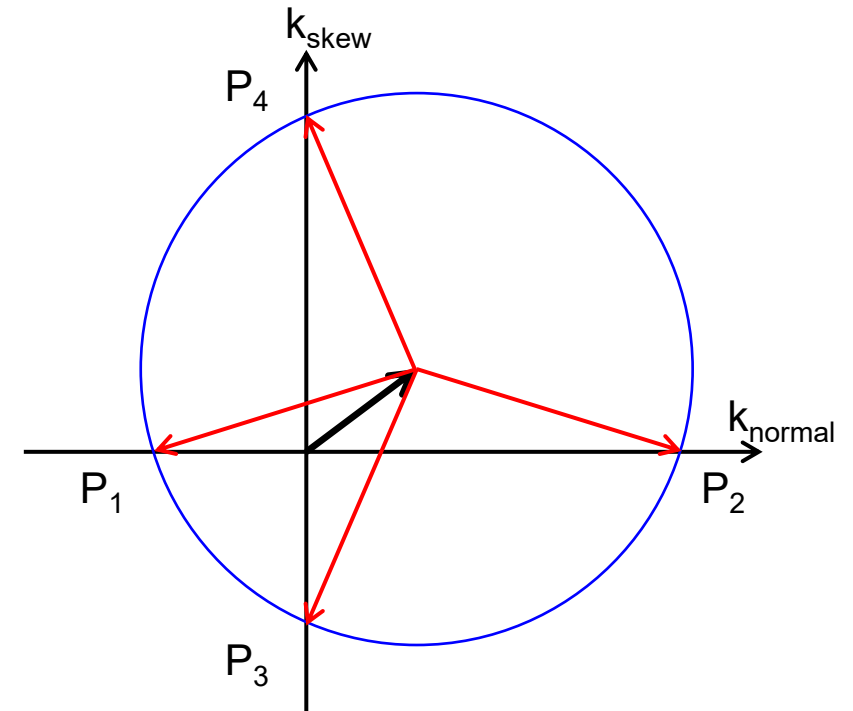
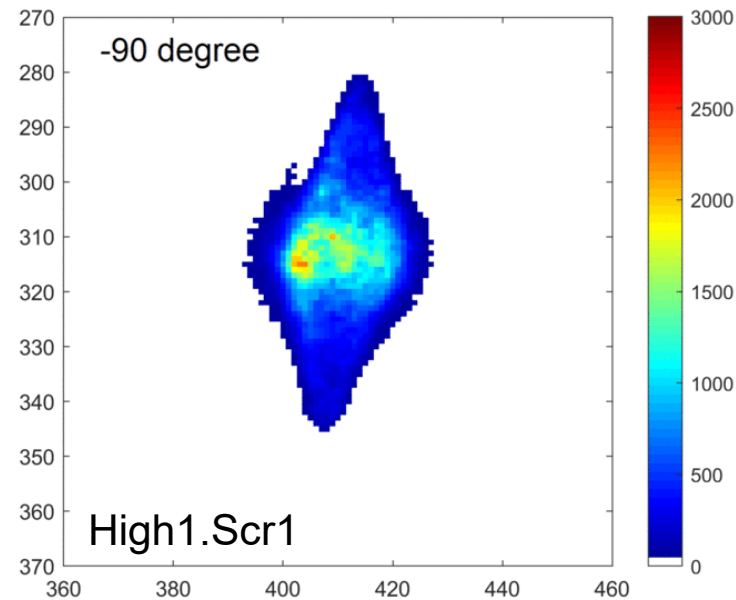


Transverse phase space coupling due to quadrupole field error and cathode laser asymmetry

26.03.2020 @ PPS
H. Qian



Outline

- Introduction
- Transverse coupling by quadrupole field error w/o space charge
- Transverse coupling by quadrupole field error w/ space charge
- Transverse coupling by cathode laser asymmetry
- Simulations & experiments
- Summary

Introduction to phase space coupling

4D phase space

- 4D beam phase space $X_{4D} = [x \ x' \ y \ y']^T$
- 4D beam covariance matrix
 - $C_{4D} = \langle X_{4D} X_{4D}^T \rangle = \begin{bmatrix} C_{XX} & C_{XY} \\ C_{XY}^T & C_{YY} \end{bmatrix}$
 - $C_{XX} = \begin{bmatrix} \langle xx \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'x' \rangle \end{bmatrix}$
 - $C_{YY} = \begin{bmatrix} \langle yy \rangle & \langle yy' \rangle \\ \langle yy' \rangle & \langle y'y' \rangle \end{bmatrix}$
 - $C_{XY} = \begin{bmatrix} \langle xy \rangle & \langle xy' \rangle \\ \langle x'y \rangle & \langle x'y' \rangle \end{bmatrix}$

} Projected phase space beam matrix
- Emittance
 - $\varepsilon_{4D}^4 = \det C_{4D}$
 - $\varepsilon_x^2 = \det C_{XX}$
 - $\varepsilon_y^2 = \det C_{YY}$

} Projected emittance

- Coupling factor: $\frac{\sqrt{\varepsilon_x \varepsilon_y}}{\varepsilon_{4D}} - 1$
- No X/Y coupling $C_{XY} = 0, \varepsilon_x \varepsilon_y = \varepsilon_{4D}^2$
- X/Y Coupling $C_{XY} \neq 0, \varepsilon_x \varepsilon_y > \varepsilon_{4D}^2$
- Most FEL main linac lattice design assumes no transverse coupling
 - Effective beam brightness $(\frac{Q}{\varepsilon_x \varepsilon_y})$
 - Injector needs to decouple X/Y phase space to make full use of 4D beam brightness $(\frac{Q}{\varepsilon_x \varepsilon_y} = \frac{Q}{\varepsilon_{4D}^2})$
- Concept can be extended to 6D phase space
 - $X_{6D} = [x \ x' \ y \ y' \ t \ \frac{dp}{p}]^T$
 - X(Y)/Z coupling \rightarrow degrade effective beam brightness
 - Coupler kick (x' & t coupling)
 - Chromatic effect (x' & $\frac{dp}{p}$ coupling)

Introduction to phase space coupling

What can cause a X/Y coupling

- Skew quadrupole (thin lens model)

- $x' = x'_0 + k_s y, y' = y'_0 + k_s x$

- Cathode residual B field

- $p_x = p_{x0} + k_c y, p_y = p_{y0} - k_c x, k_c = \frac{eB_c}{2}$

- Solenoid Larmor rotation

- Larmor rotation angle, $\theta_{Larmor} = \int \frac{B_z}{2p/e} dz$

- Assuming a non-coupled beam before rotation

$$C_0 = \begin{bmatrix} C_{XX} & 0 \\ 0 & C_{YY} \end{bmatrix}$$

- After rotation (by 4D rotation matrix R_{rot})

$$C_{rot} = R_{rot} C_0 R_{rot}^T = \begin{bmatrix} \cos^2 \theta C_{XX} + \sin^2 \theta C_{YY} & \sin \theta \cos \theta (C_{YY} - C_{XX}) \\ \sin \theta \cos \theta (C_{YY} - C_{XX}) & \sin^2 \theta C_{XX} + \cos^2 \theta C_{YY} \end{bmatrix}$$

- Solenoid Larmor rotation (cont'd)

- $C_{YY} = C_{XX}$, i.e. a symmetric beam, $C_{rot} = C_0$

- $C_{YY} \neq C_{XX}$, X/Y coupling forms after rotation

- Beam asymmetry causes

- Cathode laser shape asymmetry

- Magnetic quadrupole field error (solenoid)

- Gun coupler kick

- Cathode/laser misalignment

- Solenoid/beam misalignment

- Beam asymmetry corrections

- A solenoid with zero Larmor rotation

- Cathode laser profile optimization @virtual cathode

- Gun quads corrector

- Symmetric gun coupler

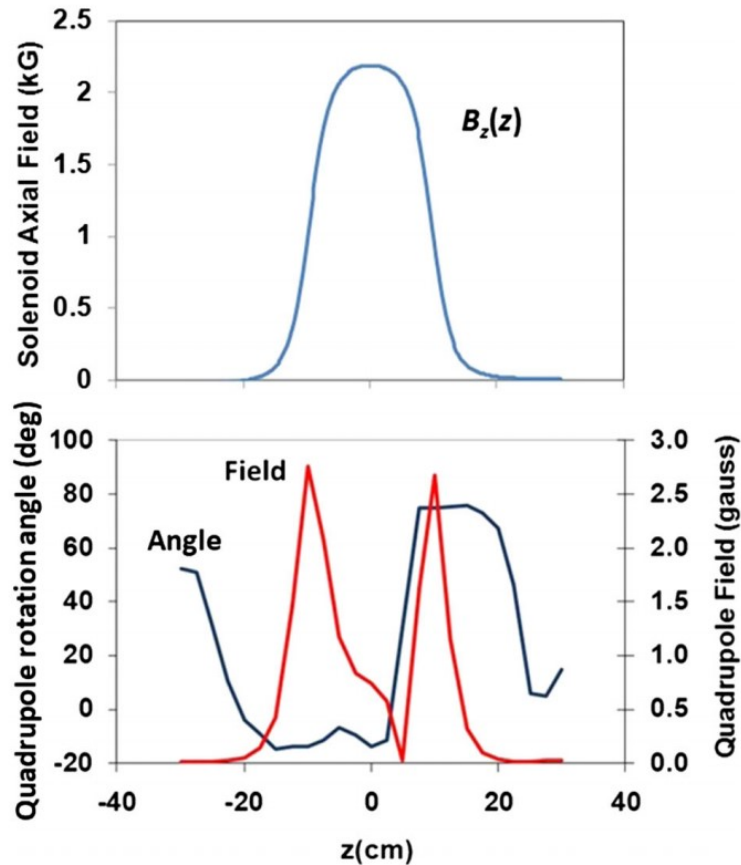
- Laser BBA

- Solenoid alignment with beam

Transverse coupling by quadrupole field error

No space charge case

- PRAB 21, 010101, by D. Dowell
- SLAC gun solenoid quad field distortion

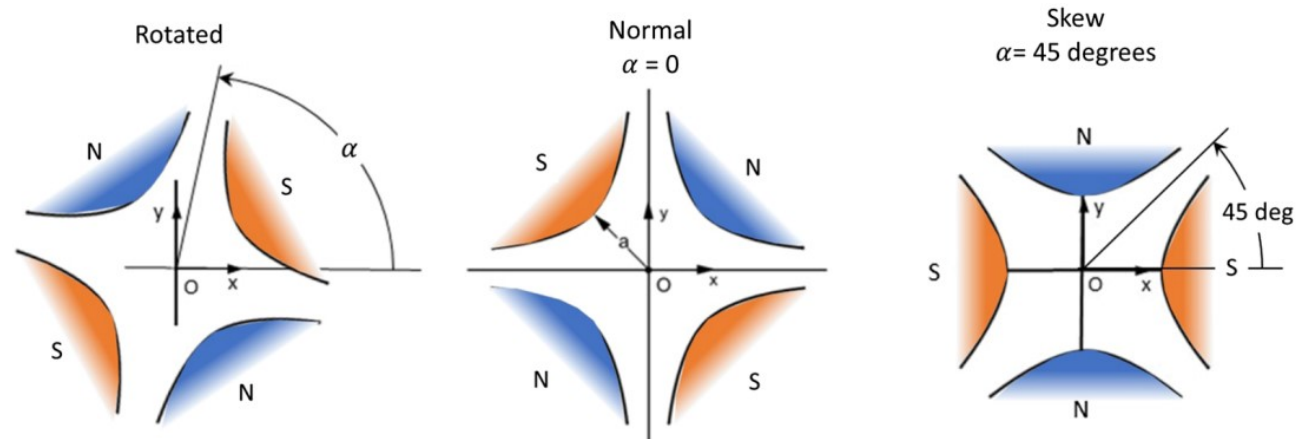


- Rotated quadrupole transfer matrix

$$R_{rotQuad} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -k_N & 1 & -k_S & 0 \\ 0 & 0 & 1 & 0 \\ -k_S & 0 & k_N & 1 \end{bmatrix} \quad k_{quad} = \frac{1}{f} \text{ (integrated quad strength)}$$

$$k_N = k \cos 2\alpha \quad \text{A normal/skew quad pair is a rotated quadrupole.}$$

$$k_S = k \sin 2\alpha$$



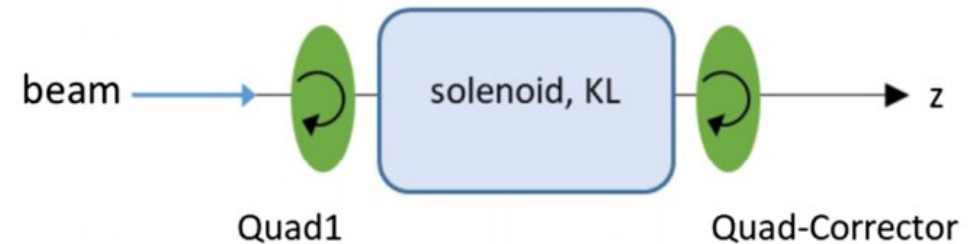
- Total transfer matrix of solenoid + quad error field
- Simplification: integrated thin lens quad model
- $R_{sol}R_{rotQuad}$

Transverse coupling by quadrupole field error

No space charge case

- PRAB 21, 010101, by D. Dowell
 - Emittance growth
 - Assuming symmetric beam before quad
 - $C_{YY} = C_{XX}$
 - By beam matrix transportation
 - $C = (R_{sol}R_{rotQuad})C_0(R_{sol}R_{rotQuad})^T$
 - $\varepsilon^2 = \varepsilon_0^2 + \Delta\varepsilon^2,$
 $\Delta\varepsilon_x = \Delta\varepsilon_y = \sigma_{beam}^2 |k_{quad} \sin 2(\theta_{Larmor} + \alpha)|$
↓
Skew quad component
 - Emittance growth is only related to the skew quad error strength
 - Emittance growth is square dependent on beam size → high charge case suffers more
 - Slice emittance grows

- Quadrupole corrector model
 - Place a rotated quad corrector at solenoid exit



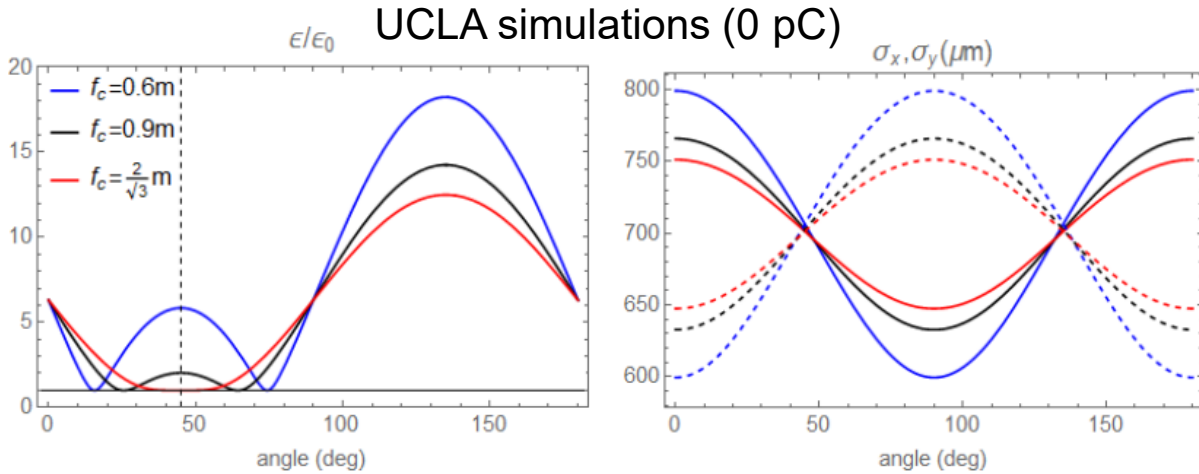
- $\Delta\varepsilon = |\sigma_1^2 k_{quad1} \sin 2(\theta_{Larmor} + \alpha_1) + \sigma_c^2 k_c \sin 2\alpha_c|$
- Tune k_c and α_c to zero emittance growth
 - Tune skew quad corrector to make $\Delta\varepsilon$ zero
 - Normal quad component is not related
 - Infinite solutions to make $\Delta\varepsilon$ zero
 - X and Y emittance still equals
 - Beam is not round downstream
 - Not critical for no space charge case

Transverse coupling by quadrupole field error

Experiments & simulations in no (low) space charge case

- Simulations & experiments reports

- SLAC/Cornell/DESY/ANL/UCLA ...



