Study on Field Asymmetry in 1.6 cell Photocathode RF Gun

문성익#, 박 성주[1], 김 상훈, 고 인수, 조 무현, 남궁 원

포항공과대학교 물리학과, [1]포항가속기연구소

한국물리학회 봄 학술논문발표회
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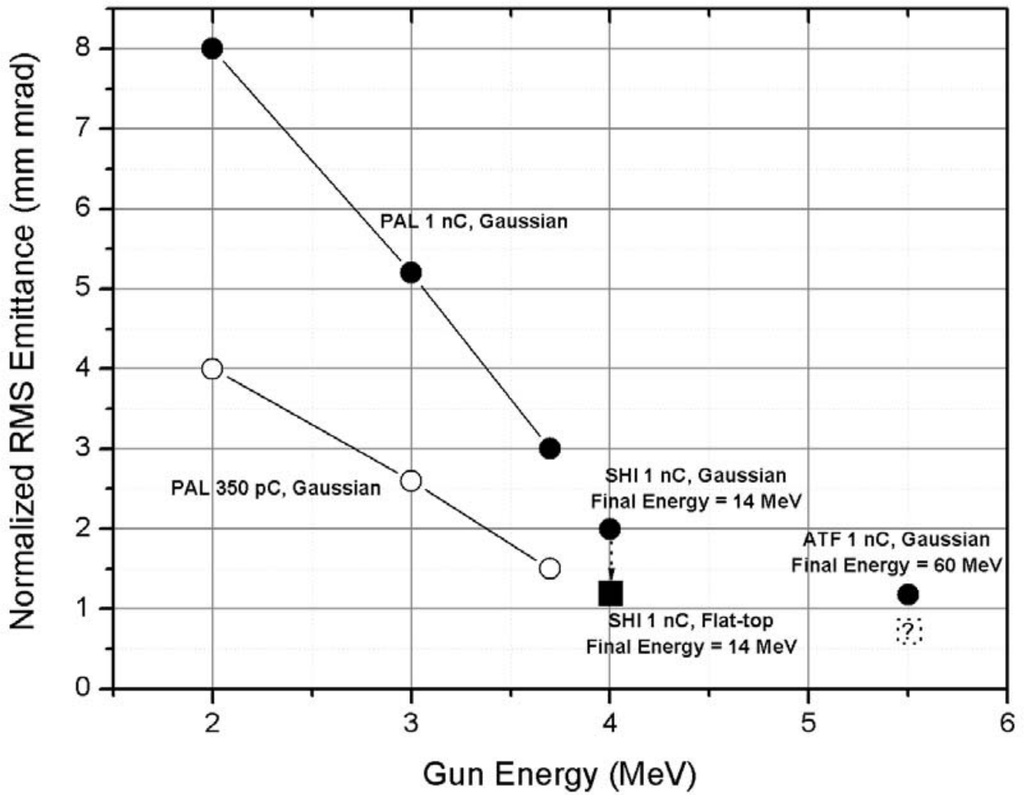
The BNL/SLAC/UCLA 1.6-cell photocathode RF gun adopts a single RF feed and a standing-wave structure. There is asymmetry in the RF fields at coupler cell, which is caused by coupling slot. In order to minimize the field symmetry which causes the transverse emittance growth, Vacuum pump out-port is placed at the opposite side of the RF input-port. But more field asymmetry reduction is required to meet rigorous transverse emittance requirement. The symmetric pumping port induces quadruple and higher order fields which causes significant emittance growth. We have studied on the method of eliminating the residual dipole offset and further reducing the higher multi-pole fields.

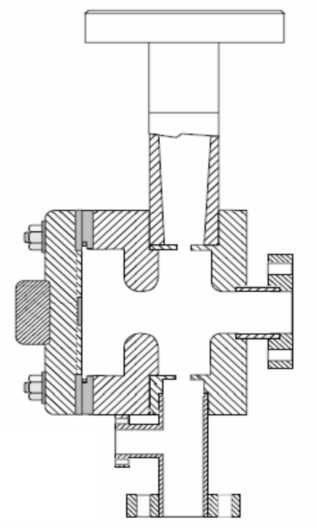


- Present status of Gun cannot satisfy of PAL XFEL requirement

- Emittance reduction by Energy Increasing and Laser shaping will be reduce until 1 mm mrad

- More reduction of emittance is required

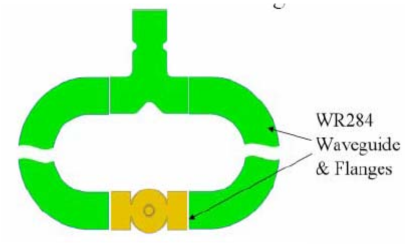
PAL XFEL, LCLS injector : 1-nC, 10 ps bunch with $\varepsilon_{n.rms} \le 1 \quad \pi \quad mm \cdot mrad$

