The Ultra-Compact X-ray Free-electron Laser: Connections to C^3

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Vision of a university-scale UC-XFEL

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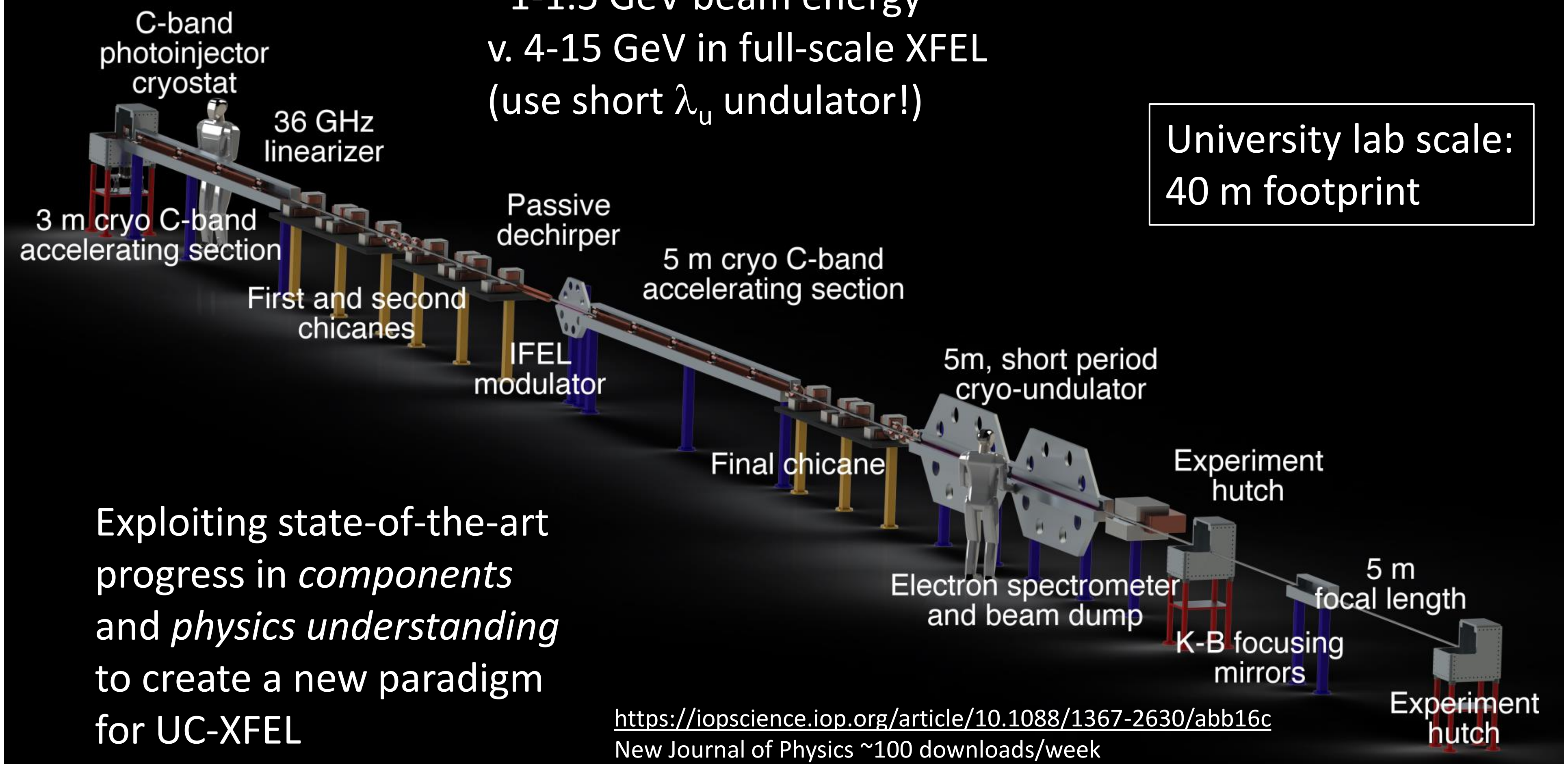
~1-1.5 GeV beam energy
v. 4-15 GeV in full-scale XFEL
(use short λ_u undulator!)

University lab scale:
40 m footprint



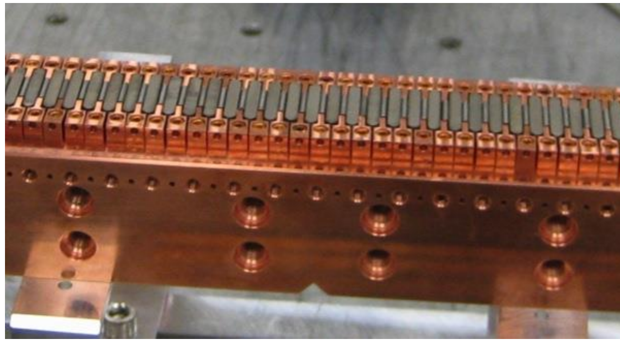
Exploiting state-of-the-art progress in *components* and *physics understanding* to create a new paradigm for UC-XFEL

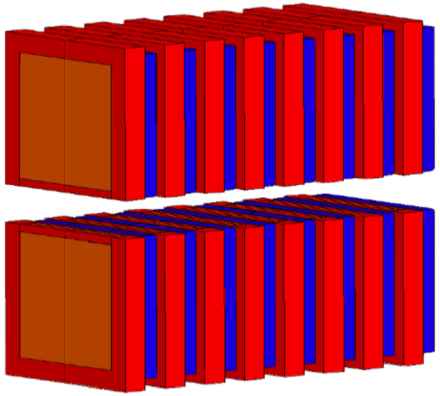
https://iopscience.iop.org/article/10.1088/1367-2630/abb16c
New Journal of Physics ~100 downloads/week

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

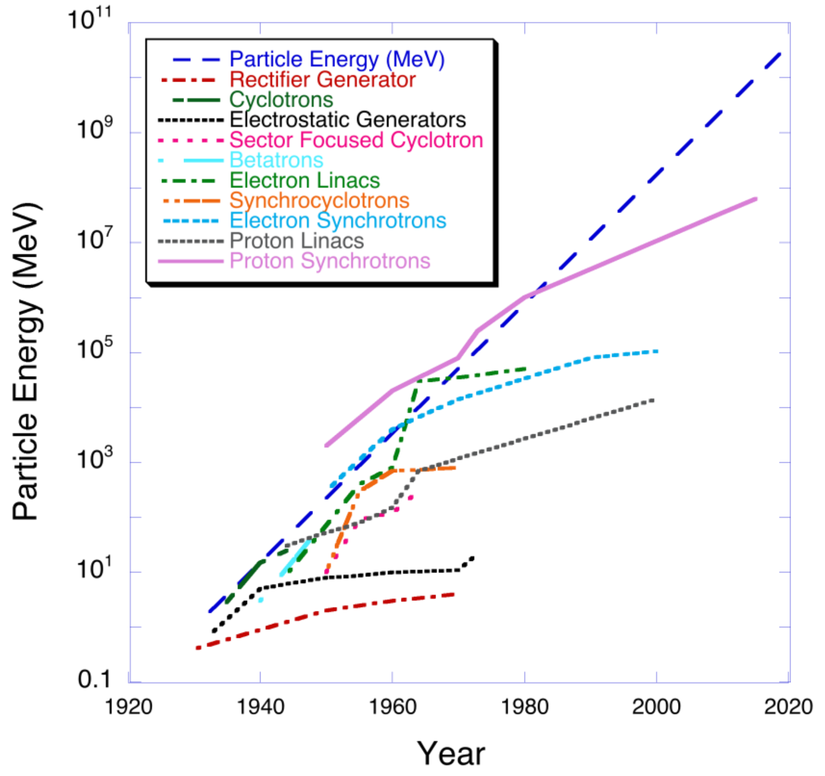




Hybrid cryo-undulator: Pr-based, SmCo sheath; ⌊ =9 mm up to 2.2 T

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

- Exponential growth over time in *available energy U*
  - Livingston plot: "Moore's Law" for accelerators
- 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 >2035**
    - **How do we move strategically?**

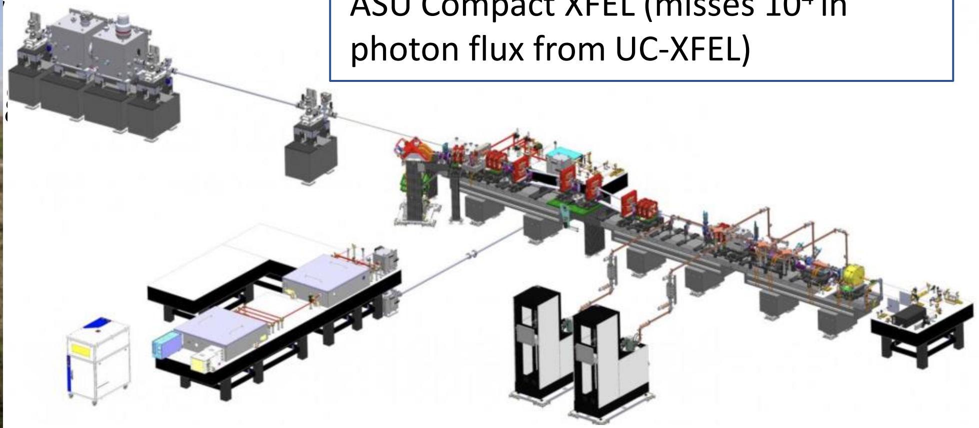


Livingston plot showing Moore's law for HEP discovery

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
  - *Arizona State Compact XFEL*
- Ultra-Compact XFEL (***UC-XFEL***) collaboration

