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The UCLA High Gradient Cryogenic RF Research Program

J. B. Rosenzweig

UCLA Dept. of Physics and Astronomy

High Gradient 2021

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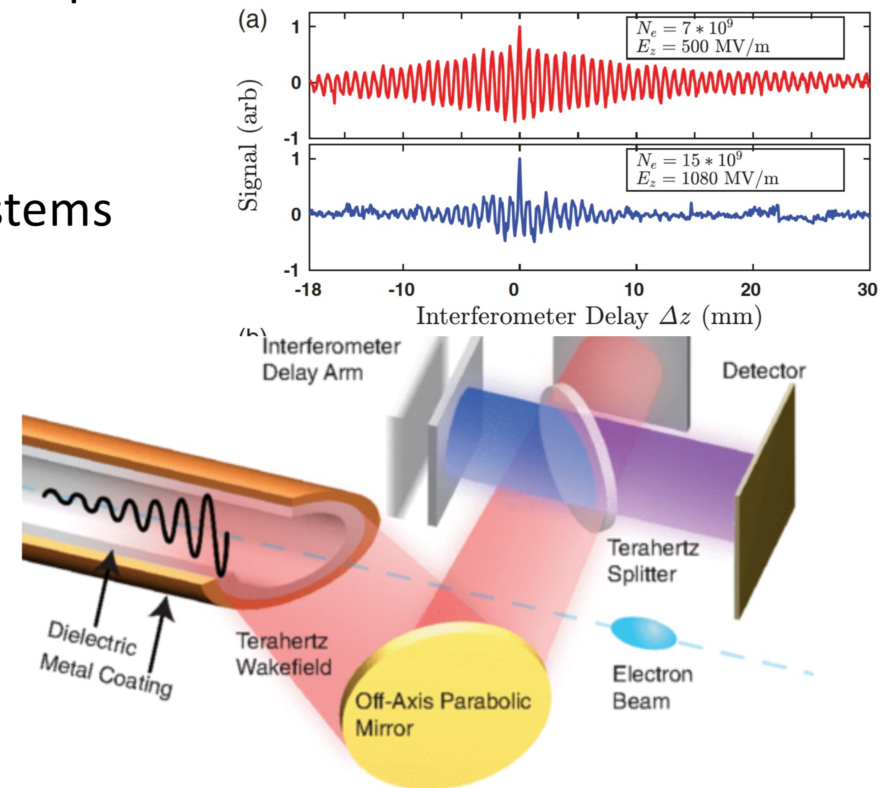
Challenges and Promise of High EM Fields in Structures

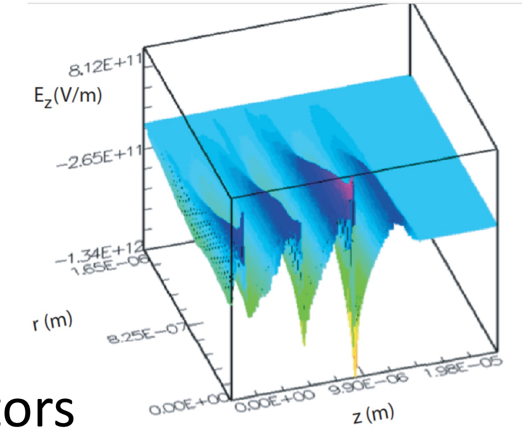
- Path to applications clearer than more exotic approaches
  - Enable next generation instruments in HEP and photon science
  - *Miniaturization* implies frequency scaling
- Exploring extreme regimes
  - TowardsGV/m fields in condensed matter systems
  - Short wavelength operation
  - Novel sources (wakefields, laser-based)
  - New geometries/symmetries
  - *Cryogenic operation*



UCLA Research into High Field *Structures*

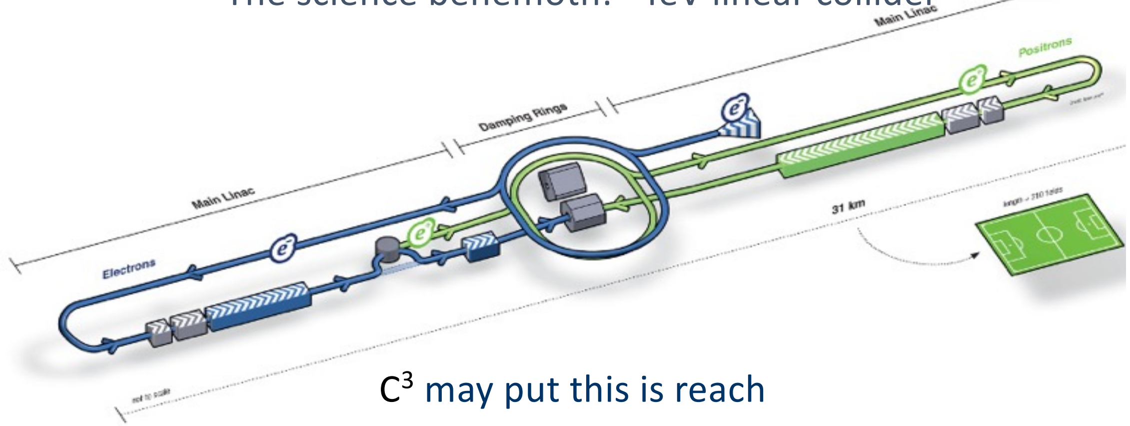
- Historical emphasis at UCLA
  - Wakefields (mm-to-THz)
  - Photoinjectors
  - Fundamental high field physics
- Recent pivot (>2015) to cryogenic RF
- Driven by urgent **applications** for compact, high impact accelerators
  - Linear collider (C^3 collaboration, UCLA flat beam injector)
  - Ultra-compact X-ray Free-Electron Laser (UC-XFFEL)
- **Fundamental aspects** of high fields
  - Beam dynamics w/large accelerating fields
  - RF breakdown
  - Dark current emission
  - Optimized design
  - Photoemission

