Sources of Emittance in Photocathode Injectors:
Intrinsic emittance, space charge emittance due to non-uniformities, optical aberrations

David H. Dowell
SLAC National Accelerator Laboratory

Jefferson Lab
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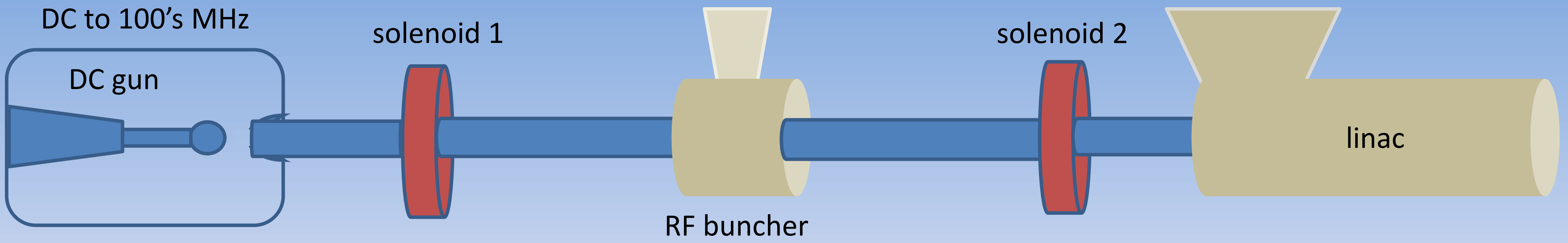
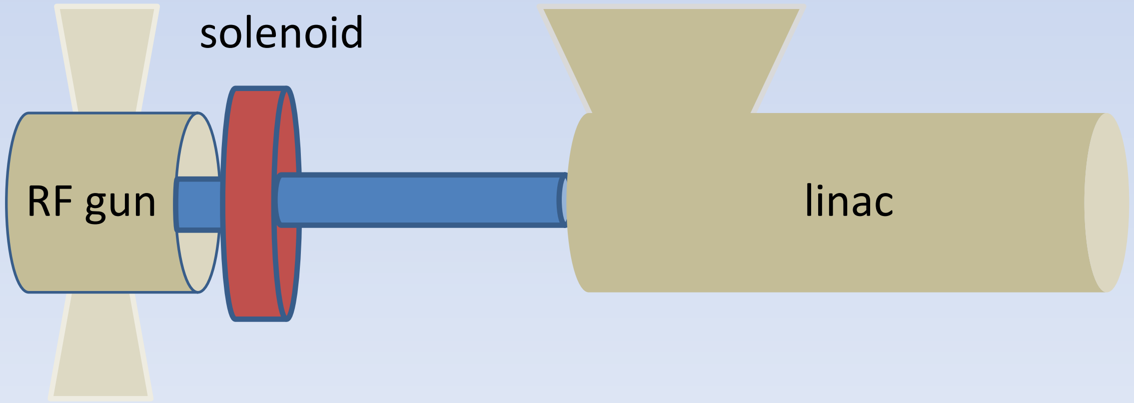
The injector configuration depends upon the cathode field and gun voltage

DC or low frequency (100's MHz) RF gun requires compressing the bunch before accelerating to high energy. Therefore the DC photoinjector includes a RF buncher with two matching solenoids:

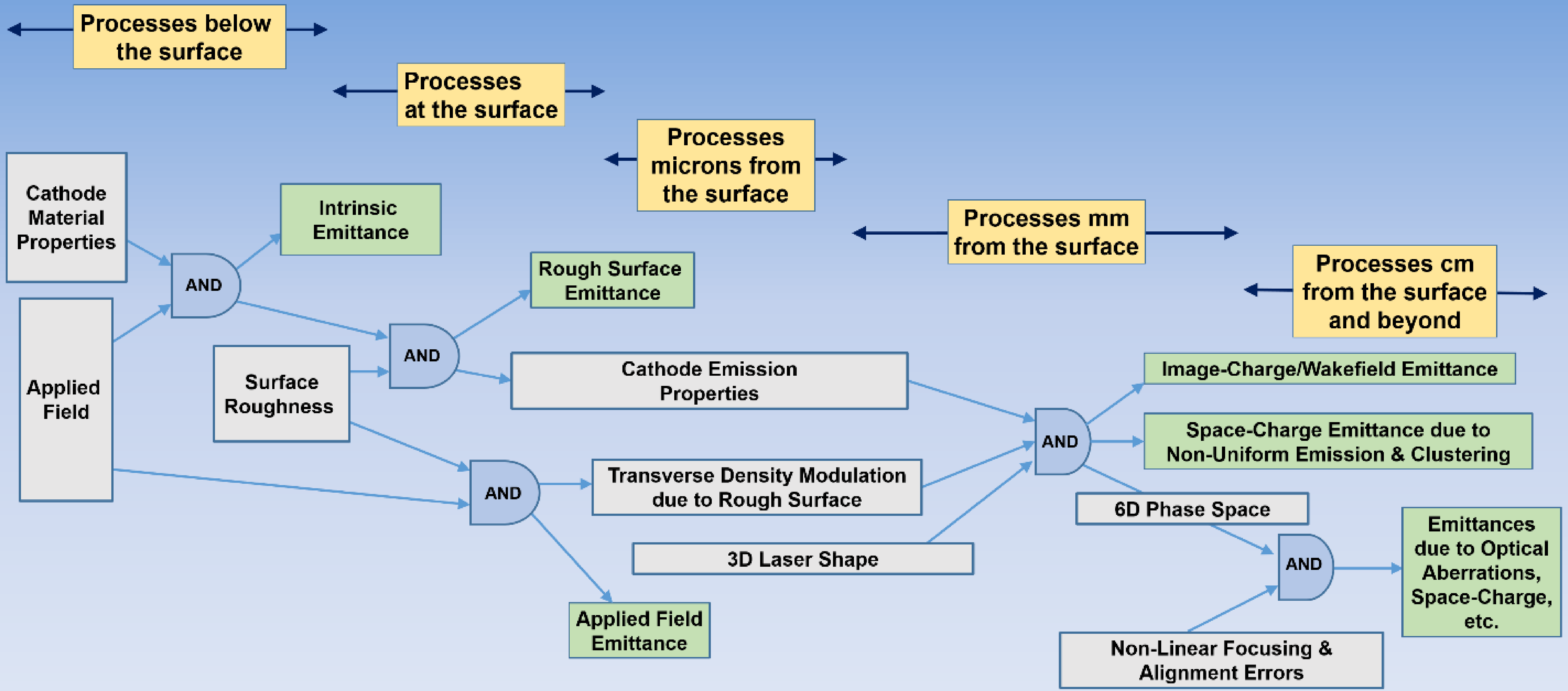


The high field (GHz to THz?) RF gun begins with a short bunch and rapidly accelerates it to relativistic energy and needs only one matching solenoid:



Analysis described here can be applied to either configuration. However this talk will mostly discuss the RF photoinjector.

Emittance generating processes vs. distance from the cathode surface.



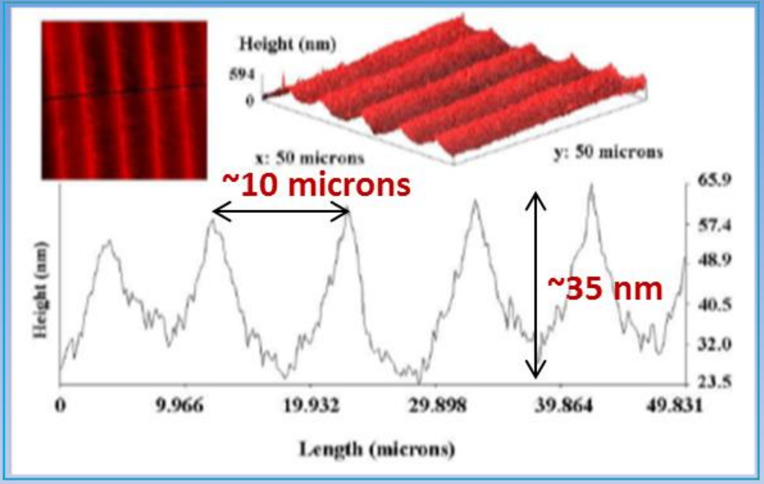
Comparison of the three surface emittances

Intrinsic Emittance

Rough Surface Emittance

Applied Field Emittance

AFM of LCLS cathode sample



LCLS gun & cathode parameters:

$a_n = 17nm$

$\lambda_n = 10 microns$

$k_n = 0.628 / micron$

$a_n k_n = 0.011$

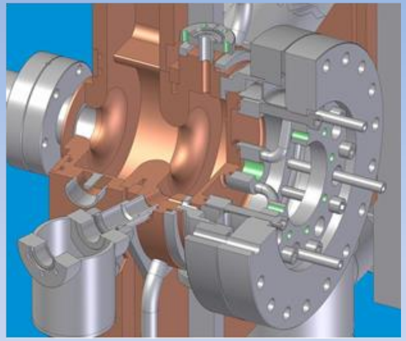
$\hbar\omega = 4.86eV$

$\phi_W = 4.8eV$

$E_a = 57.5MV / m$

$\phi_{eff}(E_0) = \phi_W - \phi_{Schottky}$

$$\phi_{Schottky} = e\sqrt{\frac{eE_0}{4\pi\varepsilon_0}} = 0.29eV$$



$$\frac{\varepsilon_{\text{intrinsic + rough + field}}}{\sigma_x} = \sqrt{\frac{(\hbar\omega - \phi_{eff})}{3mc^2}\left[1 + \frac{(a_n k_n)^2}{2}\right] + \frac{\pi e E_0}{4k_n mc^2}(a_n k_n)^2}$$