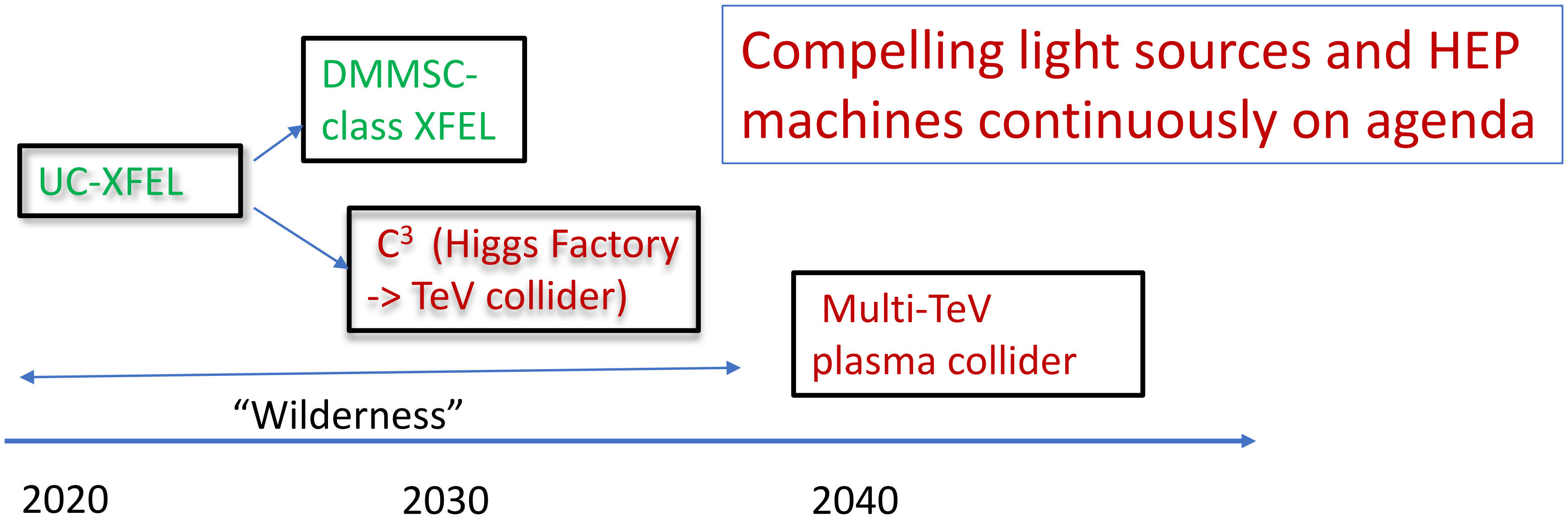
EuPRAXIA proposed campus at INFN LNF (Frascati)



ASU Compact XFEL (misses 10^4 in photon flux from UC-XFEL)

A joint road map:
UC-XFEL, large scale XFEL and linear colliders

- The path to plasma linear collider is long (-2040).
- Technological *and physics* stepping stones are needed to maintain continuous interest
  - EuPRAXIA is existence proof for stepping stone concept viability
  - Plasma-based FEL is not a very high quality light source
  - Plasma-based FEL does not aid HEP horizon immediately
- UC-XFEL aids effort in cold copper collider
  - Full scale FEL frontiers as well



The Ultra-Compact FEL Design Realized

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An ultra-compact x-ray free-electron laser

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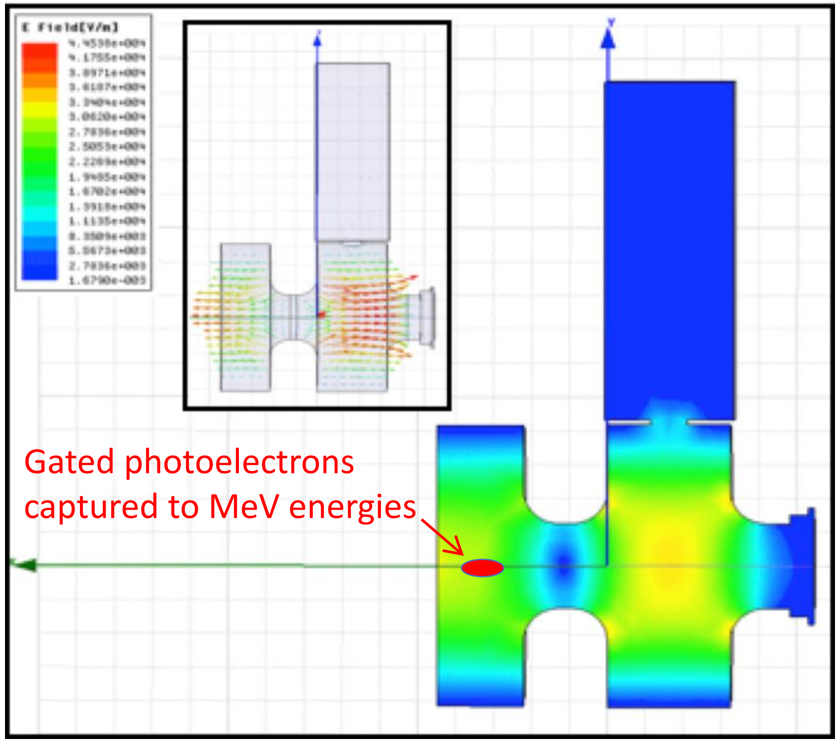
FEL begins life with high brightness electron beam source: *the RF photoinjector*

- 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
- *Key technology is high field acceleration*



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

Rethink points in red when fields much enhanced.

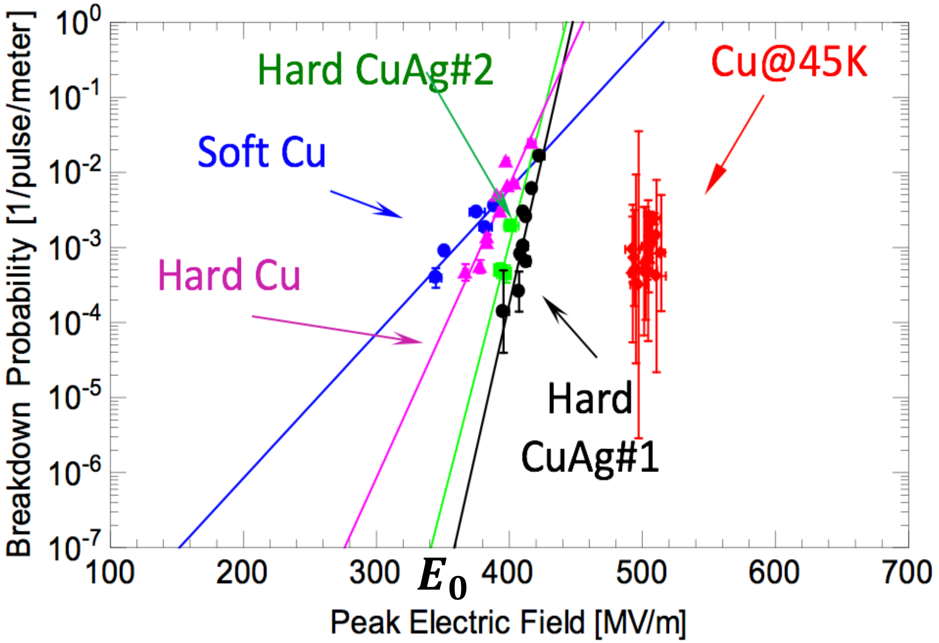
High gradient acceleration at cryogenic temperature

- 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**

$$B_{6D} \propto E_0^{5/2}$$

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

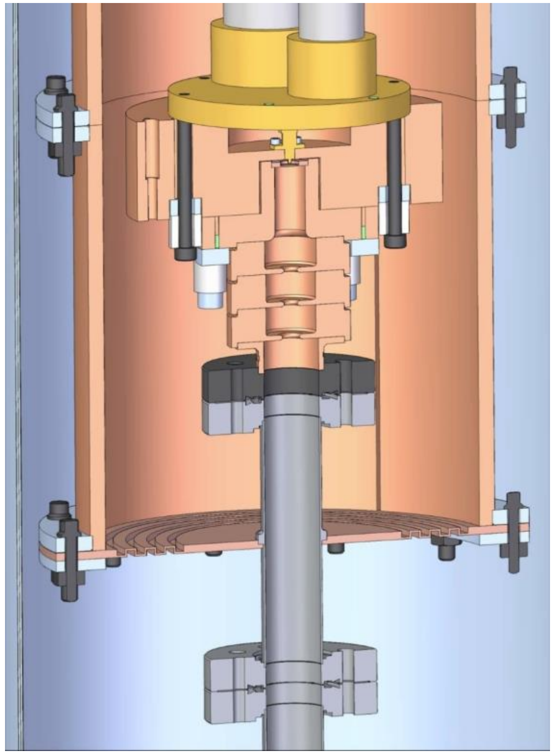
A. D. Cahill, et al., *Phys. Rev. Accel. Beams* 21, 102002 (2018)