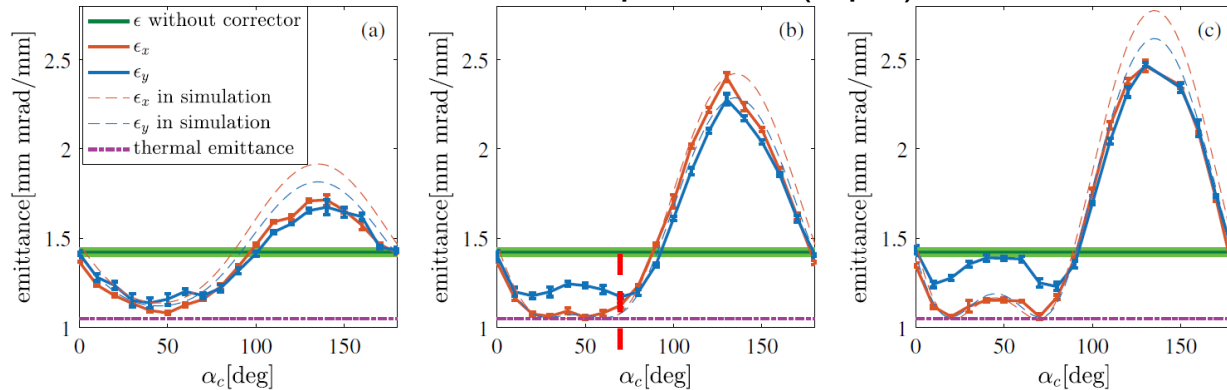
- Quadrupole corrector tuning in these studies

- Simulation to fit the integrated quad error according to measured beam profile distortions

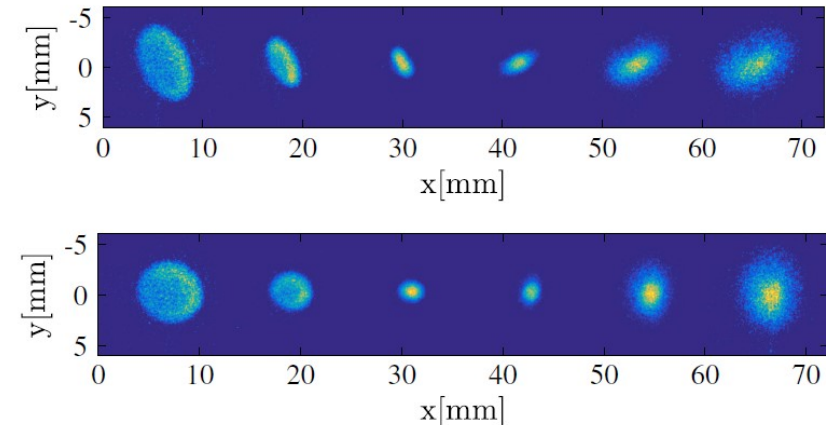
- Get roughly amplitude and angle
- Fix amplitude, scan angle to minimize $\langle xy \rangle$ or emittance

- For low charge case, simulation is not necessary, fix amplitude, scan angle can zero $\Delta\epsilon$

ANL experiment (1 pC)



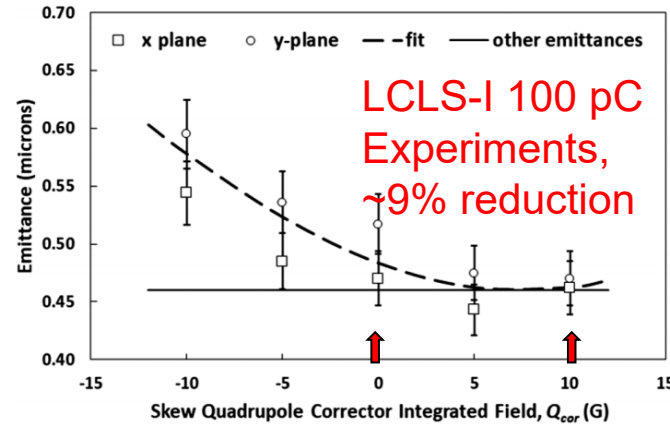
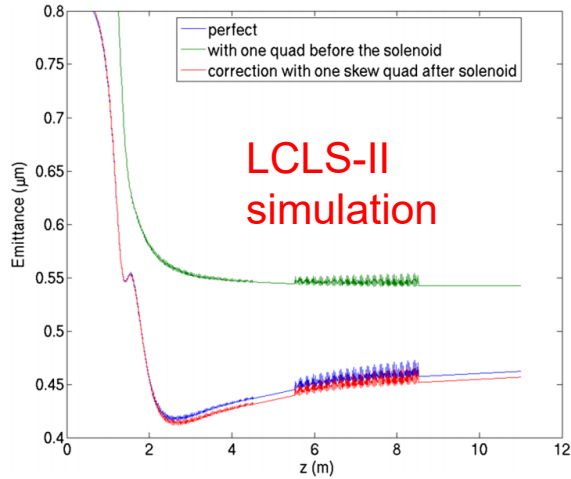
ANL experiment (1 pC)



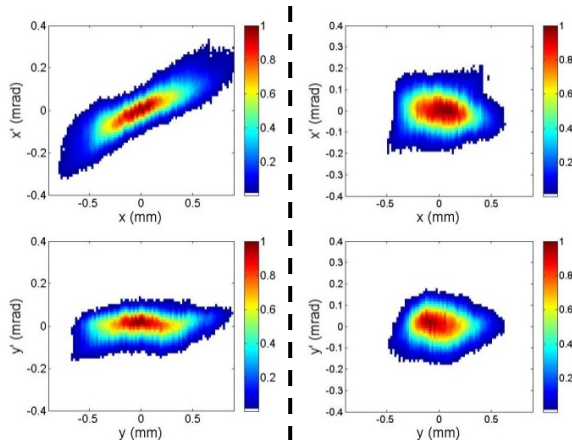
Transverse coupling by quadrupole field error

With space charge

- SLAC injector optimization by skew gun quads scan



- PITZ injector optimization by gun quads optimizer

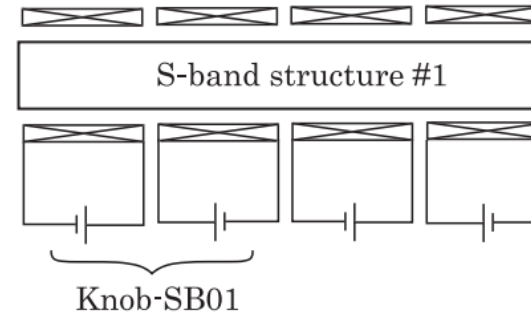


Symmetrize beam after booster by optimizer iterations before emittance measurement.

$\sim 9\%$ emit reduction for 500 pC.

- PSI injector decoupling

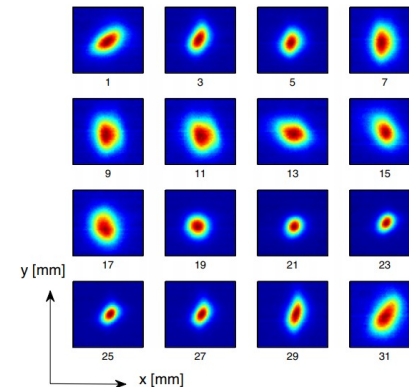
- By gun quads & booster solenoid



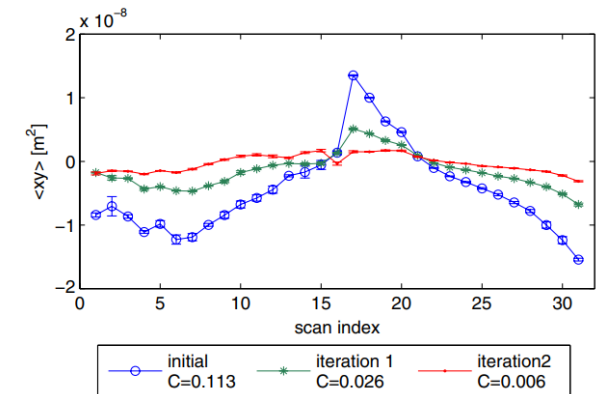
Change booster solenoid current
 \downarrow
 change Larmor angle

- Measure 4D phase space with multi-quad scan

- Measure C_{XY} response matrix to gun quads & booster solenoid
- Iterations, coupling factor $11\% \rightarrow 0.6\%$



Coupling 2.6%

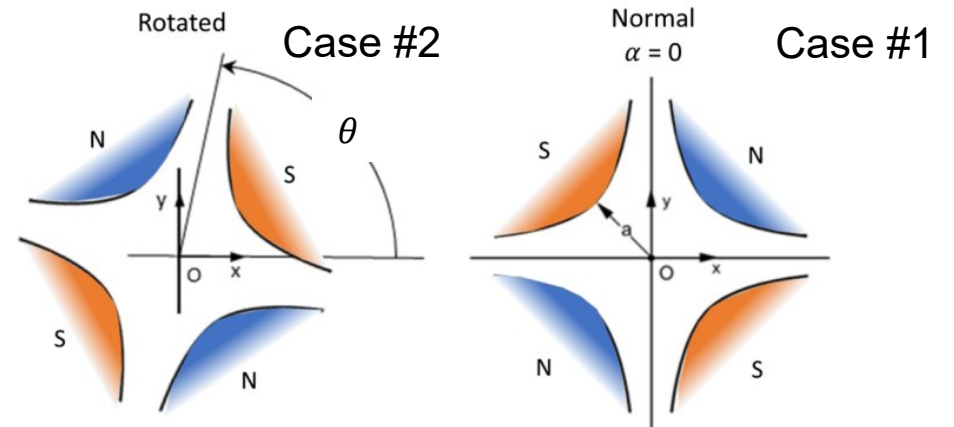


How to tune gun quads under space charge case

A new method

- Current methods
 - Simulation vs experiments to fit quad errors (ANL, UCLA, PITZ)
 - Scan skew quad, measure emittance (SLAC)
 - Corrector iterations by measured sensitivity matrix of C_{XY} vs correctors, measure 4D beam matrix (PSI)
 - Iterations by optimizer to symmetrize beam profile (PITZ)
- A new method
 - Case #1: only a normal quad error in solenoid, no skew quad error, all other elements are symmetric
 - Beam after booster, no coupling, but X/Y asymmetry
 - $C_0 = \begin{bmatrix} C_{XX} & 0 \\ 0 & C_{YY} \end{bmatrix}$
 - $C_{YY} \neq C_{XX}, \varepsilon_x \neq \varepsilon_y$

- A new method (cont'd)
 - Case #2: a rotated quad error in solenoid, rotation angle θ , amplitude is same as case #1



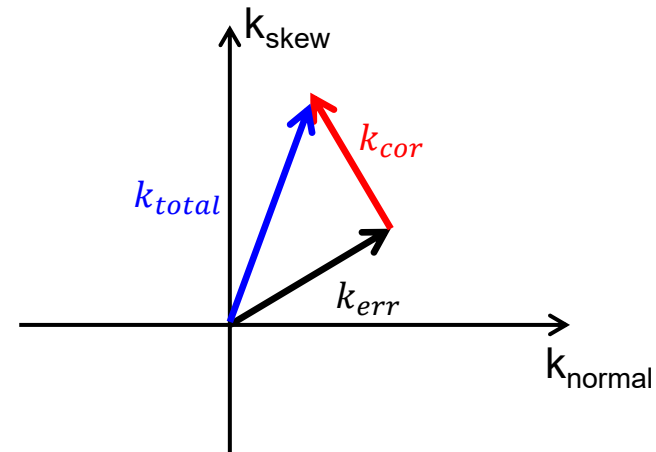
- Case #2 is equivalent to injector #1 rotated by θ
 - So beam after injector of case #2 is
 - $C_\theta = R_{rot} C_0 R_{rot}^T = \begin{bmatrix} \cos^2 \theta C_{XX} + \sin^2 \theta C_{YY} & \sin \theta \cos \theta (C_{YY} - C_{XX}) \\ \sin \theta \cos \theta (C_{YY} - C_{XX}) & \sin^2 \theta C_{XX} + \cos^2 \theta C_{YY} \end{bmatrix}$

How to tune gun quads under space charge case

A new method

- A new method (cont'd)
 - Case #2: $C_{YY} \neq C_{XX}$, so beam is X/Y coupled
 - One way to decouple the beam w/o gun quad is to design a rotation lattice line after booster, but beam will loose symmetry
 - $C_\theta = \begin{bmatrix} \cos^2 \theta C_{XX} + \sin^2 \theta C_{YY} & \sin \theta \cos \theta (C_{YY} - C_{XX}) \\ \sin \theta \cos \theta (C_{YY} - C_{XX}) & \sin^2 \theta C_{XX} + \cos^2 \theta C_{YY} \end{bmatrix}$
 - $\langle xx \rangle = \cos^2 \theta \langle x_0 x_0 \rangle + \sin^2 \theta \langle y_0 y_0 \rangle$
 - $\langle yy \rangle = \sin^2 \theta \langle x_0 x_0 \rangle + \cos^2 \theta \langle y_0 y_0 \rangle$
 - $\langle xy \rangle = \frac{1}{2} \sin 2\theta (\langle y_0 y_0 \rangle - \langle x_0 x_0 \rangle)$
 - $\langle xx \rangle = \langle yy \rangle \rightarrow \theta = \pi/4$, i.e. a pure skew quad
 - $\sigma_x = \sigma_y, \varepsilon_x = \varepsilon_y$
 - $\langle xy \rangle = 0 \rightarrow \theta = 0$, i.e. a pure normal quad
 - Largest asymmetry for X/Y planes, but no coupling

- A new method (cont'd)
 - An integrated quad error at solenoid exit + a rotated quad corrector at solenoid exit
 - Quad error $k_{err} = k_0 e^{i2\theta} = k_0 (\cos 2\theta + i \sin 2\theta)$
 - Quad corrector $k_{cor} = k_c e^{i2\alpha}$
 - Total quad $k_{total} = k_0 e^{i2\theta} + k_c e^{i2\alpha} = k_t e^{i2\phi}$
 - Quad error is fixed
 - Quad corrector is variable
 - Vector plot of quad correction

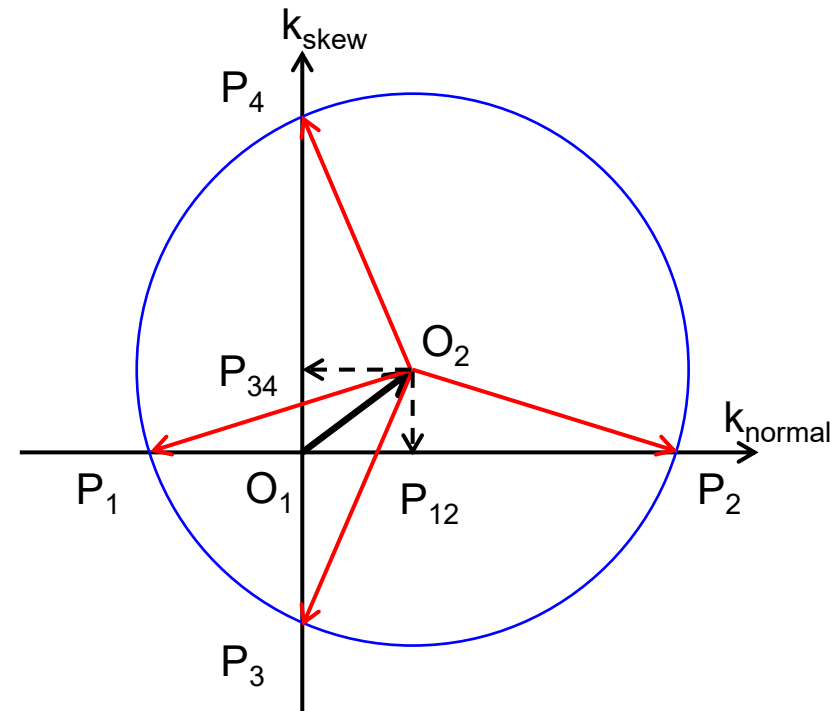


How to tune gun quads under space charge case

A new method

- A new method (cont'd)
 - Vector plot of quad correction
 - Angle scan with arbitrary corrector amplitude
 - O_2P_1 & O_2P_2 correction
 - Pure normal quad error left, $\langle xy \rangle = 0$
 - O_2P_3 & O_2P_4 correction
 - Pure skew quad error left, $\sigma_x = \sigma_y$
 - Normal/skew quad correction
 - $(O_2P_1 + O_2P_2)/2 = O_2P_{12} \rightarrow$ skew quad corrector
 - O_2P_{12} is also the skew quad axis
 - $(O_2P_3 + O_2P_4)/2 = O_2P_{34} \rightarrow$ normal quad corrector
 - O_2P_{34} is also the normal quad axis
 - $O_2P_{12} + O_2P_{34} = O_2O_1$, correction of both normal & skew quad errors