$$\frac{\varepsilon_{intrinsic}}{\sigma_x} = 0.48 microns / mm - rms$$

$$\frac{\varepsilon_{rough}}{\sigma_x} = 3.7 \times 10^{-3} microns / mm - rms$$

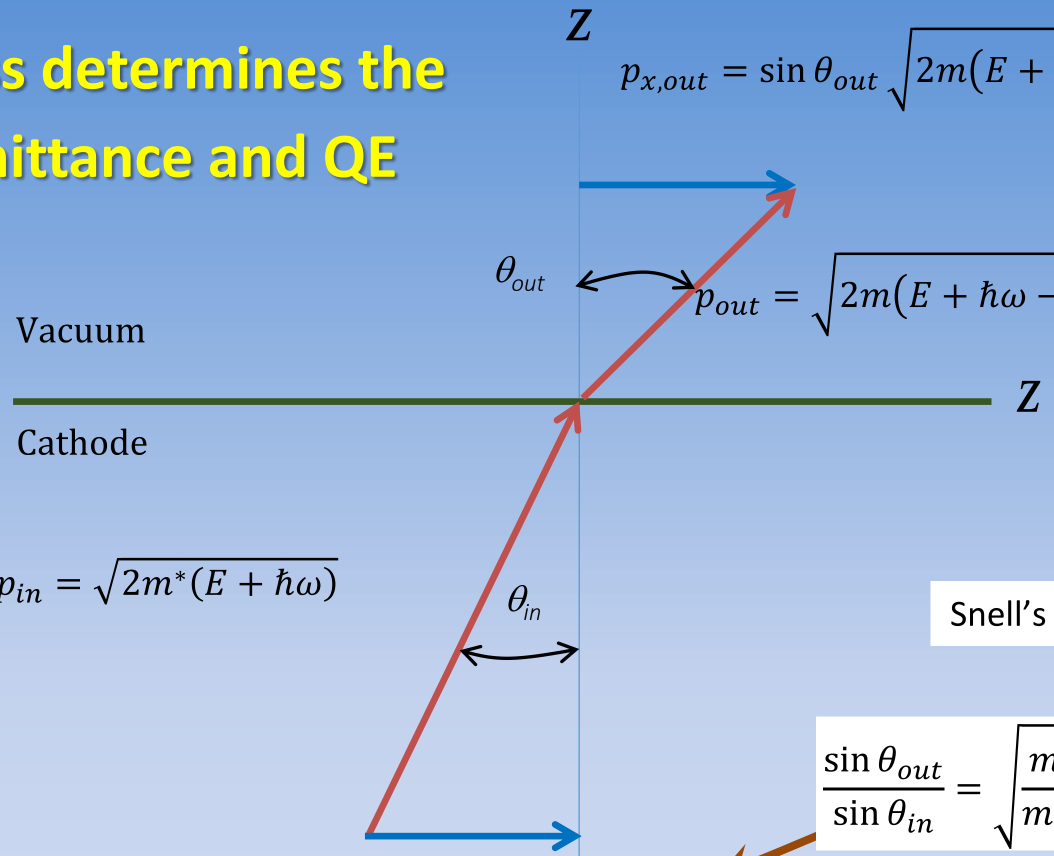
$$\frac{\varepsilon_{field}}{\sigma_x} = 0.13 microns / mm - rms$$

$$\frac{\varepsilon_{\text{intrinsic + rough + field}}}{\sigma_x} = 0.49\, microns / mm - rms$$

∴ The intrinsic emittance is the largest contributor of the three surface emittances!

Effective mass determines the Intrinsic emittance and QE

$$p_{x,out} = \sin\theta_{out}\sqrt{2m(E+\hbar\omega - E_F - \phi_{eff})}$$



$$p_{out} = \sqrt{2m(E+\hbar\omega - E_F - \phi_{eff})}$$

$$p_{in} = \sqrt{2m^*(E+\hbar\omega)}$$

Transverse momentum is continuous across the cathode/vacuum boundary

Snell's Law for photoemission

$$\frac{\sin\theta_{out}}{\sin\theta_{in}} = \sqrt{\frac{m}{m^*}\left(\frac{E+\hbar\omega-E_F-\phi_{eff}}{E+\hbar\omega}\right)}$$

$$p_{x,in} = \sin\theta_{in}\sqrt{2m^*(E+\hbar\omega)}$$

Escape momentum:

$$\cos\theta_{in}\sqrt{m^*(E+\hbar\omega)} \ \geq \ \sqrt{m(E+\ \hbar\omega-E_F-\phi_{eff})}$$

$$\cos\theta_{in,escape} \ \geq \ \sqrt{\frac{m}{m^*}\left(\frac{E+\ \hbar\omega-E_F-\phi_{eff}}{E+\hbar\omega}\right)}$$

the escape cone angle is larger for $m^* > m$, this increases QE, but also increases emittance

$$\left\{\begin{array}{c} \epsilon_{intrinsic} = \sigma_x\sqrt{\frac{m^*}{m}\left(\frac{\hbar\omega-\phi_{eff}}{3mc^2}\right)} \\[2ex] QE = \frac{1-R(\omega)}{1+\frac{\lambda_{opt}}{\lambda_{e-e}}}\,\frac{E_F+\hbar\omega}{2\hbar\omega}\left(1-\sqrt{\frac{m}{m^*}\left(\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}\right)}\right)^2 \end{array}\right\}$$

Studies of the Effective Mass could lead to Ultra-Small Intrinsic Emittance

Because the effective mass is a tensor it can be described in terms of its longitudinal and transverse components,

$$m_l^* \quad \text{and} \quad m_t^*$$

If an anisotropic crystal having a large m_l^* and a very small m_t^* is oriented with its longitudinal axis normal to the surface then the large m_l^* would increase the QE and the small m_t^* would reduce the emittance. The QE and emittance written with the asymmetric effective masses are

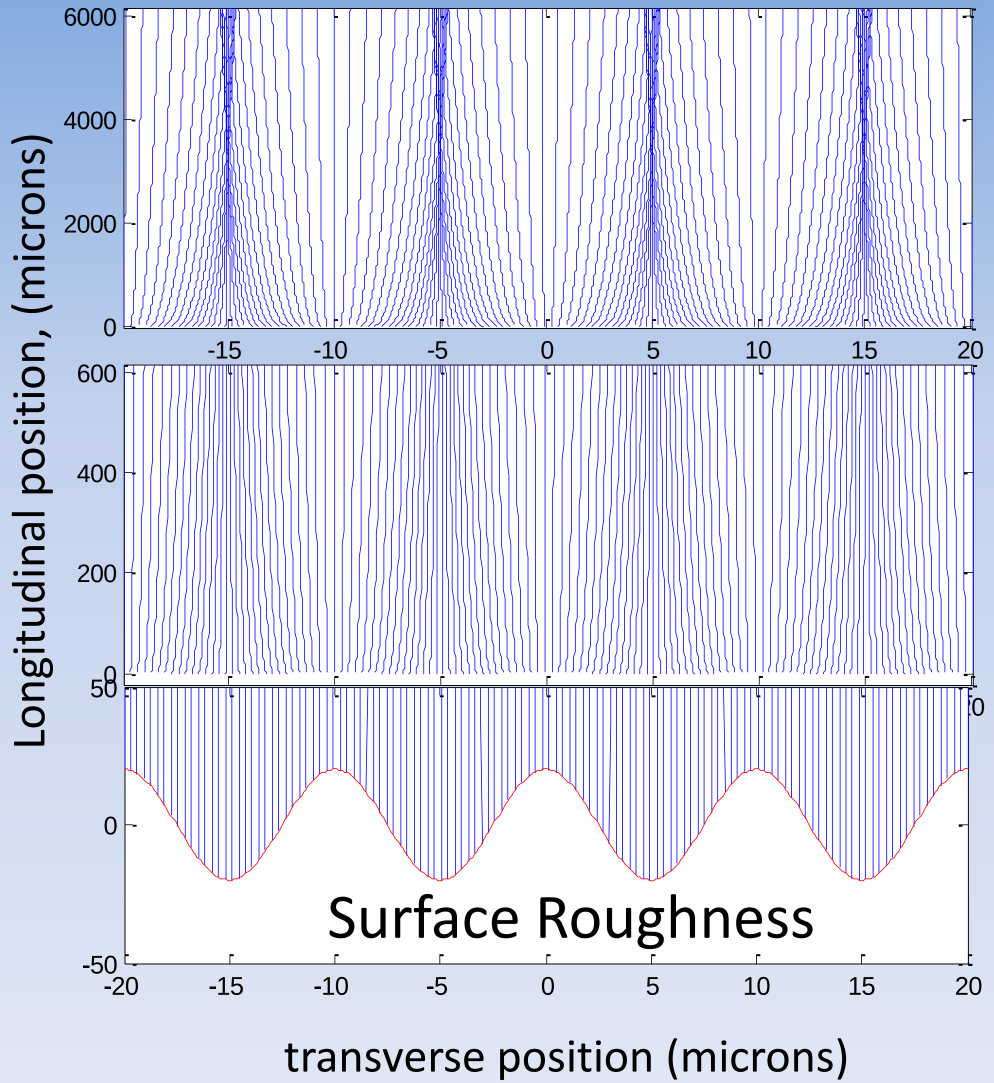
$$\epsilon_{intrinsic} = \sigma_x \sqrt{\frac{m_t^*}{m}\left(\frac{\hbar\omega - \phi_{eff}}{3mc^2}\right)} \qquad QE = \frac{1 - R(\omega)}{1 + \frac{\lambda_{opt}}{\lambda_{e-e}}} \frac{E_F + \hbar\omega}{2\hbar\omega}\left(1 - \sqrt{\frac{m}{m_l^*}\left(\frac{E_F + \phi_{eff}}{E_F + \hbar\omega}\right)}\right)^2$$

As an example: for silicon $m_l^* = 0.92\, m$ and $m_t^* = 0.19\, m$; Thus, for a properly oriented crystal, the intrinsic emittance is reduced a factor of 2! However, the QE changes very little and some other means is needed to increase it which is independent of the effective mass. C. Kittel, 'Introduction to Solid State Physics', page 205, 8th edition.

Work on semimetals possessing things called Dirac points and cones illustrates how the effective mass can become zero near the bottom of a band and how massless electrons can be produced in a material. See for example, Akrap et al., "Magneto-Optical Signature of Massless Kane Electrons in Cd3 As2, PRL **117**, 136401 (2016). It's important to study photoemission from these states as they could lead to ultra-small intrinsic emittance.

Charge Density Modulations of Surface Roughness and QE Non-Uniformity

Electrons are focused and go through a crossover a few mm from the cathode .



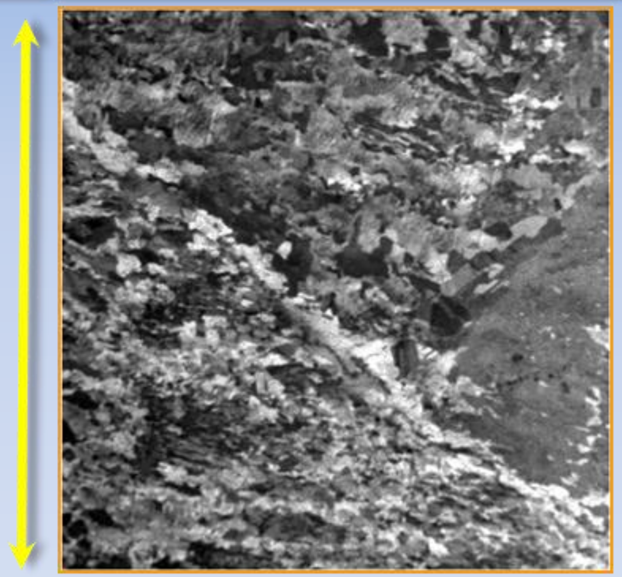
The space charge emittance near the cathode is driven by:

-Roughness focusing the beam to produce density modulations near the cathode.

-Non-uniform emission due to patchwork of QE variations from different work functions of grain and crystalline orientations as well as due to local contamination.

