LCLS Gun Development

D.H. Dowell
SLAC

P.R. Bolton
J.E. Clendenin
S.M. Gierman
C.G. Limborg
J.F. Schmerge

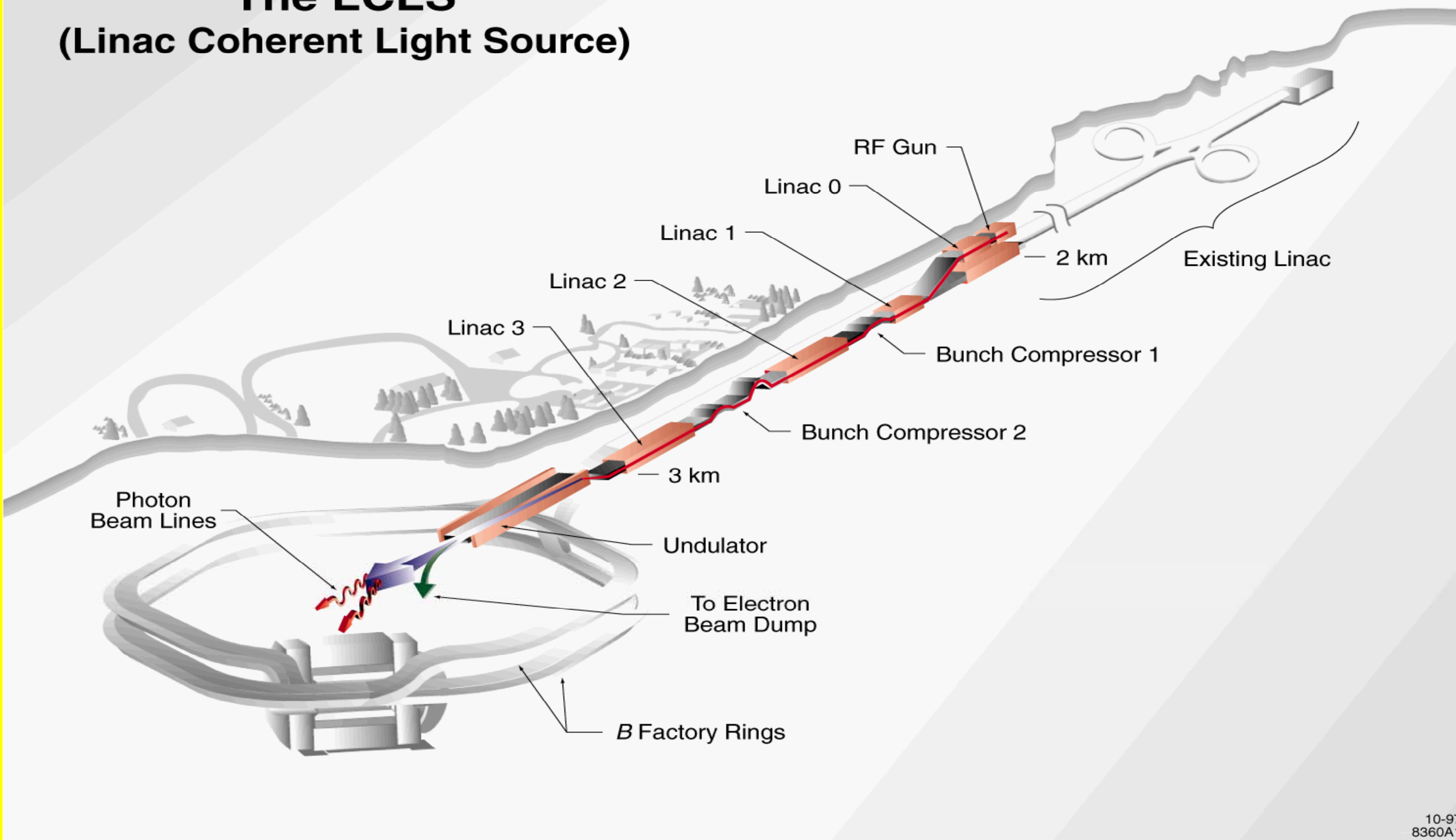
dowell@slac.stanford.edu

Outline of Talk

- Overview of the LCLS Injector
- Gun-to-Linac Diagnostics
- Cathode Load Lock
- Electro-Optical Bunch Diagnostic
  - Installation of Prototype onto GTF
  - Use Green Beam from Nd:Glass Drive Laser
- Experiments at Gun Test Facility (GTF)
  - Projected and Slice Emittances
  - Longitudinal Emittance (Discussed in Wed Talk)
  - Beginning Beam Tests with Mg Cathode

- The Two-Frequency RF Photocathode Gun

The LCLS
(Linac Coherent Light Source)

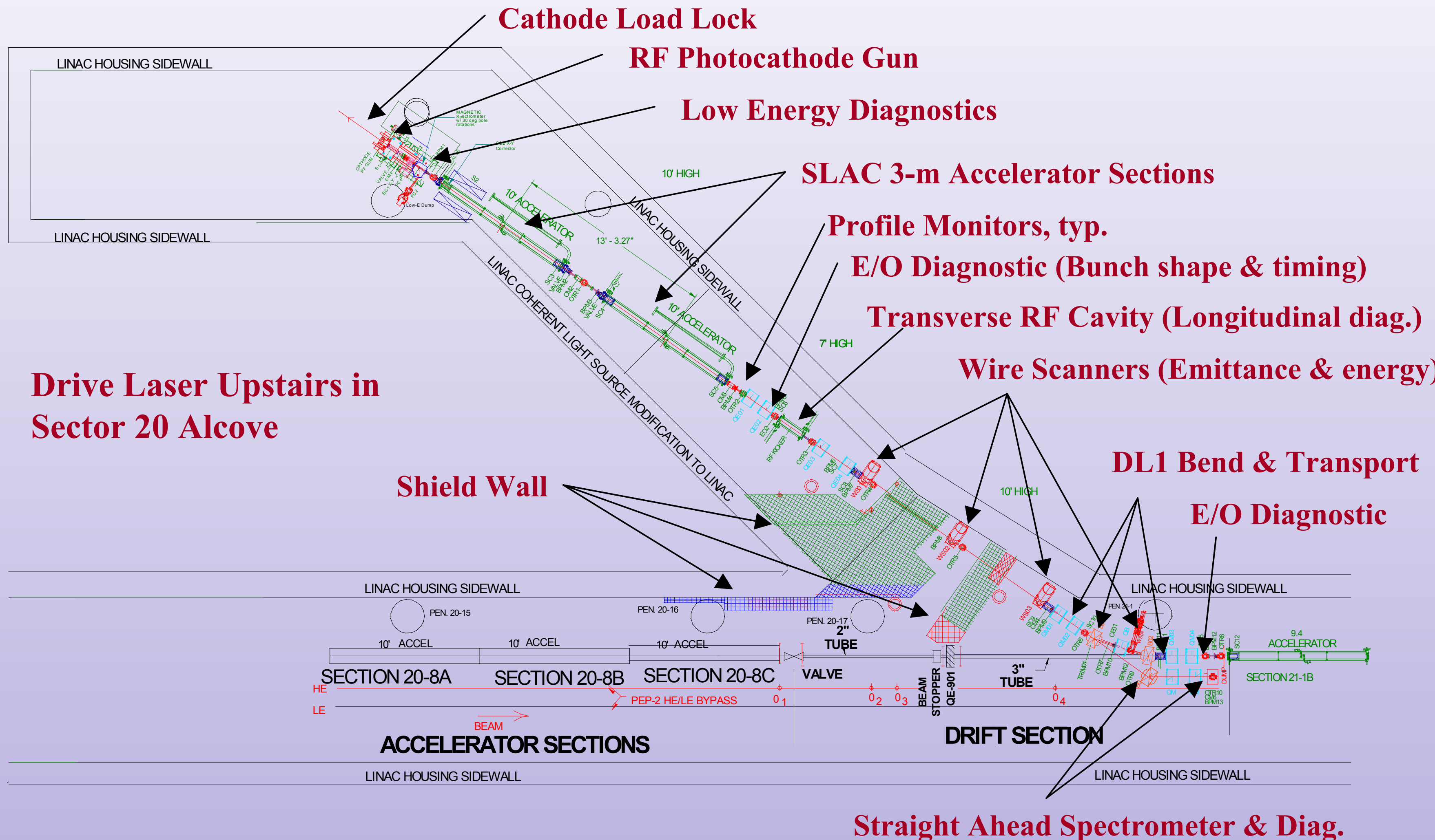


dowell@slac.stanford.edu

LCLS Injector Performance Requirements:

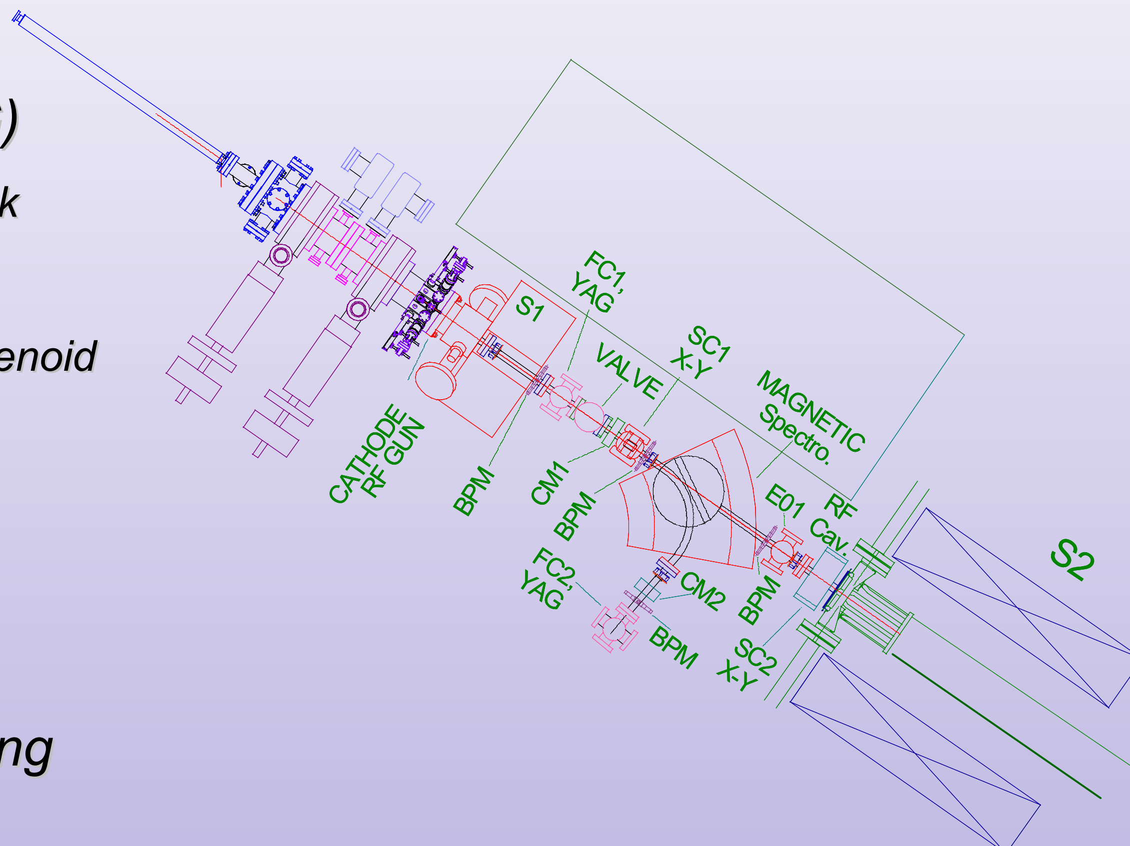
Parameter	Value
Peak current	100 A
Charge	0.2 – 1 nC
Normalized transverse emittance projected/slice	≤ 1.2 / 1.0 μm rms
Rate	120 Hz
Energy	150 MeV
Energy spread @ 150 MeV projected/slice	≤ 0.1 / 0.01 % rms
Gun laser timing stability	≤ 0.50 ps rms
Booster mean rf phase stability	0.1 ° rms
Charge stability	≤ 2.0 % rms
Bunch length stability	≤ 5 % rms

LCLS Injector

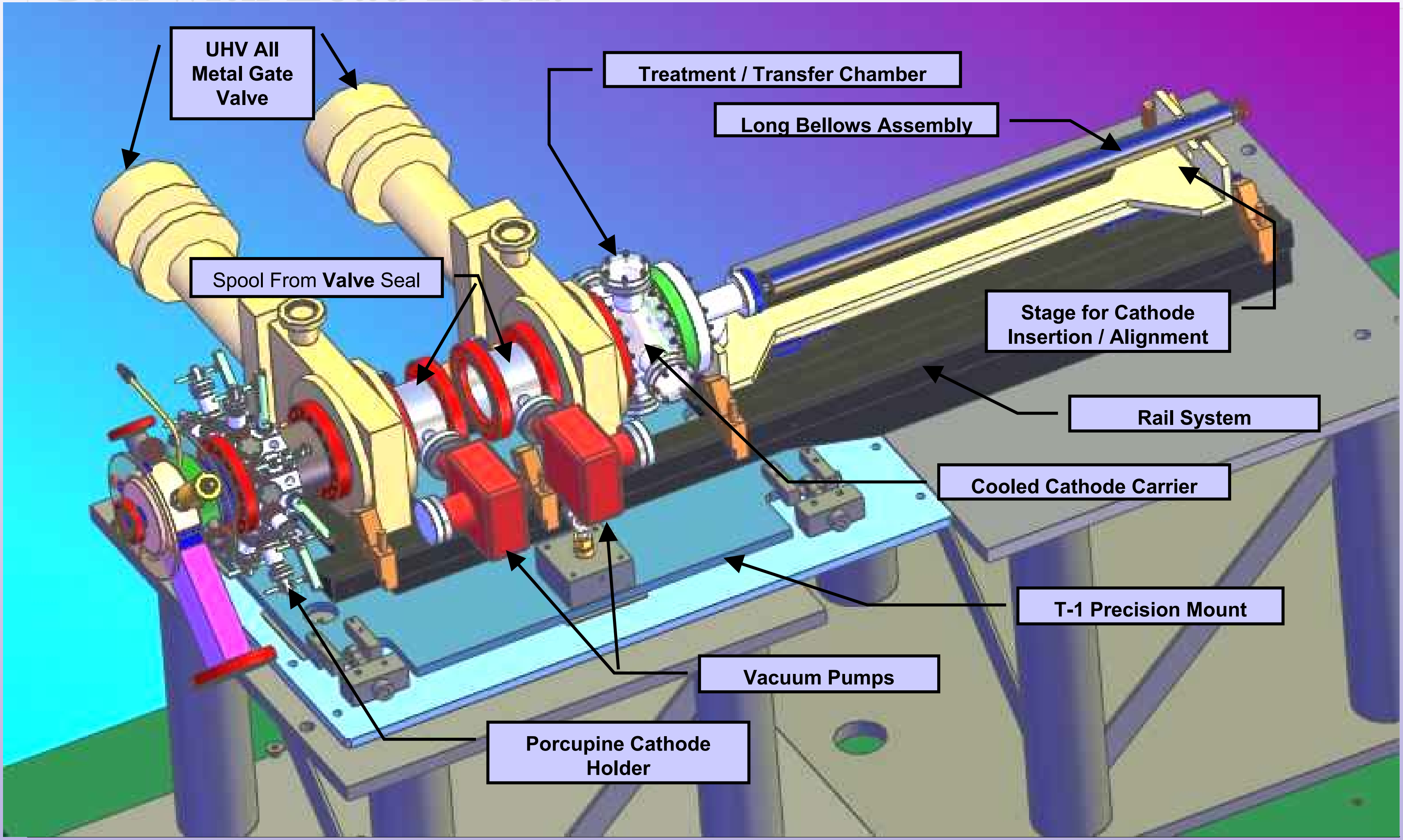


Injector Description:

