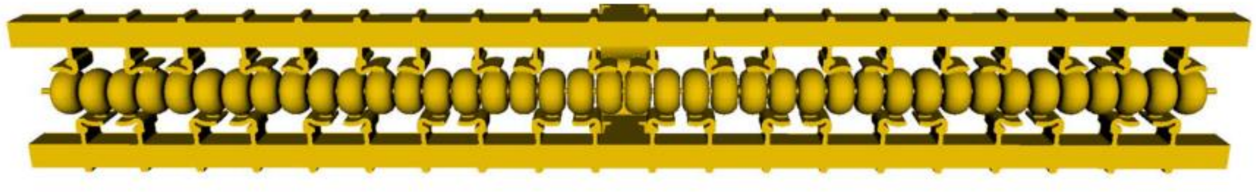
The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

RF Testing Capabilities and Results at UCLA Particle Beam Physics Lab (PBPL)

Gerard Lawler[1], James Rosenzweig[1] et al.
UCLA[1], Los Angeles, CA, USA

Cold Copper Accelerator Technology and Applications Workshop



Cornell University, August 31 – September 1, 2023

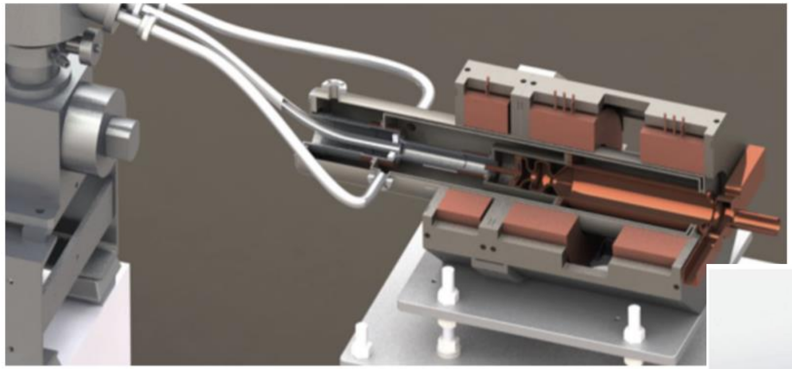
UCLA SLAC NATIONAL ACCELERATOR LABORATORY Los Alamos NATIONAL LABORATORY radiabeam TECHNOLOGIES U.S. DEPARTMENT OF ENERGY

Outline of presentation

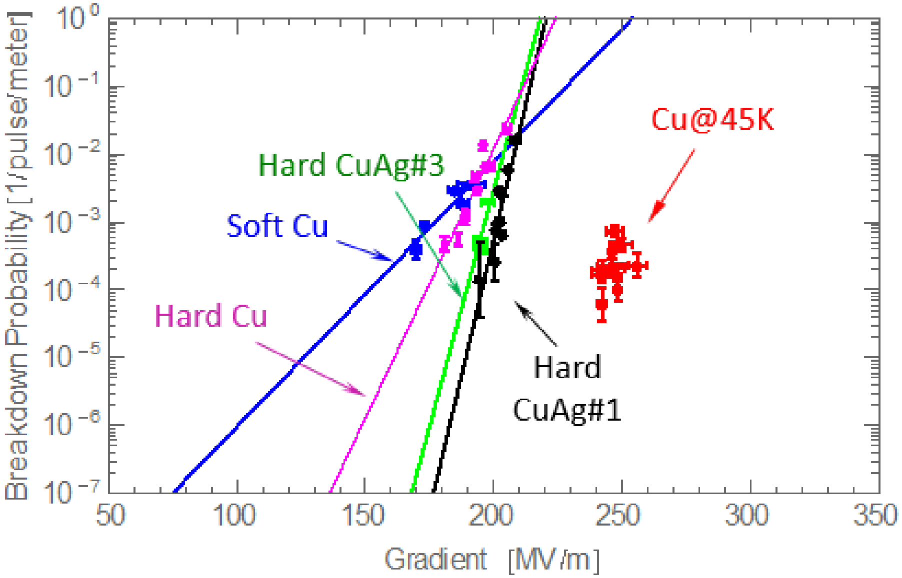
1. Background and motivation
2. Low level RF
3. High power RF
4. Future testing: near and far term
5. Conclusions

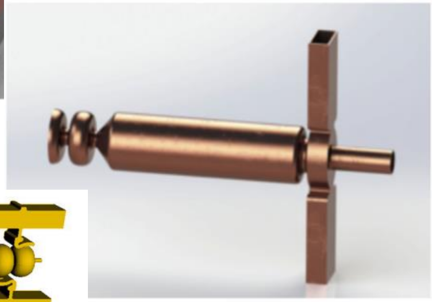
1) Background

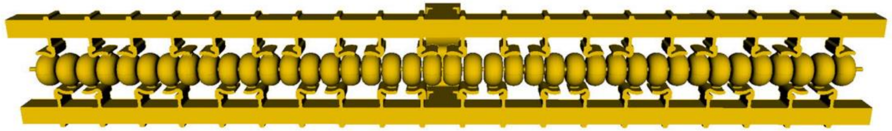
- Significant interest in photoinjector; wakefield; fundamental high field physics
- Broad interest in high gradient cavity development with focus on brightness
- SLAC cryogenic breakdown reduction ⇒ higher accelerating gradients possible
- TopGun previous development in S-band
- More cryo manageable C-band + interest in broader applications e.g. compact high brightness light sources and linear colliders

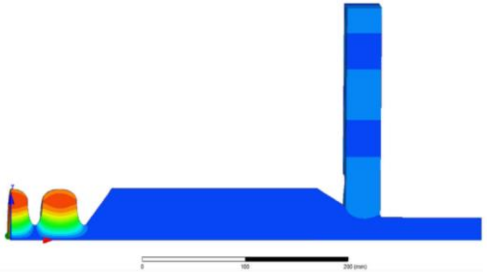


$$B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c}\left(E_0 \sin\varphi_0\right)^2$$







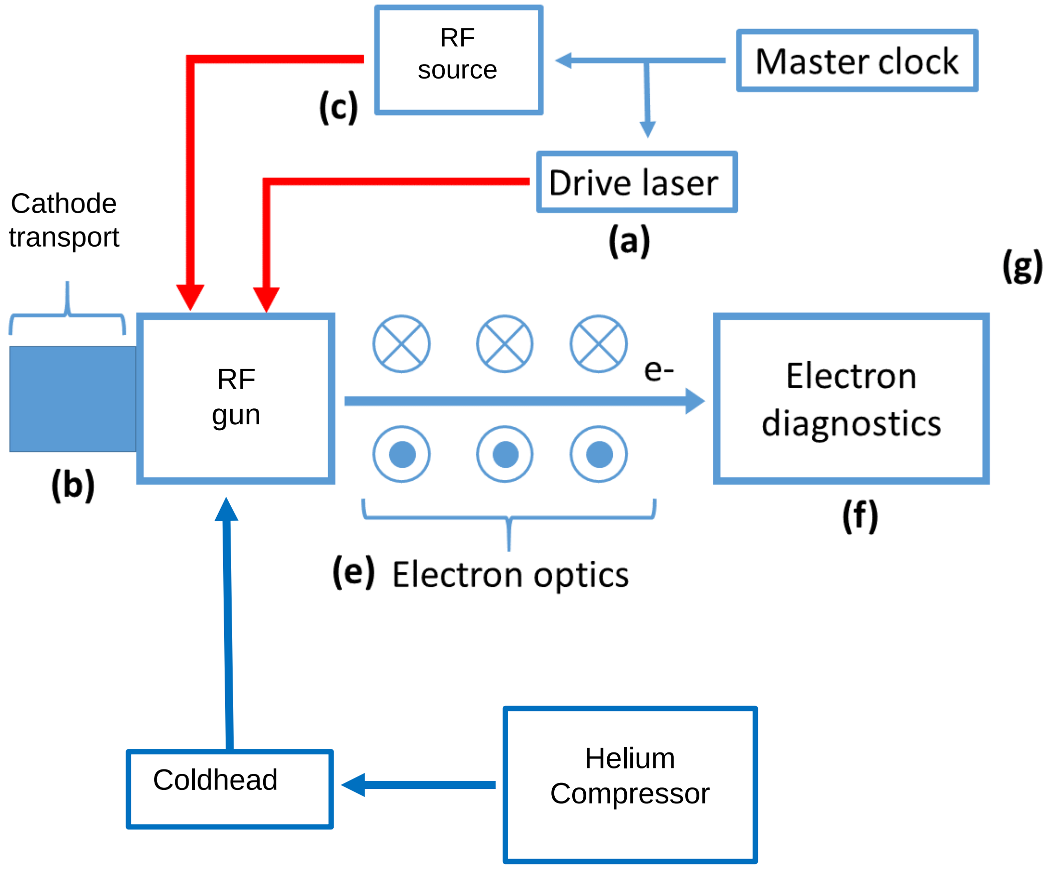


Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources
JB Rosenzweig, et al. - Physical Review Accelerators and Beams, 2019

1) CYBORG Functions

- Simplest NC RF beamline integration using CrYogenic Brightness Optimized Radiofrequency Gun (CYBORG)

1. Ultra-high gradient photoinjector prototype
   1. Integrated infrastructure template
   2. Cathode load-lock development
   3. RF prototype, black plane etc.
2. Cryogenic emission testing:
   1. Dedicated high gradient RF test stand for cathodes incl. novel semiconductors
   2. Cryogenic dark current and breakdown



1) CYBORG Function 1

- Simplest NC RF beamline integration using CrYogenic Brightness Optimized Radiofrequency Gun (CYBORG)

1. **Ultra-high gradient photoinjector prototype**
   1. **Integrated infrastructure template**
   2. **Cathode load-lock development**
   3. **RF prototype, black plane etc.**
2. Cryogenic emission testing:
   1. Dedicated high gradient RF test stand for cathodes incl. novel semiconductors
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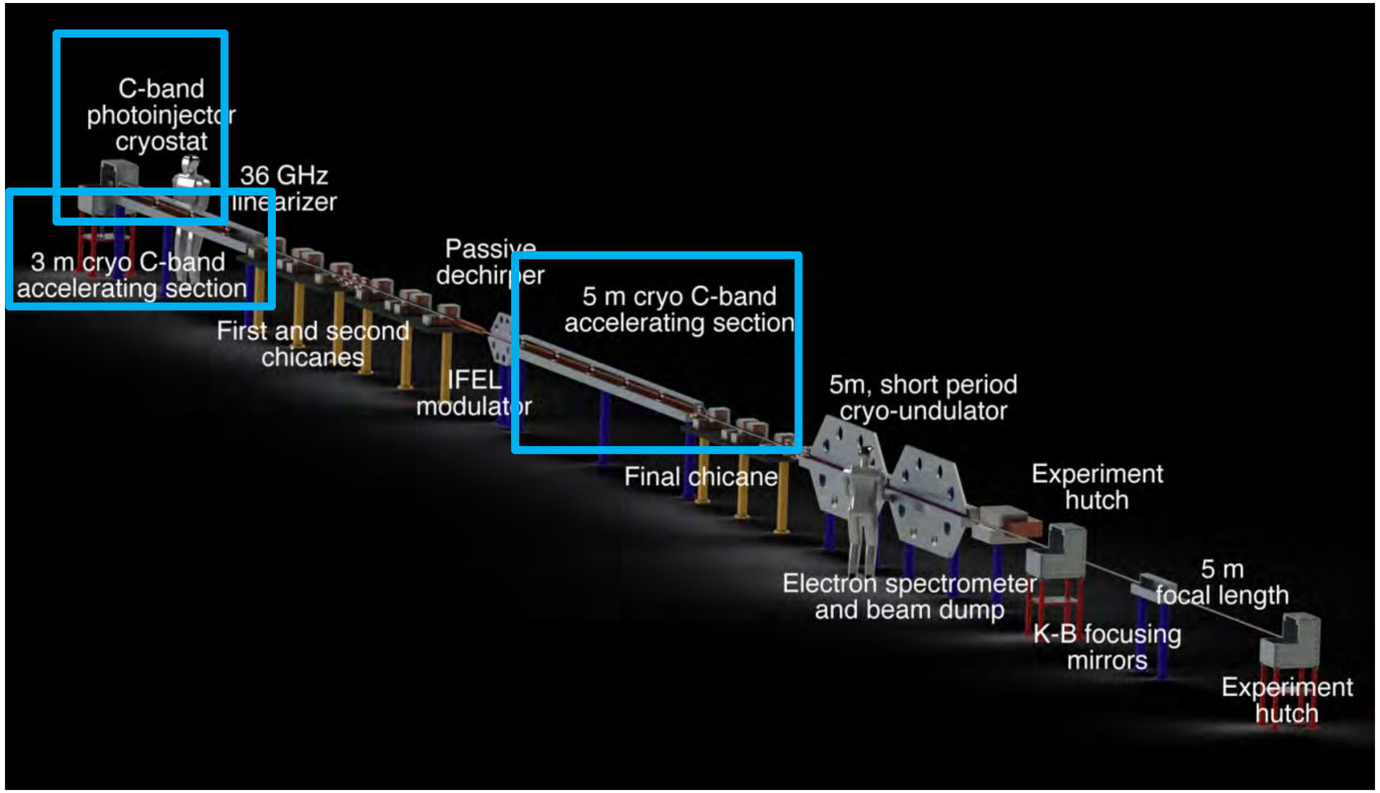
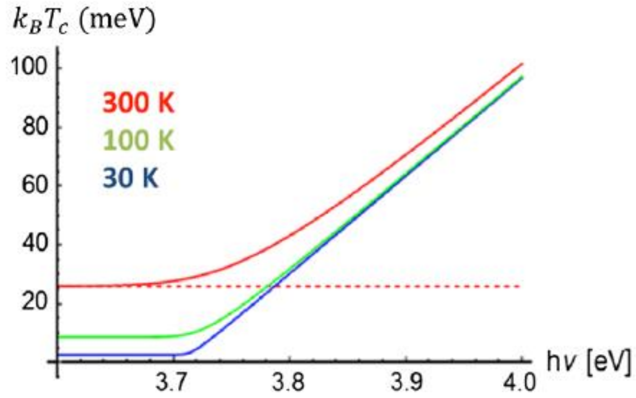