PEEM image of Cu cathode

~15 microns



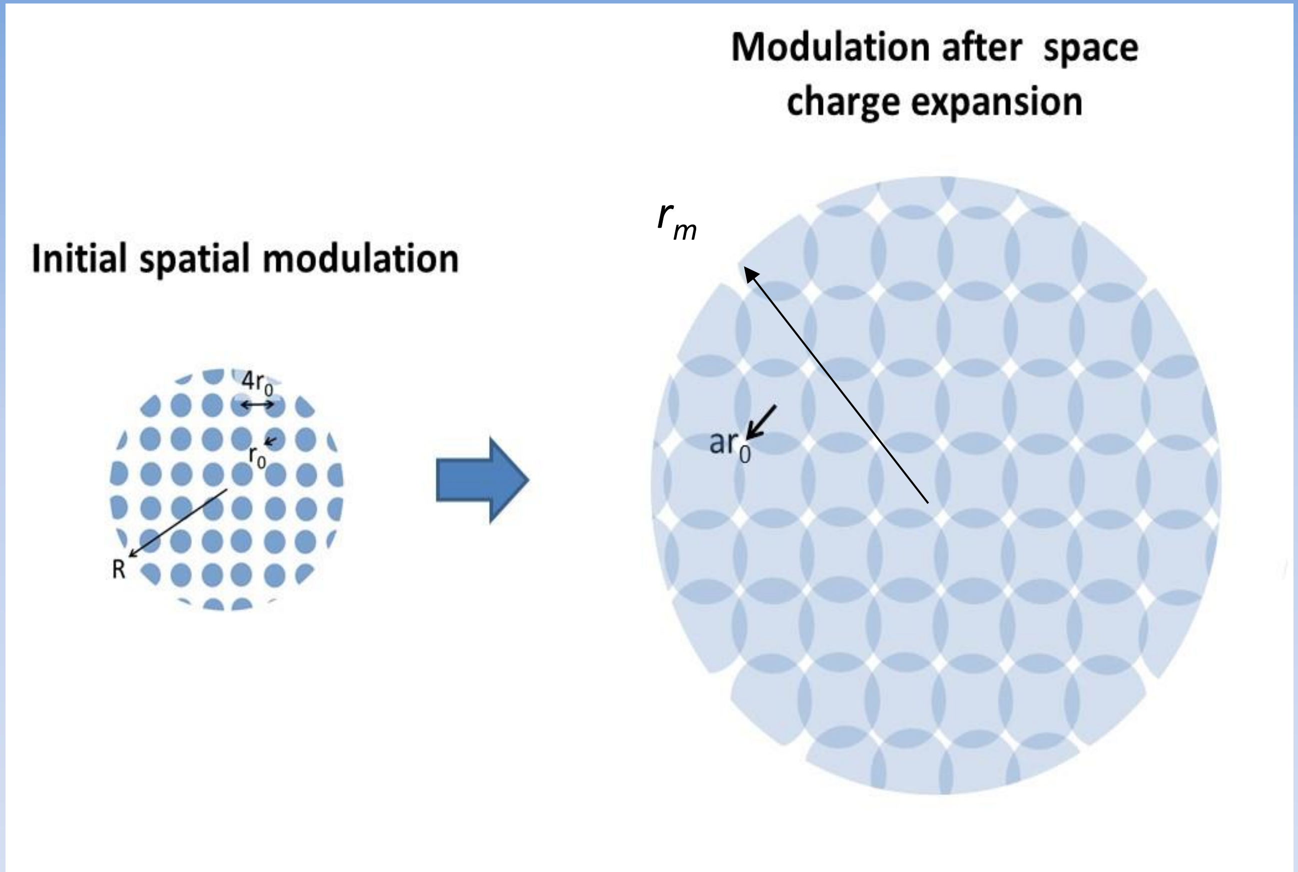
Non-Uniform Emission

compliments of H. Padmore, ALS-LBNL

For both sources of non-uniformity, there needs to be a model for the space charge effects. This s-c model can be common to both.

Beamlet Model for Space-Charge Emittance of a Transverse Modulation of Charge Density

The beamlet space charge model assumes a beam transverse distribution with overall radius R and full length l_b composed of a large number of beamlets in a rectangular pattern as shown. The transverse space-charge force causes each beamlet to expand and merge with its neighboring beamlets. This radial acceleration gives the beamlets additional transverse momentum leading to larger emittance for the total beam. A basic assumption of the model is that the transverse space charge force goes to zero once the beamlets merge and form an approximately uniform distribution. Thus after merging the non-uniformity becomes washed out and the space charge emittance becomes constant.



Solution of relativistic radial eqn. of motion with s-c for constant acceleration from rest

Radial envelope eqn. of motion

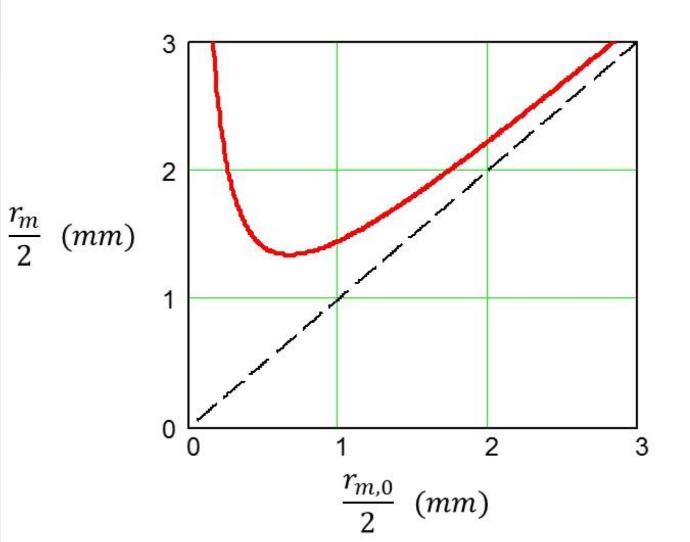
$$\frac{d^2 r_m}{dz^2} = r_m'' = \frac{K(z)}{r_m}$$

I is the peak current of the beam out to the envelope radius, r_m, and I_0 is the characteristic current.

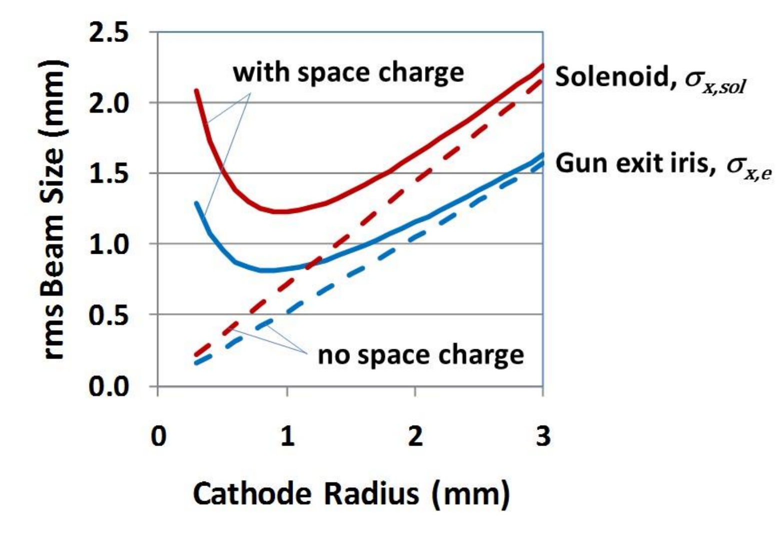
Lawson's relativistic generalized perveance, $K \equiv \frac{I}{I_0}\frac{2}{(\beta\gamma)^3}$ $\quad I_0 \equiv \frac{4\pi\epsilon_0 mc^3}{e} \cong 17000\ amps$

The beam is assumed to initially have zero energy spread and position-dependent velocity $\beta(z)$ and energy $\gamma(z) = 1 + \gamma' z$. The model assumes the electrons begin at rest at the cathode ($\gamma = 1, z = 0$) and experience constant acceleration thereafter due to the applied electric field E_a. The electron's normalized rate of energy change along the longitudinal axis is defined as $\gamma' \equiv \frac{E_a}{mc^2}$

$$r_m = r_{m,0}\left(1 + \left(\frac{8}{5}\right)^2 \frac{I}{I_0}\frac{(\gamma' z_e)^{1/2}}{\gamma'^2 {r_{m,0}}^2}\right)$$



Doesn't include RF focusing effects



GPT simulation

Space-charge emittance of a uniform mesh of beamlets

The normalized emittance for an uncorrelated distribution in *xx'* phase space is

$$\epsilon_x = \sigma_x \frac{\sqrt{\langle {p_x}^2 \rangle}}{mc}$$

assume the electrons diverge radially from the center of each beamlet and the emission from the finely distributed beamlets is all the same. Thus, the emittance is due to the beamlet divergence uniformly distributed across the full beam area and is then the beamlet divergence times the full beam size. This same approach is used to compute the intrinsic emittance.

and assume the distributions in both r and p_r are uniform, then the rms-values of their x and p_x distributions are

$$\sigma_x = \langle x^2 \rangle^{1/2} = \frac{r_{m,0}}{2} \qquad \langle {p_x}^2 \rangle = \frac{{p_r}^2}{4}$$

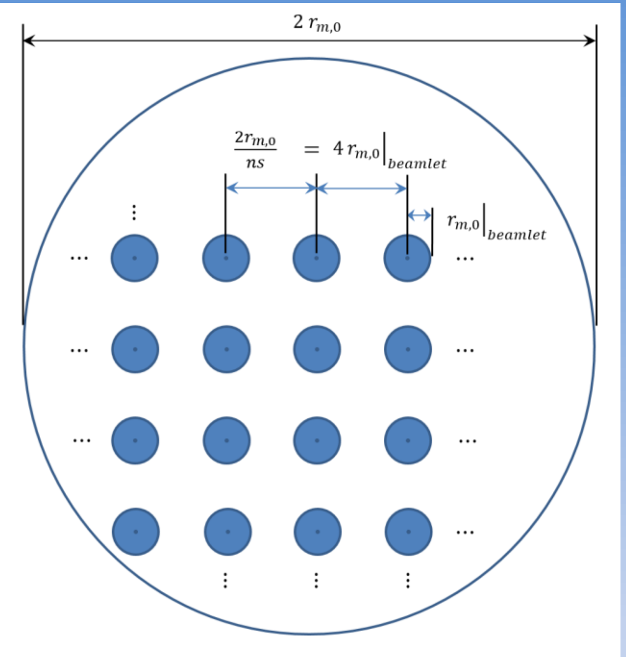
The radial momentum $p_r = \beta\gamma mc\, {r_m}'$ of an electron at the beamlet envelope is easily written since

$$r'_m = \left(\frac{8}{5}\right)^2 \frac{I}{2I_0} \frac{1}{\gamma' r_{m,0} (\gamma' z_e)^{1/2}} \qquad \text{and} \qquad \beta\gamma = \sqrt{\gamma^2 - 1}$$

one then gets

$$\frac{p_{r;beamlet}}{mc} = \left(\frac{8}{5}\right)^2 \frac{I_{beamlet}}{2I_0} \frac{\sqrt{2+\gamma' z_e}}{\gamma'\, r_{m,0;beamlet}} \Rightarrow \frac{\sqrt{\langle {p_x}^2 \rangle}}{mc} = \left(\frac{8}{5}\right)^2 \frac{I_{beamlet}}{4I_0} \frac{\sqrt{2+\gamma' z_e}}{\gamma'\, r_{m,0;beamlet}}$$