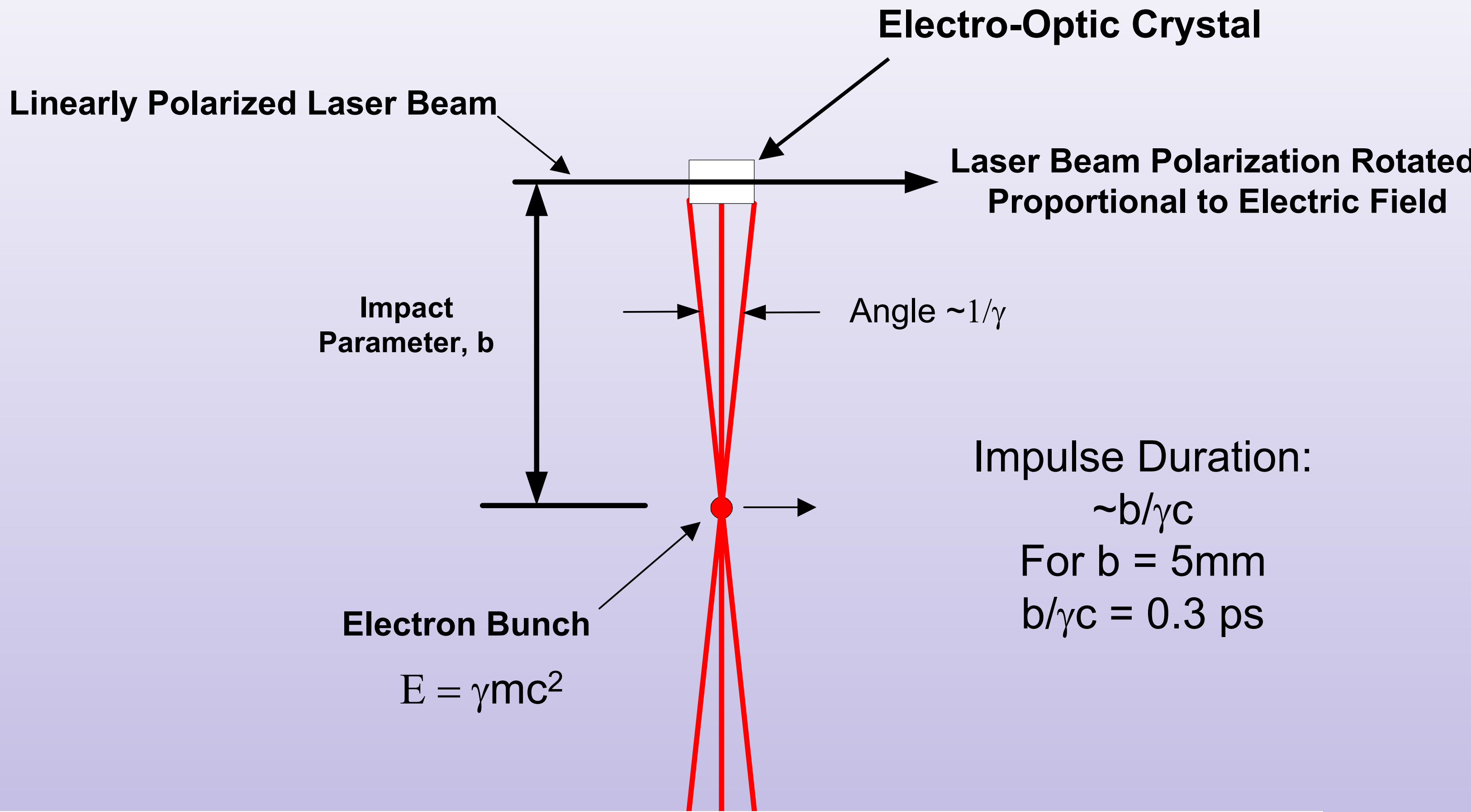
- *1.6-cell S-band rf gun (G)*
  - *Cu/Mg cathode with load-lock*
  - *Ti:sapphire laser*
  - *Emittance compensation solenoid (S1)*
- *Booster (L0)*
  - *Two SLAC 3-m sections*
  - *Symmetric RF feeds*
- *Beam matched to L0 using solenoids S1 & S2*



Gun with Load Lock:



Electro-Optical Geometry Determines Time Resolution



Impulse Duration:
~b/γc
For b = 5mm
b/γc = 0.3 ps

Electric field lines are compressed into a disk with opening angle ~1/γ

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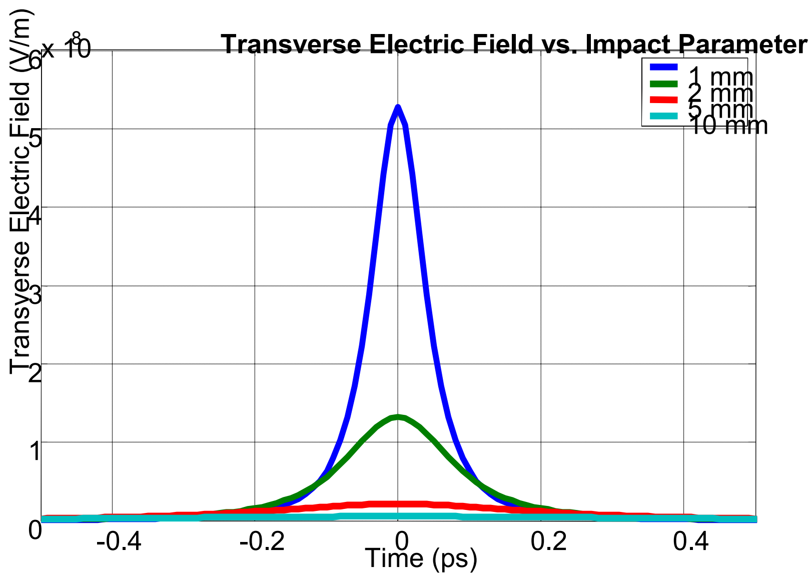
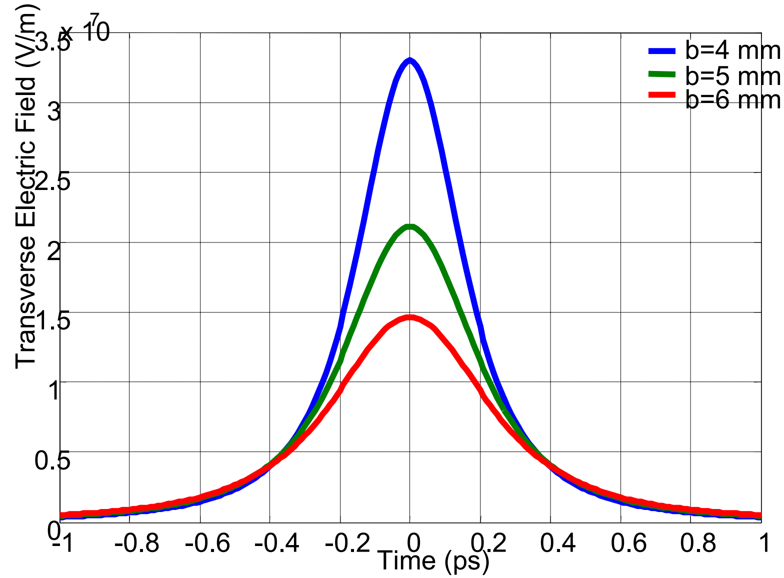
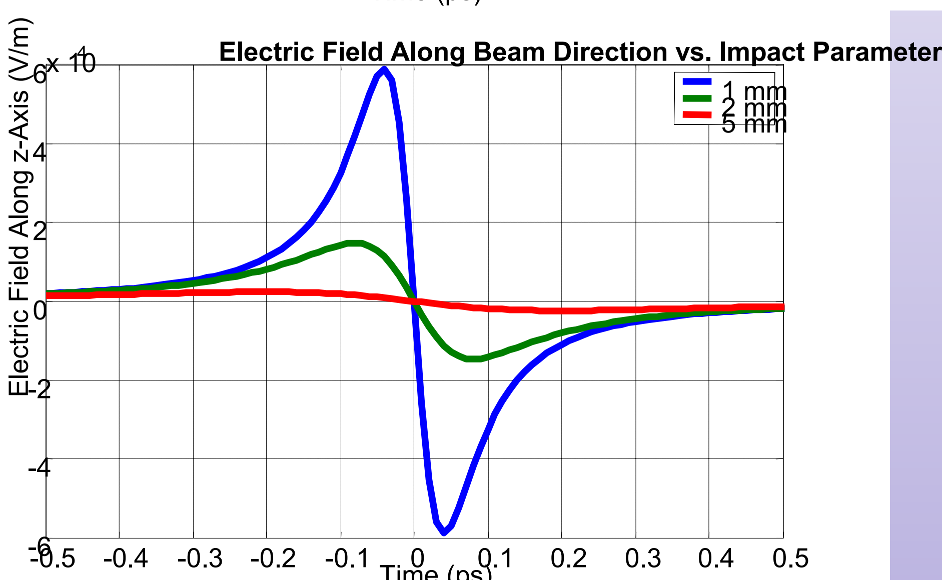
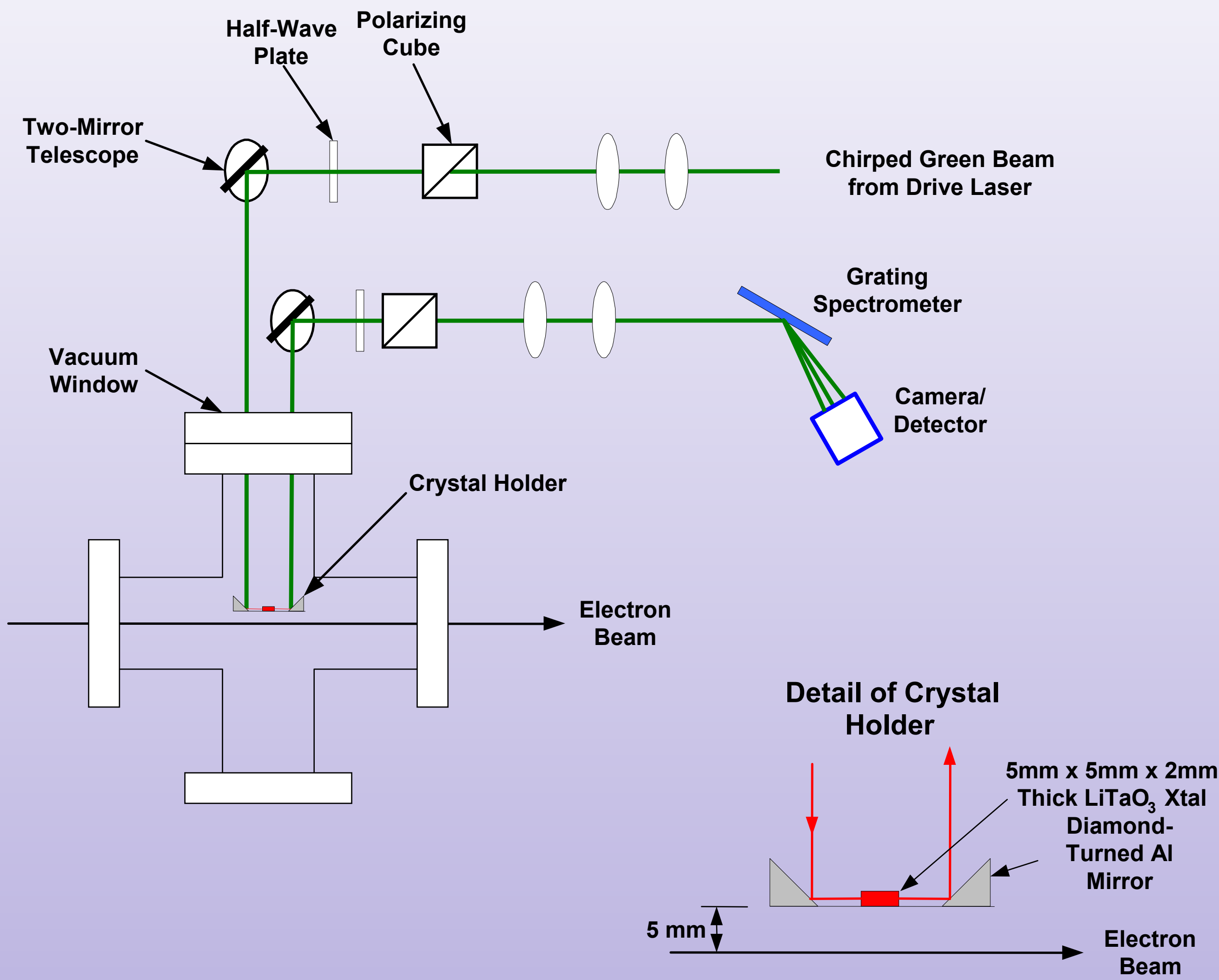




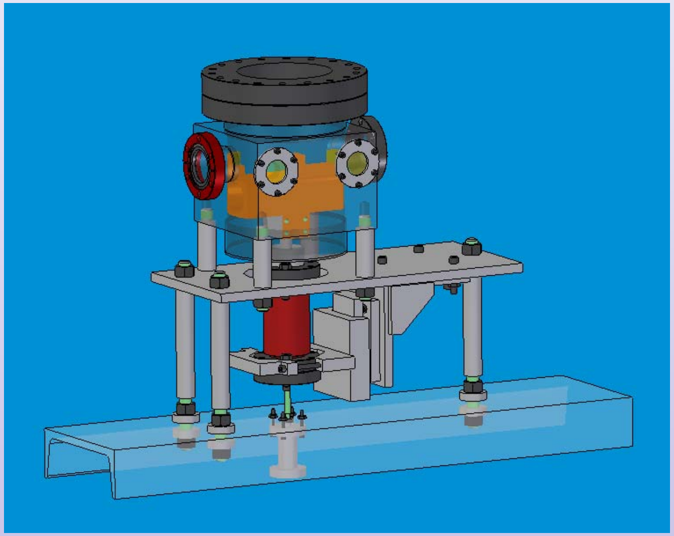


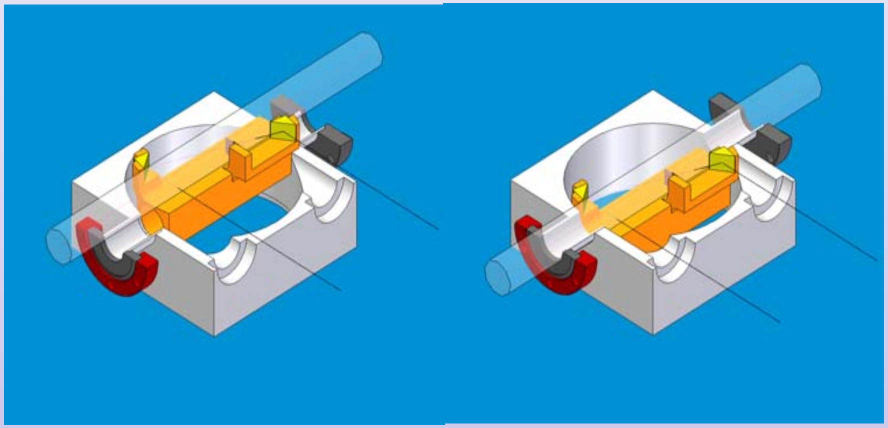
Electric Field Transients from 1nC Point Charge At 30 MeV

