Beam dynamics in RF photoinjectors – with modern applications

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Coherence in particle and photon beams: Past, Present, and Future

Argonne National Laboratory

Friday, March 15, 2019

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We gather here on the Ides of March!

(A short speech, with apologies to William Shakespeare, Marc Anthony, Julius Caesar and English literature in general)

Friends, physicists, countrymen, lend me your ears;

I come to praise Kwang-je, not to bury him.

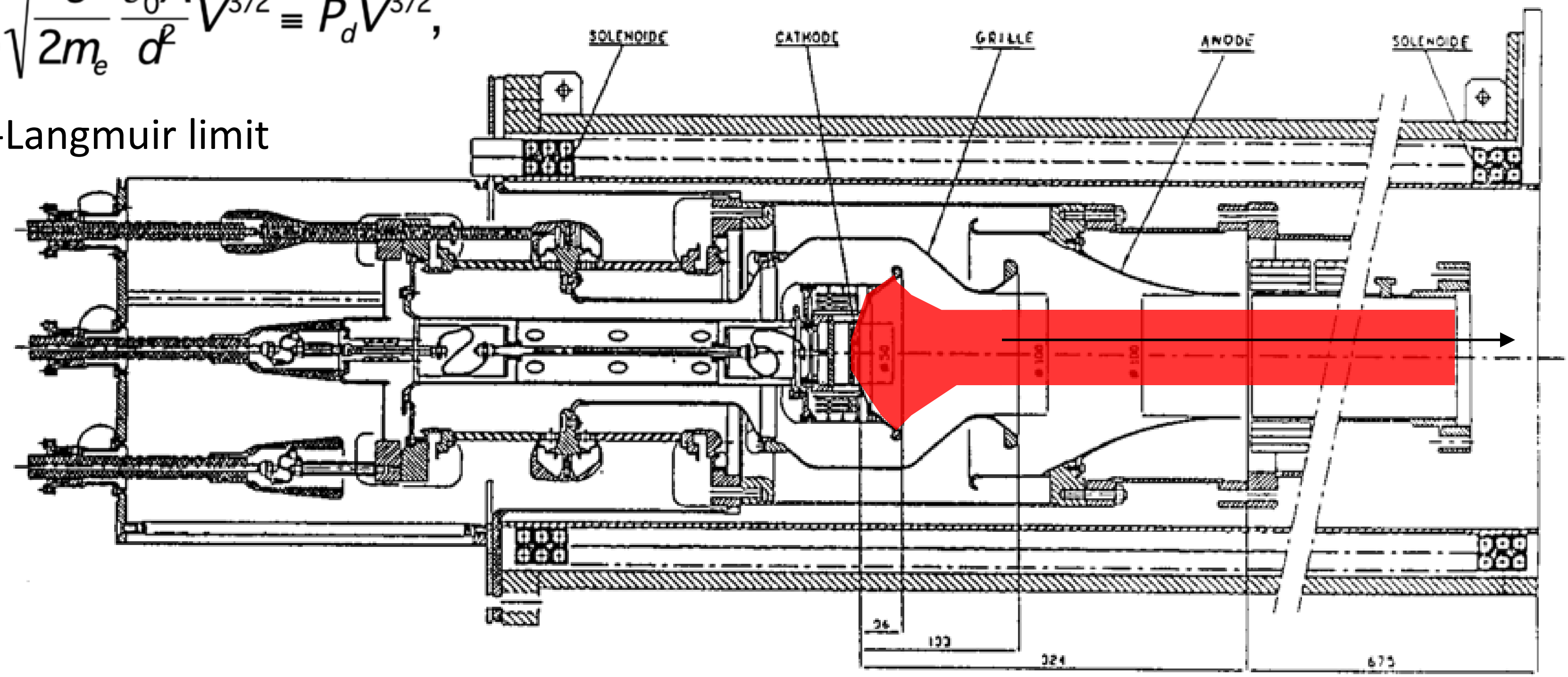
The theory that men do lives after them;

The good is oft embedded in impressive instruments…

Pre-history DC electron sources: the *diode*

$$I = \frac{8}{9}\sqrt{\frac{e}{2m_e}}\,\frac{\varepsilon_0 A}{d^2}V^{3/2} \equiv P_d V^{3/2},$$

Child-Langmuir limit

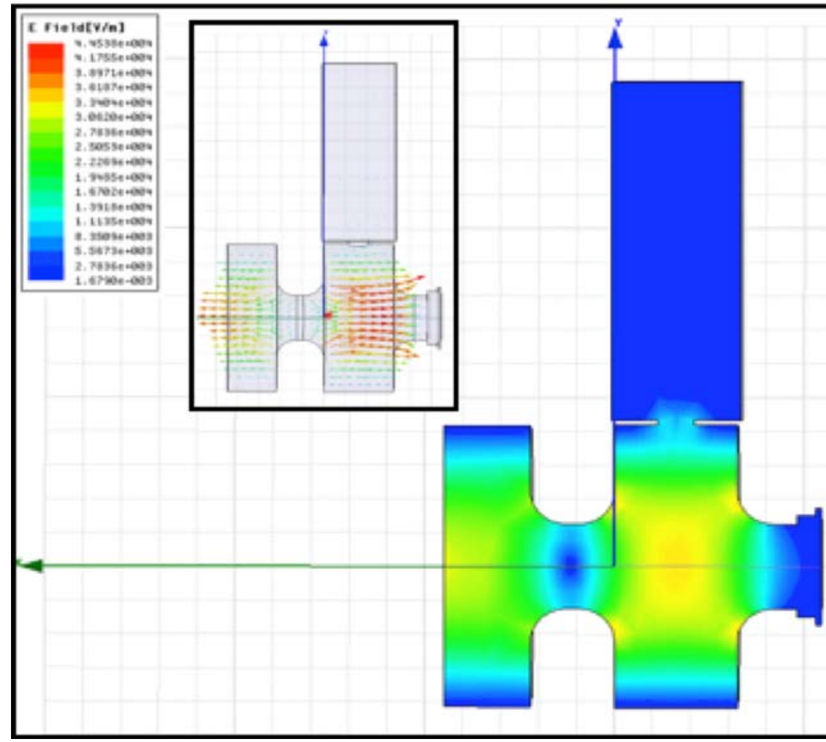


Example: DC electron source with Pierce electrode geometry

- Space-charge limited laminar flow. Fields limited to ~10 MV/m

Change the rules of the game: introduce RF photoinjector

- Laser gating to sub-picosecond level
- Capture with RF – violent acceleration
- Manage strong time-dep. RF focusing
- Preserve phase space structure
    - Control pulse expansion
    - Minimize emittance growth
    - Creation and manipulation of single component plasma
- Frontier RF engineering
- Mastery of emerging laser technique



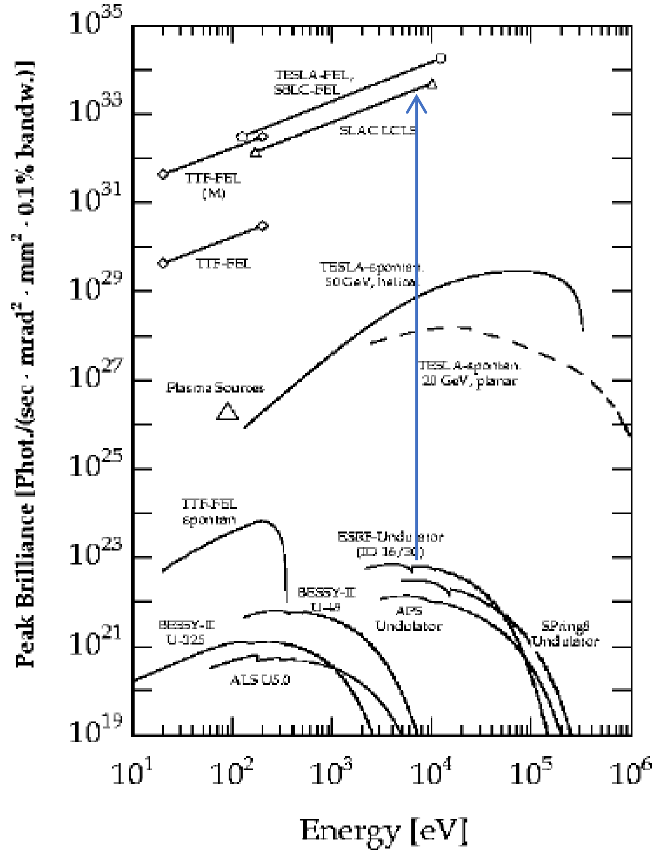
Major impact: high brightness electron sources enable XFELs

