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## Cryogenic High Gradient RF Dark Current Studies at CYBORG Beamline

Gerard Lawler<sup>1</sup>, James Rosenzweig<sup>1</sup> et al.  
UCLA<sup>1</sup>, Los Angeles, CA, USA



# Outline of presentation

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1. Background and motivation
  - Materials physics to beam brightness
2. CYBORG beamline overview
  - Lab facilities and commissioning status
3. Dark current studies
  - Preliminary measurements and existing capabilities
4. Future testing discussion



# Outline of presentation

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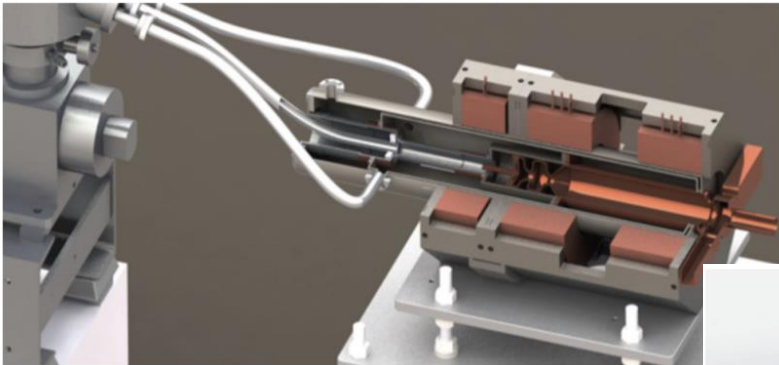
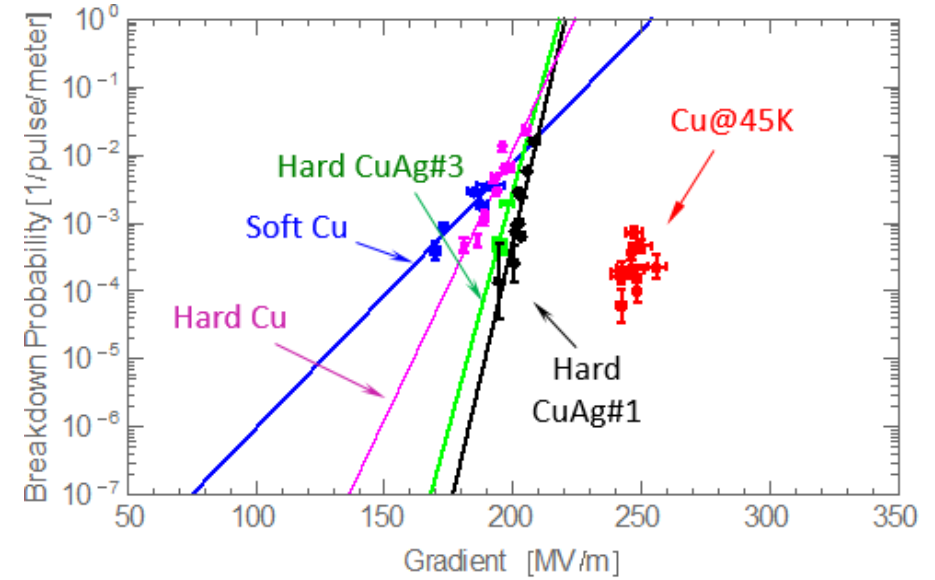
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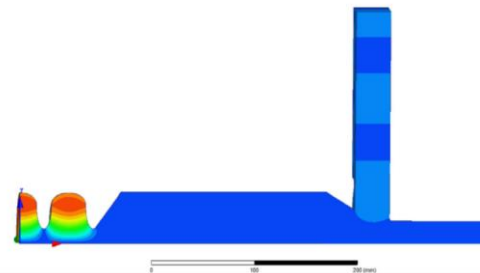
# 1) Background



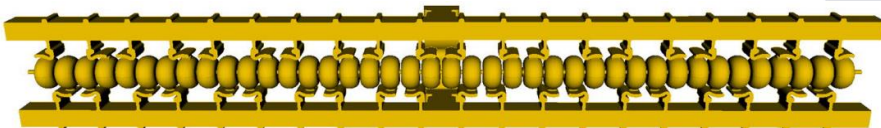
- Significant interest in photoinjector; wakefield; fundamental high field physics
- Broad interest in high gradient cavity development with focus on brightness
- SLAC cryogenic breakdown reduction  $\Rightarrow$  higher accelerating gradients possible
- TopGun previous development in S-band
- More cryo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



$$B_{e,b} \approx \frac{2ec\epsilon_0}{k_B T_c} (E_0 \sin \varphi_0)^2$$



Rosenzweig, J. B., et al. *Physical Review Accelerators and Beams* 22.2 (2019): 023403.  
<https://doi.org/10.1103/PhysRevAccelBeams.22.023403%7>

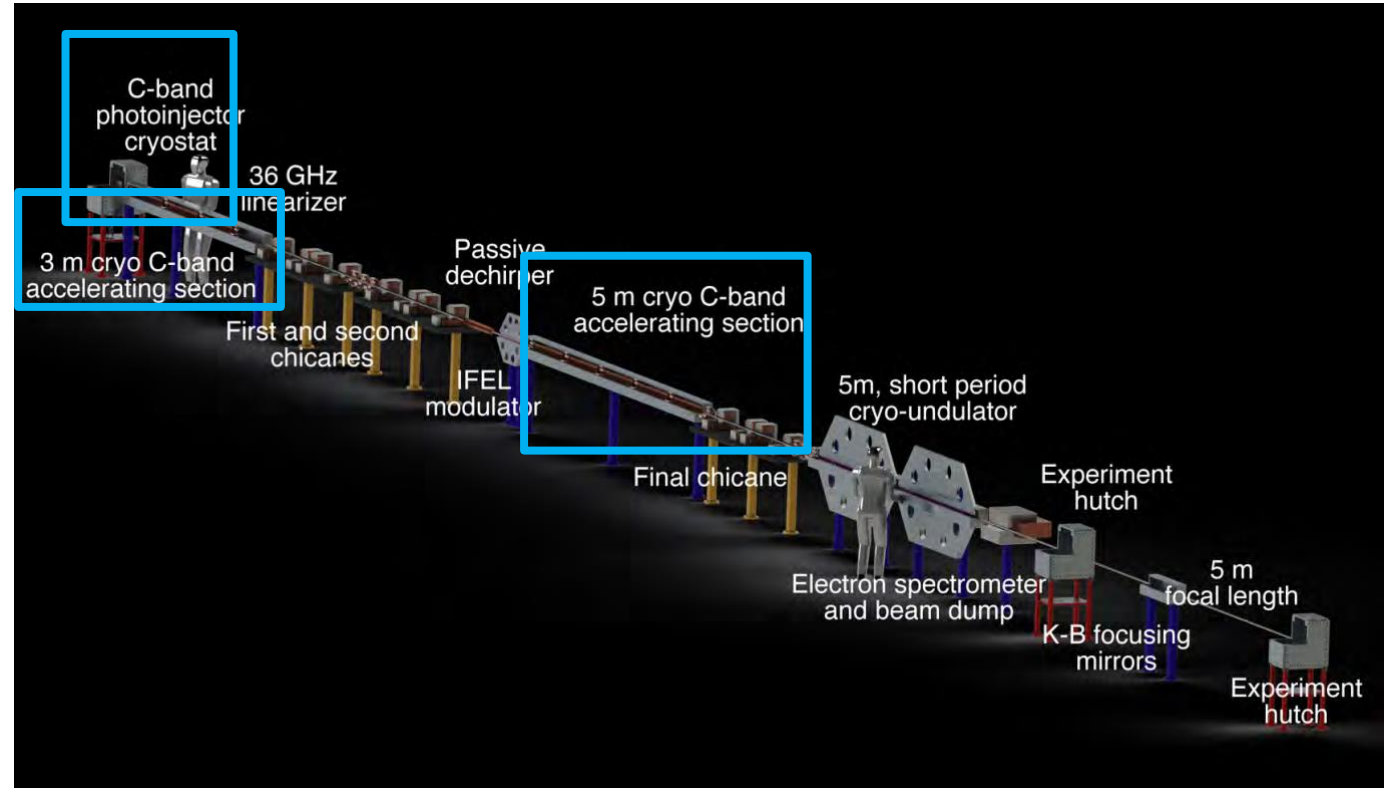




# 1) UCXFEL



- Most pertinent realization of high gradient and high brightness techniques Ultra-Compact Xray FEL (UCXFEL) concept (right)
- When combined with novel bunching and short period undulators we can approach 40m scales with several applications incl. allowing university scale XFEL access and chip metrology
- Existing plan incorporates cryogenically enabled  $>200$  MV/m photoinjector peak fields and  $\approx 70$  MV/m linacs



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. *Preprints* **2023**, 2023111639.  
<https://doi.org/10.20944/preprints202311.1639.v1>



# 1) CYBORG Function 1



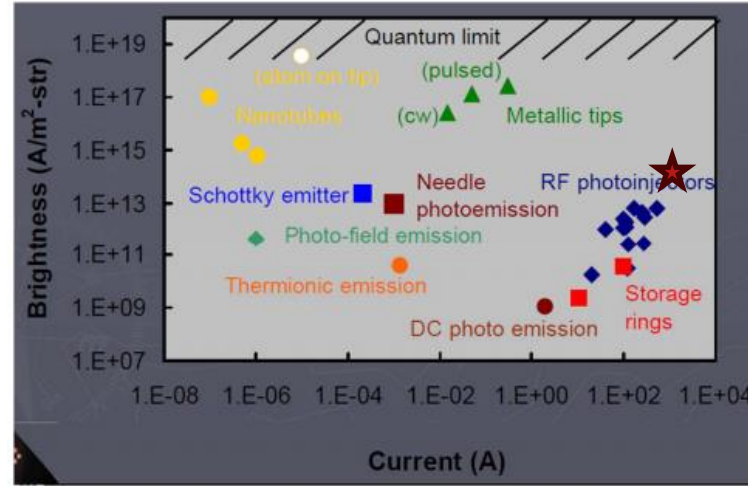
- For university scale we want simplest NC RF beamline integration using CrYogenic Brightness Optimized Radiofrequency Gun (CYBORG)

## 1. Ultra-high gradient photoinjector prototype (UCXFEL right)

1. Integrated infrastructure template
2. Cathode load-lock development
3. RF prototype, black plane etc.

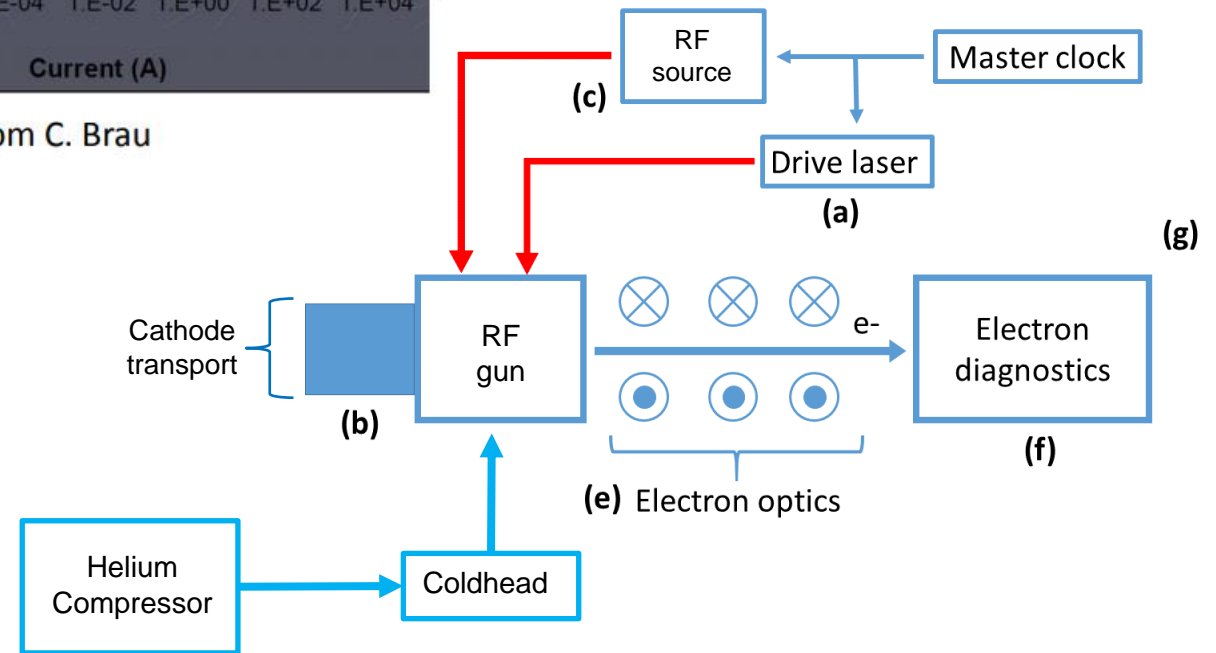
## 2. Cryogenic emission physics testing:

1. High gradient RF test stand for cathodes incl. novel high QE semiconductors
2. Cryogenic dark current and breakdown



From C. Brau

★ Approximate Cu cathode UCXFEL photoinjector performance





# 1) CYBORG Function 2



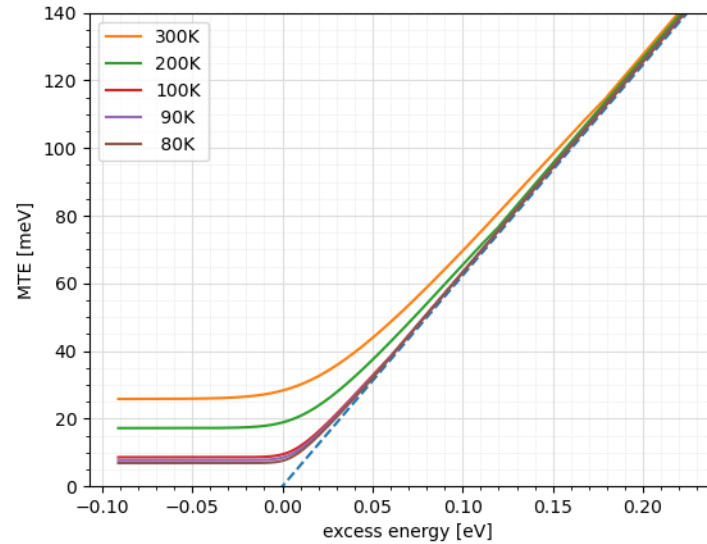
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## 1. Ultra-high gradient photoinjector prototype (UCXFEL right)

