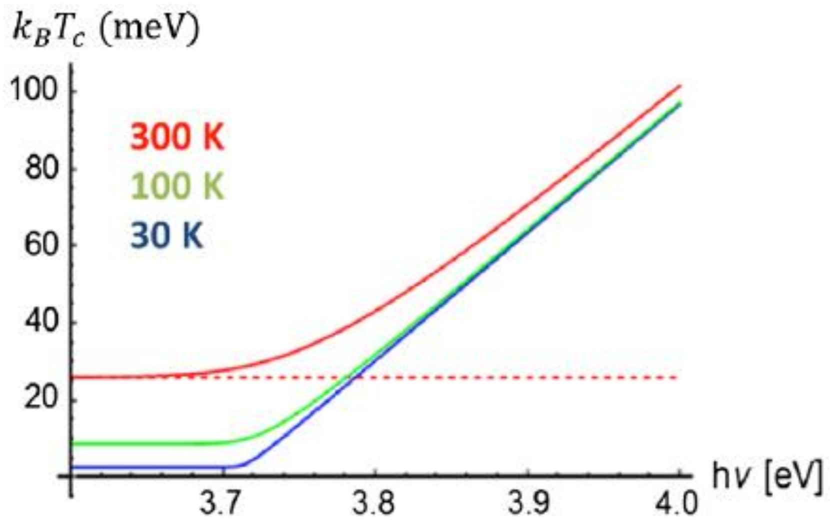
$$B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c}\left(E_0 \sin\phi_0\right)^2$$

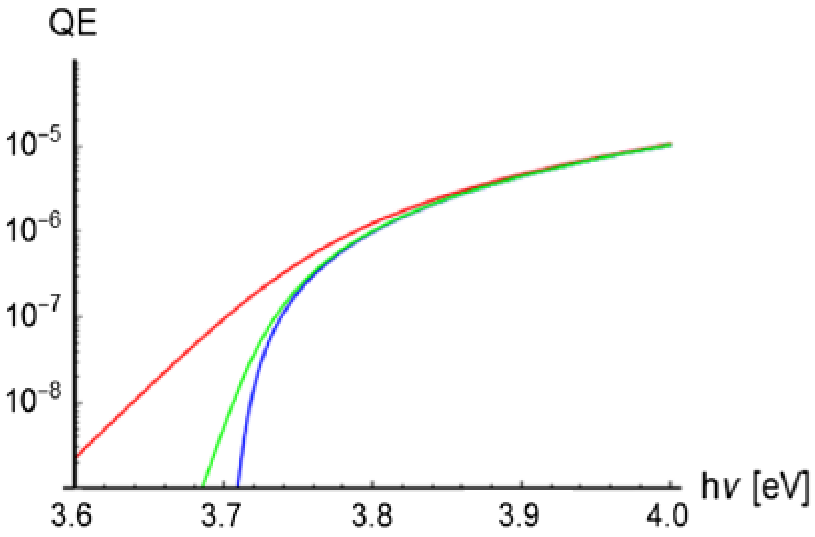
D. Dowell and J. Schmerge, Phys. Rev. ST Accel. Beams 12, 074201 (2009).



Cryogenic metallic photoemission

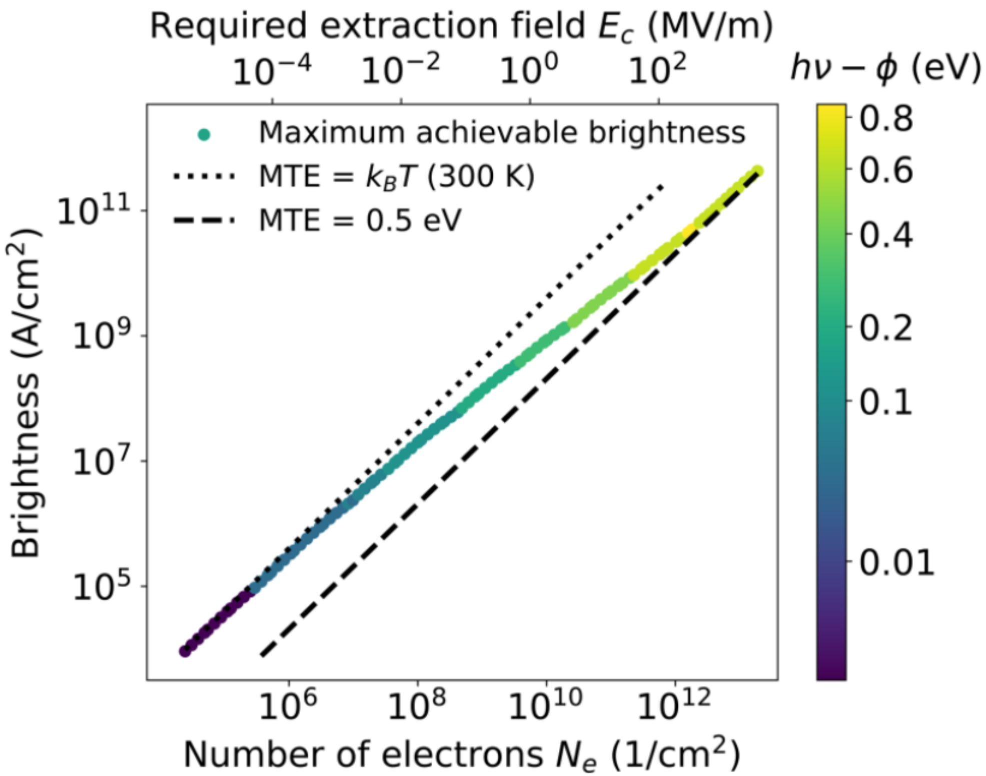
- Near threshold emission from tail of Fermi-Dirac distribution
- Now including full FD distribution with temperature dependence (right)
- hv → ϕeff, photoemission temperature approaches physical cathode temperature, k_BT_c → 26 meV at 300 K
- Very low QE, so higher laser fluence needed





Cryogenic metallic cathode issues

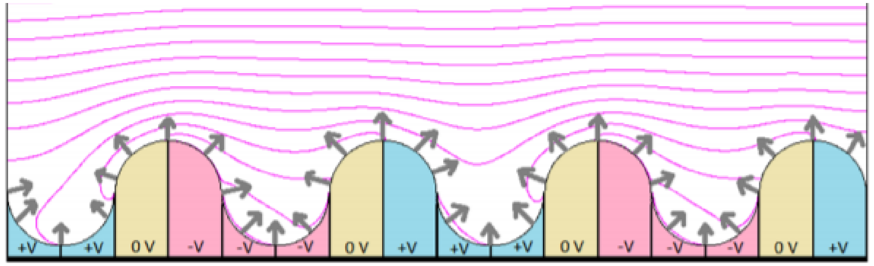
- Easiest if Cu satisfies all cathode requirements
- Extremely challenging due to non-linear emission
- 100 pC from 75 um rms spot size at 250 MV/m accelerating field, 38 nm-rad intrinsic emittance ➔ 130 meV MTE, ~10^{12} e^{-}/cm^2
- 50 fs pulse – could be better for 5 ps pulse
- Need to characterize cathodes in these extreme condition



J. K. Bae, I. Bazarov, P. Musumeci, S. Karkare, H. Padmore, and J. Maxson, J. Appl. Phys. 124, 244903 (2018).

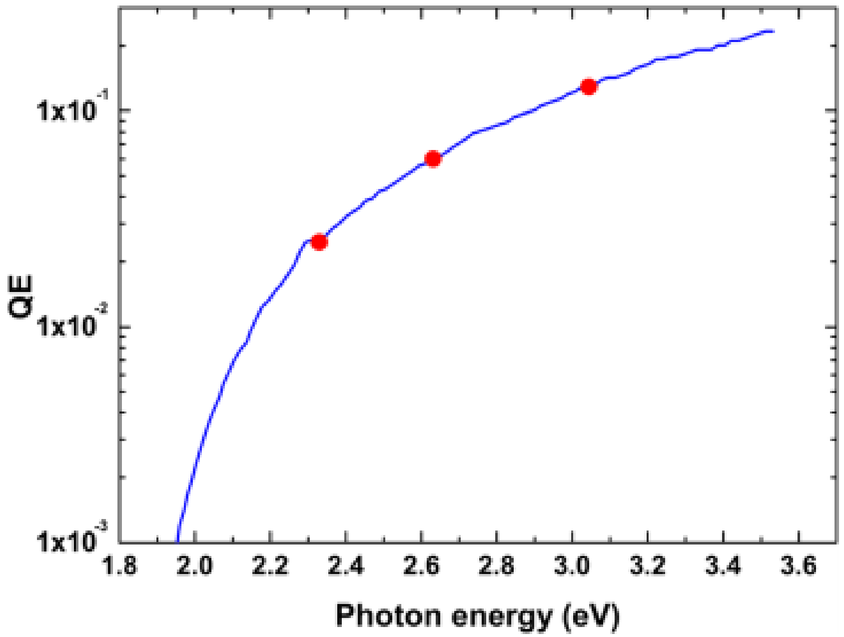
Cryogenic semiconductor cathodes

- High QE photocathode, many orders of magnitude higher than Cu, promising
- Alkali antimonides, Cs2Te
  - Field emission could be an issue due to lower work functions/roughness.
- Cs/GaN or n-doped polar GaN
  - High QE in UV, high work function
  - Could result in very low MTE
  - never been tested in photoinjectors
  - Potential vacuum concerns
- Reduction of MTE at cryogenic temps observed



G. S. Gevorkyan et al., Phys. Rev. Accel. Beams, vol. 21,p. 093 401, 9 Sep. 2018.

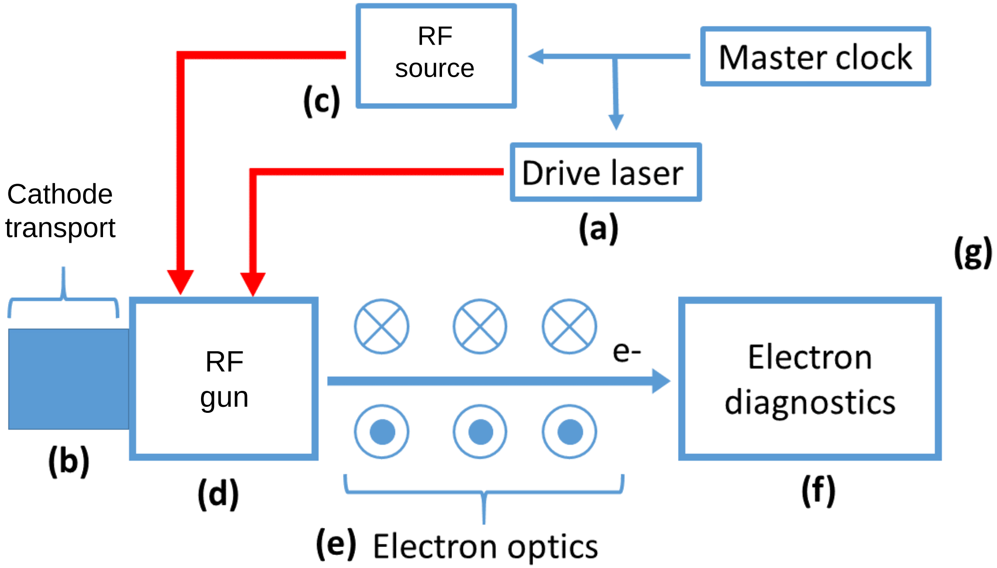
NaKSb



L. Cultrera et al., Appl. Phys. Lett. 103, 103504 (2013).

CYBORG Function 3: Infrastructure Test

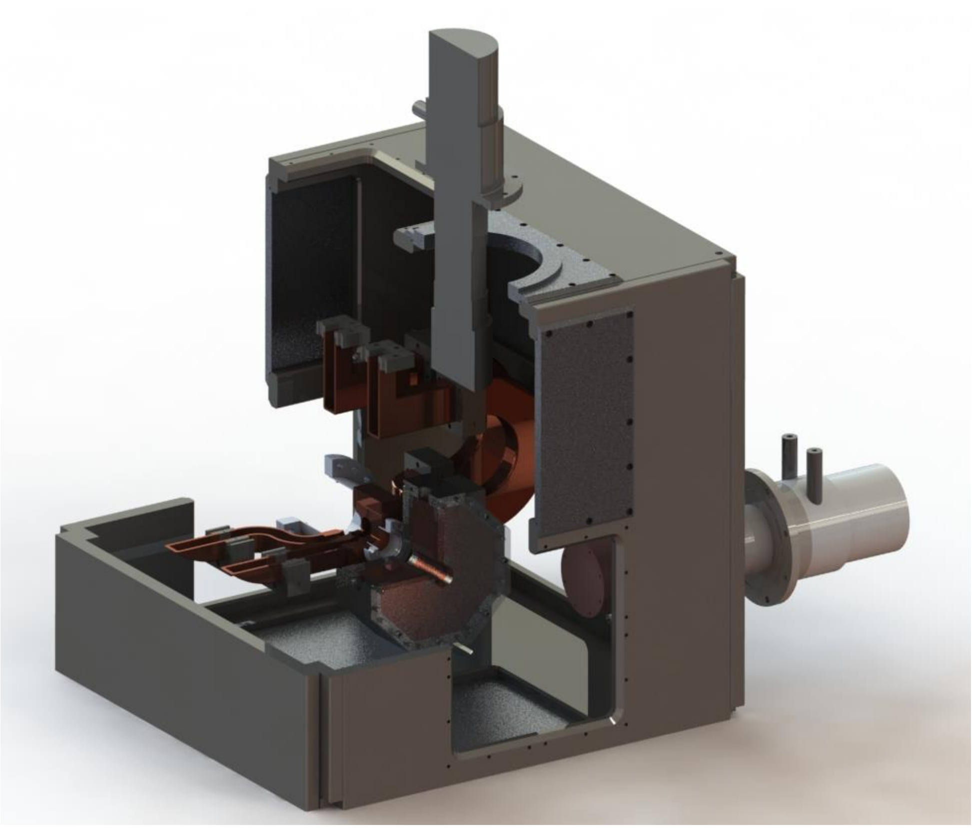
- Schematic diagram similar (right)
- Test all components, independent function, synchronization etc.
- Active conduction cryocooling cryostat development setup (below) down to 40K thus far

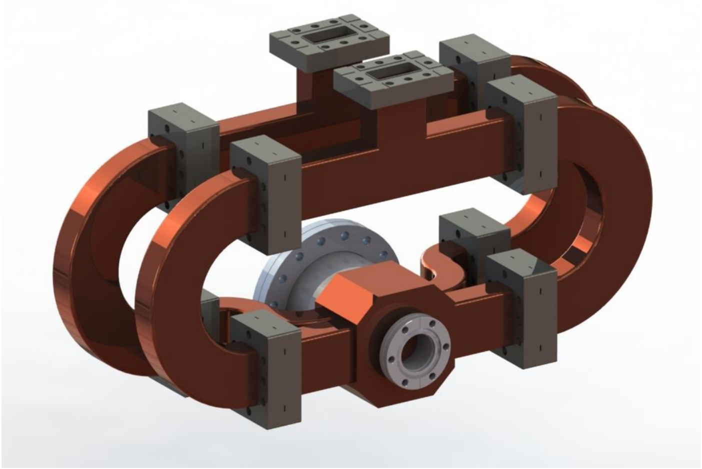


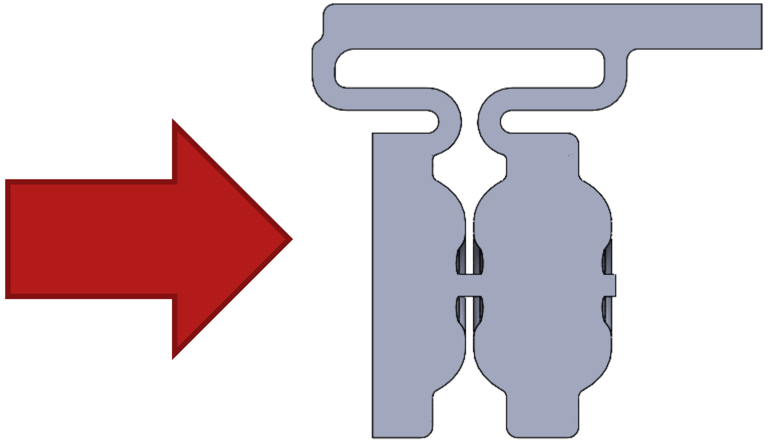
Early UCXFEL Photoinjector Concept

- 1.6 cell cavity w/ reentrant design
- Cryogenic solenoid in cryostat

- repetition rate of 100 Hz
- nominal 300 nsec RF pulses
- operating temperature of 27 K
- RF dissipation of 11 W, requiring over 0.5 kW cooling power
- Maximize shunt impedance and consequently efficiency







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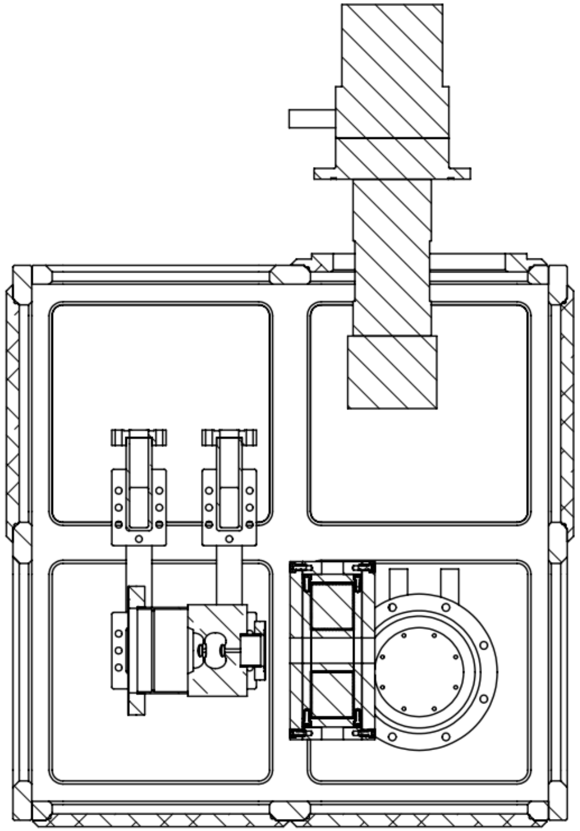

