On The Importance of Symmetrizing Coupler Fields for Low Emittance Beams

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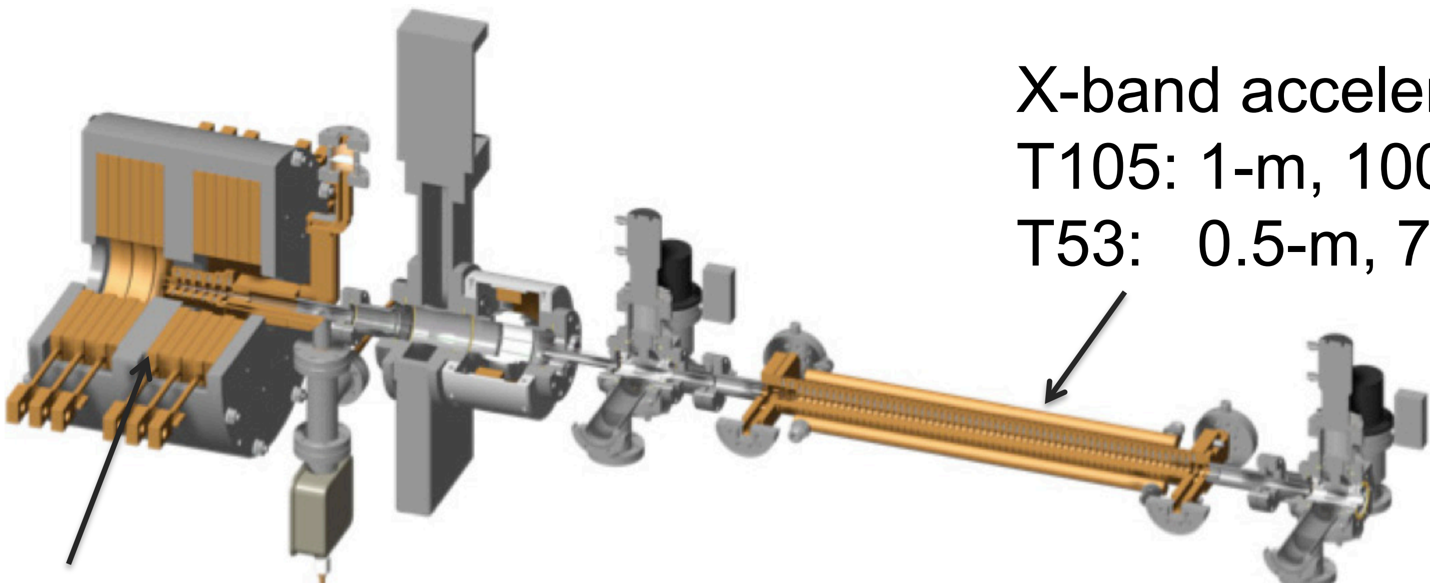
Outline

- Proposed X-Band photo injectors
- Coupler multipole field analysis
- Effect of dual-feed cylindrical cell coupler
- Symmetrized dual-feed coupler
- Summary

X-Band Injectors

- LLNL Mega-Ray: 250 MeV
- SLAC XTA: 100 MeV
- Beam Emittance: 0.4 mm.mrad

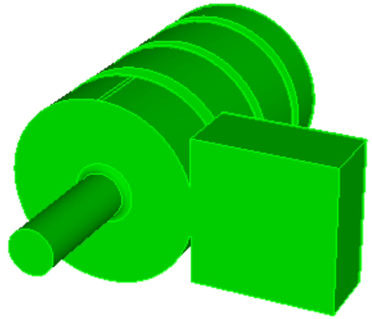
X-band accelerator:
T105: 1-m, 100MV/m
T53: 0.5-m, 70MV/m

