The Limits of Beam Brightness from Photocathode RF Guns

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In collaboration with SLAC and LBNL

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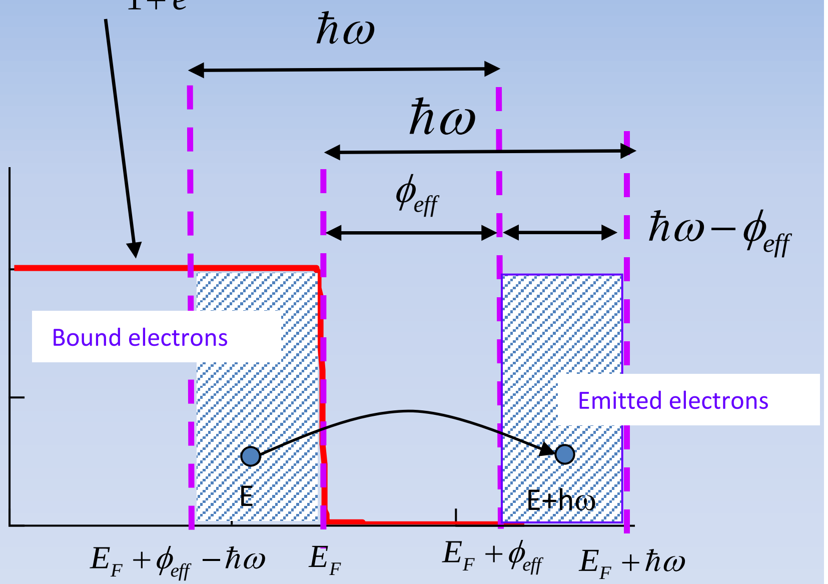
- **QE and the intrinsic cathode emittance**
- **Space charge emittance near the cathode**
- **RF contribution to the projected emittance**
- **Chromatic emittance of the gun solenoid**
- **Aberrations and field errors of the solenoid**
- **Summary and conclusions**

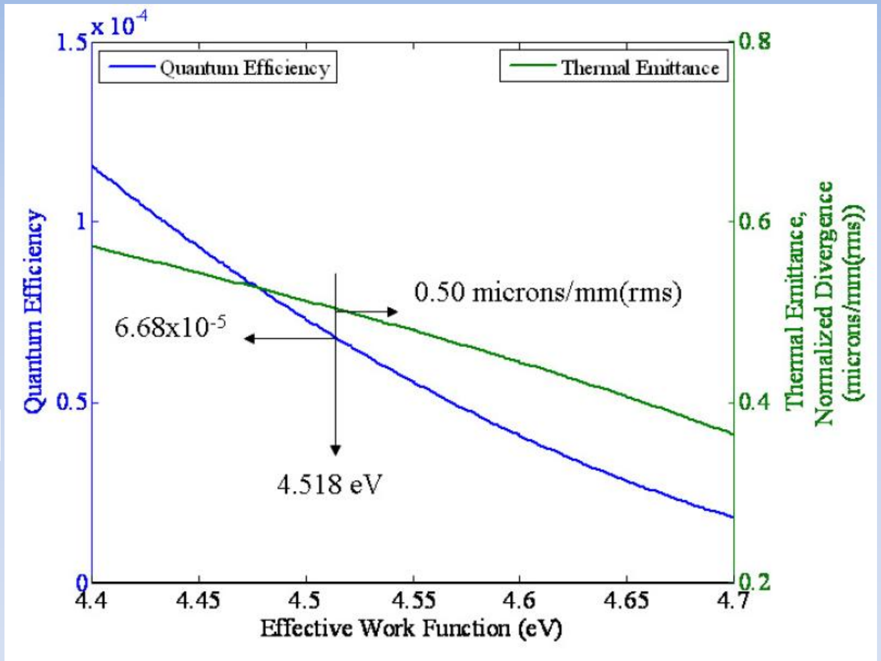
Photoemission Theory for Metal Cathodes

In this theory the QE and intrinsic emittance are connected by the excess energy: the difference between the photon energy and the work function. The greater the excess energy the greater the QE and the higher the intrinsic emittance. This is also the case for prompt emitting semi-conductor cathodes such as Cs_2Te and SbK_2Cs. However slow emitters such as GaAs can have high QE and low emittance.

$$f_{FD}(E) = \frac{1}{1+e^{(E-E_F)/k_BT}}$$



Prompt emission from the Fermi-Dirac energy distribution



$$\phi_{eff} = \phi - \phi_{schottky}$$

D.H. Dowell & J.F. Schmerge, PRST-AB 12,074201(2009)

Comparison of QE with Thermal Emittance Using a Consistent Theory for Metal Cathodes

Use QE to determine effective work function → **Use work function in emittance formula**

$$QE(\omega)=\frac{(1-R(\omega))}{1+\frac{\lambda_{opt}}{\lambda_{e-e}}}\frac{E_F+\hbar\omega}{2\hbar\omega}\left(1-\sqrt{\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}}\right)^2$$

$R(\omega)=$ Reflective at ω

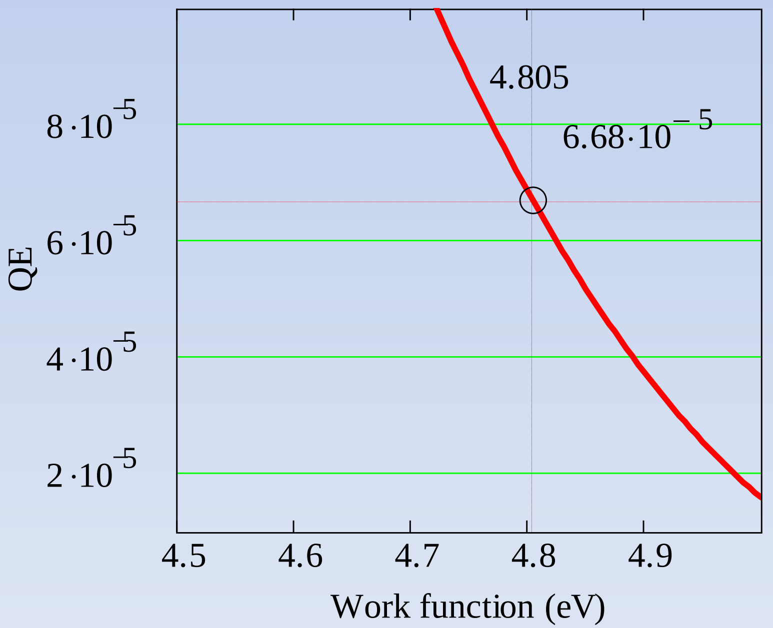
λ_{opt} = Optical absorption length

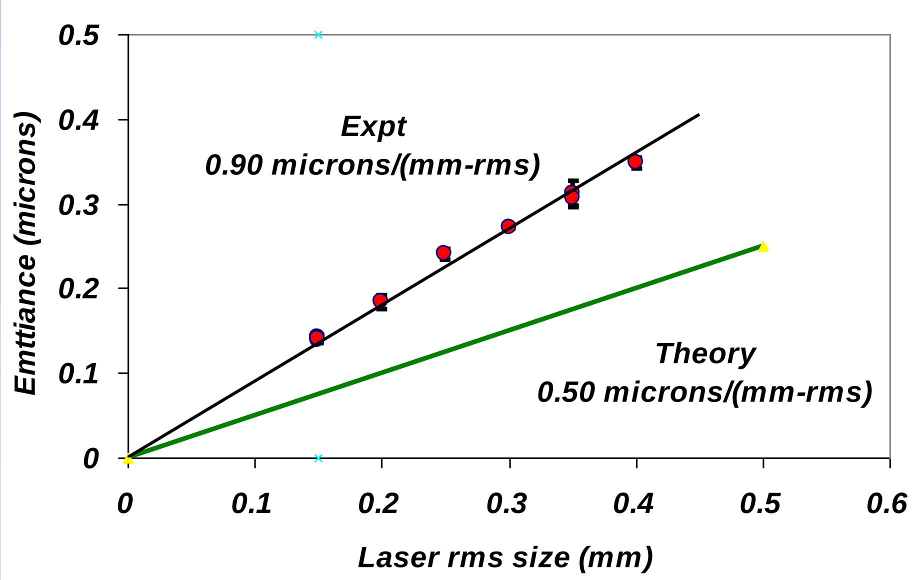
$\lambda_{e\text{-}e}$ = electron - electron scatterng length