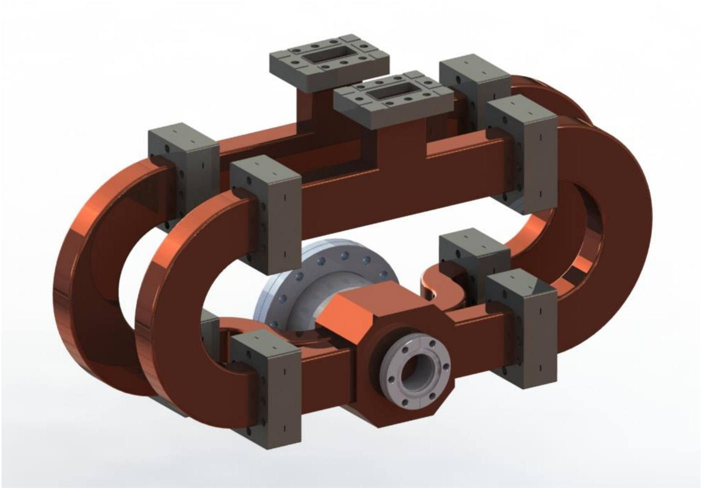

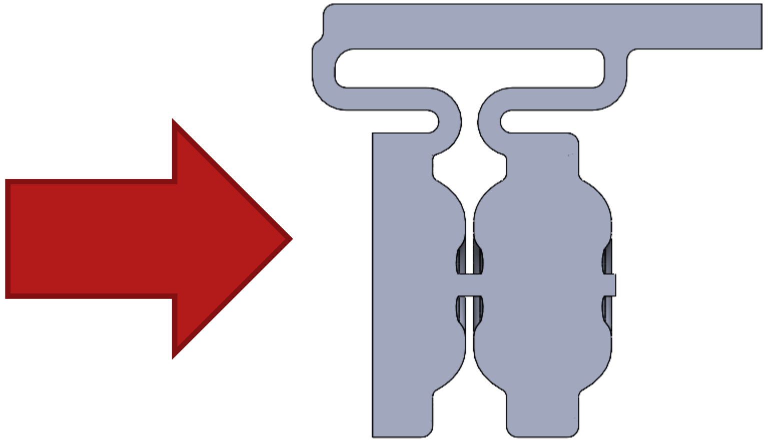

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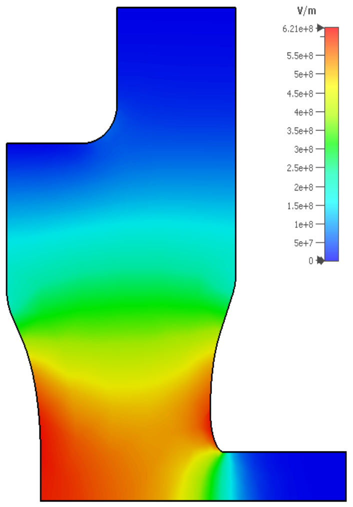
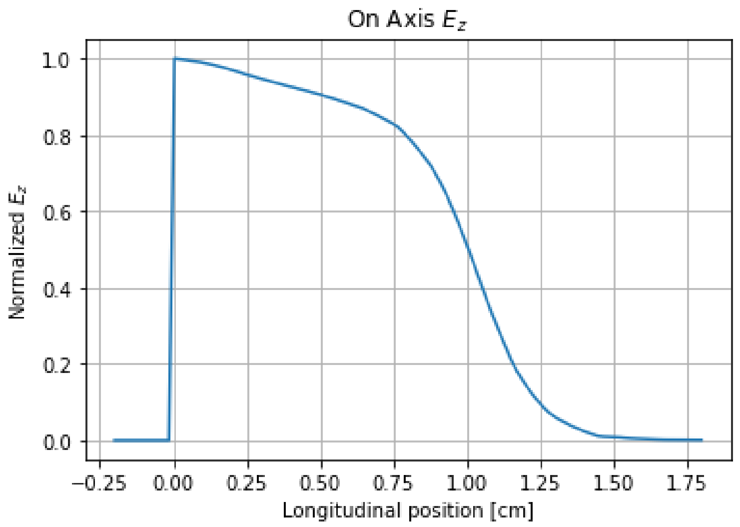
½ Cell gun specs

- Reentrant cavity with high shunt impedance Tantawi-style
- Cryogenic temperature provided RF stability and cathode studies
- 2.9 factor improvement of Q_0 from 300K to 77K
- Cryogenic load lock and replaceable cathode plug coupling

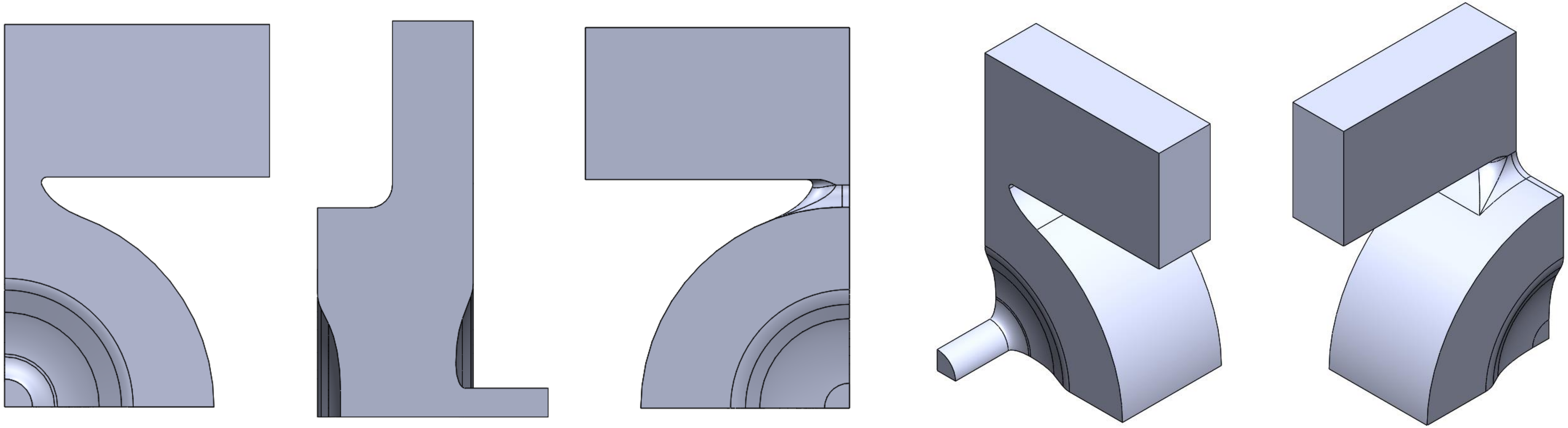
Parameters	Value
Launch field	120-250 MV/m
Operating temp	45K-77K
# of cells	½
Cavity frequency	5.712 GHz
Beta	4 @ 77K
Q_ext	6056
Q_0	24750

E field magnitude



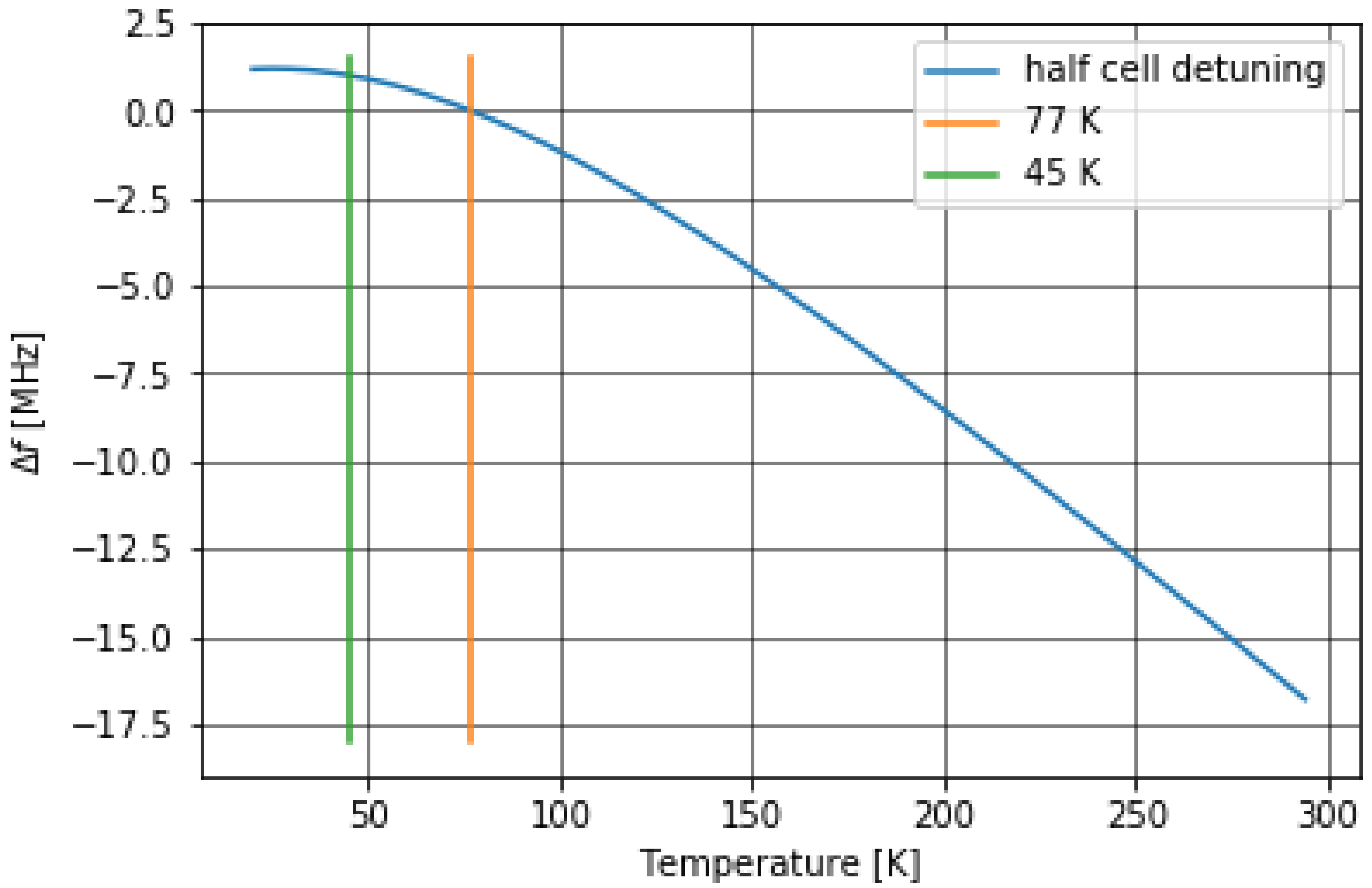


½ Cell RF Cavity



Tuning

- 5.695 GHz @ 295K (room temp)
- 5.712 GHz @ 77K
- 5.713 GHz @ 45K



Cavity Tolerances

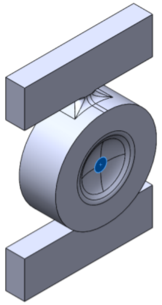
- Slater perturbation theory gives frequency change from small displacement of one surface S_i in normal direction from fields on surface
- U stored energy
- Default 10 um
- For surfaces of high field tolerance reduced to 5 um (detuning over |0.2| MHz w/ 10 um, most |10s| kHz)
- Total about 1.6 MHz from following

$$\Delta f_i = \Delta s_i \frac{f_0}{4U} \int_{S_i} \left(\mu \left|H_0\right|^2 - \epsilon \left|E_0\right|^2\right) dS$$

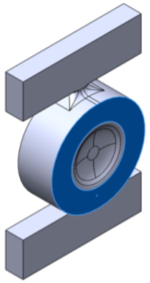
$$U = \frac{1}{2} \int_V \left(\mu \left|H_0\right|^2 + \epsilon \left|E_0\right|^2\right) dV$$

$$\Delta f_{tot} = 1 - 2 \text{ MHz} > \sqrt{\Sigma_i \left(\Delta f_i\right)^2}$$

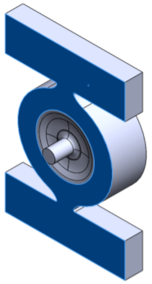
Sensitive Surfaces



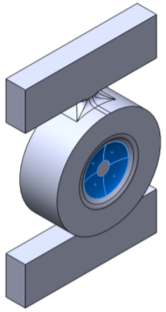
$\int \lvert H\rvert^2 dA$	$\int \lvert E\rvert^2 dA$	area [mm^2]
9.34×10^4	1.46×10^{12}	15.94
tolerance [μm]	detuning [MHz]	
10	-0.183	



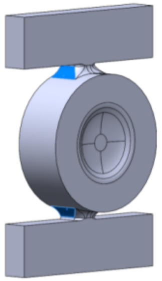
$\int \lvert H\rvert^2 dA$	$\int \lvert E\rvert^2 dA$	area [mm^2]
9.1×10^7	2.67×10^{12}	720
tolerance [μm]	detuning [MHz]	
5	0.648	



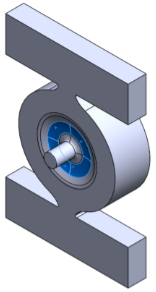
$\int \lvert H\rvert^2 dA$	$\int \lvert E\rvert^2 dA$	area [mm^2]
8.80×10^7	2.32×10^{12}	2006
tolerance [μm]	detuning [MHz]	
5	0.643	



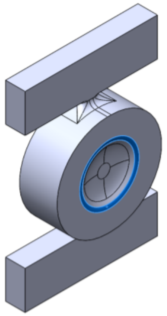
$\int \lvert H\rvert^2 dA$	$\int \lvert E\rvert^2 dA$	area [mm^2]
1.5×10^7	1.45×10^{13}	195
tolerance [μm]	detuning [MHz]	
5	-0.779	



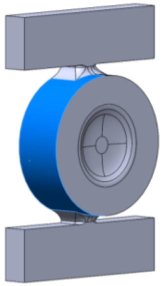
$\int \lvert H\rvert^2 dA$	$\int \lvert E\rvert^2 dA$	area [mm^2]
2.18×10^7	1.46×10^9	136
tolerance [μm]	detuning [MHz]	
5	0.196	



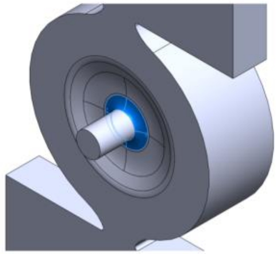
$\int \lvert H\rvert^2 dA$	$\int \lvert E\rvert^2 dA$	area [mm^2]
1.31×10^7	1.03×10^{13}	158
tolerance [μm]	detuning [MHz]	
5	-0.533	



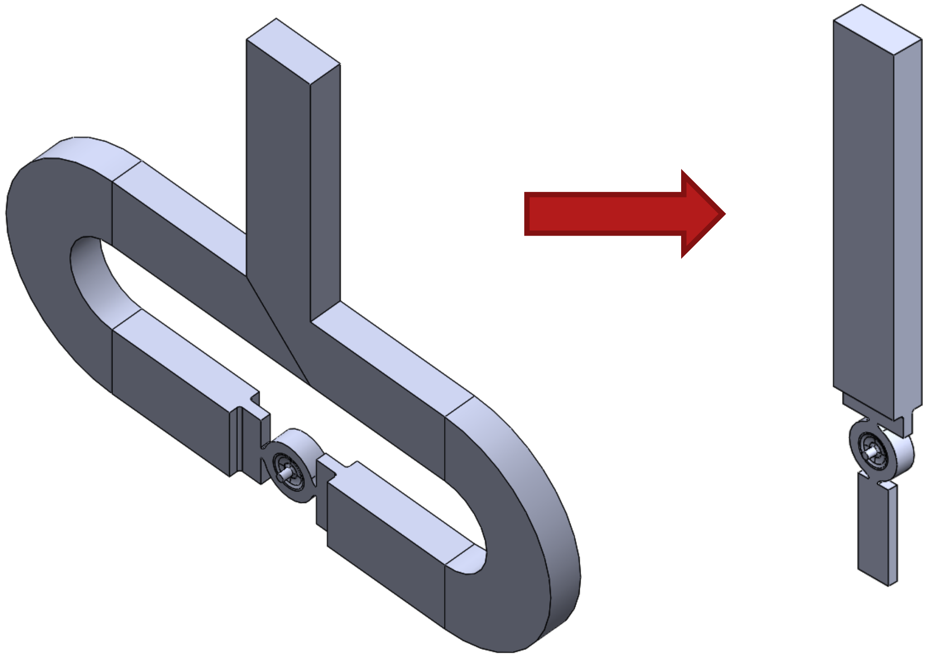
$\int \lvert H\rvert^2 dA$	$\int \lvert E\rvert^2 dA$	area [mm^2]
1.3×10^7	9.10×10^{11}	87.6
tolerance [μm]	detuning [MHz]	
5	0.110	

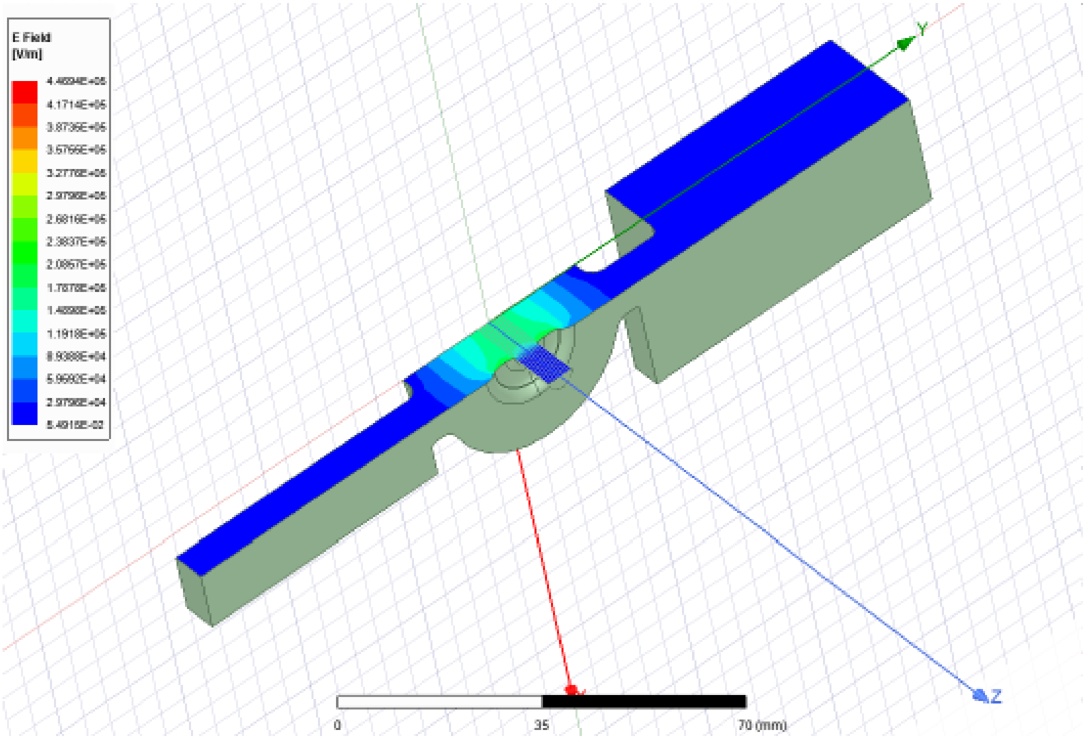


$\int \lvert H\rvert^2 dA$	$\int \lvert E\rvert^2 dA$	area [mm^2]
1.35×10^8	2.12×10^9	1301
tolerance [μm]	detuning [MHz]	
5	1.21	



$\int \lvert H\rvert^2 dA$	$\int \lvert E\rvert^2 dA$	area [mm^2]
7.39×10^5	4.22×10^{12}	49.1
tolerance [μm]	detuning [MHz]	
5	-0.261	