- RF photoinjector appears ~1986, "mature" by 2000
- FEL active medium
- ***Ultra-high fields* enable high currents and low emittances…**
  - **High brightness**

$$B_e = \frac{2I}{\varepsilon_n^2}$$

  - **In FEL** $L_{g\,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}}$

with $\rho_{1D} \propto B_e^{1/3}$



High brightness e-beams beget >10 orders of magnitude in photon brightness. **More to go?**

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Complex Physical Scenario: Enter Kwang-je Kim

- Tour-de-force analysis of beam dynamics and performance limits
- Set up the rules of the game

Nuclear Instruments and Methods in Physics Research A275 (1989) 201–218 201
North-Holland, Amsterdam

RF AND SPACE-CHARGE EFFECTS IN LASER-DRIVEN RF ELECTRON GUNS

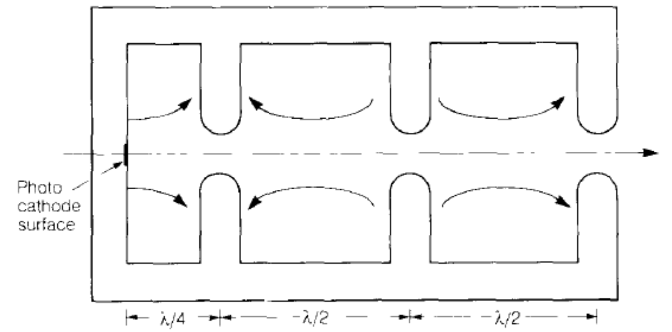
Kwang-Je KIM

Accelerator and Fusion Research Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

Received 9 September 1988

The evolution of the electron-beam phase space distribution in laser-driven rf guns is studied by taking into account both the time variation of the rf field and space-charge effects. In particular, simple formulas are derived for the transverse and longitudinal emittances at the exit of the gun. The results are compared and found to agree well with those from simulation.

Impact of Results: Scaling Guides



- Introduce "Kwang-jeKimAlpha" RF strength

$$\alpha_{RF} = eE_0 k_{RF}/2m_e c^2$$

Capture and compression…

- RF emittances

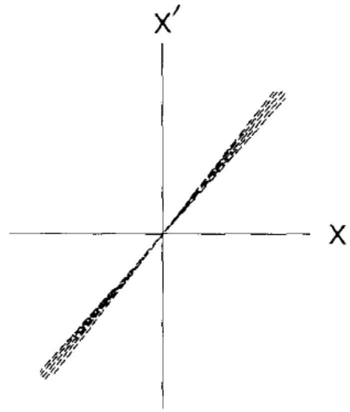
$$\epsilon_{z,RF} = \sqrt{3}(\gamma_f - 1)k_{RF}^2\sigma_z^3$$

$$\epsilon_{x,RF} = k_{RF}^3 \alpha_{RF}\sigma_x^2\, \sigma_z^2/\sqrt{2}$$

Important in high charge (e.g. wakefield acceleration, AWA), large beam applications

- Space charge emittance limits (unified *z* and *x*)

$$\epsilon_{i,SC} = \frac{\pi}{4}\frac{I}{I_0}\frac{\mu_i(A)}{k_{RF}\sin\phi_0}$$



Bow-tie phase space picture introduced for SC and RF effects

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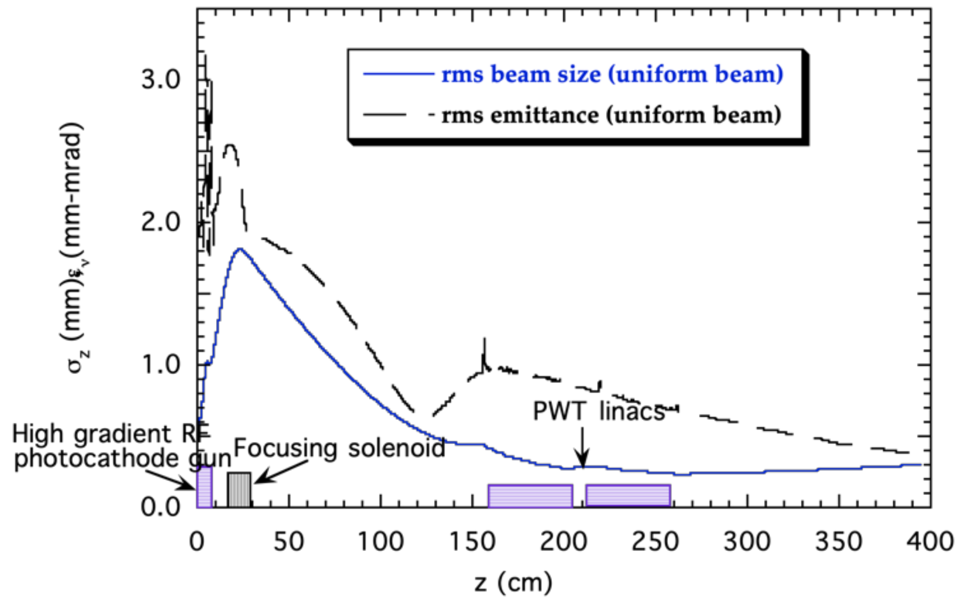
Reversing the bow-tie: Emittance compensation

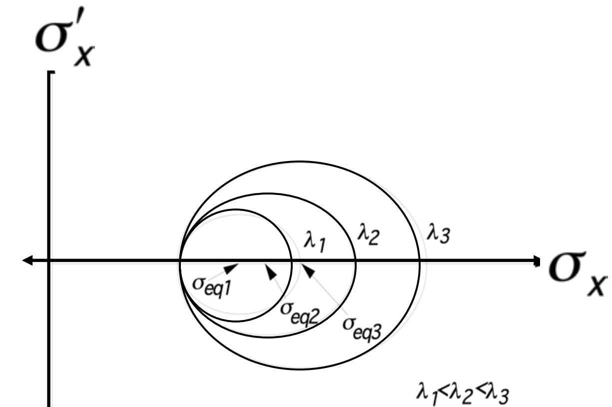
- Space-charge emittance evolution *not monotonic* in *t*
- Multiparticle simulations at LLNL (Carlsten) showed emittance oscillations, minimization possible: *Emittance compensation*
- Scaling laws? KJ Kim basis
- Analytical approach?
- Prescriptions for design



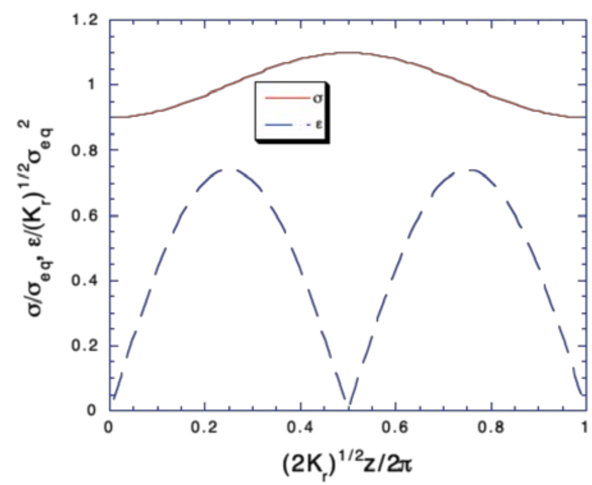
Multiparticle simulations (UCLA PARMELA)
Showing emittance oscillations and minimization

Phase space picture: coherent oscillations

- Envelope oscillations proceed about
  - different equilibria,
  - with different amplitude
  - but at the *same frequency*
- Behavior leads to emittance oscillations
  - Single component plasma
- “1st compensation”, after gun, before linac



