Commissioning a Cryogenic RF Photogun for Cathode Testing

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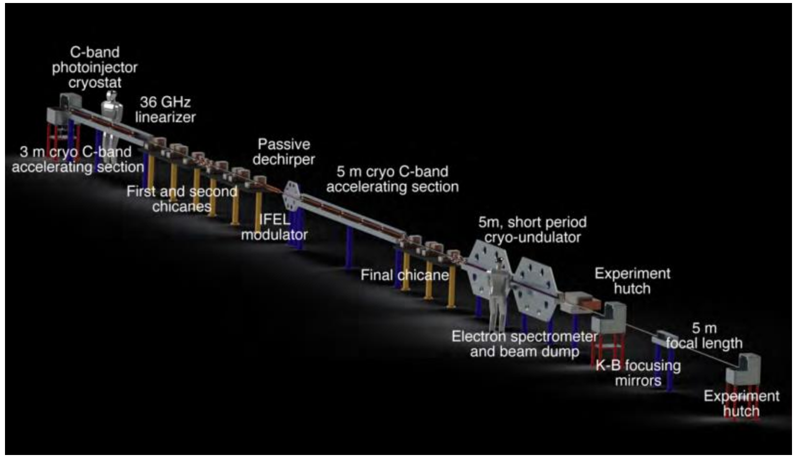
Outline of presentation

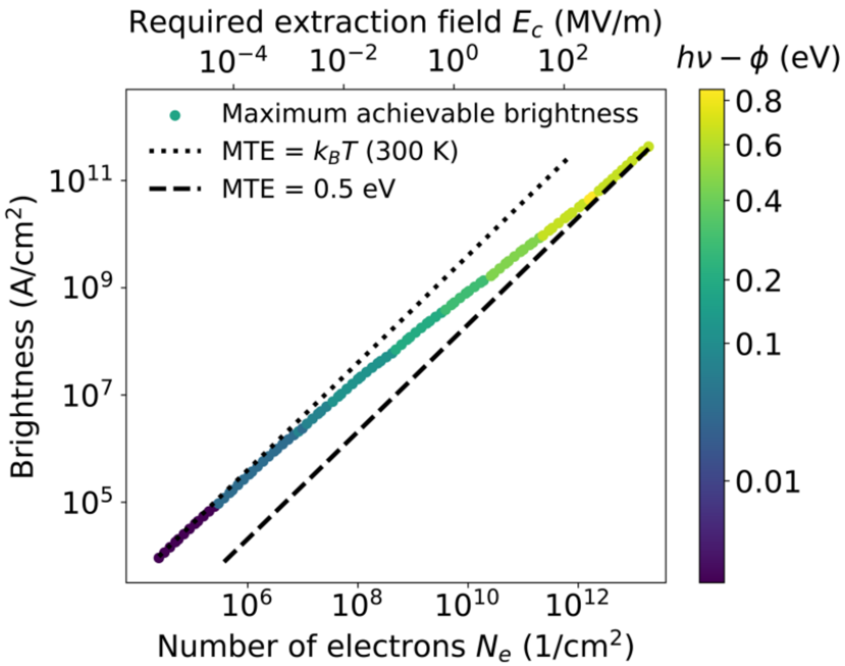
1. Motivation & Background
2. RF cathode test bed overview
3. CYBORG commissioning: cryogenics
4. CYBORG commissioning: RF power
5. Future
6. Conclusions

1) Motivation

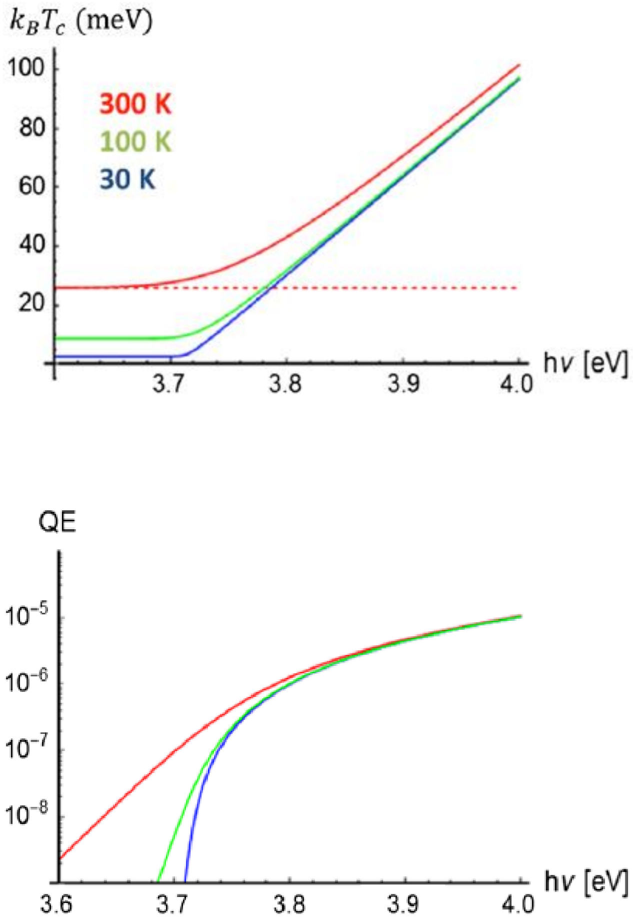
- To realize UCXFEL low MTE photocathode necessary
- 1D scaling for brightness with squared launch field and inverse T for near threshold emission
- Dedicated extremely high gradient cathode test bed > 120 MV/m in cryogenic temperatures < 100 K becomes advantageous



$$B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c}\left(E_0 \sin\varphi_0\right)^2$$



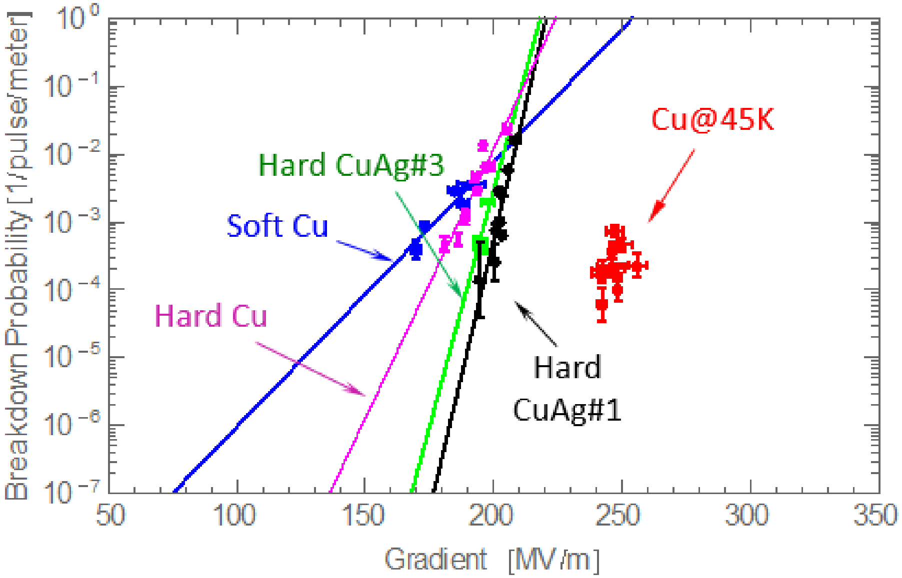
J. K. Bae, I. Bazarov, P. Musumeci, S. Karkare, H. Padmore, and J. Maxson, J. Appl. Phys. 124, 244903 (2018).

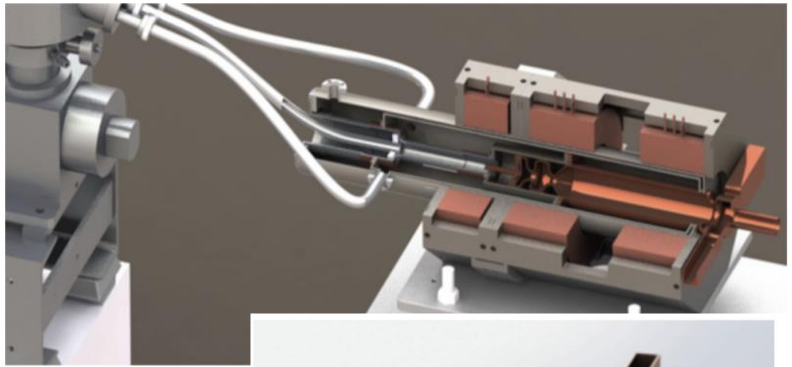


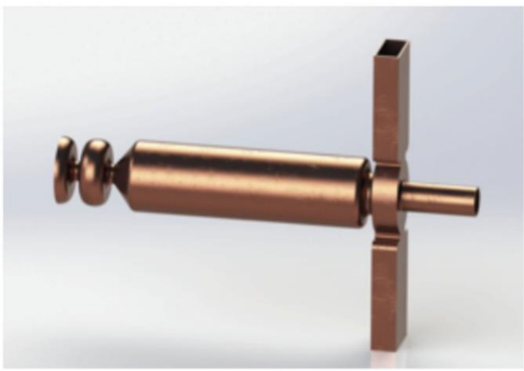
J.B. Rosenzweig et al., Nucl. Instrum. Methods Phys. Res. A, vol. 909, p. 224-228, 2018. `doi:10.1016/j.nima.2018.01.061`

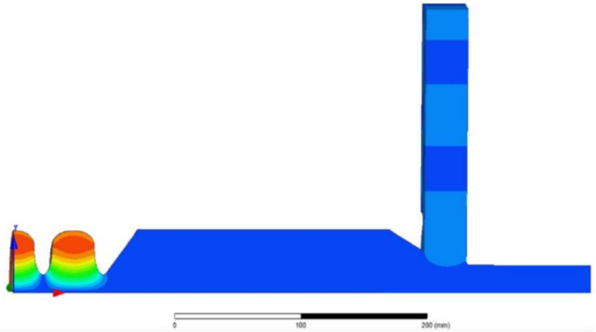
1) Background

- Broad interest in high gradient cavity development with focus on brightness
- Cryogenic breakdown reduction ⇒ higher accelerating gradients possible
- TopGun previous development in S-band
- More cryo manageable C-band
- Synergistic with additional concepts with broader applications
  - Cool Copper Collider linacs; FLASH cancer therapy, etc.









Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources
JB Rosenzweig, et al. - Physical Review Accelerators and Beams, 2019

Outline of presentation

1. Background
2. **RF cathode test bed overview**
3. CYBORG commissioning: cryogenics
4. CYBORG commissioning: RF power
5. Future
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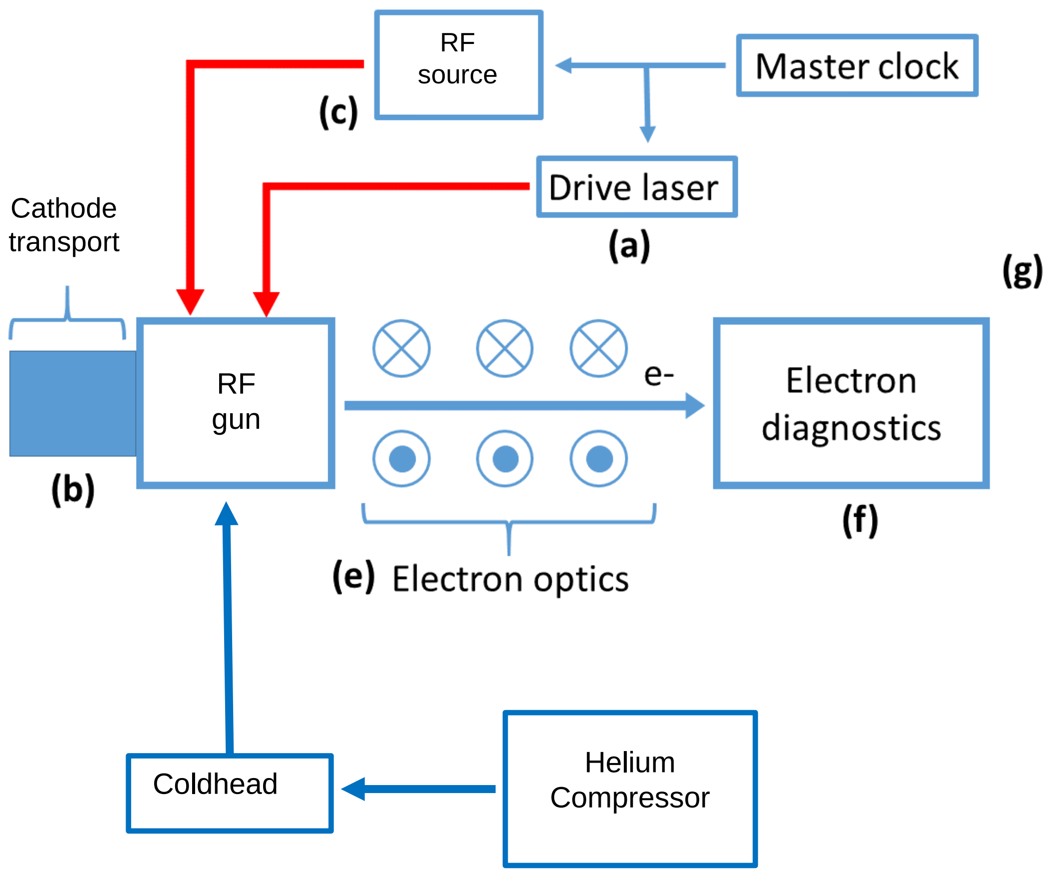
2) Test bed overview

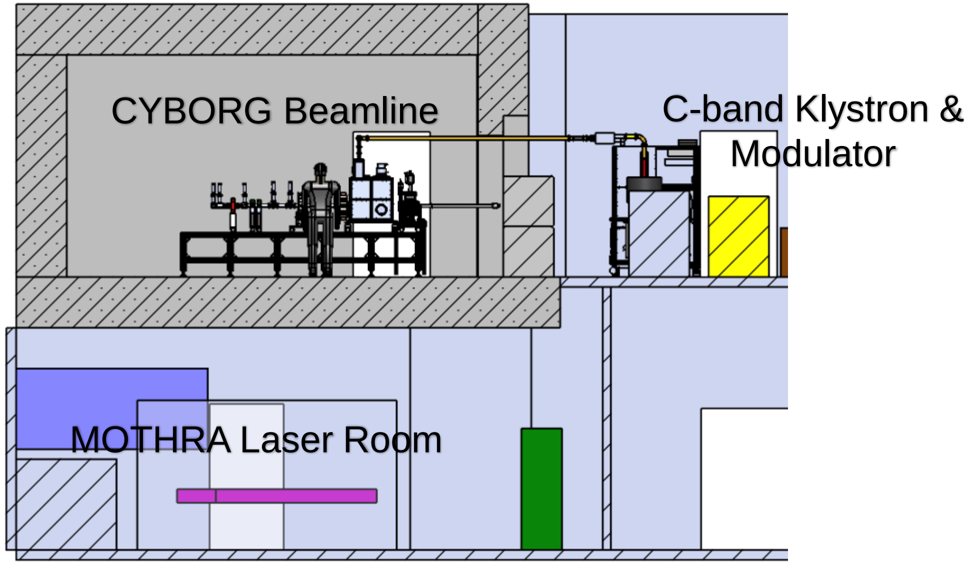
- Schematic for simplest test bed for measuring cathodes using CrYogenic Brightness Optimized Radiofrequency Gun (CYBORG)

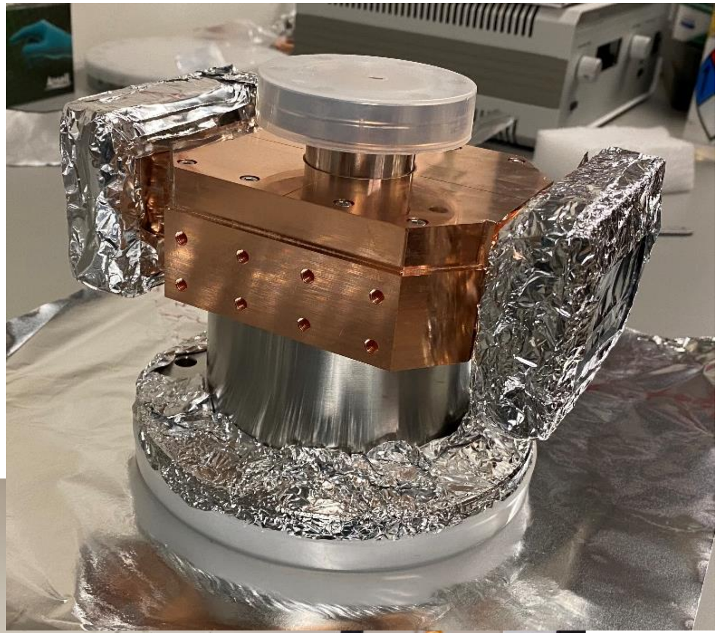
1. Cathode testing at cryogenic temperatures with high gradients:
   1. Dedicated high gradient RF test stand for diagnostic development
   2. Cryo cathode load-lock development
2. Pathway to record high gradients for improved brightness:
   1. Integrated infrastructure template
   2. RF prototype, black plane etc.
   3. Cryogenic dark current and breakdown

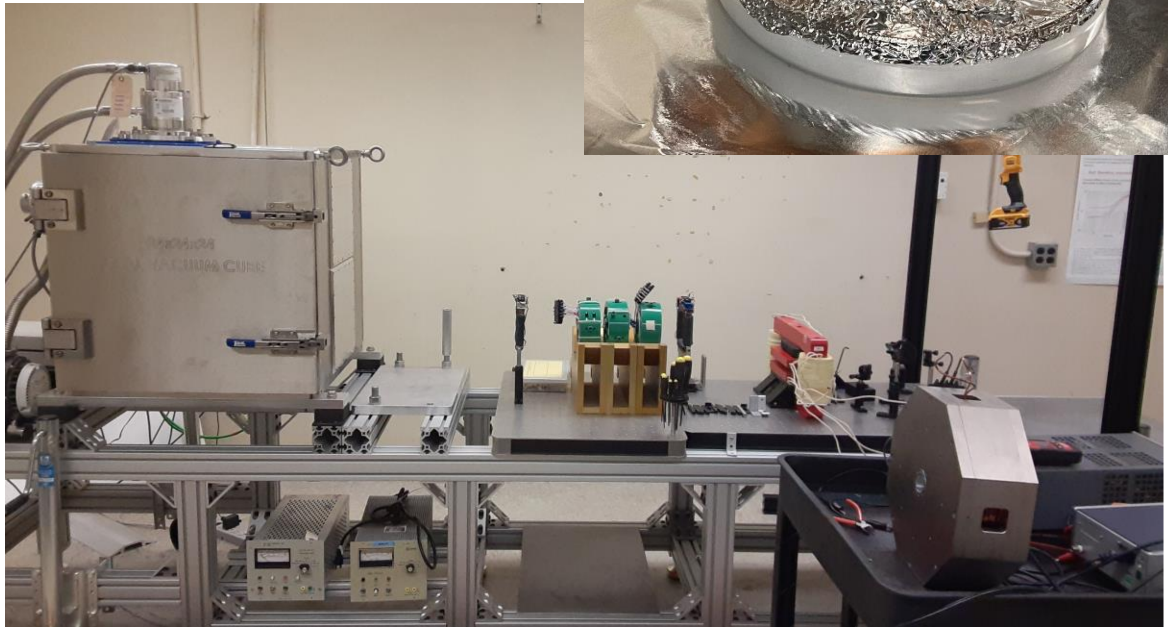


2) Lab Overview

- CYBORG beamline not trivial task
- Robust program at Multi-Option Testing for High-field Radiofrequency Accelerators (MOTHRA) laboratory (right and below) to establish knowledge basis
- Suitable for cryogenics testing; C-band infrastructure development; low energy (single MeV) beamline for cathode studies

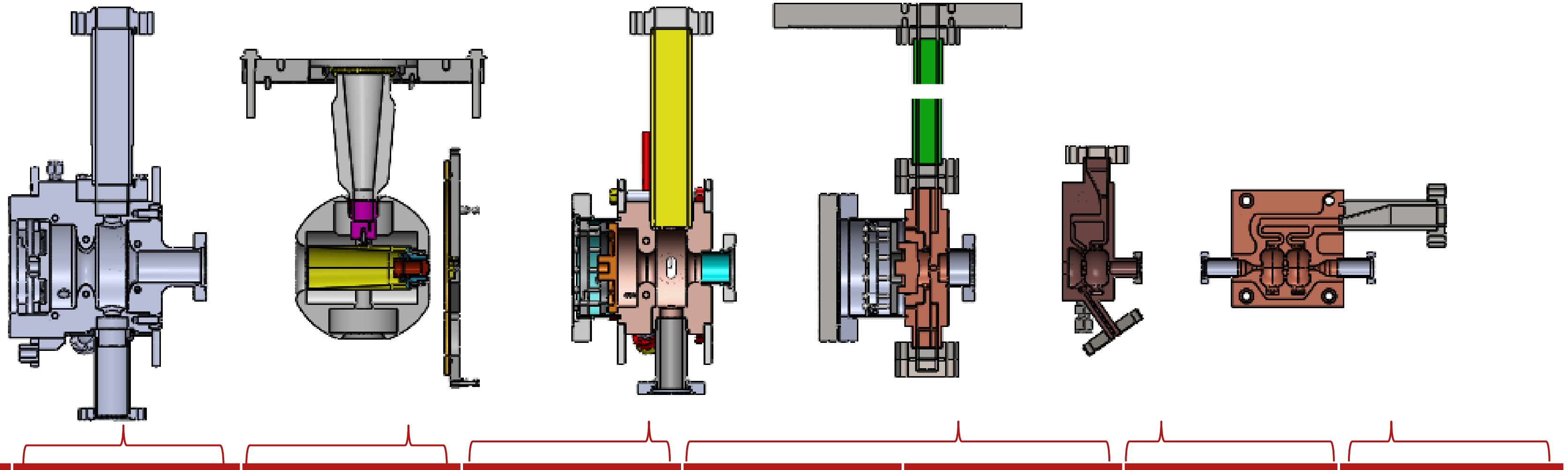






2) Gun Comparisons

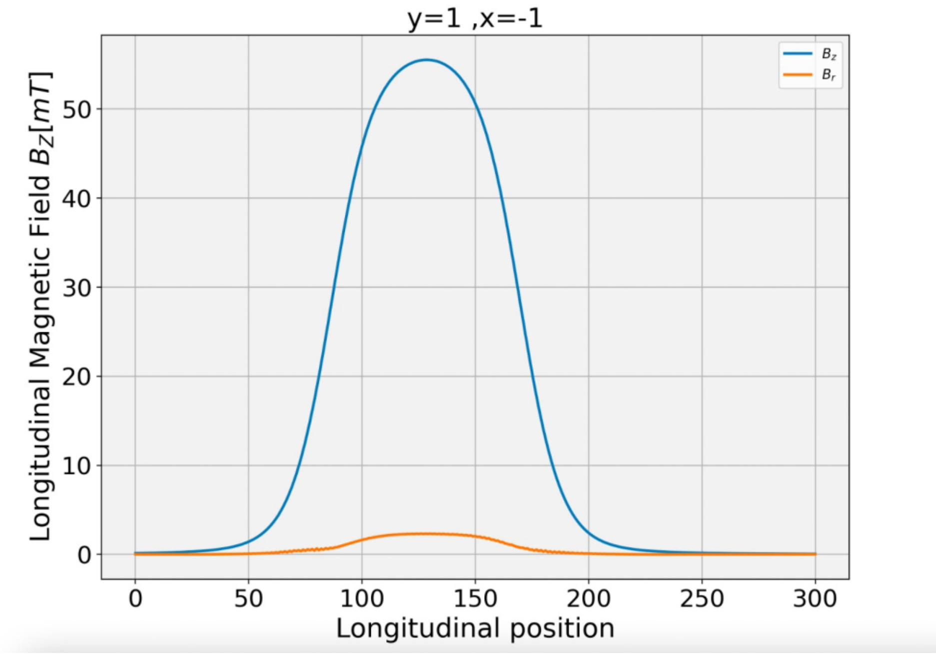
- During design and production of CYBORG influence taken from existing photoguns
- Compared here along with two related experiment designs
- Highlights also CYBORG design phases