TV/m plasma wakefields



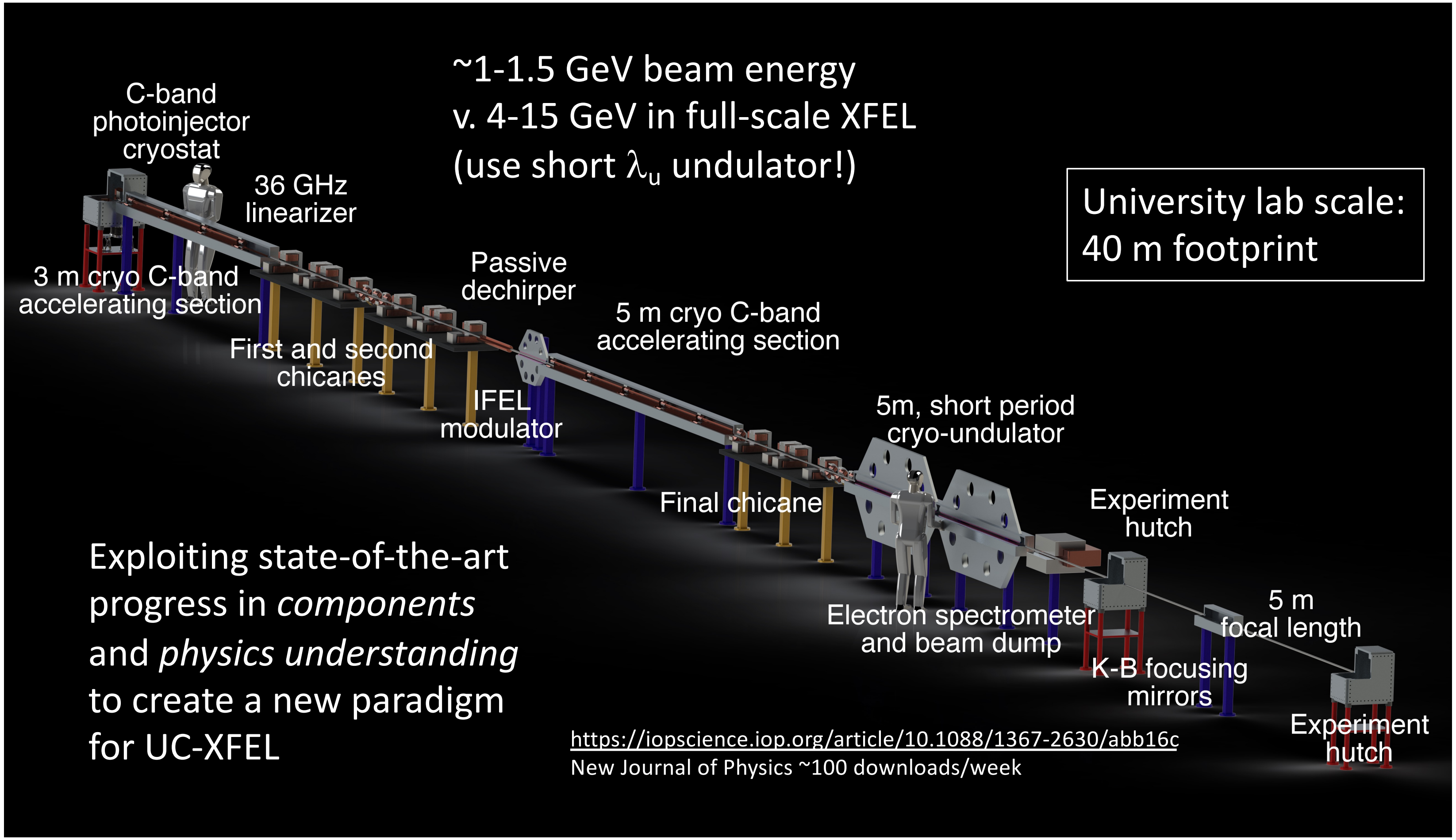
Further generation solution

The science behemoth: ~TeV linear collider



C^3 may put this is reach

Vision of a university-scale UC-XFEL



~1-1.5 GeV beam energy
v. 4-15 GeV in full-scale XFEL
(use short λ_u undulator!)

University lab scale:
40 m footprint

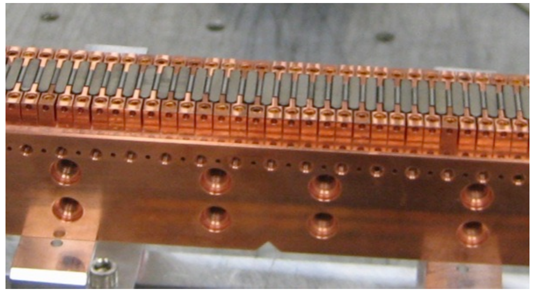
Exploiting state-of-the-art progress in *components* and *physics understanding* to create a new paradigm for UC-XFEL

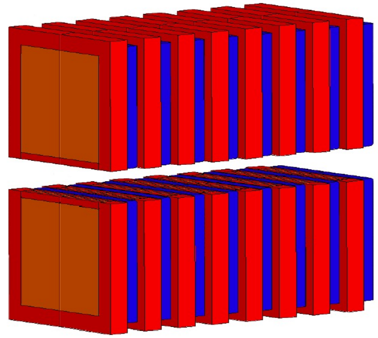
https://iopscience.iop.org/article/10.1088/1367-2630/abb16c
New Journal of Physics ~100 downloads/week

UC-XFEL Recipe Ingredients

- Ultra-high field electron cryogenic RF photoinjector source
- High gradient cryogenic accelerator
- Frontier simulation of collective effects (CSR, IBS)
- Beam measurements at micron/fs scale
- Very high frequency RF devices
- Advanced magnetic systems – micro-undulators and quads
- Machine-learning based control
- Compact X-ray optics
- Understanding of science case

First two points enable entire scenario, based on very high field cryogenic RF field research





Hybrid cryo-undulator: Pr-based, SmCo sheath; λ=9 mm up to 2.2 T

Details of UC-XFEL approach explored

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New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft

PAPER • OPEN ACCESS

An ultra-compact x-ray free-electron laser

J B Rosenzweig[15,1], N Majernik[1], R R Robles[1], G Andonian[1], O Camacho[1], A Fukasawa[1], A Kogar[1], G Lawler[1], Jianwei Miao[1], P Musumeci[1], B Naranjo[1], Y Sakai[1], R Candler[2], B Pound[2], C Pellegrini[1,3], C Emma[3], A Halavanau[3], J Hastings[3], Z Li[3], M Nasr[3], S Tantawi[3], P. Anisimov[4], B Carlsten[4], F Krawczyk[4], E Simakov[4], L Faillace[5], M Ferrario[5], B Spataro[5], S Karkare[6], J Maxson[7], Y Ma[8], J Wurtele[9], A Murokh[10], A Zholents[11], A Cianchi[12], D Cocco[13] and S B van der Geer[14]
− Hide full author list

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Citation J B Rosenzweig *et al* 2020 *New J. Phys.* **22** 093067

- 47 pages, well beyond standard guidelines
- Most highly downloaded NJP article of late 2020
- Game-changing application through high field acceleration

The Ultra-Compact FEL Design Realized

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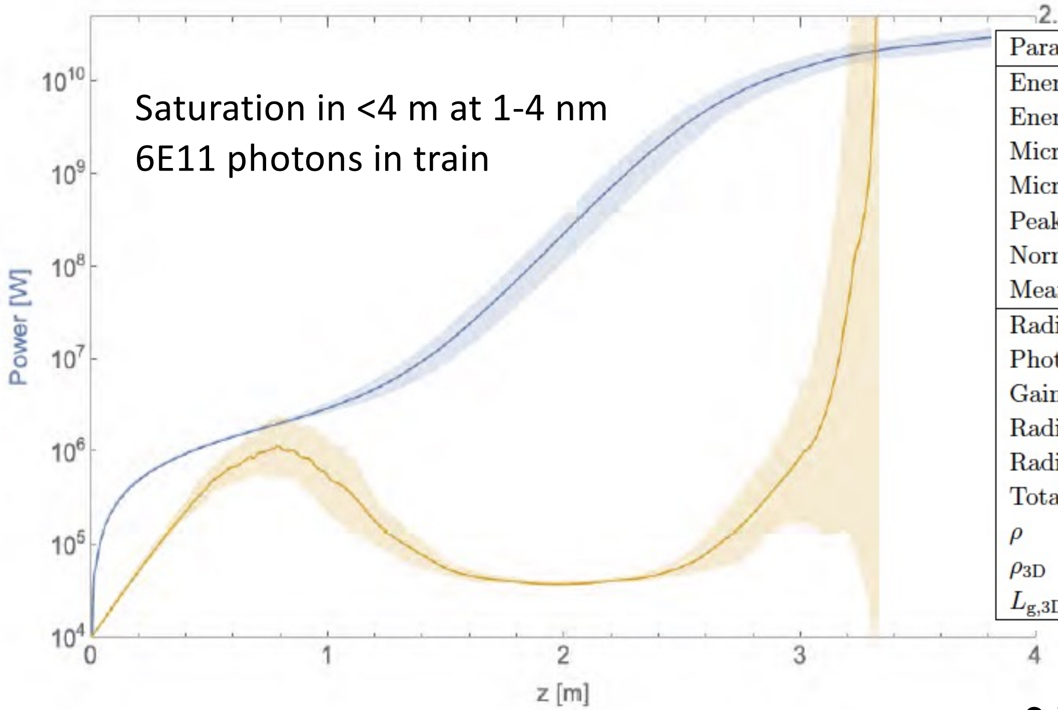


Parameter	Units	Value
Energy	GeV	1.0
Energy spread	%	0.1
Micro-bunch charge	pC	14.2
Micro-bunch rms length, σ_z	nm	424
Peak current	kA	4.0
Normalized emittance, $(\epsilon_{n,x}, \epsilon_{n,y})$	nm-rad	(80, 60)
Mean spot size, σ_r	μm	4.9
Radiation fundamental, λ_1	Å	10.0
Photon energy	keV	1.2
Gain length, $L_{g,3D}$	m	0.21
Radiation peak power	GW	25
Radiation pulse energy/μbunch	μJ	19.2
Total number of photons (train)		6×10^{11}
ρ	10^{-3}	3.1
ρ_{3D}	10^{-3}	1.4
$L_{g,3D}/L_{g,1D}$		2.2

Scaling of FEL ρ with lower energy (short λ_u)

$$\rho \approx \frac{\gamma^6}{3}\left(\frac{\lambda_r}{2\pi}\right)^4 B_{6D}$$

Also controls gain length and efficiency

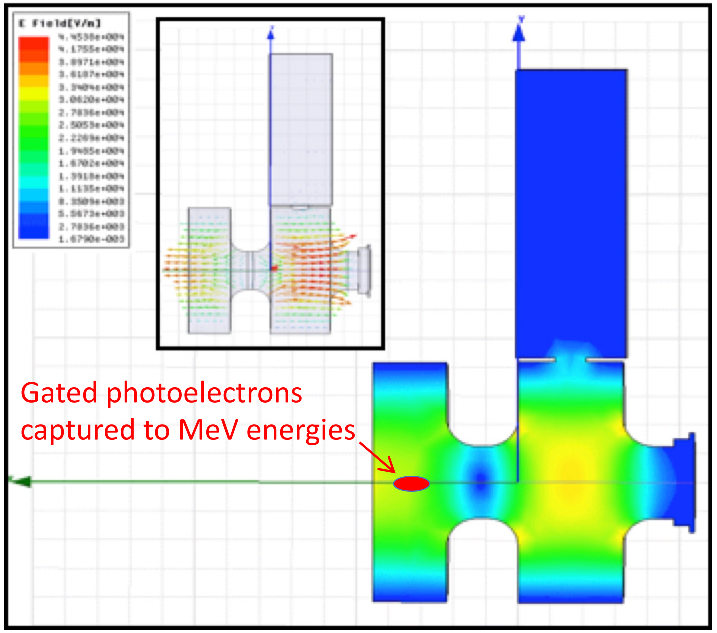
$$B_{6D} = \frac{2I(A)}{\sigma_\gamma \varepsilon_n^2}$$

Low γ (λ_u) XFEL means ***unprecedented*** **high electron beam brightness**

This is the challenge. How to solve?