Assume that beam is launched at minimum (*e.g.* at cathode)



Small amplitude oscillation model

Envelope oscillations with acceleration near invariant envelope

- Linearized envelope equation

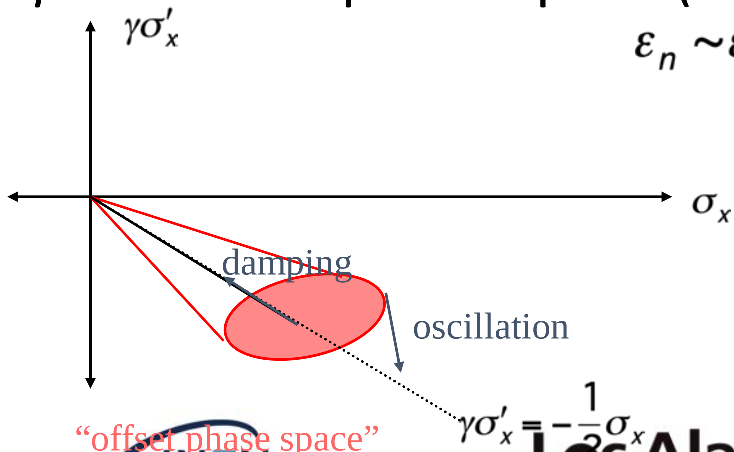
$$\delta\sigma_x'' + \left(\frac{\gamma'}{\gamma}\right)\delta\sigma_x' + \frac{1+\eta}{4}\left(\frac{\gamma'}{\gamma}\right)^2 \delta\sigma_x = 0$$

- Homogenous solution (independent of current)

$$\delta\sigma_x = \left[\sigma_{x0} - \sigma_{inv}\right]\cos\left(\frac{\sqrt{1+\eta}}{2}\ln\left(\frac{\gamma(z)}{\gamma_0}\right)\right)$$

- Normalized, projected phase space area oscillates, secularly *damps* as offset phase space (conserved!) moves in…

$$\varepsilon_n \sim \varepsilon_{offset}\sigma_{inv} \sim \gamma^{-1/2}$$

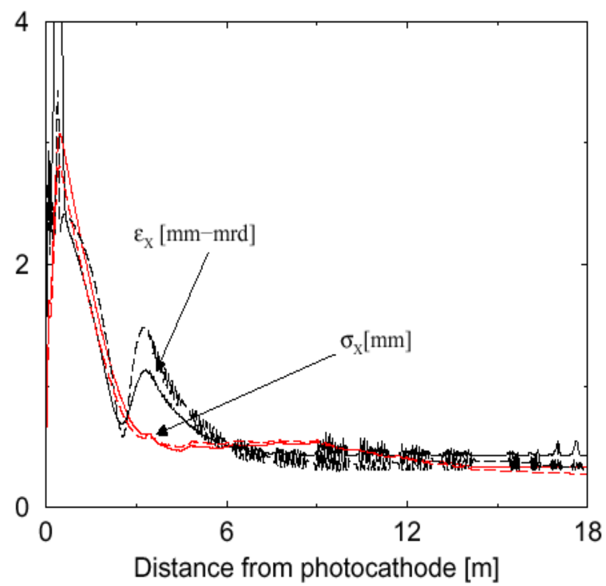


Oscillation (*generalized* matched plasma) frequency damps with energy

$$k_p = \frac{d}{dz}\left(\frac{\sqrt{1+\eta}}{2}\ln\left(\gamma(z)\right)\right) = \frac{\sqrt{1+\eta}}{2}\frac{\gamma'}{\gamma}$$

Validation of linear emittance compensation theory: LCLS injector

- Theory describes "linear" emittance oscillations
  - "Slice" code (HOMDYN) developed that reproduce multiparticle simulations. Much faster!
  - S-band LCLS photoinjector working point *discovered* with HOMDYN



Allowed generalization with scaling laws
- Foreseen by Kwang-je Kim analysis

Dash: HOMDYN
Solid: PARMELA

Charge scaling

- All accelerator-focusing parameters including ω_p constant
- Density and aspect ratio of the bunch must be preserved

$$\sigma_i \propto Q^{1/3}$$

- Contributions to emittance scale with powers of beam size
- Space-charge emittance $\varepsilon_{x,sc} \propto k_p^2 \sigma_x^2 \propto Q^{2/3}$
- RF/chromatic aberration emittance $\varepsilon_{x,RF} \propto \sigma_z^2 \sigma_x^2 \propto Q^{4/3}$
- Thermal emittance $\varepsilon_{x,th} \propto \sigma_x \propto Q^{1/3}$
- Compensating beam is SC dominated, thermal emittances do not affect beam envelope evolution
  - Compensation is preserved by keeping *plasma frequency* same

Wavelength scaling

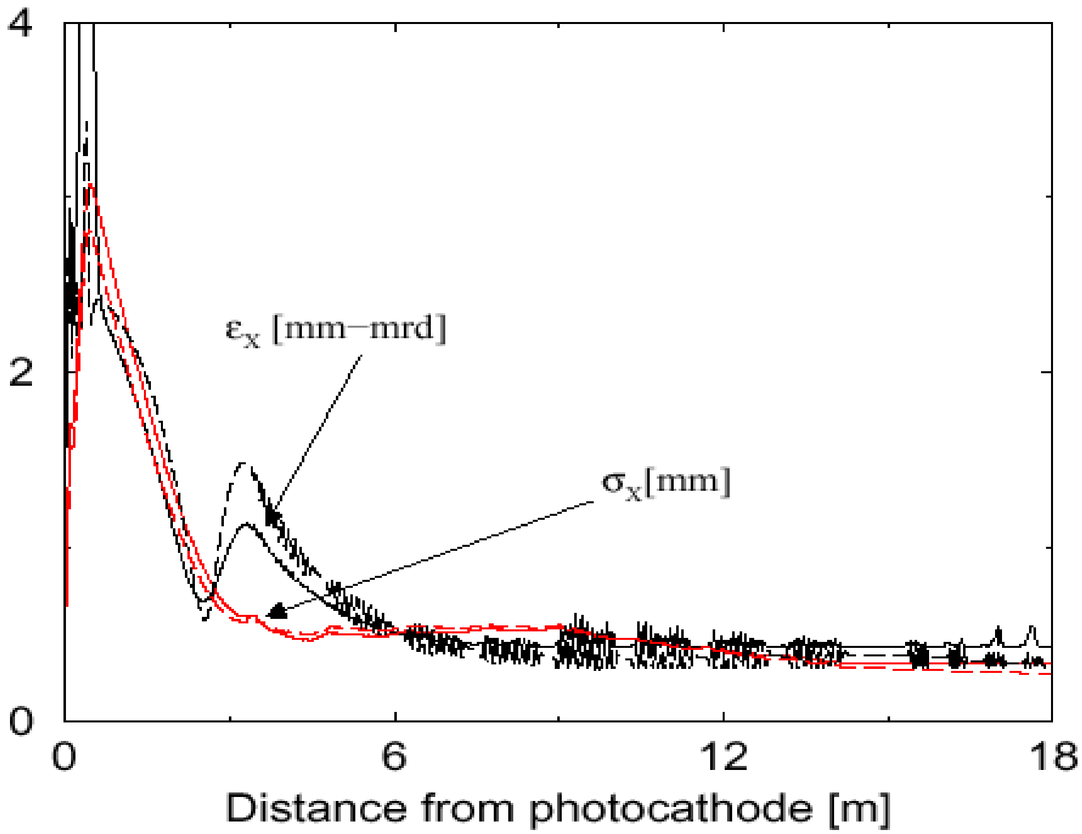
- First, make acceleration dynamics scale:
  and $\alpha_{RF} \propto E_0 \lambda_{RF} = \text{const.}$
- Focusing (betatron) wavenumbers must also scale (RF is naturally scaled, $E_0 \propto \lambda_{RF}^{-1}$). Solenoid field scales as $B_0 \propto \lambda_{RF}^{-1}$
- Correct scaling of beam size, and plasma frequency: $\lambda_{\beta,rf} \propto E_0$
- All emittances scale *rigorously* as

$$\sigma_i \propto \lambda \qquad \boxed{Q \propto \lambda} \qquad \boxed{\varepsilon_n \propto \lambda}$$

- Guns in S-band -> C-and -> L-band

Example: SC gun in L-band

- Scale Ferrario scenario to L-band, SC
- 60 MV/m peak (30 average) gun field!