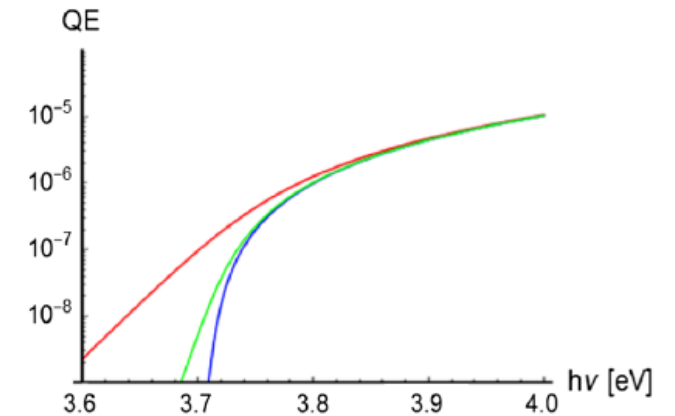
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J.B. Rosenzweig et al. *Preprints* **2023**, 2023111639.  
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J.B. Rosenzweig et al., *Nucl. Instrum. Methods Phys. Res. A*, vol. 909, p. 224-228, 2018. doi:10.1016/j.nima.2018.01.061



# 1) Gun Comparisons



- CYBORG design inspired primarily by 3 existing photoguns: PEGASUS; Cornell Cryo DC gun; FERMI
- Compared CYBORG design specs also with existing cathode test beds

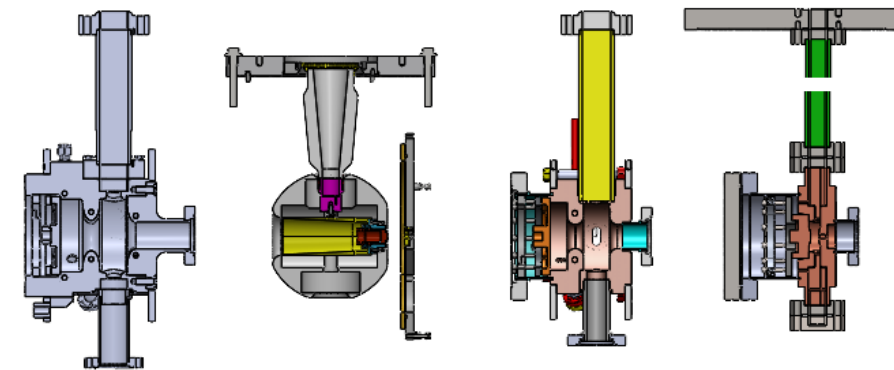
Parameter	CYBORG Phase 1	CYBORG Phase 2
Cavity type	normal conducting	-
Cavity geometry	$\frac{1}{2}$ -cell reentrant	-
Cathode Assembly	Demountable Cu backplate	Cryogenic load lock
Design frequency	5.712 GHz	5.700 – 5.720 GHz
Peak cathode field	$\geq 120$ MV/m	-
Operating temperature	300 – 95K <sup>1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

<sup>1</sup> 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.

Lawler, G. E., et al. *Instruments* 8.1 (2024): 14.  
<https://doi.org/10.3390/instruments8010014>





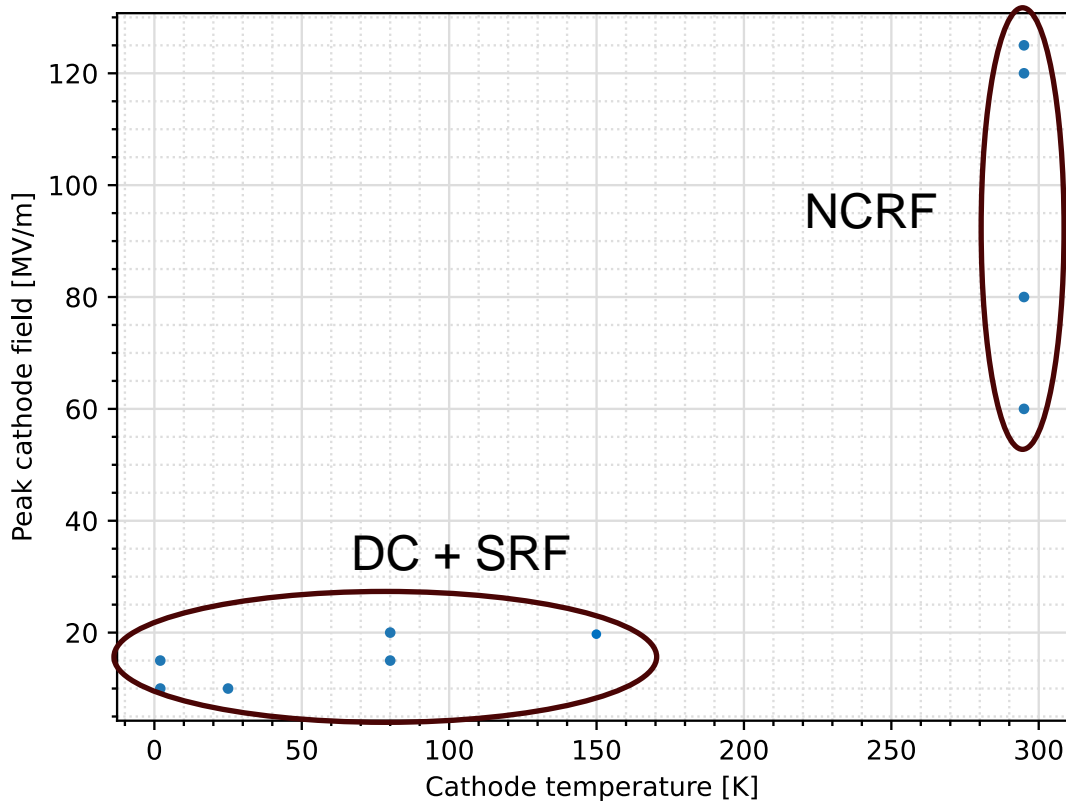


# 1) Gun Comparisons



- CYBORG design inspired primarily by 3 exis PEGASUS FERMI
- Compare also with

Photoguns	FE
Cavity type *	
Cavity geometry *	1.6
Cathode assembly	Det Cu
Design frequency	2.0
Peak cathode field	12
Min cathode T	≥ room T

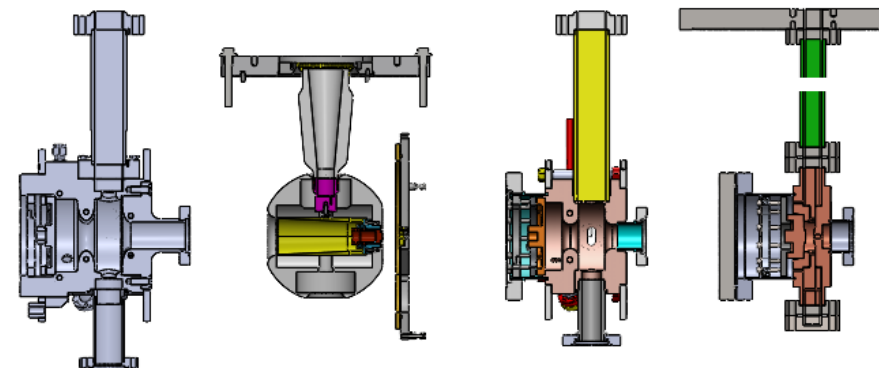


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	$\frac{1}{2}$ -cell reentrant	-
	Demountable Cu backplate	Cryogenic load lock
	5.712 GHz	5.700 – 5.720 GHz
	≥ 120 MV/m	-
	300 – 95K <sup>1</sup>	300 – 77K

with additional plans for 77 K operation

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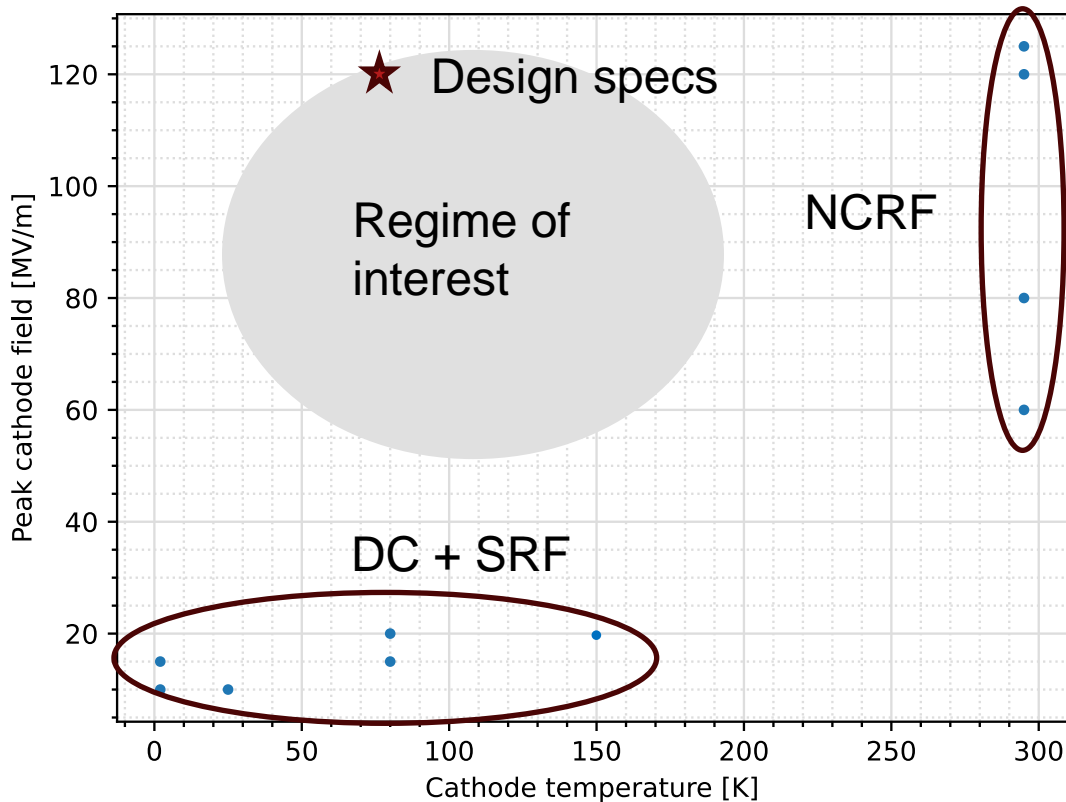


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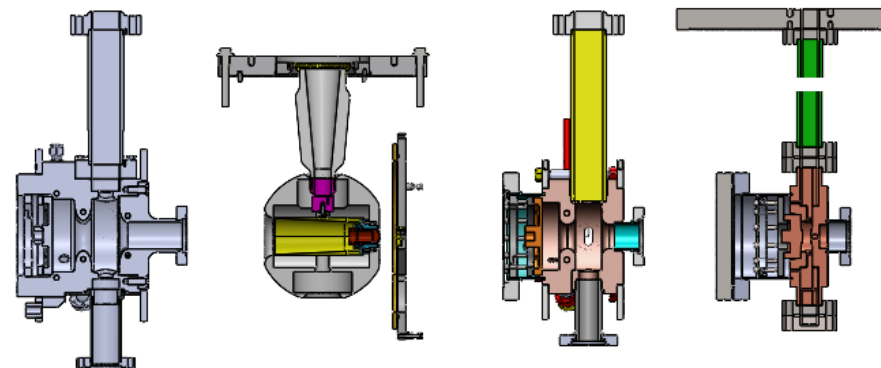


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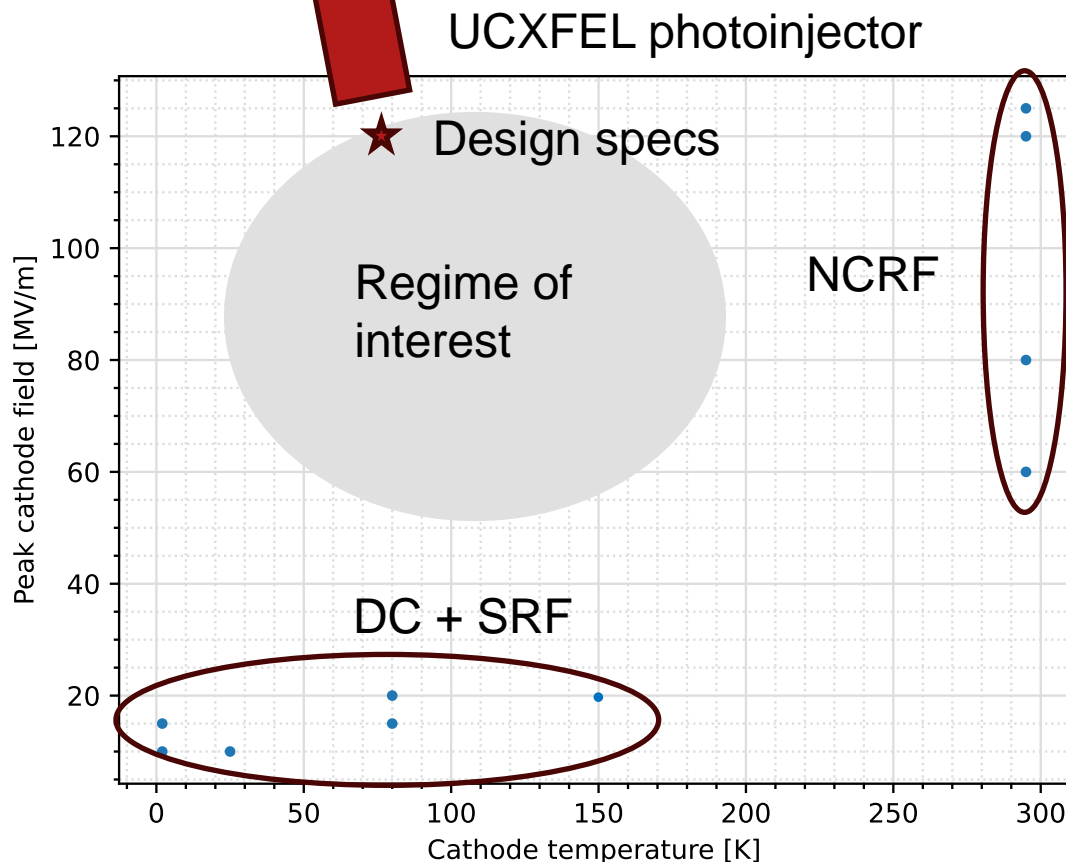


- CYBORG design inspired primarily by 3 existing photoinjectors: PEGASUS, FERMI, and NCRF.
- Compare also with DC + SRF technology.