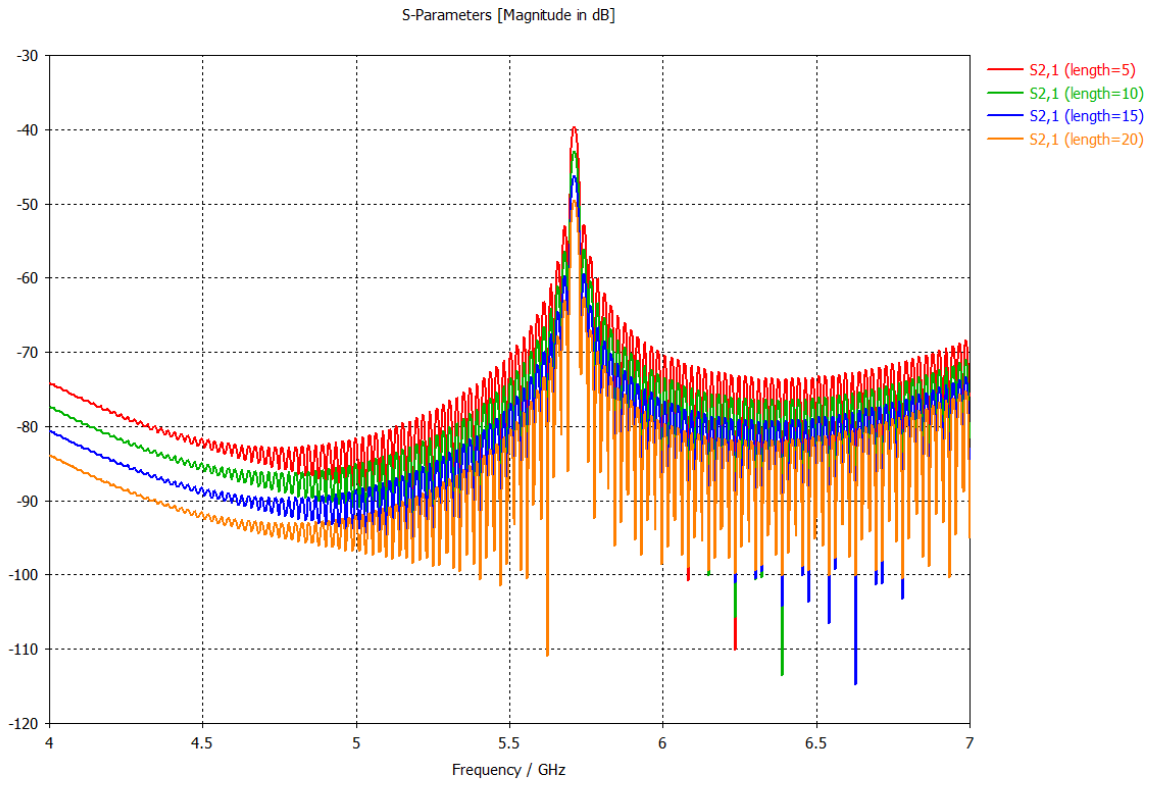


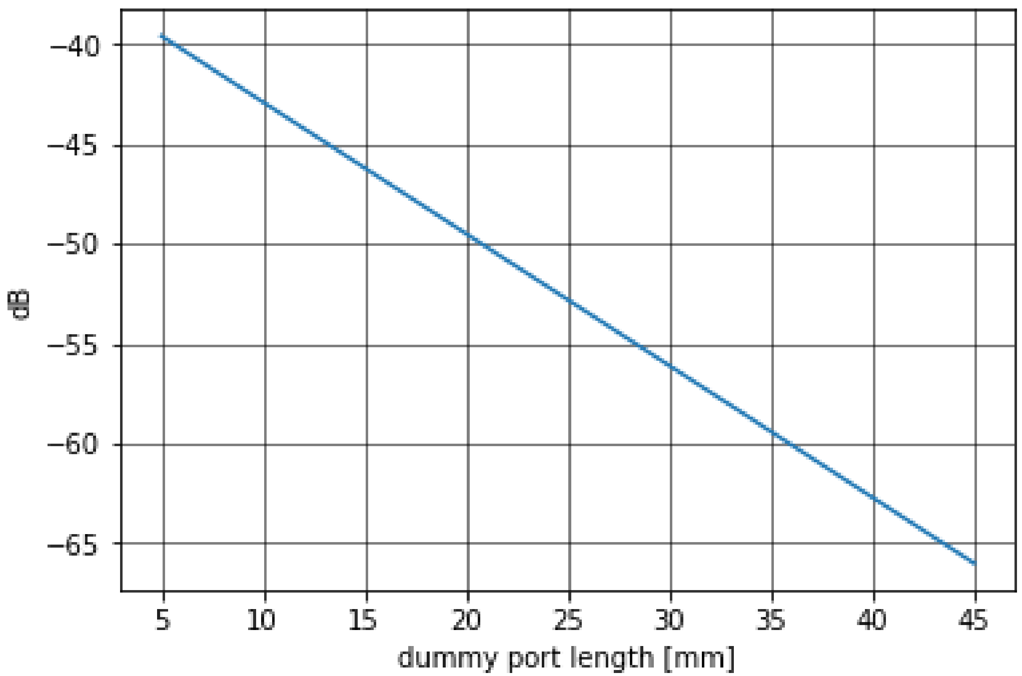


E Field
[V/m]
Y
Z
0
35
70 (mm)

Dummy Port Length

- Choke on dummy port for RF diagnostic probe



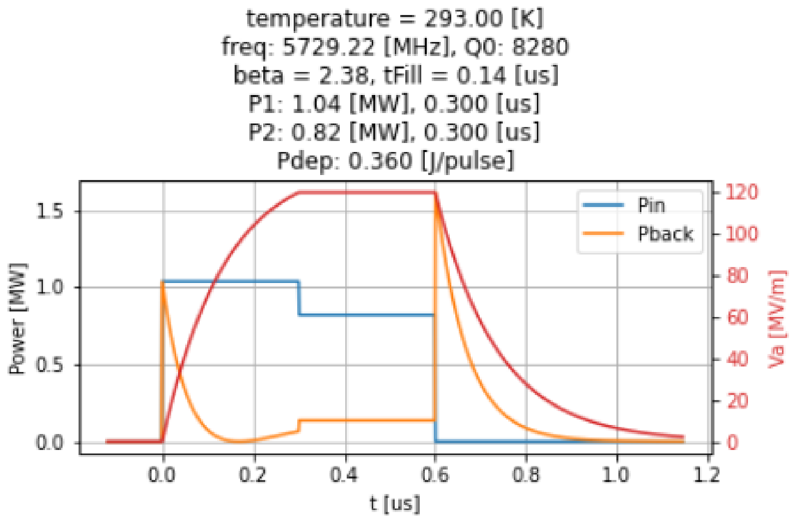


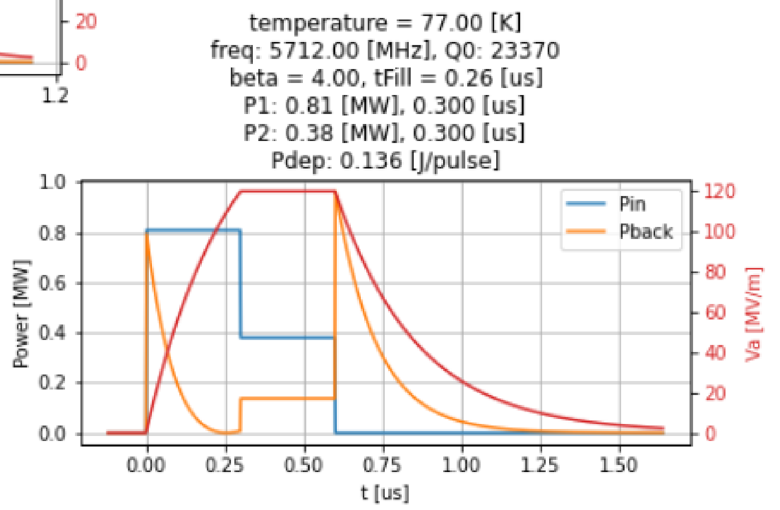
Cavity RF Filling

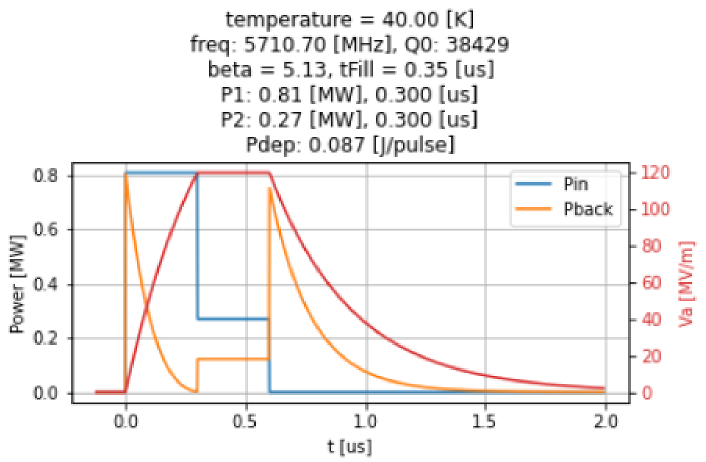
- @ cryogenic temp, RF filling time scales like $\tau_{\text{rf}} \sim f_{\text{rf}}^{-5}$
- RF pulse lengths using same input power can be shorter leading to less pulse heating
  - Greater than factor of 3 reduction in filling time for Sband to Cband
- Power needed to drive scaled geometry at constant gradient scales like

$$P \sim f_{\text{rf}}^{-2}$$

  - Greater than factor of 4 reduction for Sband to Cband

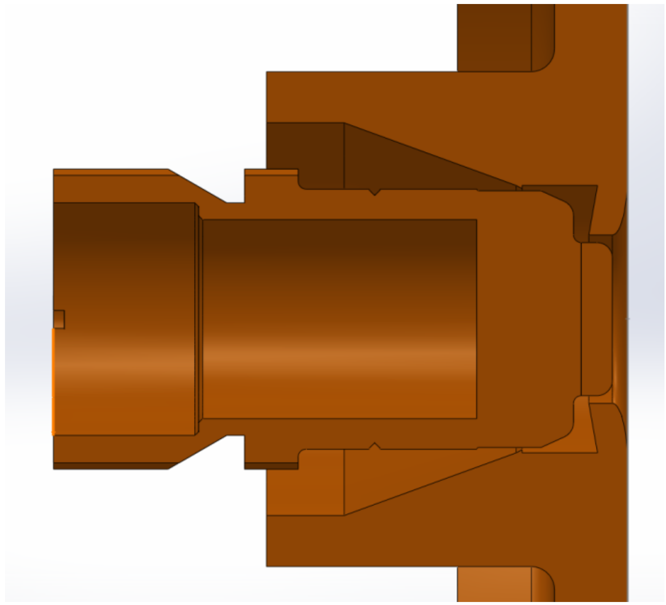


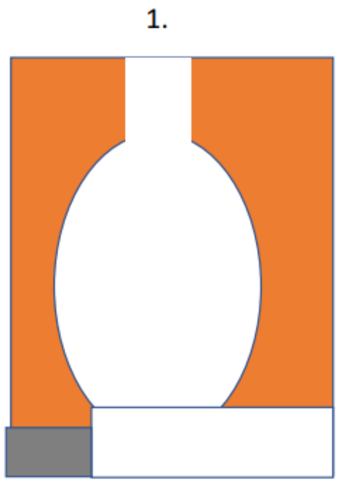




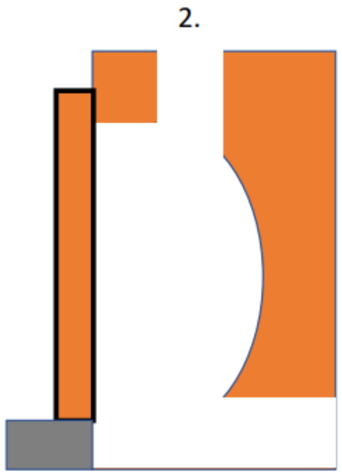
Forward Compatibility: Cathode Interface

- Forward compatibility needed for INFN style mini puck
- Pegasus knife edge seal (left) difficult at cryogenic temperatures
- Cavity configuration options to right considered

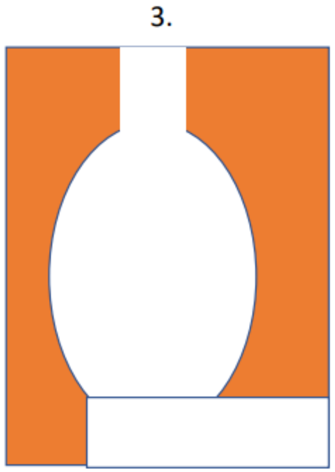




- Plug directly into cavity
- Useful for 1.6 cell to max gradient



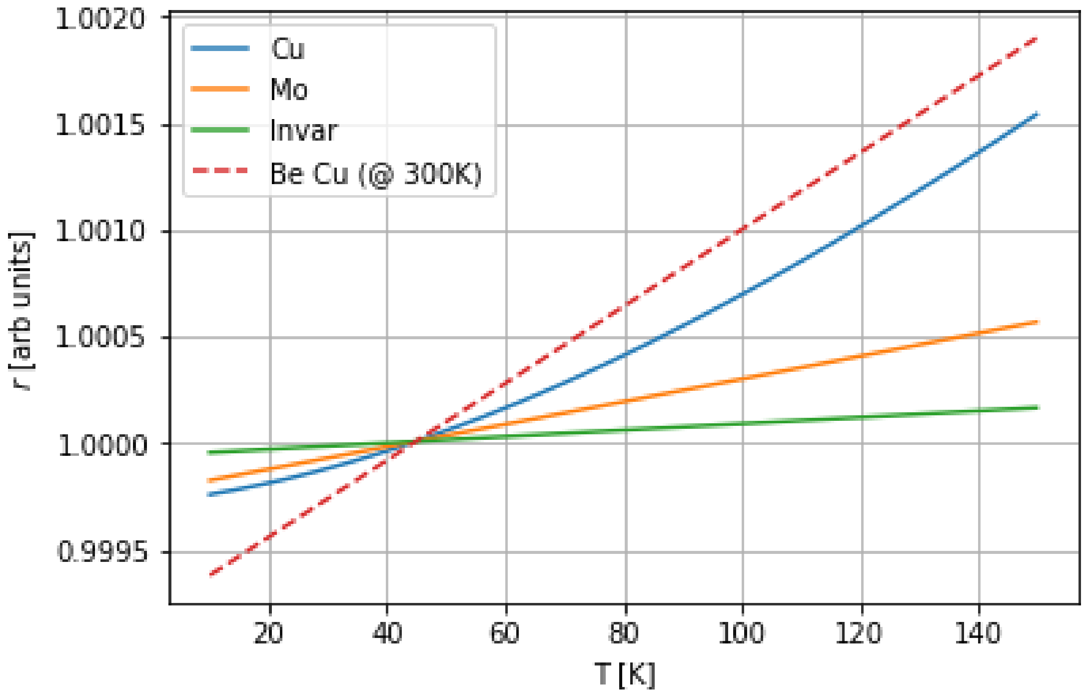
- Good for cathode tests
- High gradient (> 120 MV/m) but lower than plug alone

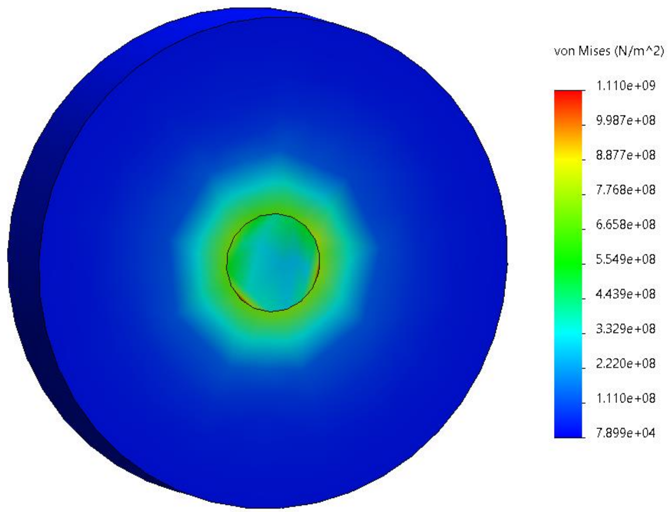


- No cathode exchange
- Highest achievable gradients

Cathode integration cont.

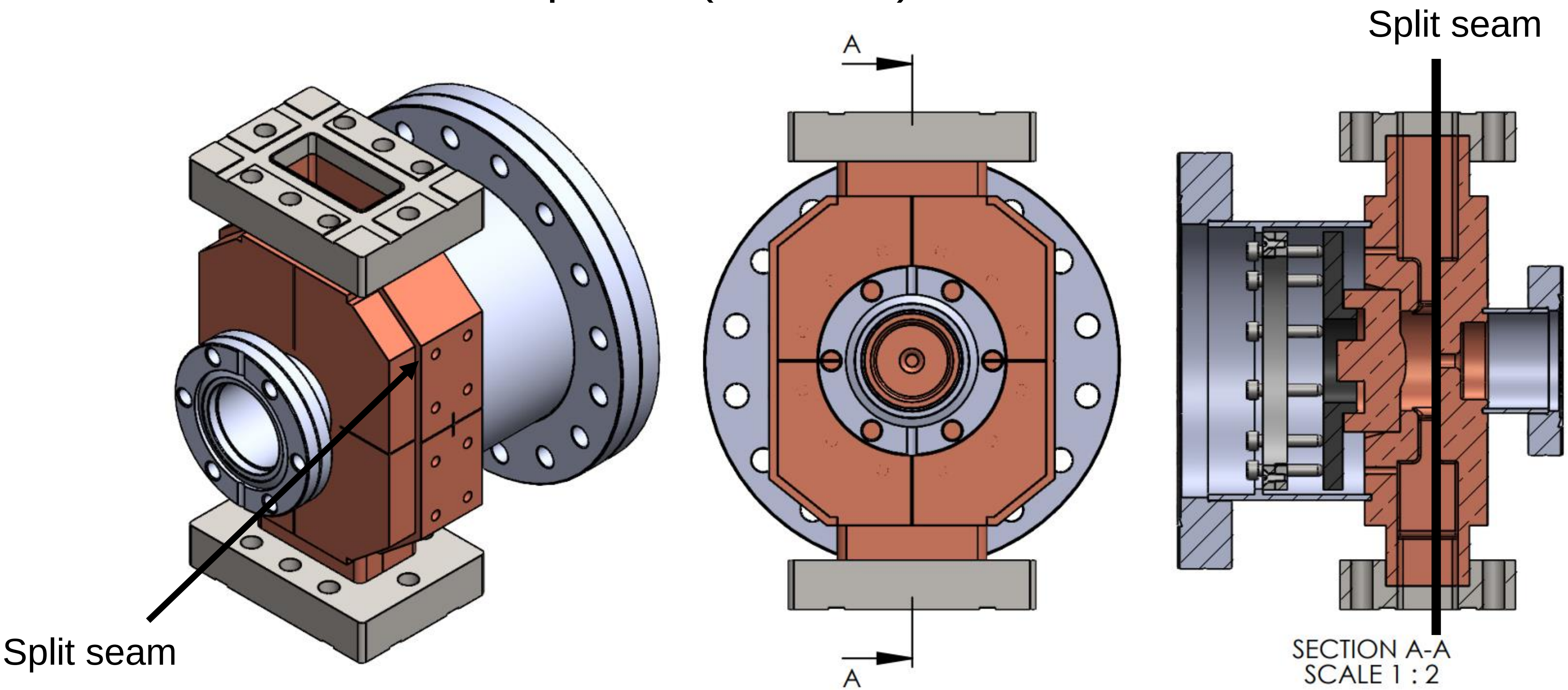
- For 1st phase of test bed, CF flange sealed off w/ blank from back of cavity and test copper cathode
- Later test involving UHV transfer of cathodes from transfer chamber into gun cell
- Molybdenum substrate puck difficult to achieve knife edge seal UCLA Pegaus experience
- Calculation of radii of hole and plug below and stress from contraction on plug to right and stress calculations below
- Cornell-style leaf spring plug holder complex
- Simplest setup for properties tests at cryogenic temperature (right)





½ Cell Gun Drawings

- Drawings with fully removable backplane based on FERMI gun design
- Comeb fabrication completed (en route)



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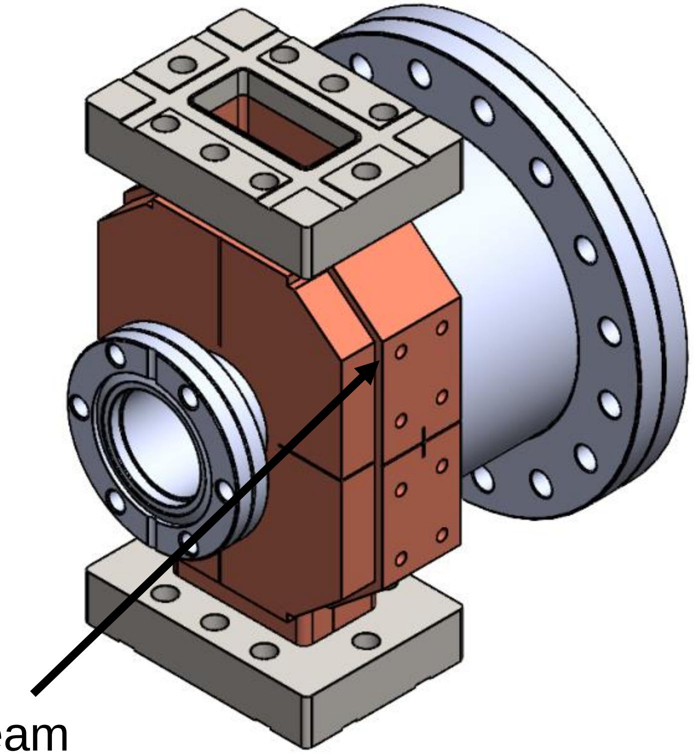
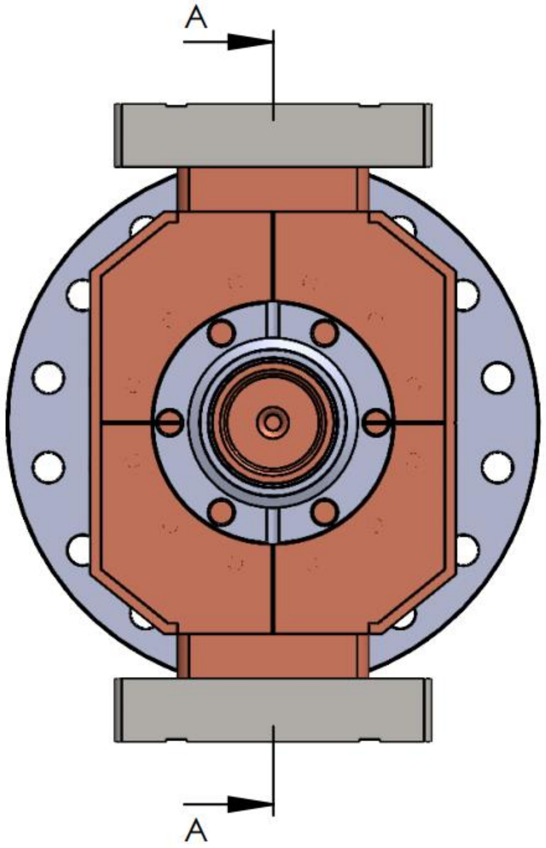
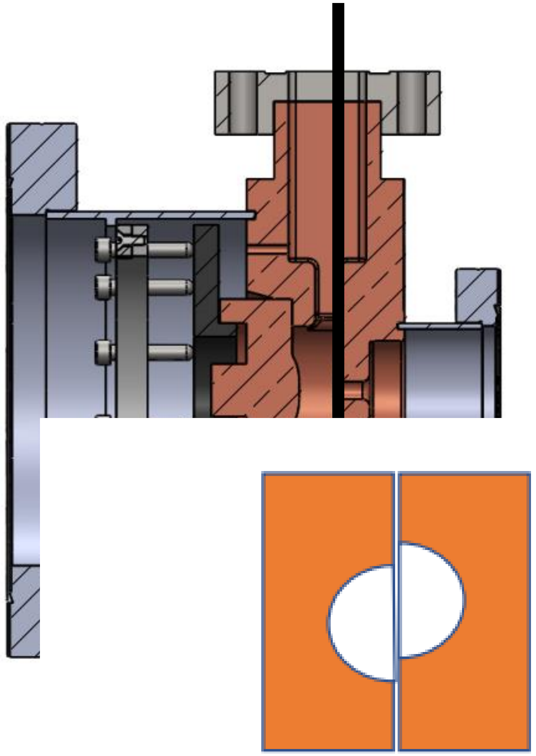