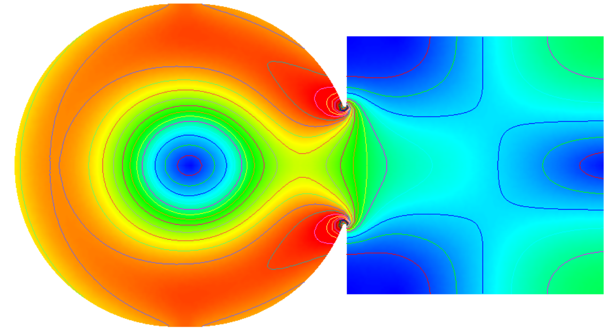


5.6-cell X-band Gun:
Cathode field 200MV/m

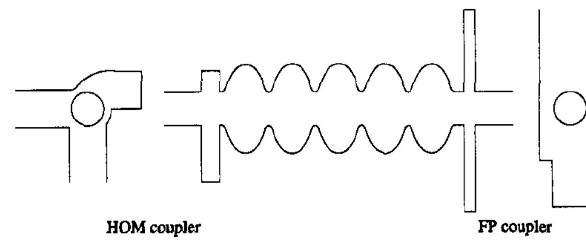
Coupler Break Field Symmetry

- NC structure

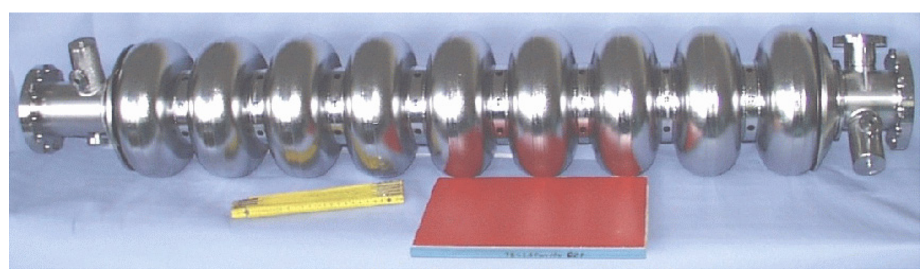




- SCRF cavity
  CEBAF 5-cell
  FPC, HOM

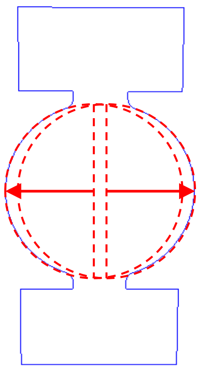


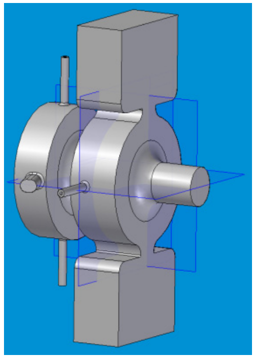
- ILC 9-cell
  FPC, HOM

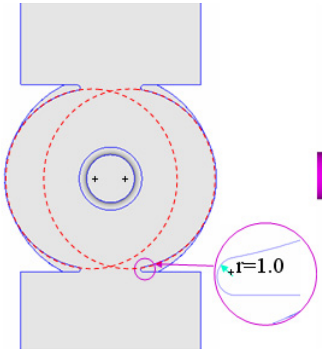


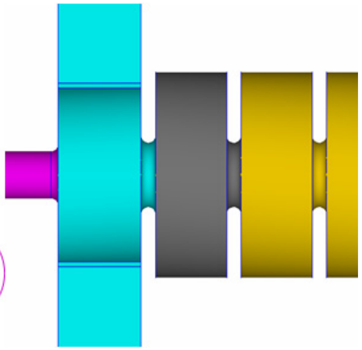
Example: LCLS Injector RF Gun & Structure

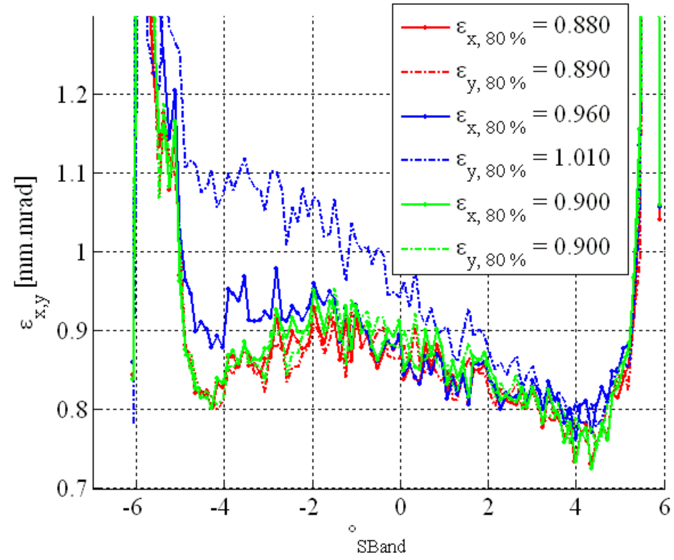
- Without quad compensation – significant head-tail emittance growth
- With symmetrized coupler, emittance growth negligible











Emittance along bunch without coupler summetrizing (C.Limborg)

Multipole Fields In X-band Structutrrs

- Multipoles are potential source of emittance growth
- X-band photo injectors
  - higher frequency
  - higher gradient
  - possiblly higher multipole fields due to the RF couplers
- Important to minimize such fields in the design

Multipole Analysis

- Equation of motion:

$$E_z(r,\theta,z,\zeta_z) = \sum_{m=0}^{\infty} A_m J_m(\eta_r r)\cos(m\theta)e^{-j\zeta_z z} + \sum_{m=0}^{\infty} B_m J_m(\eta_r r)\sin(m\theta)e^{-j\zeta_z z}$$

- Panofsky-Wenzel theory

$$\Delta(\gamma\vec{\beta}_{m\perp}) = -\frac{ie}{m_0 c\omega}\nabla_\perp \int E_z(r,\theta,z)e^{i\omega z/v}dz$$

RF Multipoles

- To first order of *r*:

$$\Delta(\gamma\vec{\beta}_{\perp}) = \frac{ie}{m_0 c\omega}\left(\frac{\eta_r A_1}{2}\hat{x}_0 + \frac{\eta_r B_1}{2}\hat{y}_0 - \frac{\eta_r^2 A_0}{2}(x\hat{x}_0 + y\hat{y}_0)\right)$$

$$+\frac{ie}{m_0 c\omega}\left(\frac{\eta_r^2 A_2}{4}(x\hat{x}_0 - y\hat{y}_0) + \frac{\eta_r^2 B_2}{4}(y\hat{x}_0 + x\hat{y}_0)\right)$$

$$= D_x\hat{x}_0 + D_y\hat{y}_0 + F(x\hat{x}_0 + y\hat{y}_0) + Q(x\hat{x}_0 - y\hat{y}_0) + S(y\hat{x}_0 + x\hat{y}_0)$$

D: dipole
Q,S: quad & skew quad
F: RF focusing
F inversely proportional to beamenergy
D,Q,S independent beam energy

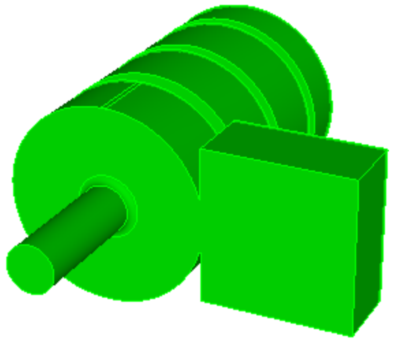
Head-Tail Effect

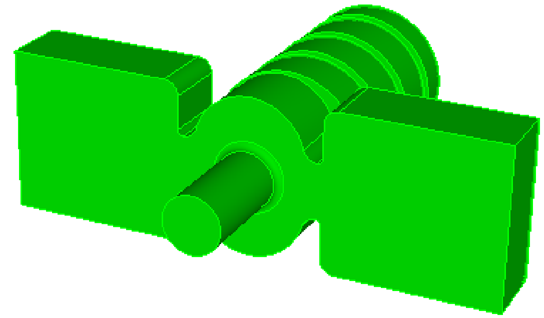
$$\varepsilon_{n,final} = \sqrt{\varepsilon_{n,initial}^2 + \sigma_x^2 \left(\frac{\sigma_{\Delta p_x}}{m_0 c} \right)^2} = \varepsilon_{n,initial} \left(1 + \frac{\sigma_x^2 \sigma_{\Delta(\gamma\beta_x)}^2}{2\varepsilon_{n,initial}^2} \right)$$

