

Next Generation High Brightness Electron Beams From Ultra-High Field Cryogenic Radio-frequency Photocathode Sources

Prof. J. Rosenzweig

UCLA Dept. of Physics and Astronomy

ICHEP - Chicago

August 6, 2016

Abstract

Recent studies of the performance of radio-frequency (RF) copper structures operated at cryogenic temperatures have shown a dramatic increase in the maximum surface electric field that may be reached. We propose to utilize this development to enable a new generation of photoinjectors operated at cryogenic temperatures that may attain, through enhancement of the launch field at the photocathode by a factor of four, well over an order of magnitude increase in peak electron beam brightness. We present detailed studies of the beam dynamics associated with such a system, concentrating on an emittance-compensated S-band photoinjector that may directly substitute that of the LCLS X-ray free-electron laser. We show in this case that the increase in brightness leads directly to a factor of two reduction in gain length, with attendant increase in X-ray radiative efficiency. Extreme low emittance scenarios obtained at low operating charge, appropriate for dramatically pushing performance limits of ultrafast electron diffraction and microscopy experiments, are reviewed. Further, a scheme for achieving very low, asymmetric emittances for eliminating the electron damping ring in a linear collider is discussed. While much of the gain in brightness is due to increase of the emission current density via field enhancement, further increases in brightness due to lowering of the intrinsic cathode temperature in cryogenic operation is also enabled. The potential to probe fundamental brightness limits in these cold, dense beam systems is examined. Issues in experimental implementation, including cavity optimization for lowering cryogenic thermal dissipation, external coupling, and cryo-cooler system are discussed.

UCLA-SLAC-INFN collaboration on next generation photoinjector

J.B. Rosenzweig¹, A. Cahill¹, V. Dolgashev², C. Emma¹, A. Fukusawa¹, R. Li², C. Limborg², J. Maxson¹, P. Musumeci¹, A. Nause¹, R. Pakter¹, R. Pompili³, R. Roussel¹, B. Spataro³, and S. Tantawi²

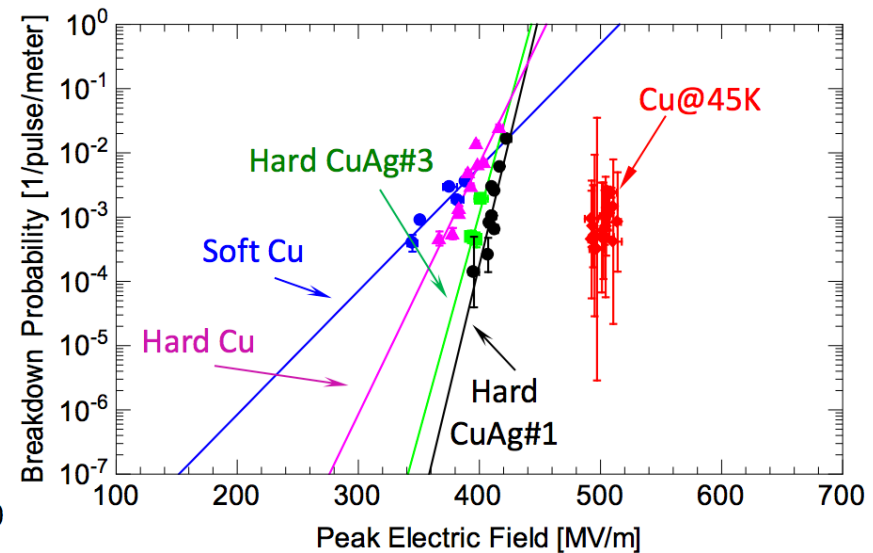
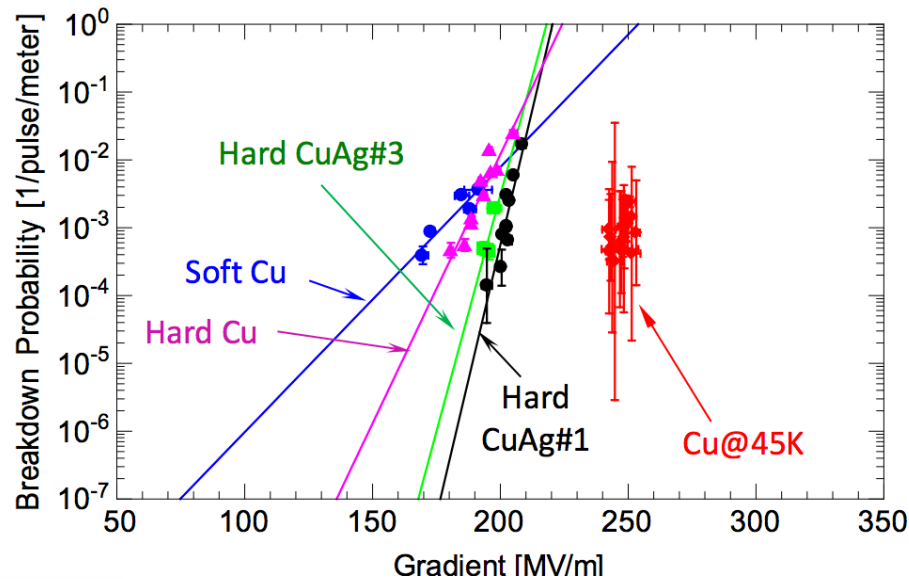
¹*Department of Physics and Astronomy, UCLA*

²*SLAC National Accelerator Laboratory*

³*Istituto Nazionale di Fisica Nucleare, LNF (Frascati, Italy)*

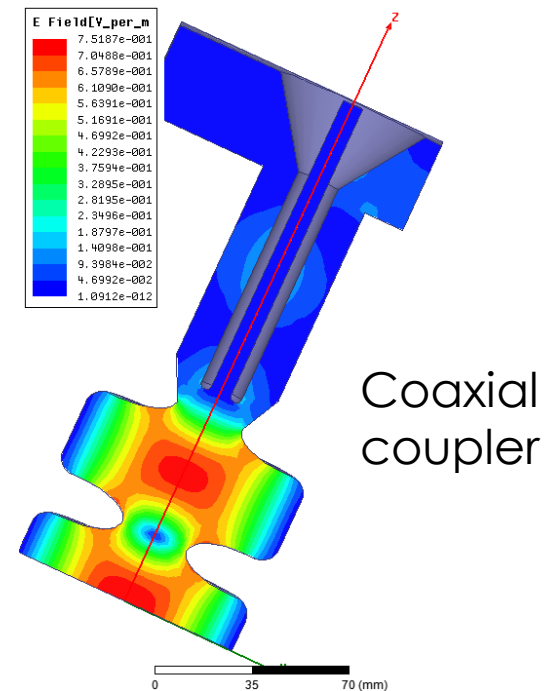
Enabling technique: dramatically higher gradients in higher yield strength material