Parameter	CYBORG Phase 1	CYBORG Phase 2
Conducting	normal conducting	-
Cavity type	$\frac{1}{2}$ -cell reentrant	-
Backplate	Demountable Cu backplate	Cryogenic load lock
Frequency	5.712 GHz	5.700 – 5.720 GHz
Field	$\geq 120$ MV/m	-
Temperature	300 – 95K <sup>1</sup>	300 – 77K

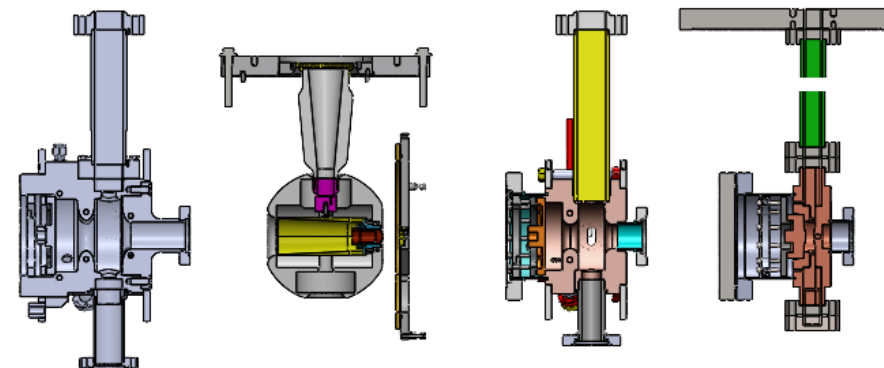
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Photoguns	FE
Cavity type *	
Cavity geometry *	1.6 cell
Cathode assembly	Detachable Cu
Design frequency	2.01 GHz
Peak cathode field	120 MV/m
Min cathode T	$\geq$ room T
	$\geq$ room T
	$\geq$ room T
	80 K
	35 K
	2 K

\* Only relevant for RF guns.





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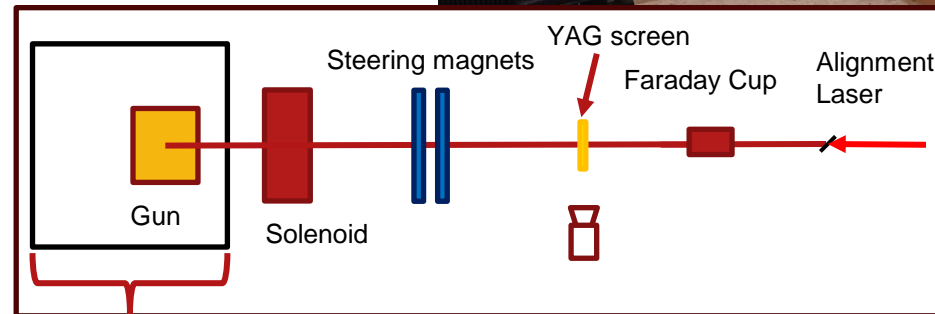
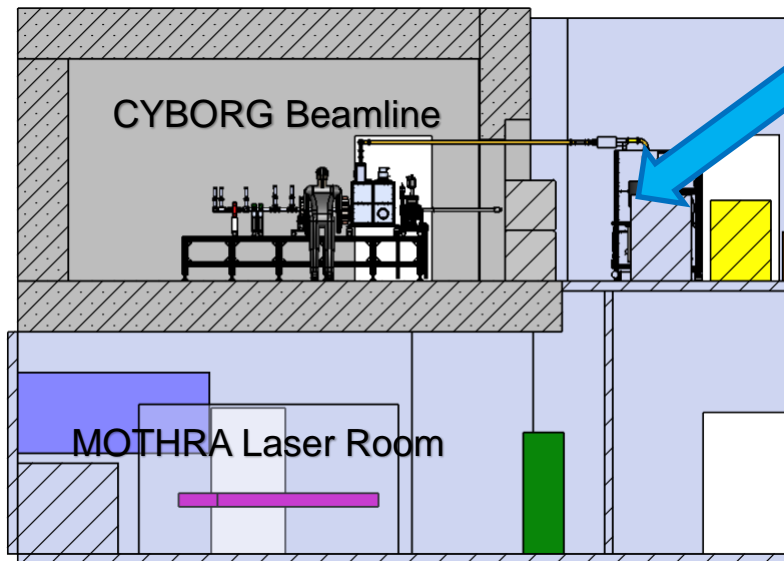
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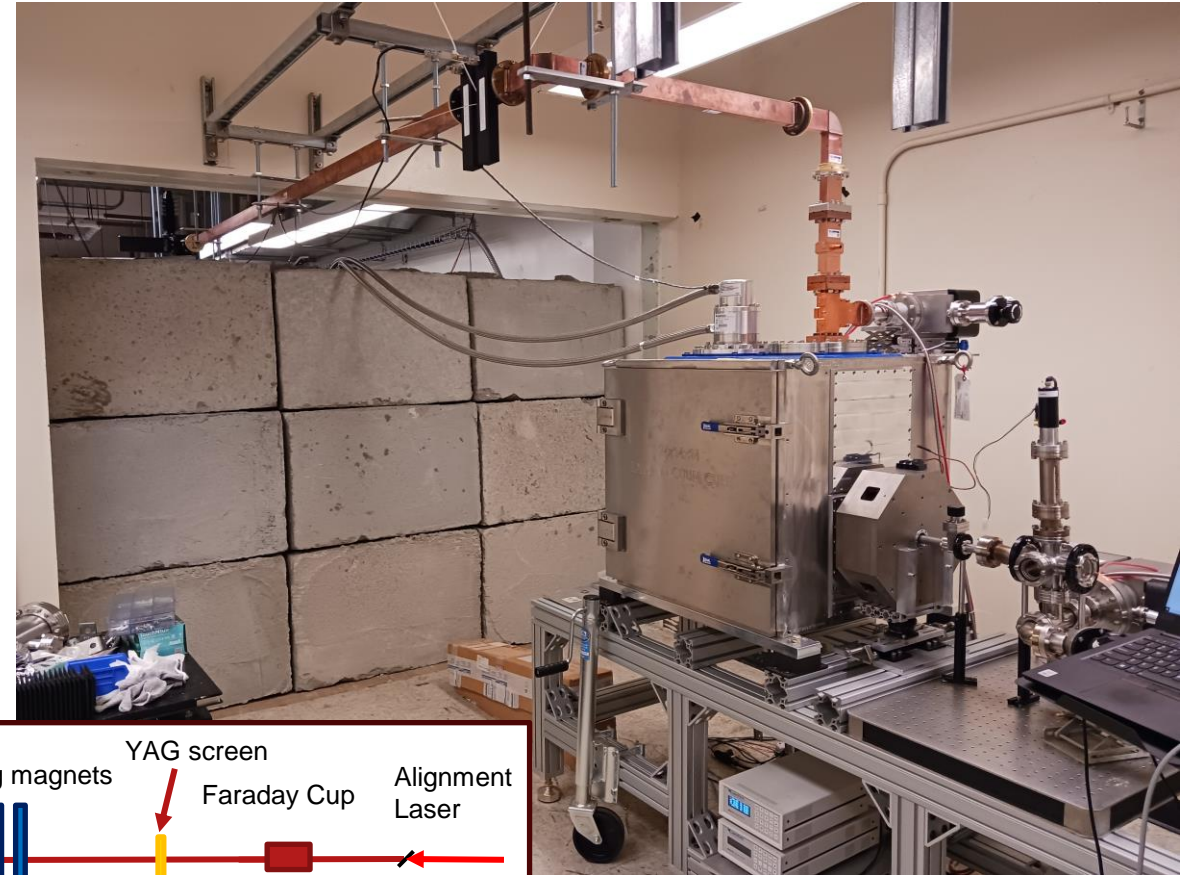
## 2) CYBORG-MOTHRA Overview



- 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



Gun Cryostat

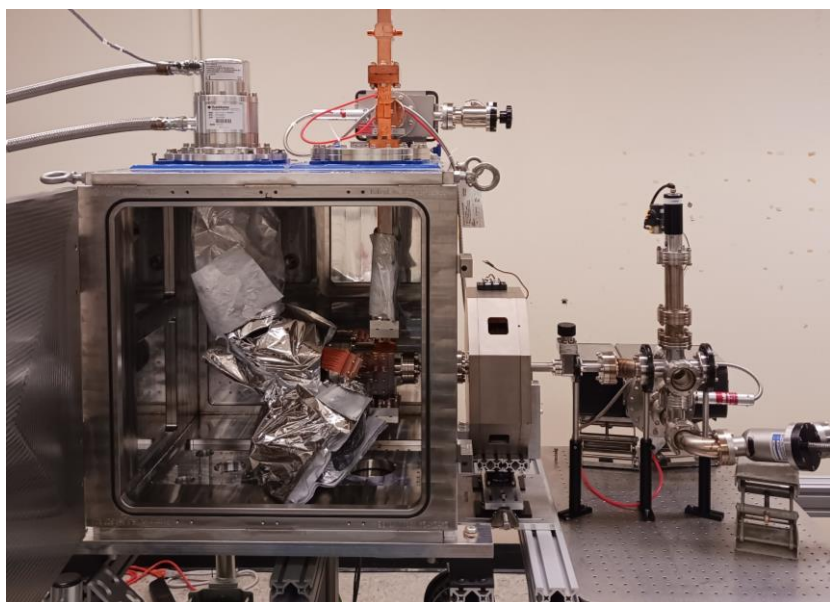




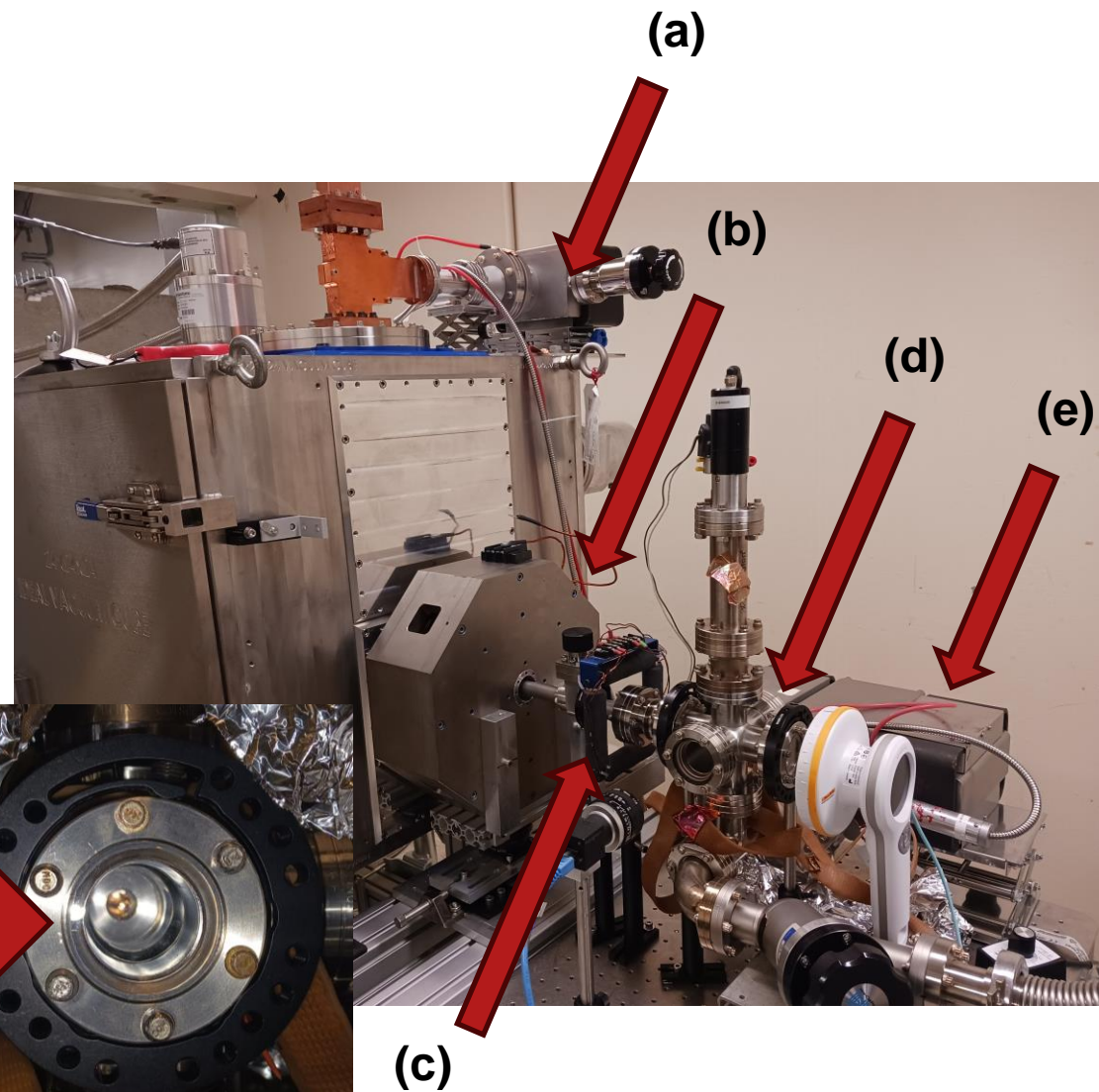
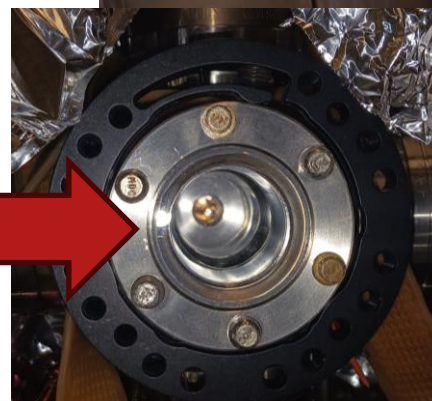
## 2) CYBORG Phase1 (cont.)