FEL begins life with high brightness electron beam source: *the RF photoinjector*

- Laser gating to fs-to-ps level
- RF capture – violent acceleration
  - Accelerating fields 10x DC sources
  - Strong RF focusing effects
- Preserve phase space structure
  - Control pulse expansion
  - Minimize emittance growth
  - Creation, manipulation of single component plasma (emittance compensation)
- Frontier RF engineering
- Photocathode physics
- Advanced laser techniques
- Apply lessons to linear collider source



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

Rethink points in red when fields much enhanced.

Higher 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 $$J_{z,b} \approx \frac{ec\varepsilon_0}{m_e c^2}\left(E_0 \sin\varphi_0\right)^2$$
- Brightness is $\boxed{B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c}\left(E_0 \sin\varphi_0\right)^2}$

B_{6D} with 3D effects is similar

  - Lower emission temperature and/or…
- **Higher launch field**
  - **Beat LCLS 120 MV/m (60 MV/m at injection)**

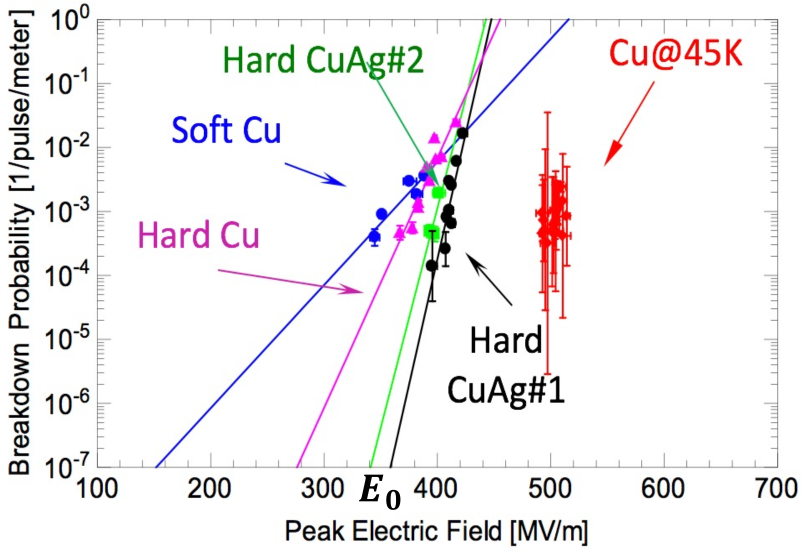
High gradient acceleration at cryogenic temperature

- Recent **X-band** work by SLAC-UCLA collaboration on cryogenic RF cavity research gives breakthrough surface fields
  - ASE lowers heating, thermal expansion small, enhanced strength
- 200 MV/m surface fields -> 500 MV/m. ~300 MV/m limit (dark current)
- Transformative applications in photoinjector **brightness**
  - **And system compactness**

$$B_{6D} \propto \boldsymbol{E_0^2}$$

➢ >order of magnitude Increase in brightness in *photoinjector*

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



Practical concern: dark current emission

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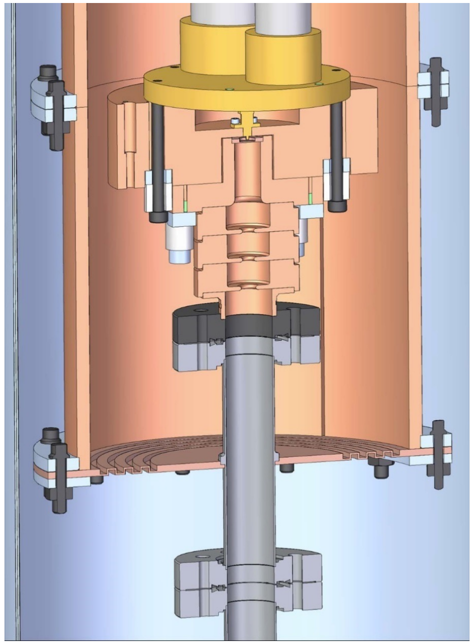
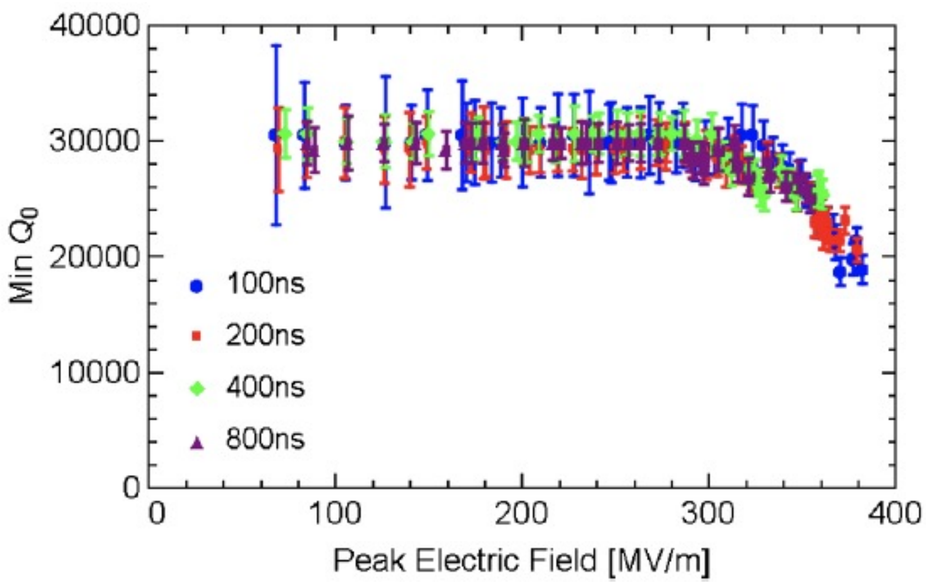
- Field emission is very large above 300 MV/m surface field
- Mitigation schemes must be explored

3-cell cryogenic X-band test cavity at SLAC





Dark current emission loads cavity >300 MV/m

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

Challenges of Dark Current

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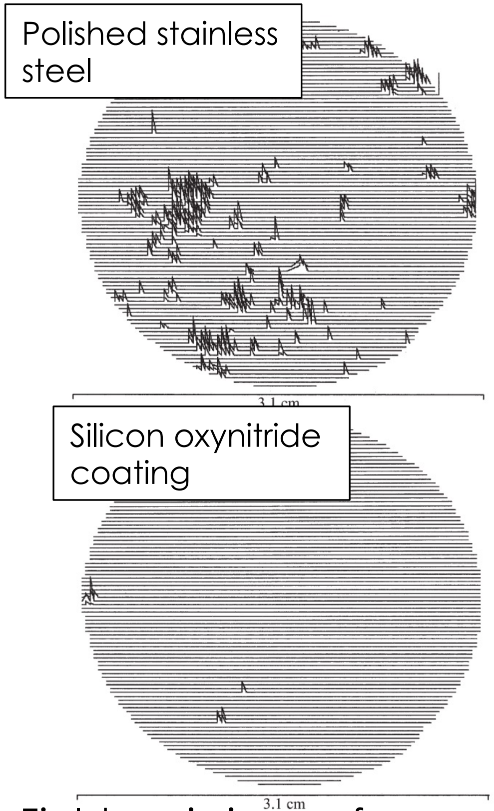
- Fowler-Nordheim emission

$$J_{\mathrm{FN}}(\mathrm{s}) = \frac{A(\beta(\mathrm{s})E_0(\mathrm{s}))^2}{\phi_w t^2(y)} \exp\left(\frac{-Bv(y)\phi_w^{3/2}}{\beta(\mathrm{s})E_0(\mathrm{s})}\right)$$