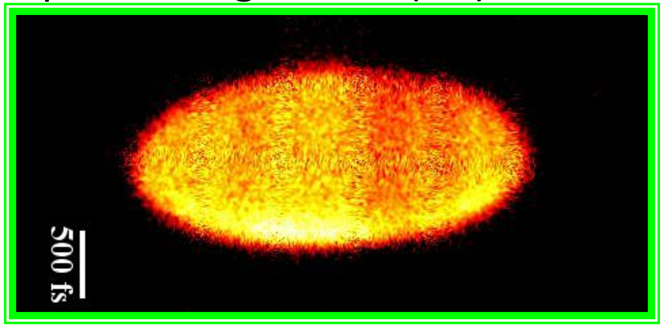


Dynamical beam shaping using longitudinal space-charge

- Assume surface charge density below maximum $\sigma_b(r) << \sigma_{b,\max} = \varepsilon_0 E_0$
- If surface charge density is uniform, leading edge of beam still defines cylinder – uniform beam

$$c\left[t_f\left(t_{0,edge}\right)\right] \cong ct_0 + \frac{1}{\gamma'\left(t_{0,edge}\right)} - \frac{1}{\gamma'_0} \approx ct_0 + \frac{\alpha(r)}{2\gamma'_0} \approx \frac{2\pi m_e c^2}{E_0^2}\sigma_b(r)$$

- Luiten-Serafini proposal:
  - Use *any temporally shaped* ultra-short pulse
  - Expansion of well-chosen shaped radial profile
  - Uniform *ellipsoidal* beam dynamically created!
  - Linear space-charge fields (3D)



3D uniformly filled ellipsoid

Implicit in original KJ Kim paper – low emittance growth

Scaling of brightness at emission

- *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
$$\boxed{B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c}\left(E_0 \sin\varphi_0\right)^2}$$
  - Lower emission temperature and/or…
- **Demands high launch field**
  - LCLS 120 MV/m (60 MV/m at injection)

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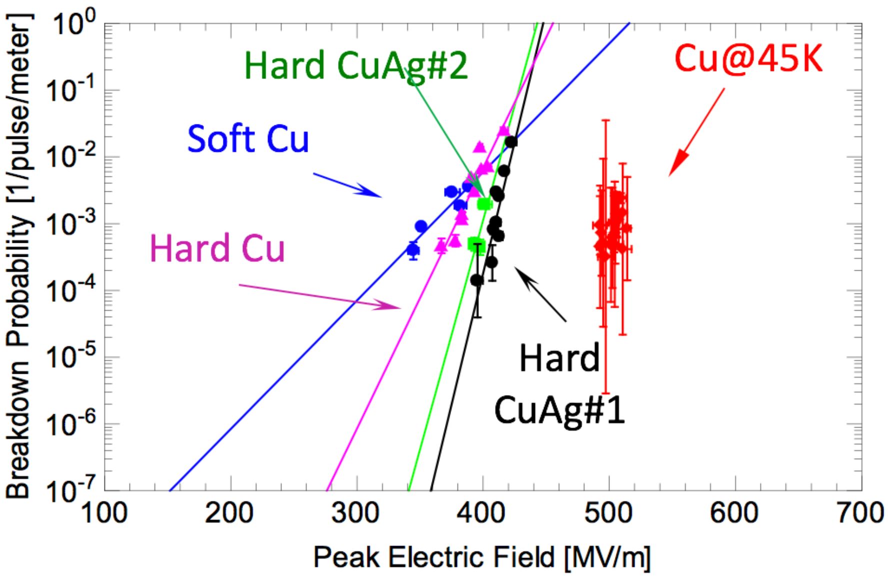
Dramatically higher gradients in higher yield strength materials

- SLAC X-band studies on hard Cu, CuAg alloy show great improvement
- ***Cryogenic structures*** (SLAC-UCLA) give **lower dissipation, higher yield strength, small coefficient of thermal exp.**
  - **Very high fields achievable**



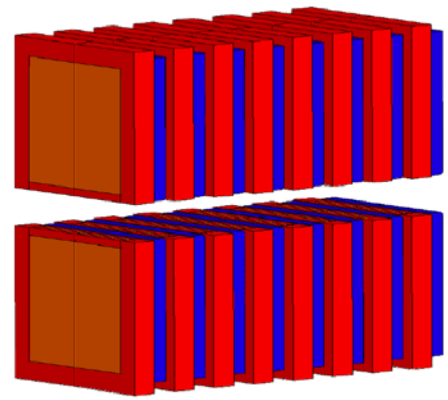
500 MV/m before breakdown

A. D. Cahill, et al., *Physical Review Accel. Beams* 21, 102002 (2018)

Insert into ultra-compact FEL recipe

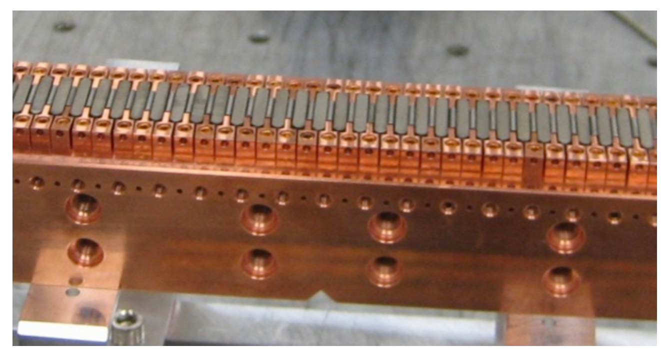
- **High field, short ⌊ undulator**
  - **(with HBB), large 〉, short *L_g***
  - **Micro-undulator**
- **High brightness beam (HBB)**
  - Ultralow emittance, enables use of micro-undulator

J.B. Rosenzweig, et al., *Nucl. Instruments Methods A,* 593, 39 (2008)



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

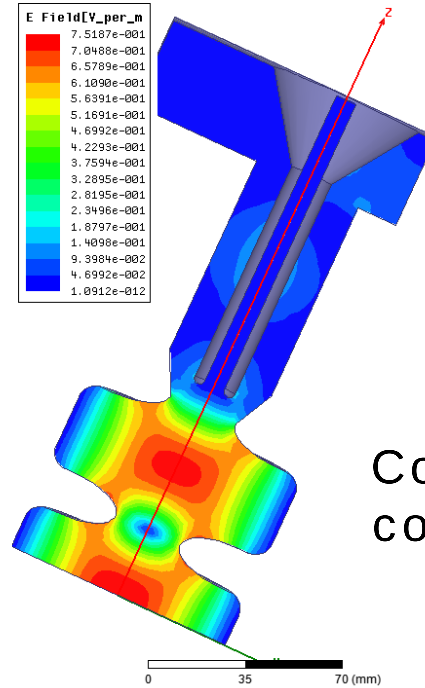
- **Lower e- energy needed** to reach short wavelength
  - ***Much smaller accelerator, undulator***
- **Rethink the accelerator**
  - **Same RF technology as HBB source – cryogenic copper with advanced designs**
- **Recipe yields credible compact XFEL concept**



F.H. O'Shea et al, PRSTAB 13, 070702 (2010)

Example for cryogenic ultra-high field photoinjector: S-band

- **UCLA-SLAC-INFN collaboration**
- **S-band operation**; option for LCLS-IIH, UEM
  - **Robust beam dynamics**
  - "Modest" peak design field: **250 MV/m**
  - Operation at ~**27K** (LNe)
  - Symmetrized RF design (dynamics)
  - Overcoupled for "fast" **<1 usec pulses**
  - Cavities optimized for **low heat load**
  - 1.45 cells **(~90° launch phase**)
- *Launch field up from present **60 MV/m to 240 MV/m … x4!***



