A Compact High Brightness C-band RF Gun for Ultrafast Electron Diffraction Applications

Chad Pennington

University of California at Los Angeles

May 19, 2026

UCLA

IPAC 2026
17th International Particle Accelerator Conference
May 17 - 22
Deauville | Normandy | France

CORNELL UNIVERSITY FOUNDED A.D. 1865

Acknowledgements

UCLA
F. Bosco (now at ALBA)
S. Carbajo
A. Fukasawa
J. Jimenez Zepeda
G. Lawler (now at TibaRay)
P. Manwani
P. Musumeci
J. Rosenzweig (PI)
Y. Sakay (now at BNL)
A. Smith (now at LANL)

LANL
E. Simakov
H. Xu
A. Alexander
P. Anisimov

Cornell
J. Maxson
A. Bartnik

ASU
S. Tantawi

INFN/La Sapienza
B. Spataro
A. Mostacci
L. Palumbo
M. Carillo

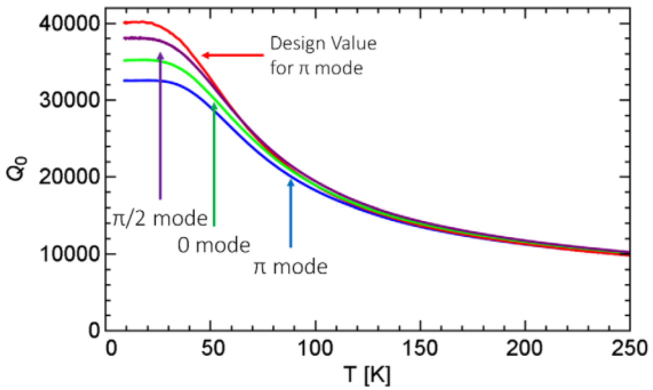
Funding Agencies
U.S. Department of Energy
U.S. National Science Foundation

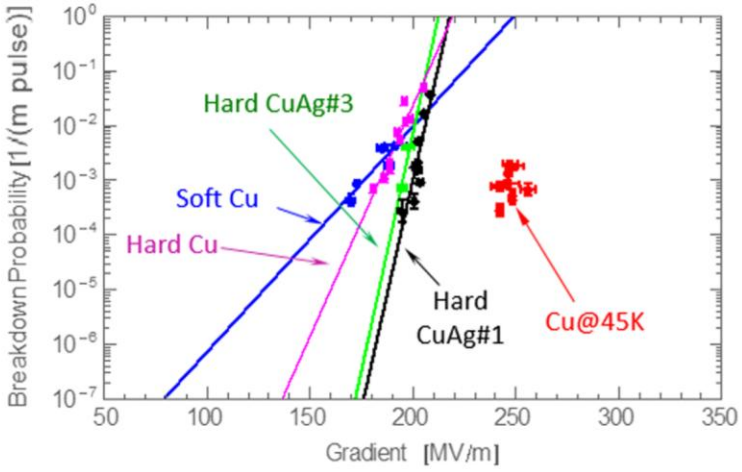
Outline

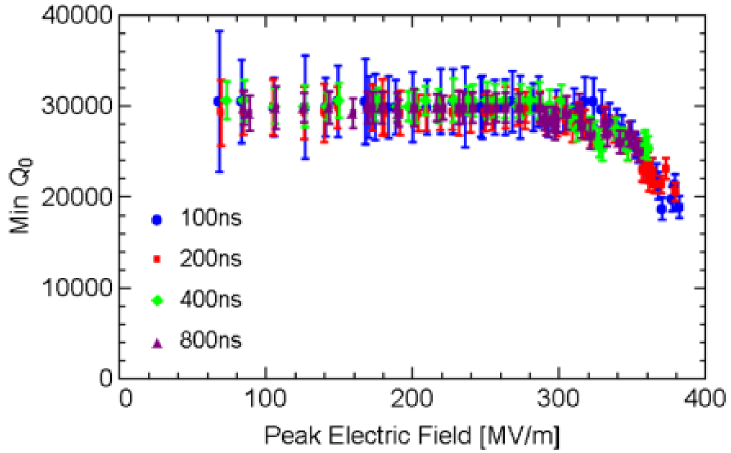
- Introduction
- The CYBORG beamline at UCLA: commissioning, experimental progress, and future upgrades
- Beam dynamics optimizations for UED applications
- Future directions: advanced photocathodes and RF pulse compression

Advantages of cryo-RF guns

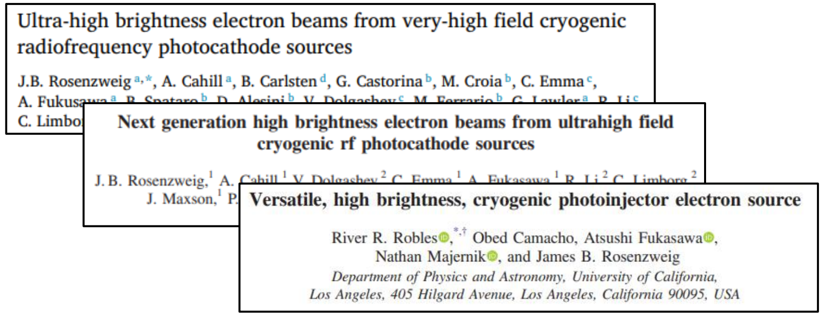
- **Higher conductivity and shunt impedance**
- **Reduced breakdown rate**
- **Lower dark current at high field**







- **Beam dynamics studies at 240 MV/m predict ultra-low emittance beams**
- **Simulations show $\epsilon_n \lesssim 100$ nm at 100 pC**
- **Near-threshold photoemission enables ultra-low MTE operation**



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

J.B. Rosenzweig, A. Cahill, B. Carlsten, G. Castorina, M. Croia, C. Emma, A. Fukusawa, ...

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

J. B. Rosenzweig, A. Cahill, V. Dolgashev, C. Emma, A. Fukasawa, R. Li, C. Limborg, J. Maxson, ...

Versatile, high brightness, cryogenic photoinjector electron source

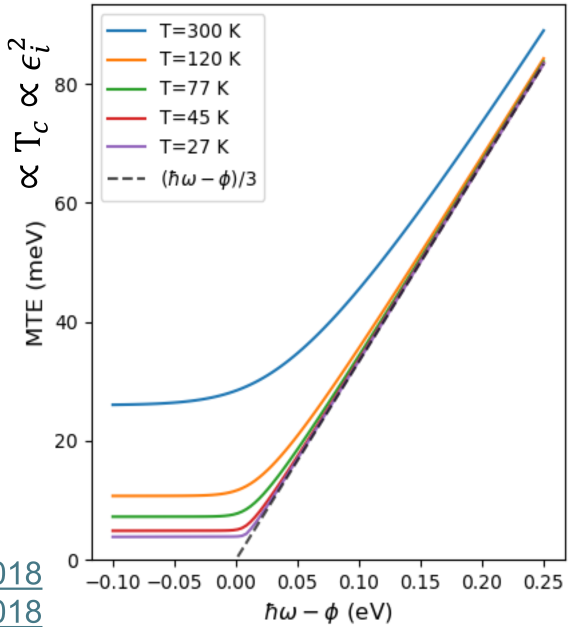
River R. Robles, Obed Camacho, Atsushi Fukasawa, Nathan Majernik, and James B. Rosenzweig

Department of Physics and Astronomy, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, California 90095, USA

$$B_{5D} \propto \frac{(E_0 \sin\varphi_0)^2}{k_B T_c}$$

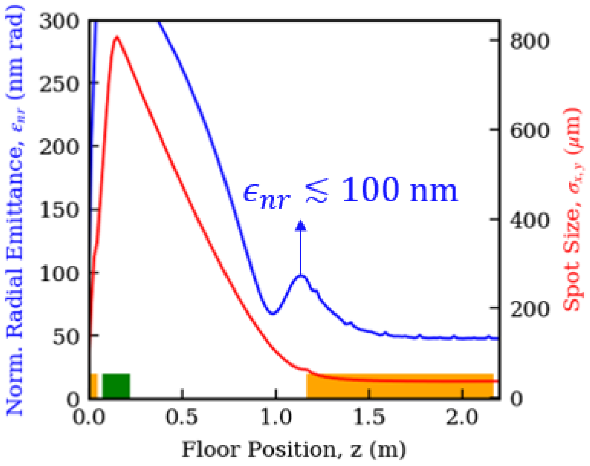
J. Rosenzweig *et al.*, NIM, 2018
J. Rosenzweig *et al.*, PRAB, 2019
R. Robles *et al.*, PRAB, 2021

