Conditioning a Cryogenic RF Photogun for High Gradient Operation

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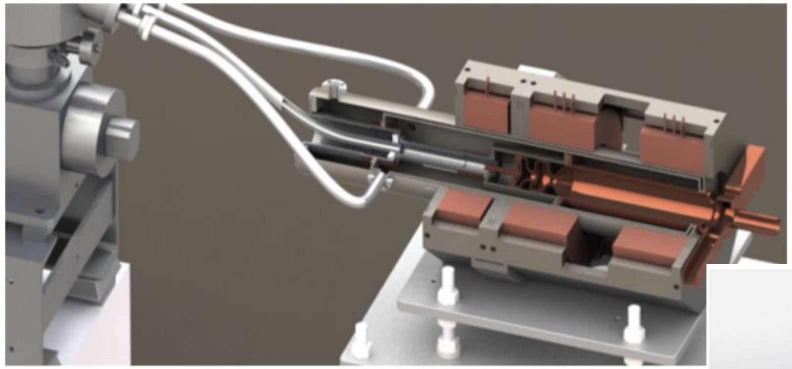
UCLA[1], Los Angeles, CA, USA

Outline of presentation

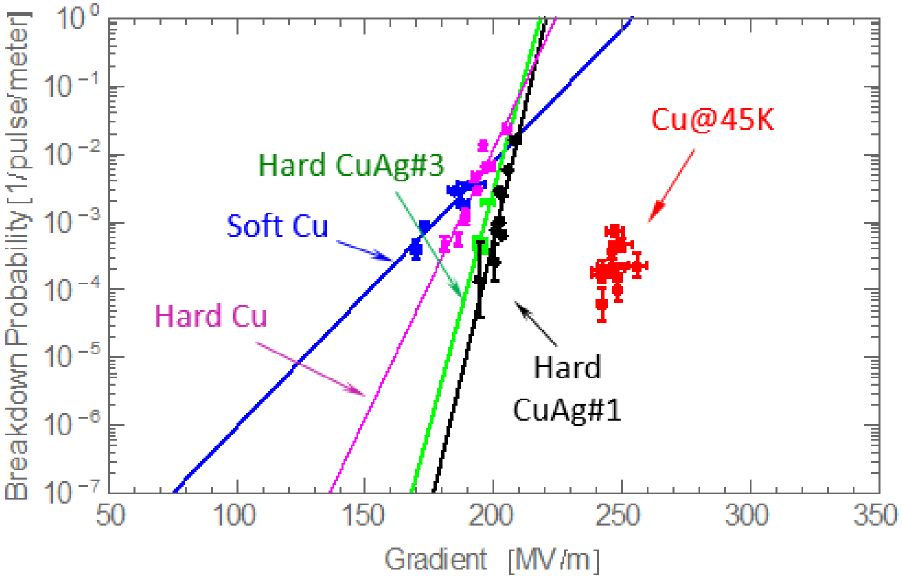
1. **Background and motivation**
2. MOTHRA + CYBORG status review
3. RF physics and gun conditioning
4. Future testing/discussion
5. Conclusions

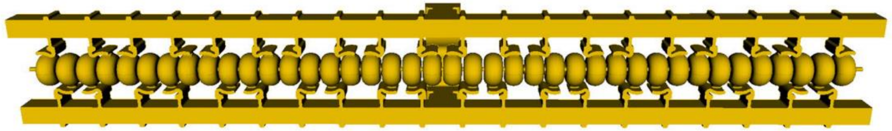
1) Background

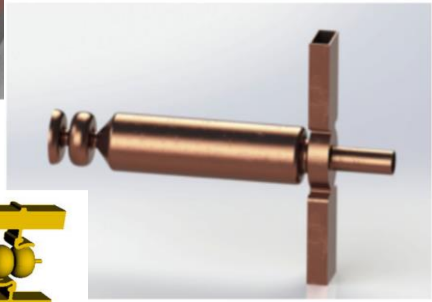
- Significant interest in photoinjector; wakefield; fundamental high field physics
- Broad interest in high gradient cavity development with focus on brightness
- SLAC cryogenic breakdown reduction ⇒ higher accelerating gradients possible
- TopGun previous development in S-band (2-3 GHz)
- More cryo manageable C-band (4-6 GHz) + interest in broader applications e.g. compact high brightness light sources and linear colliders

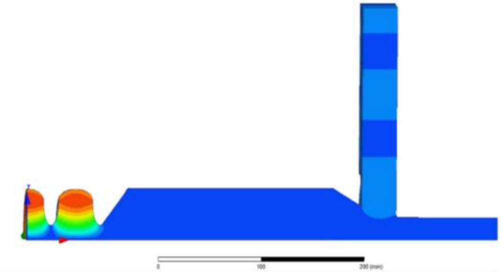


$$B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c}\left(E_0 \sin\varphi_0\right)^2$$







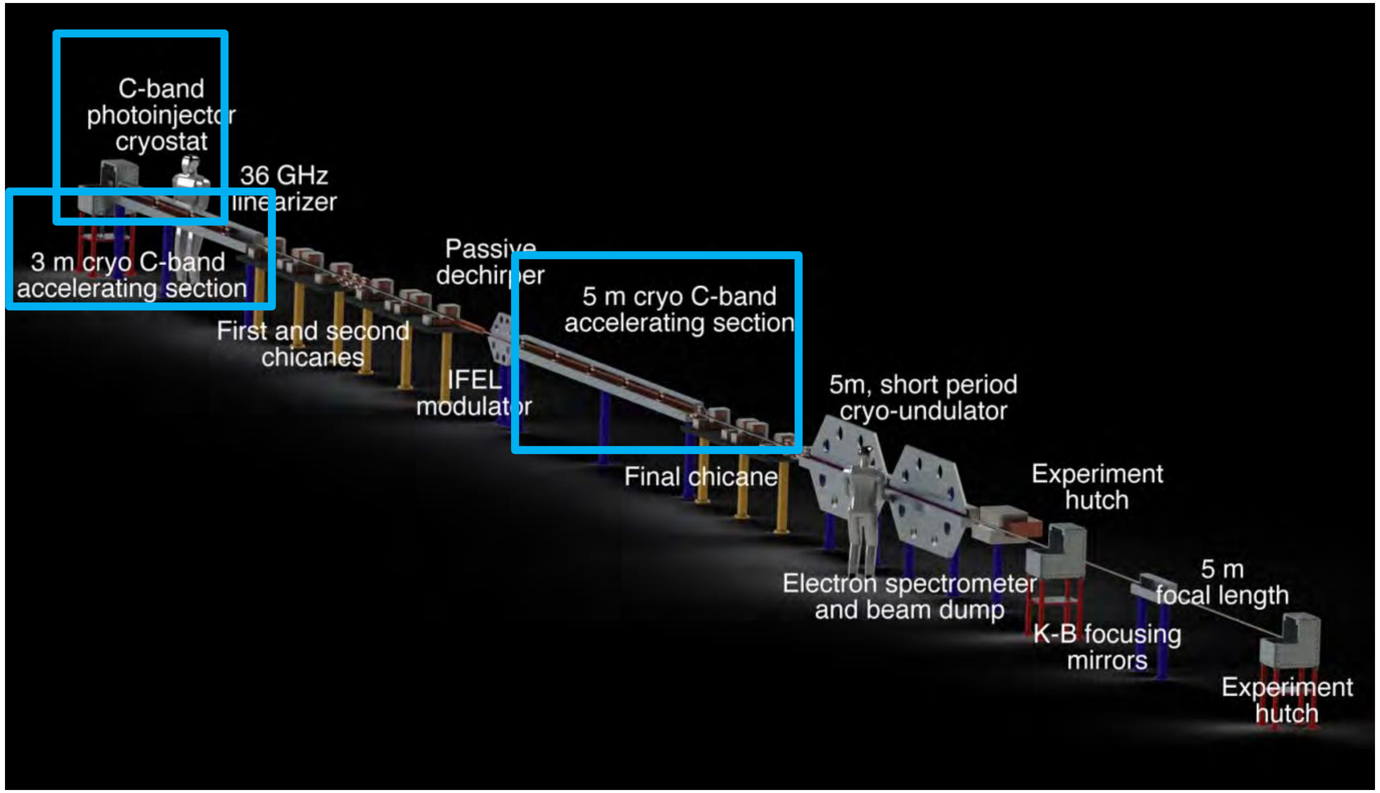


Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources
JB Rosenzweig, et al. - Physical Review Accelerators and Beams, 2019

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

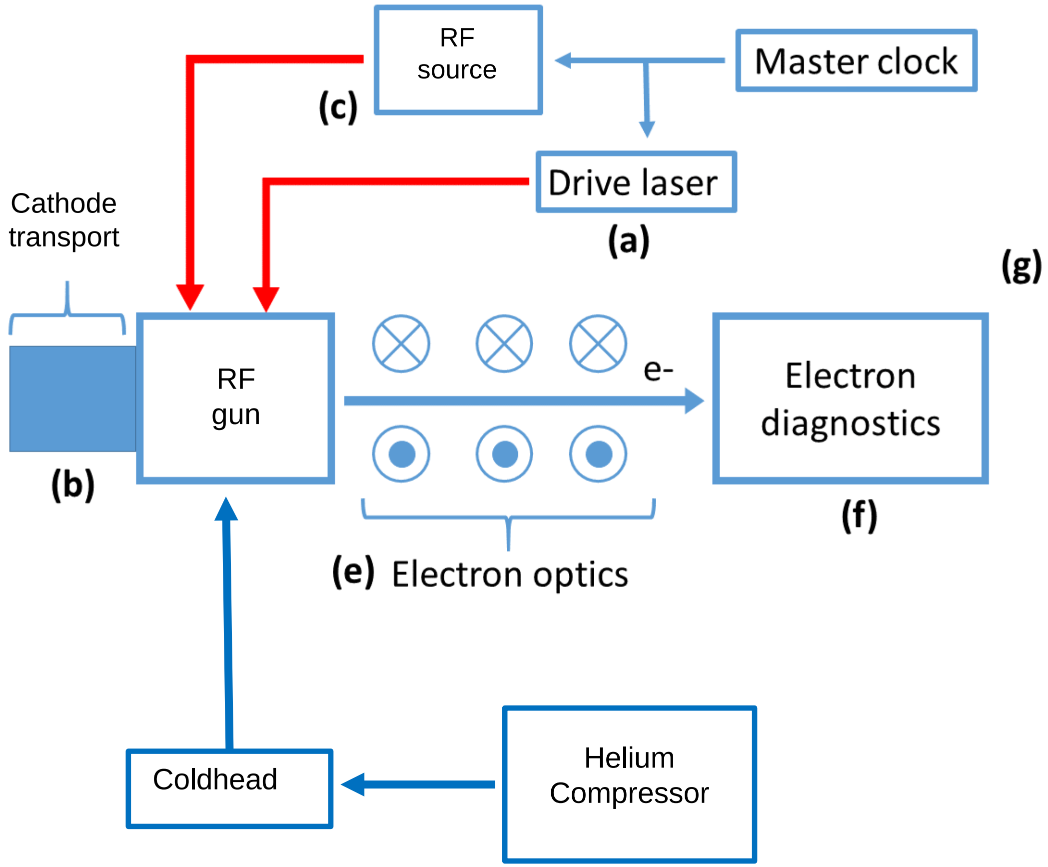
J.B. Rosenzweig et al. “A high-flux compact X-ray free-electron laser for next-generation chip metrology needs.” *Preprints* **2023**, 2023111639. https://doi.org/10.20944/preprints202311.1639.v1

1) Test bed overview

- Schematic for simplest test bed for measuring cathodes using 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

- Test bed now in position for process knows as conditioning by which gun cavity prepared for high gradient operation



1) Gun Comparisons

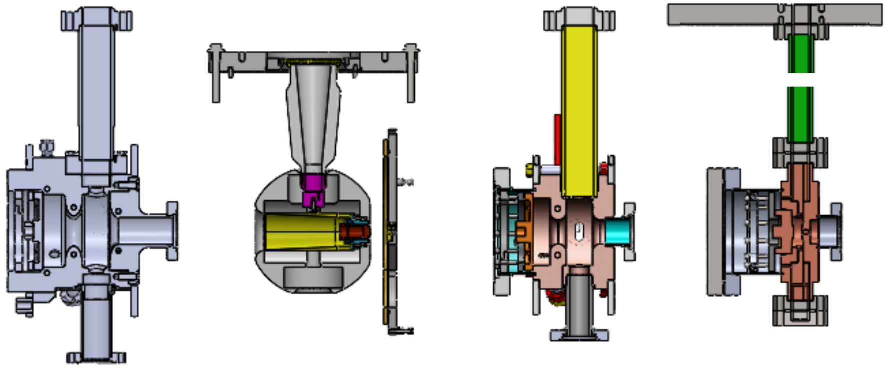
- During design and production of CYBORG influence taken from existing photoguns
- Compared here along with two related experiment designs
- Highlights also CYBORG design phases

Parameter	CYBORG Phase 1	CYBORG Phase 2
Cavity type	normal conducting	-
Cavity geometry	$\frac{1}{2}$-cell reentrant	-
Cathode Assembly	Demountable Cu backplate	Cryogenic load lock
Design frequency	5.712 GHz	5.700 – 5.720 GHz
Peak cathode field	$\geq$ 120 MV/m	-
Operating temperature	300 – 95K[1]	300 – 77K

[1] Current lowest temperature achieved with additional plans for 77 K operation

Photoguns	FERMI [20]	PEGASUS [6,21]	PITZ [22,23]	HZDR [24]/HZB [25]	Cornell [26]/ASU [27]	BNL [25,28]
Cavity type *	NCRF	NCRF	NCRF	SRF	-	SRF
Cavity geometry *	1.6 cell pillbox	1.6 cell pillbox	1.5 cell pillbox	1.5 cell elliptical	-	quarter wave
Cathode assembly	Demountable Cu backplate	Demountable Cu backplate + load-lock	Demountable Cu backplate + load-lock	Load-lock	Load-lock	Load-lock
Design frequency	2.998 GHz	2.856 GHz	1.3 GHz	1.3 GHz	DC	0.113 GHz
Peak cathode field	125 MV/m	120 MV/m (Cu backplate)	60 MV/m	15 – 20 MV/m	10 MV/m	10 – 15 MV/m
Min cathode T	$\geq$ room T	$\geq$ room T	$\geq$ room T	80 K	35 K	2 K

* Only relevant for RF guns.



