X-band Photoinjector Beam Dynamics

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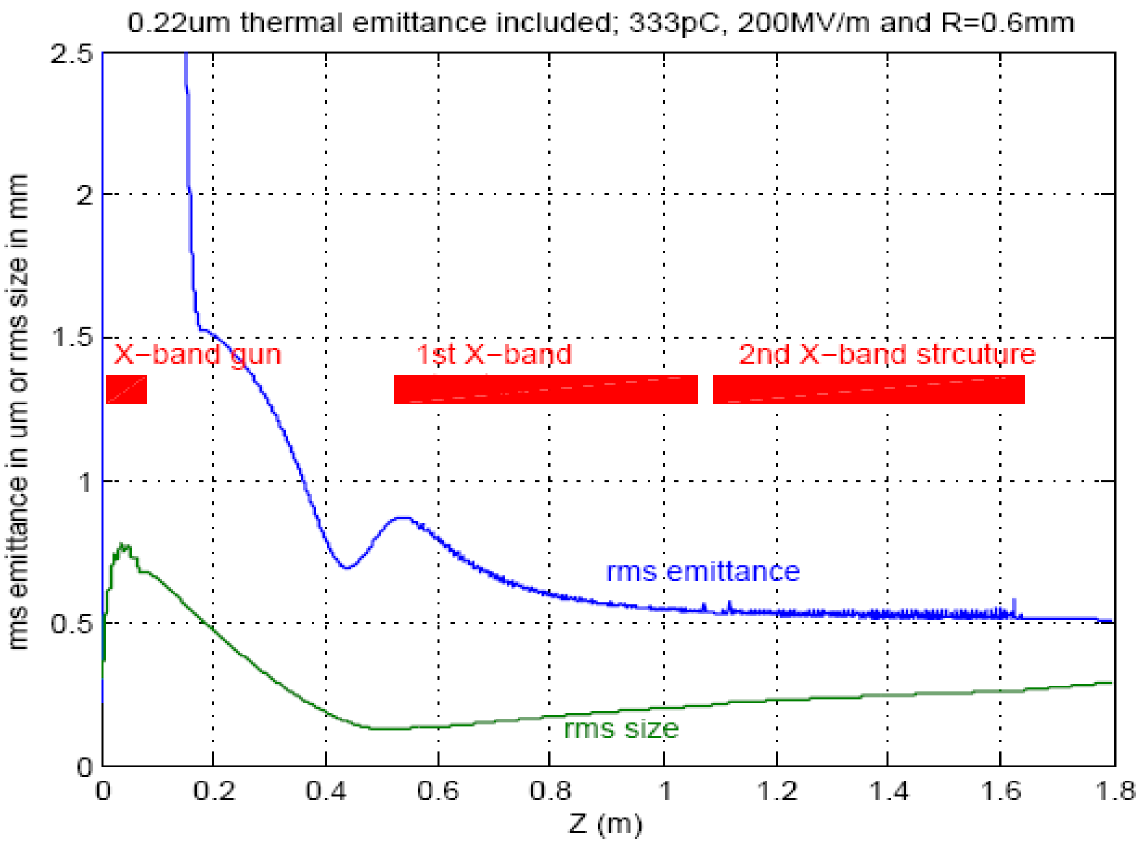
Why X-band photoinjector?

- Can operate at high gradient at least 200MV/m on cathode and 70MV/m at linac structures:
  - Advantages compared with low frequency RF gun:
    - Compact, and
    - Can produce and deliver shorter pulse from cathode, at least can save one BC for XFEL.
    - Lower emittance at low charge (@thermal emittance dominated)
  - SLAC ARD is currently collaborating with LLNL to develop a 250MeV X-band photoinjector for LLNL compact Compton source.
  - SLAC ARD is hoping to build a 300MeV X-band photoinjector at NLCTA to demonstrate high quality beam for future compact X-band FEL.
- But, some concerns on beam quality:
  - Emittance caused by RF field acceleration in X-band gun
  - Alignment , tolerance, and wakefield
  - RF quad field effect in the X-band couplers

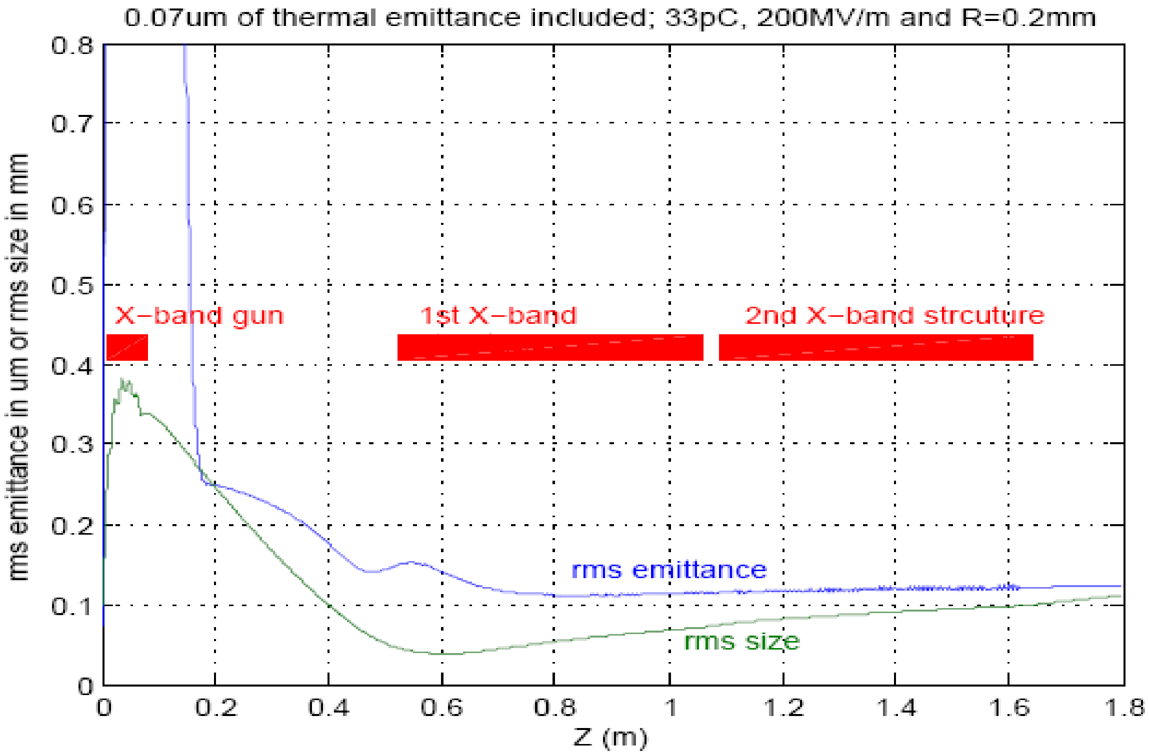
X-band injector – 333pC

- 5.5-cell X-band RF gun is designed by A. Vlieks (SLAC)
- 0.51μm rms emittance and 2.2ps FWHM simulated at 75MeV given on cathode: 333pc, 200MV/m , R=0.6mm uniform, ~2ps top flat and, 0.4ps rise and fall time respectively.
- Thermal emittance is included in the simulations.