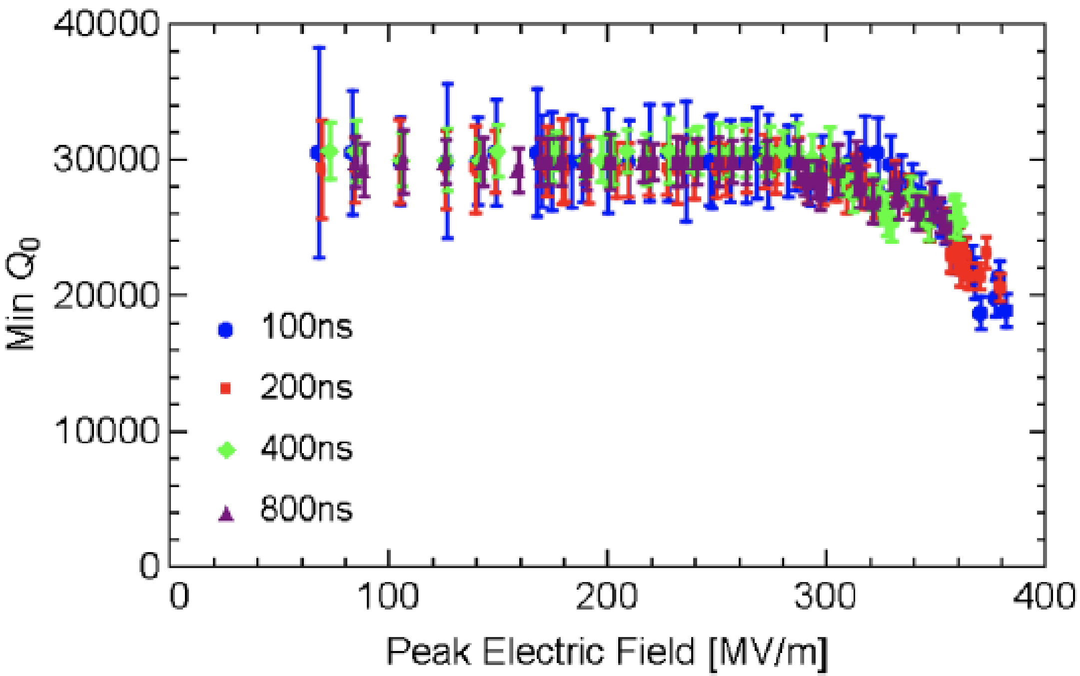


Practical concern: dark current emission

- 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





Dark current emission loads cavity >300 MV/m

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

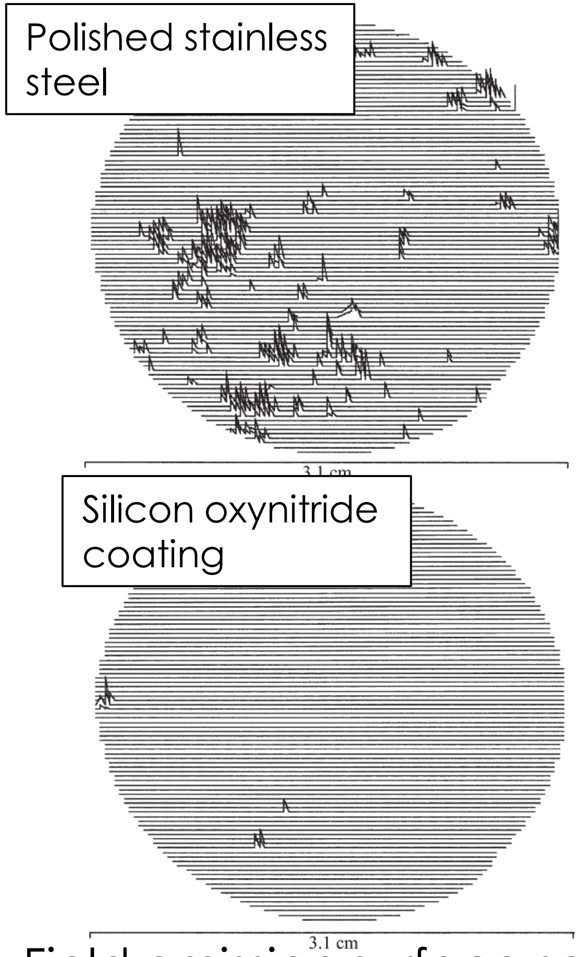
Must Meet Challenges of Dark Current

UCLA

- Fowler-Nordheim emission

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

- Field enhancement factor $\beta(s)$ 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

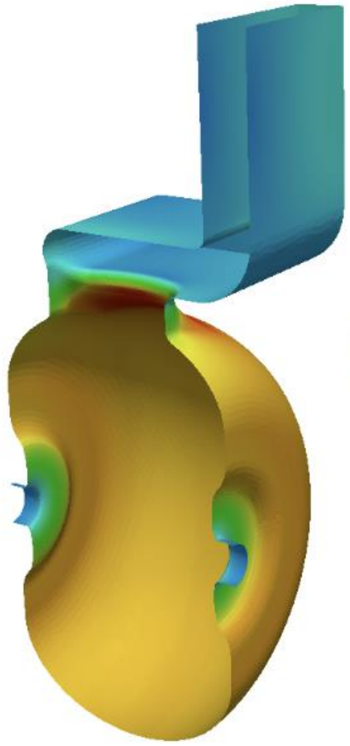


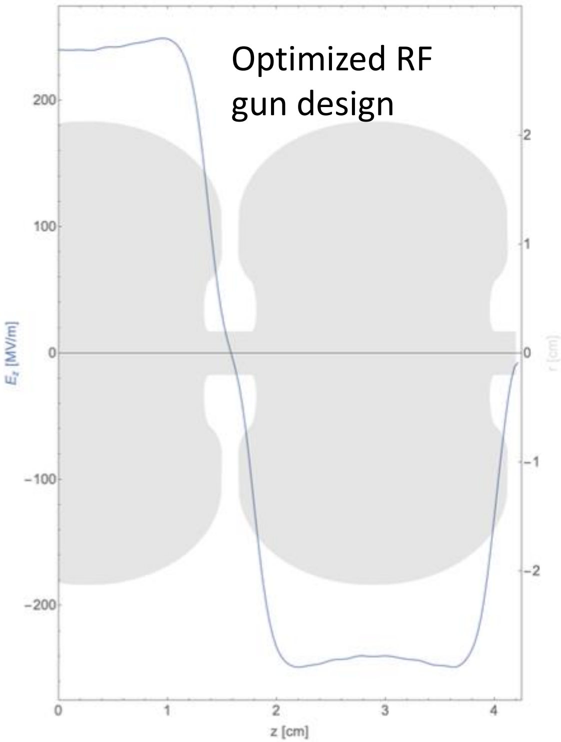
Field emission surface scan for SiNO (Theodore et al.)

UCLA C-band Cryogenic Photoinjector Project

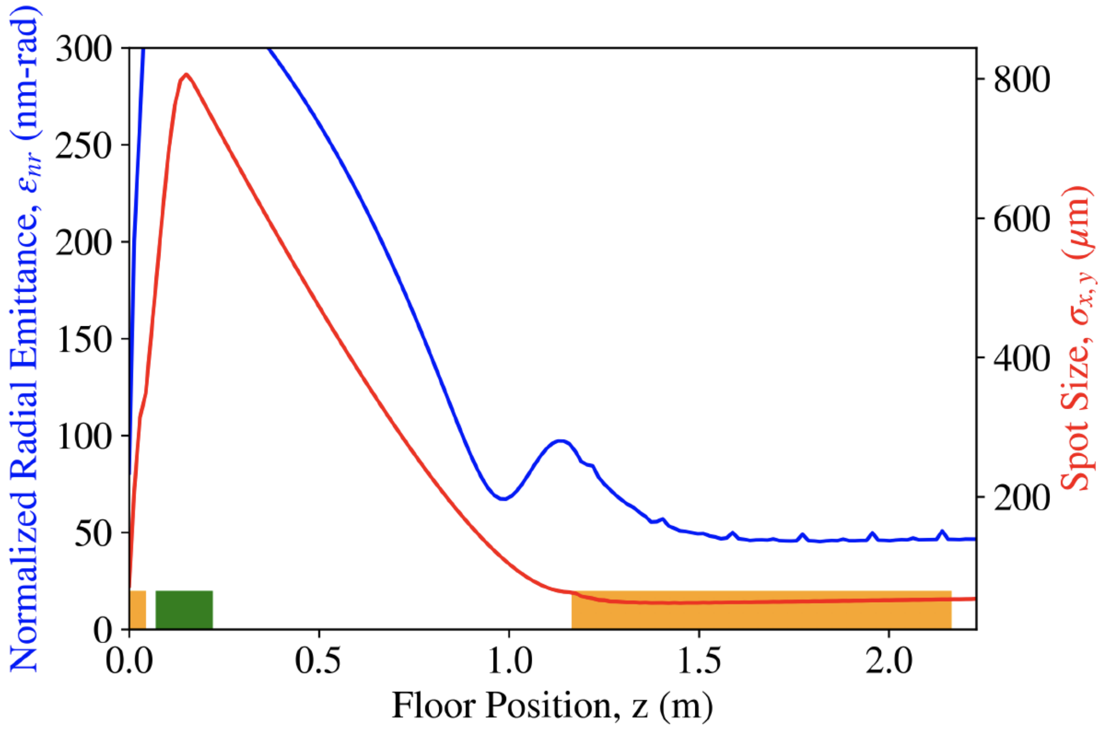
- Cryogenic C-band photoinjector at extreme high brightness for FEL

