Material Physics Testing for High Gradient Cavities at CYBORG Beamline

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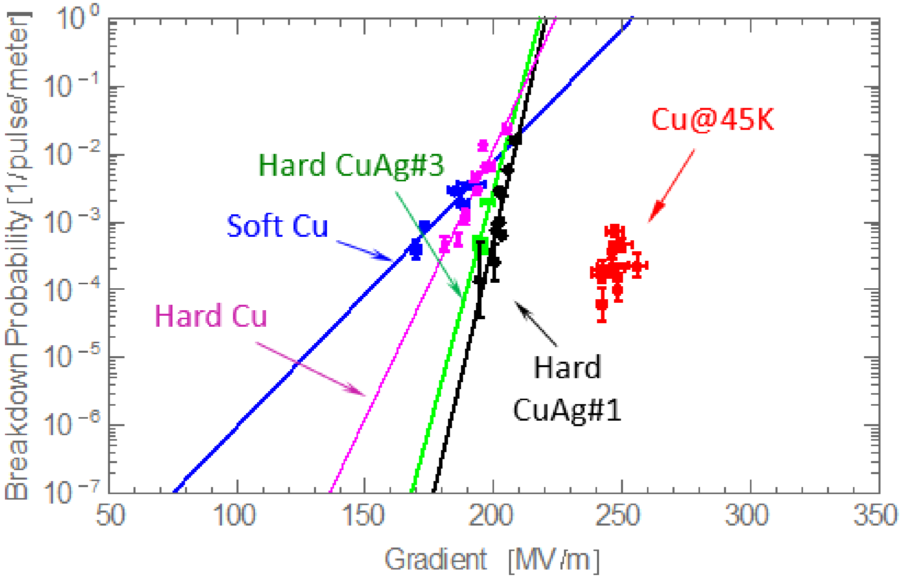
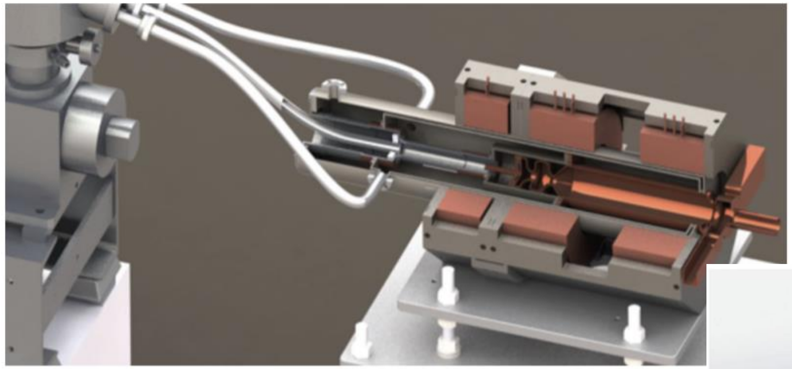
Outline of presentation

1. Background and motivation
2. CYBORG beamline overview
3. Material physics
   a) LLRF
   b) High power RF
4. Future testing/discussion
5. Conclusions

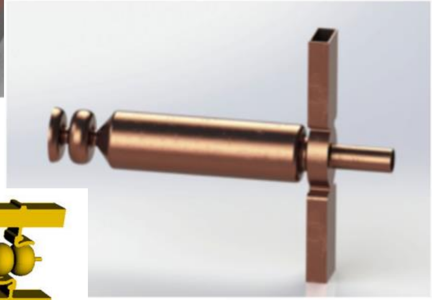
1) Background

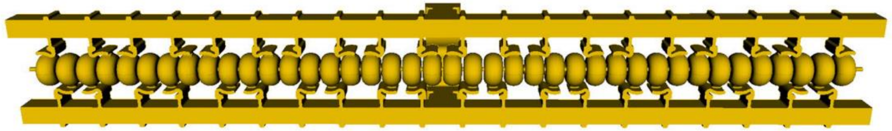
- Significant interest in photoinjector; wakefield; fundamental high field physics
- Broad interest in high gradient cavity development with focus on brightness
- SLAC cryogenic breakdown reduction ⇒ higher accelerating gradients possible
- TopGun previous development in S-band
- More cryo manageable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

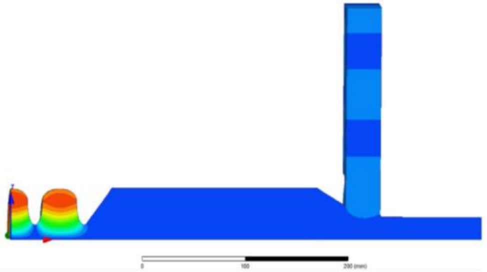




$$B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c}\left(E_0 \sin\varphi_0\right)^2$$





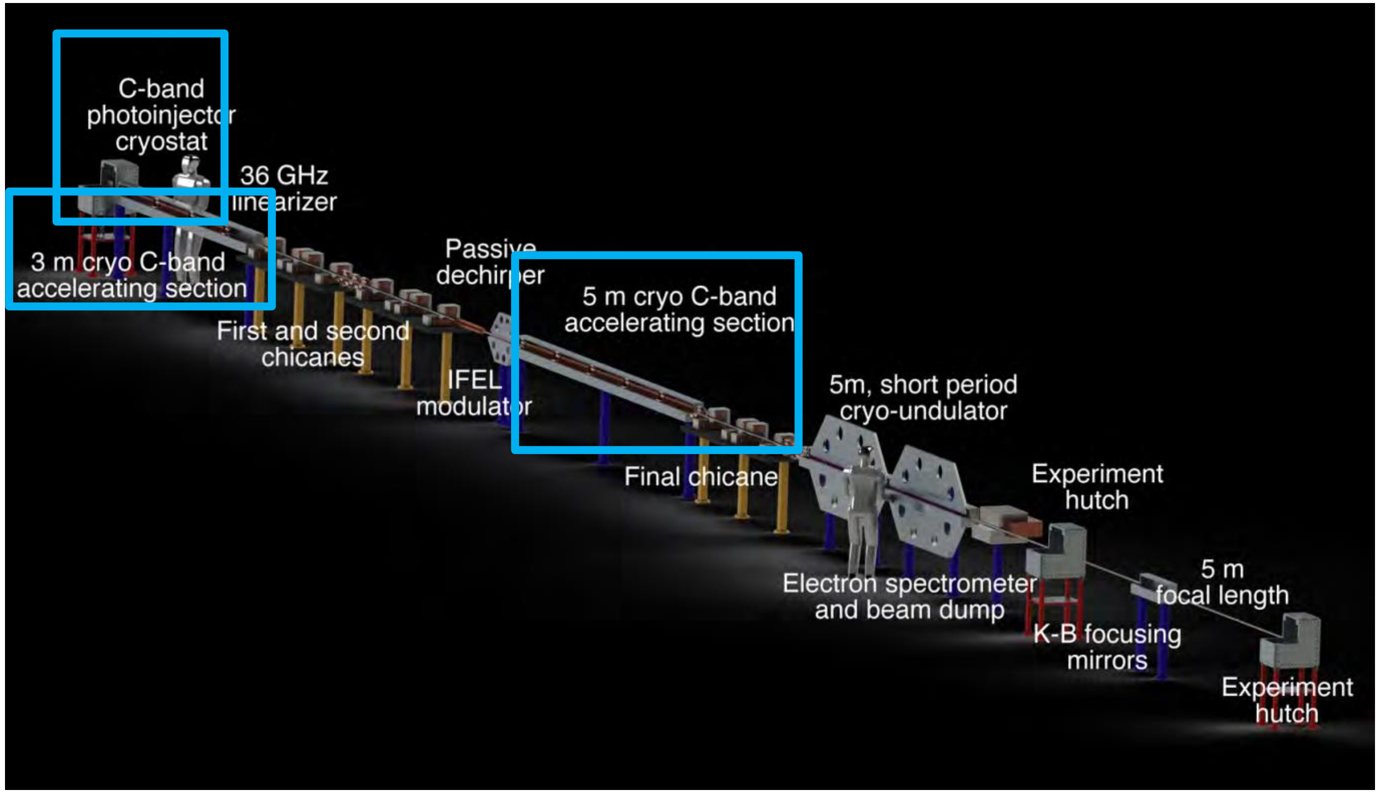


Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources
JB Rosenzweig, et al. - Physical Review Accelerators and Beams, 2019

1) CYBORG Function 1

- For university scale we want simplest NC RF beamline integration using CrYogenic Brightness Optimized Radiofrequency Gun (CYBORG)

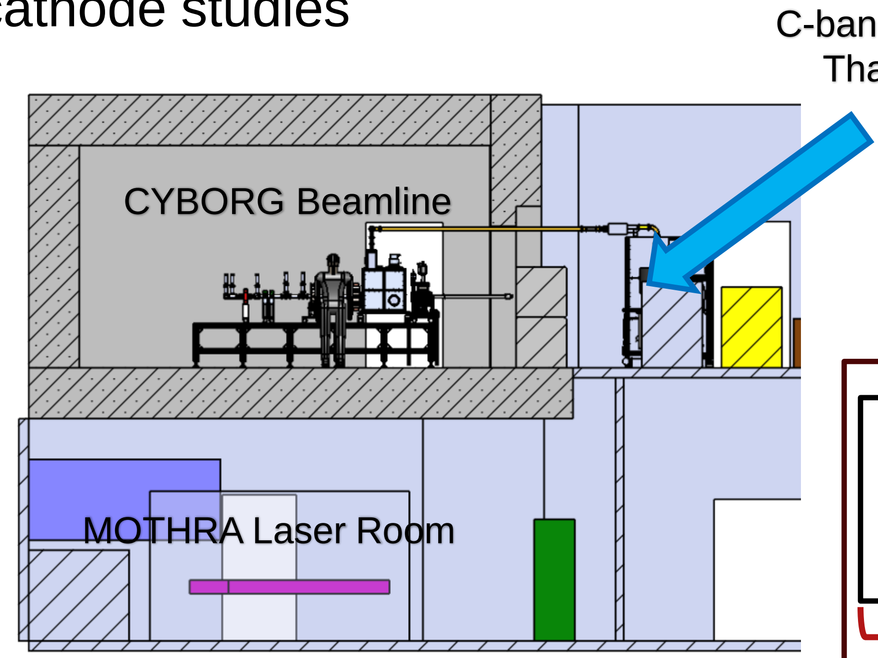
1. Ultra-high gradient photoinjector prototype (UCXFEL right)
   1. Integrated infrastructure template
   2. Cathode load-lock development
   3. RF prototype, black plane etc.
2. Cryogenic emission physics testing:
   1. Dedicated high gradient RF test stand for cathodes incl. novel semiconductors
 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