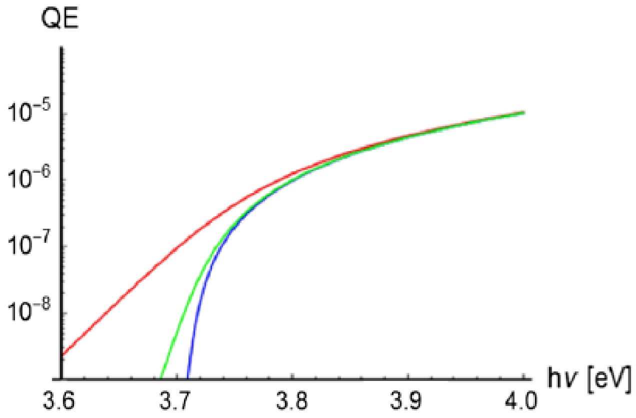
J. Rosenzweig et al., New Journal of Physics, vol. 22, no. 9, p. 093067, 2020. doi:10.1088/1367-2630/abb16c

1) CYBORG Function 2

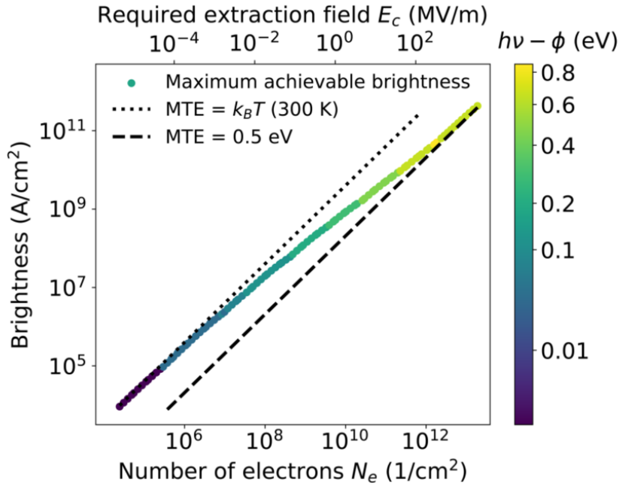
- Simplest NC RF beamline integration using CrYogenic Brightness Optimized Radiofrequency Gun (CYBORG)

1. Ultra-high gradient photoinjector prototype
    1. Integrated infrastructure template
    2. Cathode load-lock development
    3. RF prototype, black plane etc.
2. **Cryogenic emission testing:**
    1. **Dedicated high gradient RF test stand for cathodes incl. novel semiconductors**
    2. **Cryogenic dark current and breakdown**

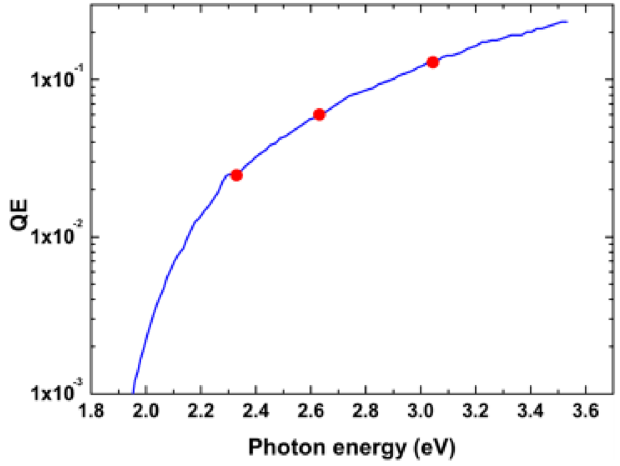




J.B. Rosenzweig et al., Nucl. Instrum. Methods Phys. Res. A, vol. 909, p. 224-228, 2018. doi:10.1016/j.nima.2018.01.061



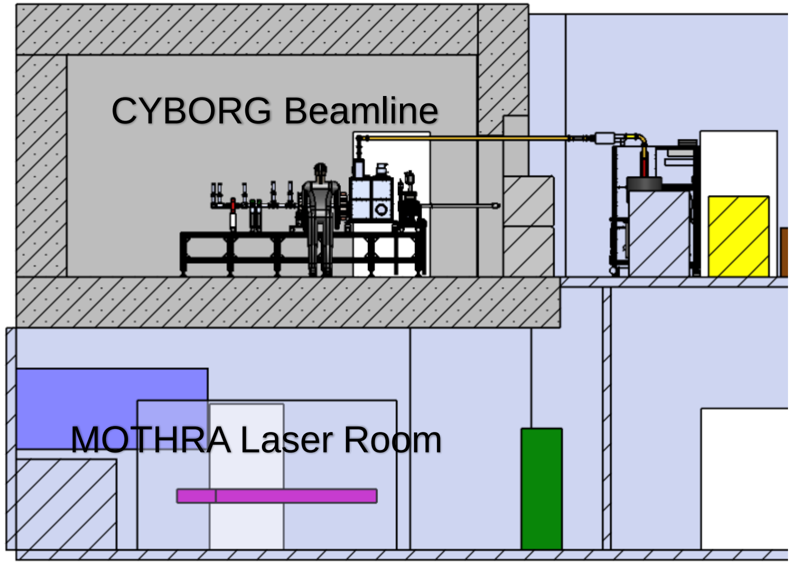
J. K. Bae, I. Bazarov, P. Musumeci, S. Karkare, H. Padmore, and J. Maxson, J. Appl. Phys. 124, 244903 (2018).

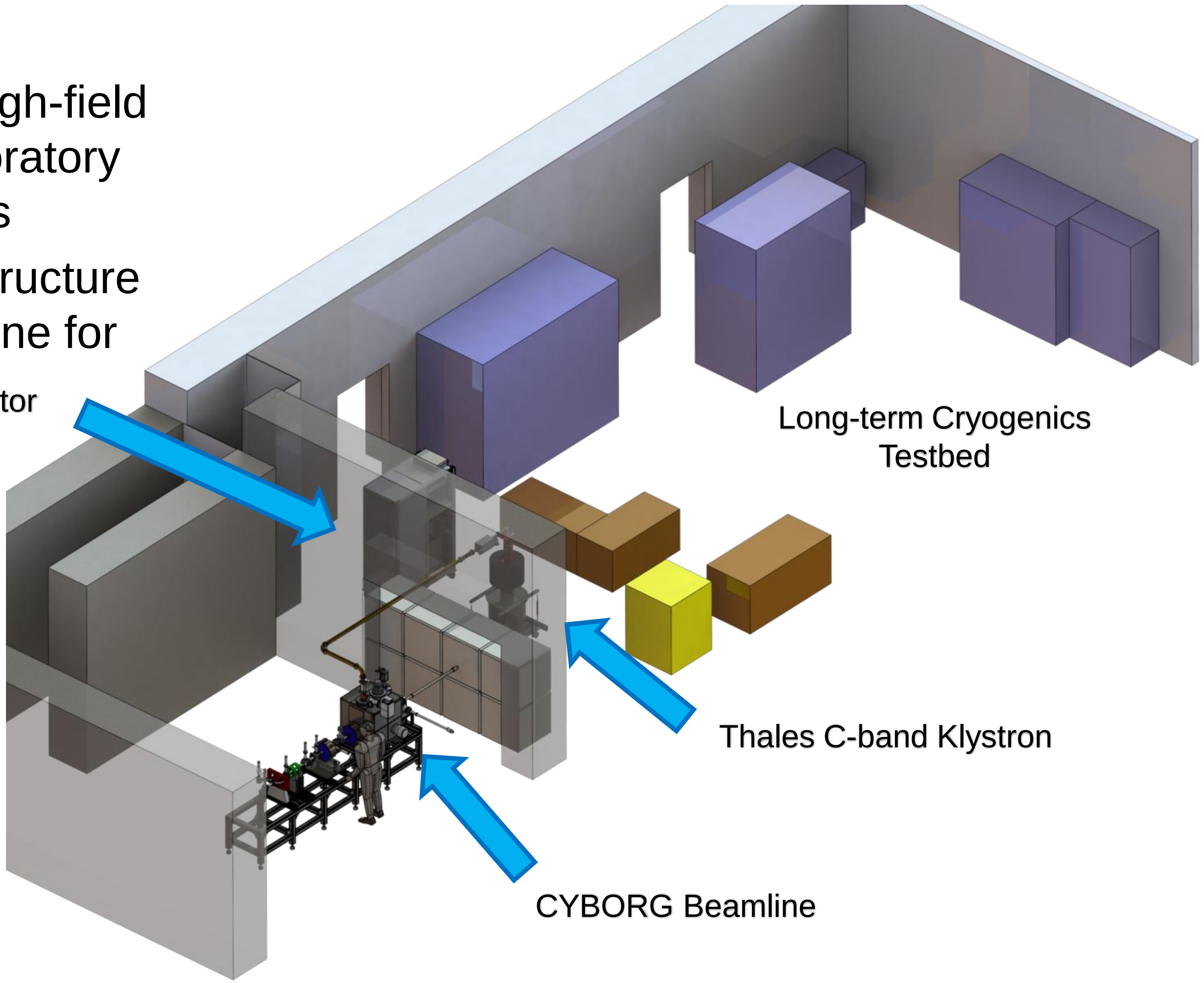


L. Cultrera et al., Appl. Phys. Lett. 103, 103504 (2013).

1) Program Overview

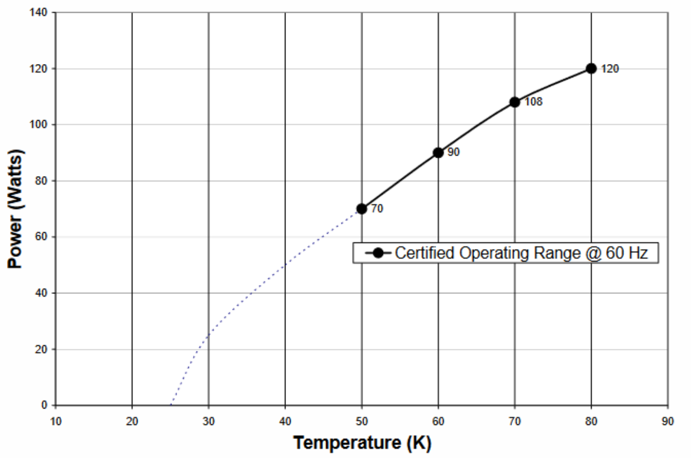
- CYBORG beamline not trivial task
- Robust program at Multi-Option Testing for High-field Radiofrequency Accelerators (MOTHRA) laboratory (right and below) to establish knowledge basis
- Suitable for cryogenics testing; C-band infrastructure development; low energy (single MeV) beamline for cathode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

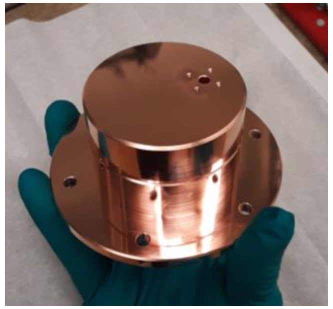




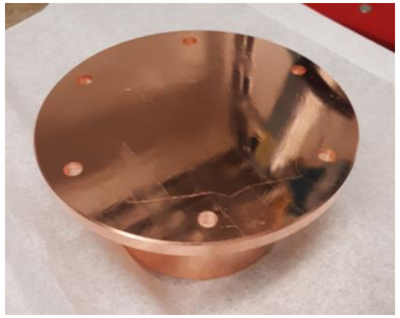
2) Cryostat v1

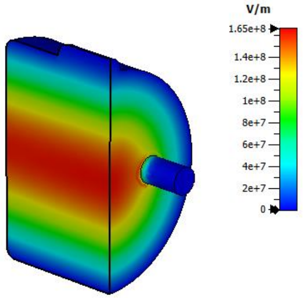
- Small test cryostat for initial cryocooler commissioning; material property studies; and LLRF tests
- C-band pillbox surface resistivity measurements as function of temperature, alloy (CuAg), surface finish etc.
- Helps inform CYBORG simulations (e.g. RF power deposition) which informs operational parameters