Coaxial coupler

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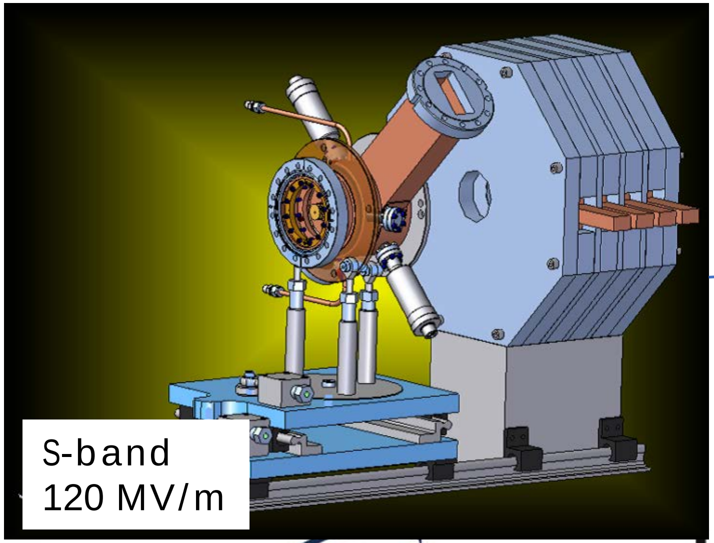
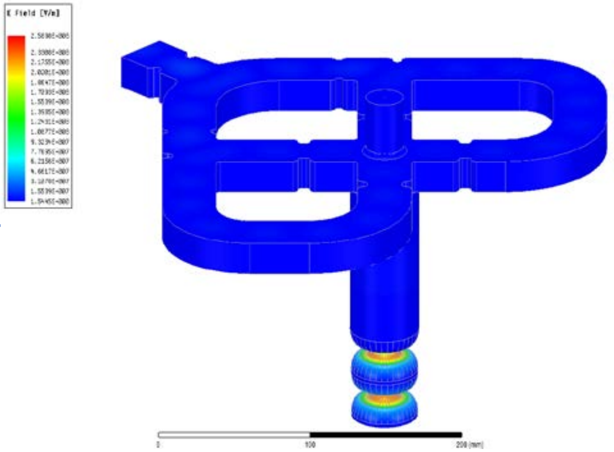
Orienting to beam dynamics: "natural scaling" with RF frequency

- LCLS photoinjector run at ~120 MV/m
- Scale naturally to C-band @240 MV/m
- ***Cigar beam* regime (non-1D)**
  - **Recent S-band study: 0.11 mm-mrad, at 200 pC**
  - Small changes to operating point (2.2 m to 1st linac)

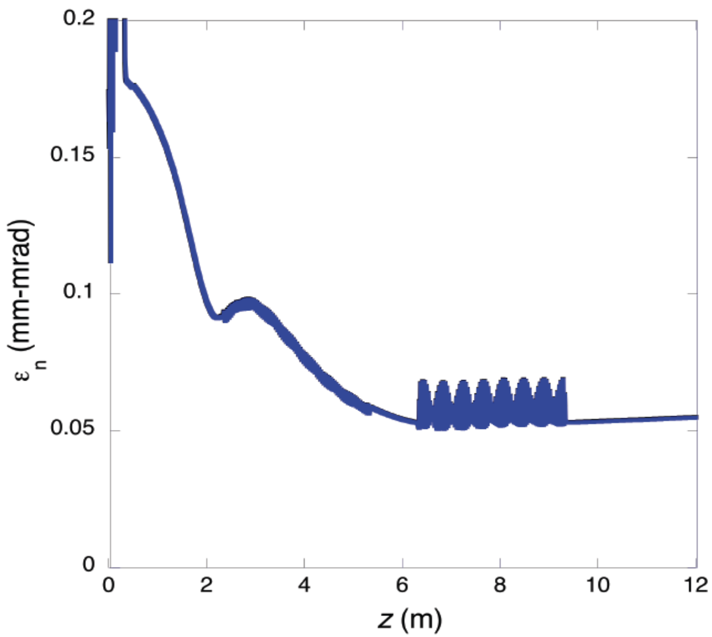


Scale it!



Scaled **C-band** (5.7 GHz) example

- Fields x2: gun E_0=240 MV/m, sol. B_0=6 kG
- Distances/2: 35 MV/m C-band linac @1.1 m
- Charge scale with f_{RF}^{-1}, to 100 pC



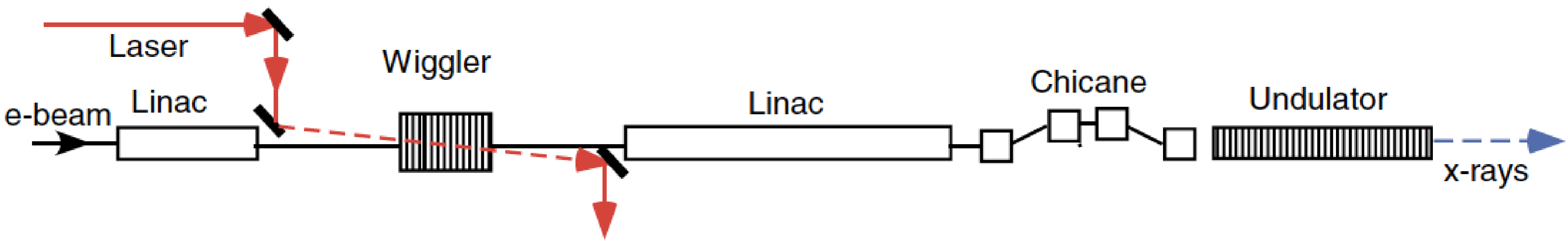
Emittance is **55 nm!** (v. 400 nm in present injector) @ 20 A as expected…

Example of highly optimized emittance compensation

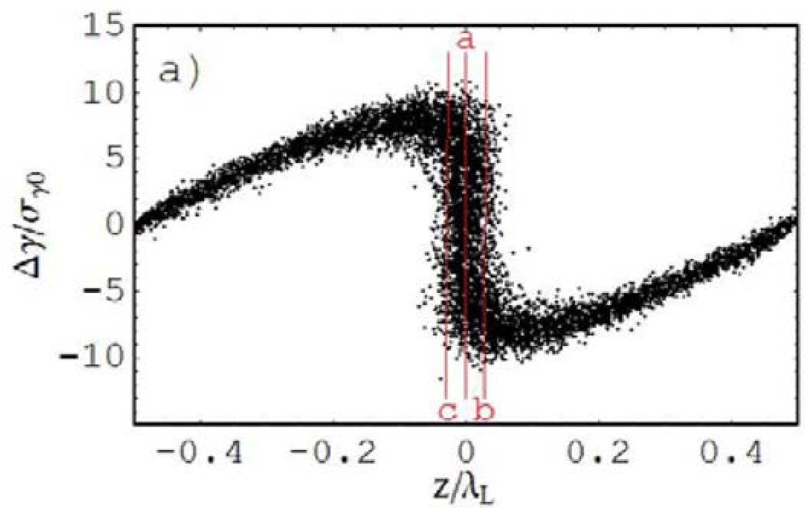
S-band, similar optics, gives **~45 nm,** and 20% reduction with collimating 5% of 200 pC beam

ESASE ideal companion to short λ_u undulator

- Low average current, small SC and resistive wall wakes

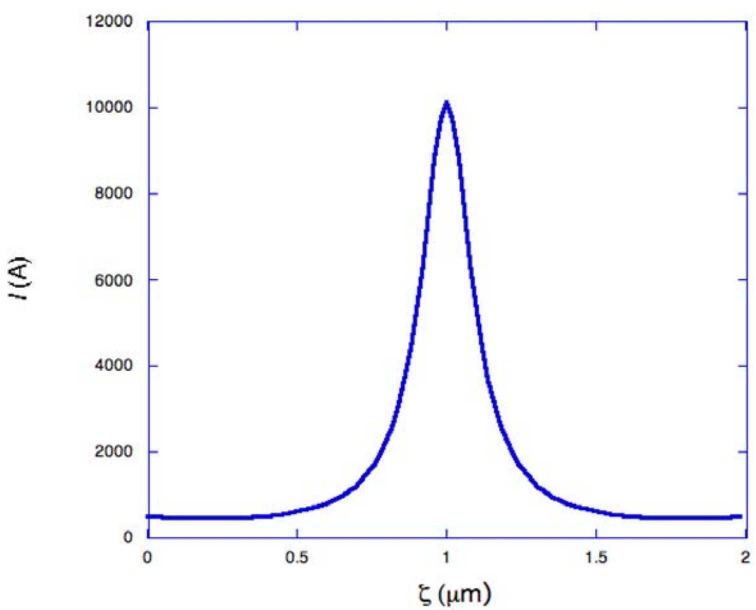


- Simulation of 100 pC case with short period undulator LCLS infrastructure (XLEAP)
- Final compression 800A->8 kA
- Slippage managed at short λ_u