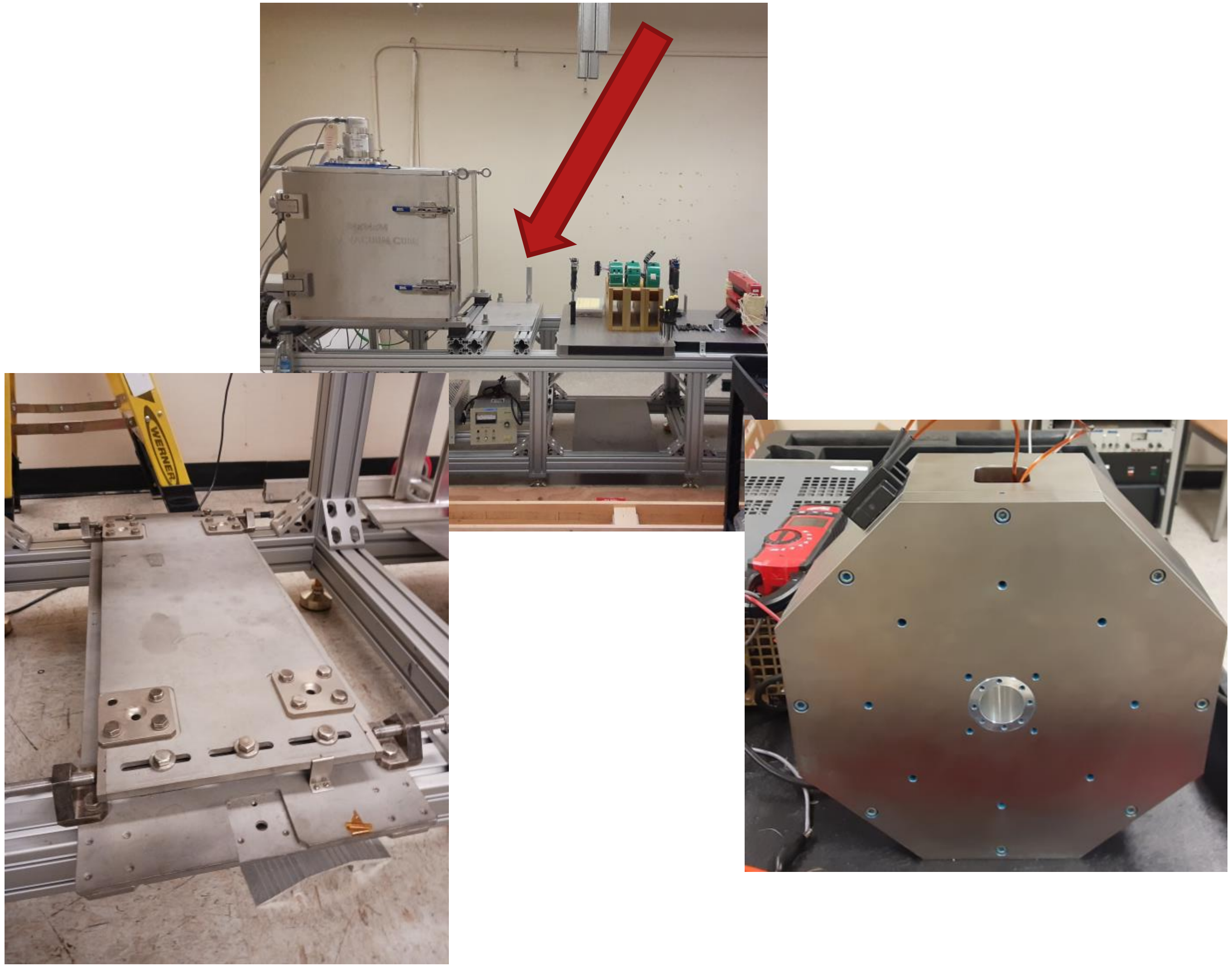


	PEGASUS Gun	Cornell Cryogun	FERMI Gun	CYBORG Phase 1	CYBORG Phase 2	CARIE Gun	Breakdown Test Cavities
Temp	295K	295K – 45K	295K	295K – under 65K	295K – under 65K	*295K*	< *77K*
Cathode	Load lock	Load lock	Demountable backplane	*Demountable backplane*	*Load lock*	*Cu backplane*	-
Accelerating Field	120 MV/m RF	10 MV/m DC	120 MV/m RF	*120 MV/m RF*	*120 MV/m RF*	*>250 MV/m RF*	*>250 MV/m RF*
Frequency	S-band	-	S-band	C-band	C-band	C-band	C-band
Laser Illumination	Off-axis	Off-axis	Off-Axis	On-axis	On-axis	Off-axis	-

2) Diagnostics

- Beamline components existing with mounts in progress manufacturing and modifying

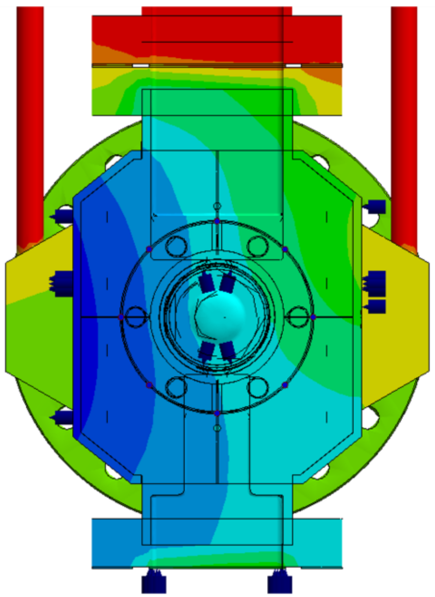


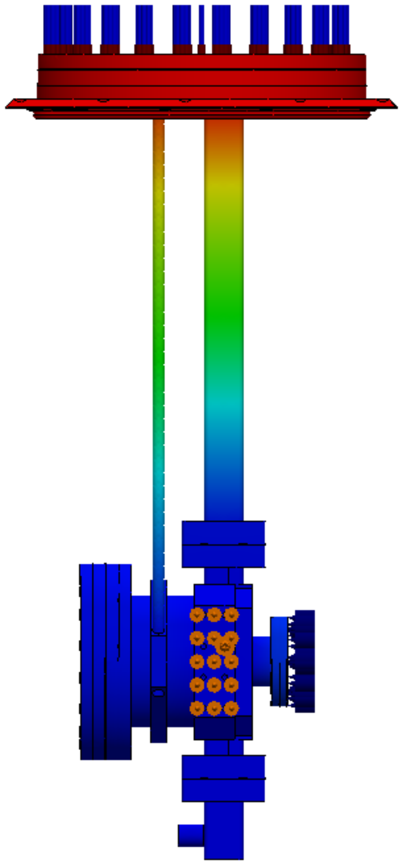


Outline of presentation

3) Thermal Balancing

- Primary initial and ongoing testing of CYBORG examining thermal balancing
- Full power RF power into gun requires additional radiation shielding underway now
- Accounting of major heat leaks below with simulation of temperature gradients

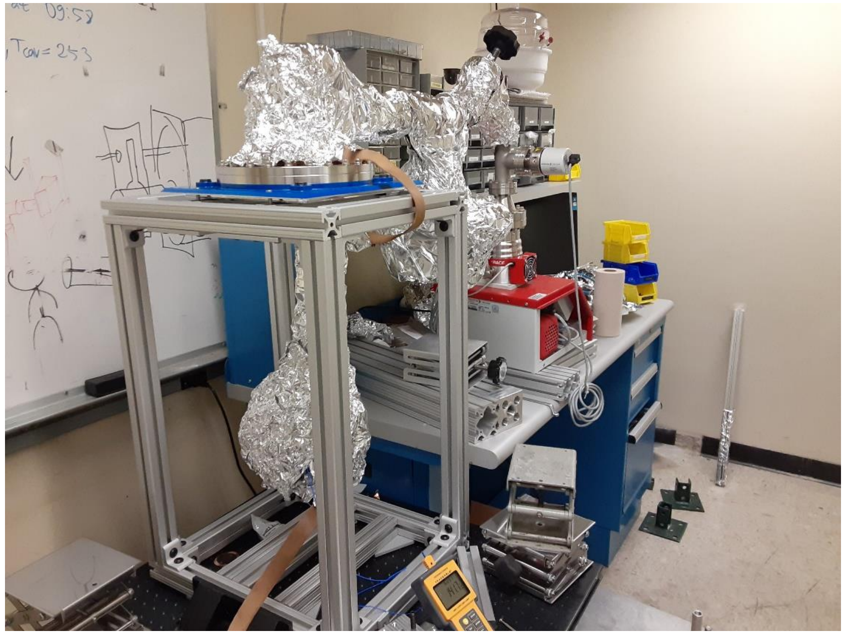




Description	Materials	Equivalent Area	Equivalent Power
6” plug flange	Stainless steel (CF flange), edge welded bellows	436 mm^2	< 1 W
2.75” downstream flange	Stainless steel (CF flange), edge welded bellows	85 mm^2	< 1 W
Waveguide	Stainless steel	588 mm^2	Approx 10 W
Supports	Stainless steel, aluminum, G10	TBD	TBD
Diagnostic probes	Copper wiring of various gauges	50 mm^2	5 W
Alignment rails	TBD	TBD	TBD
Radiation (MLI shielded)	-	25000 mm^2	< 1 W
RF pulse heating	-	-	variable
Pumping on dummy side	-	-	-

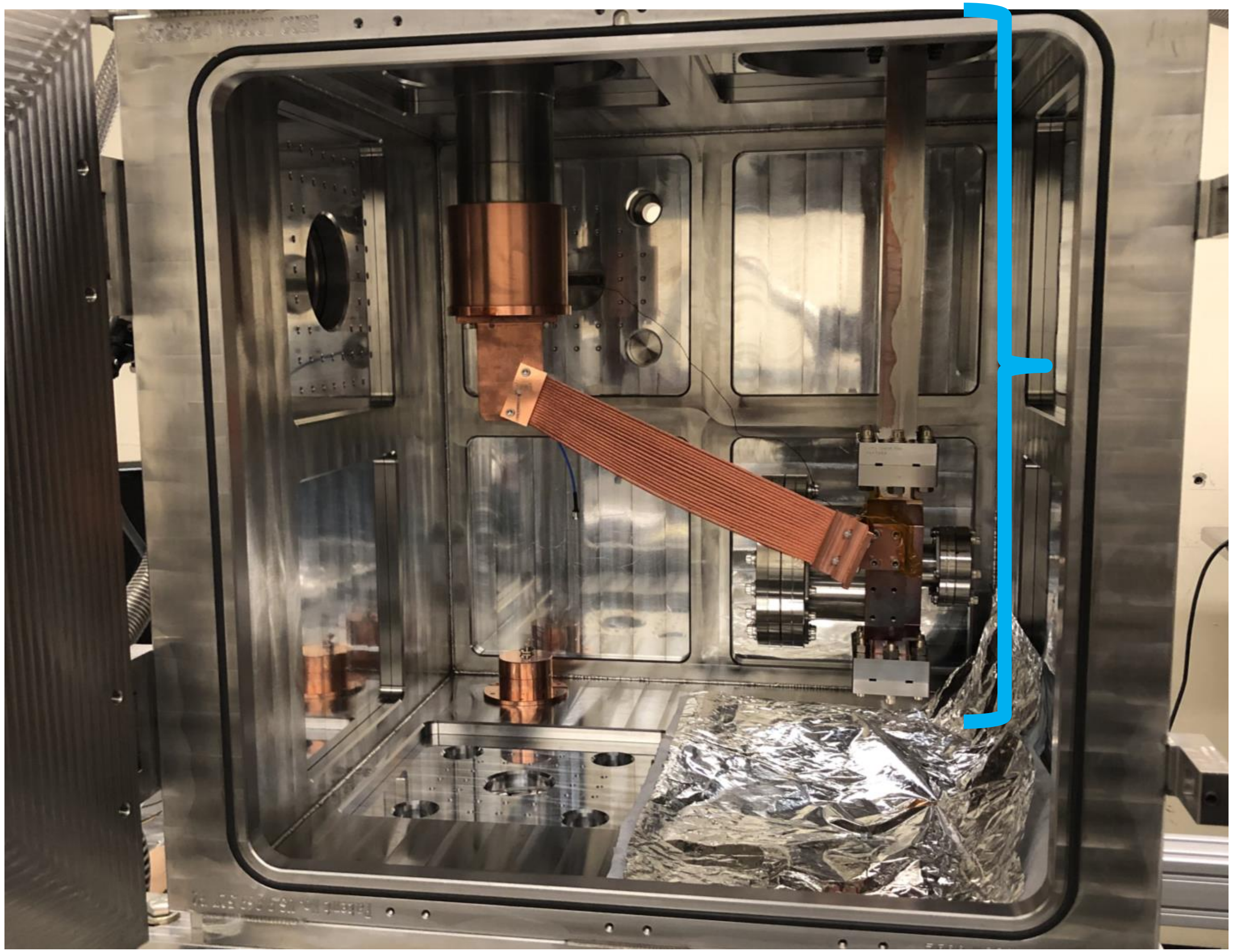
3) CYBORG setup

- Drop down gun section in external assembly frame (right)
- Successful bake with rubber heater tape between 120-150 C (below)
- MLI rated for 110 C, in situ possibility if higher and sufficient aluminum covering
- 10^-8 torr on turbo pump sufficient before long term ion pump turn on and addition of NEG pump



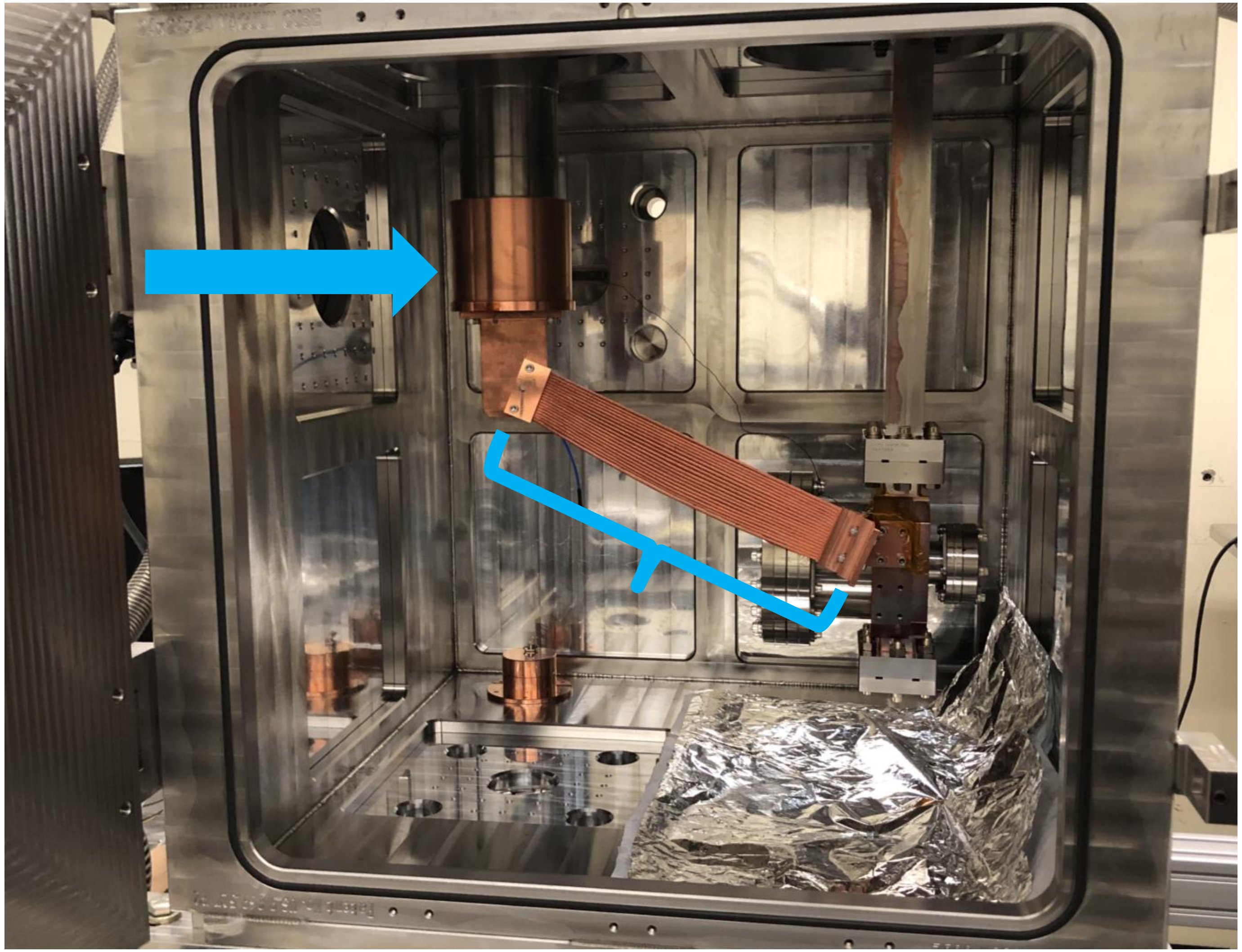
3) Thermal Balancing study part 1

- Drop-down section placed into gun cryostat to right



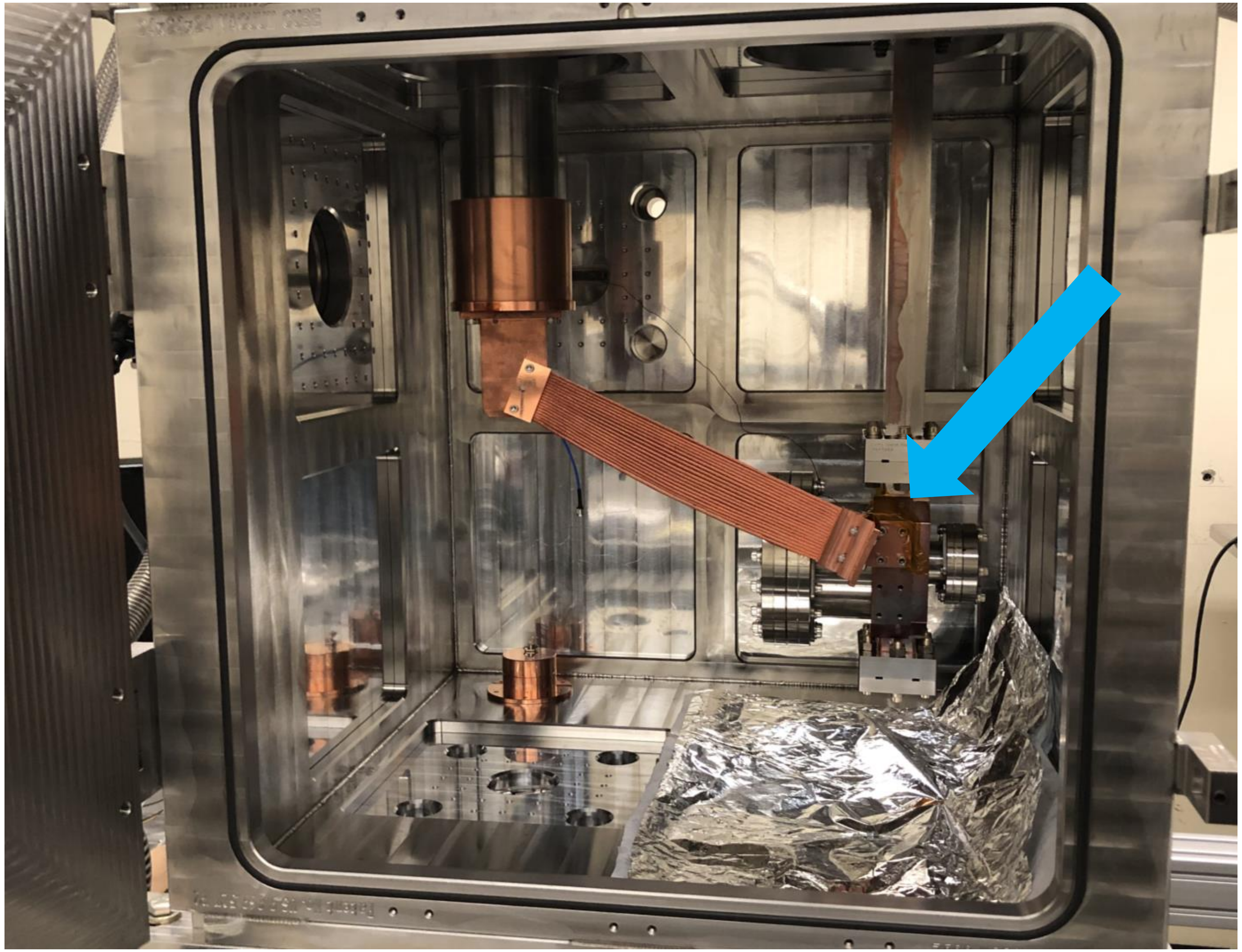
3) Thermal Balancing study part 1

- Drop-down section placed into gun cryostat to right
- Connected via flexible thermal braid to cryocooler



3) Thermal Balancing study part 1

- Drop-down section placed into gun cryostat to right
- Connected via flexible thermal braid to cryocooler
- Location of temperature sensor outside gun cavity on cooling face
- Note: Large volume of chamber necessitated for ease of assembly and future compatibility with load-lock and possible in cryostat solenoid



