UCLA

UCLA Research on C^3 (and connections to XFEL)

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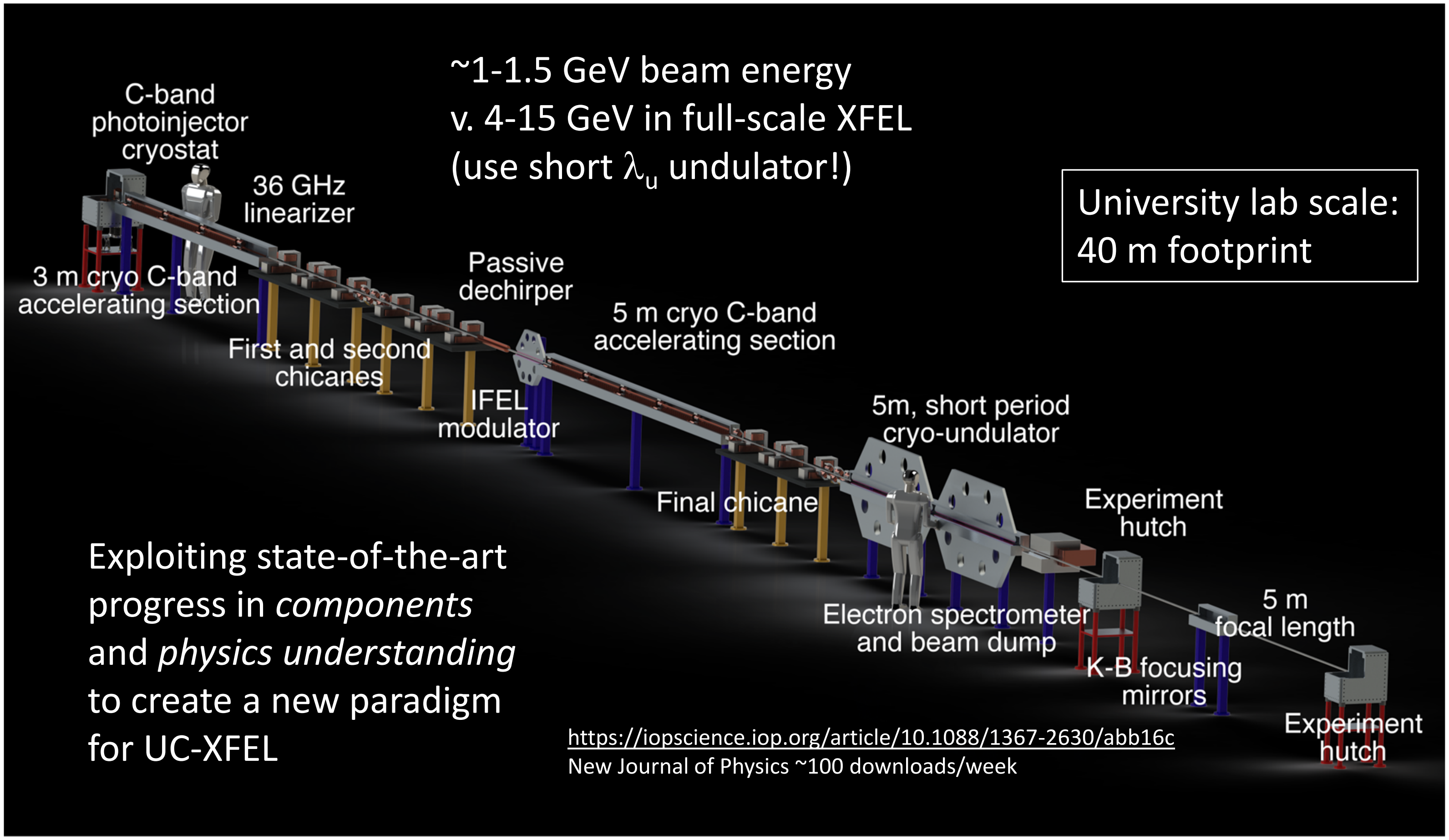
Future Collider Workshop

January 21, 2022

*Work supported by NS Award PHY-1549132, Center for Bright Beams and US DOE HEP grants DE-SC0009914 and DE-SC0020409

Vision of a university-scale UC-XFEL

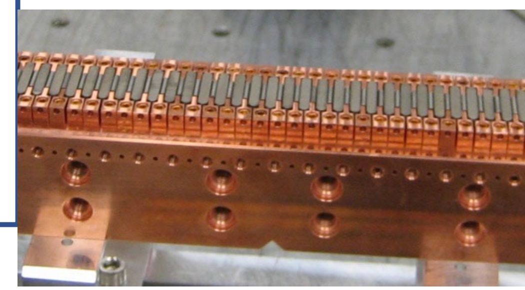


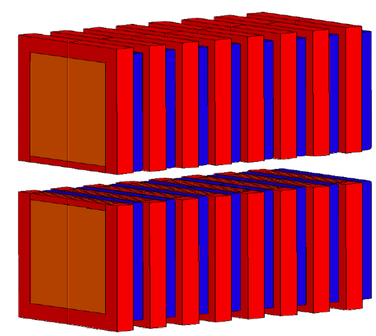
Very strong overlap with C^3 test facility

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 - the ”killer application”

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

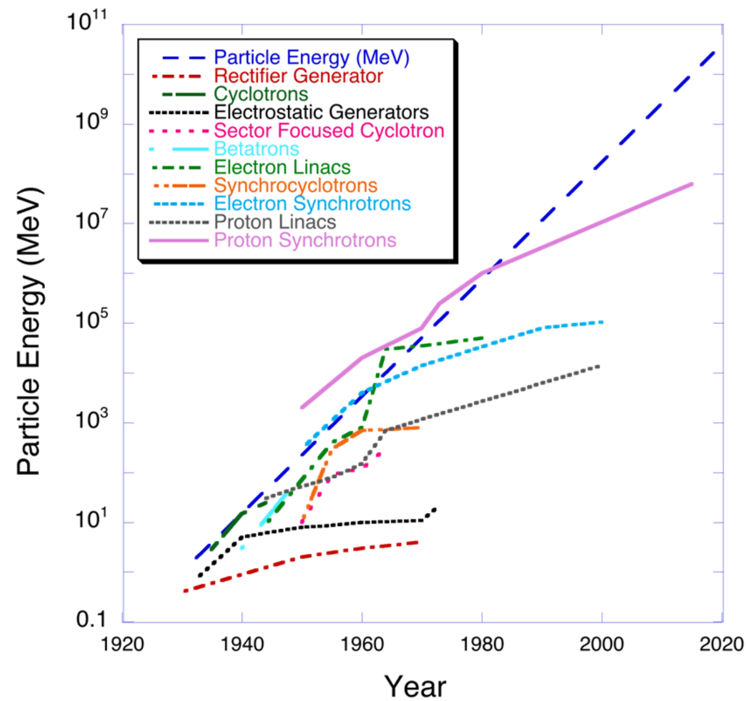




Hybrid cryo-undulator: Pr-based, SmCo sheath; ⎣ =9 mm up to 2.2 T

UC-XFEL as stepping stone for particle physics: pushing linear collider energy frontier

- Exponential growth over time in *available energy U*
  - Livingston plot: HEP "Moore's Law"
- Generational history
- Next generation will operate at much higher fields
  - **US GARD Panel**: regardless of technique **GV/m** for multi-TeV e+e-
  - **Fields higher by >30.** New methods needed
  - Exotic techniques: **plasma**, direct laser, dielectric, **advanced RF**
  - **There is a long road to GeV/m**
    - **Multi-TeV plasma collider >2050 (Snowmass)**
    - **How do we move strategically?**



Actual energy *Livingston plot* showing Moore's law for HEP discoveries

Compact XFEL is intertwined with future colliders

- Major investments in “factory” scale XFEL (European XFEL, LCLS-II) counter-balanced by **5th generation-inspired** initiatives
  - *BELLA* laser-plasma accelerator
  - *EuPRAXIA* plasma accelerator FEL, “stepping stone” to HEP
    - On ESFRI roadmap, 300MEuro project hitting the real axis
  - *CompactLight*, X-band RF spin-off from CERN