- Field enhancement factor β(s) typically ~50
    - Surface contamination at atomic level
    - Large dark current
    - Threat to applications (esp. low charge)
    - ***Active measures* (fast kickers)**
- Add surface coating
    - Silicon oxynitride eliminates emitters; high work function
    - Graphene (transparent)
    - **Experimental demonstration** needed
        - Needle tests at AWA
- Bulk material solutions

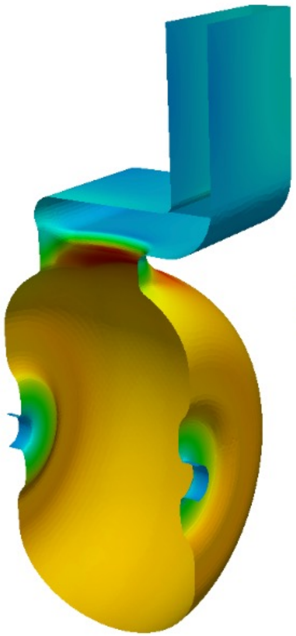


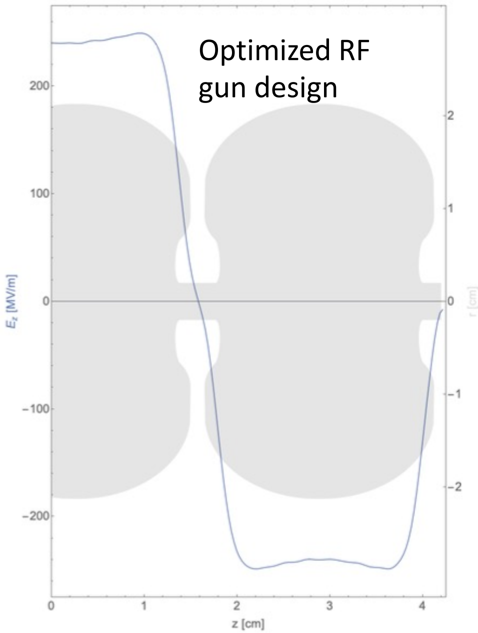
Field emission surface scan for SiNO (Theodore et al.)

UCLA C-band Cryogenic Photoinjector Project

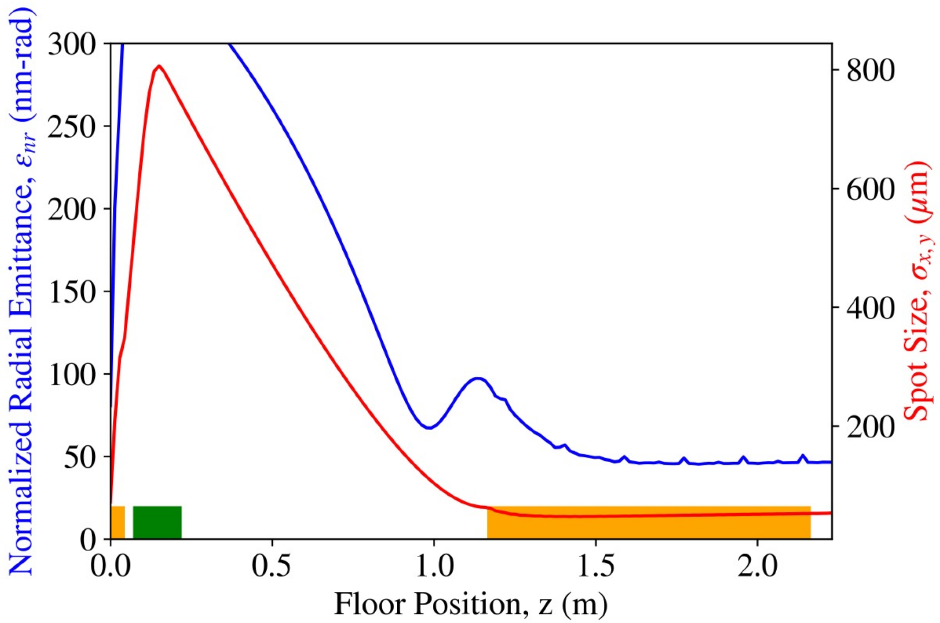
- Cryogenic C-band photoinjector at extreme high brightness for FEL

Profit from very high fields (up to 250 MV/m) on photocathode; higher spatial harmonics





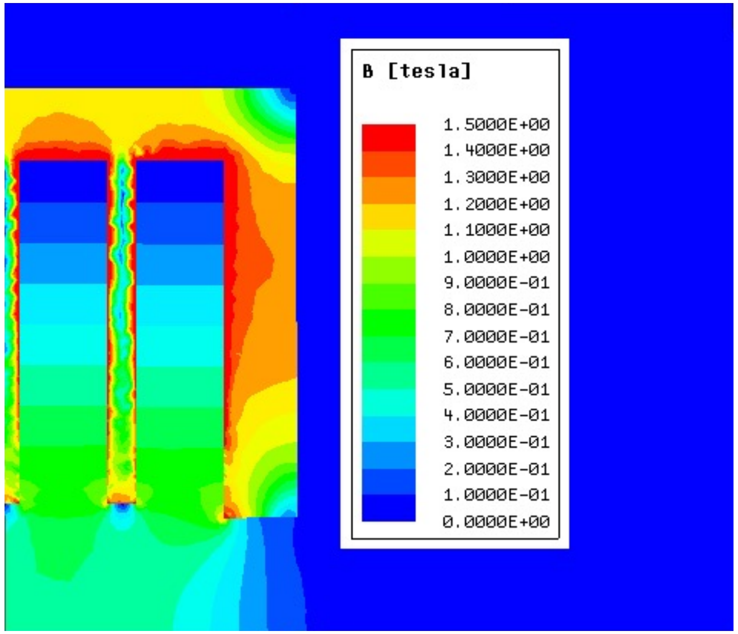
E_0=250 MV/m



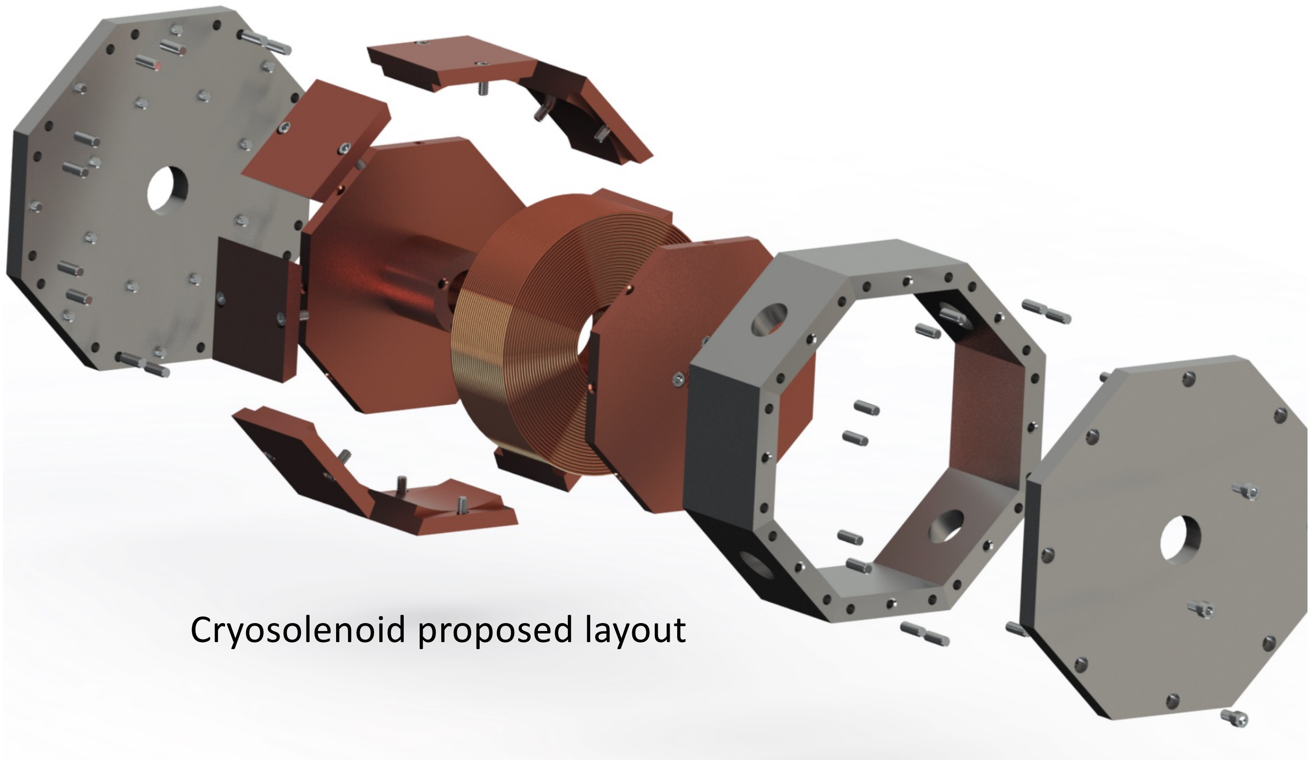
See talk by A. Fukasawa, HG 2021; also new article by UCLA group R. Robles, et al., https://arxiv.org/abs/2103.08789 (sub. to PRAB)

