Update from UCLA C^3-related research program

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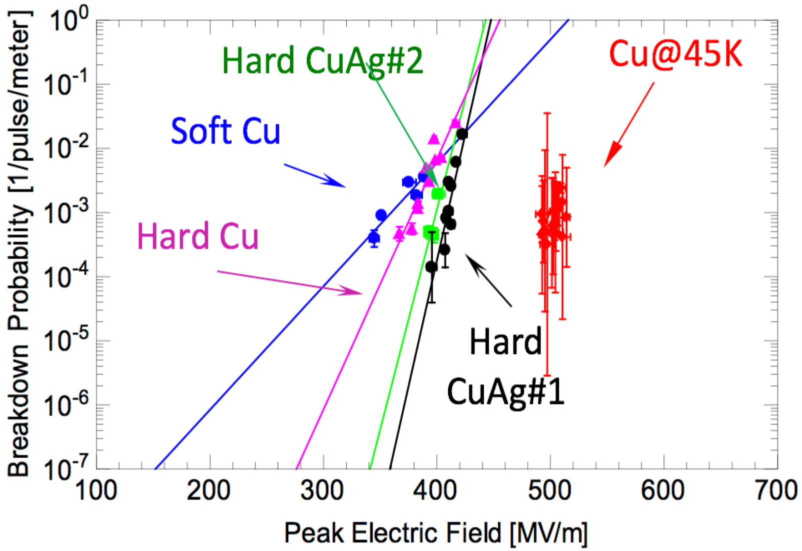
Cold Copper Collider Meeting

SLAC – February 12, 2024

UCLA origin story in cryo-RF research

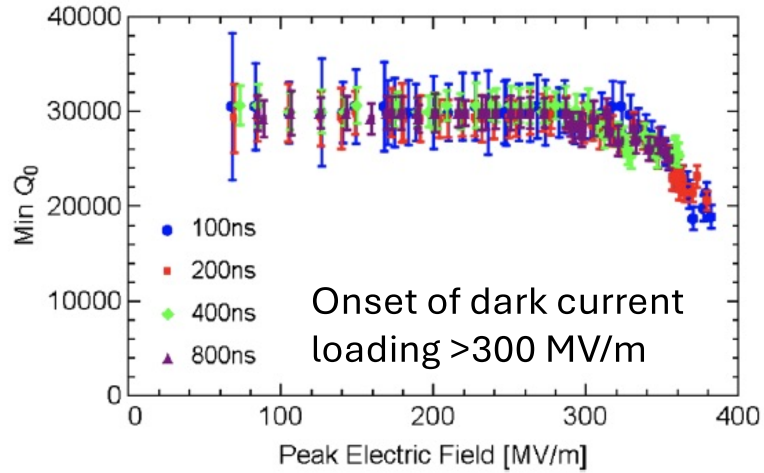
- Discovery research in SLAC-UCLA collaboration on cryogenic RF cavity in X-band
  - **Cryo-conditions lower heating, thermal expansion small, enhanced heat transport & *strength***
- 200 MV/m surface fields **-> 500 MV/m.** ~300 MV/m limit from dark current
- Transformative applications in **linear collider and XFEL**



A. D. Cahill, et al., *Phys. Rev. Accel. Beams* 21, 102002 (2018)

$B_{6D} \propto \boldsymbol{E_0^{2.5}}$

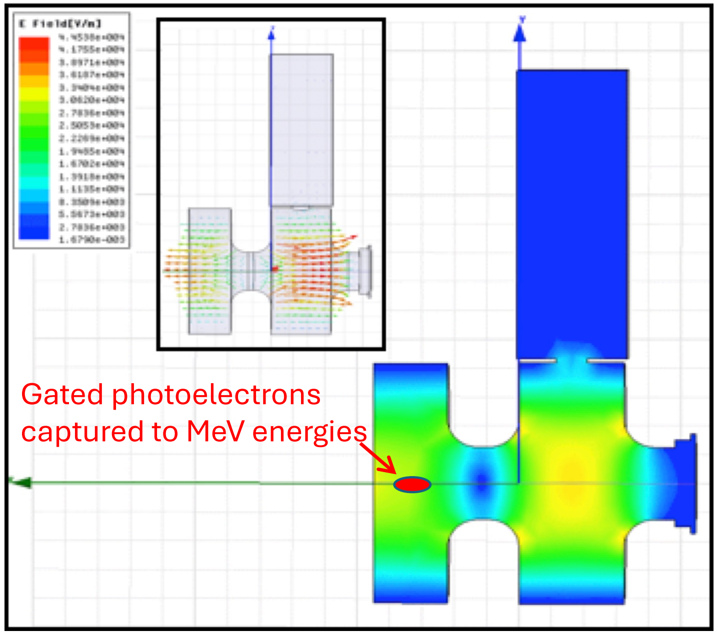
- order of magnitude Increase in brightness in *cryogenic photoinjector*



A. D. Cahill, et al., *Phys. Rev. Accel. Beams* 21, 061301 (2018)

High brightness electron beam source for FEL and LC: *the RF photoinjector*

- Laser gating to fs-to-ps level
- Capture with RF – violent acceleration
  - **Fields 10x DC sources (>100 MV/m)**
- Preserve phase space structure
  - High fields are critical for space-charge control (emittance, pulse length)
- Frontier RF engineering
  - Now more than ever!
- Photocathode physics
  - CBB research to lower MTE



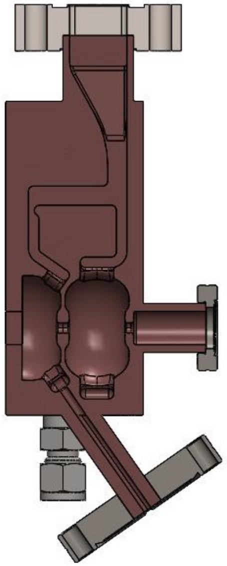
Traditional UCLA-designed RF photoinjector operated at ~100 MV/m

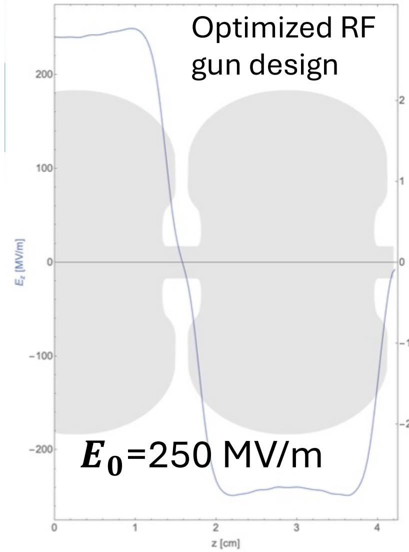
UCLA helped pioneer this transformative device, applied to: FELs, wakefield accelerators, electron diffraction, etc.

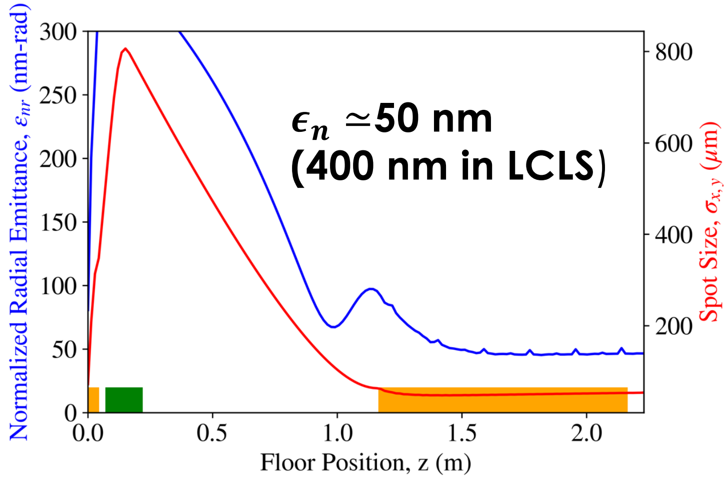
Scaling of brightness at emission

- *5D Brightness* at cathode: $B_e = \frac{2I}{\varepsilon_n^2} = \frac{2J_{\max} m_e c^2}{k_B T_c}$
- *In 1D limit*, peak current from a pulsed photocathode is
$$J_{z,b} \approx \frac{ec\varepsilon_0}{m_e c^2}\left(E_0 \sin\varphi_0\right)^2$$
- 5D Brightness is
$$B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c}\left(E_0 \sin\varphi_0\right)^2$$
$B_{6D} \sim E^{2.5}$
    - Lower emission temperature T_c and/or…
- **High launch field needed**
    - **Cryo-RF ideal solution**