EuPRAXIA proposed campus at INFN-LNF (Frascati)

nature › articles › article

Article | Published: 25 May 2022

Free-electron lasing with compact beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, M. P. Anania, S. Arjmand, M. Behtouei, M. Bellaveglia, A. Biagioni, B. Buonomo, F. Cardelli, M. Carpanese, E. Chiadroni, A. Cianchi, G. Costa, A. Del Dotto, M. Del Giorno, F. Dipace, A. Doria, F. Filippi, M. Galletti, L. Giannessi, A. Giribono, P. Iovine, V. Lollo, A. Mostacci, … M. Ferrario + Show authors

Nature **605**, 659–662 (2022) | Cite this article

4171 Accesses | **7** Citations | **50** Altmetric | Metrics

- Ultra-Compact XFEL (***UC-XFEL***) collaboration
  - Decade-long effort based on investments from DARPA, Keck, NSF, DOE
  - Extremely attractive new paradigm *for XFEL-as-university-lab-laser*
  - *Ecumenical community for new accelerator technologies*

The Ultra-Compact FEL Design Realized

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

Deutsche Physikalische Gesellscha

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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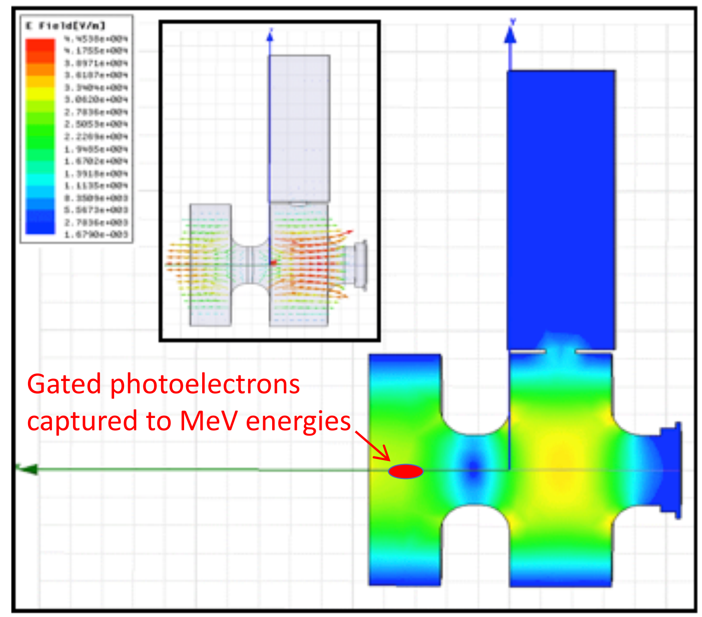
New Journal of Physics, Volume 22, September 2020

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

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

- Laser gating to fs-to-ps level
- RF capture – violent acceleration
- Preserve phase space structure
  - Control pulse expansion
  - Minimize emittance growth
- Frontier RF engineering
- Photocathode physics
- Advanced laser techniques
- Apply to linear collider source
- ***Key technology is high field acceleration***

Rethink points in red when fields are much enhanced.



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

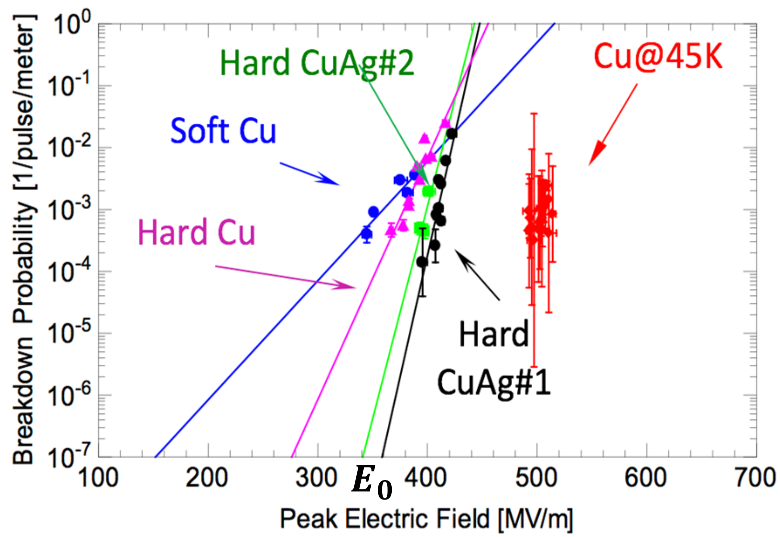
High gradient acceleration at cryogenic temperature

- 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**

$$B_{6D} \propto \boldsymbol{E}_{\mathbf{0}}^{\mathbf{5/2}}$$

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

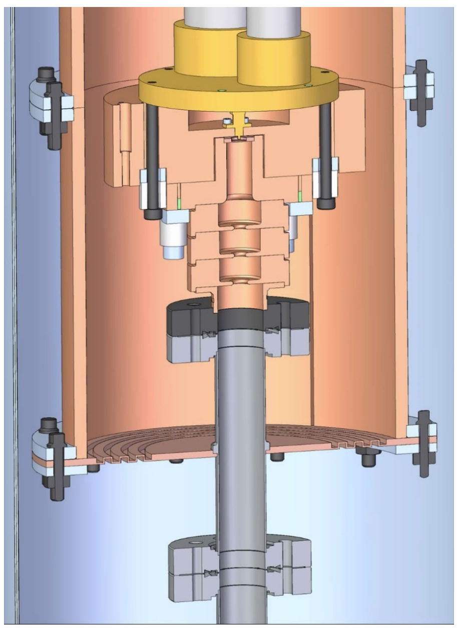
A. D. Cahill, et al., *Phys. Rev. Accel. Beams* 21, 102002 (2018)

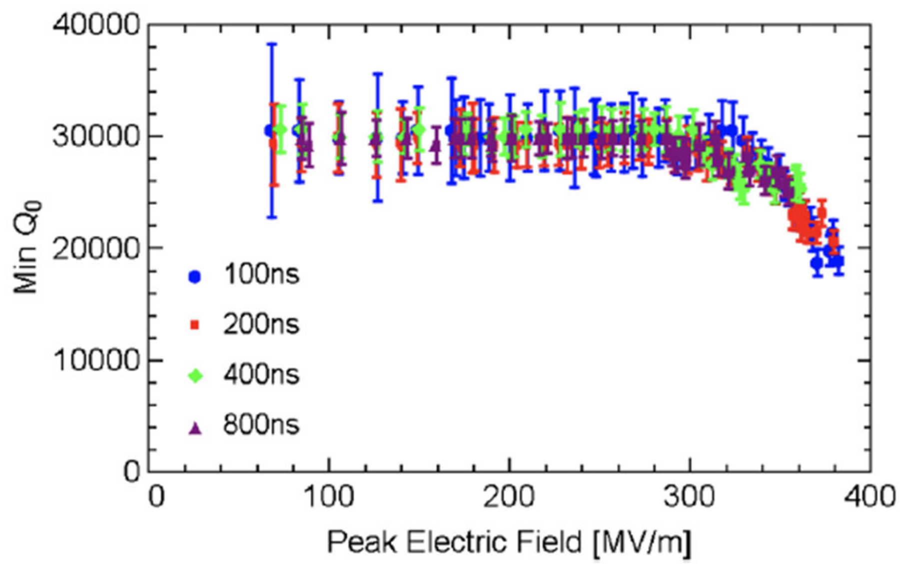


Practical concern: dark current emission

- 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





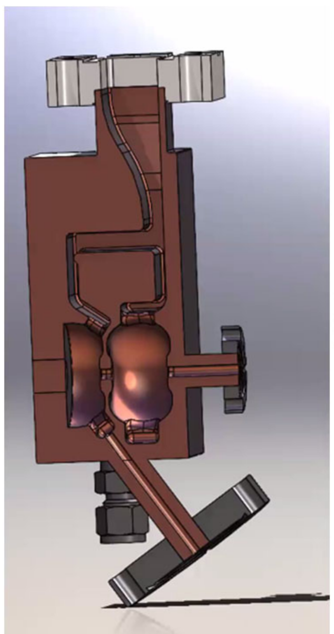
A. D. Cahill, et al., *Phys. Rev. Accel. Beams* 21, 061301 (2018)