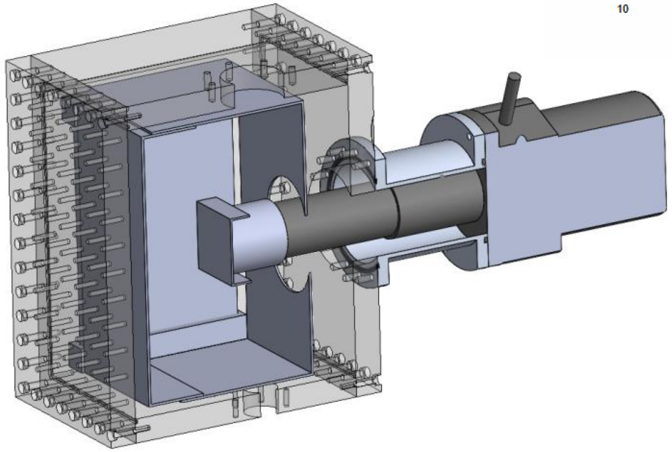




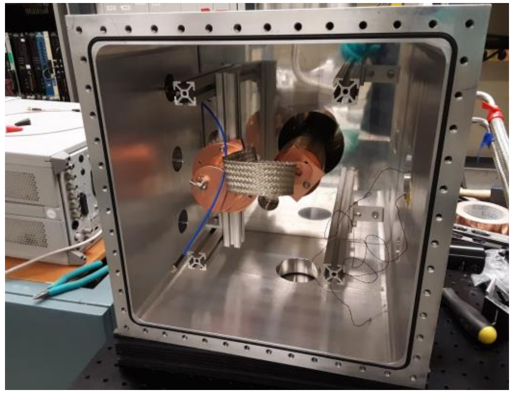
$$Q_0 = \frac{\Gamma}{R_s}$$







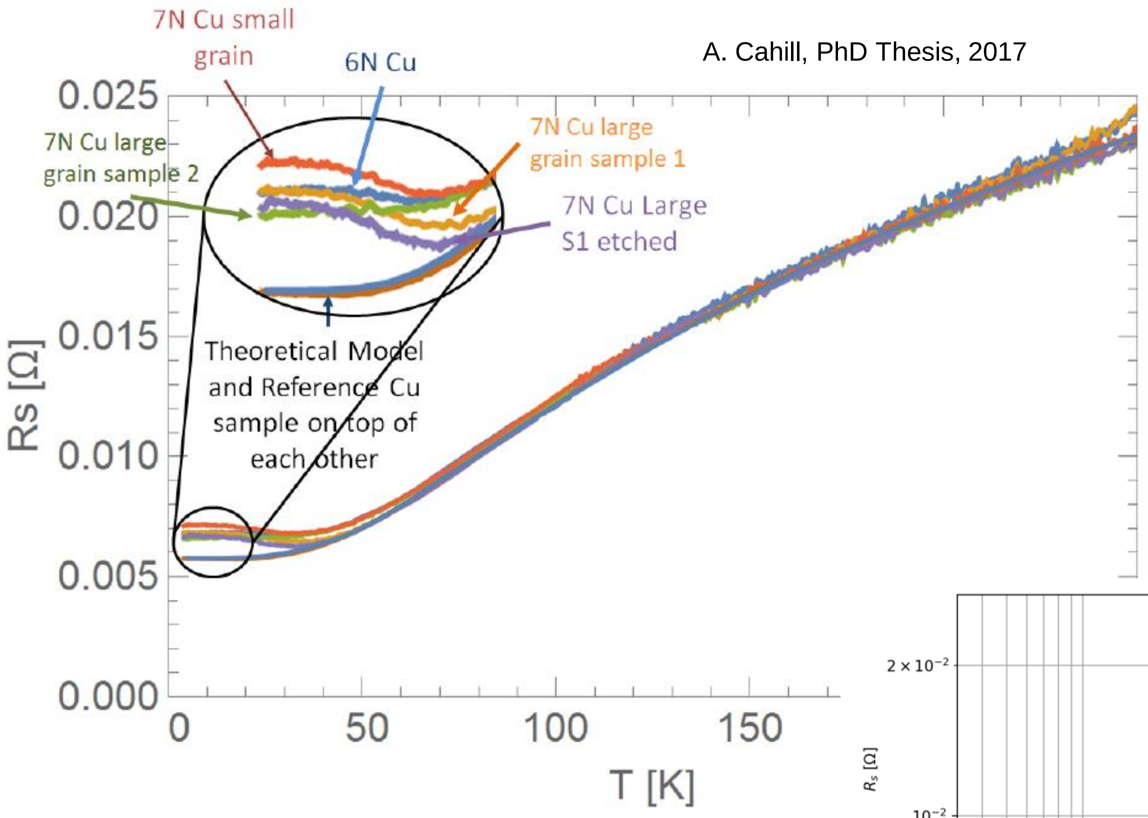
G.E. Lawler, N. Majernik, and J.B. Rosenzweig, Proc. IPAC'21, no. 12, p. 2818–2821, 2021. doi:10.18429/JACoW-IPAC2021-WEPAB098

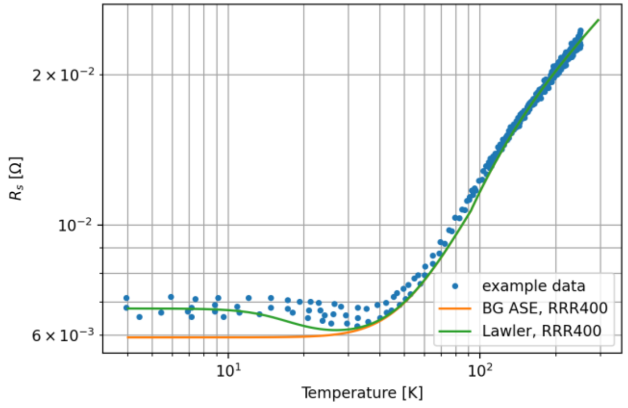


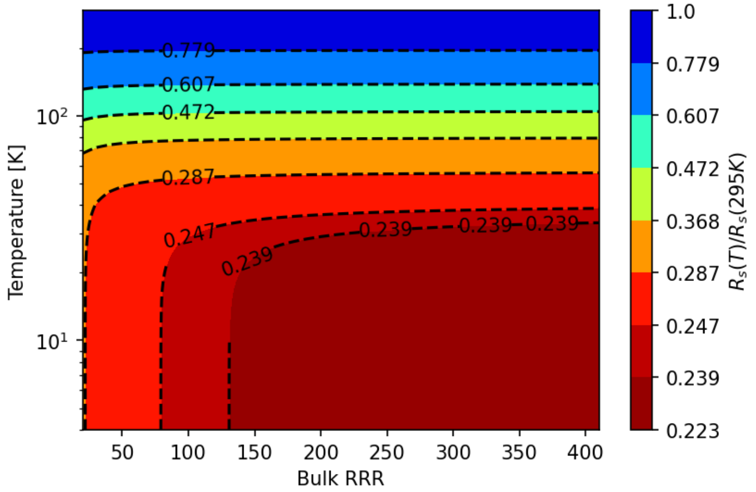
2) LLRF Theory and Motivation

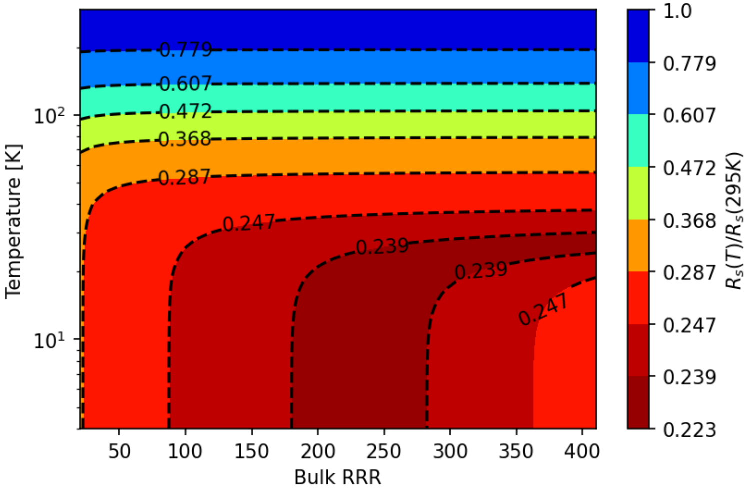
- Copper pillbox cavities used for Cband low level LLRF

A. Cahill, PhD Thesis, 2017





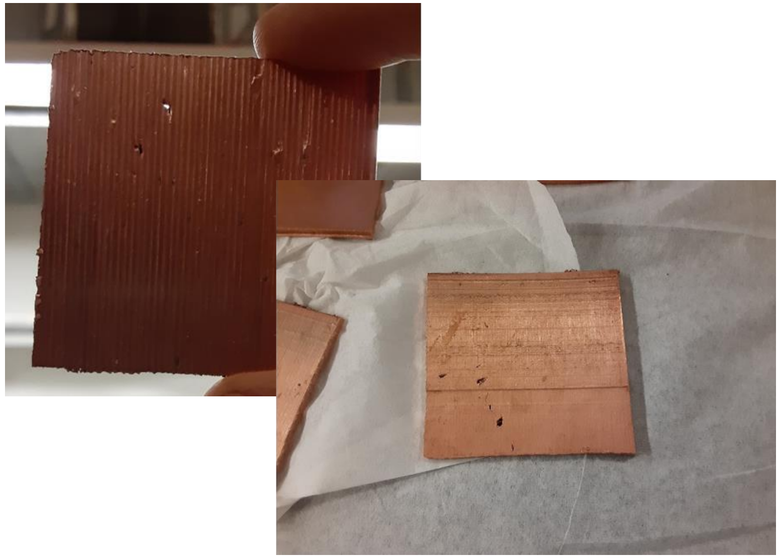


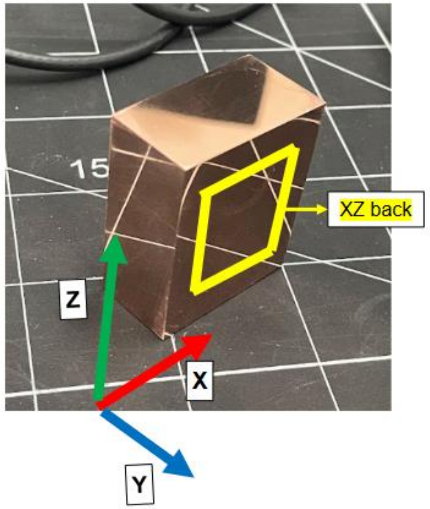


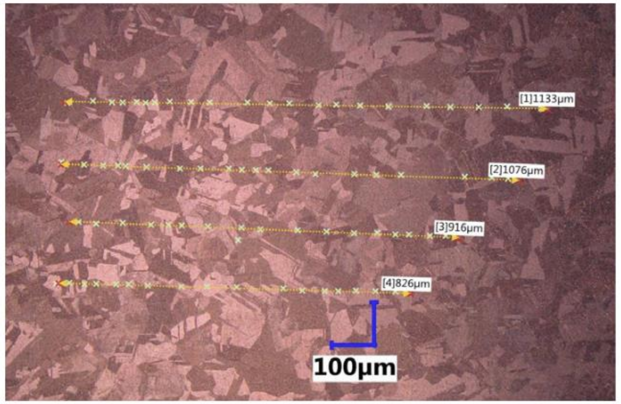
G. Lawler, A. Fukasawa, N. Majernik, and J. Rosenzweig, in Proc. IPAC'22, Bangkok, Thailand, 2022, paper THPOST045, pp. 2540–2543, doi:10.18429/JACoW-IPAC2022-THPOST045

2) Alloy Characterisation

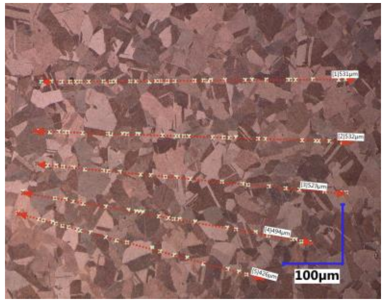
- Hard Cu alloys considered for cavity development
- CuAg alloys received from LANL characterized in collaboration with Radiabeam technologies
- 2% Ag alloy nonideal for high power cavity manufacture
  - Visible surface imperfections
  - 88ppm oxygen content compared to 5 ppm for OFE Cu
- 0.08% Ag alloy of continued interest
  - No porosity in coupon (upper right)
  - Next round of LLRF test will study alloy at cryogenic temperatures as well







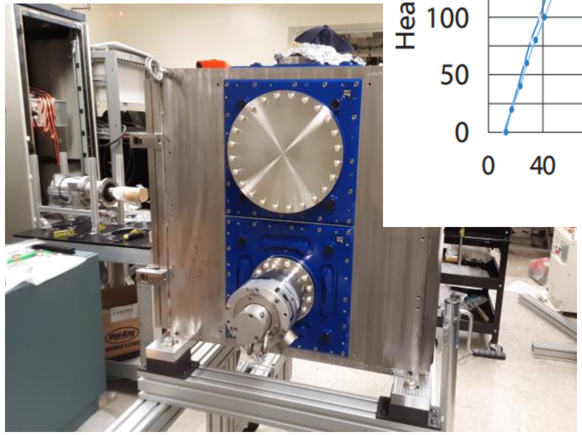
For 0.08% Ag grain size diameter of 121 ± 20um