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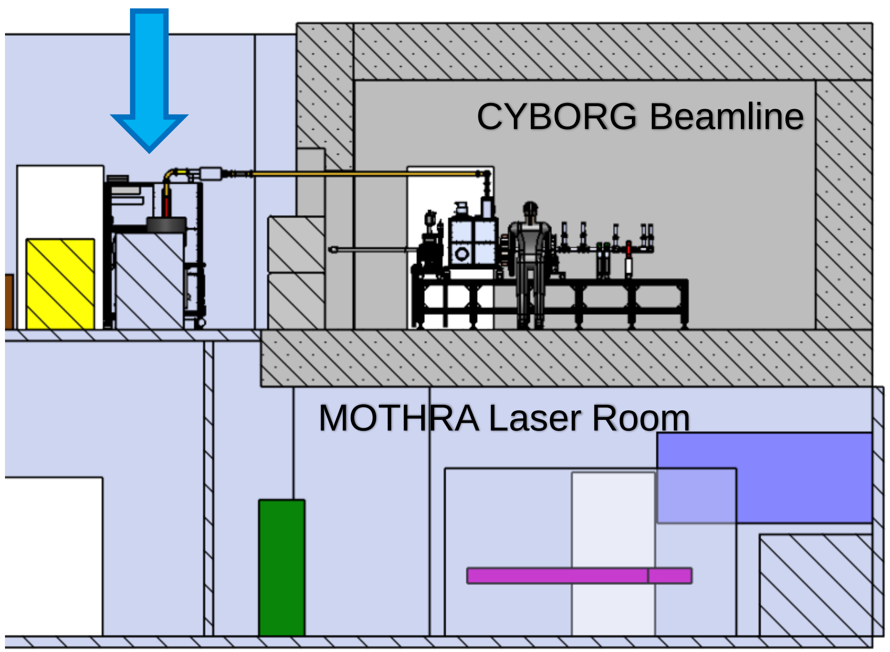
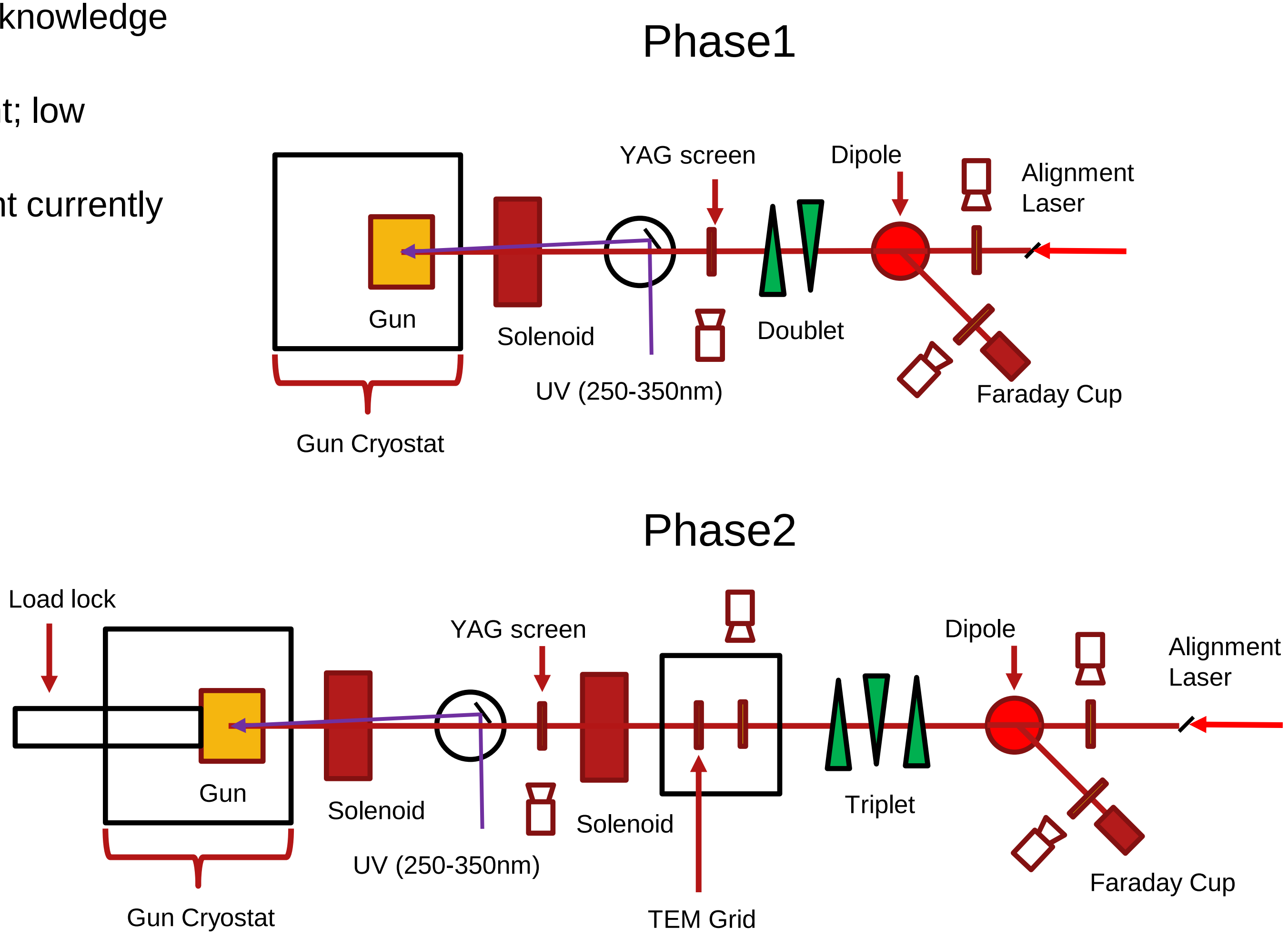
2) MOTHRA Review

- 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
- CYBORG beamline major component w/ multi-phase development currently in Phase1



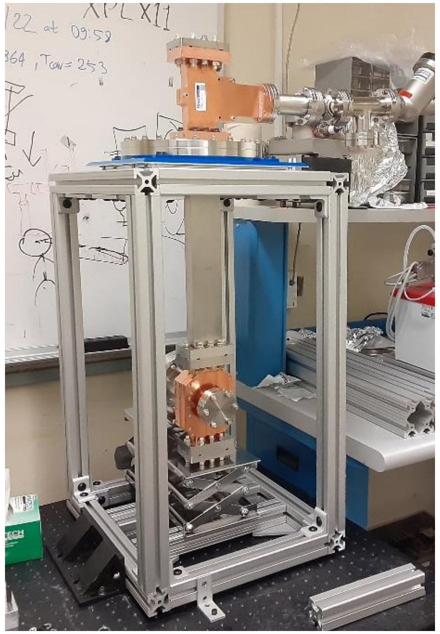


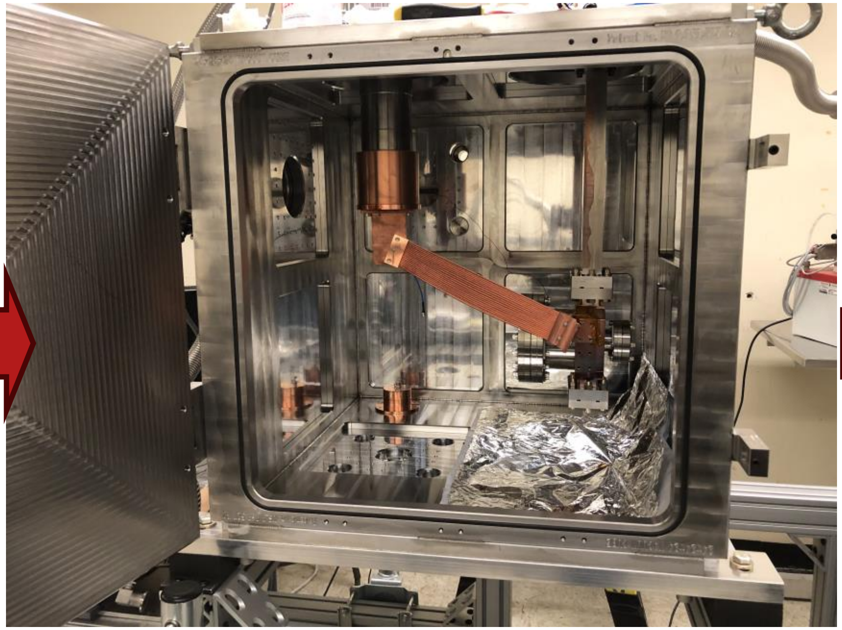
2) Previous Cryo + Low Power Updates

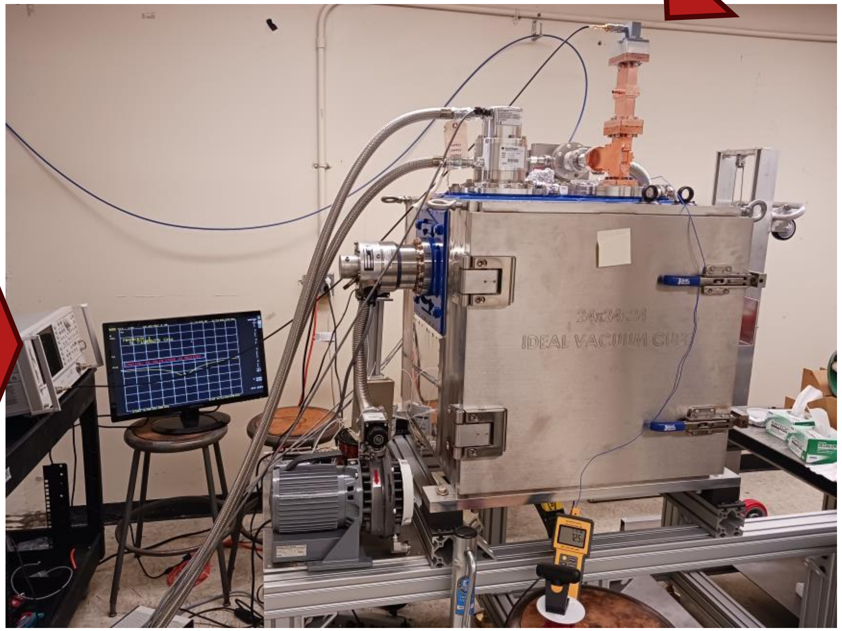
- Last status update in June had assemble gun section (left), placed in cryostat with thermal insulation (middle), and performed cool down to 90 K with low power RF antenna measurement (right)

$$\beta = \frac{\text{power loss in ext.cct}}{\text{power loss in cavity}} \qquad Q = \frac{\omega U}{P_d}$$

RF antenna

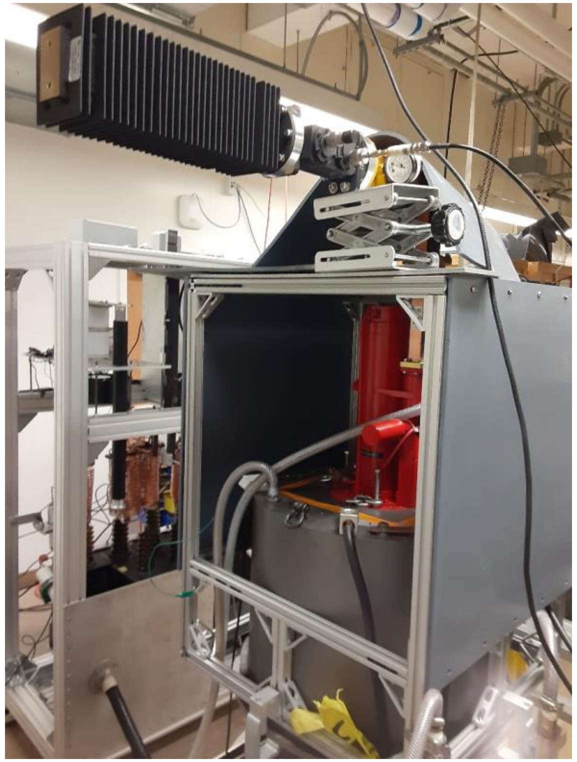


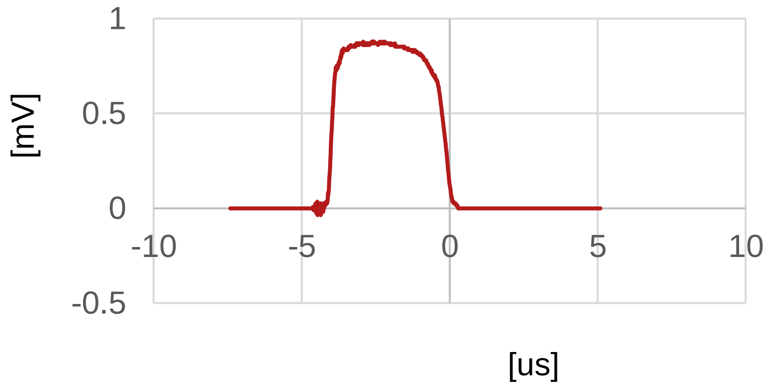




2) Previous High Power Updates

- Fired klystron RF into dummy load (middle) to tune pulse for driving gun and measured frequency bandwidth of klystron, up to 0.5 MW
- Example 4 us pulse shown (right)



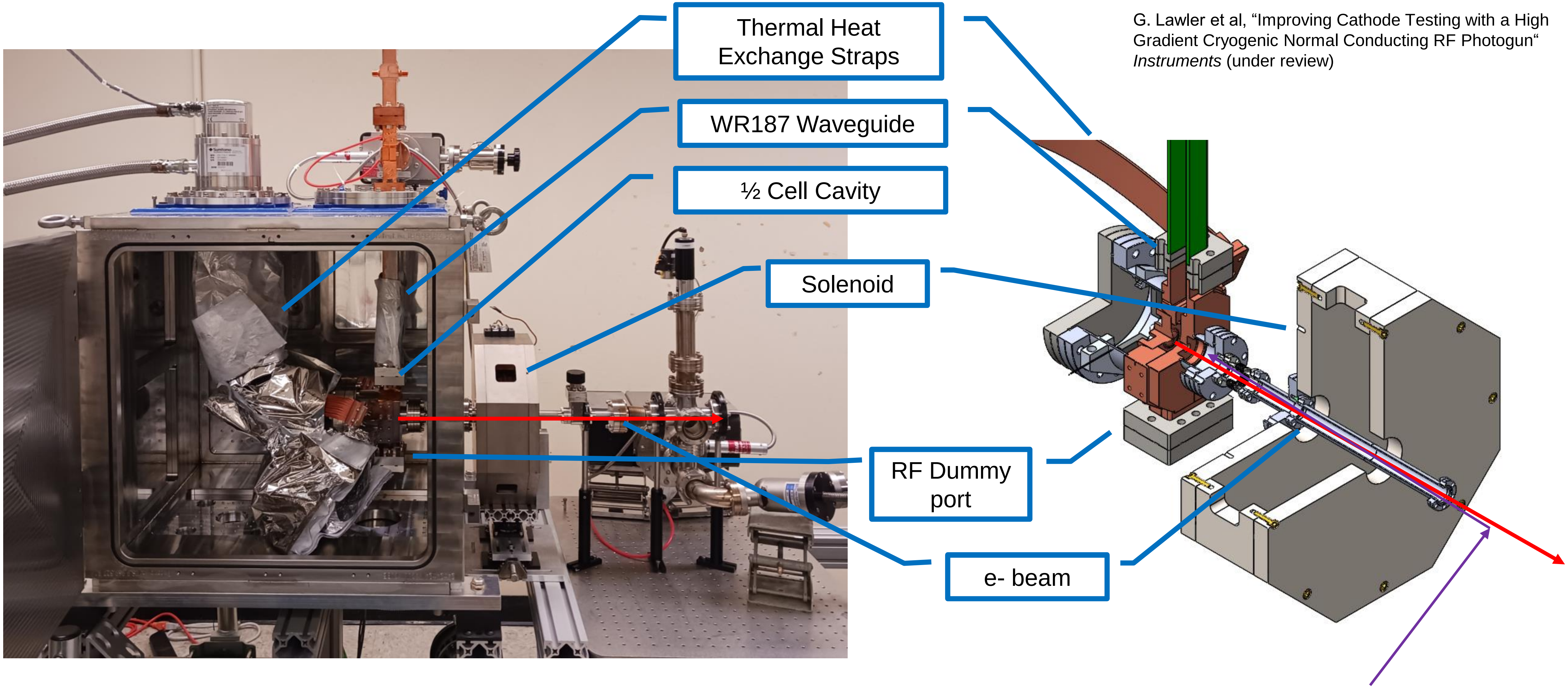


2) Beamline Updates

- Put in concrete bricks to shield beamline (gap to be filled with smaller stacked lead bricks when necessary)
- Connected waveguide between gun and klystron with probes for monitoring RF power

2) Phase1 Progress

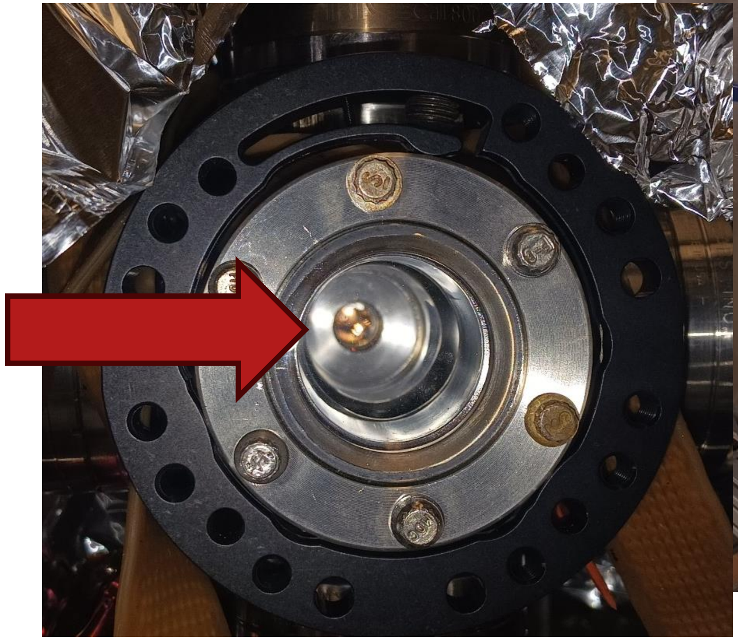
G. Lawler et al, “Improving Cathode Testing with a High Gradient Cryogenic Normal Conducting RF Photogun“ *Instruments* (under review)