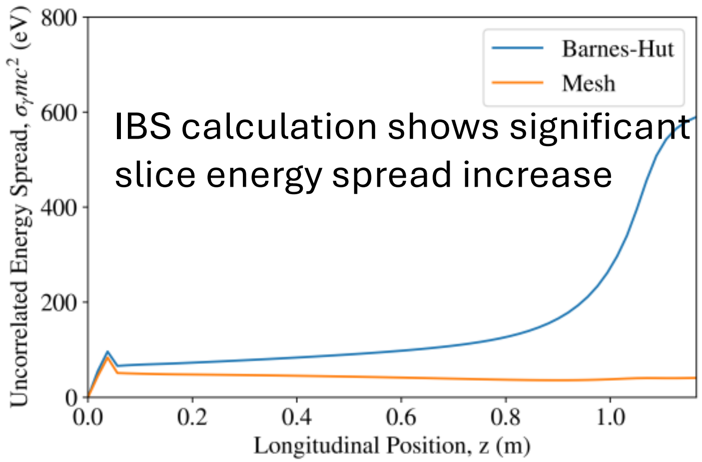
Transformative electron source from high field C-band cryogenic RF cavities







R. Robles, *et al. Phys. Rev. Accel. Beams* 24, 063401(2021)



Immediate application also in UED, HEP

Design also implemented in LANL room temp photoinjector (Simakov)

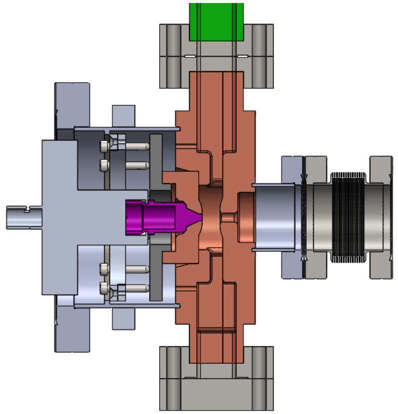
Record 6D brightness predicted

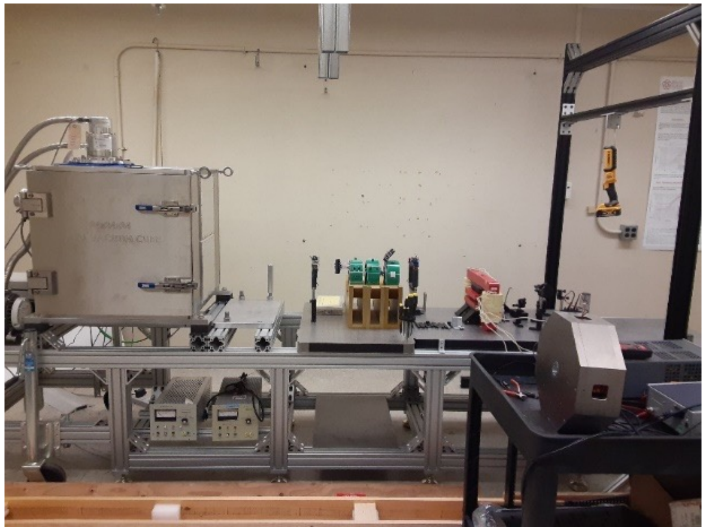
New effects: IBS, disorder induce heating

Further improvements from cryo-emission

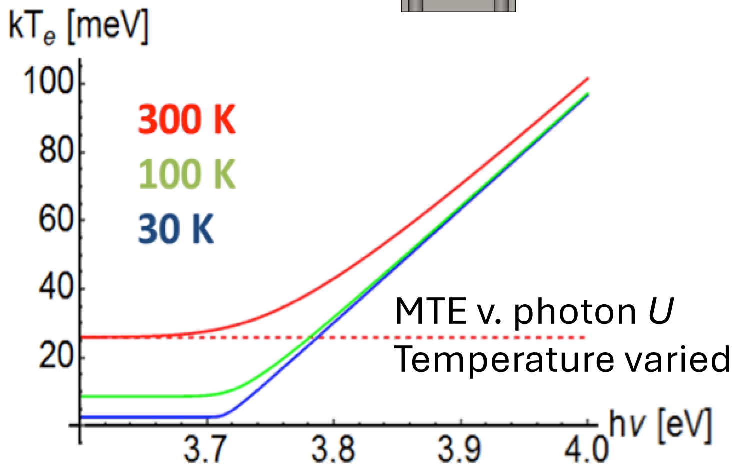
- Cryogenic emission promises much lower MTE (thermal emittance)
- First tests in 0.5 cell C-band cryo-gun at UCLA Commissioning now
- Operation just above threshold
  - Tradeoff with QE

O.5 cryo-gun
with load lock





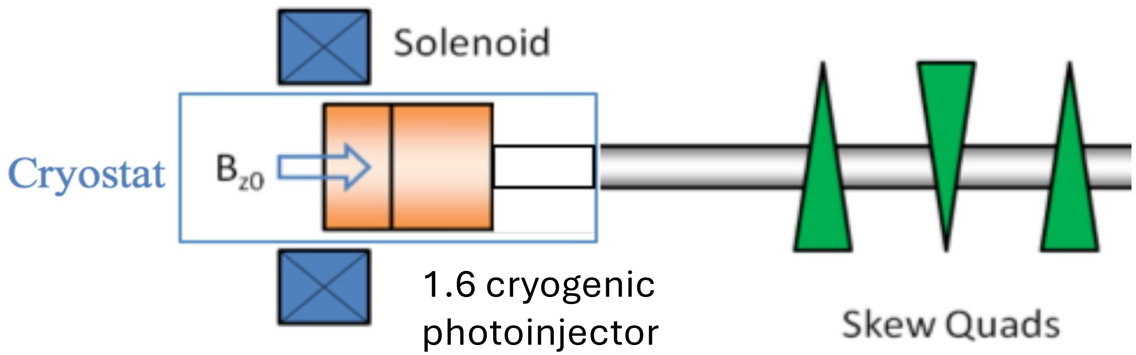
Cryostat, CYBORG beamline components
at UCLA MOTHRA

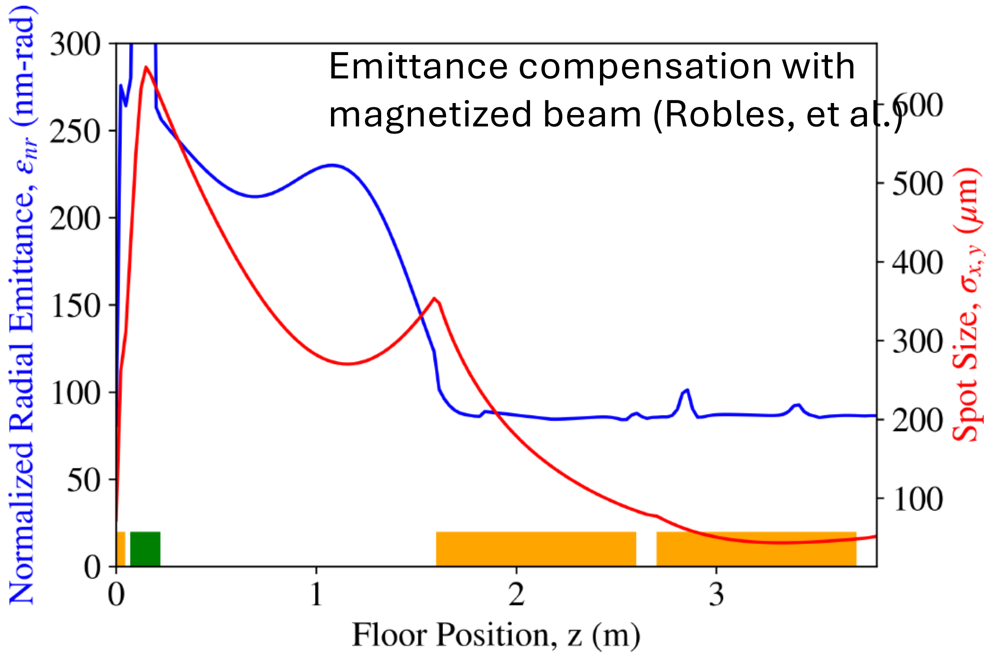


MTE v. photon *U*
Temperature varied

Asymmetric emittance beams for linear colliders

- Eliminate electron damping ring
- Round-to-flat beam transformation
- Very small 4D transverse emittance needed
  - Consistent with *magnetized photocathode* and very high gradient