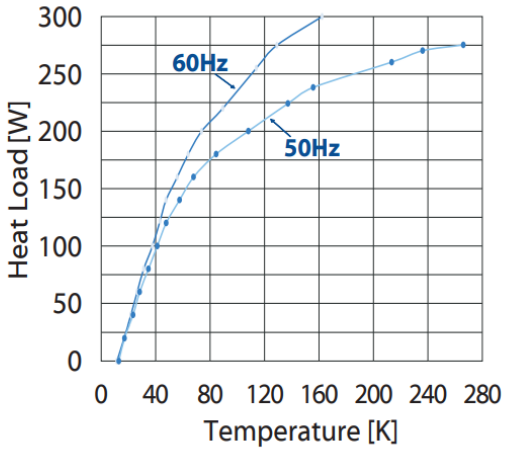


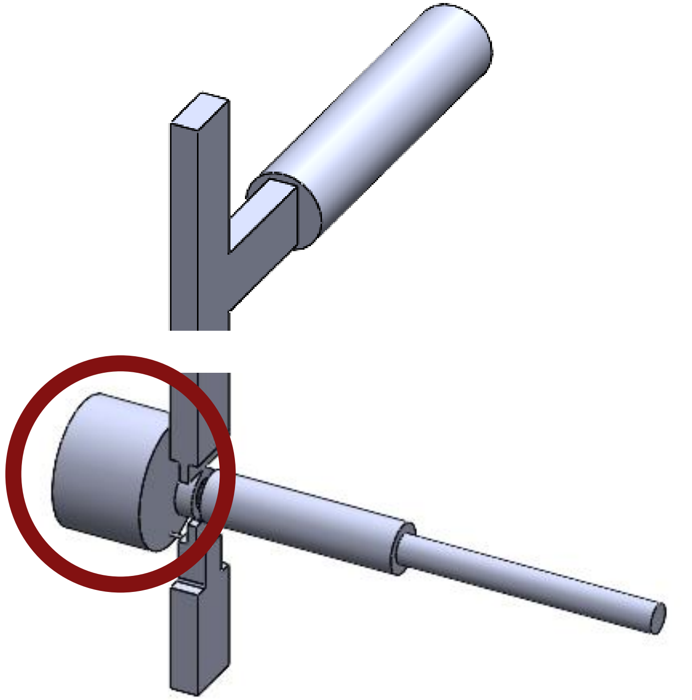
For 2% Ag grain size diameter of 106 ± 20um

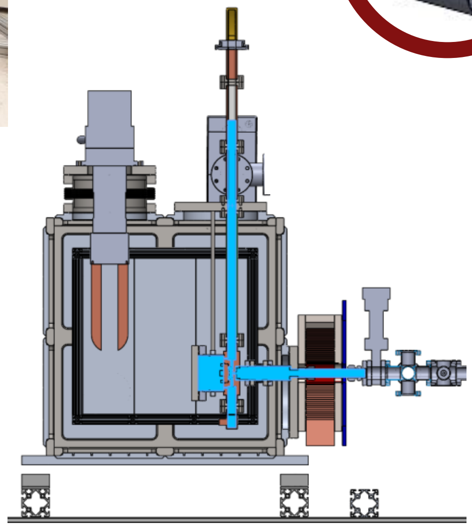
2) Cryostat v2

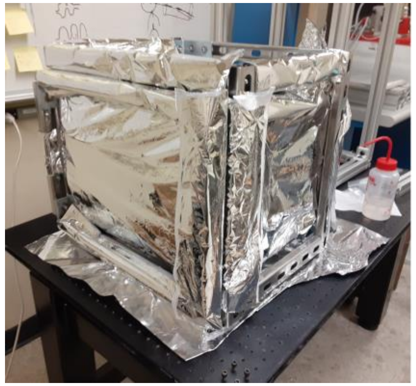
- Much larger cryostat needed for CYBORG with waveguide, beam pipe etc.
- Many considerations to consider
- Size of chamber, multiple layer insulation needed for radiation shielding, nested UHV vacuum chamber far from easy pumping locations, cryocooler power limitations, etc.







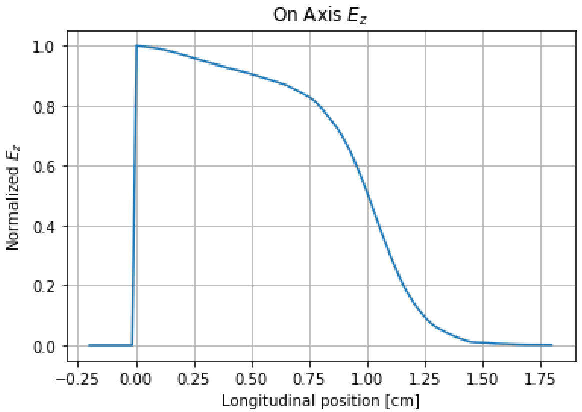




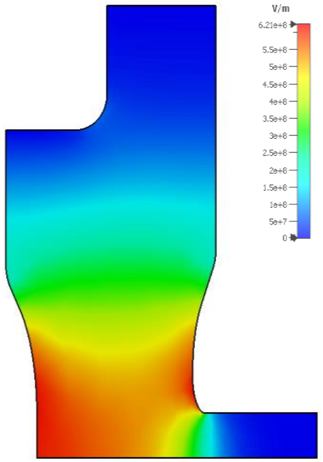
3) Photogun specifications

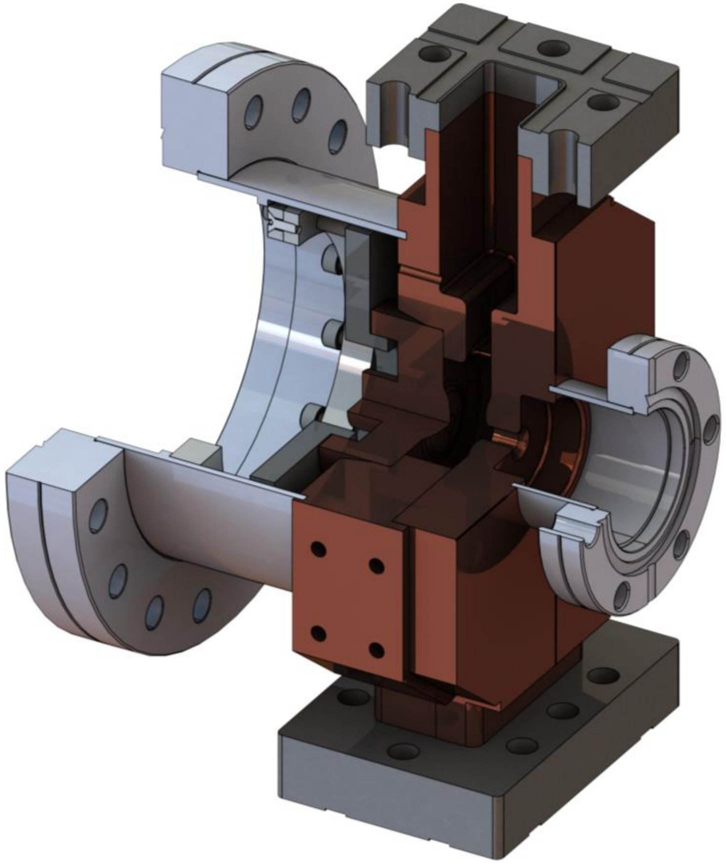
- Reentrant cavity with high shunt impedance
- Cryogenic temperature provided RF stability and cathode studies
- 2.9 factor improvement of Q_0 from 300K to 77K
- Cancel quadrupole moment

Parameters	Value
Launch field	>120 MV/m
Operating temp	295K down to < 65K
Cavity frequency @	5.710 GHz
Beta	4 @ 77K
Q_ext	6056
Q_0	24750



E field magnitude

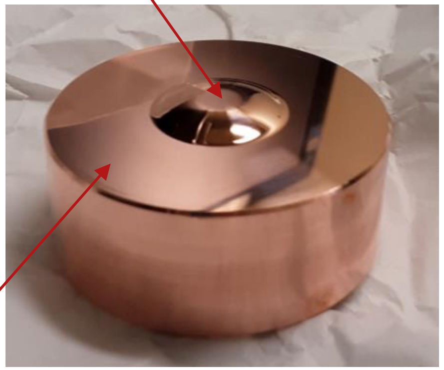


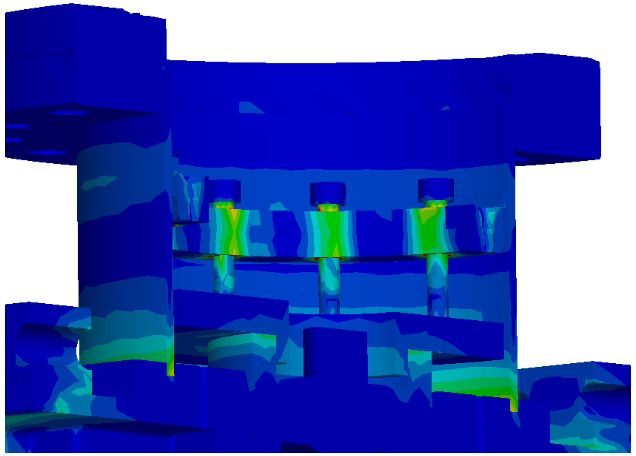


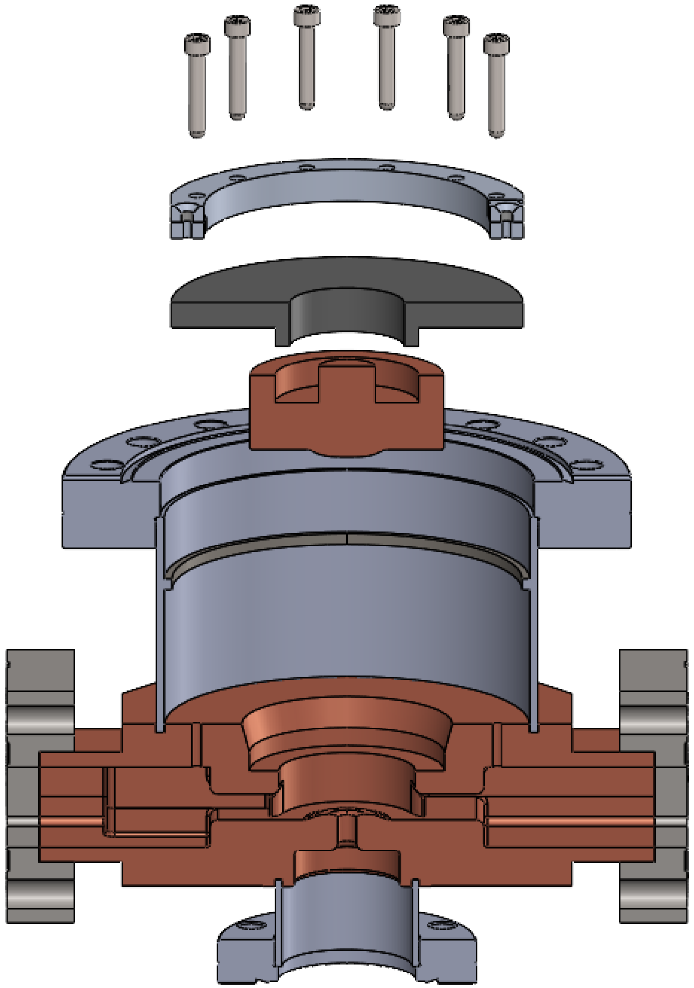
G. E. Lawler et al., Proc. IPAC'22, no. 13, p. 2544–2547, 2022.
doi:10.18429/JACoW-IPAC2022-THPOST046

3) Phase1 Cathode

- Phase1 of CYBORG Cu cathode tests
- Cathode backplane press fit to begin
- Functional at Elettra lab in Trieste, Italy for FERMI seeded FEL
  - Uses high gradient BNL/SLAC/UCLA 1.6 cell electron gun
- Slow exchange not intended for final cathode testing but allows versatility with respect to cathode load lock integration







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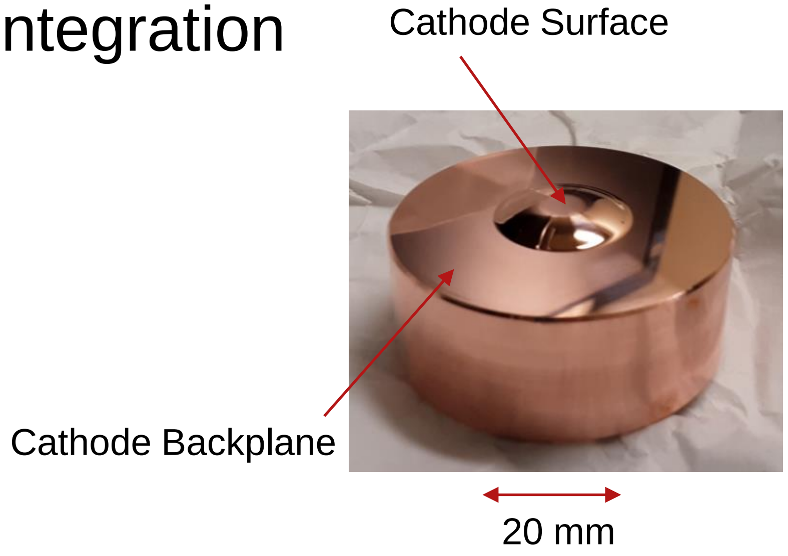