Split seam



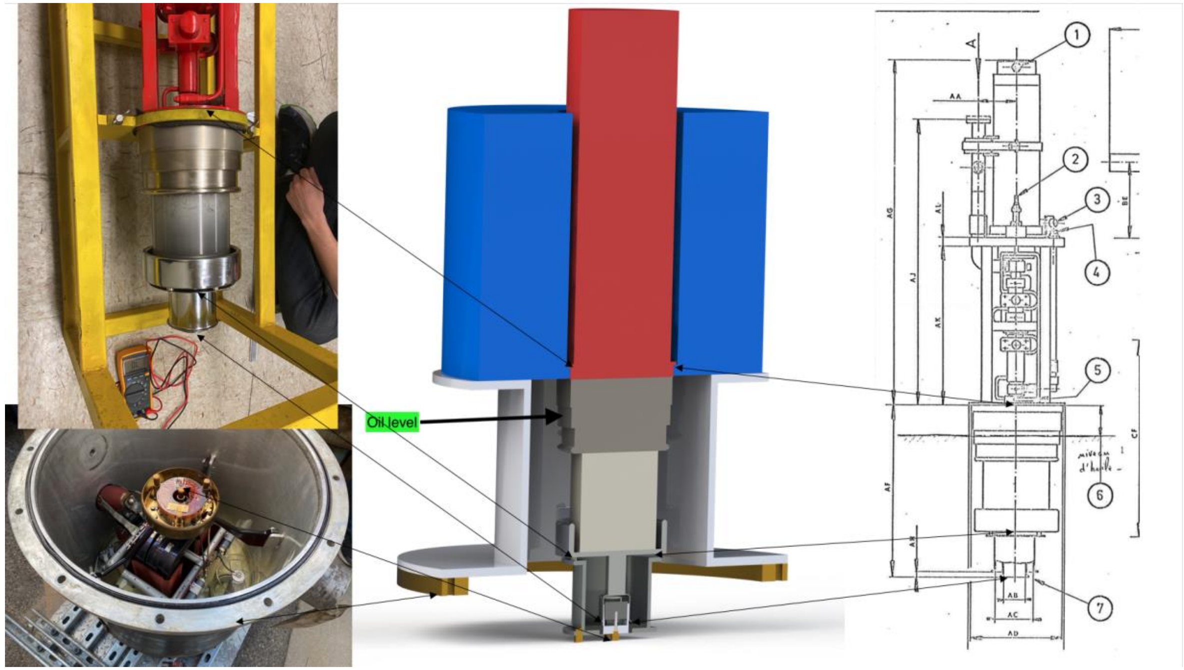
Split seam

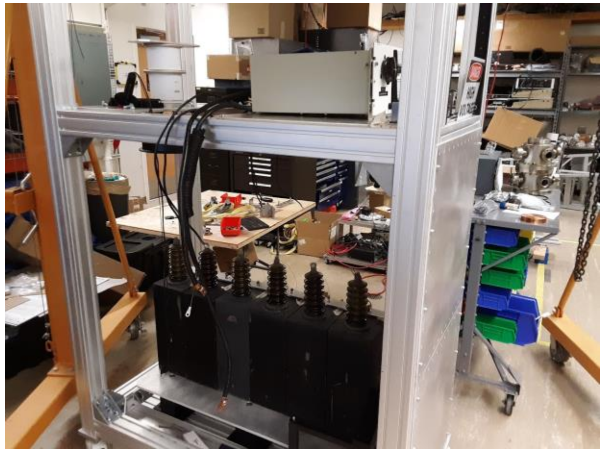


misalignment in case of split configuration.

RF Power

- Resurrected Thale Cband klystron several MW power sufficient





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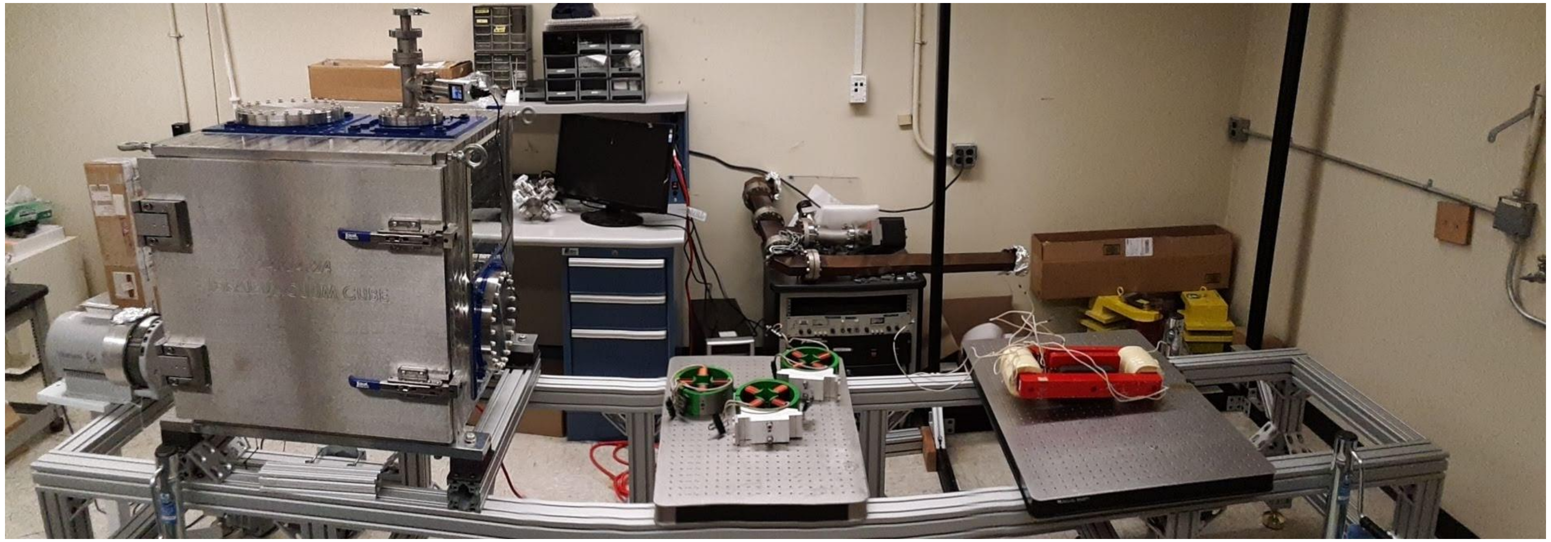
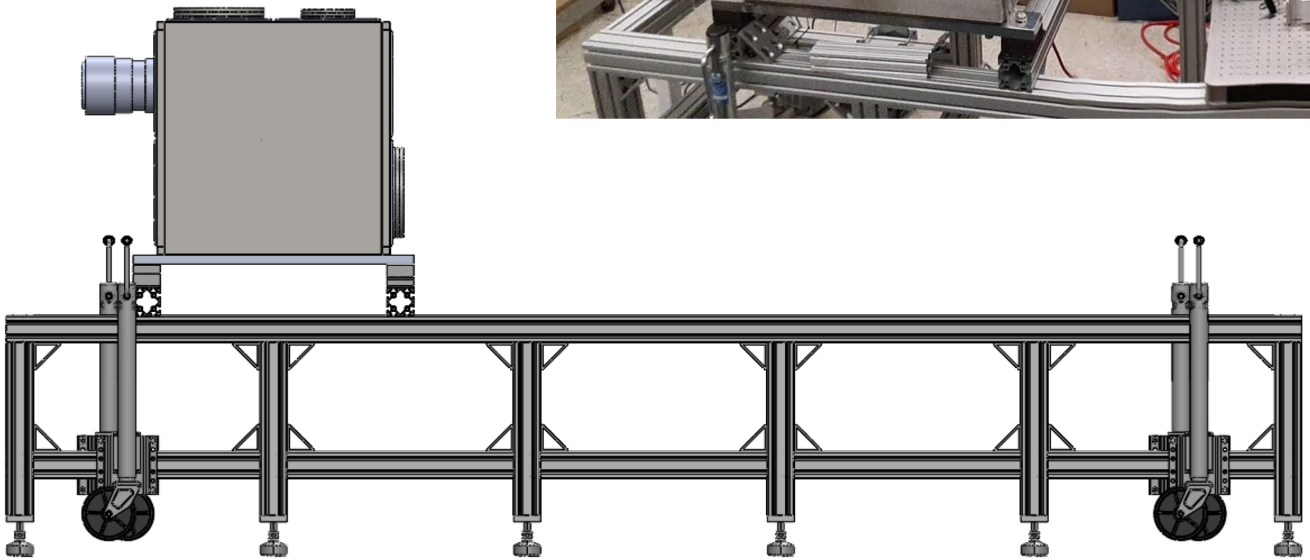
1. Motivations and background, relation to UCXFEL and CBB themes
2. RF and gun design
3. **Cryogenics and phase 1 diagnostics**
4. Phase 2 diagnostics
5. Status & future outlooks

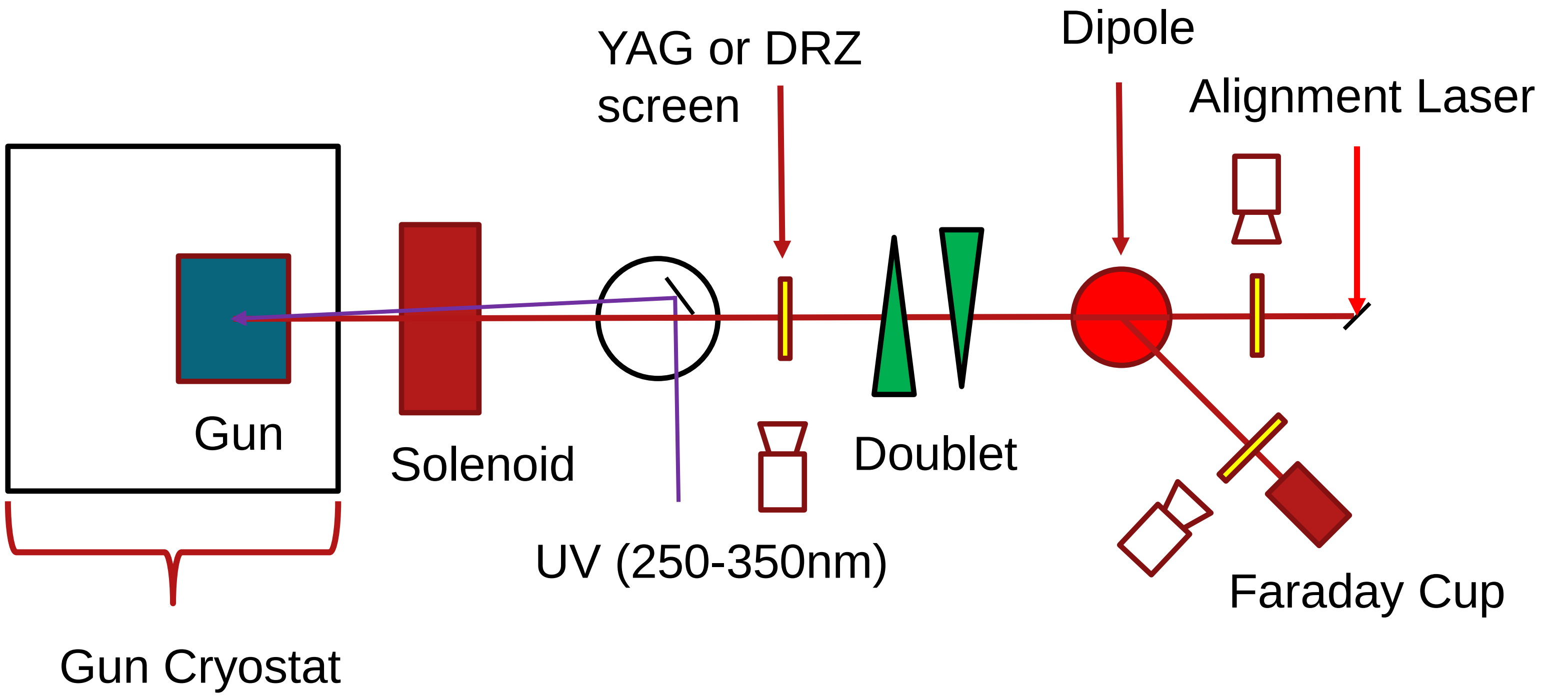
5. Status





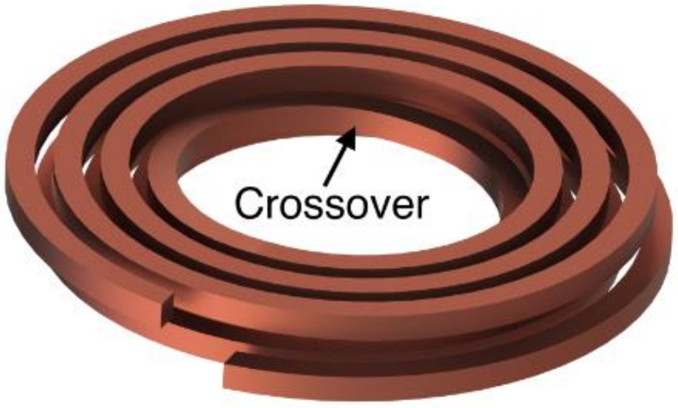
Phase 1 Diagnostic Line

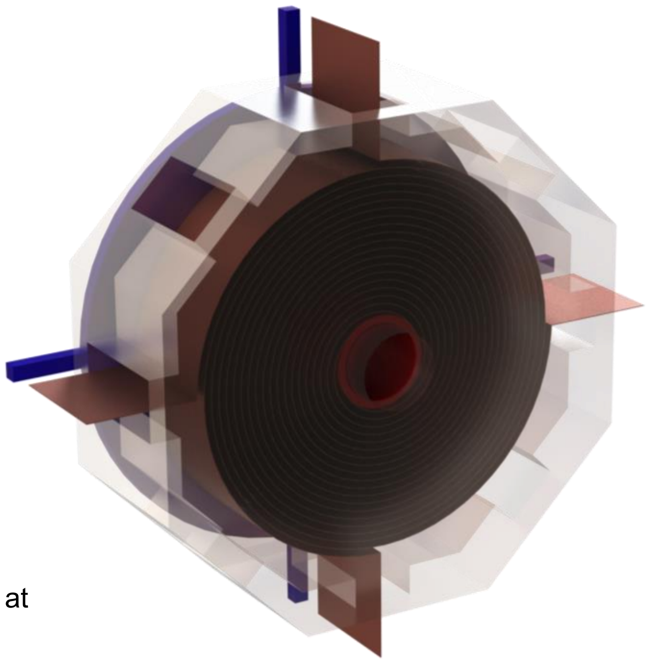
- Simplified phase 1 of cryogenic test bed design
- Completion condition: copper cavity QE measurement down to cryo temps

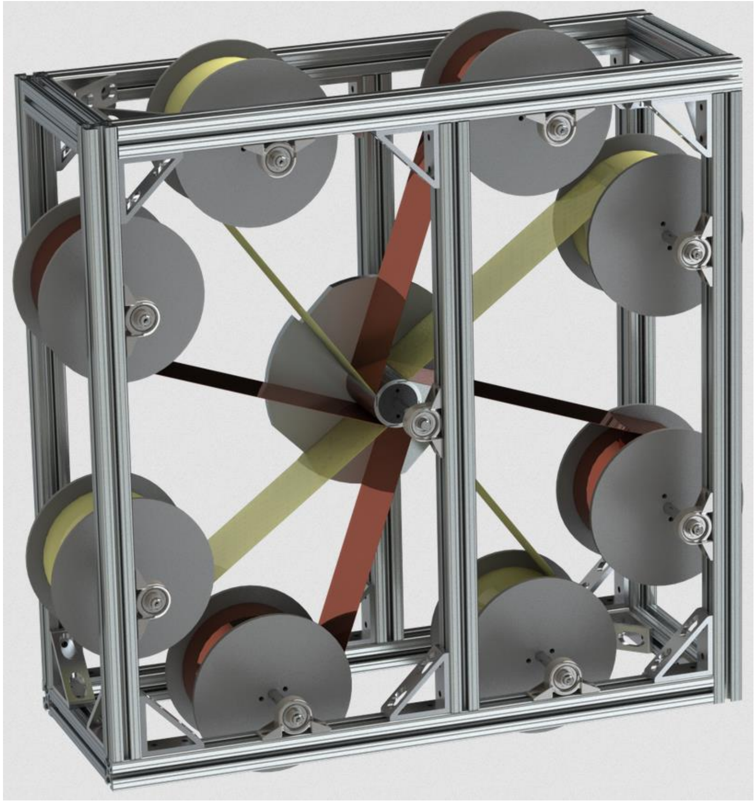


Foil-Wound Solenoid

- Very low emittance beamline
- Goal to identify any and eliminate all sources of unanticipated emittance growth
- Try to eliminate solenoid field crossover error