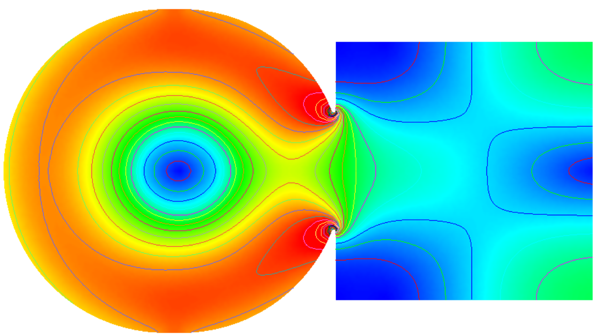
$$\approx \varepsilon_{n,initial} \left(1 + \frac{\beta_{[lattice]} \sigma_{\Delta(\gamma\beta_x)}^2}{2\varepsilon_n \gamma} \right)$$

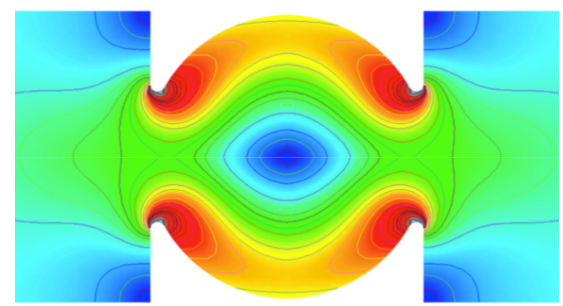
- Effect is quadratic in beam size & kick angle
- Dipole head-tail emittance growth - $1/\gamma$
- Quad head-tail emittance growth - $1/\gamma^2$

Single-feed to Dual-feed



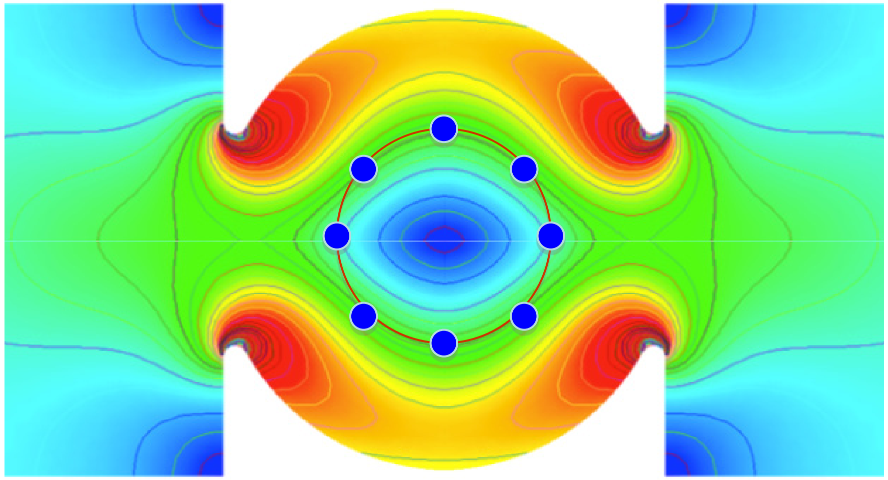






- Desirable to remove ($1/\gamma$) dependent dipole fields
- Dual-feed eliminates both geometric & phase related dipole effects
- Quad field remains due to geometry and phase asymmetry

Multipole Field Calculation



- Track particle at different azimuthal positions

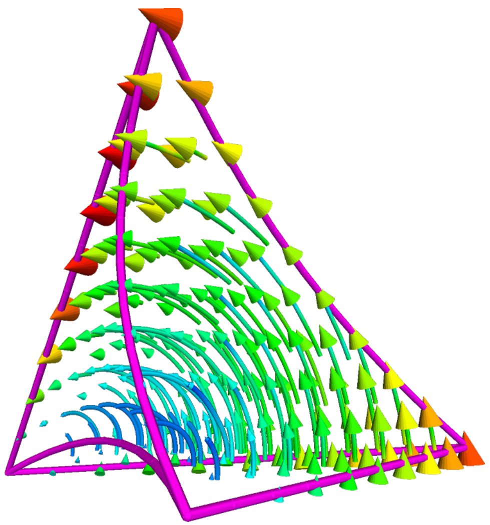
$$\Delta(\gamma\vec{\beta}_{m\perp}) = -\frac{ie}{m_0 c\omega}\nabla_\perp \int E_z(r,\theta,z)e^{i\omega z/v}dz$$

- Fourier decompose to obtain multipole terms D,F,Q,S
- Require high accurate fields

RF Modeling With ACE3P Codes

- Omega3P: Complex eigensolver
- S3P: S-parameter solver for matching field excitation