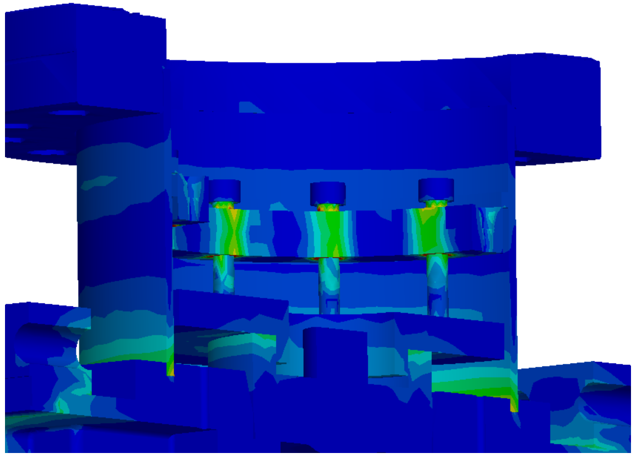

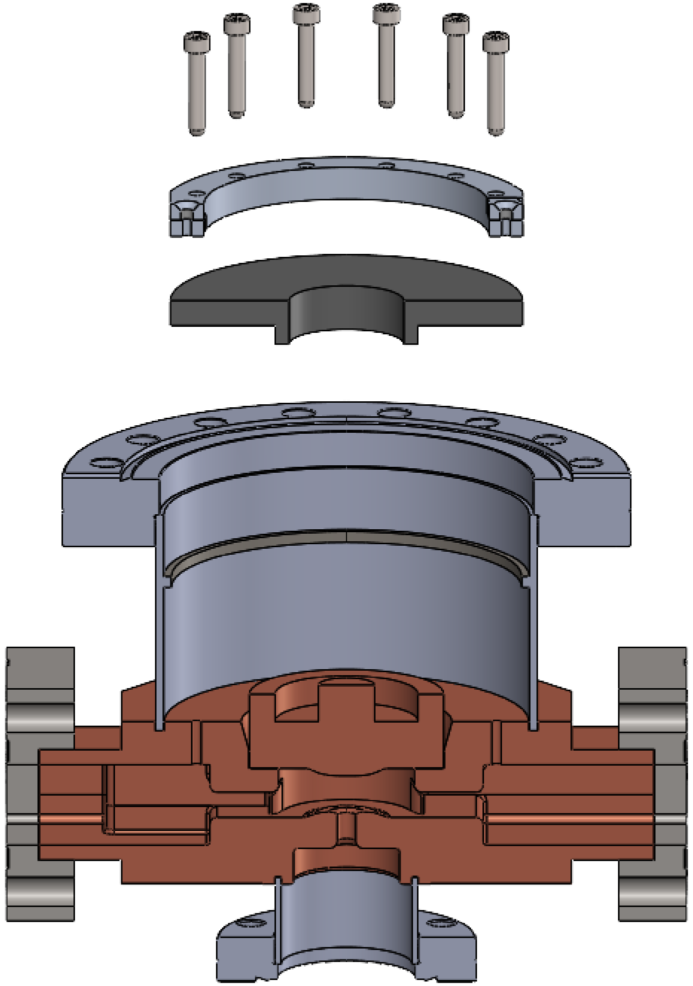

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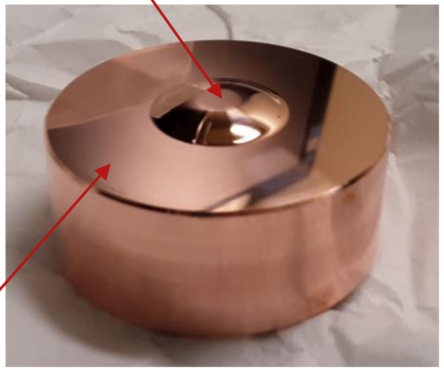
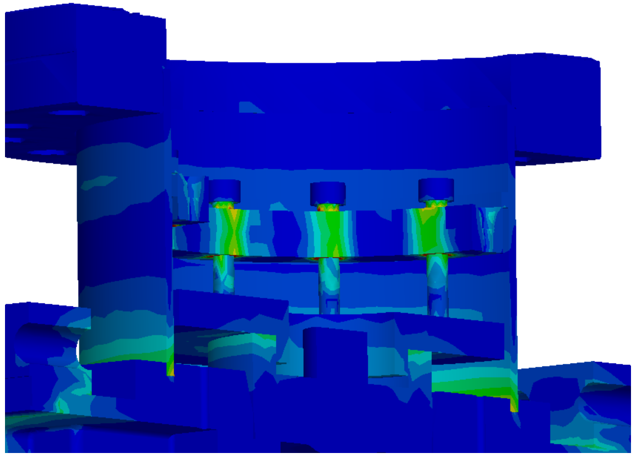
Cathode Surface

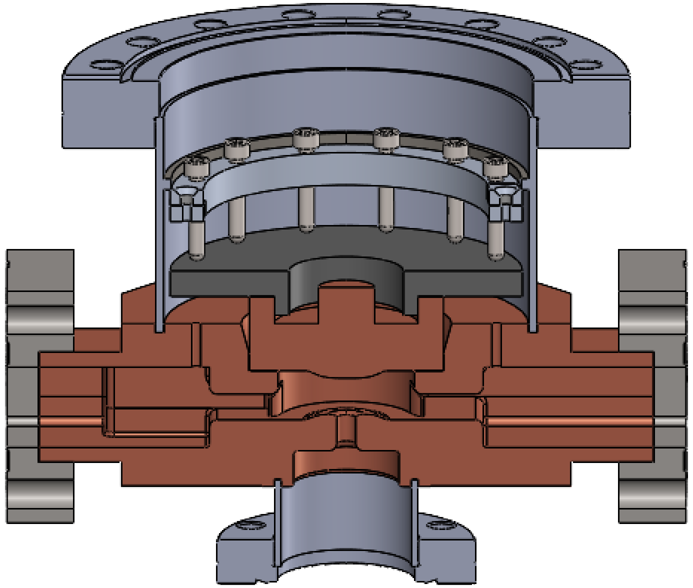


Cathode Backplane

20 mm



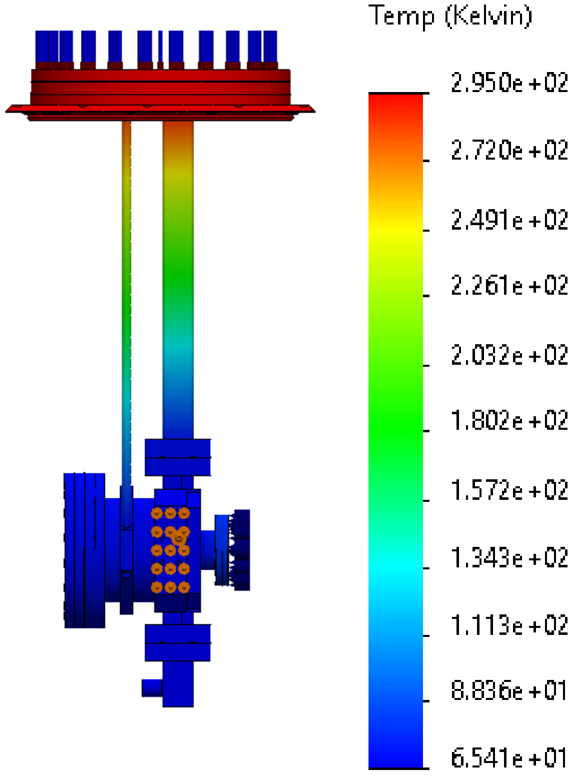
For use in Phase1

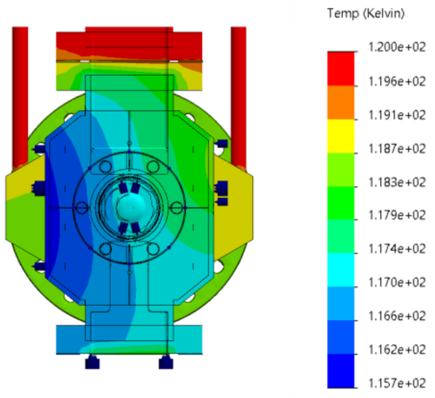


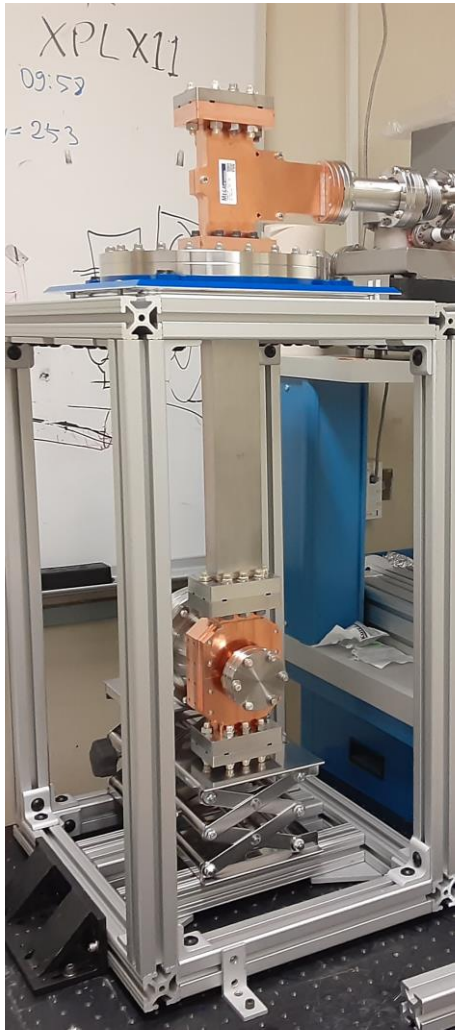
3) Thermal Balancing

- 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

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			

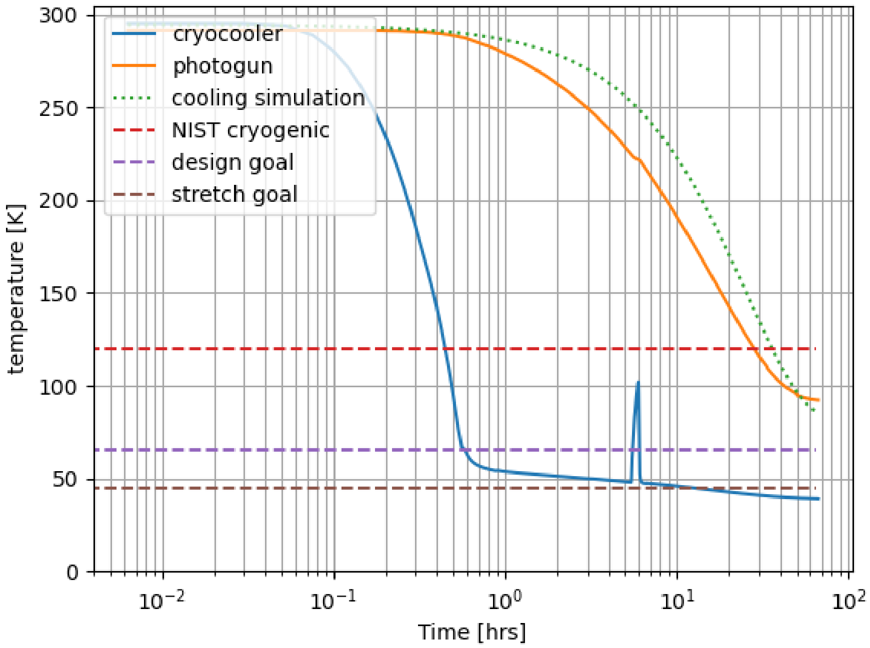


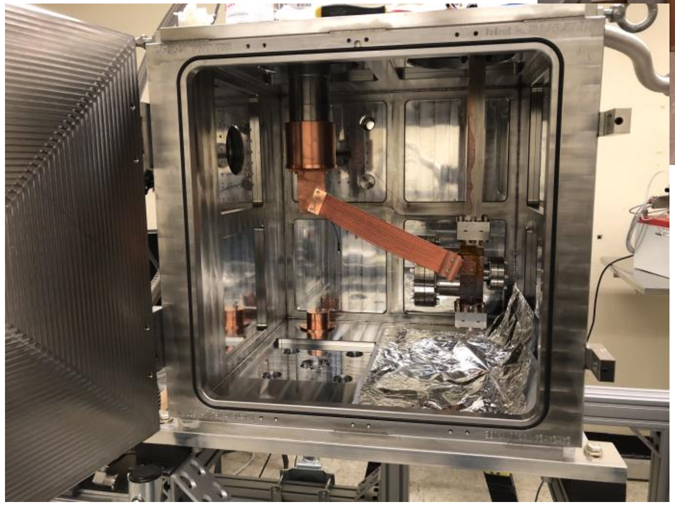


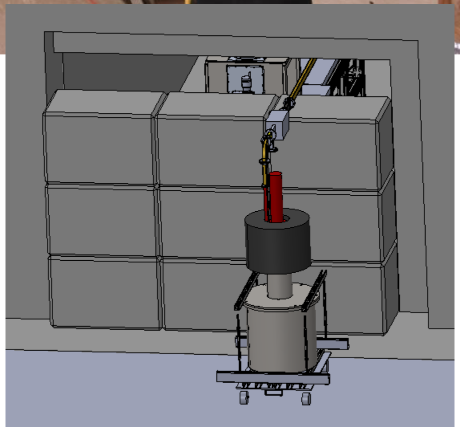


3) Commissioning status

- Cavity down to approx. 90K w/ improvements planned
- Sufficient for Phase1 copper cathode studies
- New radiation bunker wall in place for high power gun testing