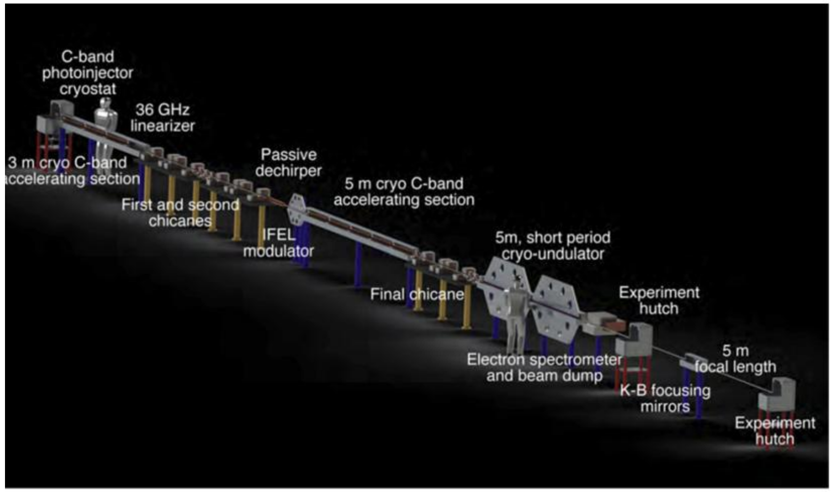
Cahill *et al.*, PRAB, 2018
Cahill *et al.*, PRAB, 2018



Target applications

Ultra-compact X-ray Free Electron Laser (UCXFEL)



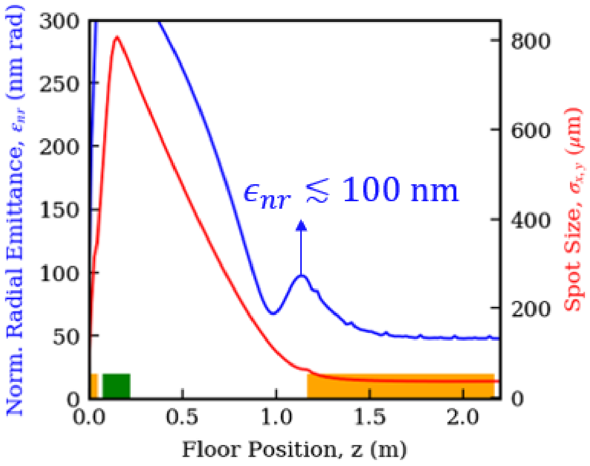


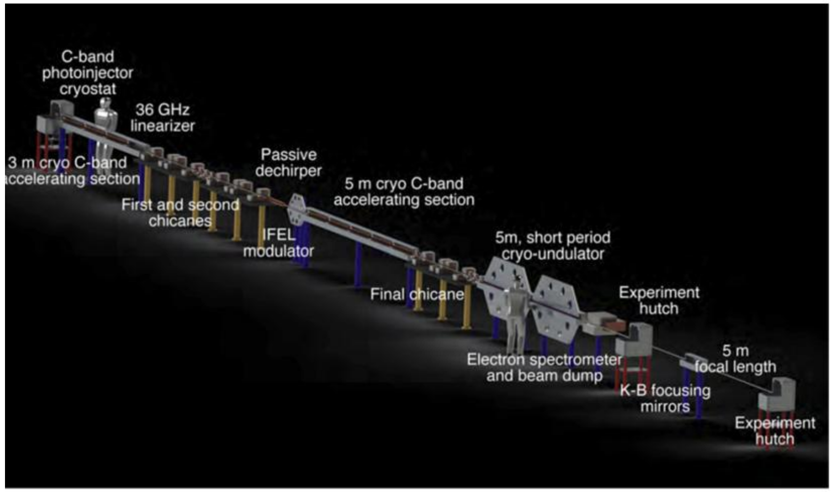
J. Rosenzweig *et al.*, New Journal of Physics, 2020
J. Rosenzweig *et al.*, Instruments, 2024

- **C-band (5.712 GHz), cryogenic operation (77 K)**
- **240 MV/m launch field**
- **Predicted sub-100 nm rms emittance at 100 pC**
- **Matched linac compensation to ~50 nm**

Target applications

Ultra-compact X-ray Free Electron Laser (UCXFEL)

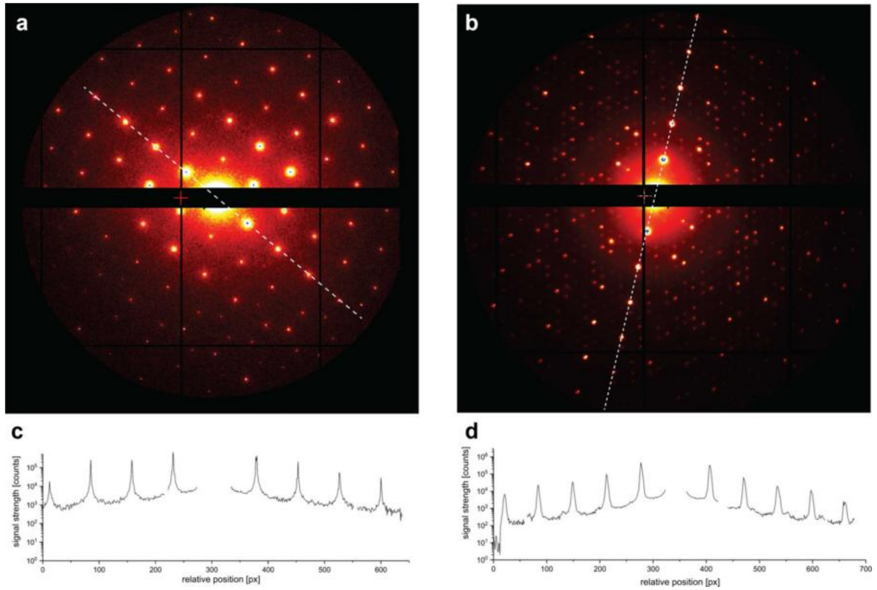




J. Rosenzweig *et al.*, New Journal of Physics, 2020
J. Rosenzweig *et al.*, Instruments, 2024

- **C-band (5.712 GHz), cryogenic operation (77 K)**
- **240 MV/m launch field**
- **Predicted sub-100 nm rms emittance at 100 pC**
- **Matched linac compensation to ~50 nm**

High-brightness source for MeV UED



Hennicke *et al.* Volume 13 | **Part 3** | May 2026 | Pages 282–290 |
10.11107/S2052252526002782

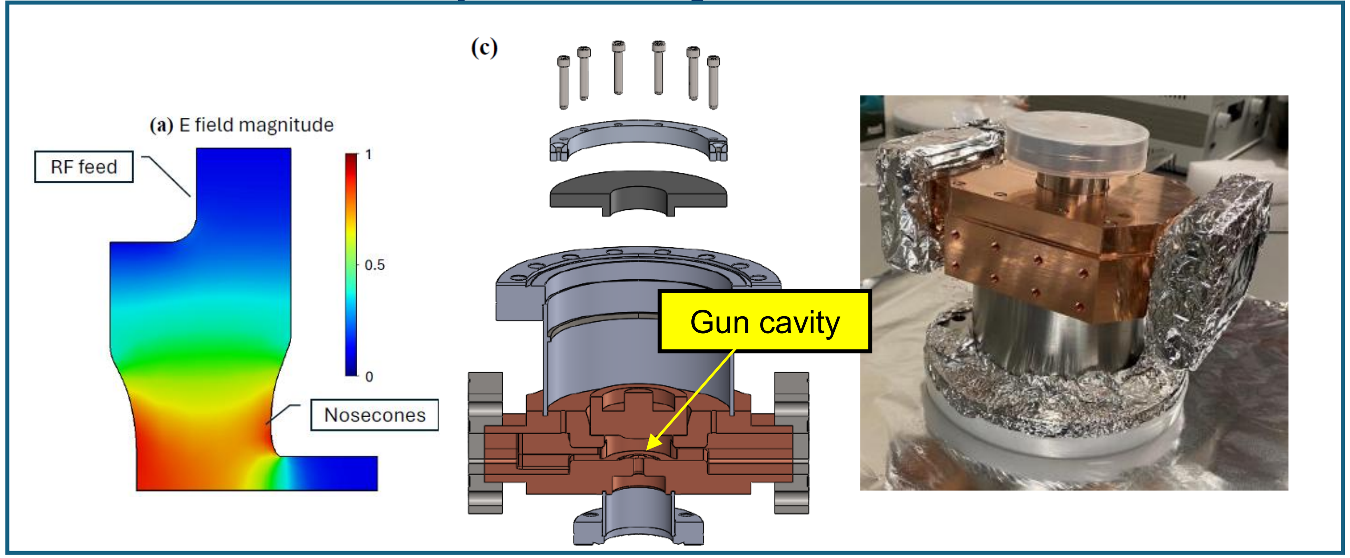
- **Femtosecond temporal resolution**
- **High transverse coherence (brightness)**
- **MeV-scale operation mitigates space charge**