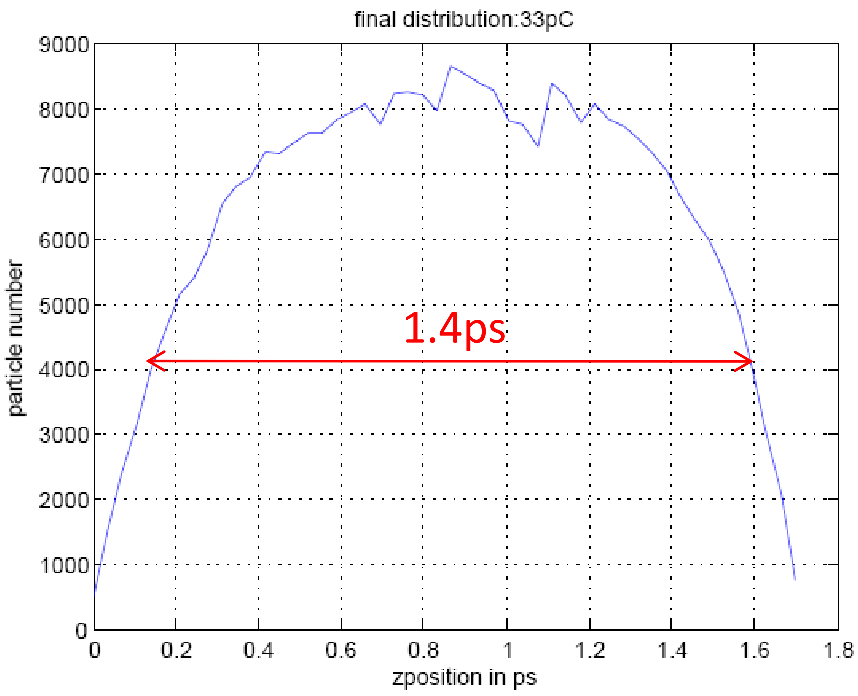


Low charge mode – 33pC @200MV/m

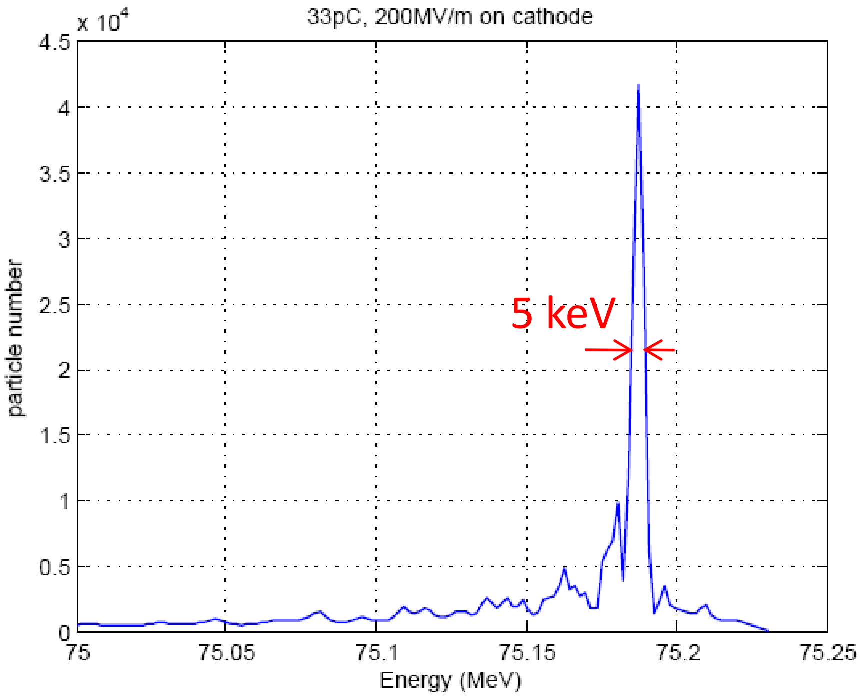
- Emittance 0.12μm rms (thermal included), short pulse 1.4ps FWHM, and energy spread 5keV FWHM @75MeV.
- Favors high gradient on cathode since the emittance caused by RF field acceleration in the gun is negligible due to its short pulse and small size. Emittance can be further improved with higher gradient.