Dark current emission loads cavity >300 MV/m

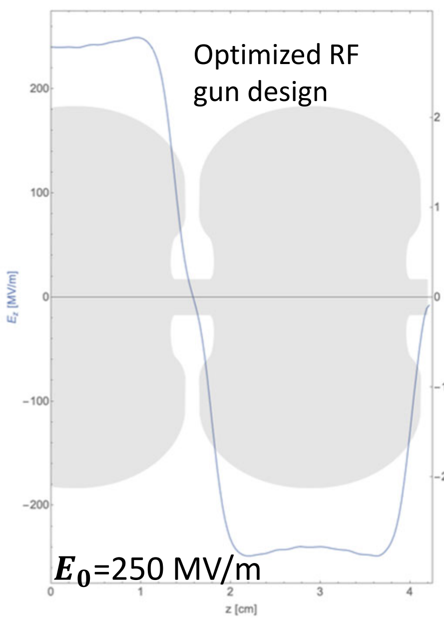
UCLA C-band Cryogenic Photoinjector Project

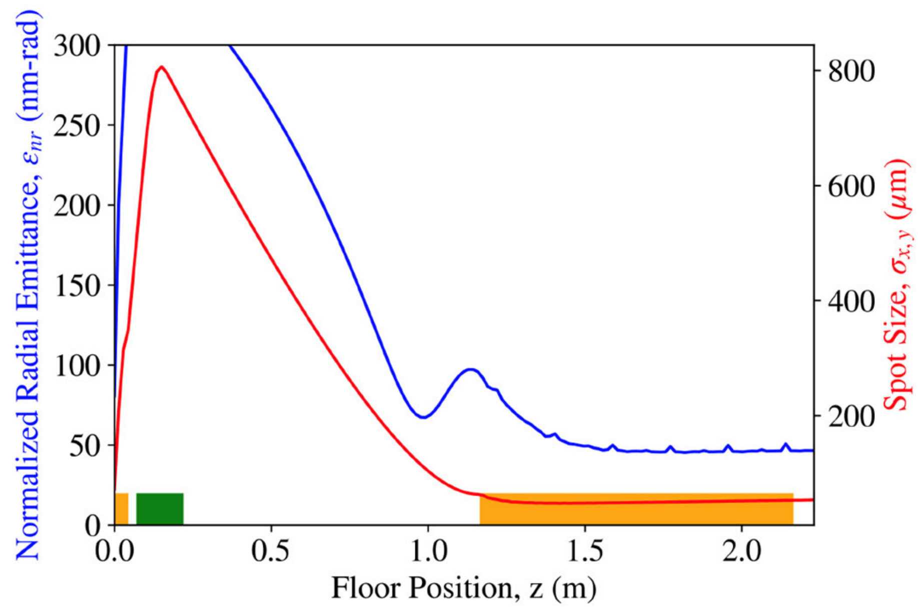
- Cryogenic C-band photoinjector at extreme high brightness for FEL

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



On to *realization*
(joint work w/SLAC and LANL)



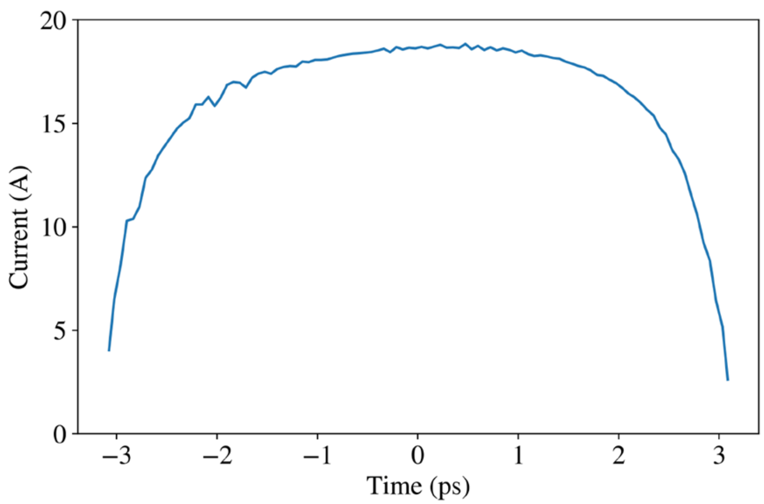


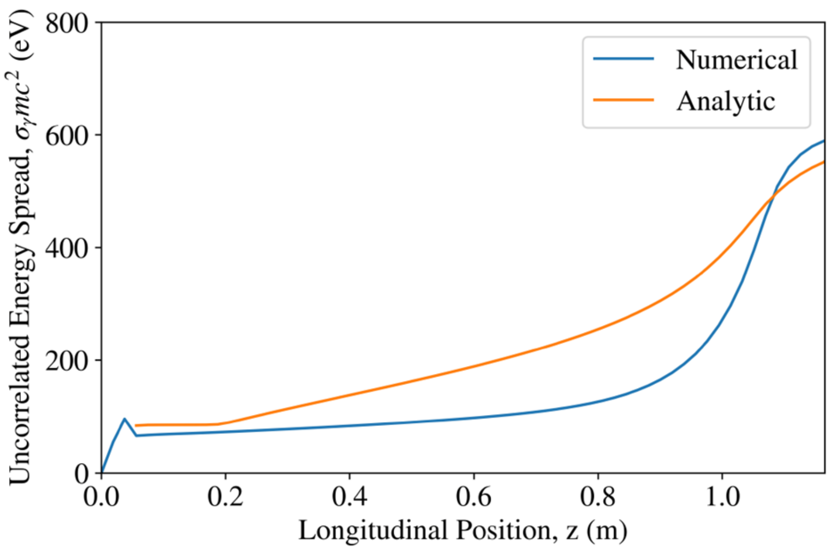
R. Robles, et al., Phys. Rev. Accel. Beams 24, 063401 (2020)