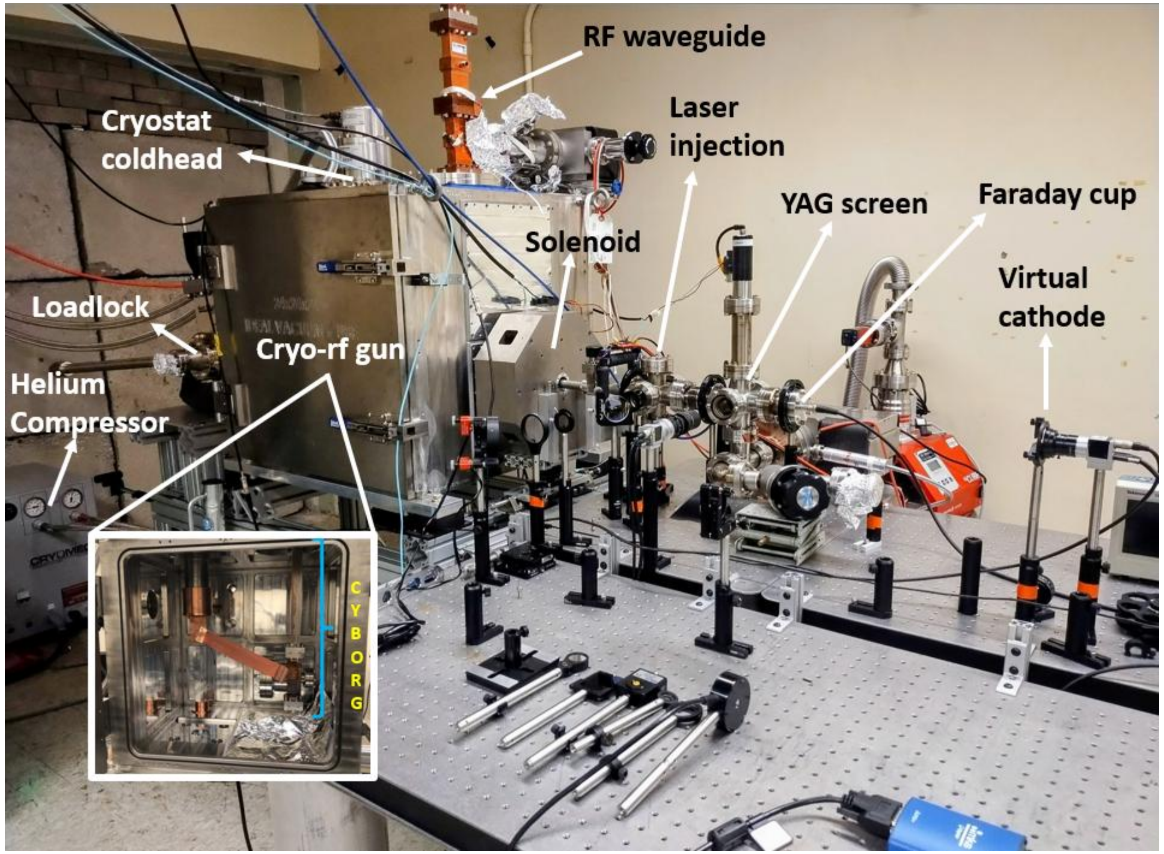
CYBORG: Normal conducting cryo-RF gun

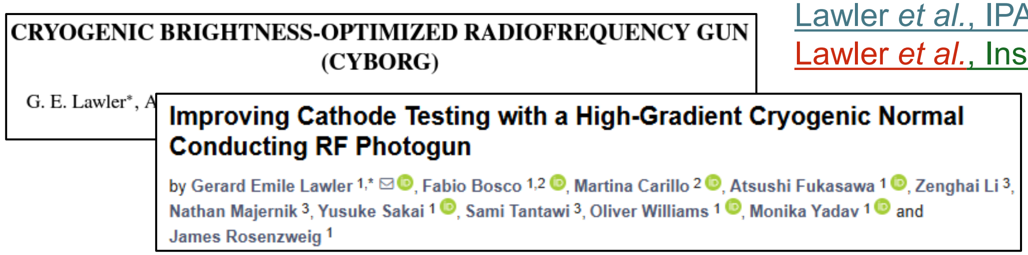
- CYBORG (CrYogenic Brightness-Optimized Rf Gun) beamline at MOTHRA Lab (UCLA)
  - C-band (5.712 GHz) half cell cavity with demountable back plane (upgradable for insertable cathodes)
  - 120 MV/m at ~80 K achievable with ~0.8 MW power
  - Helium compressor cryo-coolers

CYBORG: Normal conducting cryo-RF gun

- CYBORG (CrYogenic Brightness-Optimized Rf Gun) beamline at MOTHRA Lab (UCLA)
  - C-band (5.712 GHz) half cell cavity with demountable back plane (upgradable for insertable cathodes)
  - 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

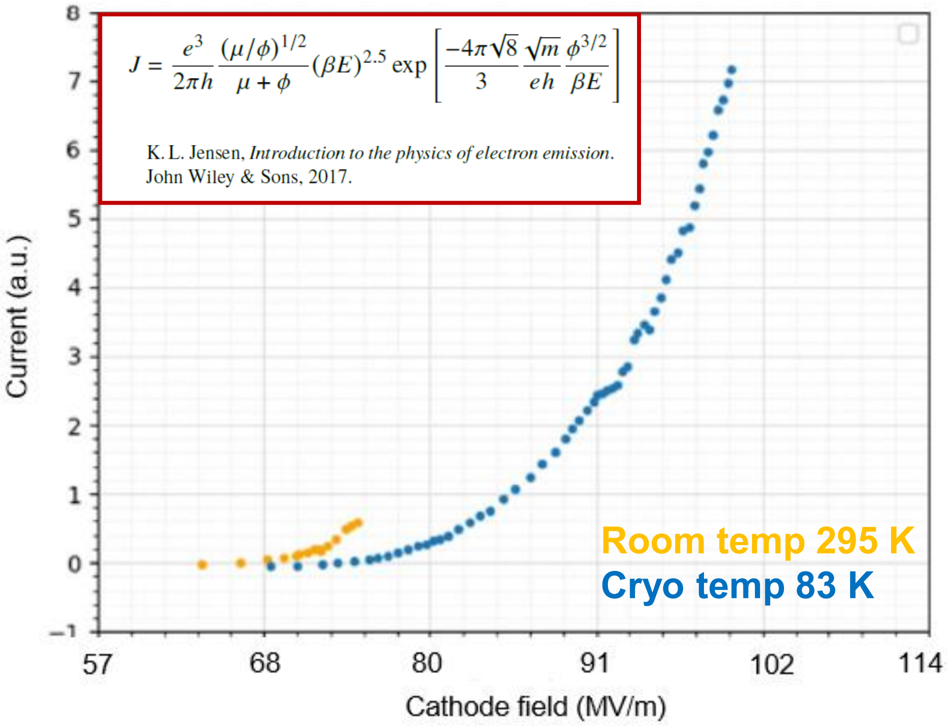
Improving Cathode Testing with a High-Gradient Cryogenic Normal Conducting RF Photogun