Longitudinal phase spaces @33pC

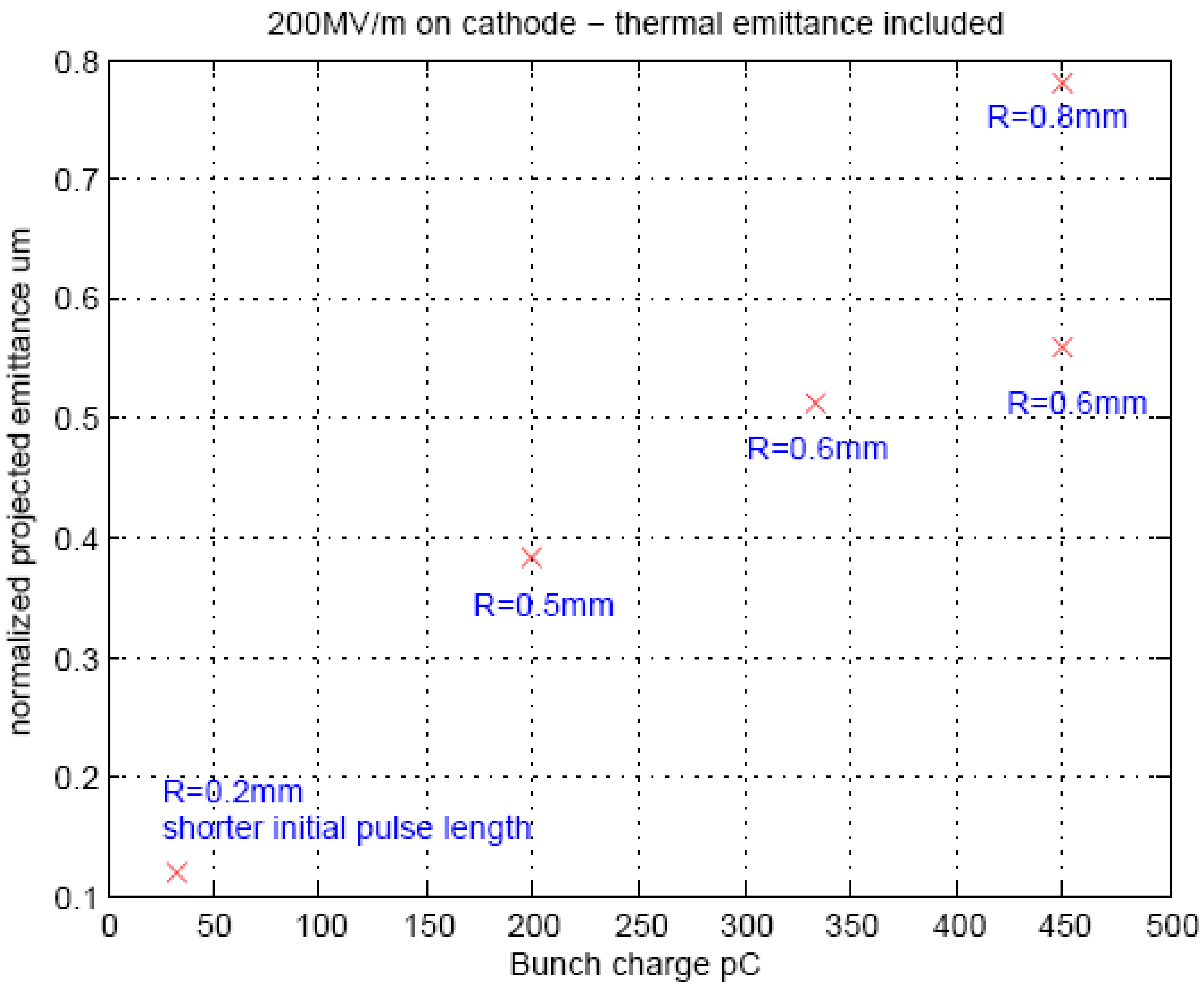


Bunch length

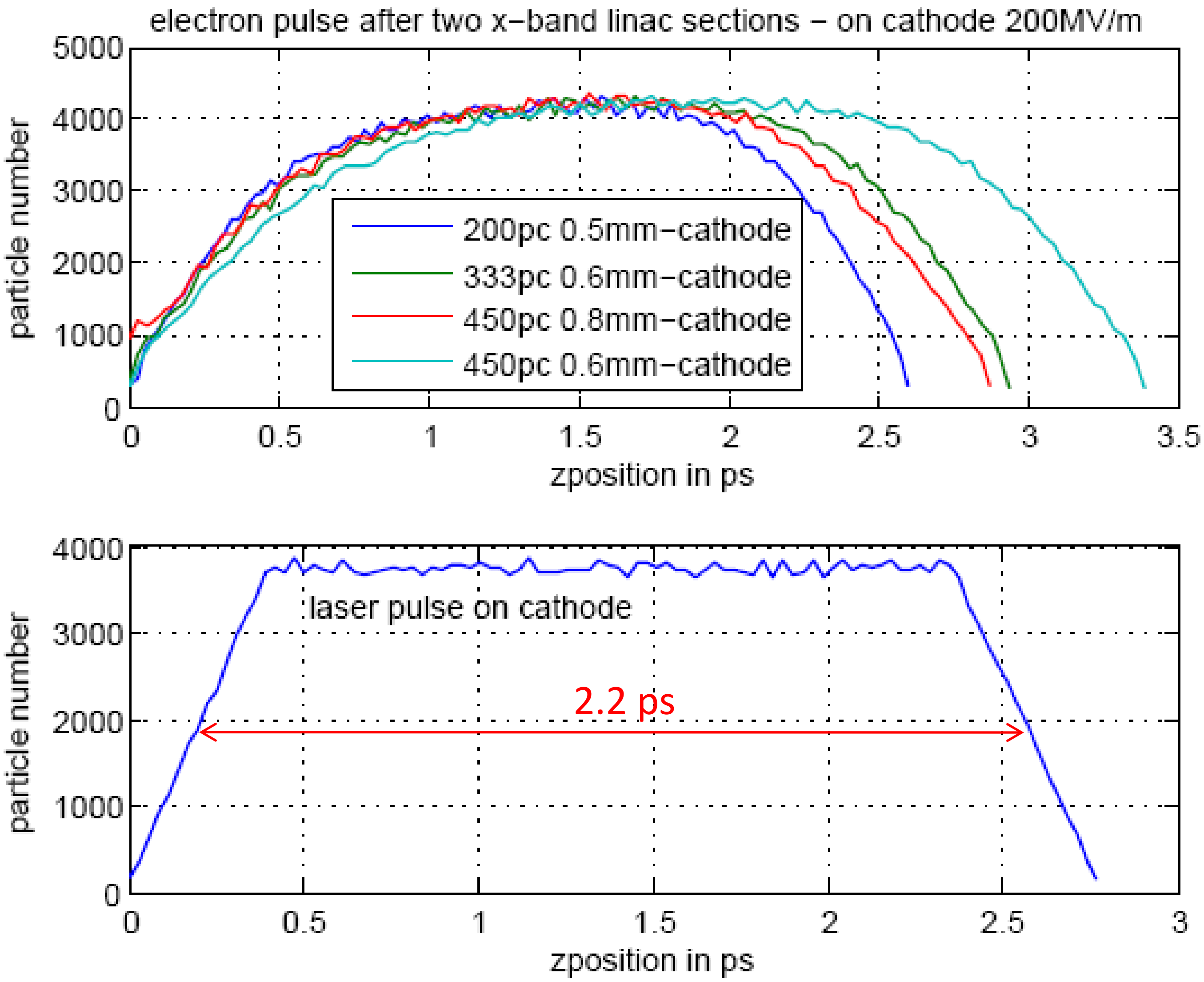


Energy spectrum

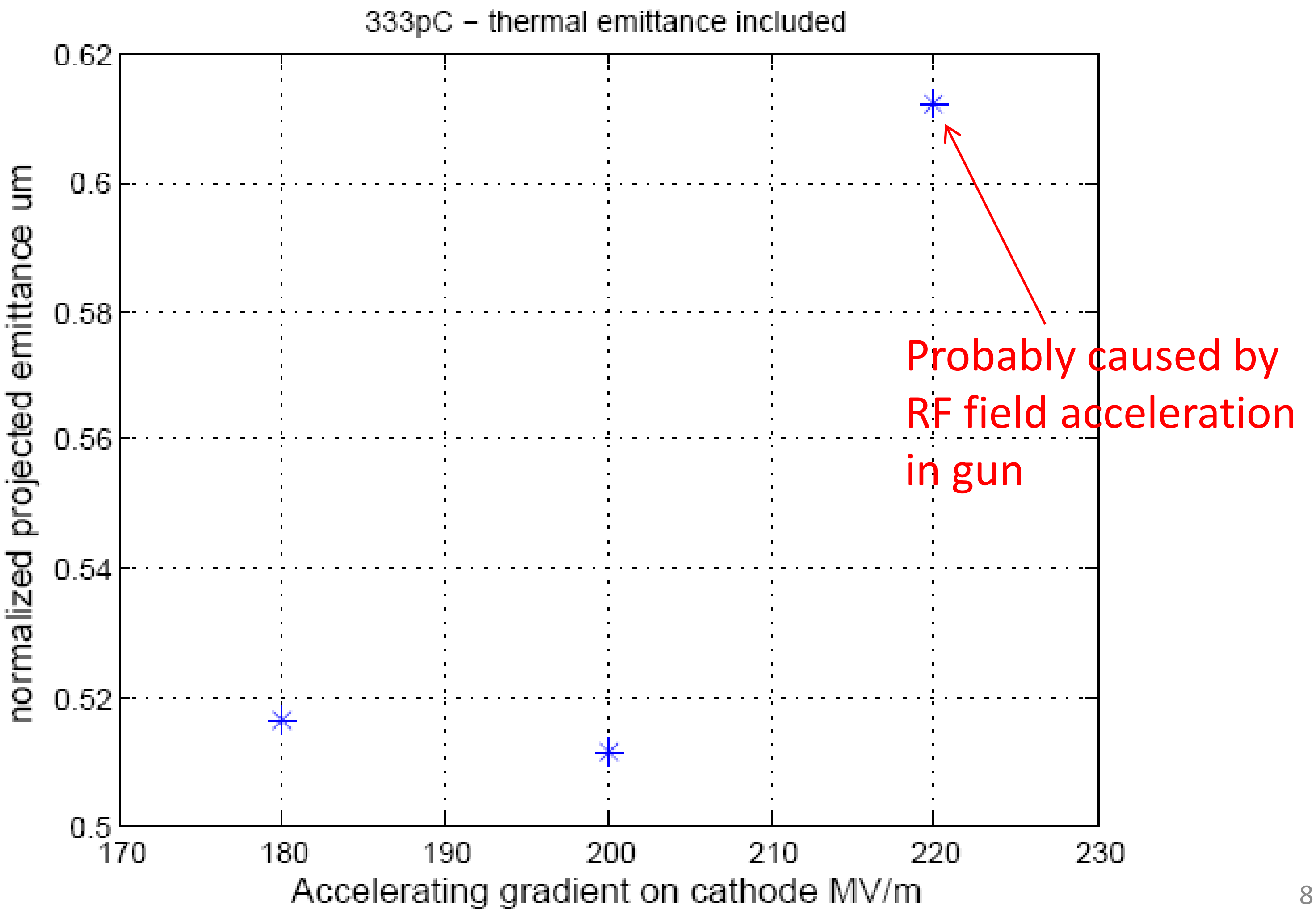
Variable charge: emittance @200MV/m on cathode (thermal included)