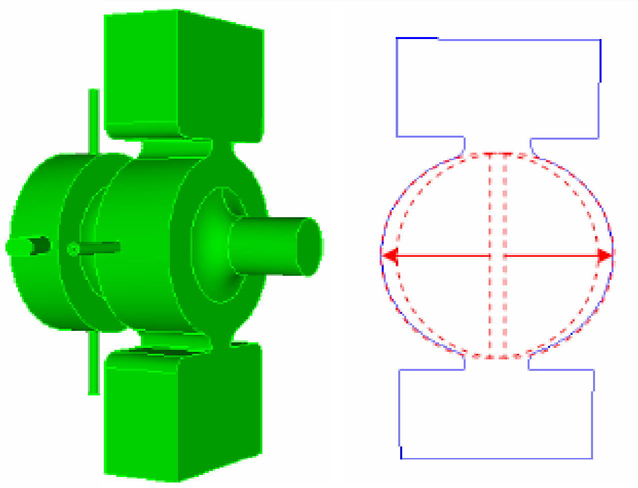


Q_t	1 nC
$\varepsilon_{n,rms}$	1.2 π mm mrad
σ_z	10 psec

BNL/ATF Photocathode RF gun/injector system (BNL Gun III)

J. Yang et al. “Low-emittance electron-beam generation with laser pulse shaping in photocathode radio-frequency gun”, J.App. Phys. 92, 1608 (2002)





The advantage of the photocathode rf gun
: capability of producing beam quality (1 π mm mrad)
BNL type RF gun : magnetic side coupling
Advantage : Suppressing the zero mode
Disadvantage : The RF asymmetry

Design of New LCLS photo injector
Dual feed strategy
for dipole mode elimination
Racetrack shape
for the quadrupole mode elimination

Emittance growing by multi-pole fields

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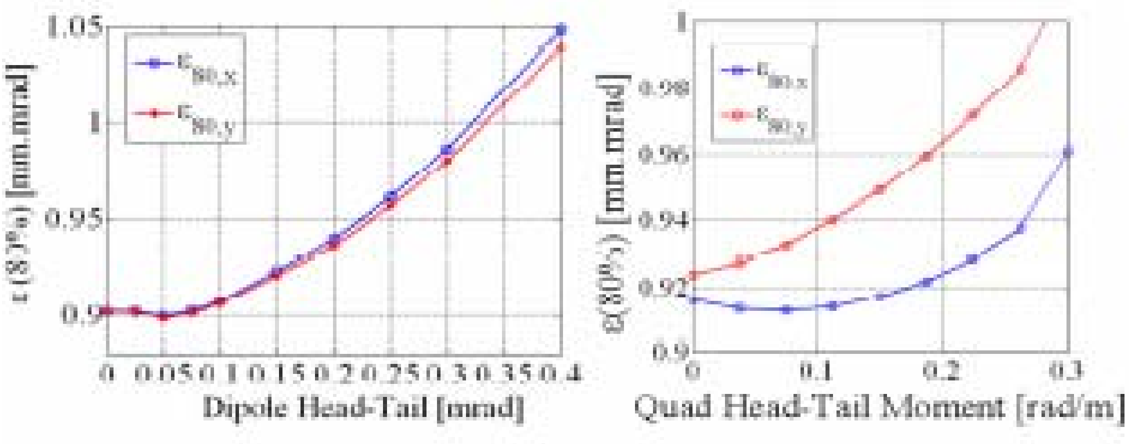
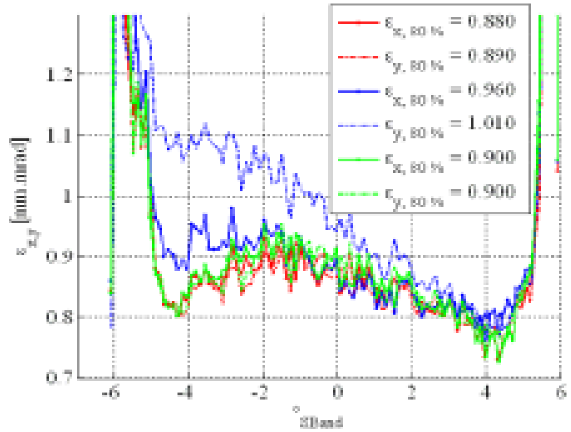


Emittance degradation due to dipole and quad head tail effects

Zenghai Li et al. "Coupler Design for the LCLS Injector S-band Structures", proc. of 2005 PAC



Hor./Ver. slice emittance for 100 slices

C. Limborg-Deprey et al. "Modifications on RF Components in the LCLS Injector", proc. of 2005 PAC

Estimation of projected emittance growth by head-tail effect :

$$\varepsilon_{n-final} = \sqrt{\varepsilon_{n-initial}^2 + \sigma_x^2 \left(\frac{\sigma_{\Delta p_x}}{mc}\right)^2}$$