- SLAC X-band studies on hard Cu, CuAg alloy show great improvement
- **Cryogenic structures** give give higher gradients, and lower dissipation

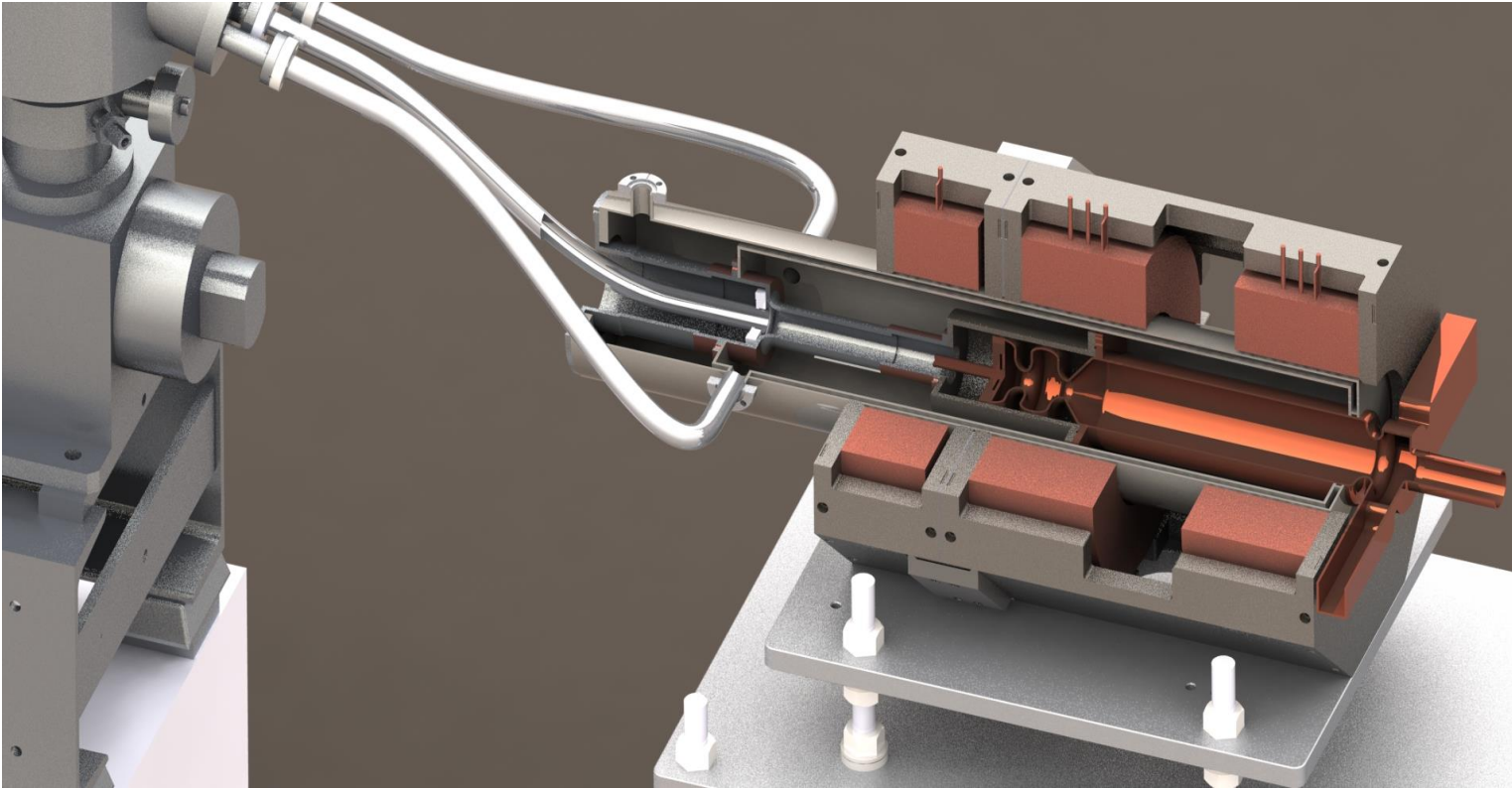


Next generation photoinjector: ultra-high field cryogenic “TopGun”

- TopGun: UCLA-SLAC-INFN collab.
- S-band operation; option for LCLS II
 - Robust beam dynamics
- Peak design field **>250 MV/m**
- Operation at **~27K** (liquid Ne)
- Symmetrized RF design
- Overcoupled for **<1 usec pulses**
- Cavities optimized for low heat load
- 1.45 cells ($\sim 90^\circ$ launch phase)
- *Launch field up from present MV/m to 240 MV/m ... x4!*



Conceptual layout



**S-band cryogenic gun with cryostat, focusing magnets;
drop-in replacement for NC injector at LCLS II**

Motivation: brightness!

- *Brightness* at cathode: $B_e = \frac{2I}{e_n^2} = \frac{2J_{\max} m_e c^2}{k_B T_c}$
- In 1D limit, peak current from a pulsed photocathode is