E_F = Fermi energy

$$\varepsilon_N=\frac{R_{cathode}}{2}\sqrt{\frac{\hbar\omega-\phi_{eff}}{3mc^2}}=\sigma_x\sqrt{\frac{\hbar\omega-\phi_{eff}}{3mc^2}}$$

$$\phi_{eff}=\phi-\phi_{schottky}$$





Y. Ding et al., PRL 102, 254801(2009)

Comparison of Expt. and Theory for the Intrinsic Emittance

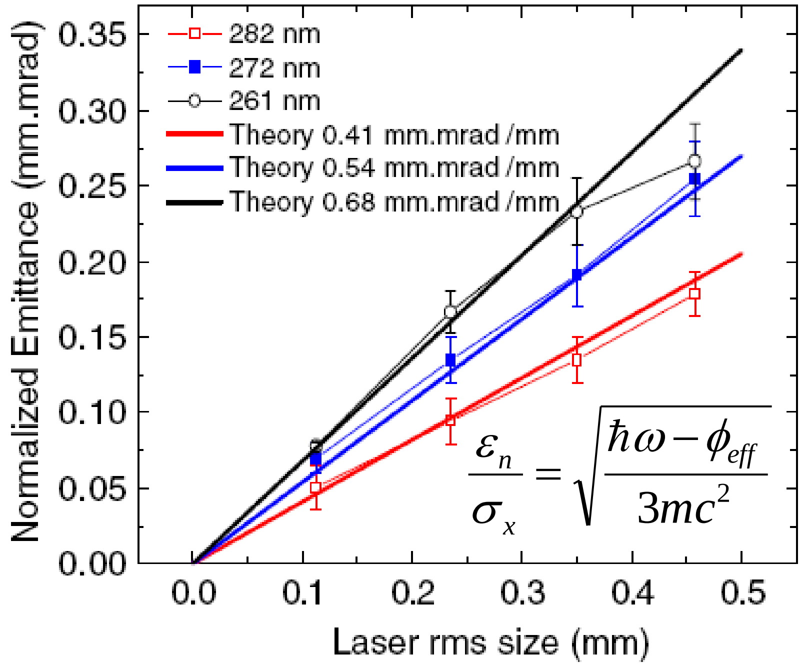
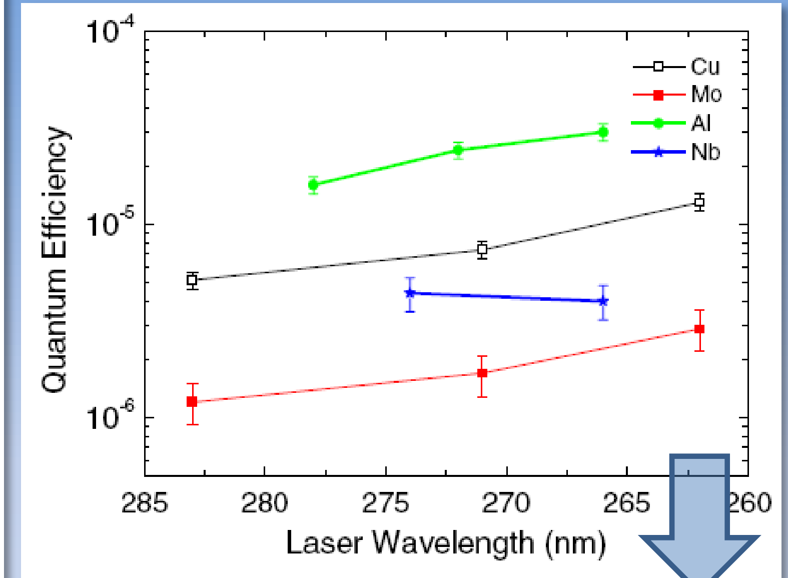
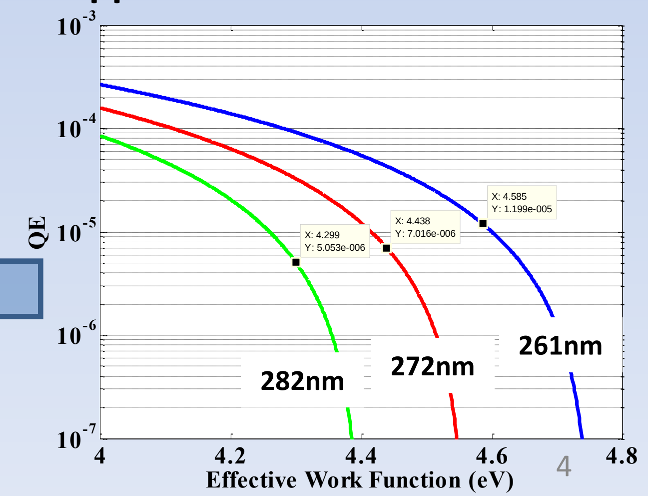


FIG. 4 (color online). Normalized projected emittance versus laser spot size for 3 different wavelengths on copper. ($Q < 1$ pC; solenoid scan method, Cu inset). Theory corresponds to Eq. (1) assuming $\Phi_{Cu} = 4.3$ eV (thermal effects not included).

C.P. Hauri et al., PRL **104**,234802(2010)



QE of Copper vs. Effective Work Function



261nm : $\phi_{eff} = 4.58$ eV : $\varepsilon_n / \sigma_x = 0.33$ vs. 0.68expt.
272nm : $\phi_{eff} = 4.44$ eV : $\varepsilon_n / \sigma_x = 0.28$ vs. 0.54expt.
282nm : $\phi_{eff} = 4.30$ eV : $\varepsilon_n / \sigma_x = 0.25$ vs. 0.41expt.

Expt.-to-theory is ~2, consistent with other experiments

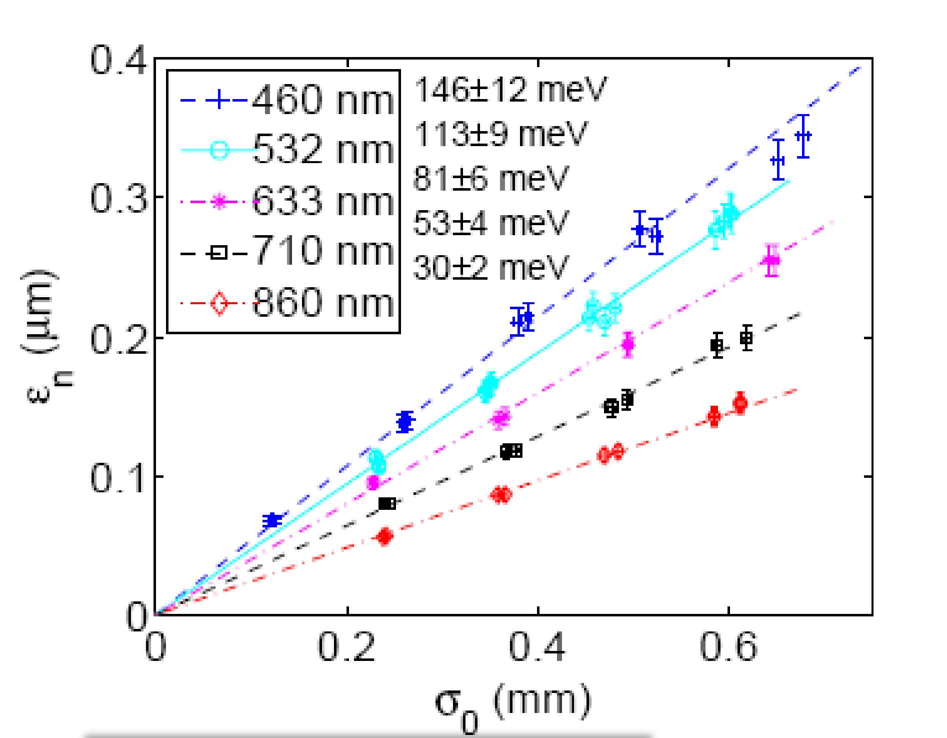
Thermal Emittance and Response Time of GaAs

Lowest Intrinsic(Thermal) Emittance

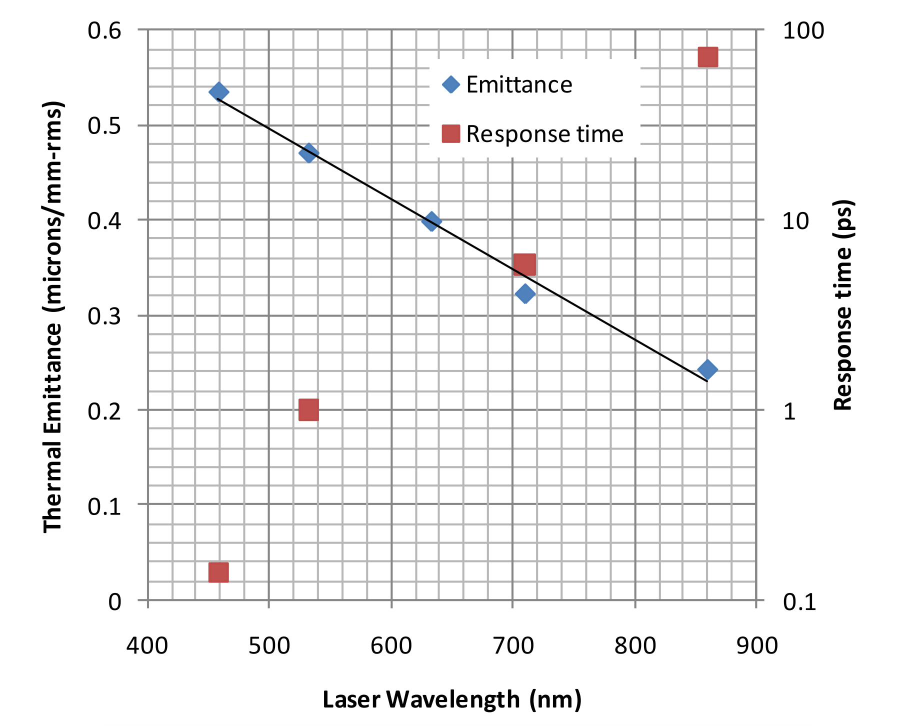
Response time and emittance depend upon photon wavelength

Due to electron-phonon scattering the delayed-emission electrons can reach thermal equilibrium with the lattice, giving the intrinsic emittance of GaAs a thermal-like emission component (given by kT) as well as prompt emission(given by the excess energy) part.

$$\frac{\varepsilon_{GaAs,n}}{\sigma_x} = A_{slow}\sqrt{\frac{k_B T}{mc^2}} + A_{fast}\sqrt{\frac{\hbar\omega - E_G - E_A}{3mc^2}}$$