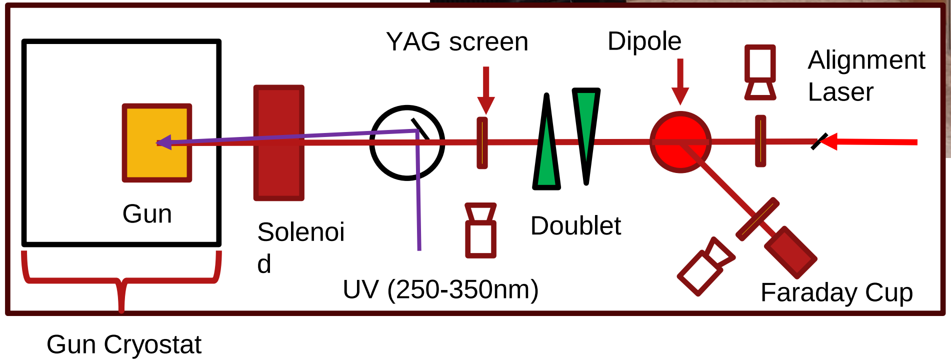


J. Rosenzweig et al., New Journal of Physics, vol. 22, no. 9, p. 093067, 2020. doi:10.1088/1367-2630/abb16c

2) CYBORG-MOTHRA Overview

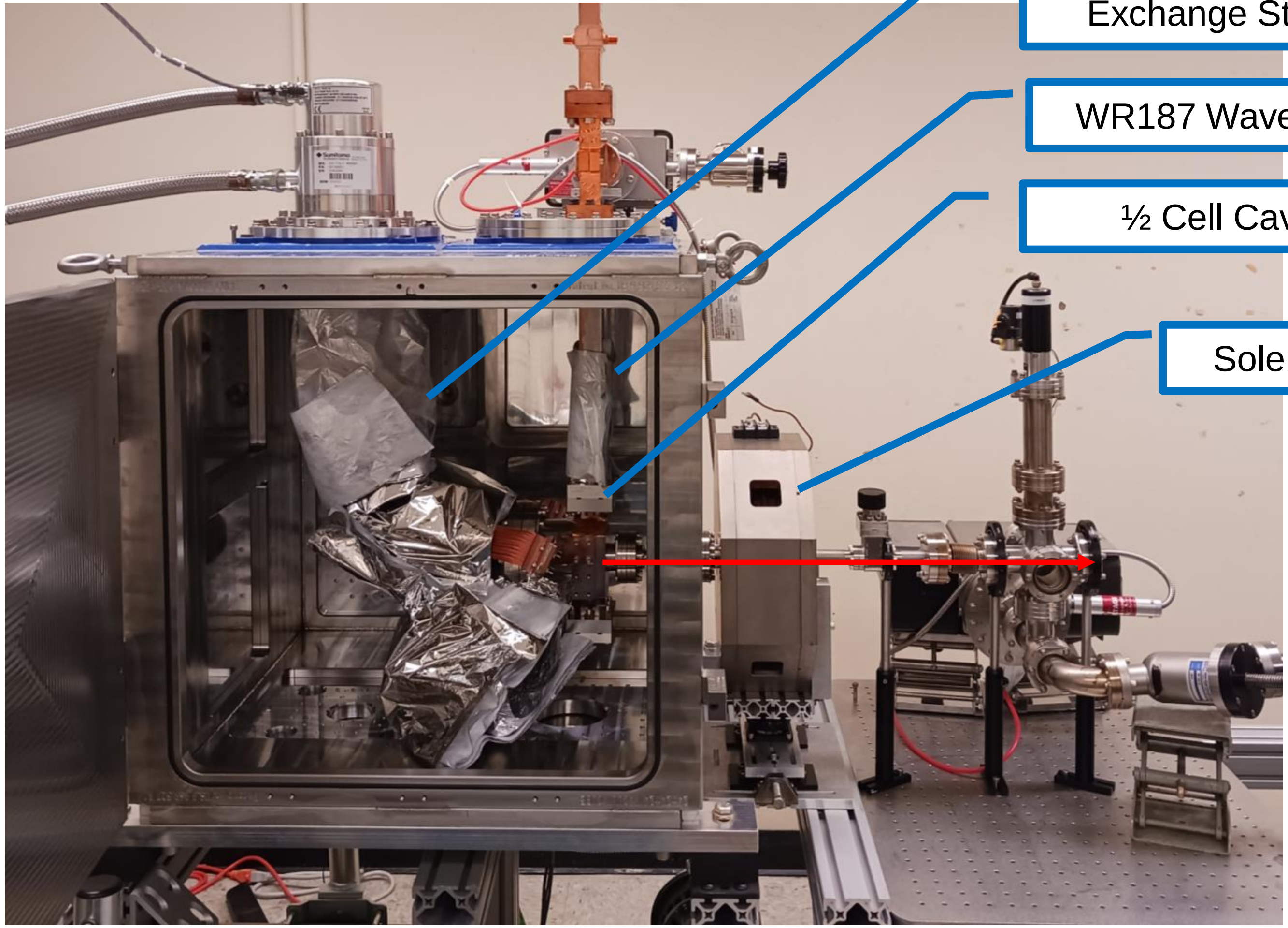
- CYBORG beamline not trivial task
- Robust program at Multi-Option Testing for High-field Radiofrequency Accelerators (MOTHRA) laboratory (right and below) to establish knowledge basis
- Suitable for cryogenics testing; C-band infrastructure development; low energy (single MeV) beamline for cathode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

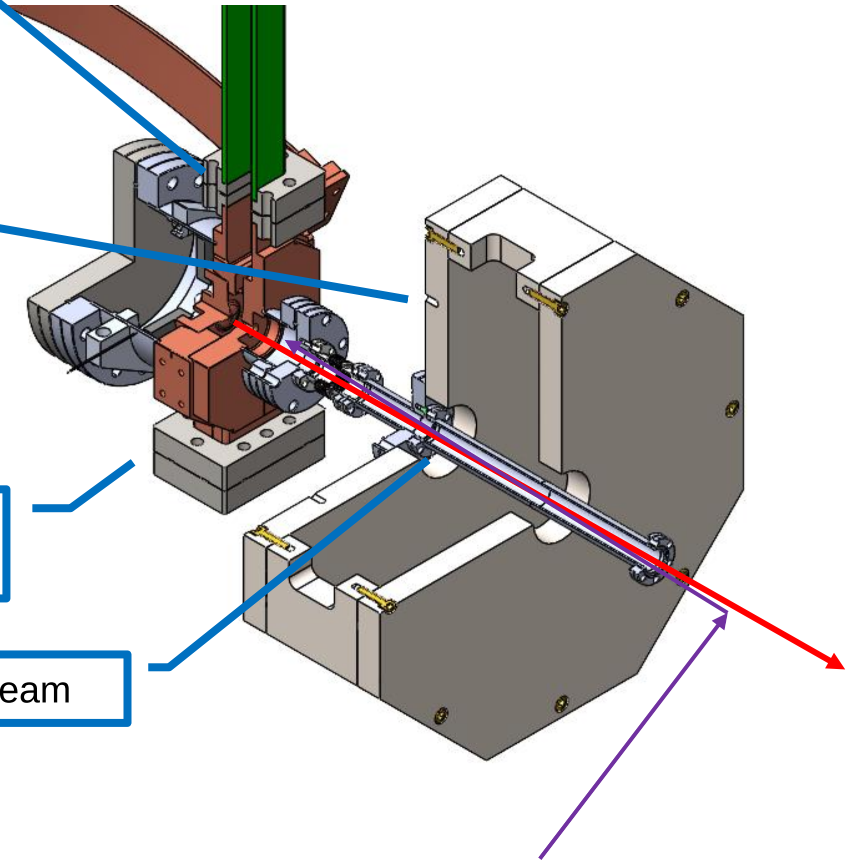




2) CYBORG Phase1

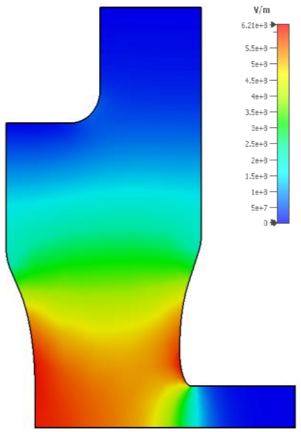
G. Lawler et al, "Improving Cathode Testing with a High Gradient Cryogenic Normal Conducting RF Photogun" Proceedings of HBB23 Instruments (submitted)

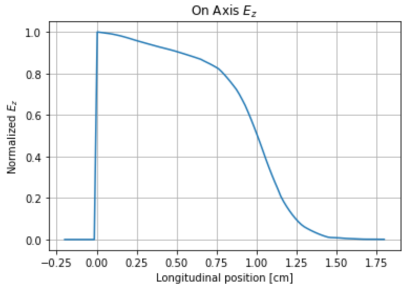




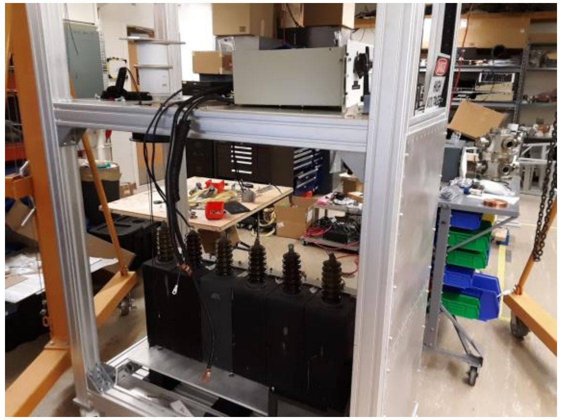
2) RF Power

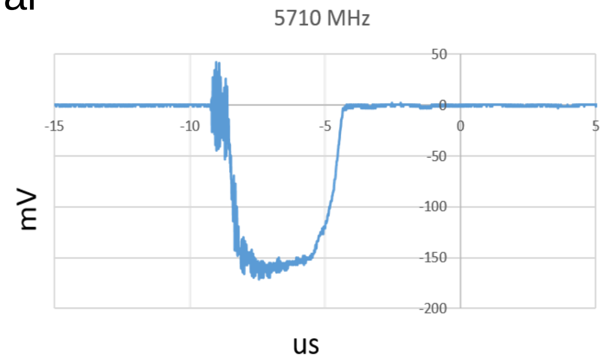
- Resurrected Thales C-band klystron to single MW power sufficient for 1st cryogenic beamline (right)
- In-house built modulator for C-band completed and functioning nominally
- Measured bandwidth greater than spec allowing full temperature range CYBORG operation
- Possible C-band SLED development in collaboration with SLAC
- Tube specs in 1-2 MW range, slowly working up with 0.5 MW into gun thus far

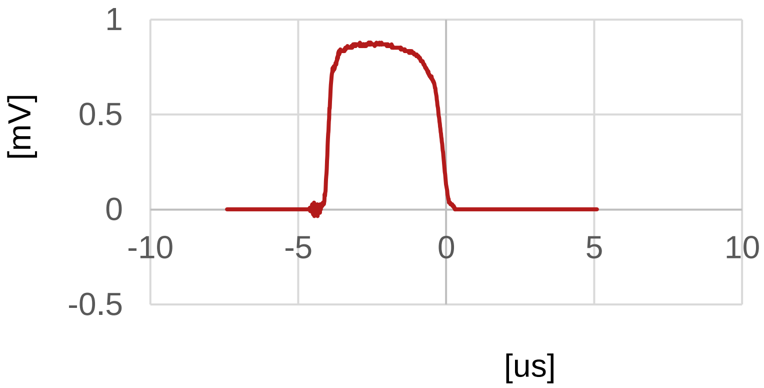




Parameters	Value
Launch field	>120 MV/m
Operating temp	295K down to < 45K
Cavity frequency @	5.721 GHz @ 77K
Beta	2 @ 77K
Q_ext	6056
Q_0	23600 @ 77K