Schematic Layout of GTF E-O Experiment

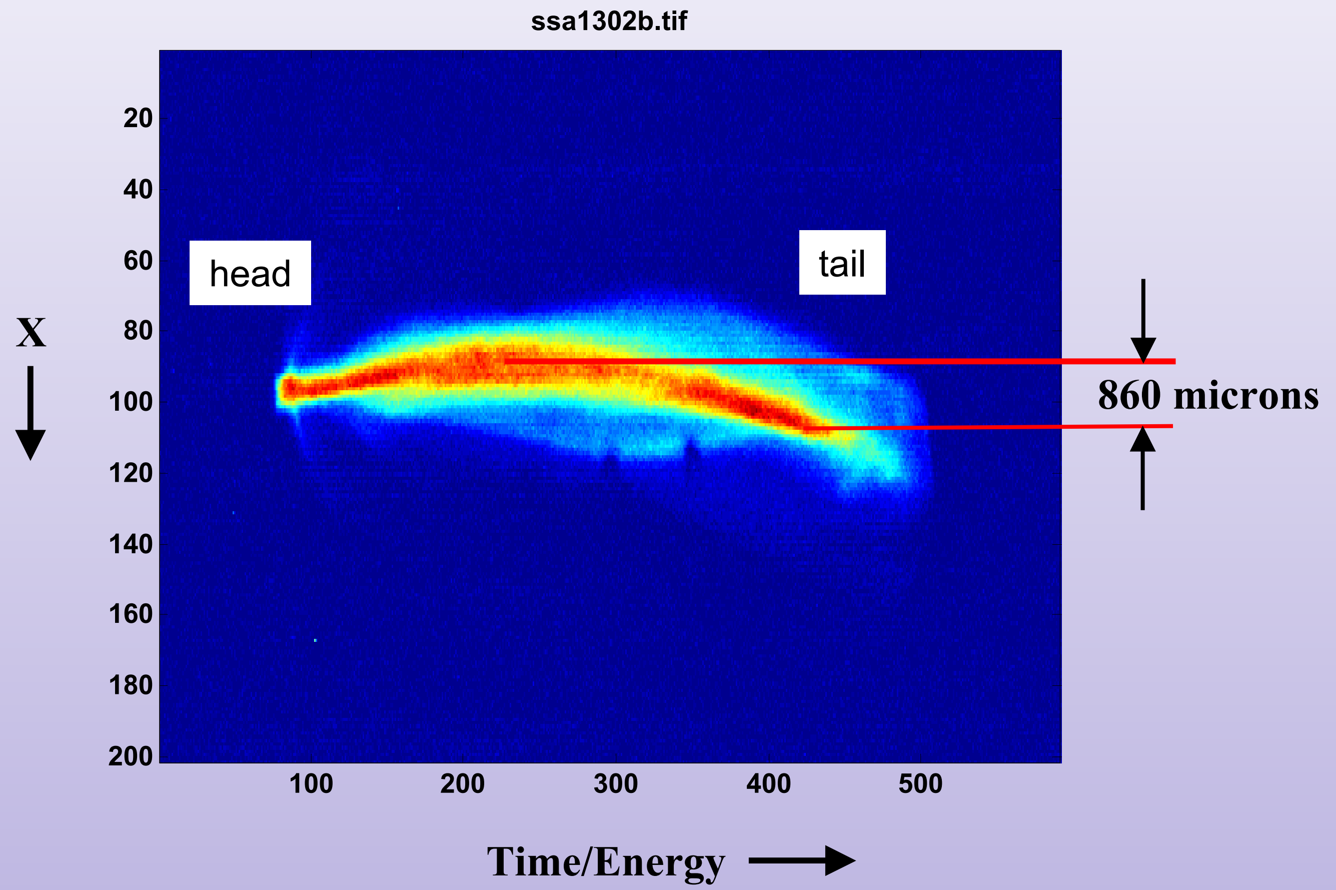


Electro-Optical Bunch Length Diagnostic GTF Prototype with Wakefield Plug

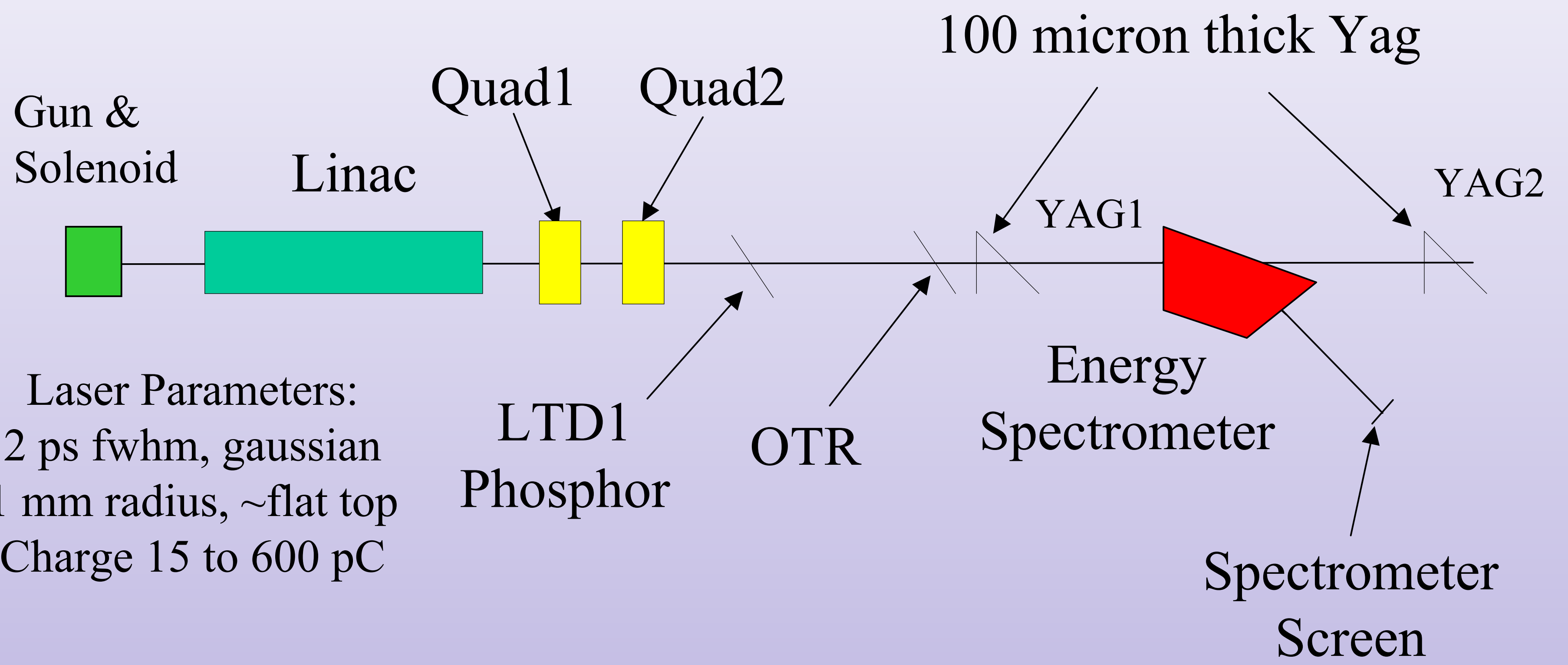




Slice emittance studies at GTF show large x-z centroid correlations

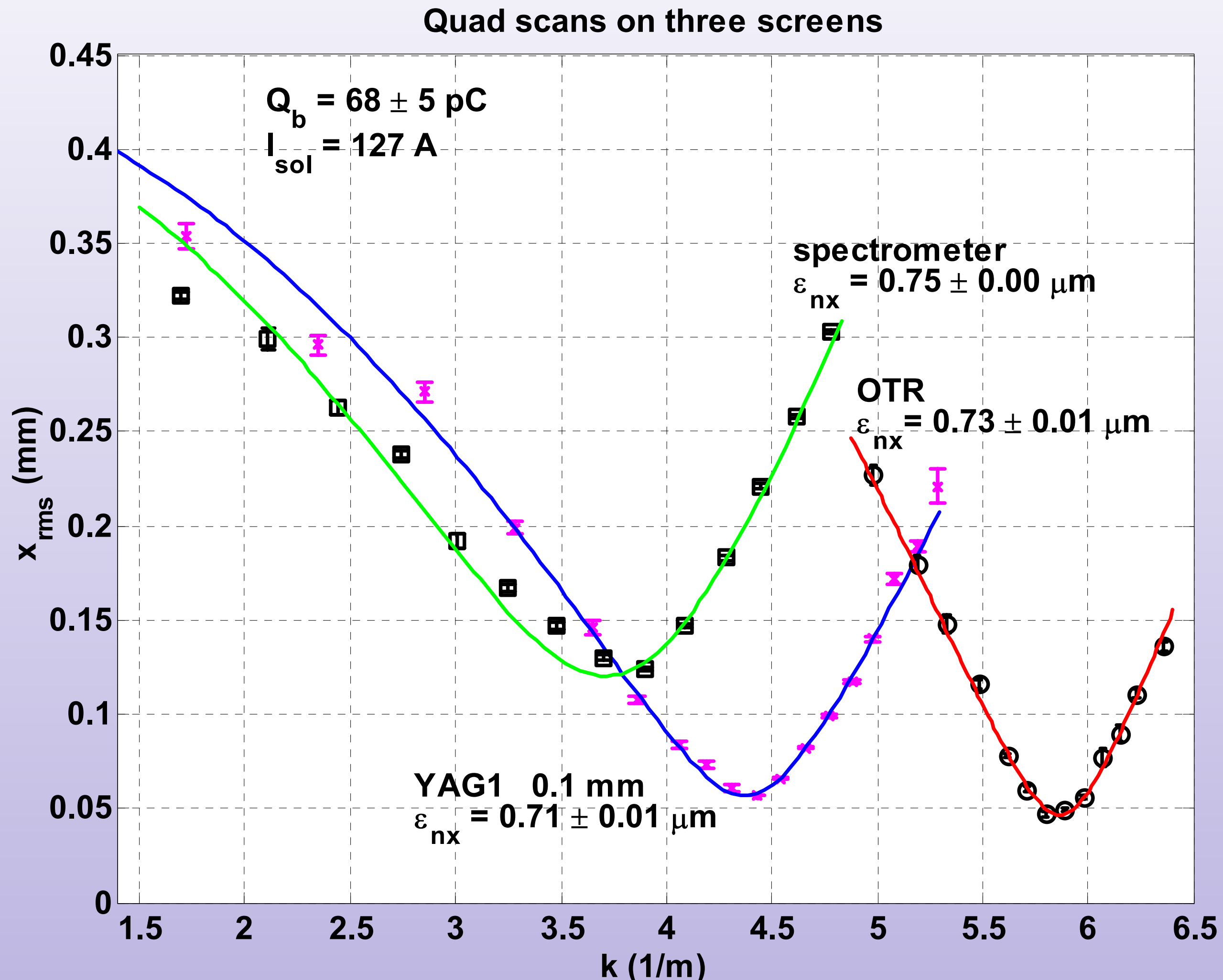


GTF Diagnostics and Transport



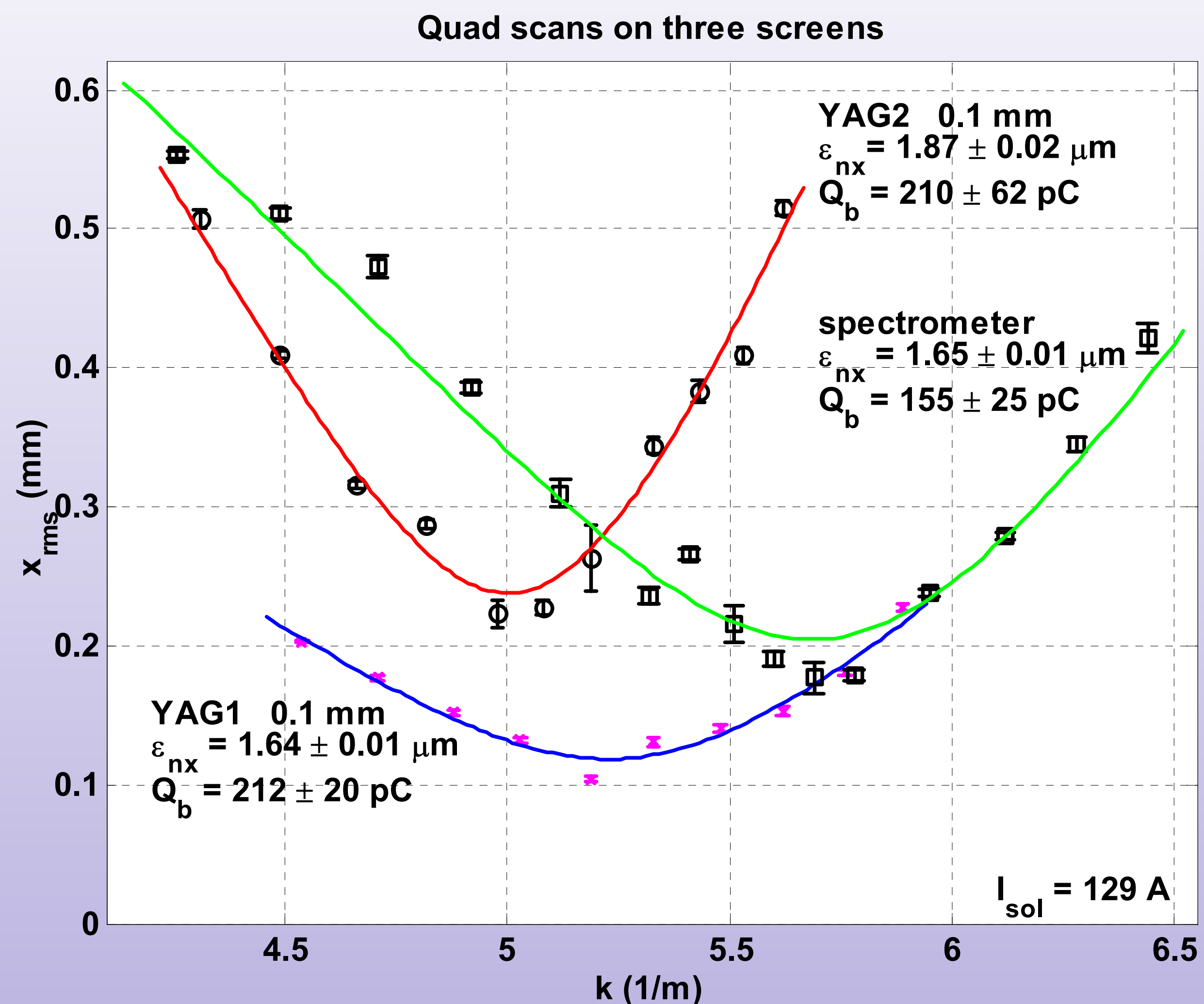
Laser Parameters:
2 ps fwhm, gaussian
1 mm radius, ~flat top
Charge 15 to 600 pC

Redundant Measurements at Separate Locations Verify Emittance



23 July 2002

Some Differences are Observed at Higher Charge



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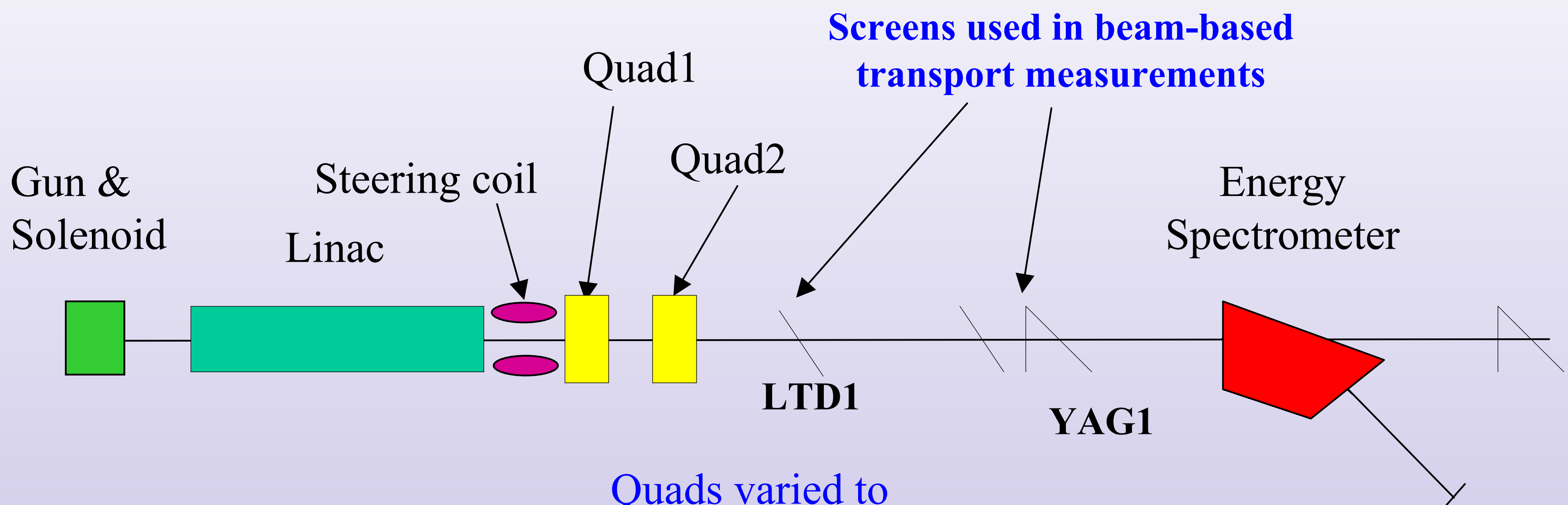
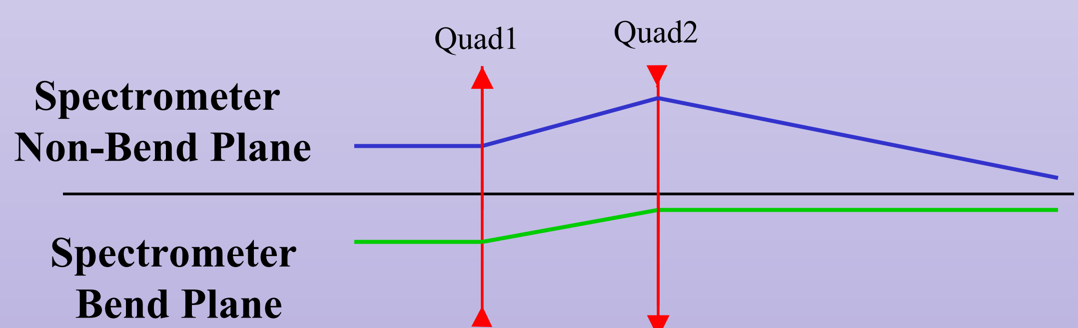
GTF Slice Emittance Experiment