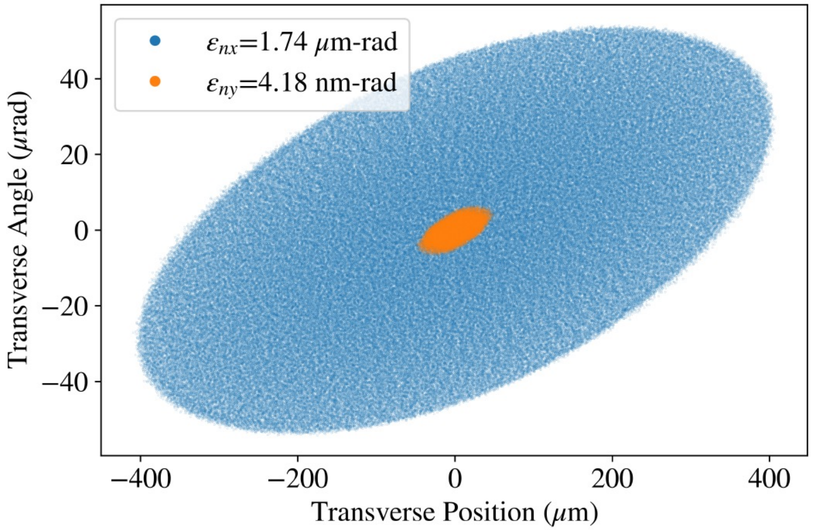


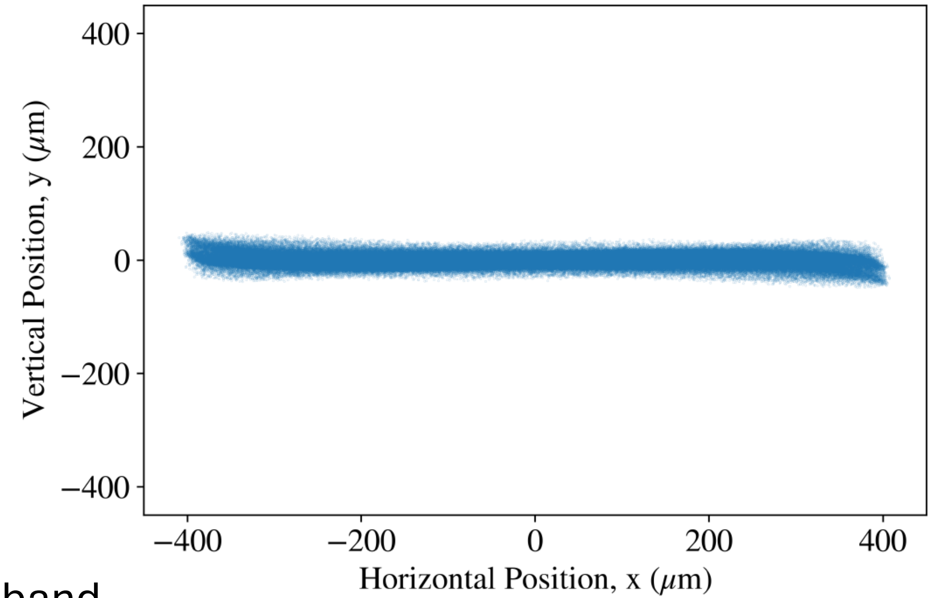


Angular momentum $\mathcal{L} = (eB_0/2m_e c)\sigma_0^2$

Performance of round-to-flat beam transformation

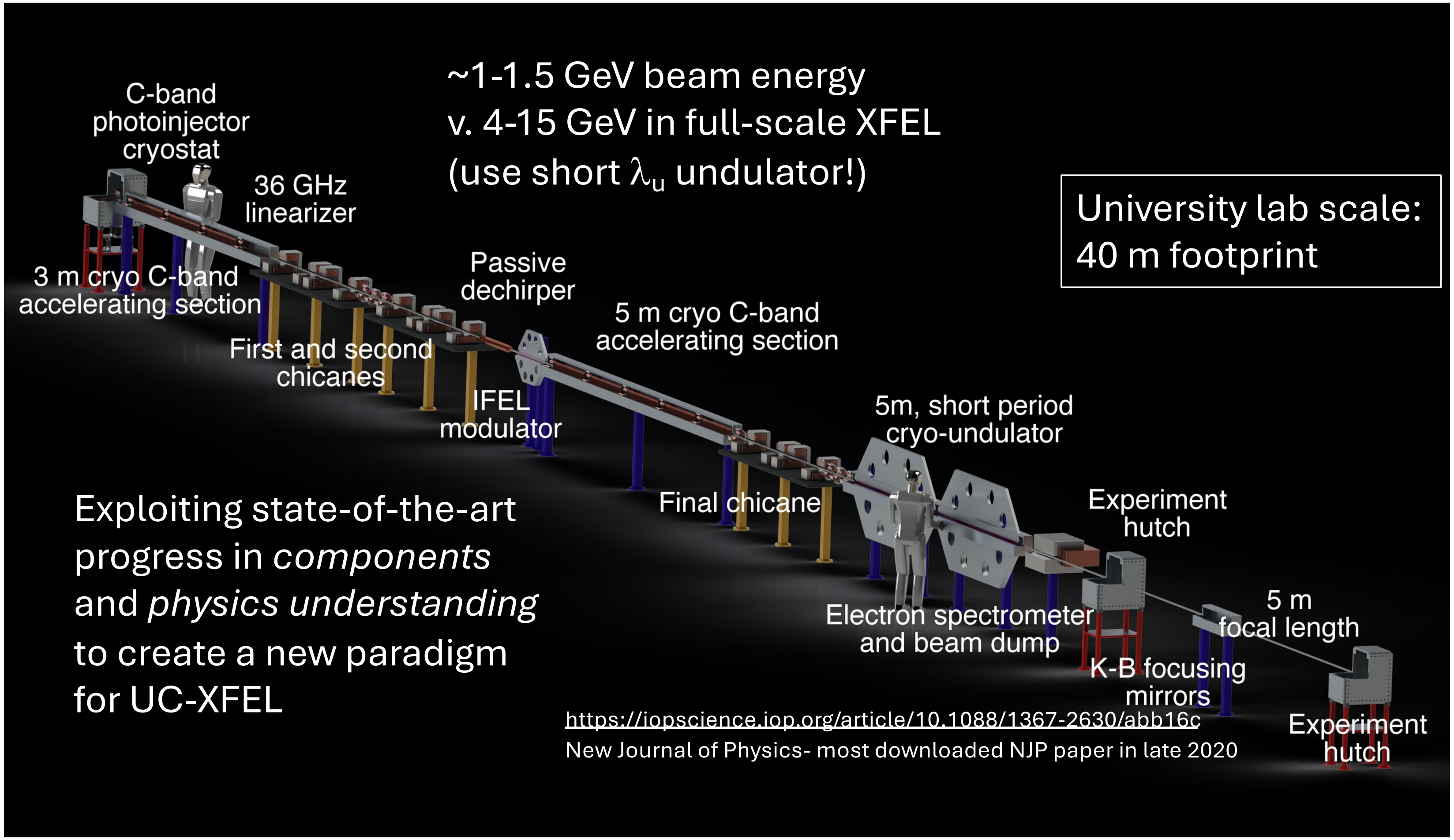
- Emittance 90 nm-rad before splitting (increase of 75% over XFEL case)
- Splitting nearly ideal in simulation, including space-charge effects
- Very high brightness test beams for BBU studies, P-O-P on emittances