Enhanced 6D Brightness with high field

UCLA

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



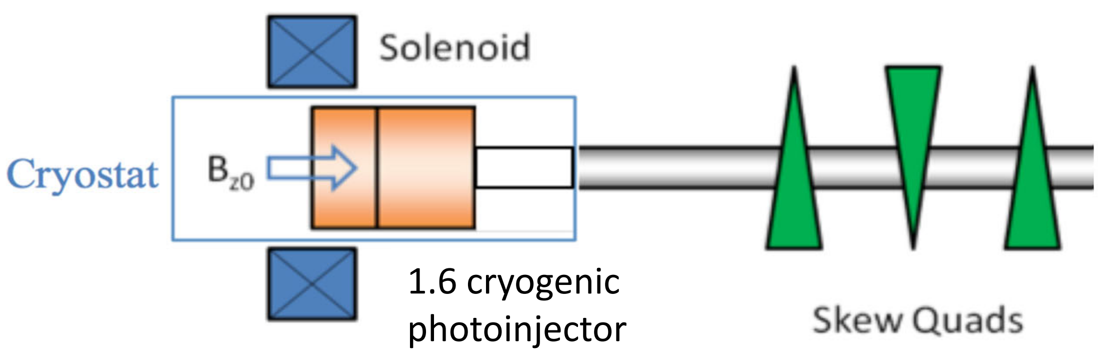


Record 6D brightness predicted, factor of >40 above original LCLS

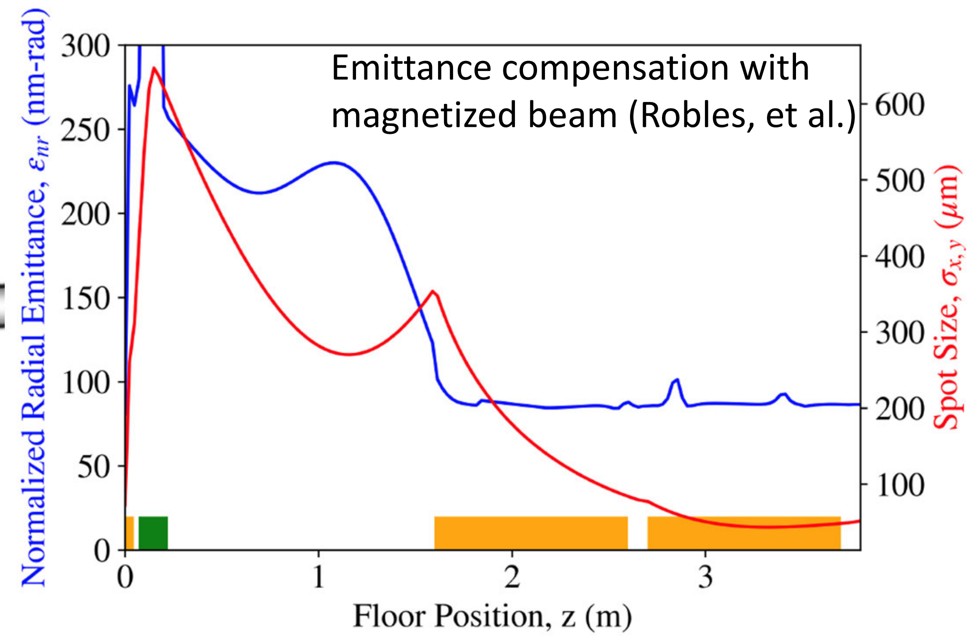
-IBS implications for beam compressibility in UC-XFEL and C^3
- Experiments planned at UCLA with cryo-RF gun

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

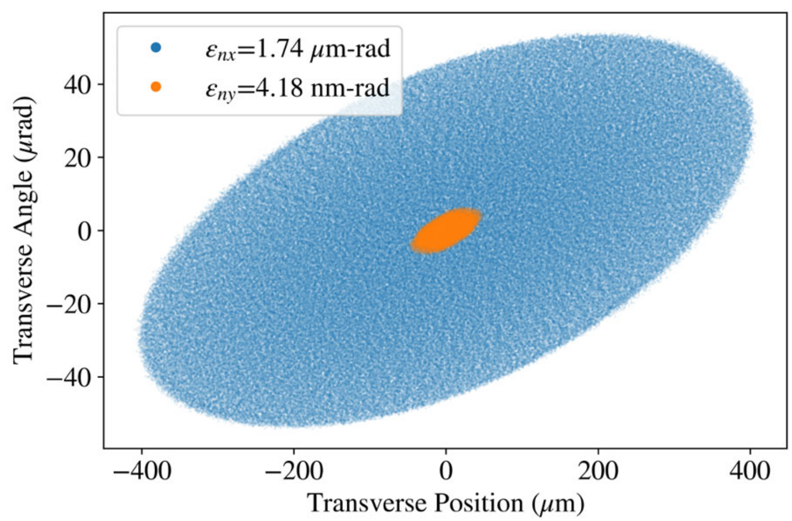


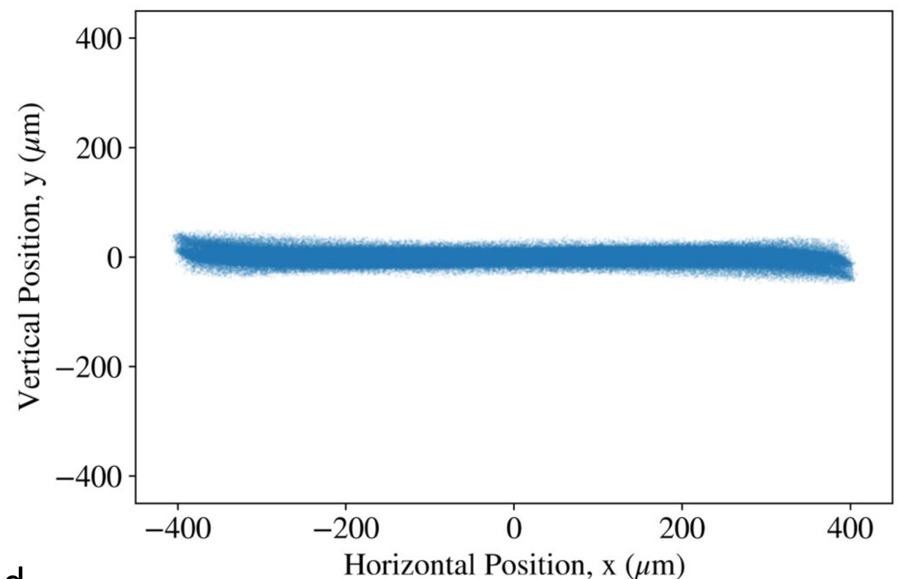
Angular momentum $\mathcal{L} = (eB_0/2m_ec)\sigma_0^2$



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
- Very high brightness test beams for BBU studies, P-O-P on emittances