Spectrometer Screen

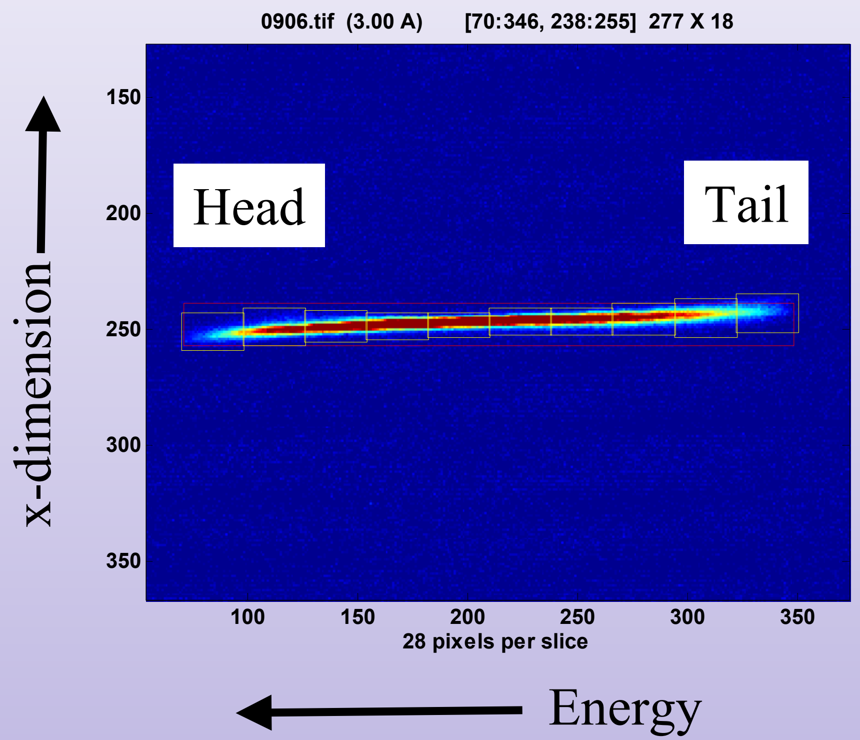
Linac puts energy-chirp onto electron bunch

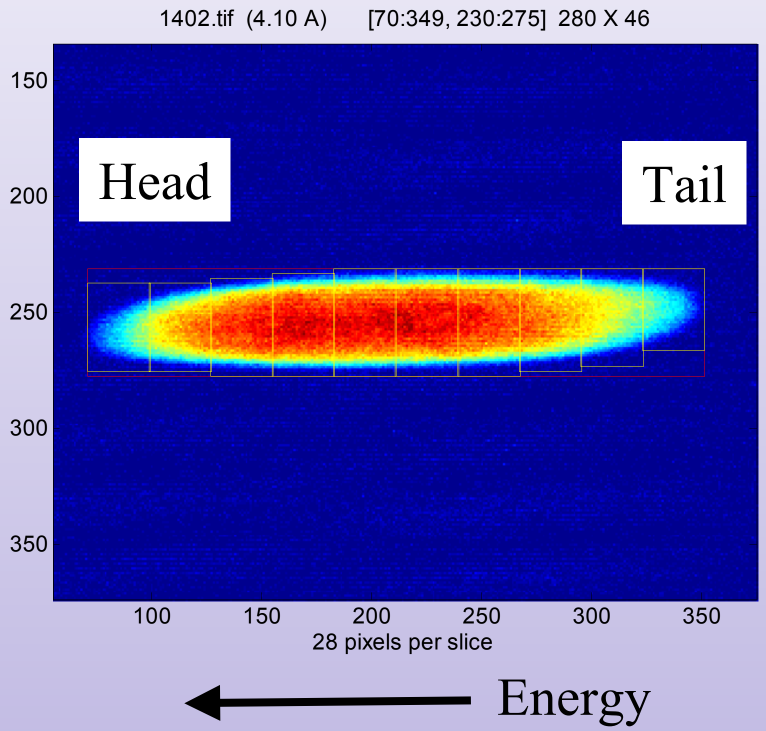
Quads varied to scan beam sizes at spectrometer screen

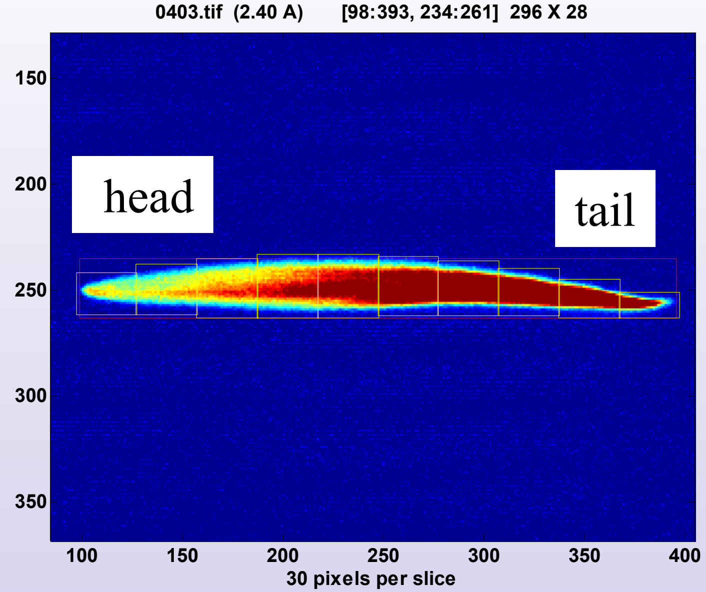


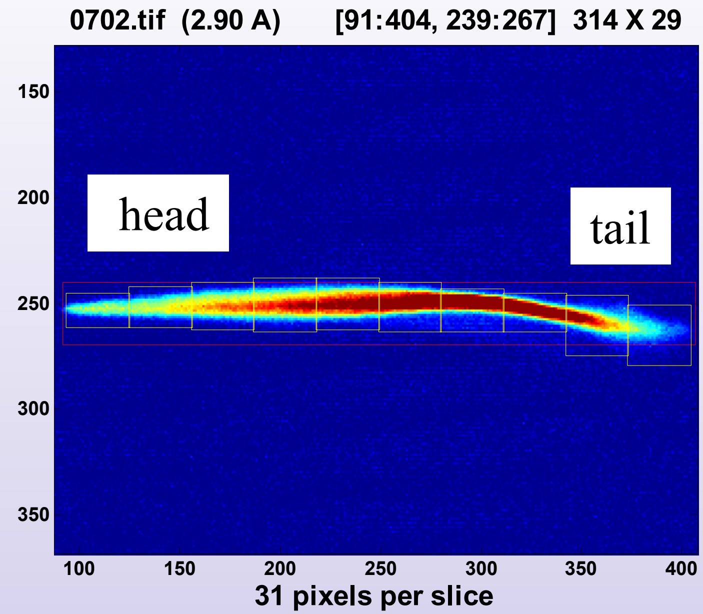
Measure energy-dispersed images vs. quad current.
Energy => Time
Transverse size => Emittance

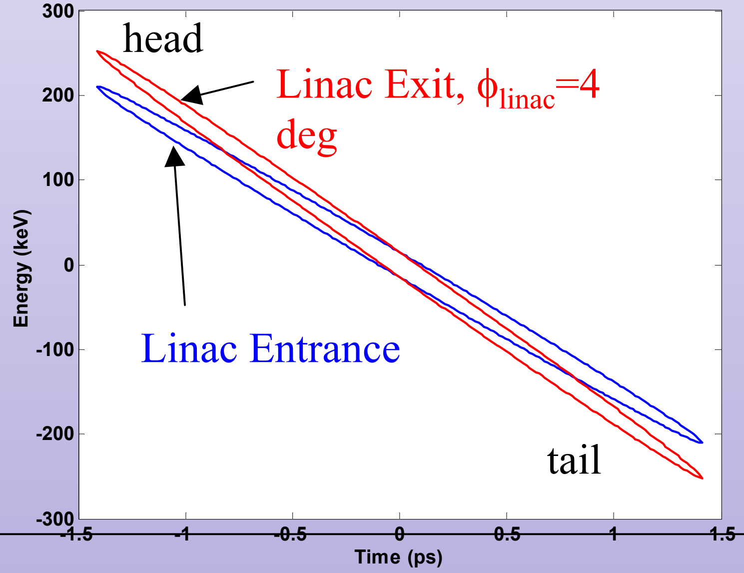
Chirped beam at 15 pC, I-solenoid=104 amps, for two quad fields









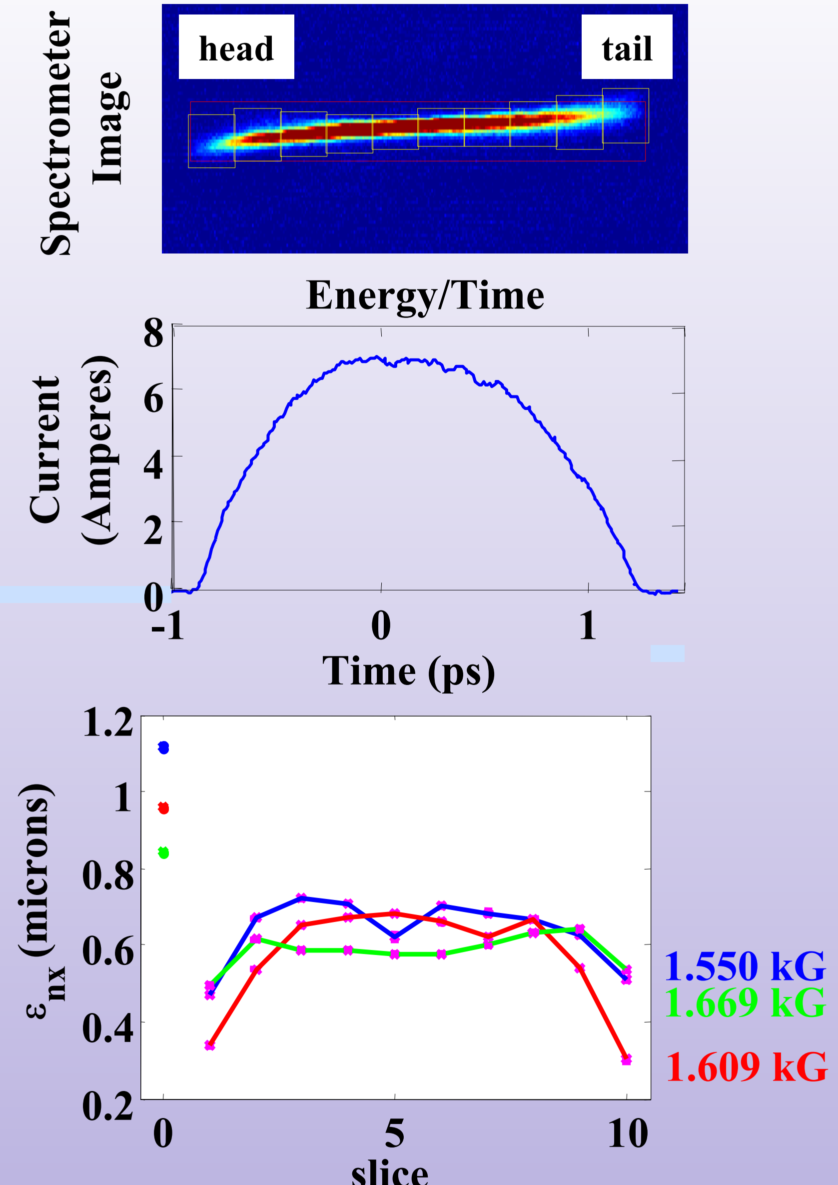


Longitudinal Phase Space at 300 pC Gives Conversion from Energy to Time (Linear Analysis)

Bunch chirp is 180 keV/ps

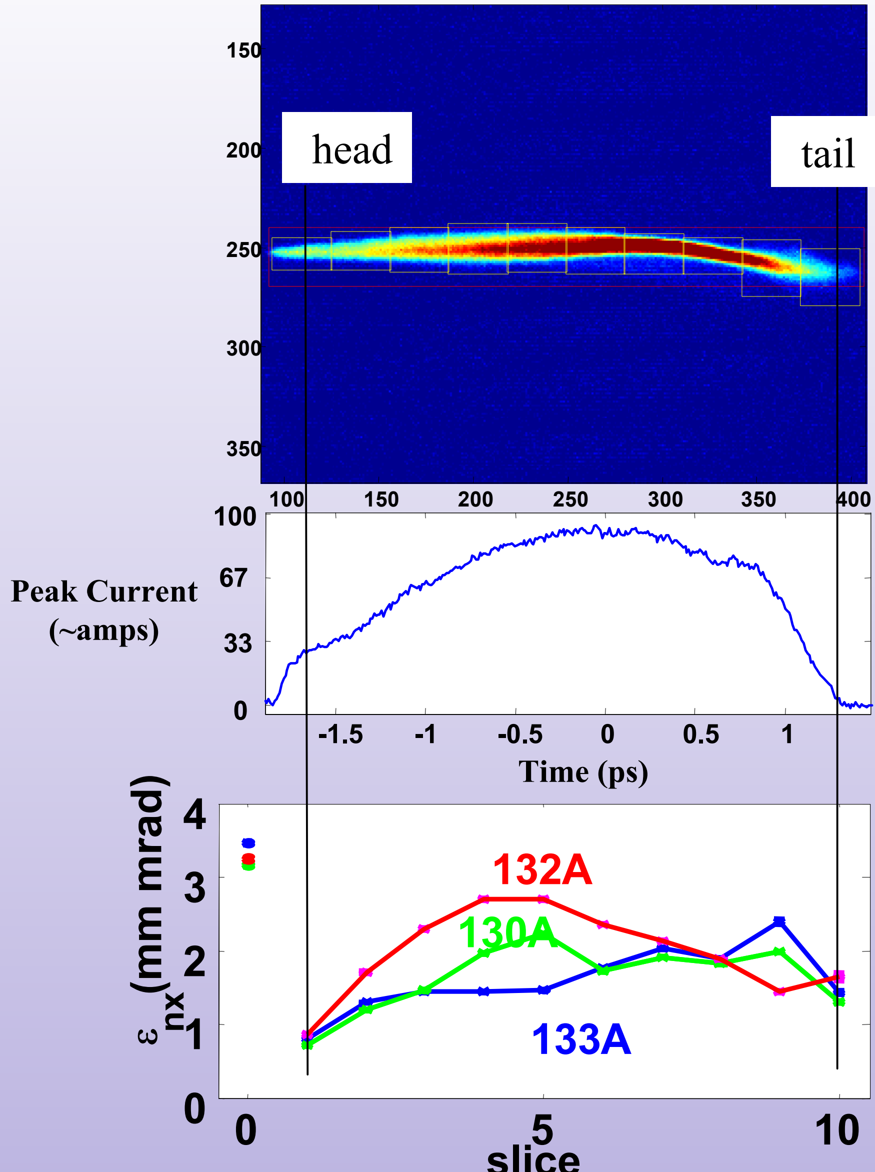
15 pC Slice Analysis

Slice and projected emittances for 15 pC bunch charge. The top image is of the spectrometer screen with the bunch energy chirped in the horizontal direction. The regions used for the 10 slices are outlined with yellow boxes. The bunch is sliced into equal time intervals, each being 220fs long. The instantaneous beam current is given in the center panel. The slice and projected emittances are plotted in the bottom panel. The projected emittances are given as Slice 0. The solenoid fields in are shown in kilogauss (kG). Although the projected quantities are approximately 1.5 times the largest slice emittance, both are minimized at the same solenoid field of 1.669 kilogauss.