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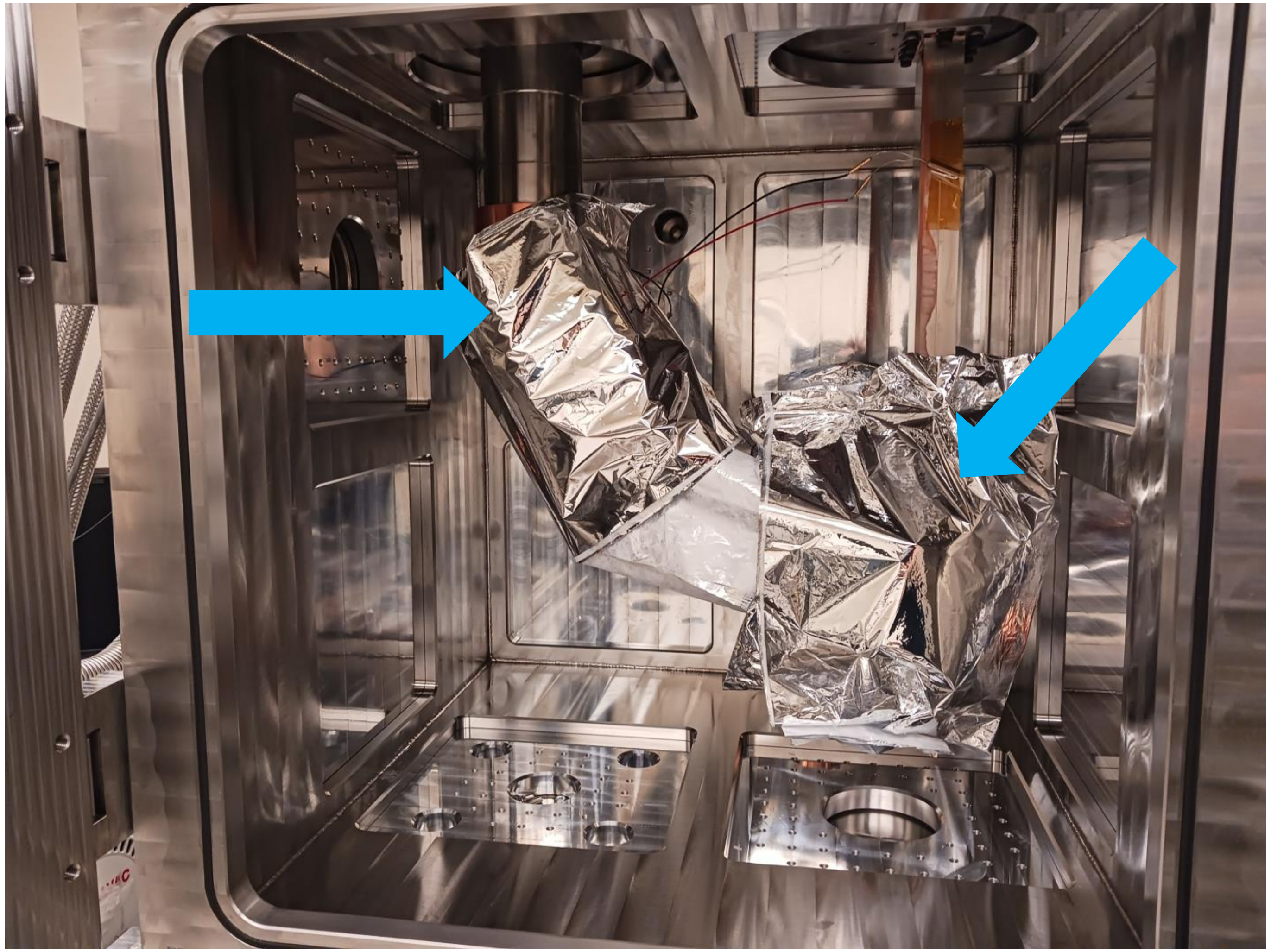
- Drop-down section placed into gun cryostat to right
- Connected via flexible thermal braid to cryocooler
- Location of temperature sensor outside gun cavity on cooling face
- Note: Large volume of chamber necessitated for ease of assembly and future compatibility with load-lock and possible in cryostat solenoid
- Partially wrapper in multi-layer insulation for radiation shielding

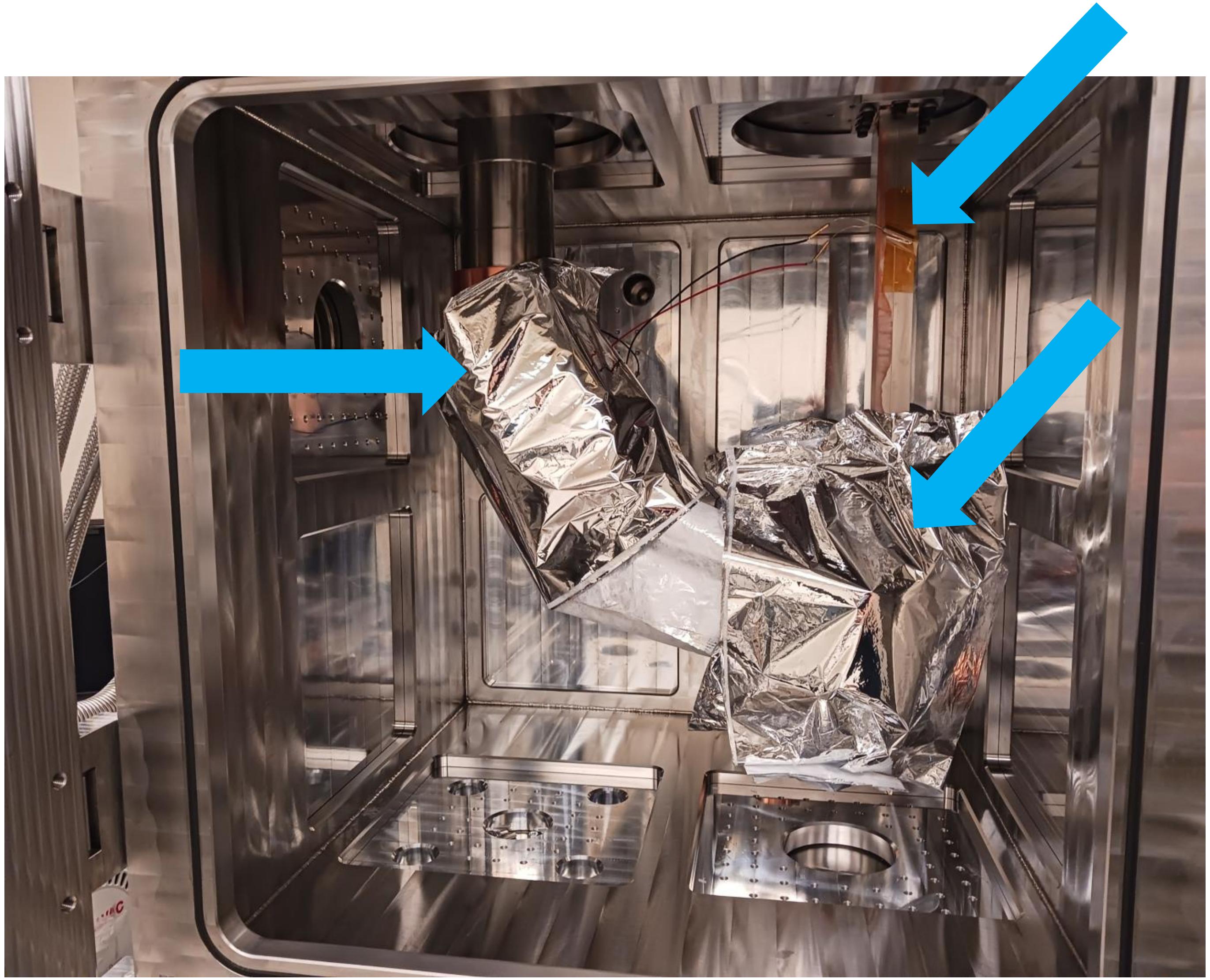
3) Thermal Balancing study part 1

- Location of additional cryocooler temperature sensors



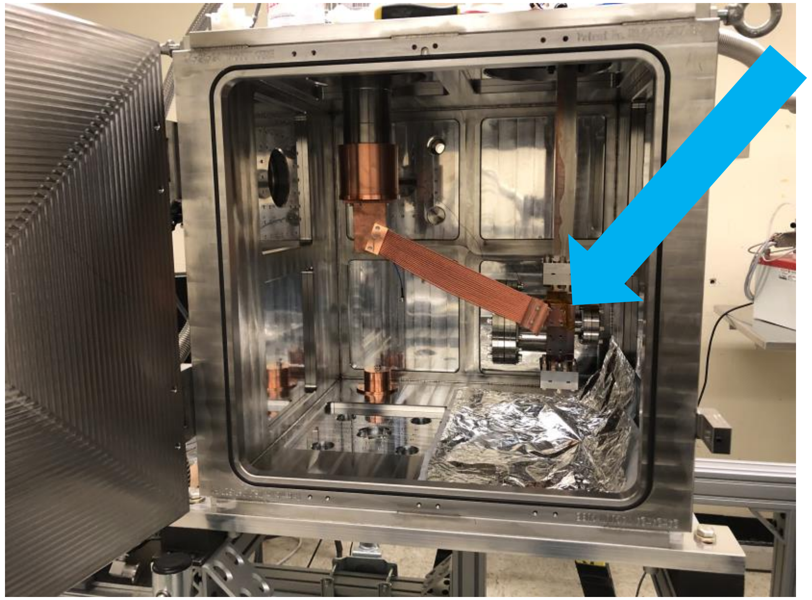
3) Thermal Balancing study part 1

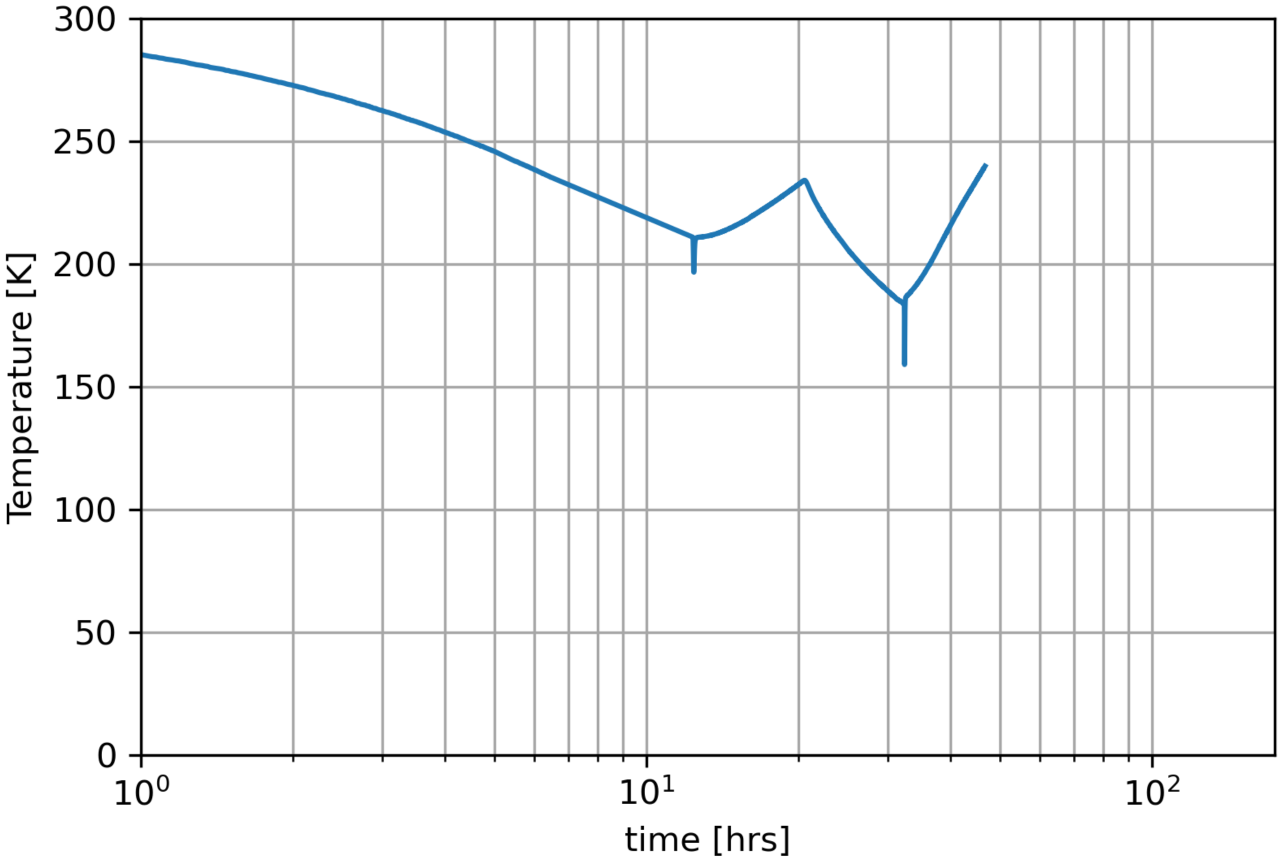
- Location of additional cryocooler temperature sensors
- Resistive heater location
- Necessary for adjusting temperature and heat up of gun in reasonable time for access



3) Thermal Balancing study part 1

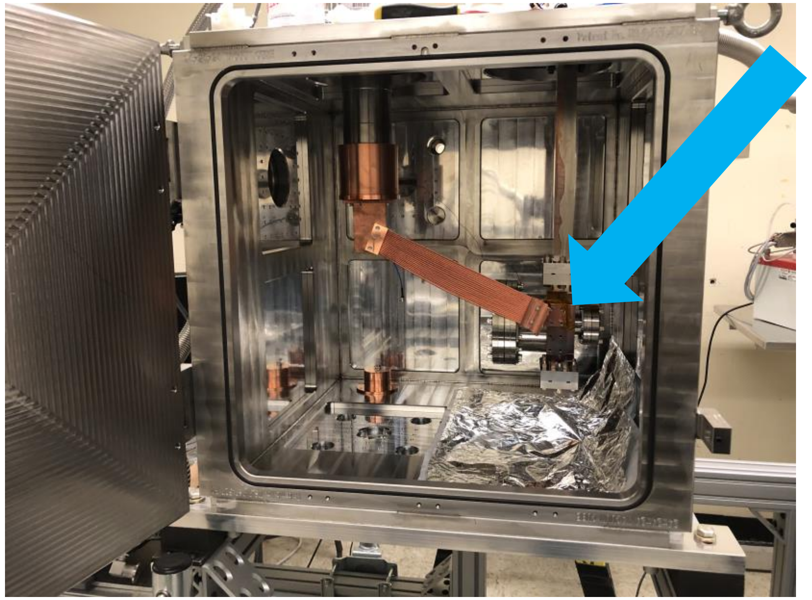
- Preliminary long cooldown testing
- Minimal MLI around gun

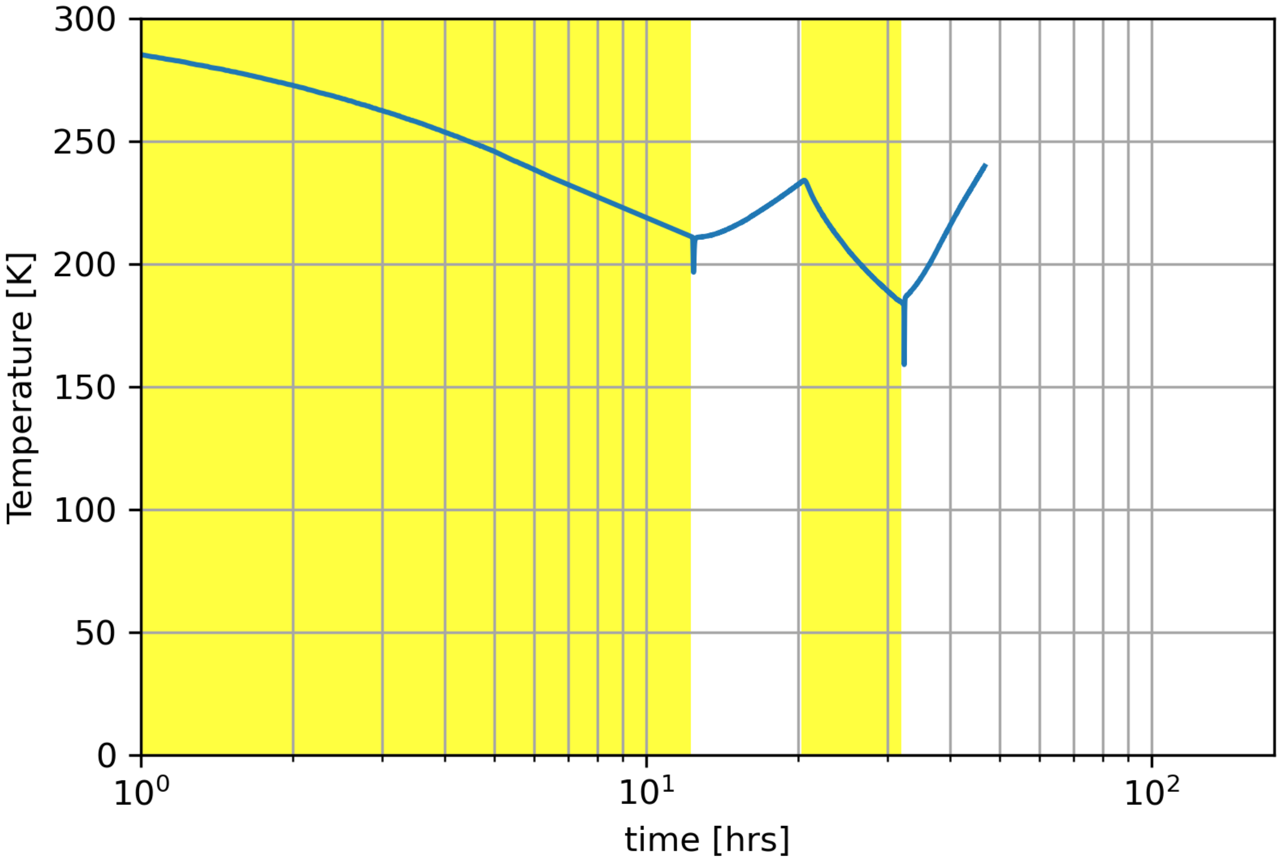




3) Thermal Balancing study part 1

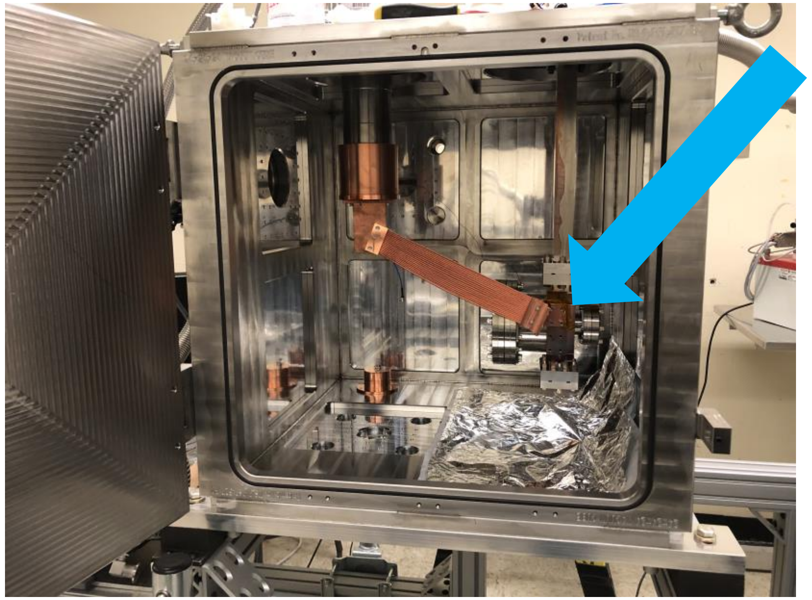
- Total time on: 24.25 hrs
- 17 hrs => 184 K