Space-charge emittance for a uniform mesh of beamlets

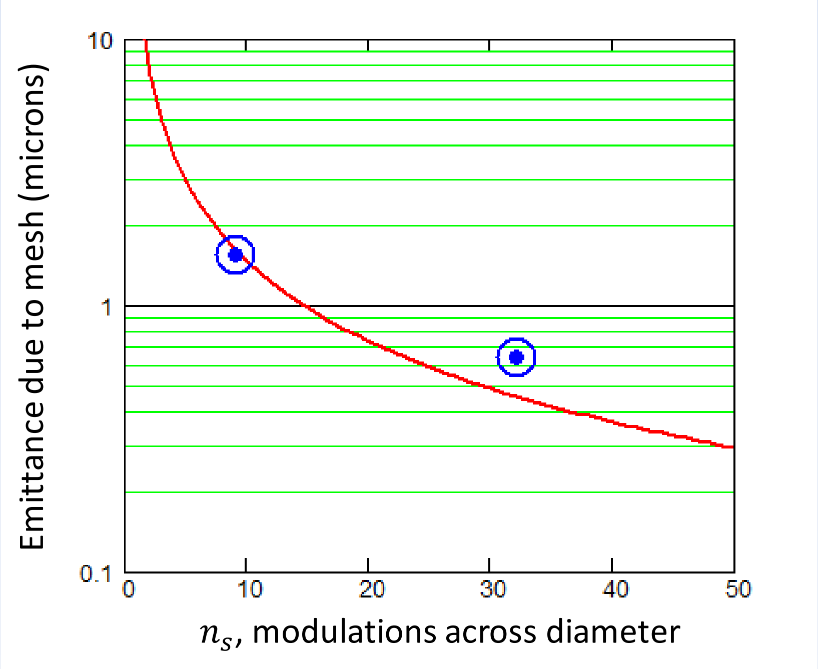


The mesh pattern has n_s beamlets or current modulations across the beam diameter. The beamlet center-to-center spacing is 4-times the beamlet radius. Relating this beamlet spacing with that of the modulation period gives the initial beamlet radius in terms of the full beam envelope radius,

$$r_{m,0;beamlet} = \frac{r_{m,0}}{2n_s}$$

Since the full beam current of all the beamlets is *I*, the current of a single beamlet would be *I* divided by the number of beamlets. The number of beamlets is the full beam area in units of n_s or

$$N_{beamlets} = \frac{\pi}{4}{n_s}^2$$



The beamlet current is the total current divided by the number of beamlets,

$$I_{beamlet} = \frac{4}{\pi n_s^2} I$$

The emittance is:

$$\epsilon_{x,sc-mesh} = \frac{1}{2\pi}\left(\frac{8}{5}\right)^2 \frac{I}{I_0}\frac{\sqrt{2+\gamma' z_e}}{\gamma' n_s}$$

Close to the cathode:

$$\epsilon_{x,sc-mesh} = \frac{1}{\sqrt{2}\pi}\left(\frac{8}{5}\right)^2 \frac{I}{I_0}\frac{1}{\gamma' n_s}$$

n_s is the number of modulations or cycles across the diameter

γ' is the cathode field normalized to the electron mass, $\gamma' = \frac{eE_{cathode}}{mc^2}$

I is the total beam peak current

z_e is the length of the cathode field

RF Emittance

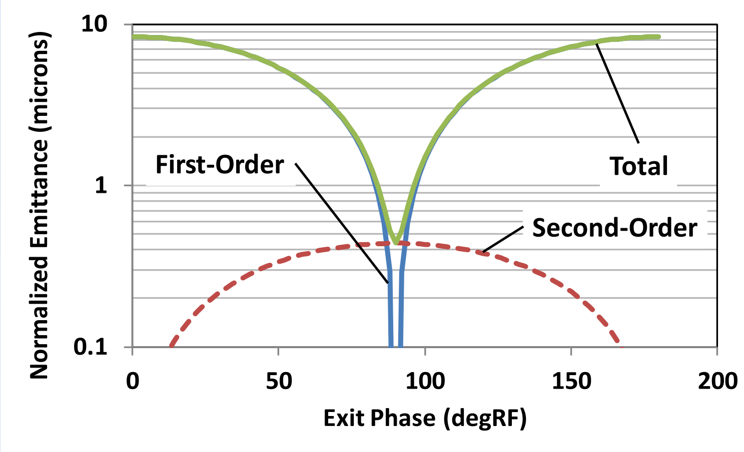
The total emittance can be expanded in powers of the rms bunch length, σ_ϕ, and combined as the sum of the squares of the first-order and second-order RF emittances. The total RF emittance is given as,

$$\epsilon_{n,rf} = \sqrt{\epsilon_{1st}{}^2 + \epsilon_{2nd}{}^2}$$

The first- and second-order emittances have been computed by Kim which here are written as the sum in quadrature,

$$\epsilon_{n,rf} = \frac{eE_{rf}}{2mc^2}\sigma_x{}^2\sigma_\phi\sqrt{cos^2\phi_e + \frac{\sigma_\phi{}^2}{2}sin^2\phi_e}$$

Here σ_x is the rms beam size and σ_ϕ is the rms bunch length in radians at the RF frequency. Both are evaluated at the exit of the gun where the bunch-rf phase is given by ϕ_e. E_{rf} is the peak RF field of the gun and is the electron phase relative to the RF waveform when the electron bunch reaches the exit of the gun.



The RF emittance is the emittance due to the time-dependent RF lens of the gun and is minimized by having the bunch on crest at the exit of the last gun cell as well as by balancing the cell-to cell RF field amplitudes.

Chromatic Aberration of the Gun Solenoid

Due to the strong defocusing of the RF gun it is necessary to use a comparably strong focusing lens to collimate and match the beam into the high energy booster linac. If this focusing is done with a solenoid, then its focal strength in the rotating frame of the electrons is [16]

$$\frac{1}{f_{sol}} = K\sin KL, \qquad K \equiv \frac{B(0)}{2B\rho_0} = \frac{eB(0)}{2p} \tag{32}$$

where $B(0)$ is the peak field of the solenoid, L is the solenoid effective length, $B\rho_0$ is the magnetic rigidity, e is the electron charge and p is the beam momentum. The rigidity can be expressed in the following useful units as

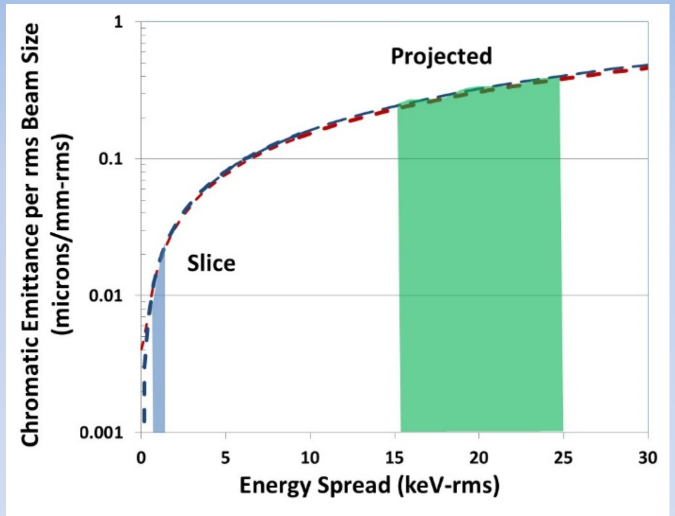
$$B\rho_0 = \frac{p}{e} = 33.356\,p\left(GeV/c\right)kG-m \tag{33}$$

with p being the electron momentum. It can be shown that the normalized emittance due to the chromatic aberration of a lens is [17, 18]

$$\varepsilon_{n,chromatic} = \beta\gamma\sigma_{x,sol}^2\sigma_p\left|\frac{d}{dp}\left(\frac{1}{f_{sol}}\right)\right| . \tag{34}$$

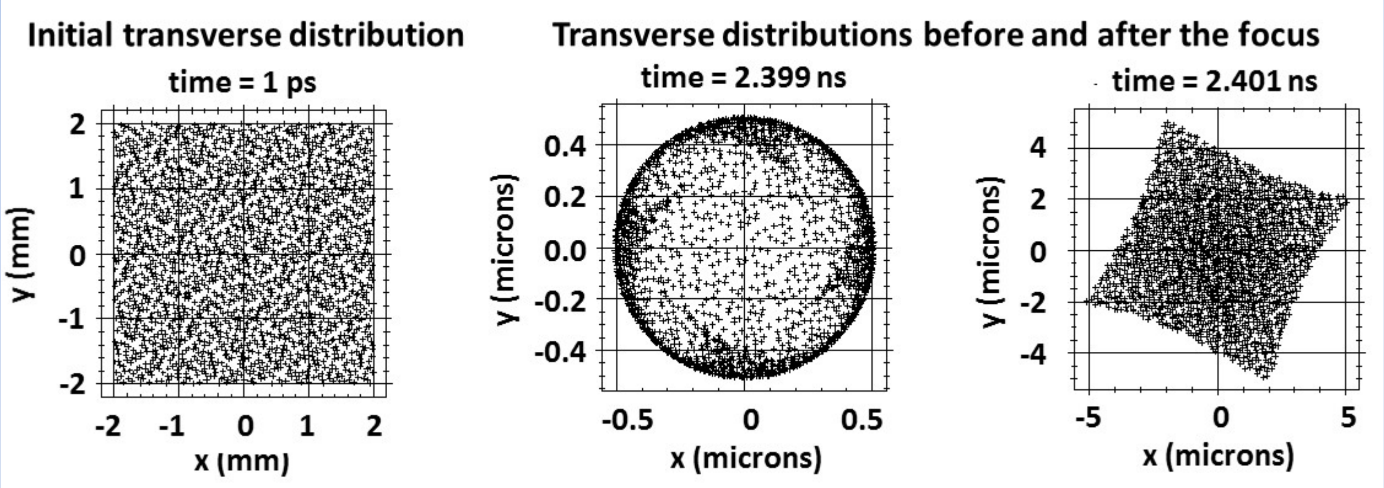
Here β is the beam velocity divided by the speed of light, γ is the beam's Lorentz factor, $\sigma_{x,sol}$ is the transverse rms beam size at the entrance to the solenoid and σ_p is the rms momentum spread of the beam. Using Eqn. (32) in Eqn. (34) gives the chromatic emittance as

$$\varepsilon_{n,chromatic} = \sigma_{x,sol}^2\frac{\sigma_p}{mc}K\left|\sin KL + KL\cos KL\right| . \tag{35}$$