I. V. Bazarov et al., Proceedings of PAC07



Plot of data taken from I.V. Bazarov et al., Appl. Phy. 103 (2008)054901 and Proceedings of PAC07

Cathode Surface Roughness

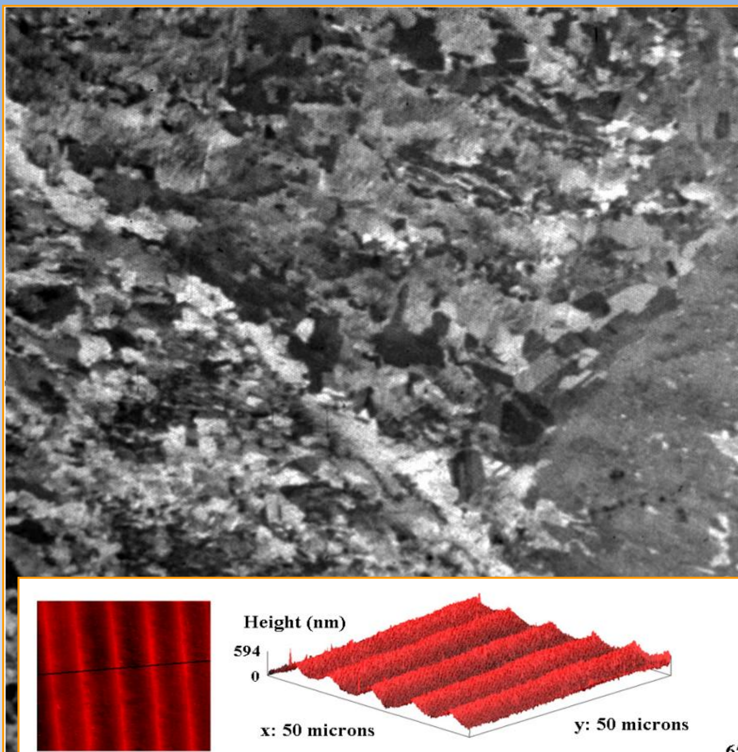
Emittance Growth Due to Non-Uniform Emission & Field Enhancement

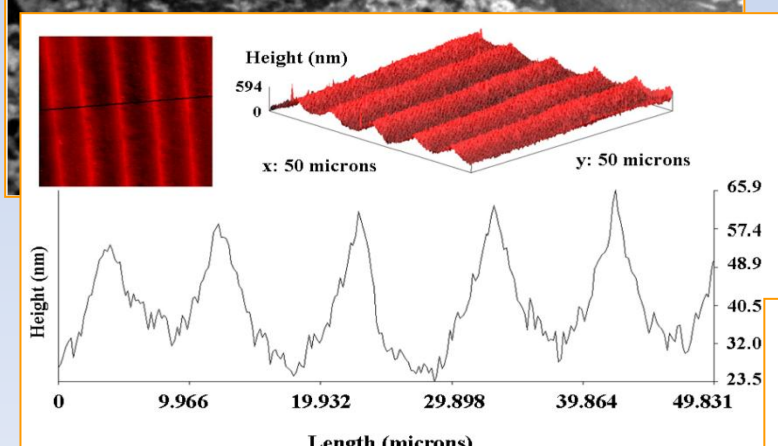
-Highest cathode field not necessary best emittance-

266 nm PEEM image of polycrystalline Cu sample

~ 14 micron field of view, p-pol illumination

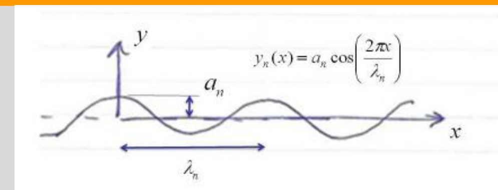
Image compliments of H. Padmore, ALS-LBNL





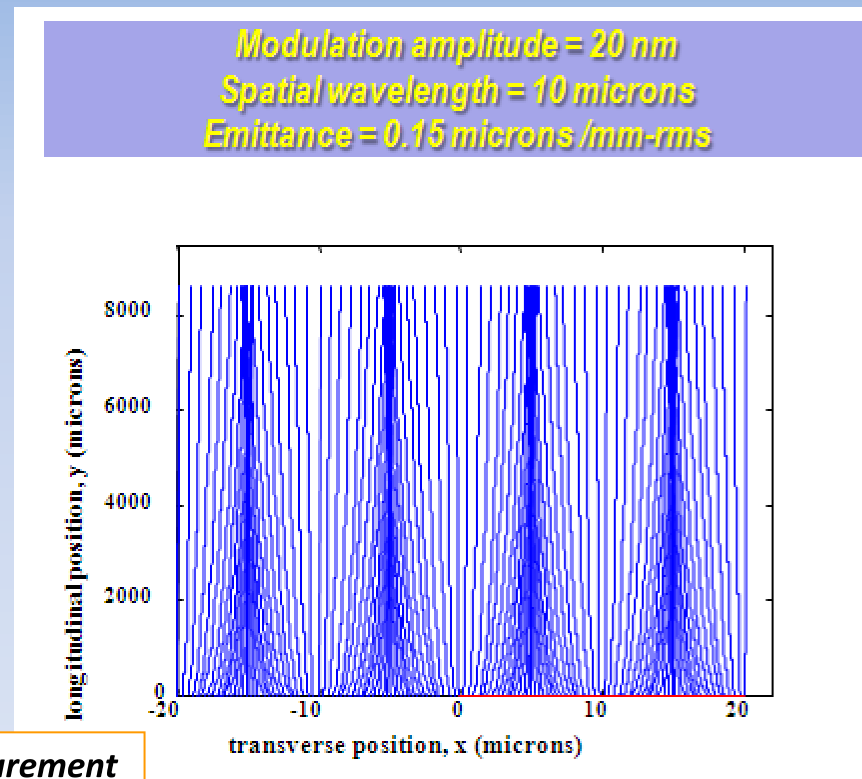
AFM measurement of a sample cathode surface

Emittance Growth Due to Field Enhancement



$$\gamma\varepsilon_{n,s} = \sigma_x \sqrt{\frac{e\pi^2 a_n^2 E_{RF} \sin\theta_{RF}}{2mc^2\lambda_n}}$$

D. Xiang et al., PAC07, pp. 1049-1051



The Brightest Beam Possible*
- How much can the LCLS gun emittance be lowered? -

Assume all linear and non-linear space charge effects can be corrected/compensated for, assume the cathode is perfectly flat and the cathode physics is correct. Then the lower limit on the emittance depends on the thermal emittance for the divergence and the space charge limit for the beam size:

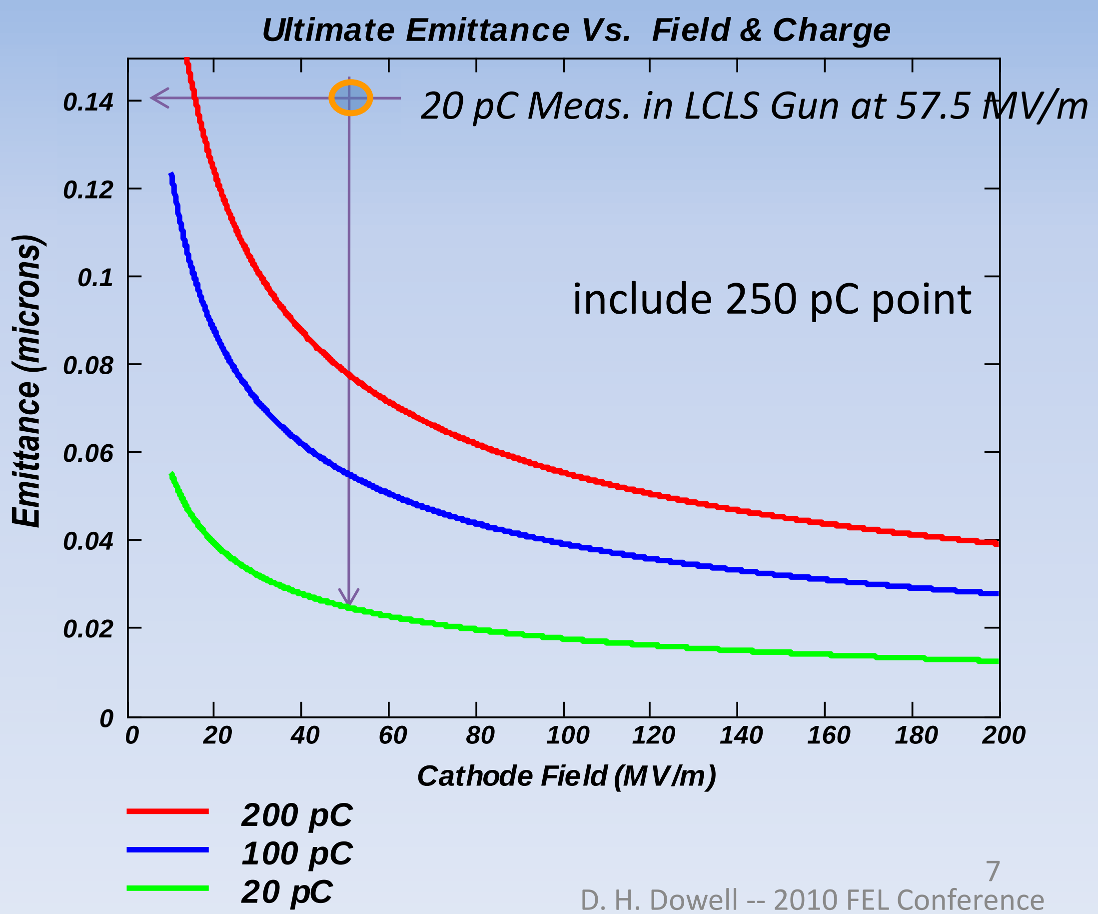
$$\varepsilon_{smallest} = \sigma_{x,SCL}\left(E_{cathode}\right) \times \frac{\varepsilon_{thermal}}{\sigma_x}\left(microns/mm-rms\right)$$

$$\frac{\varepsilon_{thermal}}{\sigma_x} = \sqrt{\frac{\hbar\omega - \phi_{eff}}{3mc^2}}$$

$$E_{cathode} = \frac{\sigma_{\text{surface charge density}}}{\varepsilon_0} = \frac{Q_{bunch}}{\pi R^2_{cathode}\varepsilon_0}$$

$$\sigma_{x,SCL} = \sqrt{\frac{Q_{bunch}}{4\pi\varepsilon_0 E_{cathode}}}$$

$$\varepsilon_{smallest} = \sqrt{\frac{Q_{bunch}\left(\hbar\omega - \phi_{eff}\left(E_{cathode}\right)\right)}{12\pi\varepsilon_0 E_{cathode} mc^2}}$$