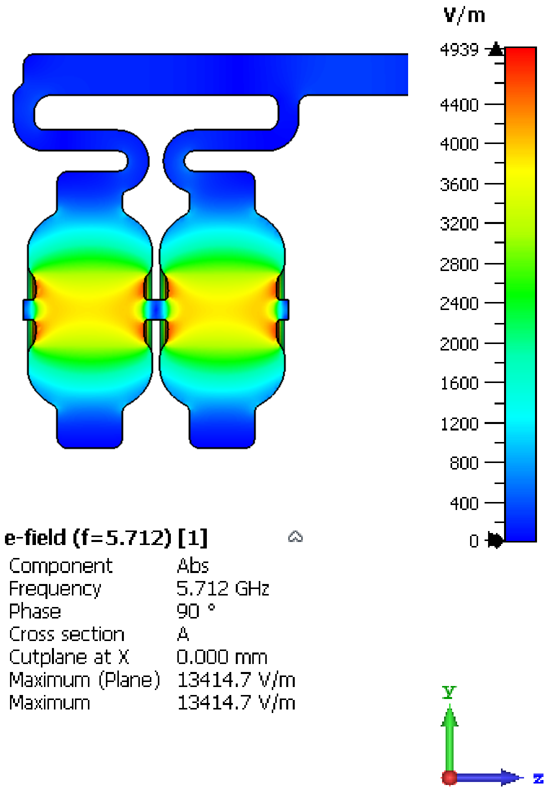


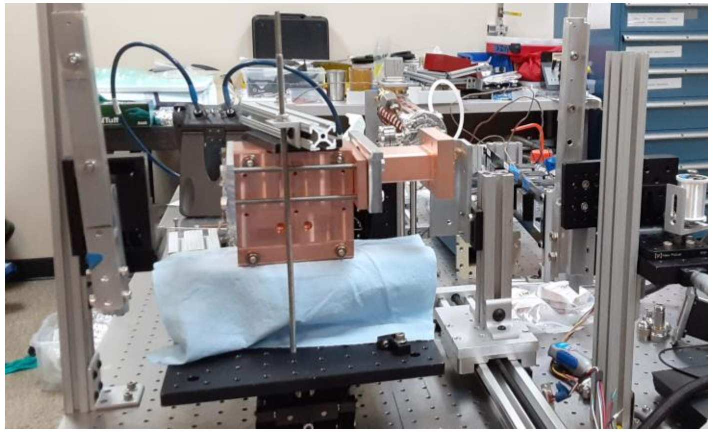


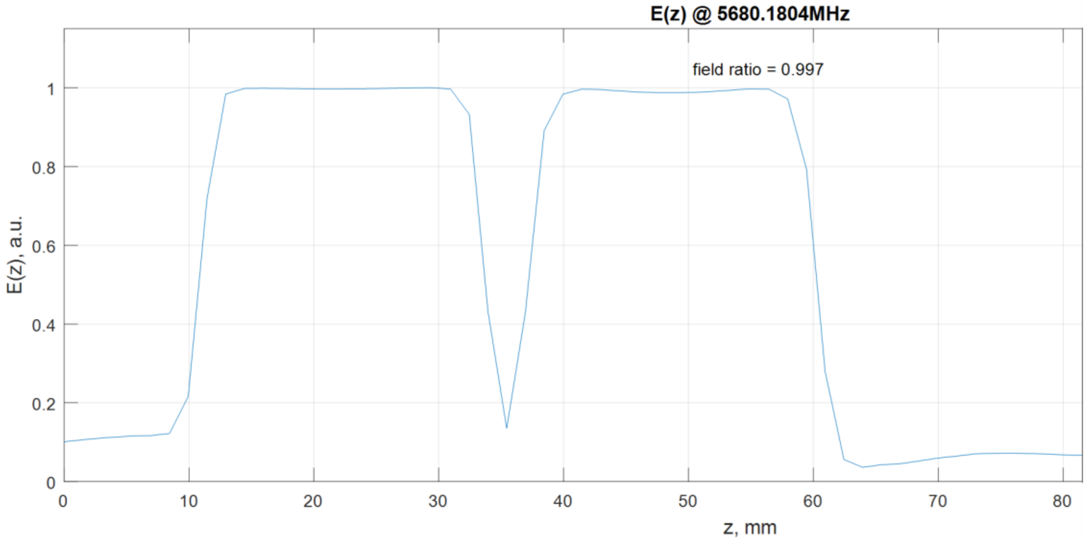


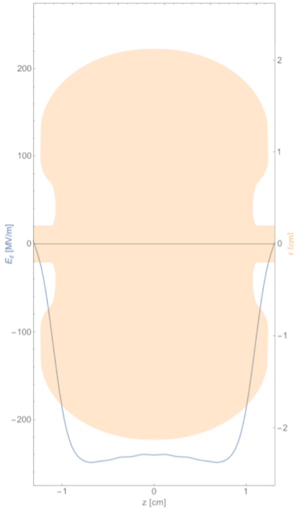
3) Breakdown limit test cavities

- Create test bed for hosting multiple different experiments into various structures and material alloys
  – Brazeless joint testing, copper-silver and more exotic alloys perhaps w/ Mo etc.
- Logic of cryogenics, assembly, and general diagnostics for actual experiments
- Example here using 2 cell distributed-coupling in Cband (to right)
- Full cell cavity geometry chosen for future UCXFEL photoinjector





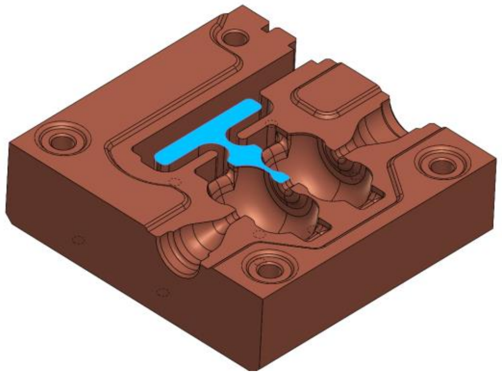


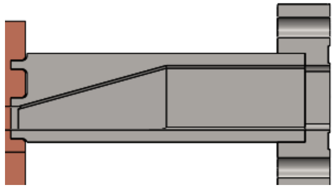


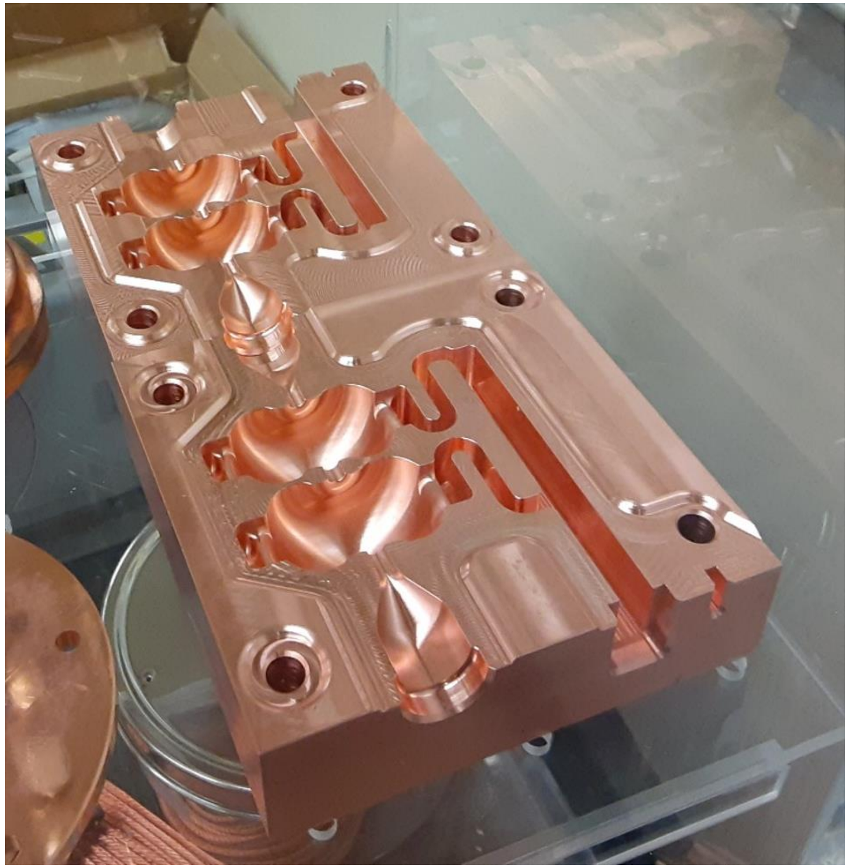
R. Robles et al., Phys. Rev. Accel. Beams, vol. 24, no. 6, p. 063401, 2021. doi:10.1103/PhysRevAccelBeams.24.063401

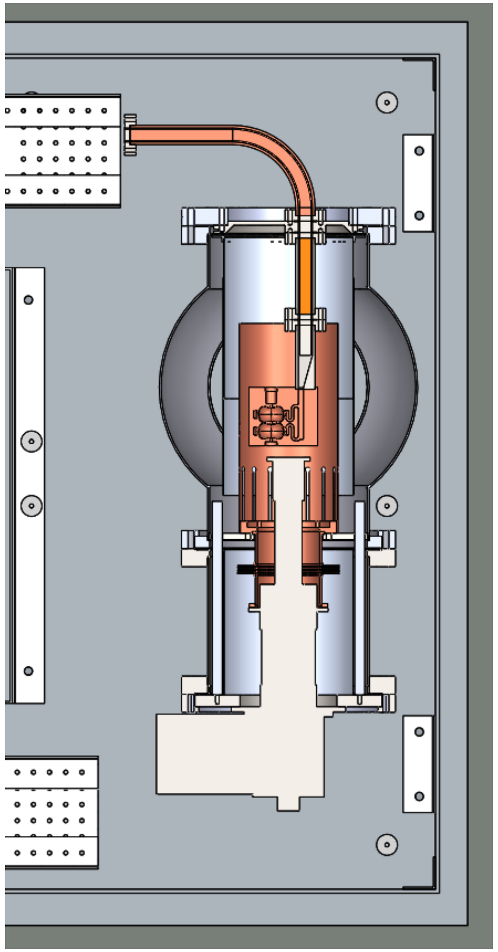
3) Breakdown limit test cavities

- Initial design for cryostat in LANL high power testing facility
- SLAC reentrant cavity design considered for linacs and photoinjector require novel shapes making bonding difficult
  - Esp. central iris surface (blue highlight)
  - Process/technique development ongoing
- Additional student-led novel diffusion bonding technique under development in parallel for future cavity tests



