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

Cryogenic Radio-Frequency Photoinjectors for High Brightness Electron Beams

F. Bosco, J. Rosenzweig *et al.*

Collaborators

UCLA
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J. Imenez Zepeda
G. Lawler (now at TibaRay)
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S. Tantawi

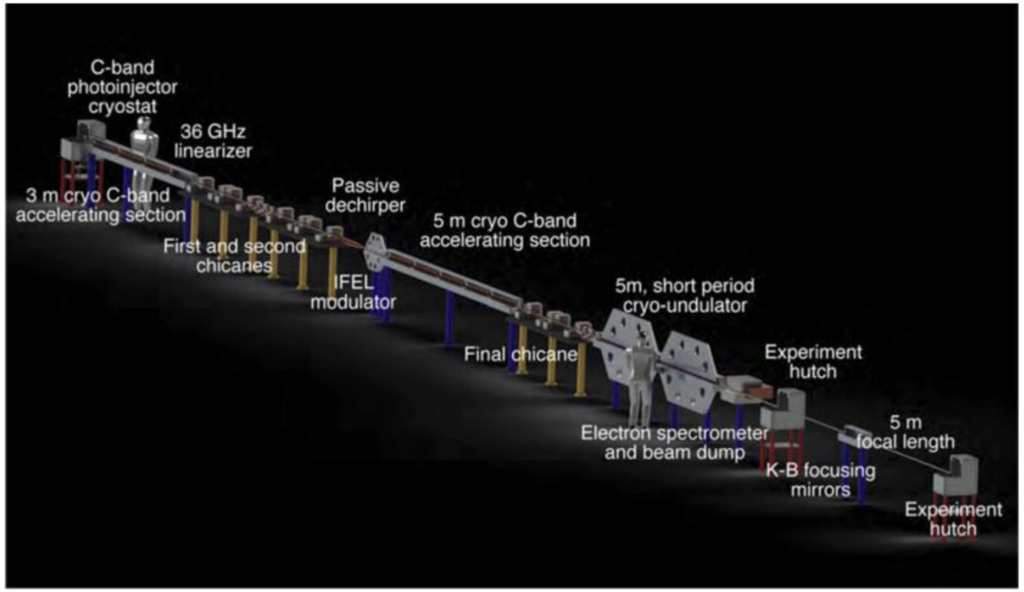
INFN
B. Spataro
A. Mostacci
L. Palumbo

Cryo-RF Gun for UCXFEL

- Proposal for a university-scale hard X-ray FEL
- Ultra-bright electron beam source: cryogenic RF gun
  - C-band (5.712 GHz)
  - Cryogenic (77 K)
  - High field (240 MV/m at cathode)
  - Expected to deliver **sub-100 nm rms emittance @ 100 pC**

$$B_e = \frac{2\pi J_{\max} m_e c^2}{k_B T_c} \cong \frac{e c \pi \epsilon_0 (E_0 \sin\varphi_0)^2}{k_B T_c}$$

$\propto J_{\max}$



An ultra-compact x-ray free-electron laser

J B Rosenzweig, N Majernik, R R Robles, G Andonian, O Camacho, A Fukasawa, A Kogar, G Lawler, Jianwei Miao, P Musumeci, B Naranjo, Y Sakai, R Candler, B Pound, C Pellegrini, C Emma, A Halavanau, J Hastings, Z Li ... B Spataro, S K ... S B van der Ge ...

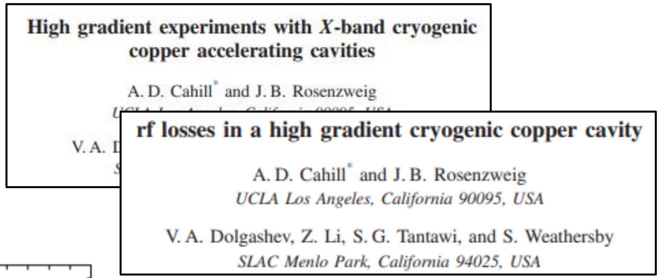
A High-Flux Compact X-ray Free-Electron Laser for Next-Generation Chip Metrology Needs

by James B. Rosenzweig [1,*], Gerard Andonian [1], Ronald Agustsson [2], Petr M. Anisimov [3], Aurora Araujo [2], Fabio Bosco [1], Martina Carillo [4], Enrica Chiadroni [4], Luca Giannessi [5], Zhirong Huang [6], Atsushi Fukasawa [1], Dongsung Kim [3], Sergey Kutsaev [2], Gerard Lawler [1], Zenghai Li [6], Nathan Majernik [6], Pratik Manwani [1], Jared Maxson [7], Janwei Miao [1], Mauro Migliorati [4], Andrea Mostacci [4], Pietro Musumeci [1], Alex Murokh [2], Emilio Nanni [6], Sean O'Tool [1], Luigi Palumbo [4], River Robles [6], Yusuke Sakai [1], Evgenya I. Simakov [3], Madison Singleton [6], Bruno Spataro [5], Jingyi Tang [6], Sami Tantawi [6], Oliver Williams [1], Haoran Xu [3] and Monika Yadav [1] — Hide full author list

J. Rosenzweig *et al.*, New Journal of Physics, 2020
J. Rosenzweig *et al.*, Instruments, 2024

Cryo-RF Gun for UCXFEL (2)

- Copper at cryogenic temperature
  - Increased conductivity (Q-factor) and hardness
  - Reduced breakdown rate and CTE
  - Tolerable dark current below 300 MV/m


High gradient experiments with X-band cryogenic copper accelerating cavities

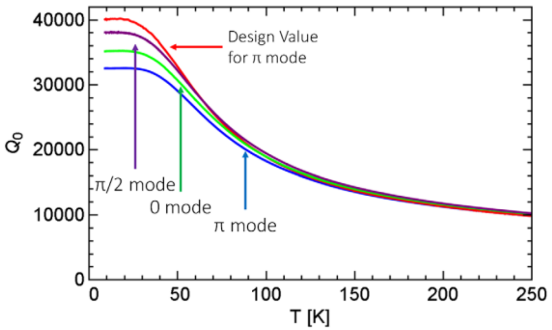
A. D. Cahill* and J. B. Rosenzweig

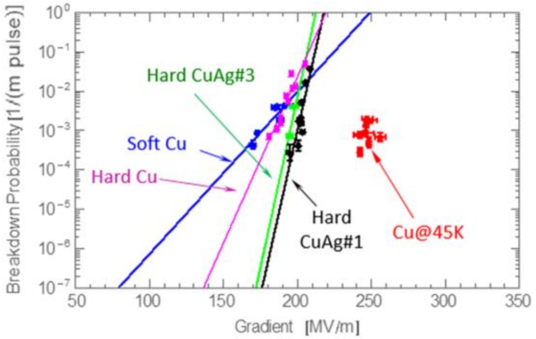
rf losses in a high gradient cryogenic copper cavity

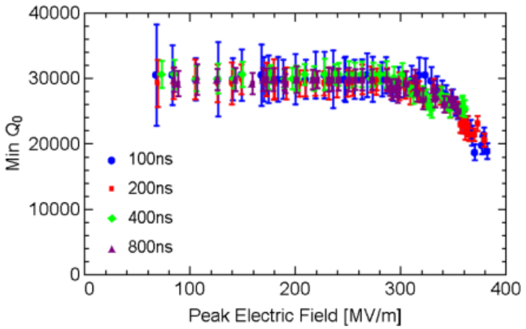
A. D. Cahill* and J. B. Rosenzweig
UCLA Los Angeles, California 90095, USA