Fourier analysis of electric field

$$E_x = E_0 \sin(\omega t - K_y y) \times \sum_{n=0}^{\infty} a_n r^n \cos n\varphi$$

Emittance growth by multi-pole modes

Dipole : $$\varepsilon_{n.rms}^{dipole} = \frac{eE_0 L^2}{m_e c^2 \pi} \times a_1 \sigma_y \sigma_z$$

Quadruple : $$\varepsilon_{n.rms}^{quadruple} = \frac{eE_0 L^2}{m_e c^2 \pi} \times 2 a_2 \sigma_y^2 \sigma_z$$

D.T. Palmer, Doctor Thesis, The Next Generation Photo-injector,1998

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Dipole offset analysis

- **Magnetic side coupling : RF asymmetry greatly increases the multi-pole fields.**
  - The expression of x component of electric fields to be as following form

$$E_x = (a_0 + a_1 y + a_2 y^2)*\sin(\omega t-K_y y)$$

  - Dipole offset y_0: deviation of the electrical center of the cavity from mechanical center

$$y_0 = -\frac{a_1}{2a_2} + \frac{a_0 K_y}{2a_2} ctg(\omega t)$$

Xin Guan et al. "Study of RF-asymmetry in photo-injector", will publish NIM A

  - Transient power flow effect wave number K_y can be estimated as

$$K_y \cong k/Q$$

J. B. Rosenzweig et al. "The Effect of RF Asymmetries on Photoinjector beam quality", proc. of 1999 PAC

- **Eliminating dipole fields**
  - Symmetrically positioning the RF coupling hole (vacuum port)
  - Optimization : coupling hole dimension, vacuum port length

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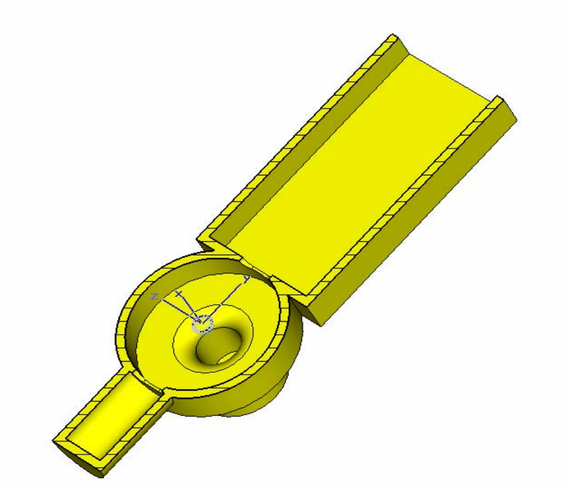
Higher multi-pole effects

- **Presence of the coupler hole and the symmetrizing port**
  - Quadrupole and higher order fields in the coupler cell
  - The quadrupole fields remains at a similar level at above design scheme.
  - LCLS design adopted a racetrack cell geometry
- **Racetrack cell geometry**
  - Advantage: minimize quadruple fields without additional structure
  - Disadvantage: fabricating cavity with racetrack cell geometry is difficult.
- **Quadruple elimination with 2-additional vacuum port**
  - Advantage: cavity shape is circular, improve vacuum condition(3-vacuum port)
  - Disadvantage: 2-additional coupler hole (coupler hole heating)

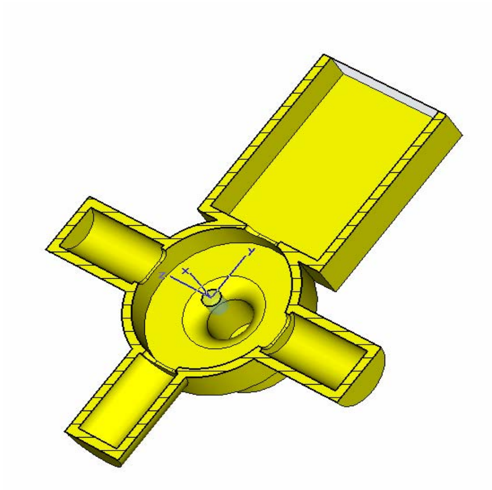
Simulation modeling

- Tool : 3D high frequency solver
- Simulation model: BNL/SLAC/UCLA 1.6-cell photocathode RF gun with input waveguide, symmetric vacuum port and part of beam transport pipe
- Cavity wall conductivity: 5.8×10^{7} S/m (power loss)
- The E_x amplitude along waveguide-vacuum port axis (y-axis)
- Fourier coefficients of multi-pole modes are monitored at r=5mm (geometrical center)