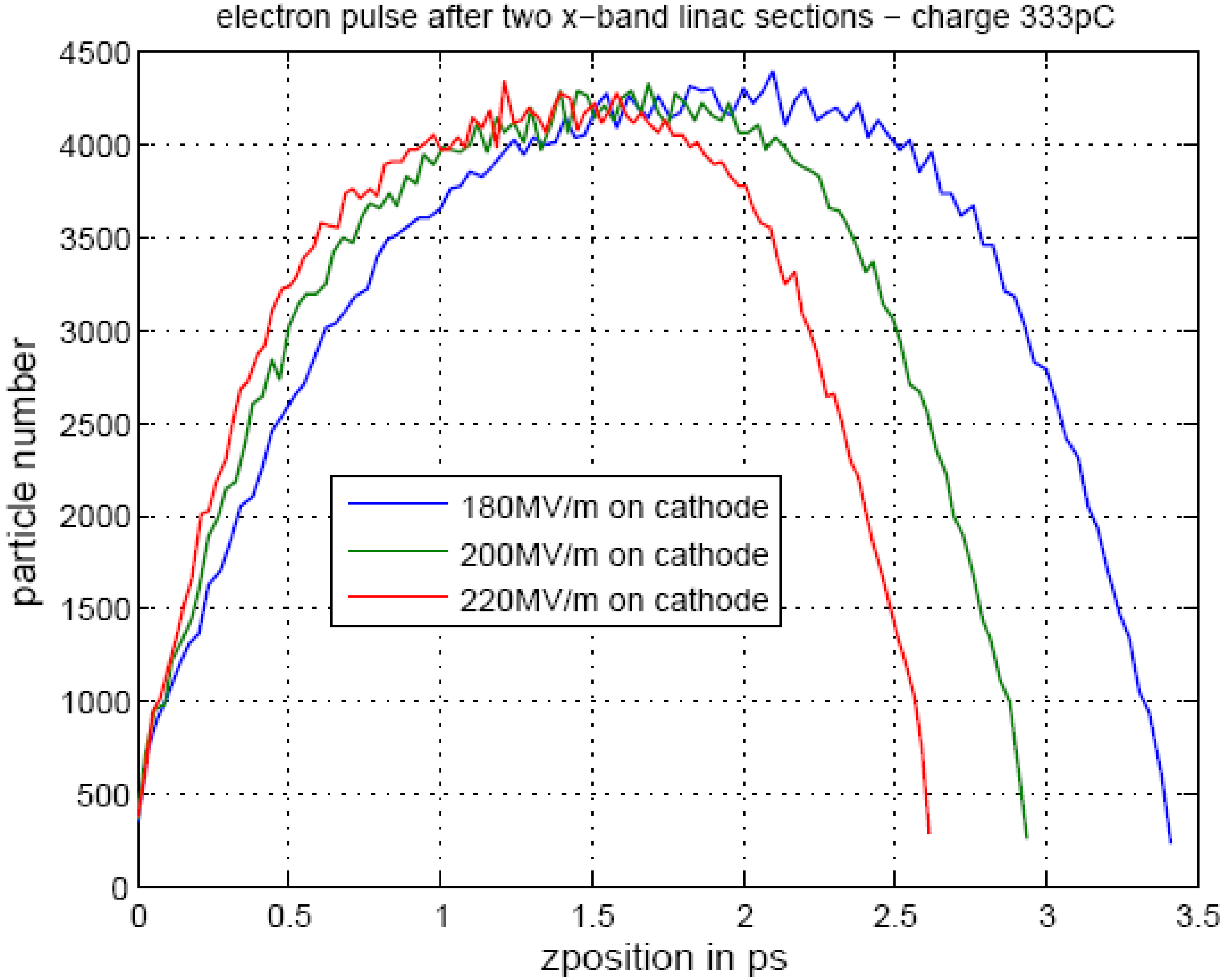
Variable charge: bunch length



Variable gradient: emittance @333pC (thermal included)