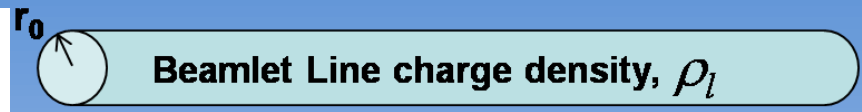


*For GaAs see: I. Bazarov et al., Phys. Rev. Lett., **102** (2009) 104801

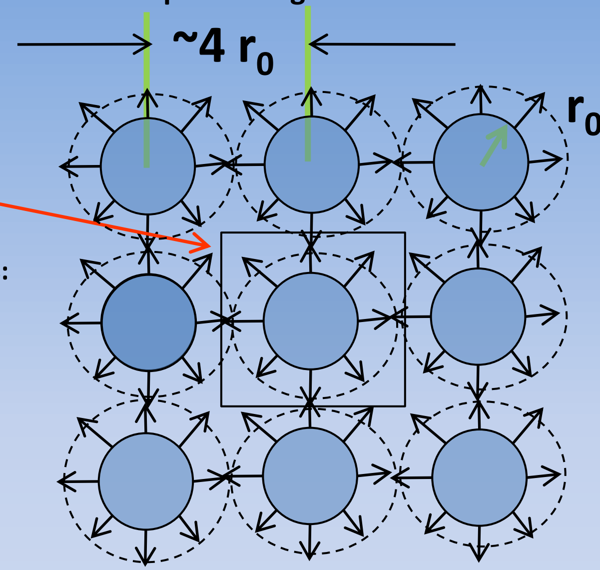
Model for Space Charge Emittance due to Emission Non-Uniformities

Basic Assumptions of Model

1. Charge is distributed in a regular array of tubes, beamlets.
2. Beamlets see radial space charge force until they overlap.
3. After overlapping the sc-force becomes small, the electrons are left with radial velocity which becomes emittance.



Beam consists of a rectangular array of beamlets, each driven outward by their radial space charge force



Area (cell) occupied by each beamlet is: $(4r_0)^2$

∴ Number of beamlets is:

$$N_b = \frac{\pi R^2}{16 r_0^2}$$

Radial electric field outside the tube/beamlet of charge:

$$E_r = \frac{\rho_l}{2\pi\varepsilon_0 r} \qquad \rho_l = \frac{Q}{N_b l_b} = \frac{16 r_0^2 Q}{\pi R^2 l_b}$$

$$E_r = \frac{8}{\pi^2}\frac{Q}{\varepsilon_0}\frac{r_0^2}{R^2 l_b r}$$

Integrate to get energy gain of an electron at radial edge of beamlet:

$$\frac{p_r^2}{2m} = \frac{8eQr_0^2}{\pi^2\varepsilon_0 R^2 l_b}\int_{r_0}^{ar_0}\frac{dr}{r} = \frac{8eQr_0^2}{\pi^2\varepsilon_0 R^2 l_b}\ln a$$

Leap of faith: Assume $\left\langle p_x^2 \right\rangle \approx \frac{p_r^2}{4}$

Then the emittance definition: $\varepsilon_n = \sigma_x \frac{\sqrt{\left\langle p_x^2 \right\rangle}}{mc}$

Gives the emittance due to the rectangular array of beamlets:

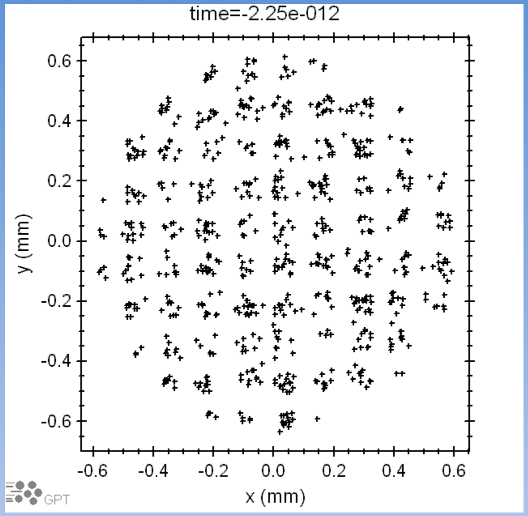
$$\Delta\varepsilon_{n,sc} \propto \sigma_x \frac{2r_0}{\pi R}\sqrt{\frac{eQ\ln a}{\varepsilon_0 mc^2 l_b}}$$

D. H. Dowell et al., Proc. FEL2009

Space Charge Emittance Near the Cathode

$$\Delta\varepsilon_{n,sc} = \sigma_x \frac{2r_0}{\pi R}\sqrt{\frac{eQ\ln a}{\varepsilon_0 mc^2 l_b}}$$

emittance for 100% modulation



In terms of the peak current: $I = \dfrac{Qc}{l_b}$

and the characteristic current: $I_0 = \dfrac{ec}{r_e} \approx 17kA$

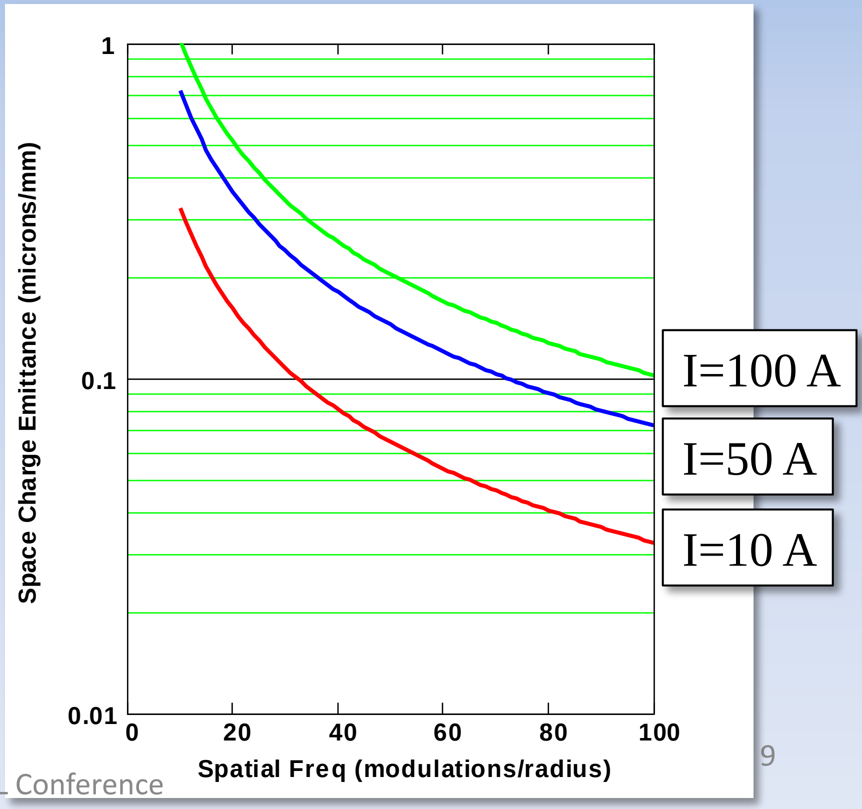
$$\Delta\varepsilon_{n,sc} = \sigma_x \frac{2r_0}{\pi R}\sqrt{\frac{I}{I_0}\ln a}$$

The spatial frequency (modulations/radius), in terms of the overall laser radius, R, and modulation spacing or period, $4r_o$, is

$$f_s = \frac{R}{4r_o}$$

Which gives the emittance due to space charge expansion of the initial modulation with spatial frequency f_s:

$$\Delta\varepsilon_{n,sc} = \sigma_x \frac{1}{2\pi f_s}\sqrt{\frac{I}{I_o}\ln a}$$