dowell@slac.stanford.edu

300 pC Analysis



Sliced Spectrometer Image of Slice Quad Scan Data

Instantaneous Peak Current

Slice Emittances (slice 0 is projected emittance)

Gun Development at LCLS

A Two-Frequency RF Photo-Cathode Gun

David H. Dowell
SLAC

Collaborators:

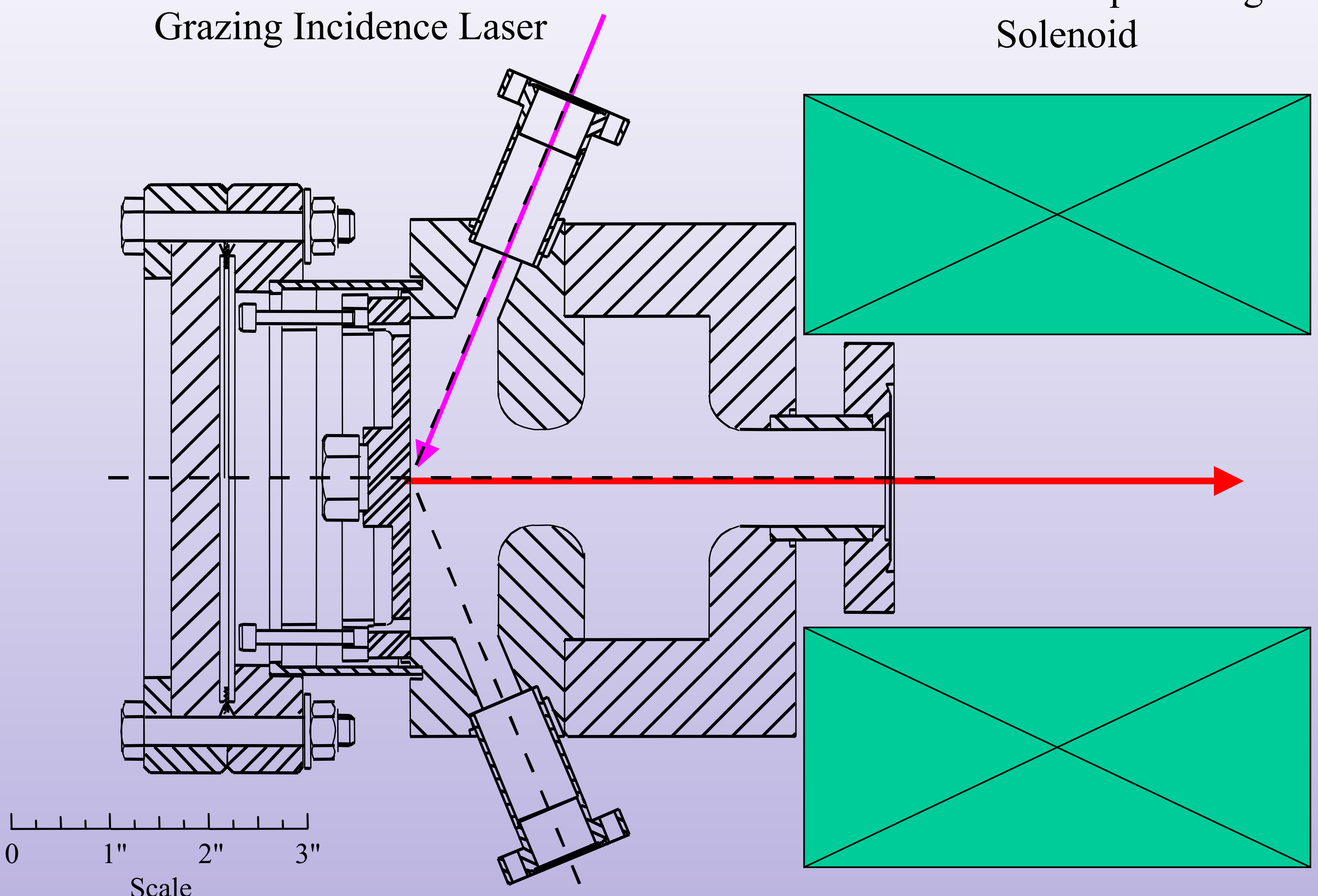
T. Kimura, Stanford University => Parmela Simulations
M. Ferrario, INFN- Frascati => 2f Homdyn
J. Lewellen, Argonne National Laboratory => RF Gun Design
C. Limborg, SLAC/SSRL => Parmela Simulations
J.F. Schmerge, SLAC/SSRL
L. Serafini, INFN- Milan => Gun Theory
T. Smith, Stanford University => Gun and Beam Design
L. Young, Los Alamos => 2f Parmela

Originally presented at 2003 FEL Conference

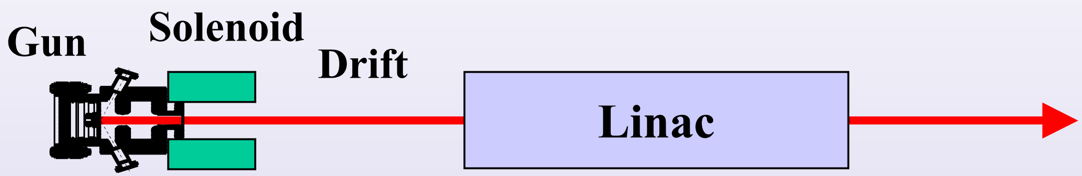
Talk Outline

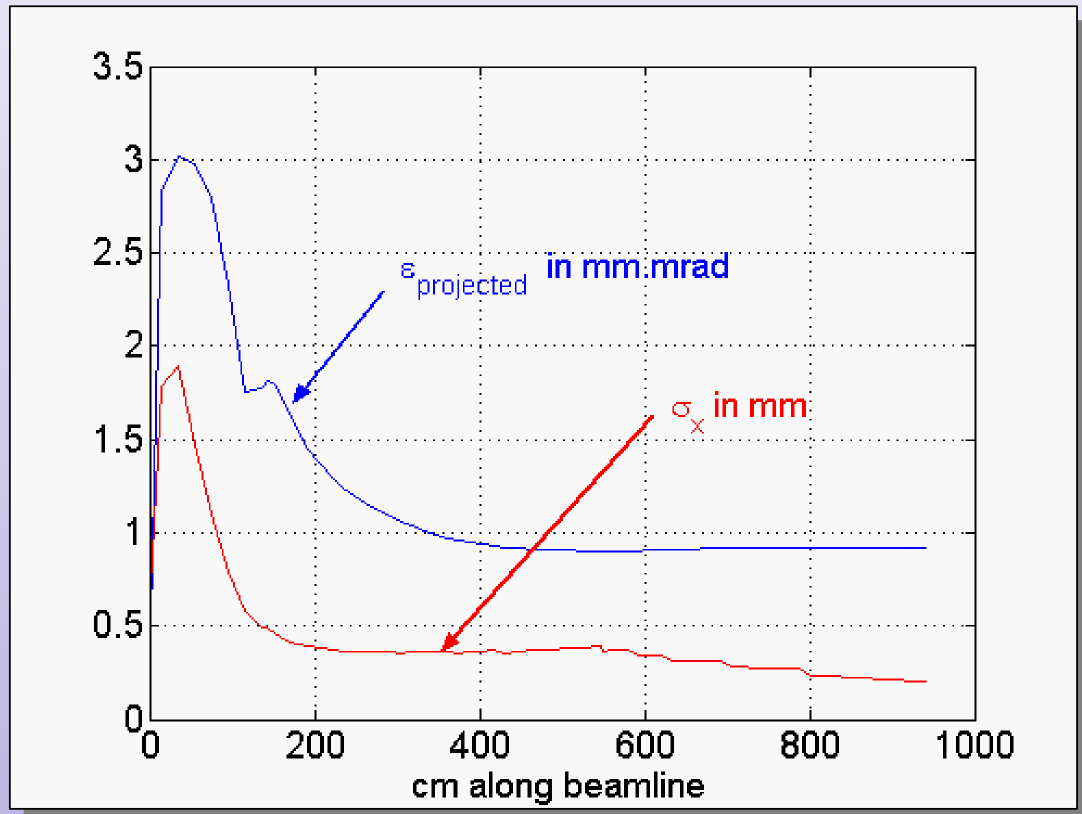
- The Current Approach to High Brightness Guns
- Contributions to the Gun Emittance
- Description and Theory of the 2F Gun
- Parmela Simulations Using Realistic Superfish Fields
- Summary and Conclusions

The BNL/SLAC/UCLA 1.6 Cell RF Gun

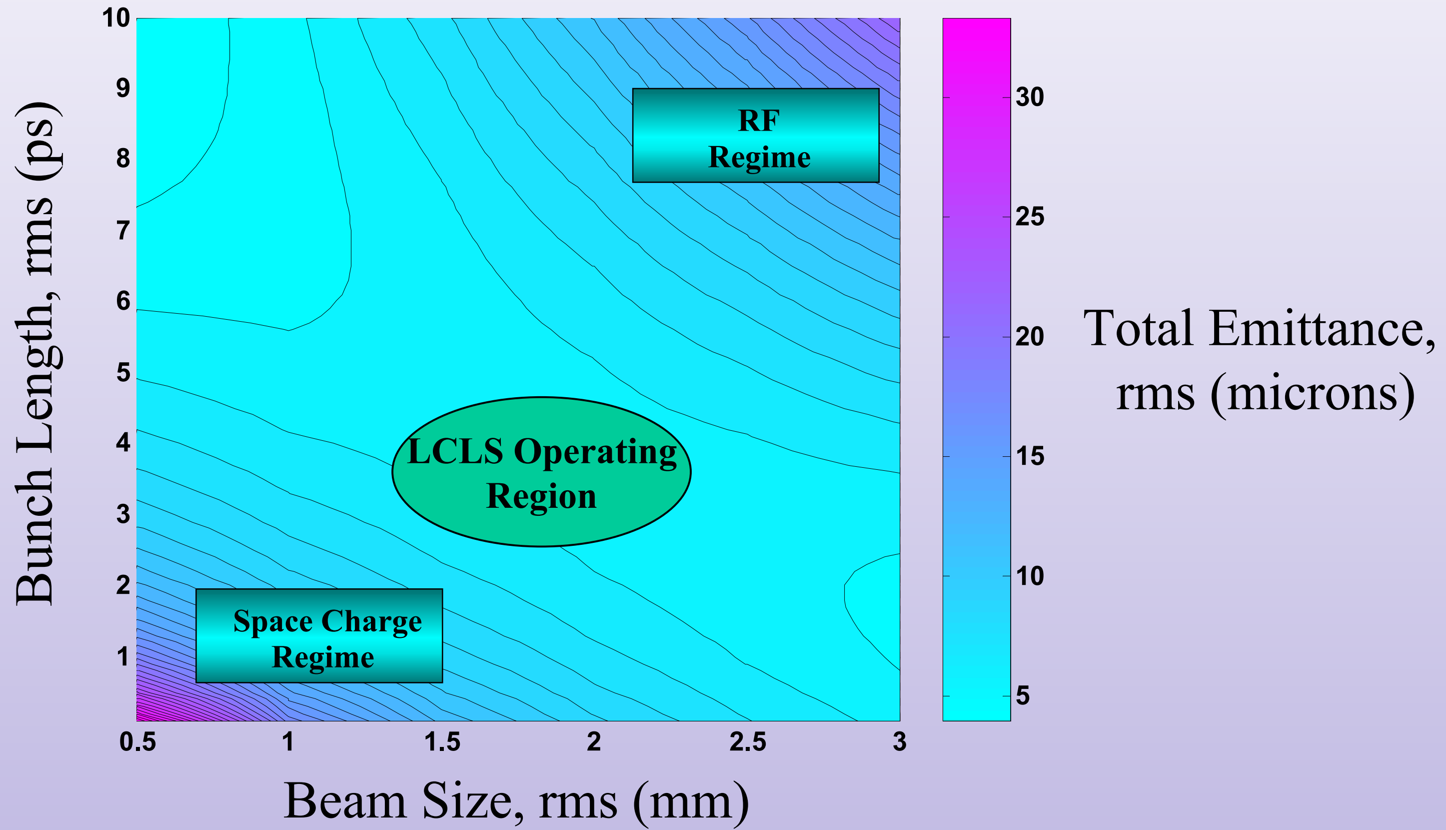


LCLS Emittance Compensation, the “Ferrario Operating Point”





Typical RF gun operates in slightly space charge dominated regime, using compensation to reduce SC emittance



Contour plot of the total emittance at the gun exit in the plane of bunch size and length. The bunch charge is 1 nC.

C. Travier, NIM A340(1994)26-39

Theory of the Two-Frequency Gun

In a 1992 paper (NIM A318(1992)301) Serafini suggested using harmonic frequencies to eliminate the time dependent RF emittance:

$$E_z(z,t) = E_0(z)\cos(kz)\sin(\omega t + \phi_0) + E_n(z)\cos(nkz)\sin(n(\omega t + \phi_n))$$

He showed that the RF emittance vanishes to 4th order and the gun energy is also linearized to 4th order when:

$$E_n = (-1)^{(n-3)/2} E_0 / n^2$$

for gun exit phase $\langle\phi\rangle = \pi/2$ and $n = 3, 7, 11, \ldots$

Not surprisingly, this is exactly the same condition needed in the x-band section to linearize the longitudinal phase space in the LCLS chicane compressors

Theory of the Two-Frequency Gun

In a 1992 paper (NIM A318(1992)301) Serafini suggested using harmonic frequencies to correct for the time dependent RF emittance growth in a RF gun:

$$E_z(z,t) = E_0(z)\cos(kz)\sin(\omega t + \phi_0) + E_n(z)\cos(nkz)\sin(n(\omega t + \phi_n))$$

Repeating Kim's method* for computing the beam energy in terms of the exit phase, ϕ, of a N+1/2 cell gun, he obtains:

$$\gamma = 1 + \alpha\left[\pi(N + 1/2)\sin\phi + \cos\phi\right] + \alpha_n\left[n\pi(N+1/2)\sin(n\phi) + \begin{cases}\cos(n\phi), & \text{n odd}\\ 0, & \text{n even}\end{cases}\right]$$

Where the normalized peak fields for the fundamental and n-th harmonics are,

$$\alpha = eE_0/(2mc^2k) \qquad \alpha_n = eE_n/(2mc^2nk)$$

*K-J. Kim, RF and space-charge effects in laser driven rf electron guns," NIM A275(1989)201-218

Now compute the harmonic field needed to give a linear energy spread out of the gun:

Letting $\phi = \langle\phi\rangle + \Delta\phi$ expand in powers of $\Delta\phi$, and let the exit phase, $\langle\phi\rangle = \pi/2$

The gun energy becomes:

$$\gamma = \left[1 + \pi(N + \frac{1}{2})(\alpha + (-1)^{(n-1)/2} n\alpha_n)\right]$$

$$- \left[\alpha + (-1)^{(n-1)/2} n\alpha_n\right]\Delta\phi$$

$$- \left[\frac{\pi}{2}(N + \frac{1}{2})(\alpha + (-1)^{(n-1)/2} n^3\alpha_n\right](\Delta\phi)^2$$

$$+ \left[\frac{1}{6}(\alpha + (-1)^{(n-1)/2} n^3\alpha_n)\right](\Delta\phi)^3 + \ldots$$

The 2nd and 3rd order terms vanish when

$$\alpha_n = (-1)^{(n-3)/2}\alpha / n^3 \quad \text{or} \quad E_n = (-1)^{(n-3)/2} E_0 / n^2$$

Not surprisingly, this is exactly the same condition needed in the x-band section to linearize the longitudinal phase space in the LCLS chicane compressors