Variable gradient: pulse length



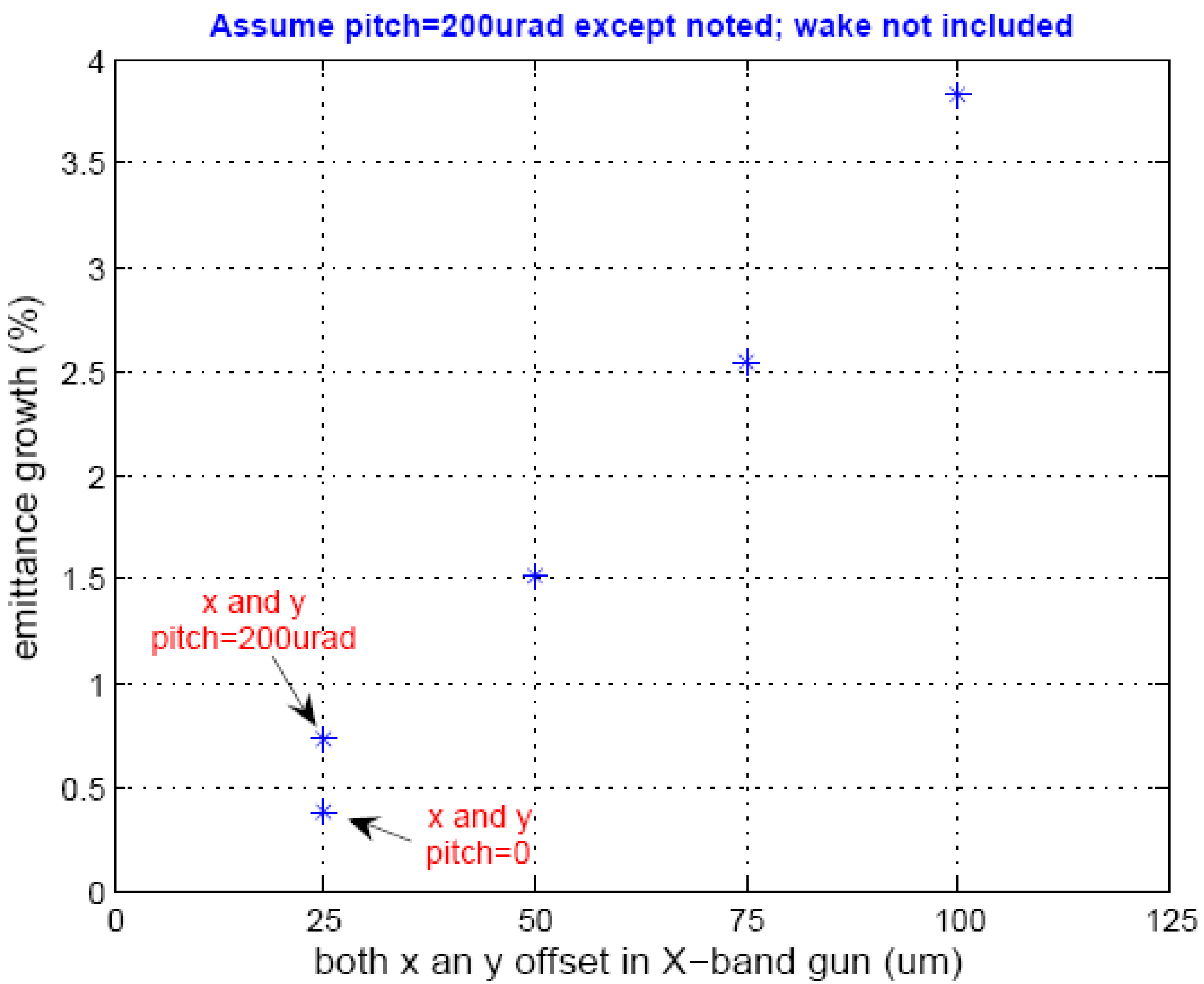
RF field acceleration in X-band gun

- RF acceleration in gun: longitudinal Gaussian distribution and, correlation of rf field and sc is not considered (K-J. Kim, NIM 1989):

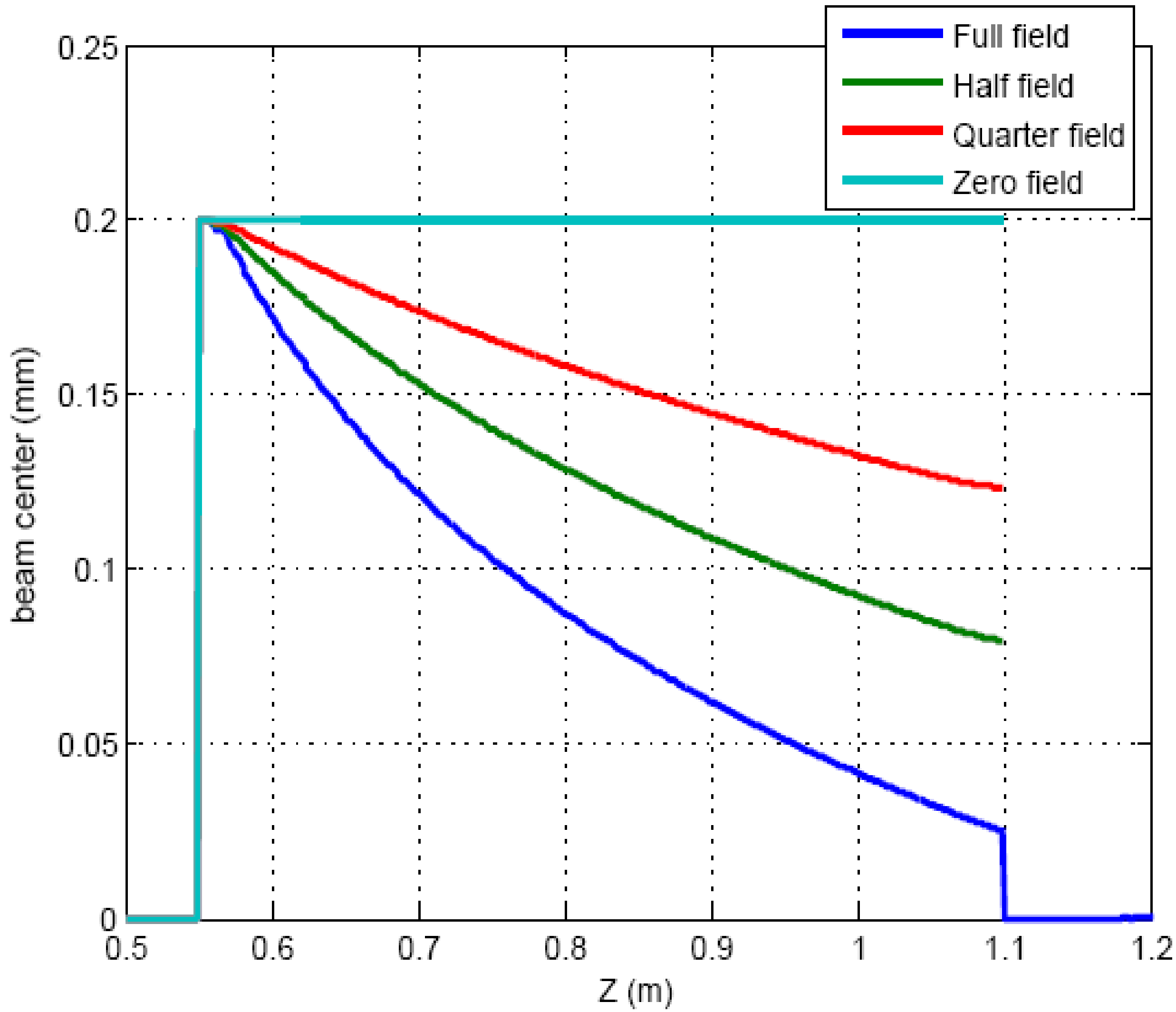
$$\varepsilon_x^{rf} = \frac{\alpha k^3 \sigma_x^2 \sigma_z^2}{\sqrt{2}} \quad \alpha = \frac{eE_0}{2mc^2 k}$$

- Given σ_x=0.7mm/σ_z=220μm (333pC),E_0=220MV/m, k=240/m, and α=0.897:
  - RF field emittance 0.2μm, not negligible
  - Thermal emittance 0.22μm
  - Simulated emittance 0.51μm@200MV/m, 0.61μm@220MV/m
- But, this effect is negligible in low charge (e.g. 33pC) at 200MV/m due to its short pulse and small size :
  - 0.0157μm by RF field, much smaller than thermal 0.074μm
  - Simulated emittance 0.12μm@200MV/m; it can be further improved with gradient higher than 200MV/m.