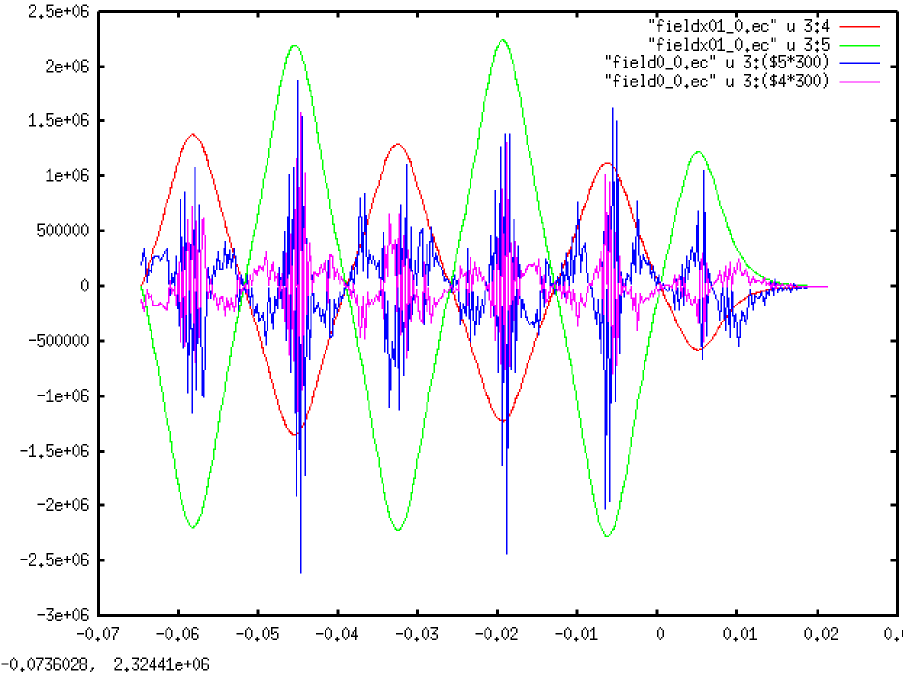
  - Conformal (tetrahedral) mesh with quadratic surface
  - Higher-order elements (p = 1-6)
  - Parallel processing (memory & speedup)

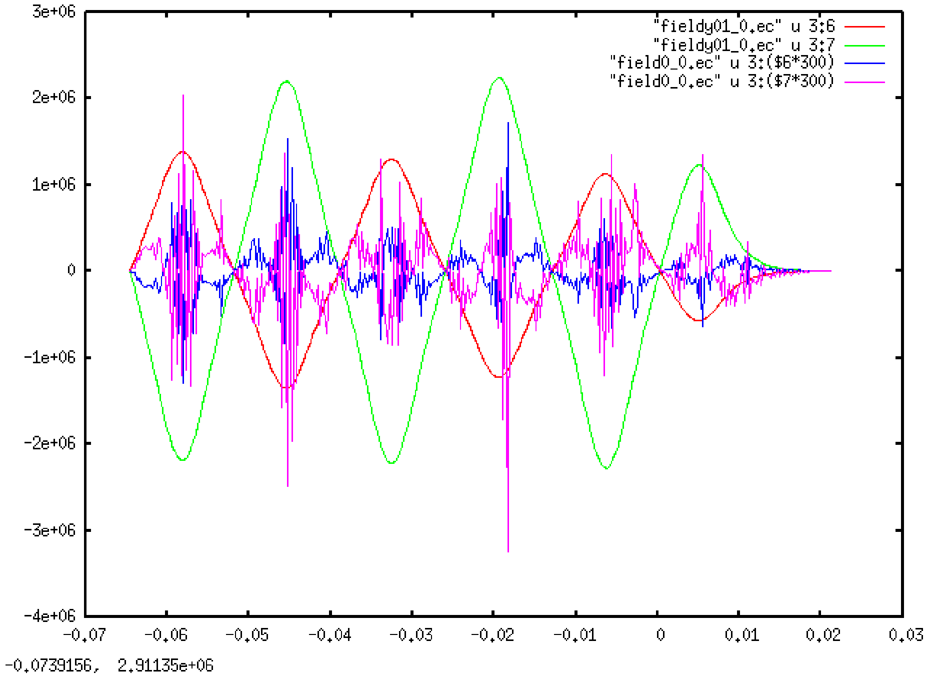


Higher Order FE Modeling For Accuracy

- Multipole relatively low in amplitude
- Using higher order finite elements in Omega3P/S3P to obtain accurate fields

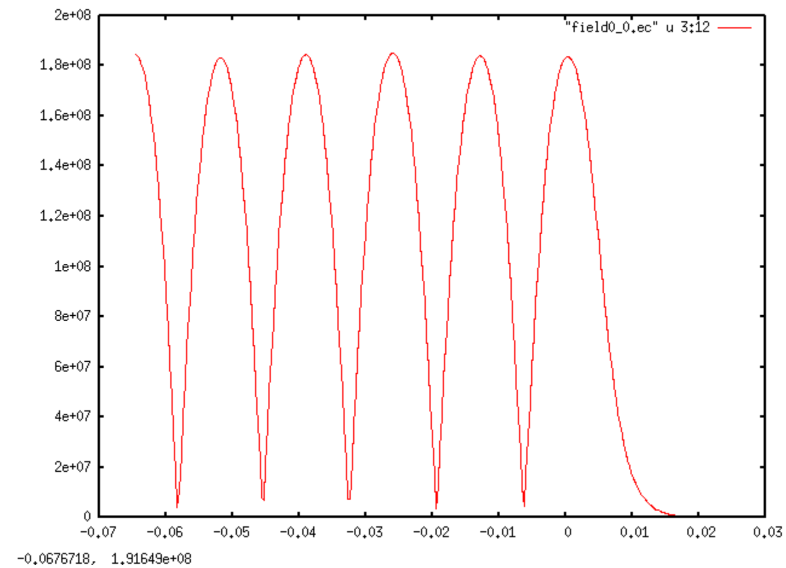
Noise vs Ex/Ey at r=0.1mm (scaled by 1000)

