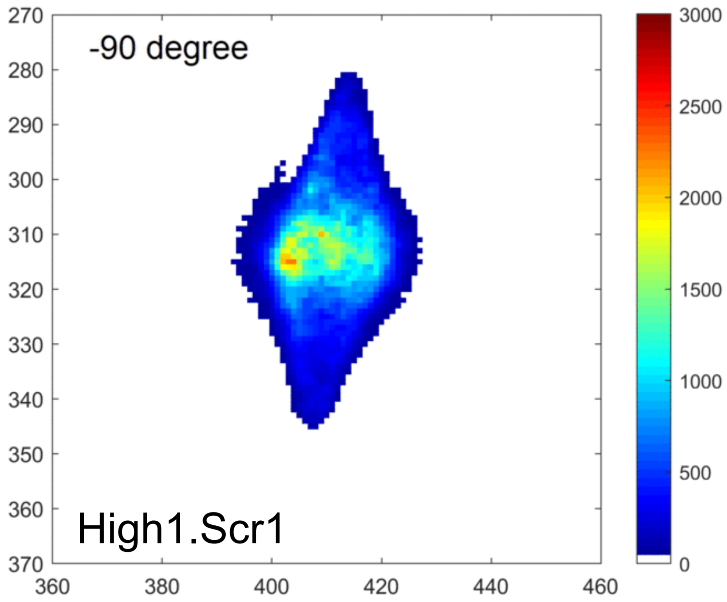
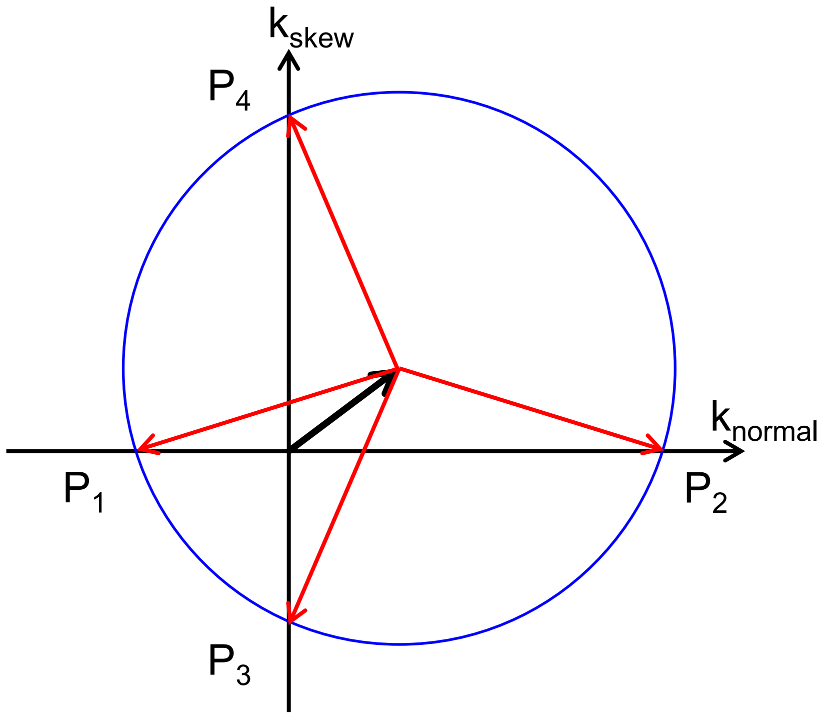
Transverse phase space coupling due to quadrupole field error and cathode laser asymmetry

26.03.2020 @ PPS
H. Qian





HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

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
  - $C_{4D} = \langle X_{4D} X_{4D}^T \rangle = \begin{bmatrix} C_{XX} & C_{XY} \\ C_{XY}^T & C_{YY} \end{bmatrix}$
  - $C_{XX} = \begin{bmatrix} \langle xx \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle xx' \rangle \end{bmatrix}$
  - $C_{YY} = \begin{bmatrix} \langle yy \rangle & \langle yy' \rangle \\ \langle yy' \rangle & \langle y'y' \rangle \end{bmatrix}$
  - $C_{XY} = \begin{bmatrix} \langle xy \rangle & \langle xy' \rangle \\ \langle x'y \rangle & \langle x'y' \rangle \end{bmatrix}$

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

  (ε_x, ε_y: 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
  - $X_{6D} = \left[x\ x'\ y\ y'\ t\ \frac{dp}{p}\right]^T$
  - X(Y)/Z coupling → 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})