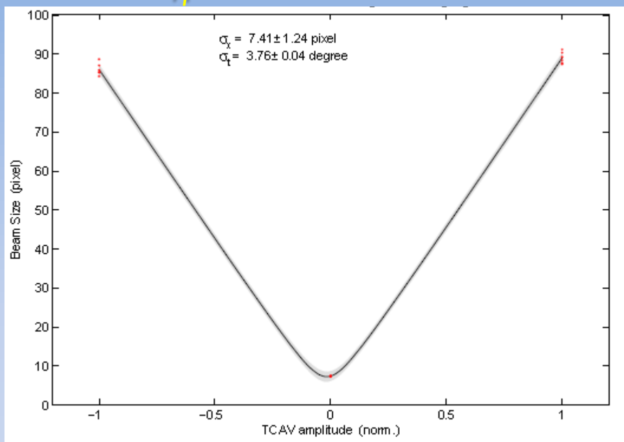
RF Emittance Contribution

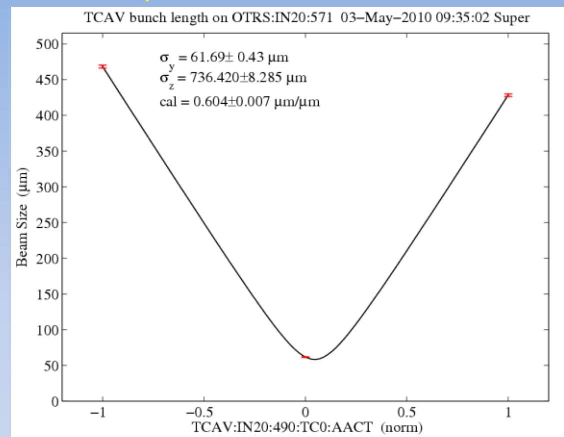
RF emittance given by Kim: $\varepsilon_{n,rf} = \dfrac{eE_0}{2mc^2} \dfrac{\sigma_x^2 \sigma_\phi^2}{\sqrt{2}}$

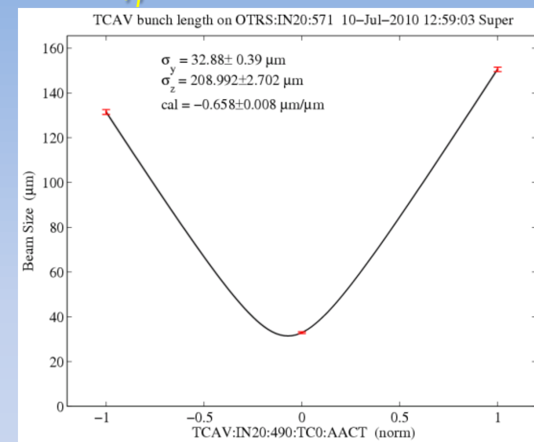
$E_0 = 115MV/m$

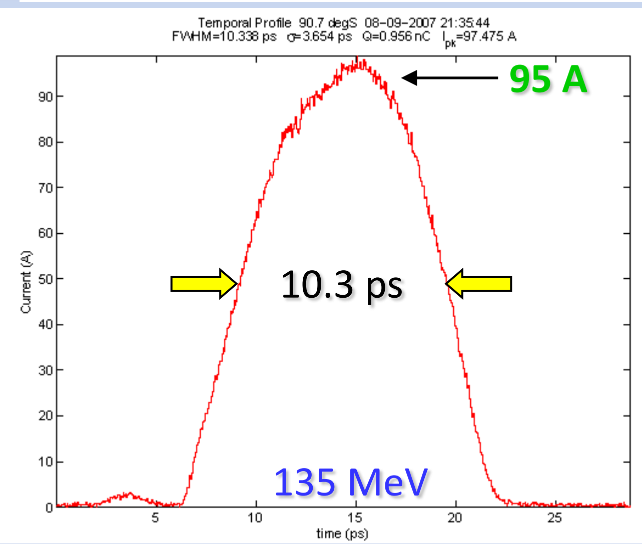
$\sigma_x = 1mm$

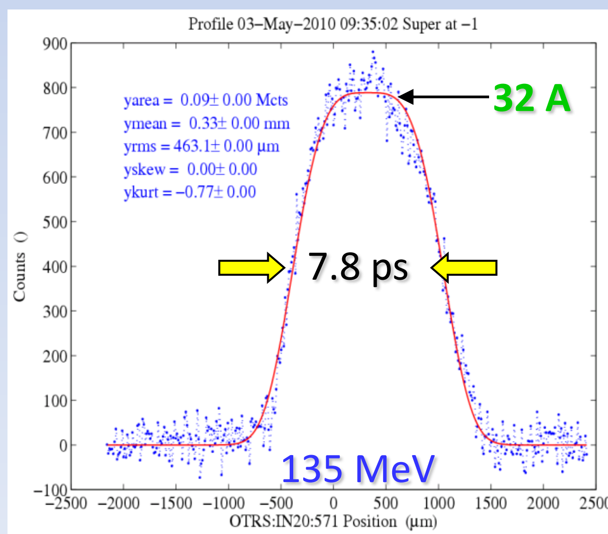
1 nC	0.25 nC	0.020 nC
$\sigma_z = 1.10$ mm rms	$\sigma_z = 0.74$ mm rms	$\sigma_z = 0.21$ mm rms
σ_ϕ=0.064 rad rms	σ_ϕ=0.043 rad rms	σ_ϕ=0.012 rad rms
$\varepsilon_{rf} = 0.326$ microns	$\varepsilon_{rf} = 0.15$ microns	$\varepsilon_{rf} = 0.011$ microns

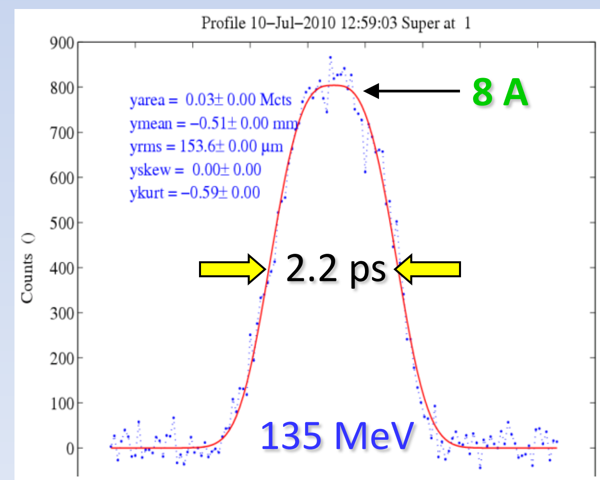










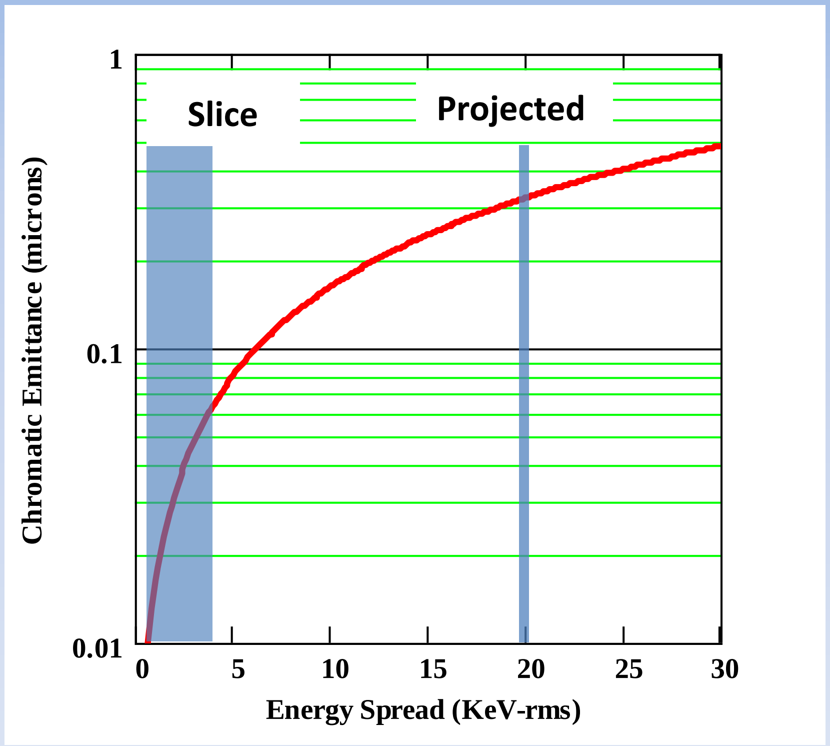


Slide compliments P. Emma

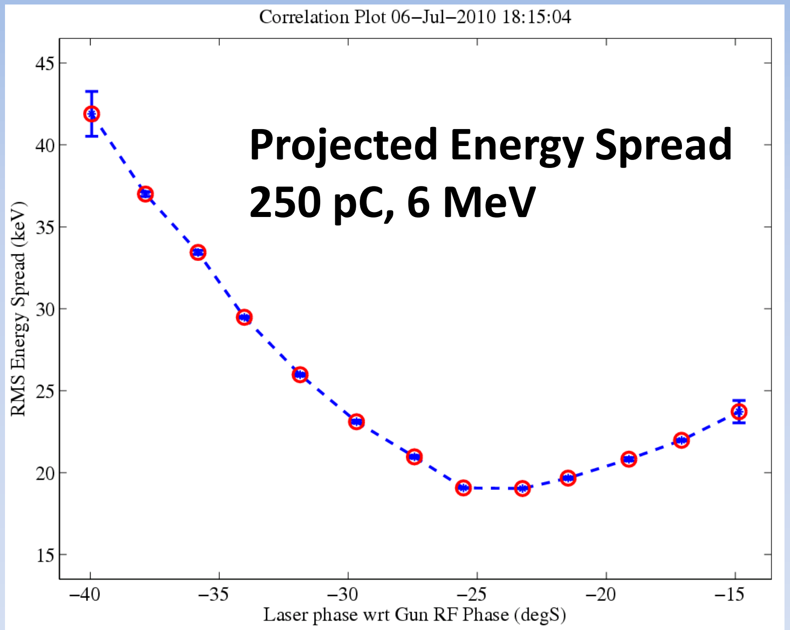
Optical Aberrations: Chromatic Effects of the Solenoid

$$\varepsilon_{n,chromatic} = \beta\gamma\sigma_x^2\sigma_p \left| \frac{d}{dp}\left(\frac{1}{f_{sol}}\right) \right| \qquad \frac{1}{f_{sol}} = K\sin KL, \quad \mathrm{K} = \frac{\mathrm{B(0)}}{2\mathrm{B}\rho_0}$$

$$\varepsilon_{n,chromatic} = \beta\gamma\sigma_x^2 K\left(\sin KL + KL\cos KL\right)\frac{\sigma_p}{p}$$