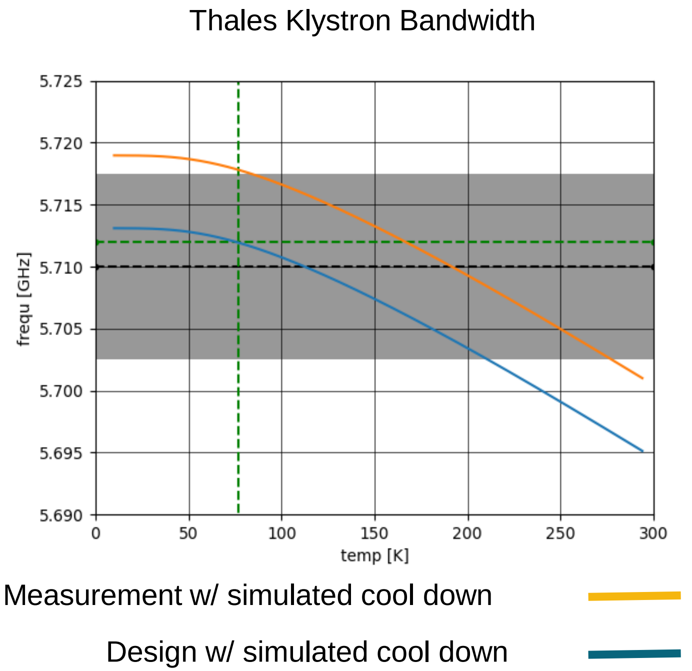


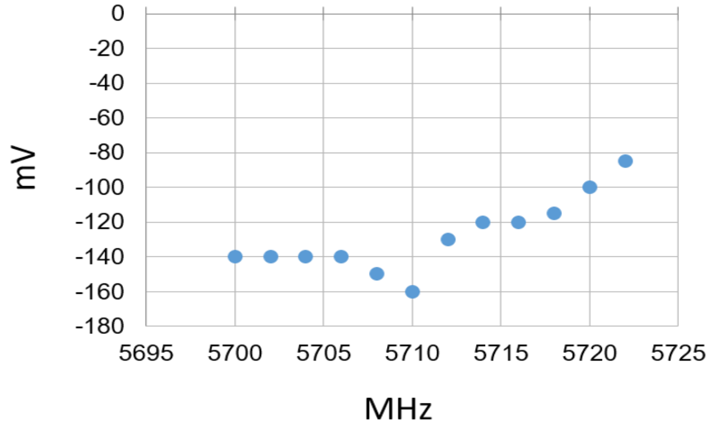


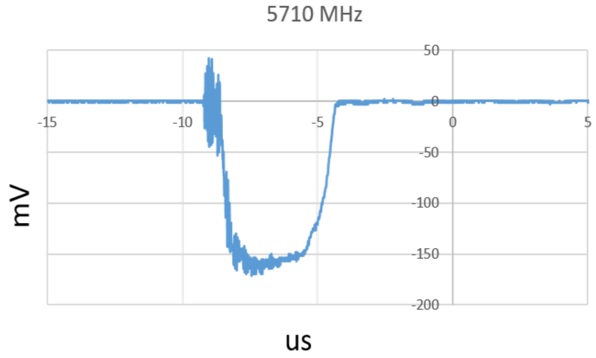


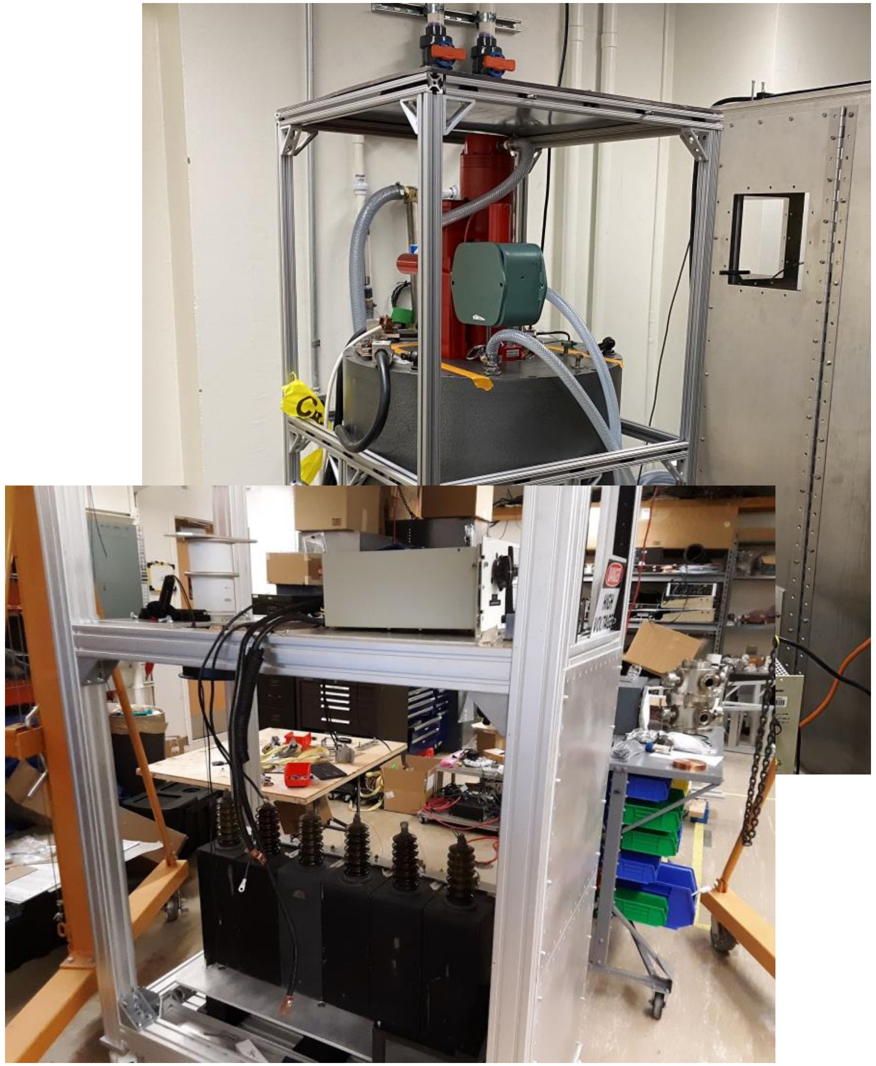
3) Cband RF Power

- Resurrected Thales C-band klystron to single MW power sufficient for 1st cryogenic beamline (right)
- In-house built modulator for C-band completed and functioning nominally
- Measured bandwidth greater than spec allowing full temperature range CYBORG operation
- Possible C-band SLED development in collaboration with SLAC