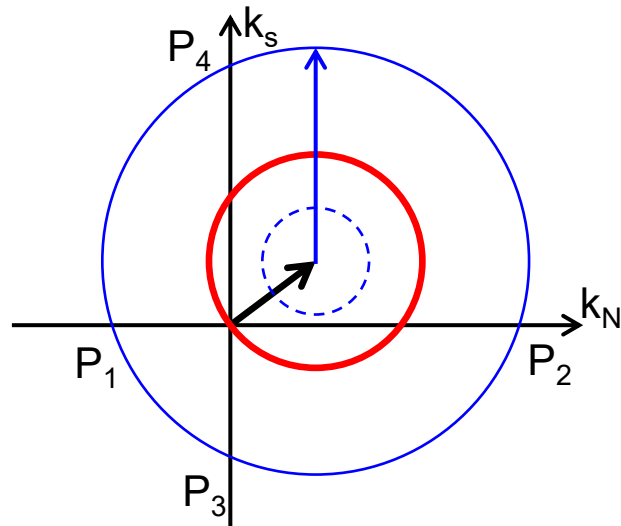
- Advantages of such a method
 - No prior knowledge of quad error angle or amplitude needed, no simulation fit needed
 - No emittance measurement required
 - In ideal case, no iterations



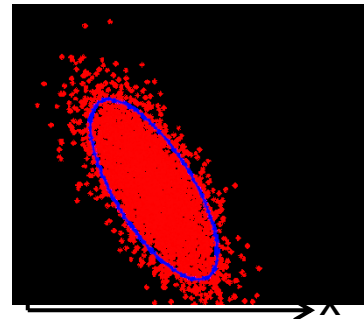
How to tune gun quads under space charge case

A new method

- A new method (cont'd)
 - Special cases
 - When corrector amplitude much smaller than quad error amplitude
 - no P1/2/3/4
 - When corrector amplitude equals error amplitude
 - P1/P3 become one point



- How to find P1/2/3/4
 - Take one corrector amplitude I_0
 - Measure $\langle xy \rangle$, $\langle xx \rangle$, $\langle yy \rangle$, vs corrector angle
 - Find the 4 angles for $\langle xy \rangle = 0$ & $\sigma_x = \sigma_y$
 - The corrector solution is $I_c = \frac{1}{2} I_0 \sum_{n=1}^4 e^{i2\alpha_n}$
 - Gun Q1: $re(I_c)$
 - Gun Q2: $im(I_c)$
- Normalized beam profile properties
 - RMS ellipse $gx^2 + 2axy + by^2 = e$
 - $e = \sqrt{\langle xx \rangle \langle yy \rangle - \langle xy \rangle^2}$
 - $b = \langle xx \rangle / e$
 - $g = \langle yy \rangle / e \Rightarrow b=g, a=0$
 - $a = -\langle xy \rangle / e$



How to tune gun quads under space charge case

A new method

- A new method (cont'd)
 - Special cases like FLASH/XFEL injector
 - 1st screen after booster is already after a quadrupole based lattice
 - The transport matrix from before the 1st high energy quad to the 1st screen
 - $R = \begin{bmatrix} R_X & 0 \\ 0 & R_Y \end{bmatrix}, R_X \neq R_Y$
 - In case #2, the beam on the 1st screen is
 - $C_{scr} = RC_\theta R^T$

$$\begin{bmatrix} R_X(\cos^2 \theta C_{XX} + \sin^2 \theta C_{YY})R_X^T & \sin \theta \cos \theta R_X(C_{YY} - C_{XX})R_Y^T \\ \sin \theta \cos \theta R_X(C_{YY} - C_{XX})R_Y^T & R_Y(\sin^2 \theta C_{XX} + \cos^2 \theta C_{YY})R_Y^T \end{bmatrix}$$

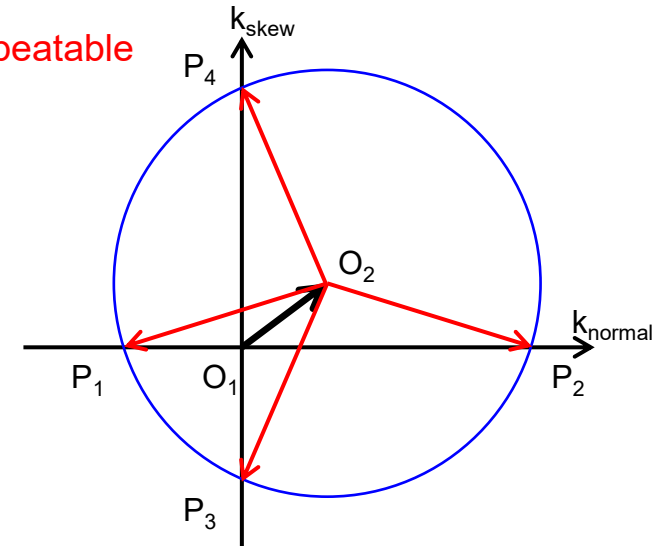
- A new method (cont'd)
 - Special cases like FLASH/XFEL injector
 - $\theta = 0$, i.e. a pure normal quad $\rightarrow \langle xy \rangle = 0$
 - $\theta = \pi/4$, i.e. a pure skew quad

$$\frac{1}{2} \begin{bmatrix} R_X(C_{XX} + C_{YY})R_X^T & R_X(C_{YY} - C_{XX})R_Y^T \\ R_X(C_{YY} - C_{XX})R_Y^T & R_Y(C_{XX} + C_{YY})R_Y^T \end{bmatrix}$$

$$\sigma_x \neq \sigma_y$$

- P1/P2 can be found
 - Skew quad correction repeatable
- P3/P4 can not be found

Normal quad correction not repeatable, unless do emittance measurement, otherwise variable normal quad component leads to burden on injector matching.



Transverse coupling by cathode laser asymmetry

- No space charge case

- Assumption

- Small cathode laser asymmetry between x and y, $\langle xy \rangle = 0$
- Twiss parameter similar between x and y planes inside Larmor coordinate
- No quad errors

- Beam matrix after solenoid rotation

$$C_{rot} = \begin{bmatrix} \cos^2 \theta C_{XX} + \sin^2 \theta C_{YY} & \sin \theta \cos \theta (C_{YY} - C_{XX}) \\ \sin \theta \cos \theta (C_{YY} - C_{XX}) & \sin^2 \theta C_{XX} + \cos^2 \theta C_{YY} \end{bmatrix}$$

- Projected emittance

$$\varepsilon_x = \cos^2 \theta \varepsilon_{x0} + \sin^2 \theta \varepsilon_{y0}$$

$$\varepsilon_y = \sin^2 \theta \varepsilon_{x0} + \cos^2 \theta \varepsilon_{y0}$$

- $\varepsilon_x \varepsilon_y \geq \varepsilon_{4D}^2 = \varepsilon_{x0} \varepsilon_{y0}$

- Additional effects with space charge

- Assumption

- 3D ellipsoidal case with a small non-equal x and y semi axis
 - $r_x = r_0(1 + \delta)$, $r_y = r_0(1 - \delta)$

- Space charge force asymmetry

$$E_{sx} = coef * \frac{x}{r_x} = k_0(1 - \delta)x$$

$$E_{sy} = coef * \frac{y}{r_y} = k_0(1 + \delta)y$$

- Equivalent to a symmetric case plus a normal quadrupole
- The final quad error angle will be decided by the solenoid rotation and initial laser asymmetry axis

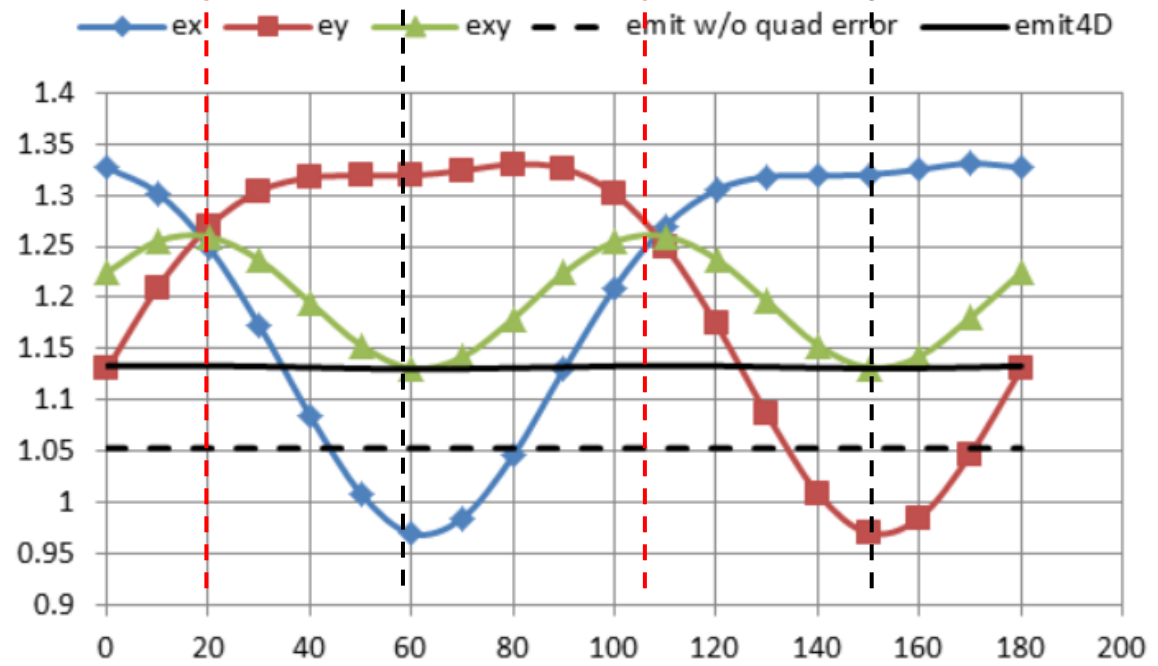
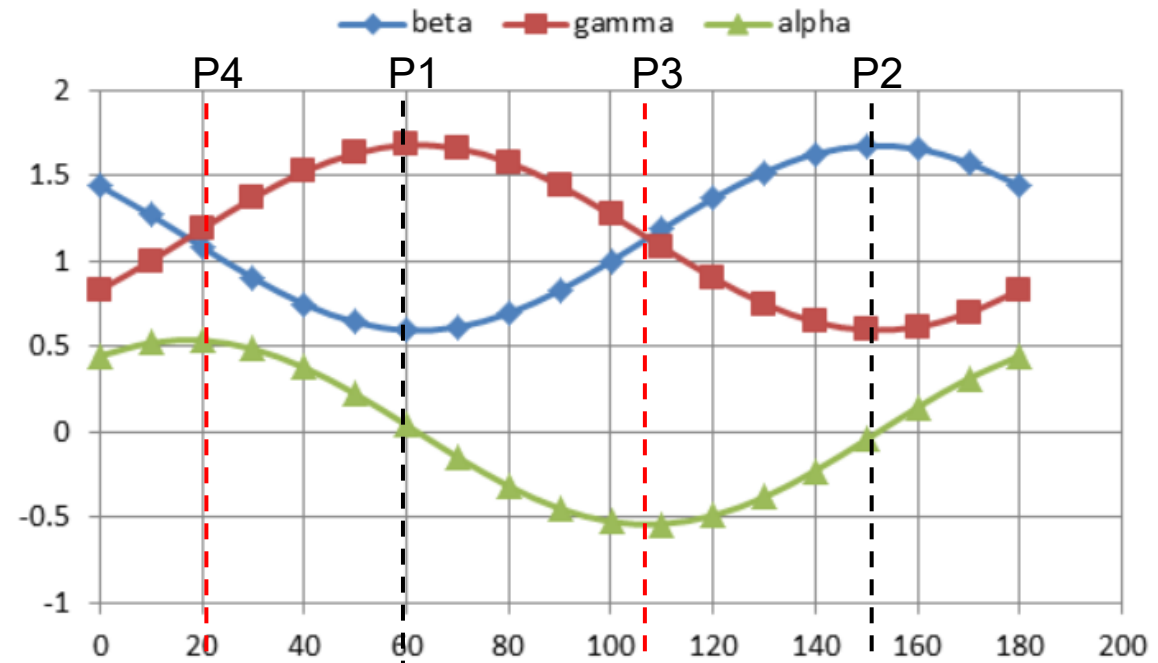
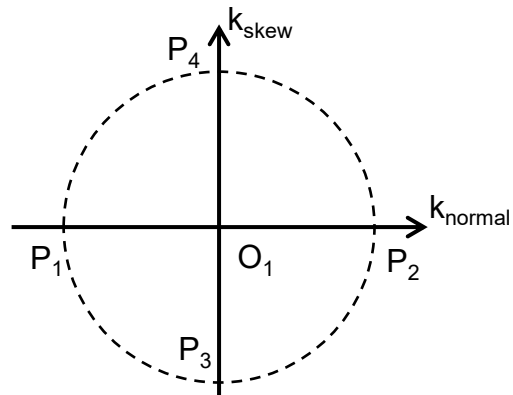
Simulations

- Simulation setup
 - Laser, 6 ps FWHM, BSA 1.3 mm, 500 pC (PITZ experiment optimizations)
 - PITZ setup, gun 6.3 MeV/c + booster
 - A distributed quadrupole error field like SLAC measurement
 - Using gun solenoid field map as a quad field map, inspired by the ANL study, quad angle can be configured in ASTRA
 - Quadrupole error strength assumption in simulation
 - Typical solenoid focusing strength k is $\sim 3.5 \text{ m}^{-1}$
 - Integrated focusing strength k is $\sim 0.01 \text{ m}^{-1}$, focal length $\sim 100 \text{ m}$ (typical range 50–100 m), roughly $\sim 0.3\%$ compared to solenoid strength
- Simulation setup (cont'd)
 - Rotated quad corrector model
 - Around current Gun Q1/Q2 position
 - 5 cm effective length
 - Angle and gradient variable
 - Case studies
 - Quadrupole error study
 - Quad error only, angle and amplitude scan
 - Quad error + quad corrector
 - Laser asymmetry
 - No corrector
 - With quad corrector