Condition for Longitudinal Linearization

$$\alpha_{\mathrm{n}} = (-1)^{(\mathrm{n}-3)/2}\alpha/\mathrm{n}^3 \quad \text{or} \quad \mathrm{E}_{\mathrm{n}} = (-1)^{(\mathrm{n}-3)/2}\mathrm{E}_0/\mathrm{n}^2$$

$$\gamma = \left[1+\pi(N+\frac{1}{2})(\alpha+(-1)^{(n-1)/2}n\alpha_n)\right] - \left[\alpha+(-1)^{(\mathrm{n}-1)/2}n\alpha_n\right]\Delta\phi + \mathrm{O}(\Delta\phi^4)$$

Beam energy reduced by E_1/n^2 for n=3

Correlated Energy Spread

$$\gamma = \left[1+\pi(N+\frac{1}{2})\frac{eE_1}{2kmc^2}(1+\frac{(-1)^{n-2}}{n^2})\right] - \left[\frac{eE_1}{2kmc^2}(1+\frac{(-1)^{n-2}}{n^2})\right]\Delta\phi + \mathrm{O}(\Delta\phi^4)$$

Correlated energy spread for E_1=100MV/m and n=3 is 13 keV/degree

The effect in transverse phase space is more interesting. Again, beginning with Kim's work, Serafini adds the nth harmonic require for linearizing the longitudinal phase space to the exit transverse momentum:

$$p_r = \alpha k r \sin\phi + \frac{\alpha k r}{n^2}\sin(n\phi)$$

To obtain the rms normalized RF emittance:

$$\varepsilon_x = \alpha k \left\langle x^2 \right\rangle \left\{ \left\langle (\sin\phi + \sin(n\phi)/n^2)^2 \right\rangle - \left\langle \sin\phi + \sin(n\phi)/n^2 \right\rangle^2 \right\}^{1/2}$$

Which expanded in powers of $\Delta\phi$ gives

$$\frac{\varepsilon_x^2}{\alpha^2 k^2 \left\langle x^2 \right\rangle^2} = \left[\frac{1}{4}(\left\langle (\Delta\phi)^4 \right\rangle - \left\langle (\Delta\phi)^2 \right\rangle^2\right]\left[\sin\langle\phi\rangle + \sin(n\langle\phi\rangle)\right]^2$$

$$+\left[\left\langle (\Delta\phi)^2 \right\rangle - \frac{1}{3}\left\langle (\Delta\phi)^4 \right\rangle\right]\cos^2\langle\phi\rangle$$

$$+\left[\frac{1}{n^2}\left\langle (\Delta\phi)^2 \right\rangle - \frac{1}{3}\left\langle (\Delta\phi)^4 \right\rangle\right]\cos^2(n\langle\phi\rangle)$$

$$+\frac{2}{n}\left[\left\langle (\Delta\phi)^2 \right\rangle - \frac{1}{6}\left\langle (\Delta\phi)^4 \right\rangle(1+n^2)\right]\cos\langle\phi\rangle\cos(n\langle\phi\rangle) + \ldots$$

The RF-emittance vanishes for n=3,7,11 at $\langle\phi\rangle = \pi/2$

Parmela Simulations*

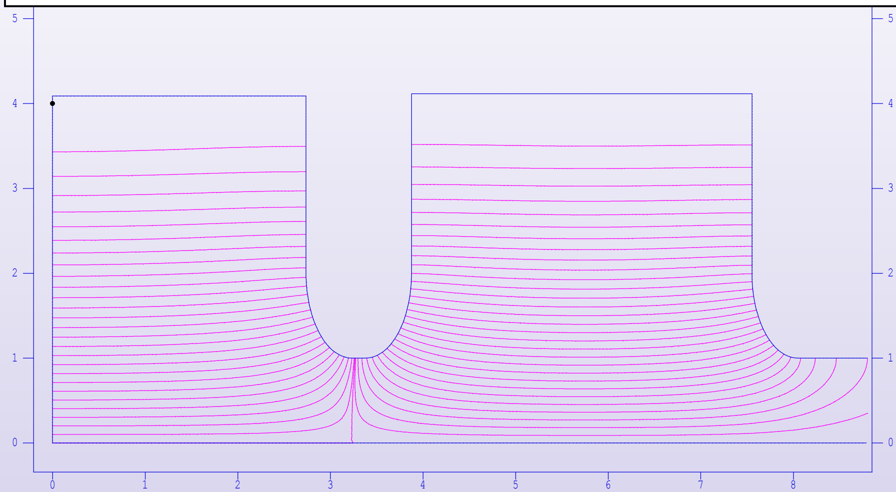
- Parmela was modified to allow superimposed fields in same cell
- RF fields computed using Superfish
- Simulations ignore thermal emittance and assume 100 MV/m.
- The initial distributions are uniform both transversely and longitudinally.
- Three groups of simulations were performed:
  - -Short bunches (10 ps long) => Space charge dominated regime.
  - -Long bunches (40 ps long) => RF dominated regime.
  - -Emittance Compensation (30 ps long) => Emittance compensation.
- Short and long bunch cases are computed to exit of the gun, no solenoid field.
- The emittance compensated case included solenoid, drift and s-band linac.
- Both field and phase of 3rd harmonic were varied to minimize emittance:

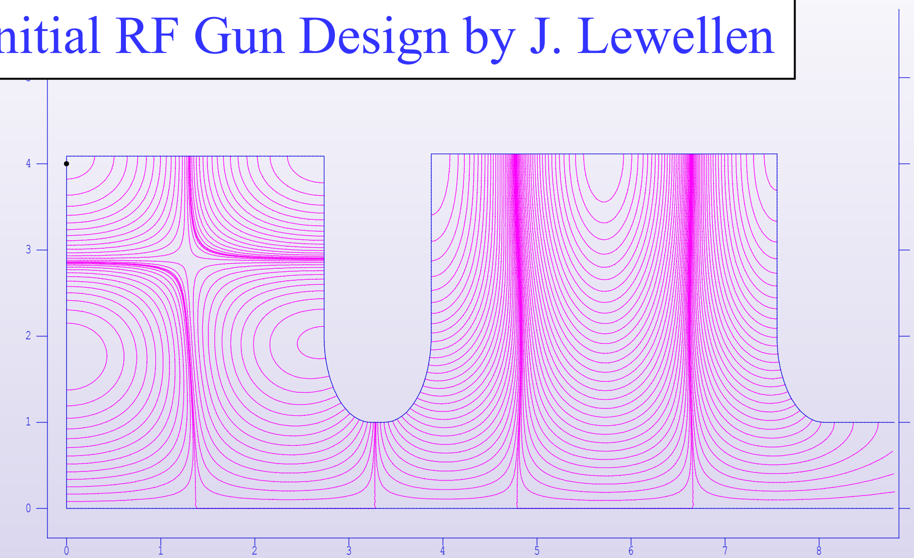
$$E_z = E_0 \cos(kz)\sin(\omega t + \phi_0) + E_3 \cos(3kz)\sin(3(\omega t + \phi_3))$$

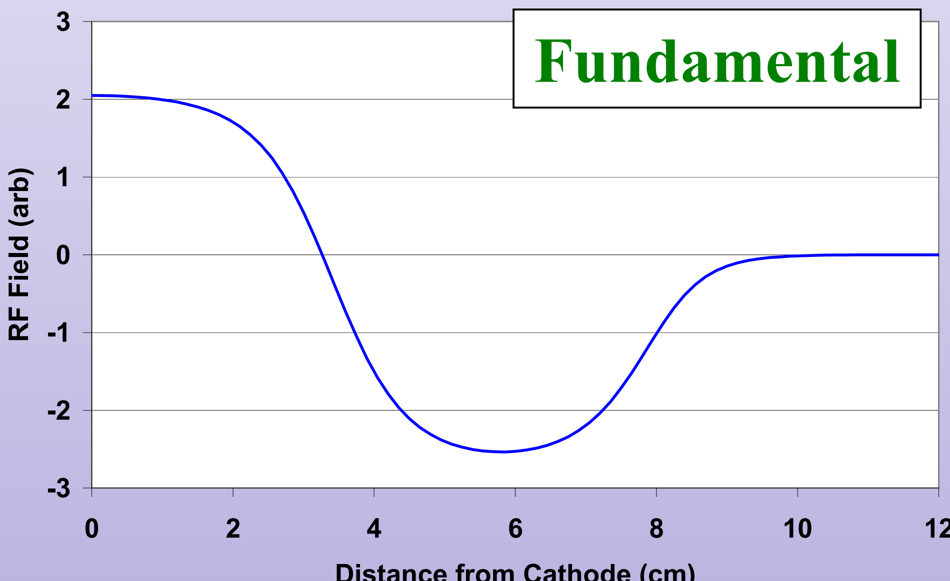
*Parmela Calculations by T. Kimura with advice and tools from C. Limborg
New version of Parmela with superimposed fields in same cell by L. Young