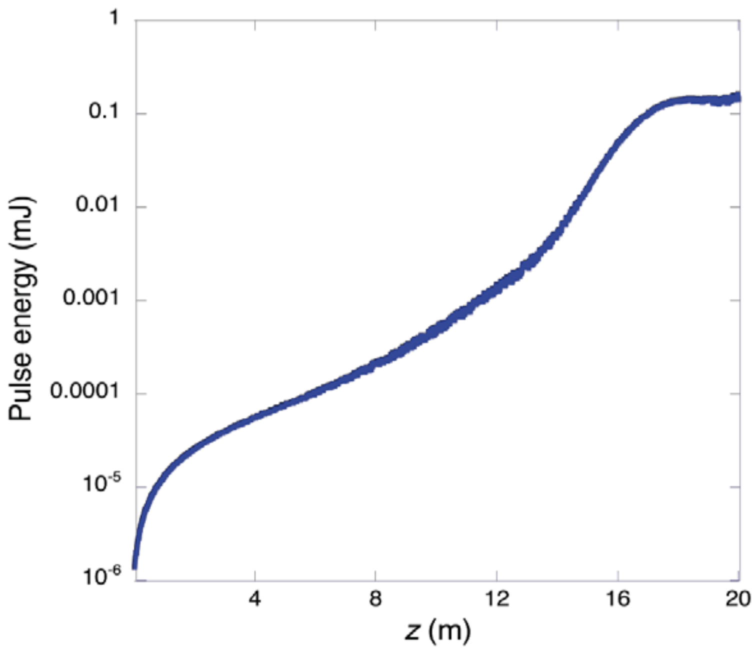


ESASE results excellent

- **C-band 100 pC** (5 ps), 55 nm emittance
- Short period *cryo-undulator*, λ=9 mm, K=1.8
- Operation at 14 GeV gives **80 keV X-ray**
- Saturation in <20 m, with 70 GW peak



Current profile (10 kA)



Energy evolution

Compact XFEL: micro-machined *undulator*

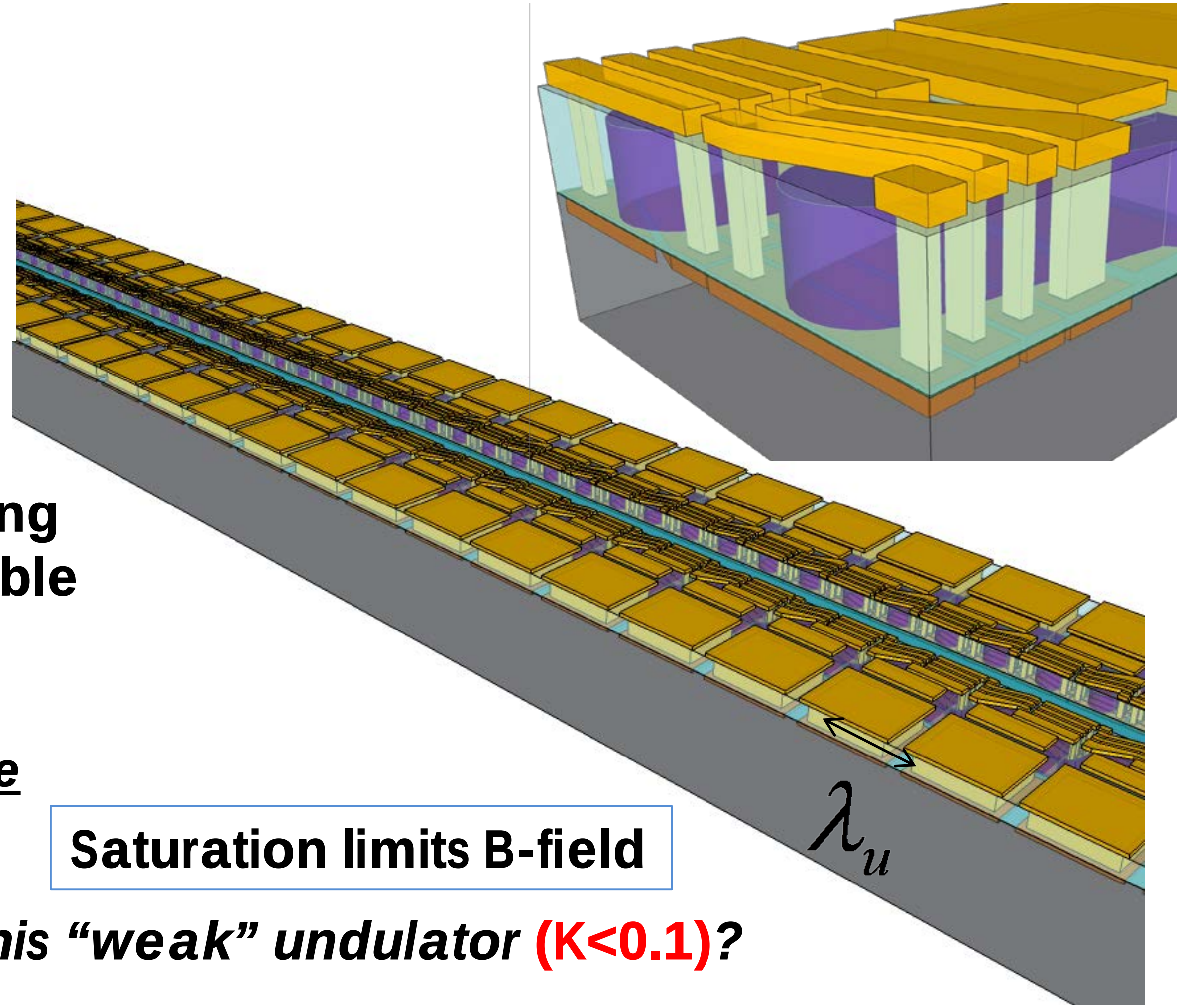
- Both advantages and challenges with new technology

$$\lambda_r = \frac{\boxed{\lambda_u}\left(1+K^2/2\right)}{2\gamma^2}$$

λ scaling favorable

$$K = \frac{qB_0\boxed{\lambda_u}}{2\sqrt{2}\pi m_0 c}$$

Scaling a *challenge*



Saturation limits B-field

How do we use this "weak" undulator (K<0.1)?