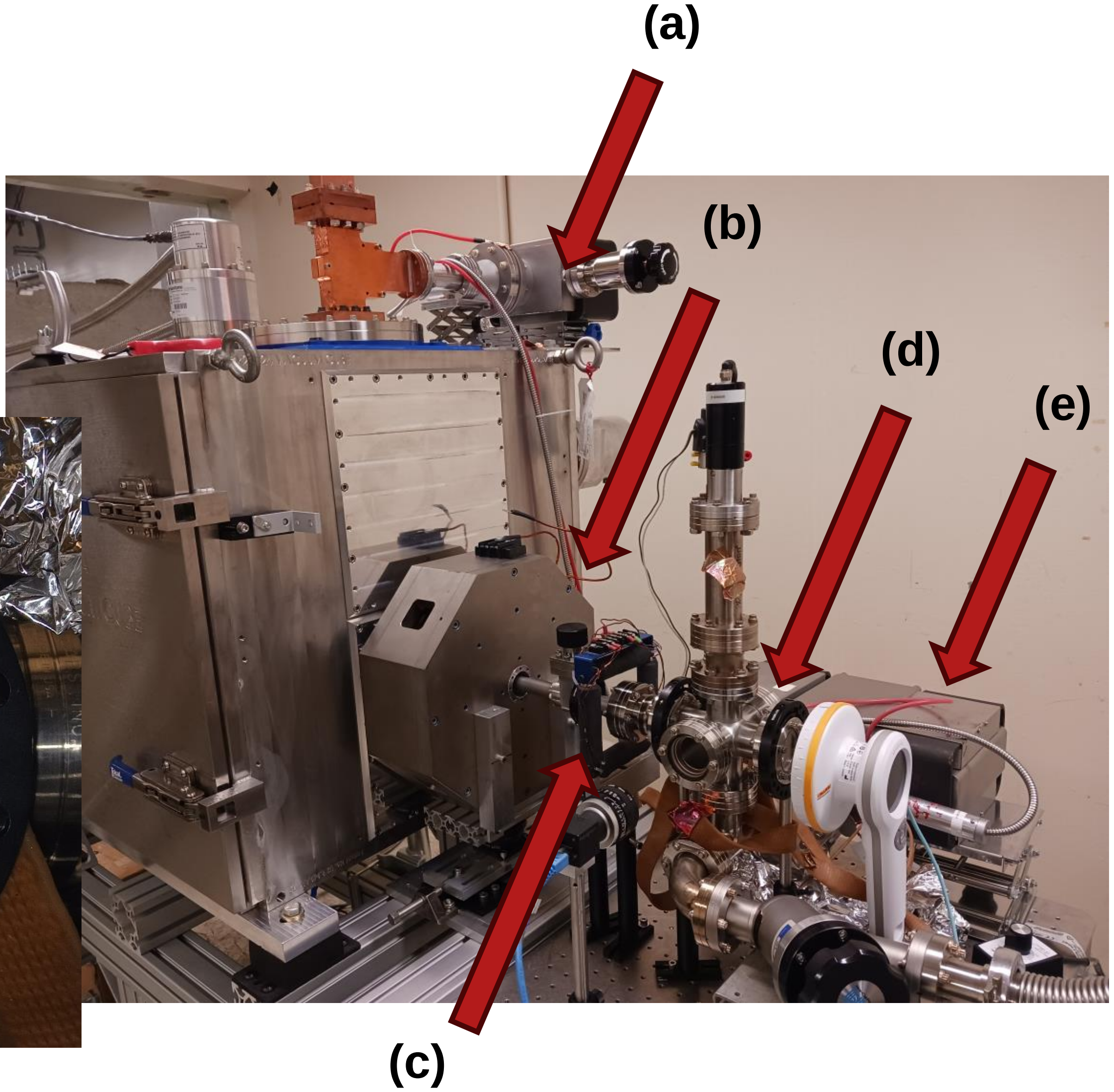


2) Beamline for Conditioning

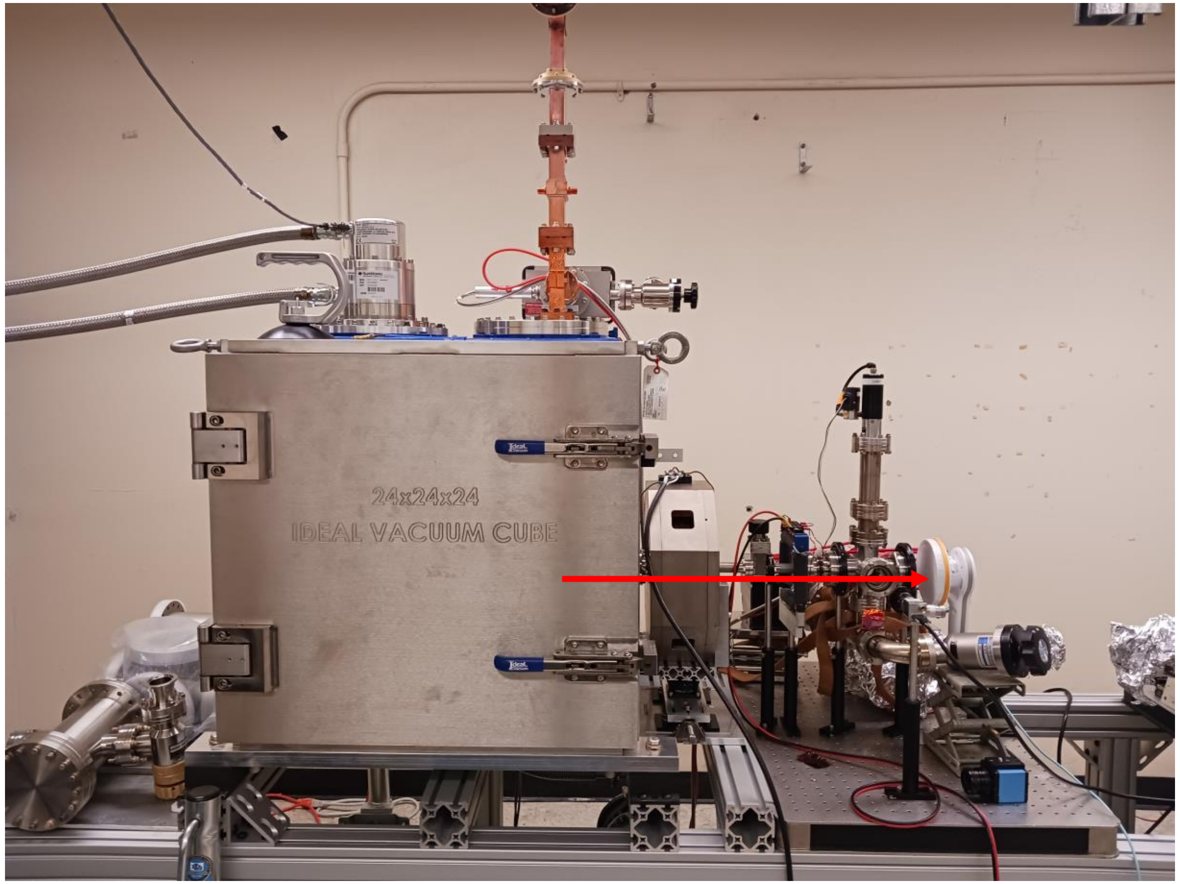
- Added preliminary beamline section sufficient for gun conditioning: **(a,e)** 2x ion pumps , **(b)** solenoid, **(c)** steering magnet **(d)** YAG screen
- < 10^-8 torr (2uA; 5 uA) at gun and screen
- Custom solenoid mount has 4 degrees of freedom
  - 3 transverse + rotation about x (vertical axis)

Cu cathode visible down the barrel of the gun

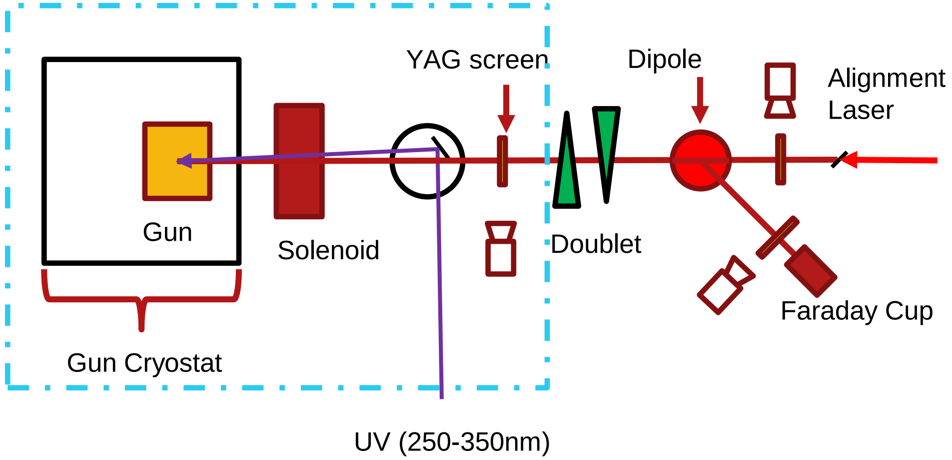


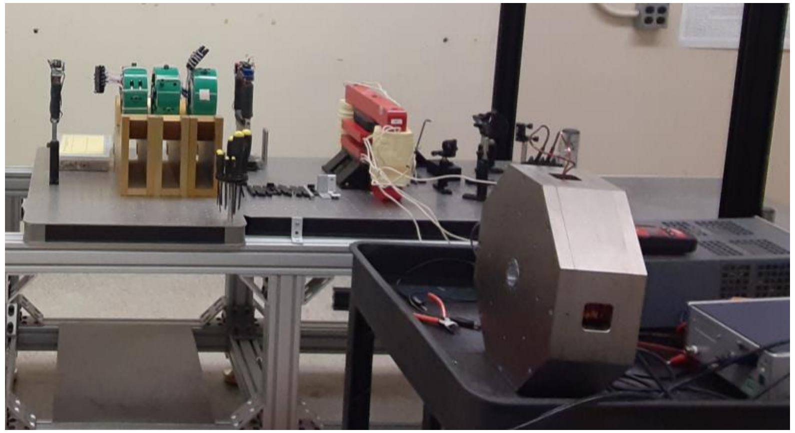


2) CYBORG Phase1



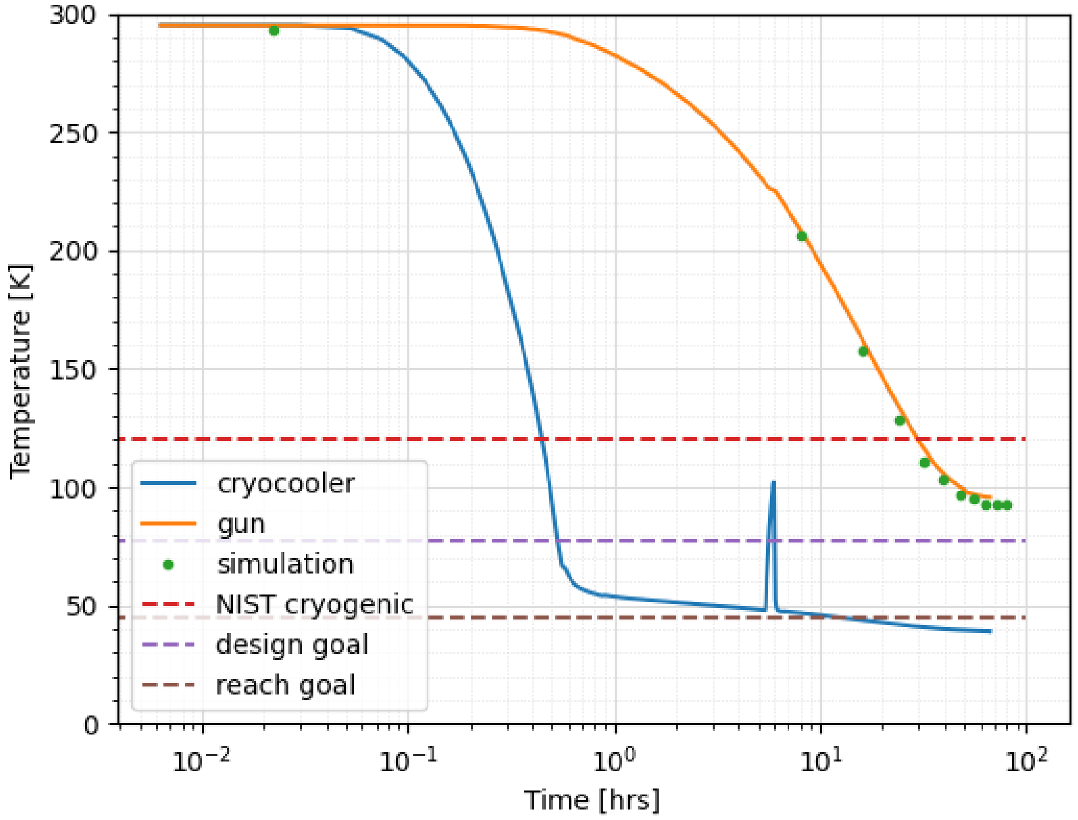
Phase1





2) Gun Cooldown w/ Beamline

- Previous cooling (right) for comparison
- Added beamline feedthrough giving additional heat leak and
- 50 hours of cooling: 74 K on cold head and 105 K on gun
- Braid conductance much better (35 K grad vs. 60 K gradient)
- 10 K warmer due to addition of beamline connection since 95 K test
  - More thermal shielding to come



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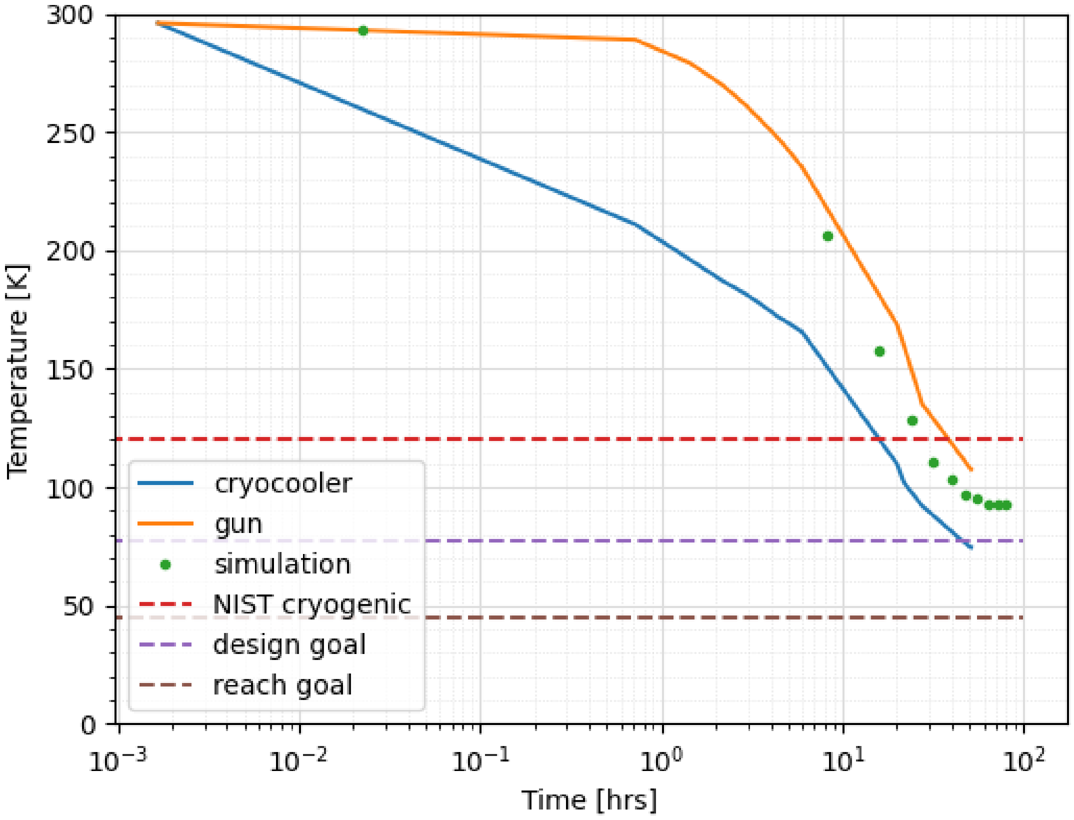
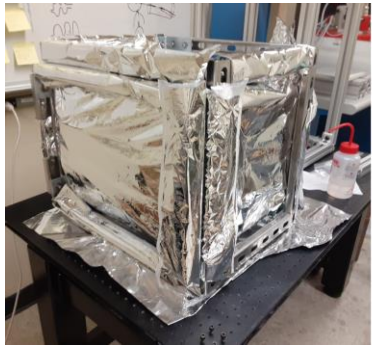