Tolerance in X-band gun (wake not included in the gun)

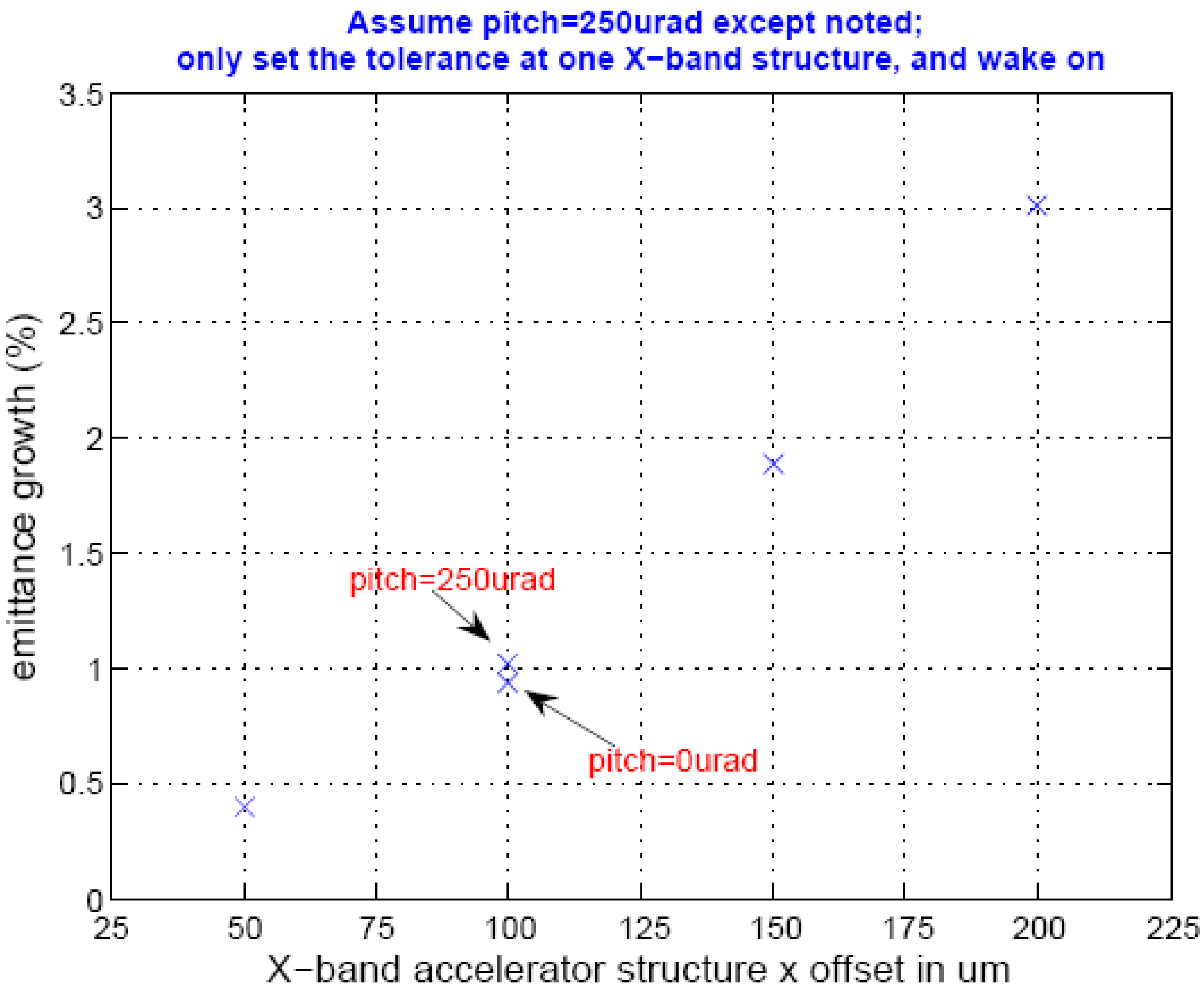


Tolerance in X-band accelerator: beam center vs accelerating field



Tolerance: X-band accelerator (wake included in one structure)

(note: the offset in the plot is at the entrance of the structure



Simulation vs analytical estimate

- X-band structure wake function (SLAC-PUB-9663, K. Bane):

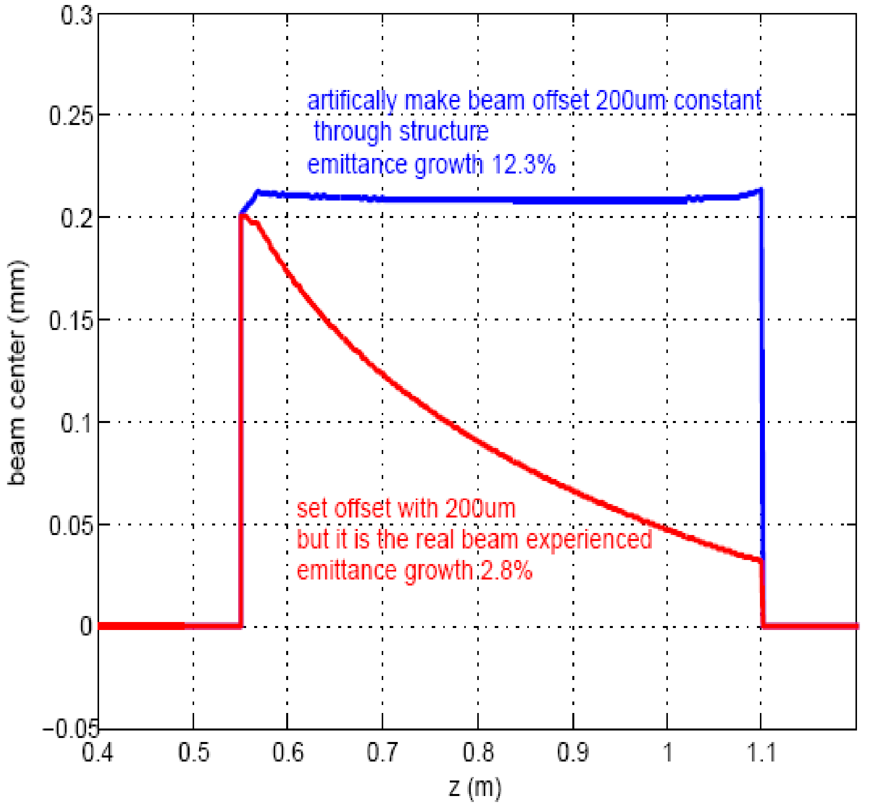
$$W_{\perp} = \frac{4 z_0 c s_0}{\pi a^4}\left[1-\left(1+\sqrt{\frac{s}{s_0}}\right)\exp\left(-\sqrt{\frac{s}{s_0}}\right)\right]$$