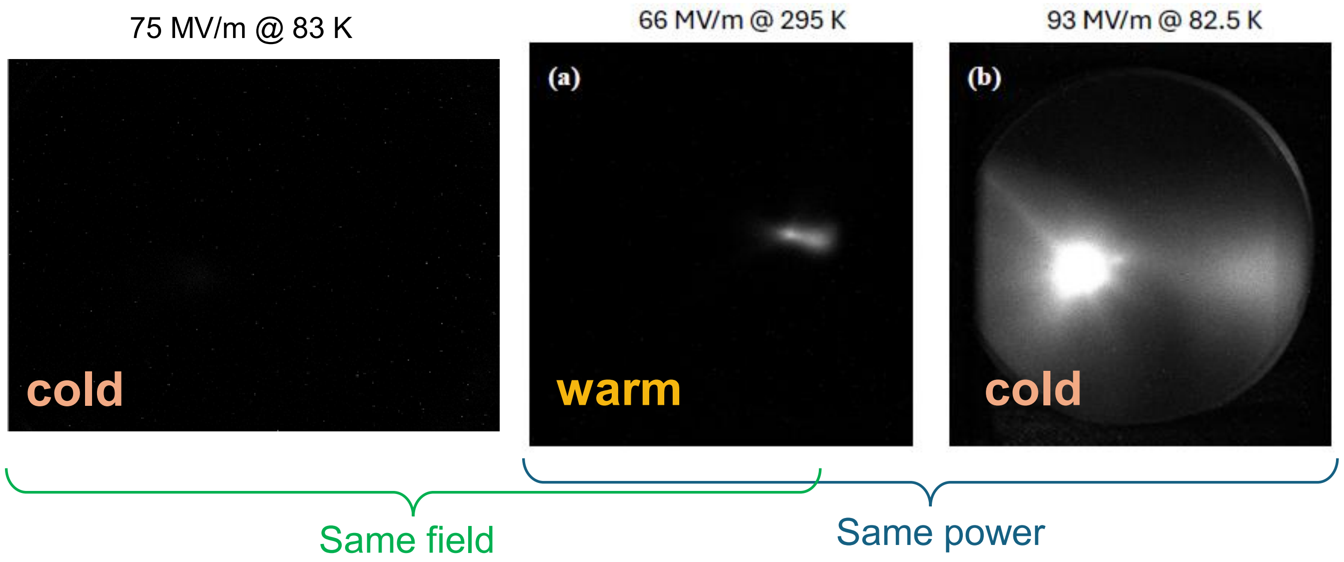
by Gerard Emile Lawler [1,*], Fabio Bosco [1,2], Martina Carillo [2], Atsushi Fukasawa [1], Zenghai Li [3], Nathan Majernik [3], Yusuke Sakai [1], Sami Tantawi [3], Oliver Williams [1], Monika Yadav [1] and James Rosenzweig [1]

Lawler *et al.*, IPAC 22, 2022

Lawler *et al.*, Instruments, 2024

Dark current studies and first photoelectrons



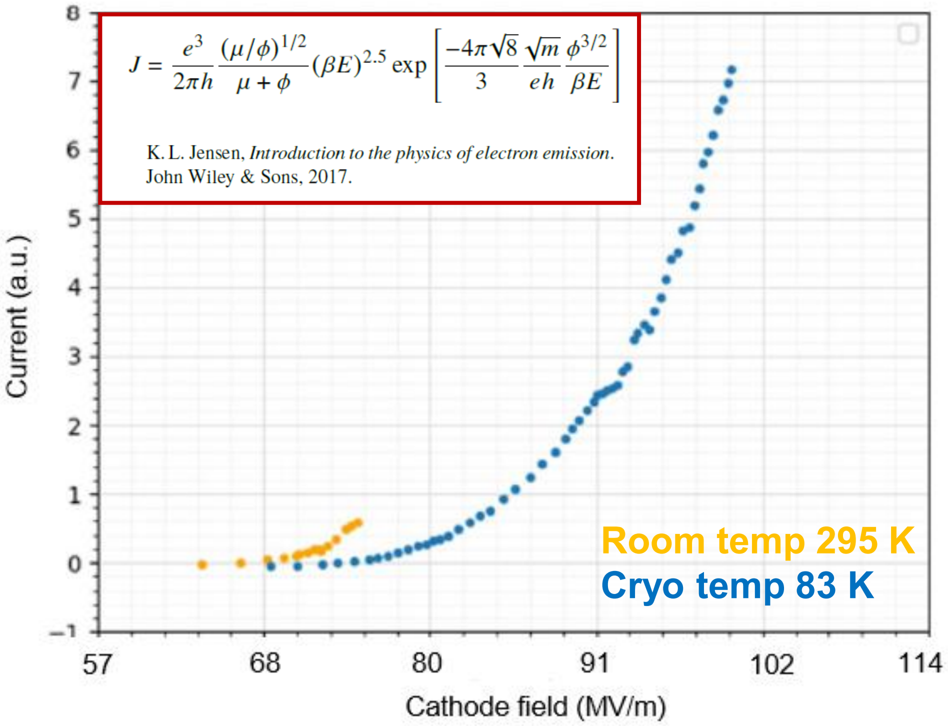


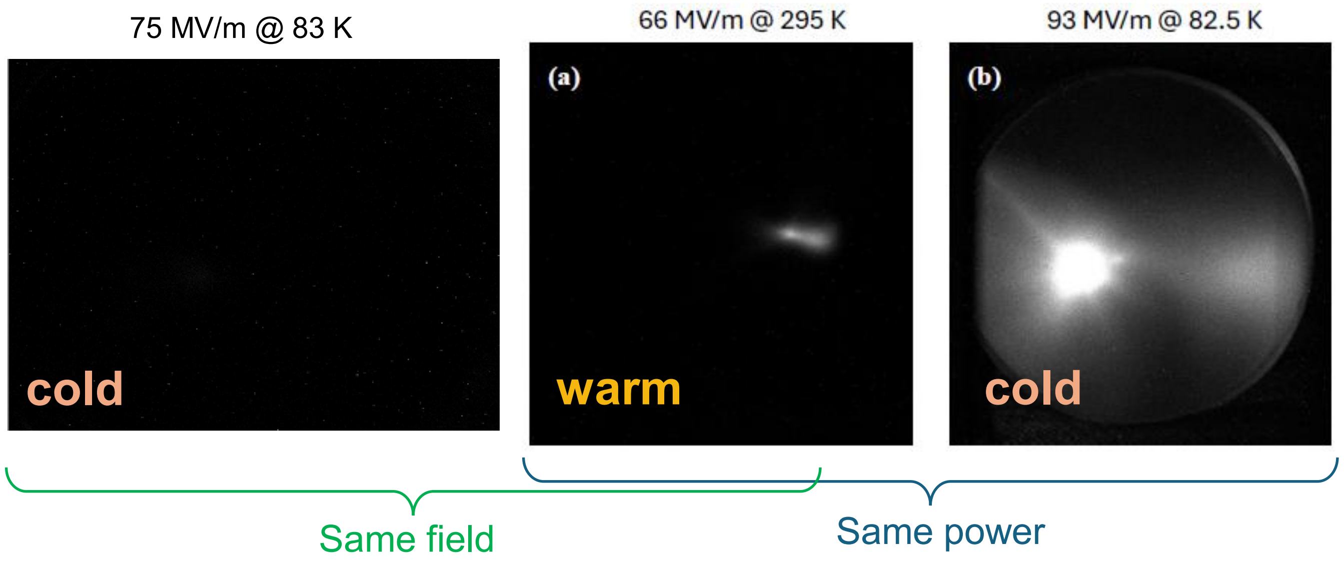
- **Maximum input power ~0.5 MW* (~75 MV/m at room temp, ~95 MV/m at 83 K)**
- **Reduction of dark current at cold temperature**