$$J_{z,b} \gg \frac{ece_0}{m_e c^2} (E_0 \sin j_0)^2$$

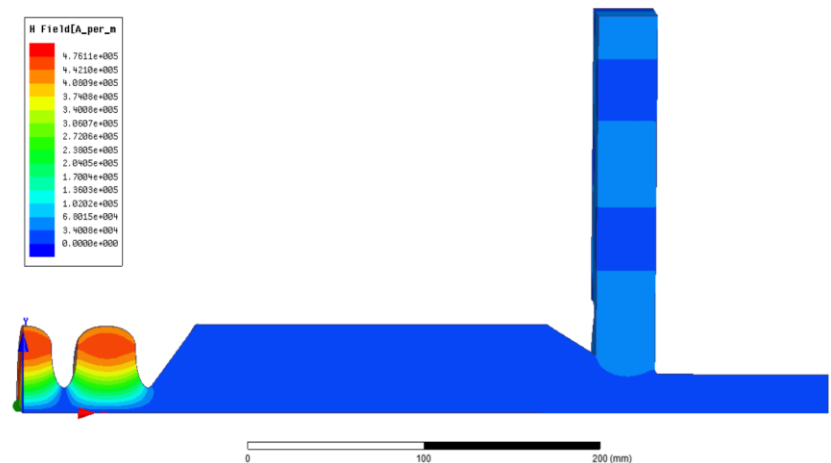
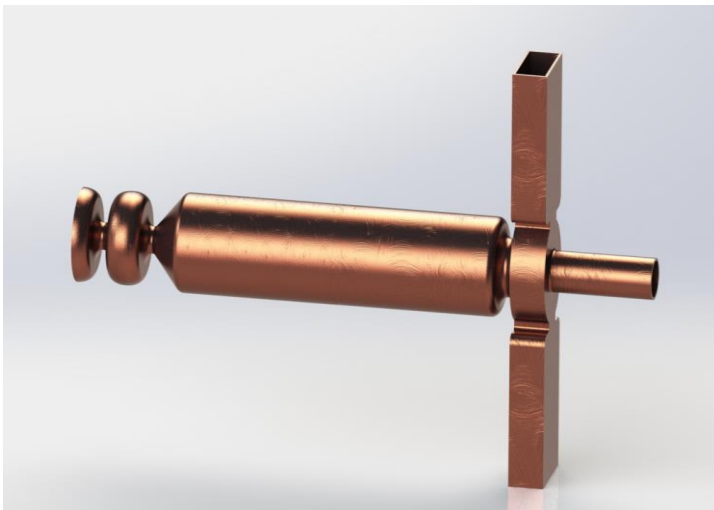
- Brightness is

$$B_{e,b} \gg \frac{2ece_0}{k_B T_c} (E_0 \sin j_0)^2$$

- **Factor of 16 from field increase alone**
- (Improved cathode T_c at low temp.)

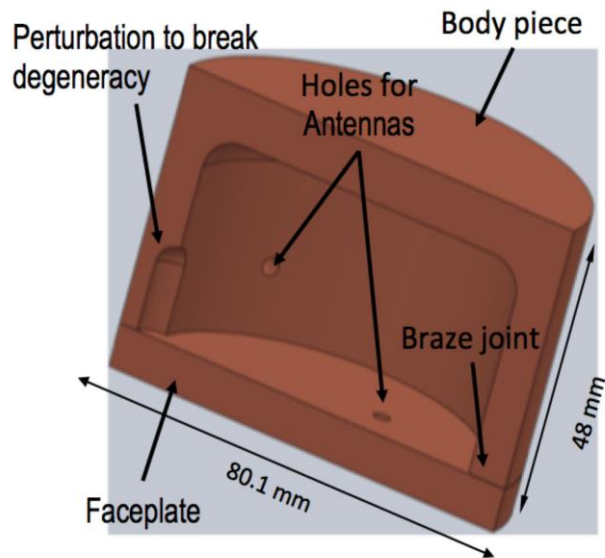
Employ optimized cavity design

- Minimized B-field, dissipation (cryo-load)
- Over-coupling (fast), coupler symmetry
- Avoid multi-pacting in coupler

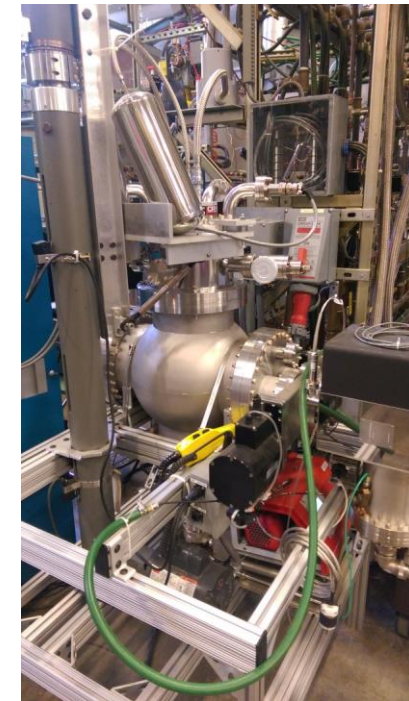
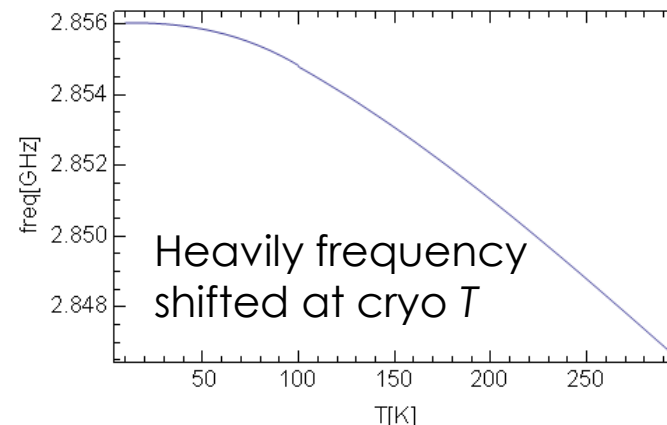
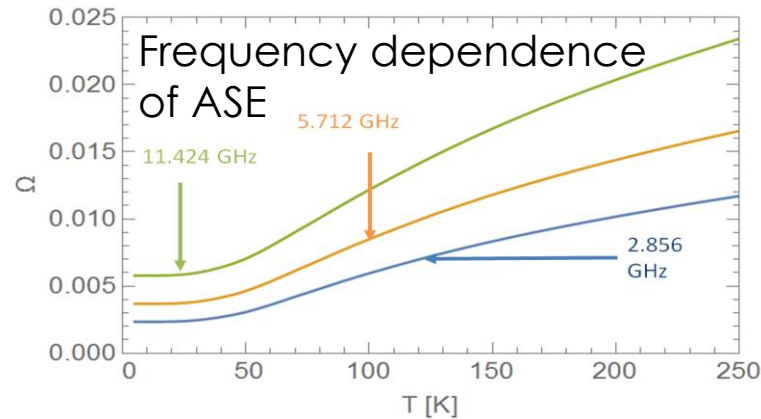


Cryogenic S-band Q-enhancement

- Anomalous skin effect; higher Q shown
 - Factor of 4.63 over room temperature
 - S-band experiments (Cahill, UCLA)