Quadrupole error study

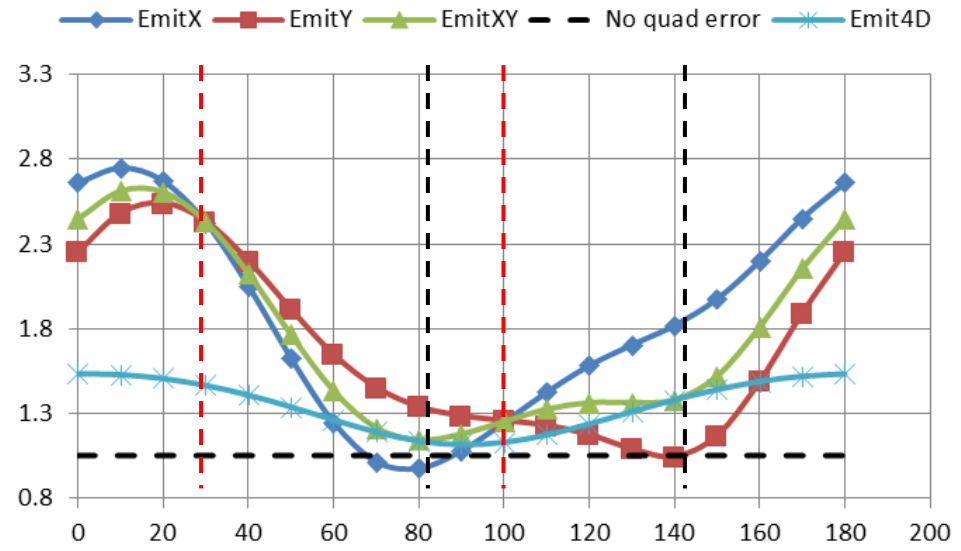
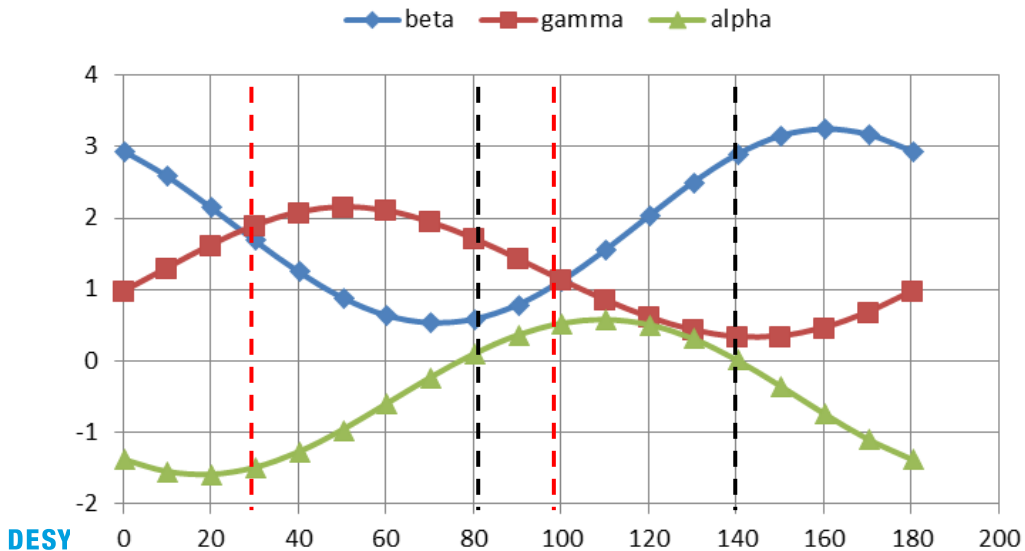
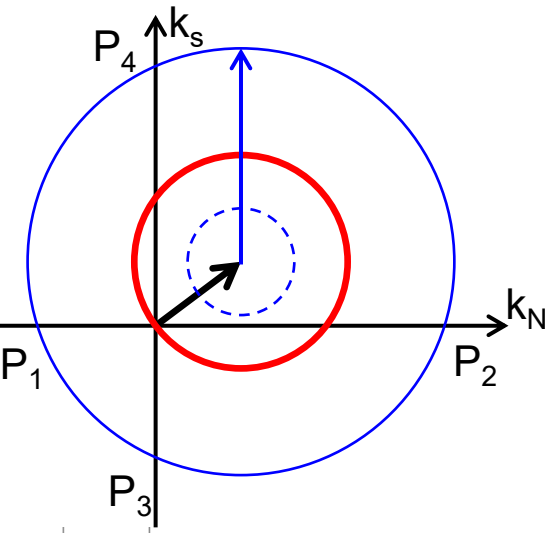
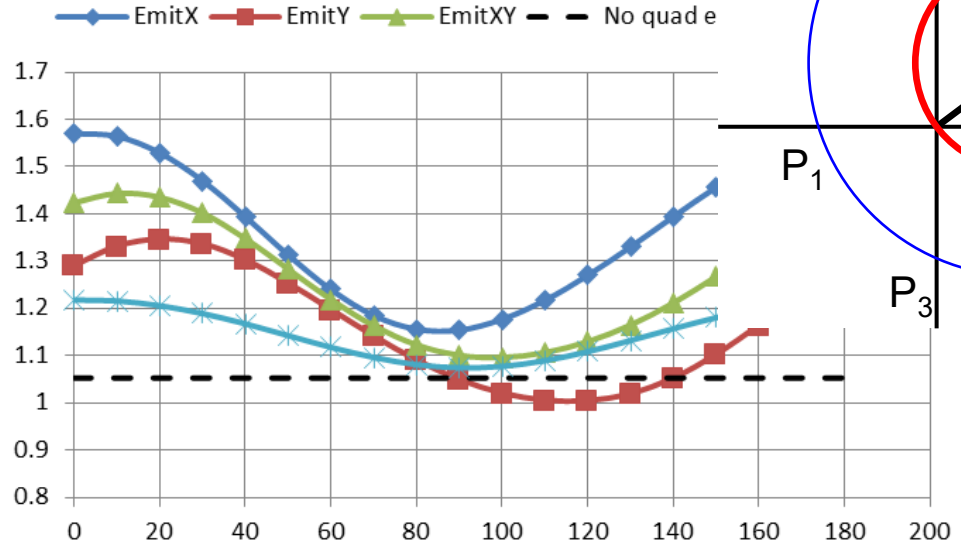
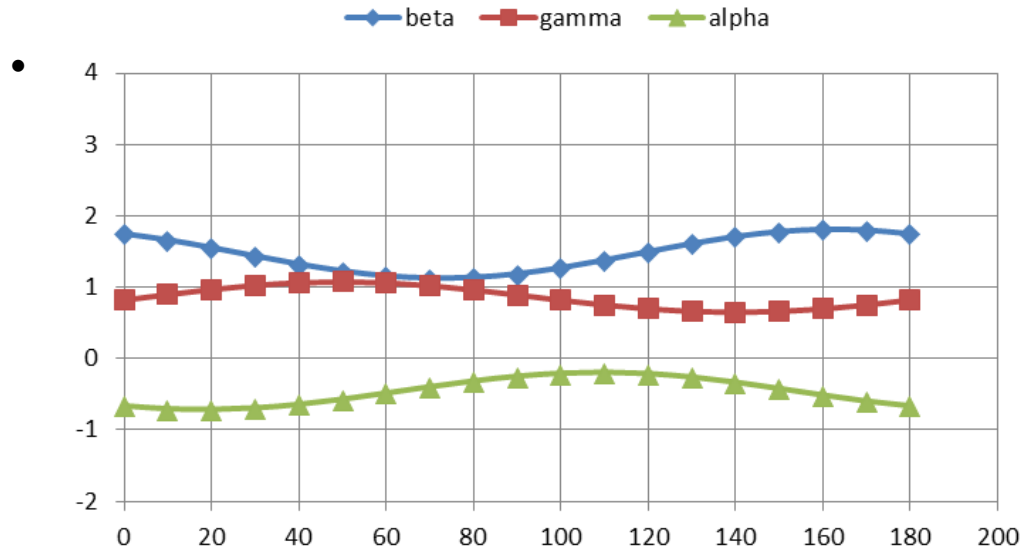
Quad error only, angle scan with step 10 degree

- ASTRA simulations w/ 3D space charge
- Observations:
 - Regular oscillations of parameters vs quad error angle
 - In contrast to no space charge case, emitX and emitY are not equal
 - 4D emittance is constant w.r.t. angle
 - 4D emittance with quad error larger than 4D emittance without quad error, in contrast to no space charge case
 - Best emittance, no coupling, worst X/Y symmetry
 - Simulation consistent with beam matrix rotation



Quadrupole error study

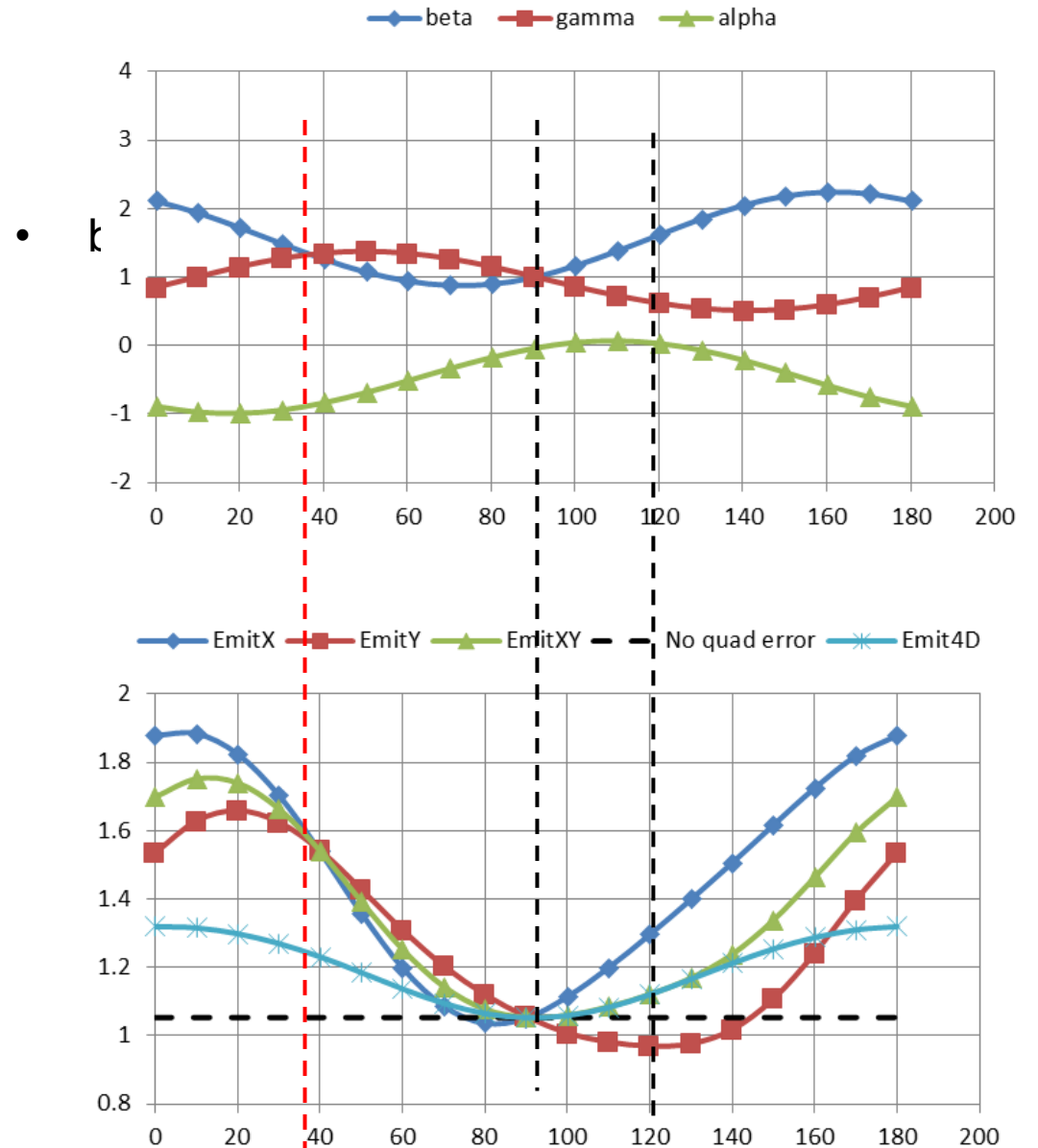
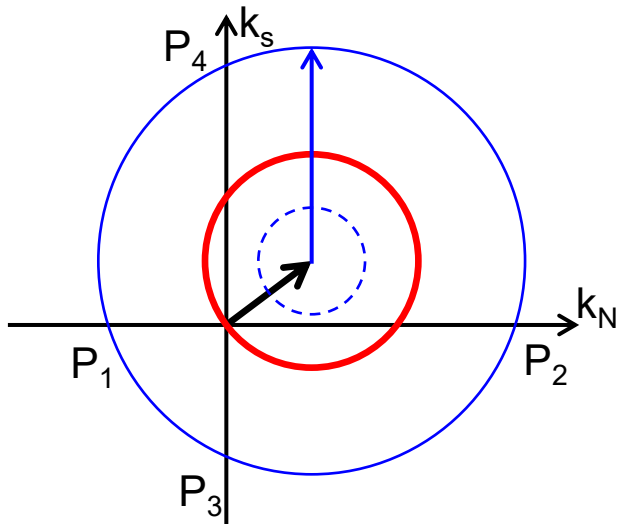
Quad error + quad corrector



Quadrupole error study

Quad error + quad corrector

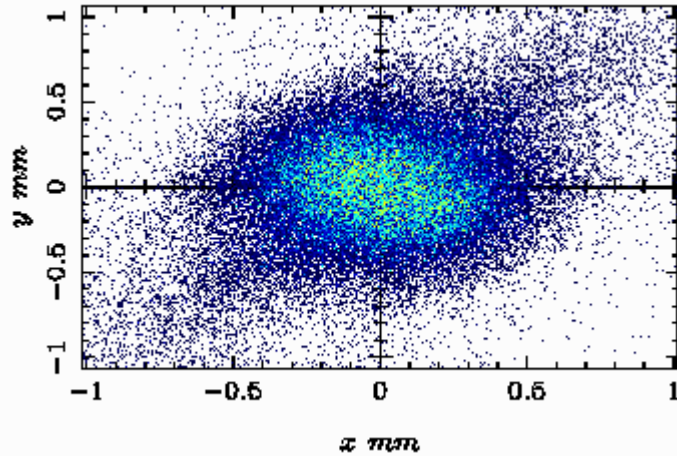
- Corrector amplitude matches error amplitude by manual scan, both emit and beam size symmetry
- Amp 60 G/m, angle 90 deg
- Analytical formula prediction, $I_c = \frac{1}{2} I_0 \sum_{n=1}^4 e^{i2\alpha_n}$
 - 63.78 G/m, angle 92.1 deg
 - Consistent results when scanning quad corrector angle with variable strength



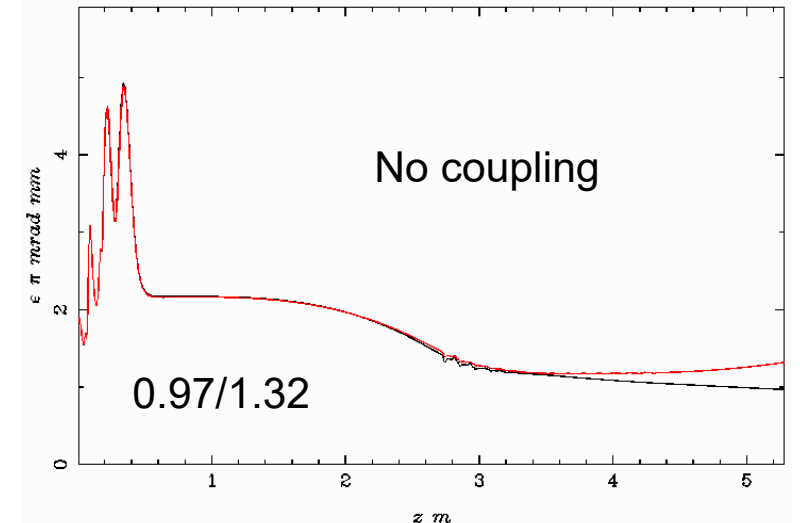
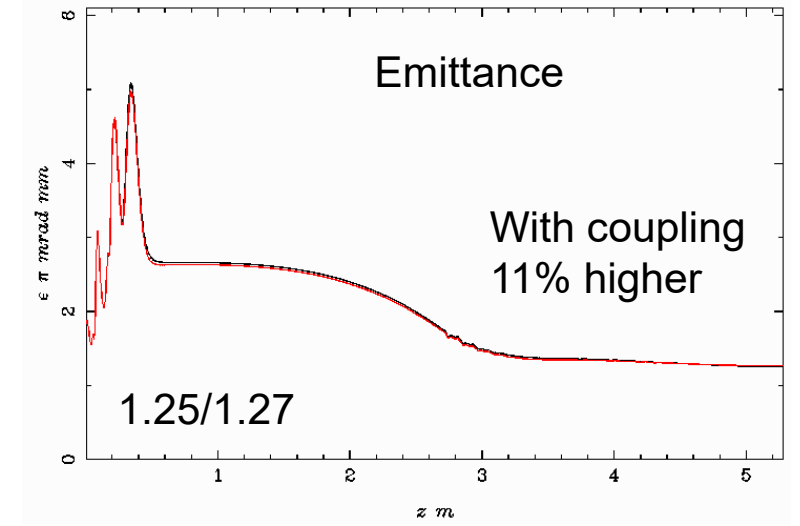
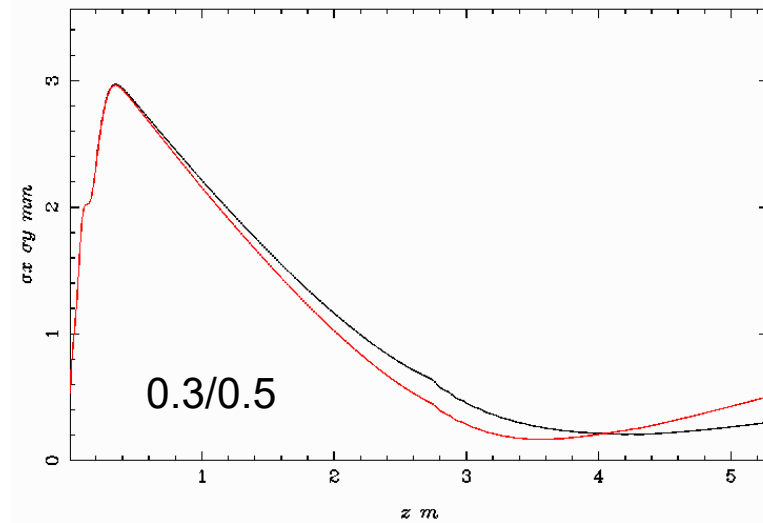
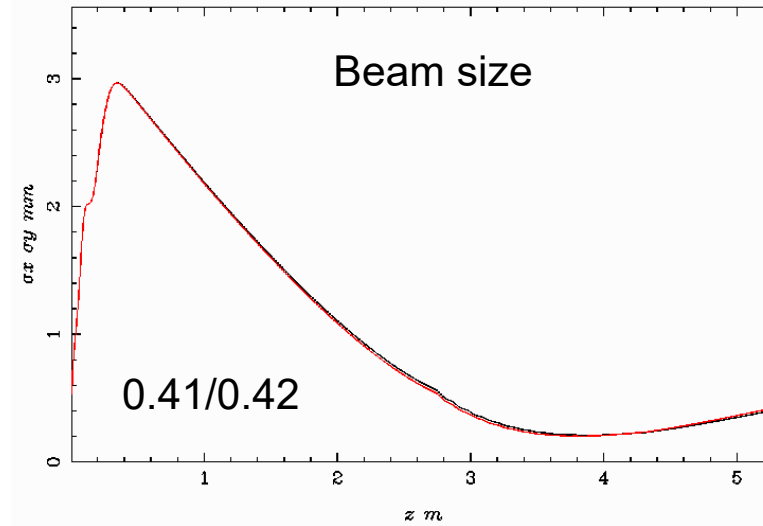
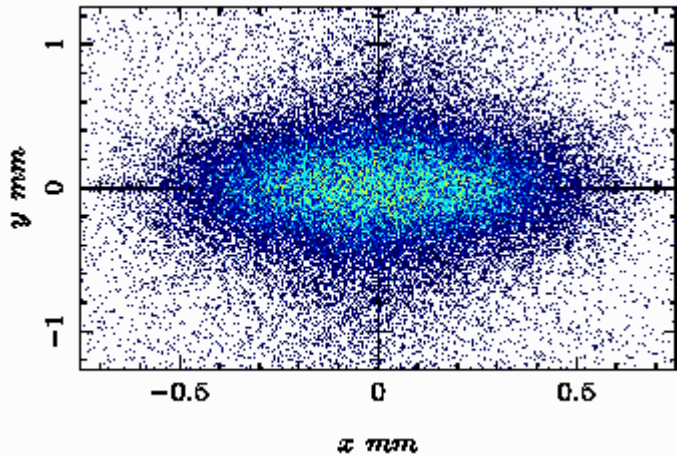
Before correction