V. A. Dolgashev, Z. Li, S. G. Tantawi, and S. Weathersby
SLAC Menlo Park, California 94025, USA

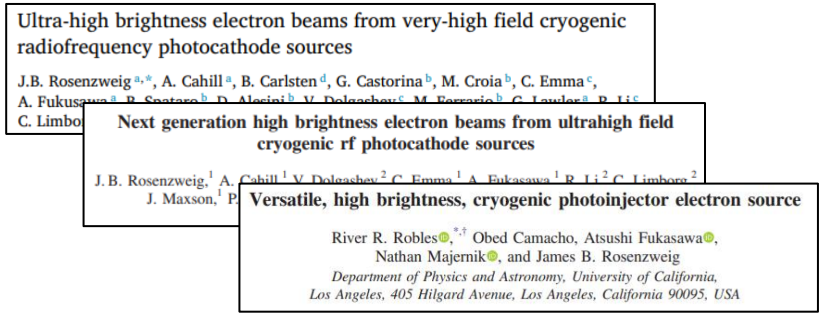
Cahill *et al.*, PRAB, 2018
Cahill *et al.*, PRAB, 2018







- Beam dynamics studies based on C-band cryo-RF guns at 240 MV/m
  - Results show $\lesssim 100\ \mathrm{nm}$ rms emittance from RF gun @ 100 pC
  - Emittance compensation shows ~50 nm after the booster linac


Ultra-high brightness electron beams from very-high field cryogenic radiofrequency photocathode sources

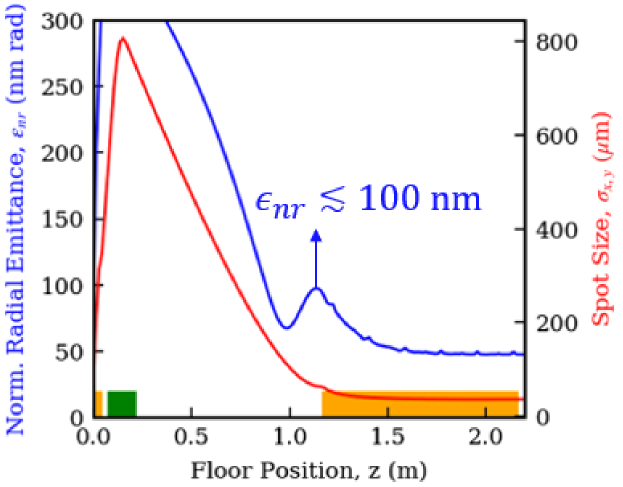
J.B. Rosenzweig[a,*], A. Cahill[a], B. Carlsten[d], G. Castorina[b], M. Croia[b], C. Emma[c],

Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources

Versatile, high brightness, cryogenic photoinjector electron source

River R. Robles[*,†], Obed Camacho, Atsushi Fukasawa, Nathan Majernik, and James B. Rosenzweig
Department of Physics and Astronomy, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, California 90095, USA

J. Rosenzweig *et al.*, NIM, 2018
J. Rosenzweig *et al.*, PRAB, 2019
R. Robles *et al.*, PRAB, 2021

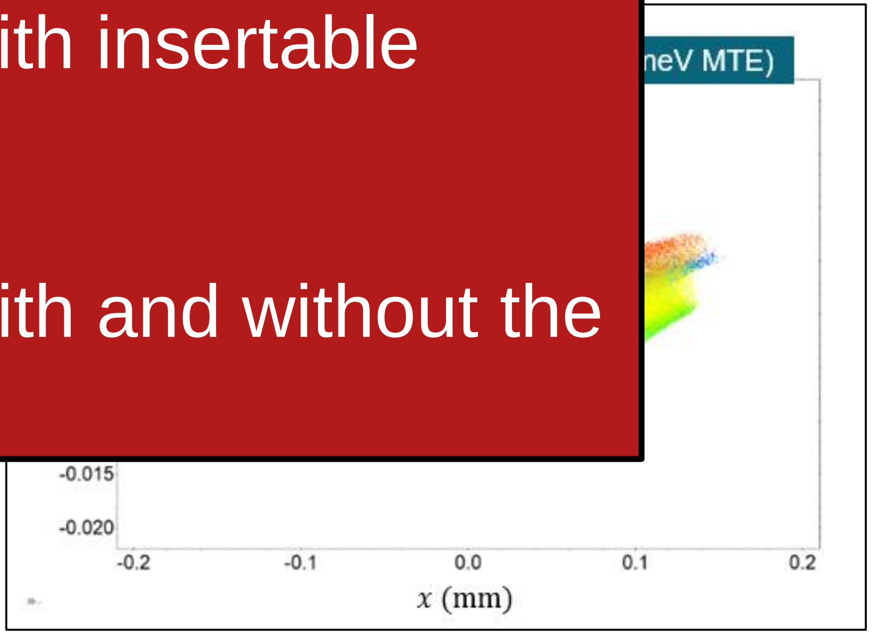


Cryo-RF Gun for UCXFEL (3)

- 1.6 cell cryogenic, distributed coupling RF gun at C-band (5.712 GHz) with 240 MV/m peak field
- Expected challenges
  - Manufacturing (distributed coupling, tuning..)
  - Susta
  - Integ

Intermediate steps:

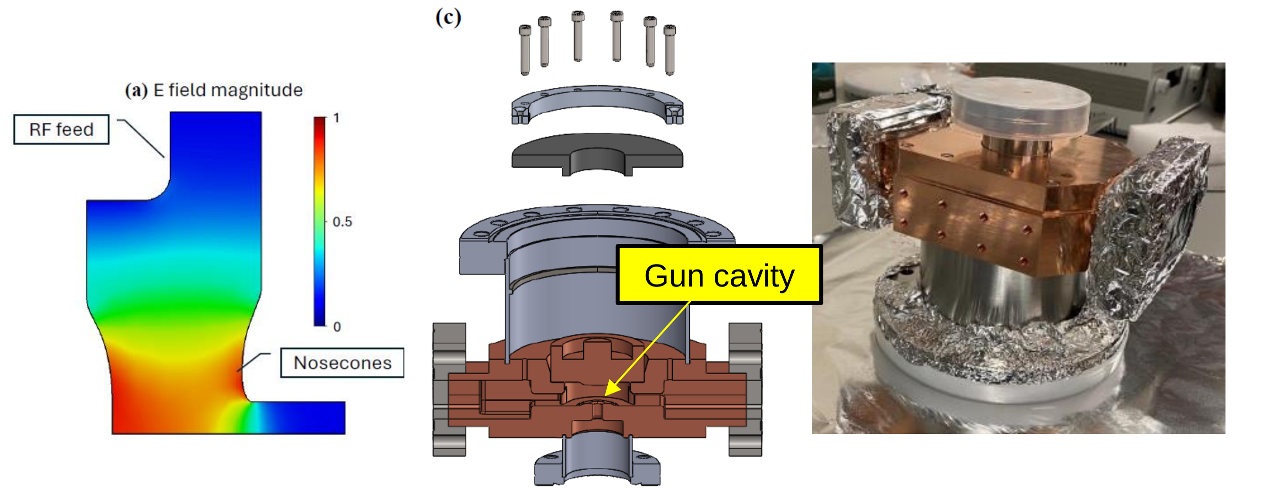
- UCLA: Simplified geometry (0.5 cell), lower target field (120 MV/m) but cryogenic system with insertable cathodes
- LANL: Room temperature version with and without the insertable cathodes at ~200 MV/m