-Operate at low γ! Coupling is K/γ

-Higher gain medium: *focus beam harder*

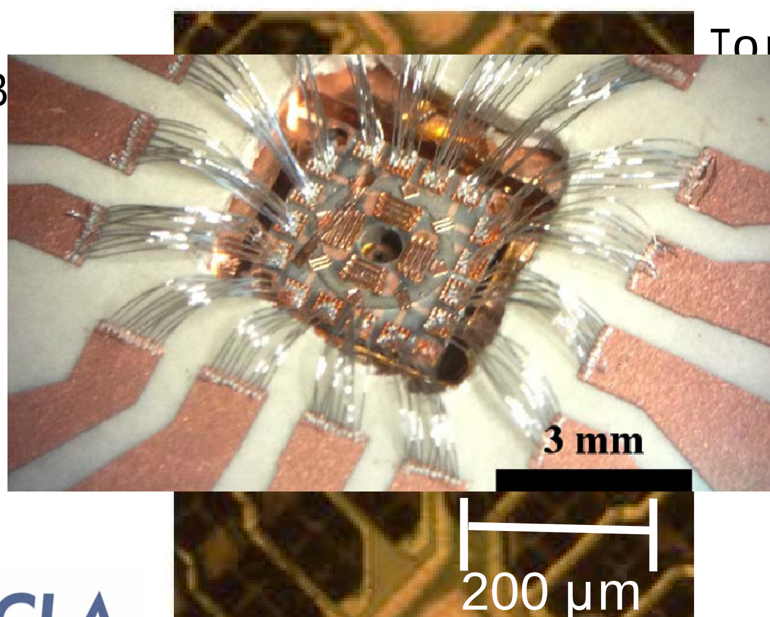
MEMS electromagnetic *quadrupoles*

J. Harrison, Y. Hwang, O. Paydar, J. Wu, E. Threlkeld, J. Rosenzweig, and R. Candler,
Phys. Rev. ST Accel. Beams **18**, 023501

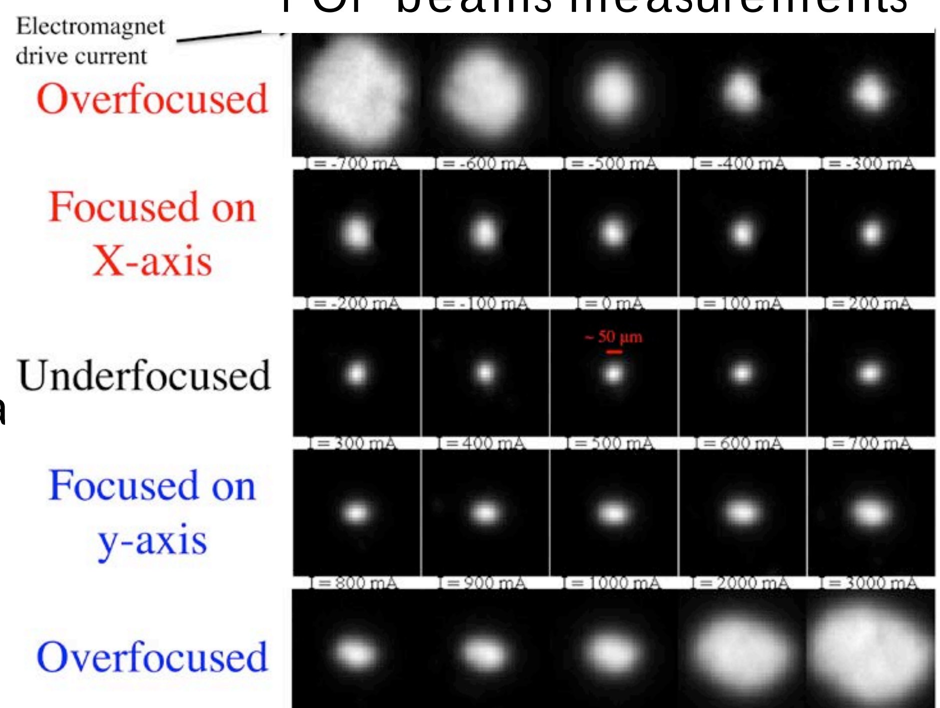
R. Candler presentation

	Currently Available	Future
Technology	Permanent magnet quadrupole	Machined electromagnets
∇B	560 T/m	**>3,000 T/m**
Inner diameter	5 mm	200 μm
Tuning	Axial translation of magnets	Electromagnet

Top View



POP beams measurements



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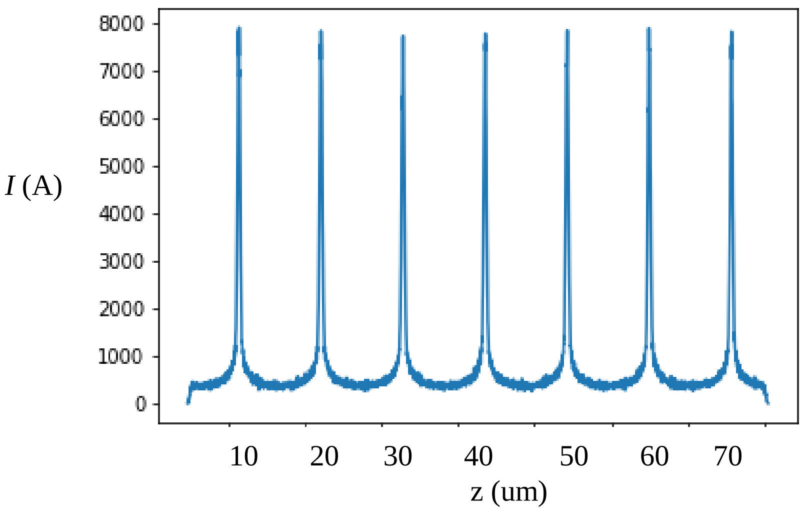
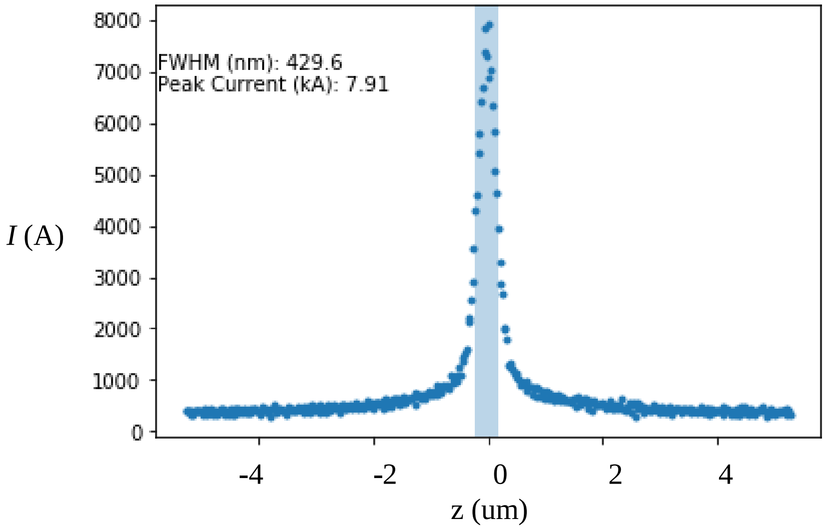
Microbunching with C-band compact linac

- Compression from 20 A to 400 A (both C-band and S-band)
  - Studies ongoing
- ESASE approach with 10 um laser to compensate lower current
- First results encouraging – enhance with “double buncher”

Pulse train



Single pulse



An Ultra-compact 1.5 Angstrom FEL

Electron beam and linac parameters		X-ray FEL parameters	
Peak accelerating field $\mathbf{E_0}$	250 MV/m	Undulator period	1.2 mm
Average accelerating field	125 MV/m	Radiation wavelength	1.57 Å
Total beam charge Q_b	200 pC	Undulator strength K_u	0.12
Current before microbunching I	800 A	Microbunching wavelength	3.2 µm
Current after microbunching $\mathbf{I_p}$	8 kA	Beam rms spot size in undulator	3.1 µm
Emittance ϵ_x	45 nm-rad	Micro-bunch length (FWHM)	320 nm
Electron energy U	1 GeV	3D gain length $\mathbf{L_{g,3D}}$	14.5 cm
Relative rms energy spread	4.8×10^{-4}	Saturation length	2.9 m
Linac active length	8 m	Saturation energy	125 µJ

- 1st steps: Current workshop!
  - To be proposed to NSF as *MRI* (UCLA-SLAC team is core)
- Hosted at UCLA SAMURAI Laboratory