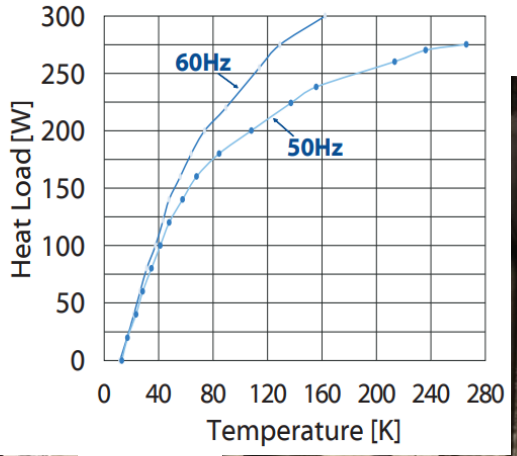


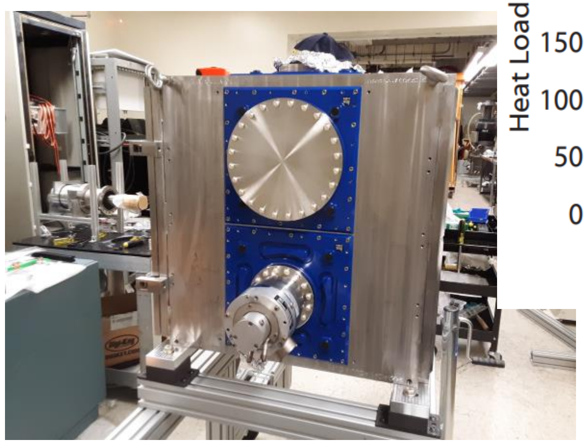


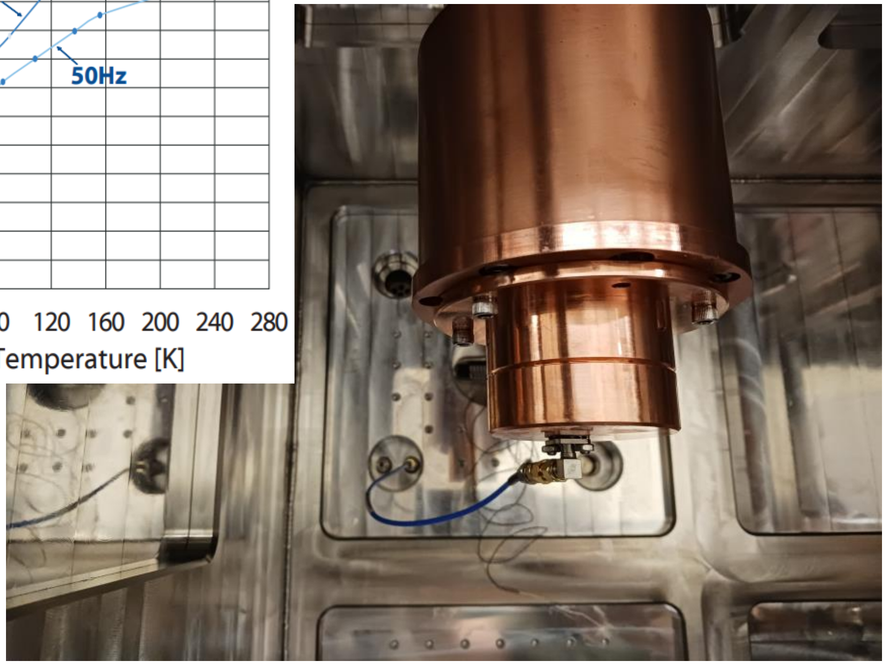


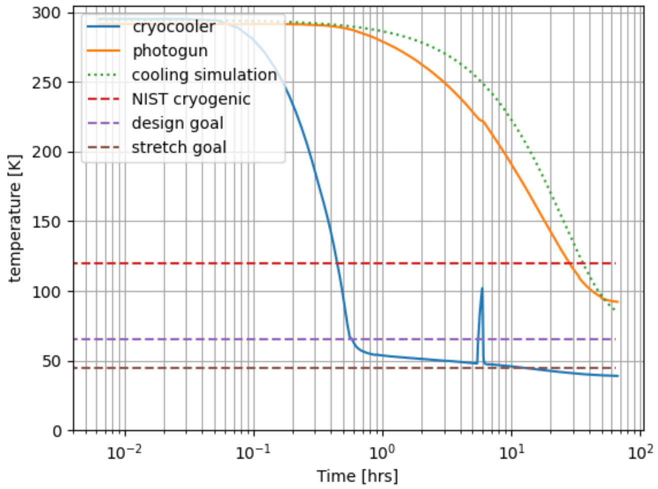
2-3a) Cryostat

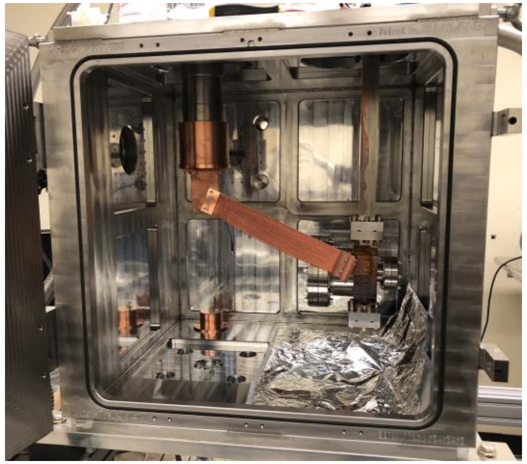
- Much larger cryostat needed for CYBORG with waveguide, beam pipe etc.
- Many considerations to consider
- Size of chamber, multiple layer insulation needed for radiation shielding, nested UHV vacuum chamber far from easy pumping locations, cryocooler power limitations, etc.

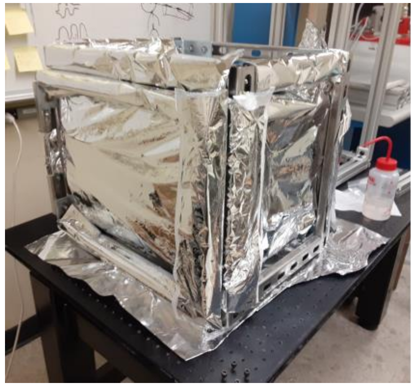








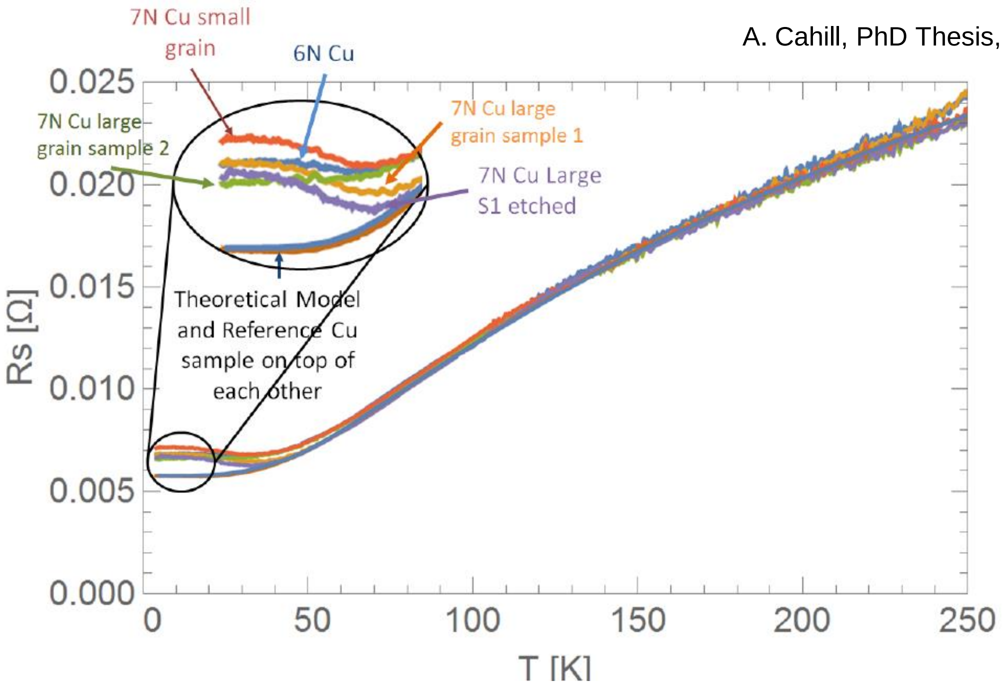


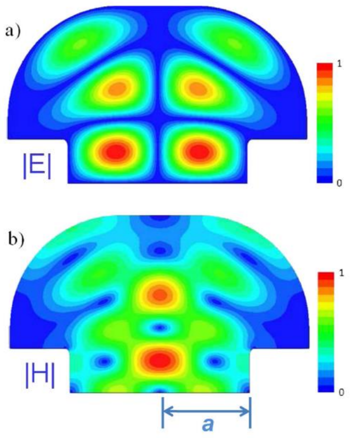


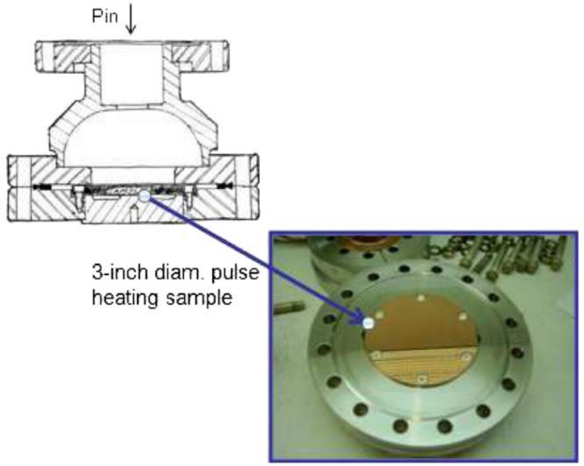
3a) LLRF Motivation

- Rs relevant to RF pulse heating
- high purity Cu (6N-7N) samples from Xband SLAC tests higher Rs than standard 4N Cu @ cryo
- Minimum in around 33 K
- Slight grain size dependence
- Another effect in addition to Reuter-Sondheimer-Chambers ASE theory implied
- Indeed RSC misses intermediary temperature effects via formulation for calculation (below)

A. Cahill, PhD Thesis, 2017







Laurent et al. (2011) DOI: 10.1103/PhysRevSTAB.14.041001

$$\rho(T) = A\left(\frac{T}{\Theta_R}\right)^n \int_0^{\Theta_R/T} \frac{t^n}{(e^t-1)(1-e^{-t})}dt + C$$

$$R_s(T\to\infty) = Re(Z_s) = \sqrt{\frac{2\pi f \mu_0 \rho}{2}} \qquad R_s(T\to 0) = Z_0\left[\frac{\sqrt{3}v_f}{16\pi c}\left(\frac{\omega}{\omega_p}\right)^2\right]^{\frac{1}{3}}$$

$$R_s(T\to 0) = R_\infty\left(1 + a\alpha^{-b}\right) \qquad \text{for } \alpha \geq 3$$

3a) LLRF Theory

- Theory already exists which predicts minimum in Rs at intermediary T via Gurzhi based (effect of additional electron-electron interaction)
- Known in world of thin film physics

R. Gurzhi, "Contribution to the theory of the skin effect in metals at low temperatures," Sov. Phys. JETP, vol. 20, pp. 1228–1230, 1964.

$$\ell_{eff} \sim \frac{\delta^2}{\ell_{ee}}$$

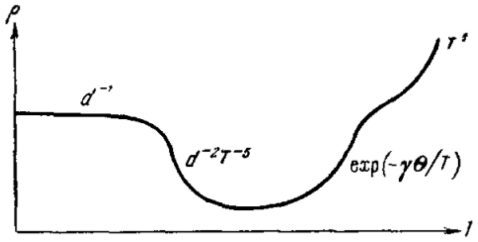
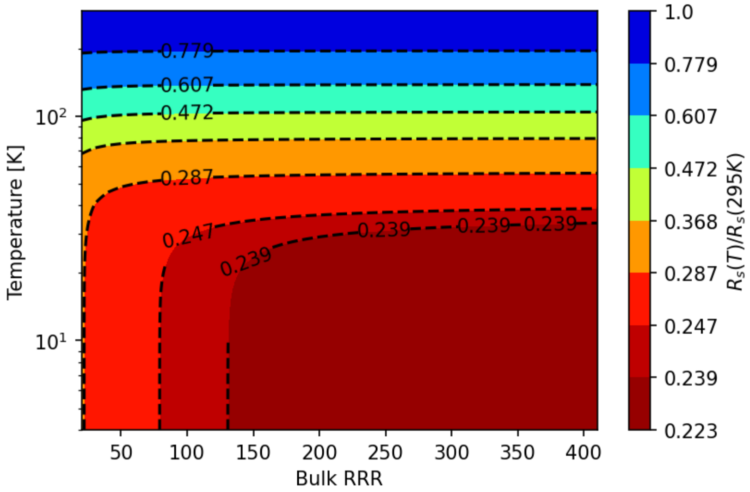


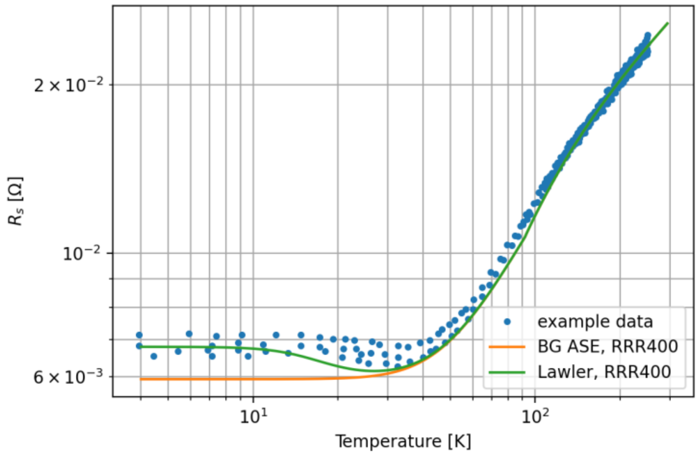
FIG. 4.