2) Further Cooling Improvements

- Previous outer shielding difficult to integrate without thermal shorts (below) due to MLI movement



- Assembling improved version with aluminum sheets for extra rigidity

AL125 for outer shielding

CH110LT covered in MLI (inner shielding)

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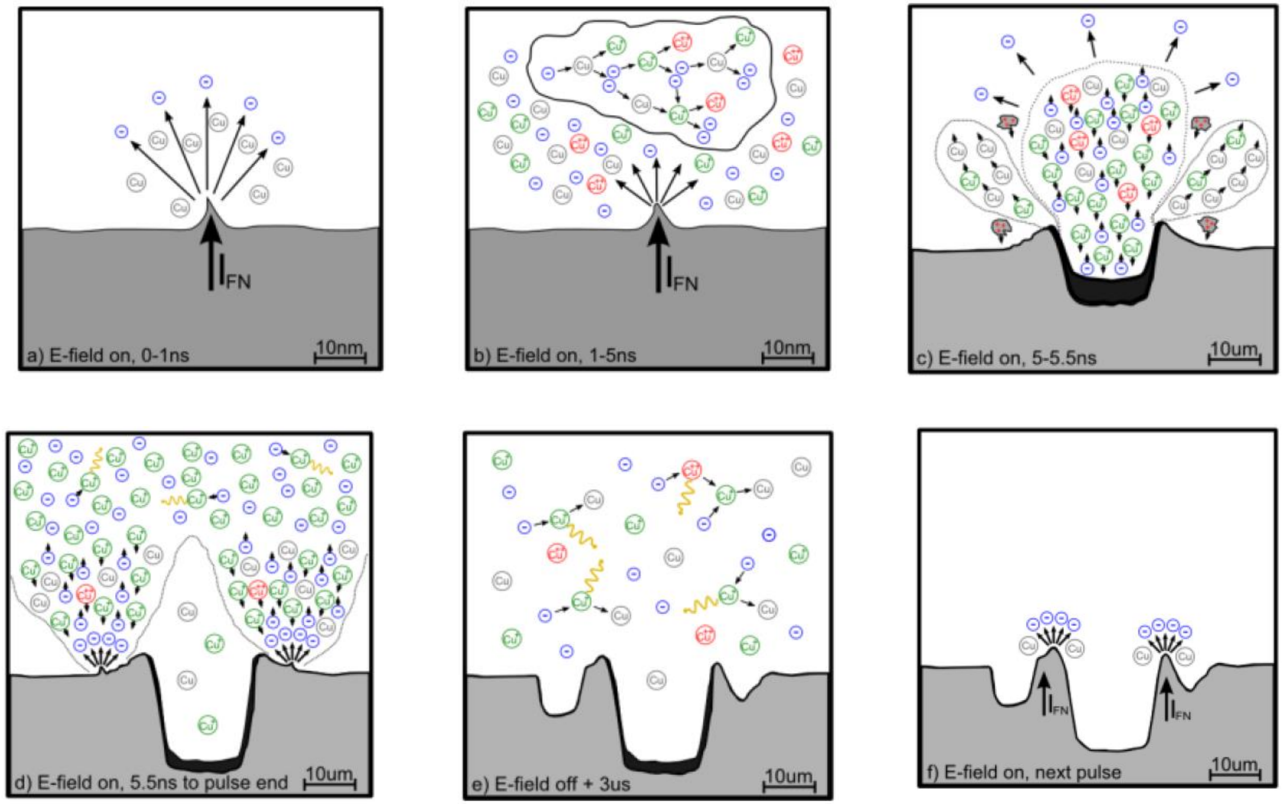
3) Qualitative RF Breakdown Theory [18]

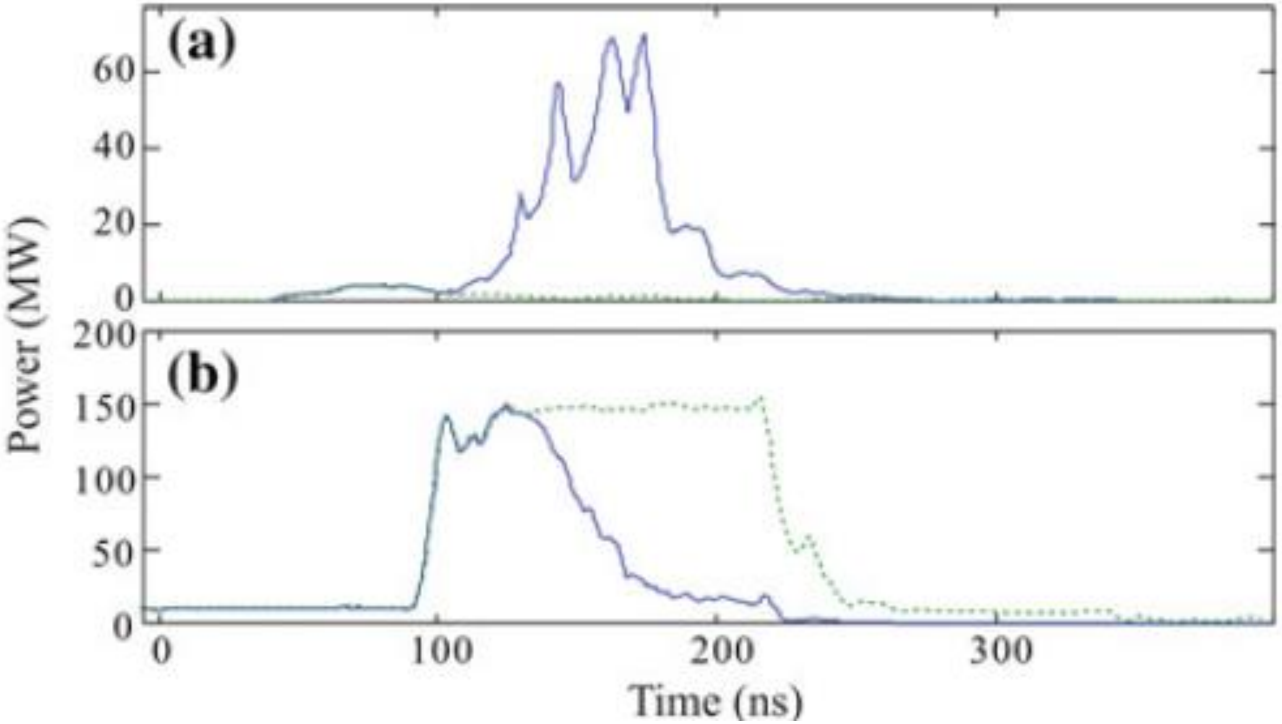
- RF breakdown rate (BDR) increases exponentially with accelerating gradient
- Prevailing thesis is caused by field emission from cavity microstructure reaching 10 GV/m leading to 10^11 A/m^2 currents which by Joule heating vaporize the emitters on the 10s of nm scale
- (a) Metal gas ionized by field emission current and (b) ions form sheath near surface or hit the surface (c) leading to more field emission and eventually explosive electron emission (EEE) melting microdroplets and craters
- (d-f) Crater-microdroplet system forms more field emitters until stored energy in RF structure would be absorbed until it could no longer sustain the process



3) RF Breakdown Signal [17]

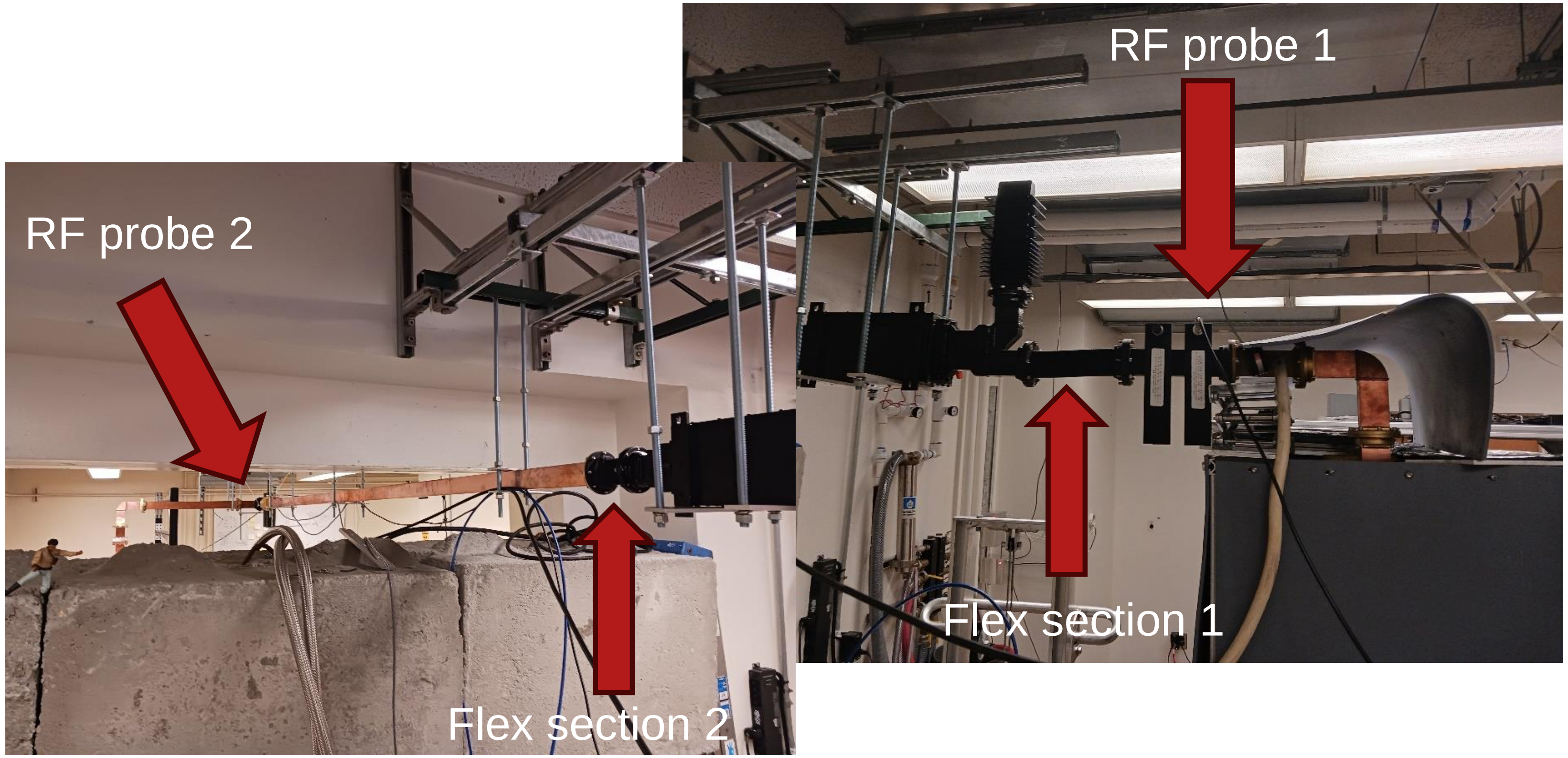
- Reflected power shown in (a)
- Forward power shown in (b)
- Green dashed no breakdown
- Blue with breakdown
- Also measured via downstream screens or pressure rise (below, compressed 30 minutes @ 1 Hz rep rate)

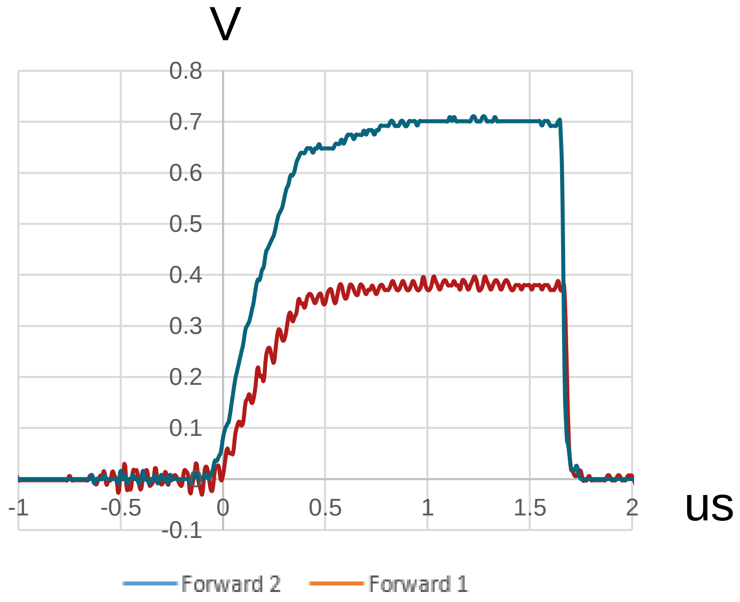
$$\text{BDR} = \frac{\text{Number of breakdowns}}{\text{Number of pulses} \times \text{Length}}$$



3) Waveguide Test

- No waveguide breakdown for 700 mV => 320 kW and 1.5 us pulse

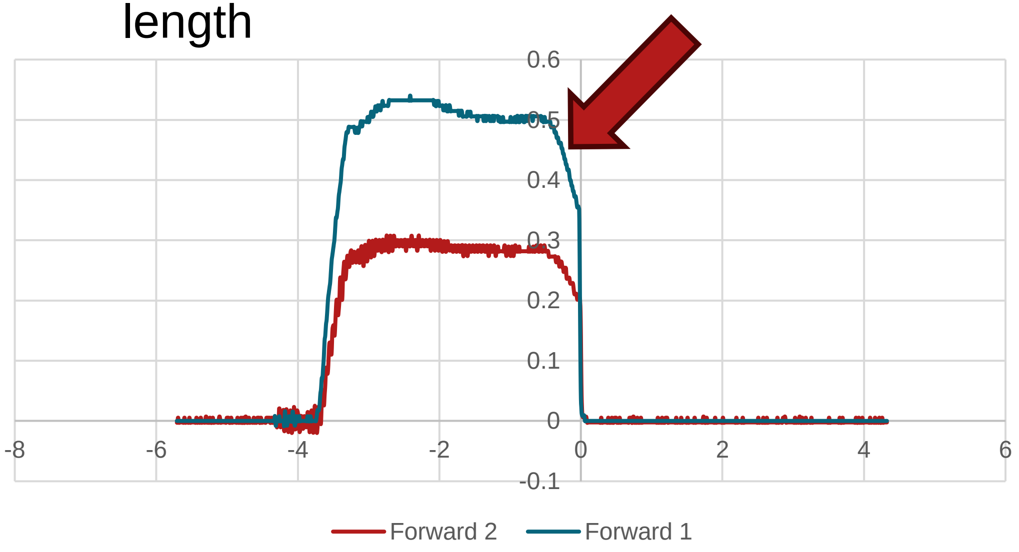




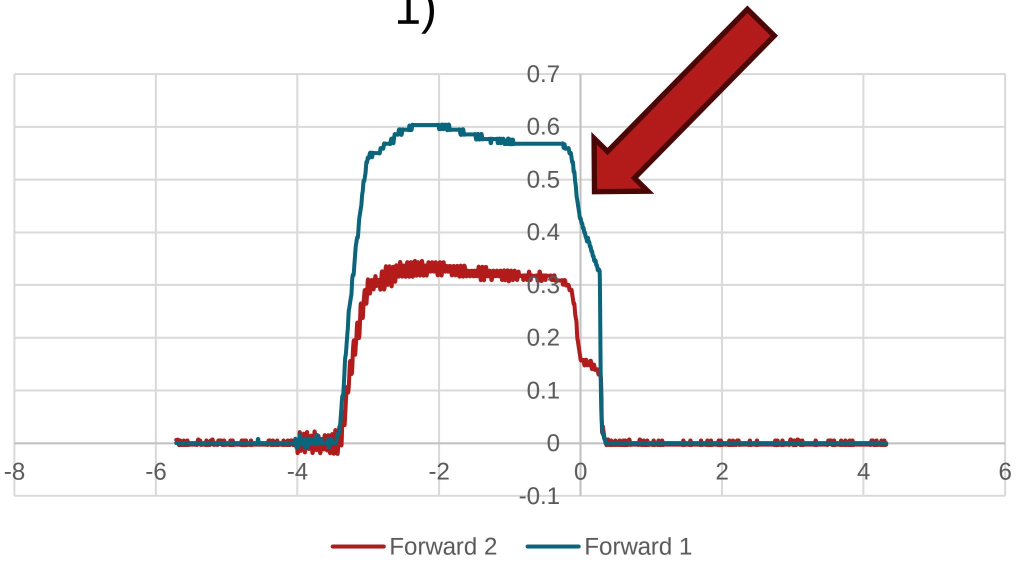
3) Waveguide Test

- Extend pulse length long enough see breakdown before entering gun
- Longer pulse has something that may be tube breakdown
- Gun operation for 2 us pulses so should not be major problem