1 vacuum port

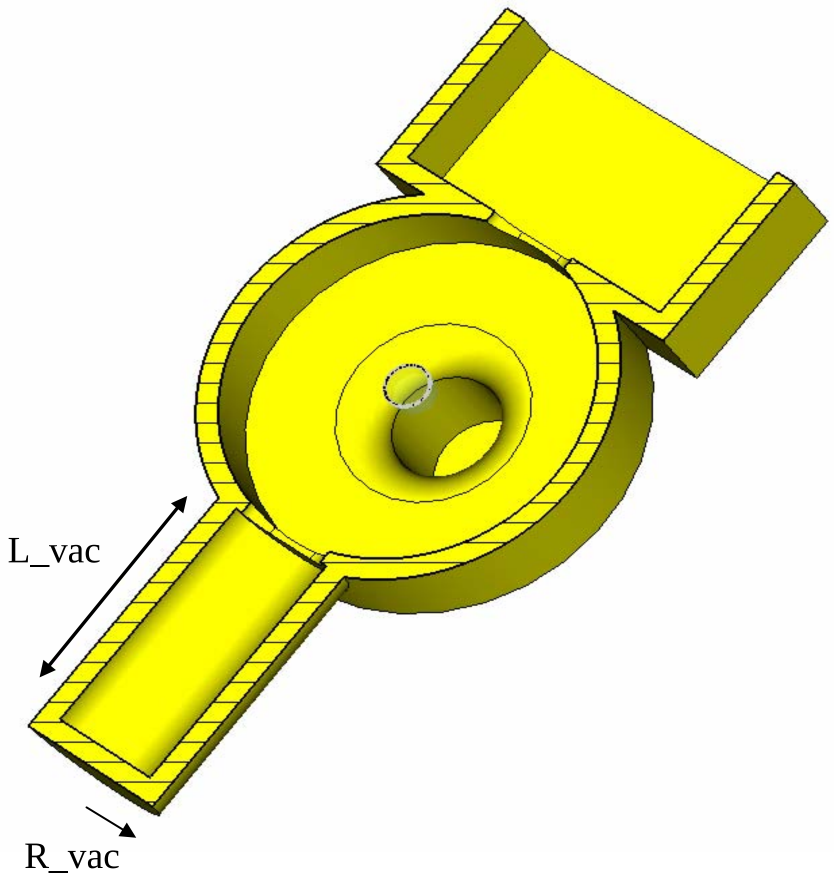
Dipole field elimination



3 vacuum port

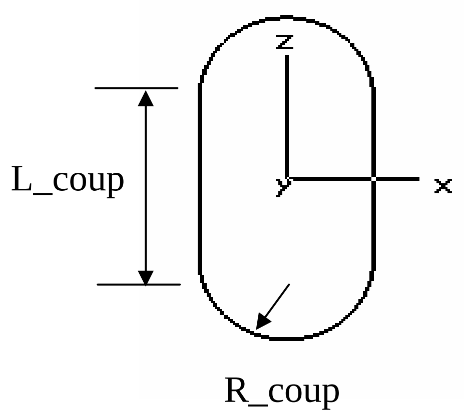
Quadrupole field elimination

Optimization parameter



Simulation model

Coupler optimization



Coupler hole dimension

R_coup : 5.5 mm

L_coup : 11.0-12.0 mm

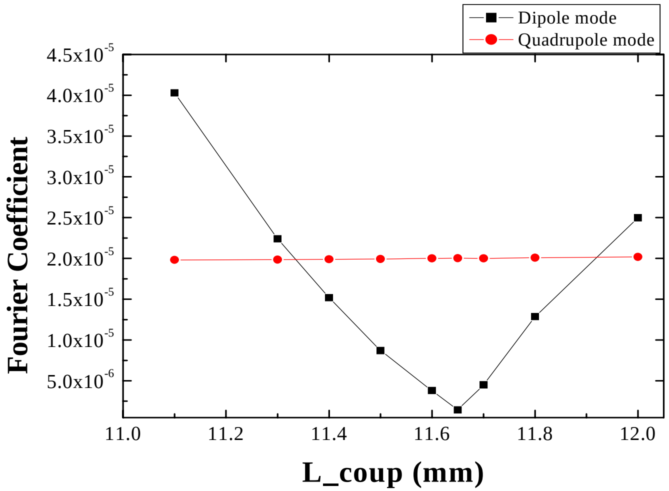
Vacuum port optimization

R_vac = 13.045 mm ($f < f_c$)