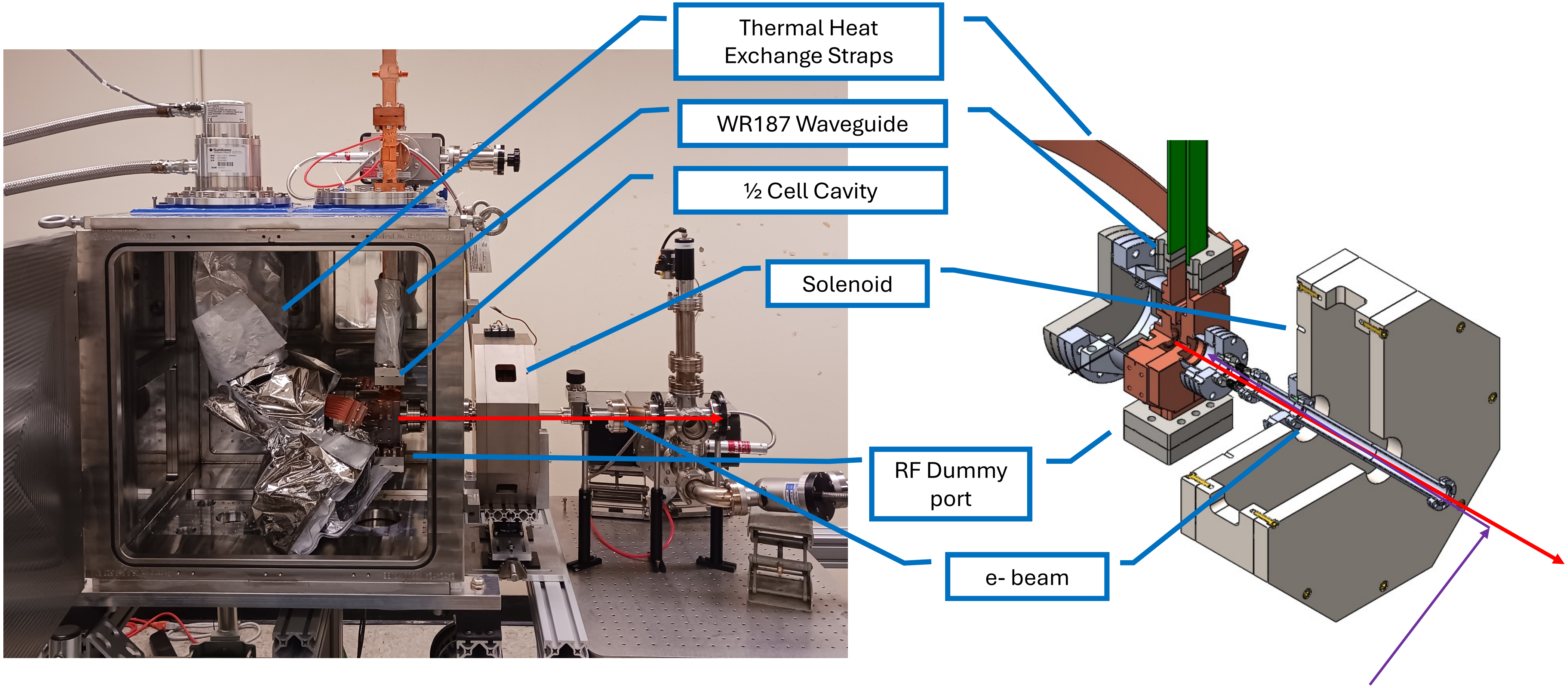
C-band implies low charge (0.25 nC). Higher *Q* -> S-band

First use of cryo-RF gun and linacs: university-scale UC-XFEL



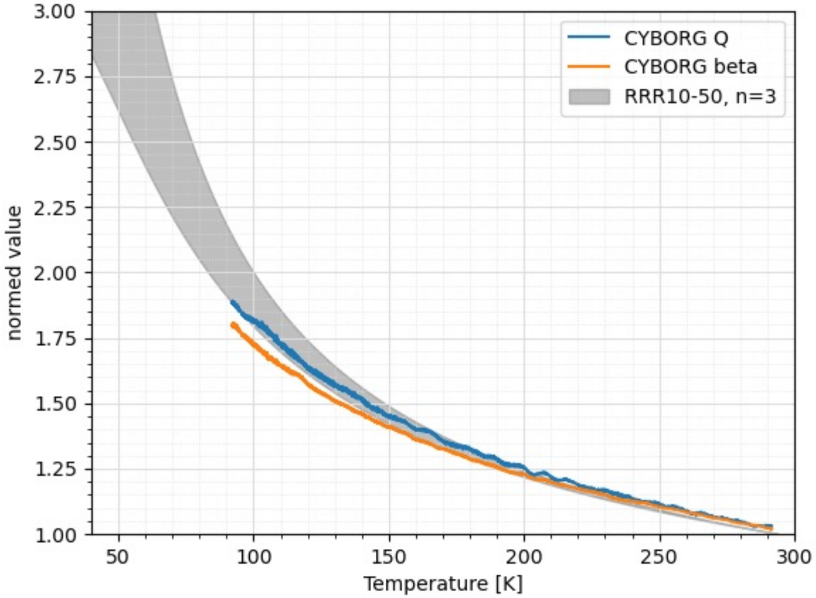
More below.

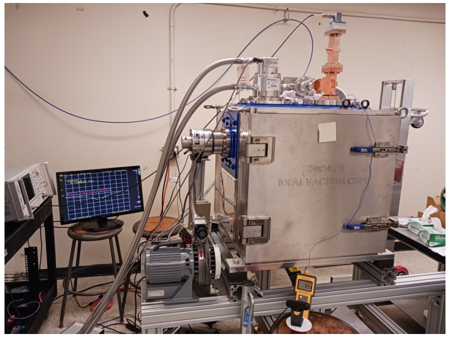
“CYBORG” Status (Lawler)