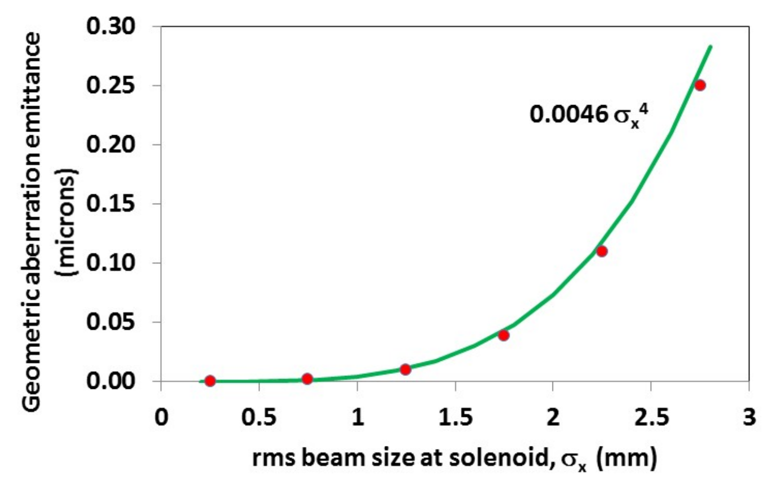


The Solenoid's Geometric Aberration

Simulations were performed with only the solenoid followed by a simple drift. Maxwell's equations were used to extrapolate the measured axial magnetic field, $B_z(z)$, to obtain the radial fields [20]. The axial field is shown below in Figure 135. Following tradition, the aberration is illustrated using an initial beam square, 2 mm $\times$ 2 mm, distribution. The simulation assumed perfect collimation (zero divergence = zero emittance), zero energy spread and an energy of 6 MeV. The transverse beam profiles show how an otherwise "perfect" solenoid produces the characteristic "pincushion" distortion. A 4 mm $\times$ 4 mm (edge-to-edge) object gives 0.01micron rms emittance, while 2 mm $\times$ 2 mm square results in only 0.0025 microns.

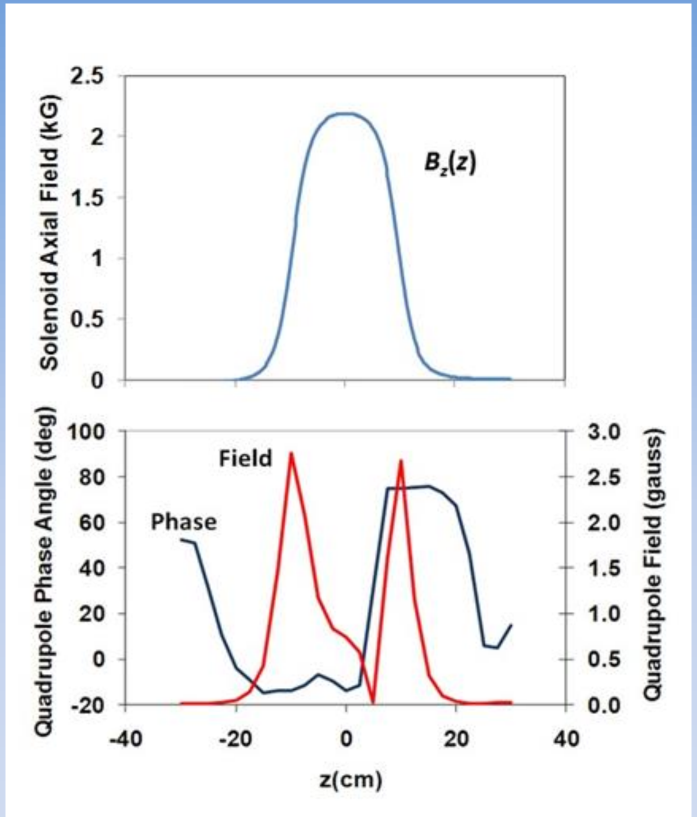


Ray tracing simulation of the geometric aberration of the LCLS gun solenoid. Left: the initial transverse particle distribution before the solenoid with zero emittance and energy spread. Center: The transverse beam distribution occurring slightly before the beam focus after the solenoid illustrating the third-order distortion. Right: The beam distribution immediately after the beam focus showing the third-order distortion evolving into the iconic "pincushion" shape of the rotated geometric aberration.

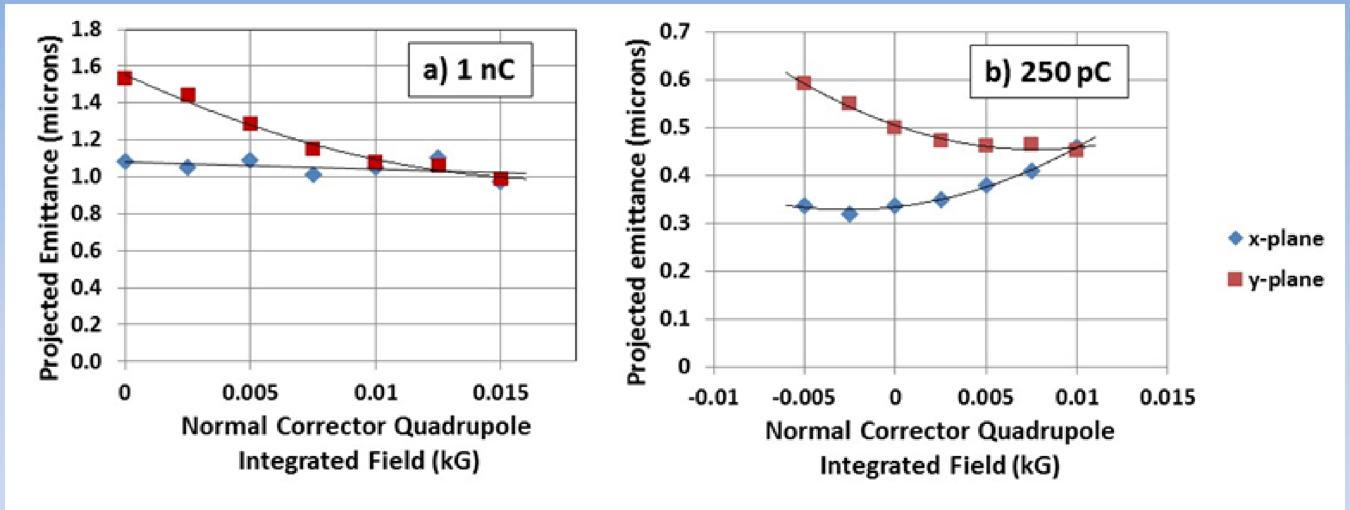


The geometric aberration for the gun solenoid: emittance vs. the x-rms beam size at the lens. The simulation (points) used the axial magnetic field measured for the LCLS solenoid. The initial beam has zero emittance and zero energy spread.

Quadrupole Field Errors in a Solenoid Magnet



Magnetic measurements showed small quadrupole fields at the ends of the LCLS solenoid with equivalent focal lengths at 6 MeV of 20 to 30 meters for the solenoid.



a) Measured *x*-plane (blue) and *y*-plane (green) emittances vs. the normal corrector quadrupole strength for a 1 nC bunch charge. b) Similar measurement for 250 pC. The lines are shown to guide the eye.

Emittance Due to an Anomalous Quadrupole Field

assuming a simple thin quadrupole lens followed by a solenoid with the 4×4 *x-y* beam coordinate transformation given by

$$R_{sol}R_{quad} = \begin{pmatrix} \cos^2 KL & \frac{\sin KL \cos KL}{K} & \sin KL \cos KL & \frac{\sin^2 KL}{K} \\ -K\sin KL\cos KL & \cos^2 KL & -K\sin^2 KL & \sin KL \cos KL \\ -\sin KL \cos KL & -\frac{\sin^2 KL}{K} & \cos^2 KL & \frac{\sin KL \cos KL}{K} \\ K\sin^2 KL & -\sin KL\cos KL & -K\sin KL\cos KL & \cos^2 KL \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ -\frac{1}{f_q} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{1}{f_q} & 1 \end{pmatrix}$$

As in the derivation for the chromatic emittance: L is the effective length of the solenoid, $K = \frac{B_z(0)}{2(B\rho)_0}$,

$B_z(0)$ is the interior axial magnetic field of the solenoid, $(B\rho)_0$ is the magnetic rigidity of the beam and f_q is the focal length due to the anomalous quadrupole field. The beam is rotated through the angle KL by the solenoid.

The 4×4 beam covariance matrix after the combined quadrupole and solenoid is then

$$\sigma(1) = (R_{sol}R_{quad})\ \sigma(0)\ (R_{sol}R_{quad})^T \ ,$$

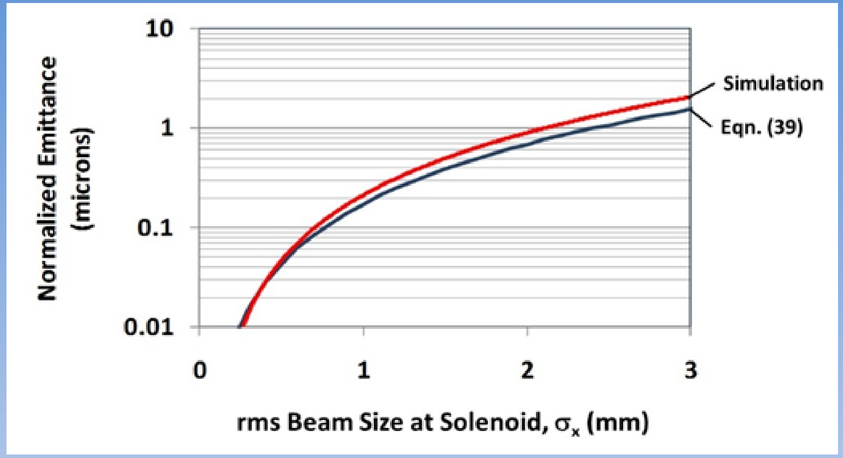
with the *x*-plane emittance after the quadrupole and solenoid being given by the determinate of the 2×2 sub-matrix,

$$\gamma\varepsilon_{x,qs} = \beta\gamma\sqrt{\det \sigma_x(1)} = \beta\gamma\sqrt{\det\begin{pmatrix} \sigma_{11}(1) & \sigma_{12}(1) \\ \sigma_{12}(1) & \sigma_{22}(1) \end{pmatrix}}$$