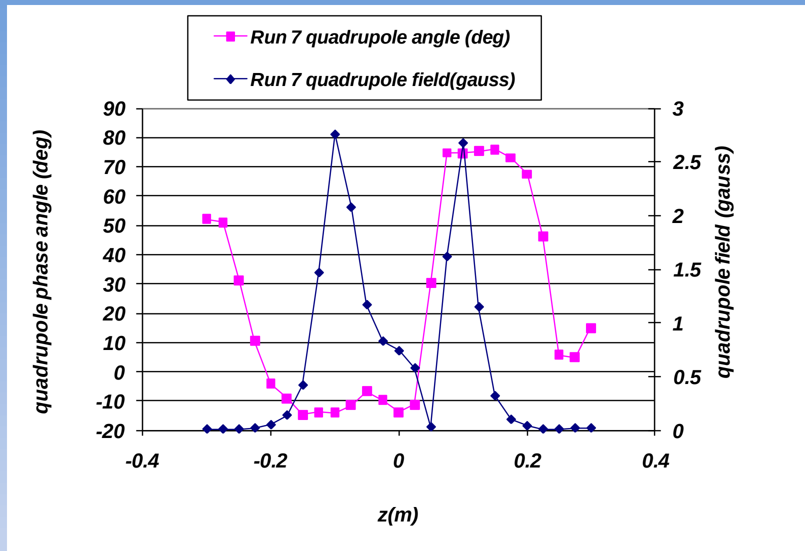
Assumes 1 mm rms beam size at solenoid

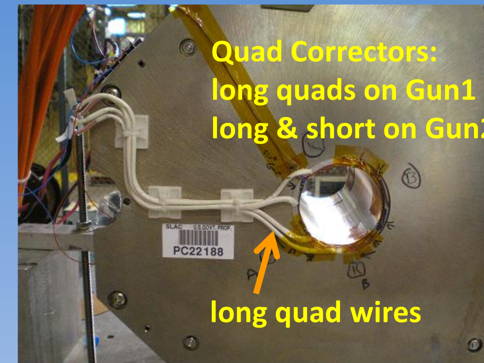


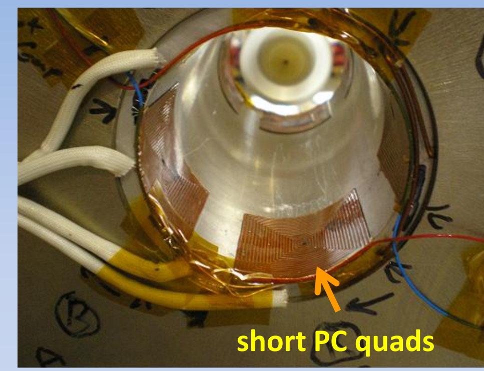
Solenoid chromatic aberration is a significant contributor to the projected emittance. For a slice energy spread of 1 KeV, gives ~0.02 microns

Quadrupole Field Error of Gun Solenoid

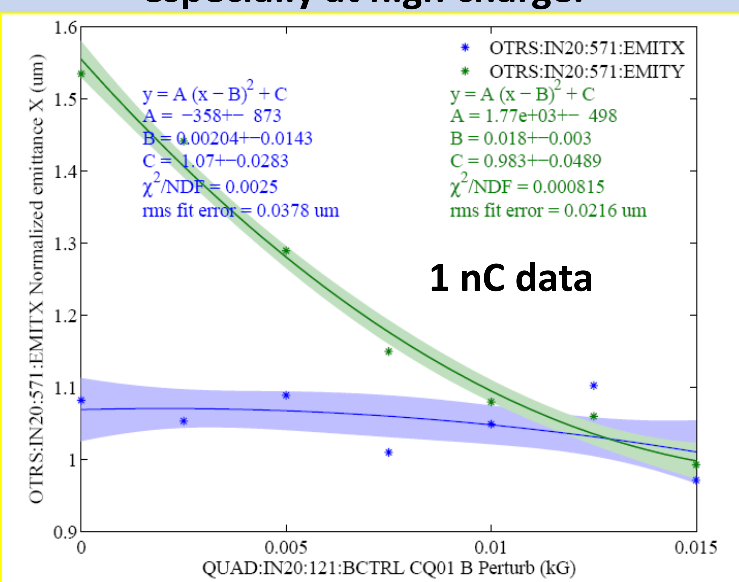
Normal and Skew quad correctors were installed to compensate small quad fields at ends of gun solenoid

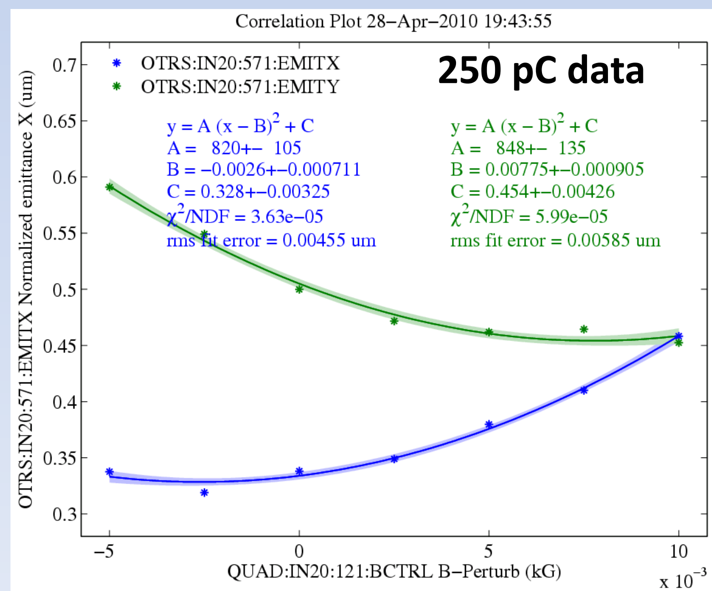






Relatively strong effect on the beam emittance, especially at high charge.

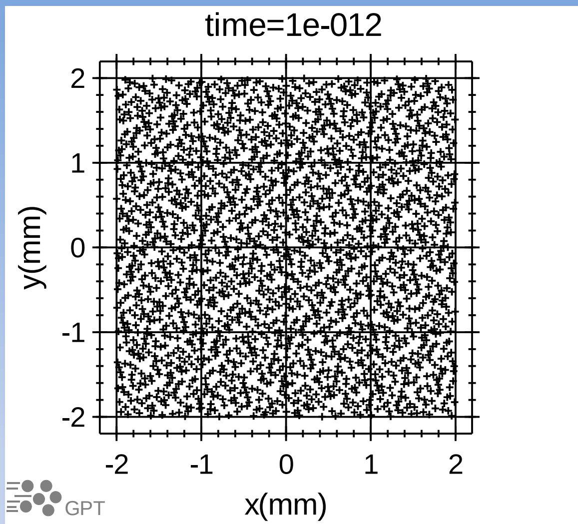




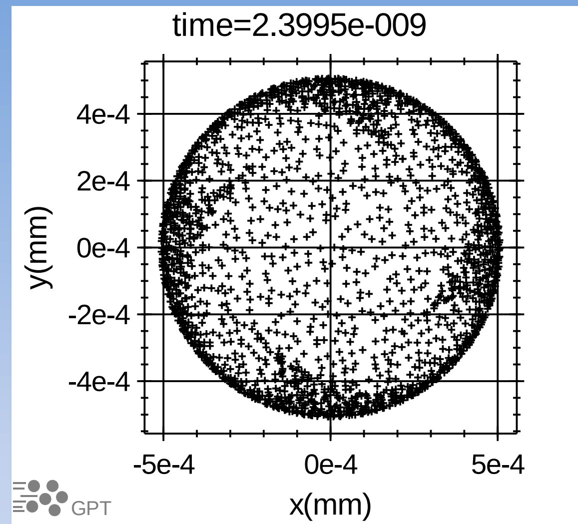
Aberration of Gun Solenoid with "Perfect" Axial Field

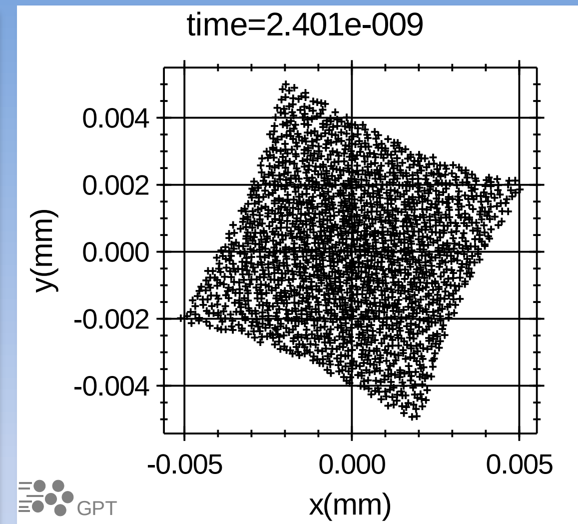
Begin with a uniform, square distribution
having zero emittance and zero energy spread