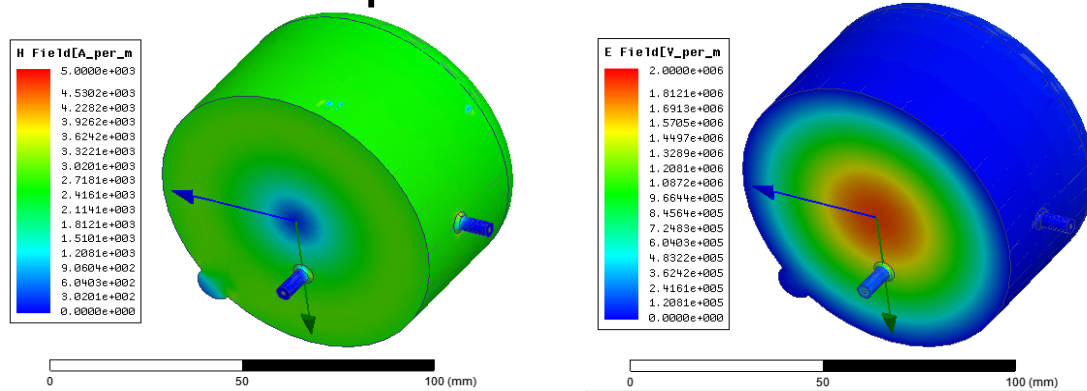


Test cell geometry

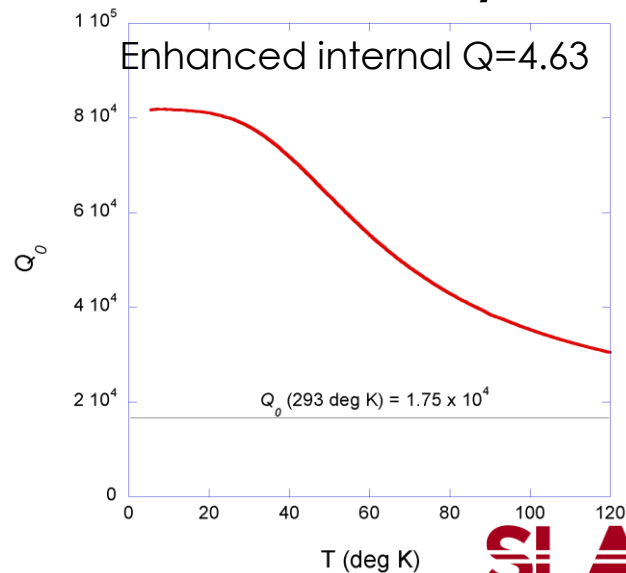
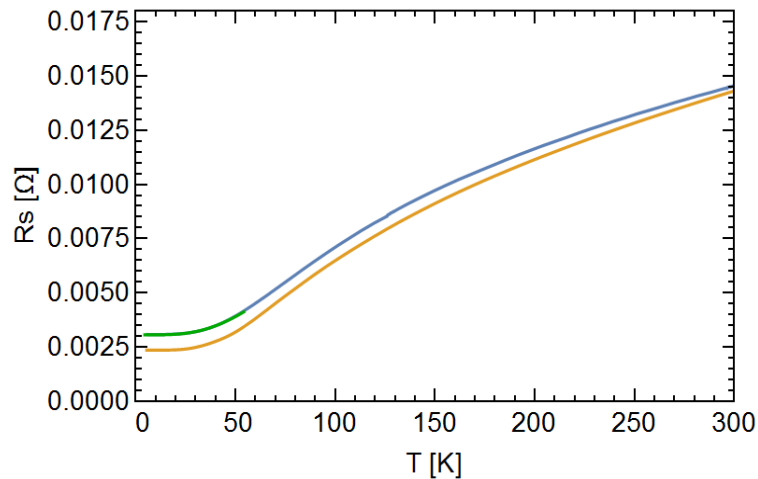


S-band test cell measurements

- E- and B-field profiles

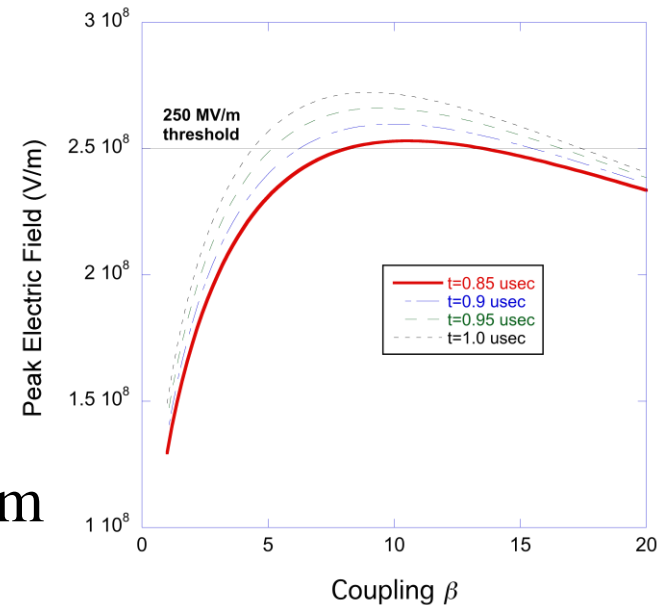


- Two cells (UCLA and SLAC fab)



RF cavity design based on results

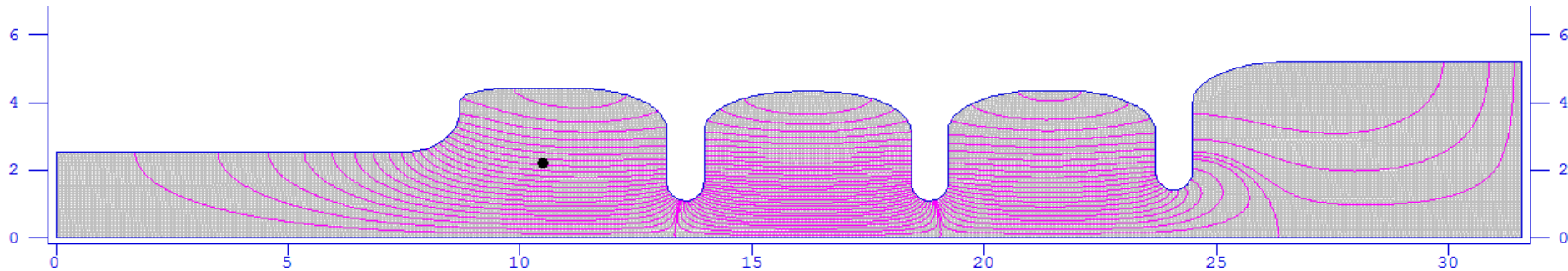
Internal quality factor Q_0 300 K	13,483
Internal quality factor Q_0 27 K	62,425
Input power	50 MW
Normalized shunt impedance R/Q	136 W
Peak field at end of RF fill	250 MV/m
Fill time ($b=9$)	0.9 msec
Energy dissipated/pulse ($t=0.9$ ms)	4.25 J (510 W at 120 Hz)