Cryogenic solenoid

- High field, compact solenoid; high current density
- Cryogenic operation gives robust solution



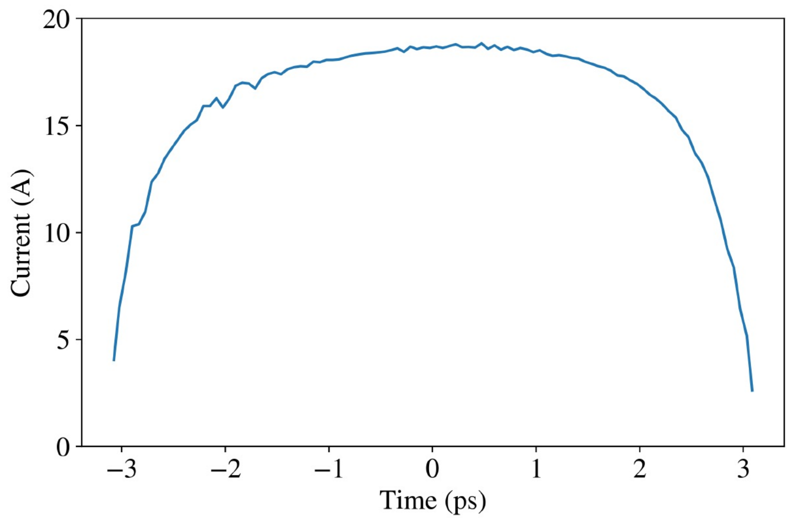
Previus 6 kG design challenging

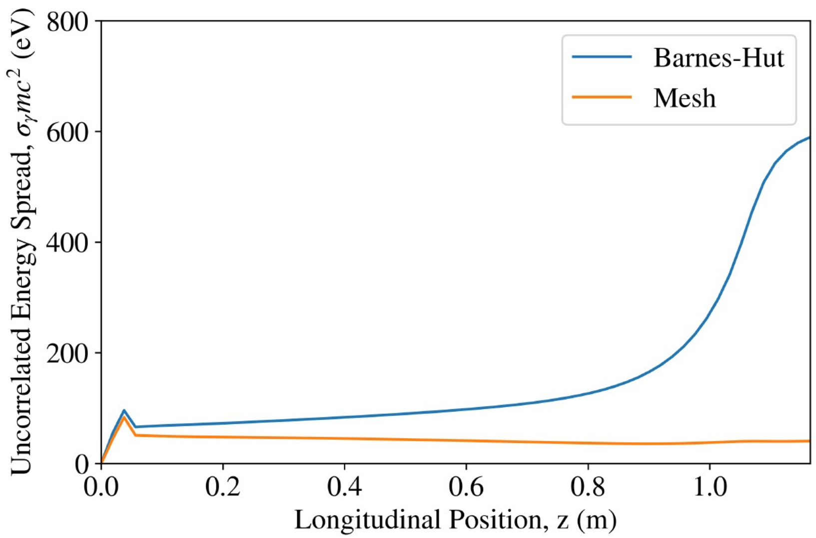


Cryosolenoid proposed layout

Enhanced 6D Brightness with high field

- High current (nearly 20 A) at 100 pC
- Very low energy spread – required new approach to IBS calculation





Record 6D brightness predicted, factor of >40 above original LCLS

Higher brightness through lower emission temperature

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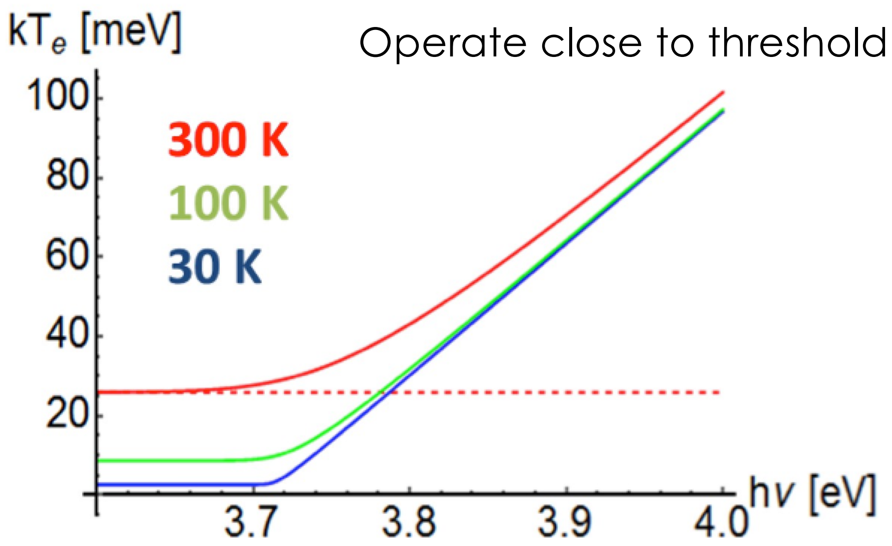
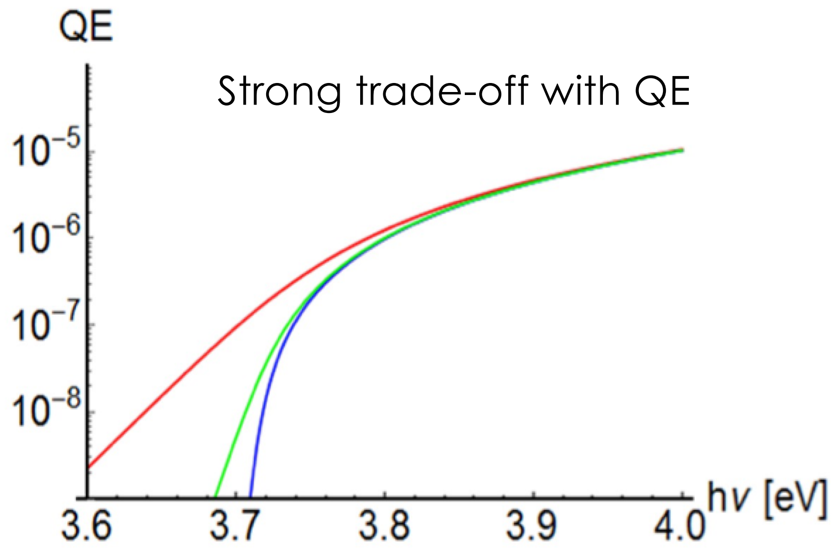
- MTE of photo-electrons can be notably lower at cryo-temperatures
- Eliminate Fermi-Dirac tail. *Cold* beams