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





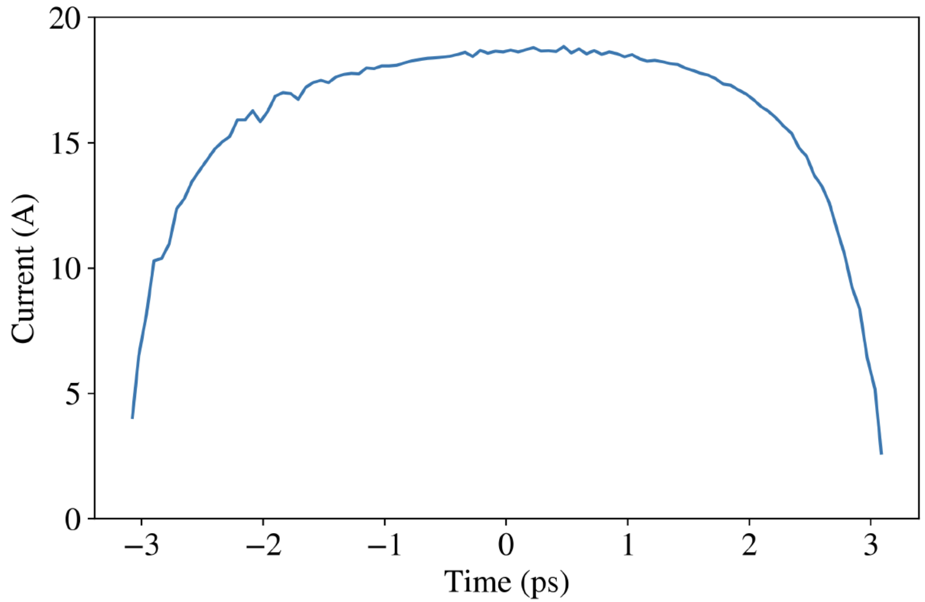
E_0=250 MV/m

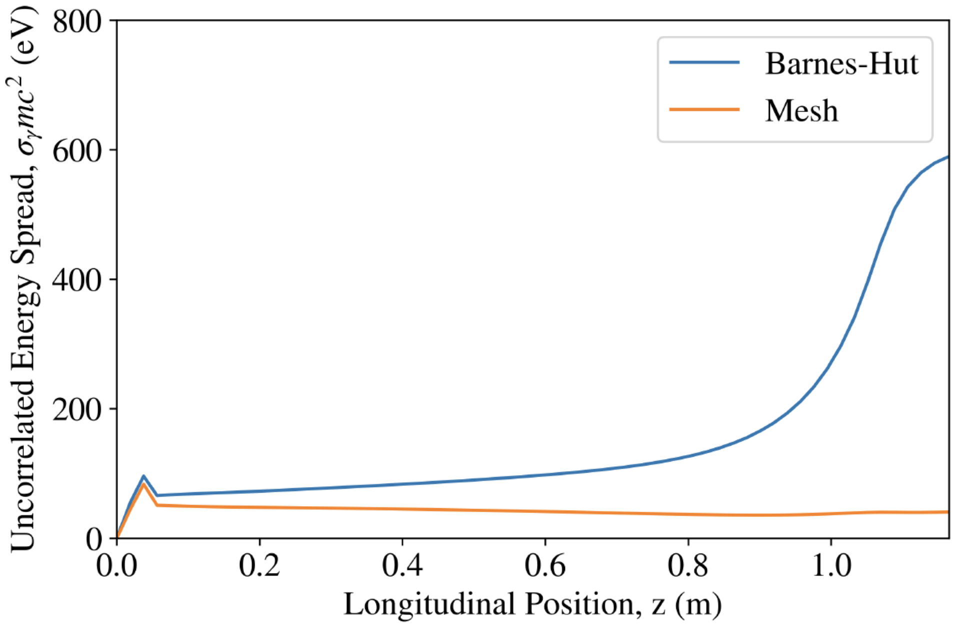


R. Robles, et al., Phys. Rev. Accel. Beams 24, 063401 (2020)

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

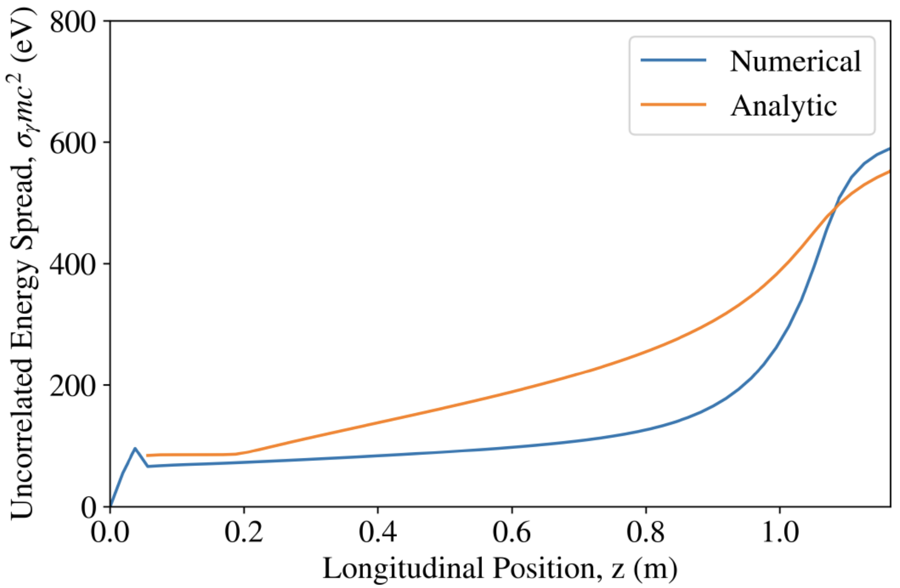
Intra-beam scattering and slice energy spread

- At high beam density, the slice energy spread may be dominated by intra-beam scattering

$$\frac{d\sigma_\gamma^2}{dz} = \frac{2r_e^2 N_b}{\sigma_x \sigma_z \epsilon_{nx}}$$

Implicit scaling on E_0

- Challenging simulations of state-of-art problem (GPT with Barnes-Hut algorithm)



IBS theory due to
Z. Huang (SLAC-PUB)

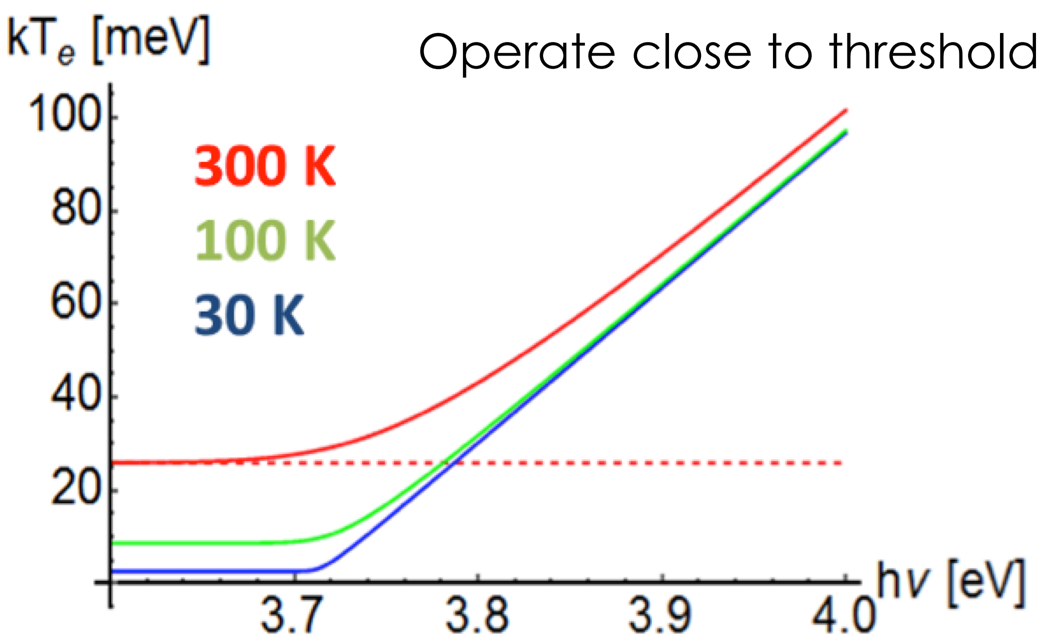
See Robles et al. PRAB,

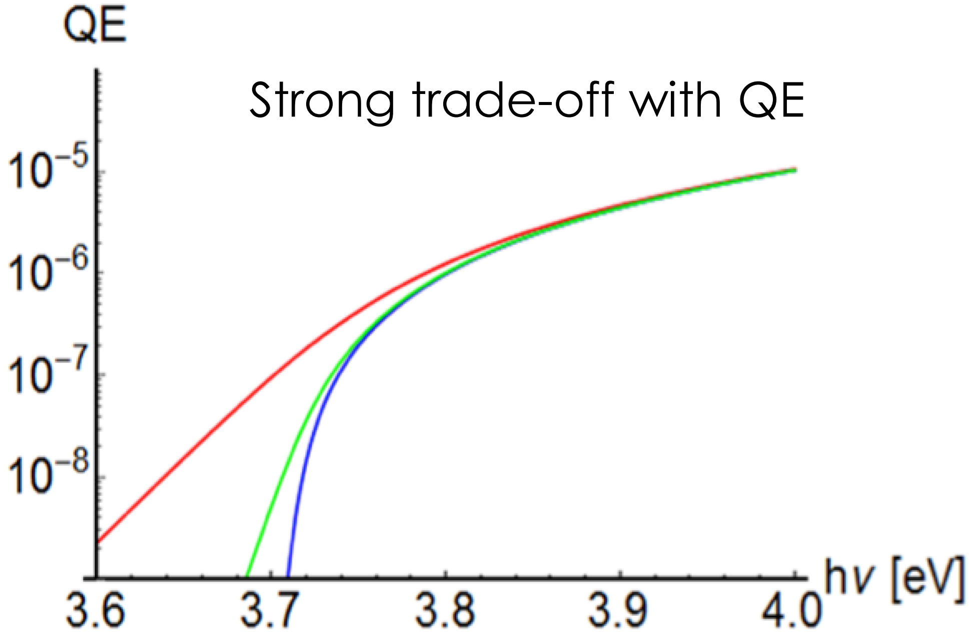
-Implications for beam compressibility in UC-XFEL and C^3