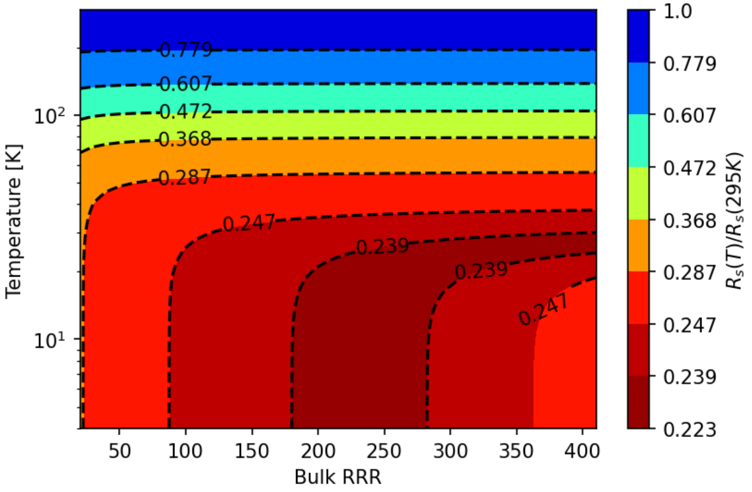


- Solve for above cutoff for RRR450 gives approx. 35K-40K
- Proof of concept easier toy model built which has some of same features and easier to compute for now (below + right)
- Effective thin film modification to bulk via Fuchs-Sondheimer

$$\frac{\rho_{film}}{\rho_{bulk}} \approx \left[1.0 - \frac{C_0}{\rho^{3/2}}(1-p)\right]^{-1}$$

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



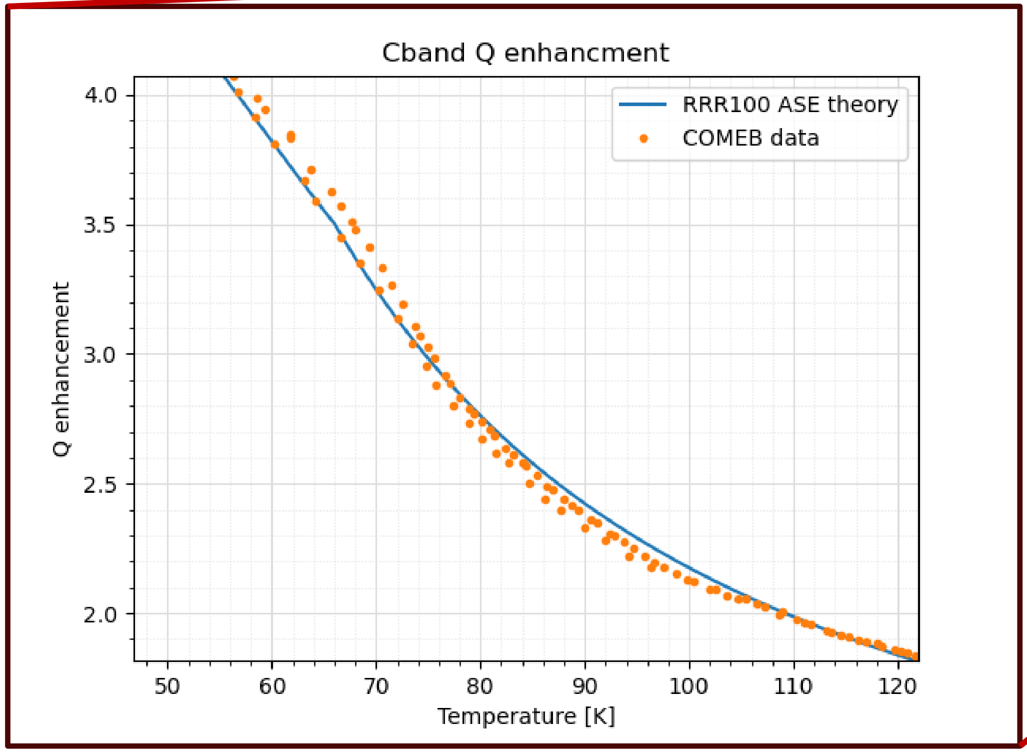


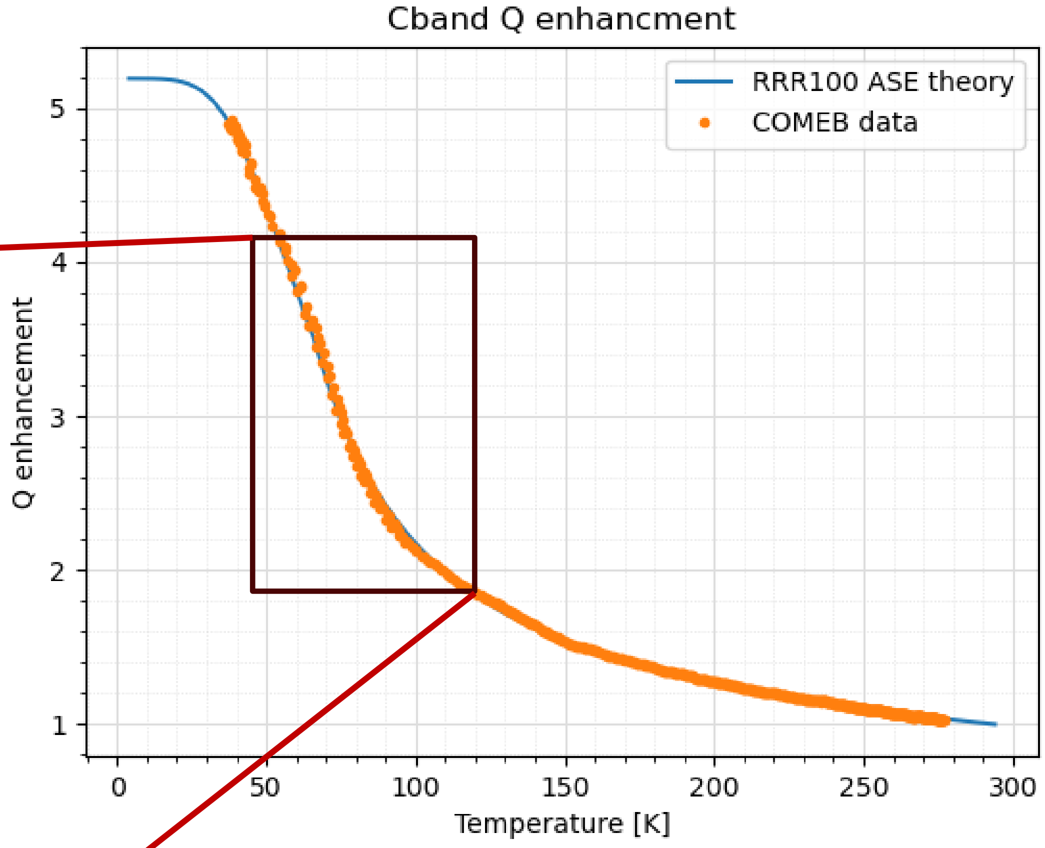
3a) LLRF Measurements

- Q0 enhancement measurements for COMEB pillbox cavity room temperature down to 38K
- Geometric factor (simulated value) leads to Rs values
- 77K relevant for UCXFEL + C^3 linacs; 45K relevant for UCXFEL photoinjector
- Excellent agreement w/ RSC outside of 60-100K

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

G. Lawler, F. Bosco, and J. Rosenzweig, “Improving Interface Physics Understanding in High-Frequency Cryogenic Normal Conducting Cavities“ arXiv (submitted)



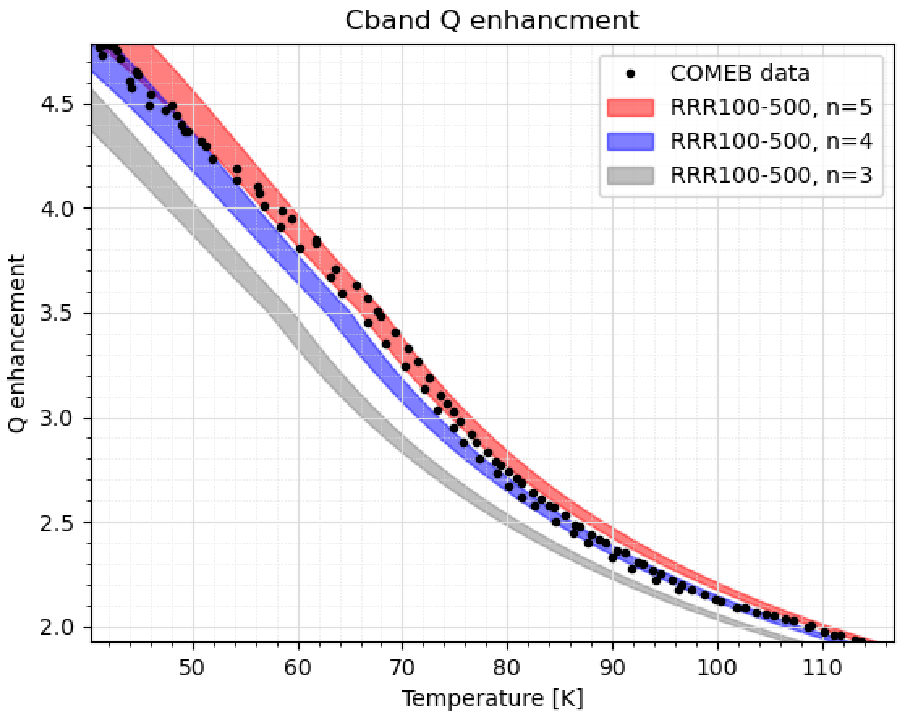


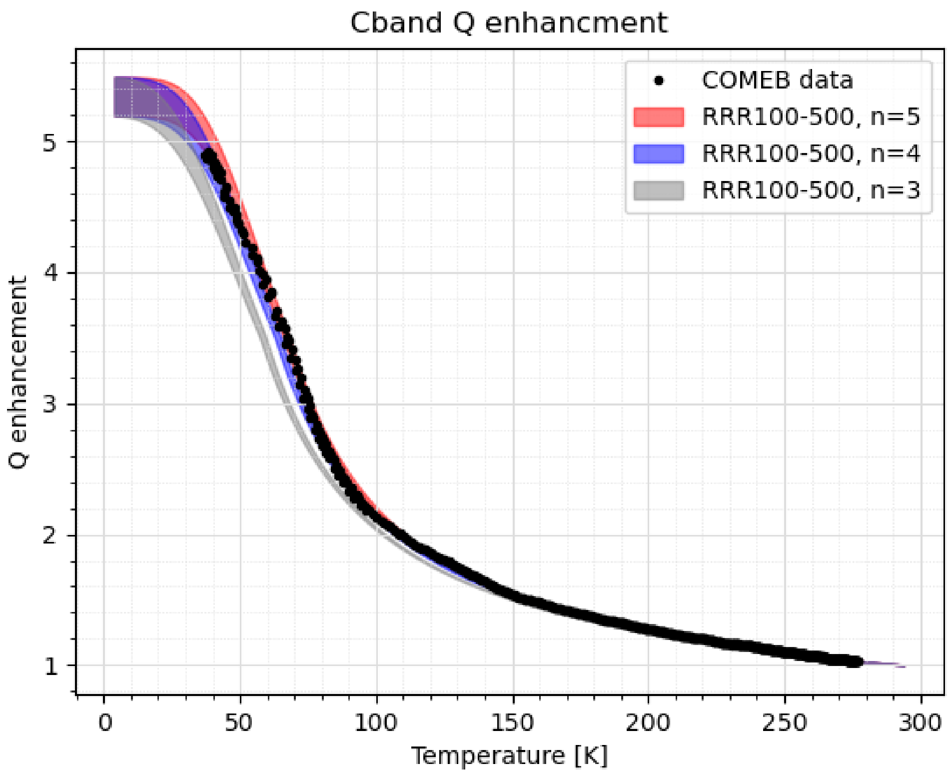
5.718 GHz cavity	295K	77K	45K
Δf [MHz]	0	17.8	18.7
Q_0 enhancement	1	2.89 ± 0.05	4.61 ± 0.05
R_s [Ω m]	3×10^{-2}	1.05×10^{-2}	6.5×10^{-3}