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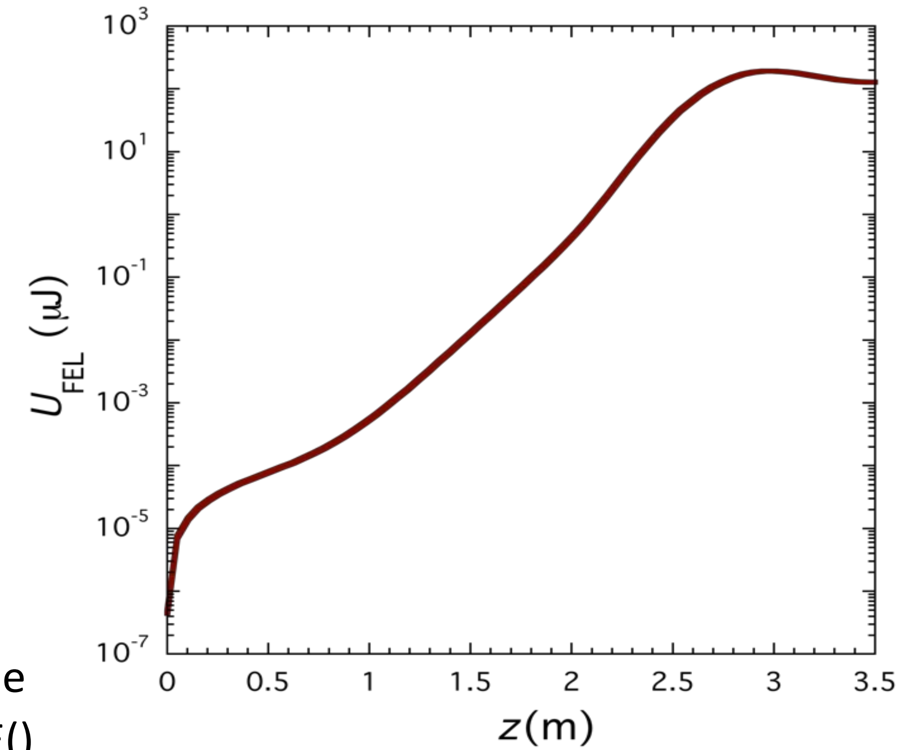
Compact XFEL performance

- Hard X-rays at 1.5 Angstrom
- Saturating in 3 m
- Gain robust despite low *K*
    - Coupling is K/γ, not *K*
- Total energy per pulse 125 μJ
- Far-field rms angle of 4 urad
- Footprint in 10's of m
- **New experimental possibilities**
    - Enhanced access, university scale
    - Unique time structure for pump-probe
    - Advanced technology for FELs (MaRIE()
- Now looking at soft X-rays



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Beyond FELs: Flat Beams from Photoinectors

- Seminal contribution from KJK
- First experiments at FNAL

Round-to-flat transformation of angular-momentum-dominated beams

Kwang-Je Kim

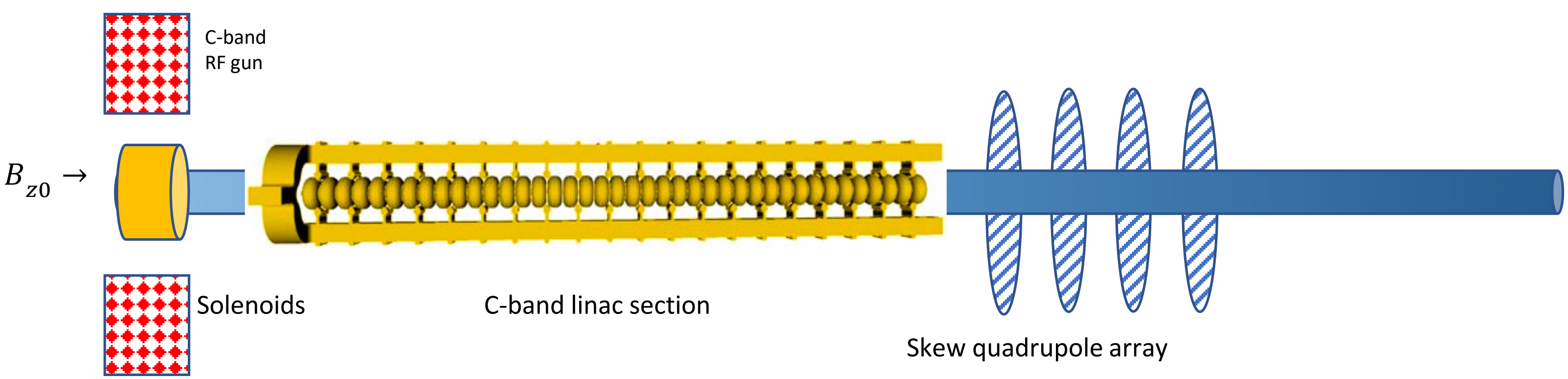
Advanced Photon Source, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439, USA

(Received 13 June 2003; published 30 October 2003)

A study of round-to-flat configurations, and vice versa, of angular-momentum-dominated beams is presented. The beam propagation in an axial magnetic field is described in terms of the familiar Courant-Snyder formalism by using a rotating coordinate system. The discussion of the beam transformation is based on the general properties of a cylindrically symmetric beam matrix and the existence of two invariants for a symplectic transformation in 4D phase space.

Asymmetric emittances… for linear colliders

- High *Q*, very low 4D emittance needed
  - *Eliminate expensive e- damping ring*
- Very high field cryo-RF gun
- Current proposal to HEP test stand at UCLA SAMURAI
  - SLAC-UCLA, with LANL



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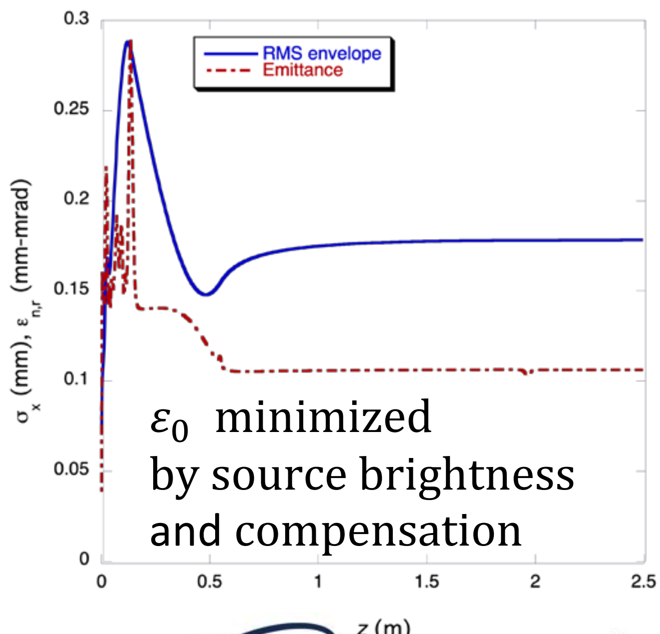
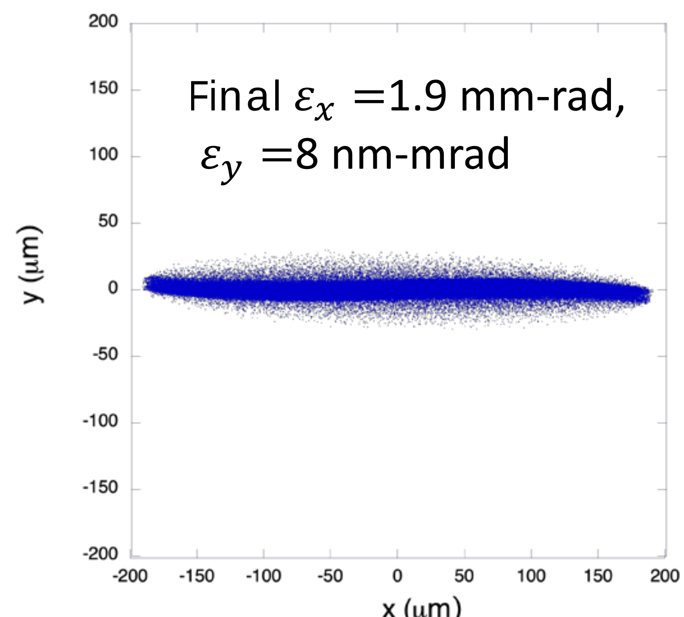
Round-to-flat beam transformation

- Magnetize beam at cathode (~6 kG)
- Skew quads remove angular momentum

$$\mathcal{L} = (eB_0/2m_c c)\sigma_0^2$$

- Split emittances $\varepsilon_y \sim \varepsilon_0^2/\mathcal{L}$, $\varepsilon_x \sim 2\mathcal{L}$





Happy Birthday, Kwang-je!

We are preparing your presents, in the form of interest compounded on your original physics investment