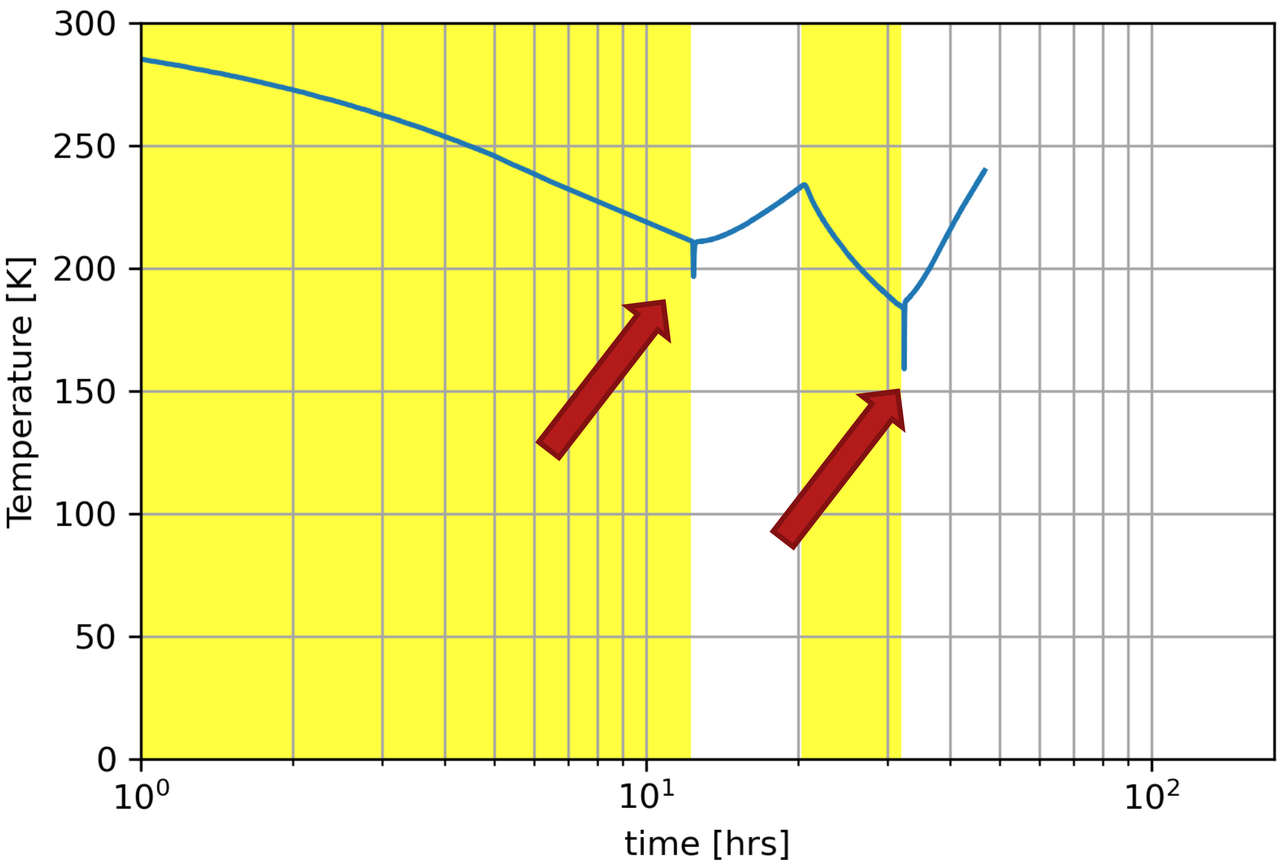




3) Thermal Balancing study part 1

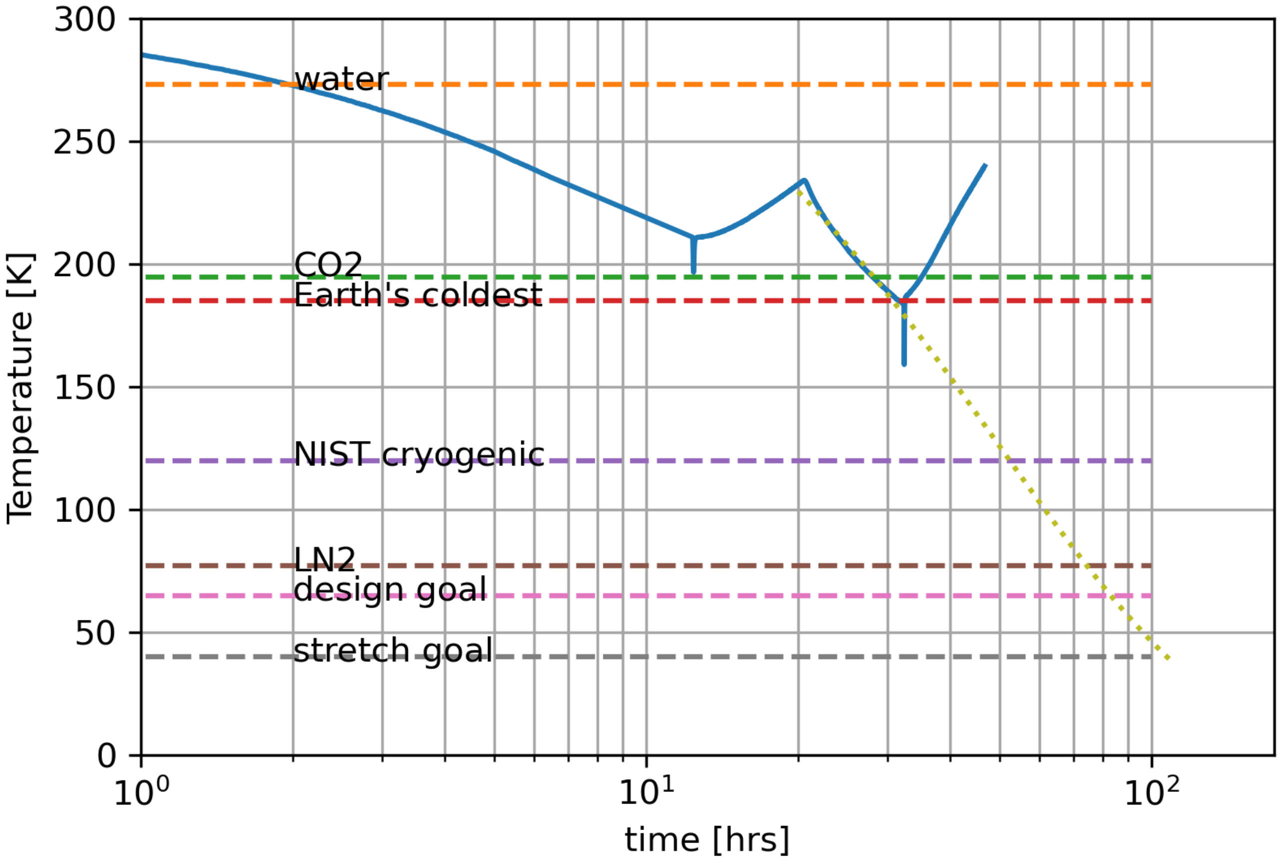
- Total time on: 24.25 hrs
- 17 hrs => 184 K
- Thermalization drop at gun => min of 159 K





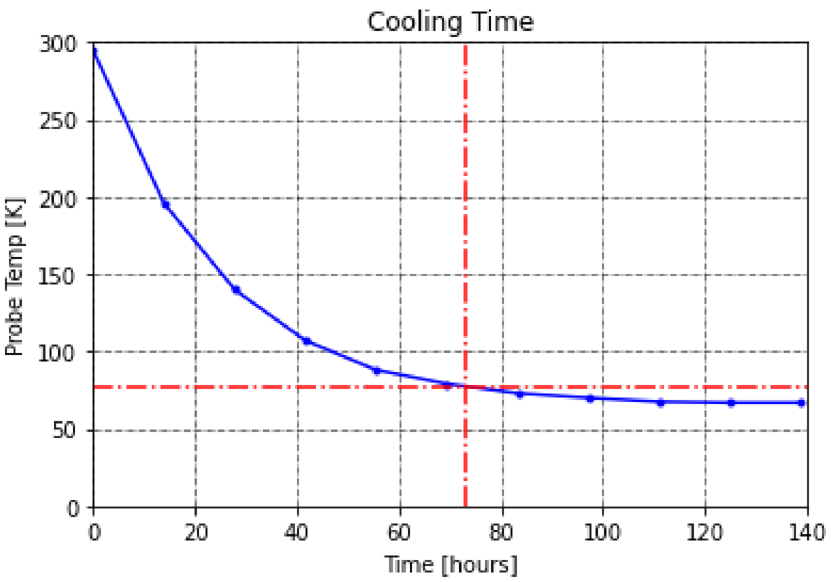
3) Thermal Balancing study part 1

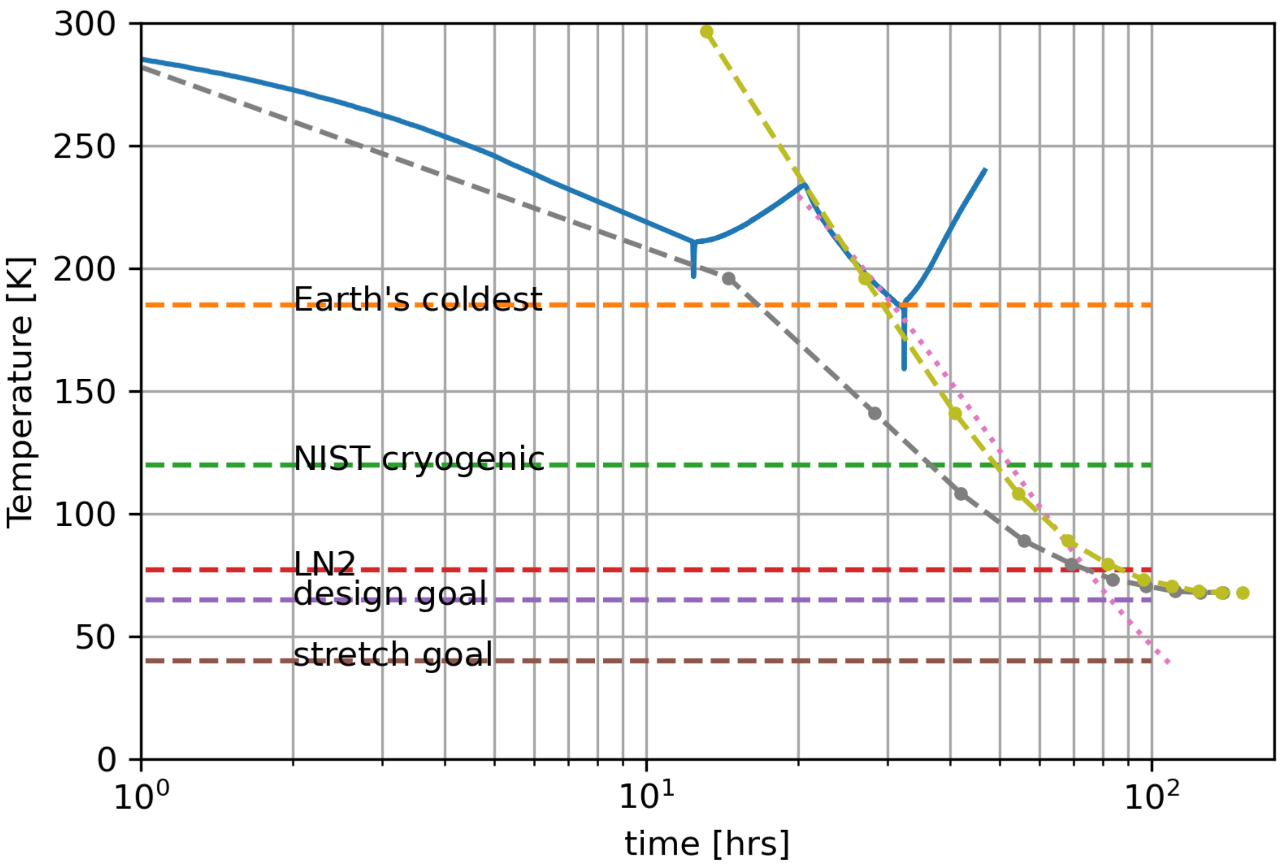
- Addition of certain temperature landmarks
  - Coldest naturally occurring place on earth, definition of cryogenic according to NIST, etc.



3) Thermal Balancing study part 1

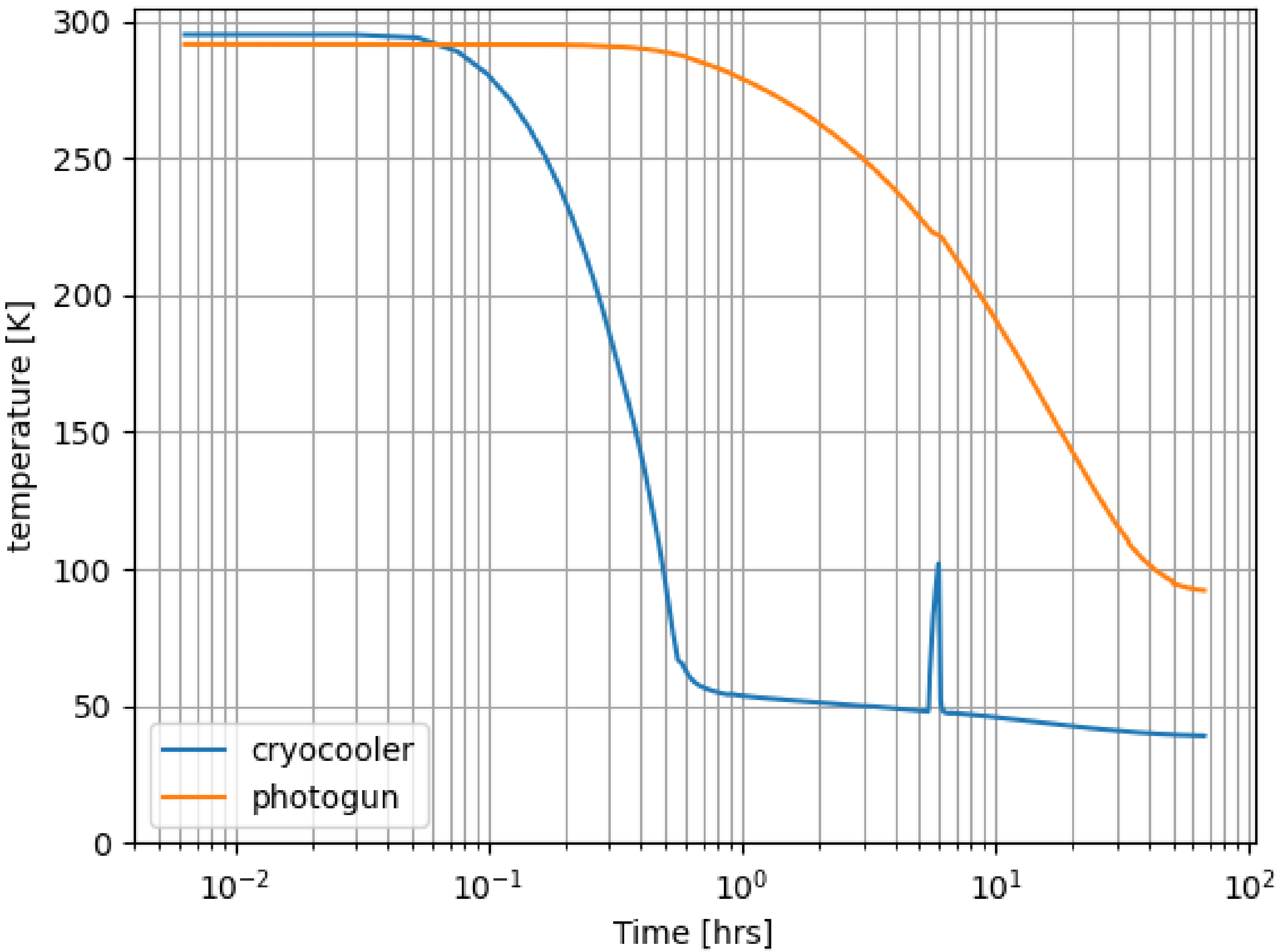
- Addition of certain temperature landmarks
  - Coldest naturally occurring place on earth, definition of cryogenic according to NIST, etc.
- Comparison with simulation
- Long projection 140 hrs cooling time to design goal of 65 K
- Stretch goal of 45 K operation not possible here
- Heat leak estimate possible





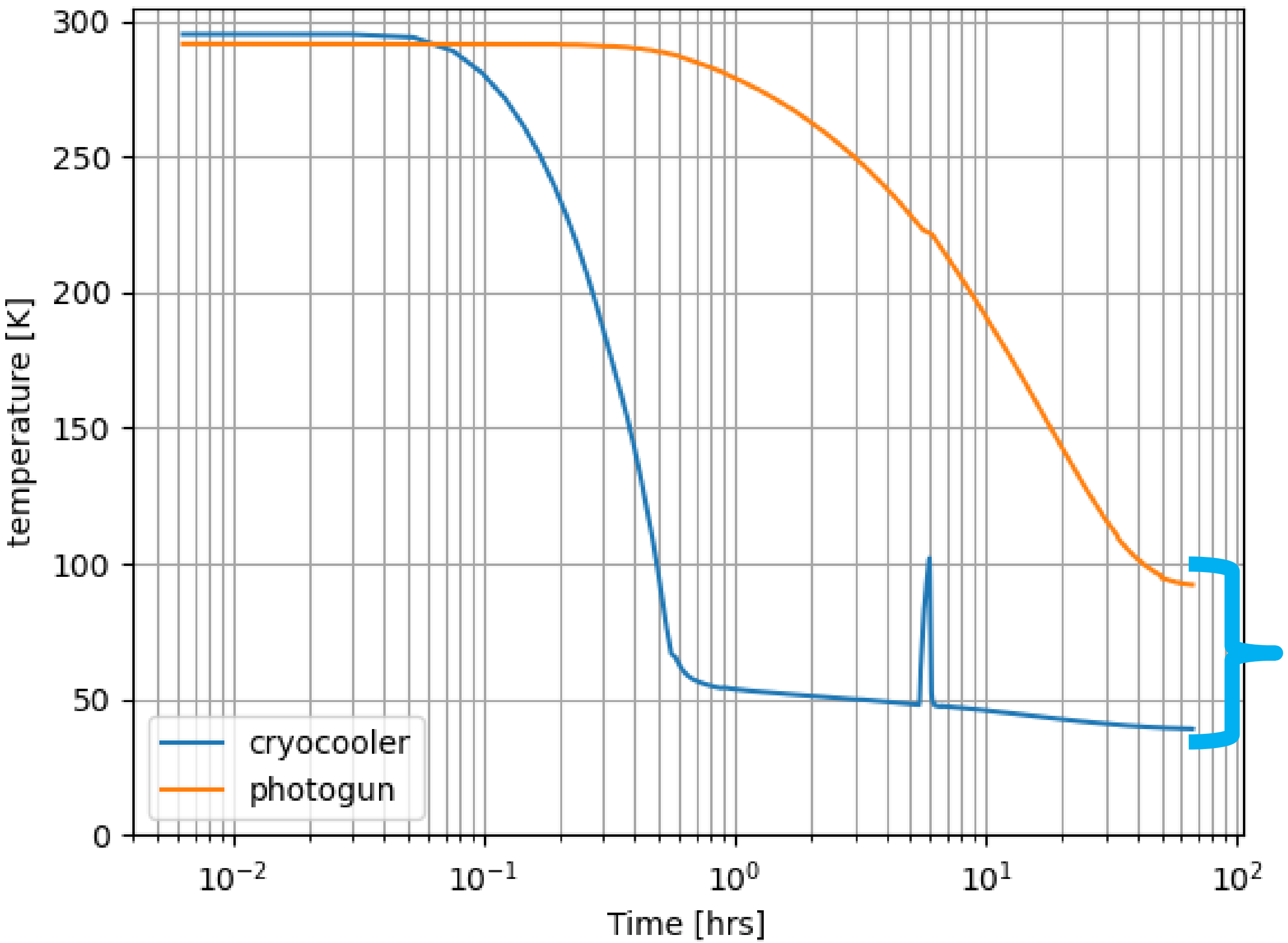
Thermal Balancing study part 2

- Longer term multi day cooling
- MLI coverage over >75% of cold area
- Gun down to 92 K & cold head down to 39 K



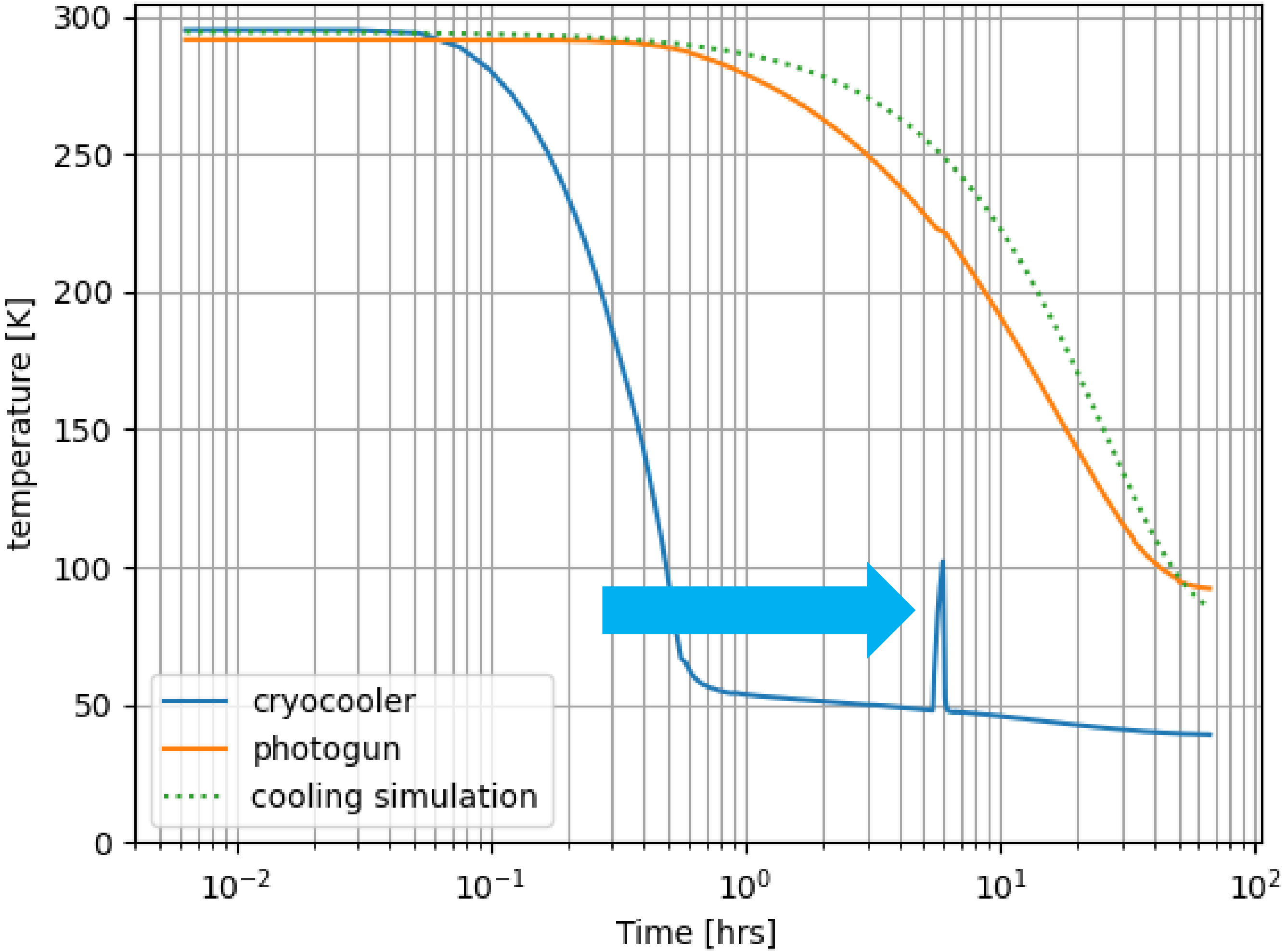
Thermal Balancing study part 2

- Longer term multi day cooling
- MLI coverage over >75% of cold area
- Gun down to 92 K & cold head down to 39 K
- MLI sufficient for stopping absolute radiation heat leak
- Thermalization/temperature gradient between cryocooler and gun more notable
- Significant room for improvement
- Improved conductance of thermal braid connection underway