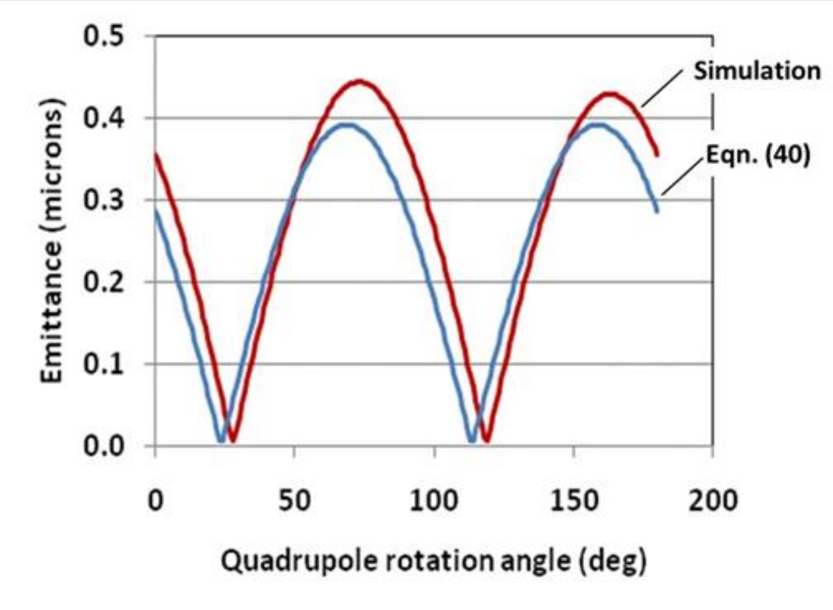
And finally, the anomalous quadrupole field emittance is found to be

$$\gamma\varepsilon_{x,qs} = \beta\gamma\sigma_{x,sol}\sigma_{y,sol}\left|\frac{\sin 2KL}{f_q}\right| .$$

The x and y transverse rms beam sizes are the entrance to the solenoid are $\sigma_{x,sol}$ and $\sigma_{y,sol}$.



The quadrupole-solenoid coupling with a particle tracking simulation for the LCLS solenoid. For a beam energy of 6 MeV the quadrupole focal length was 50 meters and the solenoid had an integrated field of 0.46 kG-m.

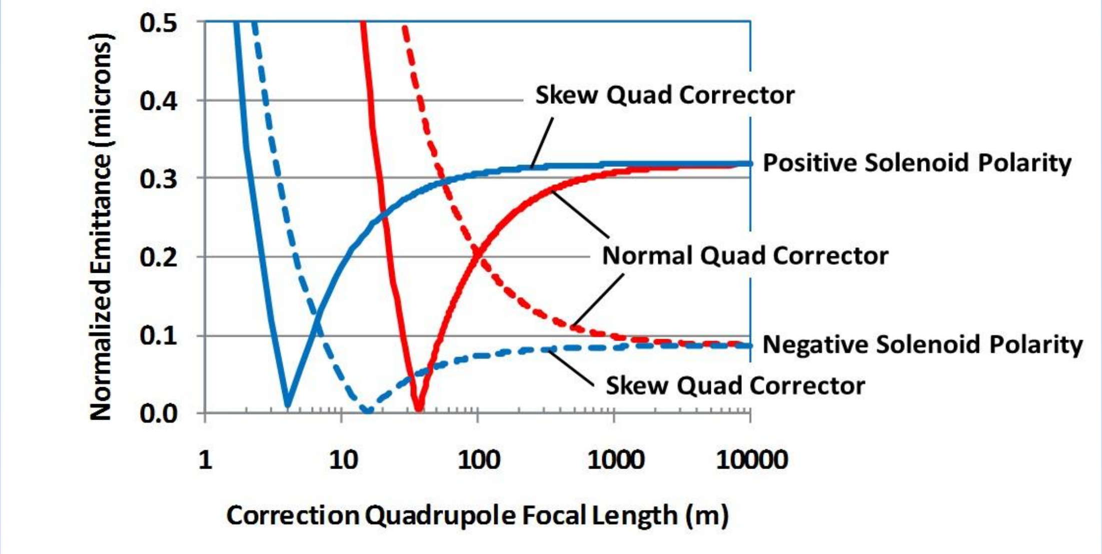


Correcting the Solenoid's Anomalous Quadrupole Field Emittance

The emittance due to the solenoid's anomalous quadrupole fields can be compensated with the addition of skew and normal corrector quadrupoles. In the LCLS solenoid these correctors consist of eight long wires inside the solenoid field, four in a normal quadrupole configuration and four arranged with a skewed quadrupole angle of 45 degrees. Thus, since corrector quadrupoles overlap the solenoid field, one would expect their skew angles should be added to *KL*. The emittance due to the composite system of a rotated quadrupole in front of the solenoid, the two corrector quadrupoles inside the solenoid and the exit rotated quadrupole can be computed as the following sum,

$$\varepsilon_{x,total} = \beta\gamma\sigma_{x,sol}\sigma_{y,sol}\left|\frac{\sin 2(KL+\alpha_1)}{f_1}+\frac{\sin 2KL}{f_{normal}}+\frac{\sin 2(KL+\pi/4)}{f_{skew}}+\frac{\sin 2\alpha_2}{f_2}\right|$$

The first and fourth terms inside the absolute value brackets are due to the entrance and exit quadrupoles with focal lengths f_1 and f_2 and skew angles of α_1 and α_2, respectively. The second and third terms are approximations for the normal and skew corrector quadrupoles with focal lengths f_{normal} and f_{skew}, respectively. And of course the skew angles of the normal and skew corrector quadrupoles are 0 and $\pi/4$.



SRF Coupler Aberration and Correction

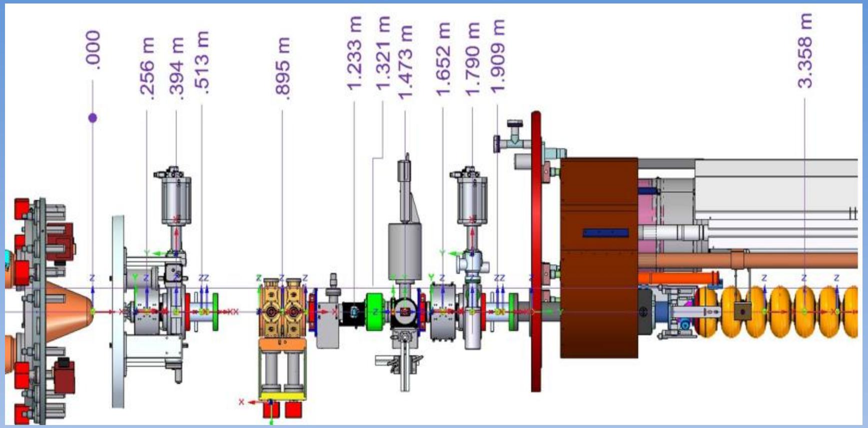
The kicks of quadrupole terms induced by RF couplers can be expressed by:

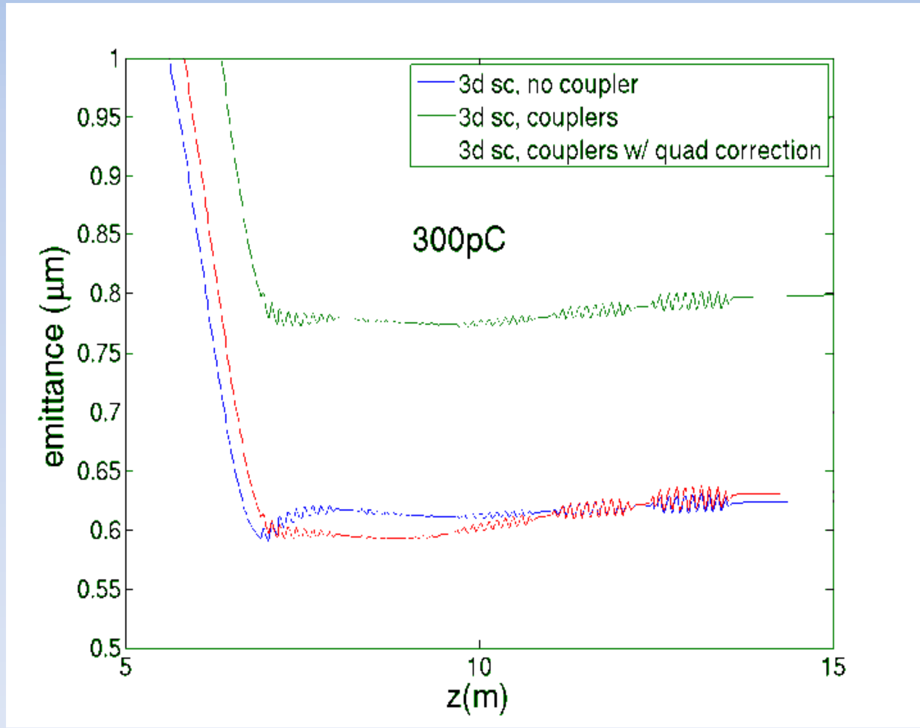
$$\begin{pmatrix} x' \\ y' \end{pmatrix}_{coupler} = \begin{pmatrix} v_{xx}x + v_{xy}y \\ v_{yx}x + v_{yy}y \end{pmatrix}$$

where v_{xx} and v_{xy} are linear terms, and v_{xy} and v_{yx} are coupled terms. The emittance growth is mostly caused by the coupled terms. The kicks of linear and coupled term can be corrected with skew quadrupole [9], which is modeled as:

$$\begin{pmatrix} x' \\ y' \end{pmatrix}_{quad} = \begin{pmatrix} \frac{\cos 2\theta_q}{f_q}x - \frac{\sin 2\theta_q}{f_q}y \\ \frac{\sin 2\theta_q}{f_q}x + \frac{\cos 2\theta_q}{f_q}y \end{pmatrix}$$

where θ_q is the quadrupole rotation angle, f_q is the quadrupole focal length. With proper quadrupole parameters (rotation angle and strength), the RF coupler induced quadrupole terms can be completely cancelled.