(*) Before klystron optimization

G. Lawler *et al.*, IPAC 24, 2024
G. Lawler *et al.*, IPAC 24, 2024

Dark current studies and first photoelectrons



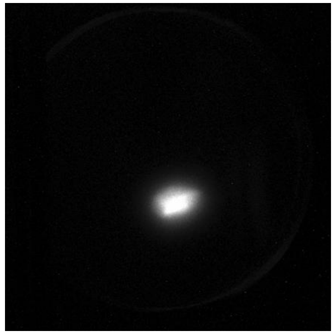


- **Maximum input power ~0.5 MW* (~75 MV/m at room temp, ~95 MV/m at 83 K)**
- **Reduction of dark current at cold temperature**

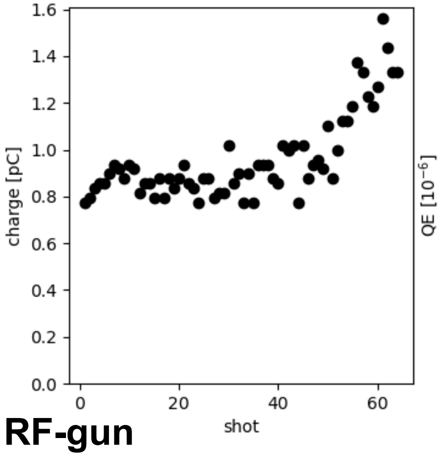
(*) Before klystron optimization

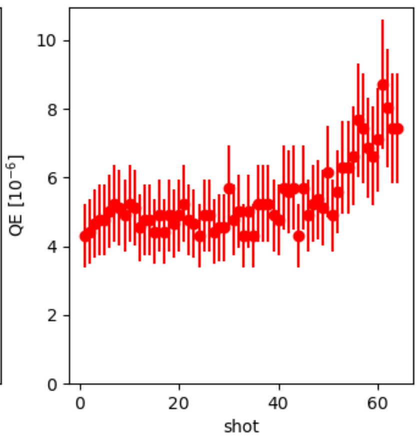
G. Lawler *et al.*, IPAC 24, 2024
G. Lawler *et al.*, IPAC 24, 2024

First photoelectrons:



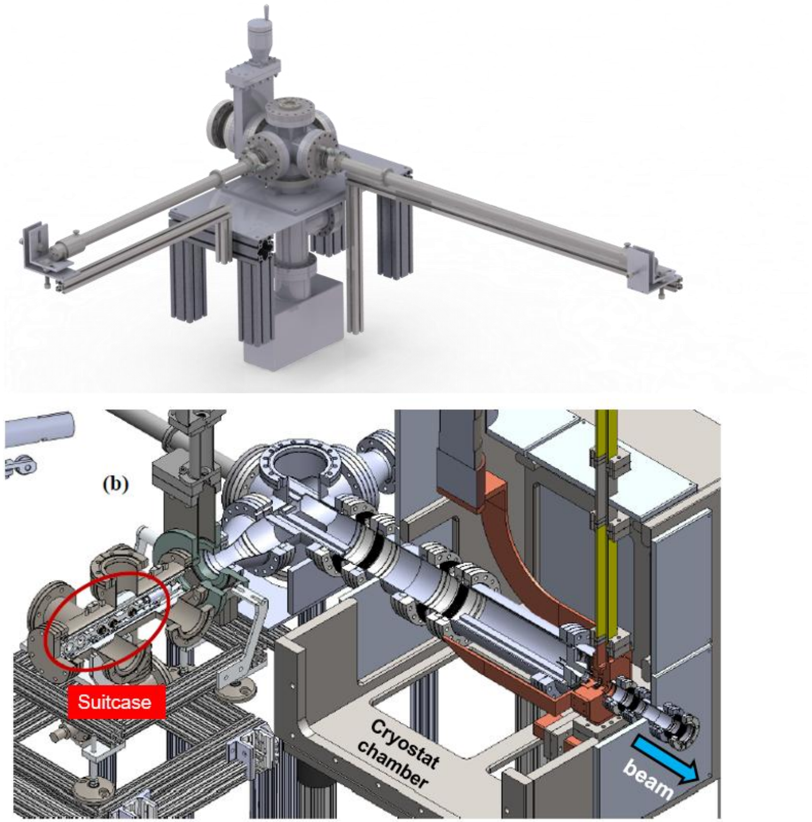
e-beam from cryogenic RF-gun (90 K, ~105 MV/m)





Load-lock integration for advanced cathode testing

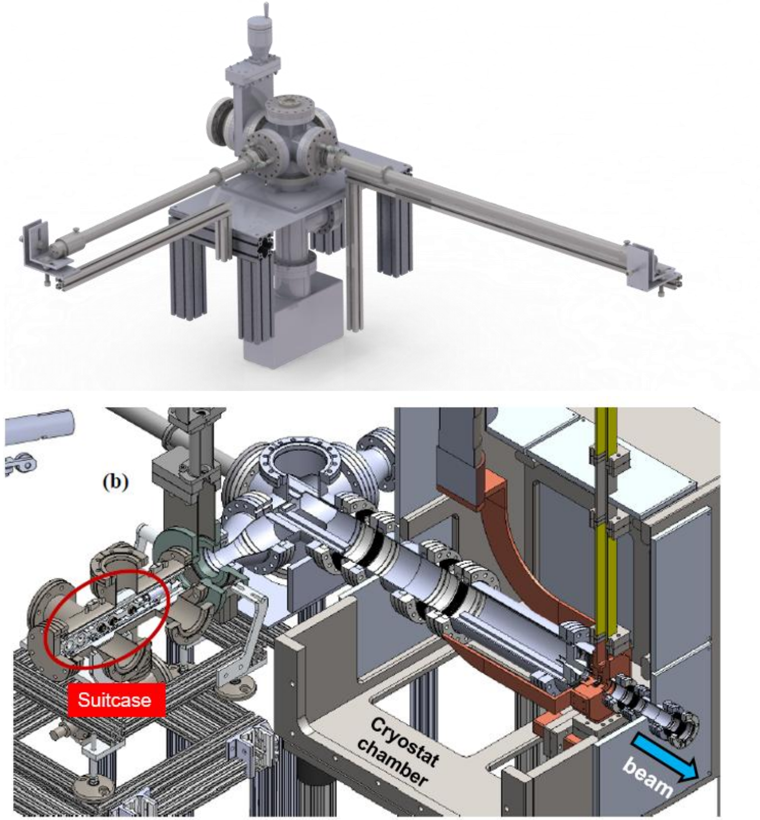
- **Load-lock at MOTHRA will enable testing of advanced cathodes (high field, low temperature environment)**
- **INFN cathode plug modified for C-band compatible geometry**



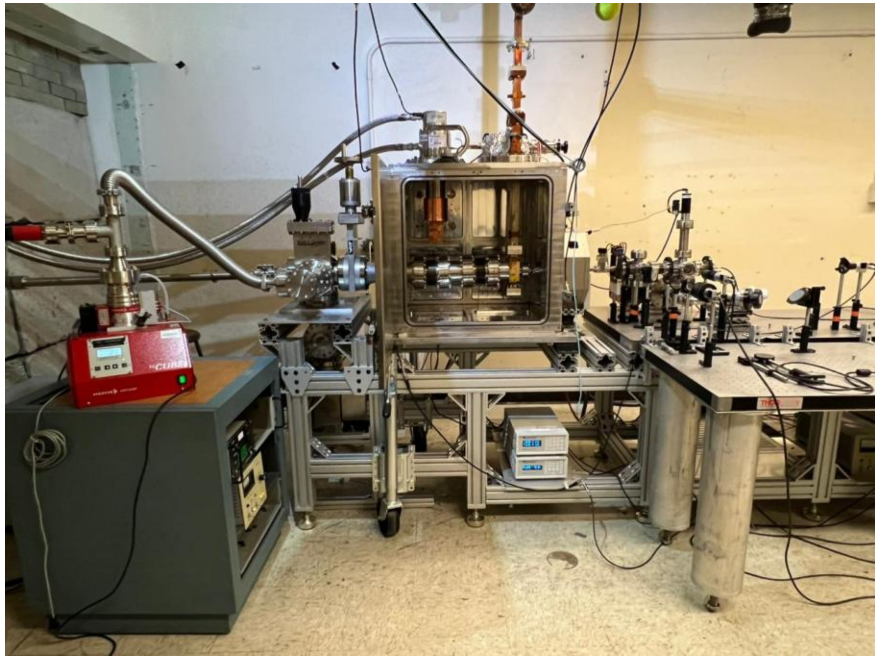
Load lock CAD model and integration with cryostat