Design parameters for cryogenic S-band RF gun

Next step: high power S-band

- Testing of high power response
 - Q, tuning to resonant frequency
- Extension of X-band methods
- Fabrication underway, tests in Fall '16



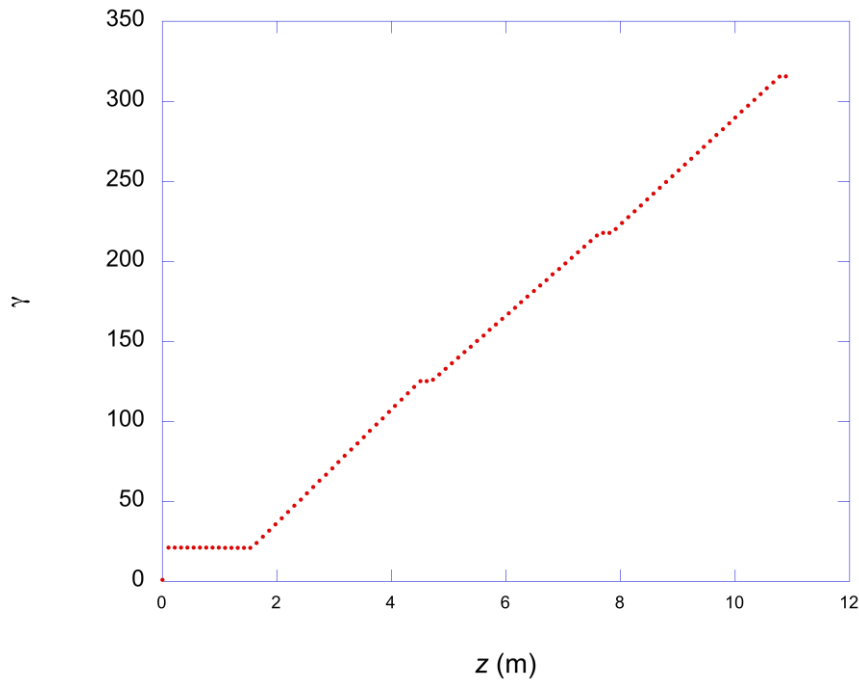
SUPERFISH simulation of “single” cell accelerating mode (A. Cahill)

Beam Dynamics Studies

- **Explore the scaling!**
- GPT simulations with:
 - High charge blowout regime for FEL
 - Low charge “cigar” regime for diffraction (UED), microscopy (UEM)
- Solenoid downstream of gun exit
- Emittance compensation, post acceleration studied
- Excellent results. Extremely high impact on LCLS II and UEM.
 - Start-to-end for FEL performed

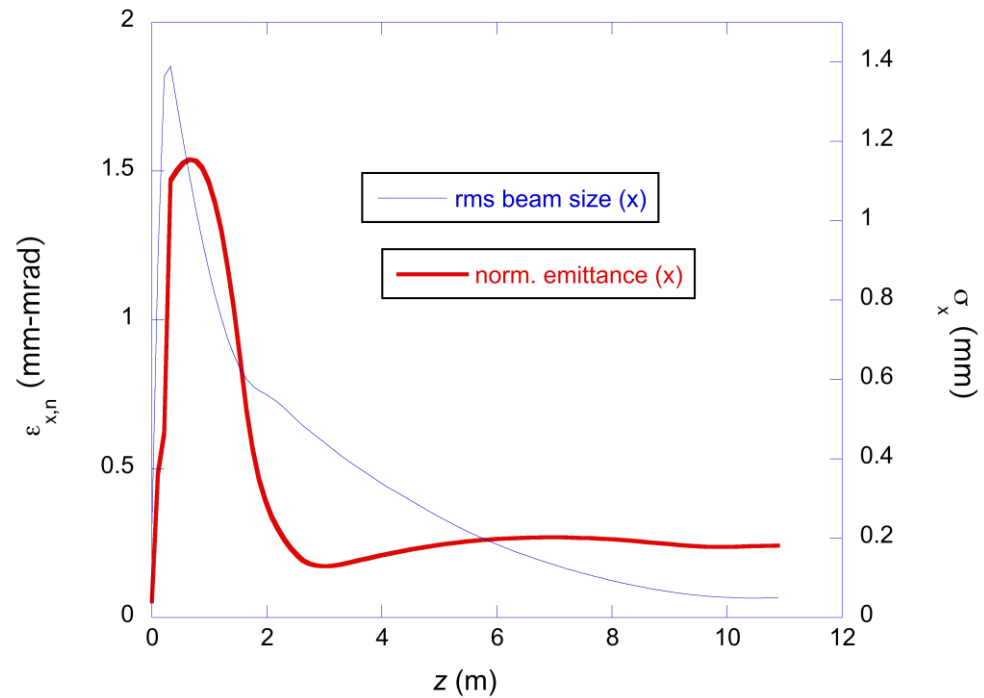
Beam Acceleration , Transverse Envelope and Emittance

GPT simulations



Acceleration to 161 MeV

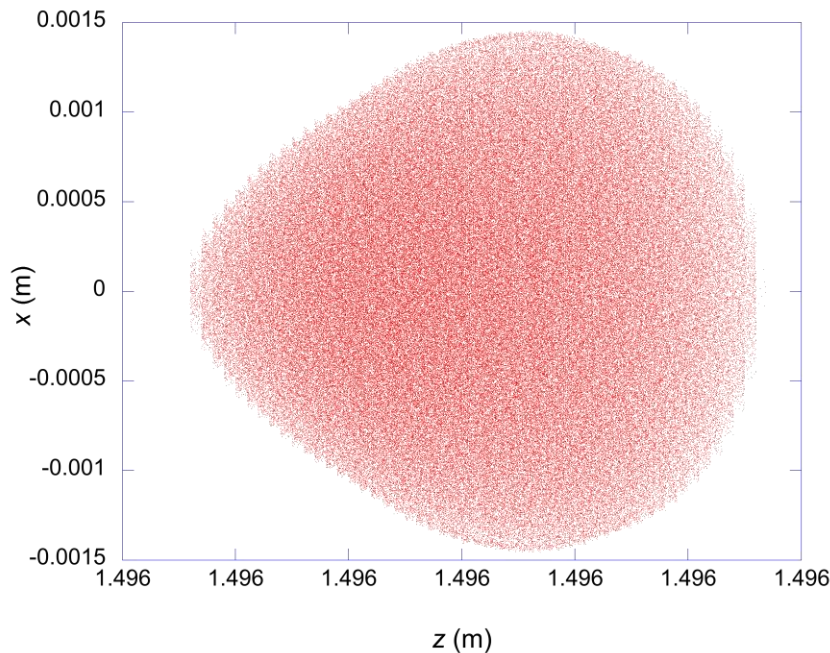
Focusing with 2 kG solenoid,
acceleration in linac starts at 1.7 m