- Experiments at UCLA

Extending brightness frontier: lower emission temperature

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



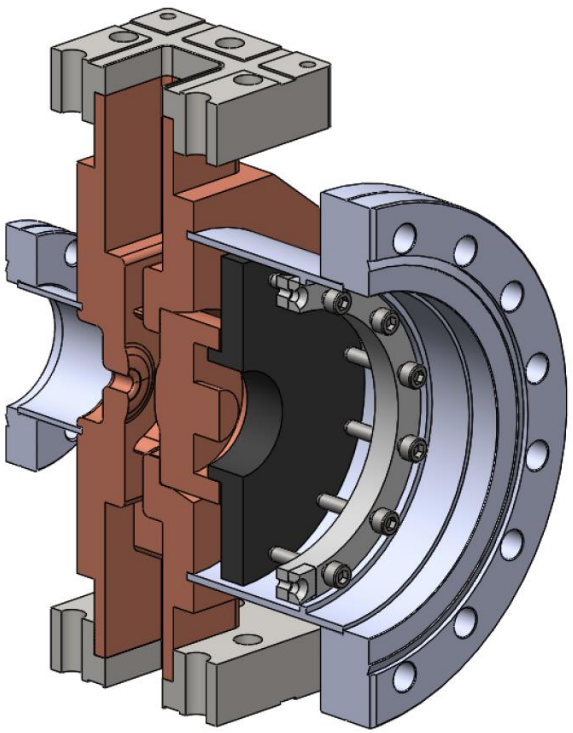


Issue: two-photon and heating effects due to high laser power

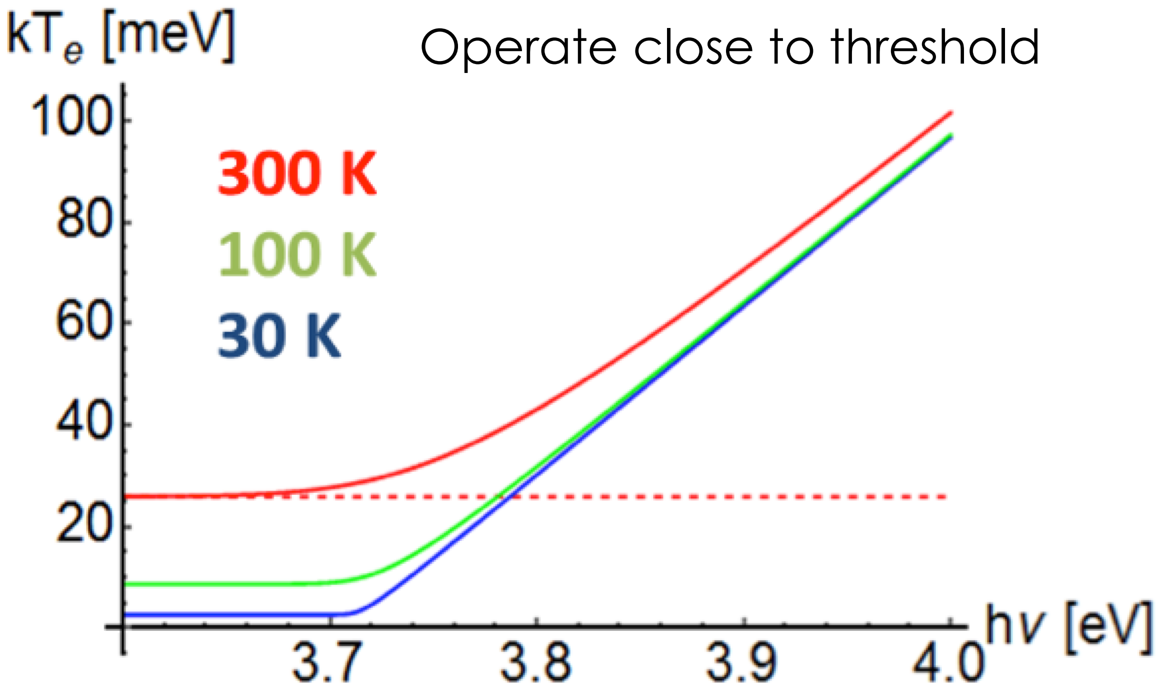
Half-cell cryogenic photo-emission test stand

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?*



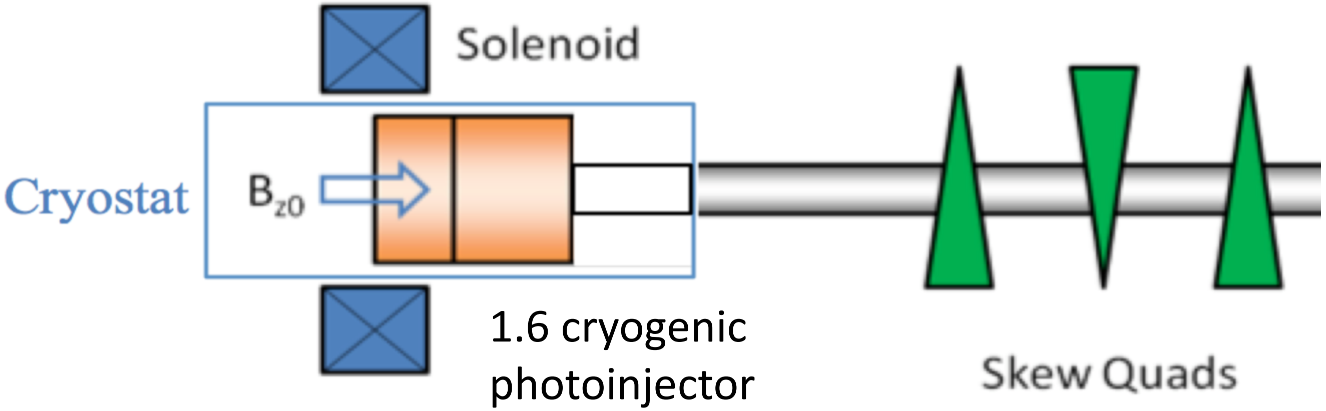
0.5 cell gun with copper cathode (no load lock)
Under construction (support from NSF CBB)