- Multiple phases of development planned
- Phase1 current setup below with copper cathode and simplified beamline
- **(a,e)** 2x ion pumps, **(b)** solenoid, **(c)** steering magnets **(d)** YAG screen
- $< 10^{-8}$  torr (1uA; 2 uA) at waveguide **(a)** and YAG screen **(e)**
- Custom solenoid mount has 4 degrees of freedom
  - 3 transverse + rotation about x (vertical axis)



Cu cathode visible down barrel of gun before Faraday cup added

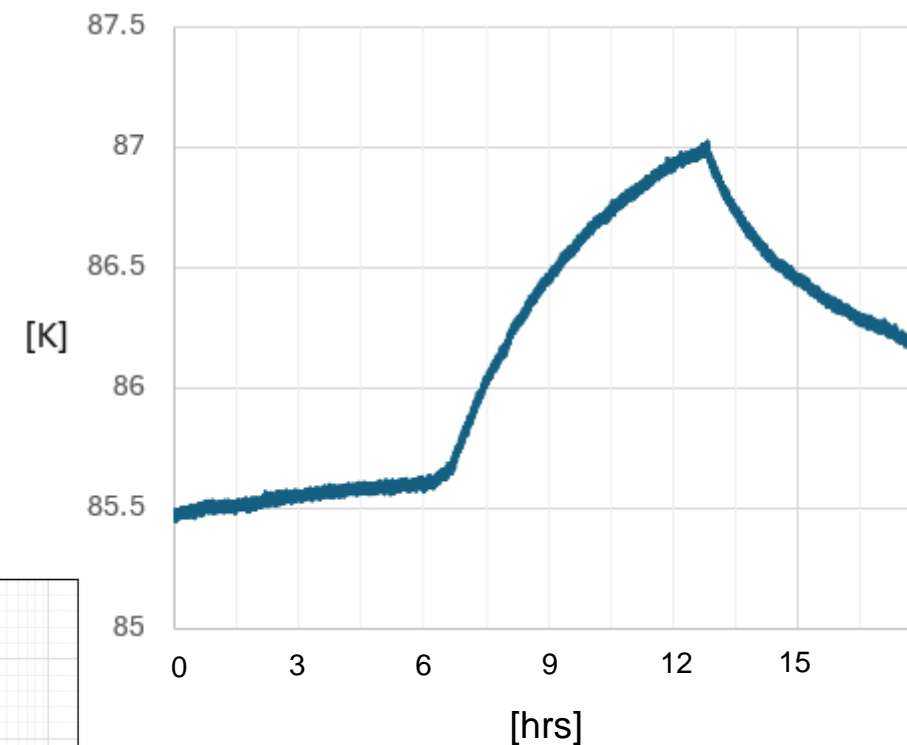
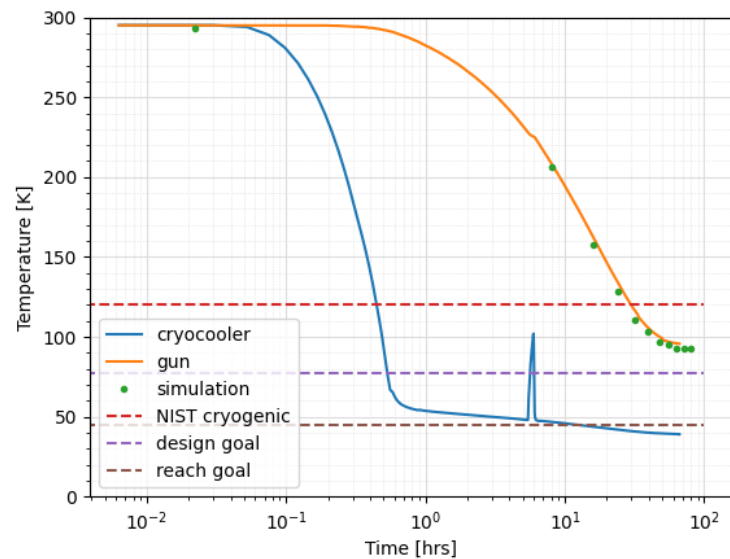
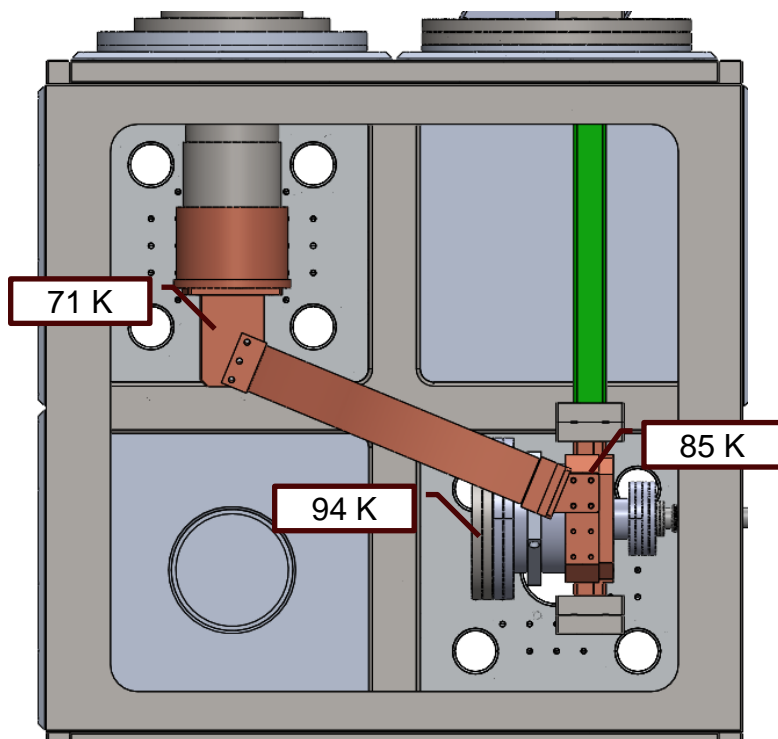




# 2) Temperature Stability



- Main gun section shown outside of cryostat (far left)
- Simplified thermal steady state simulation shown (middle) with previous cooling configuration to show accuracy of transient cooling simulations given estimated heat leaks from waveguide, beam pipe etc.
- RF heating over 6 hours (right) at 1 Hz  $\approx$  0.8 W



Lawler, G. E., et al. *Instruments* 8.1 (2024): 14.  
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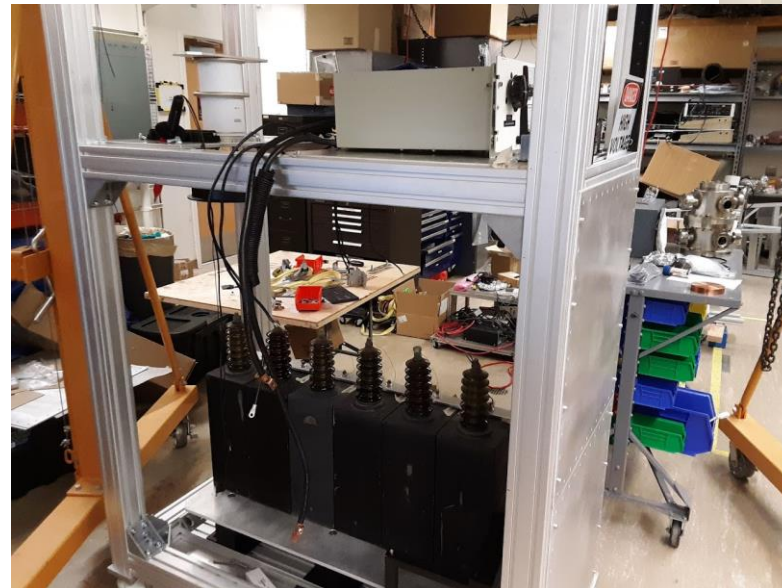
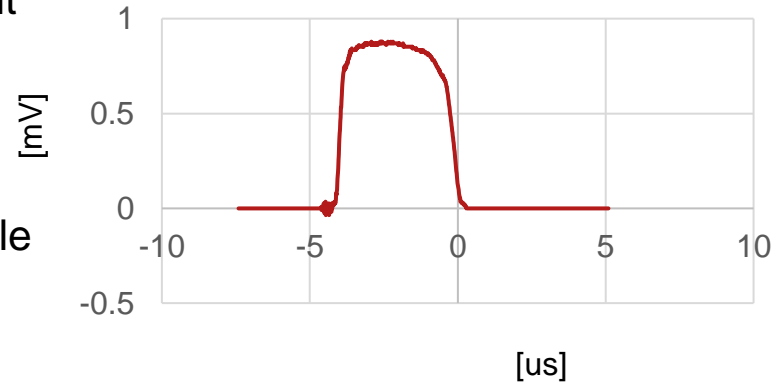
## 2) RF Power



- C-band motivation @ cryogenic temp, Power needed to drive scaled geometry at constant gradient scales like

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

- Resurrected Thales C-band klystron to single MW power sufficient for 1<sup>st</sup> cryogenic beamline (right)
- Slowly working up with 0.45 MW into gun thus far
- Max pulse length 4 us
- Current pulse 500 ns rise time w/ improvement
- 20 MHz bandwidth centered on 5710 MHz allowing full temperature range CYBORG operation
- C-band SLED development in collaboration with SLAC



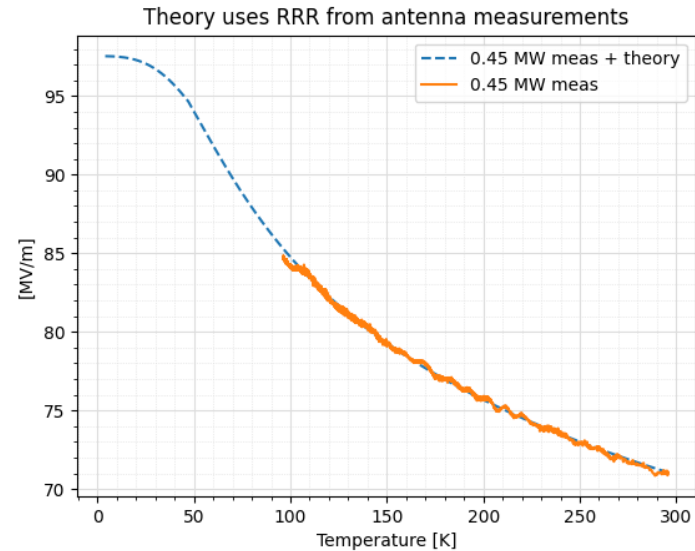
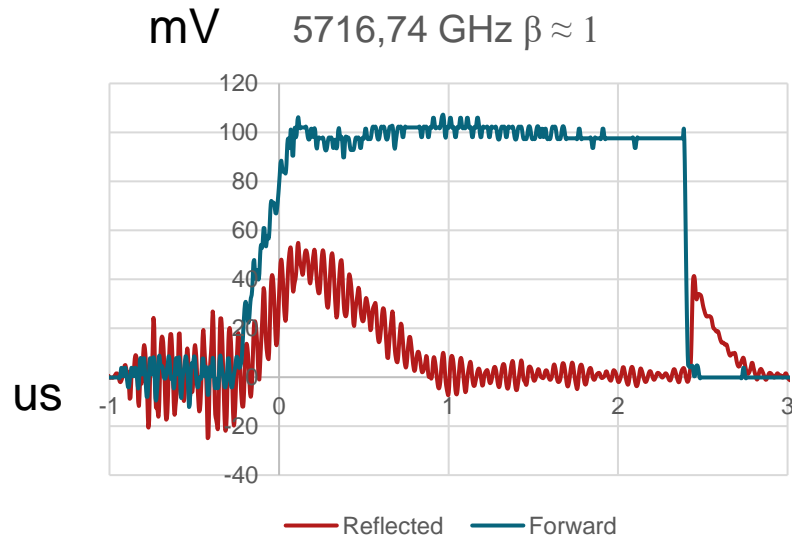
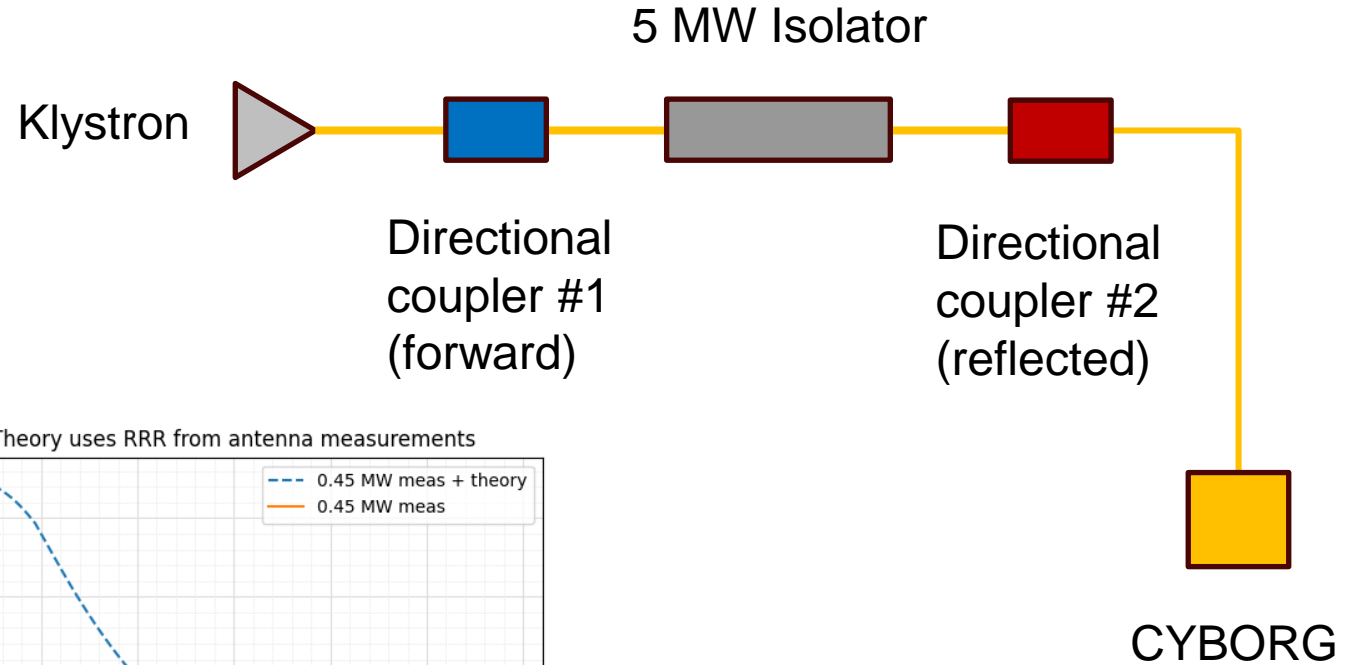




# 2) Cold Gun Feeding



- First filling of gun cavity at intermediate temperature (between 295 and 77 K) during cool at detuning and coupling  
– 150 K
- 14 kW fully filled (below) => 15 MV/m