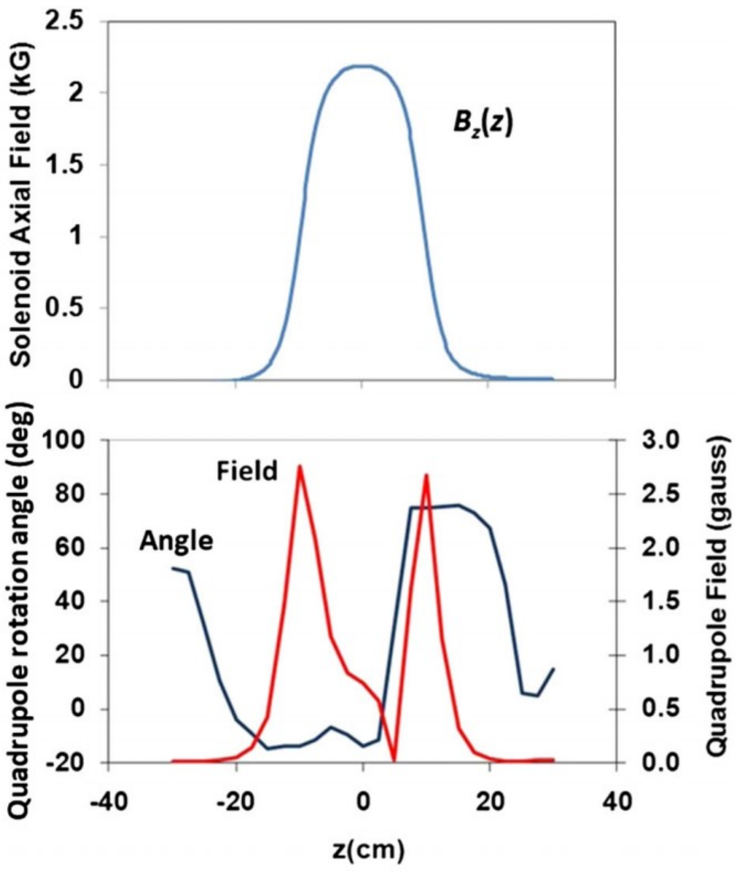
$$C_{rot} = R_{rot} C_0 R_{rot}^T$$
$$= \begin{bmatrix} \cos^2\theta\, C_{XX} + \sin^2\theta\, C_{YY} & \sin\theta\cos\theta\,(C_{YY} - C_{XX}) \\ \sin\theta\cos\theta\,(C_{YY} - C_{XX}) & \sin^2\theta\, C_{XX} + \cos^2\theta\, C_{YY} \end{bmatrix}$$