See F. Zhou et al, 2015 FEL conference, MOP021

Comparing the solenoid's largest three aberrations: Chromatic, Anomalous Quadrupole and Geometric

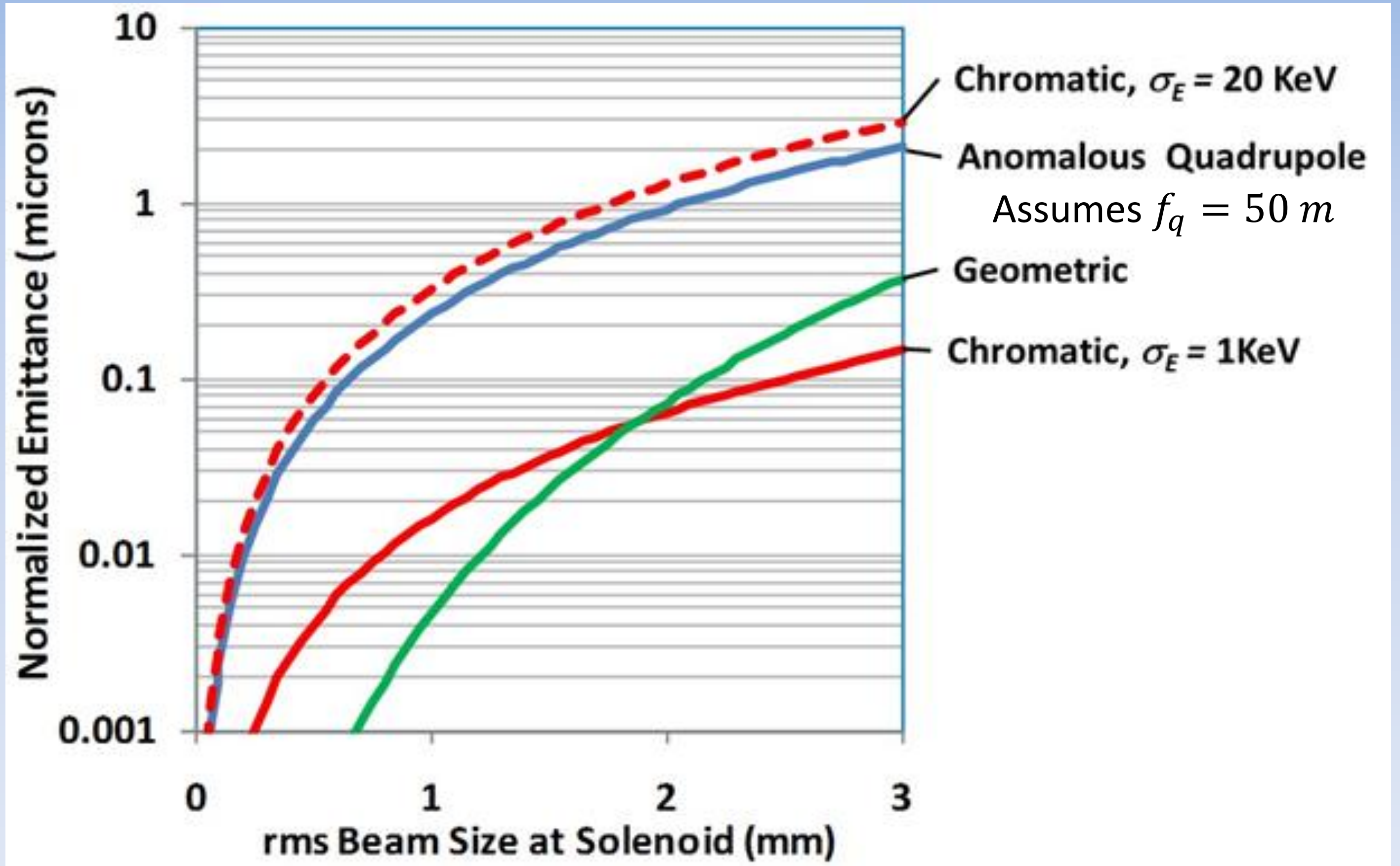
The chromatic emittance is given as $\epsilon_{chromatic} = \beta\gamma\sigma_{x,sol}^2 K|\sin KL + KL\cos KL|\frac{\sigma_p}{p}$

The geometric emittance is proportional to the 4th power of the rms beam size at the solenoid with the assumption that the beam is circular,

$$\epsilon_{geometric} = 0.0046\left(\frac{microns}{mm^4}\right)\sigma_{x,sol}^4$$

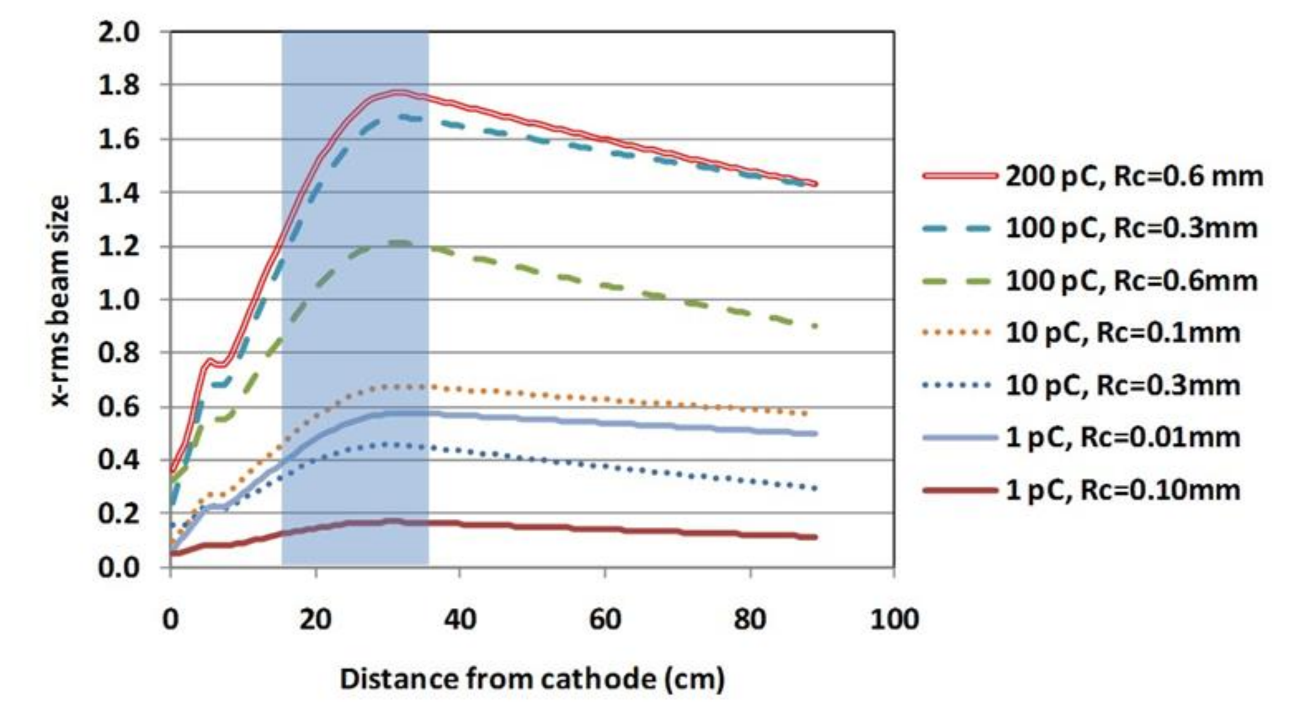
And the emittance for a non-skewed anomalous quad field at the entrance of a solenoid is

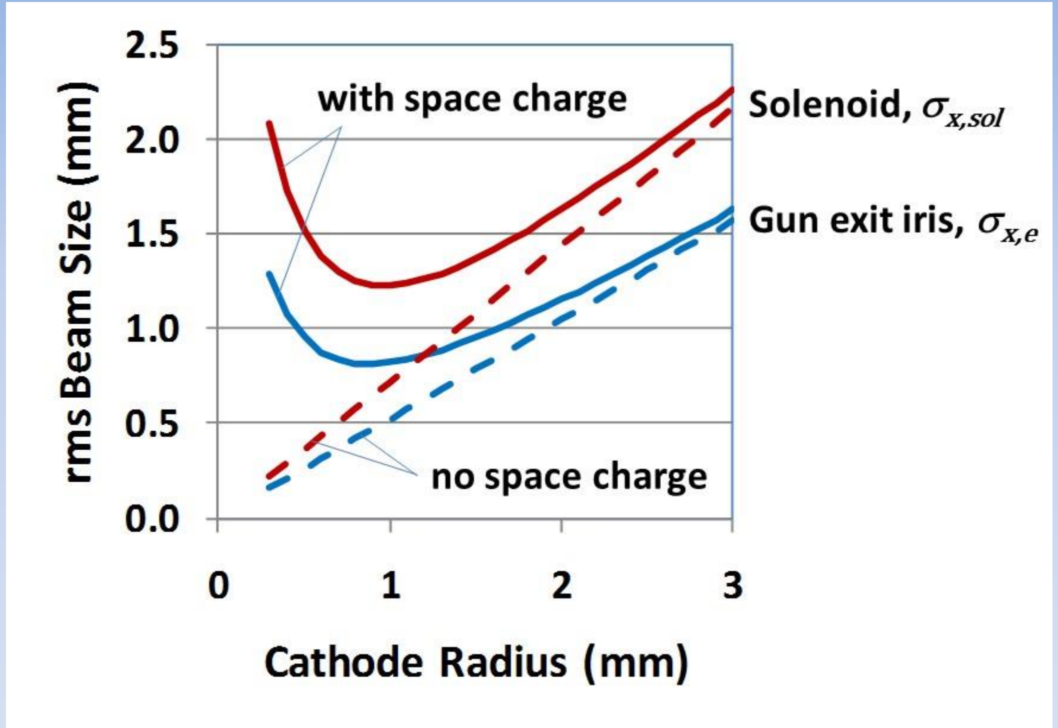
$$\epsilon_{quad-sol} = \beta\gamma\sigma_{x,sol}^2\left|\frac{\sin 2KL}{f_q}\right|$$



Beam Size at the Solenoid

To compute the solenoid's aberrations for comparison with the cathode emittances, we need to know the beam size at the solenoid as a function of its size at the cathode. This size is very dependent upon the initial cathode radius and bunch charge. The model for the injector emittance uses the sizes computed using GPT for the LCLS injector with 250 pC bunch charge.





Summing the five fatal emittances!