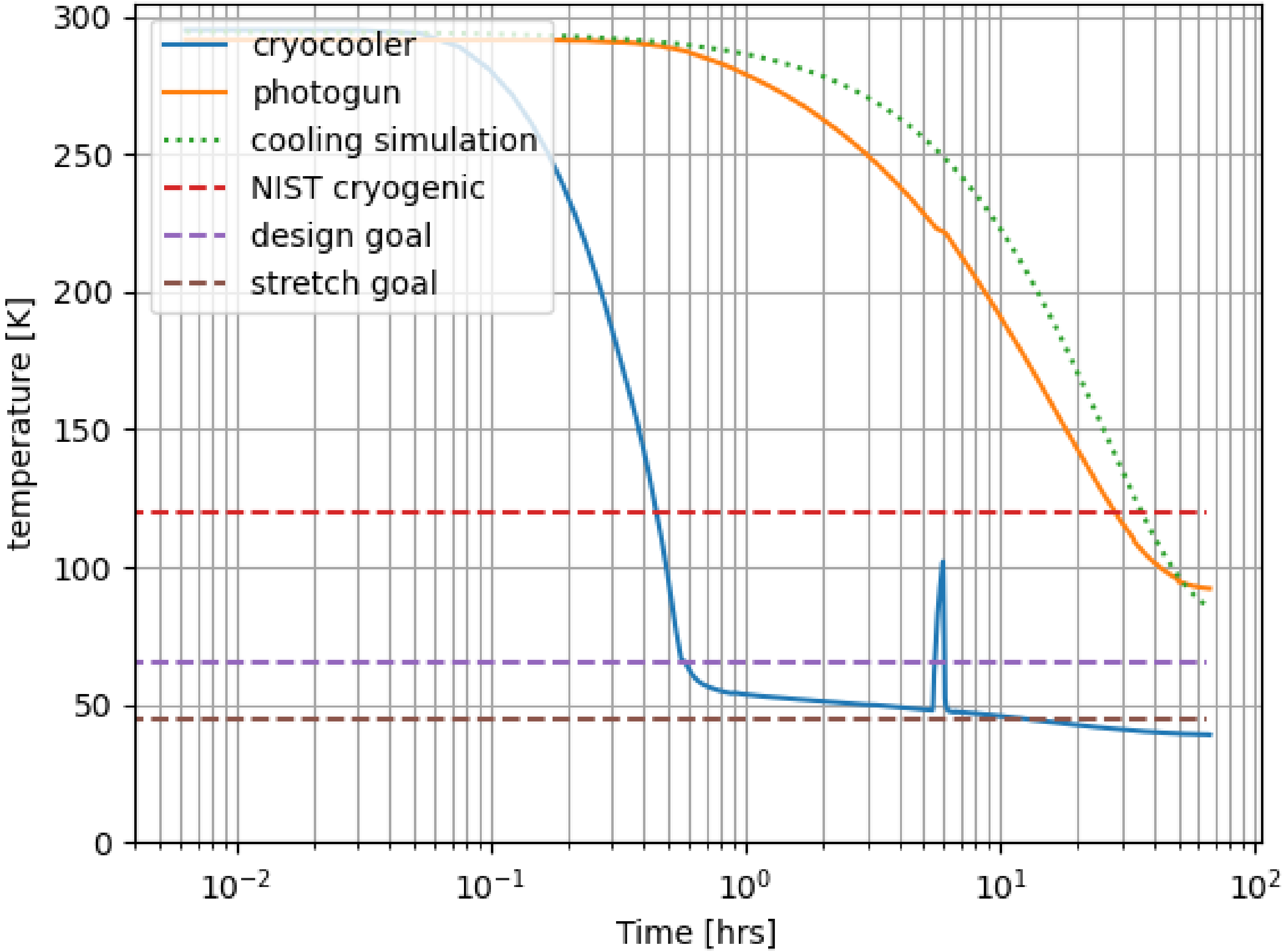
Thermal Balancing study part 2

- Comparison with cooling simulation shows significant improvement of cool down speed from previous iteration
- Attempted to observe same thermalization drops after first cool down by turning off cryocooler
- Extra stability from insulation perhaps



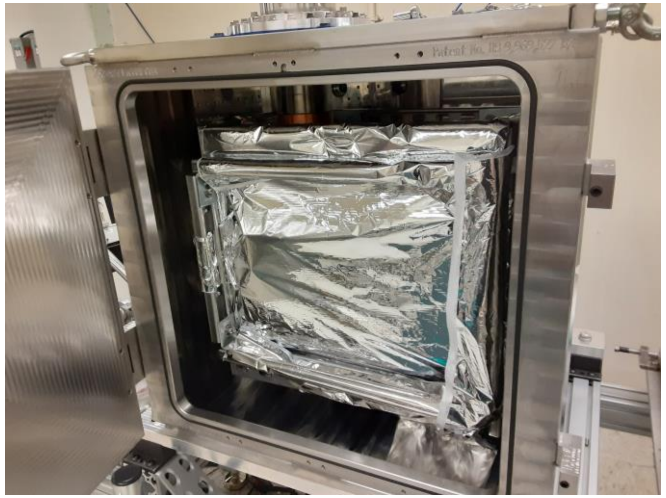
Thermal Balancing study part 2

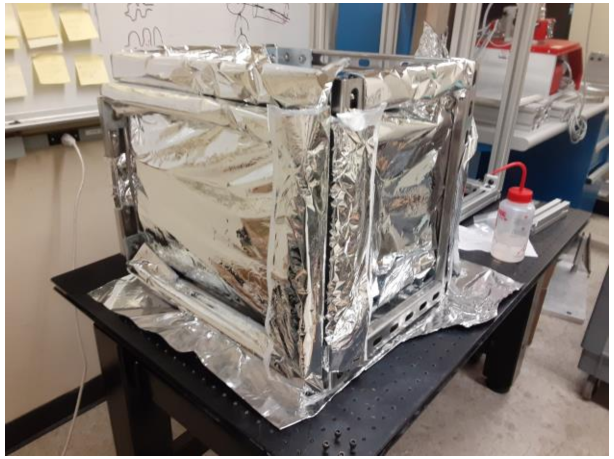
- Comparison with cooling simulation shows significant improvement of cool down speed from previous iteration
- Added some of the temperature milestones from before

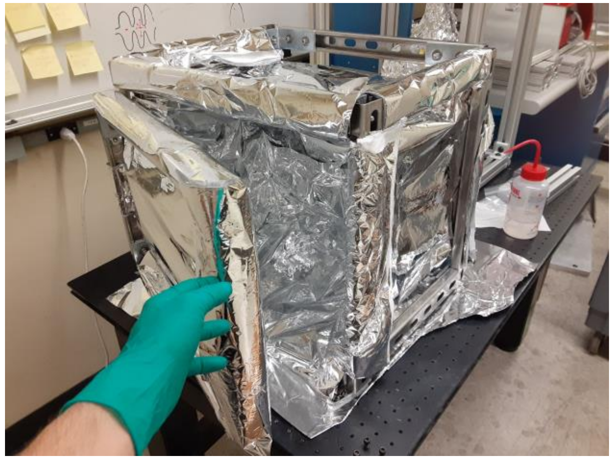


Additional Cryogenics

- If necessary additional layer of MLI can be added
- Only useful if thermally isolated from inner layer and cryostat wall, proved to be difficult in previous tests (right)
- Note door for easier access to sample volume (below)







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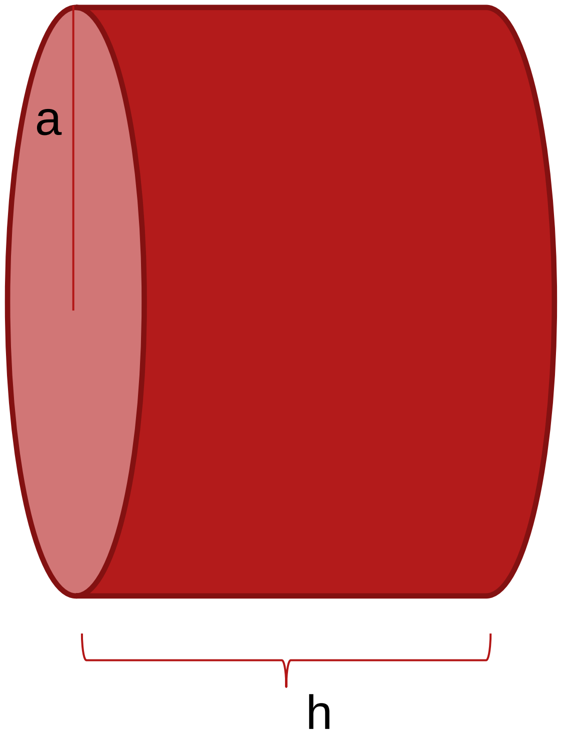
4) RF Theory

- Practical figures of merit for evaluating RF gun performance necessary
- Quality factor, conversion efficiency of RF to beam, efficiency of energy storage, shunt impedance, etc.
  - Most if not all improved at cryogenic temperatures
- Also consider mechanical issues such as deformation and existence of higher order modes in the structures
- Consider Q and coupling beta for CYBORG
- Profoundly dependent on temperature



$$Q = \frac{\omega U}{P_d}$$

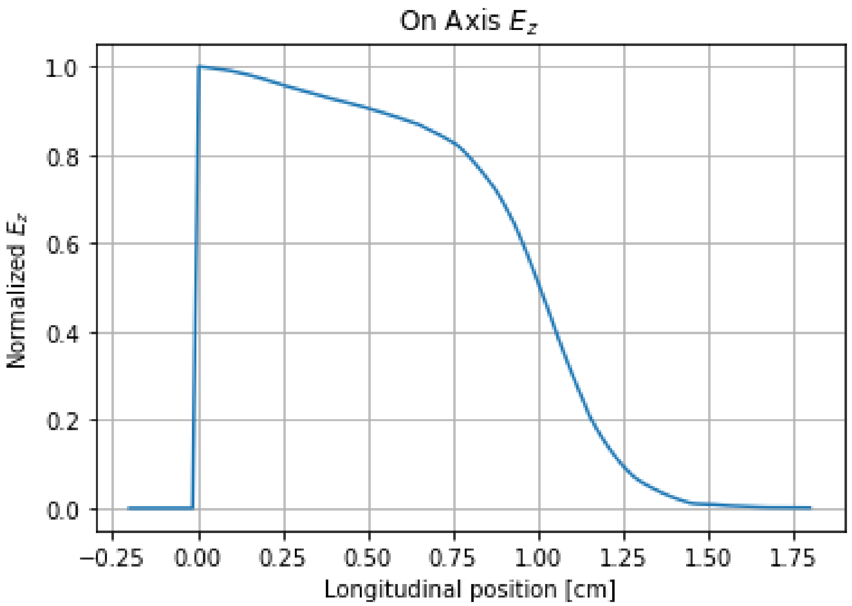
$$Q = \frac{\chi_{01}\eta}{2R_s}\frac{1}{1+a/h}$$

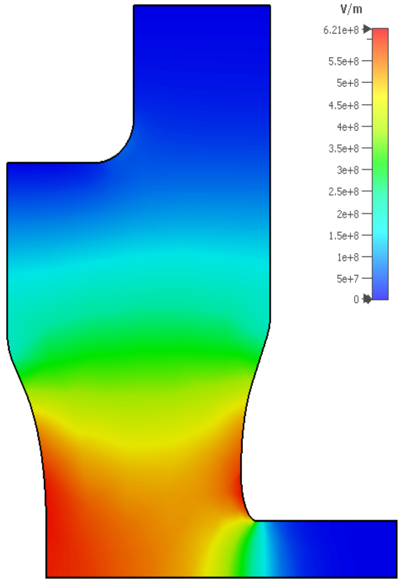
$$\beta = \frac{power\ loss\ in\ ext.cct}{power\ loss\ in\ cavity}$$

4) Photogun specifications

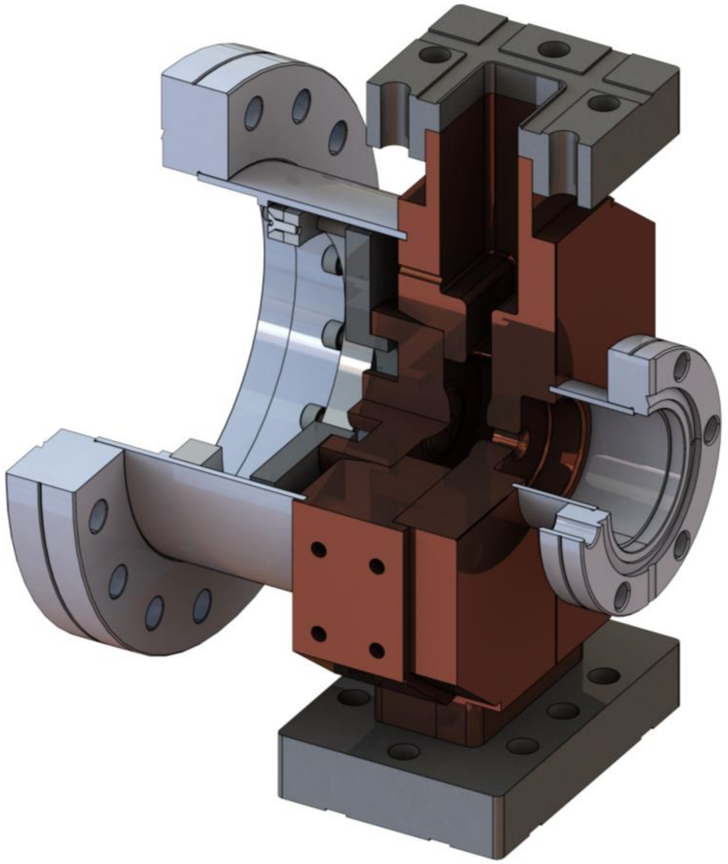
- Reentrant cavity with high shunt impedance
- Cryogenic temperature provided RF stability and cathode studies

Parameter	295K	100K	77K	40K
Frequency	5.695 GHz	5.711 GHz	5.712 GHz	5.713 GHz
Q_0	8579	18668	24200	39812
β	0.7	1.53	1.98	3.26
Filling time	-	0.41 μs	0.45 μs	0.52 μs
RF power	-	1.19 MW	1.13 MW	1.04 MW
Energy deposition	-	0.191 J/pulse	0.15 J/pulse	0.097 J/pulse





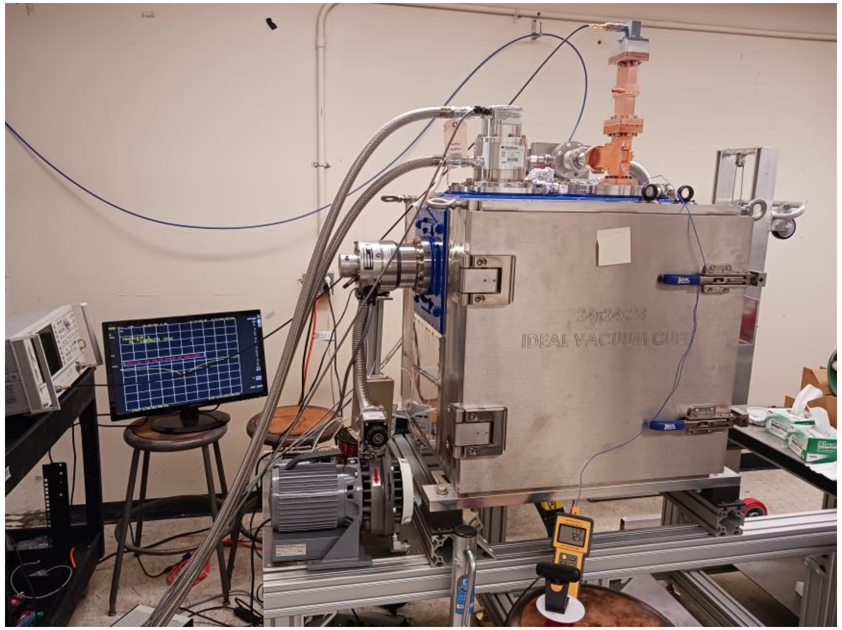
E field magnitude

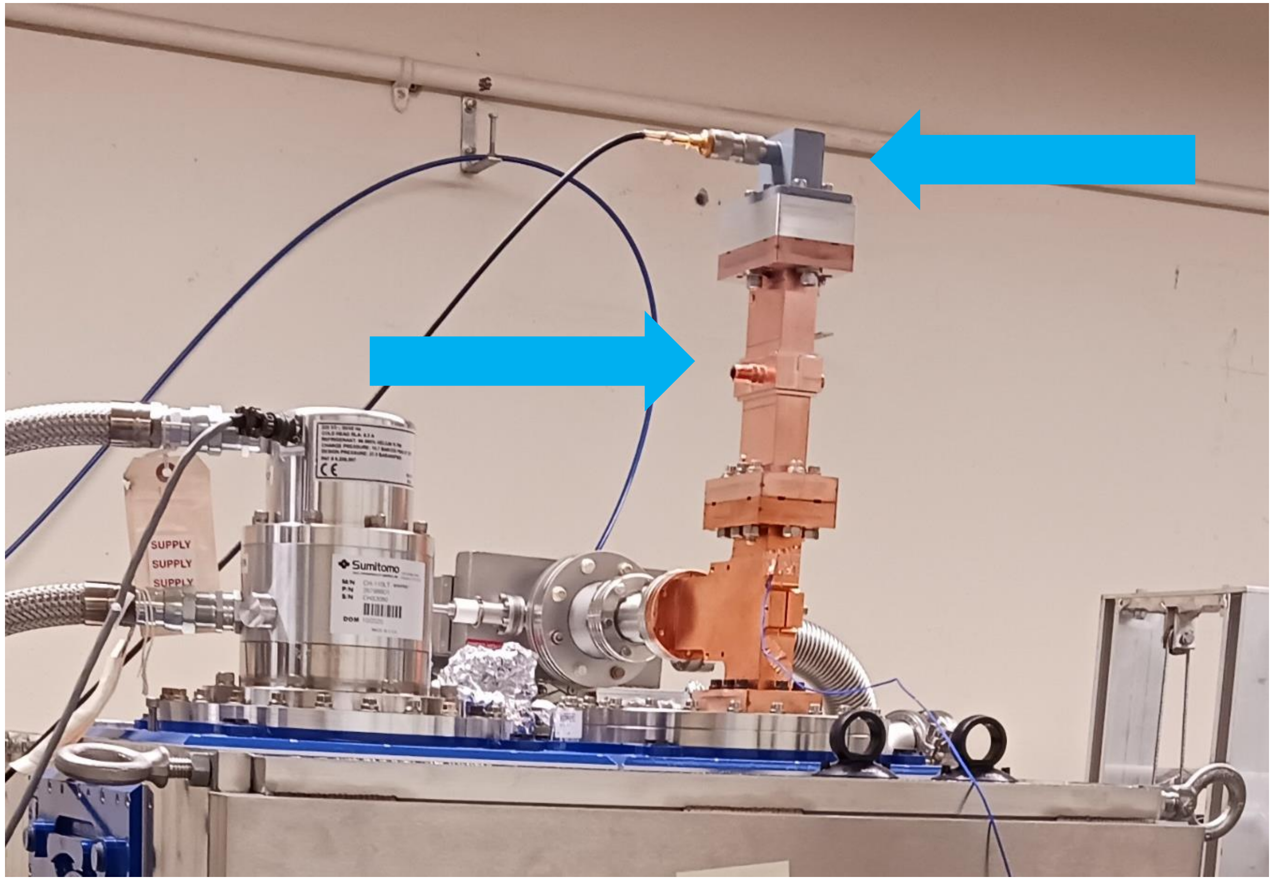


G. E. Lawler et al., Proc. IPAC'22, no. 13, p. 2544–2547, 2022.
doi:10.18429/JACoW-IPAC2022-THPOST046

4) CYBORG Cooldown

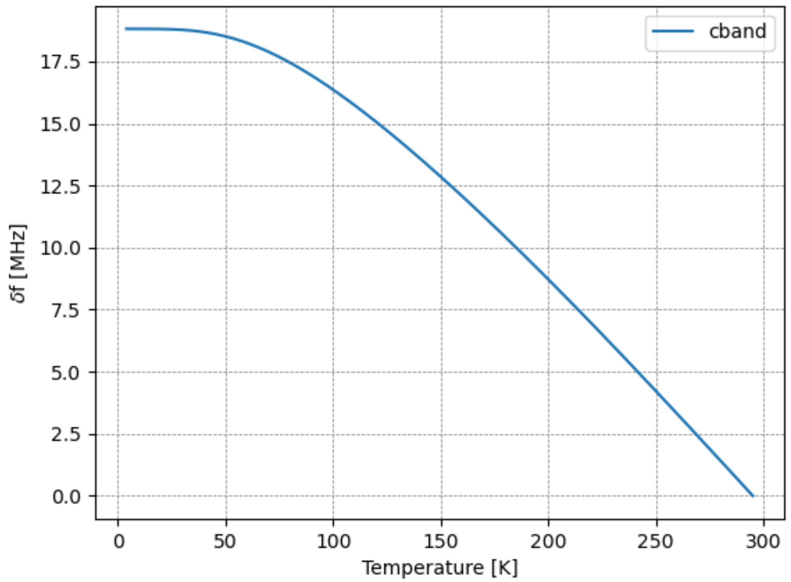
- Add RF window in waveguide and llrf launcher
- Measurement reflection coefficient while cooling

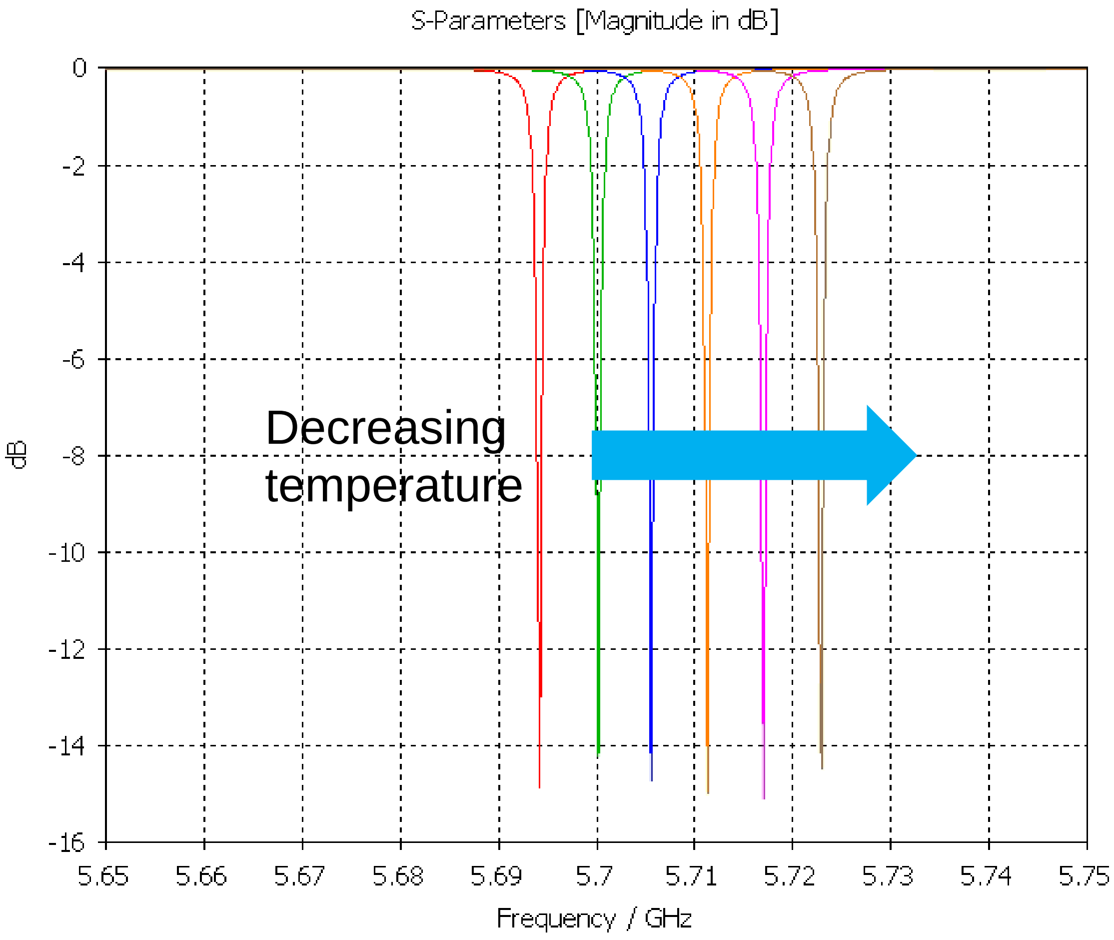




RF Simulations

- Measurements are reflection coefficient S11 from llrf antenna
- Can be used to calculate Q and coupling beta plus location of minimum gives resonance frequency
- As cavity cools it contracts and eigenmode increases, electrical, and thermal conductivities also mostly increase change Q and coupling