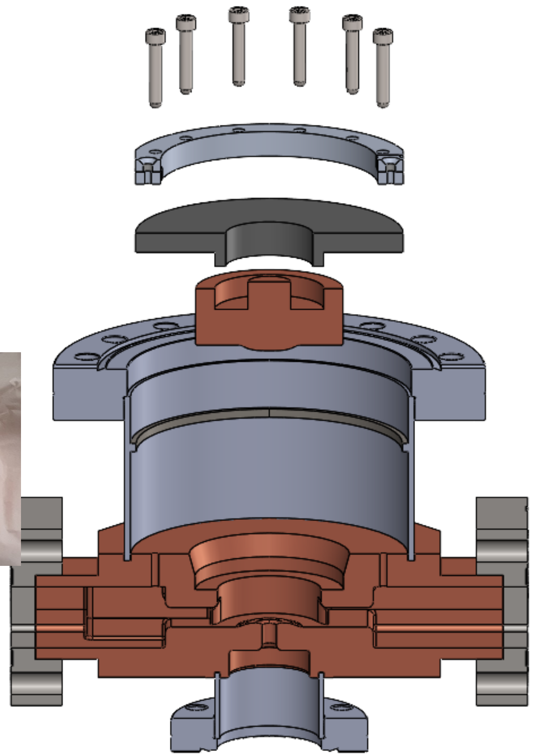
CYBORG Low Power RF

- Q increase verified in situ



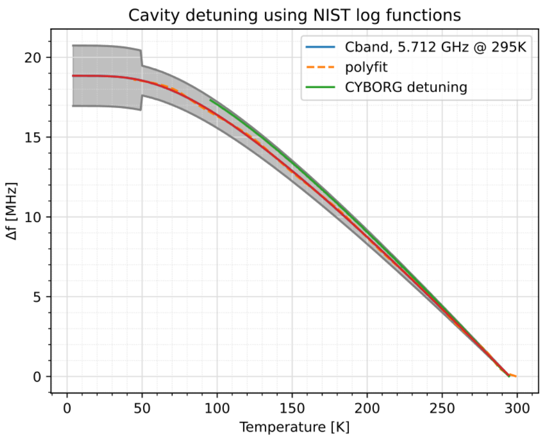


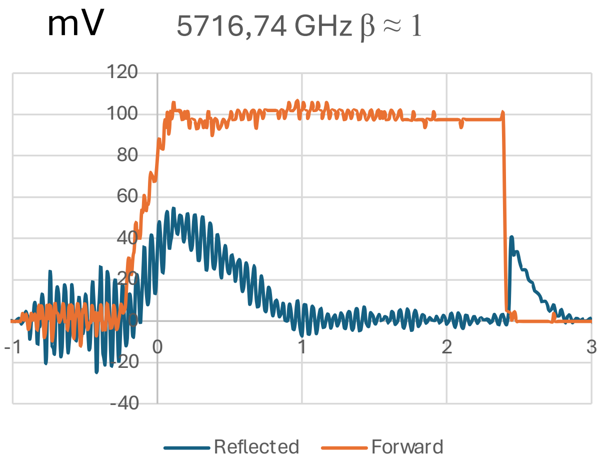
20 mm

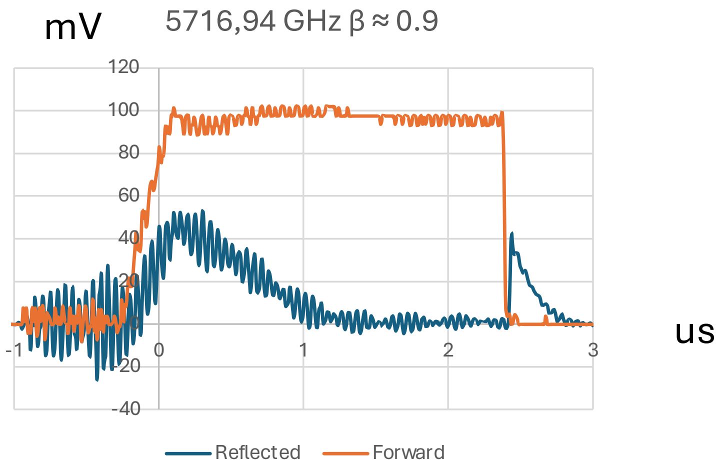


Cold Gun High Power RF Testing

- First filling of gun cavity at intermediate temperature during cool down to 150 K to look at detuning
- Up to 350 kW in half-cell, operating below 95 K
- Fully filled @ 2.5 us, 80 MV/m.





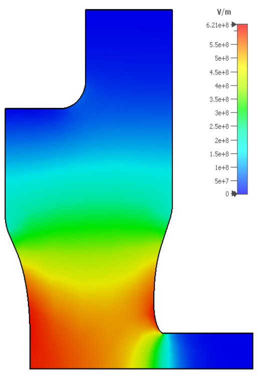


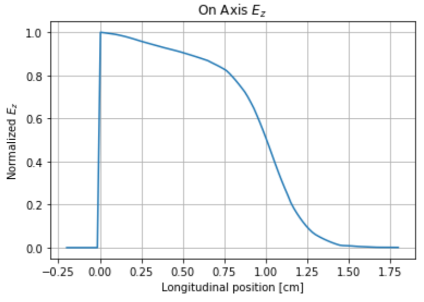
Cryo RF Performance Overview

- **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

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





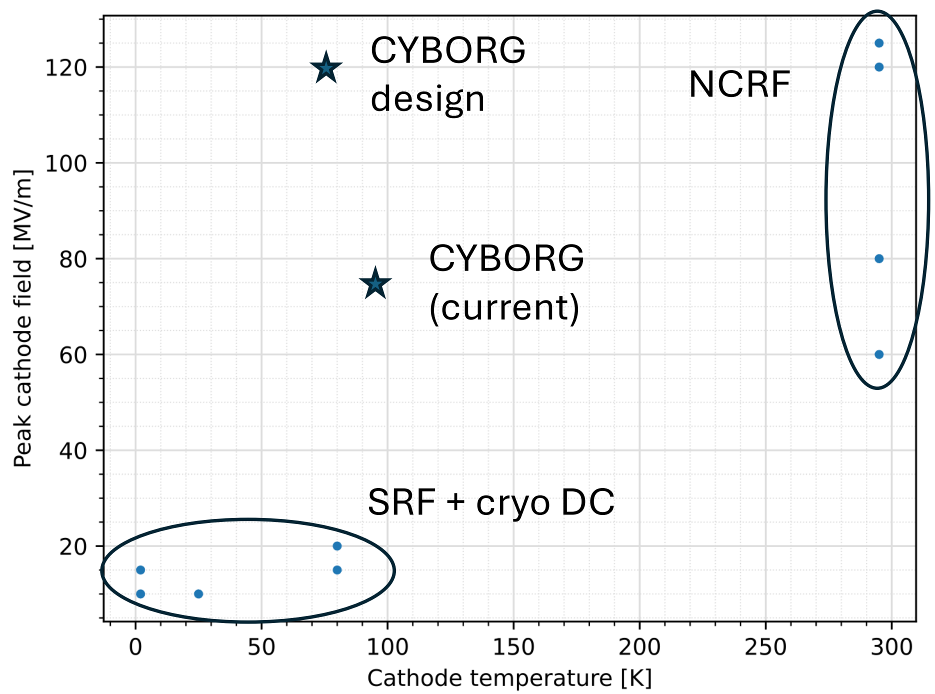
Parameter	295 K	95 K	77K	45 K
f_0 [MHz]	5703.6 ± 0.1[1]	5720.410 ± 0.003[1]	5721 ± 3	5722 ± 4
Q_0	7808 ± 13[1]	14326 ± 12[1]	21000 ± 3600	30000 ± 9900
Coupling β	0.608 ± 0.002[1]	1.069 ± 0.002[1]	1.60 ± 0.44	2.4 ± 0.9
Filling time [μs]	0.271 ± 0.01[1]	0.386 ± 0.001[1]	0.44 ± 0.01	0.49 ± 0.03
Power [MW] 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

This gun operated at 180 MV/m peak is state-of-art UED electron source

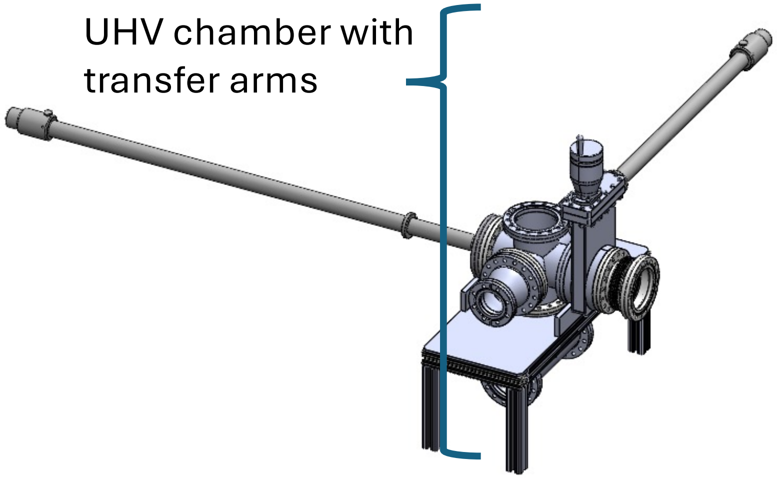
Cathode Testing Comparison

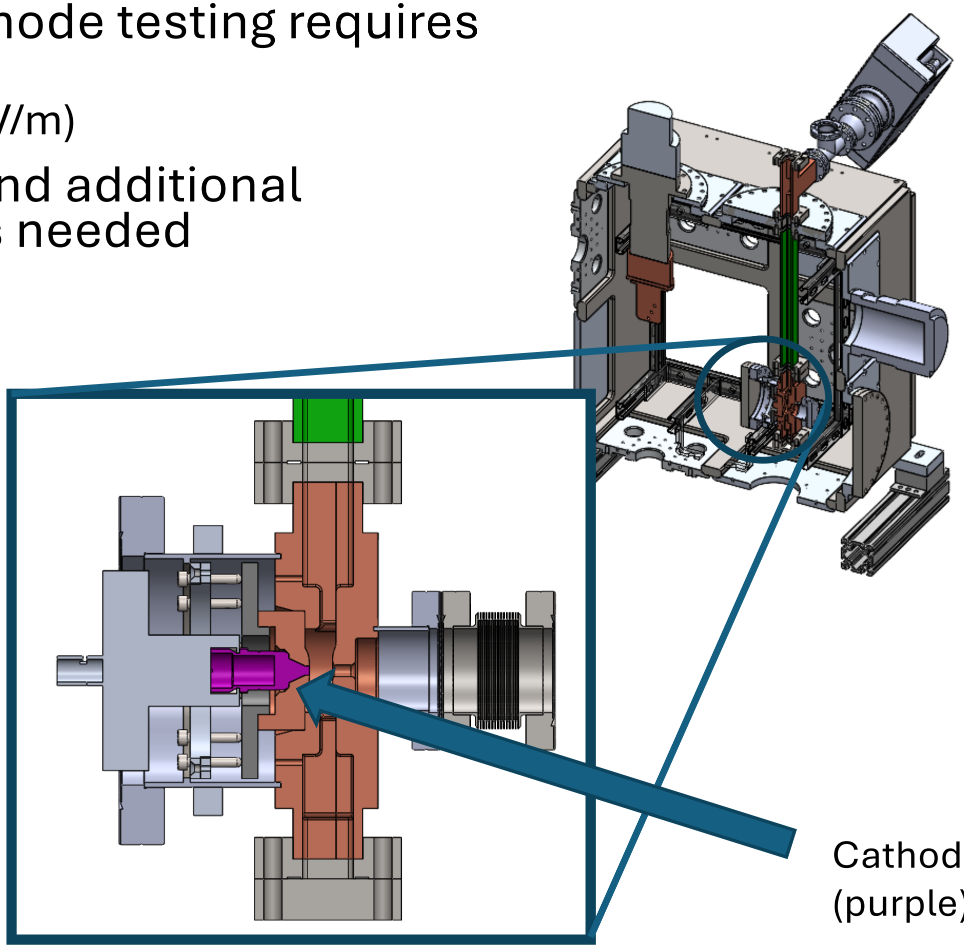
- Plotting of CYBORG parameters compared to existing cathode gun testing environments
- CYBORG conditioning ongoing but current gradient is 75-80 MV/m with target of 120 MV/m
- 95 K with improvements to 77 K underway