- H1.scr1

Pure skew quad error

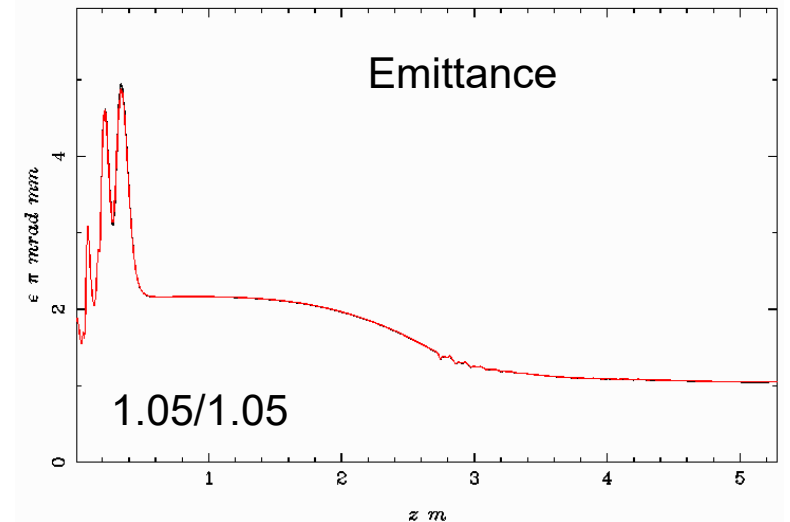
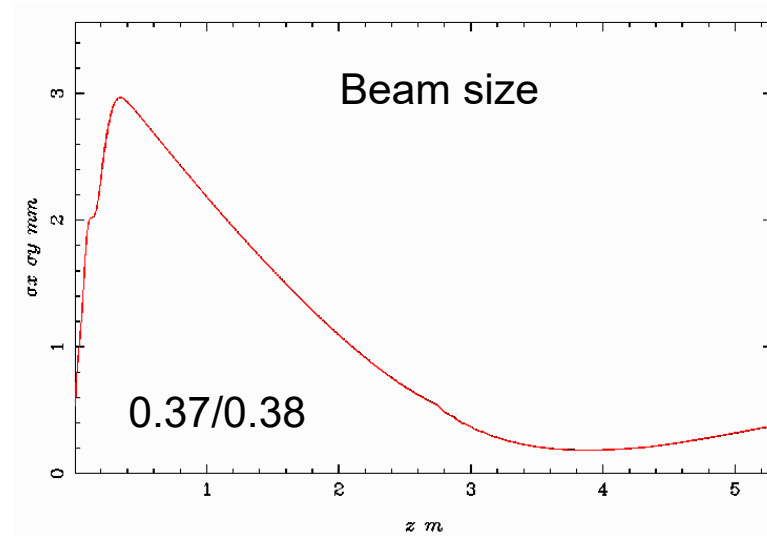
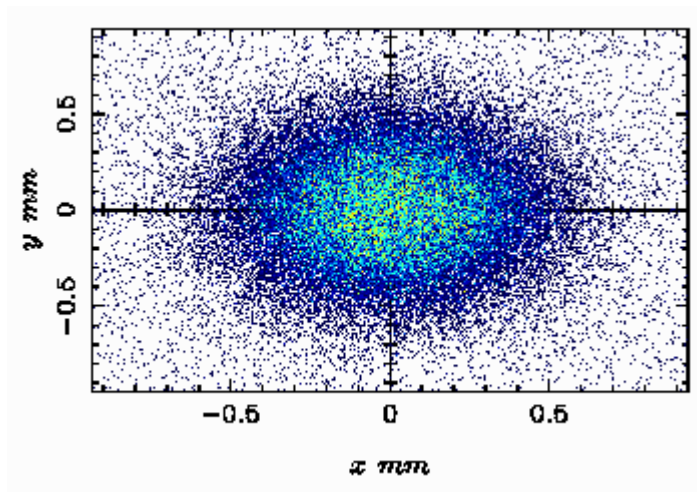


Pure normal quad error



After correction

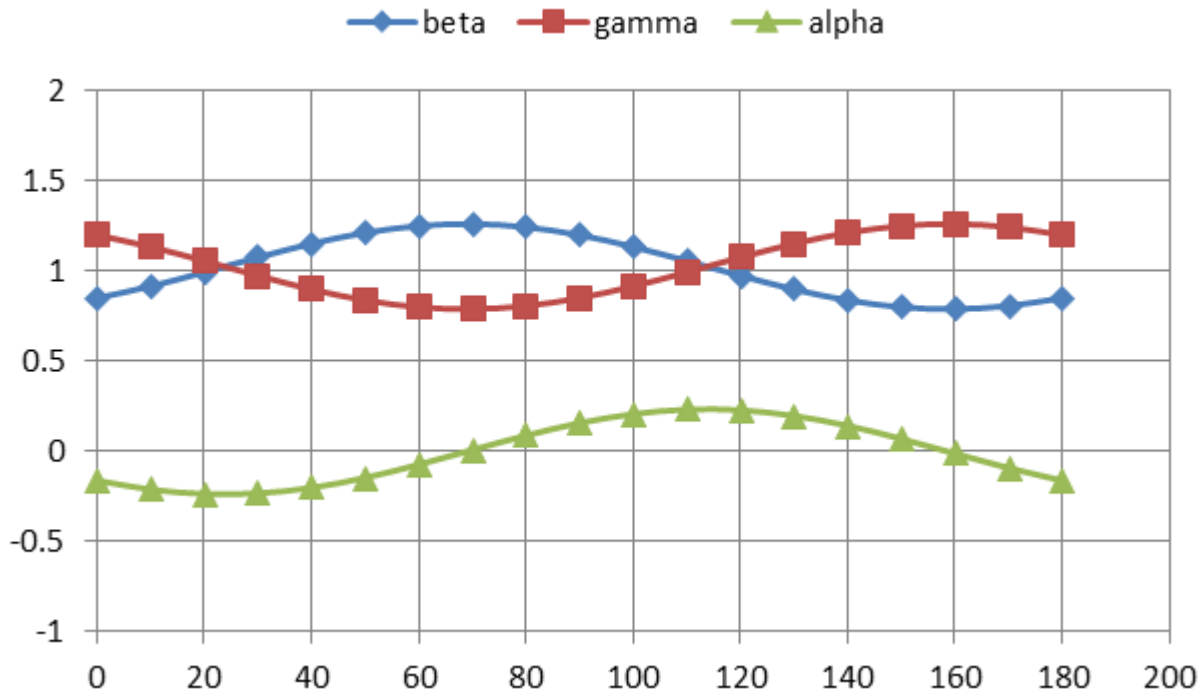
- Both beam size and emittance symmetry restored
- Emittance is same again as case without any quad error



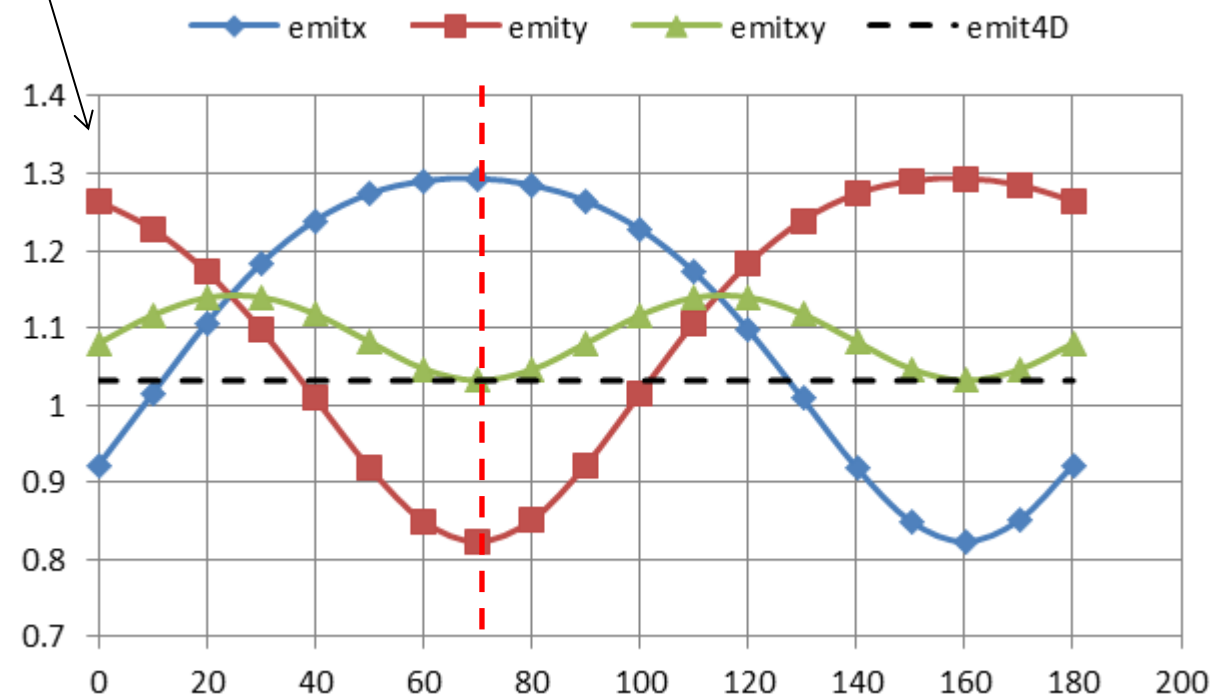
Laser asymmetry 10% p-p

w/o quad correction

- Rotation of asymmetric cathode laser on cathode
 - Smaller effect on beam size asymmetry than quad error in solenoid of strength 0.01 m^{-1}
 - Larger effect on beam emittance asymmetry
 - 4D emittance is same as symmetry case



Upright case



Laser asymmetry 10% p-p

w/ quad corrector

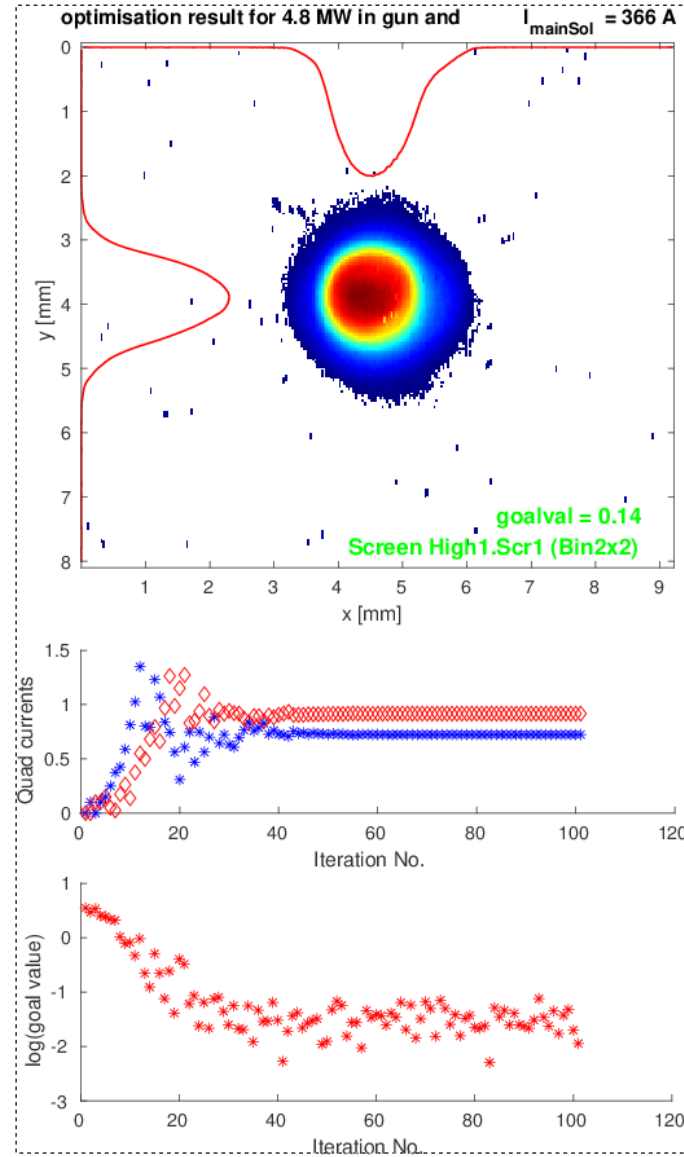
- Formula prediction
 - 35.3 G/m, -46 degree for upright laser asymmetry
- Partial correction
 - 0.36/0.36 mm
 - 0.95/1.17 mm.mrad

Experiment 1 (2020/0312N)