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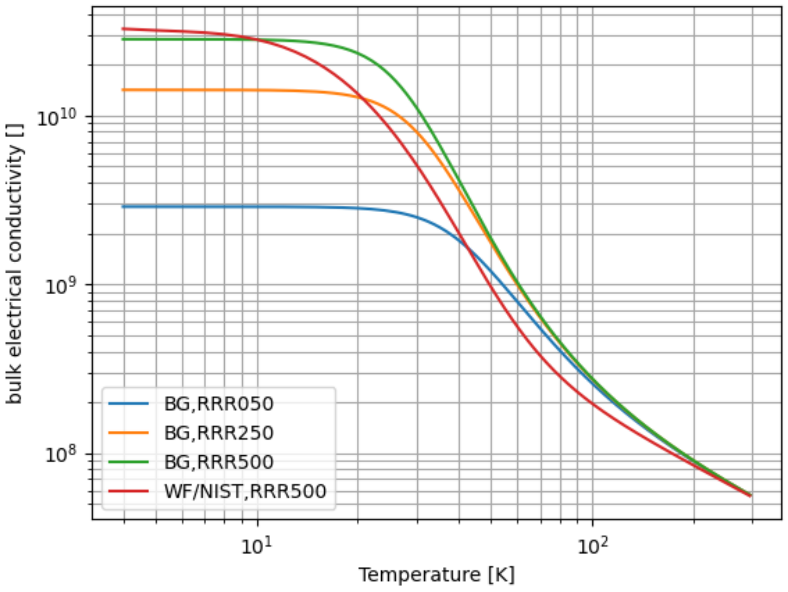
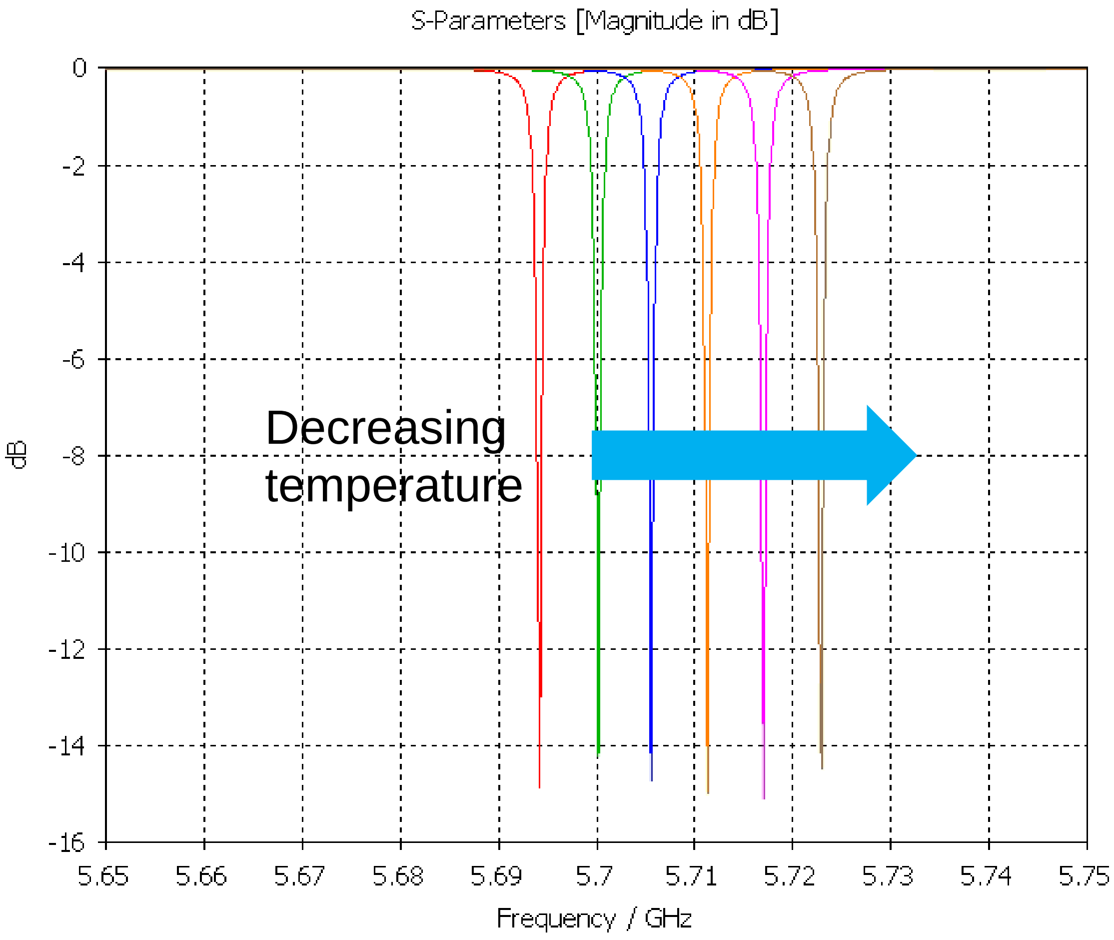
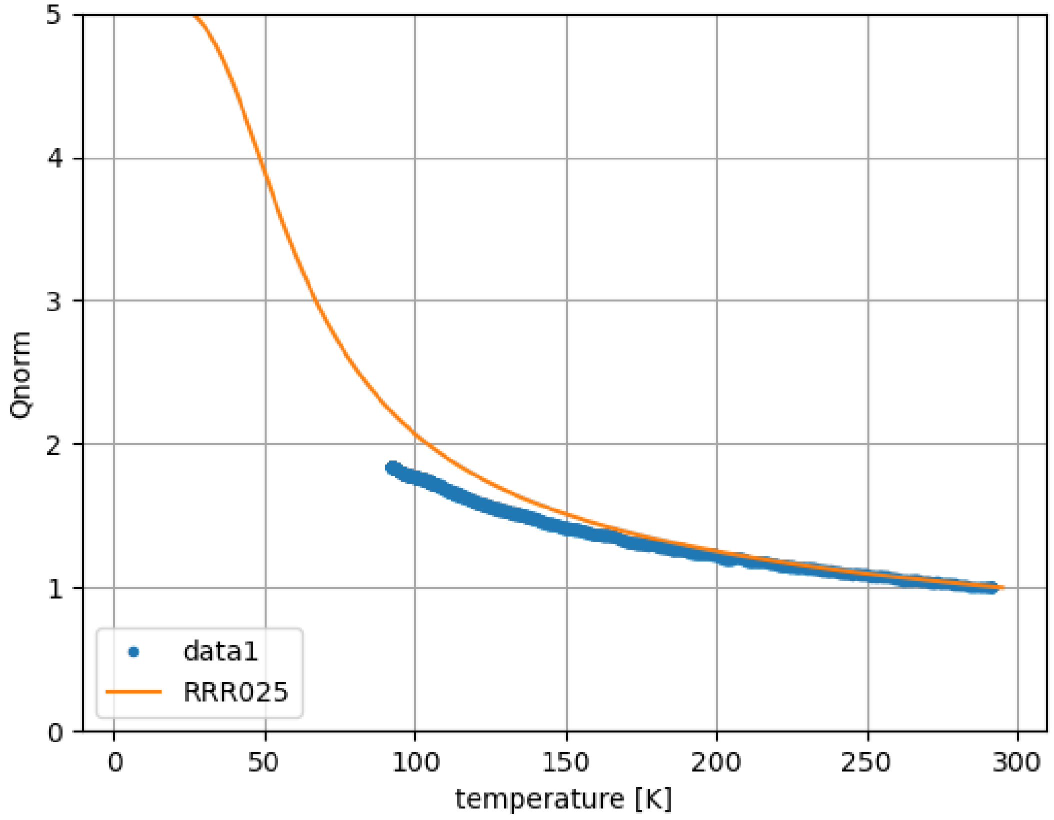
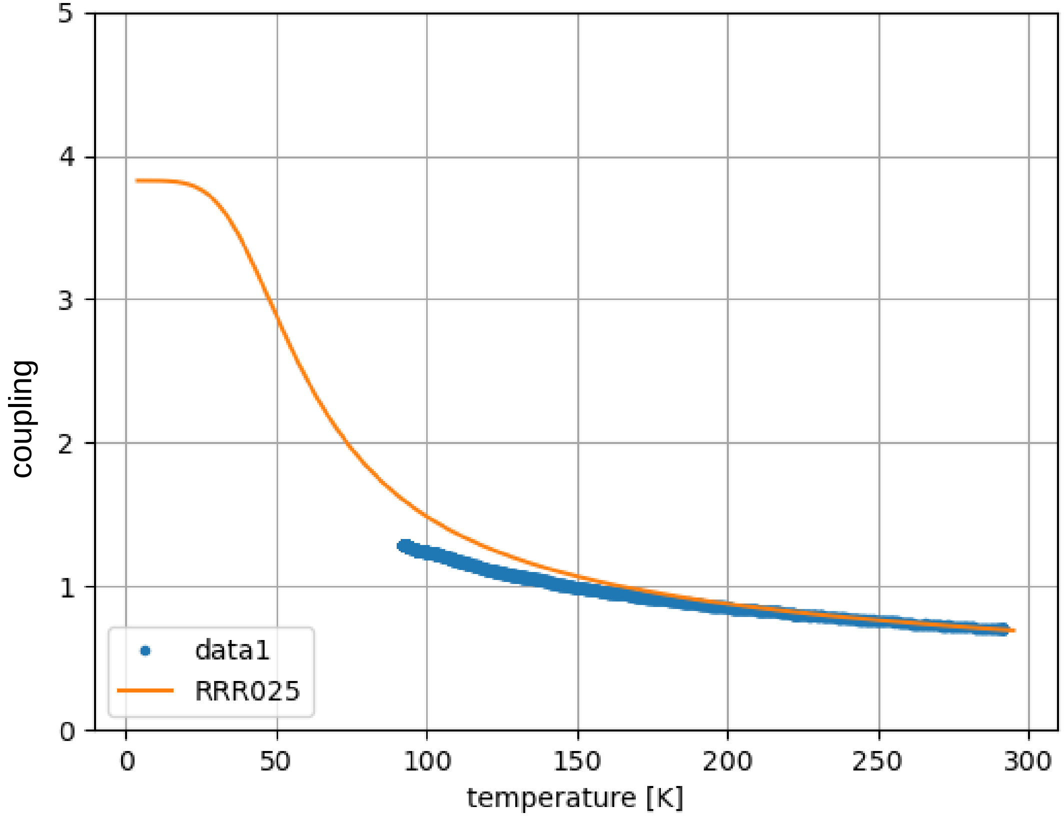




CYBORG LLRF

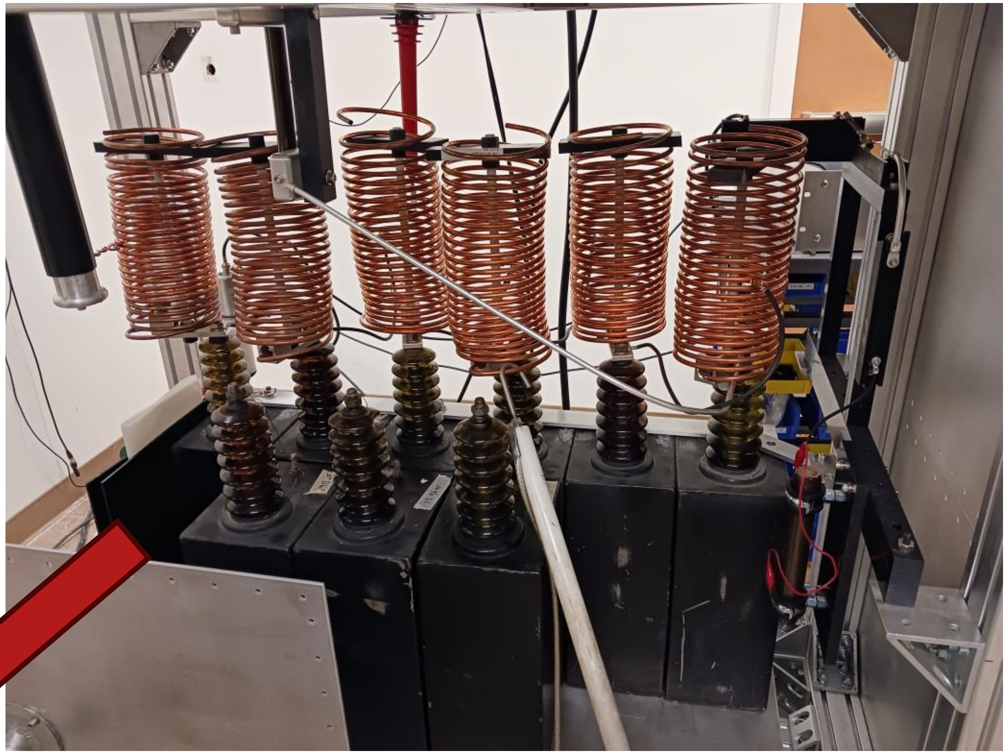
- Undervalued Q (here normalized to room temp value) and coupling compared to design simulations
- Somewhat expected due to large cooling gradient
- Better thermalization should improve results





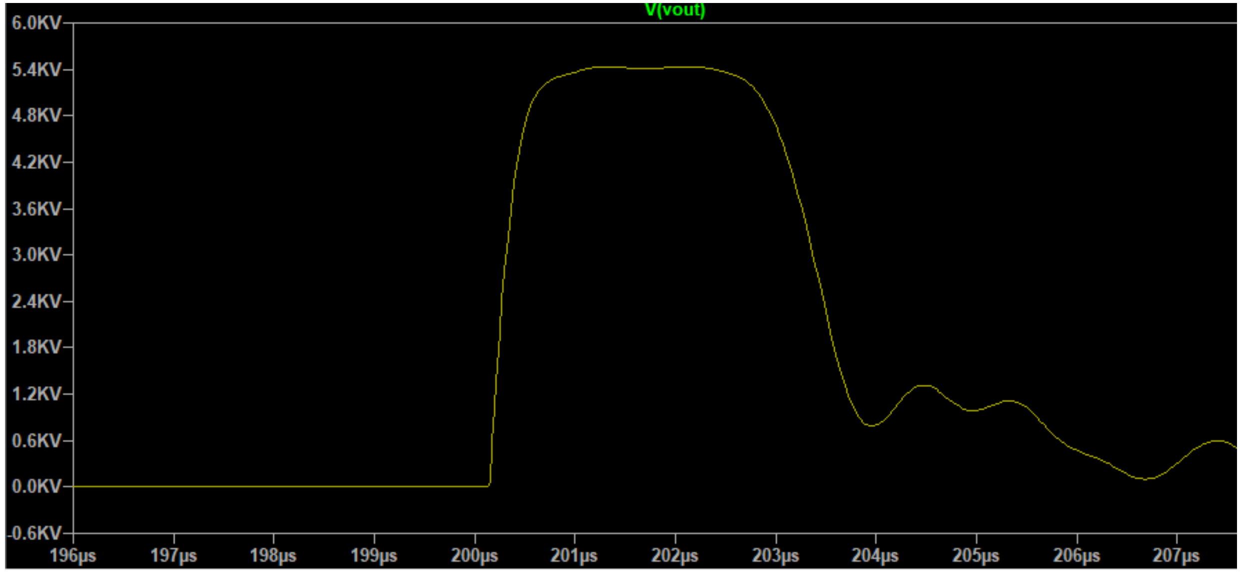
High Power RF

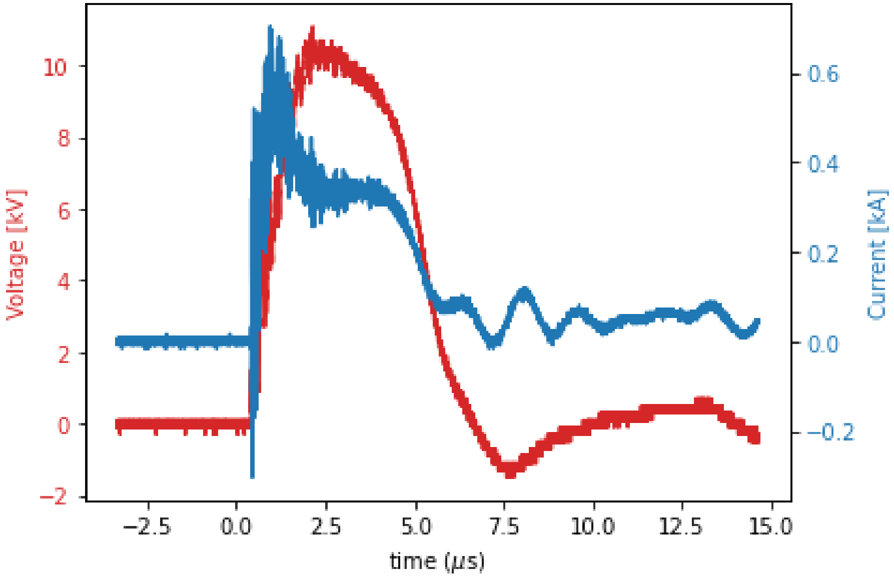
- RF pulse to power photogun formed via charged and discharged capacitor bank called pulse forming network PFN
- Pause now for filling in gap in bunker with bricks via forklift for radiation safety

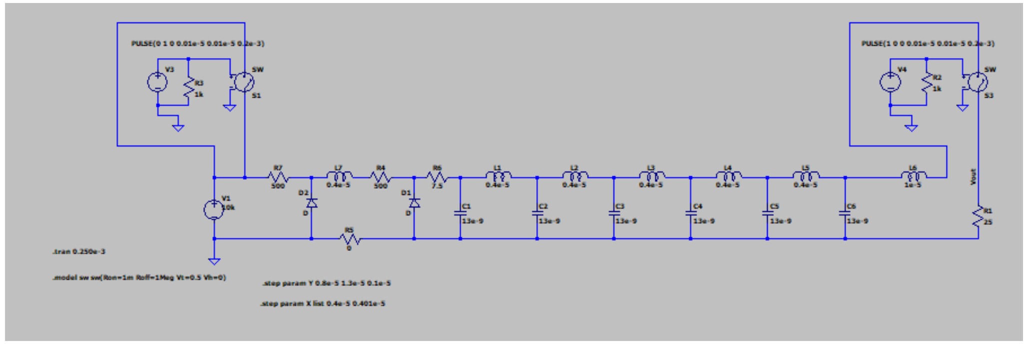


Klystron Input

- Initial simulation to the right
- Thales klystron fired up with load and functioning modulator
- All subsystems operating nominally
- 400A; 11kV PFN pulse below (note ramped up voltage needed to clean up signal)