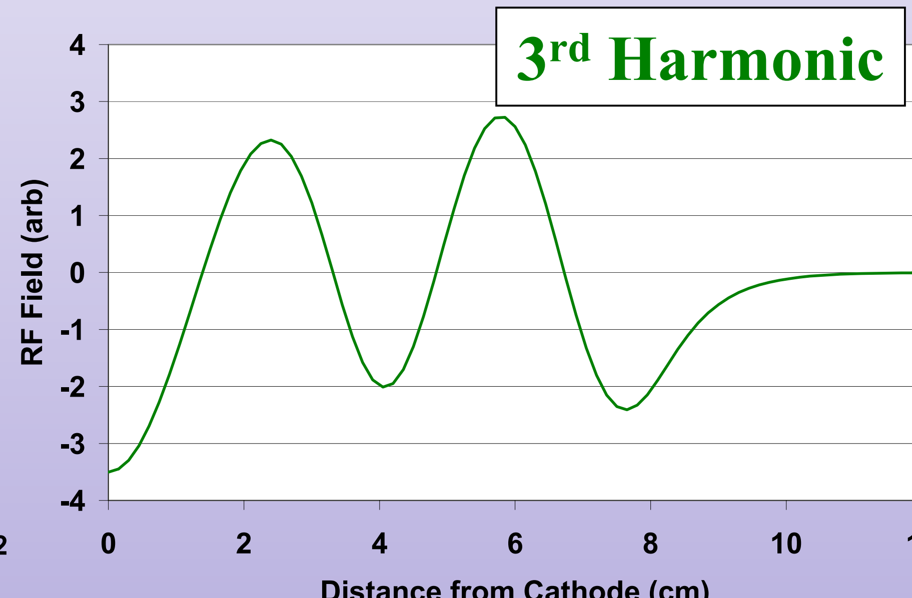
dowell@slac.stanford.edu

Superfish Generated RF Fields, Initial RF Gun Design by J. Lewellen

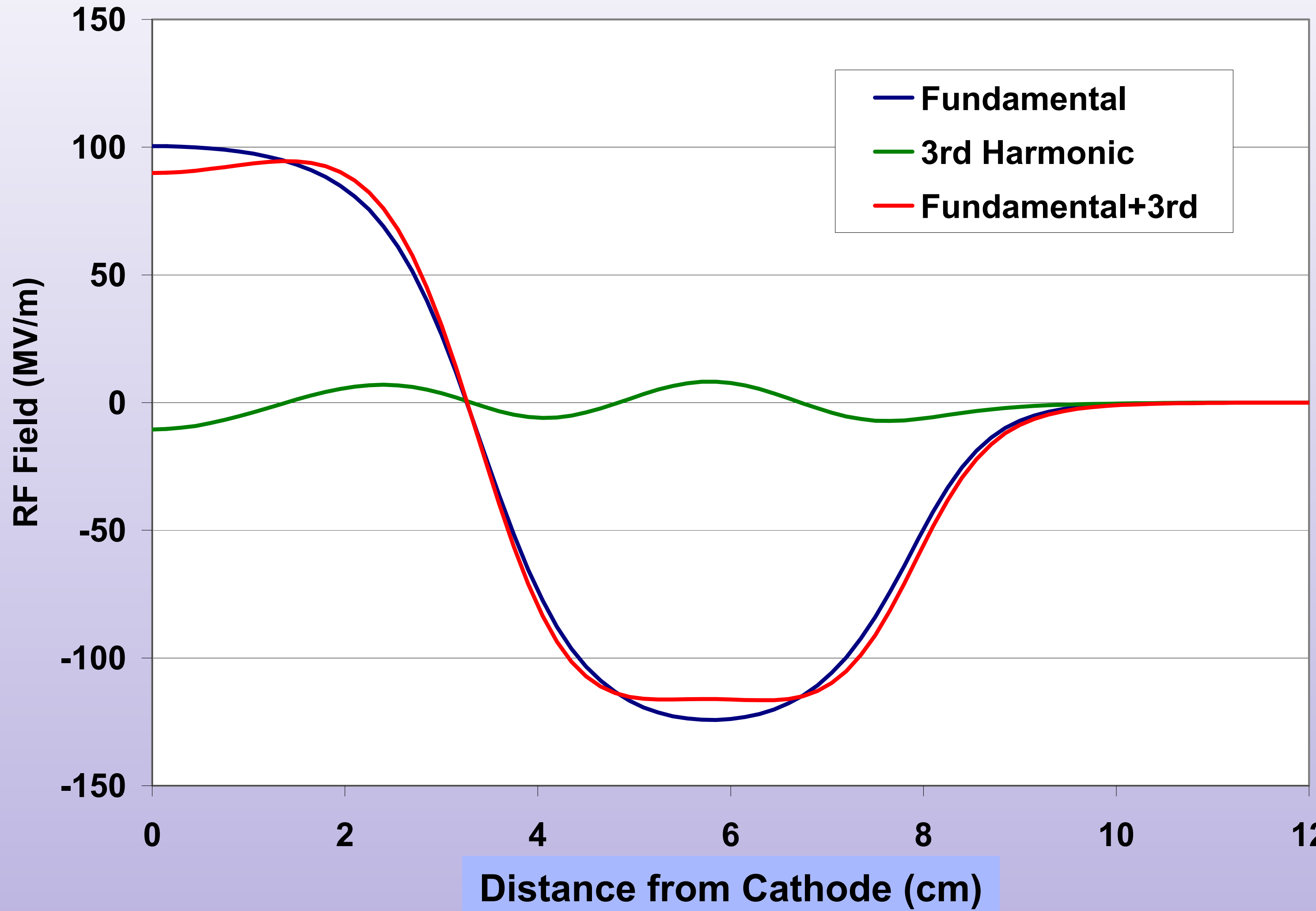








Superimposed Superfish RF Fields Used in 2f Parmela



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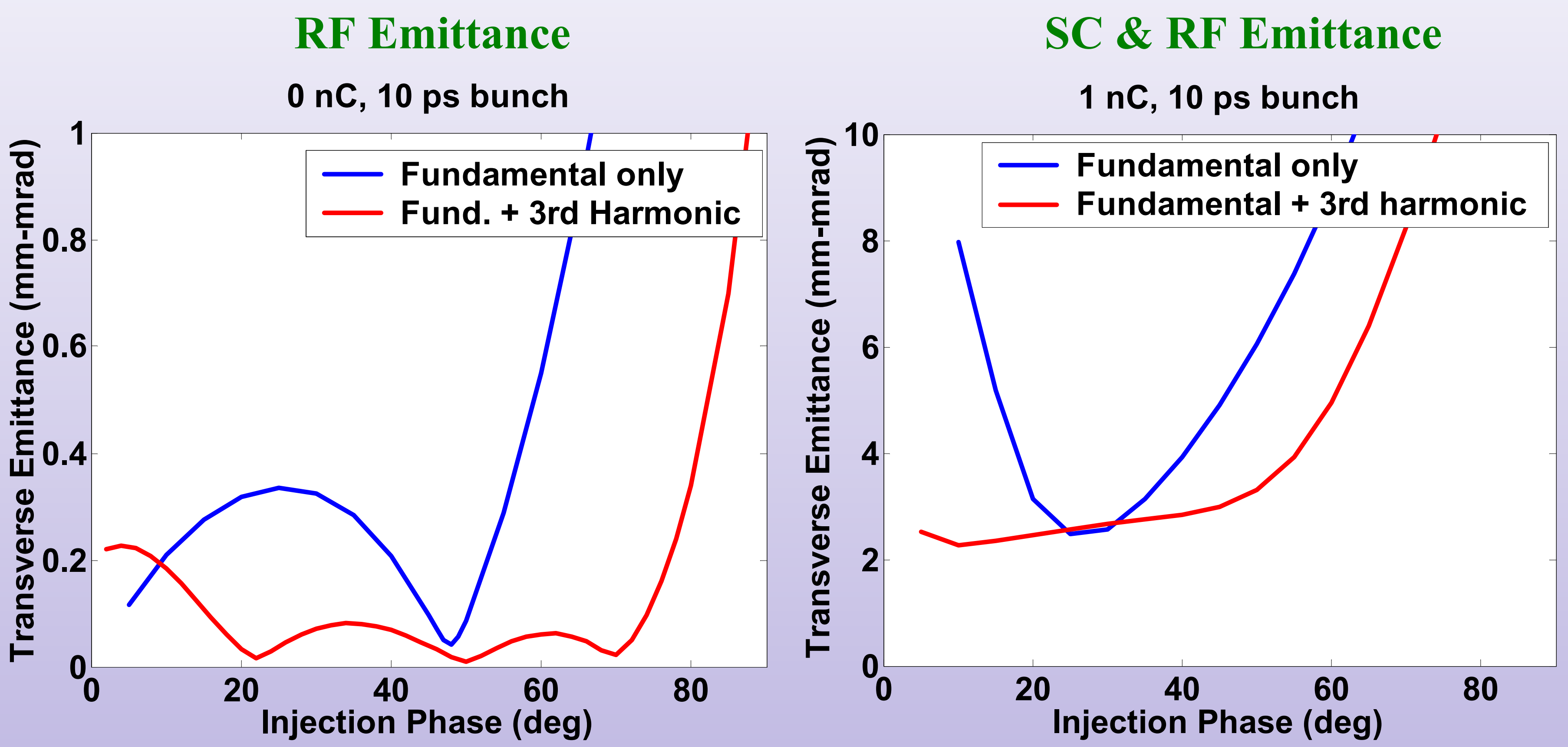
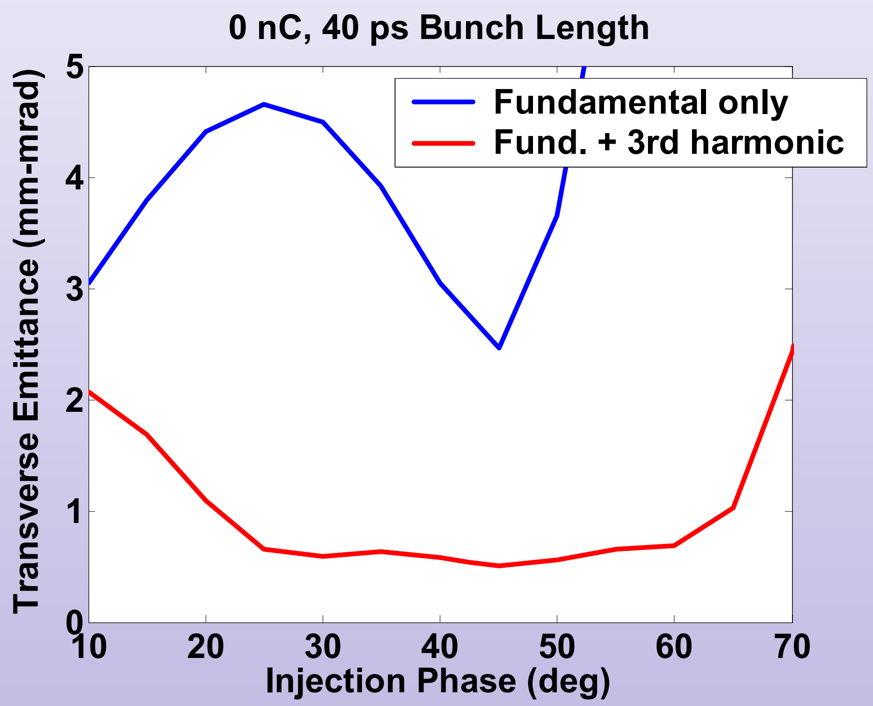
Short Bunch, Space Charge Dominated Regime

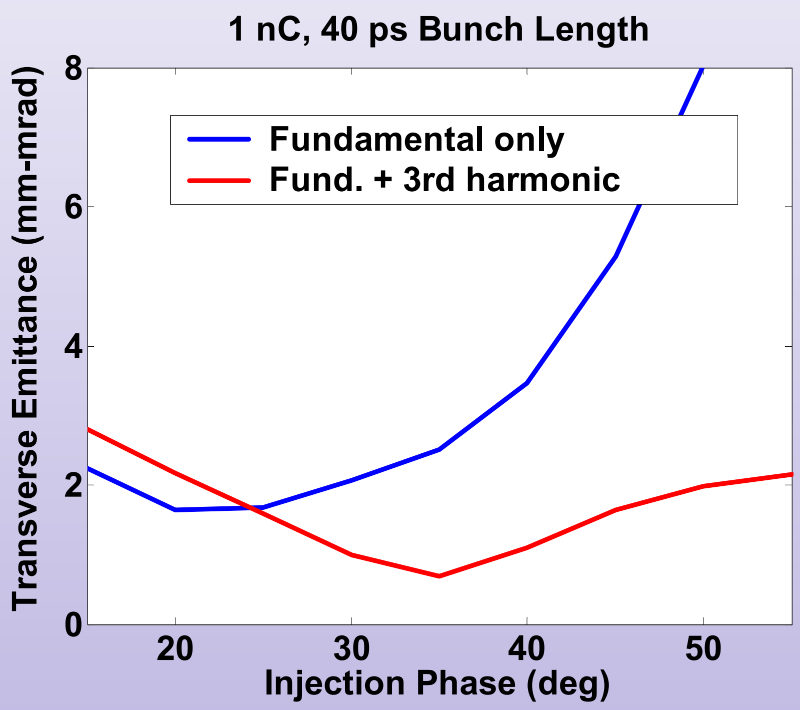


Long Bunch, RF Dominated Regime

RF Emittance



SC & RF Emittance



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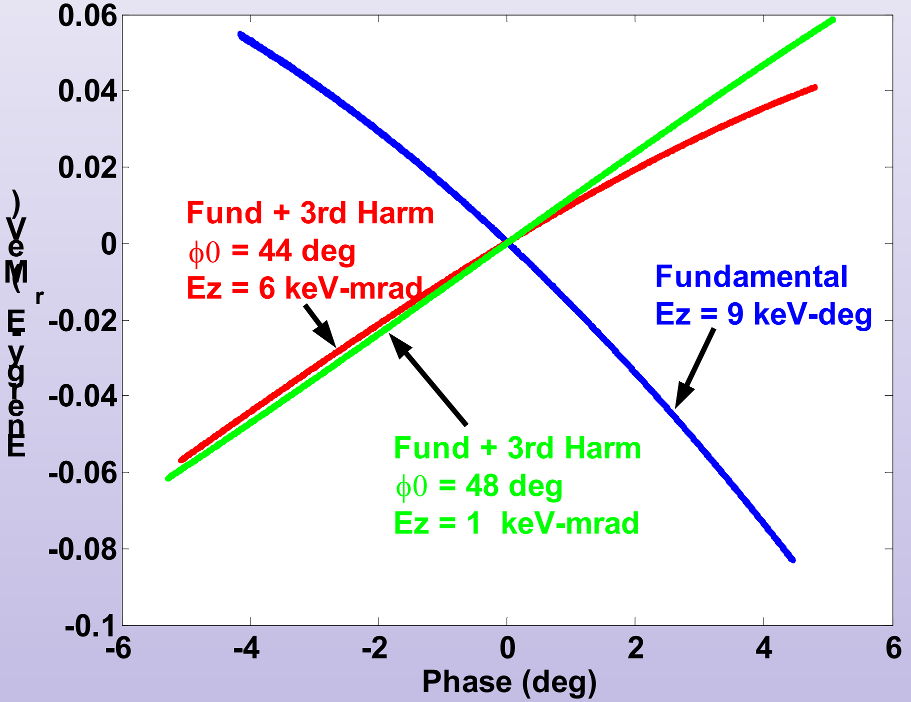
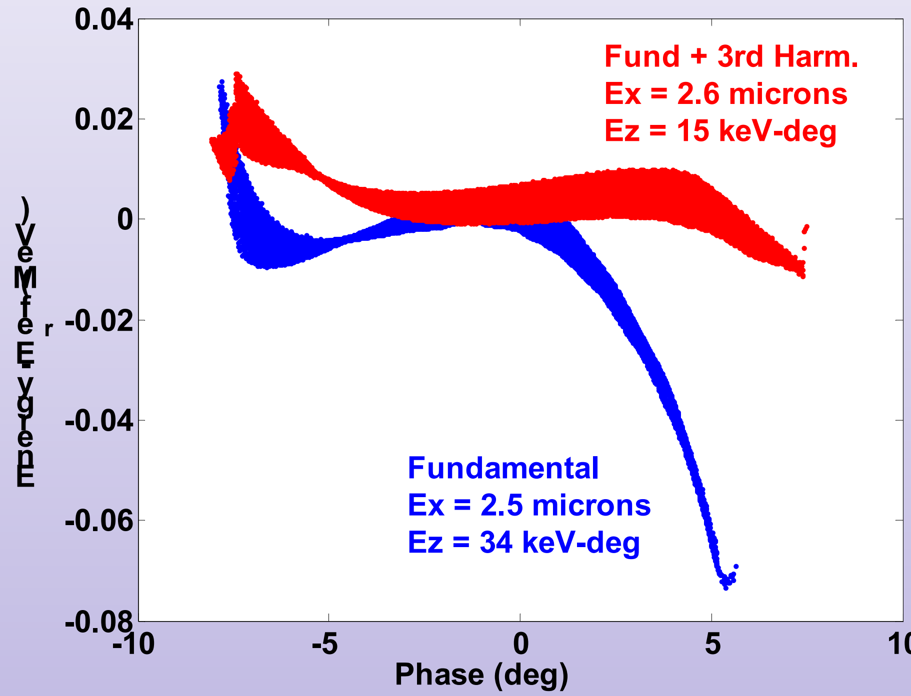
Longitudinal Phase Space for 10 ps Long Bunches