3a) Additional LLRF Improvements

- Consider again assumptions
- n=5 for ideal metals
- Literature has n=3 for transition metals
- n=4 sometimes when more complicated phenomena present

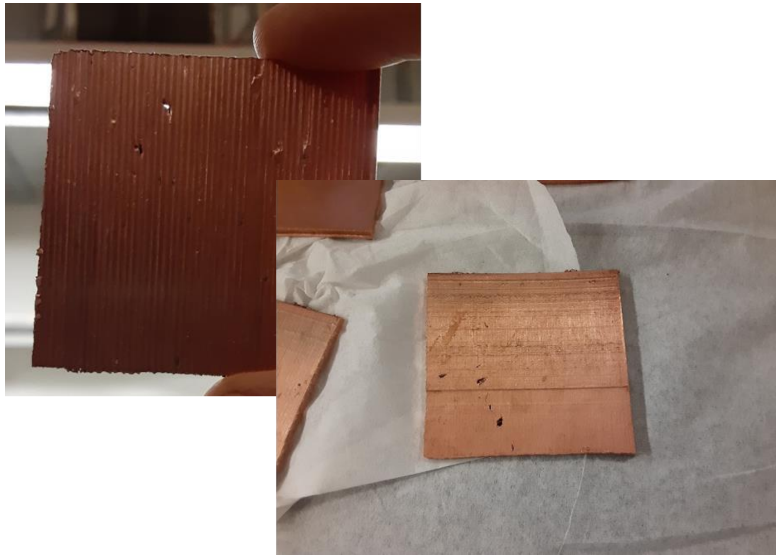
$$\rho(T) = A\left(\frac{T}{\Theta_R}\right)^n \int_0^{\Theta_R/T} \frac{t^n}{(e^t-1)(1-e^{-t})}dt + C$$

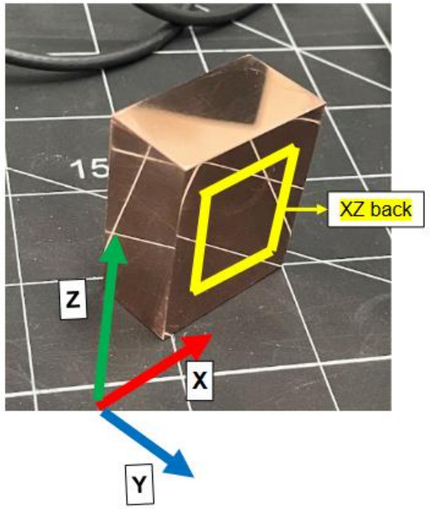


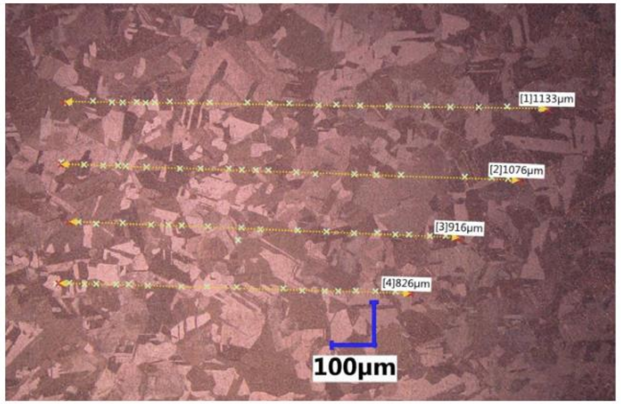


3a) Alloy Characterisation

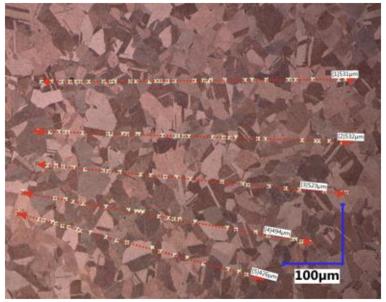
- Hard Cu alloys considered with same pillbox design
- CuAg alloys received from LANL characterized in collaboration with Radiabeam technologies
- Existing 2% Ag alloy brick nonideal for high power cavity manufacture still interesting for LLRF
  - 88ppm oxygen content compared to 5 ppm for OFE Cu
  - Only definitive statement on 2%: metallurgy an art more than science
- 0.08% Ag alloy of continued interest for both
- Brazing step needs deeper consideration







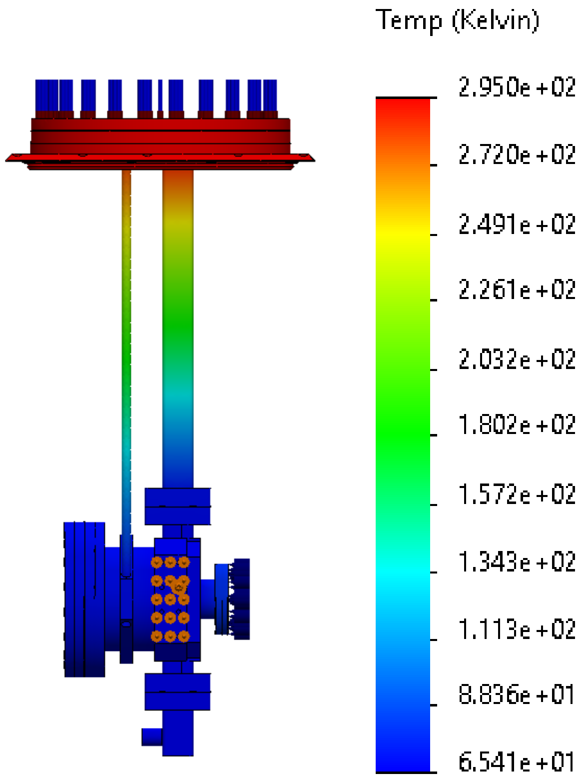
For 0.08% Ag grain size diameter of 121 $\pm$ 20um

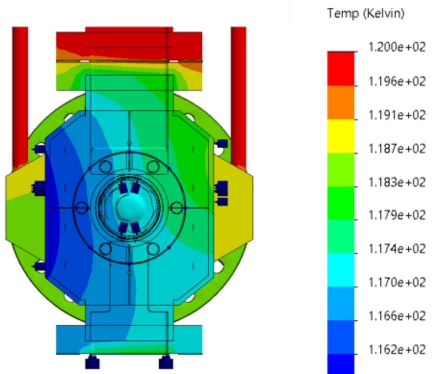


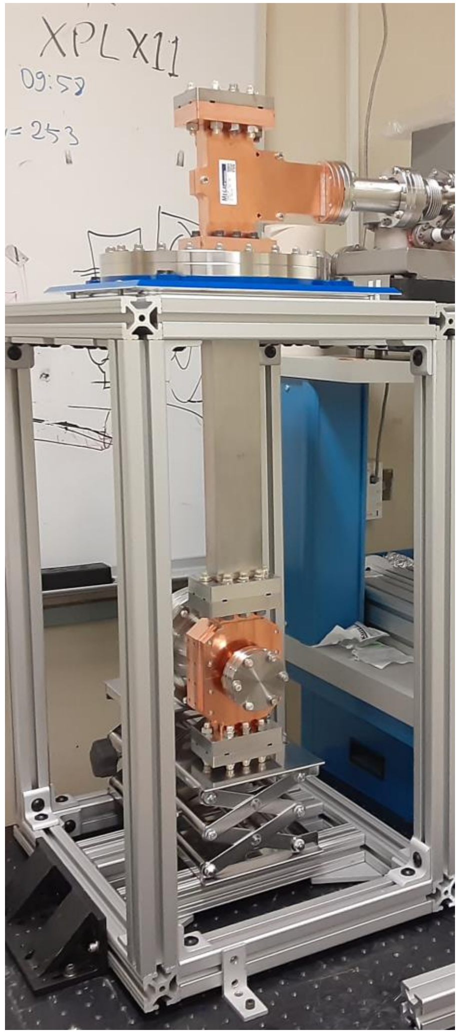
For 2% Ag grain size diameter of 106 $\pm$ 20um

3b) Thermal Balancing

- Additional option to measure Rs via RF pulse heating in CYBORG
- Initial CYBORG study of thermal balancing implies that study could be possible if we go higher rep rates







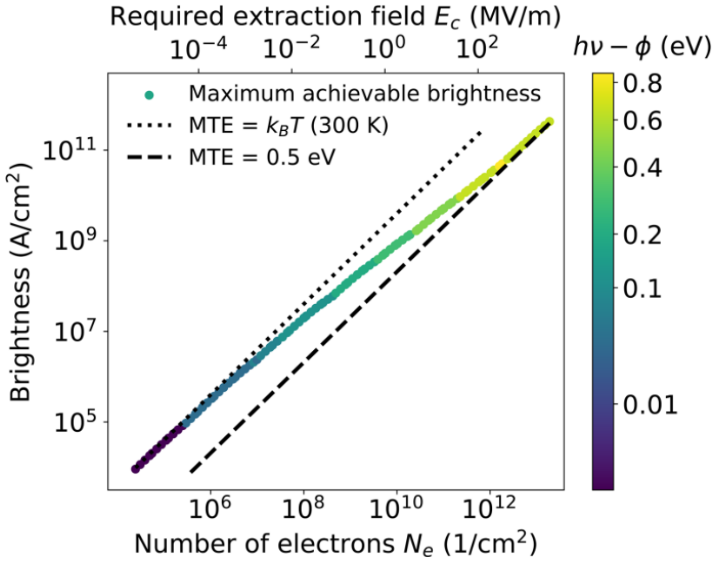
ID	Description	Materials	Equivalent Area	Equivalent Power
001	6" plug flange	Stainless steel (CF flange), edge welded bellows	436 mm^2	< 1 W
002	2.75" downstream flange	Stainless steel (CF flange), edge welded bellows	85 mm^2	< 1 W
003	Waveguide	Satinless steel	588 mm^2	Approx 10 W
004	Supports	Stainless 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			

Parameter	295K	95K	77K	45K
f_0	5703[1]	5720 ± 1	5721 ± 1	5722 ± 3
Q_0	8488[1]	19480 ± 660	23600 ± 1440	32890 ± 3910
β	0.7[1]	1.61 ± 0.05	1.95 ± 0.13	2.71 ± 0.32
τ [μs]	0.28	0.419 ± 0.005	0.45 ± 0.01	0.50 ± 0.02
P @ 120 MV/m	3.2	1.4 ± 0.04	1.17 ± 0.07	0.84 ± 0.10
J/pulse	16	7.33 ± 0.25	6.05 ± 0.36	4.35 ± 0.50
MV/m @ 0.5 MW	47	71.5 ± 1.1	78.5 ± 2.4	92.7 ± 5.4