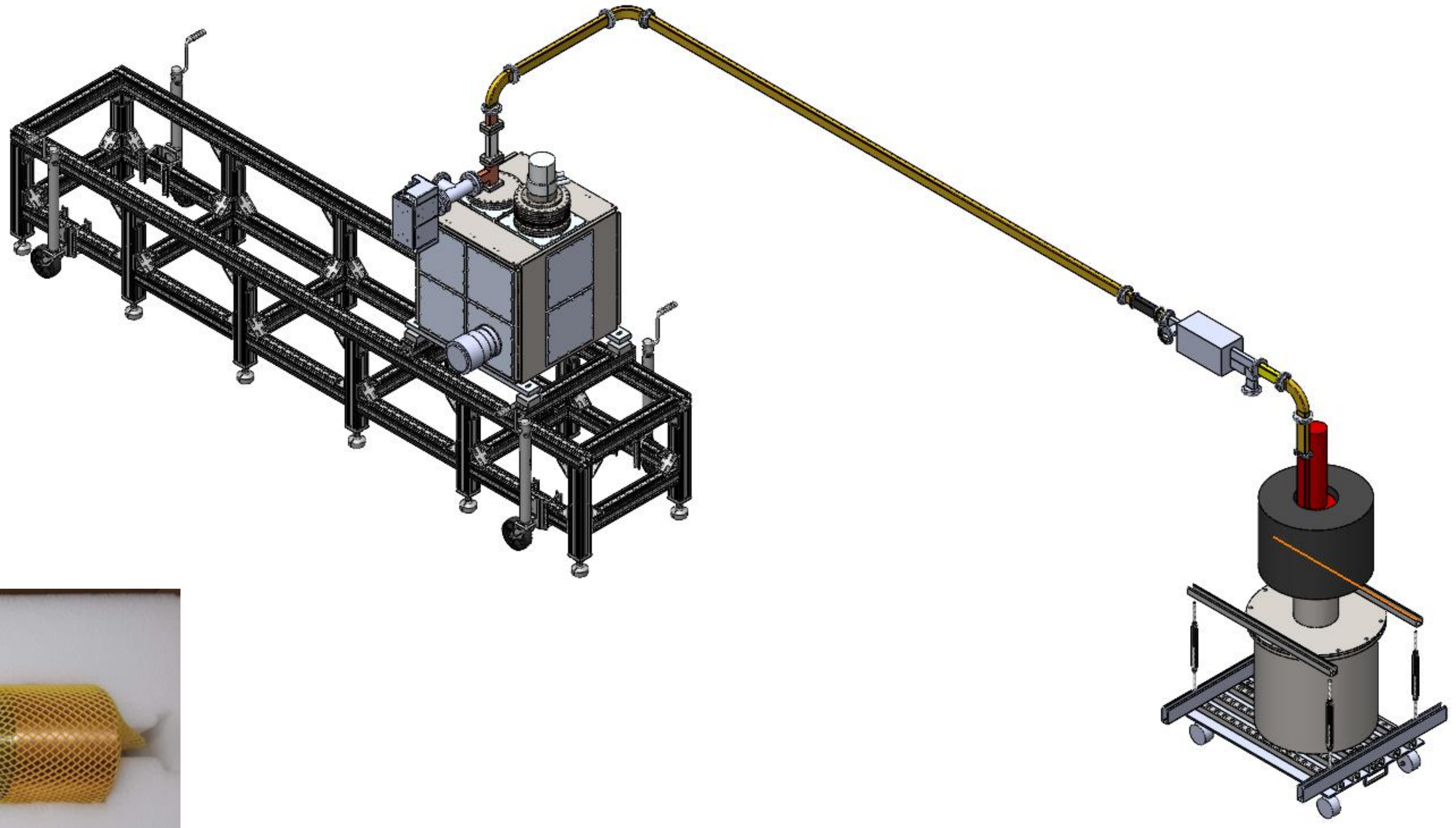




N. Majernik, A. Fukasawa, J. B. Rosenzweig, and A. Suraj, “Multi-start foil wound solenoids for multipole suppression”, presented at the 12th Int. Particle Accelerator Conf. (IPAC’21), Campinas, Brazil, May 2021, paper TUPAB094

Phase 1: Config 1

- Goals:
  - SHI vibration isolation
  - Waveguide setup
  - UHV
  - CYBORG cooldown & temperature stability
  - LL and high power RF tests
  - Optimize RF pulse heating + cooling



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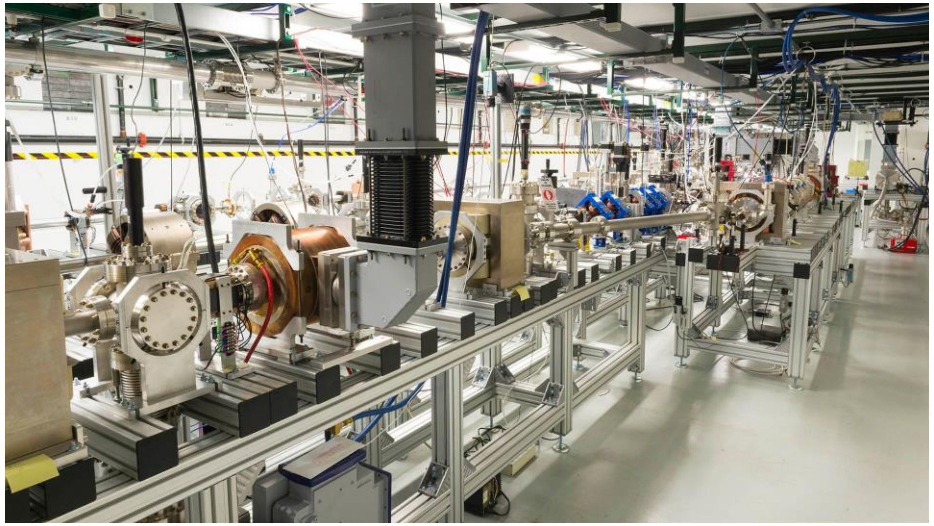

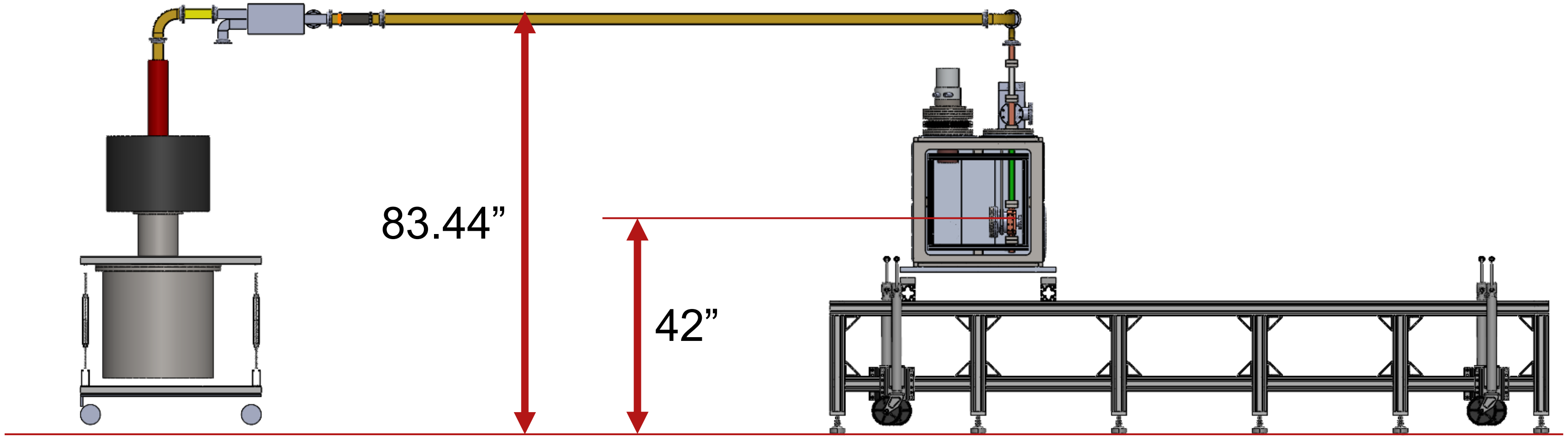

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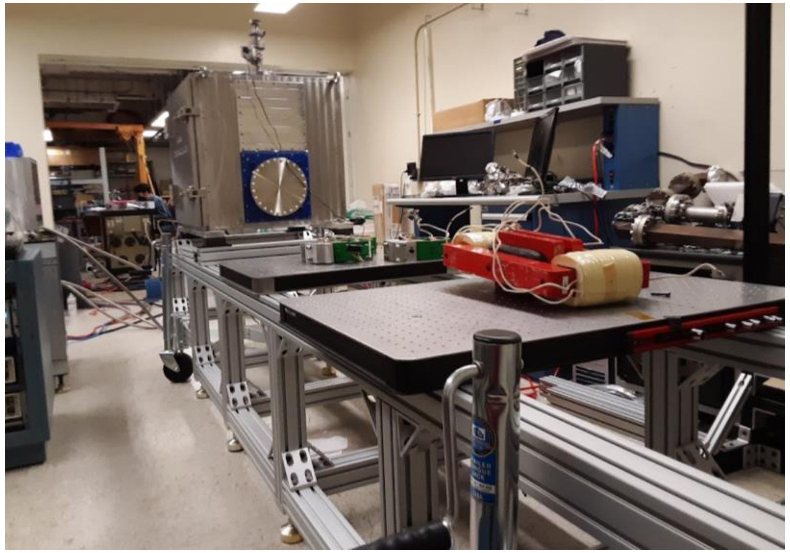
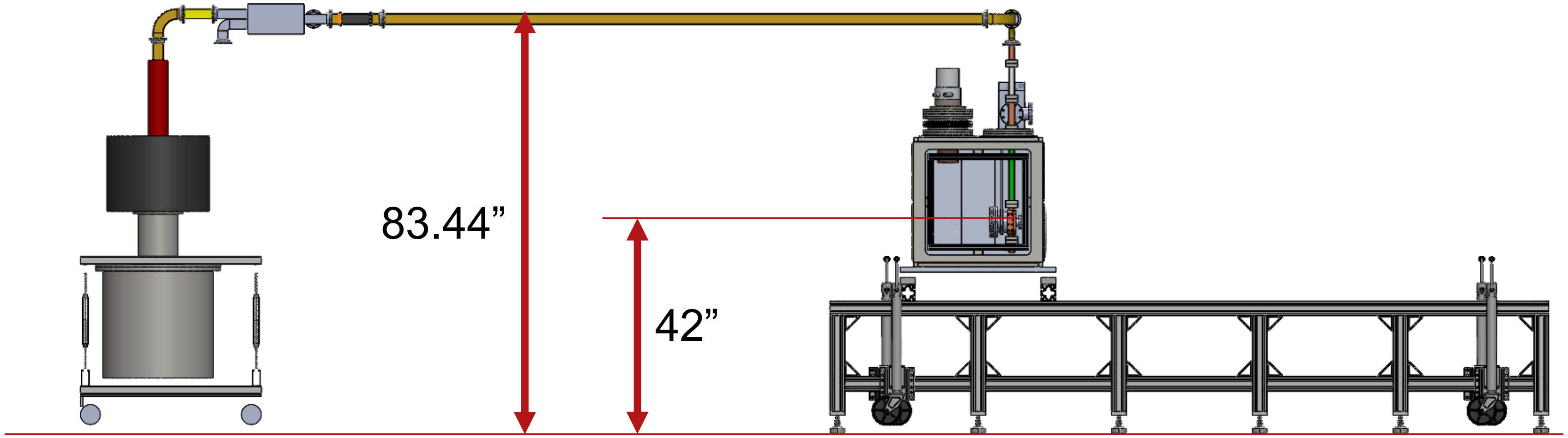
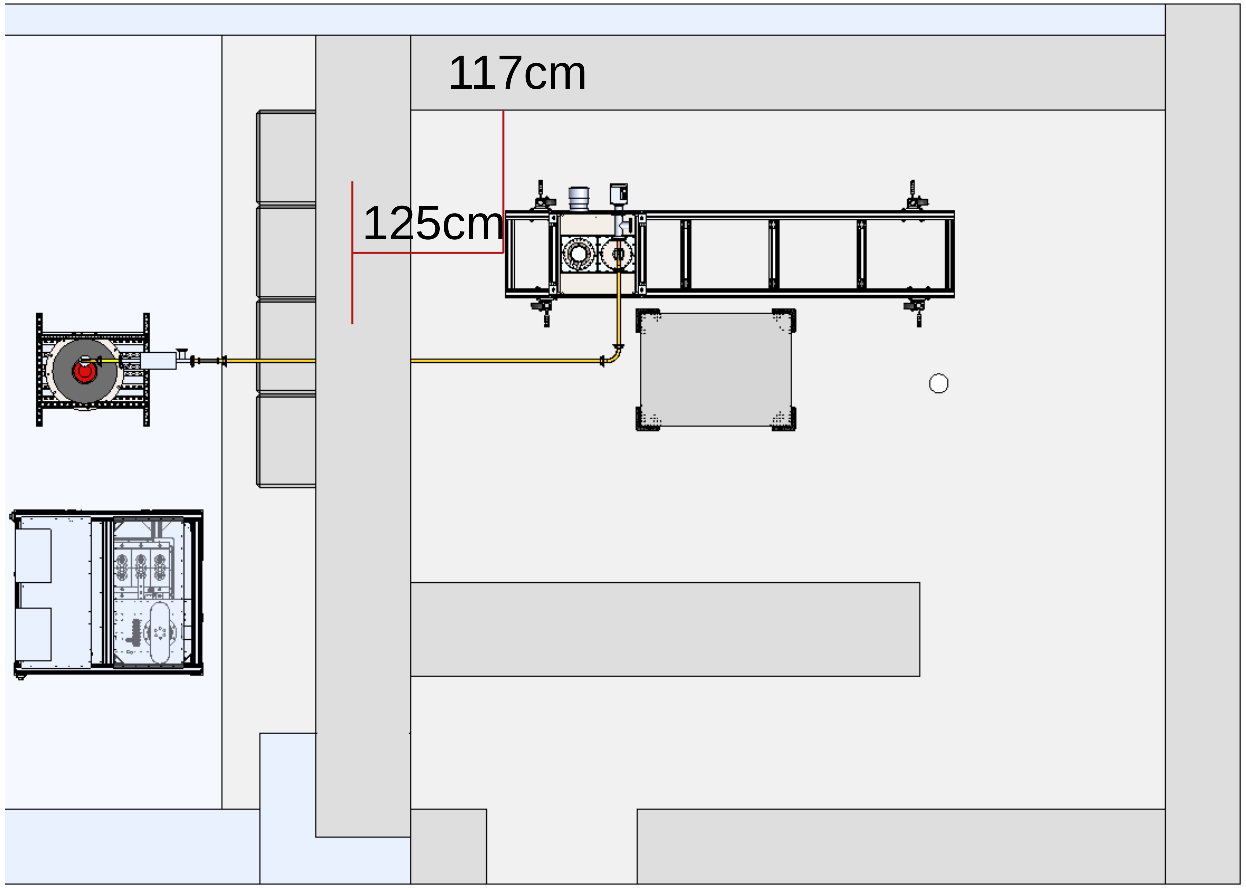




Phase 1: Config 1

- 117cm east, 125cm north, for load lock arms (future config)
- Currently 0.5” from 7’ bunker opening ceiling
- Flexible waveguide to lower
- Approx 5m x 1m parallel area



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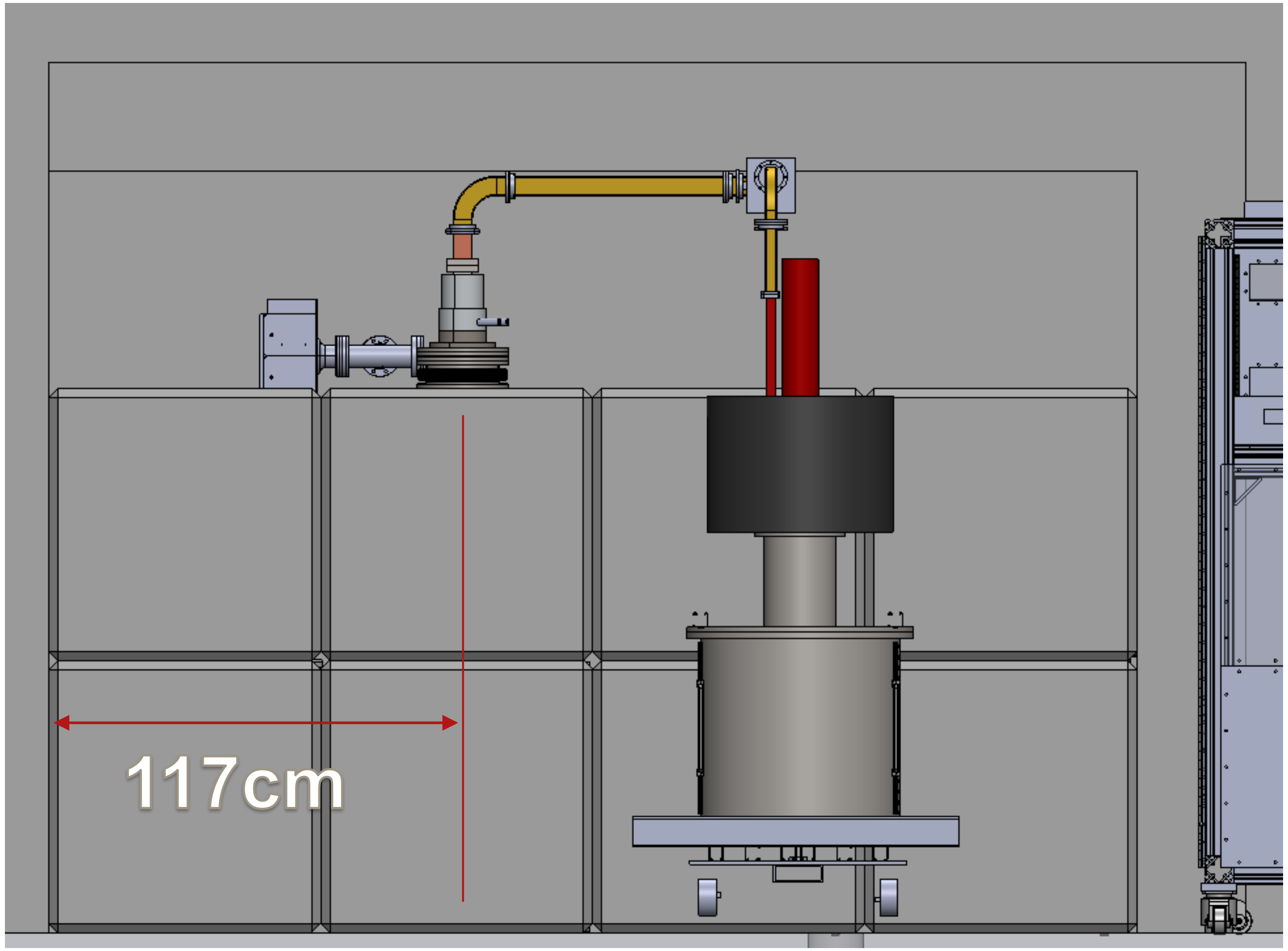
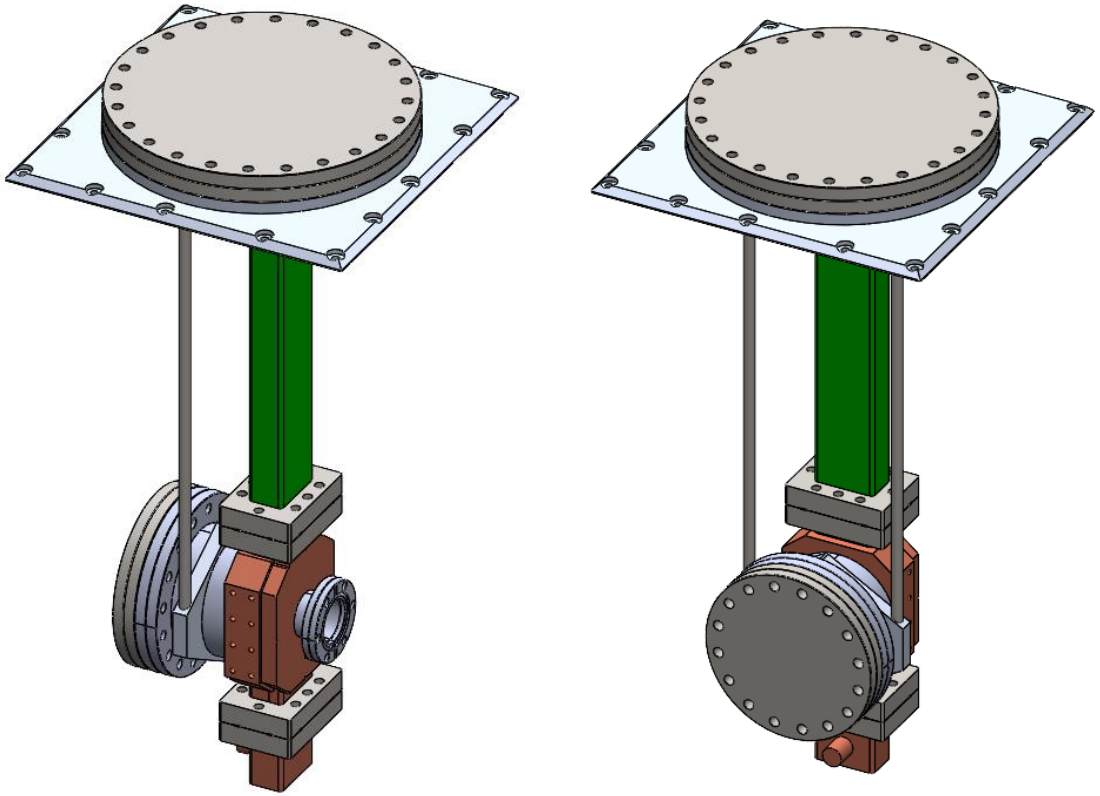