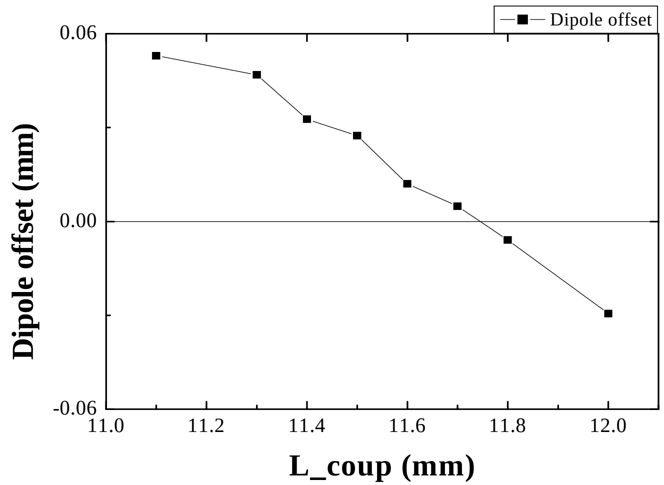
Evanescent mode

Characteristic cutoff length = 7.8 mm

Dipole Mode Elimination

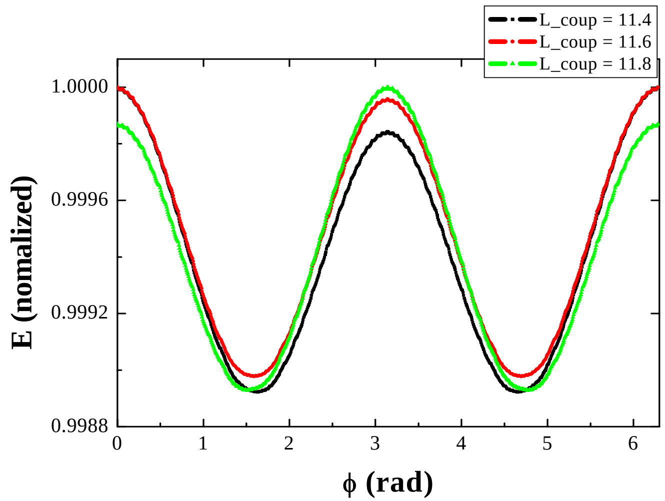


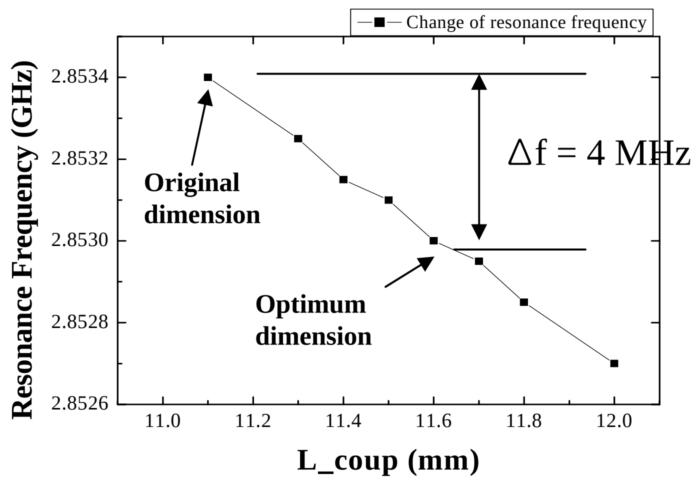
Fourier coefficient of dipole offset has minimum at L_coup =11.65



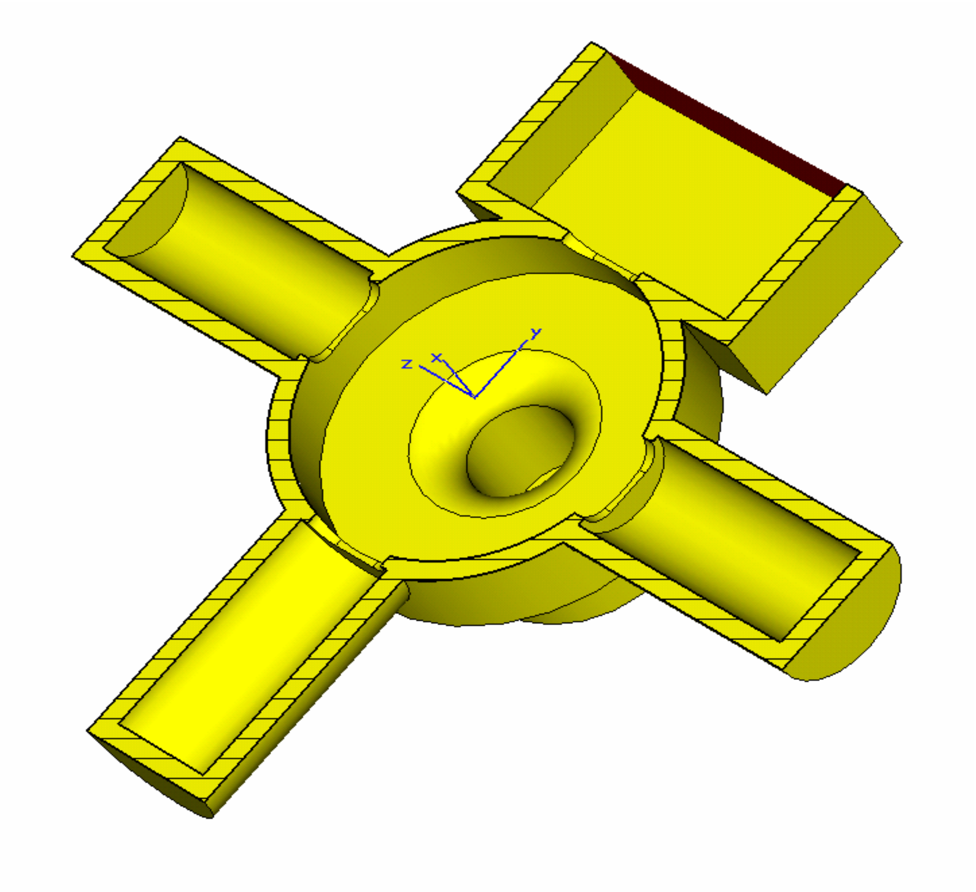
$$y_0 = -\frac{a_1}{2a_2} + \frac{a_0 K_y}{2a_2} ctg(\omega t)$$