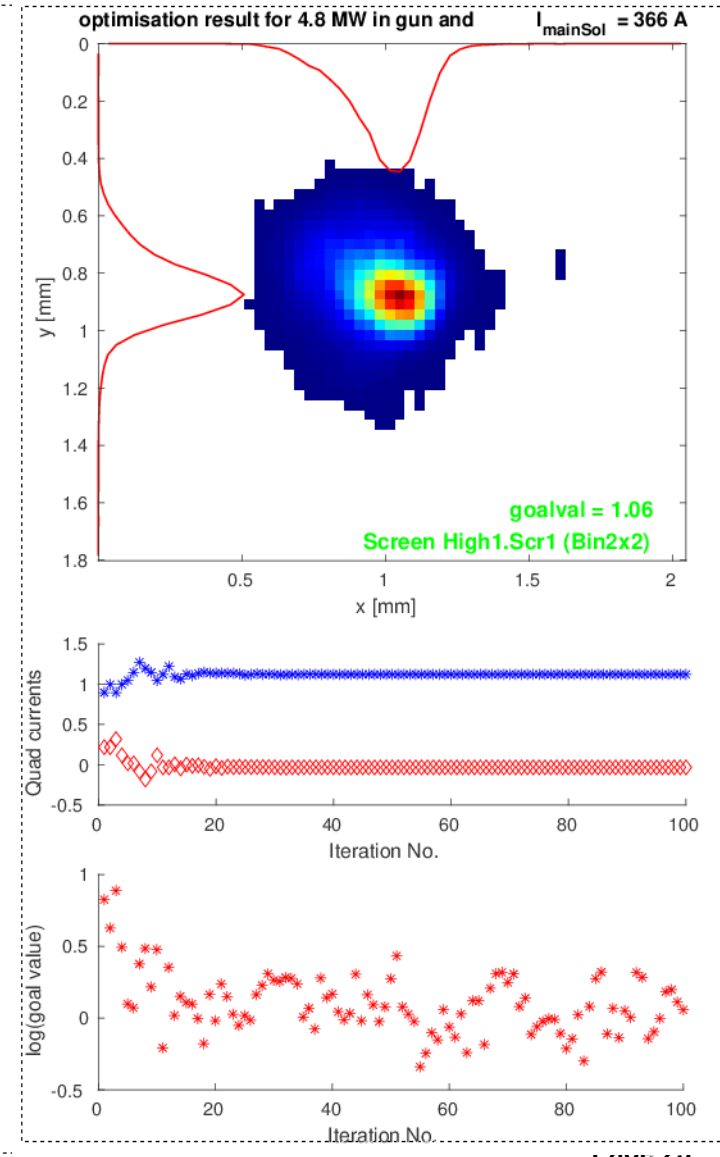
Gun quad rotation vs optimizer, vs charge

- Experiment settings
 - BSA1mm, Solenoid 366 A
 - Gun SP 59.9, MMMG, 6.3 MeV/c
 - Booster SP 16, MMMG, 19.7 MeV/c
- 30 pC gun quad optimizer
 - $I_{q1} = 0.724$ A, $I_{q2} = 0.917$ A
 - Amp: 1.17 A, angle: 25.8°
- 300 pC gun quad optimizer
 - $I_{q1} = 1.122$ A, $I_{q2} = -0.033$ A
 - Amp: 1.12 A, angle: -0.8°
- For both charge, 3 gun quad scans
 - 0.5x amp, 0:10:180 degree
 - 1x amp, 0:10:180 degree
 - 2x amp, 0:10:180 degree

30 pC with EMSY1 LYSO



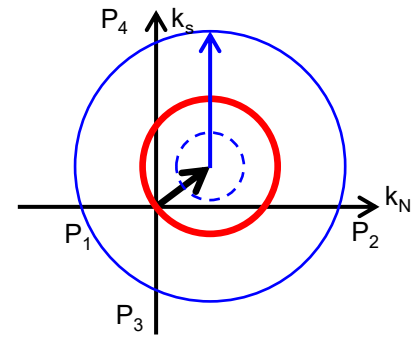
300 pC with EMSY1 YAG



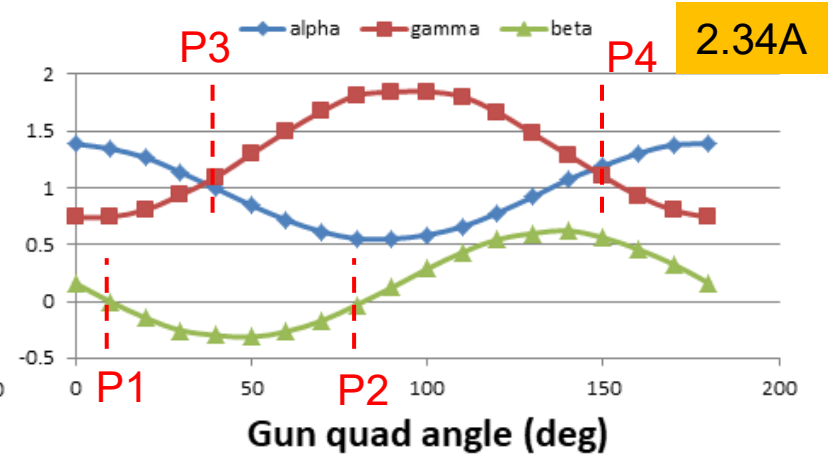
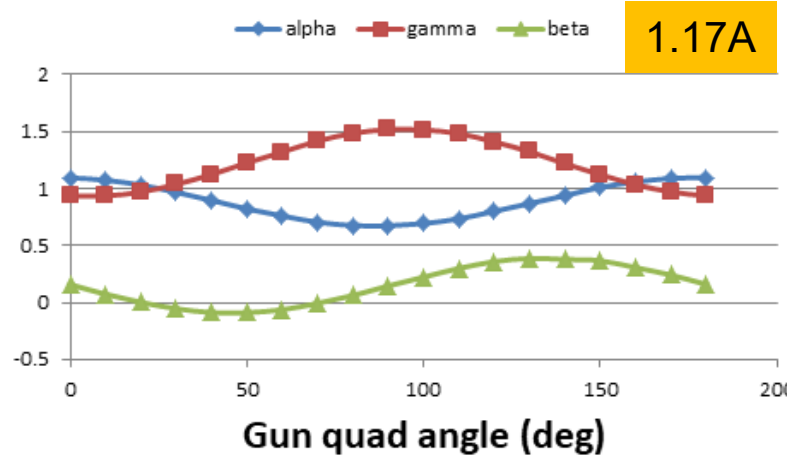
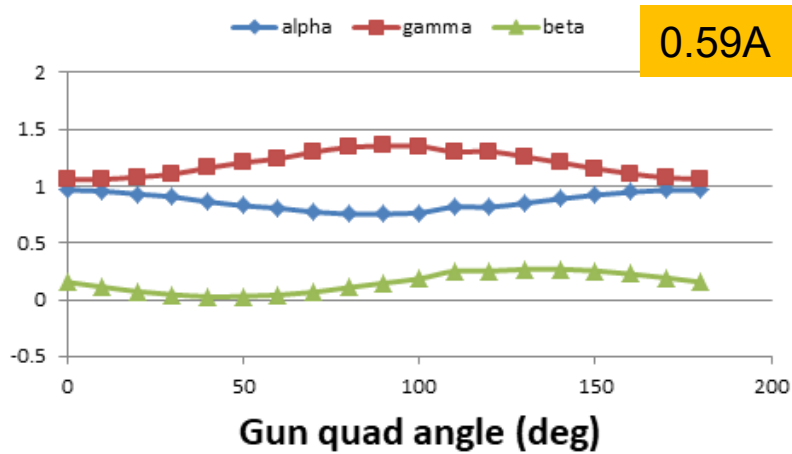
Experiment 1 (2020/0312N)

Gun quad rotation vs optimizer, vs charge

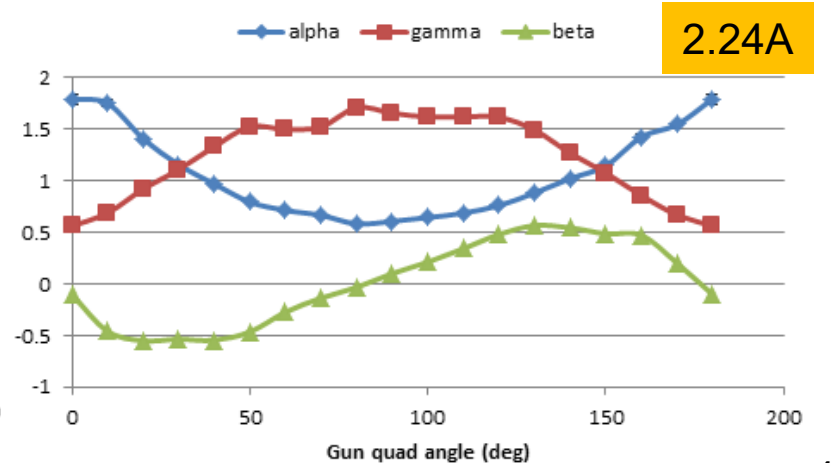
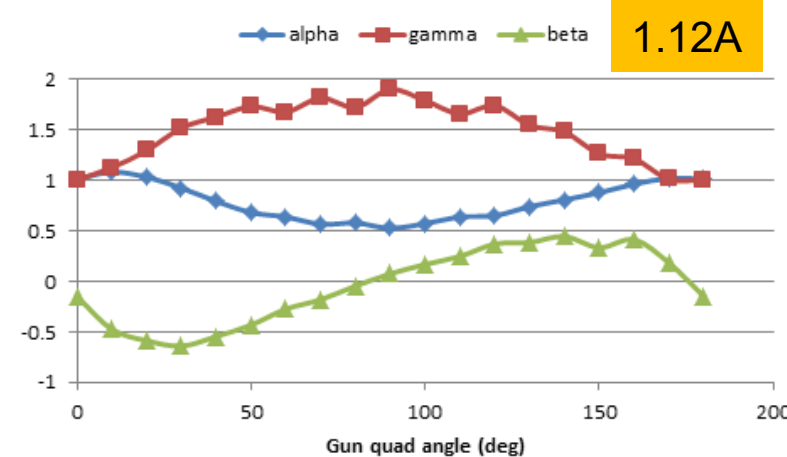
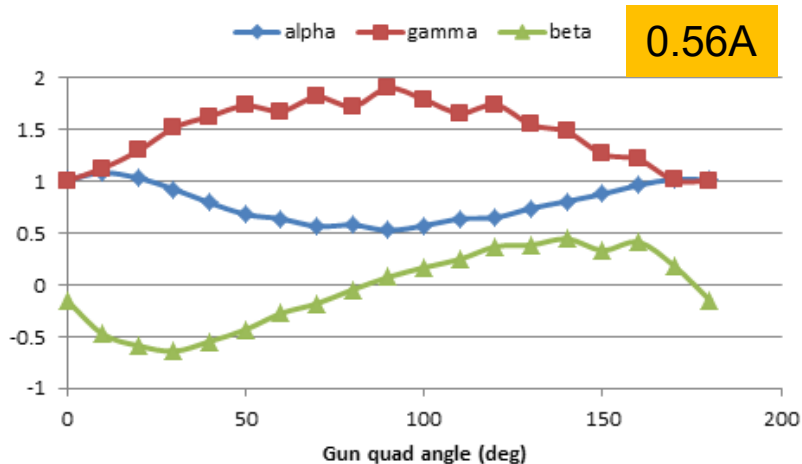
$$I_c = \frac{1}{2} I_0 \sum_{n=1}^4 e^{i2\alpha_n}$$



- 30 pC (sum of pixel during rotation, ~1% rms variation, EMSY1 lyso screen)



- 300 pC (sum of pixel during rotation, ~8% rms variation, EMSY1 YAG screen)



Experiment 1(2020/0312N)

Gun quad rotation vs optimizer, vs charge

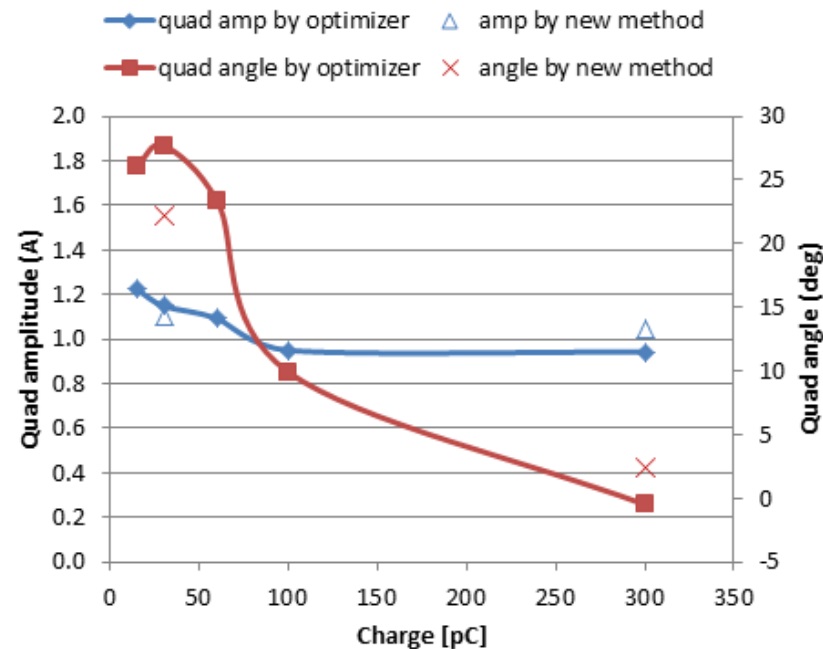
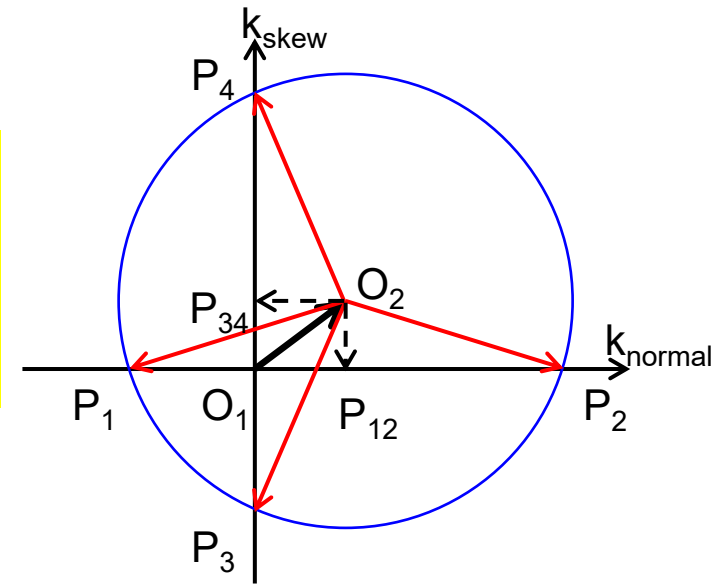
- 30 pC (sum of pixel during rotation, ~1% rms)
 - Based on scan with 1x amp: 1.11 A, 22.4°
 - Based on scan with 2x amp: 1.10 A, 22.3°
 - Gun quad optimizer: 1.17 A, 25.8°
- 300 pC (sum of pixel during rotation, ~8% rms)
 - Based on scan with 1x amp: 1.06 A, 0.8°
 - Based on scan with 2x amp: 1.05 A, 4.1°
 - Gun quad optimizer: 1.12 A, -0.8°
- 15-300 pC (by gun quad optimizer)

charge	Q1	Q2	pulses	Amp	phase
15	0.749	0.967	10	1.22	26.1
30	0.653	0.946	8	1.15	27.7
60	0.75	0.795	3	1.09	23.3
100	0.894	0.322	10	0.95	9.9
300	0.942	-0.016	3	0.94	-0.5

Vs charge scan:

- Amplitude change is small
- Phase is sensitive to charge
 - Not consistent with simulation

Q (pC)	Amp	angle
30	0.532	93.2°
500	0.552	87.4°



All measurements show:

P12 ~45x2 deg
gun Q2 happens to be skew axis

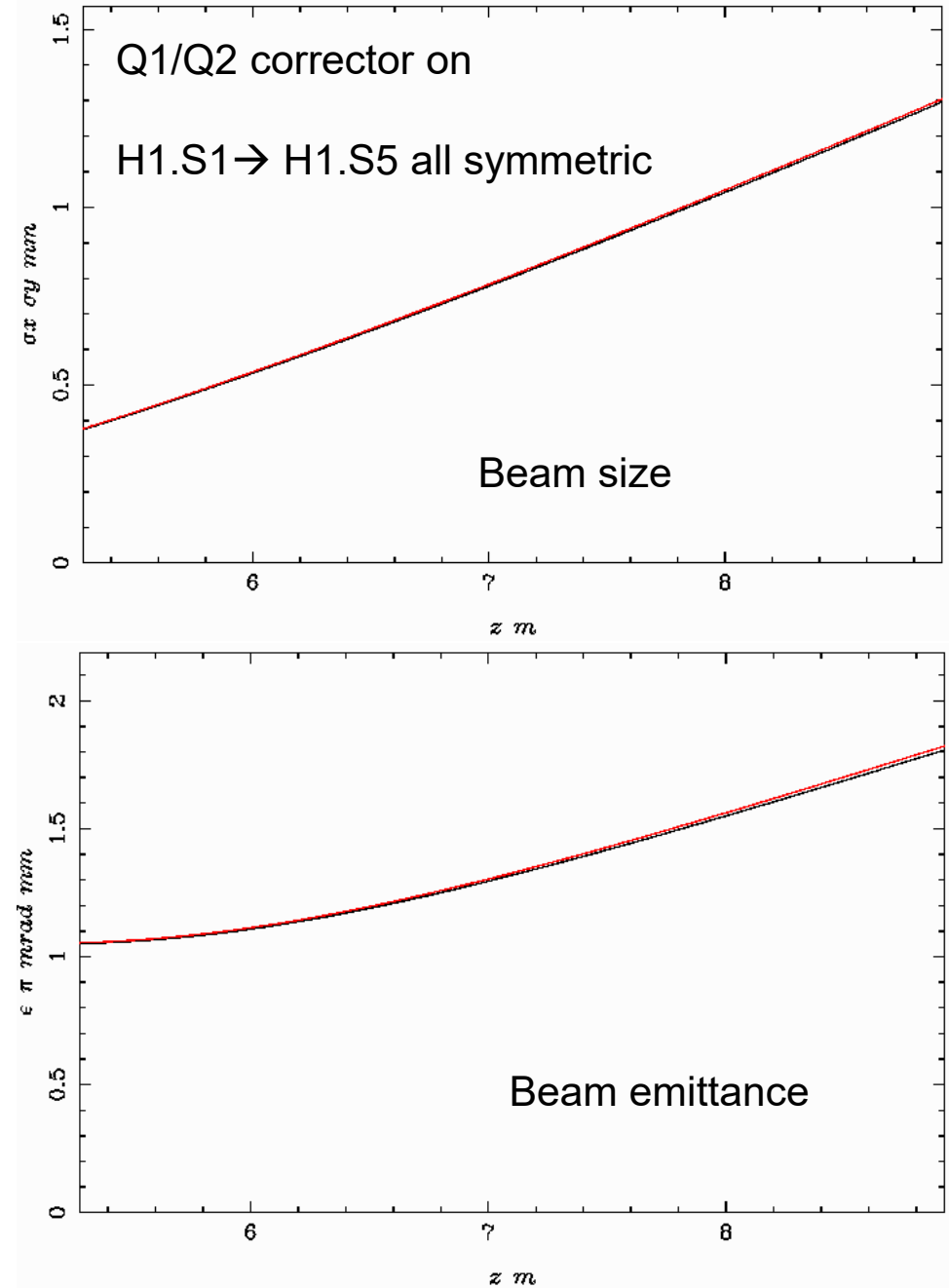
P34 ~90x2 deg
Gun Q1 happens to be normal axis

Integrated quad error O1O2
~0 deg around 250pC, pure normal quad, no coupling, only breaks beam symmetry

Experiment 2 (2020/0315A)

Gun quad rotation vs screen

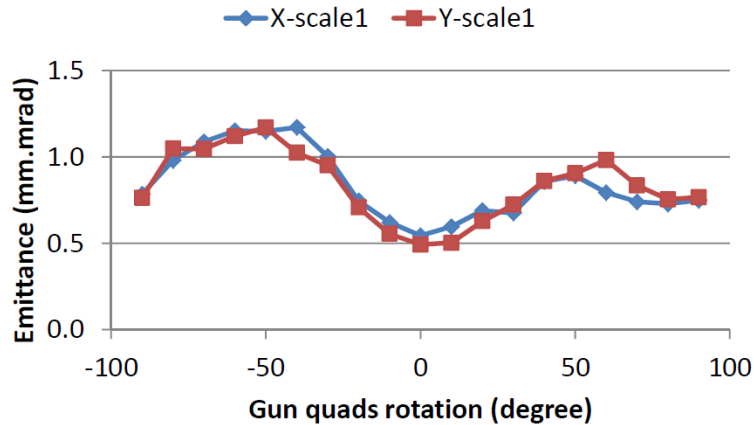
- Experiment settings
 - BSA1mm, Solenoid 360 A, 30 pC
 - Gun SP 59.9, MMMG, 6.3 MeV/c
 - Booster SP 16, MMMG, 19.4 MeV/c
- H1.S1 by optimizer: 1.04 A, 22.5°
 - Quad rotation: 1.03 A (+/-0.03 A), 26.6° (+/-0.1°)
- H1.S5
 - Quad rotation: 0.97 A (+/-0.02 A), 20.5° (+/-0.4°)
- Possible reasons for difference
 - Beam is already slightly asymmetric on cathode
 - Not possible to reach full symmetric beam again
- Simulation
 - Beam symmetric on cathode
 - Distributed quadrupole field error along solenoid
 - Gun Q1/Q2 corrector predicted by rotation analysis



Experiment 3

Emittance vs gun quad angle

- 250 pC (BSA1mm, laser 6 ps FWHM)
 - 2019/1019



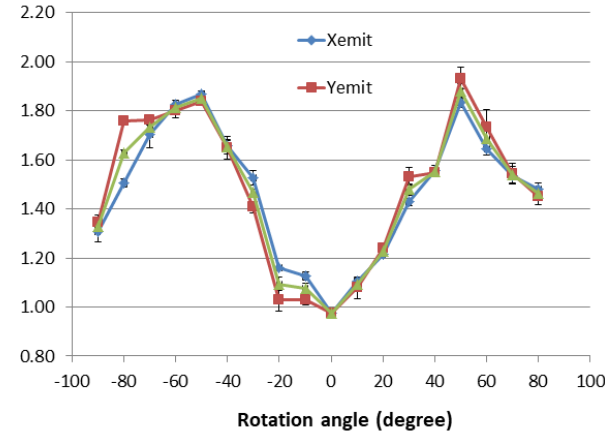
Quad by optimizer: 1.07 A, 1.8° @250 pC
(very similar after 5 months, 1.05A, 2.5° @300pC)

Best scale1: 0.52 mm.mrad
Best scale2: 0.61 mm.mrad
Xrms/Yrms=1.1

Worst emittance with wrong correction angle: 1.2 mm.mrad

Effective quad error for both charges happens to be a pure normal quad error.
That's why emittance improvement is only ~7%.

- 500 pC (BSA1.3mm, laser 6 ps FWHM)
 - 2019/1120



(quads off)
Best scale1: 1.06 mm.mrad
Best scale2: 1.46mm.mrad

Xrms/Yrms=0.8
Xscale1/Yscale1=0.98
Xscale2/Yscale2=0.65

Quad by optimizer: 1.20 A, -0.0° @500 pC
(similar to 250 pC)

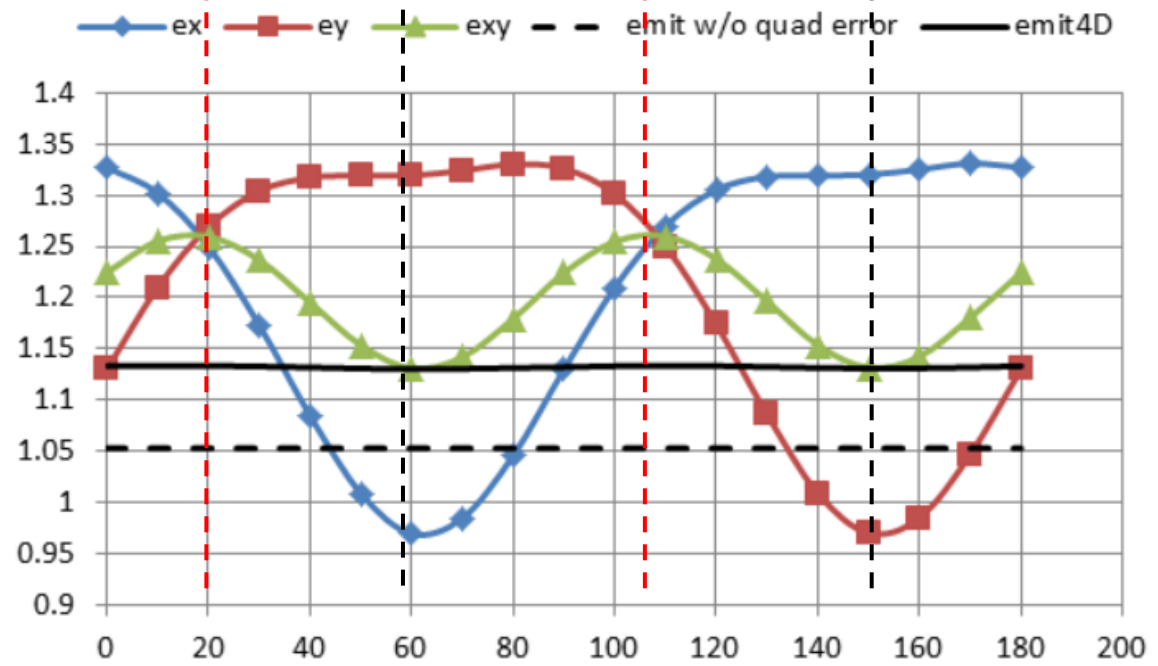
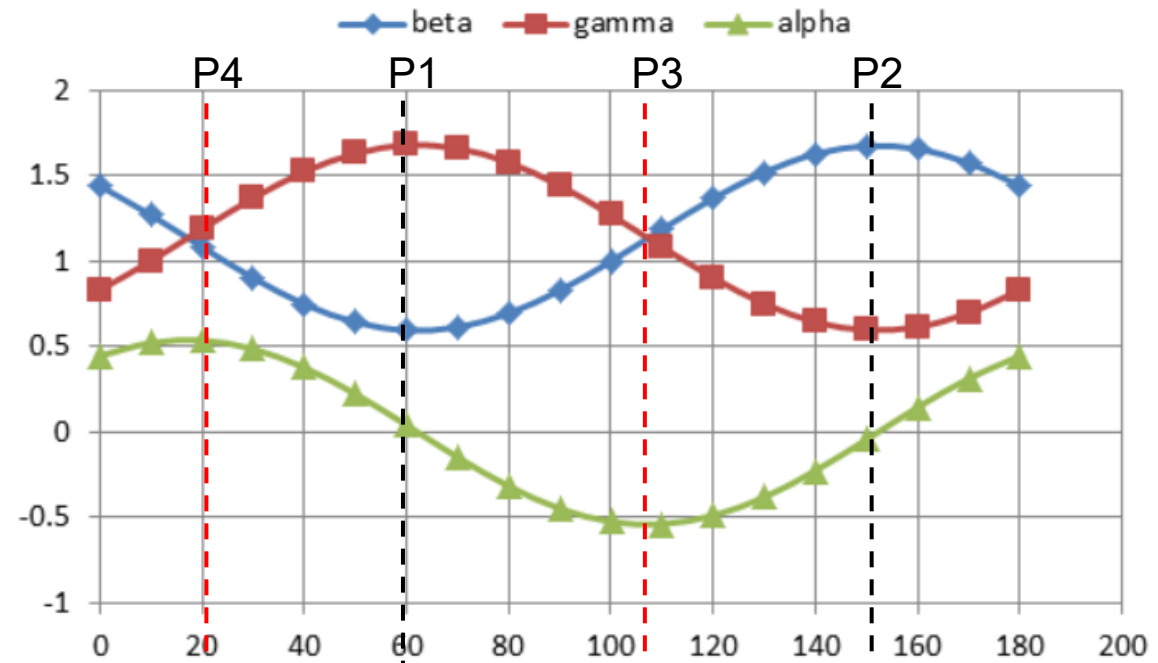
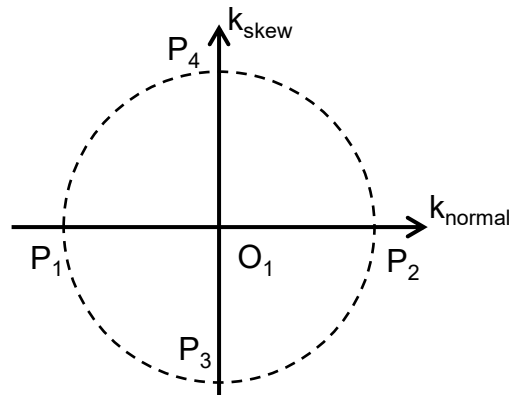
Best scale1: 0.98 mm.mrad (uniform laser)
Best scale2: 1.37mm.mrad
Xrms/Yrms=1.02, Xscale1/Yscale1=1.0, Xscale2/Yscale2=0.9

Worst emittance with wrong correction angle: 1.9 mm.mrad

Quadrupole error study

Quad error only, angle scan with step 10 degree

- ASTRA simulations w/ 3D space charge
- Observations:
 - Regular oscillations of parameters vs quad error angle
 - In contrast to no space charge case, emitX and emitY are not equal
 - 4D emittance is constant w.r.t. angle
 - 4D emittance with quad error larger than 4D emittance without quad error, in contrast to no space charge case
 - Best emittance, no coupling, worst X/Y symmetry
 - Simulation consistent with beam matrix rotation



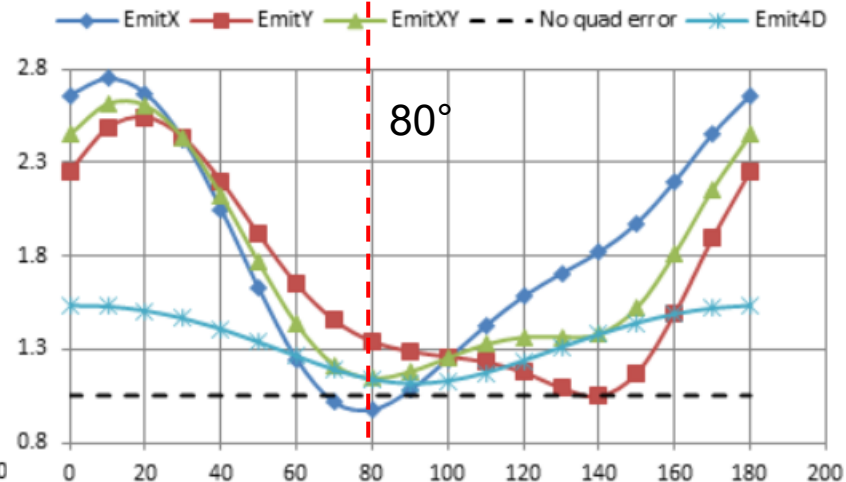
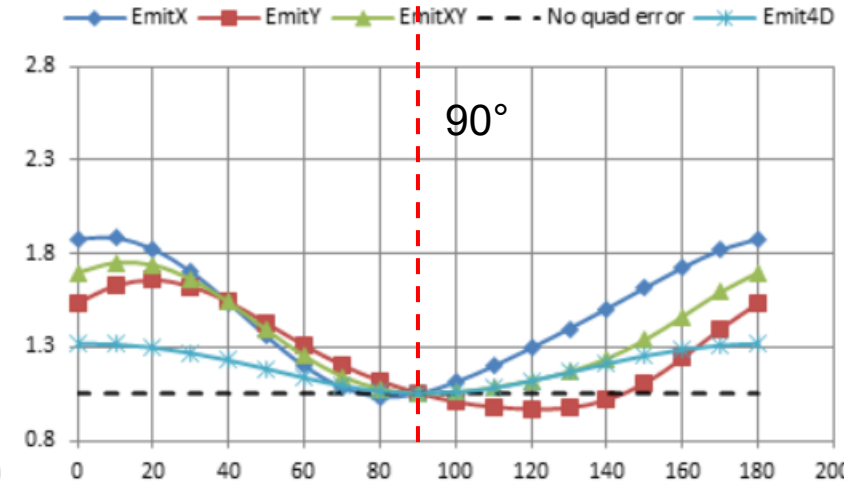
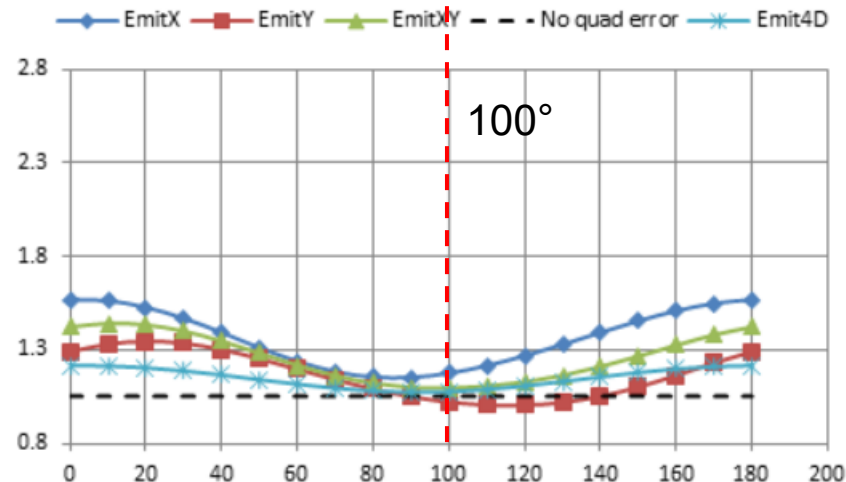
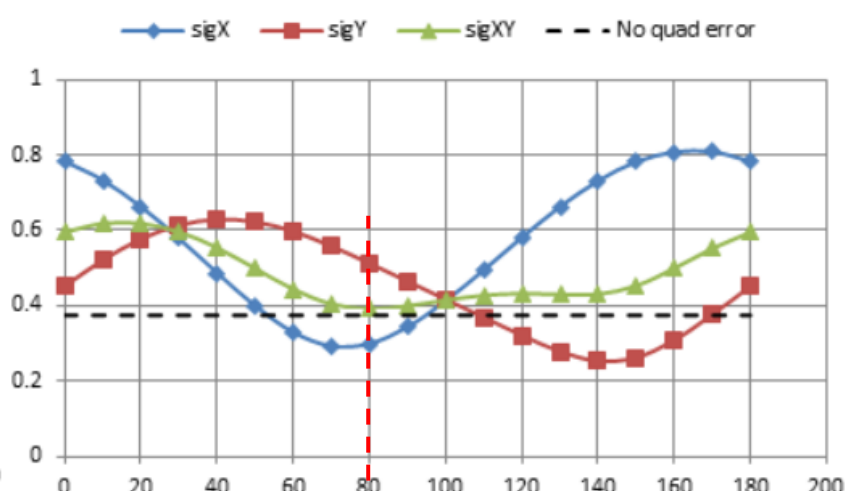
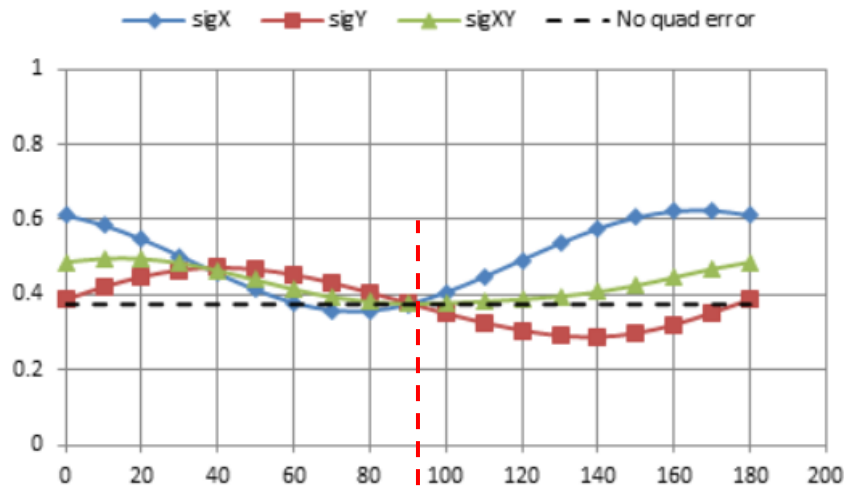
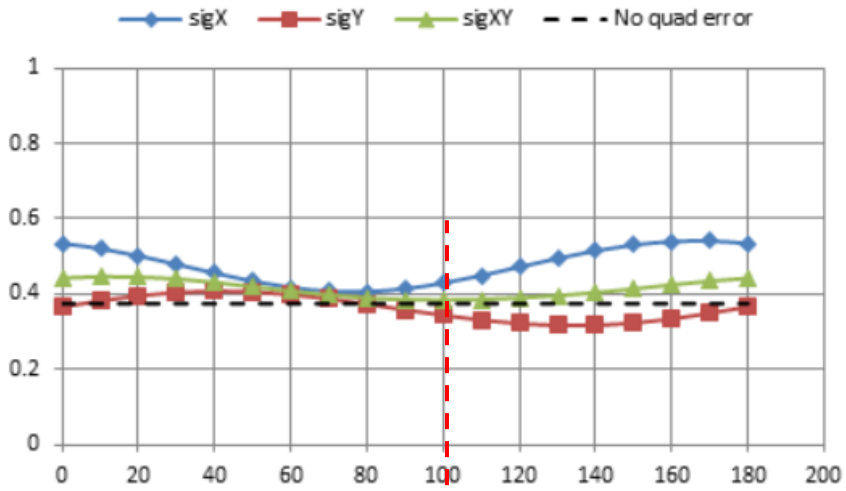
Experiment 4 (2019/1120)