Cathode Load Lock Chamber

- Long term use of CYBORG for cathode testing requires UHV chamber ($<10^{-10}$ torr)
  - Consistent with polarization (120 MV/m)
- Development of pumping setup and additional cathode plug manipulator studies needed
- First tests with Cs_2Te

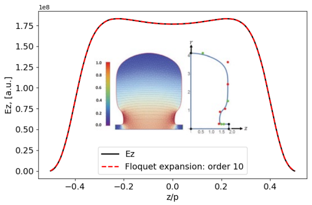




BBU modelling – Beam Physics Challenges

(Bosco)

- Inherent **focusing** from high gradient RF linacs
  - 1st order focusing: transitions from field-free to non-zero field regions
  - 2nd order focusing: non-synchronous *space harmonics* in the accelerating cells



$$\begin{pmatrix} x \\ x' \end{pmatrix} \mapsto \begin{pmatrix} 1 & 0 \\ \mp\frac{\gamma'}{2\gamma} & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}$$

$$\begin{pmatrix} x \\ x' \end{pmatrix} \mapsto \begin{pmatrix} \cos\left(\nu \ln \frac{\gamma_2}{\gamma_1}\right) & \frac{\gamma_1}{\nu\gamma'} \sin\left(\nu \ln \frac{\gamma_2}{\gamma_1}\right) \\ -\frac{\nu\gamma'}{\gamma_2} \sin\left(\nu \ln \frac{\gamma_2}{\gamma_1}\right) & \frac{\gamma_1}{\gamma_2} \cos\left(\nu \ln \frac{\gamma_2}{\gamma_1}\right) \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}$$

J. Rosenzweig and L. Serafini, *Transverse particle motion in radio-frequency linear accelerators*, Physical Review E 49, 1599 (1994).

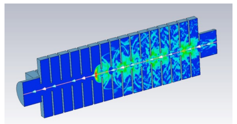
S. C. Hartman and J. B. Rosenzweig, "Ponderomotive focusing in axisymmetric rf linacs," *Phys. Rev. E*, vol. 47, pp. 2031–2037, Mar 1993.

- Strong **wakefields** due to the small cell irises
  - Intra-beam coupling due to SRWFs (field diffraction from the irises)
  - Inter-beam coupling due to LRWFs (HOMs excitation)

$$w_{\parallel}(s) = \frac{Z_0 c}{\pi a^2} \exp\left(-\sqrt{\frac{s}{s_0}}\right)$$

$$w_{\perp}(s) = \frac{4 Z_0 c s_1}{\pi a^4} \left(1 - \left(1 + \sqrt{\frac{s}{s_1}}\right) \exp\left(-\sqrt{\frac{s}{s_1}}\right)\right)$$

SRWF



$$w_{\parallel}(\tau) = \frac{\omega_0 R_{\parallel}}{Q} e^{-\alpha\tau} \left(\cos(\omega_n \tau) - \frac{\alpha}{\omega_n} \sin(\omega_n \tau)\right)$$

$$w_{\perp}(\tau) = \frac{\omega_0 R_{\perp}}{Q} e^{-\alpha\tau} \sin(\omega_n \tau)$$

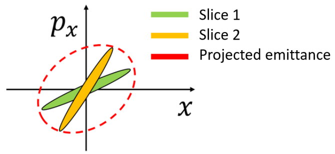
LRWF

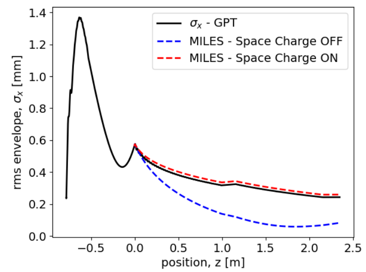
J. D. Lawson, "Radiation from a ring charge passing through a resonator", Rutherford High Energy Laboratory, Chilton, England, Rep. RHEL/M144, 1968.

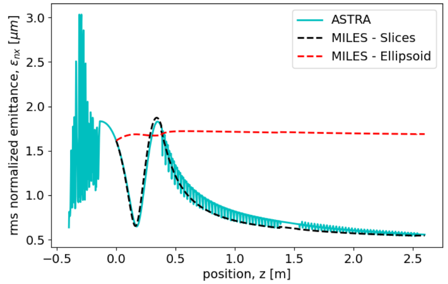
K. Bane, "Short-range dipole wakefields in accelerating structures for the NLC", SLAC, Menlo Park, USA, Rep. SLAC-PUB-9663, Mar. 2003. doi:10.2172/812954

- Notable impact from **space charge** mechanisms
  - Nominal focusing at injection too strong in absence of SC forces
  - Emittance compensation process and other slice-dependent effects

L. Serafini and J. B. Rosenzweig, Envelope analysis of intense relativistic quasilaminar beams in rf photoinjectors: A theory of emittance compensation, Physical Review E 55, 7565 (1997).







Important for FEL, ICS and C3

The Code MILES

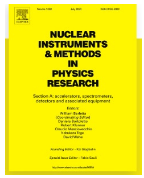
Dedicated tracking code

- Motivation to investigate **wakefields effects** in linacs in presence of non-negligible **space charge** endangering the nominal beam quality
- Use of simple **semi-analytical models**: *flexible* and *time-efficient* tool (**factors ~1/40-1/10**) with acceptable reduction of the accuracy
- Main applications: investigation of misalignment effects and design of possible **correction** schemes

Miles Davis (May 26, 1926 – September 28, 1991)

MILES = Multi-bunch and Intra-beam effects in Linacs Evaluating Stability

F. Bosco et al., "Fast models for the evaluation of self-induced field effects in linear accelerators," NIM-A vol. 1056, p. 168642, 2023 https://doi.org/10.1016/j.nima.2023.168642



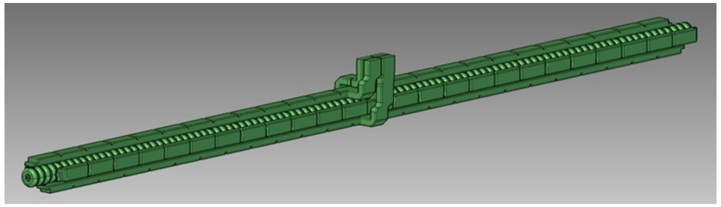
Modeling overview and comparison with other codes

	MILES approach	Commonly utilized approaches
Space Charge	Equivalelent ellipsoid or Multi-slice superposition	Particle in cell (PIC)
Wakefields	Algebraic formalism	Convolution integral or FFT equivalent

Long-range BBU in the C^3 Linac

- BBU studies for the **250 GeV CM** working point of the C^3 **linear collider**
- Center of mass **oscillations** and **beam loading effects** in multi-bunch operation: sequence of point-like, structureless macro-particles carrying the whole bunch charge

Parameter Note	Unit			Baseline	Compact
Center of Mass Energy	GeV	91	250	550	550
Luminosity	x10^{34} cm^{-2}s^{-1}	0.4	1.3	2.4	2.4
Single Beam Power	MW	0.7	2	2.5	2.5
Single Linac Active Length	km	0.56	1.83	2.45	1.9
Injection Energy Main Linac	GeV	10	10	10	10
Train Rep. Rate	Hz	120	120	120	120
Bunch Charge	nC	1	1	1	1
Flat-Top RF Pulse Length	ns	700	700	260	195
Bunch Spacing	Periods (ns)	30 (5.26)	30 (5.26)	20 (3.5)	15 (2.6)
Bunches per Train		133	133	75	75
Average Current	μA	16	16	9	9
Peak Current	A	0.19	0.19	0.3	0.385
Loaded Accel. Gradient	MeV/m	70	70	120	155
RF Power for Structure	MW/m	30	30	80	140



3π/4 structure!