$$s_0 = 0.169\frac{a^{1.79} g^{0.56}}{L^{1.17}}$$

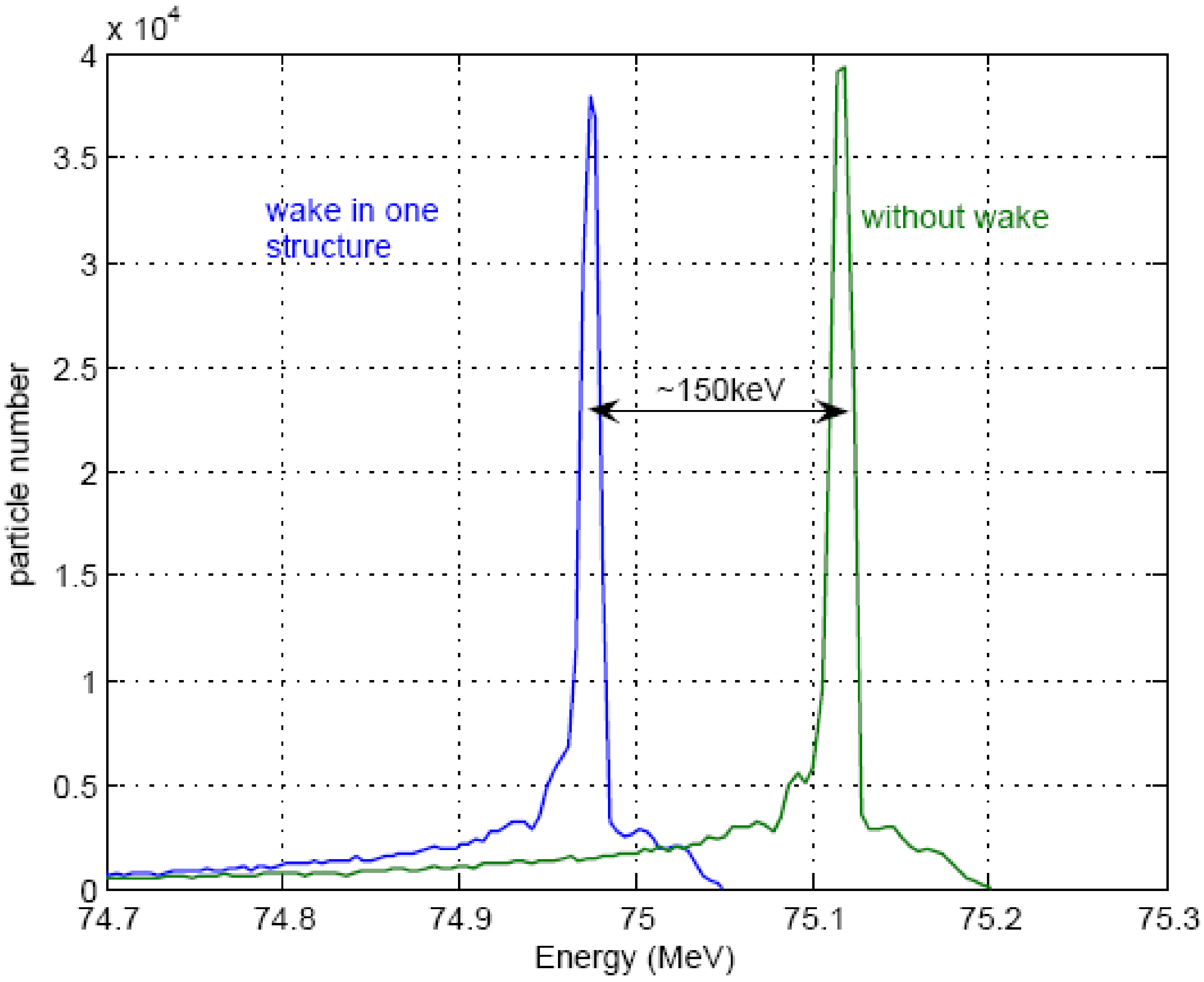
- Divergence caused by the wake:

$$x' = \frac{\int eq\cdot\Delta x\cdot W_x dz}{E} \approx \frac{eq\cdot\Delta x\cdot W_x\cdot l}{E}$$

- For 1/3nC charge, 200 μm constant offset, emittance growth 34% (analytical estimate) vs 12% (ImpactT simulation).

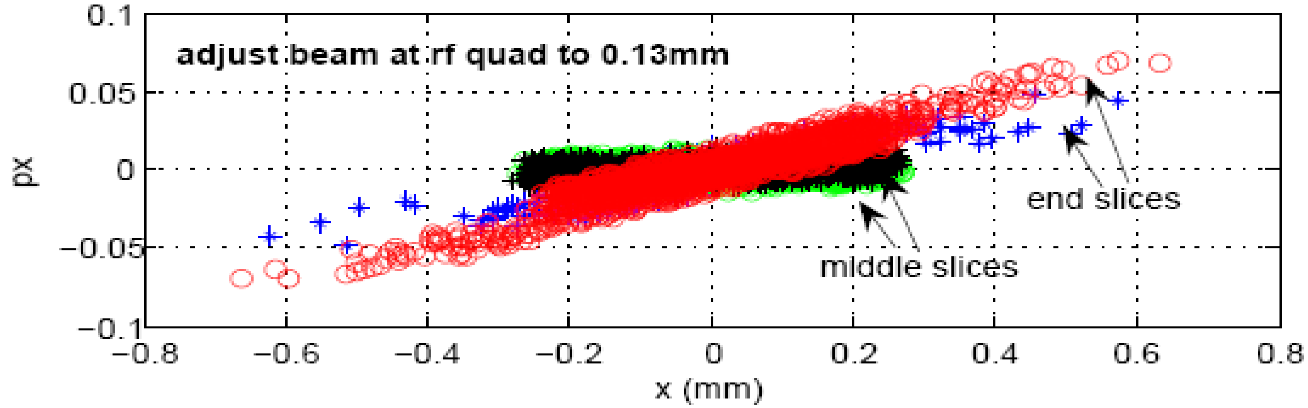


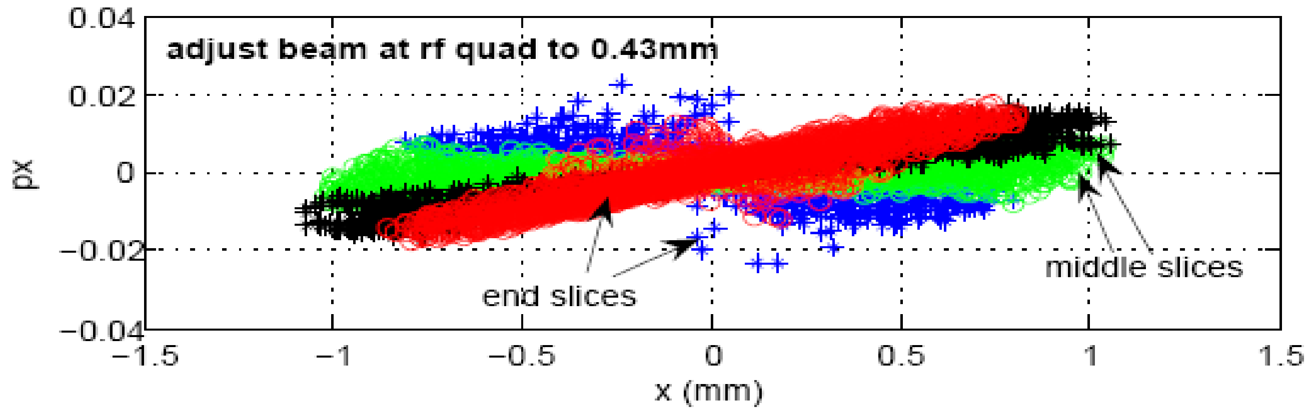
Beam loading in one structure (@333pC)



Understanding RF quadrupole effects @(∂B/∂x)*L=0.5T

- Dual feed couplers break the azimuthal symmetry and induce quad field component in the coupler cell.