Intrinsic Emittance

Space-Charge Emittance due to Non-uniform Emission & Clustering

Three Emittances due to Optical Aberrations

$$\epsilon_{total} = \sqrt{\epsilon_{intrinsic}^2 + \epsilon_{sc}^2 + \epsilon_{rf}^2 + \epsilon_{chromatic}^2 + \epsilon_{geometric}^2}$$

For this analysis the experimental intrinsic emittance is used which is approximately twice the theoretical value and assume the x-plane rms size is half the cathode radius. The one-half assumes a uniform radial distribution.

$$\epsilon_{x-intrinsic} = \frac{R_{cathode}}{2}\ 0.9\ \ microns/mm - rms$$

The space charge emittance for a partially modulated beam is obtained by substituting the full beam current with the peak-to-peak modulation depth current. Assume n_s equals 10 periods of modulation across the bunch diameter and a current modulation depth which is ten percent of the peak current or ΔI is 4 amperes.

$$\epsilon_{x,s-c} = \frac{1}{\sqrt{2}\pi}\left(\frac{8}{5}\right)^2 \frac{\Delta I}{I_0}\frac{1}{\gamma' n_s}$$

The beam bunch is assumed to exit the gun on crest to give the minimum RF emittance. $E_{cathode}$ is 115/2 MV/m to account for the 30 degRF laser launch phase and the bunch length is 0.74 mm-rms (σ_ϕ = 0.043 radians)

$$\epsilon_{rf} = \frac{eE_{cathode}}{2\sqrt{2}mc^2}\sigma_{x,exit}{}^2(R_{cathode})\sigma_\phi{}^2$$

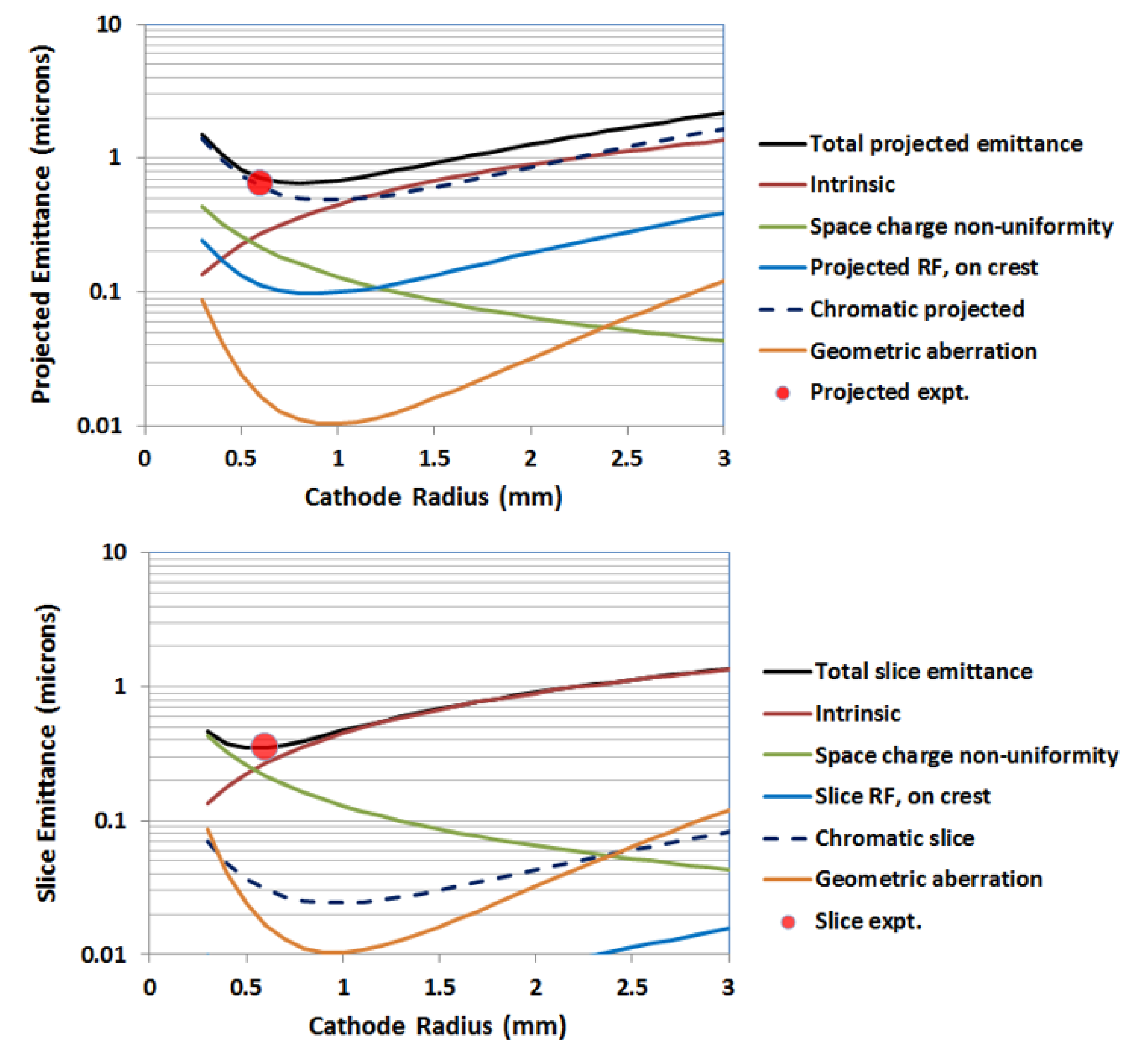
The chromatic emittance is $\epsilon_{chromatic} = \sigma_{x,sol}(R_{cathode})^2\frac{\sigma_p}{mc}K_{sol}\left|\sin K_{sol}L_{sol} + K_{sol}L_{sol}\cos K_{sol}L_{sol}\right|$

4th power fit to the simulated geometric emittance vs. the beam size at the solenoid ($\sigma_{x,sol}$ in units of mm) is:

$$\epsilon_{geometric} = 0.0046\sigma_{x,sol}{}^4(R_{cathode})$$

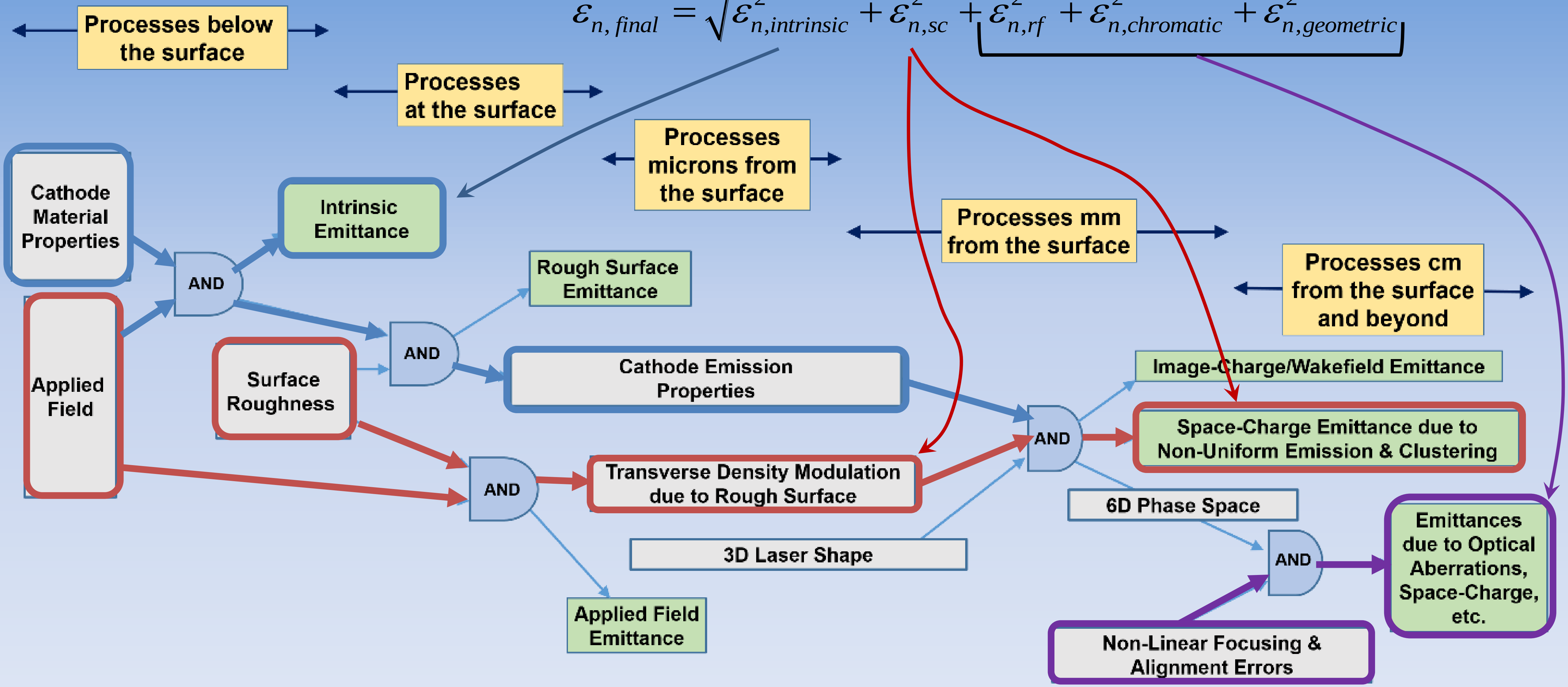
The five major emittances of the LCLS-I injector

constants and parameters		
Ksol=	5.990758326	/m
Lsol=	0.1935	m
KL=	1.159211736	
B0=	2.397932817	kG
B0L=	0.464	kG-m
Ebeam=	6	MeV
(Brho0)=	0.200136	kG-m
Cbunch charge=	2.5E-10	Coul
delta peak current=	0.1	fraction
peak current=	43.12823462	amps
r0, beamlet radius	33	microns
spatial wavelength=	0.24	mm
bunch length, rms=	0.74	mm-rms
bunch length, fwhm=	1.739	mm-fwhm
bunch phase length, rms=	2.466666667	degRF-rms
bunch phase length=	0.043051455	radians-rms
peak electric field	115	MV/m
rms energy spread, proj.	20	KeV
intrinsic emittance/mm-rms=	0.9	microns/mm-rms
Rcathode/(2r0)	9.090909091	
number of beamlets across dia. of 1mm	5	
rms energy spread, slice	1	KeV
fwhm bunch length	5.796666667	ps
number of slices	5	
slice length	0.008610291	radians-rms
laser launch field, MV/m	57.5	
gamma-prime	112.5244618	



The five emittances occur at three length-scales along the injector

$$\varepsilon_{n,\,final} = \sqrt{\varepsilon_{n,intrinsic}^{2} + \varepsilon_{n,sc}^{2} + \varepsilon_{n,rf}^{2} + \varepsilon_{n,chromatic}^{2} + \varepsilon_{n,geometric}^{2}}$$



Summary and Conclusions

- Illustrated the mechanisms for emittance generation in a photoinjector at various length scales from the cathode

- Developed analytic expressions for the various emittances produced in the injector.

- Showed that there are five major emittances in the RF photoinjector:
  - Intrinsic emittance (below and at the surface)
  - Space charge (non-uniform emission) emittance (microns to mm from the cathode)
  - RF emittance (cm)
  - Chromatic emittance (cm to m)
  - Geometric aberration emittance (cm to m)

- Theoretical and experimental work is needed to connect the effective mass with the intrinsic emittance and QE. Potential for dramatic reduction of intrinsic emittance!

- Since the 'surface lens' is non-linear it can also produce geometric aberrations and increase the emittance. Plus the time dependence of the RF field which changes the focusing with time near the cathode where the beam lingers the longest. In other words, phase slippage is large near the cathode.

- A cathode load lock and cathode stalk designed to operate at very low cryogenic temperatures is needed to demonstrate exotic effects like Dirac points and cones. Such a load lock should operate in a NCRF gun.

For all the details please see: http://arxiv.org/abs/1610.01242