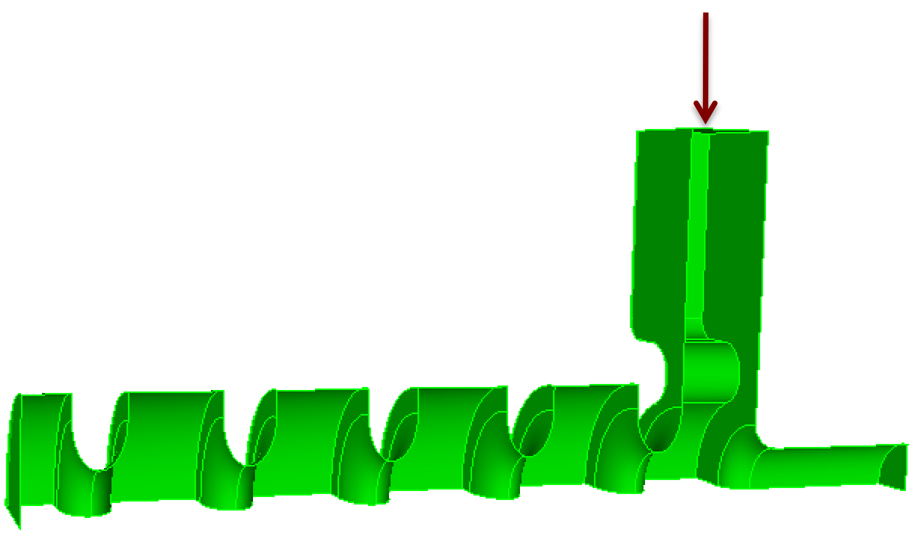


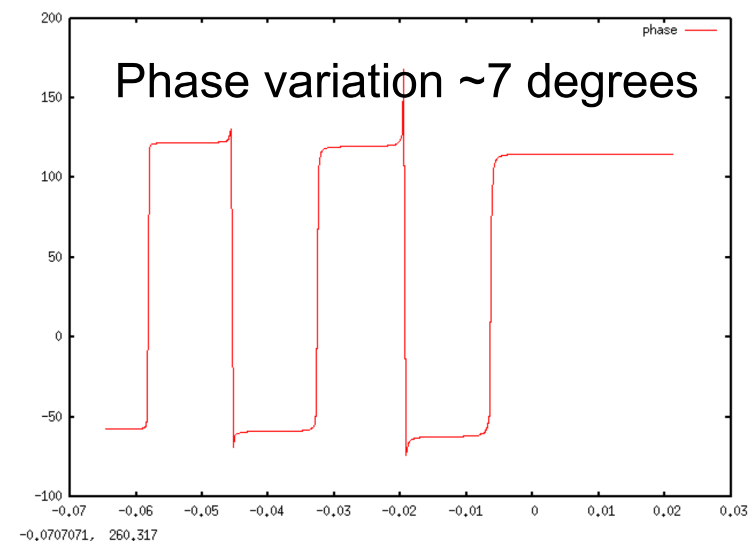


RF Field Calculation Using S3P

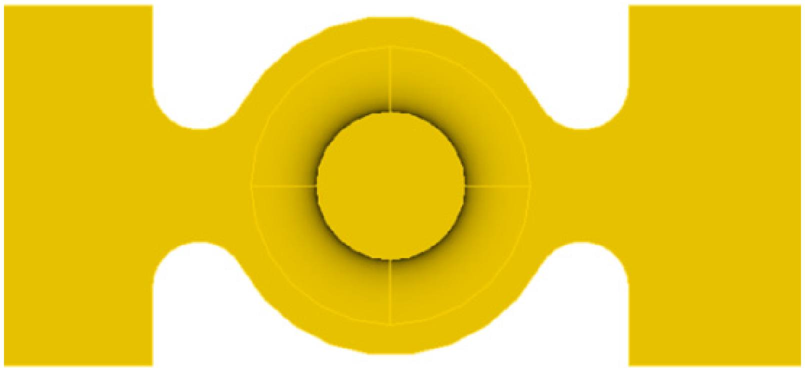
- Using S3P to drive the cavity with impedance boundary loss
- Phase variation due to power flow included
- Simulating realistic operation condition