>4 us drop not breakdown, just PFN pulse max length



Additional drop maybe tube breakdown (happens before coupler 1)



3) Filling Resonant Cavity

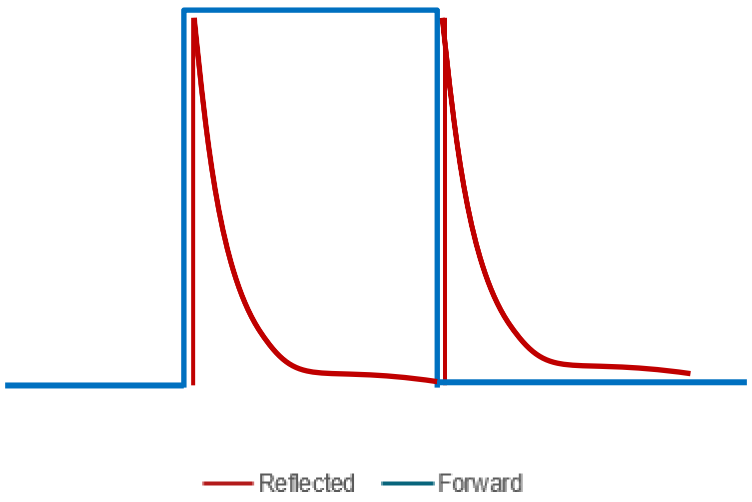
- Ideal gun filling looks qualitatively like (right)
- Additional C-band motivation @ cryogenic temp, RF filling time scales as

$$\tau_{\rm rf} \sim f_{\rm rf}^{-5/3}$$

- 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

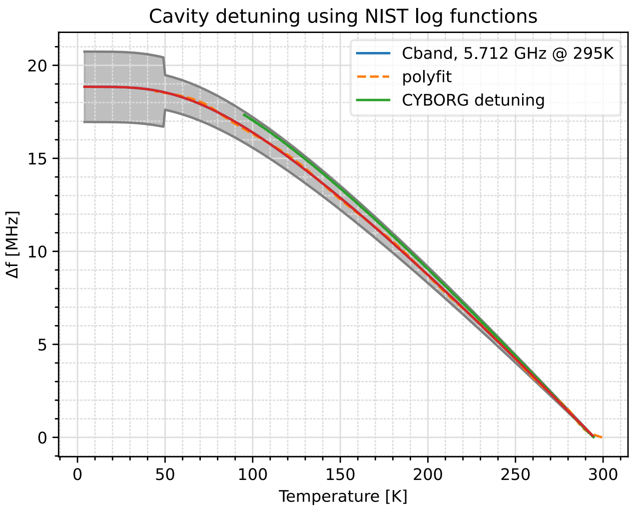
$$P \sim f_{\rm rf}^{-2}$$

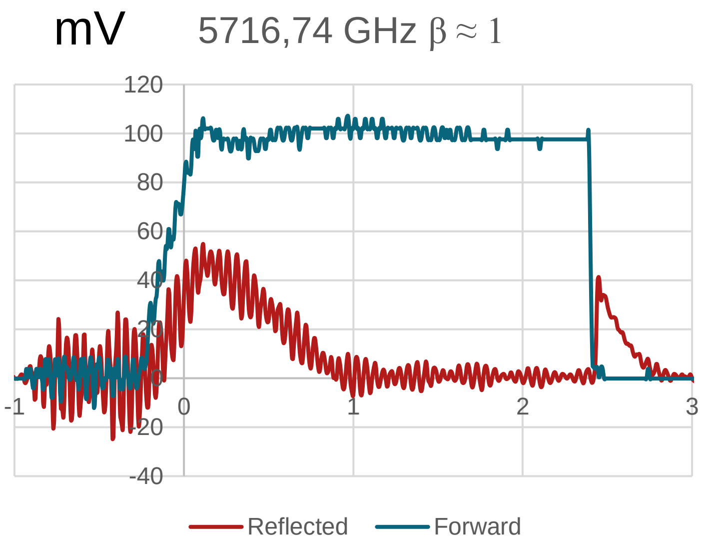
  – Greater than factor of 4 reduction for Sband to Cband

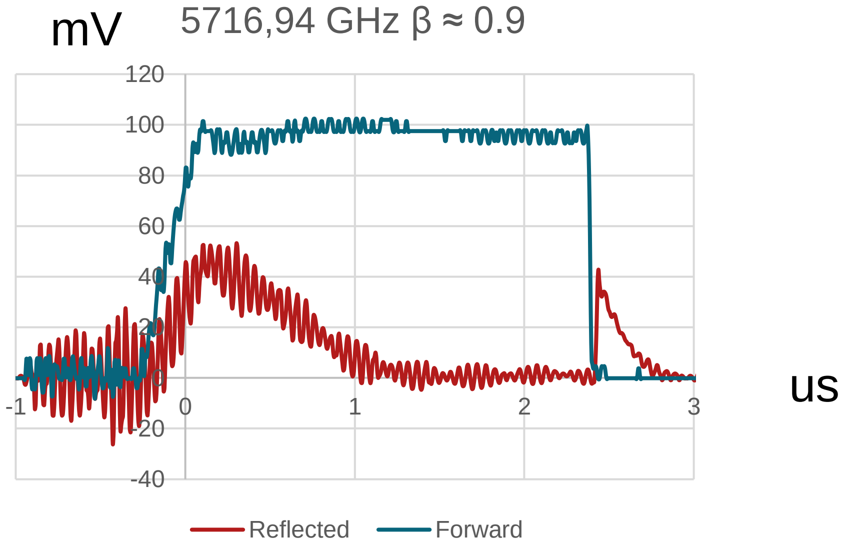


3) Cold Gun Feeding

- First filling of gun cavity at intermediate temperature during cool down to 150 K to look at detuning
- 100 mV => 14 kW
- Fully filled @ 2.5 us => 15 MV/m

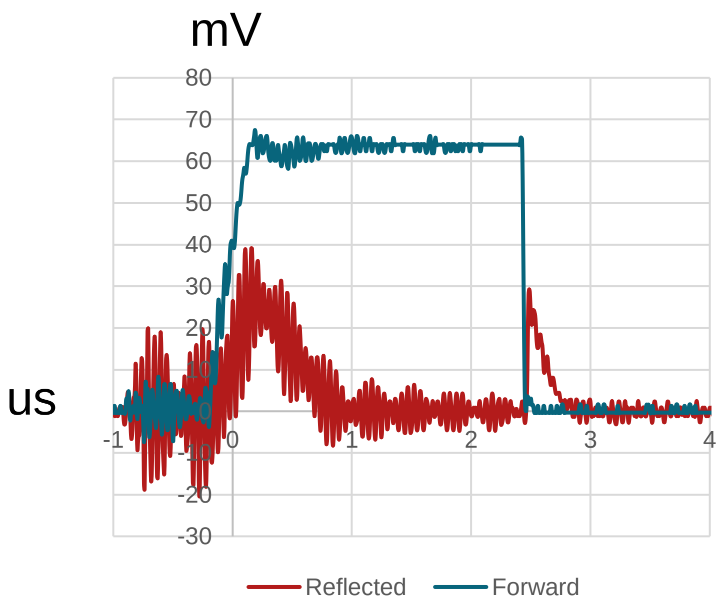


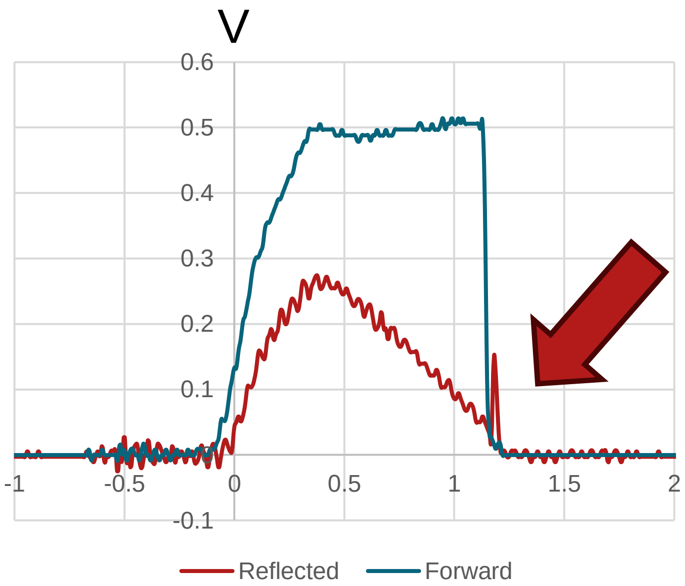


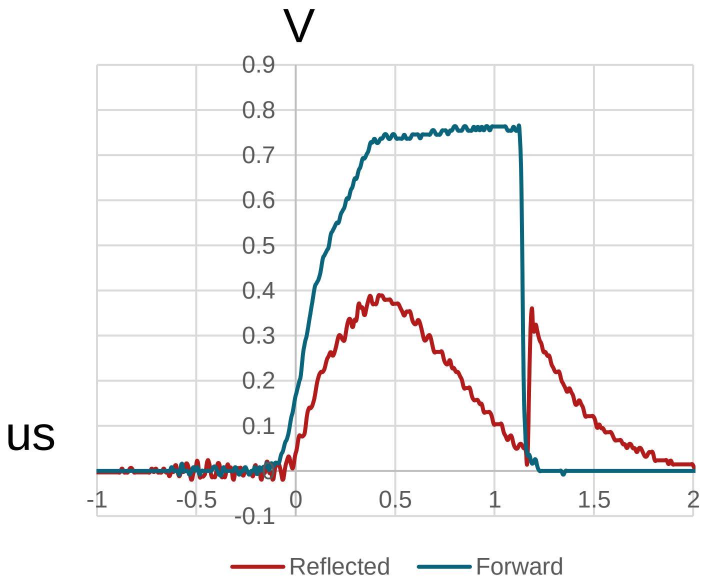


3) Cryo Gun Conditioning

- Down to 105 K for conditioning
- **(a)** 2.5 us pulse low power (8 kW) to find resonance @ 5719.2 GHz (left) **(b)** shortened pulse to 1 us **(c)** ramped up power pausing when breakdown events observed and let run until breakdown events cease (middle) **(d)** repeat until max power (right)
  - Up to ≈ 350 kW (right), when fully filled @ 2.5 us => 75 MV/m
- Go back to lowest input power level incrementally increase pulse length and repeat up to highest power until operational power and pulse length experience no breakdown events.







3) RF Surface 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.

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

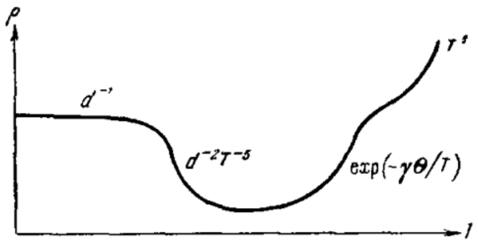
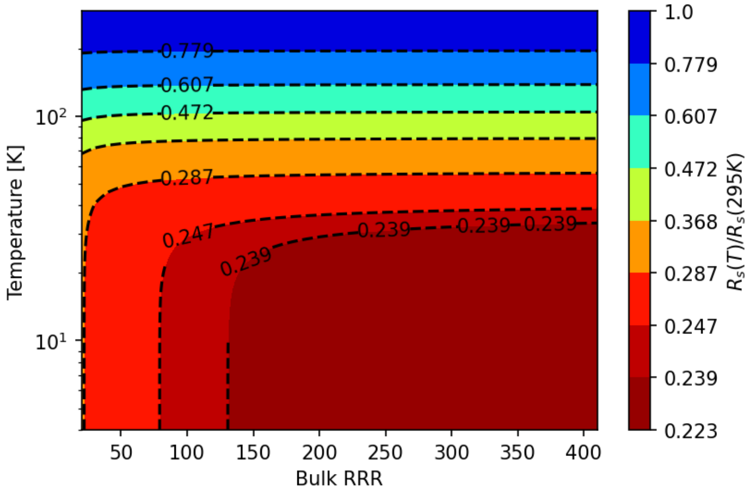


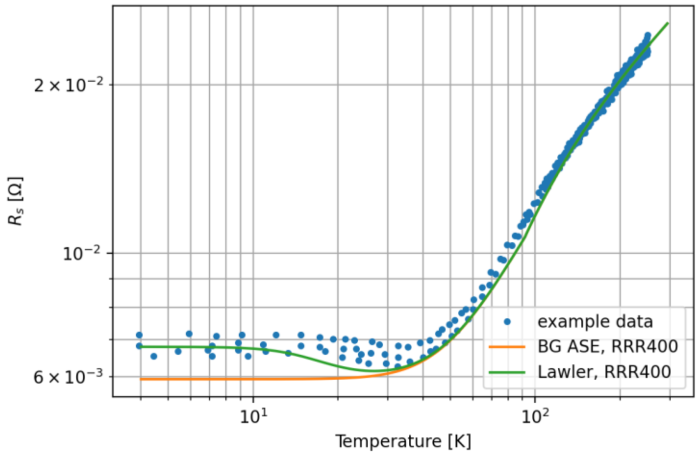
FIG. 4.