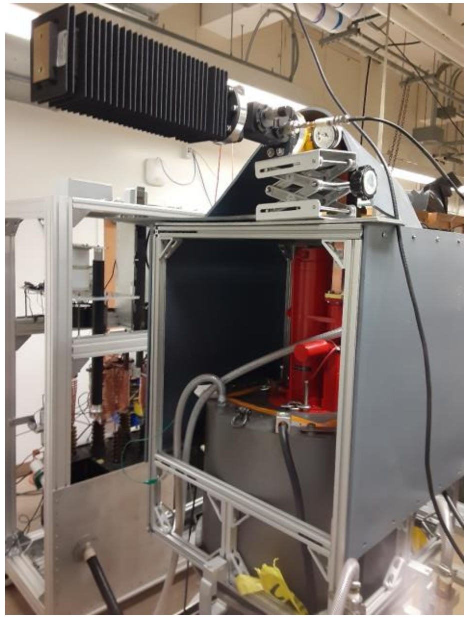


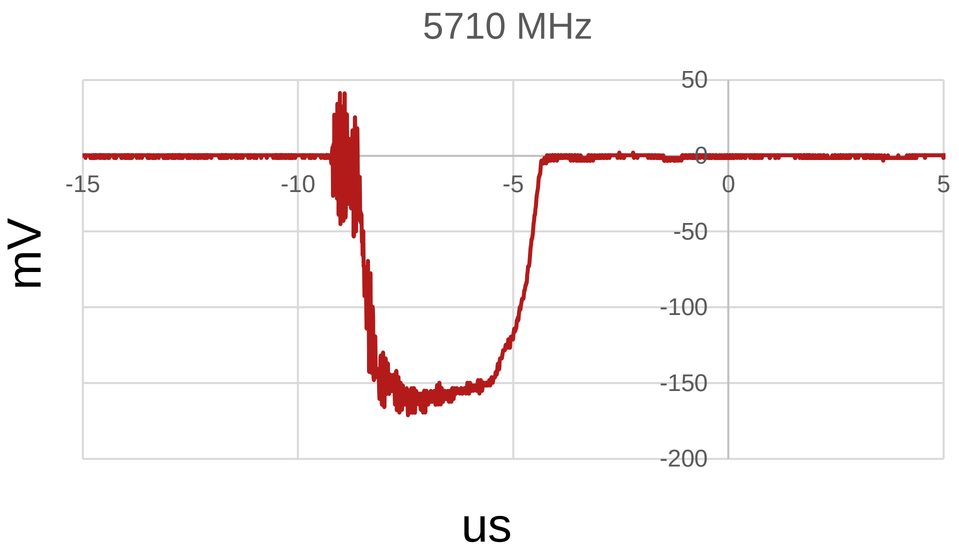


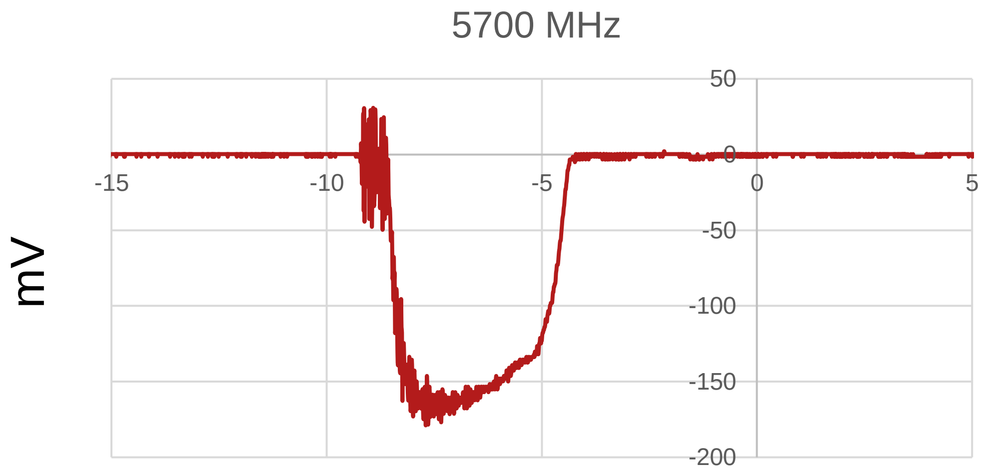


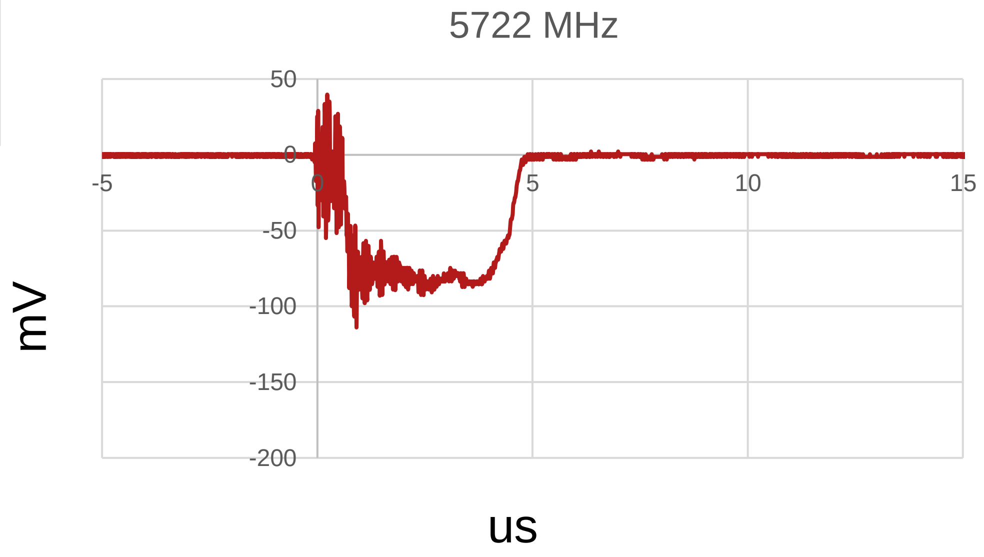
Klystron RF Output

- Klystron output at RF coupler for several frequencies



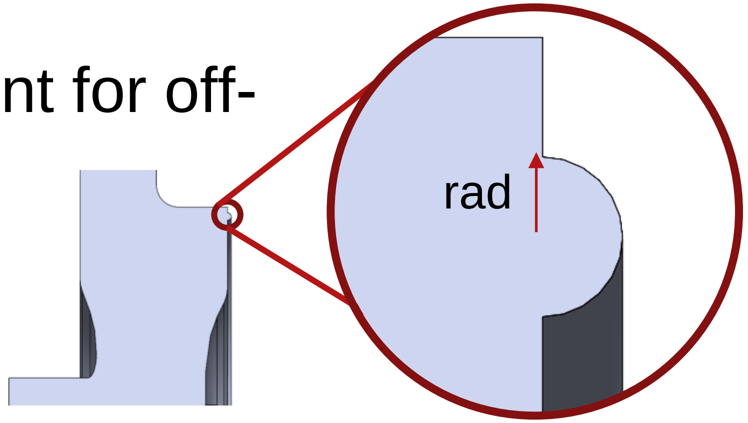




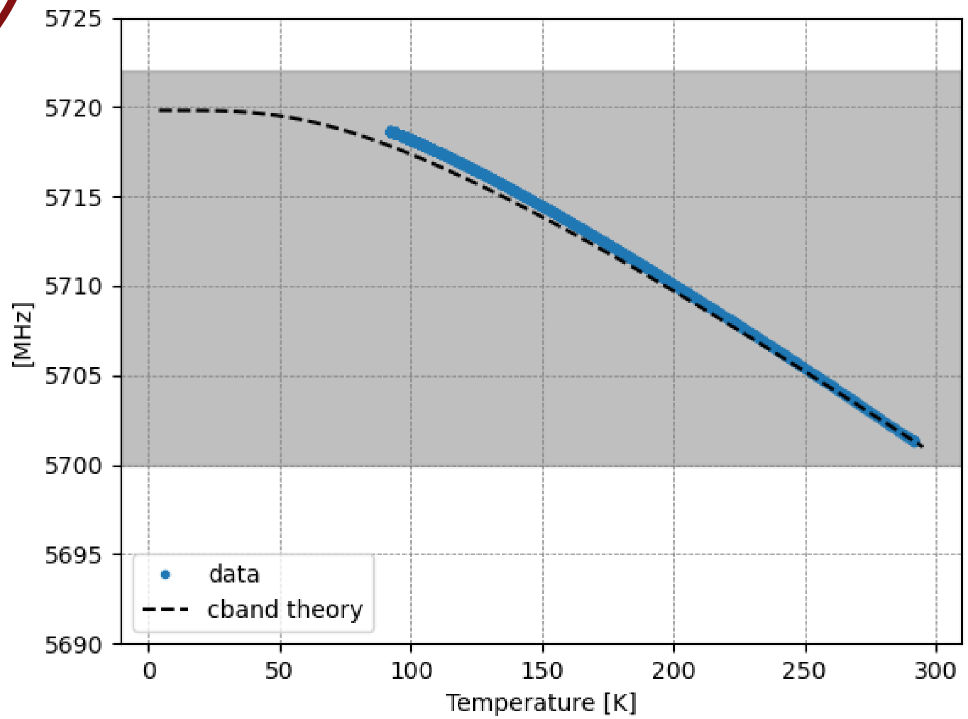


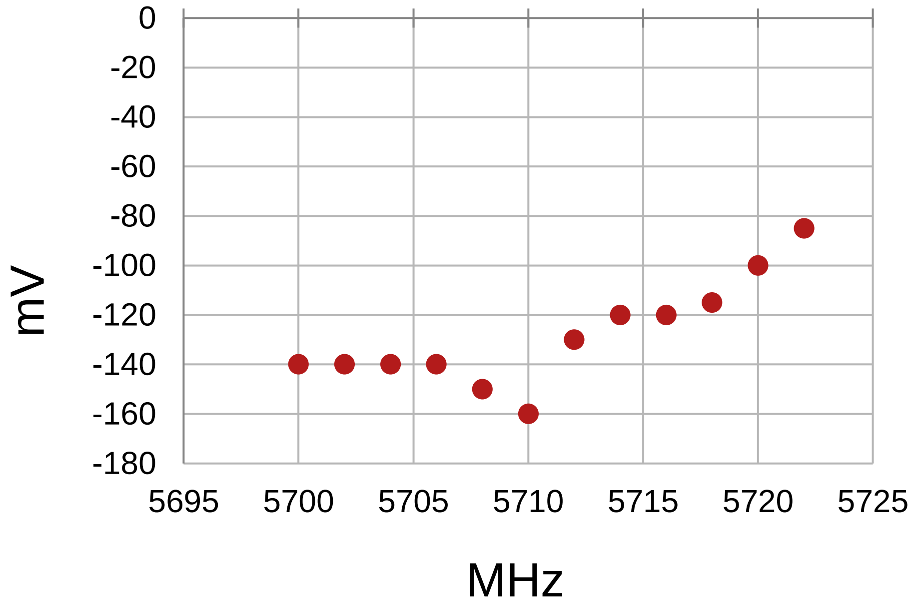
Klystron Bandwidth

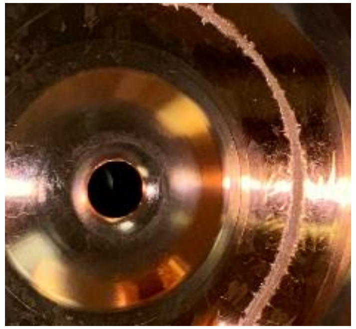
- Bandwidth measurement for off-resonance CYBORG



Thales Klystron Bandwidth





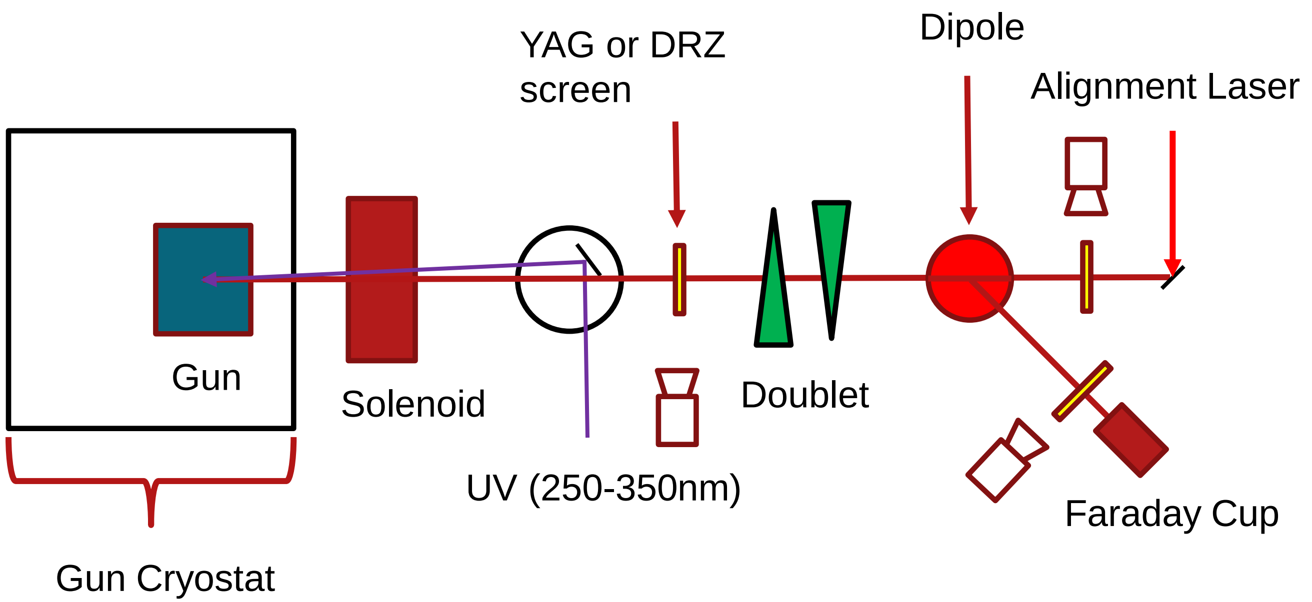


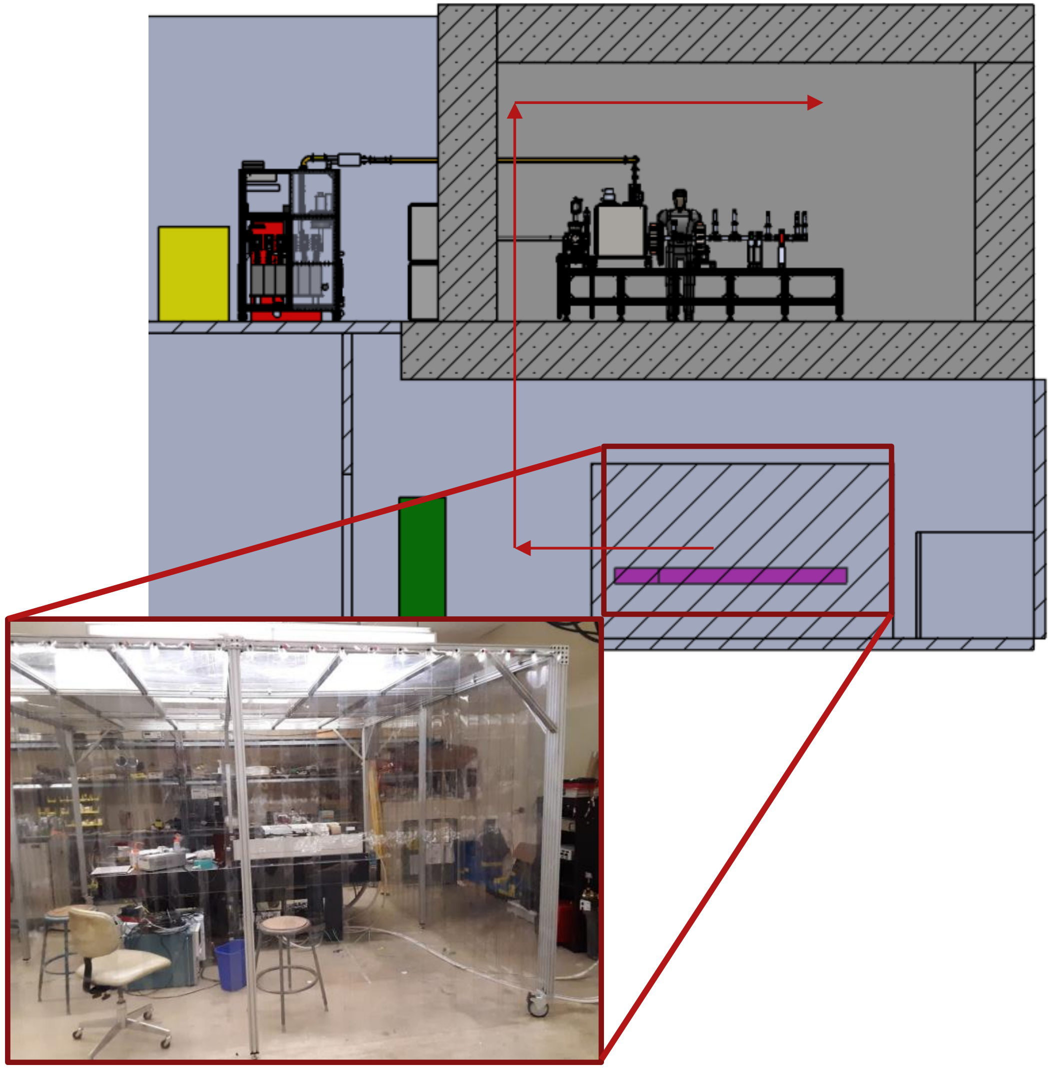
Outline of presentation

1. Background
2. RF cathode test bed overview
3. CYBORG commissioning: cryogenics
4. CYBORG commissioning: RF power
5. **Future**
6. Conclusions

5) Phase1

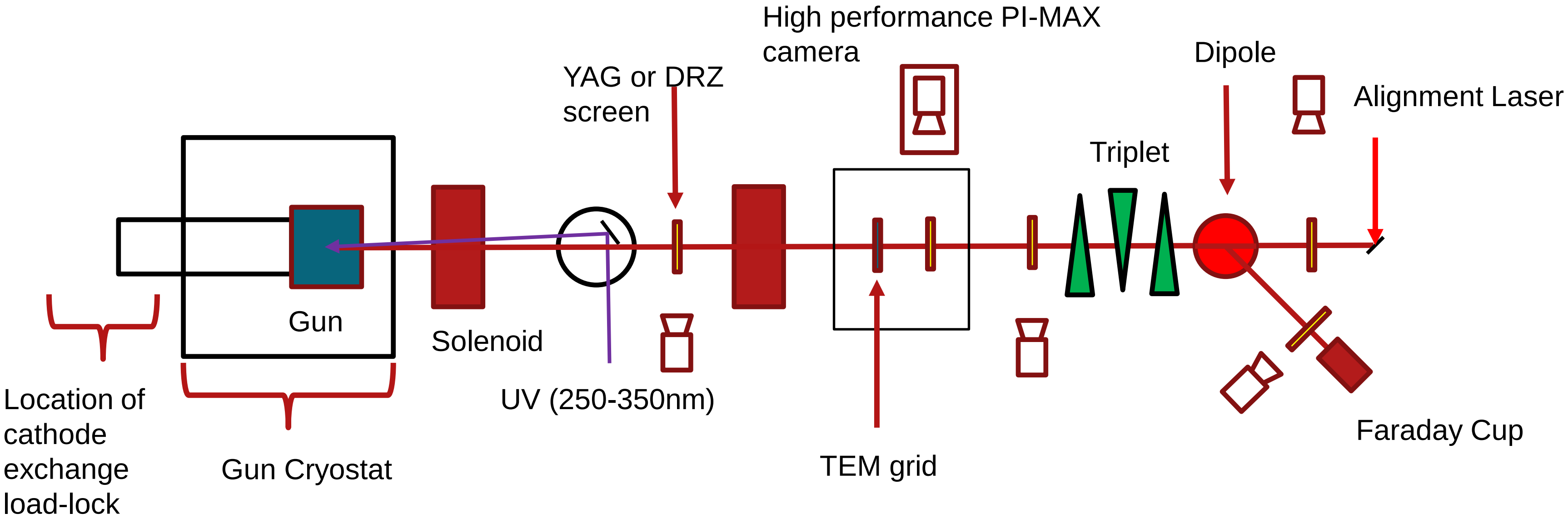
- Config2 goals:
  - Cryogenic copper photoemission
  - Cryogenic QE
  - Preliminary lower prevision MTE measurement





5) Phase2

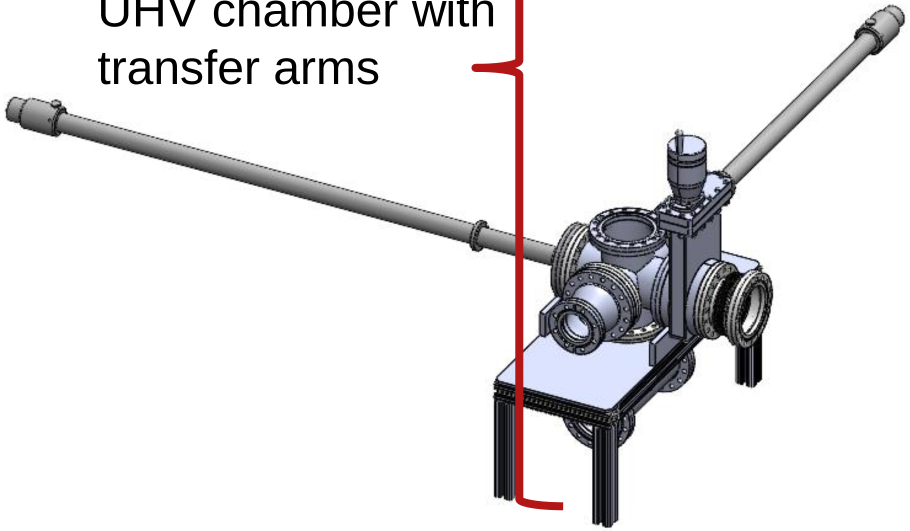
- load lock and phase 2 diagnostics (schematic below)
- High precision MTE measurement setup needed
- Cathode coupling work in parallel underway using interference fit idea (right) with analog Mo and Cu structures
  - RF spring and knife edge seals difficult for cryo
- INFN minipuck for initial consideration

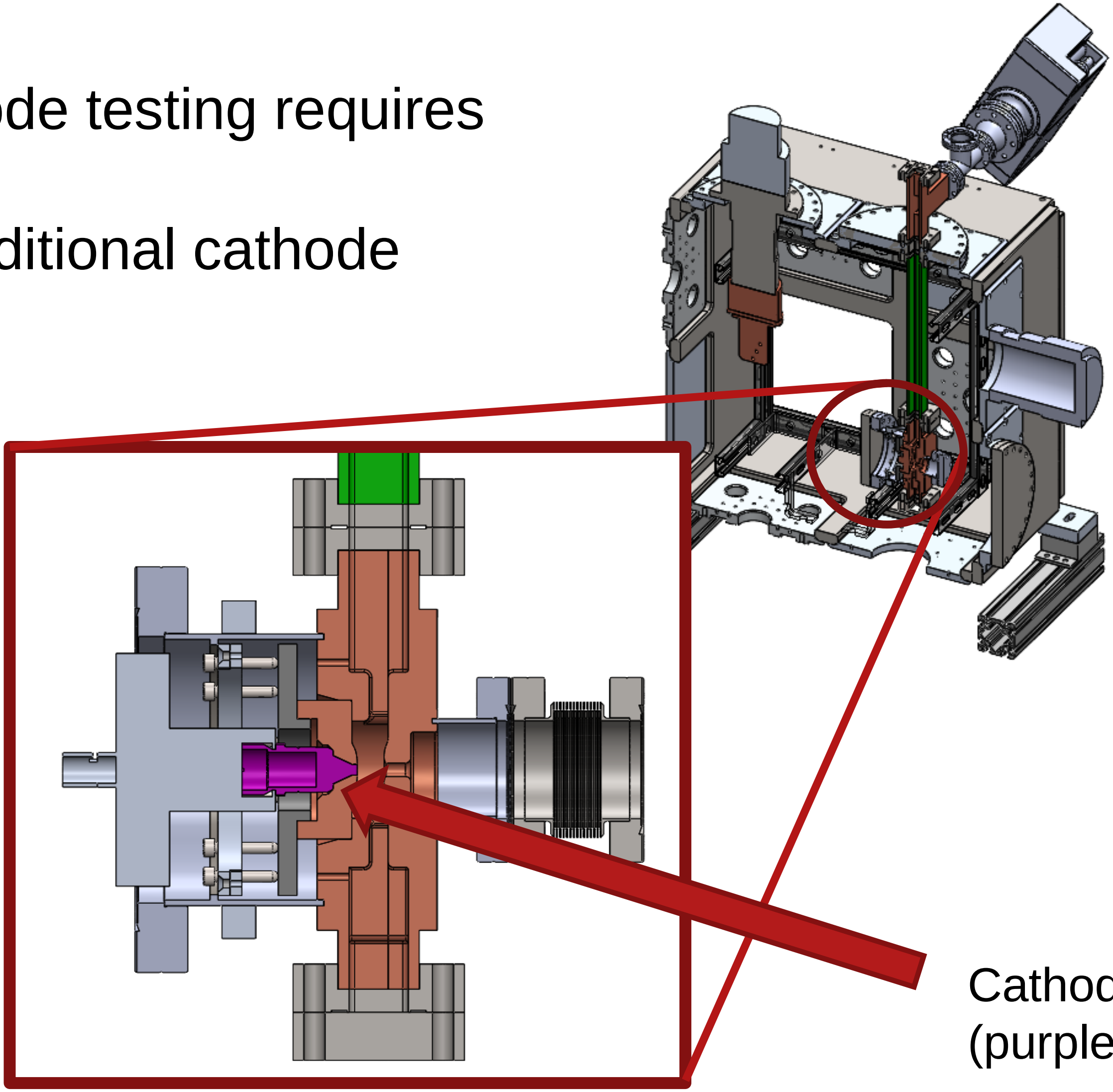


Phase2 Cathode Storage Chamber

- Ready to move to assembly stage
- Long term usage of CYBORG for cathode testing requires UHV chamber (<10^-10 torr)
- Development of pumping setup and additional cathode plug manipulator studies necessary