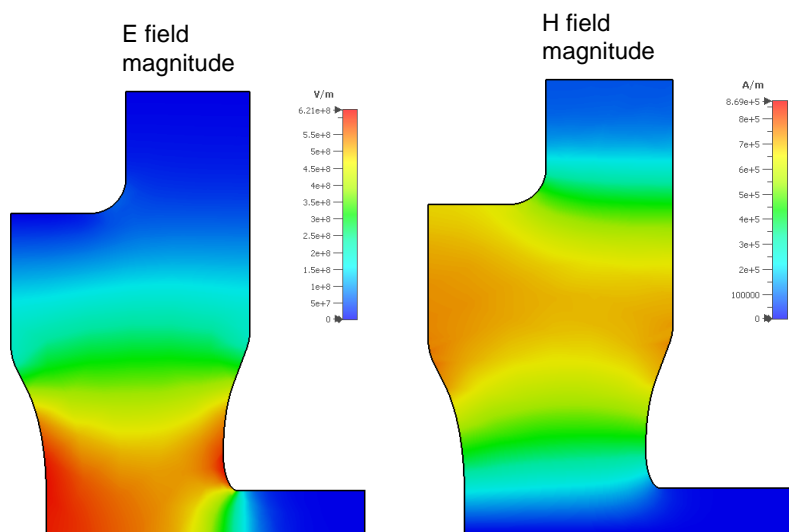
# 2) Cryo RF Performance Overview



- 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
$\beta$	0.7	1.53	1.98	3.26
Filling time	-	0.41 $\mu$ s	0.45 $\mu$ s	0.52 $\mu$ s

Lawler, G. E., et al. *Instruments* 8.1 (2024): 14.  
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Parameter	295 K	95 K	77K	45 K
$f_0$ [MHz]	$5703.6 \pm 0.1^1$	$5720.410 \pm 0.003^1$	$5721 \pm 3$	$5722 \pm 4$
$Q_0$	$7808 \pm 13^1$	$14326 \pm 12^1$	$21000 \pm 3600$	$30000 \pm 9900$
Coupling $\beta$	$0.608 \pm 0.002^1$	$1.069 \pm 0.002^1$	$1.60 \pm 0.44$	$2.4 \pm 0.9$
Filling time [ $\mu$ s]	$0.271 \pm 0.01^1$	$0.386 \pm 0.001^1$	$0.44 \pm 0.01$	$0.49 \pm 0.03$
Power [MW] for 120 MV/m	$1.23 \pm 0.10$	$0.85 \pm 0.08$	$0.79 \pm 0.01$	$0.70 \pm 0.09$
Energy [J] per $2\mu$ s pulse	$2.45 \pm 0.01$	$1.70 \pm 0.02$	$1.58 \pm 0.03$	$1.40 \pm 0.19$
Cathode field @ 0.5 MW	$77 \pm 3$ MV/m	$92 \pm 5$ MV/m	$93 \pm 3$ MV/m	$102 \pm 7$ MV/m

<sup>1</sup> Values experimentally measured or computed directly from low power measurements

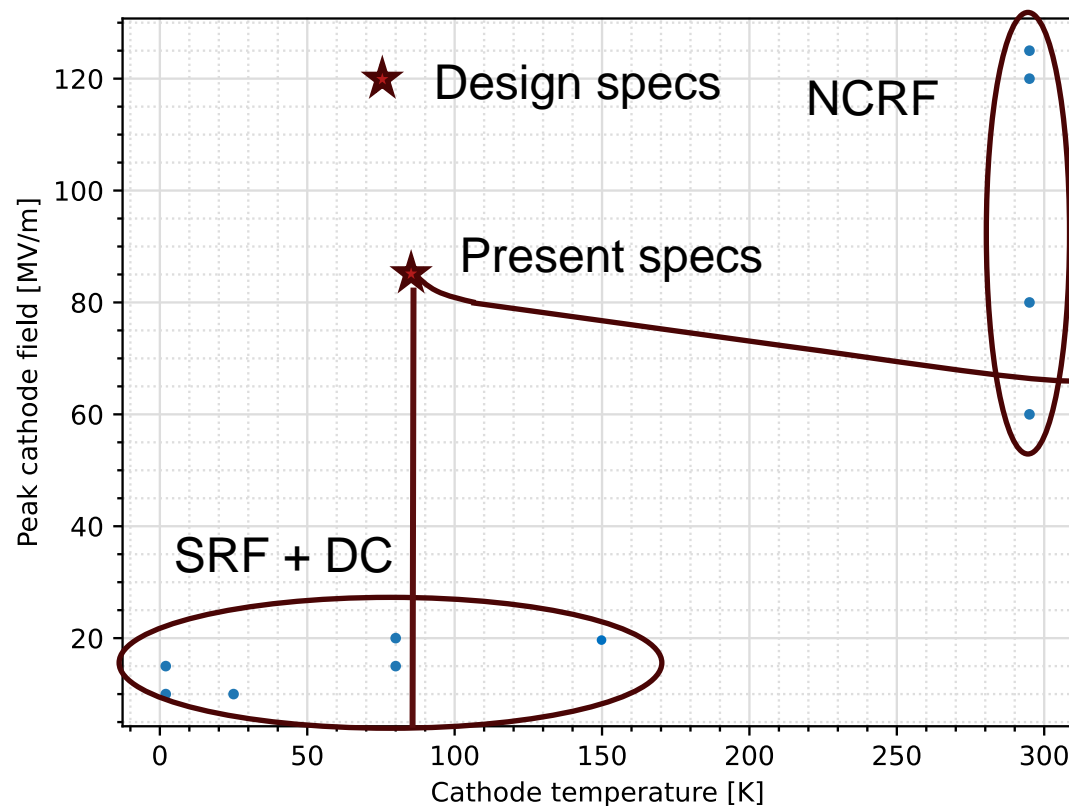
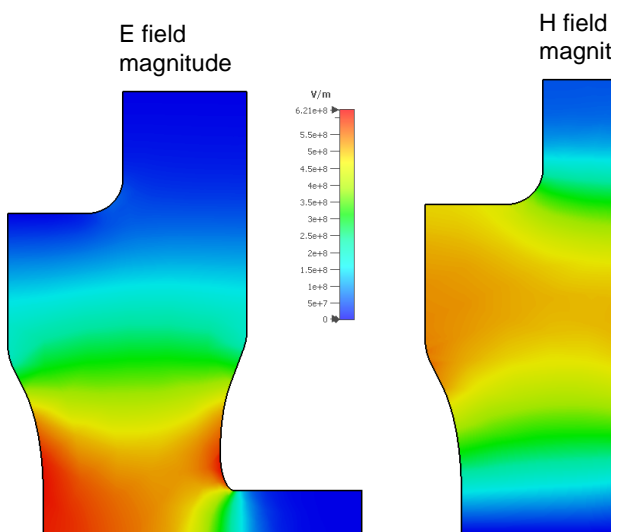


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	21000 $\pm$ 3600	30000 $\pm$ 9900
	1.60 $\pm$ 0.44	2.4 $\pm$ 0.9
	0.44 $\pm$ 0.01	0.49 $\pm$ 0.03
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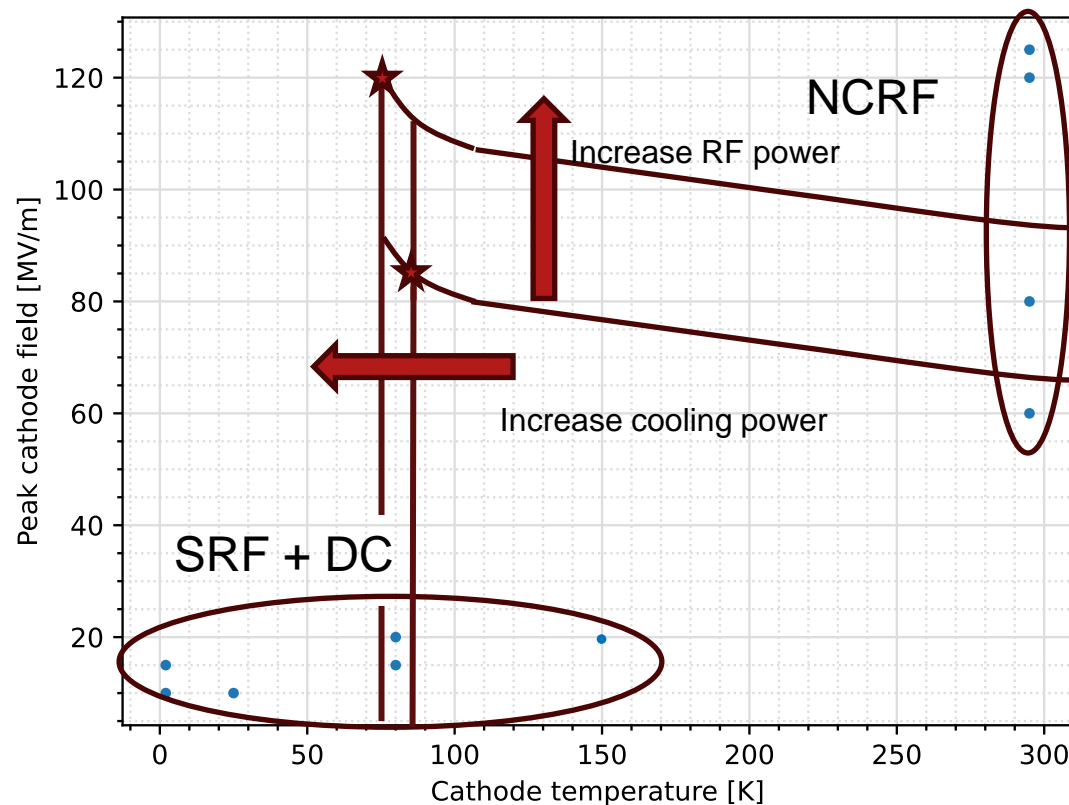
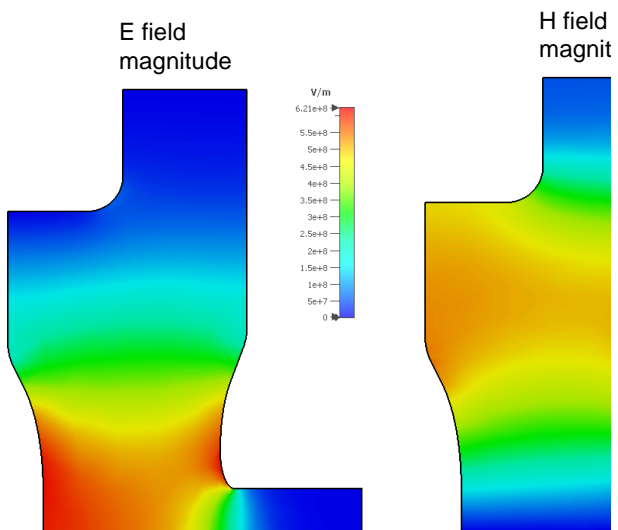


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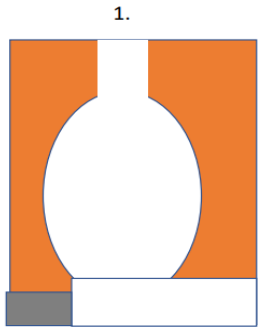
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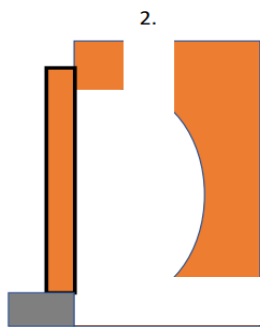
# 3) Gun topology



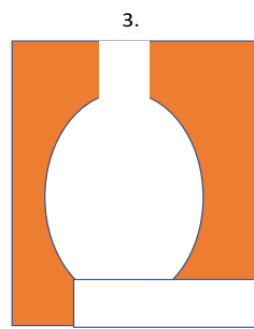
- Comparison of possible topologies originally considered shown below



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



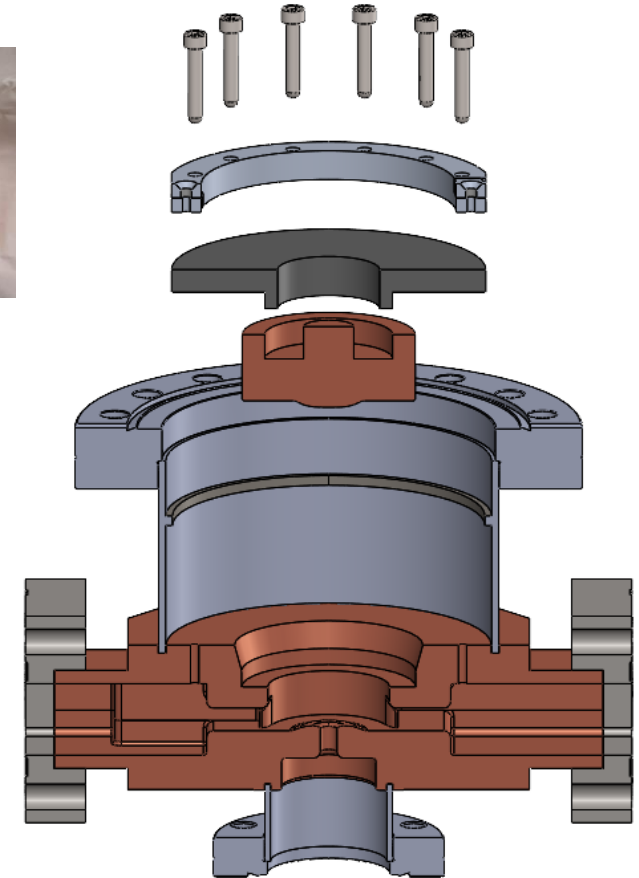
- Good for cathode tests
- High gradient (120 MV/m) but lower than plug alone



- No cathode exchange
- Highest achievable gradients



20 mm



- Design philosophy of gun focused on maximum versatility
- Original design for fully removable backplane focused on allowing testing of multiple cathode insertion coupling designs
- Further useful for examination of cavity surface after field emission and breakdown