RF only

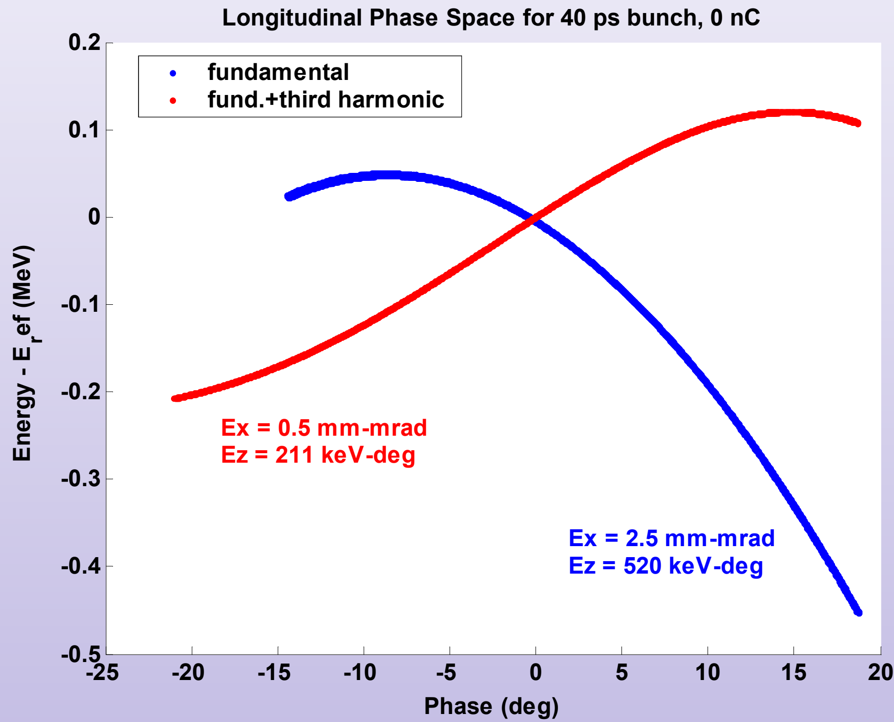


SC & RF

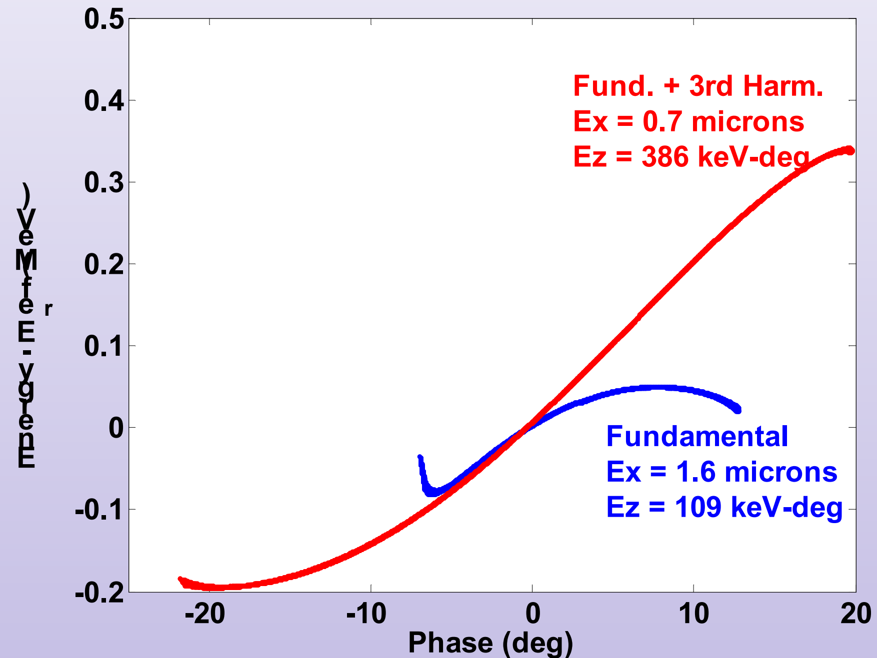


Longitudinal Phase Space for 40 ps Long Bunches

RF only

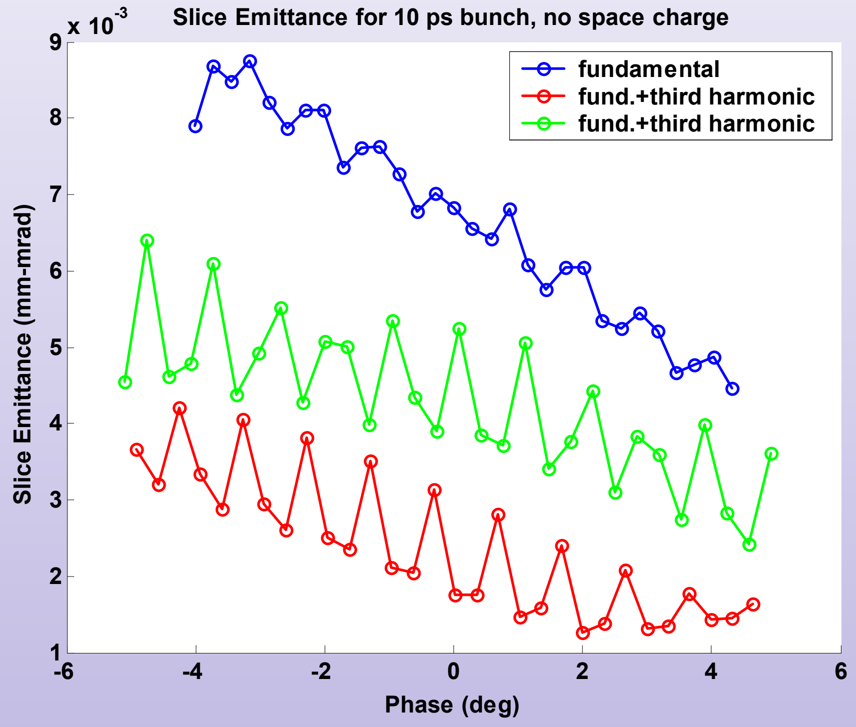


SC & RF

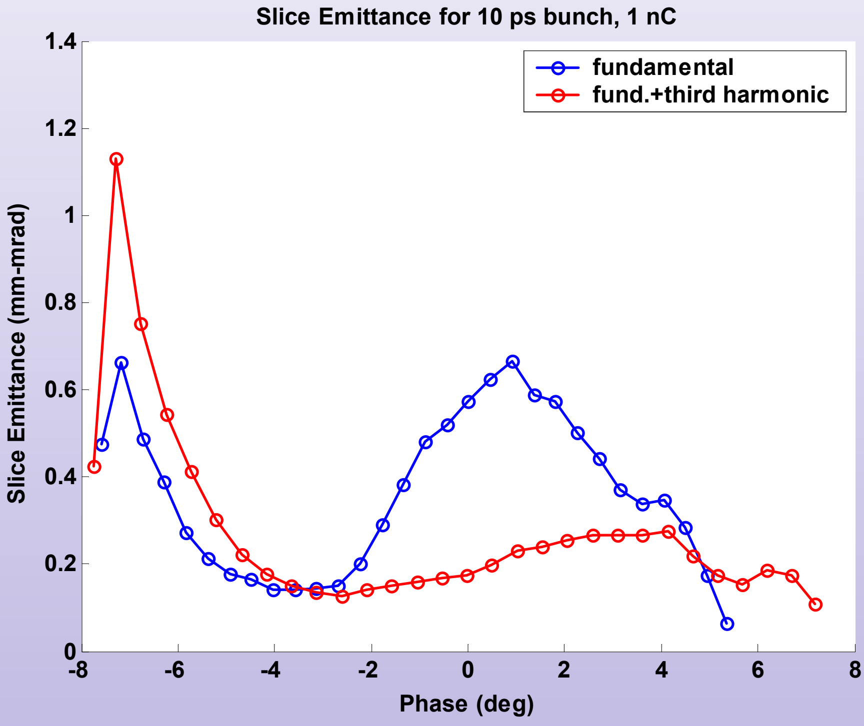


Slice Emittance for 10 ps Long Bunches

RF only

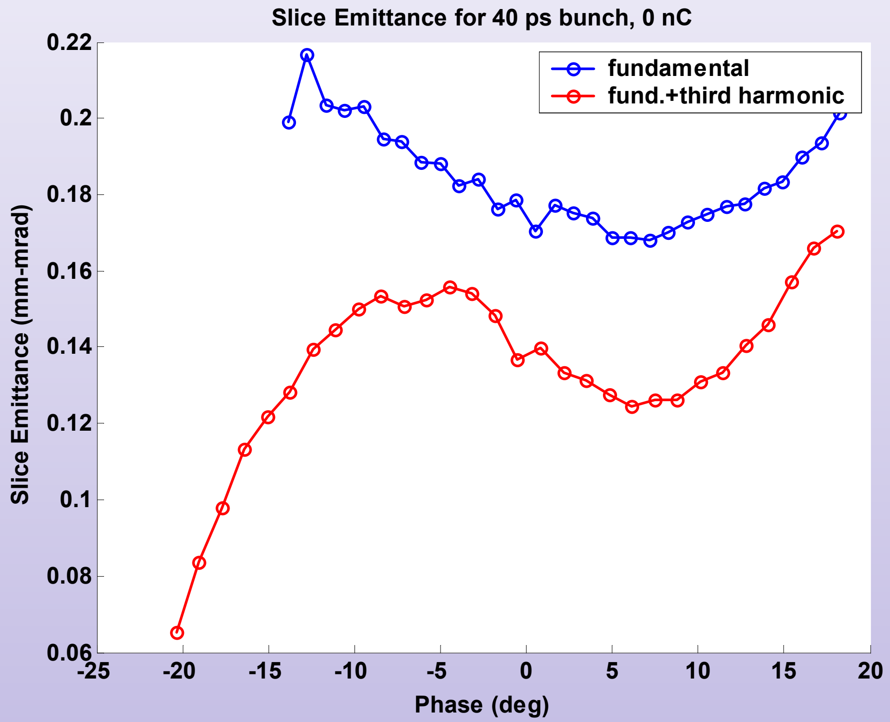


SC & RF

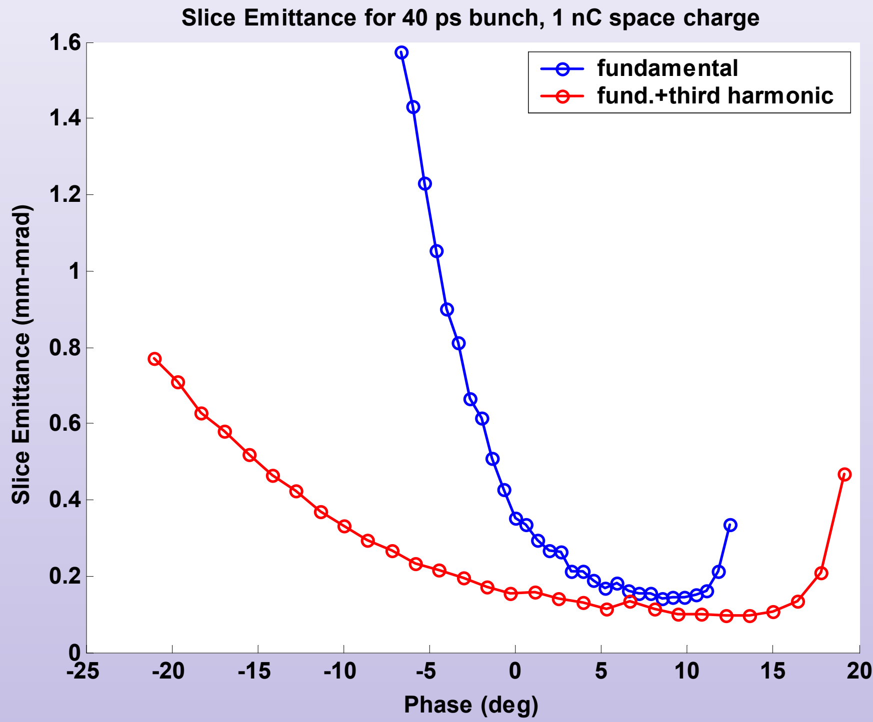


Slice Emittance for 40 ps Long Bunches

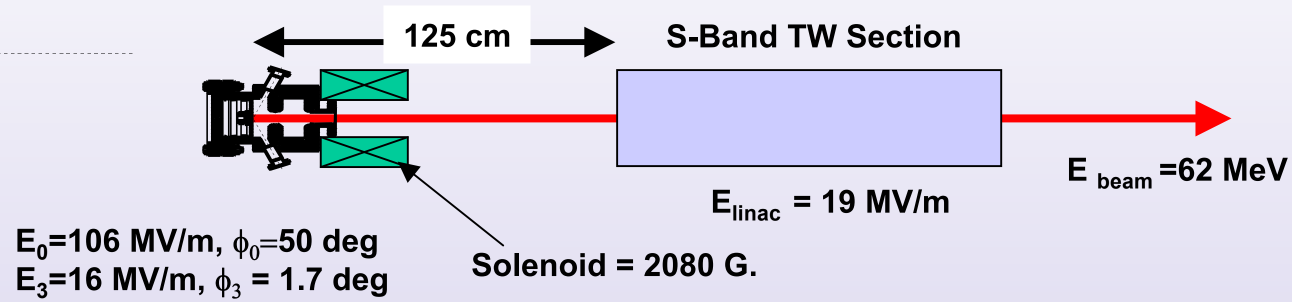
RF only

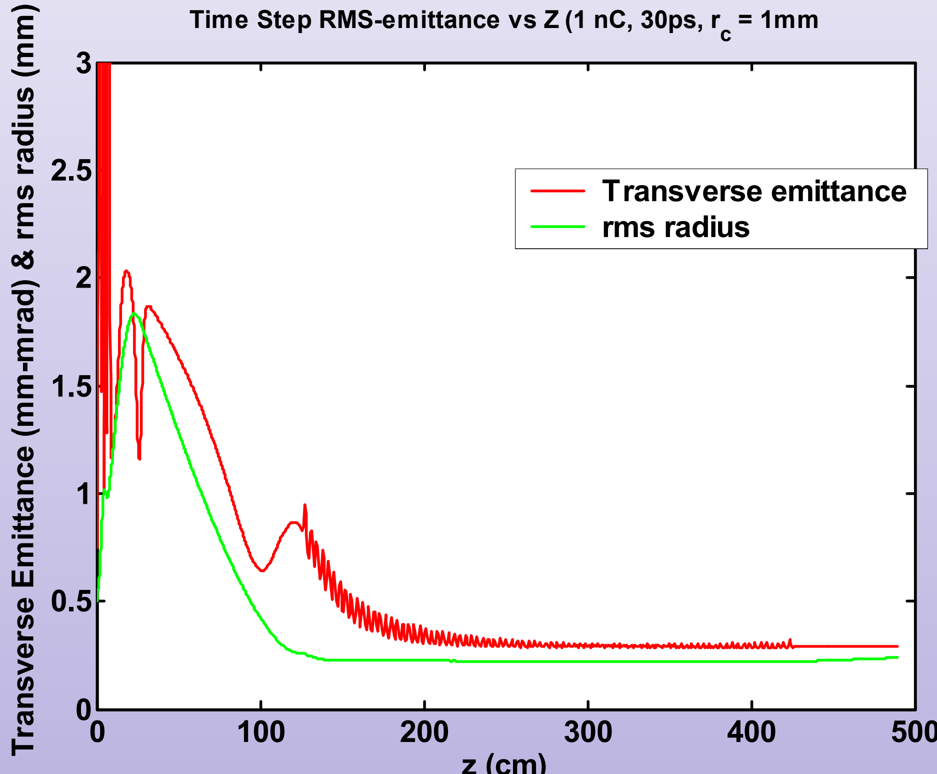


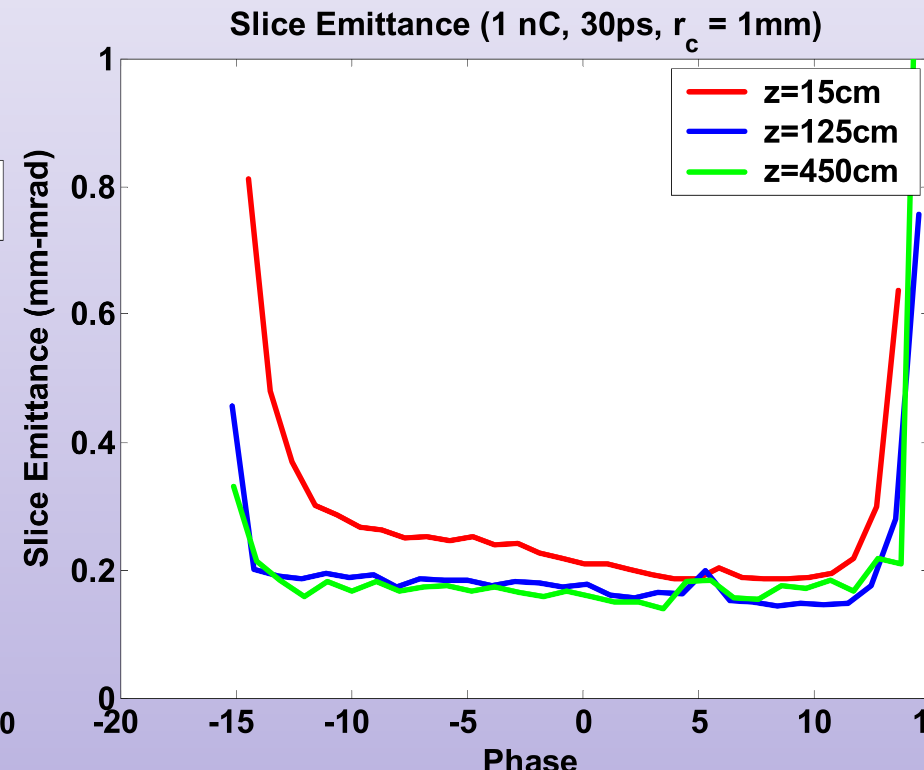
SC & RF



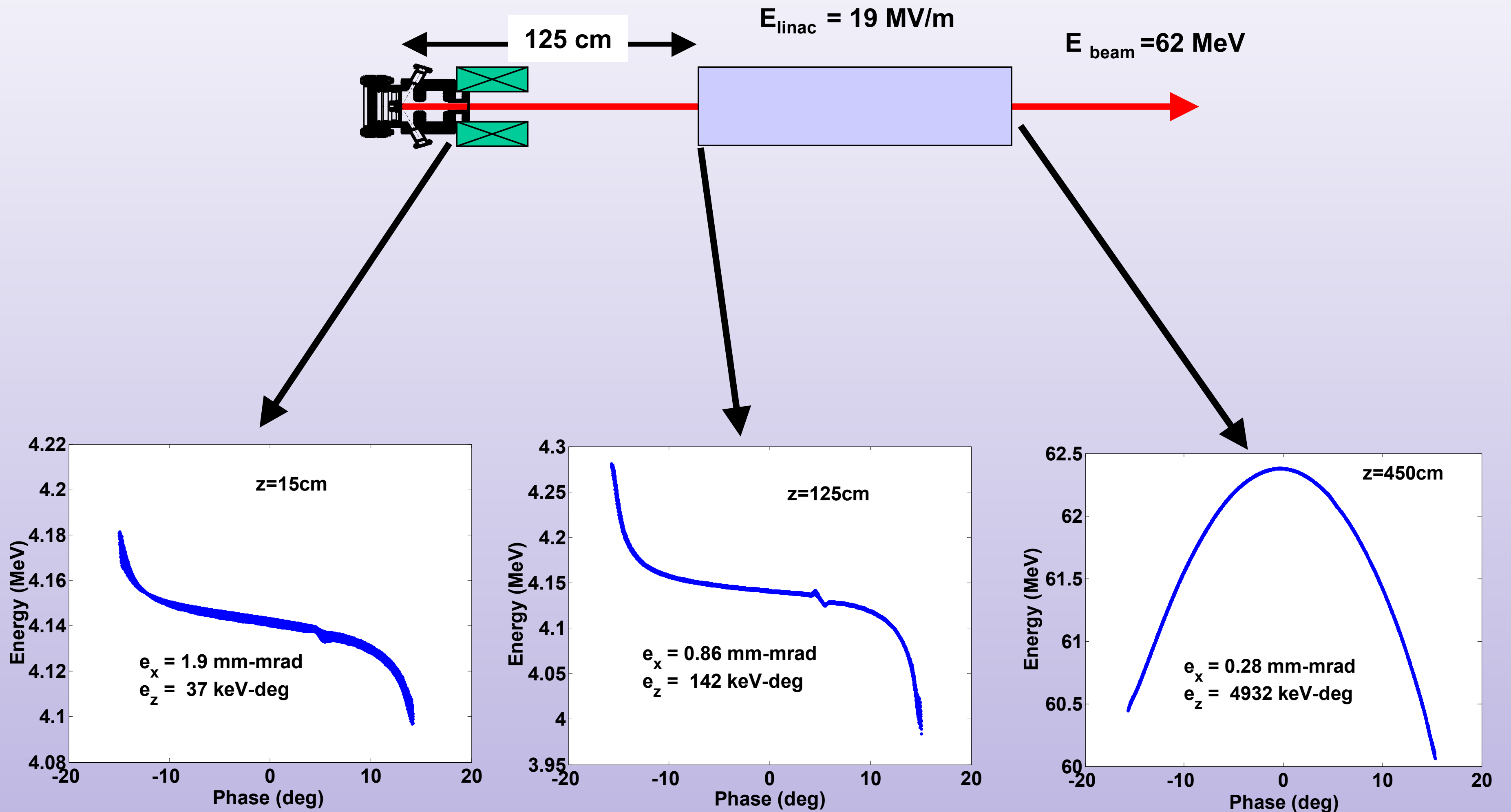
Two-Frequency Gun with Emittance Compensation







Longitudinal Phase Space



Summary and Conclusions

- Reviewed the Contributions to Emittance from the RF Gun
  - Regimes of RF and Space Charge Dominated Operation
- Described Serafini's Proposal for a Two-Frequency RF Gun
- Motivated new Parmela with superimposed fields in same cell
- Generated RF fields for a Realistic Two-Frequency Gun
- Parmela Simulations Verified the Advantages of the 2f Gun in the Long Bunch Regime
- Combined 2f gun with emittance compensation

  => Very low emittance!!
- Future Work Will:
  - Include thermal emittance
  - Improve the RF fields
  - Combine 2f gun with ballistic and rf compression
  - Consider a Separate Cavity for the 3rd Harmonic

- 2f Gun Similar to DC Gun