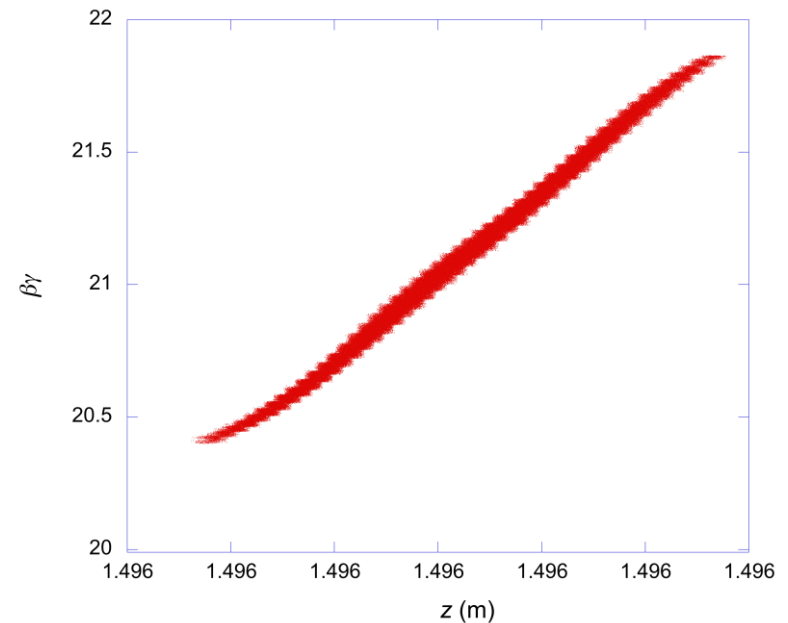
Emittance compensated finishes ~ 0.2 m-mrad

Longitudinal Expansion

- After gun, 10.5 MeV energy, ellipsoidal beam formed by longitudinal expansion



Projection (x - z) of ellipsoidal charge distribution due to blowout



Highly linear, compressible longitudinal phase space due to linear space charge fields

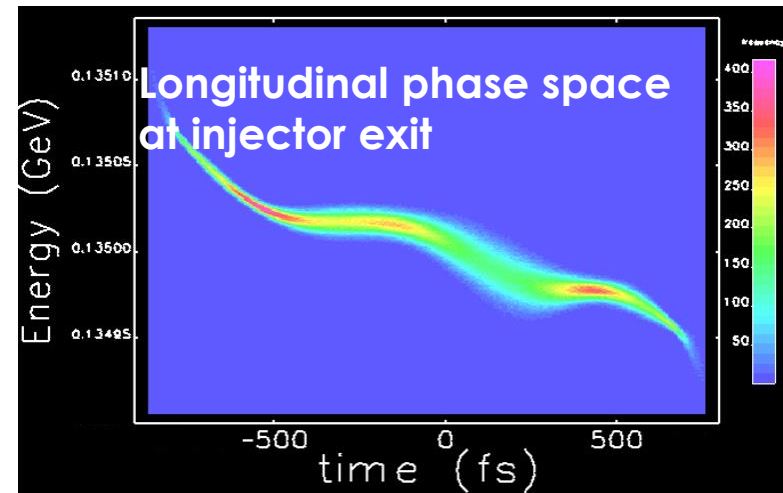
Parameters chosen to give 100A peak (original LCLS design comparison)

Start-to-end Simulations

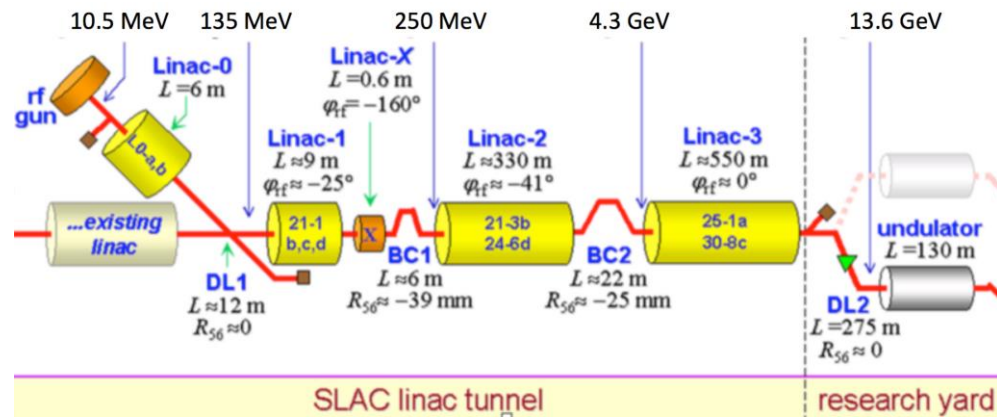
- **GPT** to 160 MeV
 - Space charge

$$B_e = 5.2 \times 10^{17} \text{ A/m-rad}^2$$

25x that of original LCLS design!