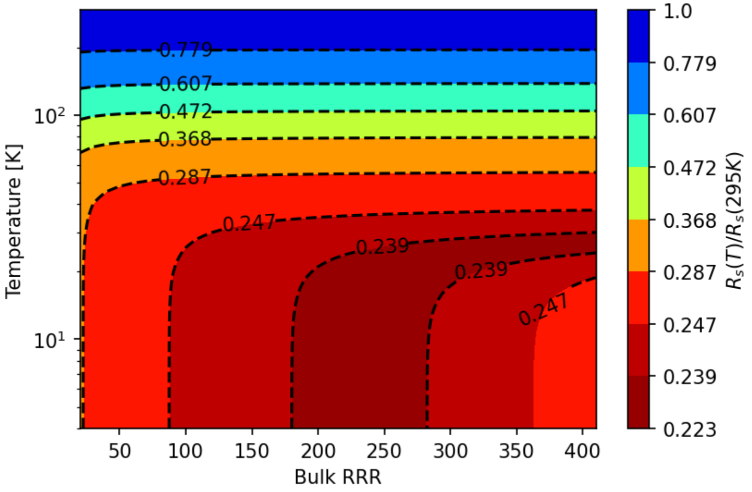


- Solve for above cutoff for RRR450 gives approx. 35K-40K
- Proof of concept easier toy model built which has some of same features and easier to compute for now (below + right)
- Effective thin film modification to bulk via Fuchs-Sondheimer

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

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

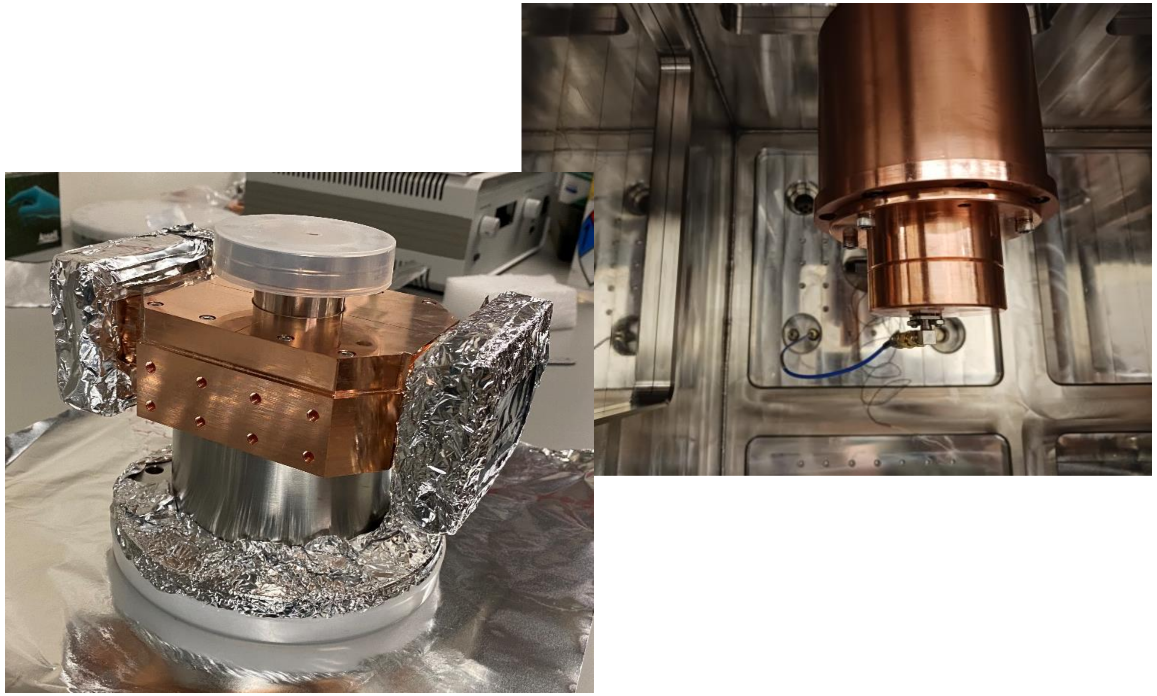




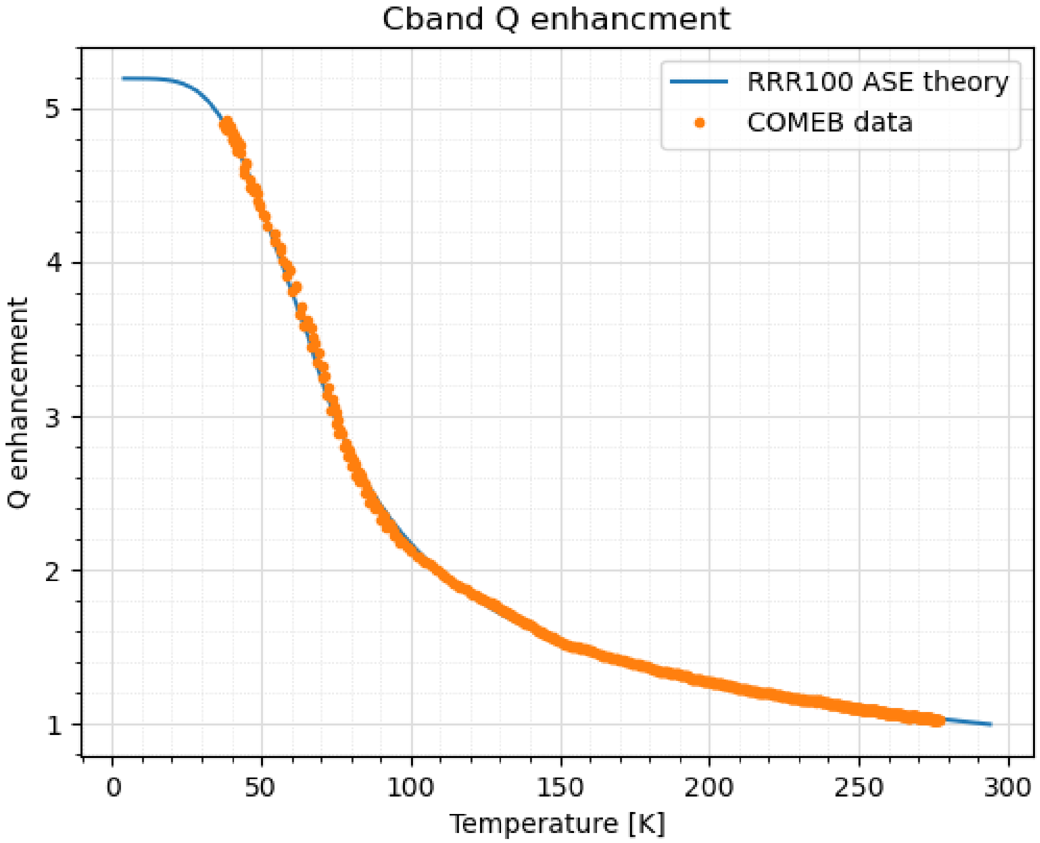
3) RF Surface Measurements

- 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}

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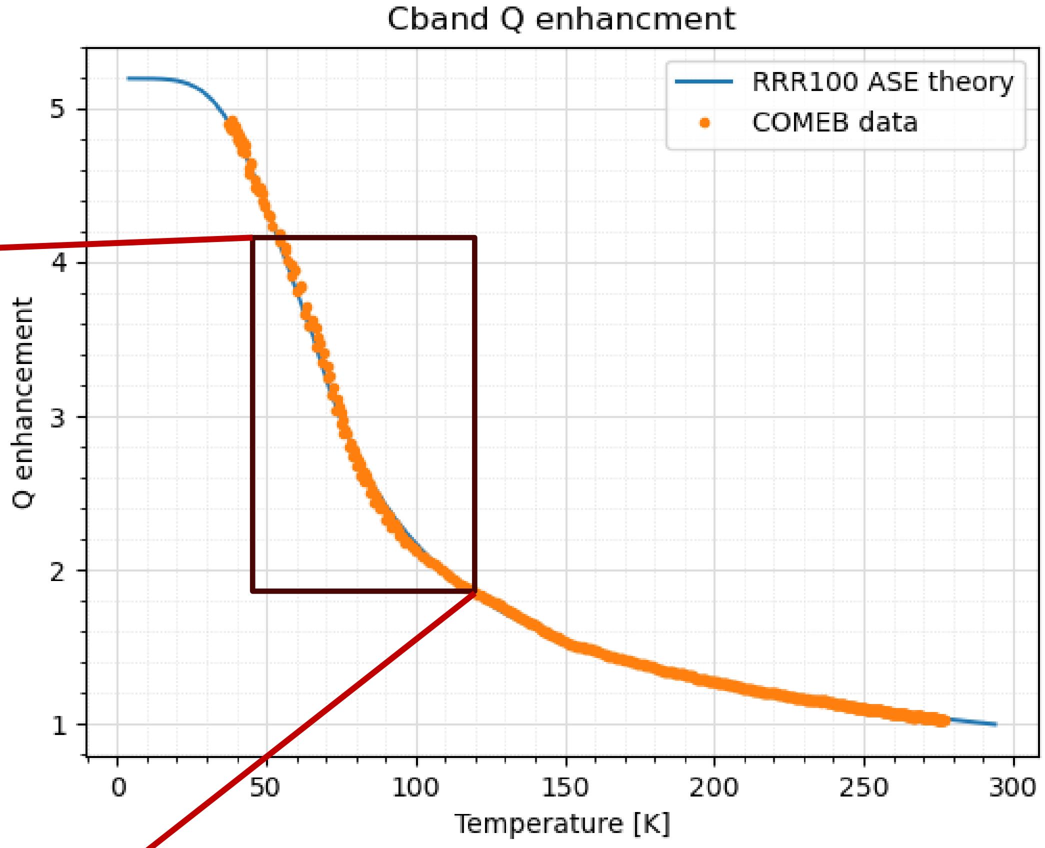

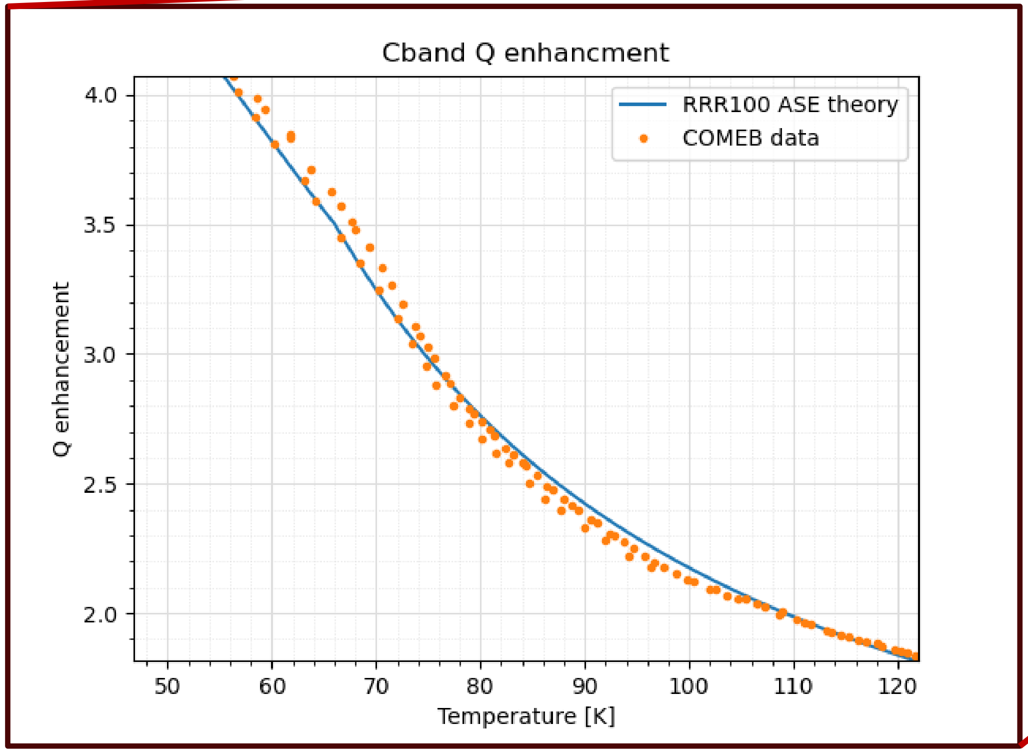

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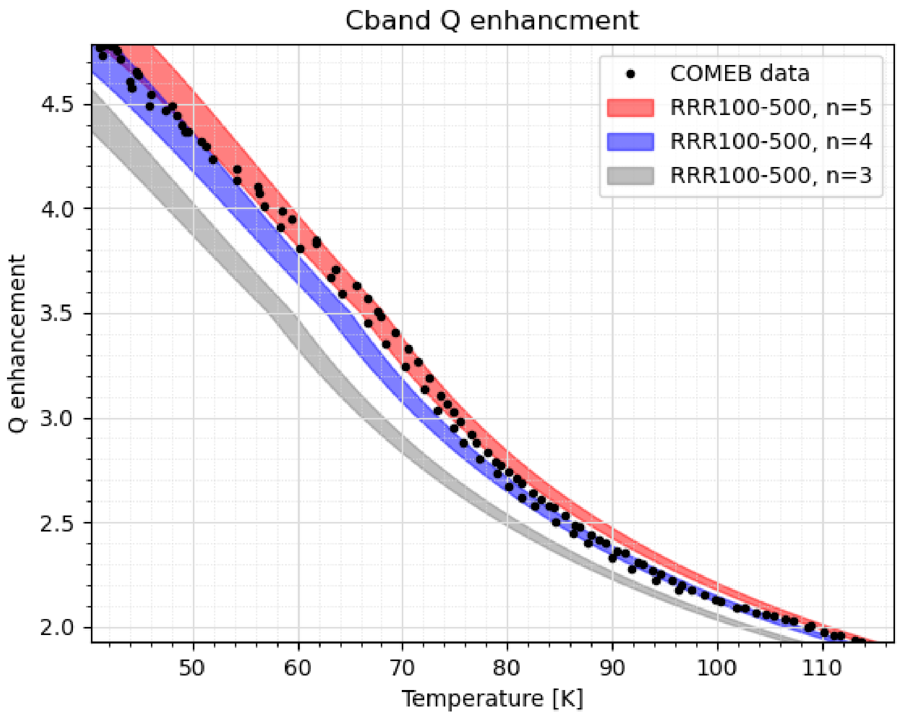
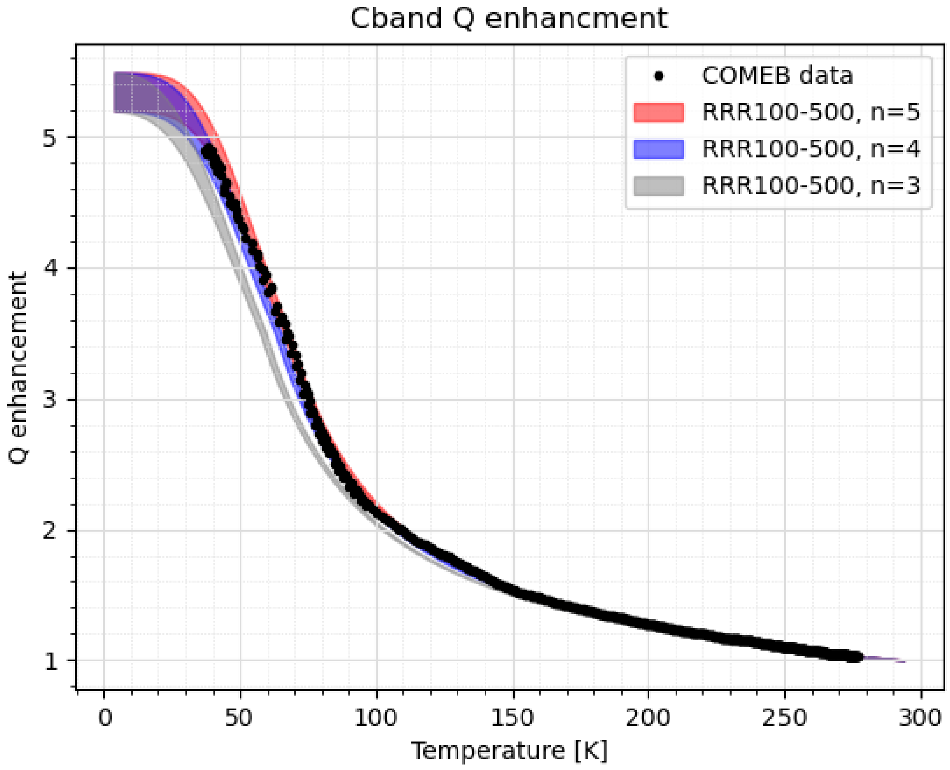
3) Additional RF Surface Theory Improvements

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

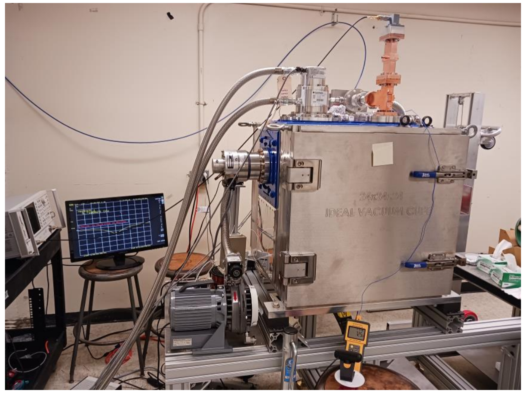
$$\rho\left(T\right)=A\left(\frac{T}{\Theta_R}\right)^n\int_0^{\Theta_R/T}\frac{t^n}{\left(e^t-1\right)\left(1-e^{-t}\right)}dt+C$$