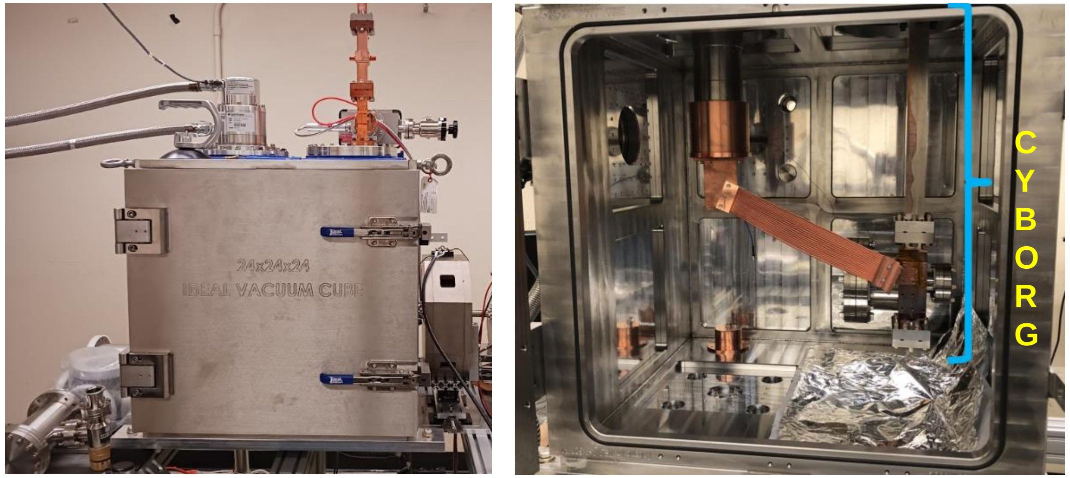


J. Rosenzweig *et al.*, "A high-flux compact x-ray free-electron laser for next-generation chip metrology needs," *Instruments*, vol. 8, no. 1, 2024. [Online]. Available: https://www.mdpi.com/2410-390X/8/1/19

UCLA – 0.5 Cell Cryo-RF Gun

- **CYBORG** (**Cr**Y**ogenic **B**rightness-**O**ptimized **R**f **G**un) beamline at MOTHRA Lab
  - C-band (5.712 GHz) re-entrant half cavity with demountable back plane
  - 120 MV/m at ~80 K achievable with ~0.8 MW power
  - Helium compressor cryo-coolers





CRYOGENIC BRIGHTNESS-OPTIMIZED RADIOFREQUENCY GUN (CYBORG)

G. E. Lawler*, A

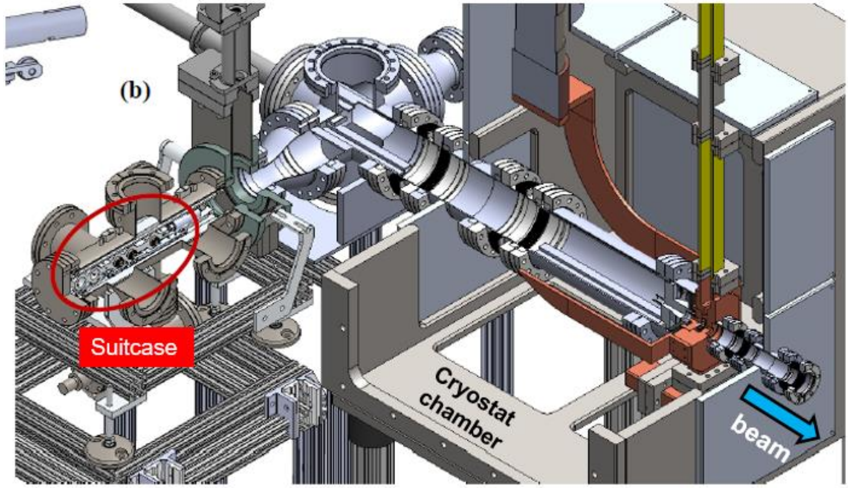
Improving Cathode Testing with a High-Gradient Cryogenic Normal Conducting RF Photogun

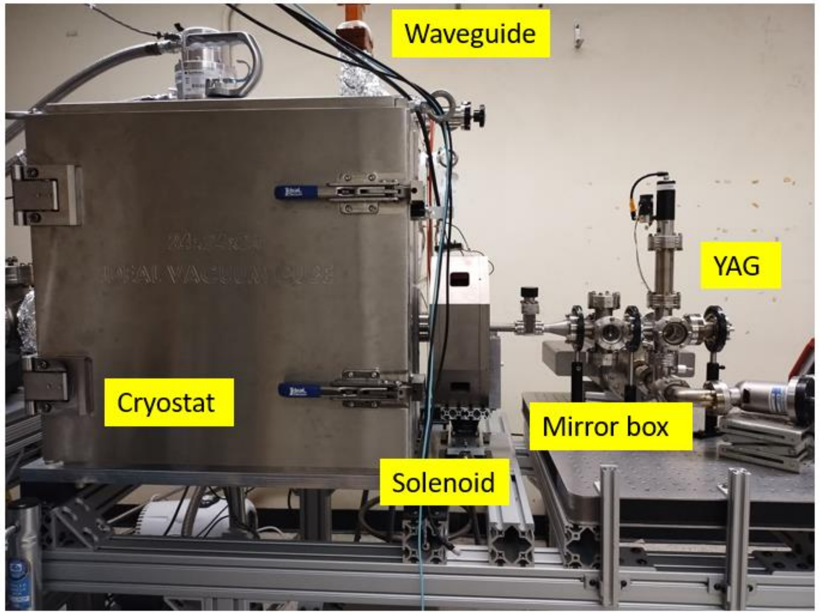
by Gerard Emile Lawler [1,*], Fabio Bosco [1,2], Martina Carillo [2], Atsushi Fukasawa [1], Zenghai Li [3], Nathan Majernik [3], Yusuke Sakai [1], Sami Tantawi [3], Oliver Williams [1], Monika Yadav [1] and James Rosenzweig [1]

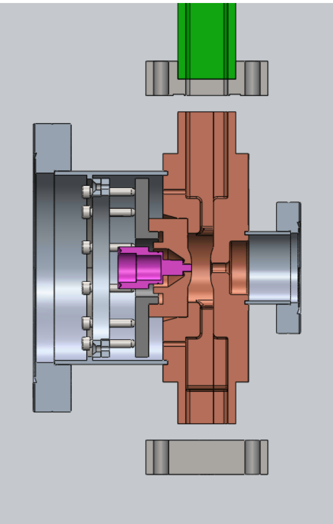
Lawler *et al.*, IPAC 22, 2022
Lawler *et al.*, Instruments, 2024

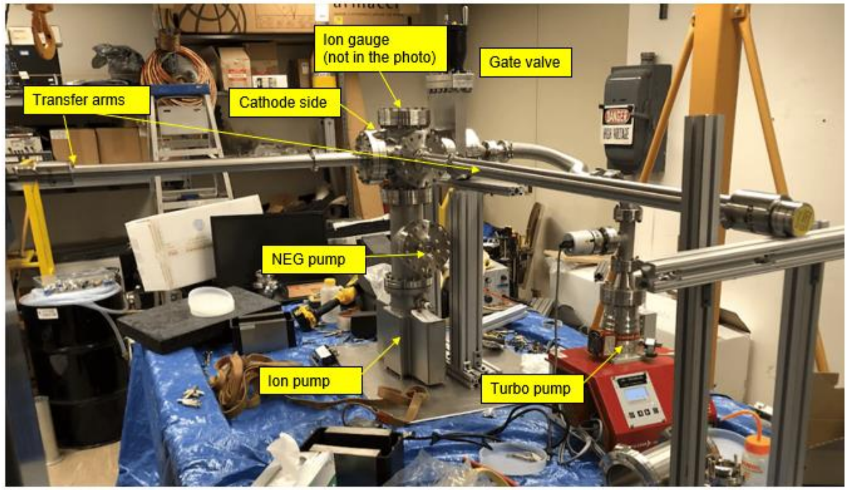
UCLA – 0.5 Cell Cryo-RF Gun (2)