Mei Bai and et al. C^3: A "cool" route to the higgs boson and beyond. *TBD*, 10 2021. URL https://www.osti.gov/biblio/1831907.

Emilio Nanni et al. C^3 demonstration research and development plan, 03 2022.

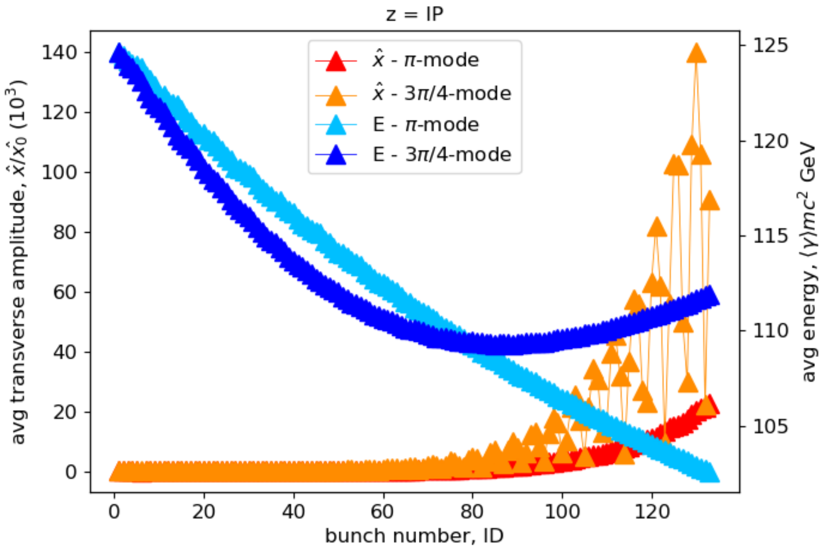
Long-range BBU in the C^3 Linac (2)

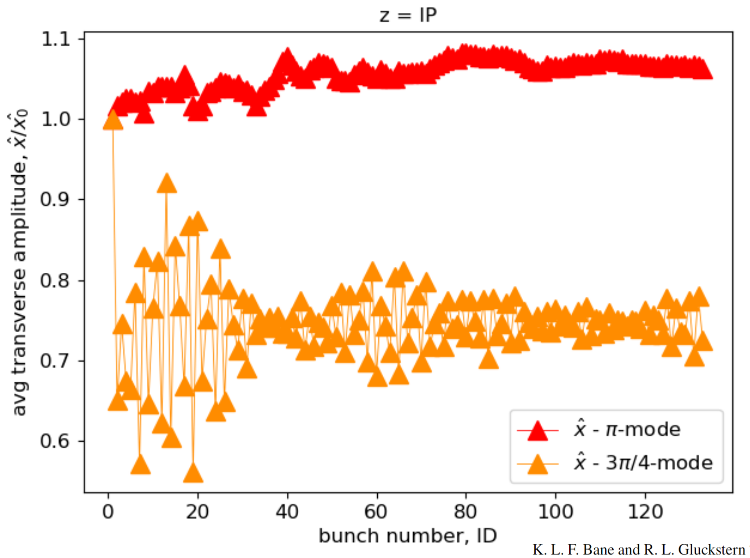
Beam Breakup and Beam loading

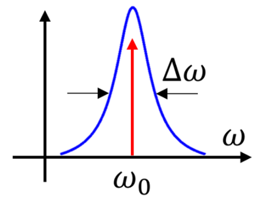
- 700 ns RF-pulse (flat-top) filled with 133 bunches, 1 nC each, and 5.26 ns separation (30 RF-periods)
- Acceleration at an avg gradient of 70 MeV/m
- Injection **100 μm off axis**: excitation of dipole HOM

Detuning of the HOMs

- **Unstable** motion if f_{HOM}/f_b is close to an integer
- Mitigation through frequency **spread** (or *detuning*)
- Small **variations** of the geometry: HOMs exhibit different **random** frequencies in subsequent sections





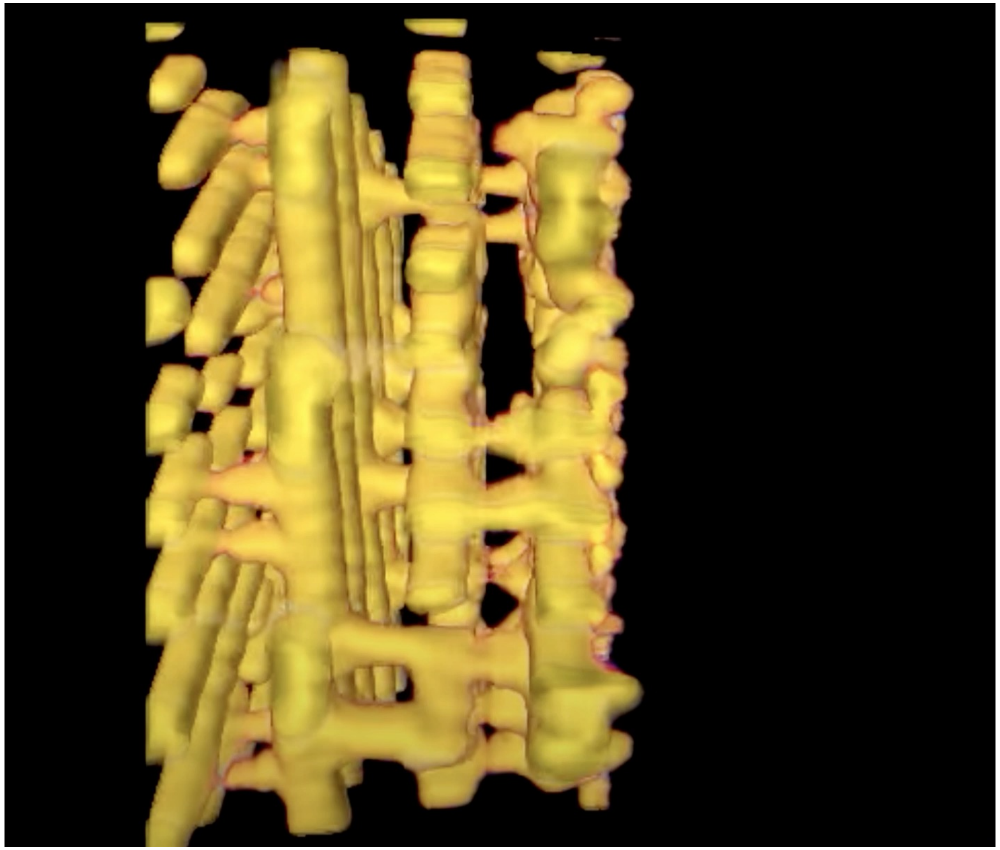


Amplitude of the transverse oscillation for each bunch in the rf-pulse at the interaction point normalized to the first bunch's amplitude