Dipole offset has minimun at L_coup =11.75



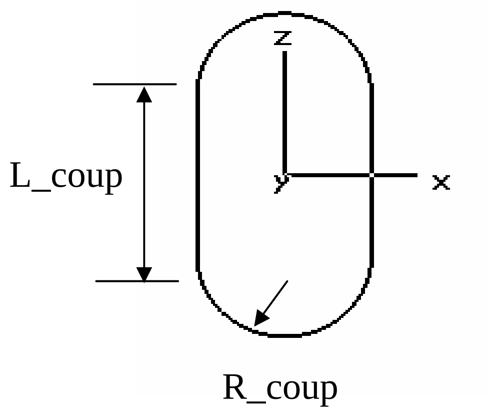


Optimization parameter



Simulation model

Coupler optimization



Quadrupole Elimination

1. Fix coupler dimension of opposite side vacuum port

   R_coup : 5.5 mm, L_coup1: 11.65 mm

   L_coup2 : 11.4-12.0

   (minimum dipole mode condition)

2. 3-coupler dimension is same

   L_coup1=L_coup2 : 11.2-11.9 mm

Quadrupole Mode Elimination

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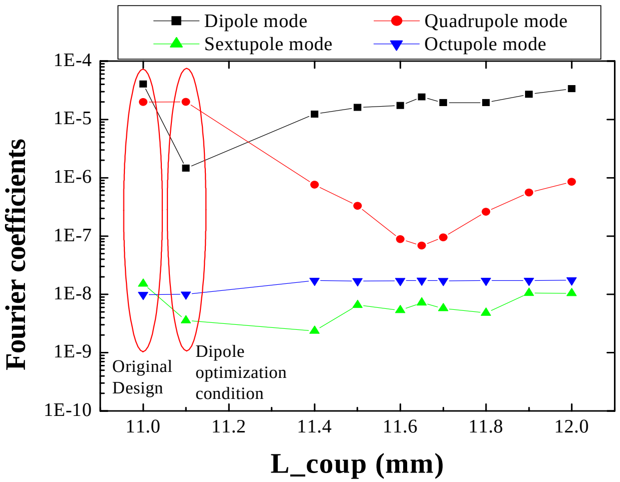
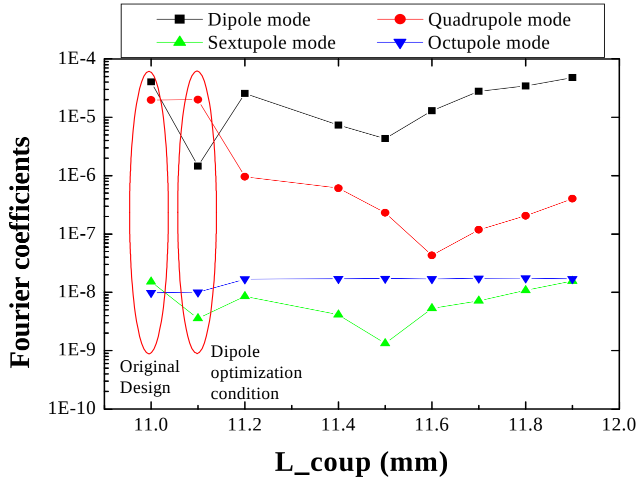
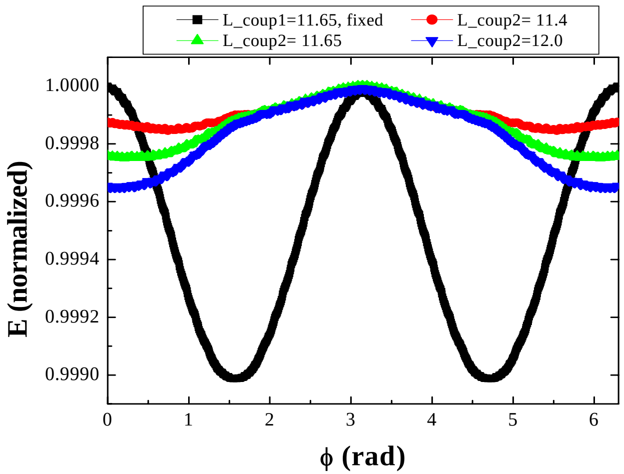
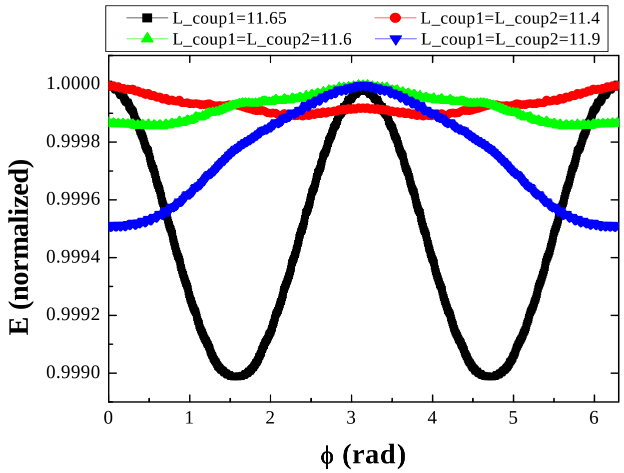