- Phase 1: Dark current studies
  - Spring 2024
- Phase 2: Photoelectrons from copper cathodes
  - First beams ~March 2025
  - Full characterization (TEM grid and spectrometer under design) ~Summer 2025
- Phase 3: Photoelectrons from insertable cathodes
  - ~Winter 2026









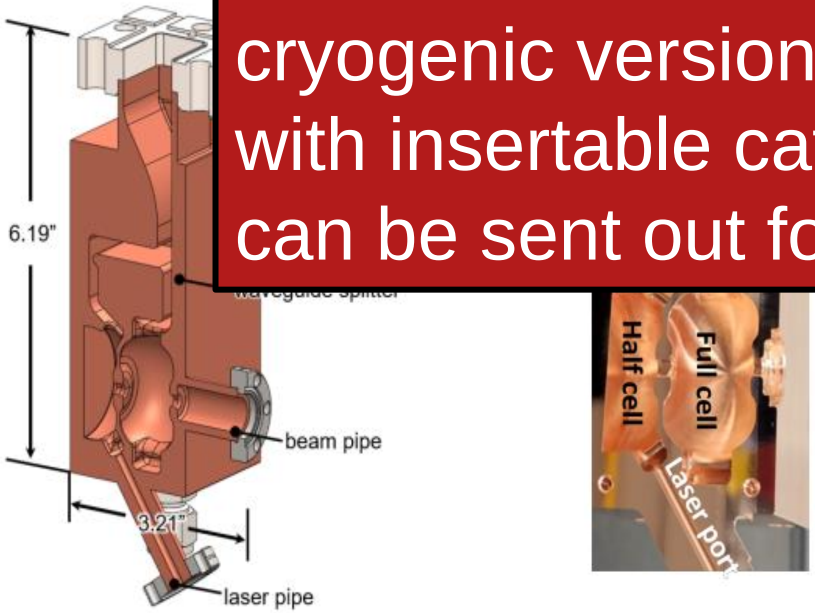
LANL – Room Temp 1.6 Cells RF Gun

- All copper, room temperature 1.6 cell RF gun
  - Goal: RF properties and tuning
  - Assemble by March and start testing from April


C-BAND PHOTOINJECTOR RADIOFREQUENCY CAVITY DESIGN FOR ENHANCED BEAM GENERATION*

H. Xu†, P. M

Los Al



[H. Xu, IPAC 23, 2023]

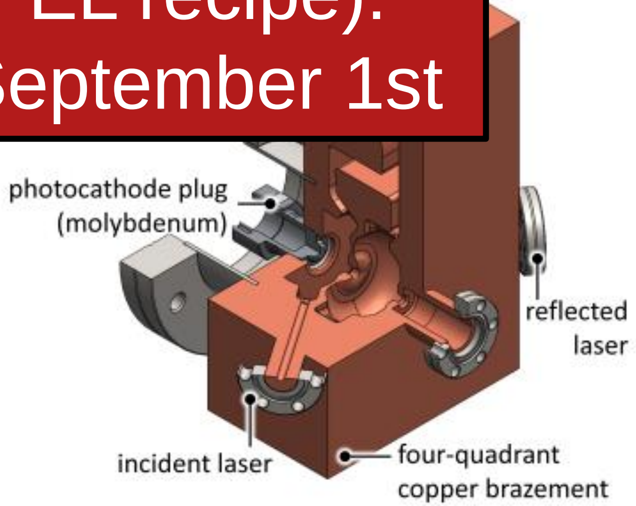
- Insertable cathodes, room temp 1.6 cell RF gun
  - Goal: Cathodes in extreme
  - Submitted for machining, assemble in July and start testing in September