- 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



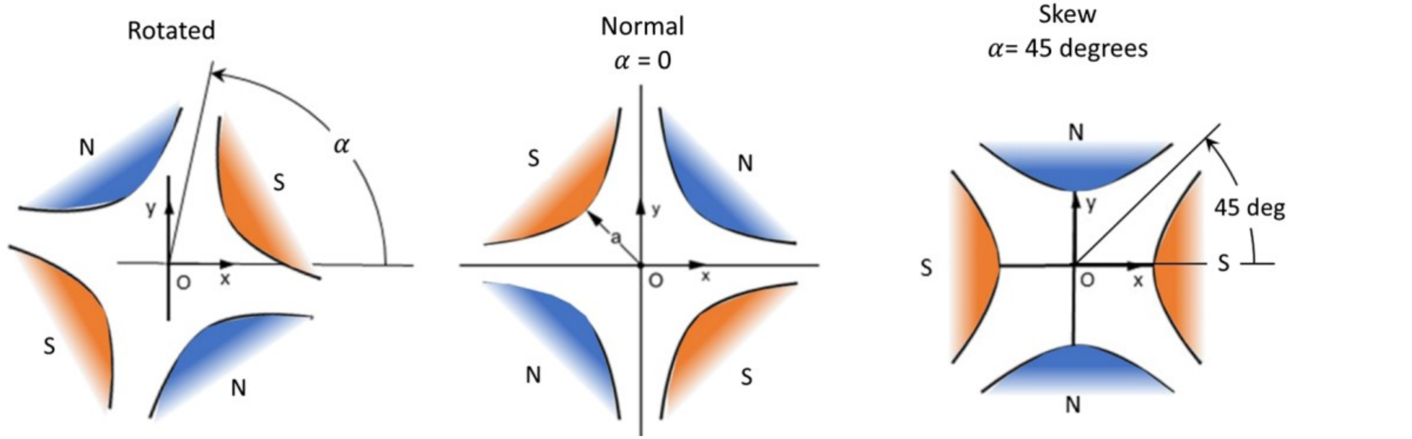
- Rotated quadrupole transfer matrix

$$R_{rotQuad} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -k_N & 1 & -k_s & 0 \\ 0 & 0 & 1 & 0 \\ -k_s & 0 & k_N & 1 \end{bmatrix}$$

$k_{quad} = \frac{1}{f}$ (integrated quad strength)

$$k_N = k \cos 2\alpha$$
$$k_s = k \sin 2\alpha$$

A normal/skew quad pair is a rotated qudrupole.



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

Transverse coupling by quadrupole field error

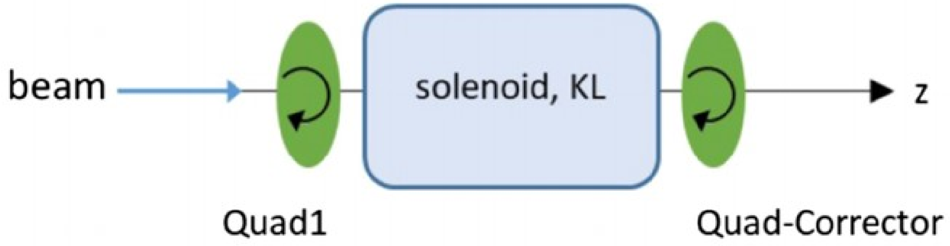
No space charge case

- PRAB 21, 010101, by D. Dowell
  - Emittance growth
    - Assuming symmetric beam before quad
      - $C_{YY} = C_{XX}$
    - By beam matrix transportation
      - $\mathrm{C} = (\mathrm{R}_{sol}\mathrm{R}_{rotQuad})C_0(\mathrm{R}_{sol}\mathrm{R}_{rotQuad})^T$
      - $\varepsilon^2 = \varepsilon_0^2 + \Delta\varepsilon^2$,
        $\Delta\varepsilon_x = \Delta\varepsilon_y = \sigma_{beam}^2 \left| k_{quad} \sin 2(\theta_{Larmor} + \alpha) \right|$

        ⇩

        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



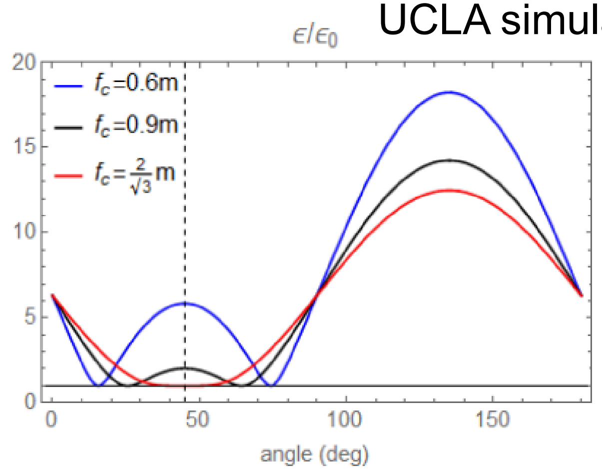
  - $\Delta\varepsilon = \left| \sigma_1^2 k_{quad1} \sin 2(\theta_{Larmor} + \alpha_1) + \sigma_c^2 k_c \sin 2\alpha_c \right|$
  - Tune k_c and α_c to zero emittance growth
    - Tune skew quad corrector to make $\Delta\varepsilon$ zero
    - Normal quad component is not related
      - Infinite solutions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

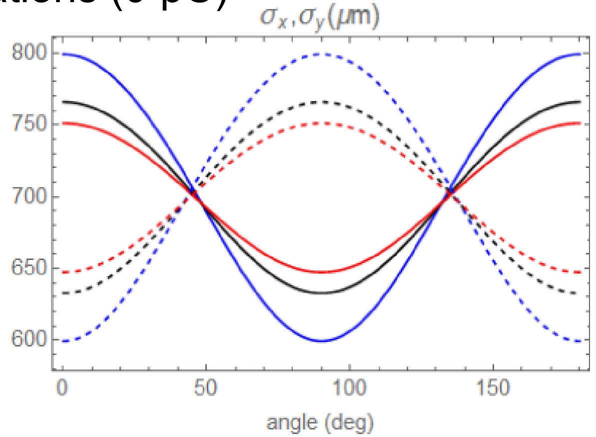
Transverse coupling by quadrupole field error