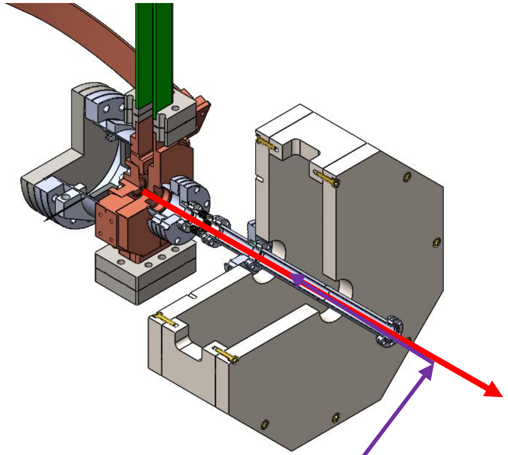


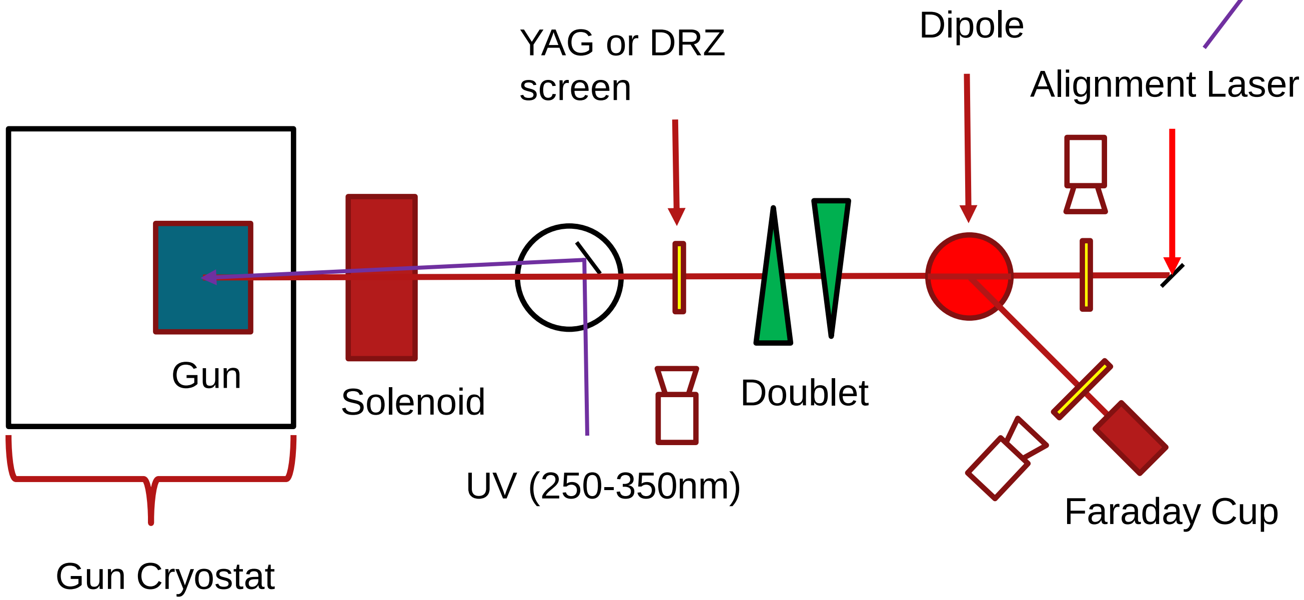


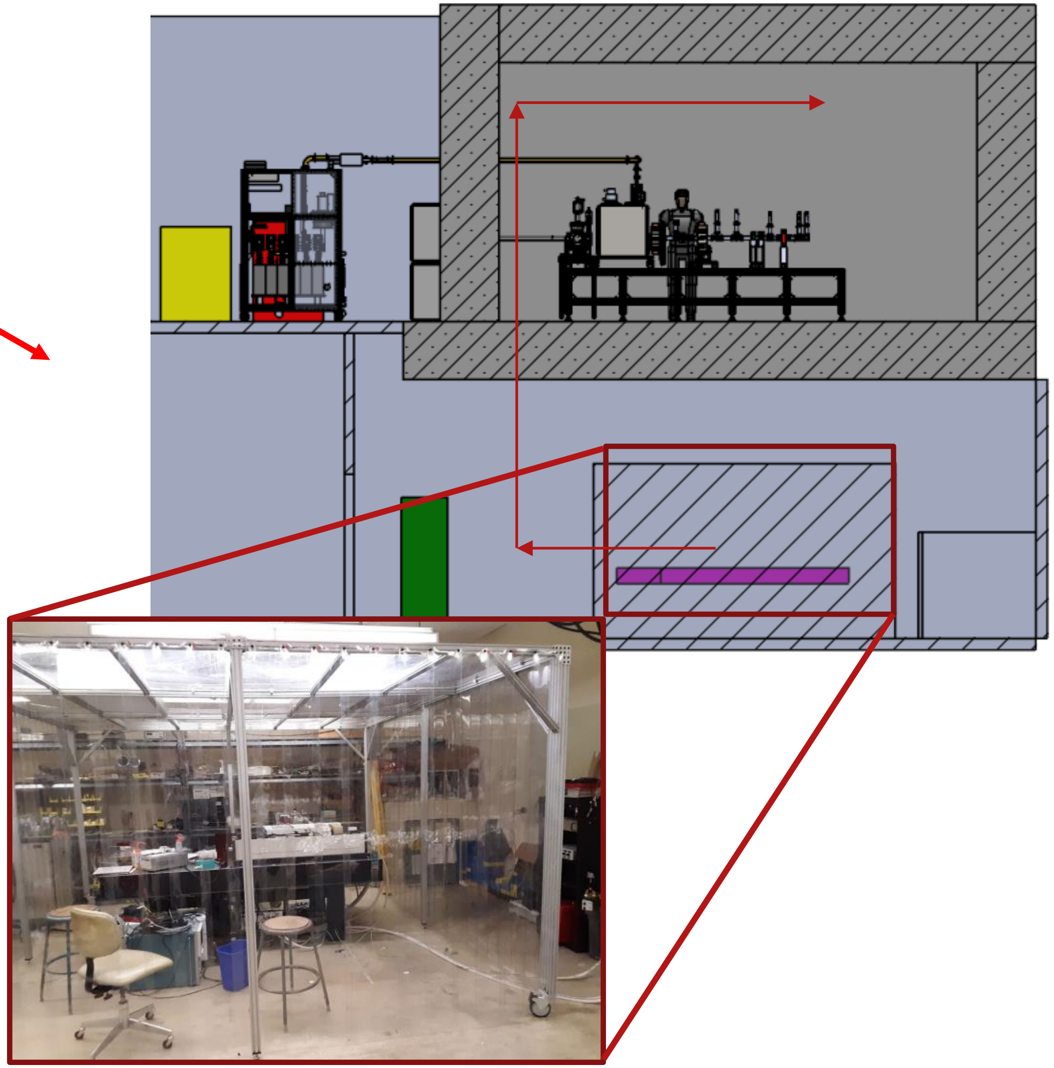


3) Phase1 Beamline

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

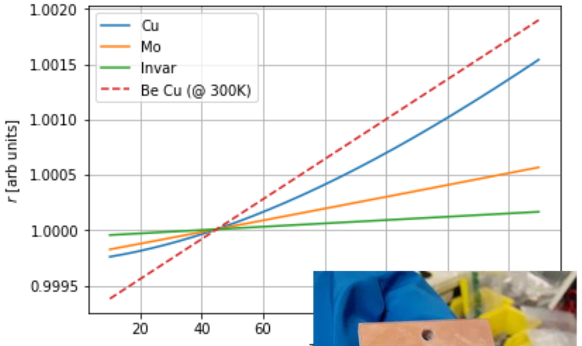


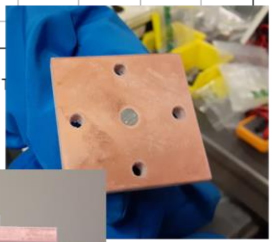


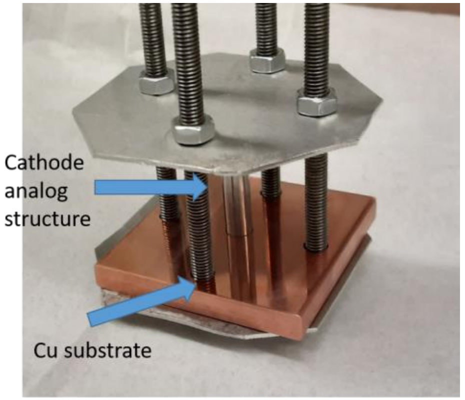


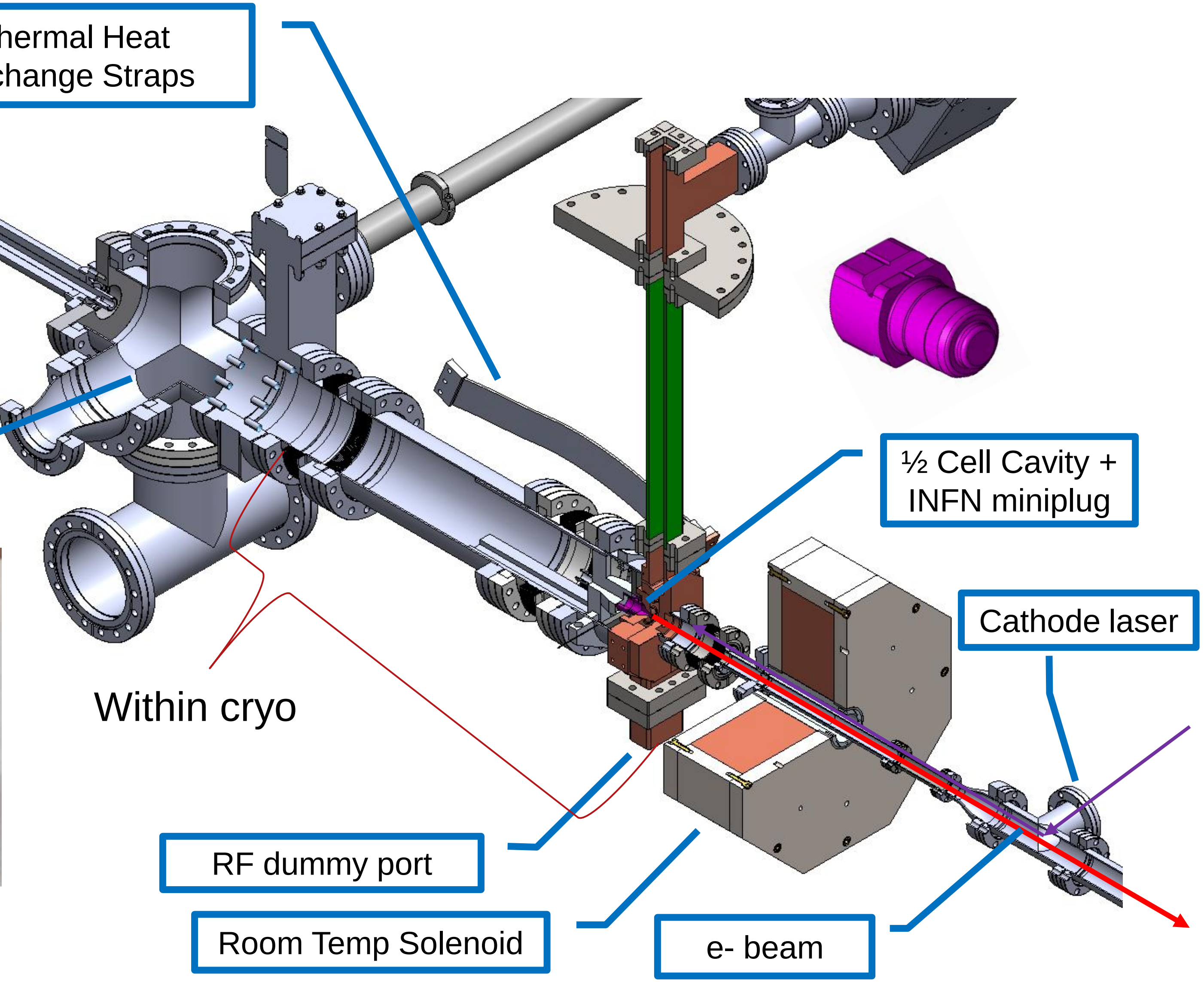
4) Phase2 CYBORG

- load lock in gun section (schematic lower right)
- 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
- Slight INFN minipuck mod needed



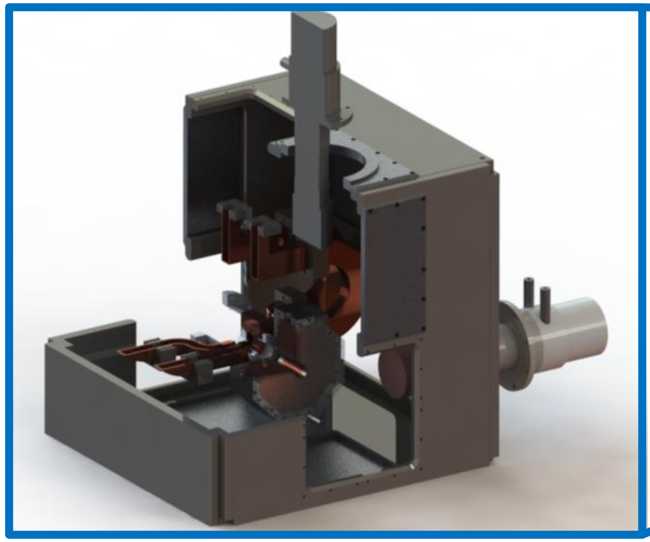


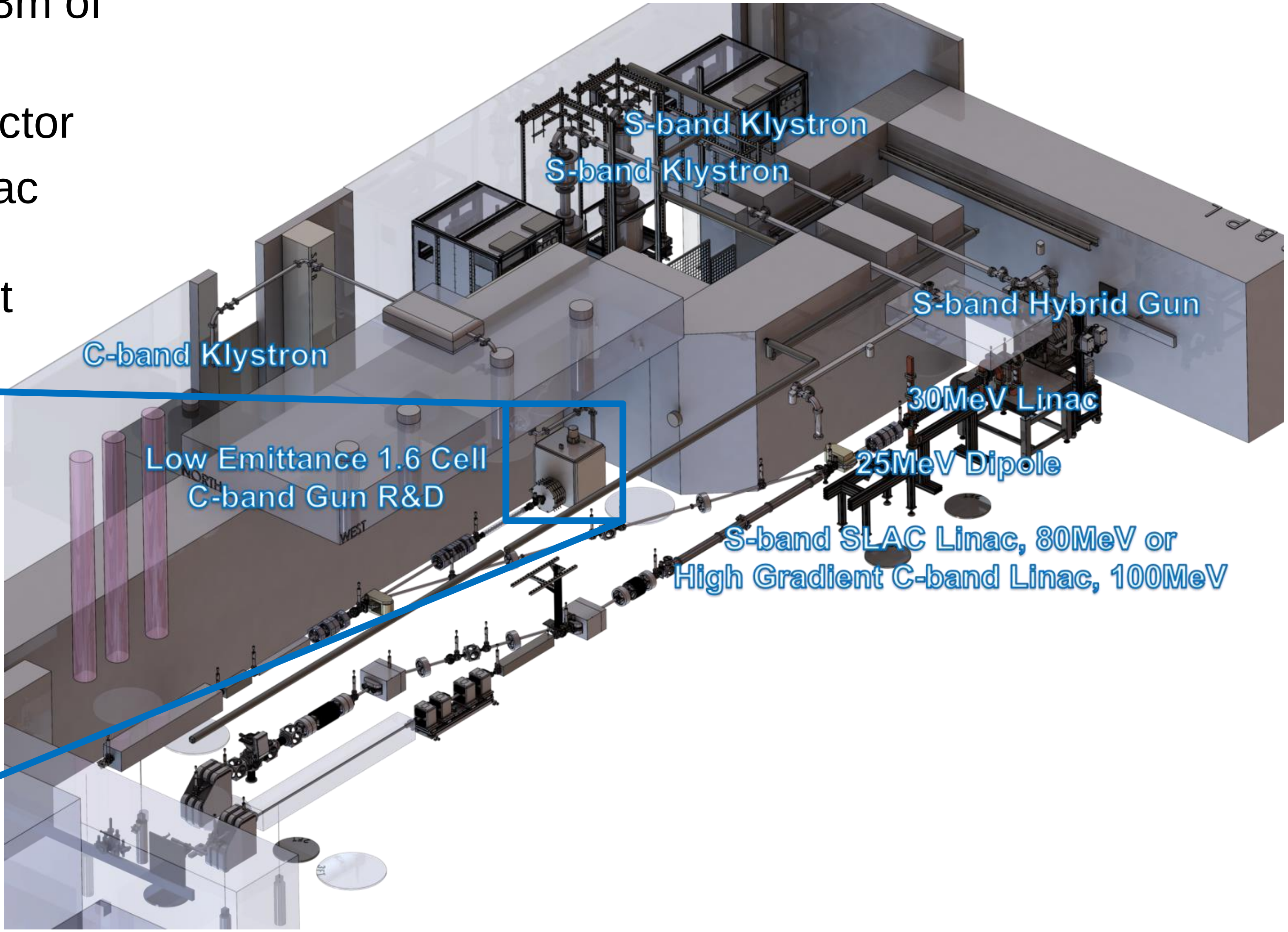




4) MITHRA Lab

- 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 demonstrator FELs; C-band high gradient photoinjector research





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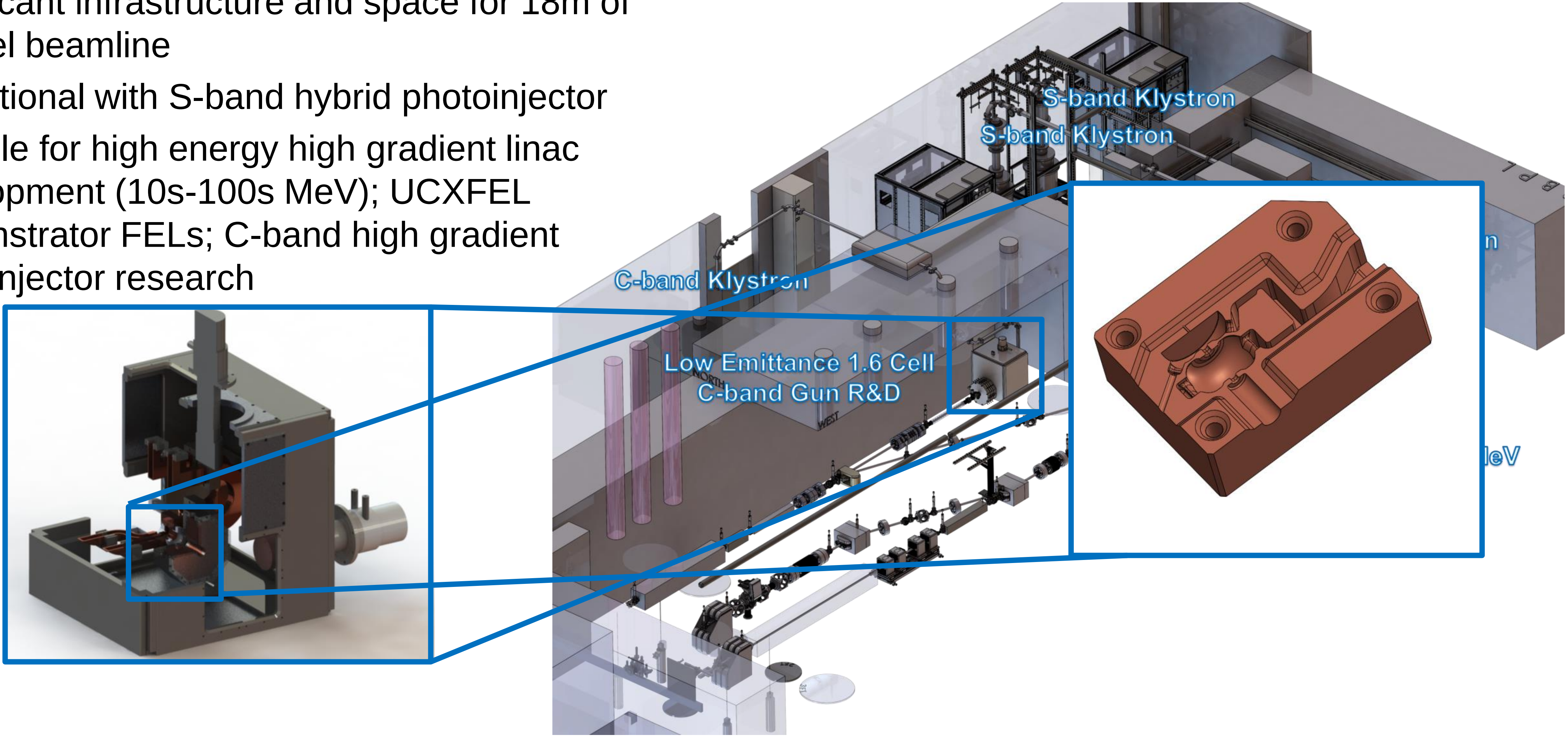

5) Conclusions

1. Not meant to be exhaustive or too in depth but to idea of breadth of UCLA research
2. CYBORG next step in long line of bright photogun work at UCLA
3. MOTHRA lab developed as robust testing ground for building pragmatic knowledge base necessary for normal conducting cryogenic cavity-based beamline commissioning
4. Lessons learned and future research trajectory important for future linac concepts such as UCXFEL and C^3

Collaborators

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- Paul Carriere, Nanda Matavalam
- Evgenya Simakov, Anna Alexander, Petr Anisimov, Haoran Xu
- Martina Carillo
- Zenghai Li, Sami Tantawi, Nathan Majernik
- Andrea Mostacci, Bruno Spataro