Issue: two-photon and heating effects due to high laser power

Half-cell cryogenic photo-emission test stand

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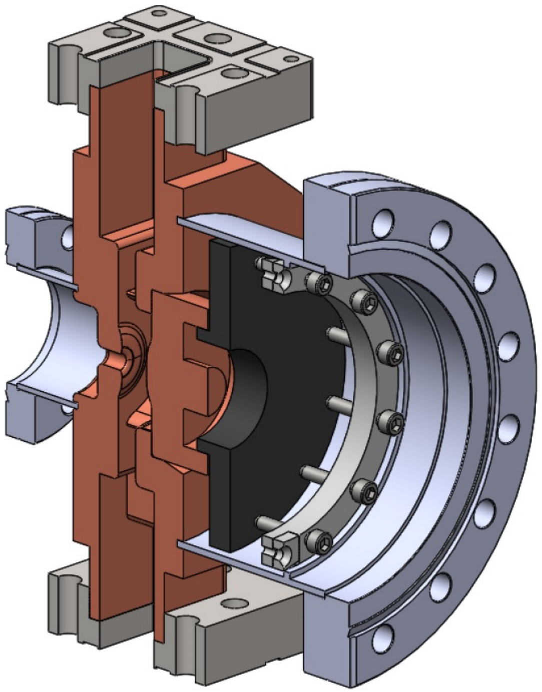
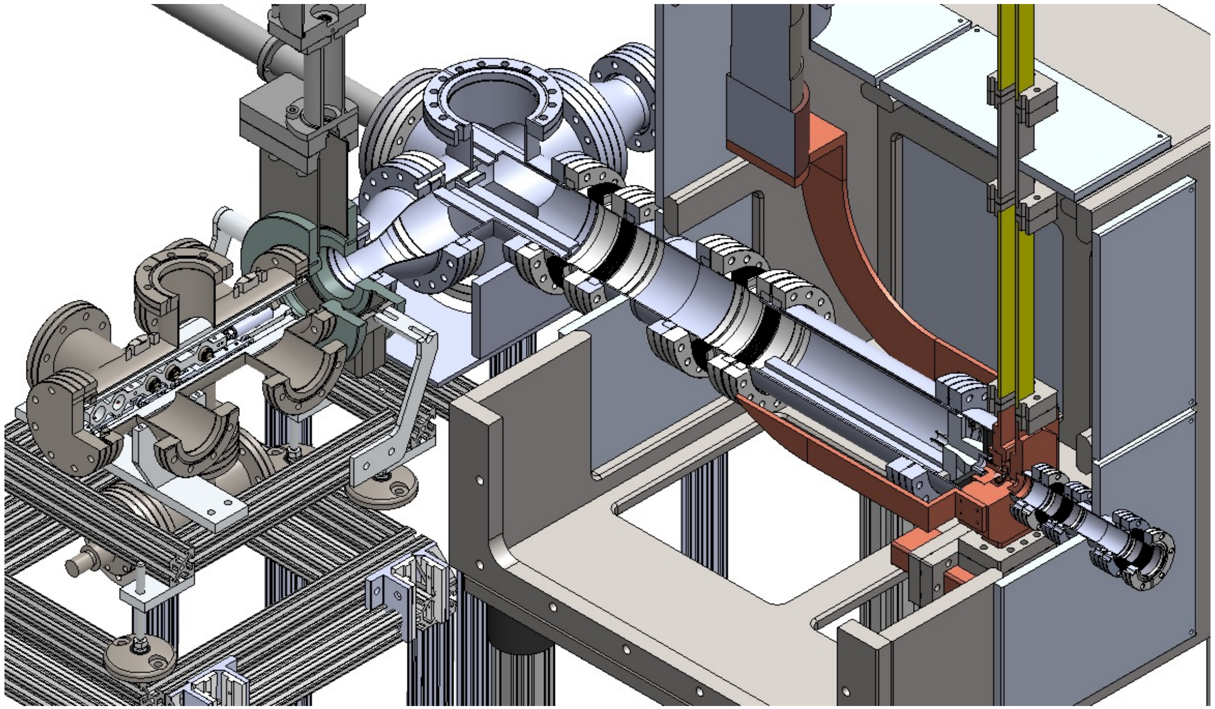
- Up to 120 MV/m field in 0.5 cell geometry, in cryostat
- Precision solenoid, very low emittance diagnostics (10 meV MTE)
- Load-lock photocathode assembly



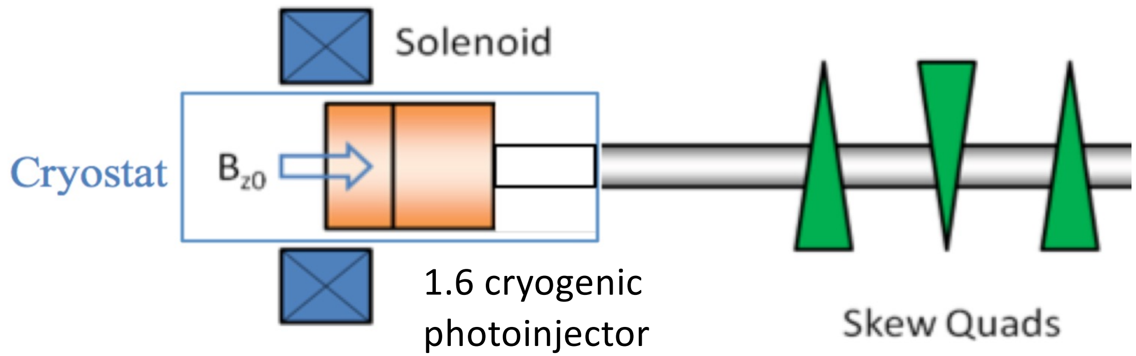
0.5 cell gun with copper cathode (no load lock)
Under construction (support from NSF CBB)