Experiments & simulations in no (low) space charge case

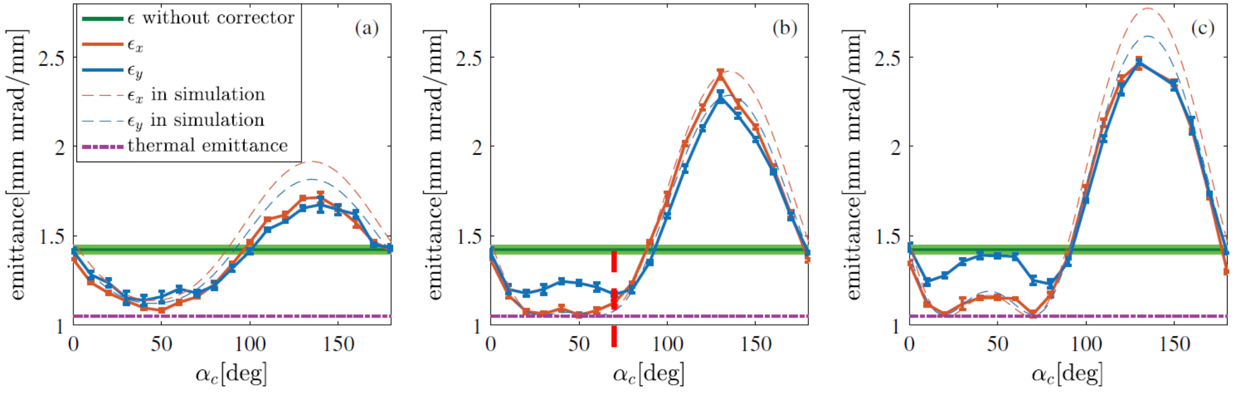
- Simulations & experiments reports
  - SLAC/Cornell/DESY/ANL/UCLA …

UCLA simulations (0 pC)





ANL experiment (1 pC)



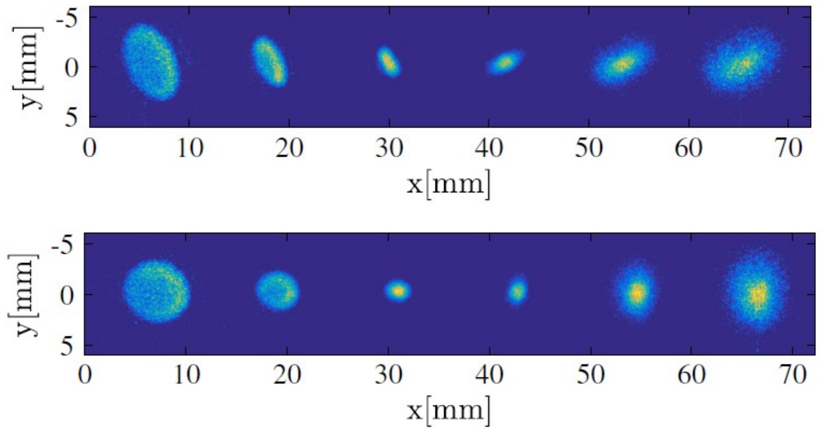
36 G/m

72 G/m

96 G/m

- 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 minize <xy> or emittance
- For low charge case, simulation is not necessary, fix amplitude, scan angle can zero $\Delta\varepsilon$

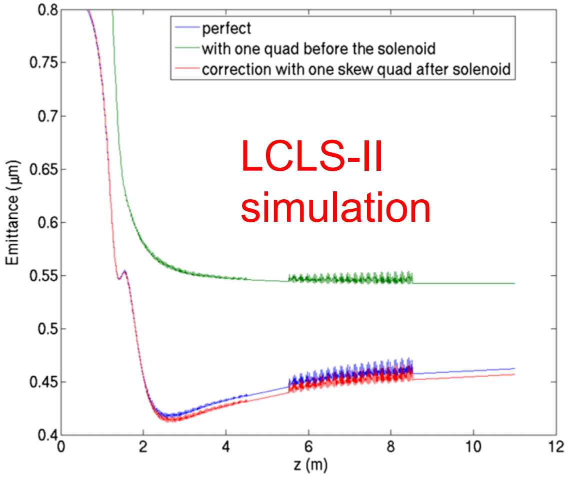
ANL experiment (1 pC)