UHV chamber with transfer arms

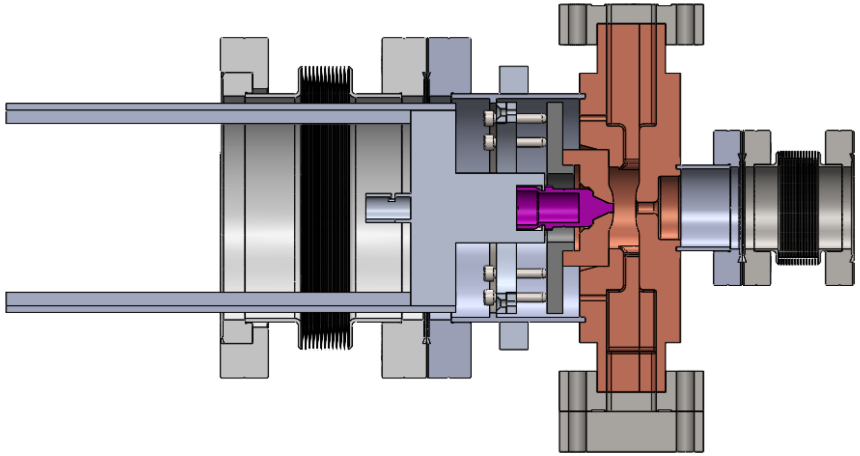


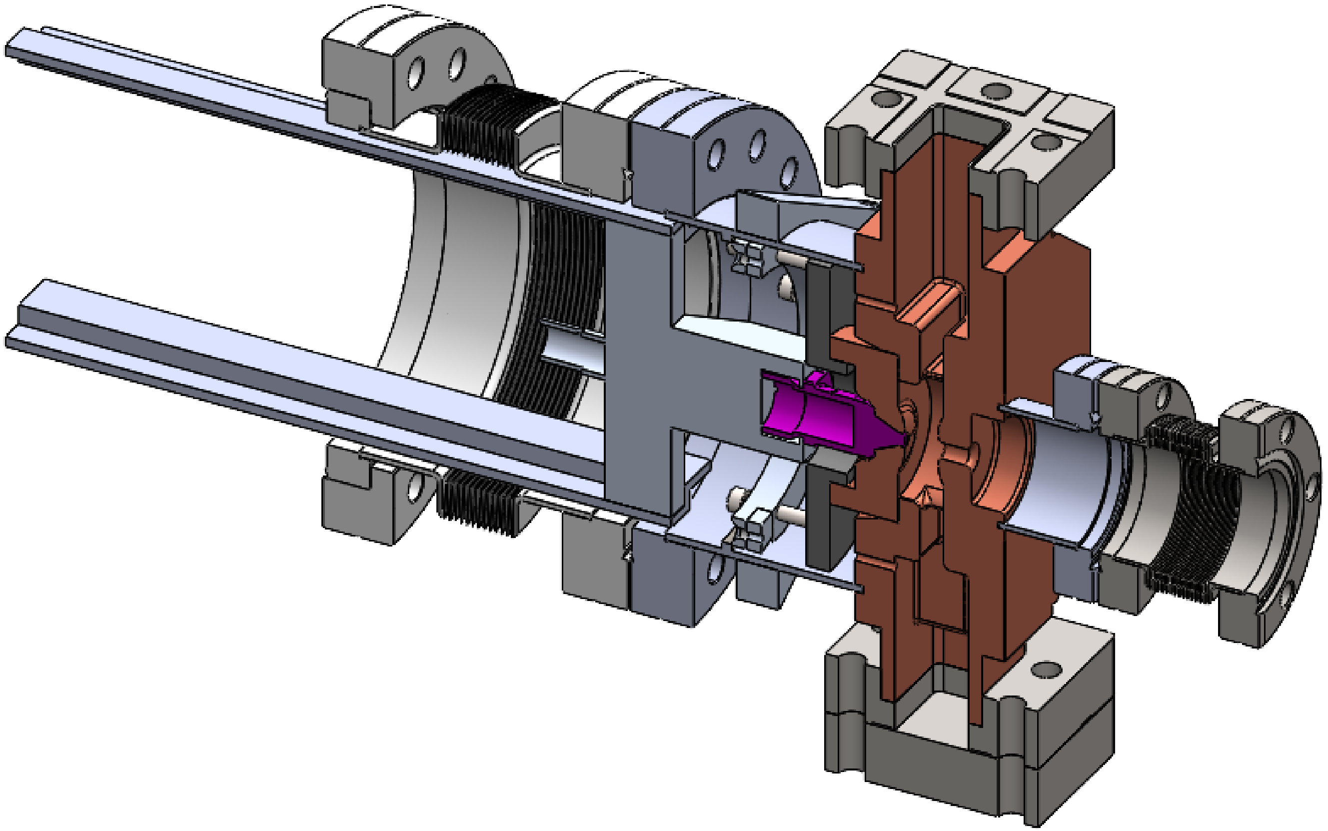


Cathode (purple)

Phase2 CYBORG

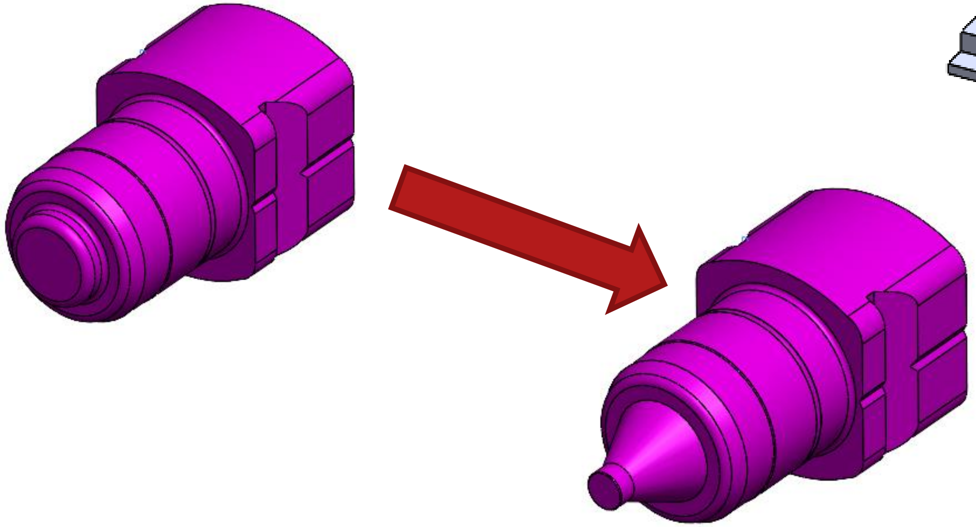
- Initial concept for phase2 CYBORG including modified backplane
- Alignment rails introduce additional heat leaks etc
- More simulations needed

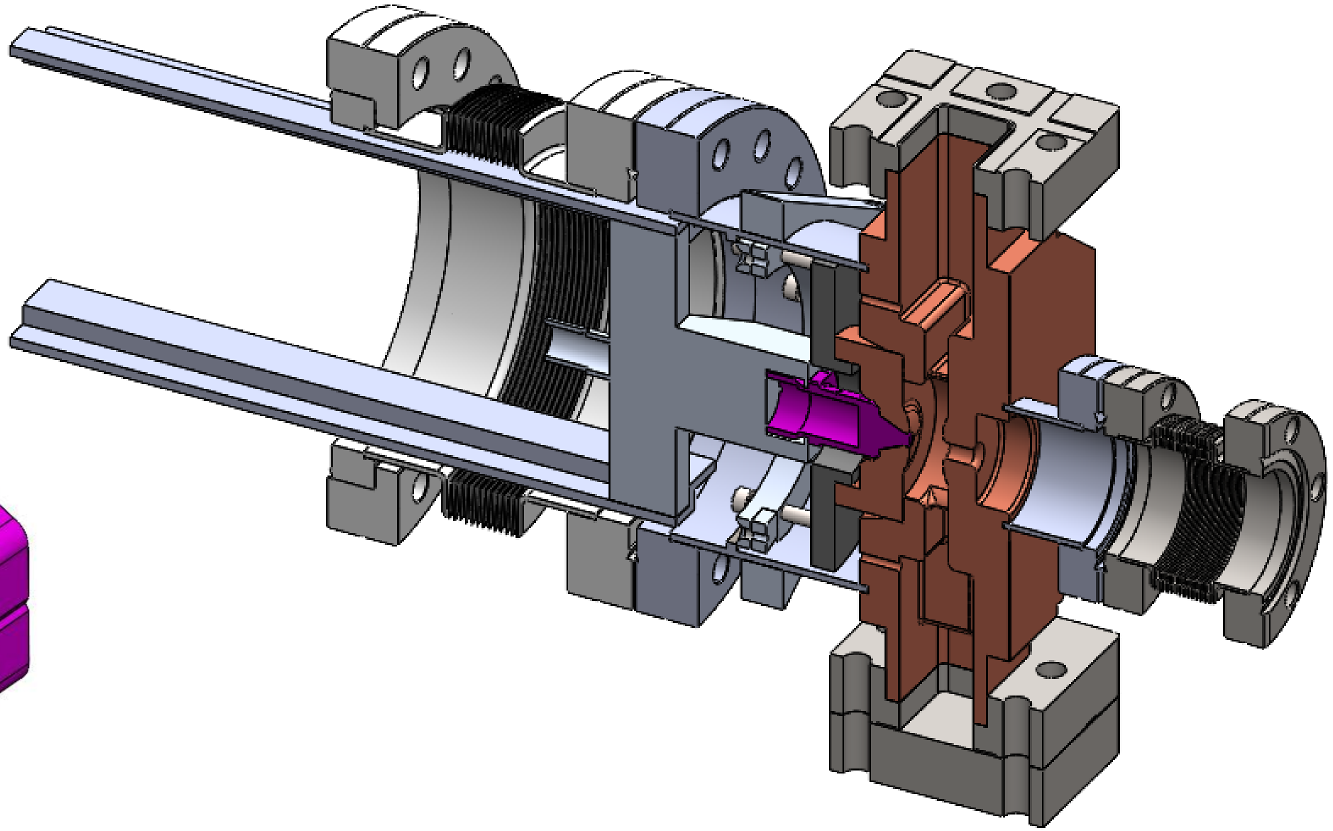




Phase2 CYBORG

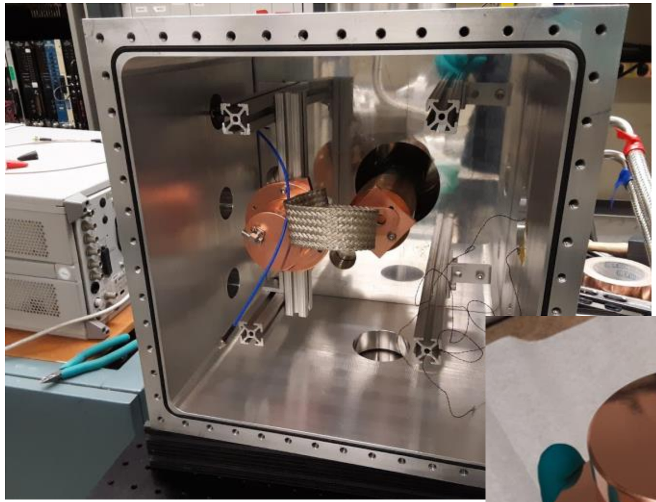
- INFN style miniplug for example with additional taper to fit within smaller cband nosecone
- Not necessary to maintain cathode geometry but provides good initial concept

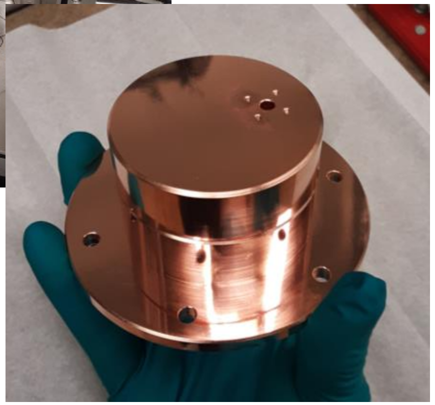


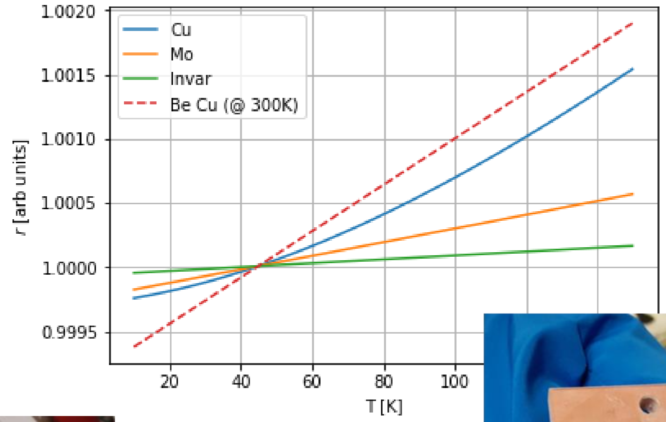


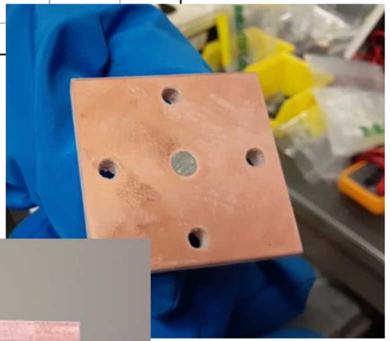
Cathode Coupling Test

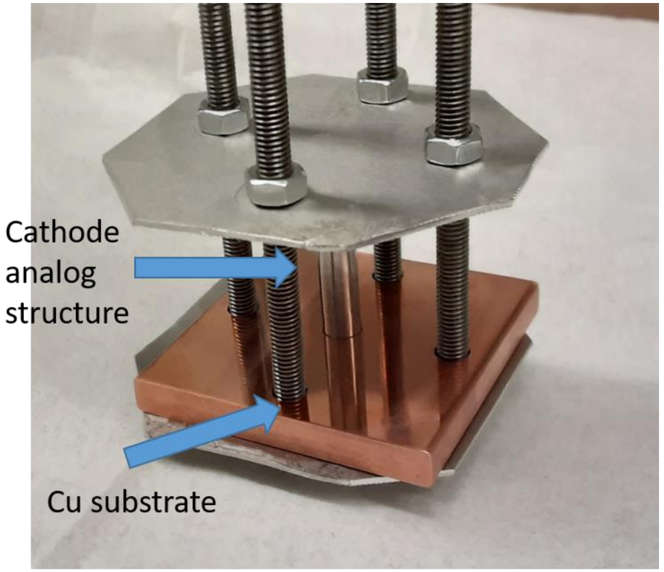
- Testing cavity-cathode coupling with interference fit using assembly designed
- Successful mechanic testing (right) moving on to RF testing in small resonant cavities (left)





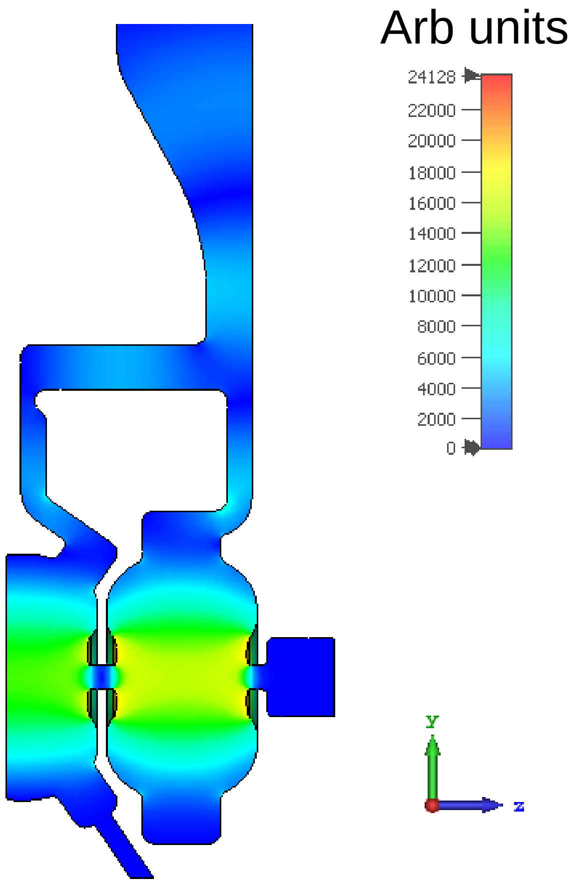


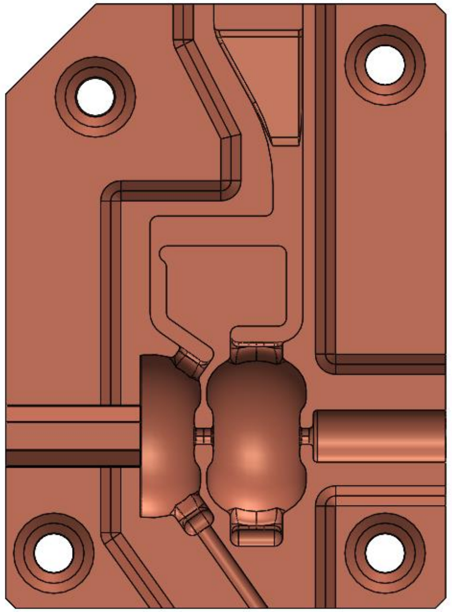


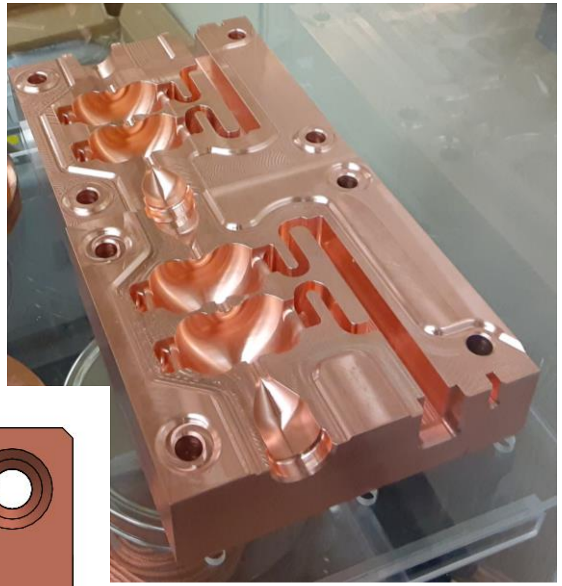


Pathway higher gradients

- Cryogenic 1.5 cell photoinjector in collab with SLAC/LANL designed and nearing state for manufacture
- Room temperature variant in production at LANL
- Both ntended for operation >240 MV/m
- Photo of cavities to far right for different experiment but give idea of geometry and surface finish etc

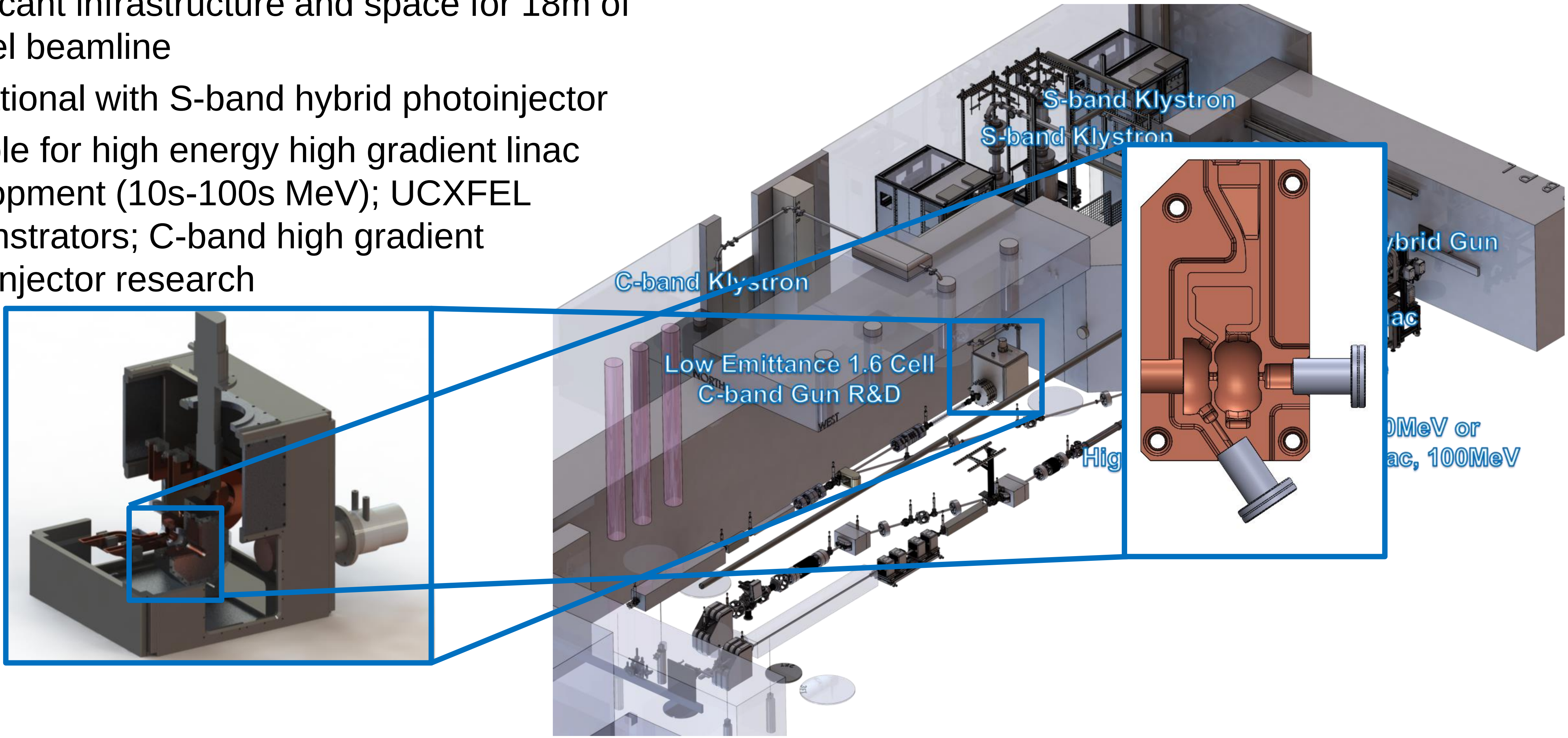






4) MITHRA Lab

- Significant infrastructure and space for 18m of parallel beamline
- Operational with S-band hybrid photoinjector
- Suitable for high energy high gradient linac development (10s-100s MeV); UCXFEL demonstrators; C-band high gradient photoinjector research



5) Conclusions

1. CYBORG commissioning progressing within acceptable parameters for intended cryogenic cathode test bed
2. Cryogenics and RF performance sufficient for high tests with iterations for improvement planned
3. Beginning steps to add appropriate radiation shielding and additional infrastructure upgrades
4. CYBORG as template highlighted path to ultra-high gradient photoinjector

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