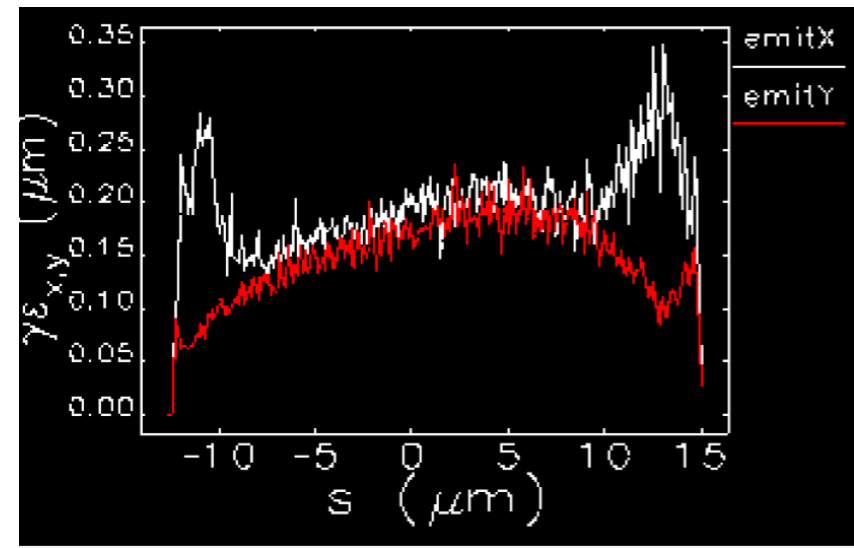
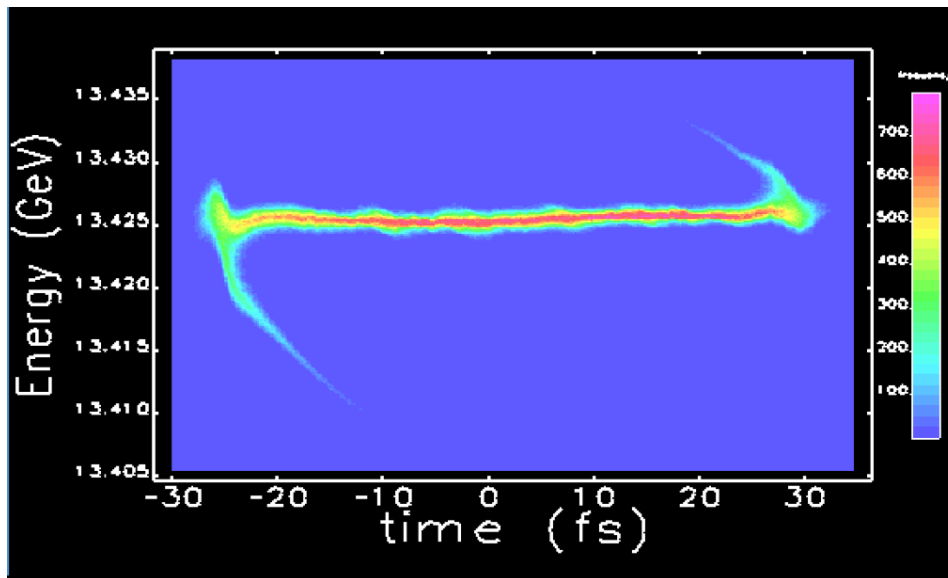


- **ELEGANT** for acceleration, compression and transport to undulator
- **GENESIS**, including tapering and self-seeding in LCLS

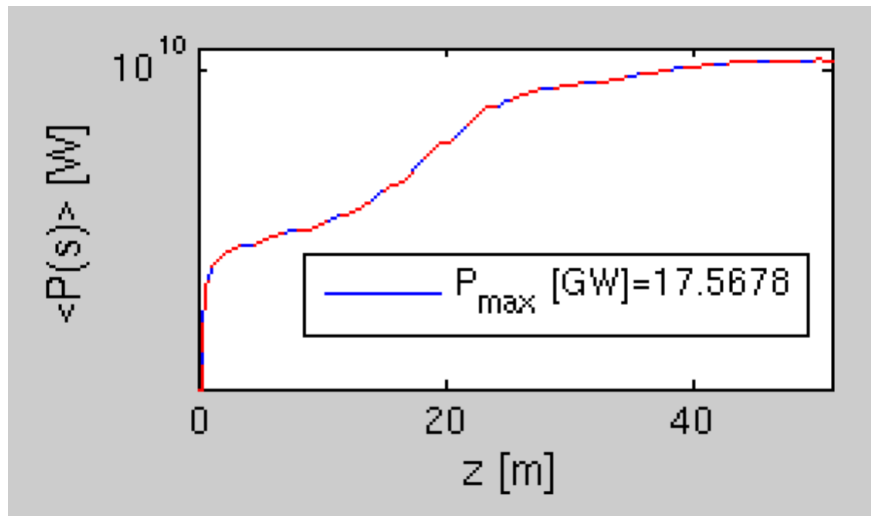


Acceleration and Compression: Elegant Simulations

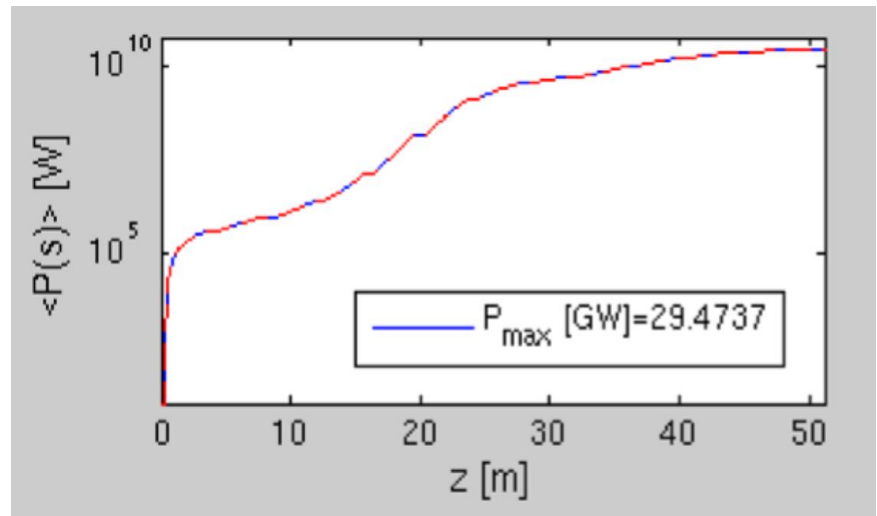
- LCLS lattice, chicanes (benchmarked)
- 2.5 kA in beam core (usual peaks in wings)
- Slice emittance $<.2 \mu\text{m}$