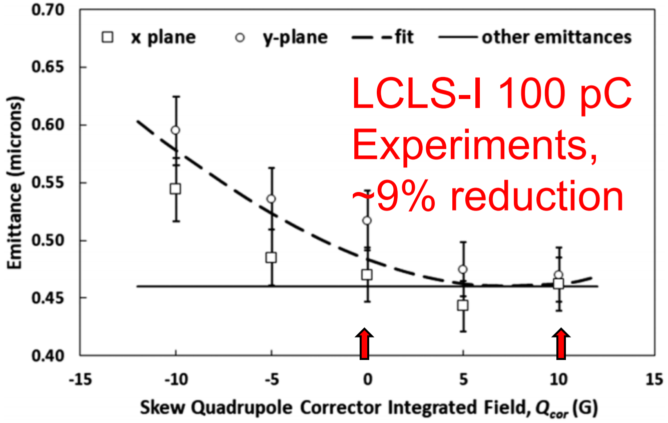


Transverse coupling by quadrupole field error

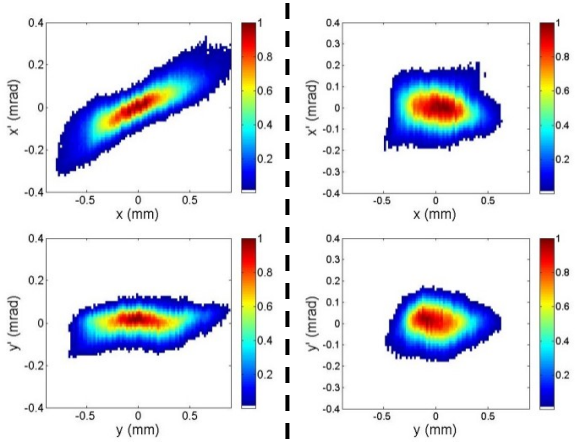
With space charge

- SLAC injector <u>optimization</u> by skew gun quads scan





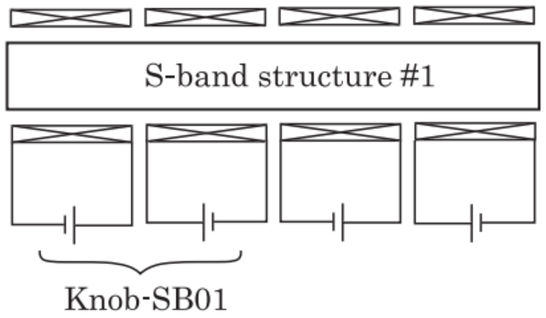
- PITZ injector <u>optimization</u> by gun quads optimizer



Symmetrize beam after booster by optimizer iterations before emittance measurement.

~9% emit reduction for 500 pC.

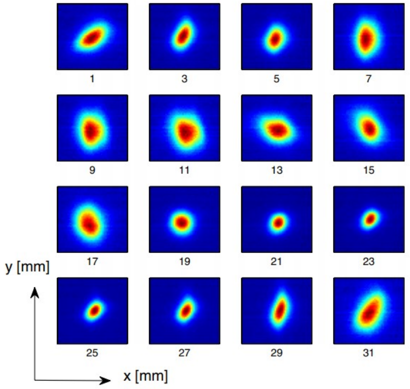
- PSI injector <u>decoupling</u>
  - By gun quads & booster solenoid



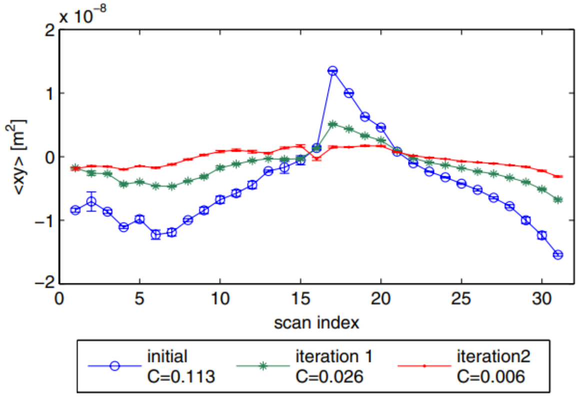
Change booster solenoid current

change Larmor angle

- <u>Measure 4D phase space</u> with multi-quad scan
  - Measure C_{XY} response matrix to gun quads & booster solenoid
  - Iterations, coupling factor 11% → 0.6%