# 3) Shunt impedance optimization

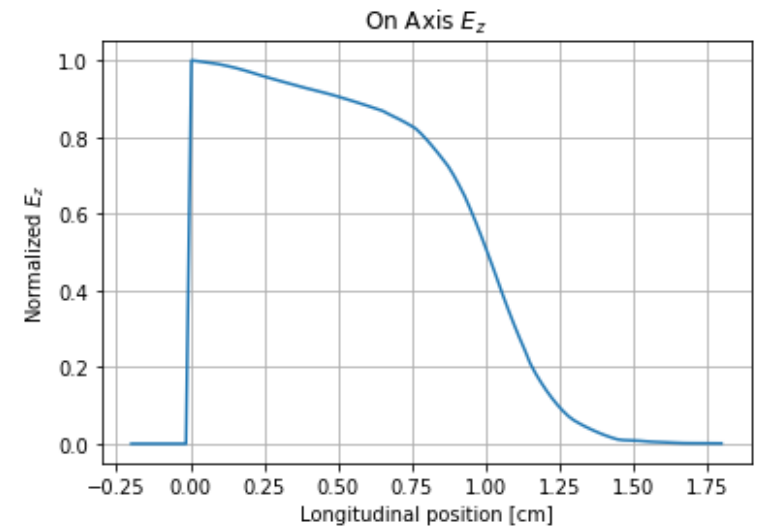
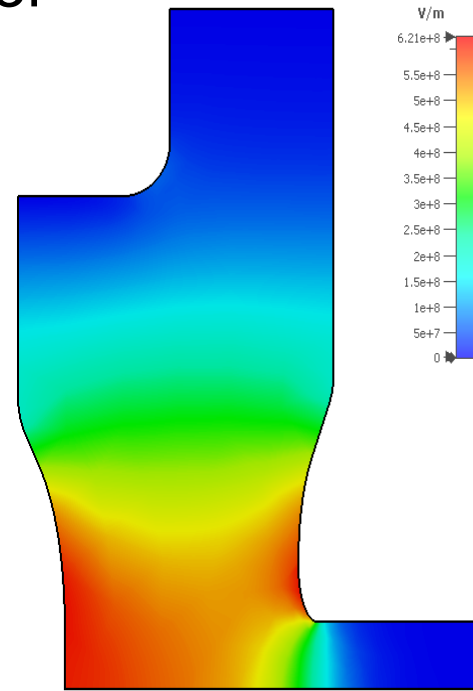


- Improved coupling of input power to coupling with geometry modifications creating higher fields with less input power

$$Z_{shunt} = Q \frac{R}{Q} = \frac{V_{acc}^2}{P_d}$$



Geometry



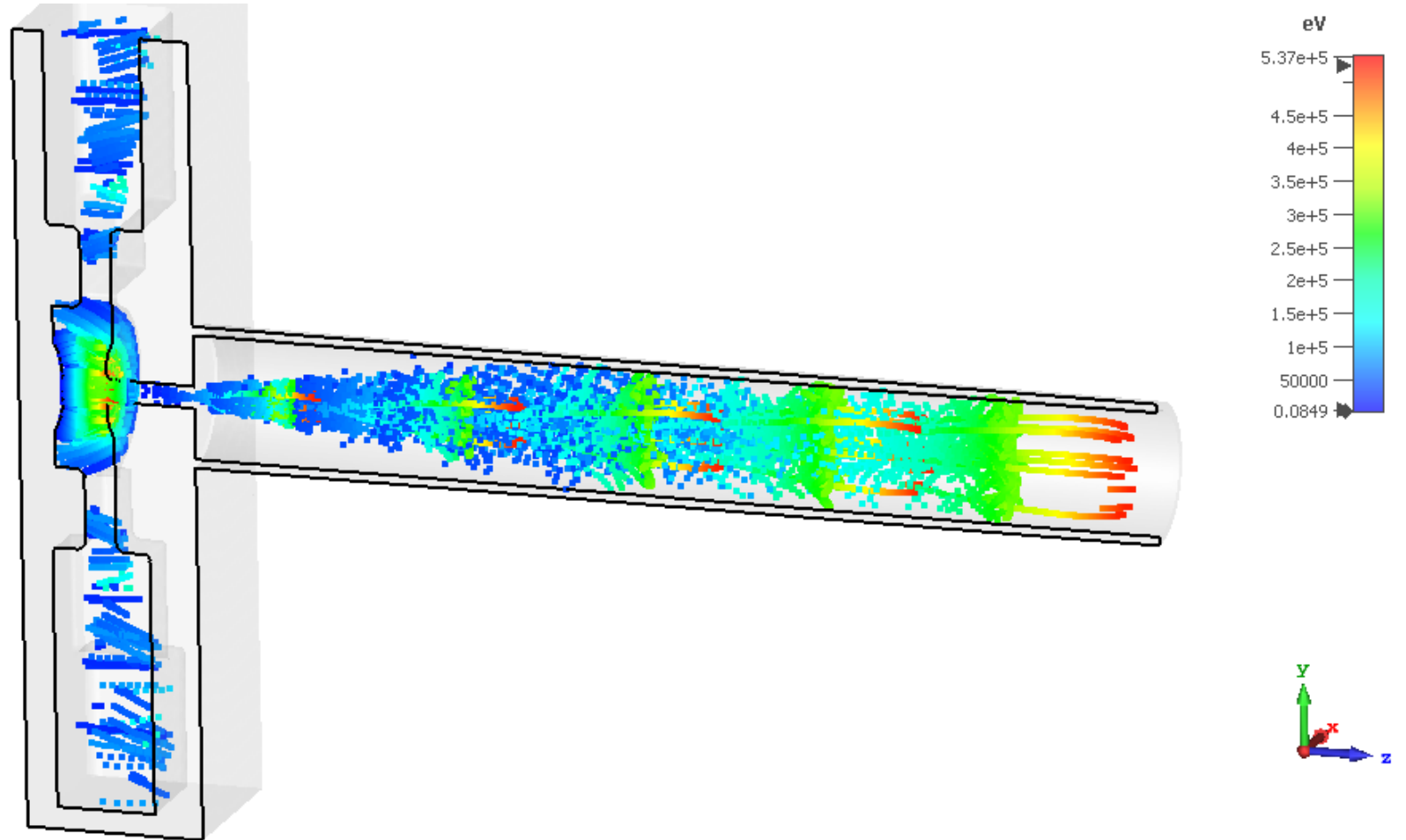
- Nose cone optimization reduces power consumption by 10% over pillbox
- Elliptical profiles localize peak electric field on axis at cathode plane



# 3) Dark current simulation



- FN emission PIC simulation via CST with peak cathode plane nosecone gradient 60 MV/m and  $\beta = 50$  needed for significant emission



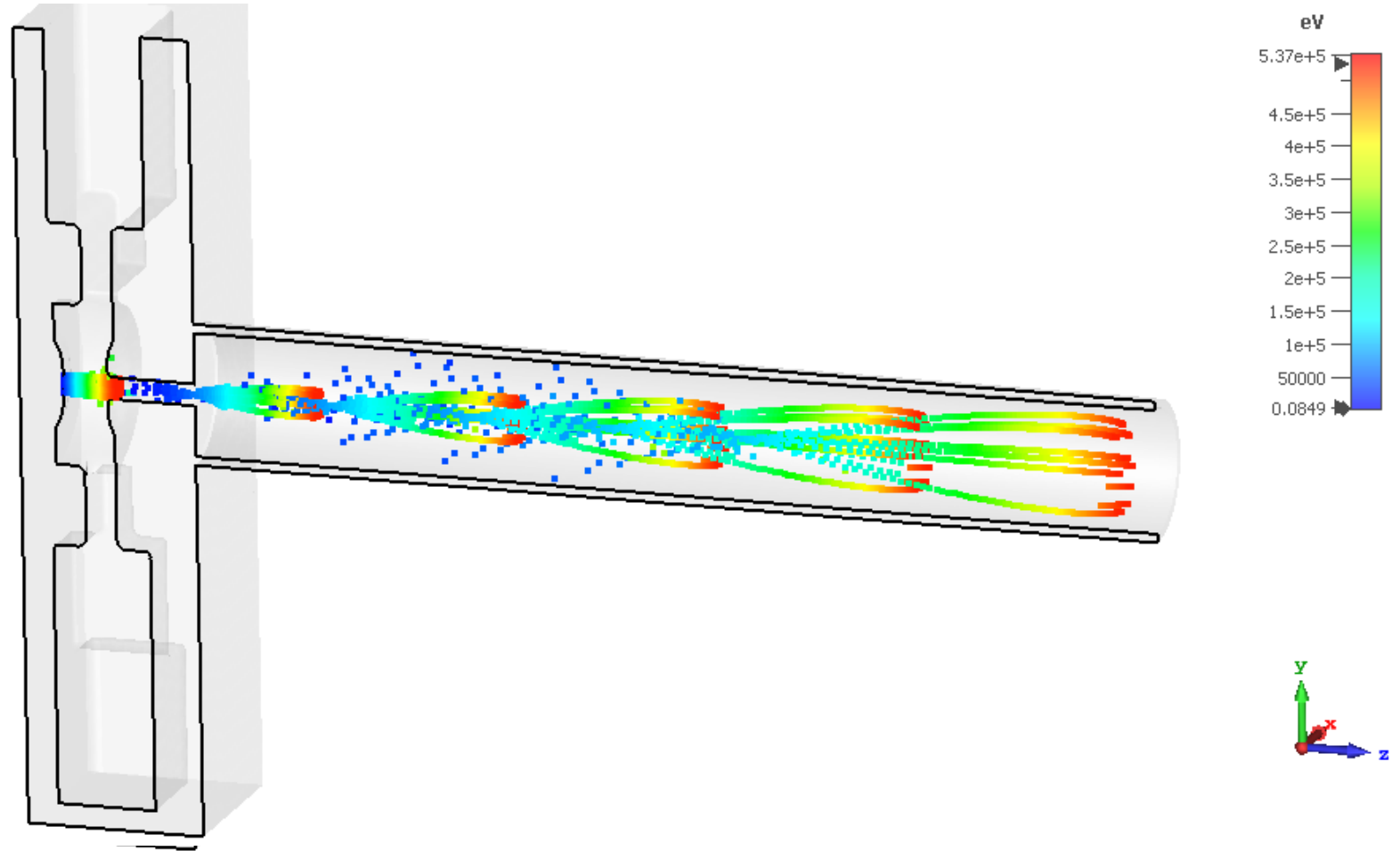




# 3) Dark current simulation



- Considering peak electric field enhancement optimized on nosecone, downstream dark current emission mostly localized to nosecone
- Isolated nosecone emission (right) showing additional collimation from iris and beam pipe

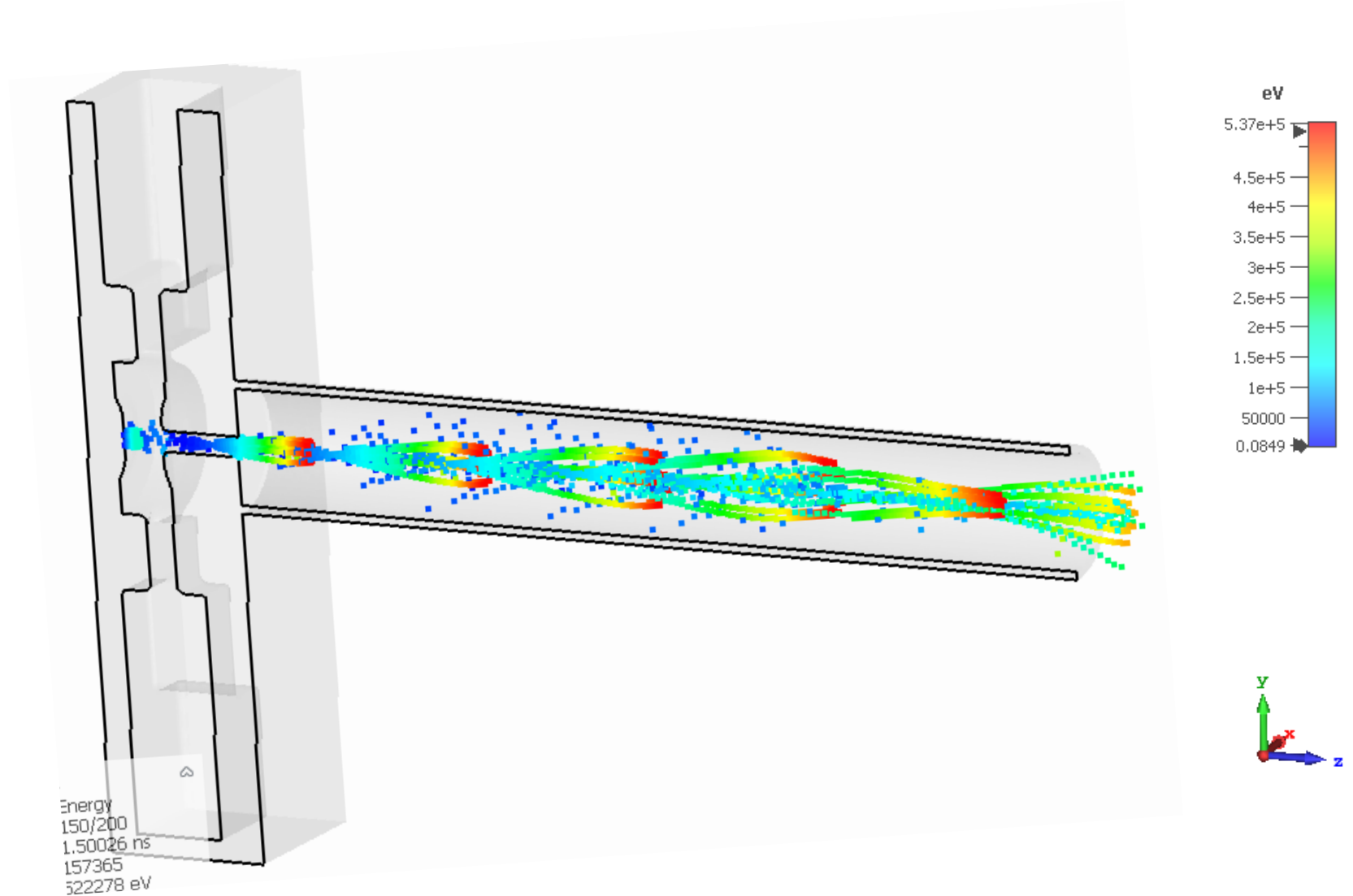




# 3) Dark current simulation



- Considering peak electric field enhancement optimized on nosecone, downstream dark current emission mostly localized to nosecone
- Isolated nosecone emission (right) showing additional collimation from iris and beam pipe
- Allows useful focusing with solenoid field