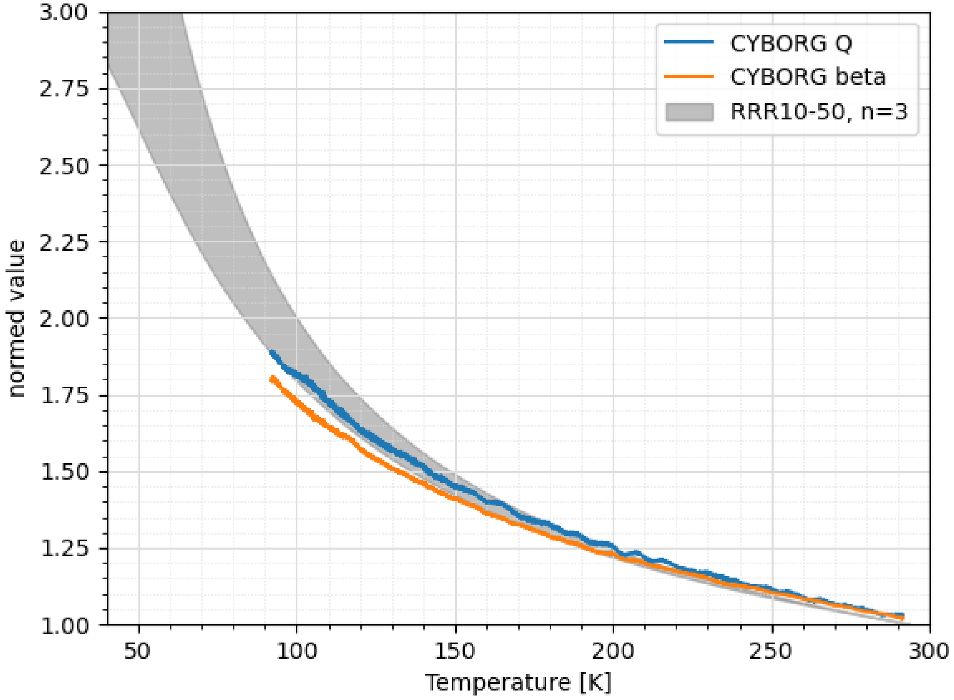


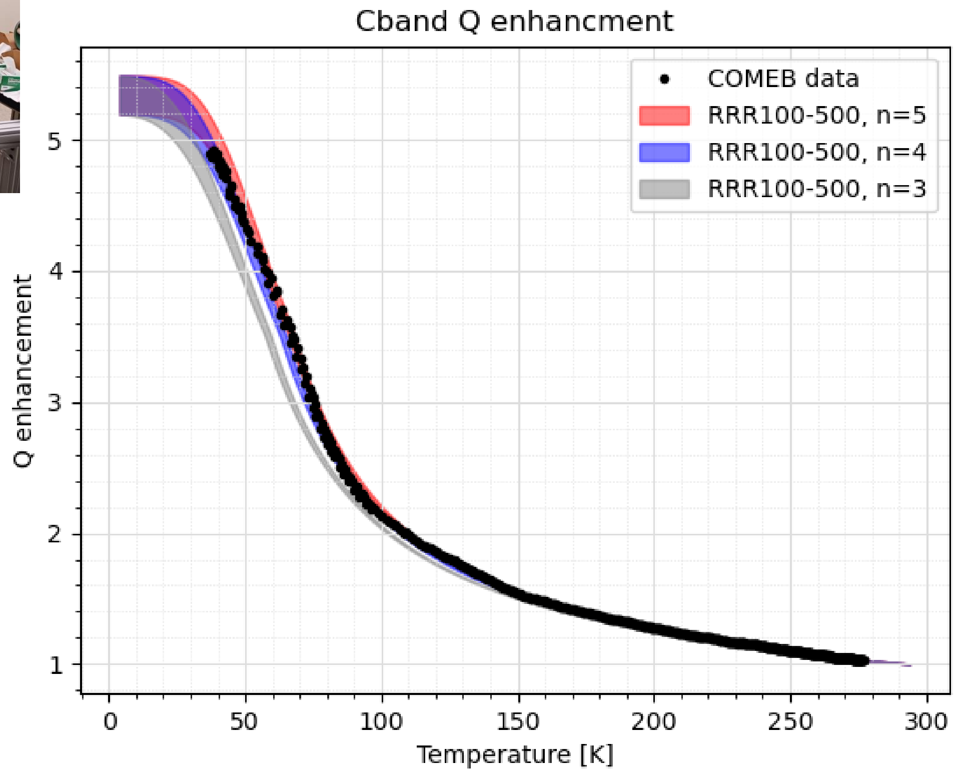


3) Additional RF Surface Theory Improvements

- When compared to CYBORG antenna measurements undervalued esp. compared to pillbox
- As conditioning continues, can measure Q and coupling during conditioning





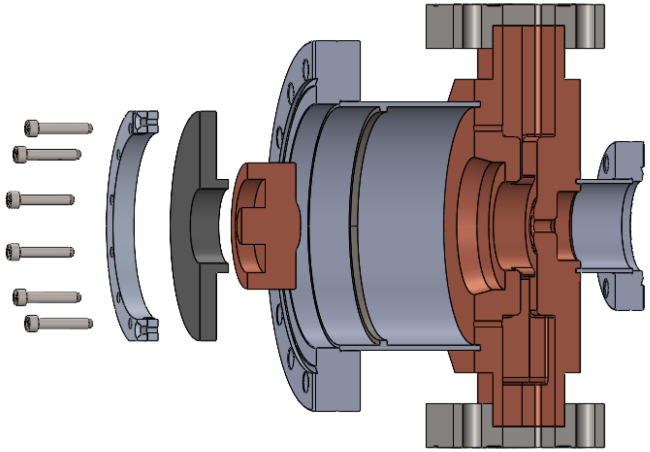


3) Cryo RF Performance Overview

- Parameters for gun thus far compared to RRR100-500 case (left) with empirical numbers measured to inform simulations (right)

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

G. Lawler et al, "Improving Cathode Testing with a High Gradient Cryogenic Normal Conducting RF Photogun" *Instruments* (under review)

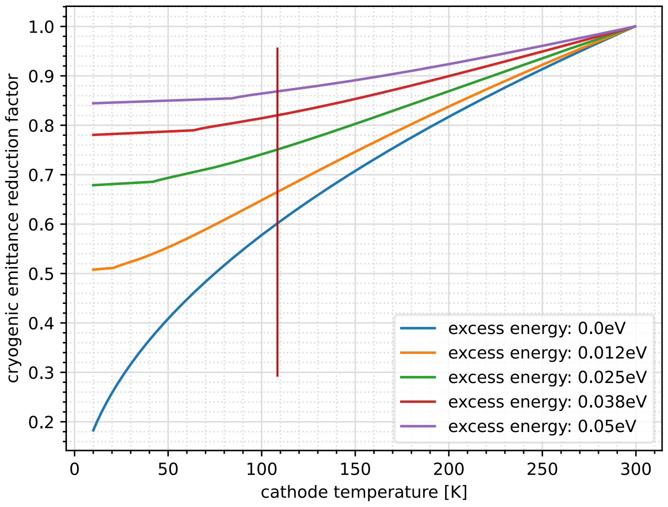


Parameter	295 K	95 K	77K	45 K
f_0 [MHz]	5703.6 ± 0.1[1]	5720.410 ± 0.003[1]	5721 ± 3	5722 ± 4
Q_0	7808 ± 13[1]	14326 ± 12[1]	21000 ± 3600	30000 ± 9900
Coupling β	0.608 ± 0.002[1]	1.069 ± 0.002[1]	1.60 ± 0.44	2.4 ± 0.9
Filling time [μs]	0.271 ± 0.01[1]	0.386 ± 0.001[1]	0.44 ± 0.01	0.49 ± 0.03
Power [MW] for 120 MV/m	1.23 ± 0.10	0.85 ± 0.08	0.79 ± 0.01	0.70 ± 0.09
Energy [J] per 2μs pulse	2.45 ± 0.01	1.70 ± 0.02	1.58 ± 0.03	1.40 ± 0.19
Cathode field @ 0.5 MW	77 ± 3 MV/m	92 ± 5 MV/m	93 ± 3 MV/m	102 ± 7 MV/m

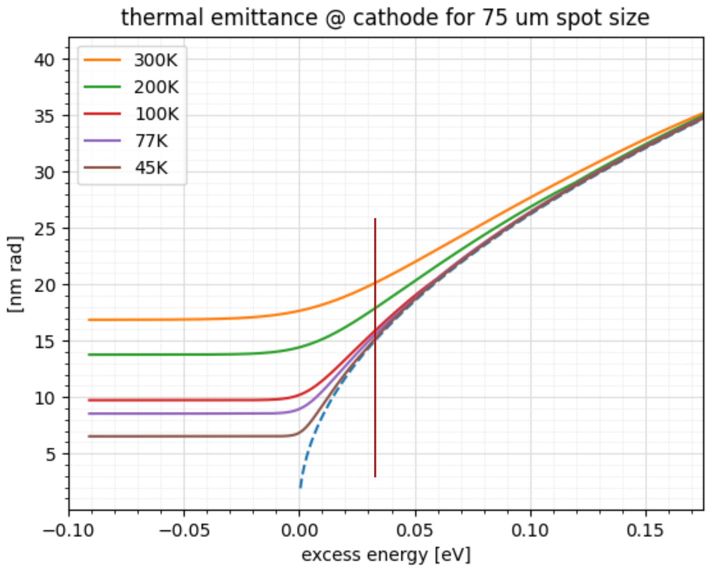
[1] Values experimentally measured or computed directly from low power measurements

3) CYBORG MTE Performance

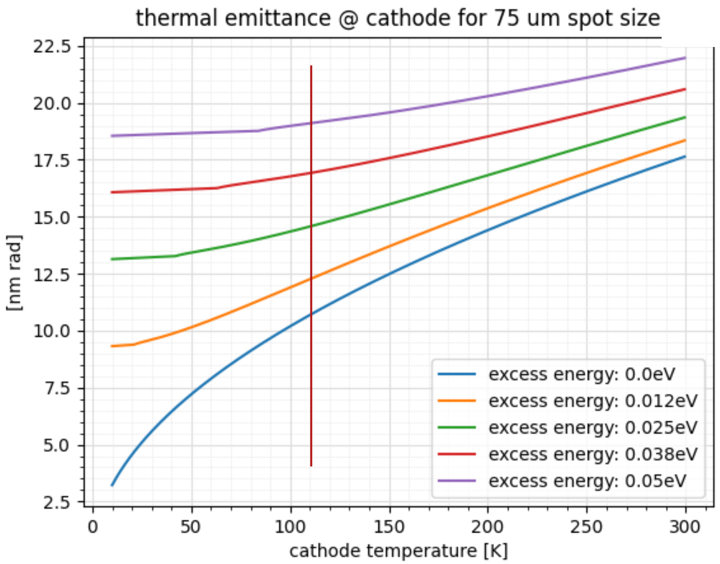
- Performance sufficient for laser @ near threshold to be main concern



(a)



(b)

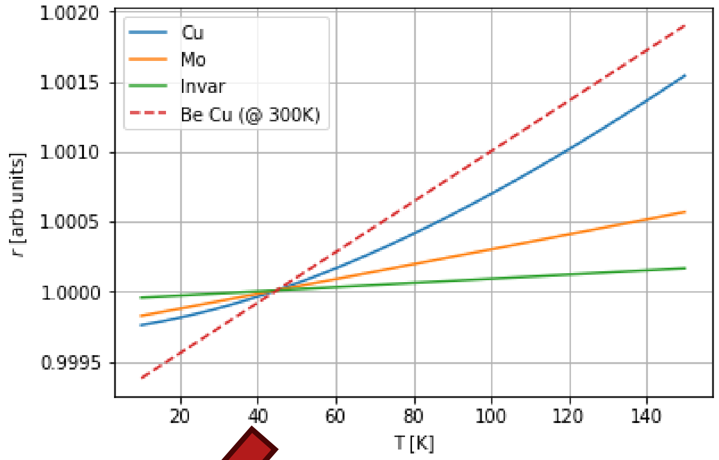


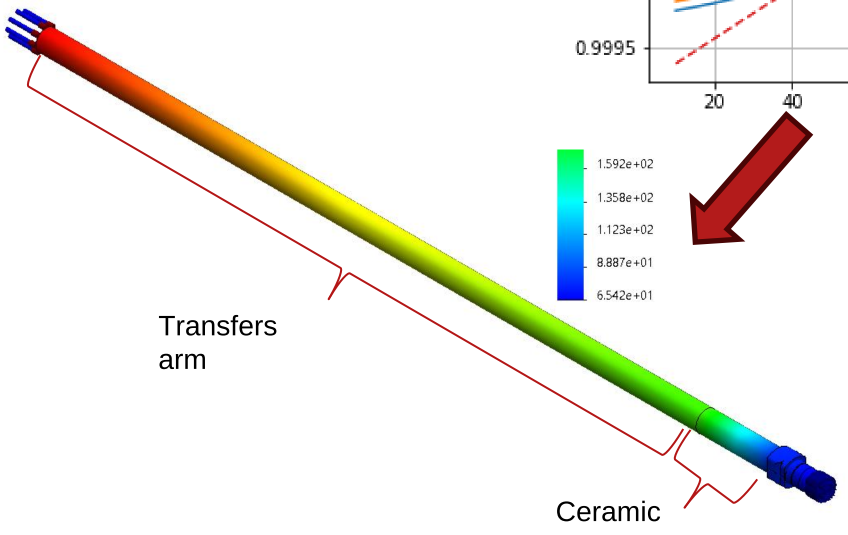
Outline of presentation

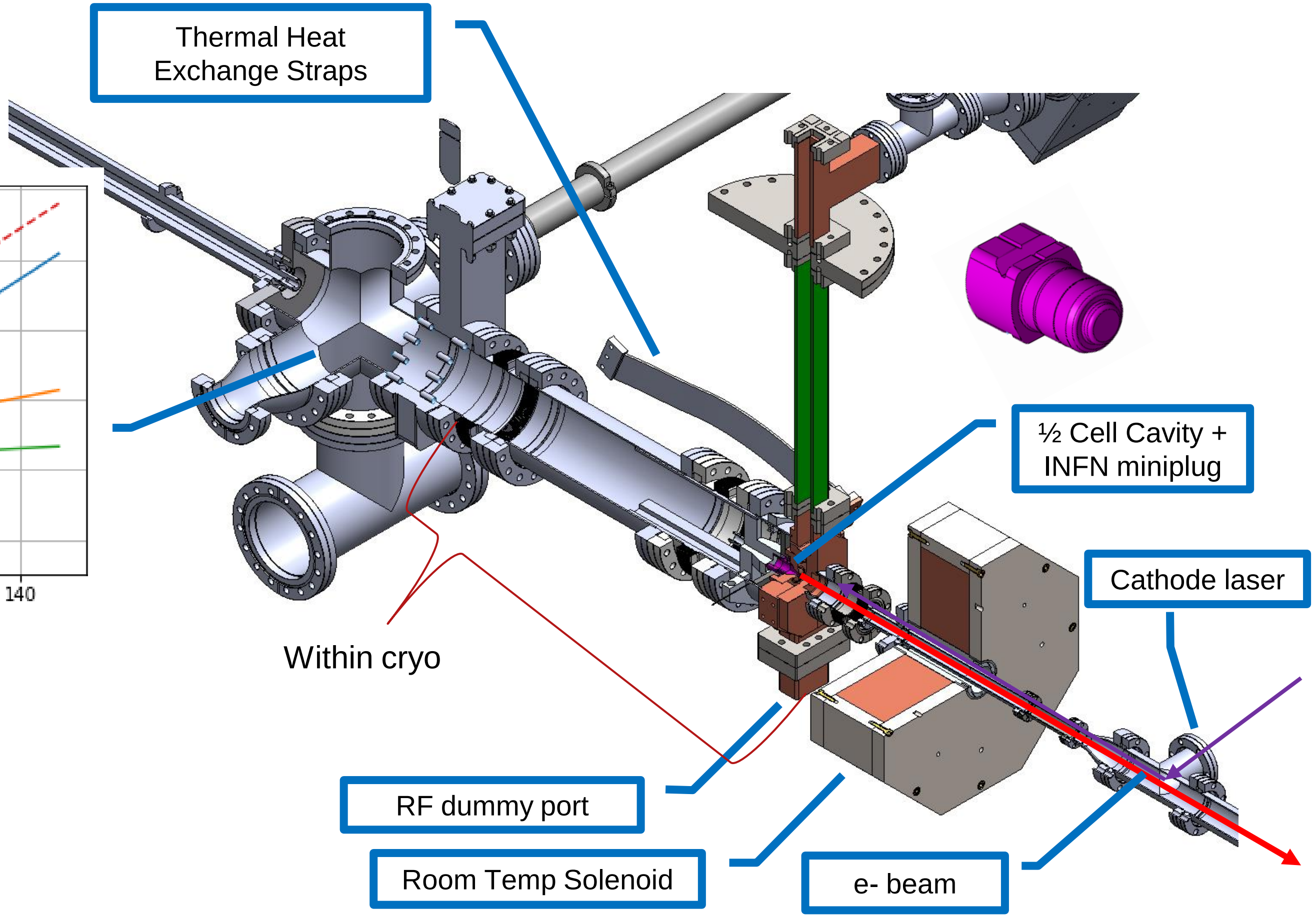
1. Background and motivation
2. MOTHRA + CYBORG status review
3. RF physics and gun conditioning
4. **Future testing/discussion**
5. Conclusions