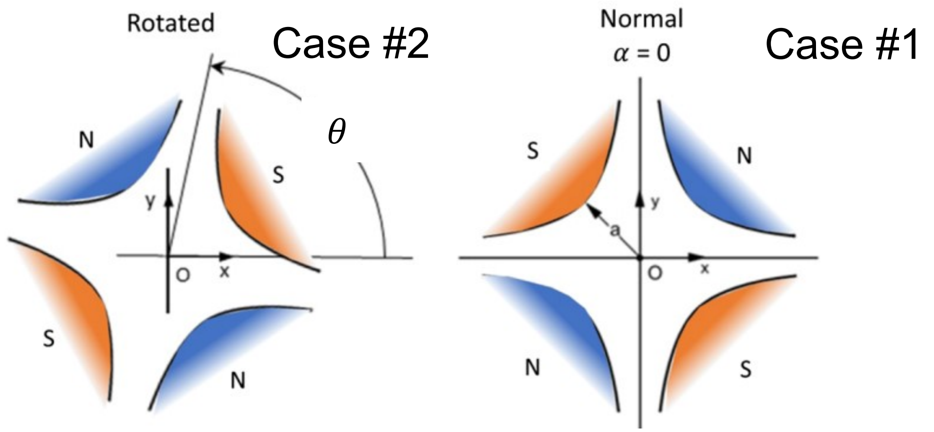
Coupling 2.6%



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



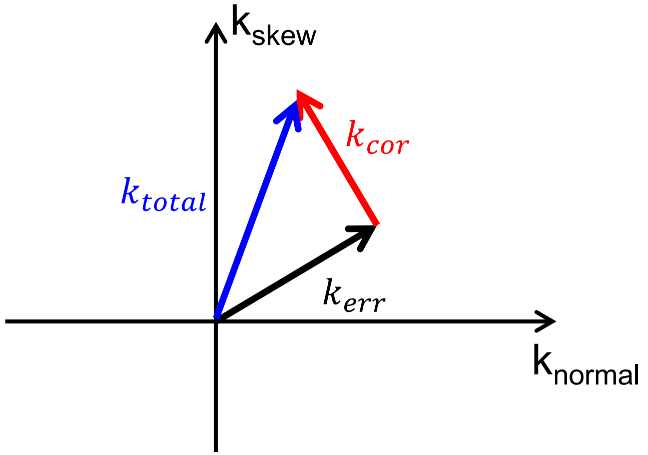
  - Case #2 is equivalent to injector #1 rotated by θ
    - So beam after injector of case #2 is
    - $C_\theta = R_{rot} C_0 R_{rot}^T = \begin{bmatrix} \cos^2\theta\, C_{XX} + \sin^2\theta\, C_{YY} & \sin\theta\cos\theta\,(C_{YY} - C_{XX}) \\ \sin\theta\cos\theta\,(C_{YY} - C_{XX}) & \sin^2\theta\,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

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
  - $C_\theta = \begin{bmatrix} \cos^2\theta\, C_{XX} + \sin^2\theta\, C_{YY} & \sin\theta\cos\theta\,(C_{YY} - C_{XX}) \\ \sin\theta\cos\theta\,(C_{YY} - C_{XX}) & \sin^2\theta\, C_{XX} + \cos^2\theta\, C_{YY} \end{bmatrix}$
    - $\langle xx\rangle = \cos^2\theta\,\langle x_0x_0\rangle + \sin^2\theta\,\langle y_0y_0\rangle$
    - $\langle yy\rangle = \sin^2\theta\,\langle x_0x_0\rangle + \cos^2\theta\,\langle y_0y_0\rangle$
    - $\langle xy\rangle = \frac{1}{2} sin\, 2\theta\,(\langle y_0y_0\rangle - \langle x_0x_0\rangle)$
  - $\langle xx\rangle = \langle yy\rangle \rightarrow \theta = \pi/4$, 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 $k_{err} = k_0 e^{i2\theta} = k_0(cos2\theta + i * sin2\theta)$
    - 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