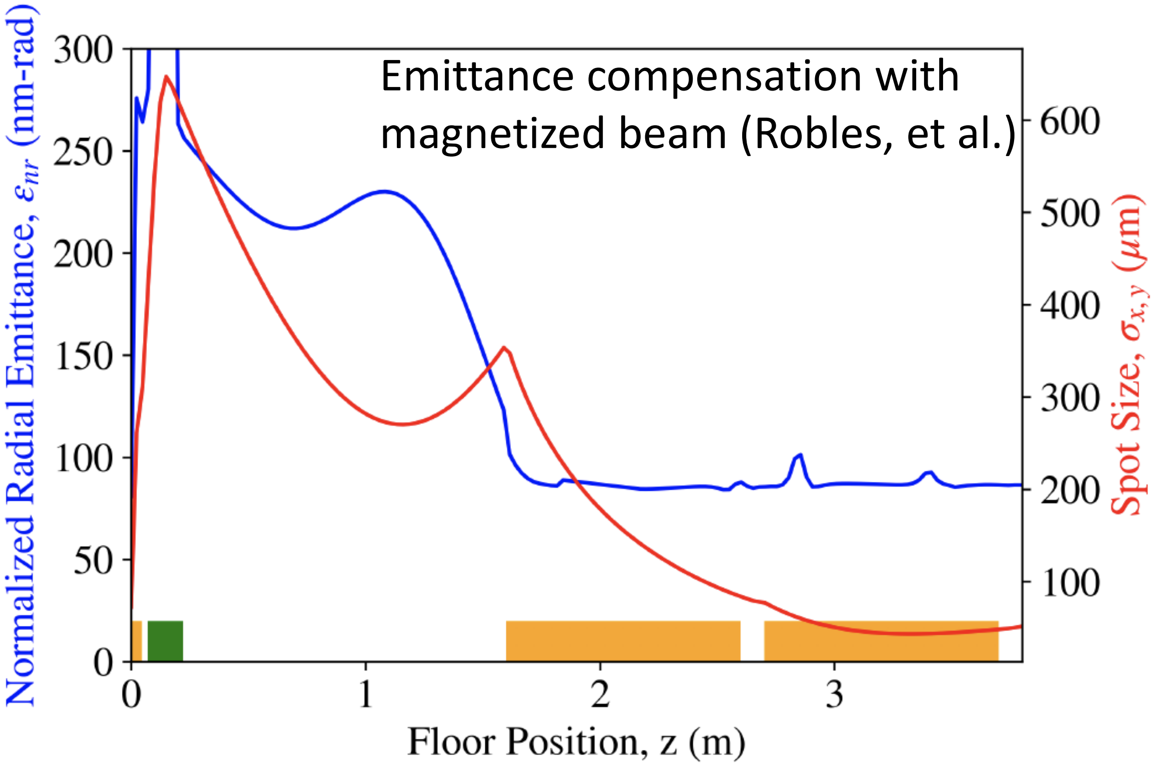


Cryo-emission eliminates Fermi-Dirac tail, ***cold beams***

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*

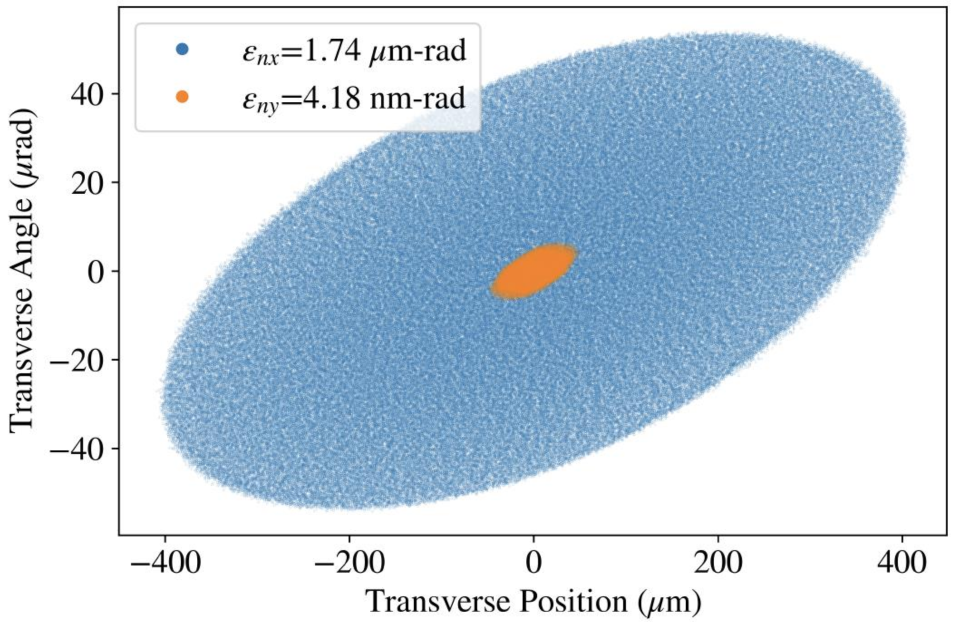


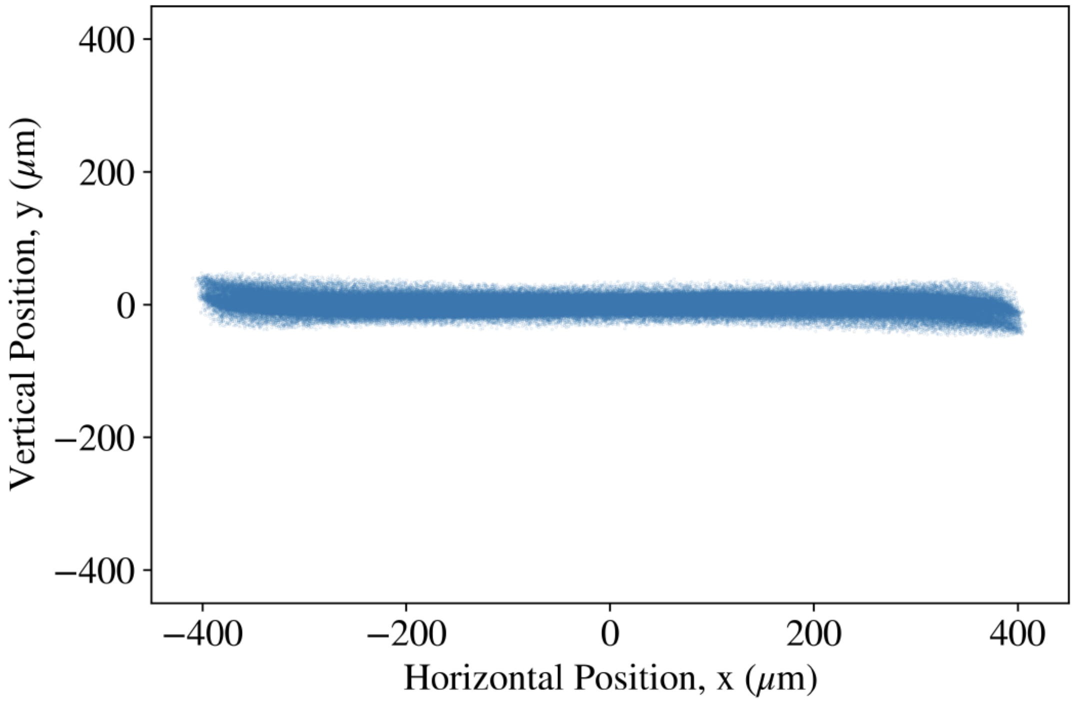


Angular momentum $\mathcal{L} = (eB_0/2m_ec)\sigma_0^2$

Performance of round-to-flat beam transformation

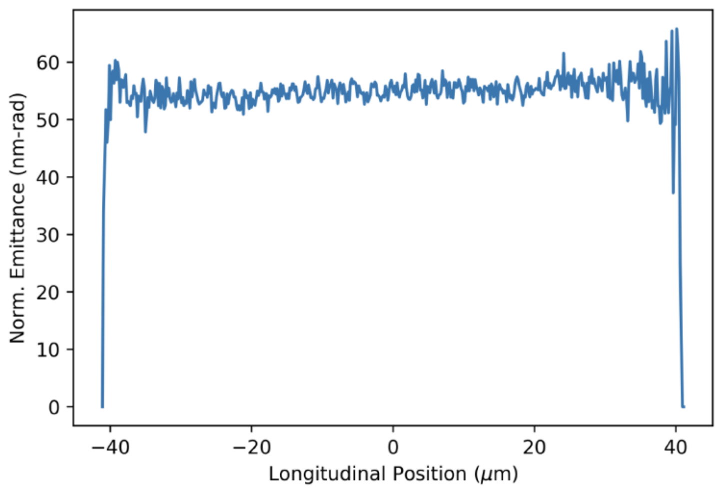
- Emittance 90 nm-rad before splitting (increase of 75% over XFEL case)
- Splitting nearly ideal in simulation, including space-charge effects
- *Scaling to nC level implies S-band operation*



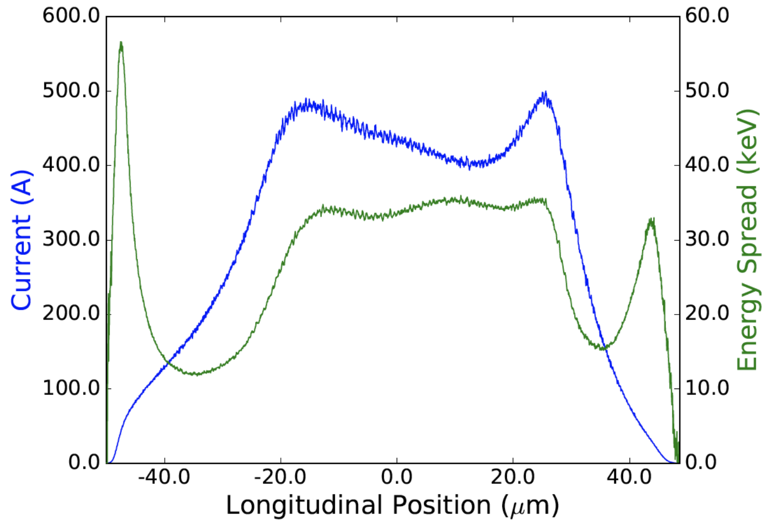


Bunch compression to 4 kA in two phases

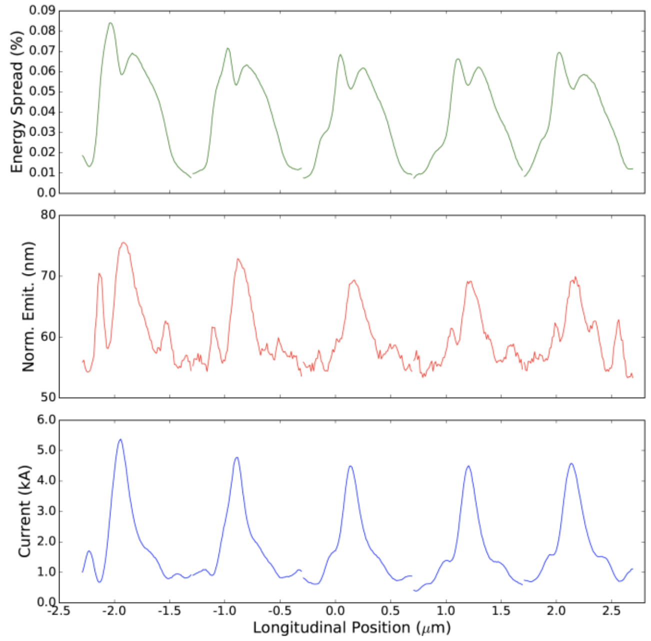
- **The good:** with high gradients, compact system, LSC-CSR microbunching instabilities do not have time to assert themselves
- **The bad:** we must preserve a much smaller emittance at the same peak current as LCLS
- **The familiar**: compress **first** at 400 MeV using two small opposing chicanes to 400 A peak current. Must **linearize LPS** using 6th harmonic cavity (34.3 GHz, from XLS project). Emittance growth very small. *Technology relevant to C^{3}compressors*
- *Apply IFEL compression for second phase – important for FELs overall (e.g. XLEAOO at SLAC)*