RF AND MULTIPACTOR ANALYSIS FOR THE CARIE RF PHOTOINJECTOR WITH A PHOTOCATHODE INSERT *

, T. P. Grumstrup,

amos, NM, USA

, USA

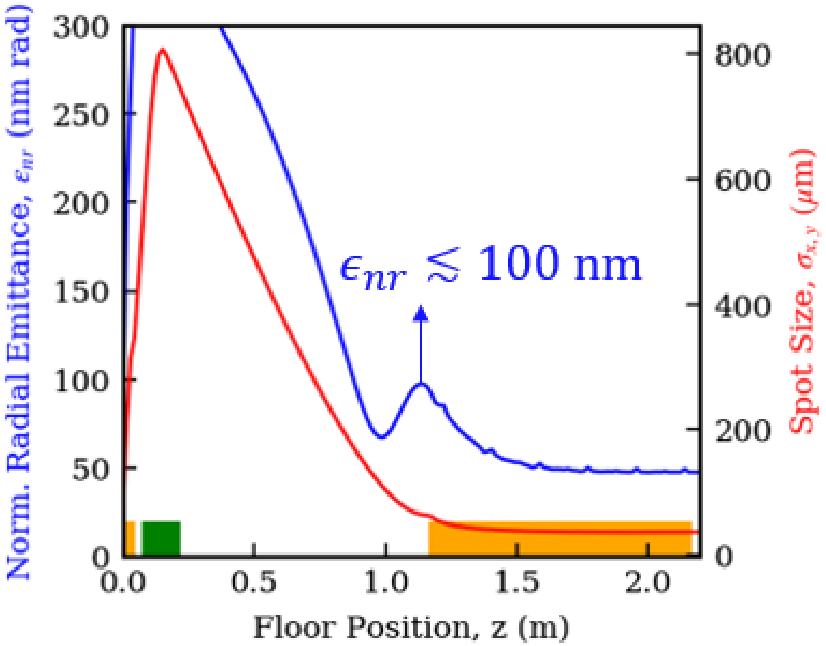


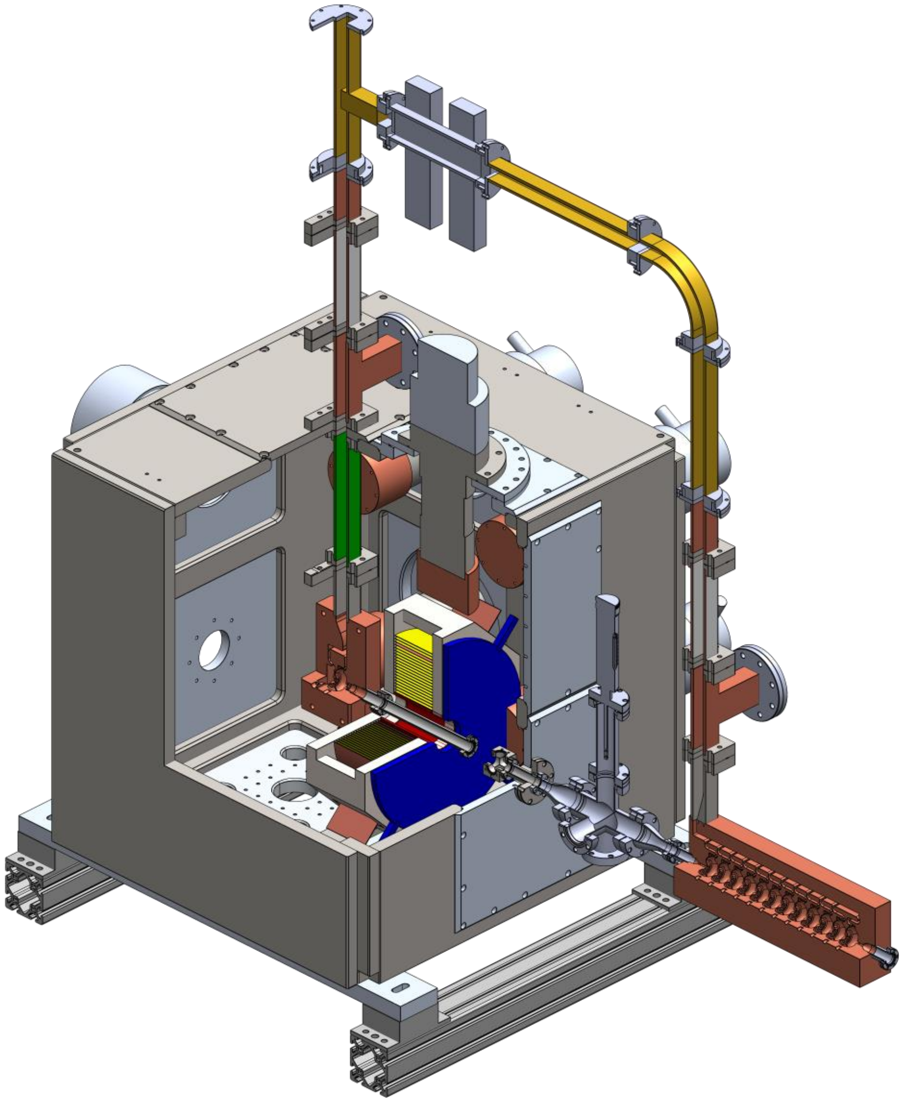
[H. Xu, IPAC 24, 2024]

UCLA and LANL are finalizing the design for the cryogenic version (77 K) of the 1.6 cell RF gun with insertable cathodes (*i.e.* UCXFEL recipe): can be sent out for machining by September 1st

Cryo-RF Gun & Mini-Linac

- Plan to get emittances ~50 nm for 100 pC beams
- Mini-linac for emittance compensation
  - Single C-band klystron with T-power splitter
  - SLED option to increase the drive power
- Assemble at LANL ~November 1st



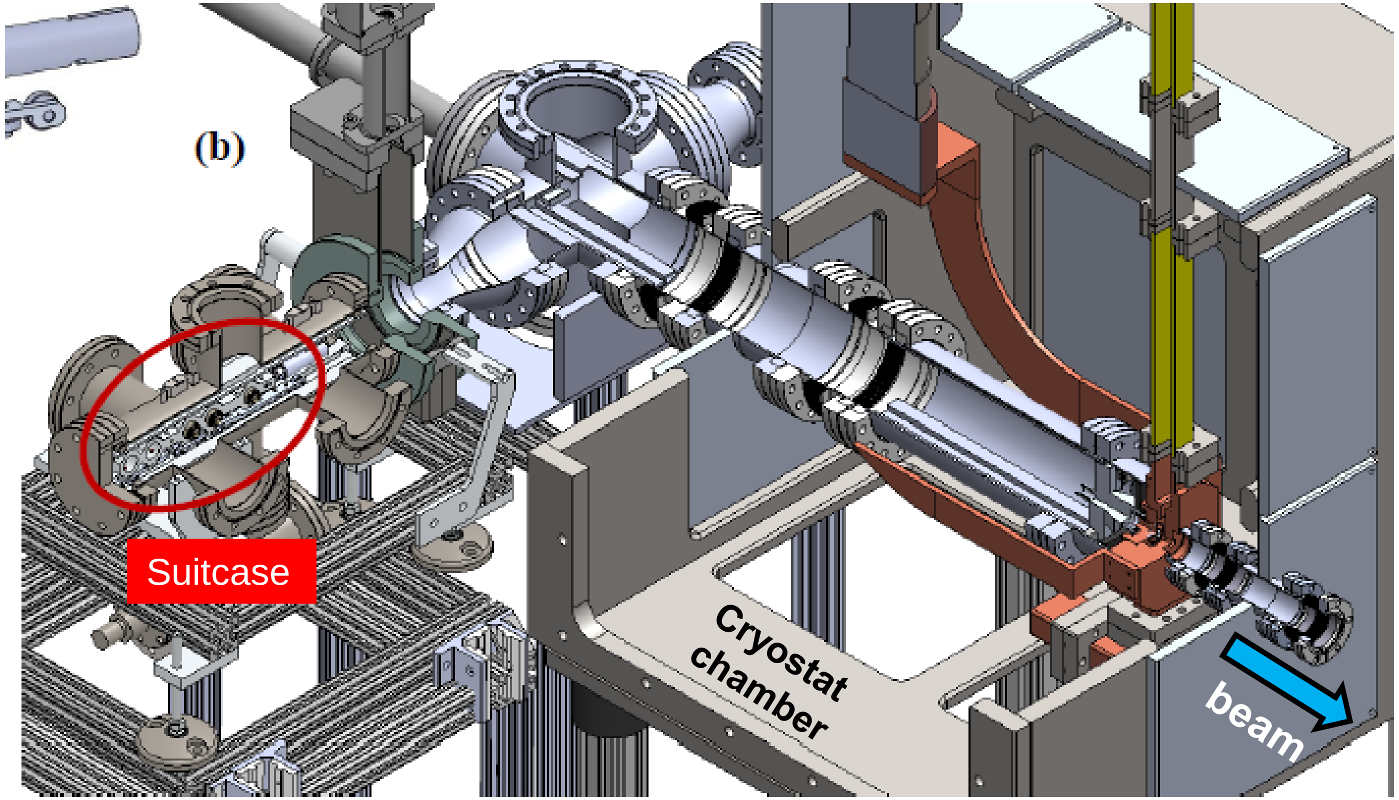


SPARE SLIDES

Loadlock - Design

- Advanced **cathode** studies (first candidate CsTe)
- Design based on **PEGASUS** (Room temp, S-band)
- Cathode **suitcase** and **transfer arm**
- INFN-style **mini puck**
- **UHV** is crucial