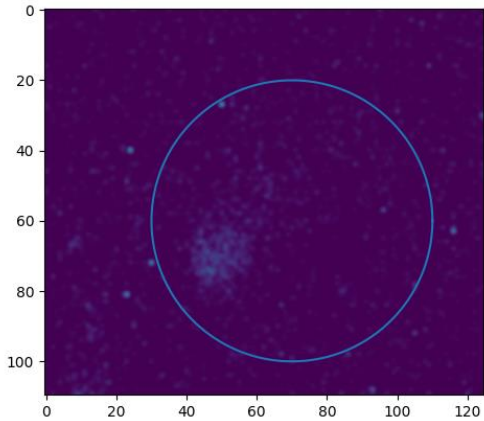


# 3) Prelim Dark Current Measurement

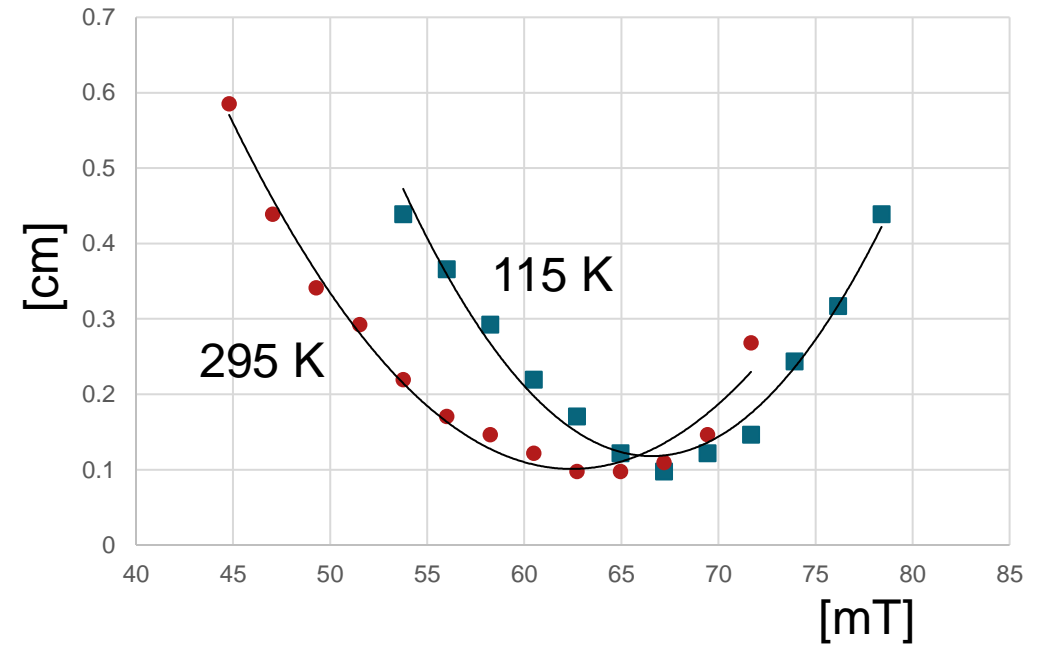
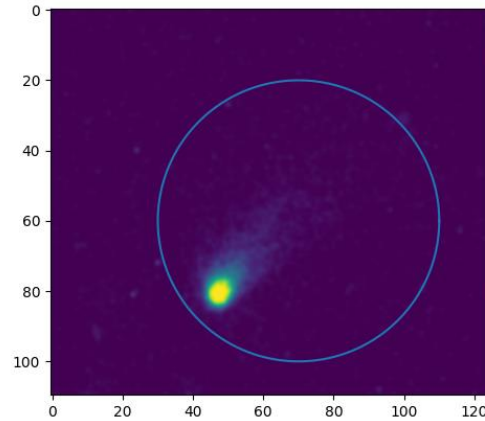


- 295 K dark current at YAG screen below showing threshold gradient around 58 MV/m (given 0.417 MW and 0.488 MW)
  - FN plot gives  $\beta = 44$
- Solenoid scan measurements @ 295 K (red) and 115 K (blue) showing expected collimated beamlike behavior for 300-500 keV e-
  - Input power for both about 0.4 MW but slightly higher field at 115 K around 61 MV/m

$\approx 56$  MV/m @ 295 K



$\approx 61$  MV/m @ 295 K

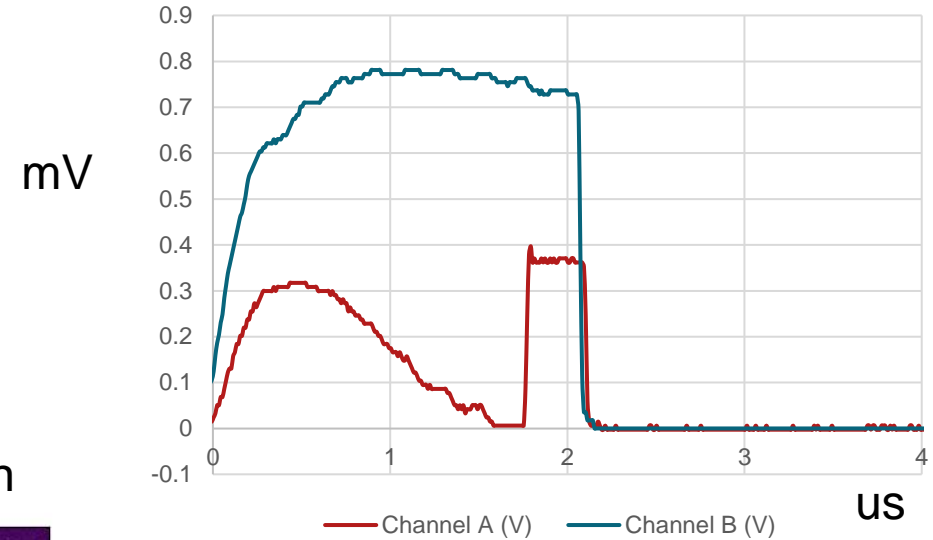




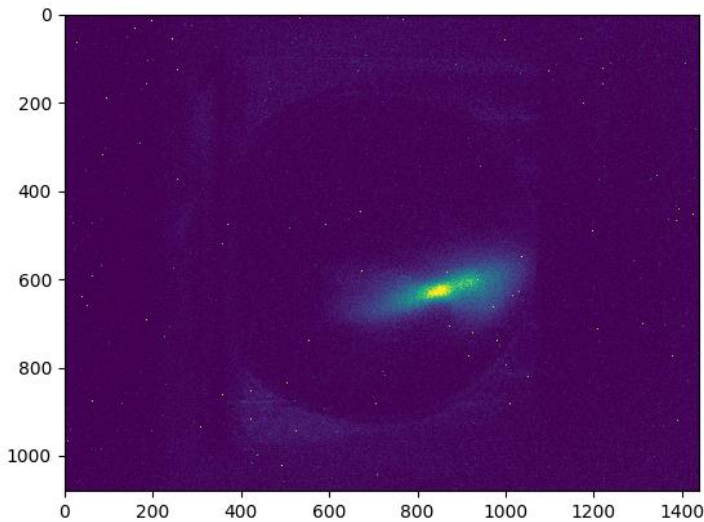
# 3) Dark Current Observation



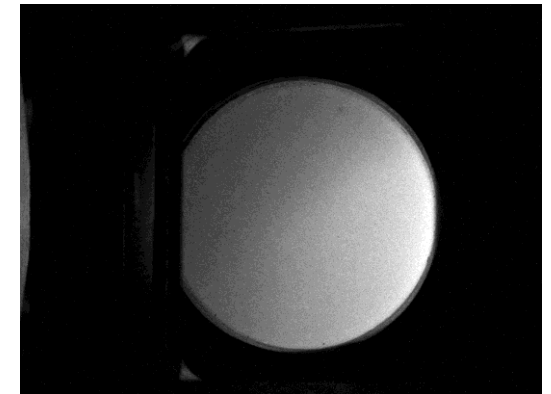
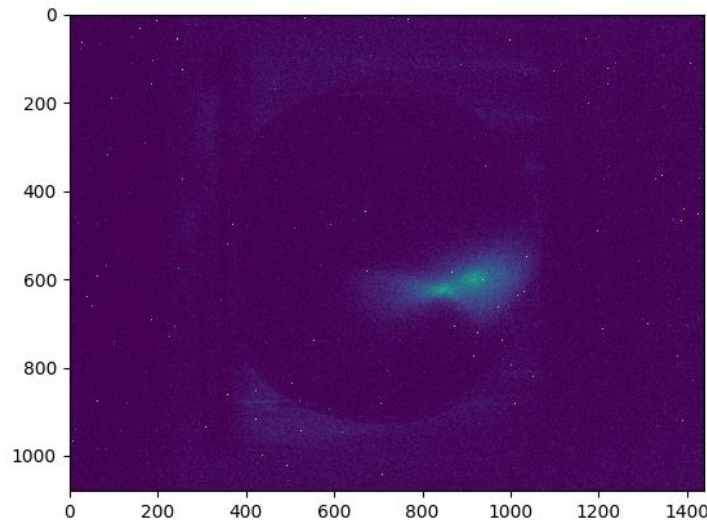
- Most analysis now focused RF stability, accumulating sufficient dark current for more analysis (1 Hz thermal limit)
- Example chain of breakdowns at 85 K (eg. RF to right) at 0.388 MW and  $\approx 74$  MV/m
- Dark current before and after @ 72 MV/m 0.368 MW input power for both



$\approx 72$  MV/m pre breakdown



$\approx 72$  MV/m post breakdown

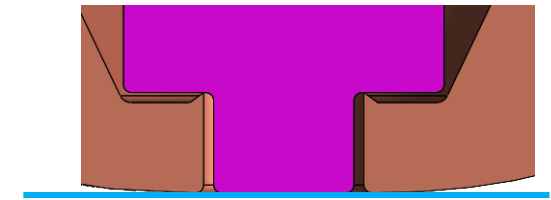
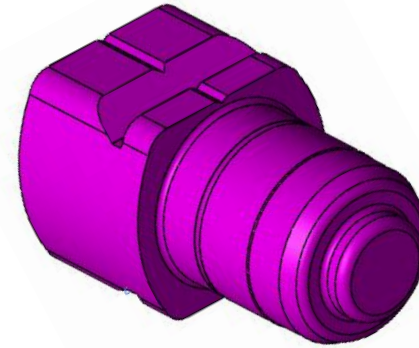




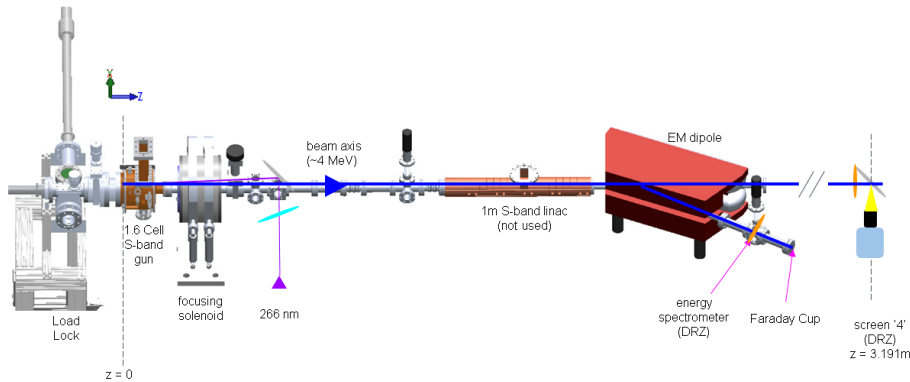
# 3) Phase2 Gun Cavity



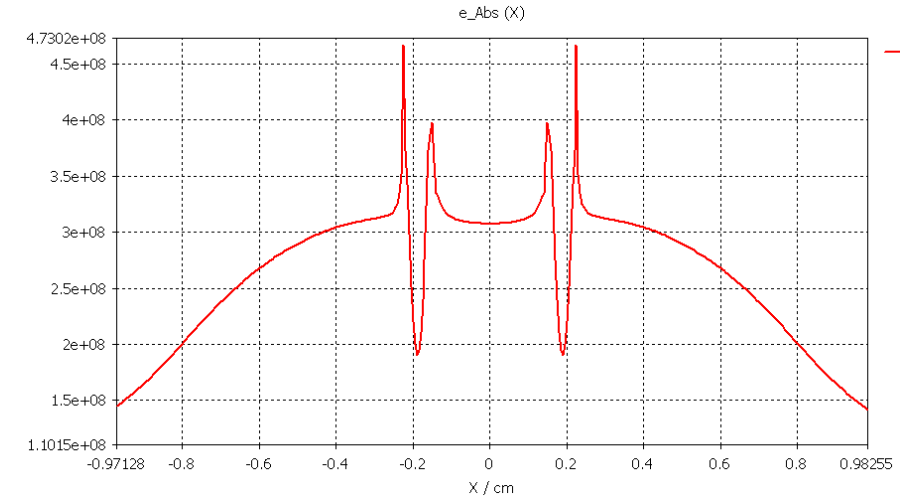
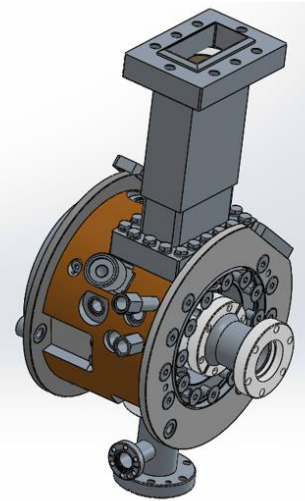
- Future cathode integration creates additional need for understanding dark current
- INFN style shown in purple (right)
- Room temperature high gradient gun with RF knife edge in use at another UCLA beamline called PEGASUS (below)
  - Effective but limited to 80 MV/m of designed 120 MV/m for several reasons including additional dark current from cathode gap
- Scaled to CYBORG backplane (right) w/ field enhancements simulated along cathode plane



250 um gap at room temp  
245 um at 77 K



Alesini, David, et al. *Physical Review Special Topics-Accelerators and Beams* 18.9 (2015): 092001.  
[https://doi.org/ 10.1103/PhysRevSTAB.18.092001](https://doi.org/10.1103/PhysRevSTAB.18.092001)