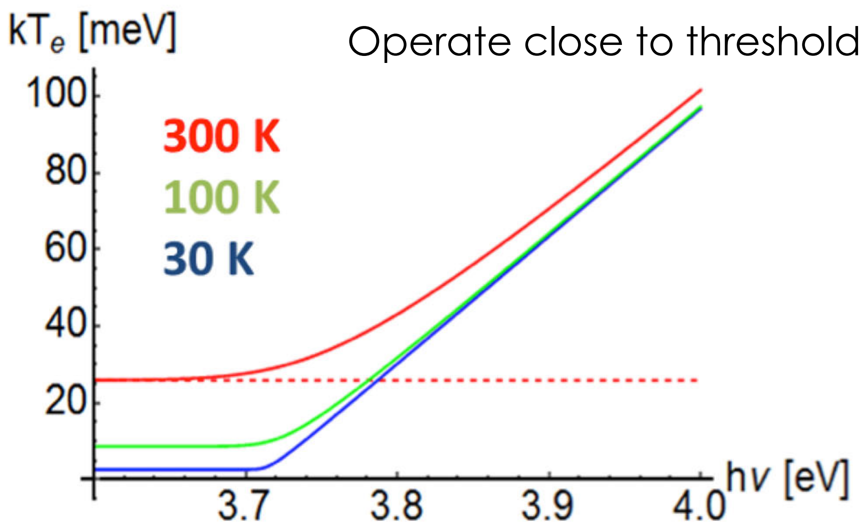


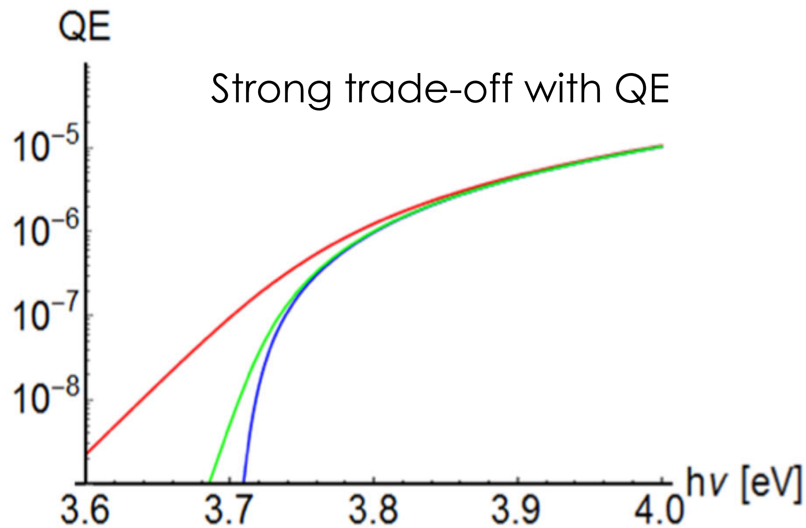


C-band implies low charge (0.25 nC). Higher Q -> S-band

Extending brightness frontier: lower emission temperature

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



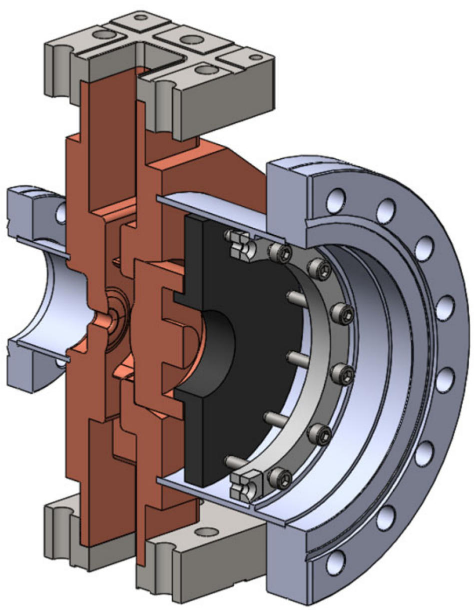


Issue: two-photon and heating effects due to high laser power

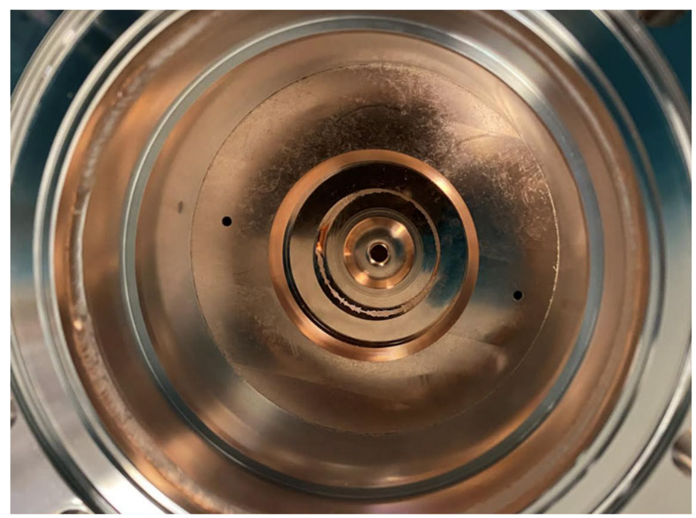
Half-cell cryogenic photo-emission test stand

UCLA

- 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. *Look to add polarized e- capabilities.*



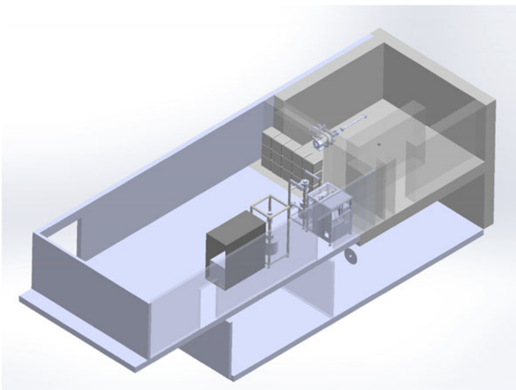
0.5 cell gun with copper cathode (no load lock)
Under construction (support from NSF CBB)



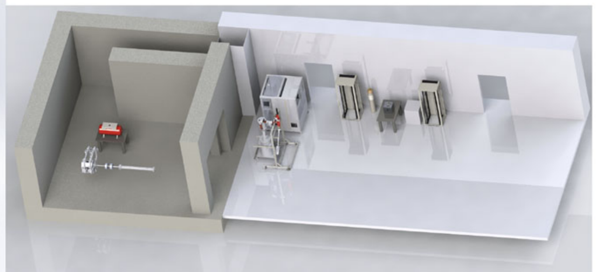
Gun after construction

Development of UCLA C-band infrastructure

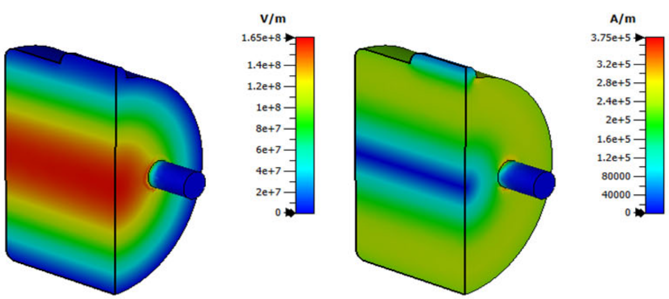
- RF and cryo-emission testing at UCLA MOTHRA Lab

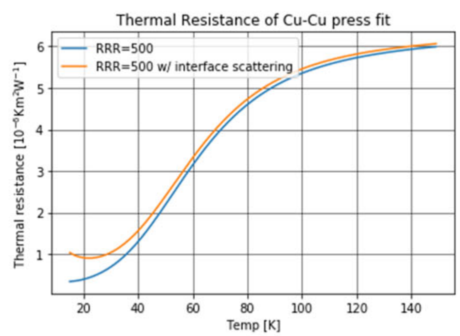


MOTHRA layout



Cryo-emission beamline



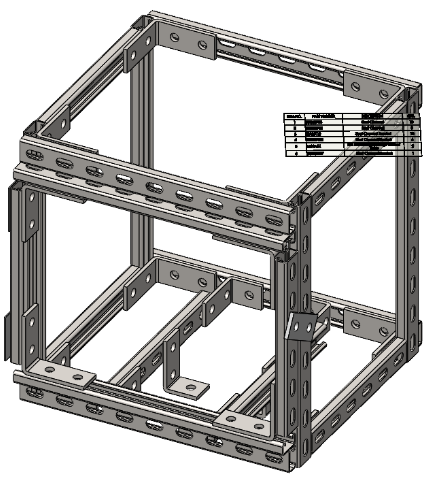


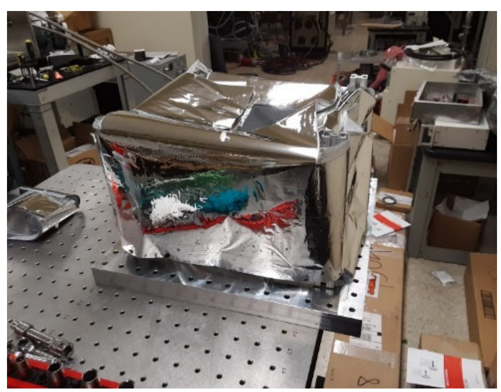
Pill-box testing for CuAg, deviations from ASE

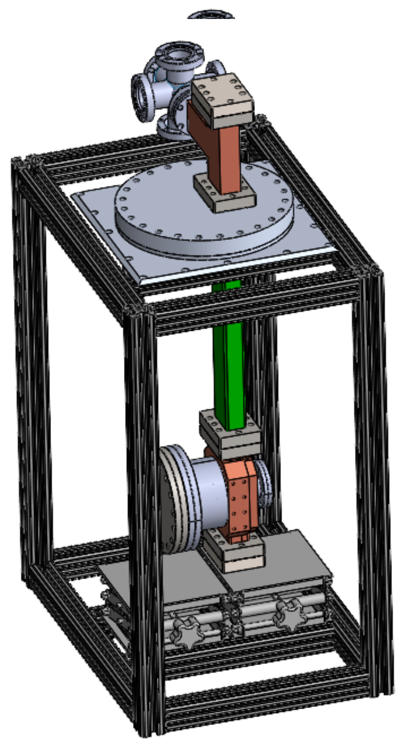
C-band klystron from SLAC recommissioned at MOTHRA.
SLED system development this year.

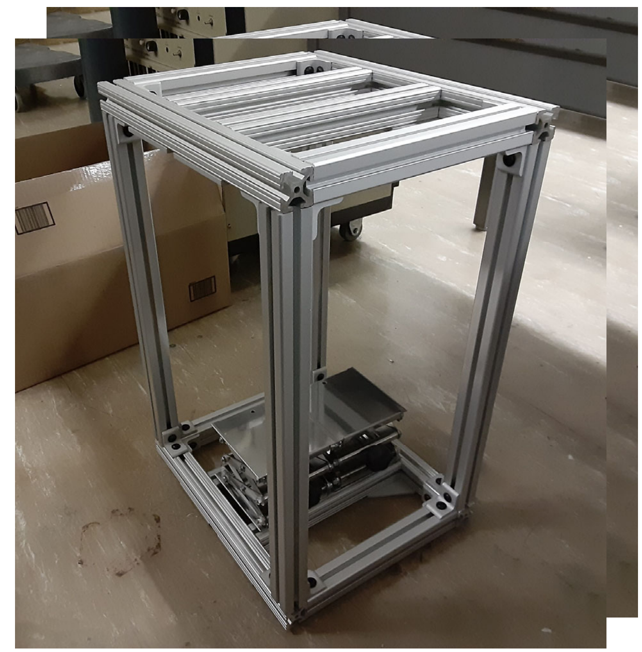
Cryostat Development

- Extra shielding layer for cryostat
- Current minimum temperature for both 40-45K range <1 hour with improvements underway