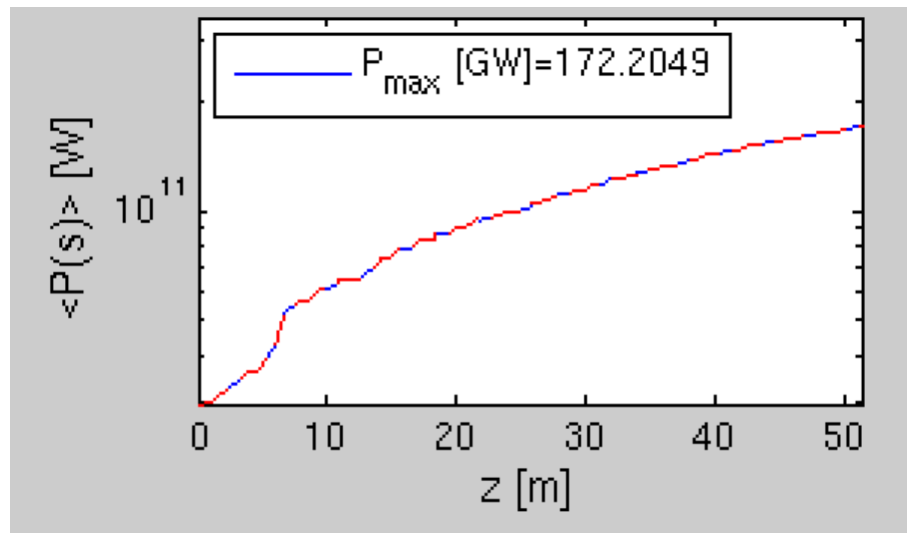
LCLS undulator GENESIS simulation:



Saturation after 25 m



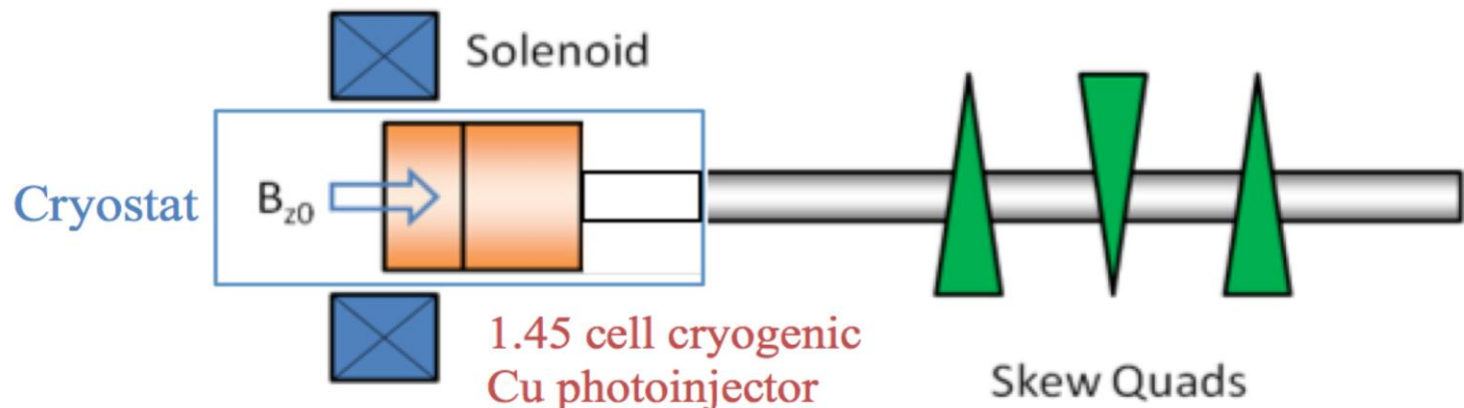
$\Delta K/K=0.1\%$ tapering after 20 m



Pulse energy
8.5 mJ @ 125 pC

Asymmetric Beam Generation: Application to Linear Colliders

- Need very small vertical emittances to give flat beams at IP
 - Beamstrahlung mitigation
- Eliminate electron damping ring?
- Use *magnetized* high brightness beam



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

Initial flat beam studies at low Q

- 1.67 pC (1E7 e-s); *eased emittance comp.*
- $B_0=0.75\text{T}$ at cathode; emittance increased

$$\varepsilon_0^2 = (k_B T_c / m_e c^2) \sigma_0^2 \quad \varepsilon_0 = 0.0065 \text{ mm-mrad}$$

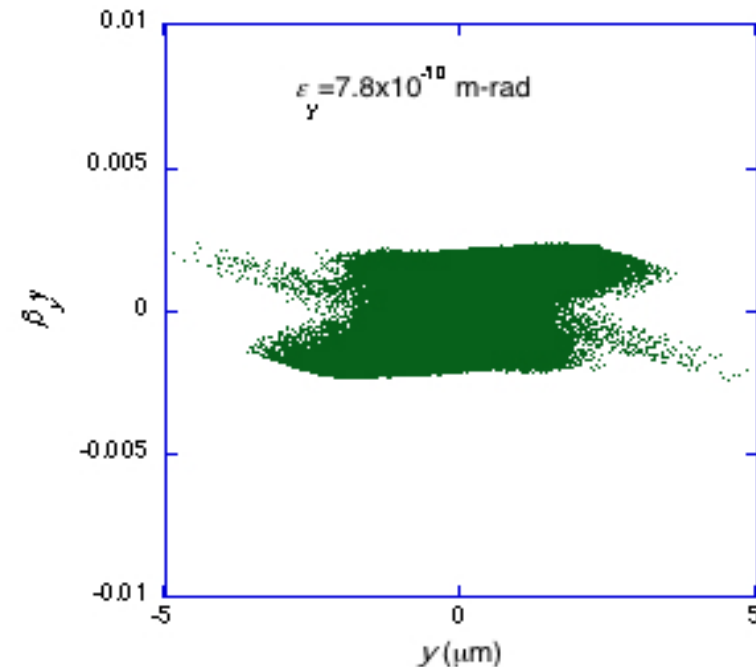
- Remove L with skew quads, split ε 's

$$\varepsilon_- \sim \frac{\varepsilon_0^2}{2\mathcal{L}} \quad \varepsilon_+ \sim 2\mathcal{L}$$

Splitting ratio: $(2\mathcal{L}/\varepsilon_0)^2=81$

$$\varepsilon_y = 7.8 \times 10^{-10} \text{ m-rad}$$

- Optimum for dielectric laser accelerator
- Need higher Q for LC applications



New technology yields new instrument

- **Cryogenic copper photoinjector gives ~25 increase in brightness compared to LCLS design**
 - S-band for compatibility with present infrastructure
- **Based on lower dissipation and higher material strength**
- **Big step forward in FEL applications**
 - Start to end yields promising results
- **Possible applications in flat beam production**
 - Linear collider-like beams; *dielectric laser accelerator*
- **Physics issues being addressed**
- **Engineering underway**
- **UCLA/SLAC/INFN collaboration underway**