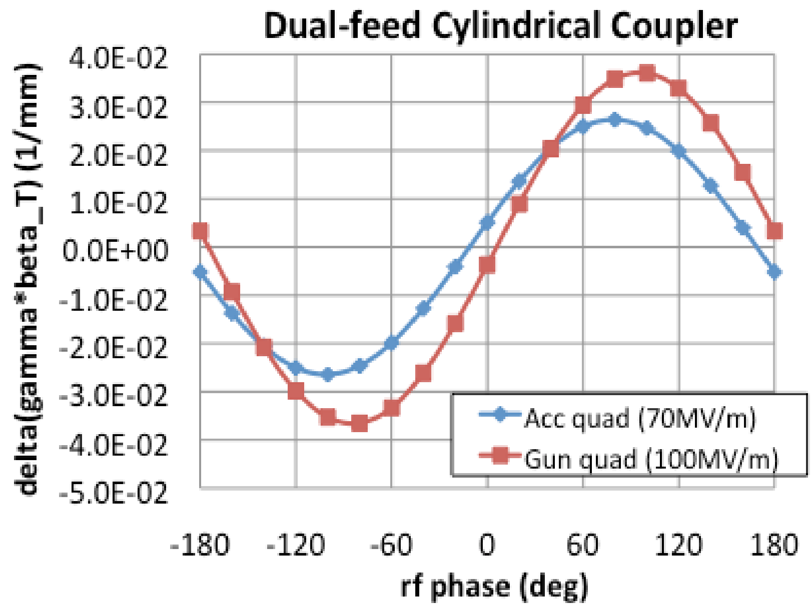






Dual-feed With Cylindrical Cell





$$dB/dx = 0.0017 d(\gamma\beta_x)/dx \ (\mathrm{T\cdot m/m})$$

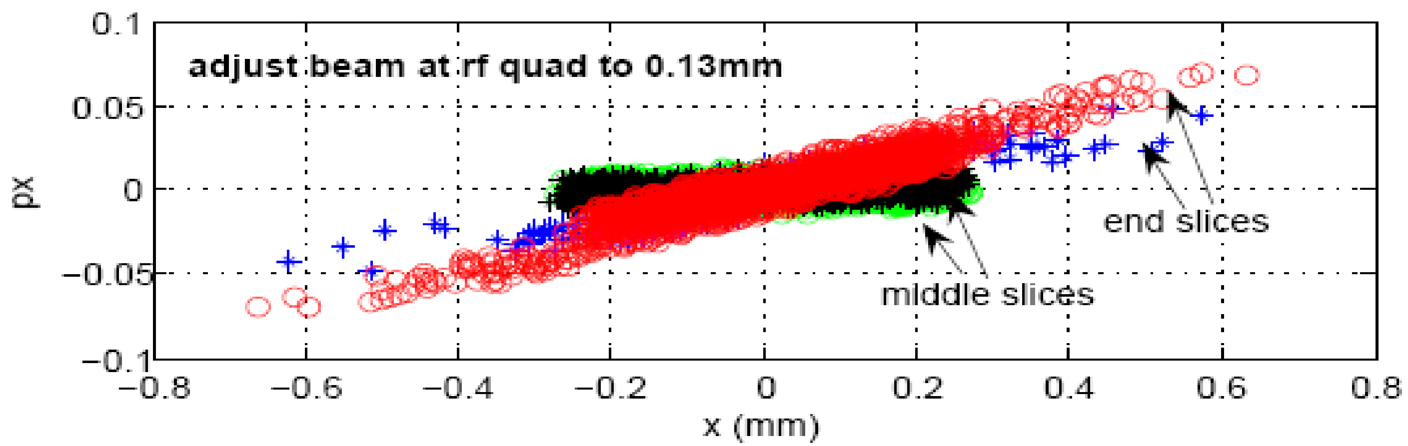
- Zero rf phase correspond to maximum acceleration
- Beam is roughly at zero crossing of quad field
- Indicating possible strong head-tail effects

Head-tail Quad Effect

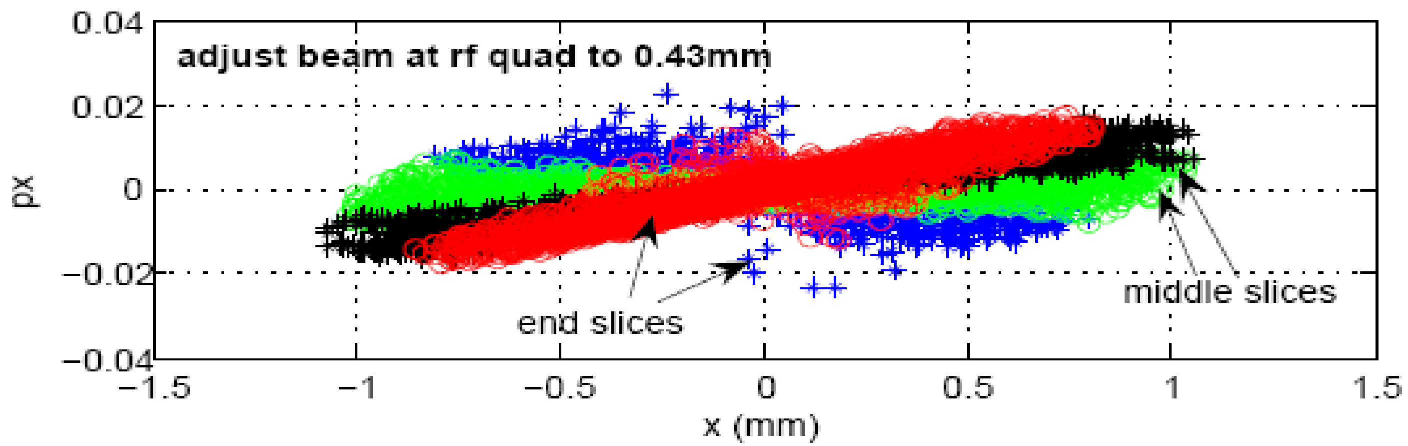
- Using a large (∂B/∂x) for demonstration only

  [(∂B/∂x)*L=0.5T (~ 50 times larger than actual)]

Small beam size



Large beam size



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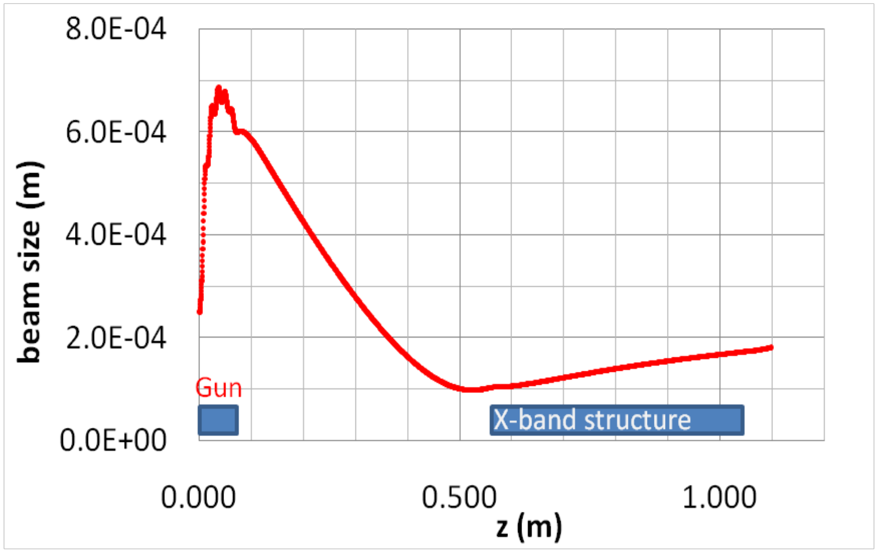
Quad Head-tail Effect in MEGa-ray/XTA Injector