Emittance vs gun quad amplitude: 500 pC simulations (BSA1.3mm, laser 6 ps FWHM)

- Corrector amp=0.5x error amp

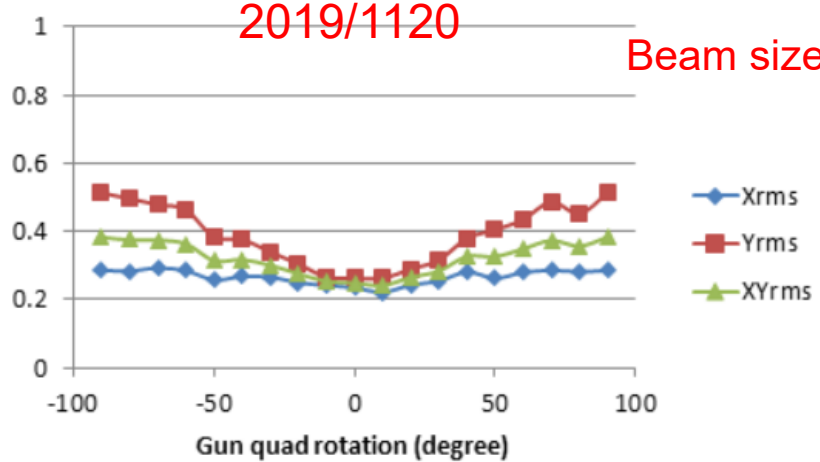
Corrector amp=1x error amp

Corrector amp=2x error amp



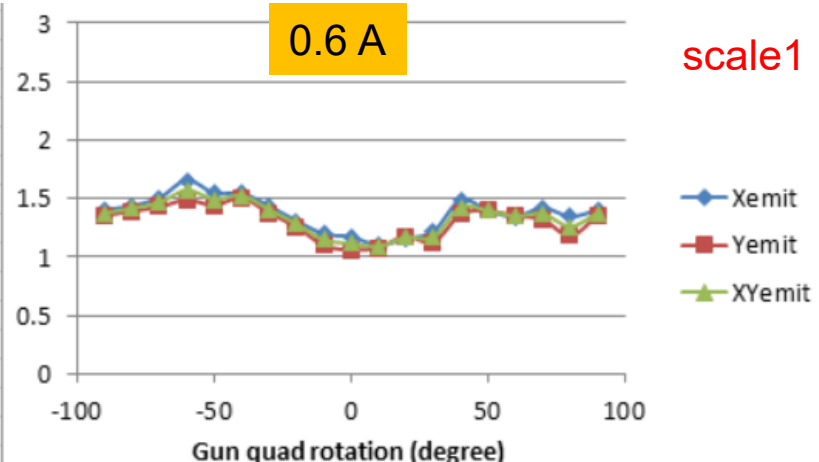
2019/1120

Beam size

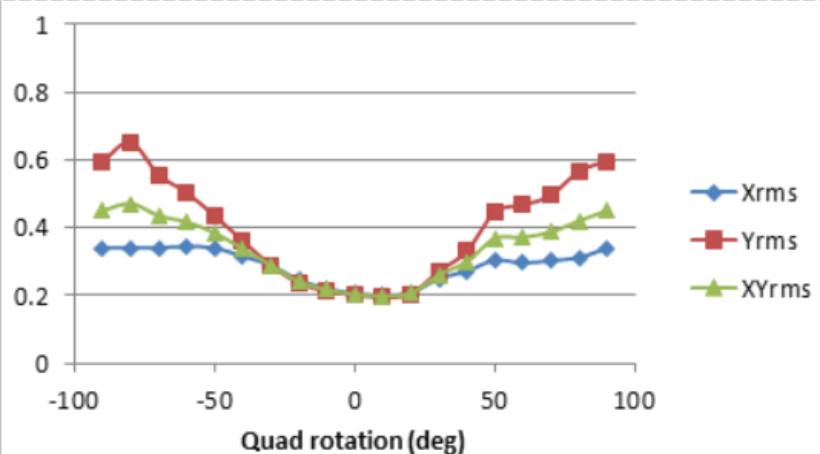
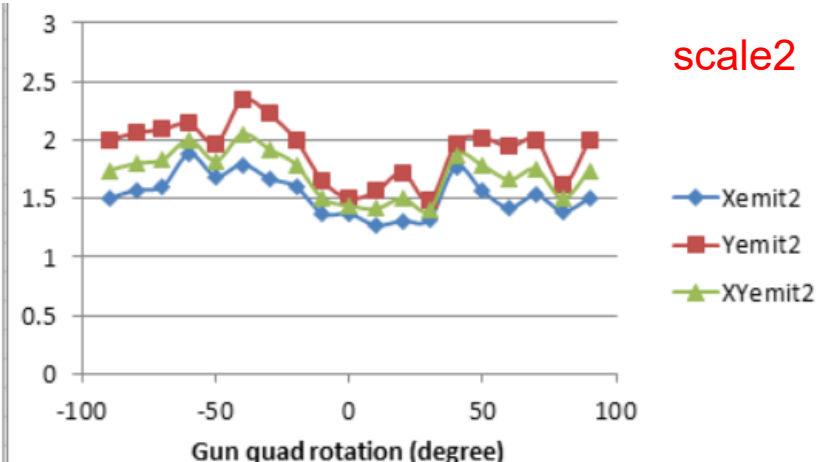


0.6 A

scale1

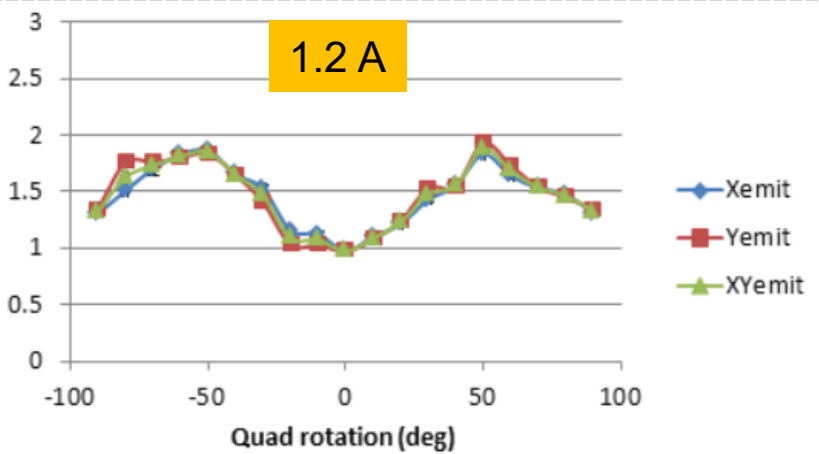


scale2

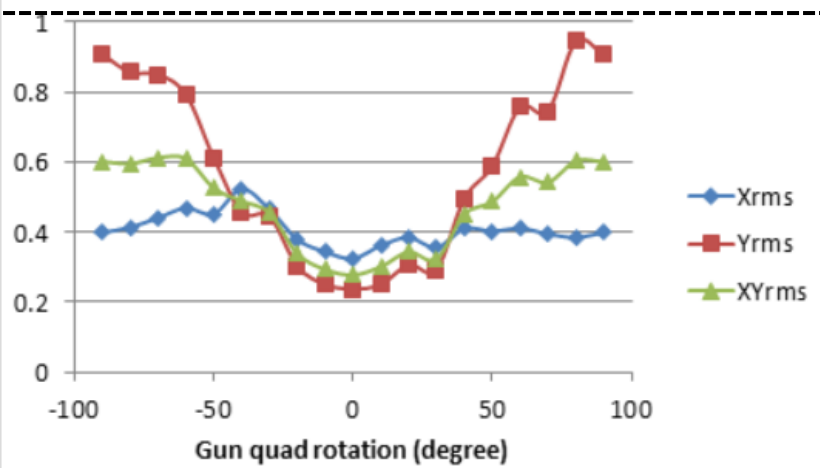
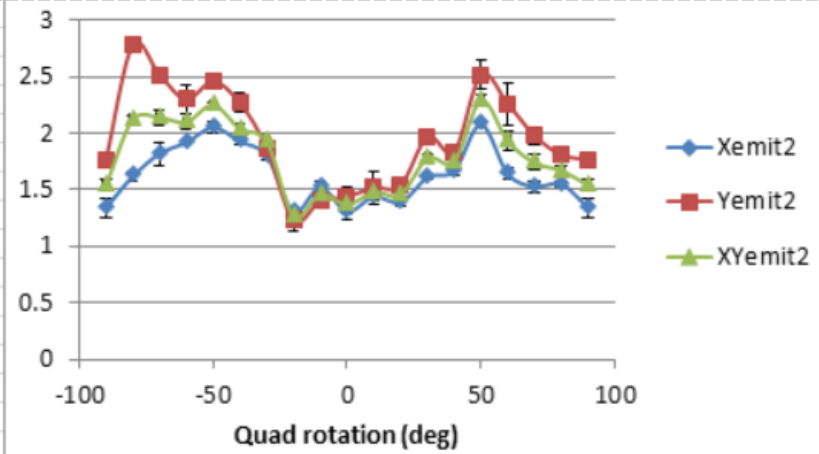


1.2 A

scale1

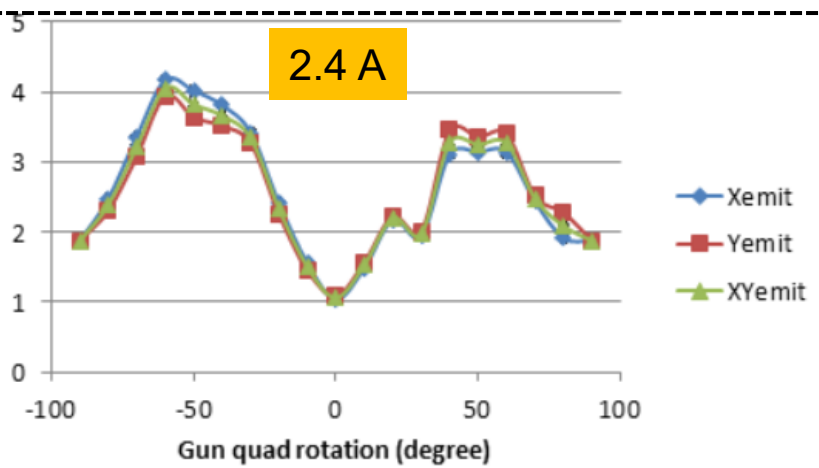


scale2

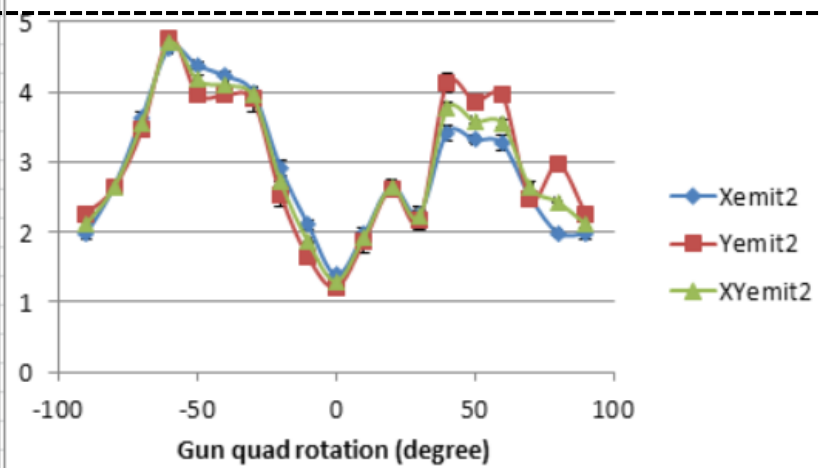


2.4 A

scale1



scale2



Experiment 4

Emittance vs gun quad amplitude

- Experiment vs simulations
 - Consistencies:
 - Larger amplitude makes best emittance more sensitive to angle
 - Larger amplitude makes worst emittance larger
 - Larger amplitude makes asymmetry larger during scan
 - Beam size symmetry @min emittance point is sensitive to quad amplitude
 - Min emittance not sensitive to quad amplitude, but emittance symmetry is.
 - Major differences
 - Beam size and emittance asymmetry pattern during quad scan is not the same as prediction by simulation and theory.
 - No emittance asymmetry in scal1 plots.
 - Measured beam size asymmetry pattern is symmetric w.r.t. the compensation angle.
 - Largest scale1 emittance during scan is consistent with simulations for the two cases of 0.5x amp and 1x amp, but much different for 2x amp