Fourier coefficient of dipole offset has minimum at L_coup =11.65

Dipole offset has minimun at L_coup =11.75





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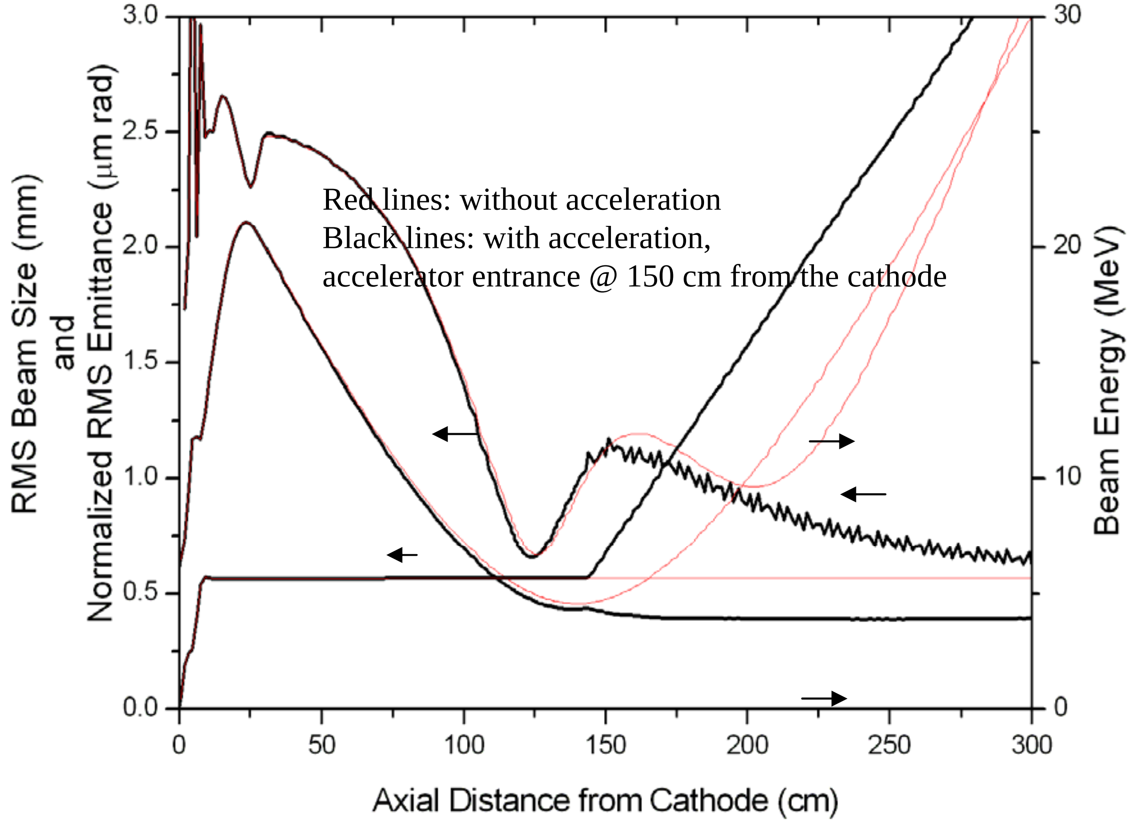
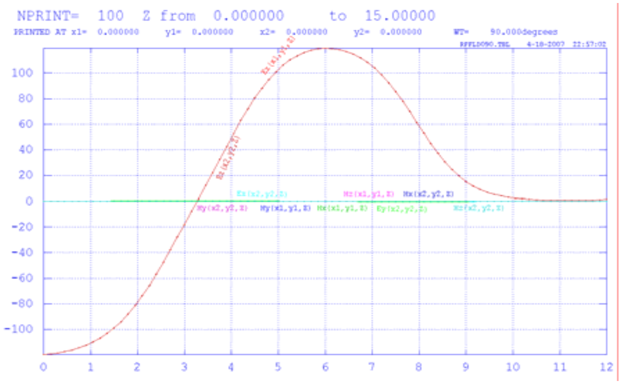
Emittance evolution