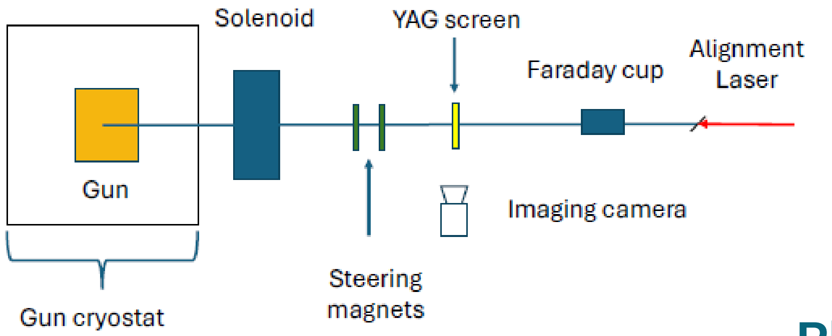
G. Lawler, PhD thesis



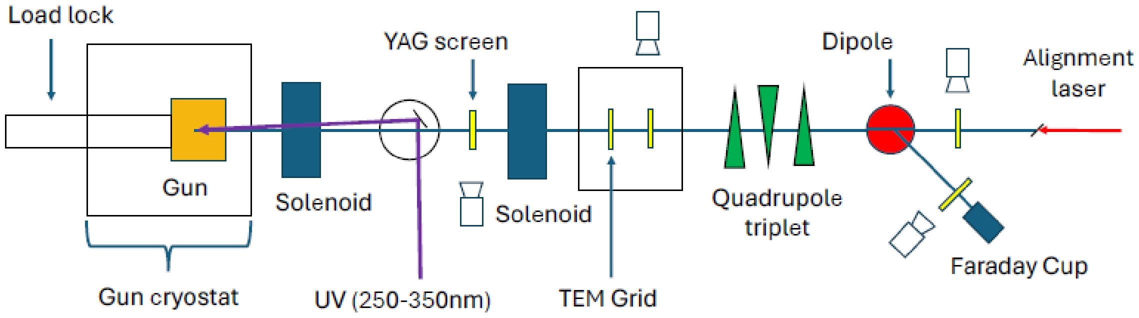
Beamline upgrade plan

- Phase 1: Cryo-rf Gun and YAG screen (no laser) → Dark current studies
- Phase 1.5: Phase 1 + Mirror box → First photoelectrons from Cu cathode
- Phase 2: Phase 1.5 + Diagnostics → Full characterization of Cu photoelectrons
- Phase 3: Loadlock + Phase 2 → Alternative cathodes (e.g. CsTe)

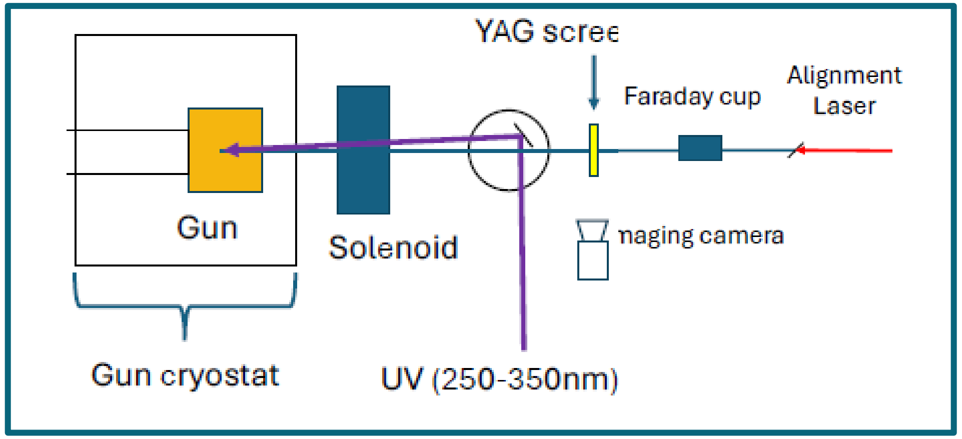
Phase 1



Phase 3



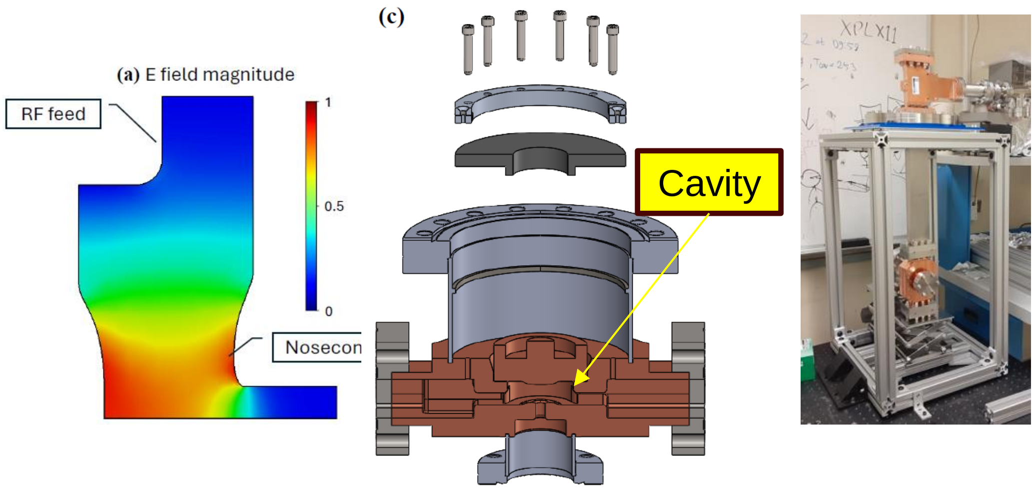
Phase 1.5



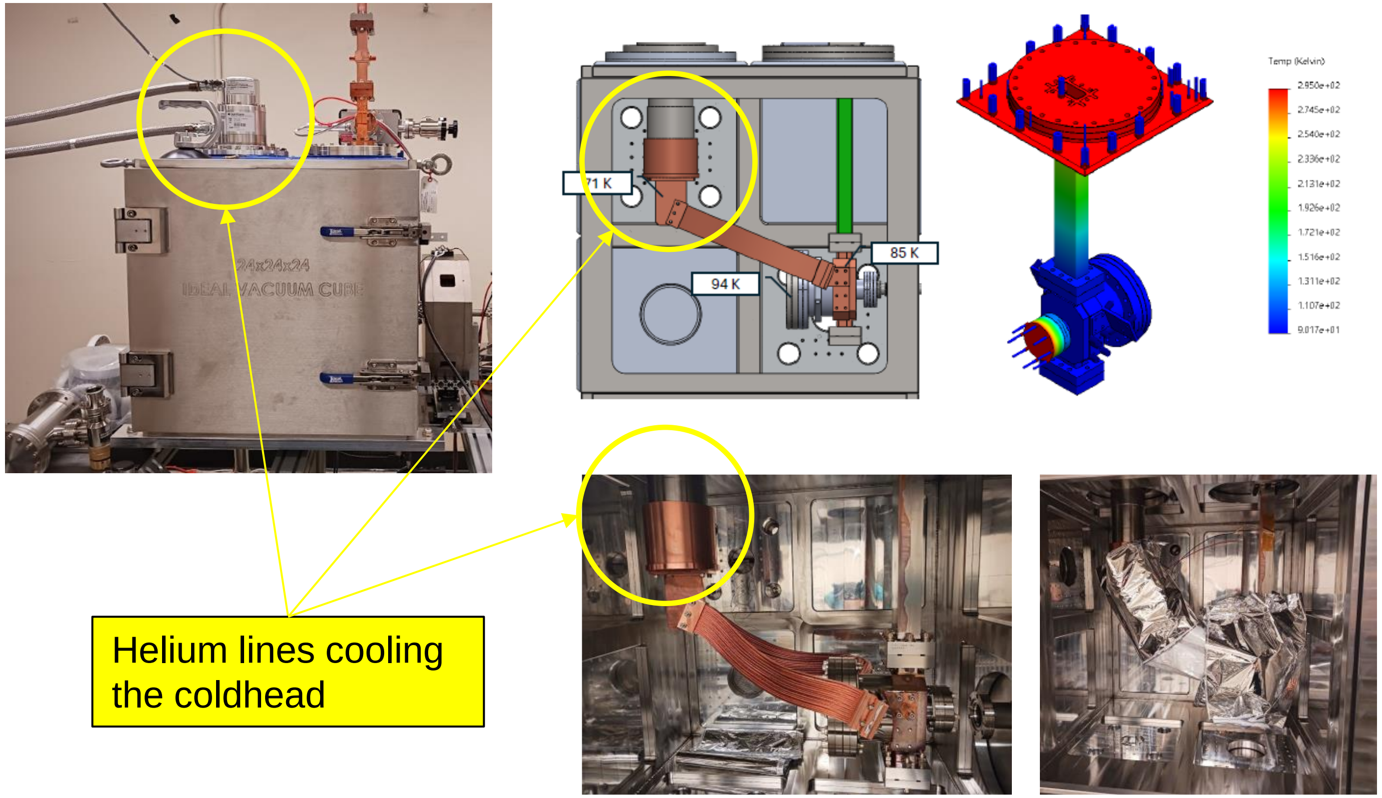
.. Phase 2 ..