Initial transverse distribution

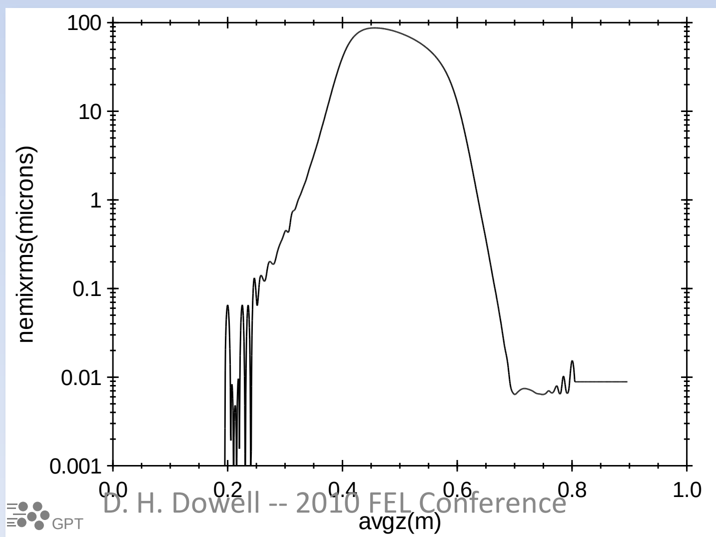


Transverse distributions near the focus after Solenoid

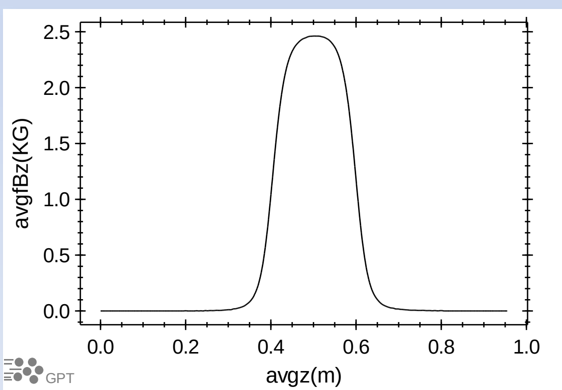




Emittance vs. z



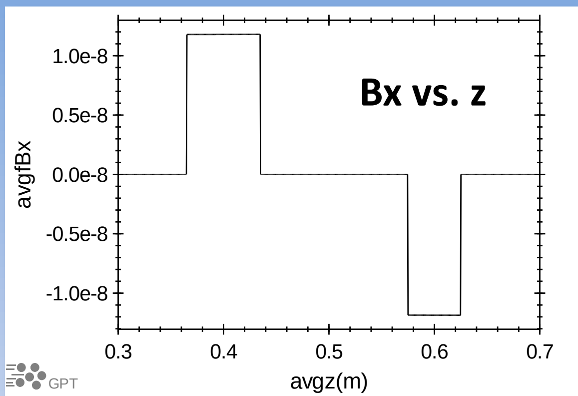
Solenoid Bz vs. z

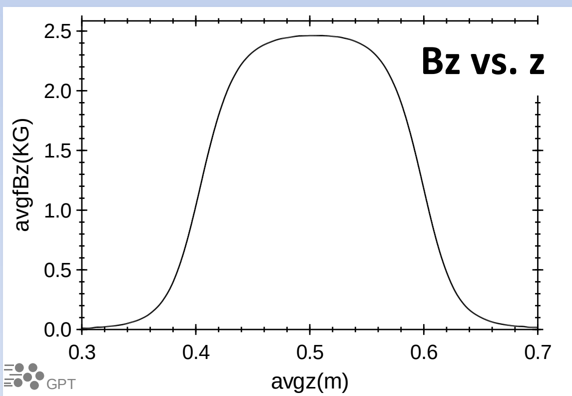


"Perfect" solenoid has a small "pincushion" distortion.
A 4 mm x 4 mm(FW) object gives 0.01 micron emittance.
Nominal beam is 1mm(rms) or 2 mm x 2 mm(FW) results in only 0.0025 microns.

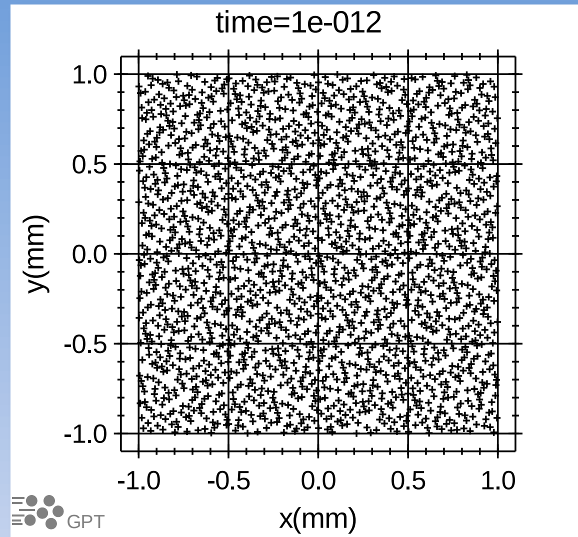
Gun Solenoid with Quadrupole Field Errors

Model the field errors with short opposing quads at solenoid ends

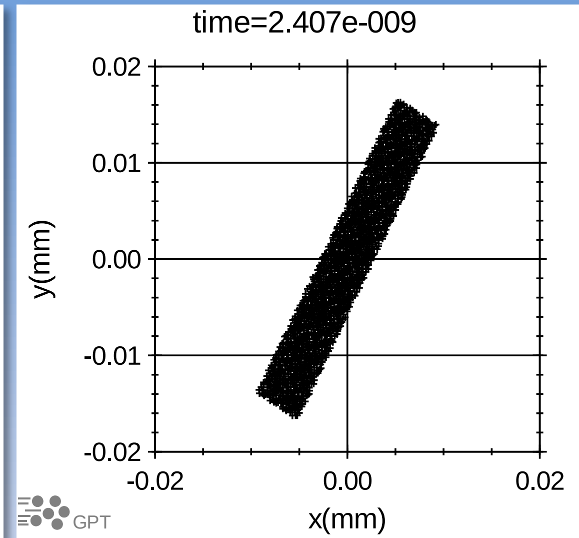




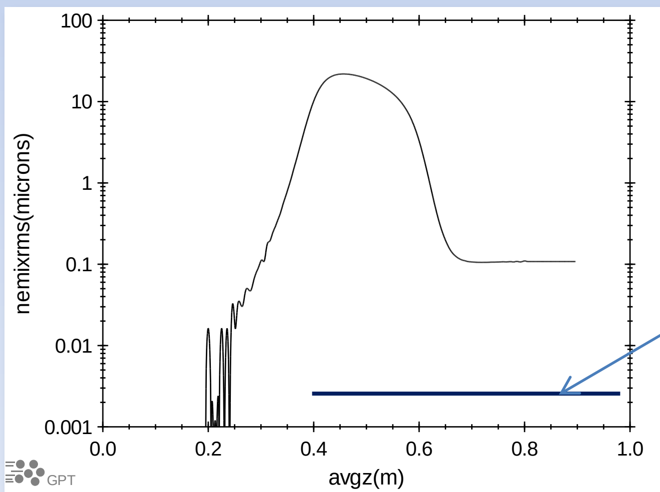
Initial transverse distribution



Transverse distribution near focus



Emittance vs. z



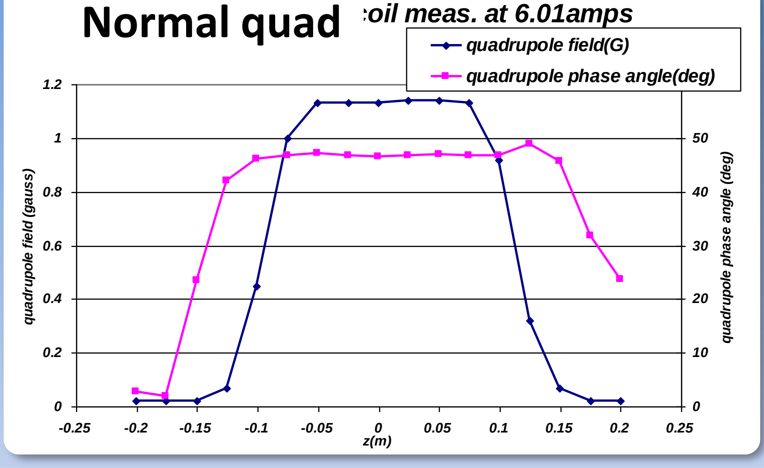
Emittance with no quad field errors

Emittance is 0.1/0.0025 = 40X larger with quad errors!