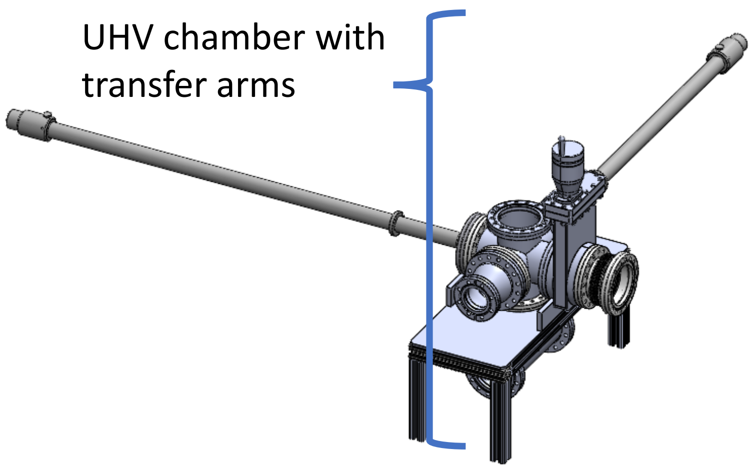


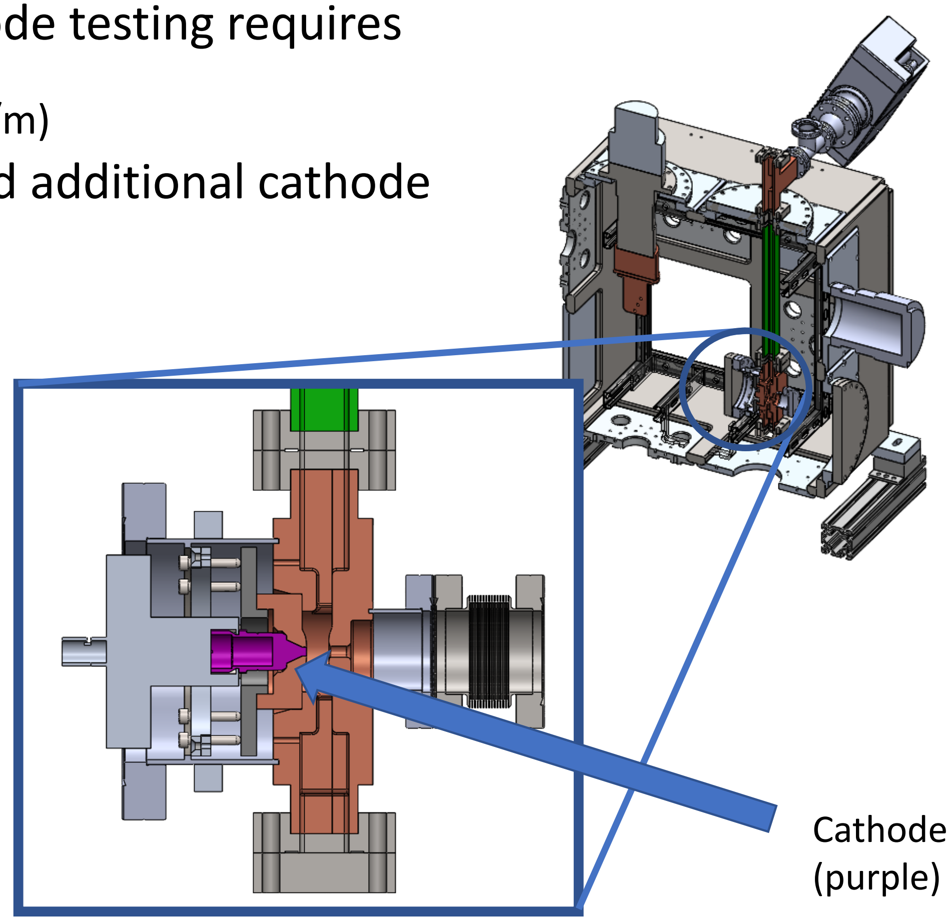


Deployment of 0.5 cell gun in cryostat

Cathode Load Lock Chamber

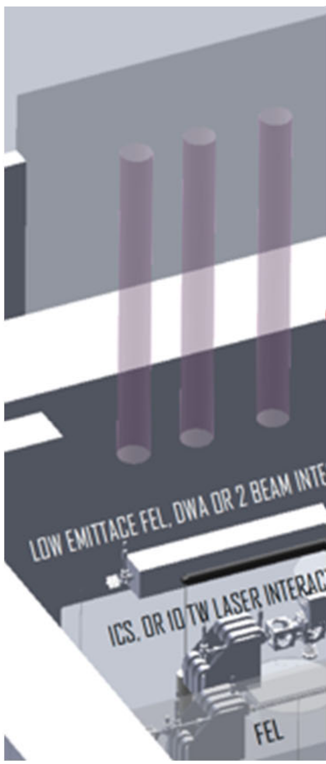
- Long term use of CYBORG for cathode testing requires UHV chamber ($<10^{-10}$ torr)
  - Consistent with polarization (120 MV/m)
- Development of pumping setup and additional cathode plug manipulator studies needed
- First tests with Cs_2Te