# Outline of presentation



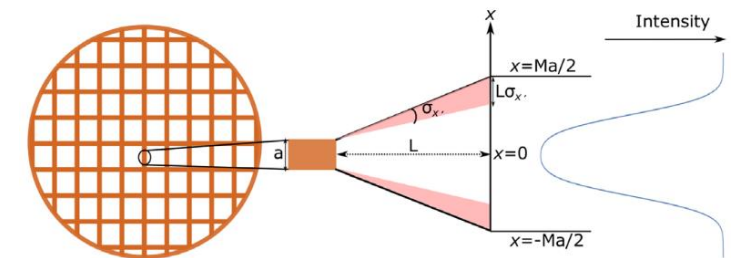
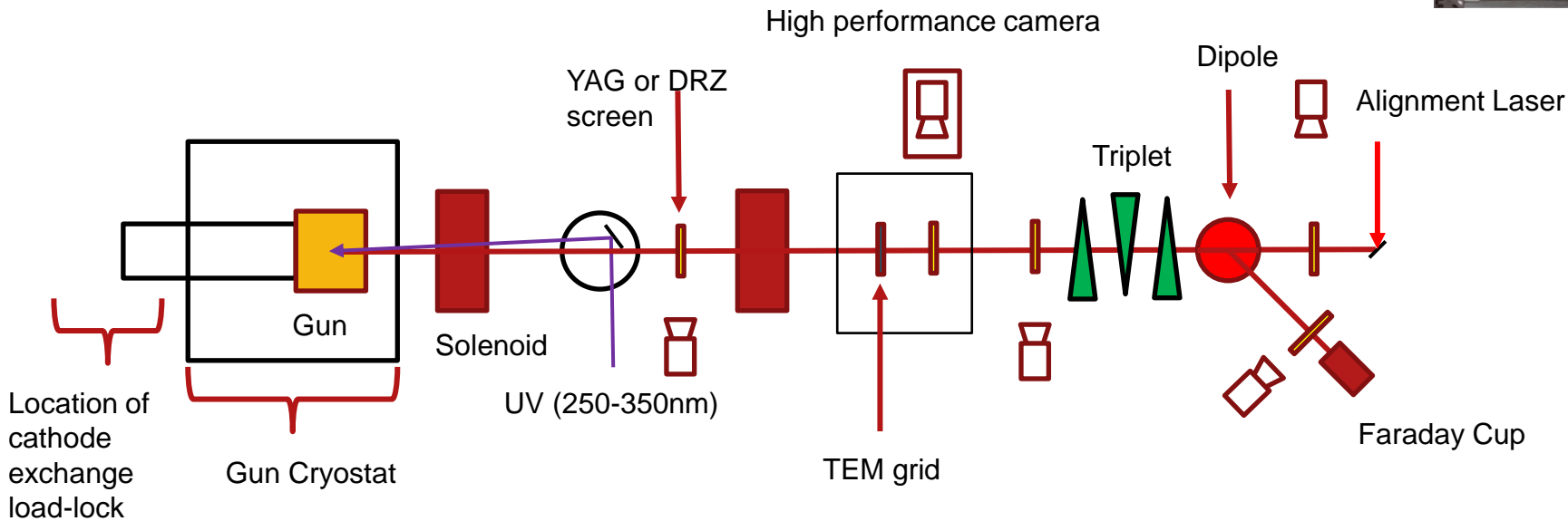
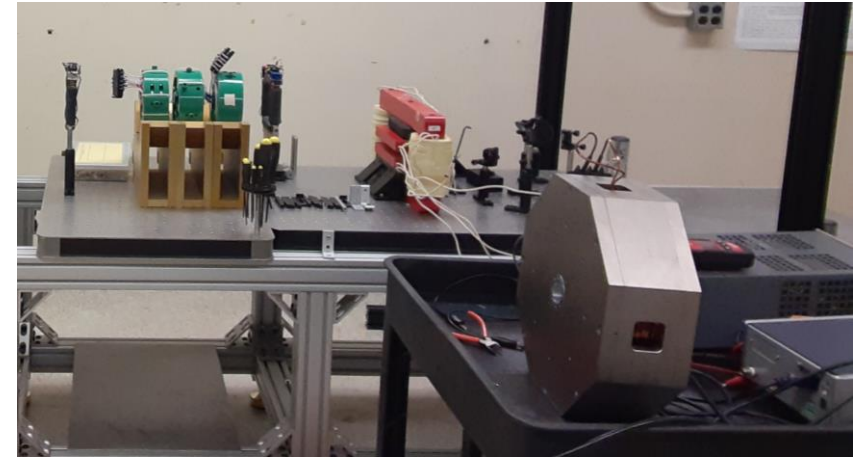
1. Background and motivation
  - Materials physics to beam brightness
2. CYBORG beamline overview
  - Lab facilities and commissioning status
3. Dark current studies
  - Preliminary measurements and existing capabilities
4. **Future testing discussion**



# 4) Phase2 Beamline



- Phase2 underway for integration of load lock for semiconductor cathode testing
- Additional magnetic elements and high precision MTE measurement setup planned, improving diagnostics for dark current + breakdown study

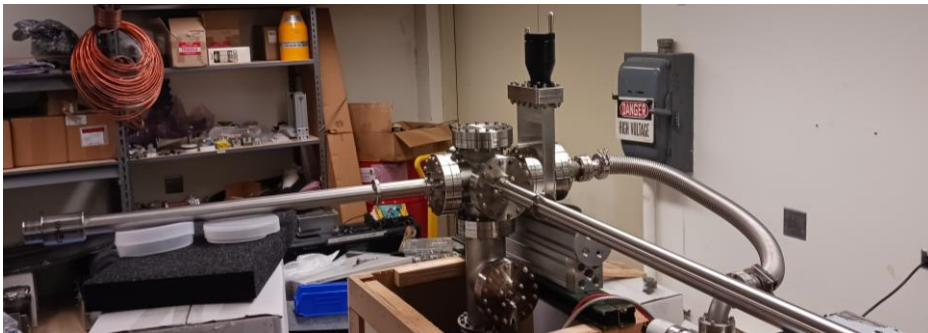
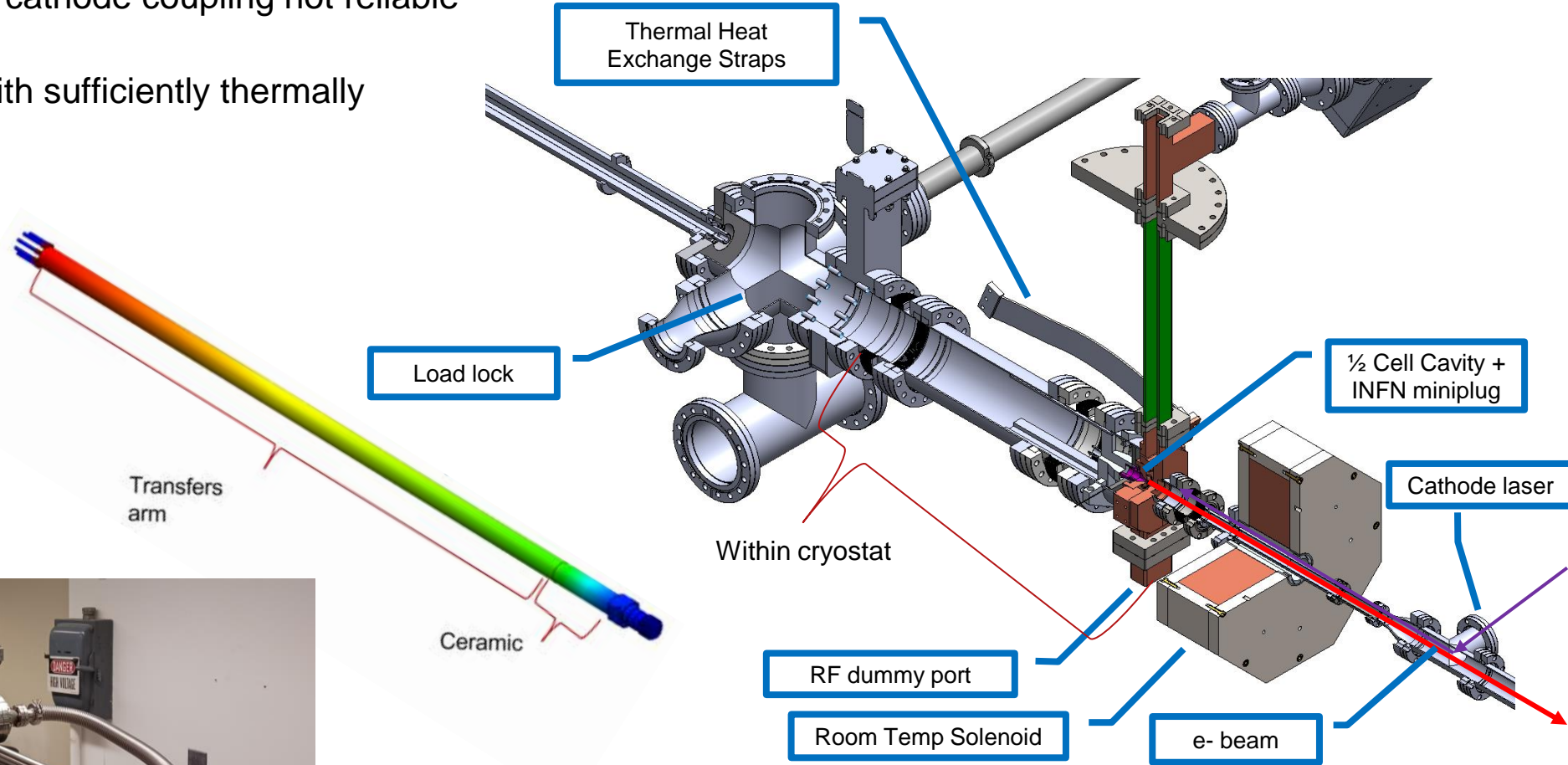


Marx, Daniel, et al. *Physical Review Accelerators and Beams* 21.10 (2018): 102802.  
<https://doi.org/10.1103/PhysRevAccelBeams.21.102802>



# 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





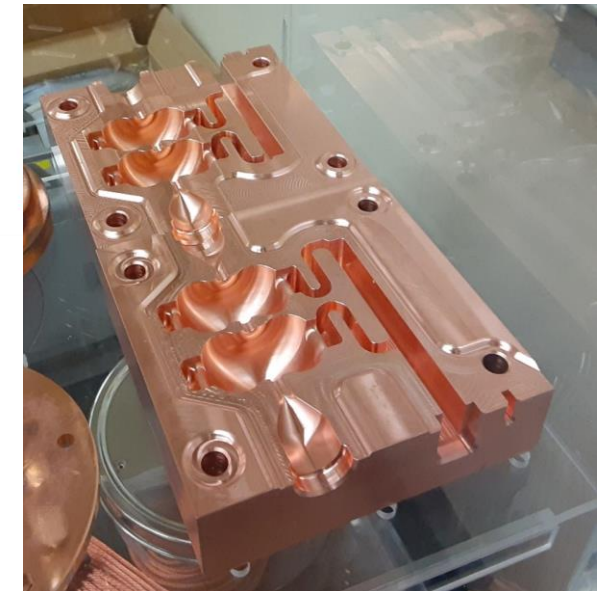
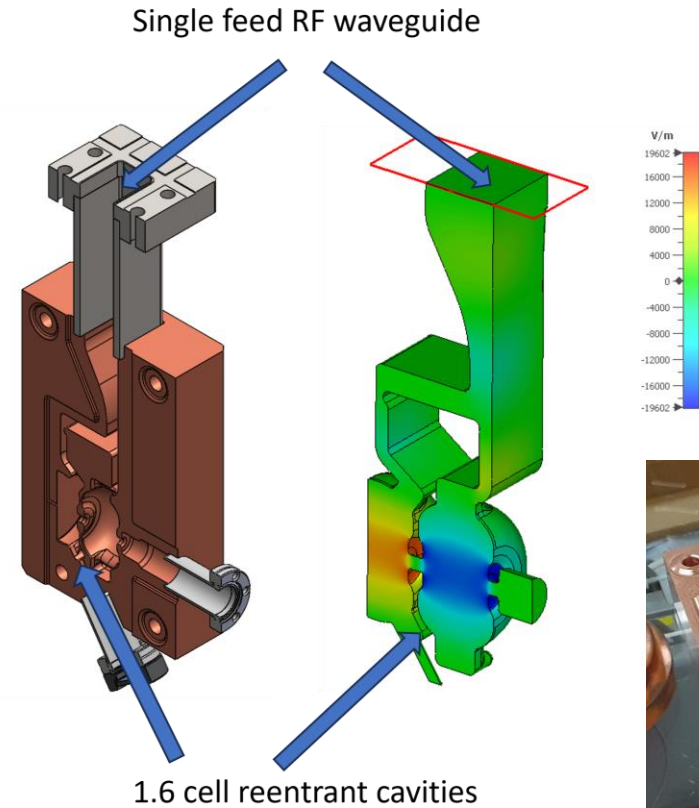
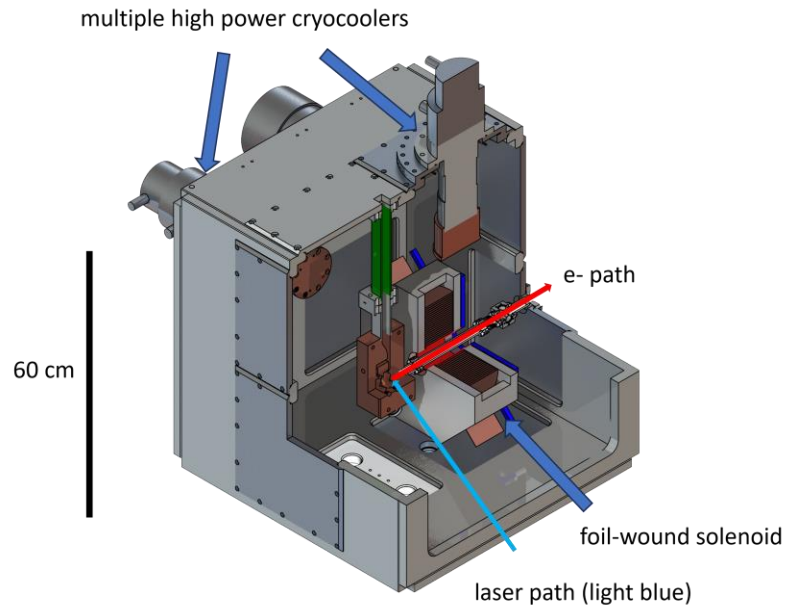




# 4) Higher gradient guns



- SLAC/Cornell collaboration for CYBORG w/ 180 MV/m fields using SLED
- Development of higher gradient 1.6 cell photoinjector beginning in earnest based on CYBORG template
- No external cathode coupling, cathode peak field aiming for >200 MV/m
- Solenoid now within cryostat
- Fabrication method close to SLAC linac method with longitudinal rather than transverse slices





## 5) Conclusions



1. CYBORG operational as cryogenic electron emission test bed in with iterative improvements planned
2. Phase1 commissioning producing useful dark current data
3. Phase2 cathode integration development will increase beamline functionality dramatically
4.  $>200$  MV/m cryogenic gun development well underway and additional experiments useful



# Collaborators



- Fabio Bosco, Obed Camacho, Atsushi Fukasawa, David Garcia, *Richard Li*, Pietro Musumeci, Brian Naranjo, Pratik Manwani, Jake Parsons, *April Smith*, *Sean O'Tool*, Yusuke Sakai, Oliver Williams, Monika Yadav



- Paul Carriere, Nanda Matavalam



- Evgenya Simakov, Anna Alexander, Petr Anisimov, Haoran Xu



- Martina Carillo, Andrea Mostacci



- Zenghai Li, Sami Tantawi, Nathan Majernik



- Bruno Spataro



- Chad Pennington, Jared Maxxson