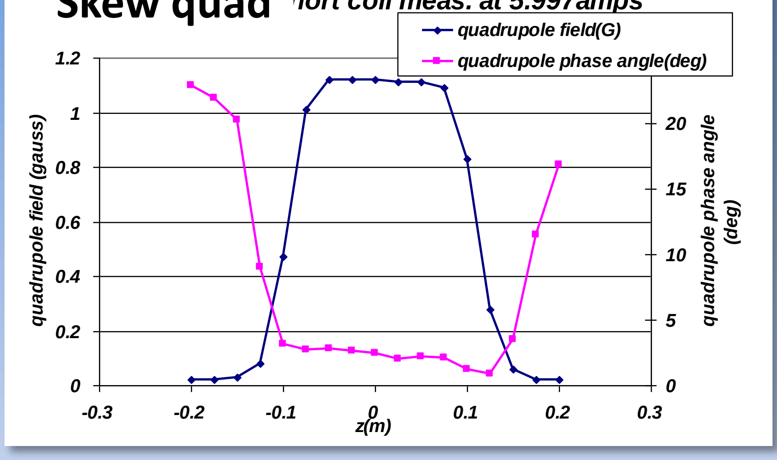
Correcting Field Errors with Quad Correctors

Quad corrector field maps

Normal quad

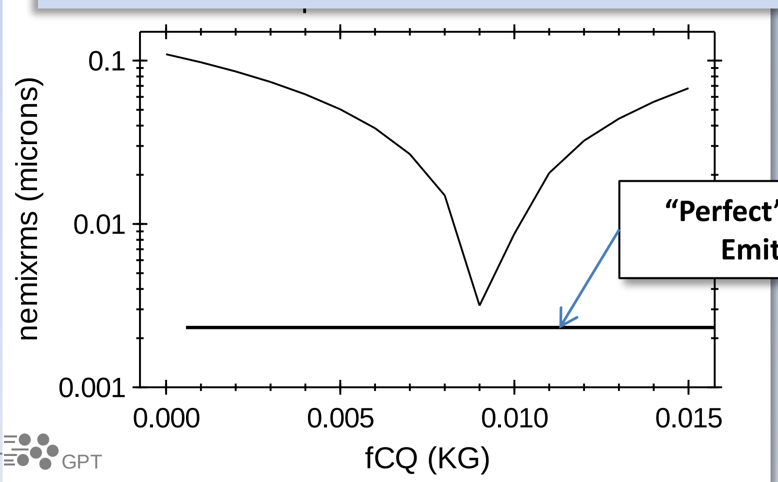


Skew quad



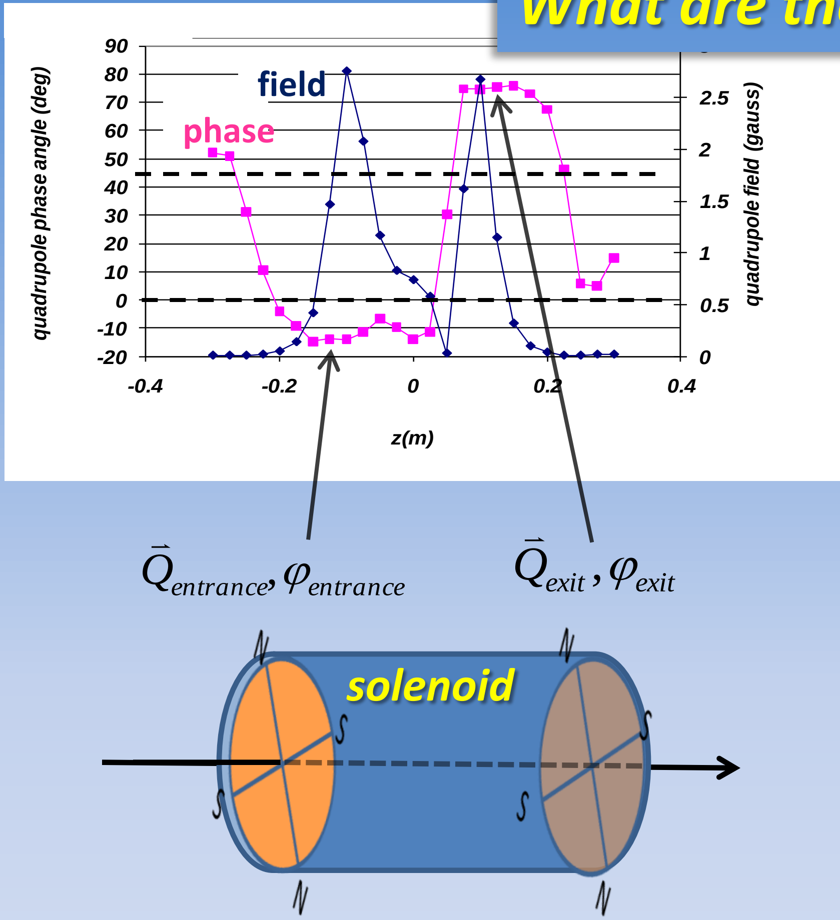
Normal and skew quad correctors installed along the full length of the solenoid to compensate for the solenoid's end quad fields.
These long quad correctors are very effective at canceling the emittance of the much shorter quad error fields.

Emittance after solenoid with quad errors vs. quad corrector field, Initial emittance = 0



"Perfect" Solenoid Emittance

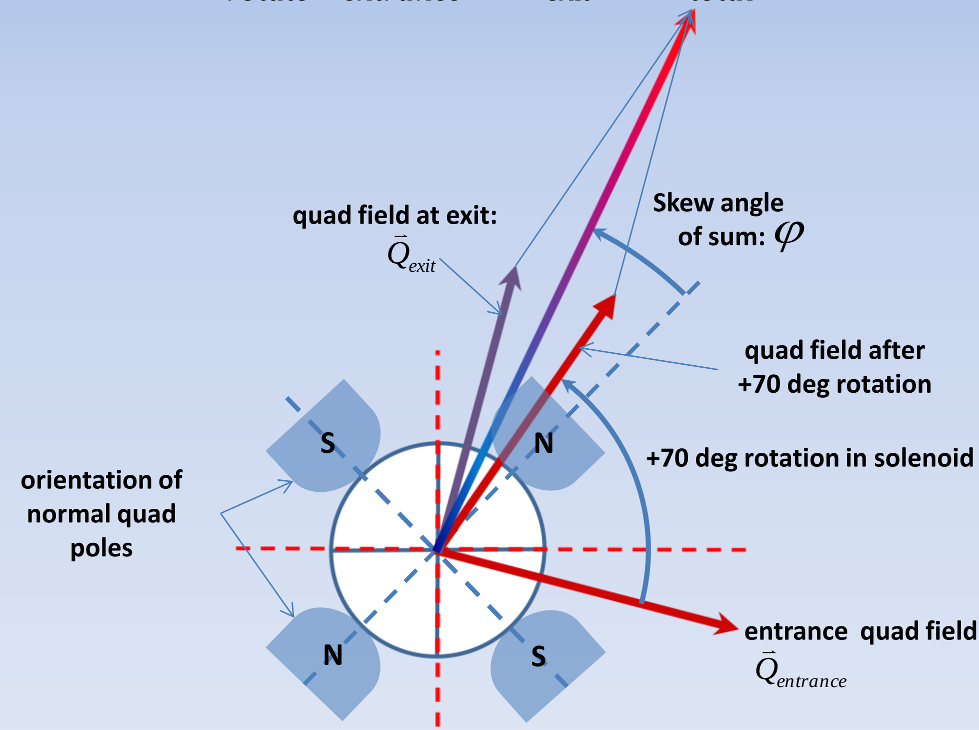
What are the Quad Correctors correcting?



Compared to a usual quad skew angle of <1 deg. In this case the skew angle can be 10's of degrees and is determined by the rotation of it's initial direction in the axial field.

The orientation of the total quad field is the vector sum of the entrance quad vector rotated by the solenoid plus the exit quad vector:

$$R_{rotate}\vec{Q}_{entrance} + \vec{Q}_{exit} = \vec{Q}_{total}$$



The skewed quad fields produce emittance growth due to coupling of the x- and y-planes (see Paul's talk),

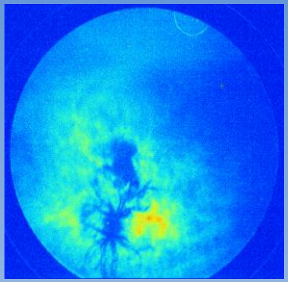
and the quad correctors remove this skew:

$$\Delta\bar{\varepsilon}_x \approx \varepsilon_{x0} \frac{\beta_{x0}\beta_{y0}}{2f^2}\left(\frac{\varepsilon_{y0}}{\varepsilon_{x0}}\right)\sin^2(2\varphi)$$

Summary and Conclusions

- **Cathode Intrinsic Emittance**
  - Self-consistent analysis of QE and emittance data indicate the theoretical emittance is factor of ~2 lower than expt.
  - Cathode surface roughness important at high cathode fields. Less than 20 nm peak-to-peak required for sub-0.1 micron emittance.
  - Lowest possible emittance given space charge limit of smallest possible size on cathode and divergence due to intrinsic emittance.
- **Transverse uniformity of laser + QE.**
  - Transverse non-uniformity drives the emittance during acceleration from rest to c.
  - High spatial frequencies (>~50 periods/radius) are small contributors to the emittance
- **RF emittance increases with charge due to longitudinal space charge**
  - Small for LCLS at 20 pC, ~ 0.01 microns
- **Solenoid optical effects seem to be the most important (after the cathode)**
  - Emittance due to chromatic aberration
    - @250pC the projected energy spread is 20 KeV => ~0.3 microns
    - For a slice energy spread of 1 KeV => ~0.03 microns
  - Emittance growth due to geometric aberrations appear to be small.
    - Spherical and pincushion distortion contribute if beam is larger than 2 mm (FW)
    - Coupling to space charge effects still need to be analyzed
  - Solenoid field errors are important
    - Skewed quadrupole field errors strongly affect emittance
    - Although field errors are at ends of solenoid, long quad correctors are effective at canceling growth

Everything is Important Below 0.1 microns!!



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