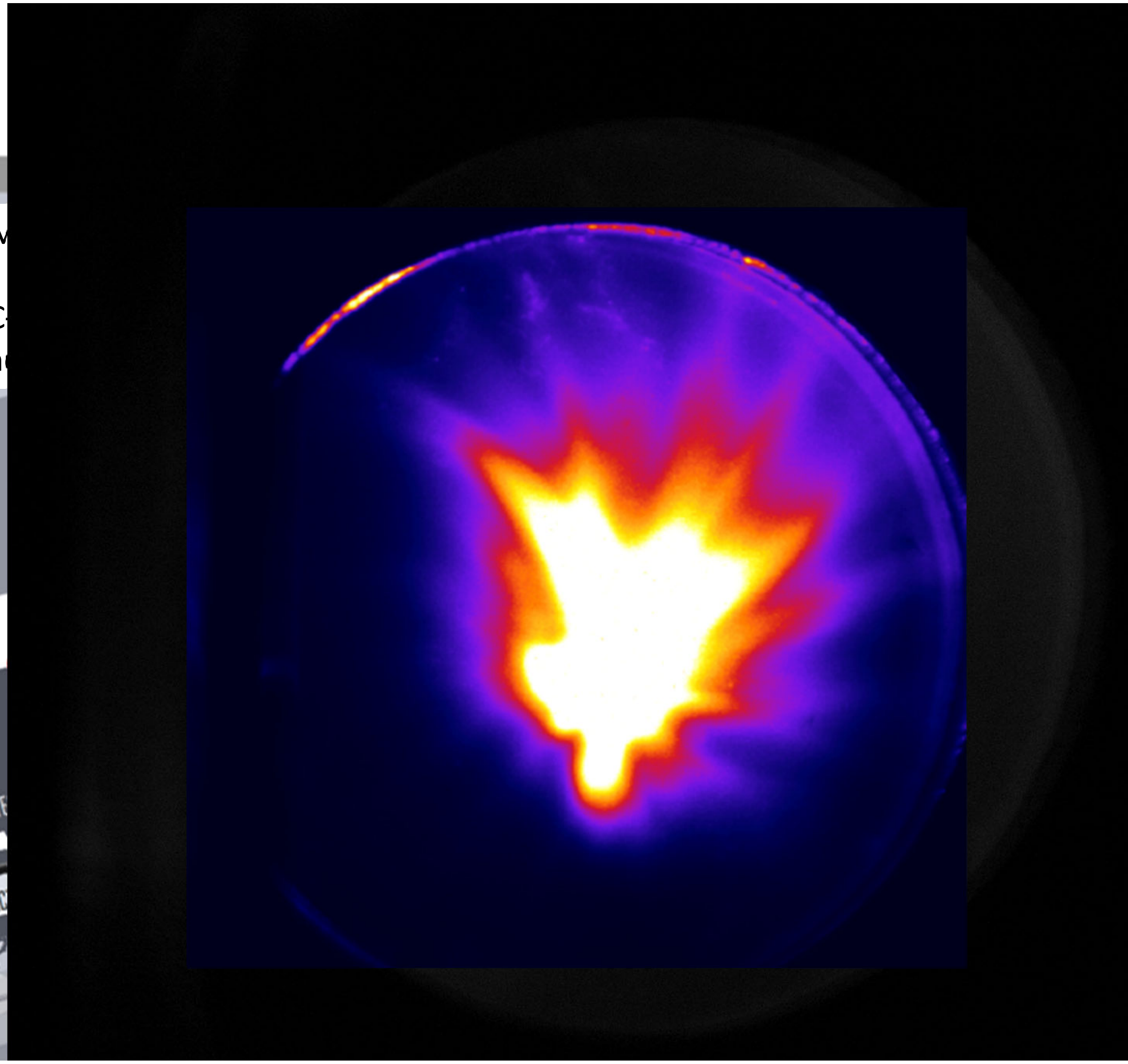


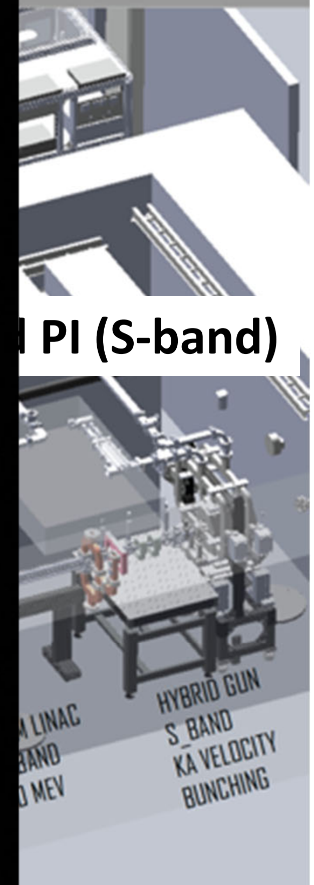


New UCLA

MITHRA Lab: 100 M
HEP advanced
accelerator and UC
(beam commission







PI (S-band)

compression

Beam Dynamics for Short Range BBU (F. Bosco)

Short range wakefield modeling

- Off-axis particles **excite** dipole wakes
- Trailing articles behind experience a transverse momentum **kick**
- Include damping, detuning, misalignments, tilts…

Very strong focusing effects

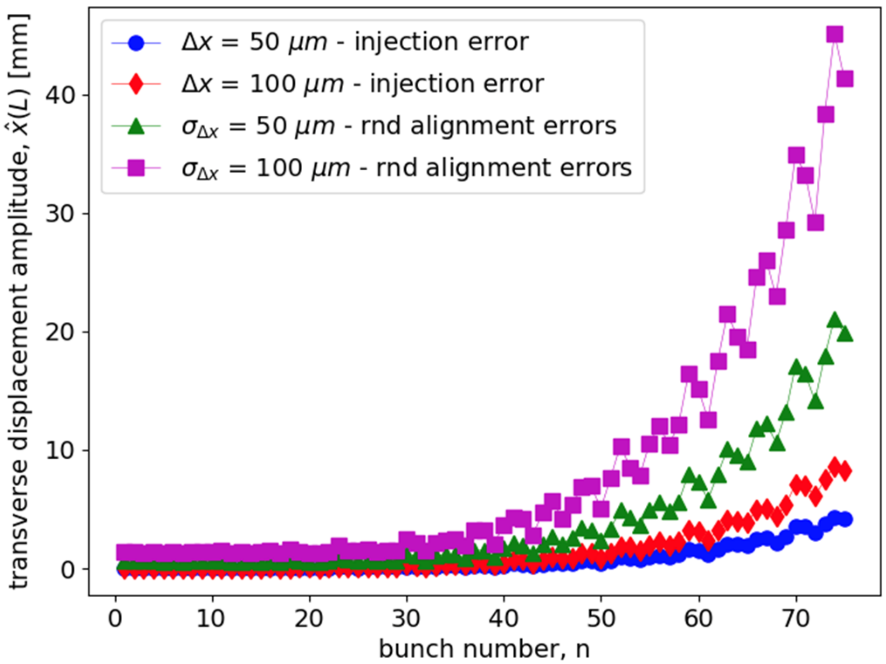
- Second order RF AG focusing
- Amplifies BBU at lower energis

Direct space charge forces

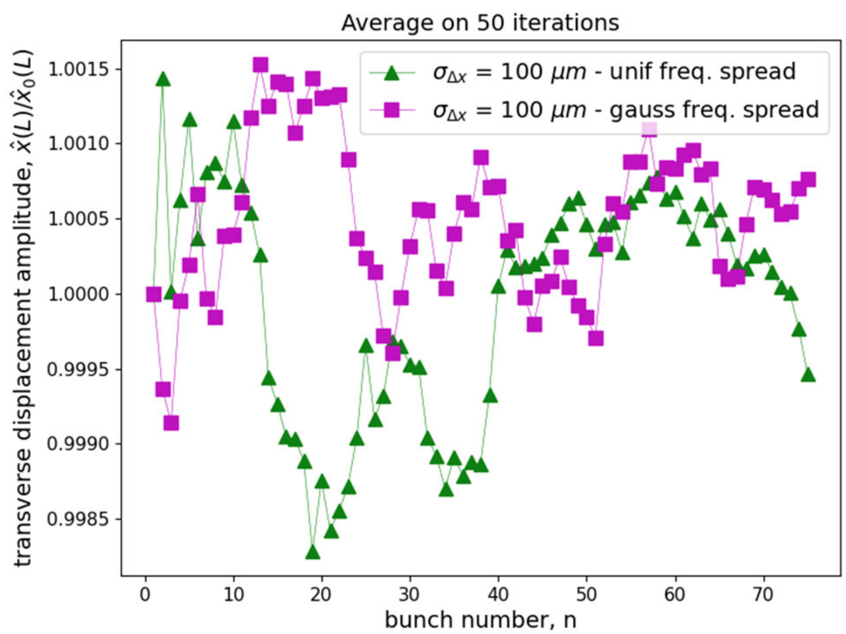
- Electromagnetic fields produced by the charge distribution
- Defocusing force requires changing of optics settings