Emittance growth from CSR/SC model negligible



400 A current after BC1

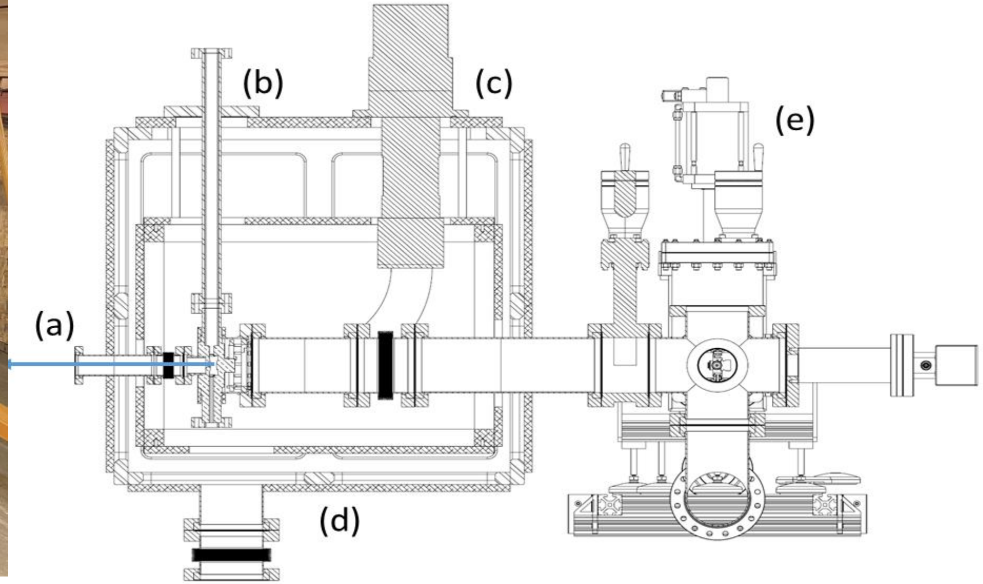


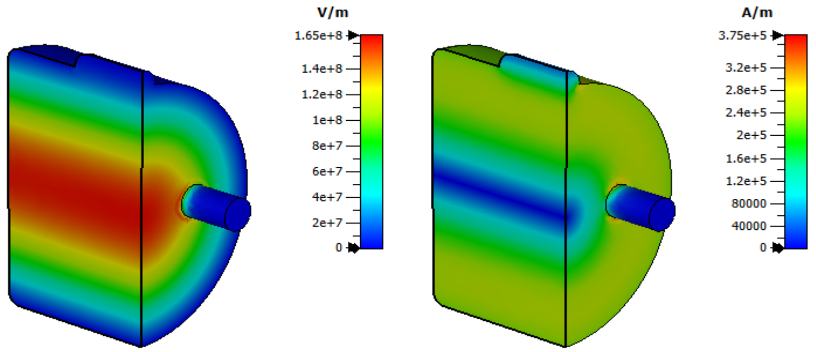
Slice energy spread (top), emittance (middle) and current profile for microbunches (bottom)

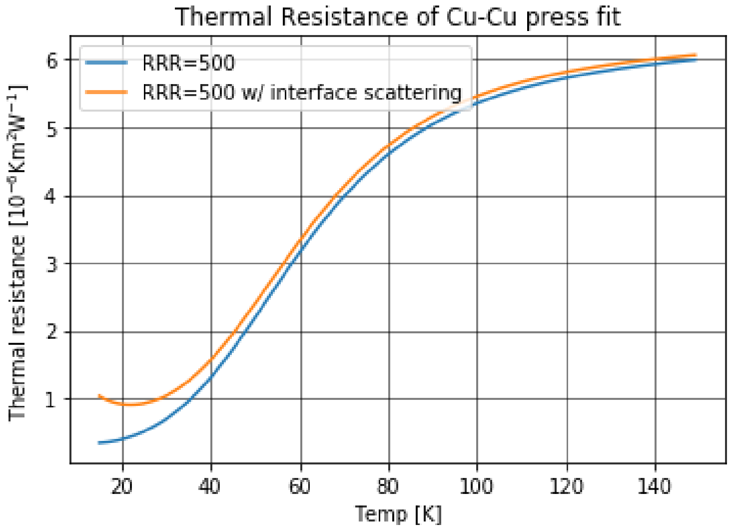
Cryo-RF for applications at UCLA

UCLA

- 50 year old C-band klystron brought back to life
- Developing generation of cryostats for testing at UCLA
  - Low power C-band cryogenic properties, *anomaly <20 deg K*
  - Cool-down dynamics, alignment
  - *Cryogenic photo-emission test stand*
- Implications for C^3 gun and test cavities



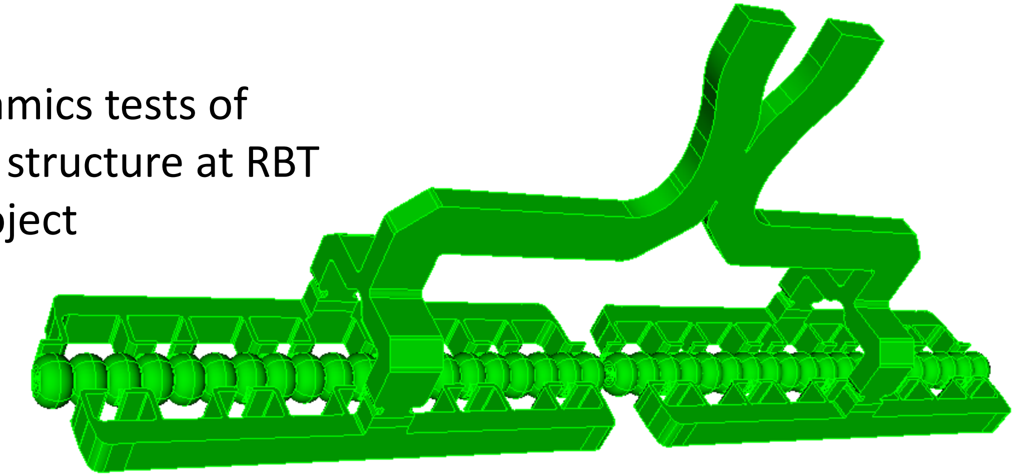


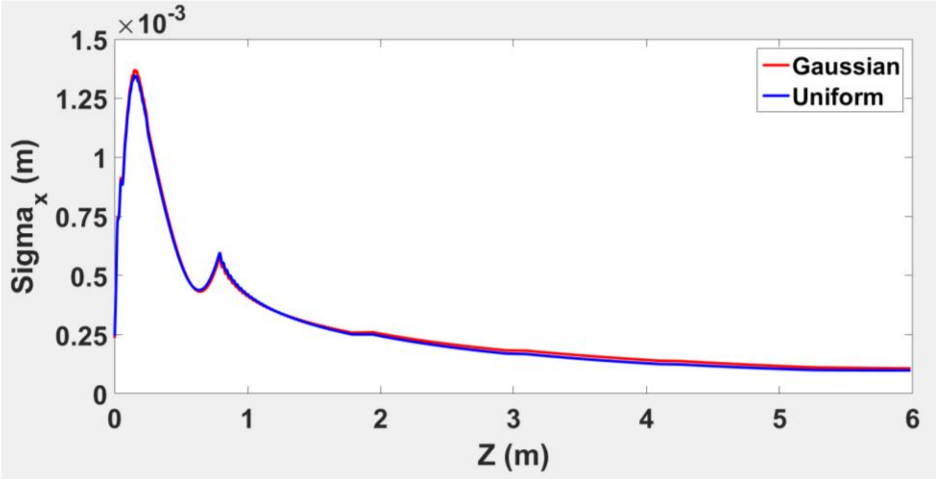


Common issues for linear accelerator sections

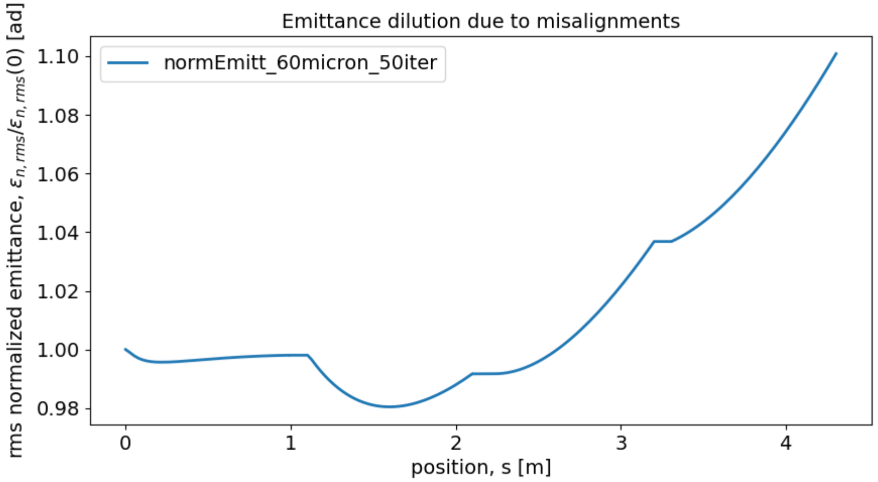
- Advantage: strong RF focusing.
  - Example in Radiabeam GRIT project, same linac structure, 40% of gradient
  - Inherent aspect of emittance control