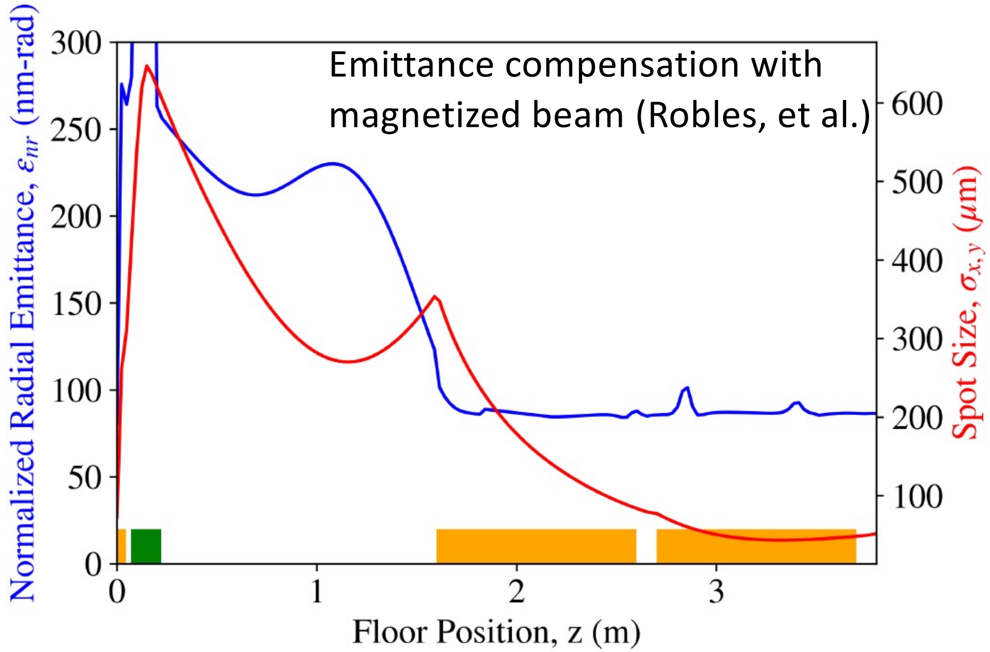
Cryo-emission test bed

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*

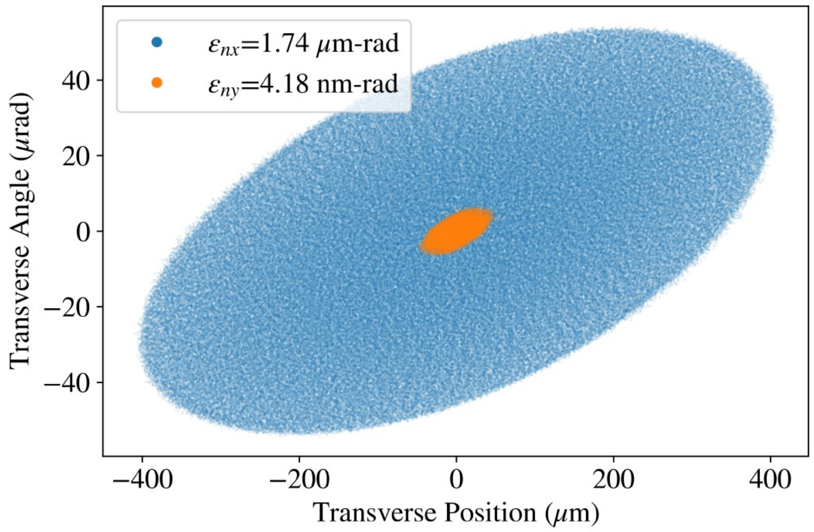


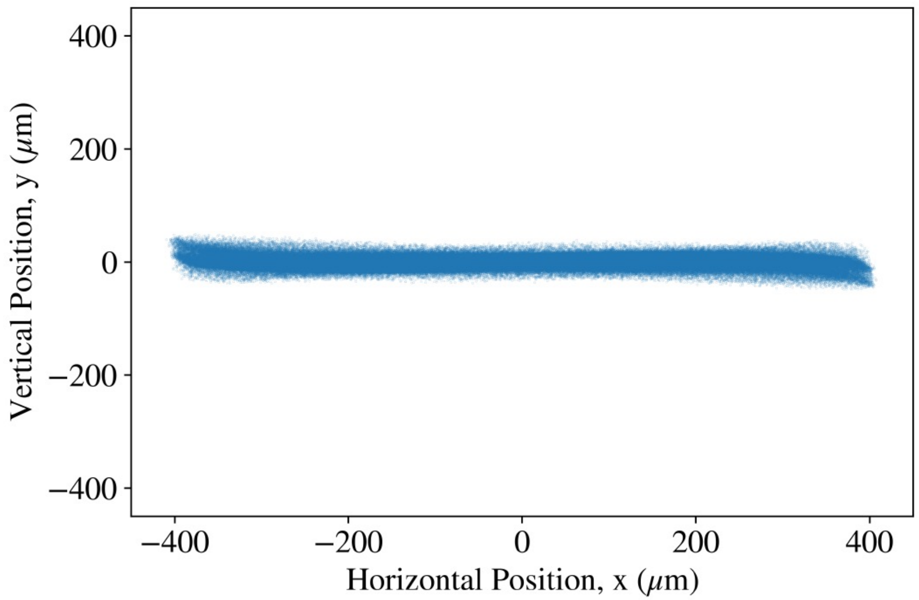
Angular momentum $\mathcal{L} = (eB_0/2m_ec)\sigma_0^2$



Performance of round-to-flat beam transformation

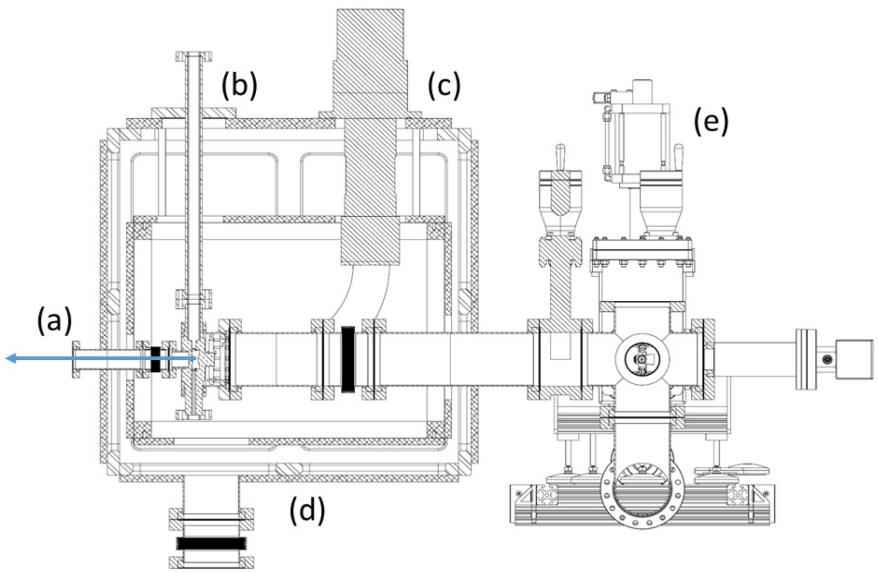
- Emittance 90 nm-rad before splitting (increase of 75% over XFEL case)
- Splitting nearly ideal in simulation, including space-charge effects

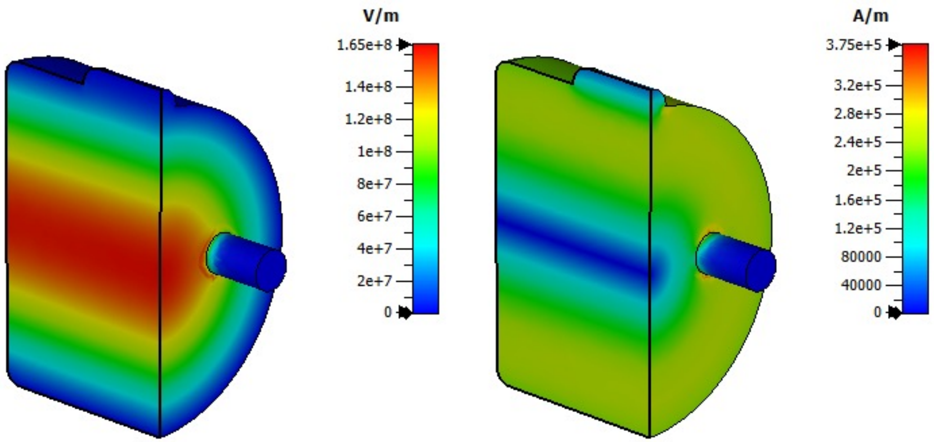




Cryostats/cryo-coolers for applications

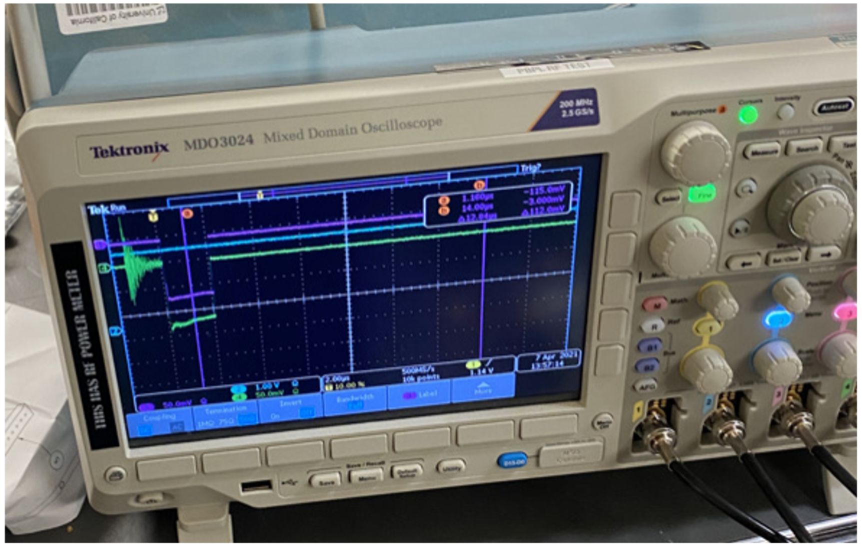
- Developing generation of cryostats for testing at UCLA
  - Low power C-band cryogenic properties (RRR)
  - Cool-down dynamics
  - Cold test high power structures
  - *Cryogenic photo-emission test stand*





C-band cryo-RF infrastructure

- C-band infrastructure at LANL; cryogenic RF collaboration ongoing
- Development of MOTHRA Lab at UCLA – 5 MW C-band klystron
  - SLED to obtain 20 MW for 1.6 cell gun project
- Parallel testing of room temperature systems at RadiaBeam



1st test of experimental tube

Testing Breakdown Field Limits

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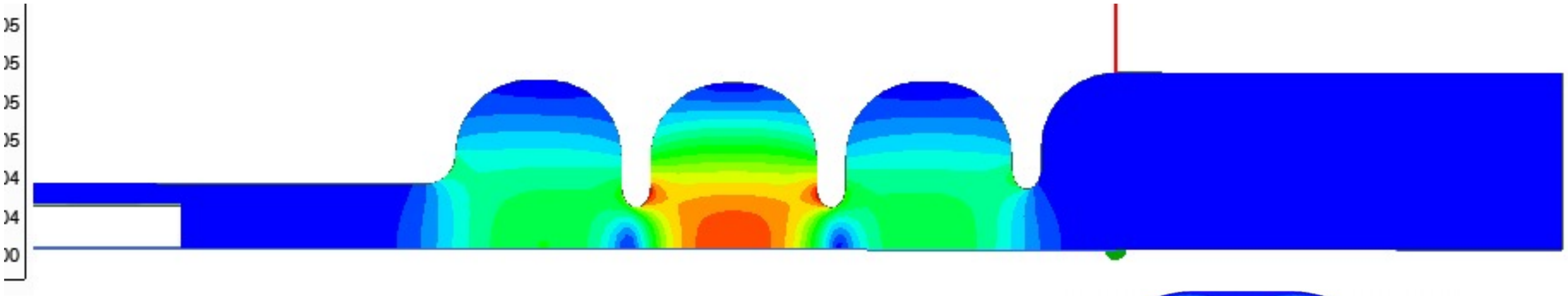
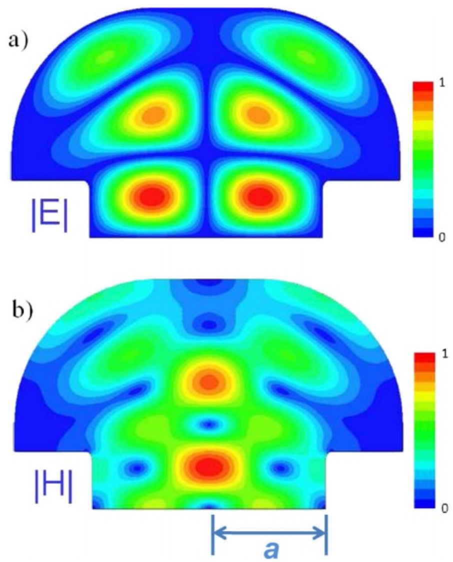
- 3-cell structure with optimized shape in **C-band**
  - Design under discussion, proceed to fabrication soon