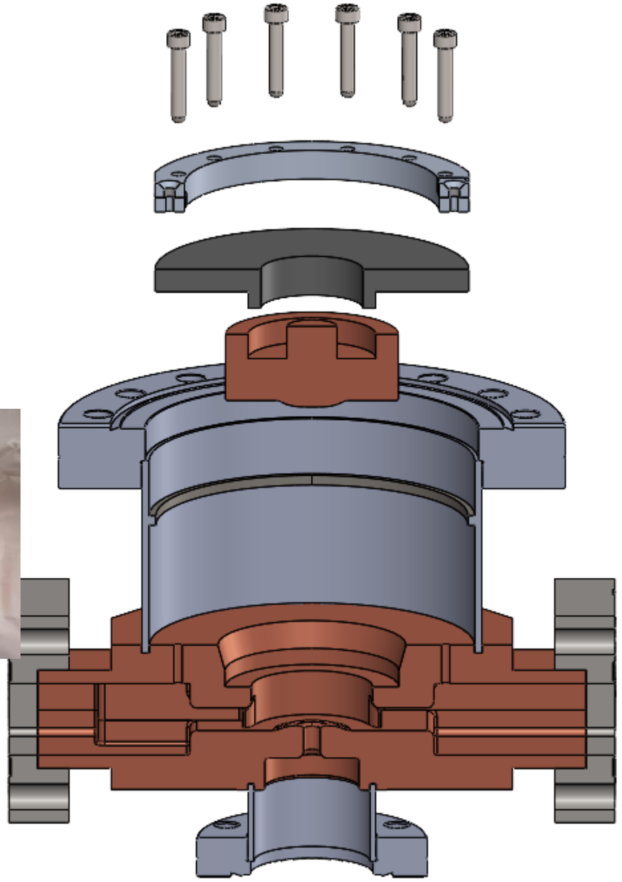
[1] Experimentally measured values

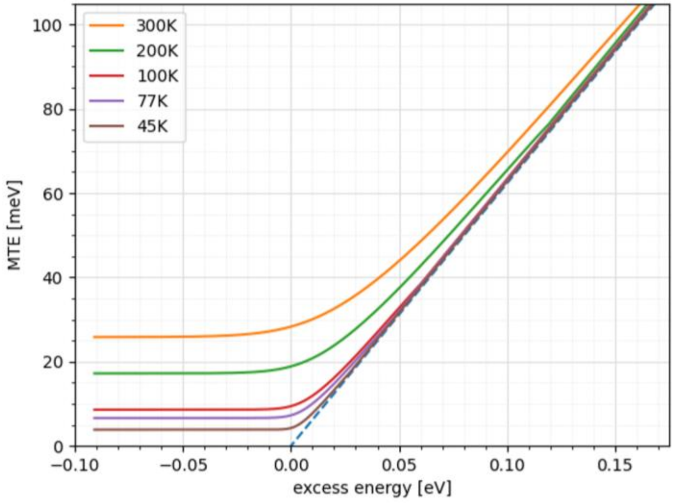
3b) CYBORG Function 2

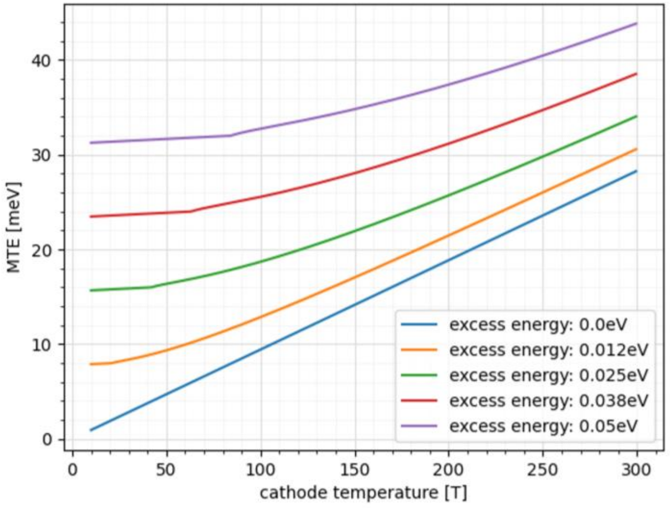
- Ultimate motivational use cryogenic emission physics so further material physics study the aim
- Near threshold photoemission means transverse energy calculations shown below for certain notable temperatures
- Verification of more advanced brightness scaling possible (middle)
- Removable backplane makes post mortem breakdown SEM possible (right)



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







20 mm

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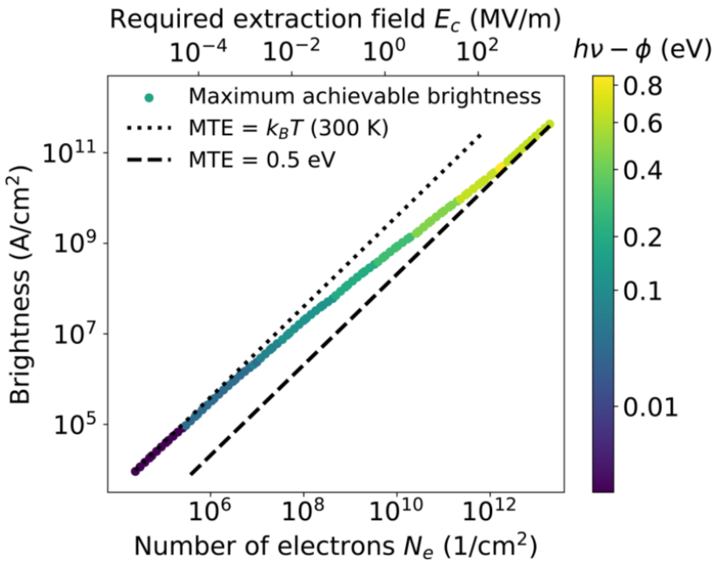
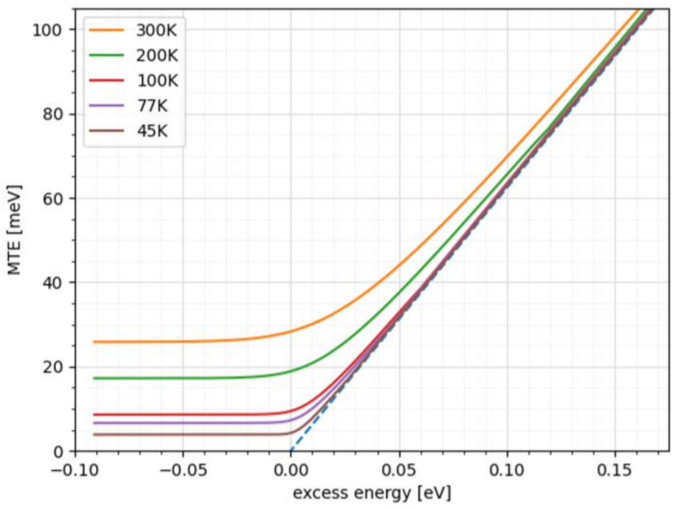
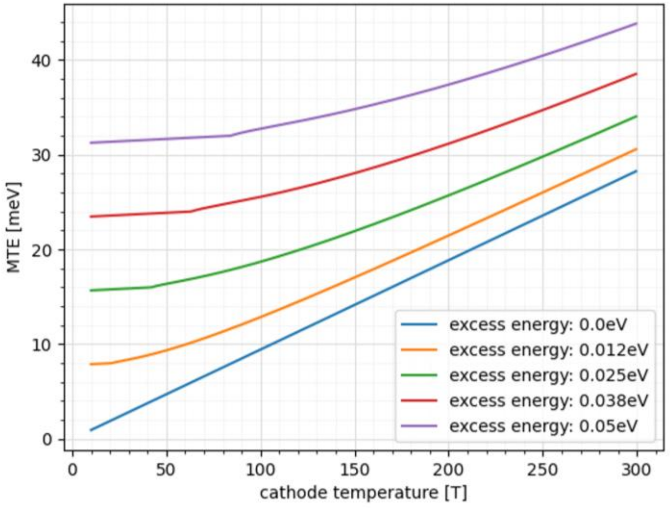
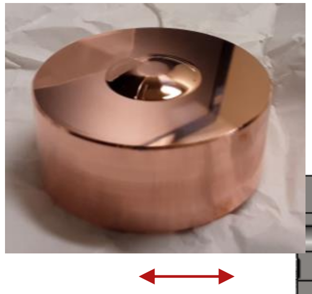