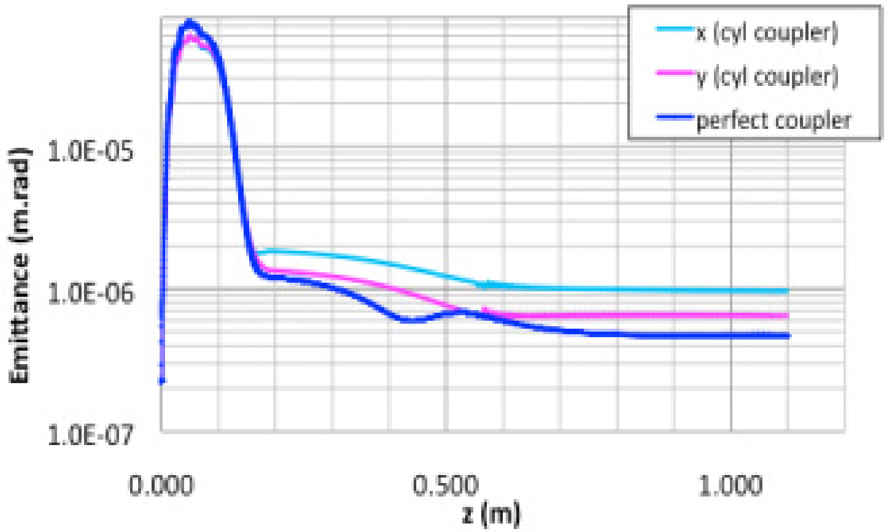
Dual-feed cylindrical coupler

- Beam dynamics simulation performed using IMPACT
- Field MAPs generated using Omega3p/S3p with 3rd order element

Projected Emittance



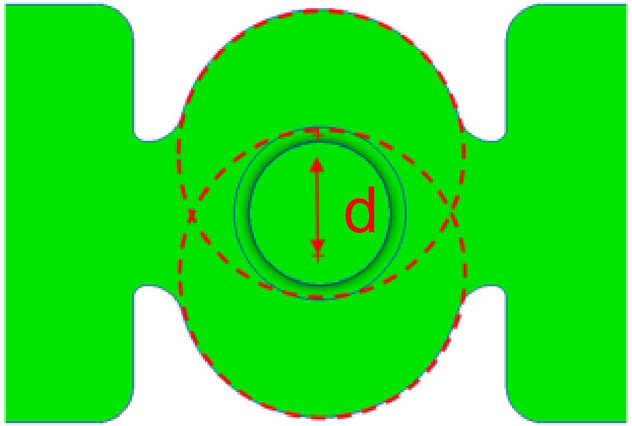
Beam size in injector

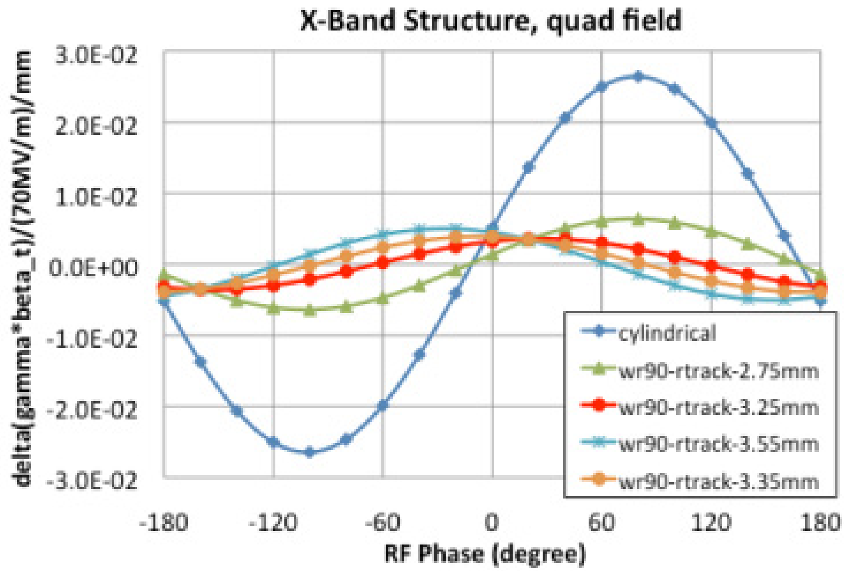


Projected emittance

- Gun quad in a cylindrical dual-feed coupler induce significant emittance growth