C^3 simulations

Study effects of frequency detuning

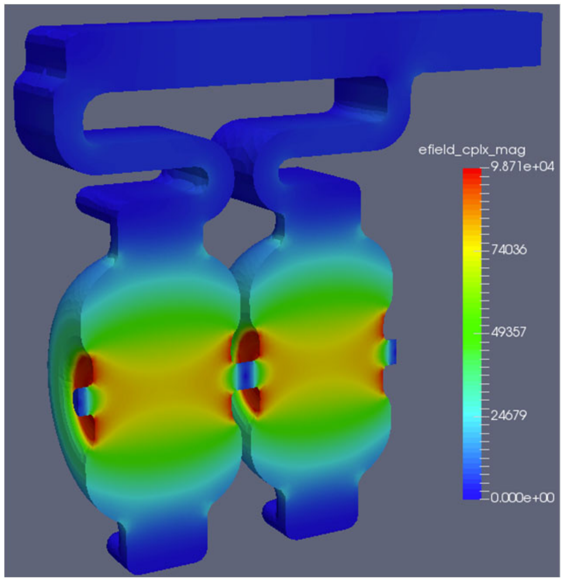


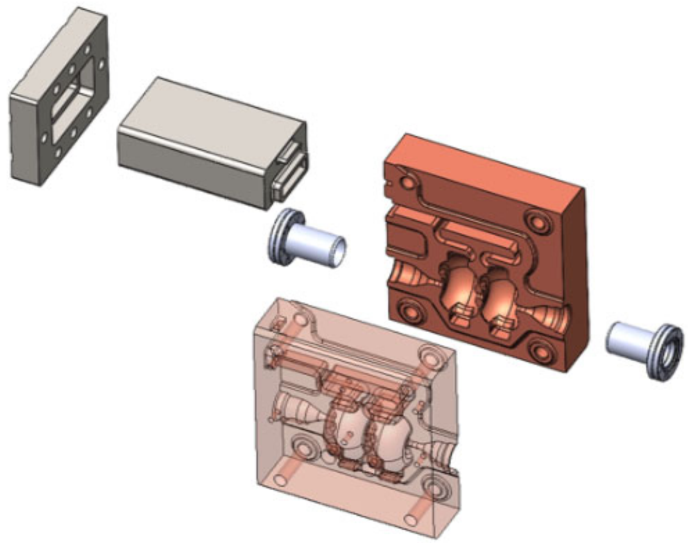
Large growth, mitigation needed



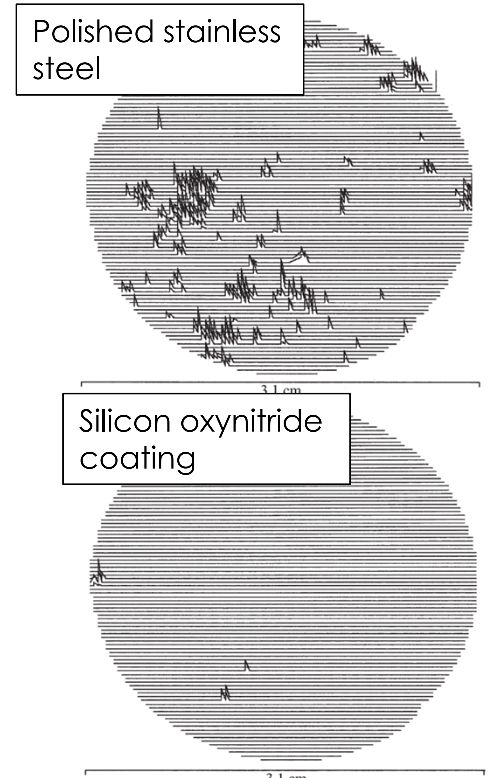
Gaussian (0.3%) and uniform
Detuning highly effective

Next steps in *fundamental* cryo-RF R&D





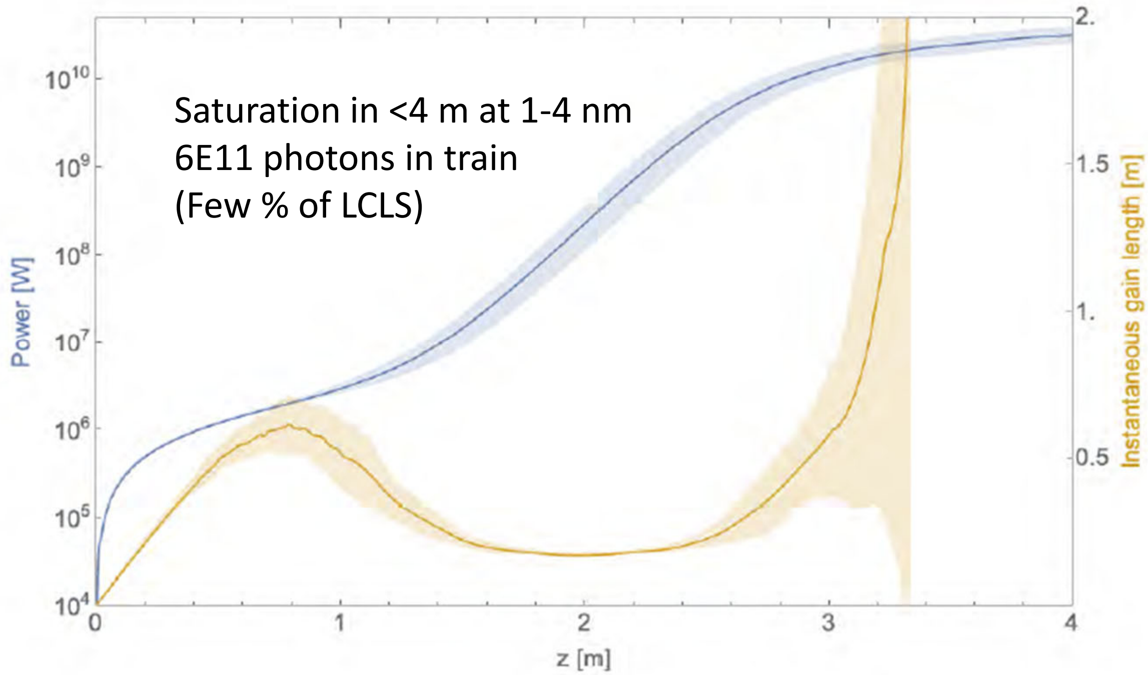
- 2-cell very high gradient (>500 MV/m surf.) tests at LANL
- Design by Zenghai Li
- UCLA fabrication, bonding (w/Tantawi)
- Explore CuAg (now in cold-test stage with pill-boxes
- Coatings for dark current



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

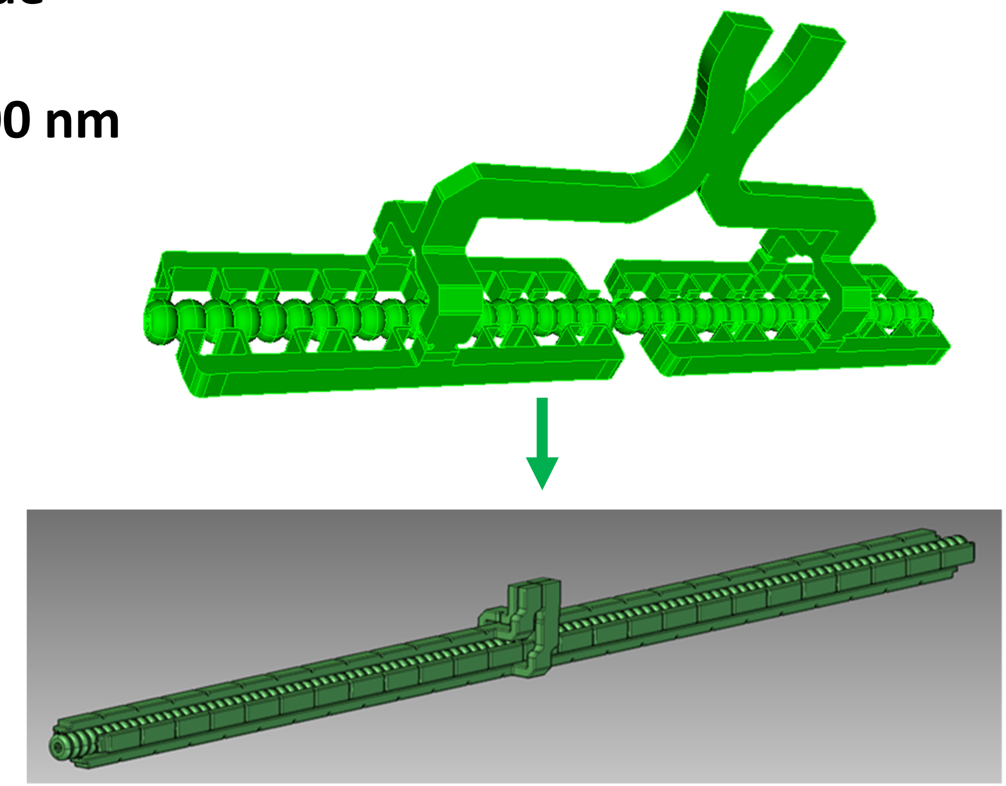
Beyond soft X-rays– next step UC-XFEL

- Impressive case for coherent soft X-ray use in basic research
- Many users would like harder X-rays, including industrial partners



A Tomographic Ptychography UC-XFEL

- **Next generation of semiconductor inspection instruments can utilize coherent X-rays in ptychographic mode**
  - **Industry, DARPA interest expressed**
- **Scanning cm-scale 3D objects with 100 nm**
- **Rethink Angstrom design**
  - **New linacs (even room temp.)**
  - **Short wavelength IFEL compressors**
  - **Brightness frontier exploratiino**
  - **Wakefields and BBU (incl. long range)**
- **New ARDAP proposal (LOI today)**
- **UCLA, SLAC, RBT**
  - **Cornell, LANL TBD**



135 degree phase advance structures

Future “5th generation” light source discussions

- Next version of *”Physics and Applications of High Brightness Beams”* ICFA workshop, June 19-23, 2023, San Sebastian, Spain
- Nexus of HEP advanced accelerators, lights sources and bright beams