First beam dynamics tests of C-band Tantawi structure at RBT DARPA GRIT project





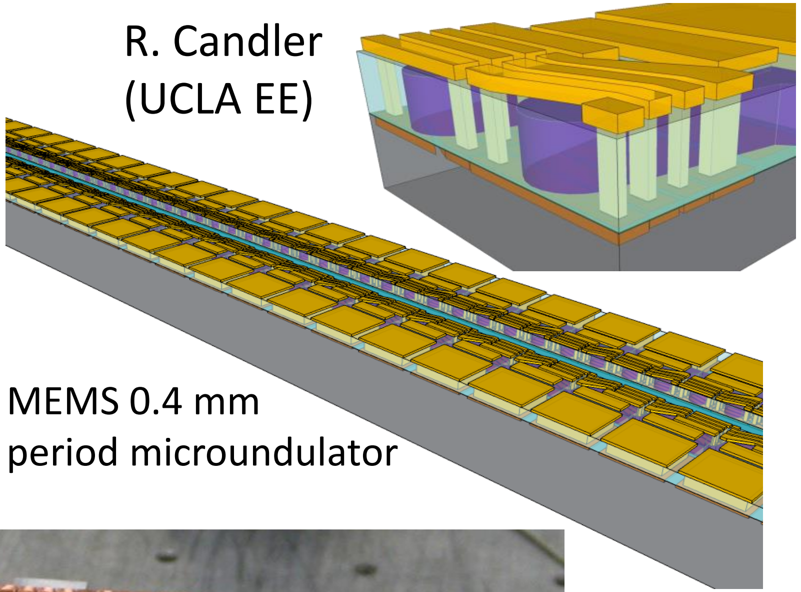
- Testing new model for emittance dilution from wakefields, space-charge



- New code to simulate short-range BBU
- Extension to long range wakes in C^3

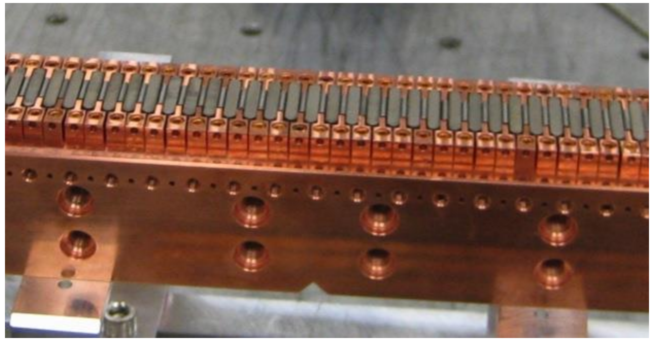
Micro- (meso-) Undulators

- mm-scale period undulators under development for 10 years
- Advanced manufacturing methods (MEMS)
- **Cryo-undulator (Pr, Dy based) already a mature technology (RadiaBeam)**
  - 6-9 mm period
  - Up to 2 T fields, narrow gap
- K_u not large, but coupling is K_u / g!
- Application to positron sourcery in LCs
- Useful at LCLS?



R. Candler (UCLA EE)

MEMS 0.4 mm period microundulator

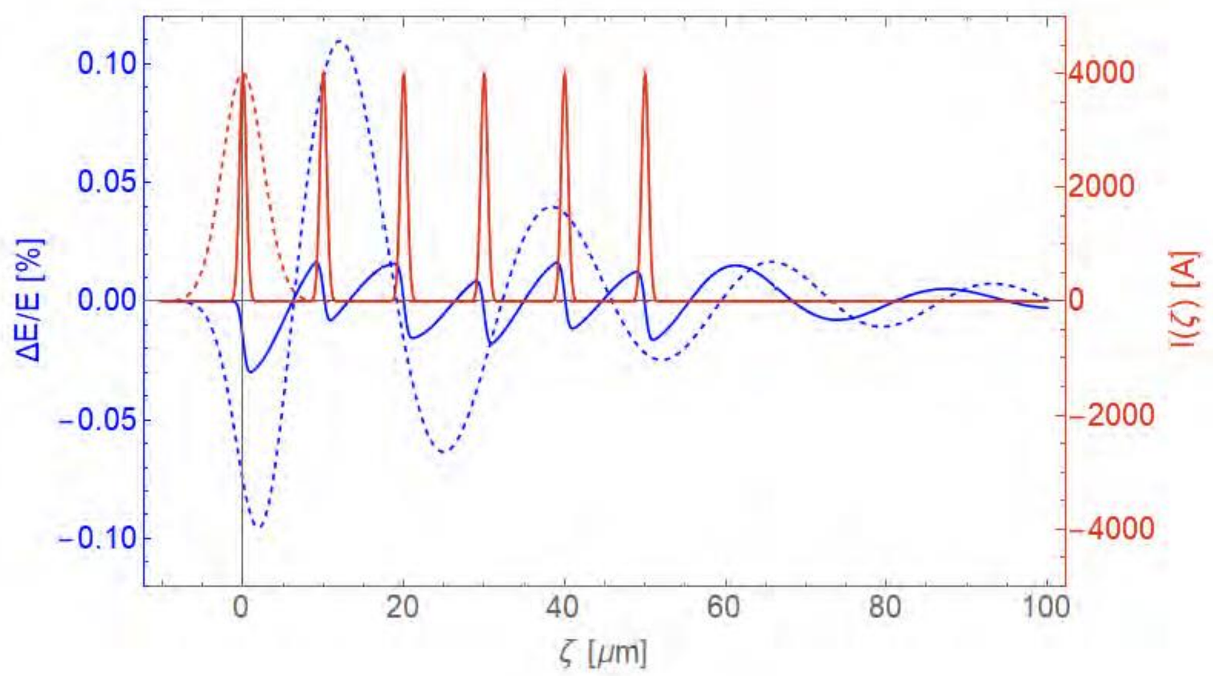


Pr-based 7 mm period cryo-undulator

Proposed manufacturing of few mm-period Halbach array

Avoiding resistive wall wakefields in undulator

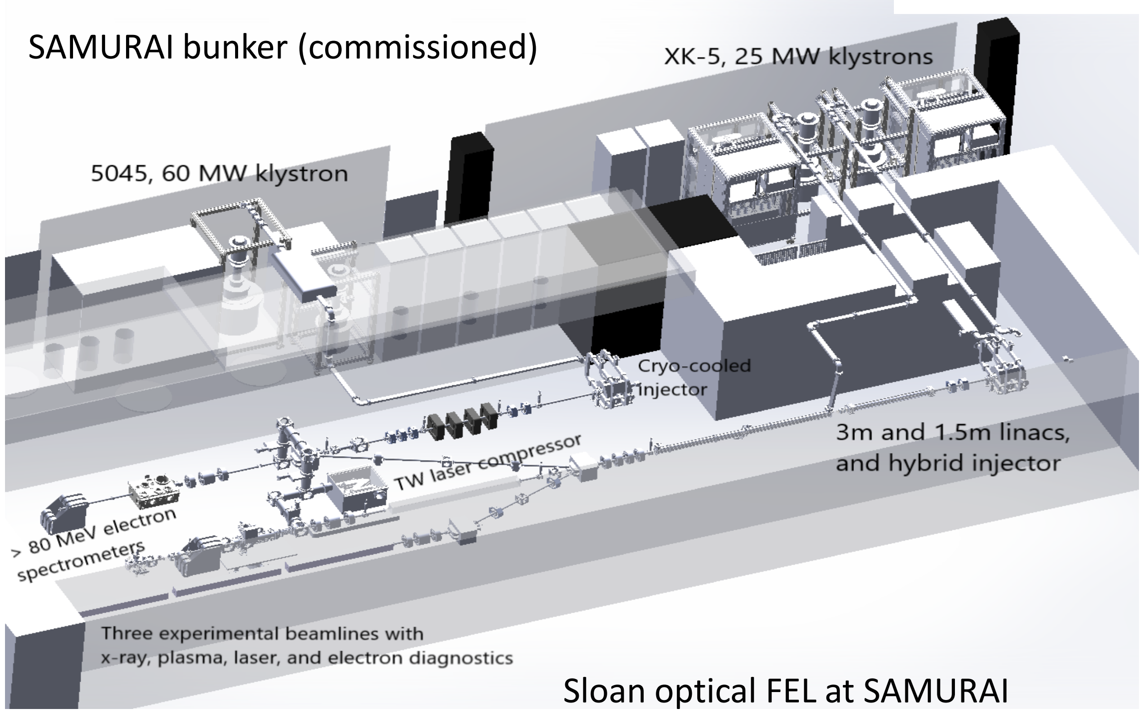
- Sub-mm gap can provoke large resistive wakes in undulator
- **Periodic microbunching alleviates this problem**
- Also under study for **MaRIE >40 keV XFEL**; key advantage in both cases



Periodic microbunching and associated resistive wall wakes

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 (asymmetric emit) and linac
  - IFEL and velocity bunching
  - Short period undulators
  - **Optical to EUV FEL**
  - C3 string test and beam testing
- Fund first prototype UC-XFEL
  - NSF Midscale pre-proposal (may go to R2)
  - EFRC path is attractive



Sloan optical FEL at SAMURAI