Load-lock integration for advanced cathode testing

- **Load-lock at MOTHRA will enable testing of advanced cathodes (high field, low temperature environment)**
- **INFN cathode plug modified for C-band compatible geometry**



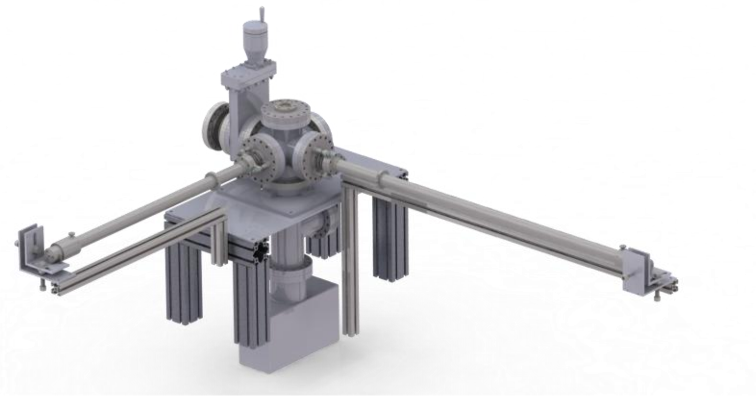
Load lock CAD model and integration with cryostat

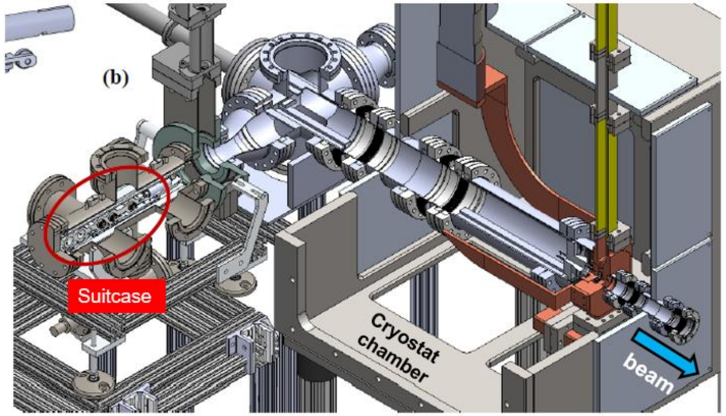


Assembled load lock behind cryostat

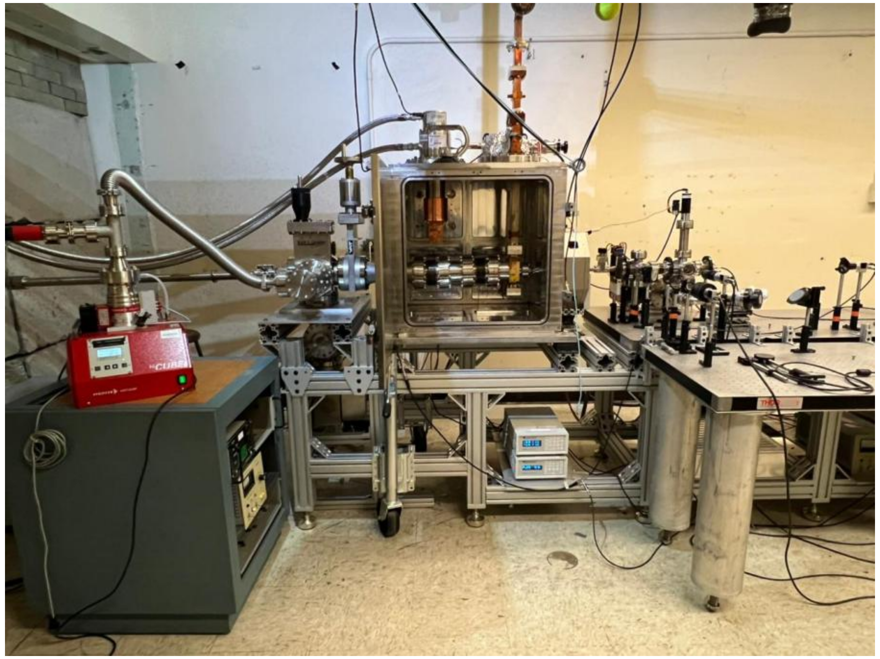
Load-lock integration for advanced cathode testing

- **Load-lock at MOTHRA will enable testing of advanced cathodes (high field, low temperature environment)**
- **INFN cathode plug modified for C-band compatible geometry**