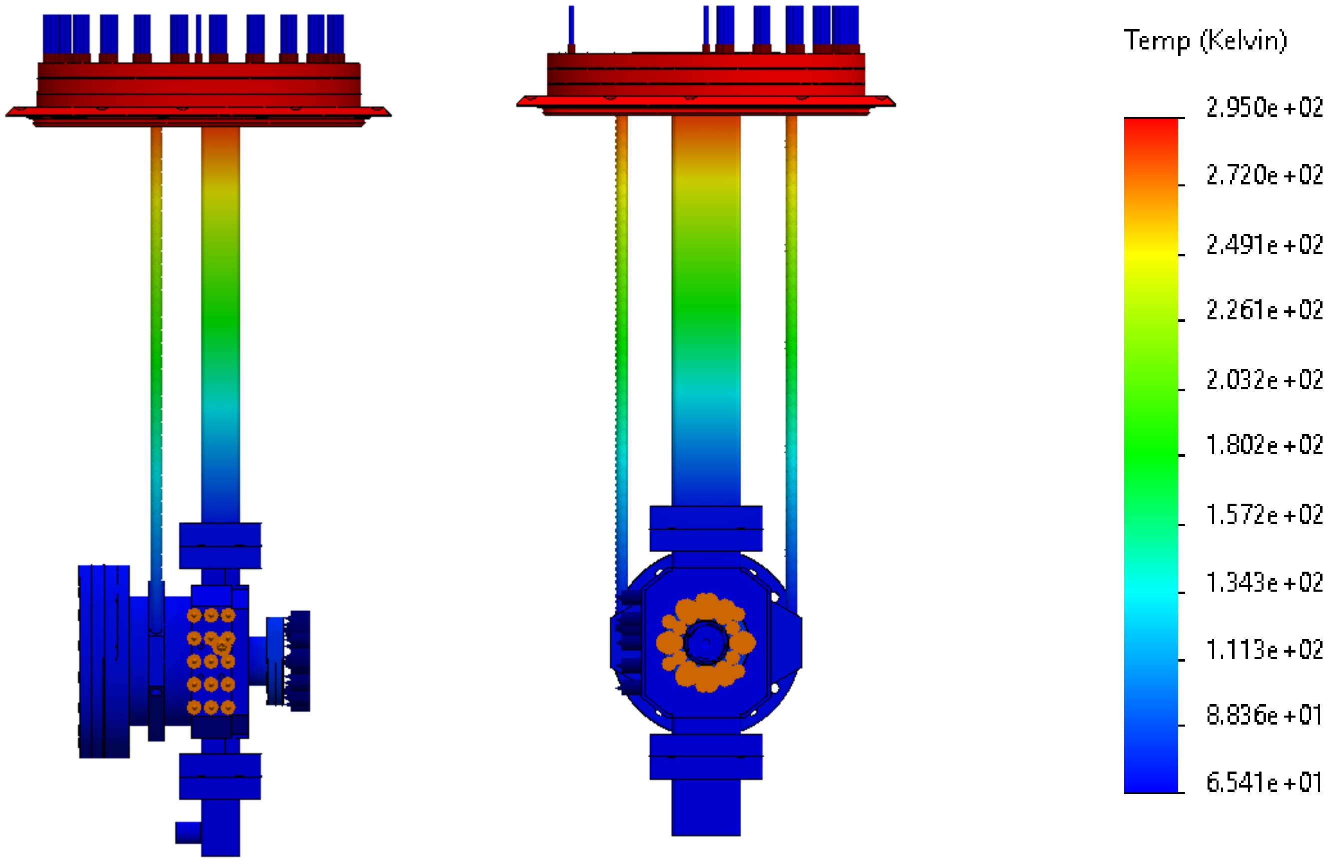
Drop down section

- Configuration 1 for copper cathode test, load locked blanked
- Drop in section for cryostat v2
- 26 kg



Steady State Thermal Sim

- Initial thermal simulation 11 W cooling from cavity side face (from thermal braid number conductance)
- 295K BC on outer flange
- 1 W heating from up stream flange
- 65 K minimum



Accounting of heat leaks

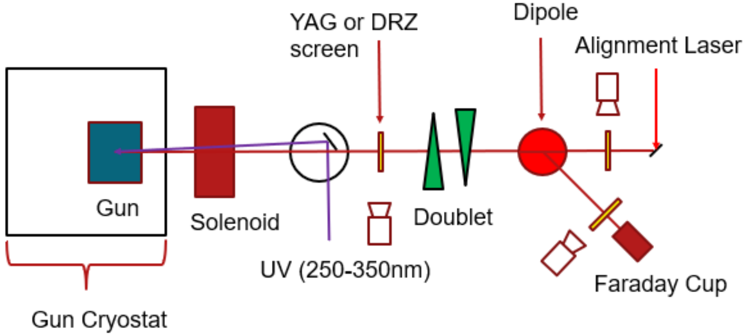
- Main sources of heat leaks to consider
- For quicker and easier to interpret cool down time estimate replace realistic conduction geometries w/ homogenous materials with effective thermal properties

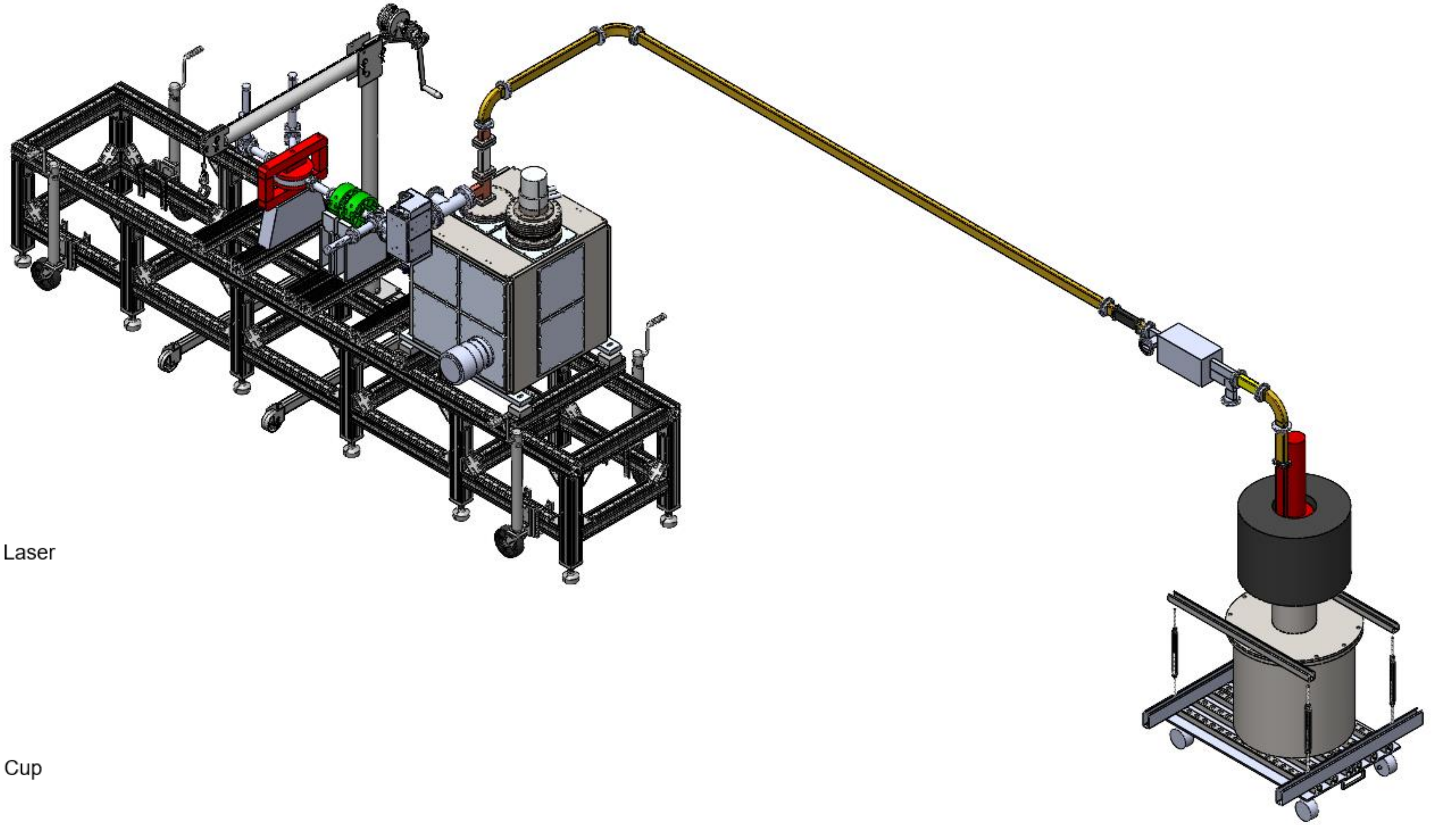
ID	Description	Materials	Equivalent Area	Equivalent Power
001	6” plug flange	Stainless steel (CF flange), edge welded bellows	436 mm^2	< 1 W
002	2.75” downstream flange	Stainless steel (CF flange), edge welded bellows	85 mm^2	< 1 W
003	Waveguide	Satinless steel	588 mm^2	Approx 10 W
004	Supports	Stainless steel, aluminum, G10	TBD	TBD
005	Diagnostic probes	Copper wiring of various gauges	50 mm^2	5 W
006	Alignment rails	TBD	TBD	TBD
007	Radiation	N/A	25000 mm^2	< 1 W
008	Pumping on dummy side			

Phase 1: Config 2

- Goals:
  - Setup and align optics
  - Measure cryogenic copper QE

- To do list:
  - Finish solenoid
  - Solenoid stand design
  - Remake dipole faces
  - Measure quad fields
  - Optimize beam dynamics
  - Finish laser path





Laser Room

- Inherited laser from SLAC former Gun Test Facility
- Space beneath main bunker
- To setup UV conversion transport upstairs into bunker

Image of laser path here

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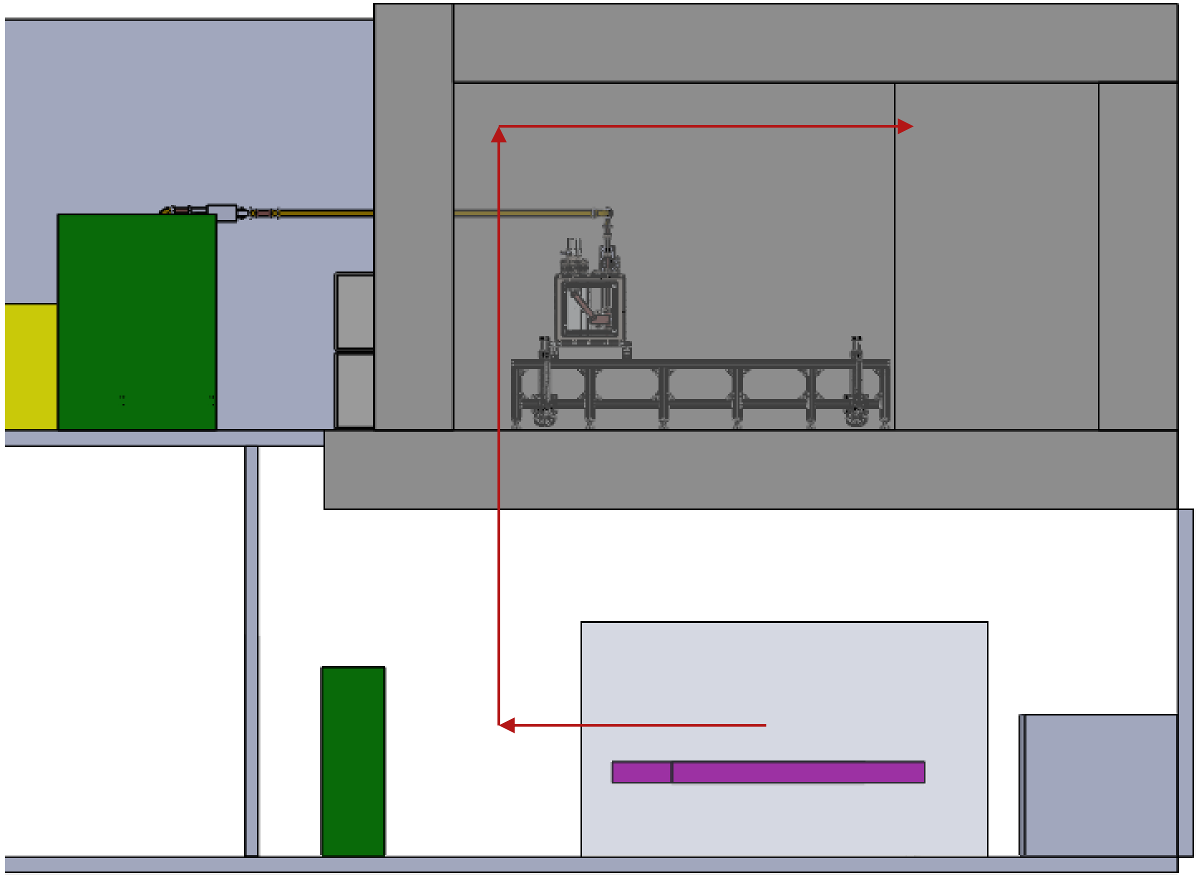

Laser Room

- Inherited laser from SLAC former Gun Test Facility
- Space beneath main bunker
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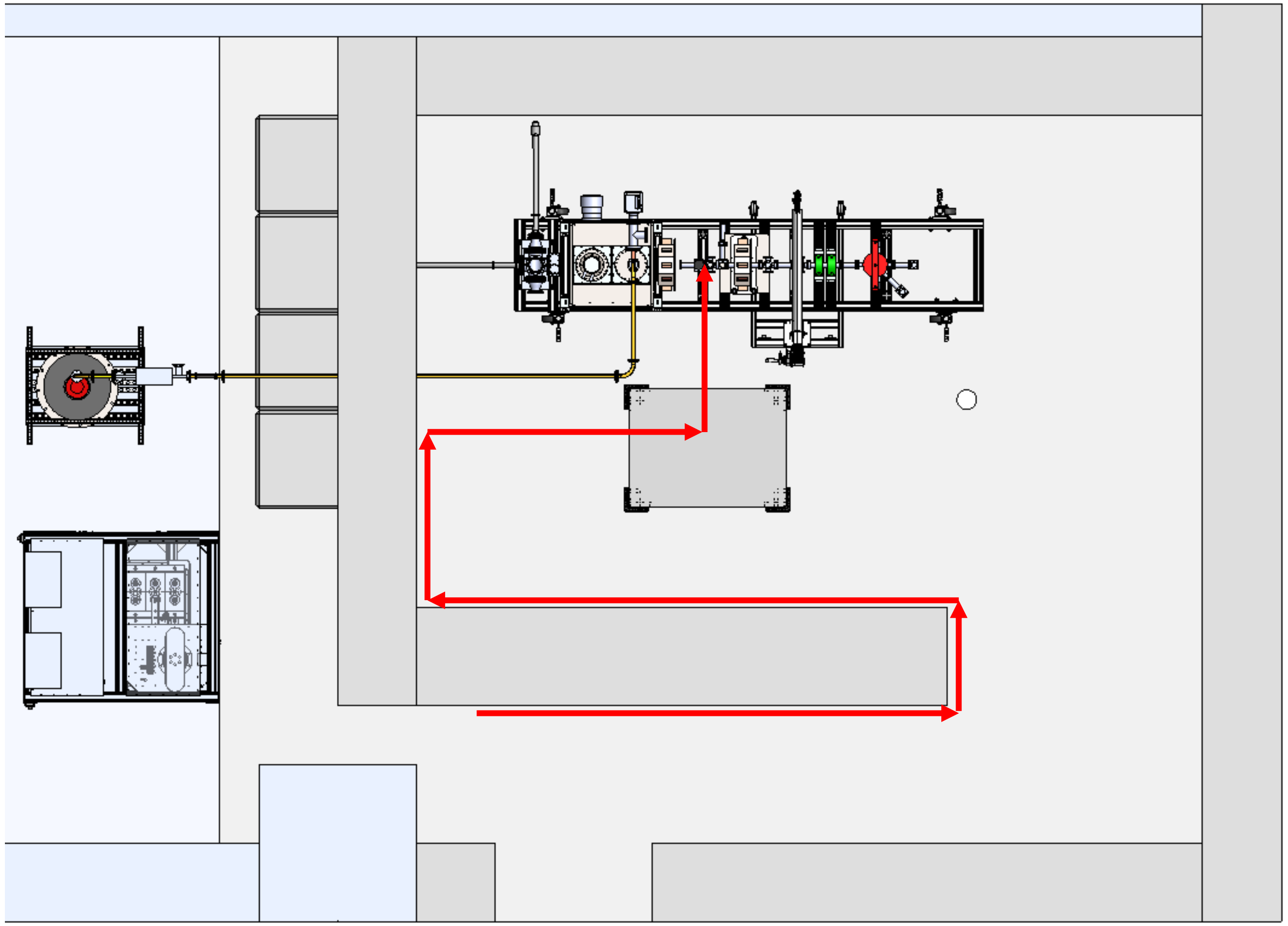

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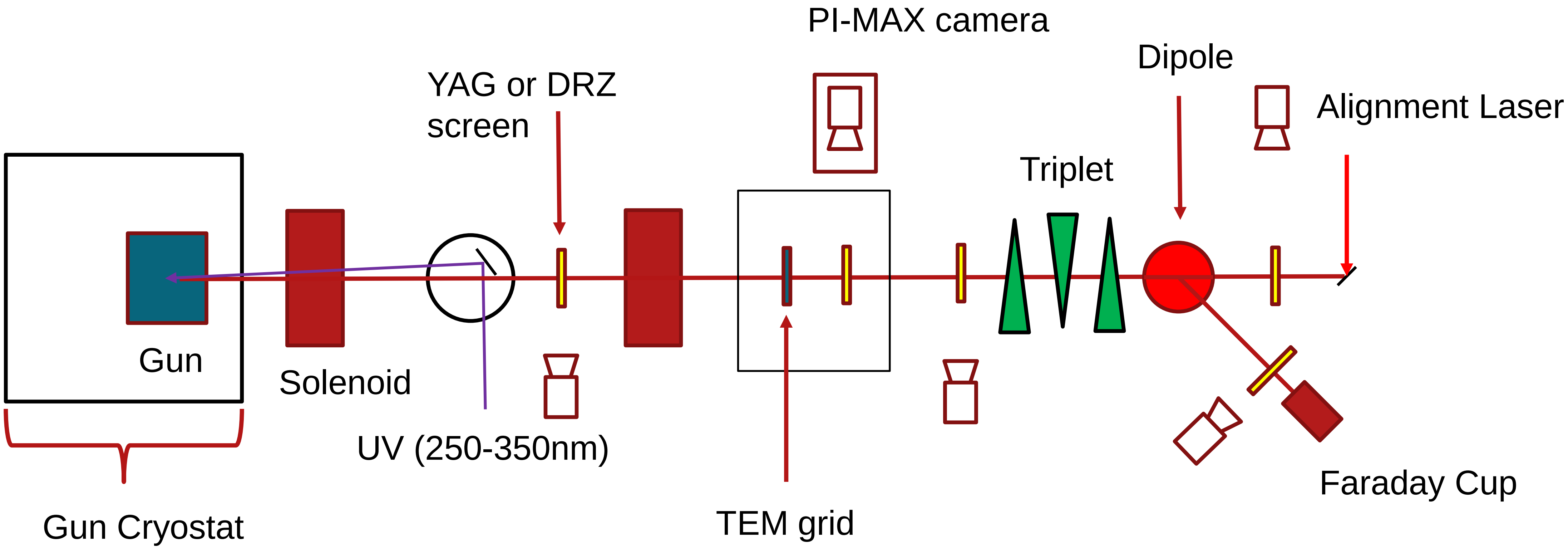
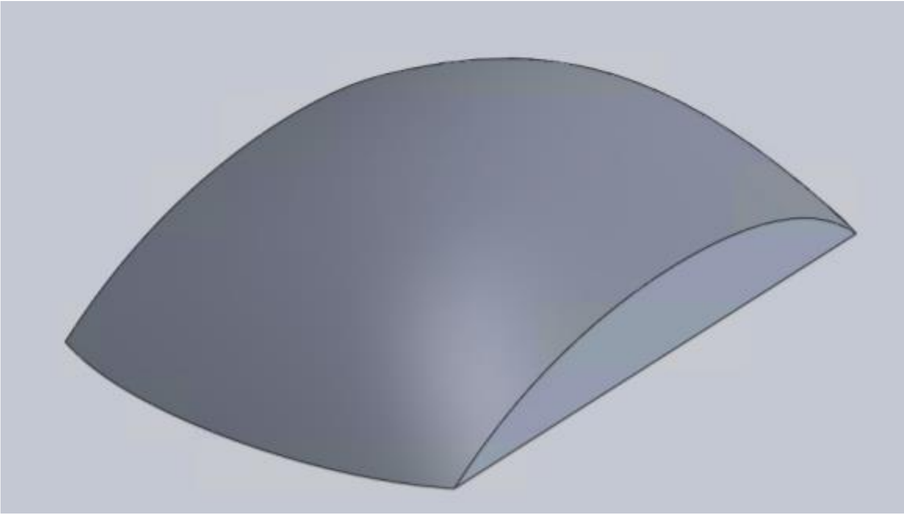
Phase 2: Config 1