J. K. Bae, I. Bazarov, P. Musumeci, S. Karkare, H. Padmore, and J. Maxson, J. Appl. Phys. 124, 244903 (2018).

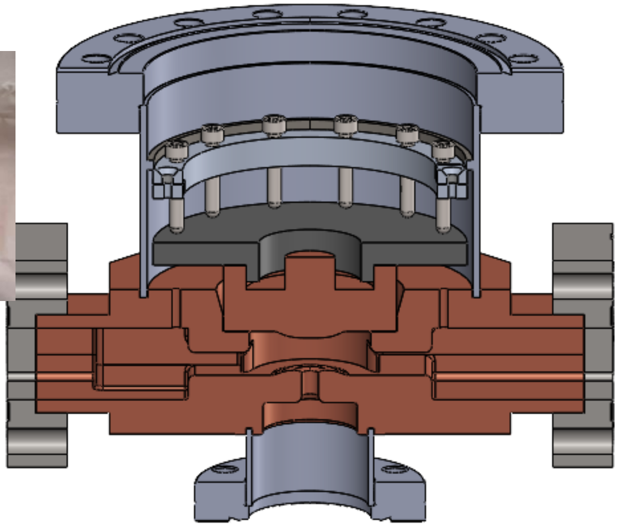
For use in Phase1





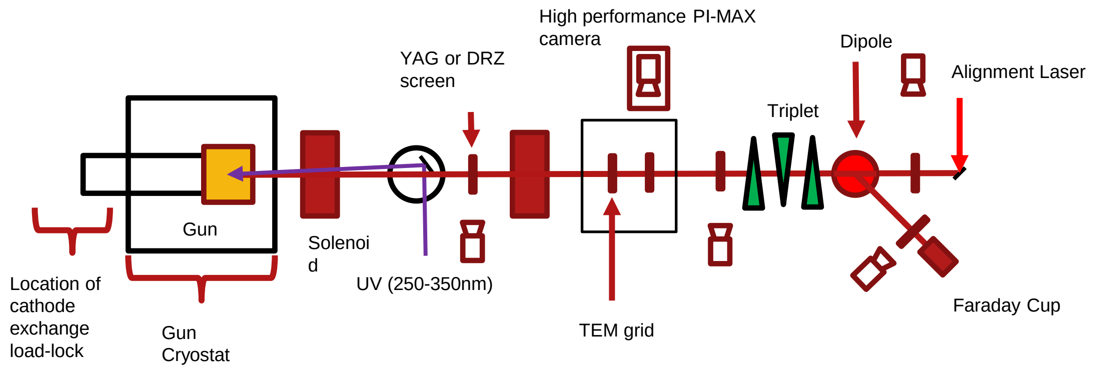


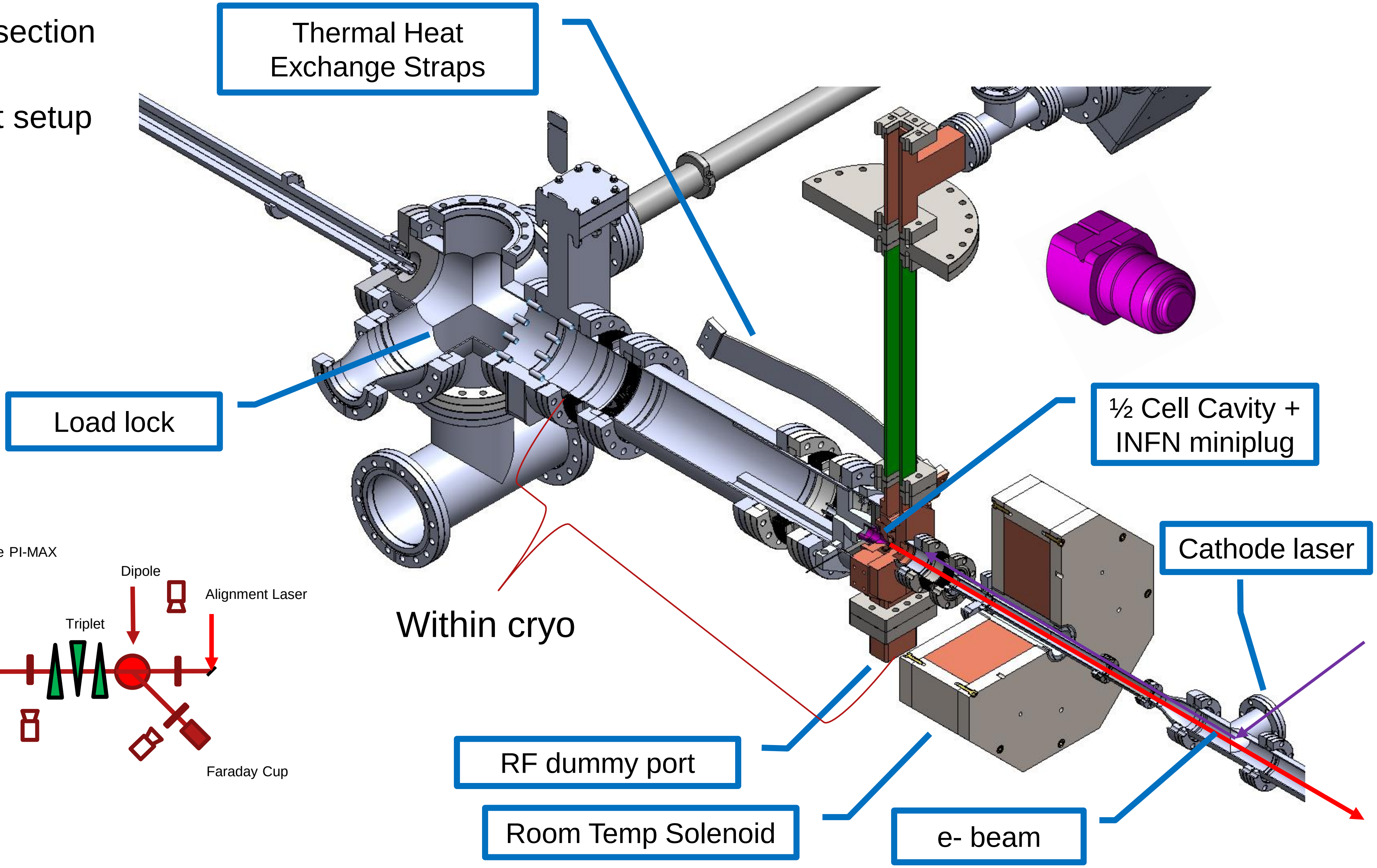
20 mm



4) Phase2 Beamline

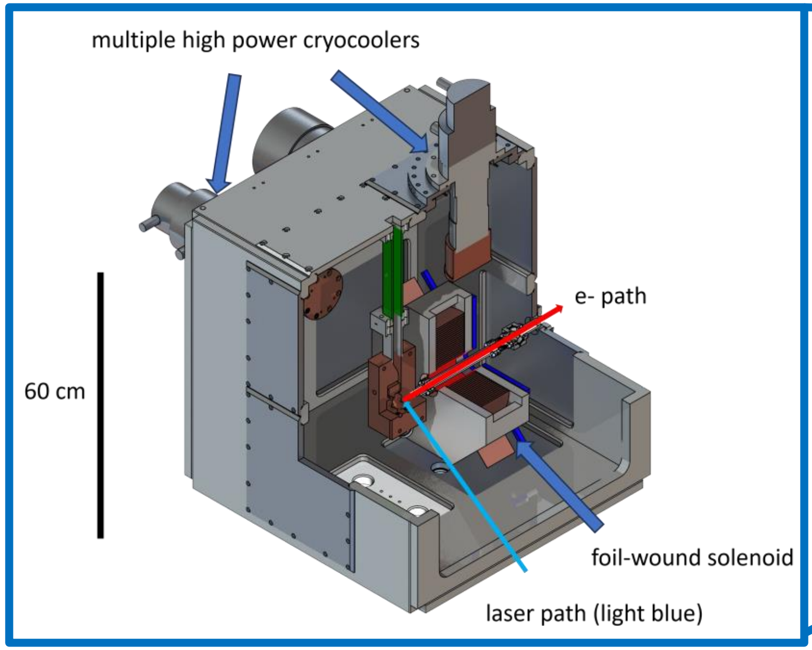
- Phase2 involves load lock in gun section for advanced cathode testing
- High precision MTE measurement setup needed
- Cathode coupling work in parallel underway

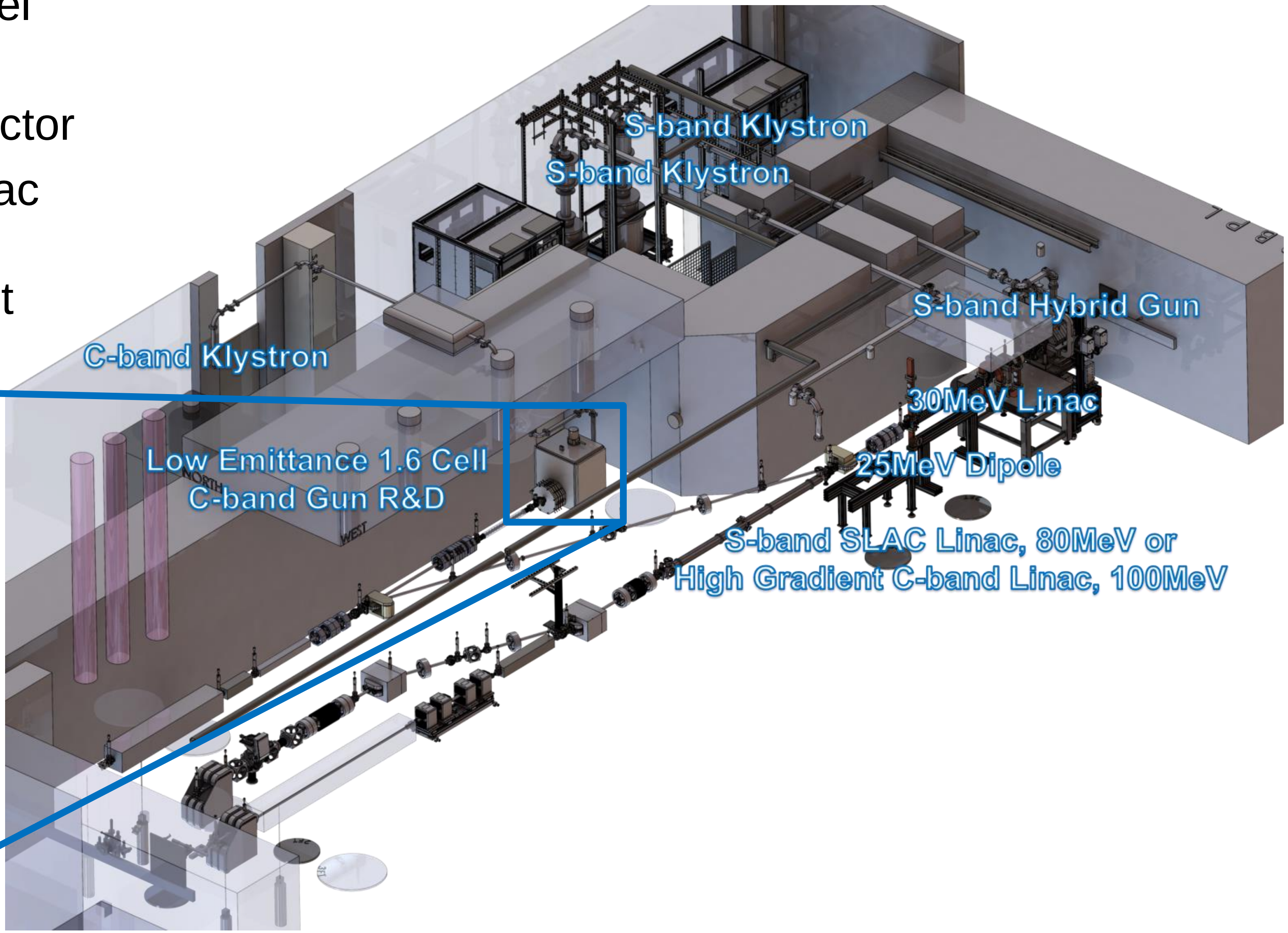




4) MITHRA Lab

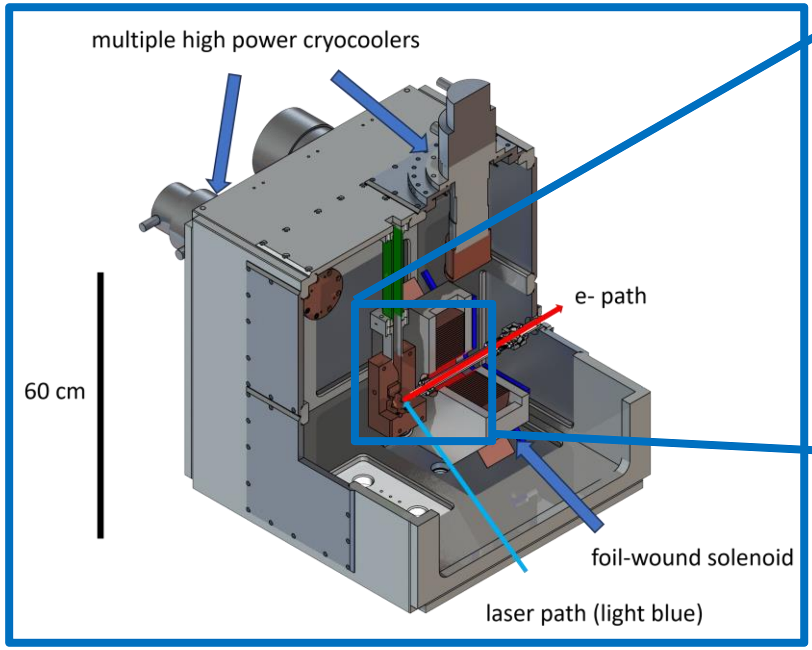
- Advertisement for MITHRA 18m of parallel beamline
- Operational with S-band hybrid photoinjector
- Suitable for high energy high gradient linac development (10s-100s MeV); UCXFEL demonstrator FELs; C-band high gradient photoinjector research

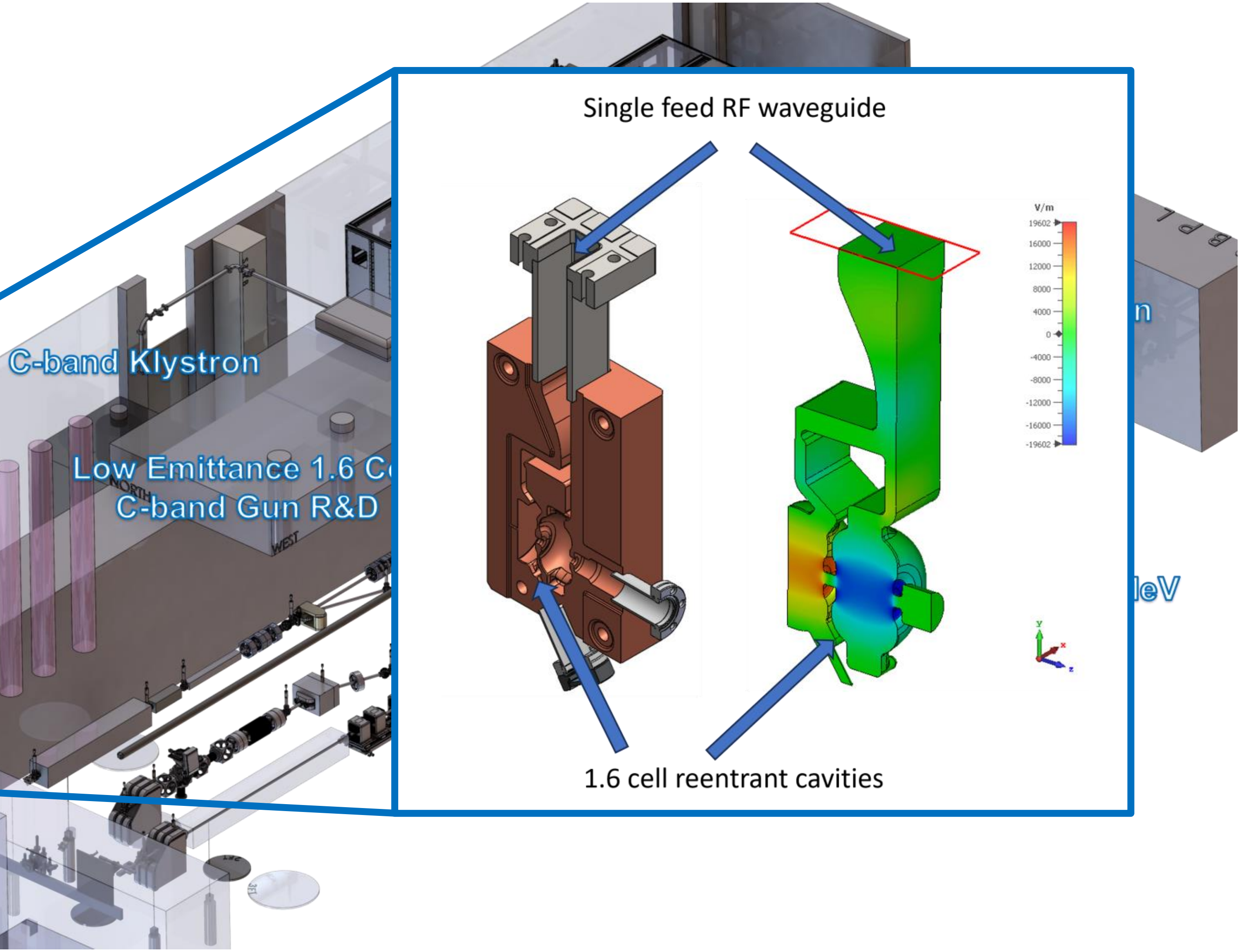




4) MITHRA Lab

- Advertisement for MITHRA 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





5) Conclusions

1. Brief update on CYBORG beamline development with more very soon
2. LLRF cavity measurements possible for fully understanding material properties via Q0/Rs
3. CYBORG useful for high power material physics testing in terms of photocathodes and RF