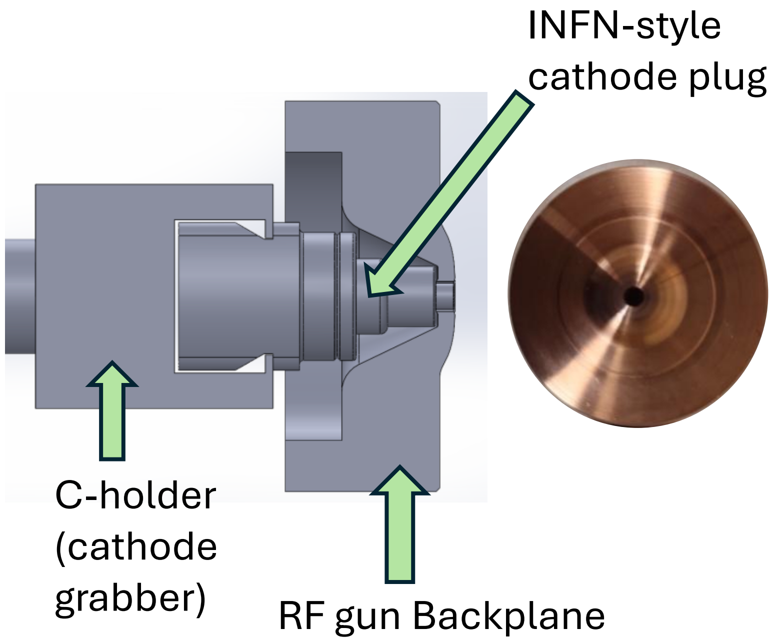




Load lock CAD model and integration with cryostat

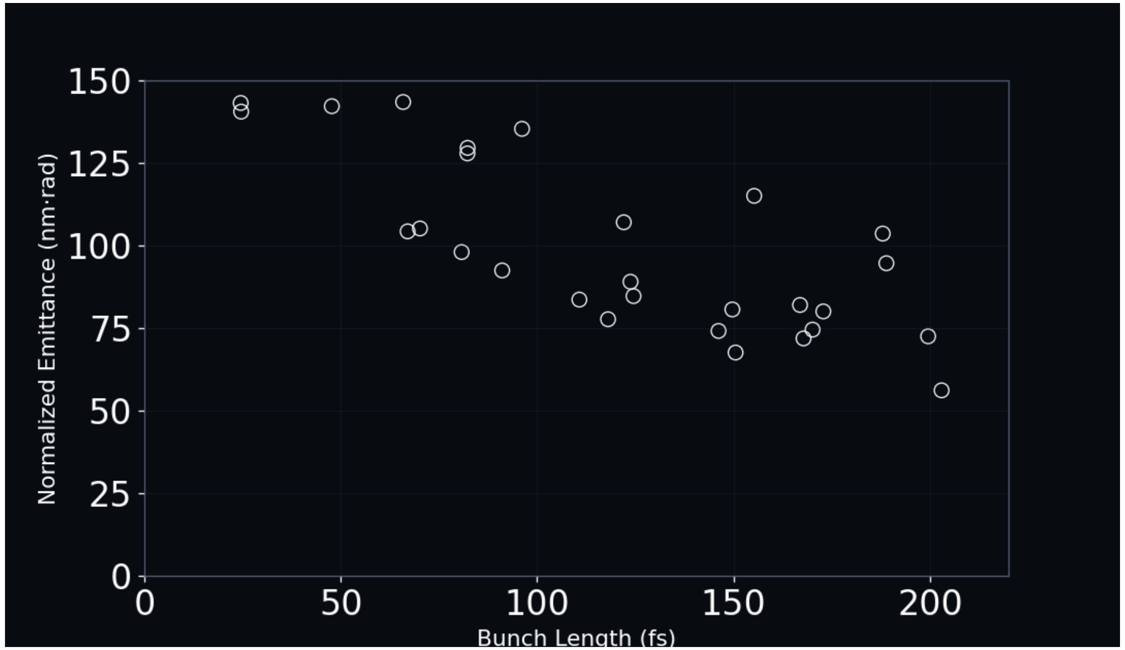


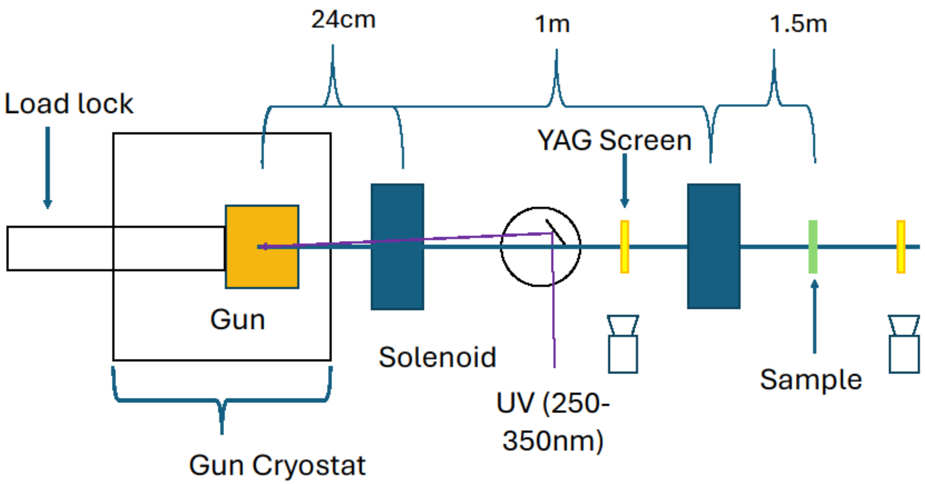
Assembled load lock behind cryostat



Target cathodes:
- **Near-threshold semiconductors (Cs_xTe)**
- **Nanostructured / small-area emitters for ultrahigh brightness**

Beam dynamics optimizations for UED operation





Simulation Constants

- **Charge: 16 fC**
- **Peak field: 180 MV/m**
- **Sample distance: 1.5 m**
- **Cathode spot size: (a) 40 μm (b) 1.2 μm**

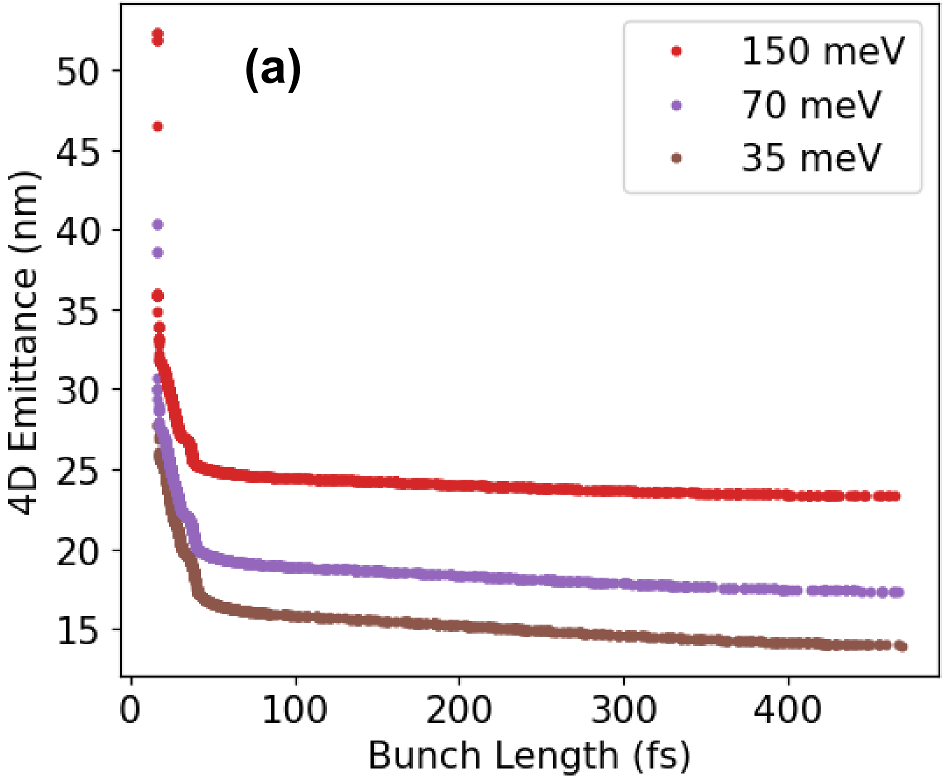
Optimization Variables

- **Gun phase offset: [−10°,10°]**
- **Solenoid position: [0.24,0.6] m**
- **Solenoid strength: [0,3] A**
- **Initial bunch length: [50,300] fs**

- **Multi-objective genetic optimization to identify operating points.**
- **Objective: minimize bunch length and 4D emittance.**