- 1st tests at LANL
- Re-explore X-band pulsed heating with *cryogenic mushroom cavity?*



Future/parallel C-band RF research

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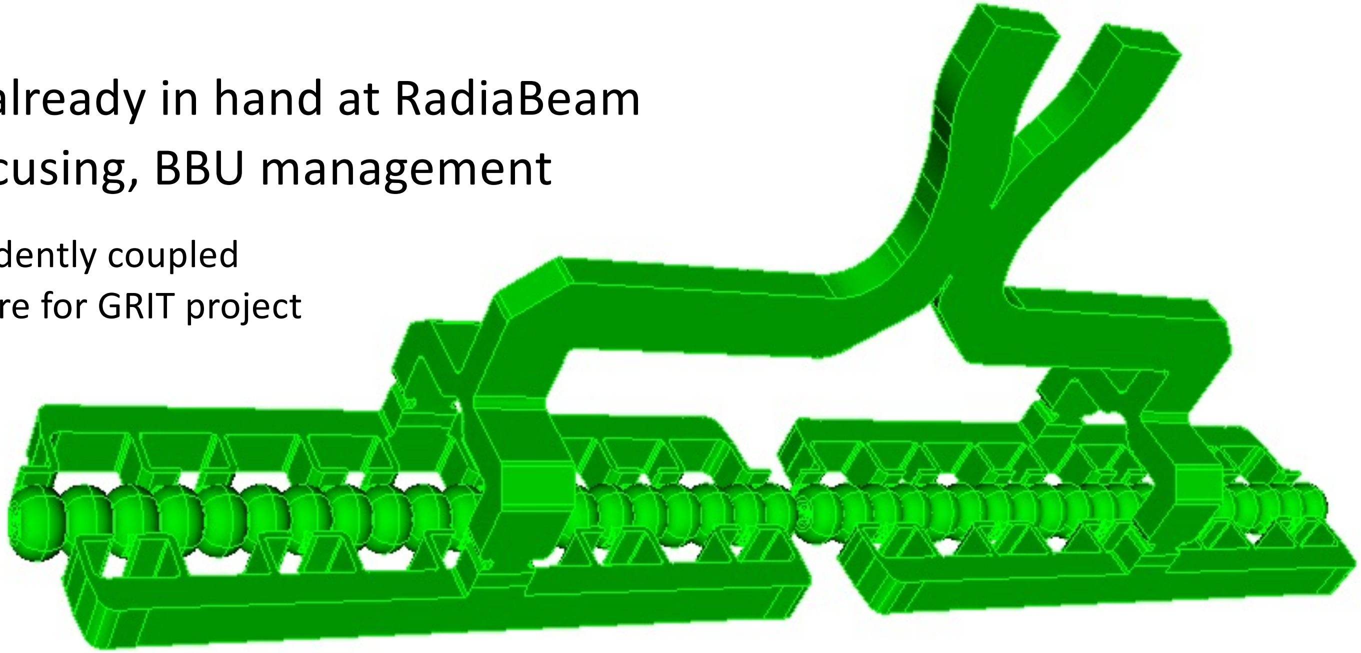
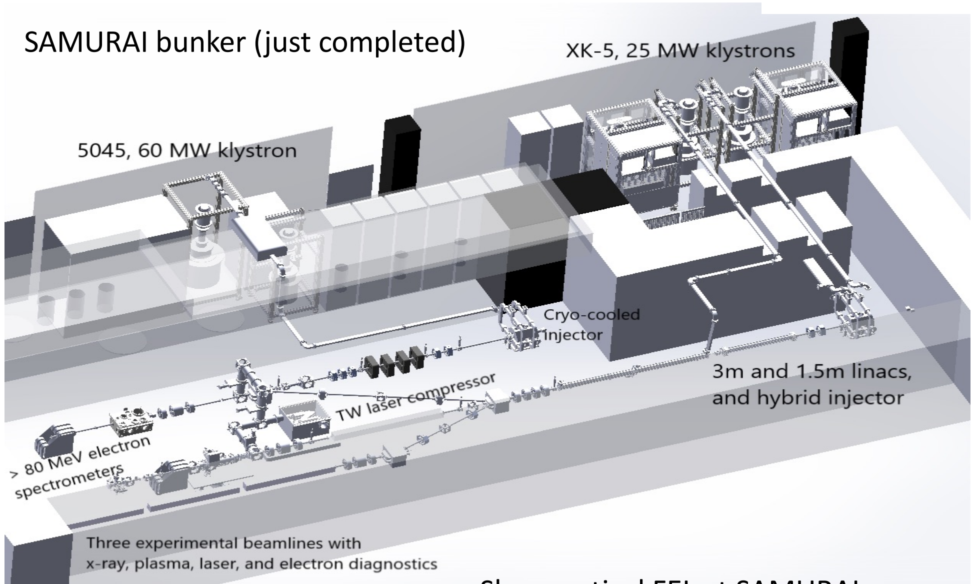
- ”Tantawi” structures under development at SLAC needed
  - Complete photoinjector dynamics process
  - Compact accelerator (8 m active length) for UC-XFEL
- Room temperature 50 MV/m, similar cavity shape, for DARPA GRIT compact ICS gamma project (RadiaBeam, SLAC, UCLA, U. Roma/INFN, LAL/Amplitude)
  - C-band klystron already in hand at RadiaBeam
  - Key issues: RF focusing, BBU management



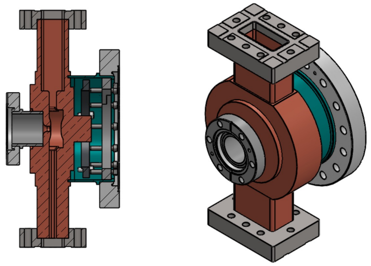
20x2 cell independently coupled
C-band RF structure for GRIT project

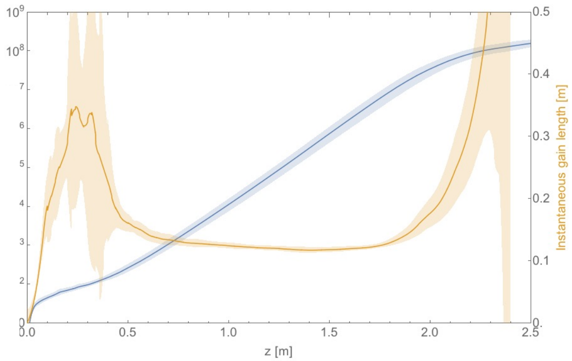
Leveraging the present to the future

- Bridge to ~$30M project needed
- UCLA SAMURAI Lab
  - $5M construction, $7M legacy eqpt.
- Investments from agencies
  - DOE HEP (injector); DARPA (C-band); NSF CBB (dynamics, cryo-emission test stand); DOE NNSA (MaRIE FEL)
- Utilize collaborative expertise
  - UCLA, SLAC, UCB, LANL, Cornell Roma, UNM, ASU, INFN, FAMU, PSI, RadiaBeam, Pulsar
  - Concentrate on key techniques
  - Cryo-RF gun and linac
  - IFEL and velocity bunching
  - Short period undulators
  - **Optical to EUV FEL**
- Fund first prototype UC-XFEL
  - Sloan Foundation proposal (pending)
  - NSF Midscale pre-proposal (may go to R2)



NSF CBB MOTHRAcryo-RF emission test stand





Sloan optical FEL at SAMURAI