Coupler Quad Compensation



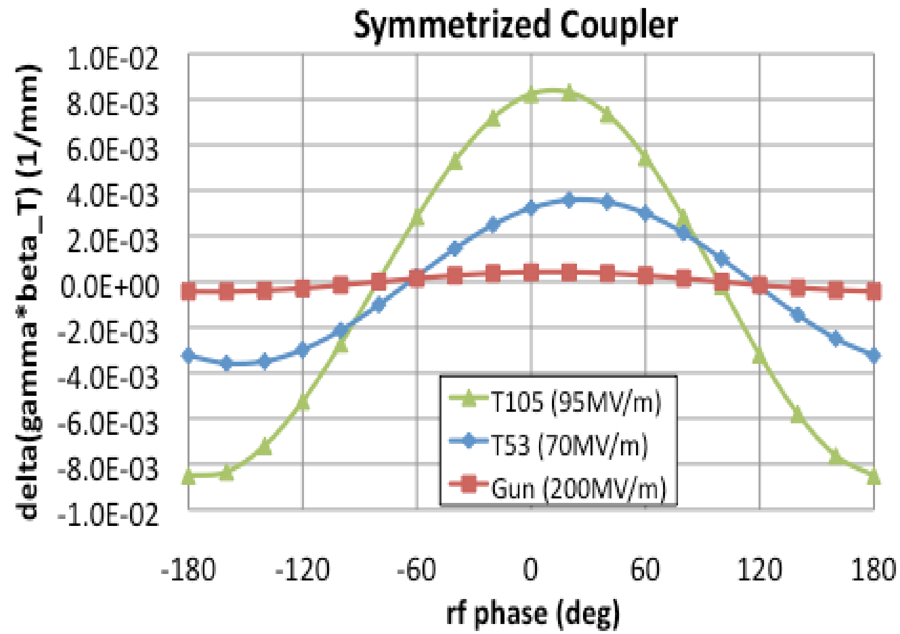


	T53	T105	5.6-cell Gun
Center-center offset d (mm)	6.5	8.0	4.85

- Geometric effect can be compensated via racetrack shape
- Phase related quad due to power flow cannot be compensated with dual-feed scheme

Phase Related Quad in Racetrack Design

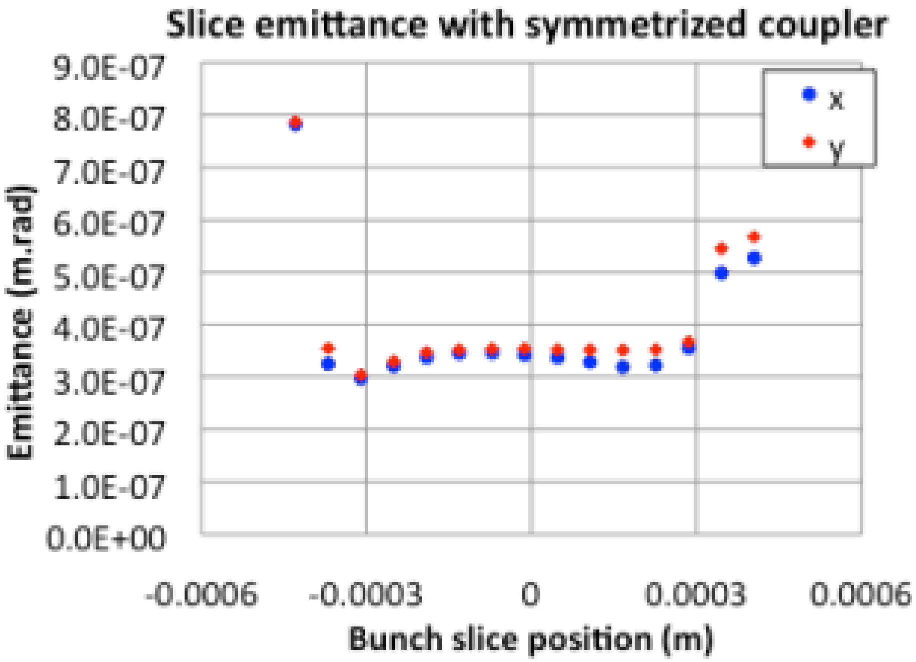
- Proportional to $P^{1/2}$
- In phase with beam
- Small head-tail expected



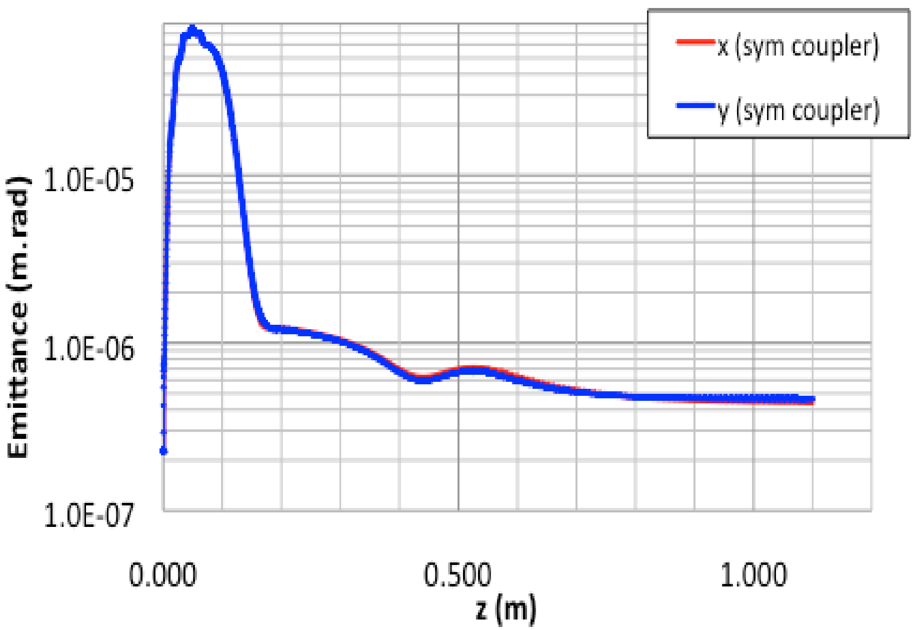
	X-band Injector			LCLS S-band Injector	
	T105	T53	5.6-cell Gun	Acc structure	1.6-cell Gun
Cylindrical coupler		26.4	36	4.5	4.4
Racetrack coupler	8.6	3.6	0.4	0.8	0.1

Emittance With Symmetrized Coupler

Slice emittance



Projected emittance



- Negligible head-tail effects in symmetrized coupler design
- MEGa-ray/XTA injectors able to produce beam emittance of 0.4mm.mrad

Summary

- Multipole fields in the power couplers can be a significant source of emittance growth in a photoinjector.
- Symmetrizing the coupler geometry will minimize their effect.
- The couplers for the X-band facilities being constructed at LLNL and SLAC have been so optimized.
- Simulations show that the X-band photo-injectors will be able to produce high quality beams that can be used for Compton scattering and FEL applications.
- RF simulation used ACE3P codes developed under DOE SciDAC support