Optimization results for UED operation

Laser spot size at cathode (a) 40 μm

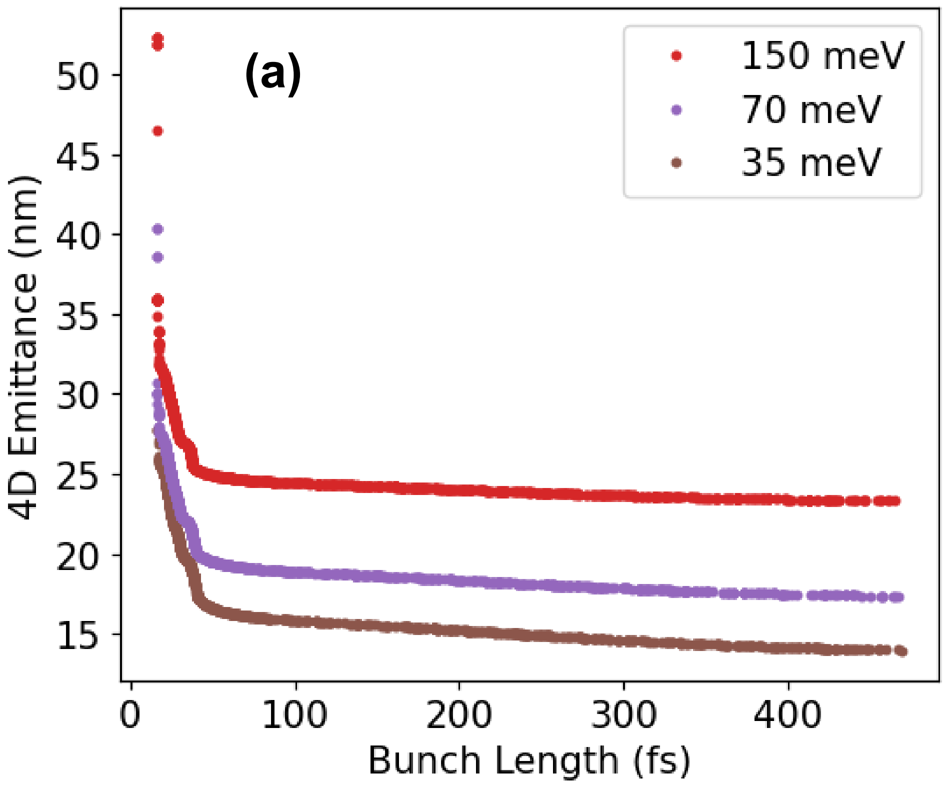


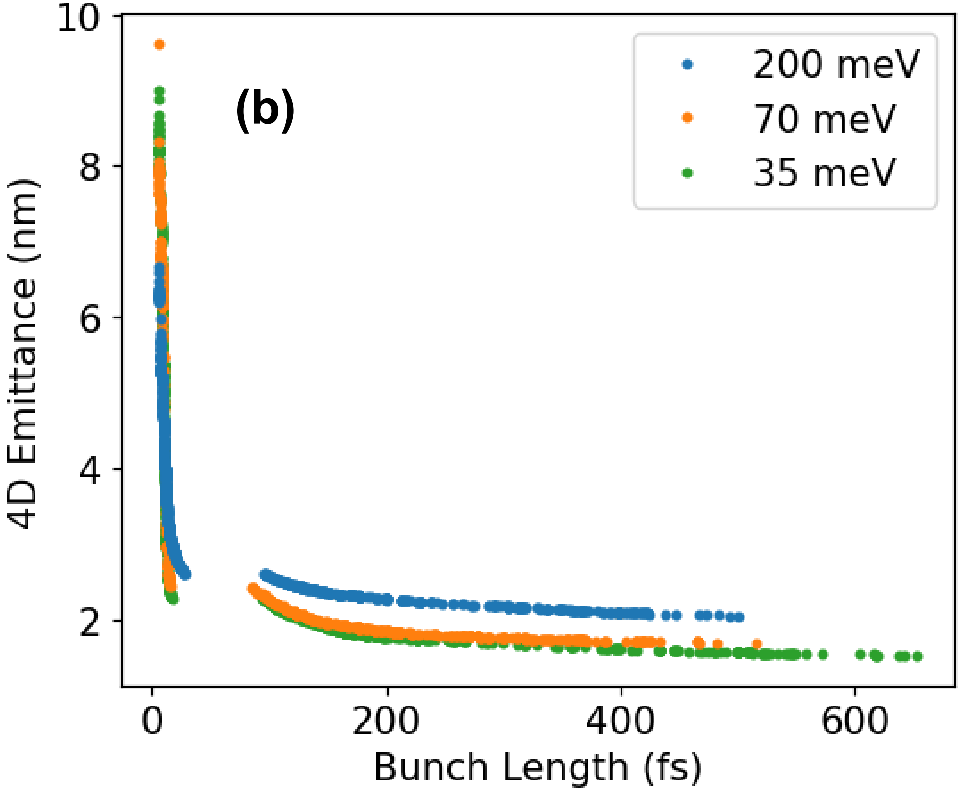
- $E_b \approx 2$ MeV
- E_0 = 180 MV/m
- Q = 16 fC

Short bunch lengths achieved without a dedicated bunching cavity

Optimization results for UED operation

Laser spot size at cathode (a) 40 μm (b) 1.2 μm



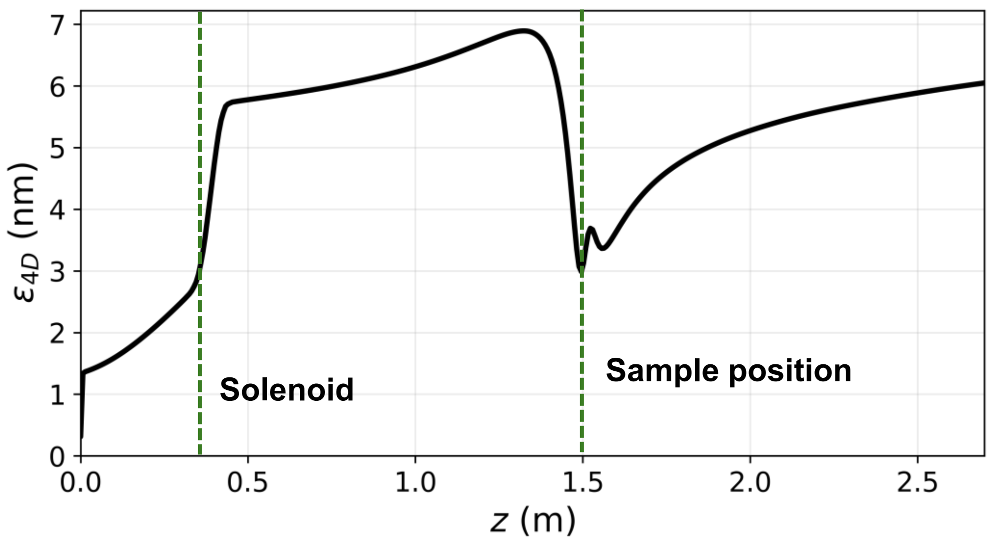


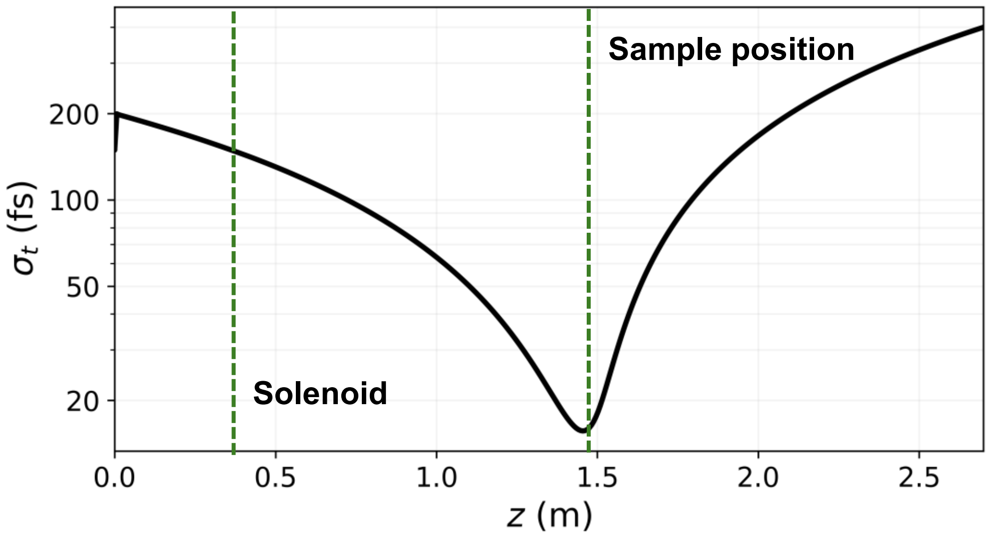
- Eb ≈ 2 MeV
- E_0 = 180 MV/m
- Q = 16 fC

Small-area emission enhances attainable brightness frontier for MeV UED

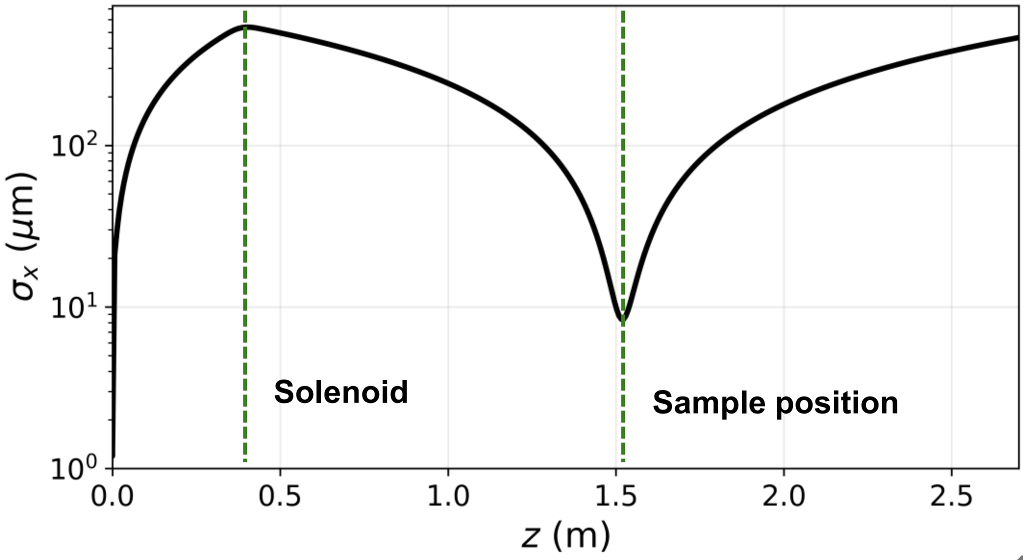
Short bunch lengths achieved without a dedicated bunching cavity

Beam evolution for an optimized solution





- **35 meV MTE, 1.2 µm emission area, 100 fs initial pulse**
- **Compression and emittance preservation compete during transport**
- **Optimized solutions are highly promising for MeV UED**



Summary and Next Steps

- Initial commissioning and beam tests of the compact cryogenic C-band photoinjector platform (CYBORG)
- Reduced dark current observed during cryogenic operation
- Beam dynamics optimizations predict promising MeV UED operating regimes
- Load-lock integration to enable advanced cathode testing

Thank you for listening!

Questions?