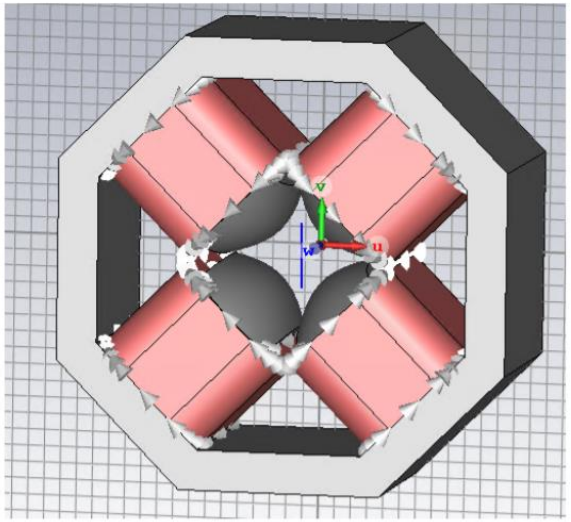
- Phase 2 beamline additions (2nd solenoid and TEM grid) for emittance measurement w/ copper backplane then high brightness cathode plugs, 18 months
- Completion condition: copper cathode QE measurement down to cryo temps
- Parallel development: load lock UHV

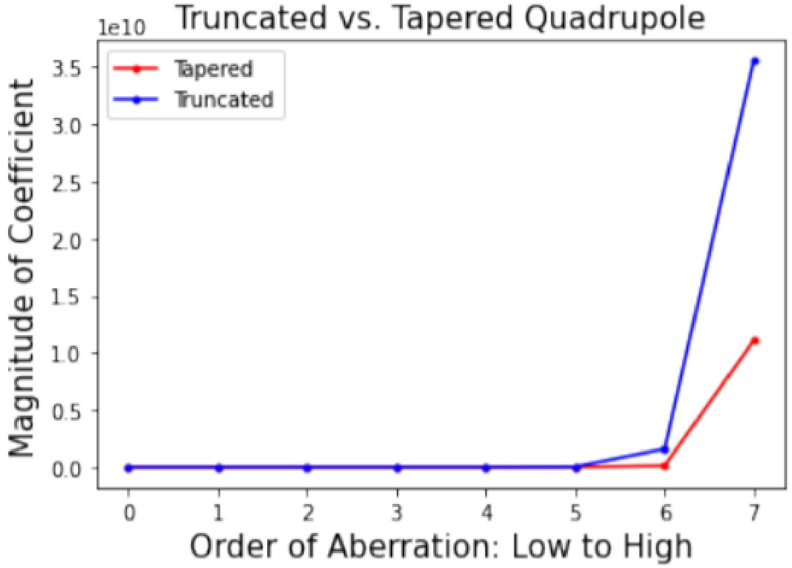


New Quad Pole Faces

- Designed lower aberration quadrupole faces
- Possible additional source of emittance growth



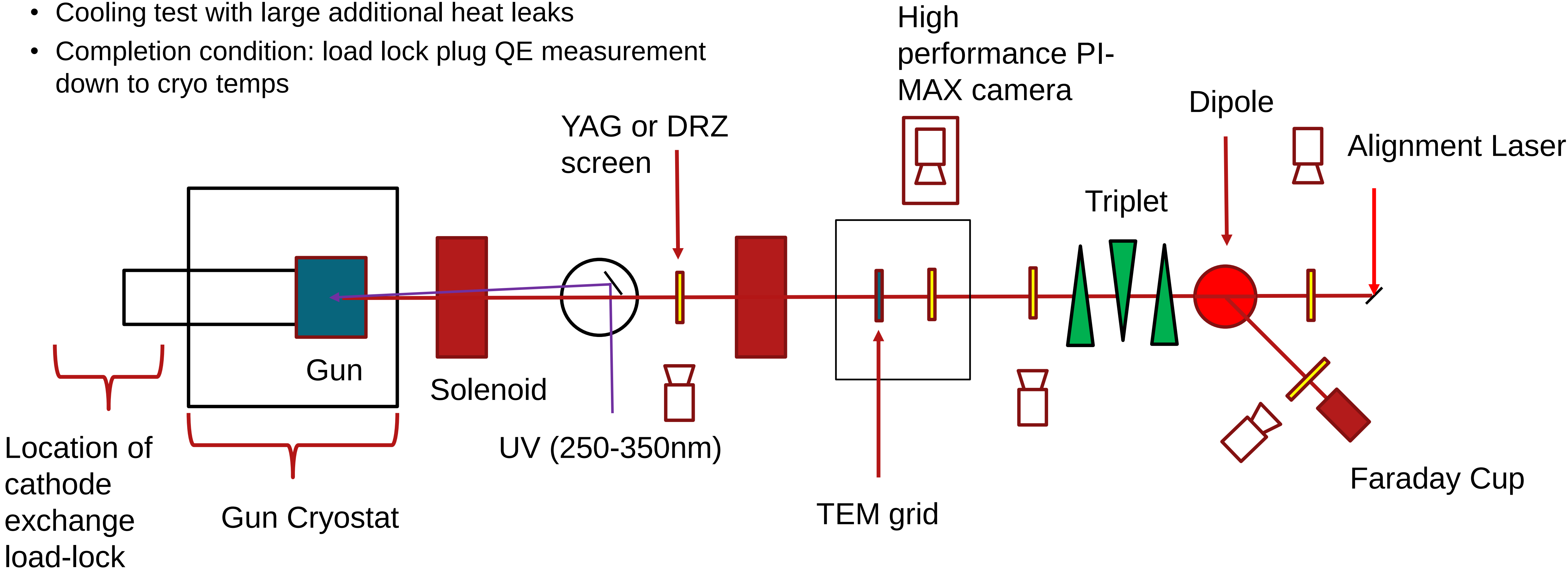




Tapered Modular Quadrupole Magnet to Reduce Higher-Order Optical Aberrations
Y Shao, B Naranjo, G Lawler, JB Rosenzweig - 2021

Phase 2: Config 2

- Same regardless of config 3, load lock and phase 2 diagnostics
- Test of back plane plug into reentrant small Cband
- Cooling test with large additional heat leaks
- Completion condition: load lock plug QE measurement down to cryo temps



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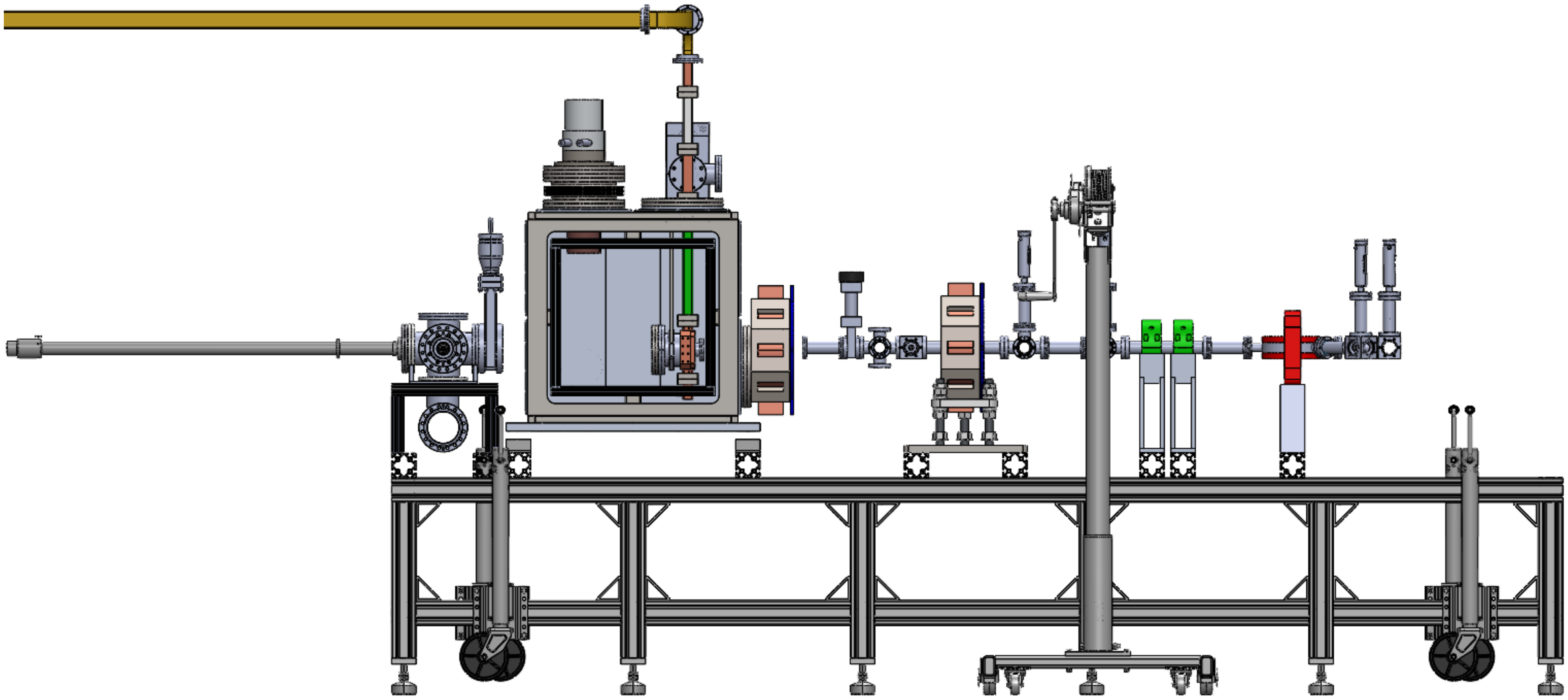
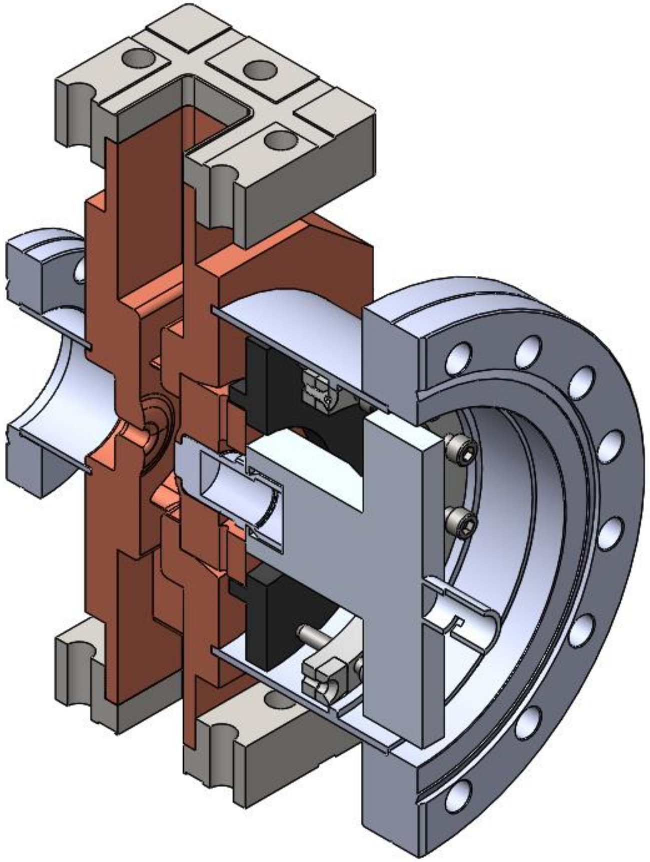
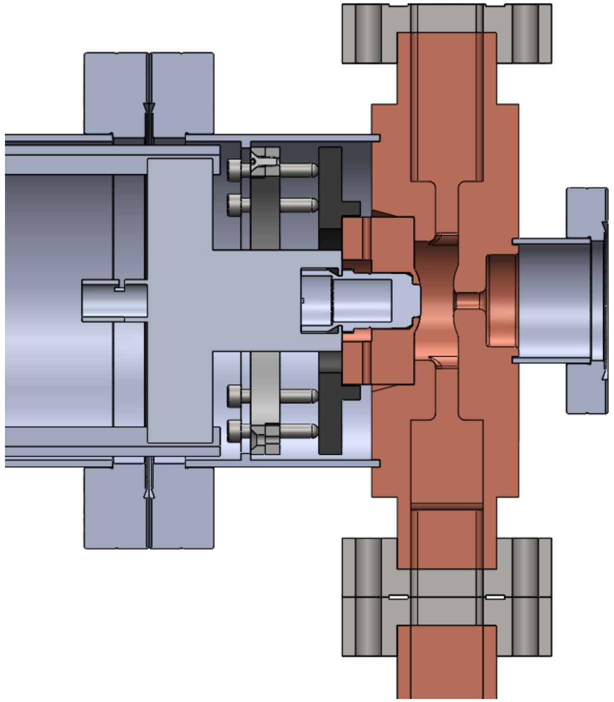
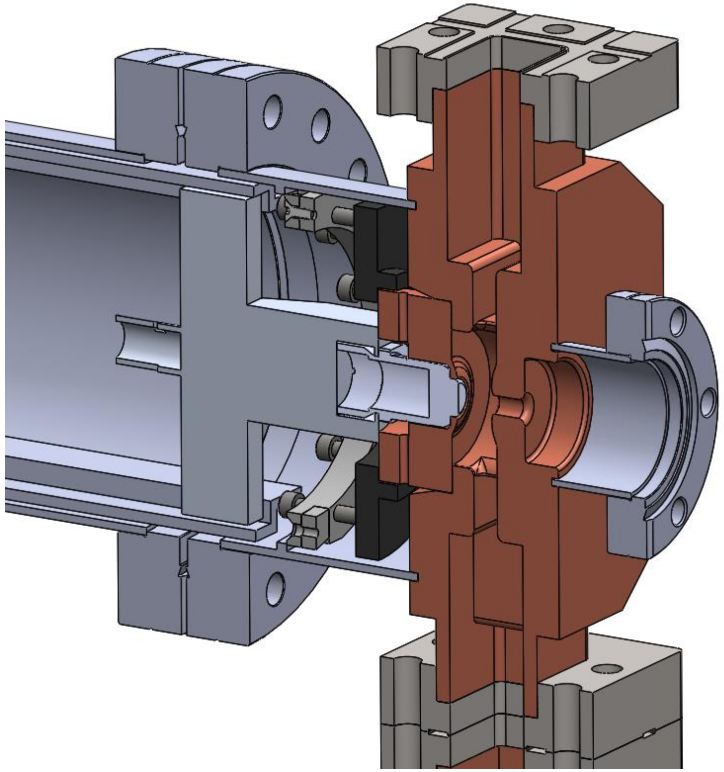


Cathode Plug-Backplane Variant

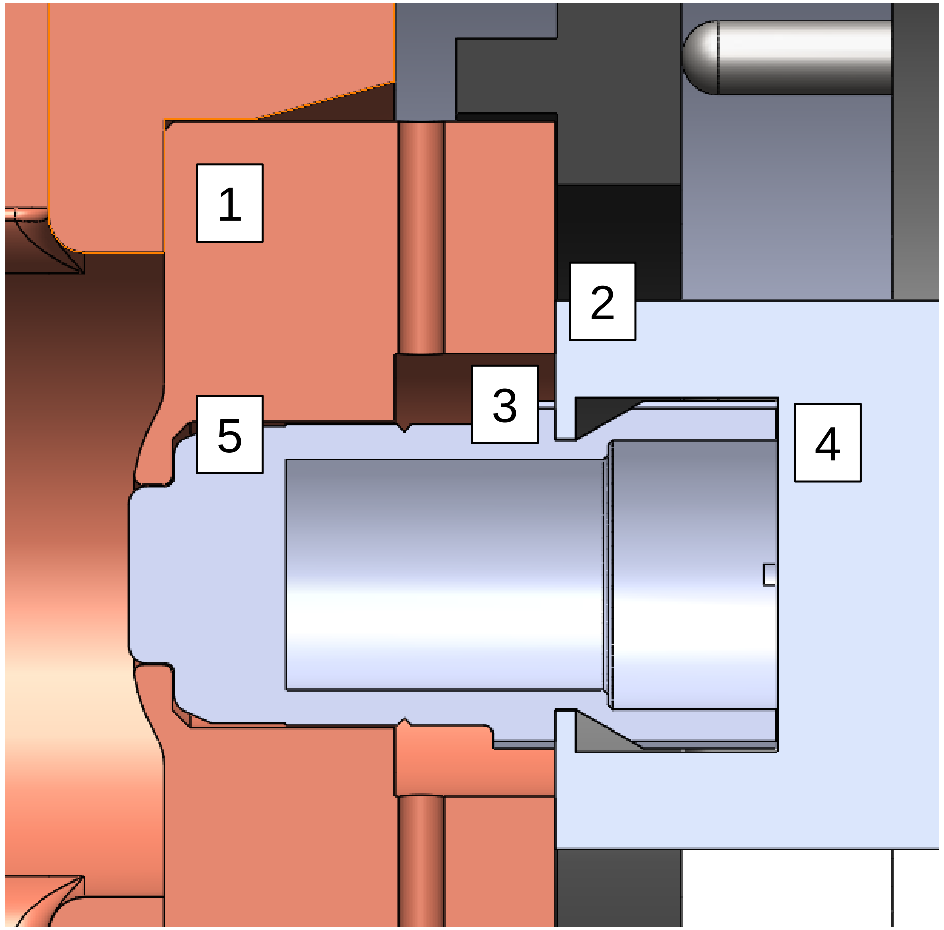






Cathode Plug Interfaces

- Interface 1 may be sufficient for cooling connection
- Interface 2, 3 and 4 are loose
- Interface 5 temperature dependent
- Interface 6 could be made with an additional shoulder but area smaller