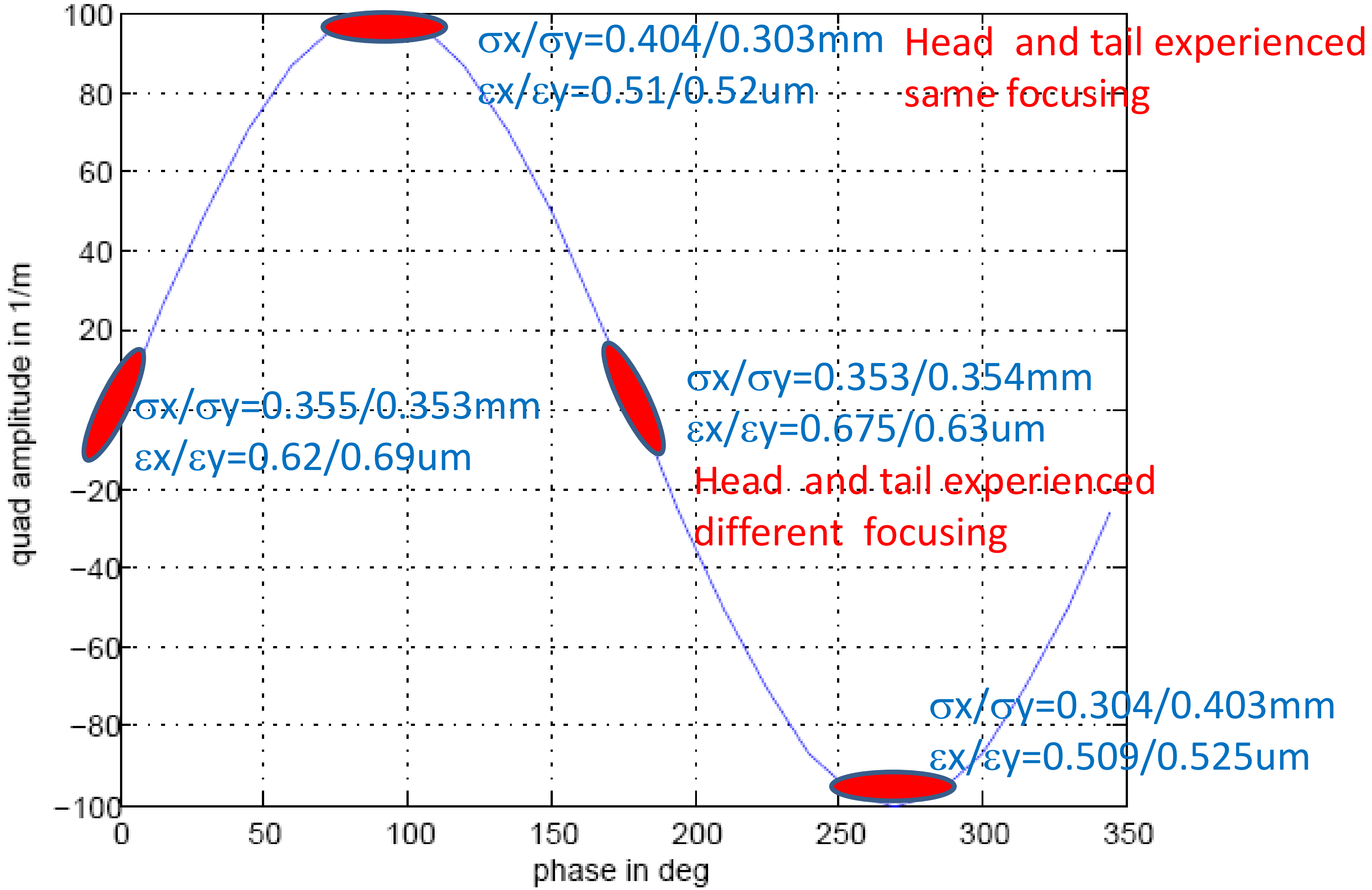
RF quad effects: Analytical vs ImpactT simulations

- The worst case for the emittance growth doesn’t happen on crest of peak quad field but at zero-crossing.
- Additional divergence caused from RF quad is calculated:

$$\delta x' = \frac{p_x}{p_z} = \frac{m_0 c \left(\frac{\gamma \beta_\perp}{x_0} \right) x_0}{m_0 c \lambda} = \frac{\left(\frac{\gamma \beta_\perp}{x_0} \right) x_0}{\gamma}$$

- Assume beam center is at zero-crossing and 5˚ half beam length, i.e., ~2.5˚ rms RF phase. The actual beam experienced RF quad field is 0.5T*sin(2.5˚):
  - For 0.135mm: 3.5% (analytical), 6% (ImpactT)
  - For 0.43mm: 210% (analytical), 180% (ImpactT)
- Beam effects strongly depends on beam size and field strength

Beam effect vs RF quad phase



Without rf quad: σx/σy=0.354/0.353mm
εx/εy=0.51/0.52um

RF quad effects at X-band couplers

	S-band	X-band (70MV/m)
Mode-Launcher	20/m	100/m?
Cylindrical	4.5-5/m	26.6/m
Racetrack	1/m	3.6/m

- Zenghai Li (SLAC) simulated RF quad components in the S- and X-band linac couplers and also reduced the RF quad strength $((\partial B/\partial x)*L)$ in X-band linac coupler to 0.006T using racetrack coupler cells.
- Simulations show that additional focusing and emittance growth from the racetrack linac couplers is negligible.
- Is evaluating RF quad in X-band gun coupler (by Z. Li) and its beam effect

Summary

- X-band photoinjector (75MeV) with 200MV/m cathode provides:
  - Rms normalized emittance 0.5μm@333pC and 0.12μm@33pC (thermal emittance included). Low charge emittance can be further improved with higher gradient.
  - Short pulse 1.4-2.2ps FWHM, and narrow energy spread 5-15keV FWHM@75MeV.
- RF acceleration effect in high gradient gun (200MV/m):
  - For 333pC, RF field induced emittance is observable, comparable to thermal emittance
  - For 33pC, RF field induced emittance is negligible compared with thermal emittance due to its short pulse and small size. For low charge its emittance can be further improved with gradient >200MV/m.

Summary (con't)

- RF quad induced emittance strongly depends on beam size and field strength:
  - With racetrack couplers in X-band linac structures, the emittance growth and additional focusing from RF quads is negligible.
  - RF quad in gun coupler is being evaluated
- Tolerances to control emittance growth below 1% from each component:
  - X-band gun 25μm/200μrad (wake not included yet)
  - X-band accelerator structure 100μm/250μrad (wake included)
- Beam loading is 150keV from each structure@333pC
- Next work:
  - 3d field (X-band gun + X-band structures) tracking
  - Setup full beamline to 300MeV and multi-particle track
  - Try to include everything (various errors) in the simulations