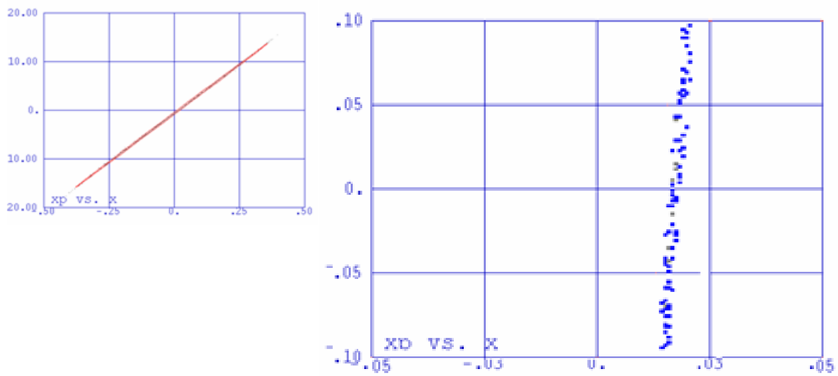
- Emittance damping by acceleration.

- Acceleration part placed at 2^{nd} maximum of emittance

Emittance reduction by multi-pole mode elimination

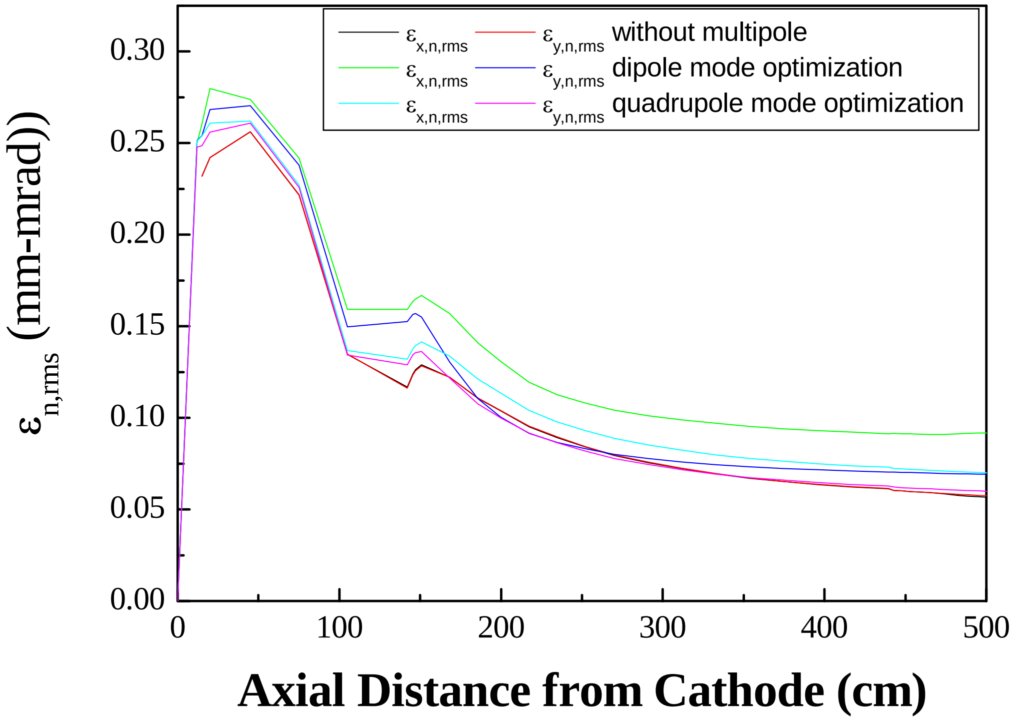


RF field profile at Gun



Phase diagram at Gun exit

Dipole offset is shown



Emittance is successfully reduced by multi-pole mode elimination

Summary

- **Dipole field elimination**
  - Fourier coefficient of dipole mode is almost eliminated by coupler hole dimension modification.
  - Fourier coefficient of quadrupole mode is found to be unchanged.
  - Dipole offset also minimized by coupler hole dimension modification. But optimum dimension is slightly different.
  - Frequency difference between optimal condition and present dimension is 4MHz.
- **Quadrupole field elimination**
  - Quadrupole mode is optimized with 2-additional vacuum port
  - Fourier coefficient of Quadrupole mode is almost eliminated by coupler hole dimension modification.
  - Fourier coefficients of higher mode are found to be decreased slightly.
  - Optimization conditions of dipole and quadrupole mode are different.
- **Emittance analysis**
  - Emittance degradation by dipole and quadrupole is not negligible.
  - Emittance is successfully reduced by multi-pole mode elimination