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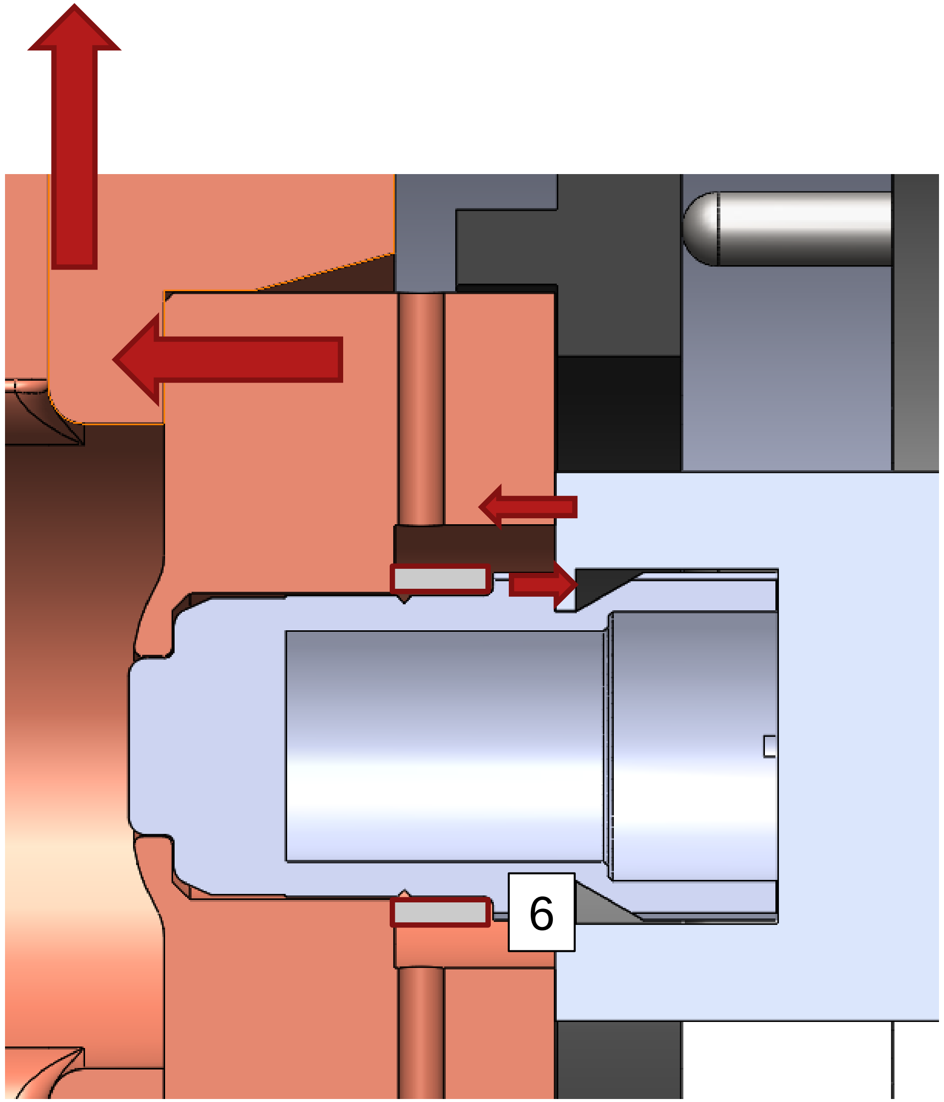
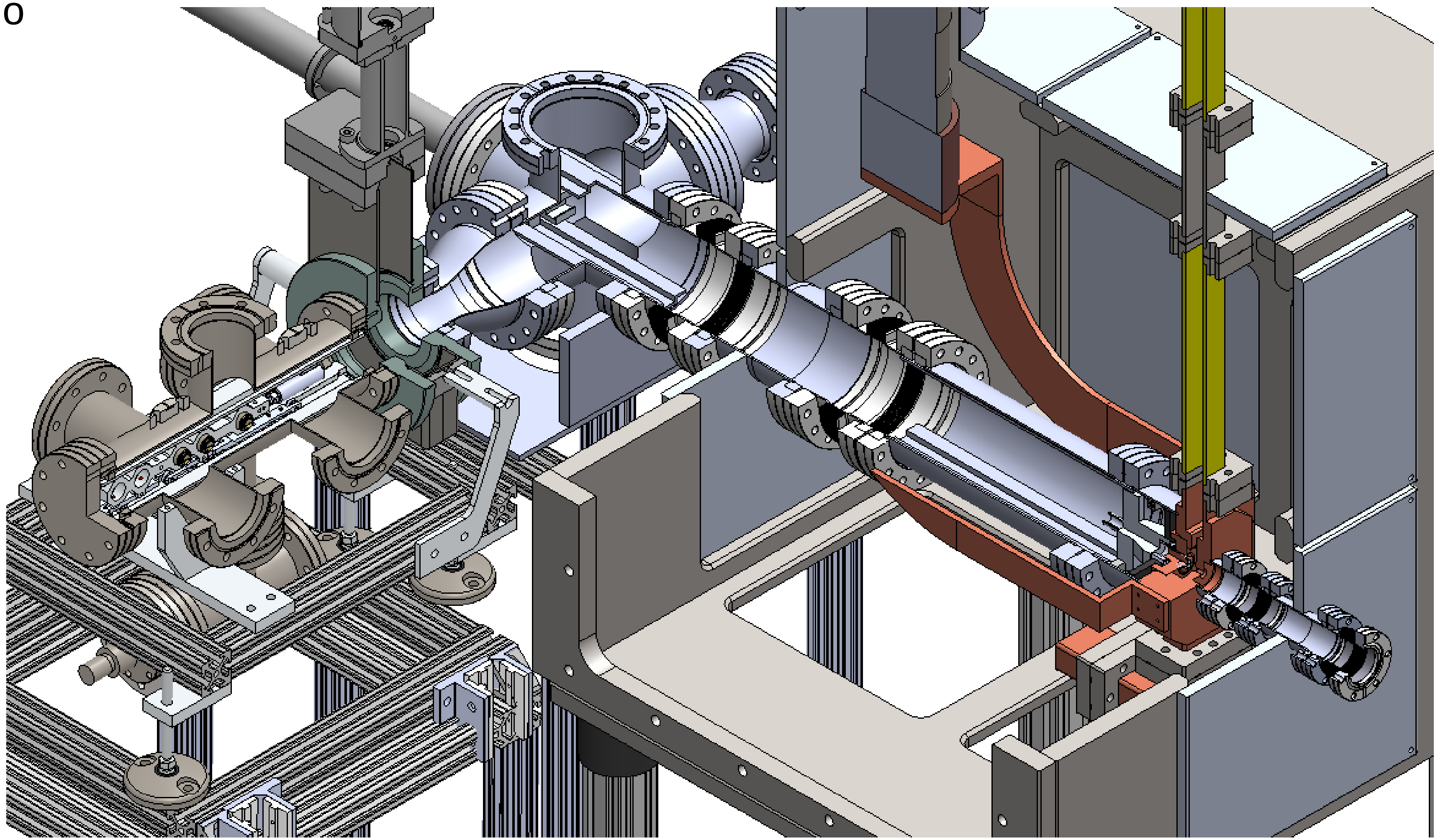
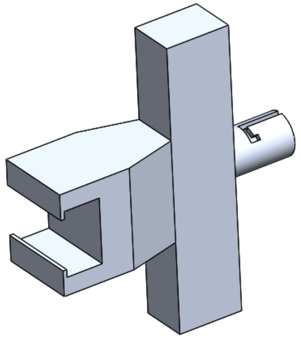


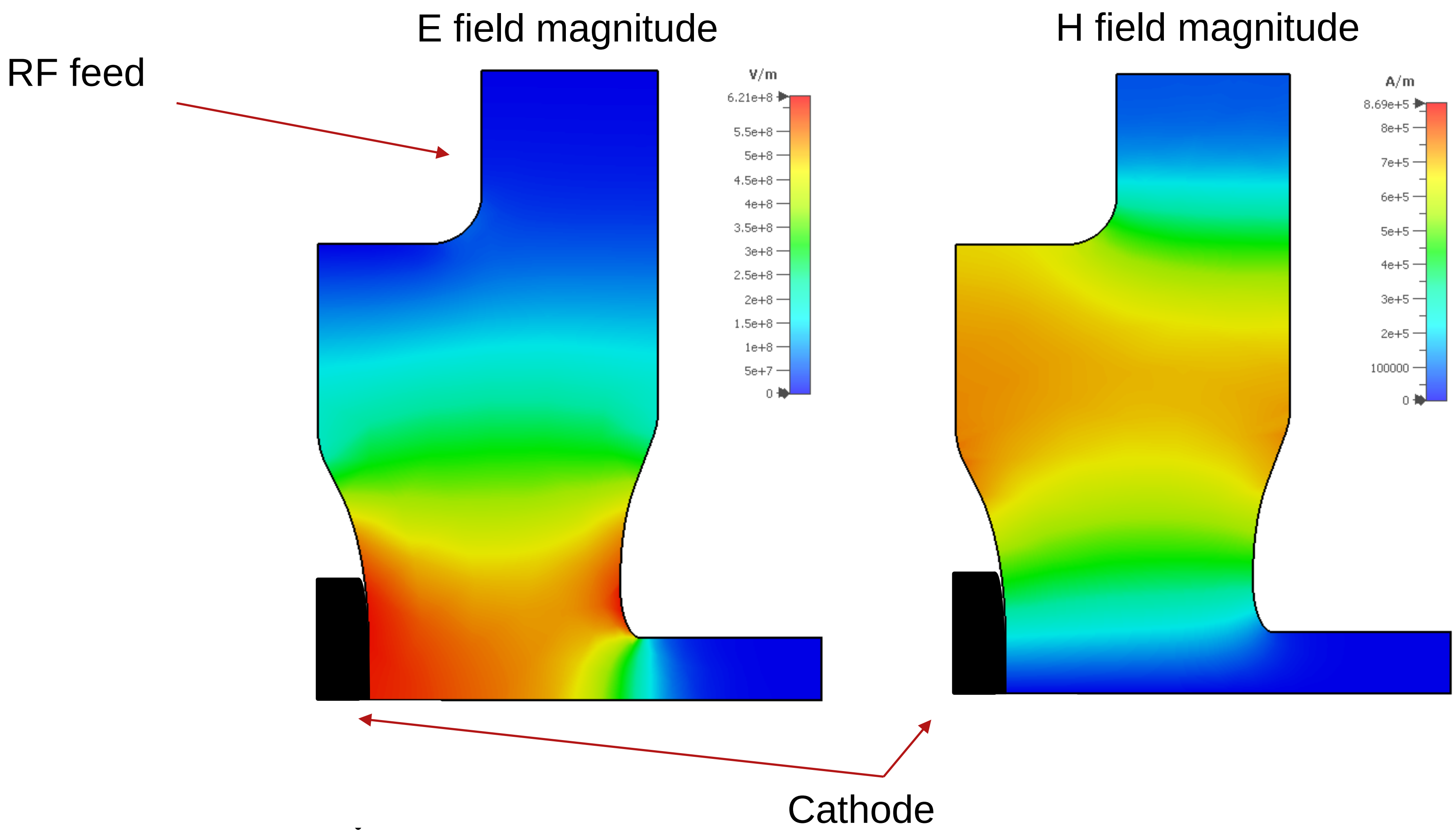
Engineering Designs

- *Pegasus* version has no plug guides rails and holds plug in w/ arm
- Cryo version uses guiding rails and decoupling section w/ an extra gap

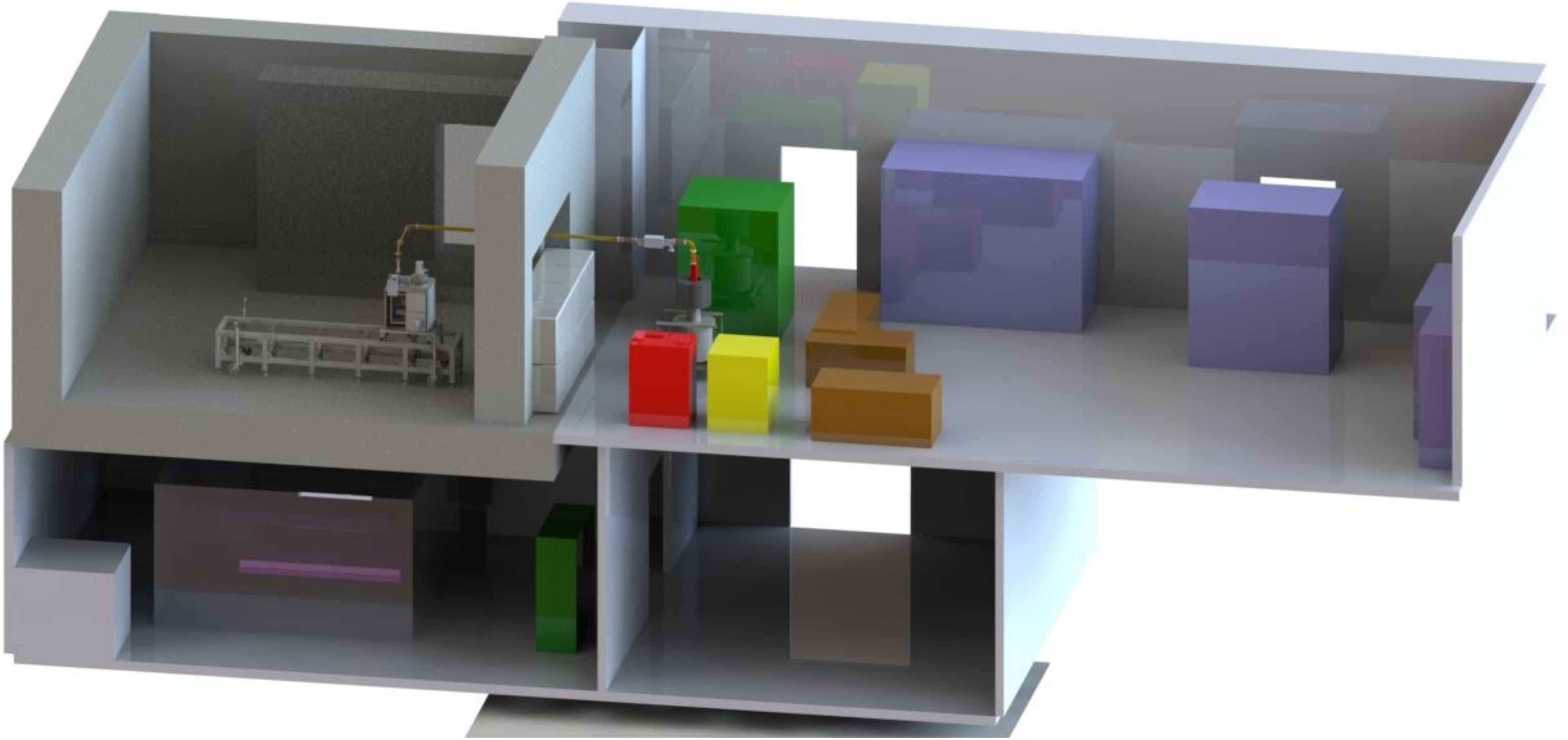




3. ½ Geometry with fields



Lab and Bunker space



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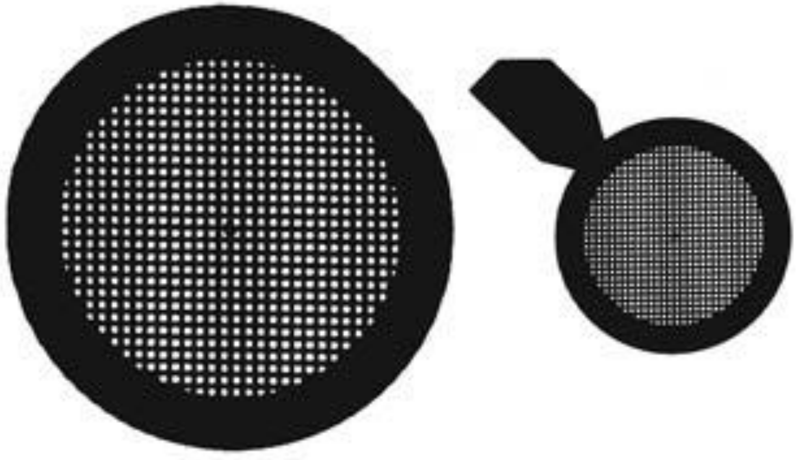
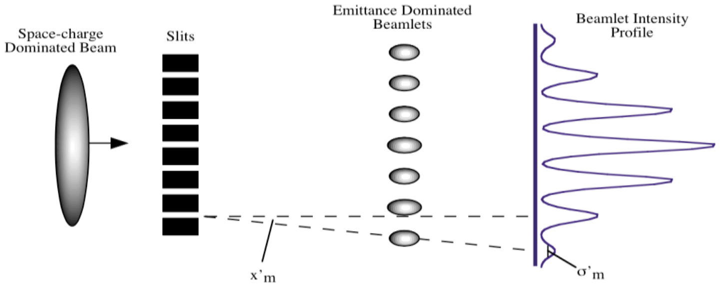
Future Directions + Outlook

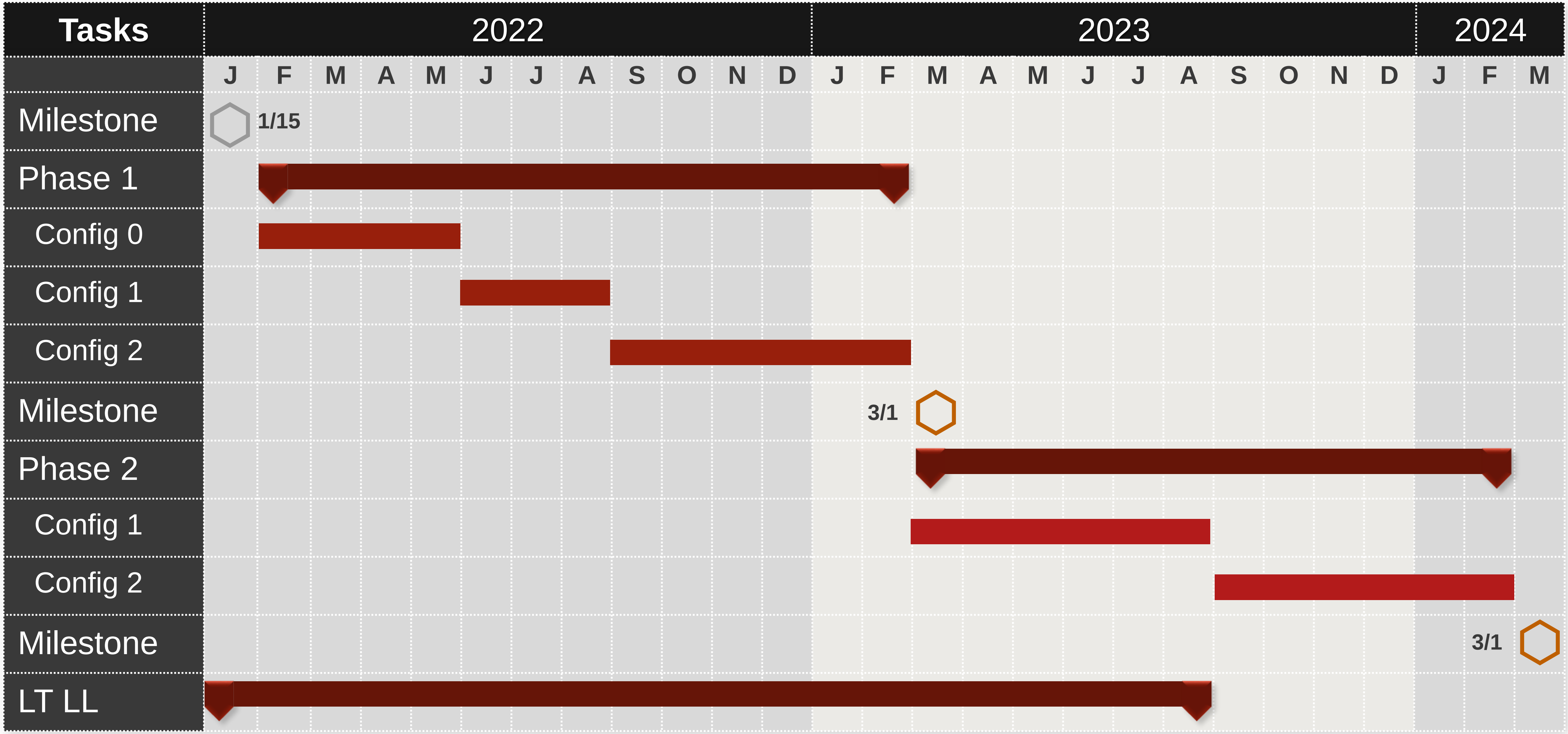
- Future phases after phase 3 include use for measurements and refinement for cathode measurements, temperatures down to 20K from the 40K phase 1-3 temperature goals, and xband cavity addition possibly for bunch length measurements

D. Marx et al. Phys. Rev. Accel. Beams 21, 102802 (2018).





Timeline Proposal



Conclusions

1. UCXFEL photoinjector needs stepping stone
2. Studies of high brightness cathodes in extreme conditions (low temperature, high field) necessary
3. CYBORG beamline test bed necessary for these studies progressing nominally

Thank You

Additional References

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