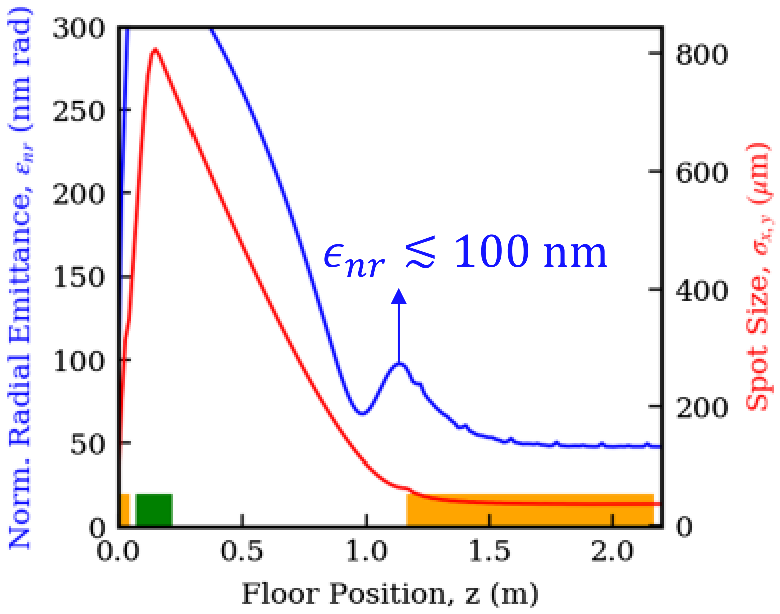
CYBORG RF Gun

- Half cell C-band gun with re-entrant nosecones
- Demountable cathode backplane for future cathode studies (insertable cathodes, FERMI-style)
- Helium compressor cryocooler
- Copper braids put the coldhead and the gun in thermal contact



G. E. Lawler et al., "Improving cathode testing with a high-gradient cryogenic normal conducting rf photogun," *Instruments*, vol. 8, no. 1, 2024. [Online]. Available: https://www.mdpi.com/2410-390X/8/1/14





Norm. Radial Emittance, ϵ_{nr} (nm rad)
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
Floor Position, z (m)
800
600
400
200
0
Spot Size, $\sigma_{x,y}$ (μm)
$\epsilon_{nr} \lesssim 100$ nm

Cryo-RF Gun for UCXFEL

An ultra-compact x-ray free-electron laser

J B Rosenzweig, N Majernik, R R Robles, G Andonian, O Camacho, A Fukasawa, A Kogar, G Lawler, Jianwei Miao, P Musumeci, B Naranjo, Y Sakai, R Candler, B Pound, C Pellegrini, C Emma, A Halavanau, J Hastings, Z Li, M Nasr, S Tantawi, P. Anisimov, B Carlsten, F Krawczyk, E Simakov, L Faillace, M Ferrario, B Spataro, S Karkare, J Maxson, Y Ma, J Wurtele, A Murokh, A Zholents, A Cianchi, D Cocco and S B van der Geer ▲ Hide full author list

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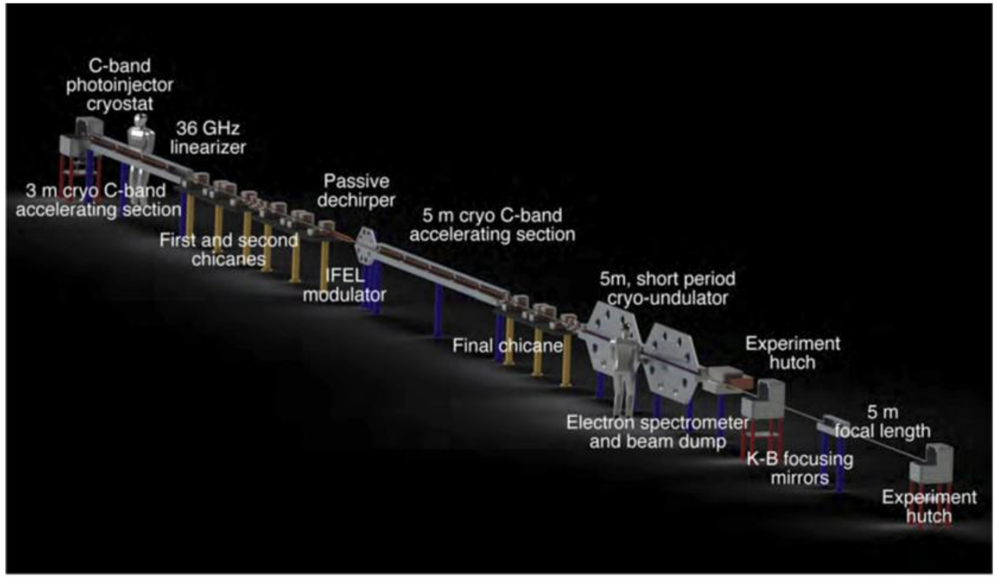

J. Rosenzweig et al., New Journal of Physics, 2020
J. Rosenzweig et al., Instruments, 2024

Ultra-high brightness electron beams from very-high field cryogenic radiofrequency photocathode sources

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A. Fukasawa [a], B. S
C. Limborg [c], J. Max

Next generation high brightness electron beams from ultrahigh field cryogenic rf photocathode sources

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J. Rosenzweig et al., NIM, 2018
J. Rosenzweig et al., PRAB, 2019
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Versatile, high brightness, cryogenic photoinjector electron source

River R. Robles [*,†], Obed Camacho, Atsushi Fukasawa, Nathan Majernik, and James B. Rosenzweig

LANL – Room Temp 1.6 Cells RF Gun

- All copper, room temperature 1.6 cell RF gun
  - Goal: RF properties and tuning
  - 240 MV/m with 10 MW power
  - Assemble by March and Start testing from April

- Insertable cathodes, room temp 1.6 cell RF gun
  - Goal: Cathodes in extreme
  - 240 MV/m with 12 MW
  - Submitted for machining, assemble in July and start testing in September