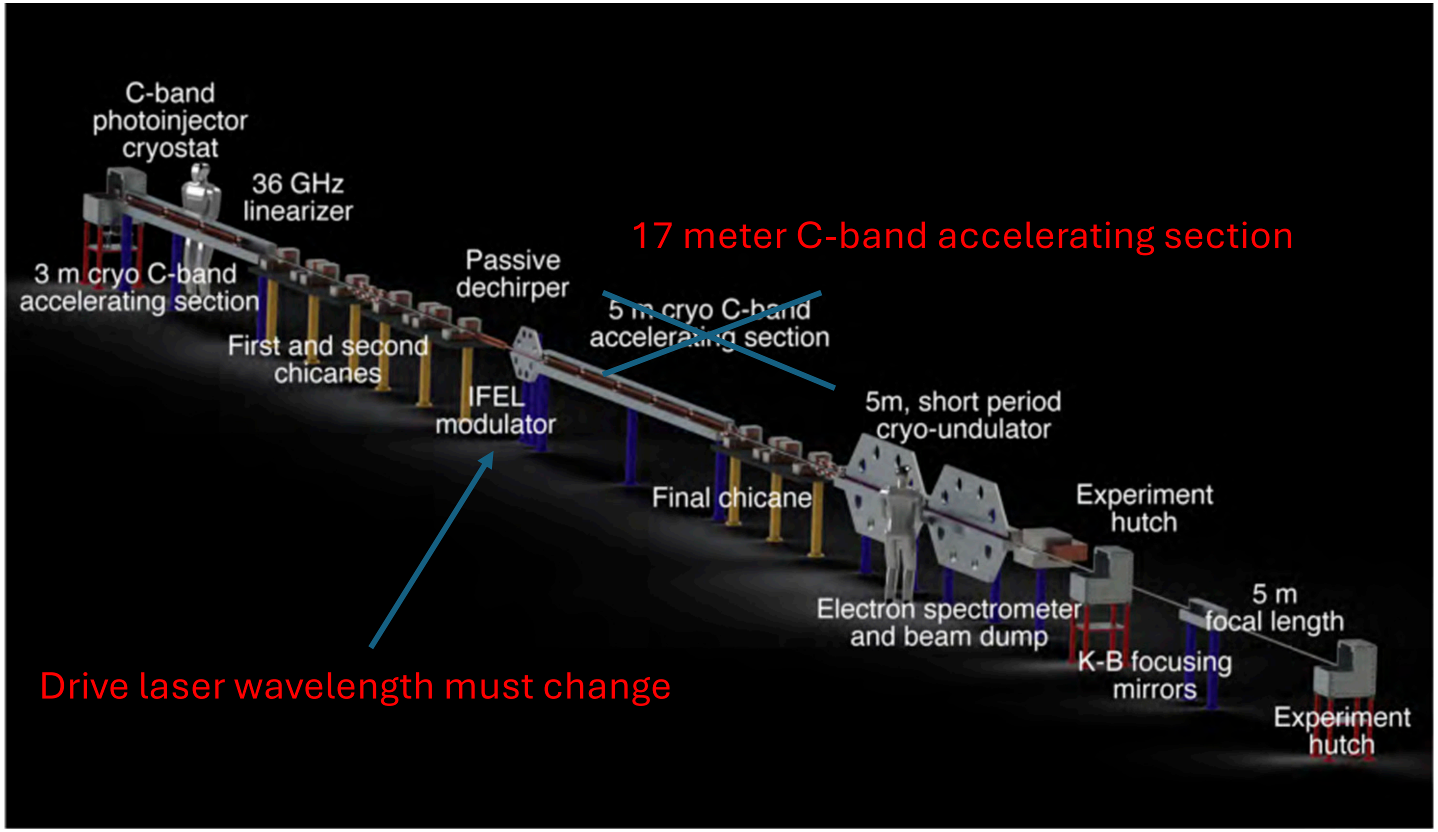
K. L. F. Bane and R. L. Gluckstern "The transverse wakefield of a detuned X-band accelerator structure", *Particle Accelerators*, Vol. 42, 1993.
K. A. Thompson, C. Adolphsen and K. L. F. Bane "Multi-bunch beam break-up in detuned structures", SLAC-PUB-6153, 1993.

Alban Mosnier. Instabilities in linacs. In *CERN Accelerator School: Course on Advanced Accelerator Physics (CAS)*, pages 0459–514, 12 1993.

Chip metrology XFEL with ptychographic laminography



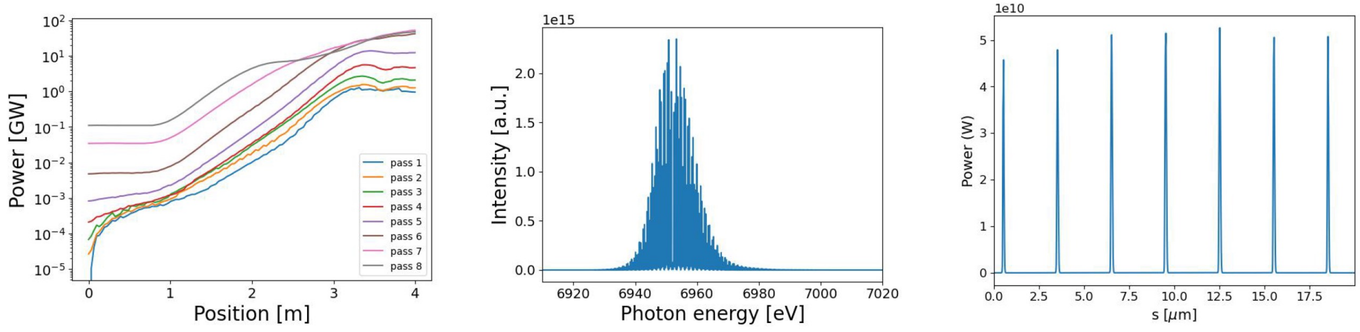
Expand the footprint to 2.45 GeV



Test stand of beam production, acceleration, compression.

XRAFEL performs very well at 7 keV

- **1E14 coherent photons** (with higher bandwidth)
  - Factor of 1E5 increase over SLS cSAXS
- Use 10 um microbunching IFEL instead?



(a) (b) (c)

Gain curve per pass   Total spectrum   Temporal dependence of *P*

XRAFEL for Ptychography

- Regenerative amplifier in hard X-ray
- Compact crystal cavity (12 m/40 ns roundtrip) encloses 4-m undulator
- Recirculate X-rays in XRAFEL configuration for 8 passes (requires 300 ns flat RF pulse duration)
- Photon energy 7 keV, use C (220) reflection at 45 deg Bragg angle

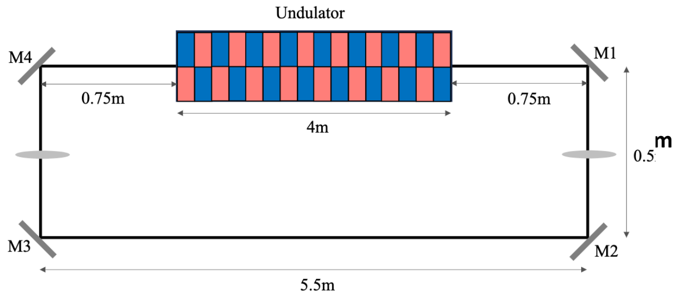
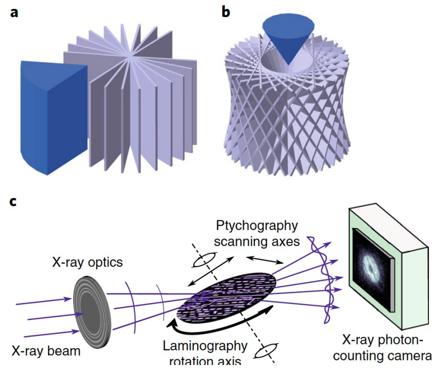


Table 1. Summary of input parameters for 1D simulation.

Parameter	Units	Value
Energy	GeV	2.44
Energy spread	%	0.03
Normalized transverse emittance	nm-rad	75
Peak current	kA	4.0
Undulator parameter, K		0.501
Undulator period	mm	6.5
Undulator length	m	4.0
Fundamental FEL wavelength	Å	1.783
Photon energy	keV	6.95
Diamond (220) bandwidth	meV	141
Cavity roundtrip length (time)	m (ns)	12 (40)
Number of electron bunches in an RF pulse		8



Ptychographic laminography enabled by coherence

Goal: increased flux and coherence

Concept accepted in *Instruments,* available on Preprints.org

Proposals now active

- NSF STTR “Semiconductor” program
- ARDAP design study
- BES Energy Frontier Research Center (now at UCLA)
- *CHIPS Act-funded activities (NIST) now under discussion*
- Private investment
- Industry interest high
    - Rayton semiconductor
    - RadiaBeam (R&D part)
    - Samsung
    - **Intel**

intel.

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Professor Rosenzweig, UCLA Dept.. of Physics and Astronomuy
Ms Aurora Araujo, RadiaBeam Technologies

January 8th, 2024

Dear Professor Rosenzweig, Ms. Araujo,

It is a great honor to write this letter of interest to show our interest and support for your proposed STTR research and development project: “Revolutionizing Next Generation Chip Metrology with a Compact, High Flux X-ray Free-electron Laser”. At Intel, we are pushing state of art high volume semiconductor manufacturing technology and process to support our public stated goal of achieving 5 nodes in 4 years and gaining technology leadership for the United States in Advanced Semiconductors Manufacturing Technology and Processes.