Collaborators

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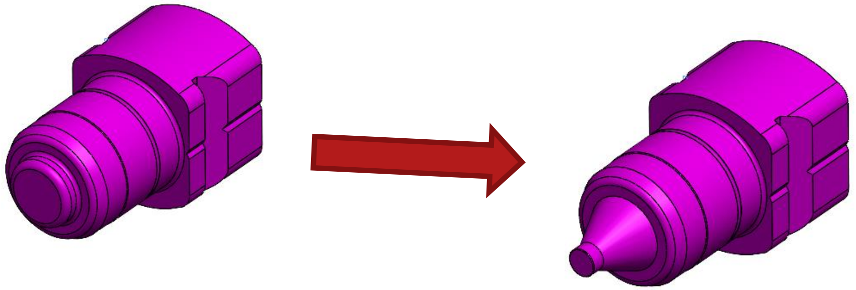
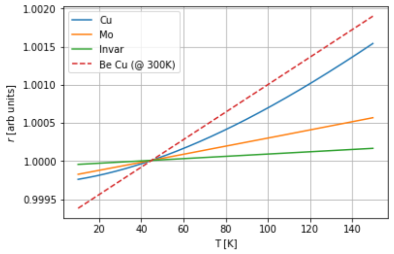
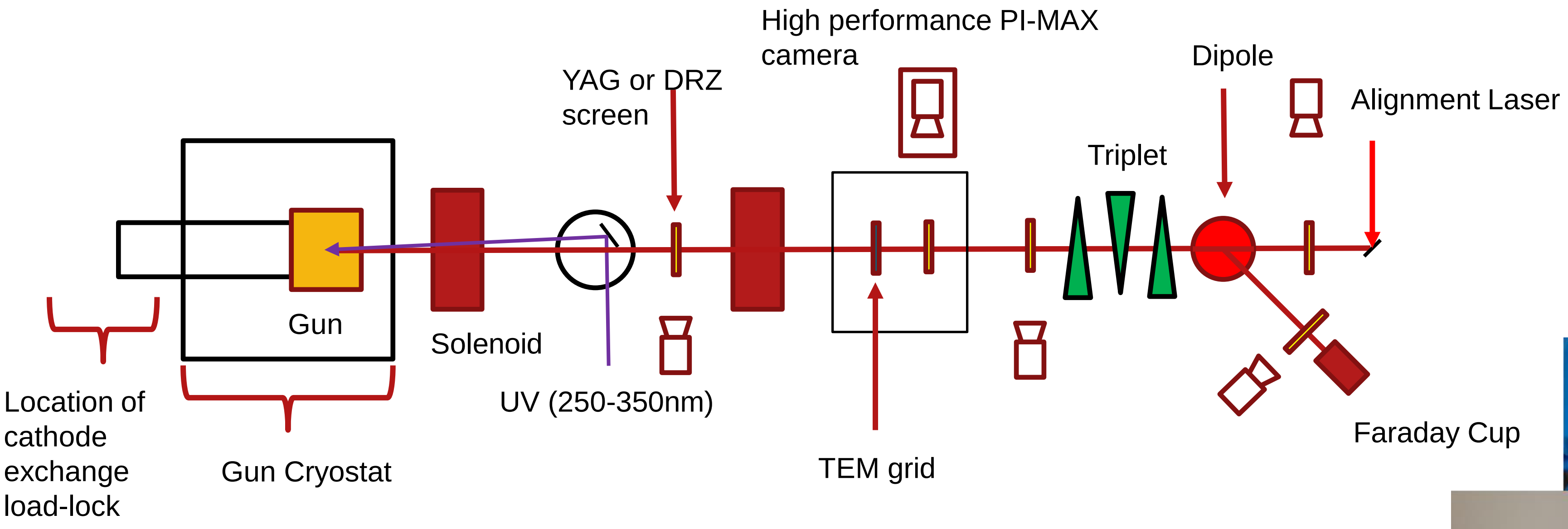
- Martina Carillo, Andrea Mostacci
- Zenghai Li, Sami Tantawi, Nathan Majernik
- Bruno Spataro

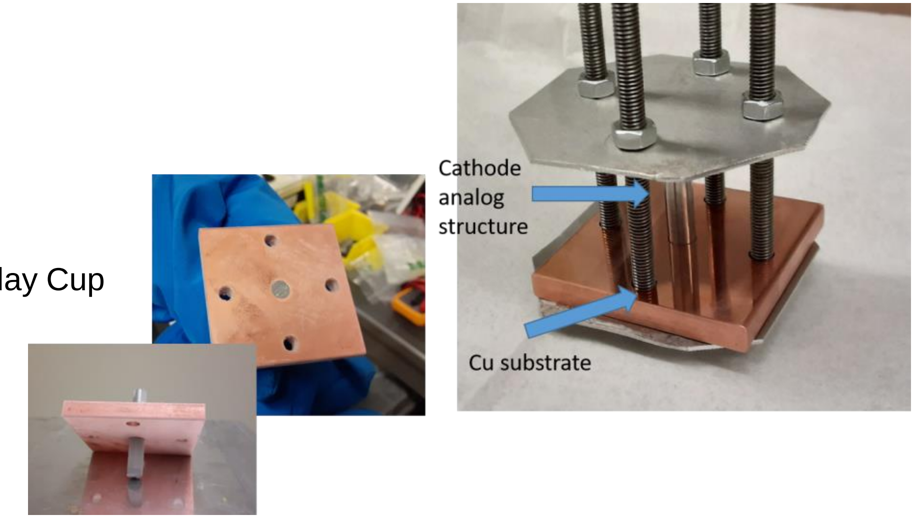
Bonus 1: Phase2 Beamline

- 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
- Slight INFN minipuck mod needed



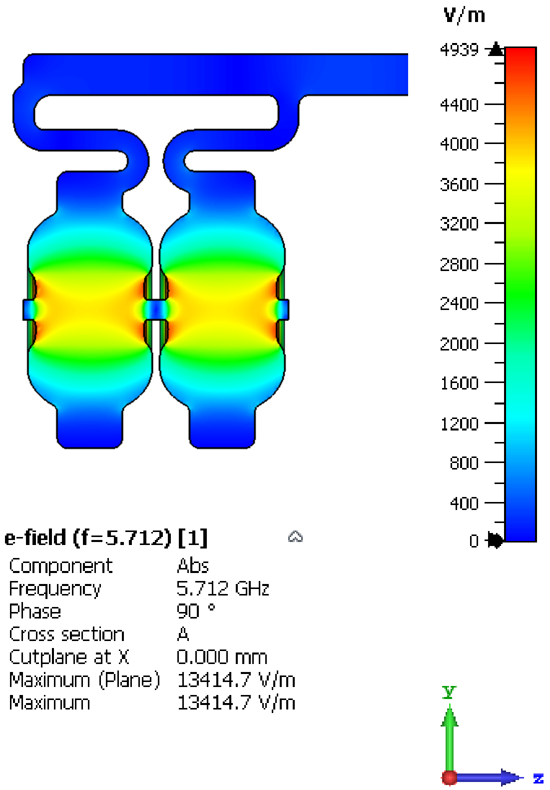


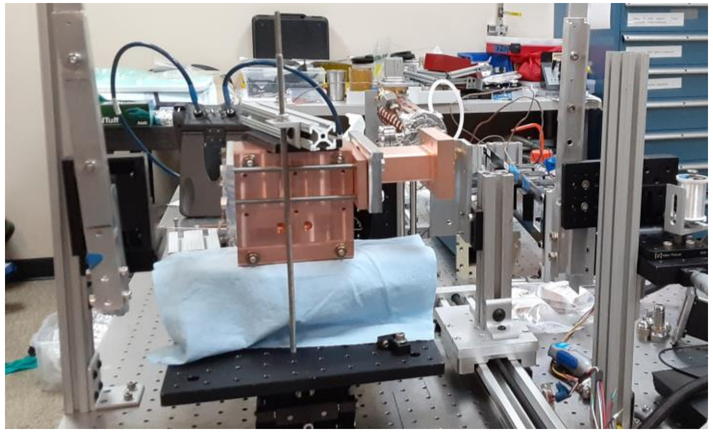


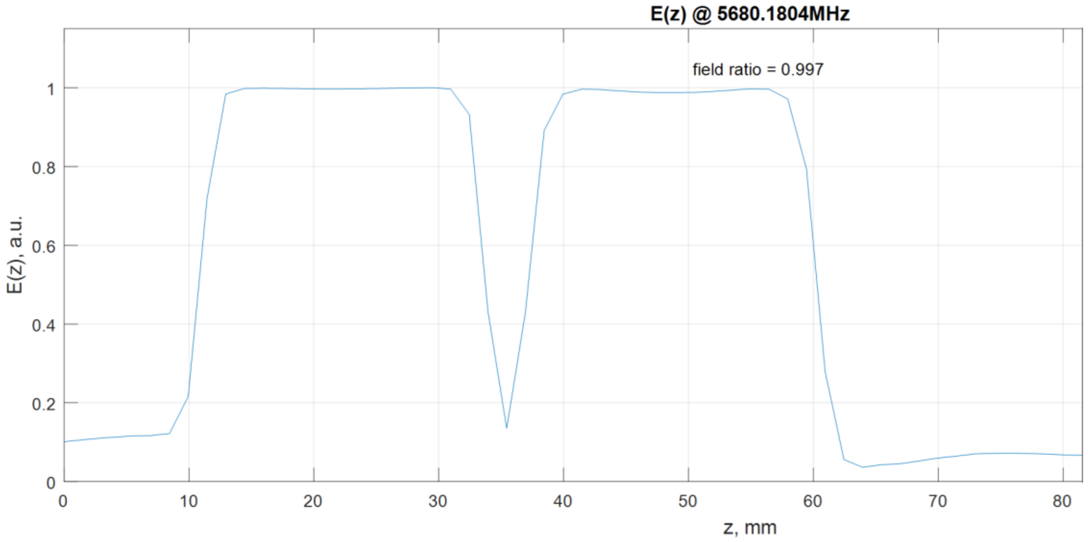


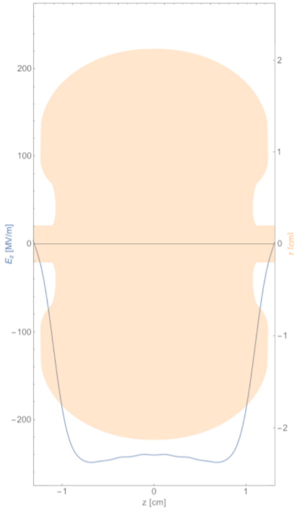
Bonus 2: Breakdown limit test cavities

- 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

Bonus 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