4) Phase2 Load lock

- Difficulty of interference fit for cathode coupling not reliable in near term
- Shift to knife edge coupling with sufficiently thermally isolated transfer arm

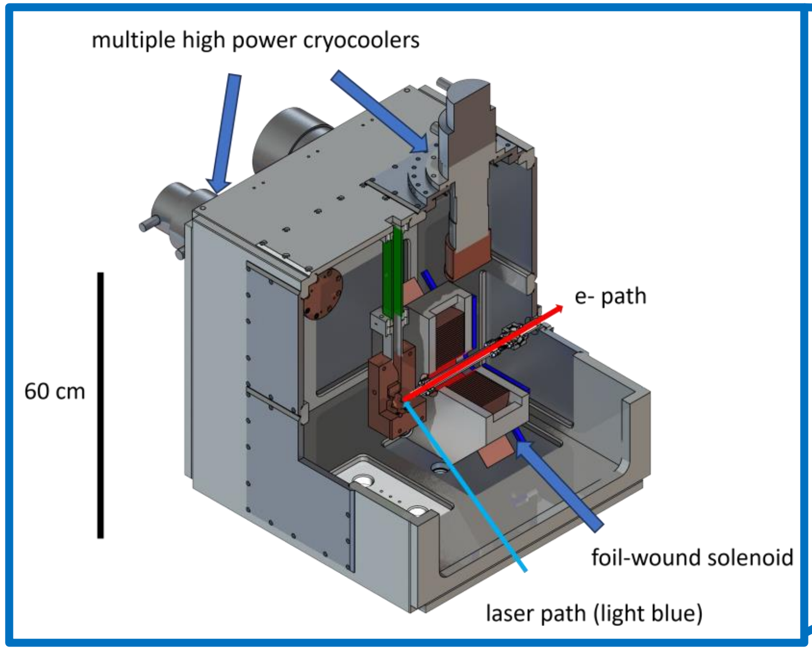


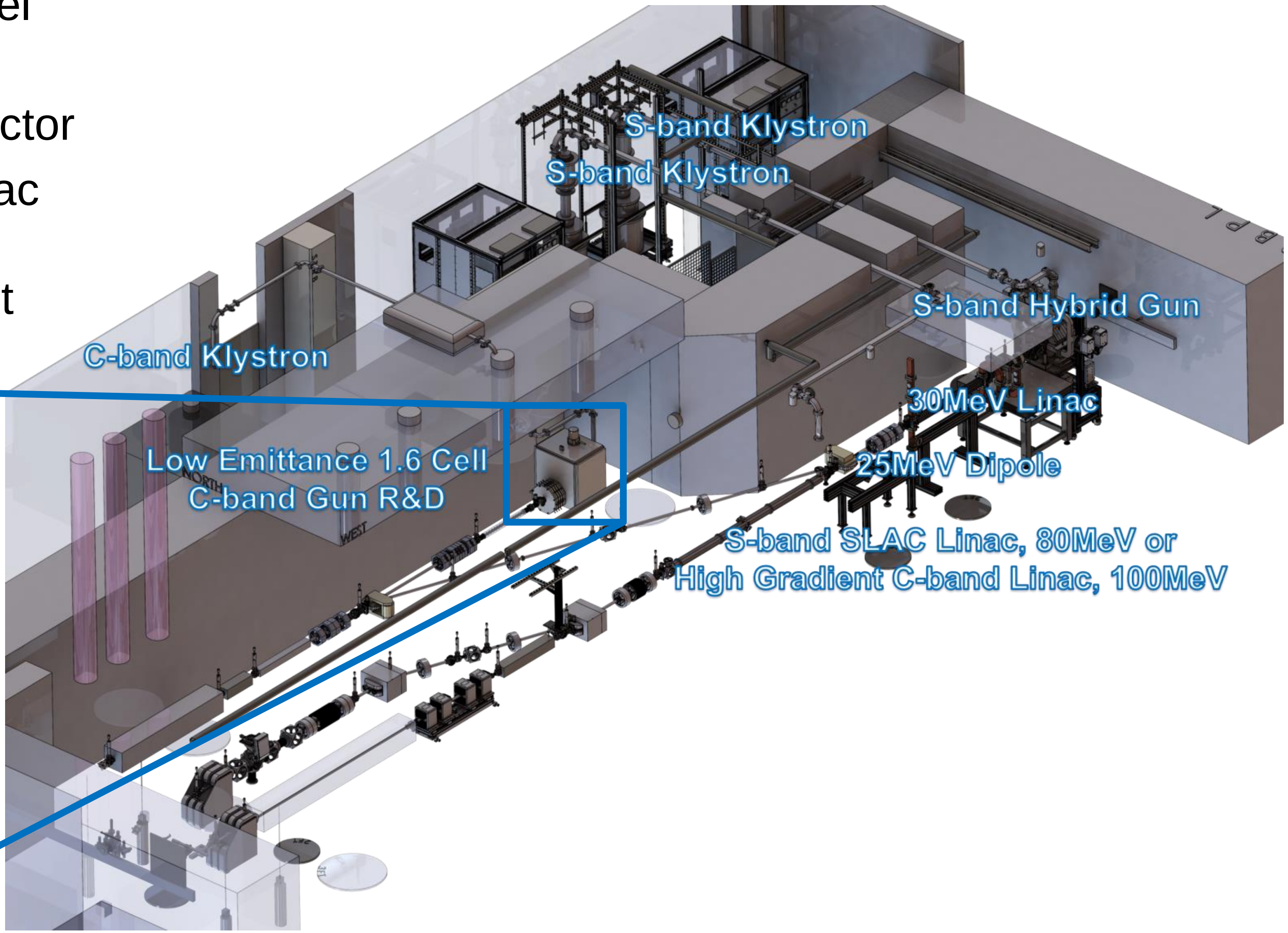




4) MITHRA Lab

- 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





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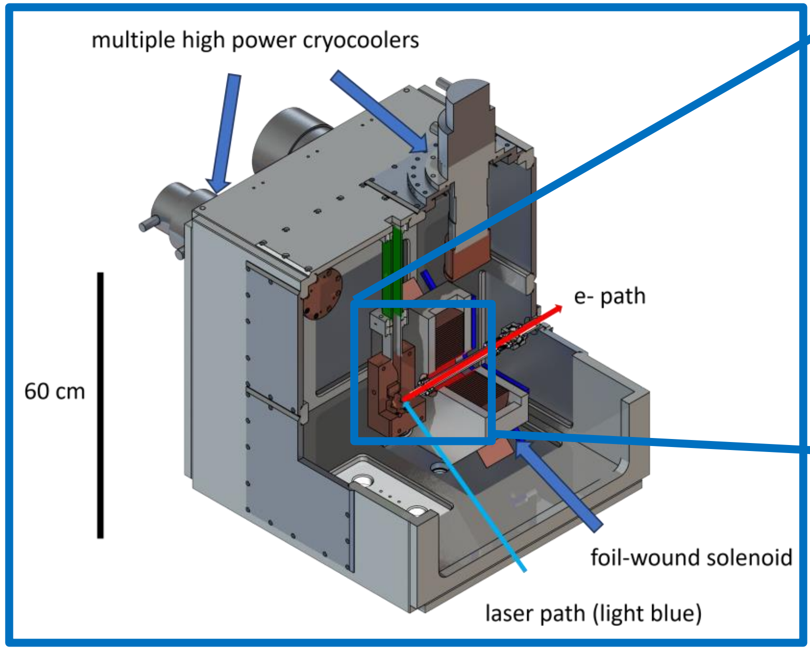
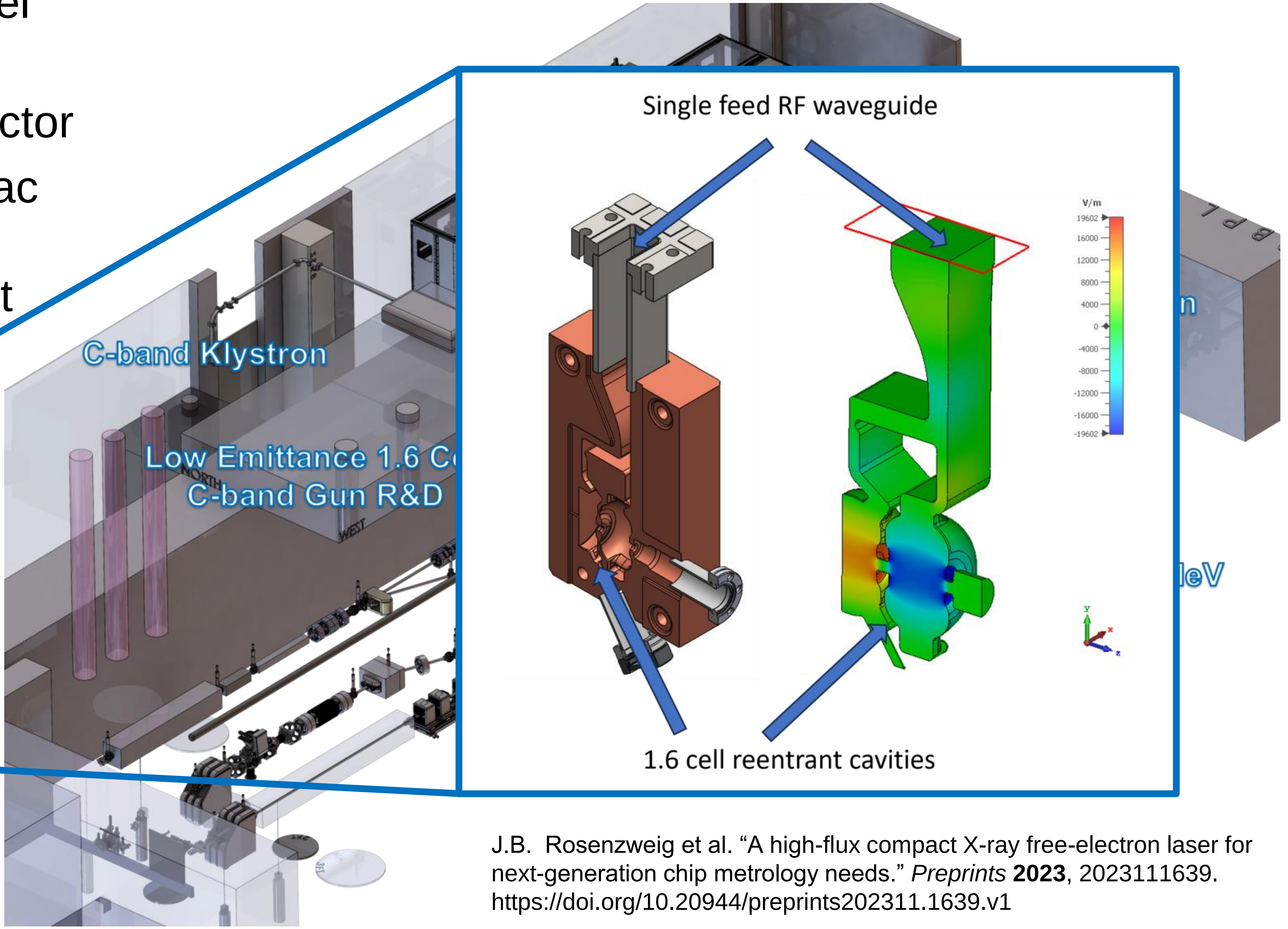




J.B. Rosenzweig et al. “A high-flux compact X-ray free-electron laser for next-generation chip metrology needs.” *Preprints* **2023**, 2023111639. https://doi.org/10.20944/preprints202311.1639.v1

4) CYBORG UED

- C-band SLED RF amplifier for collaboration with SLAC => 2 MW output power
- Considering optimization with Cornell for UED with 180 MV/m peak cathode field now
- Addition of X-band linearizer advantageous

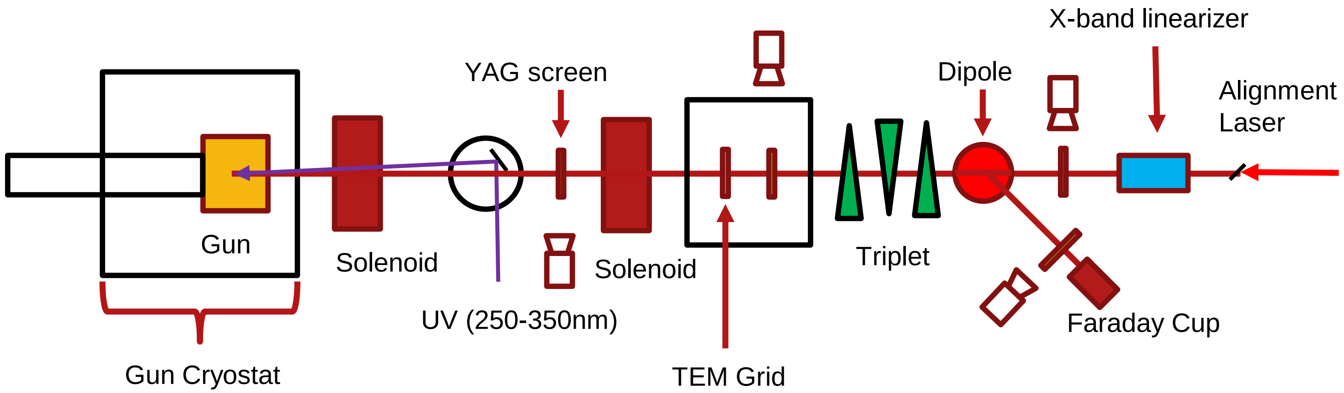
- Low charge case for UED consideration
  - 75 um spot size; Cu cathode; 77 K; 0.015 mm mrad; 25 meV MTE;
  - Simulation @ 120 MV/m
    - 1 MeV
    - rms energy spread 3e-4
    - 0.063 mm mrad & 0.081 mm mrad
  - Simulation @ 240 MV/m
    - 2 MeV
    - rms energy spread 6e-4
    - 0.022 mm mrad & 0.025 mm mrad

TABLE II. The beam parameters at the sample in the velocity bunching scheme.

Beam Energy	3.5 MeV
rms relative energy spread	9×10^{-4}
bunch charge	50 fC (3×10^5 e^-)
normalized rms emittance	0.08 mm-mrad
transverse rms spot-size	0.25 mm
rms bunch length	4 fs

R. K. Li, P. Musumeci, H. A. Bender, N. S. Wilcox, M. Wu; *J. Appl. Phys.* 1 October 2011; 110 (7): 074512. https://doi.org/10.1063/1.3646465

Phase3



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