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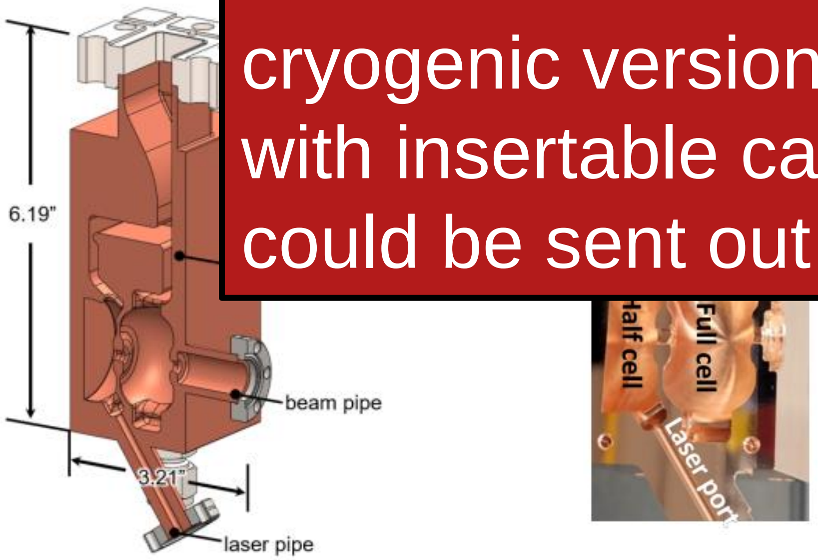
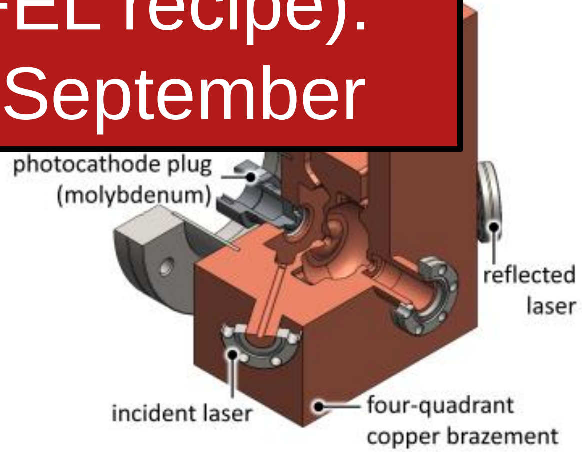


H. Xu, IPAC 23, 2023



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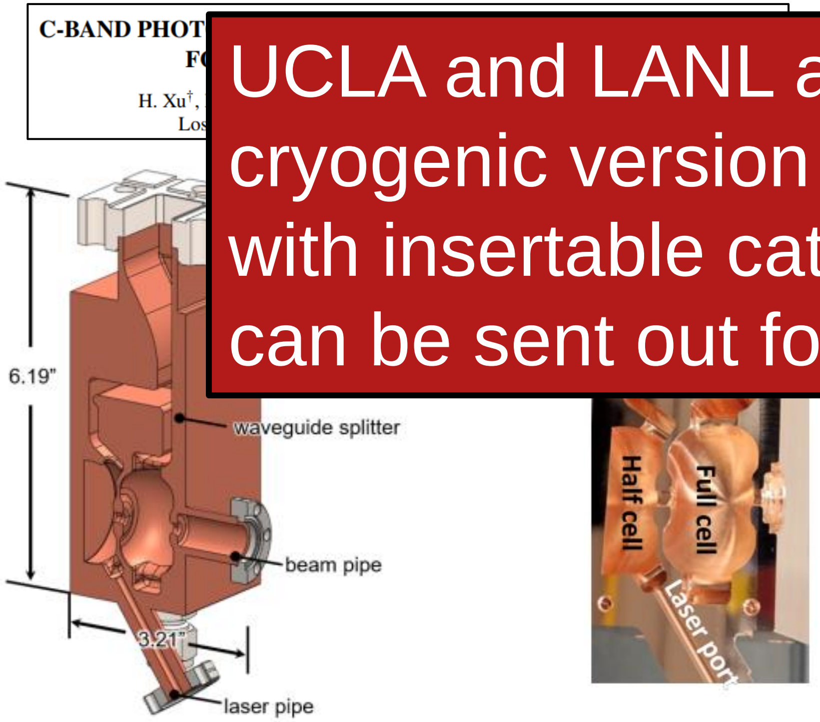
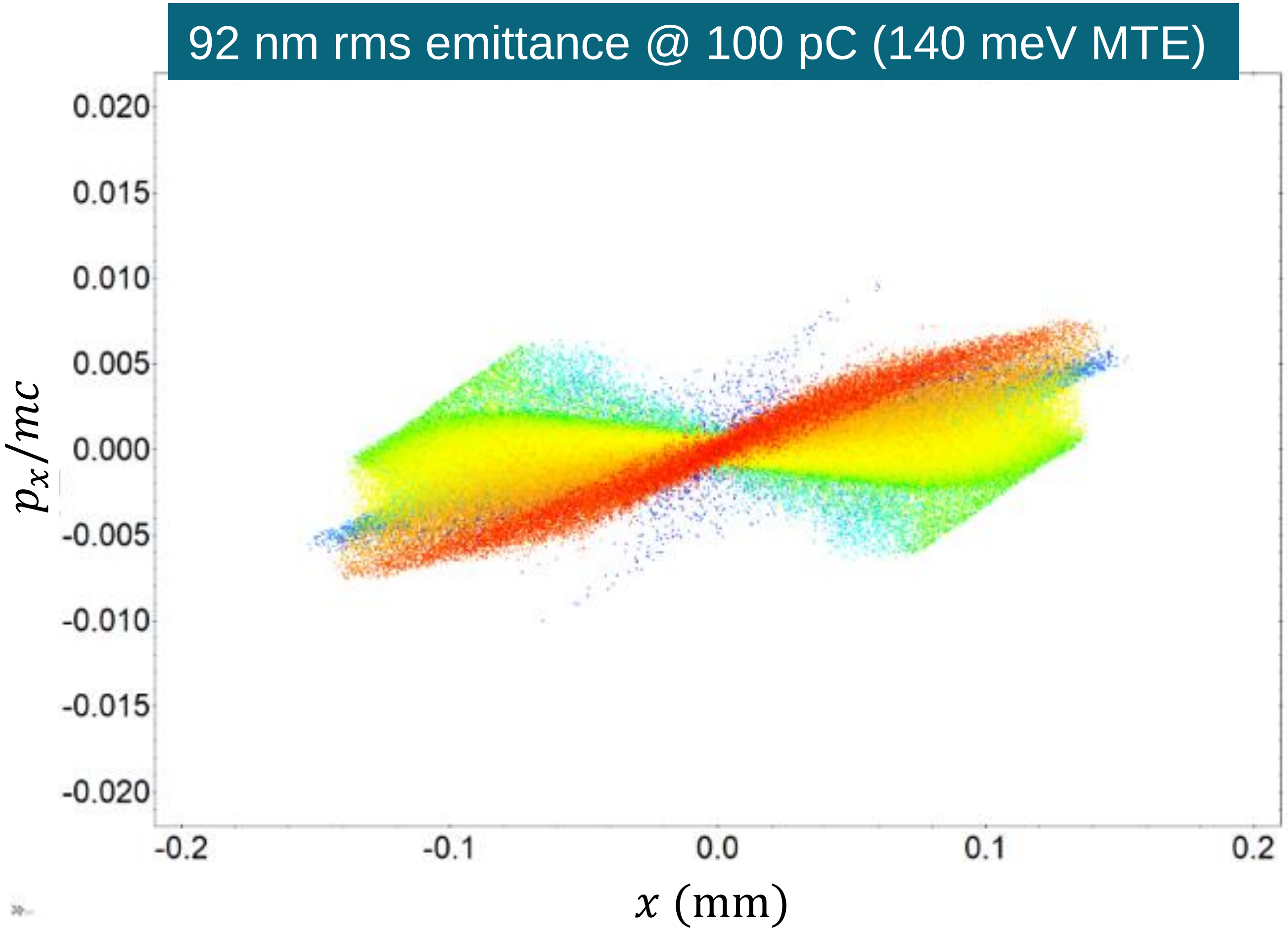


H. Xu, IPAC 23, 2023

H. Xu, IPAC 24, 2024


92 nm rms emittance @ 100 pC (140 meV MTE)
0.020
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
p_x/mc
-0.2
-0.1
0.0
0.1
0.2
x (mm)