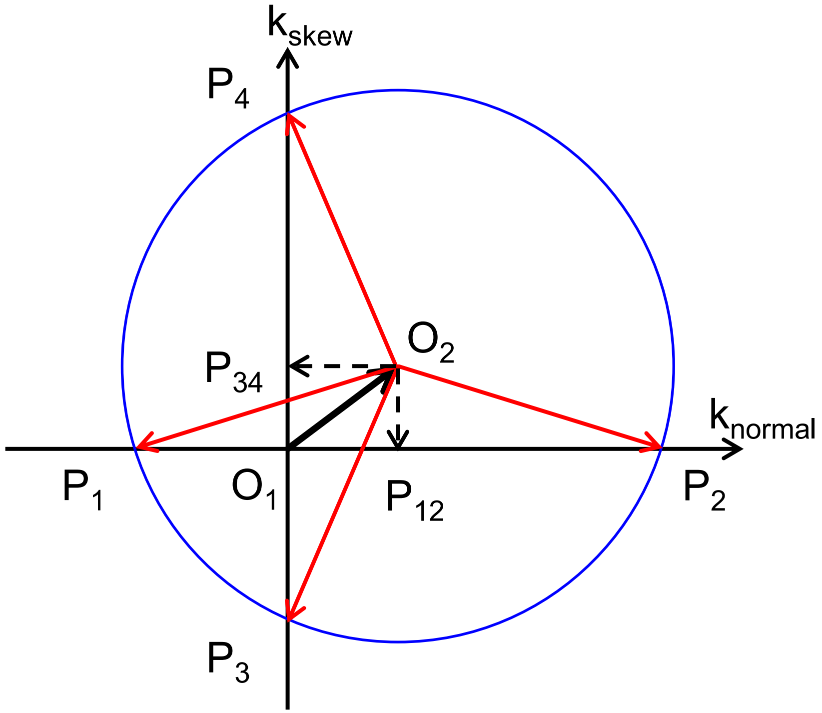


How to tune gun quads under space charge case

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
    - $(O_2P_1 + O_2P_2)/2 = O_2P_{12}$ → skew quad corrector
      - O_2P_{12} is also the skew quad axis
    - $(O_2P_3 + O_2P_4)/2 = O_2P_{34}$ → 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

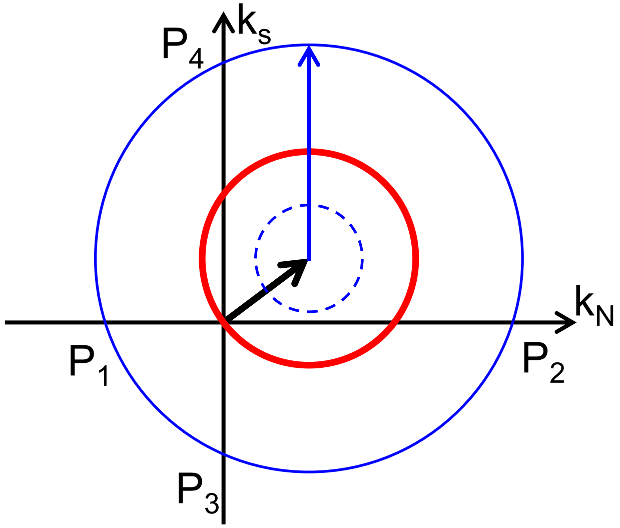
- Advantages of such a method
  - No prior knowledge of quad error angle or amplitude needed, no simulation fit needed
  - No emittance measurement required
  - In ideal case, no iterations



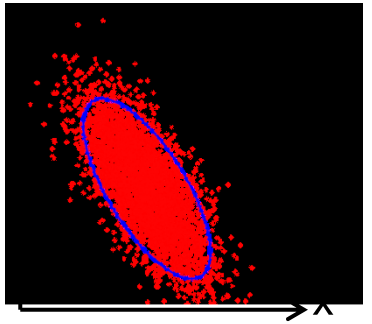
How to tune gun quads under space charge case

A new method

- A new method (cont'd)
  - Special cases
    - When corrector amplitude much smaller than quad error amplitude
      - no P1/2/34
    - 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 $gx^2 + 2axy + by^2 = e$
    - $e = \sqrt{\langle xx\rangle\langle yy\rangle - \langle xy\rangle^2}$
    - $b = \langle xx\rangle/e$
    - $g = \langle yy\rangle/e$ ⇨ 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
    - $C_{scr} = R C_\theta R^T$

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

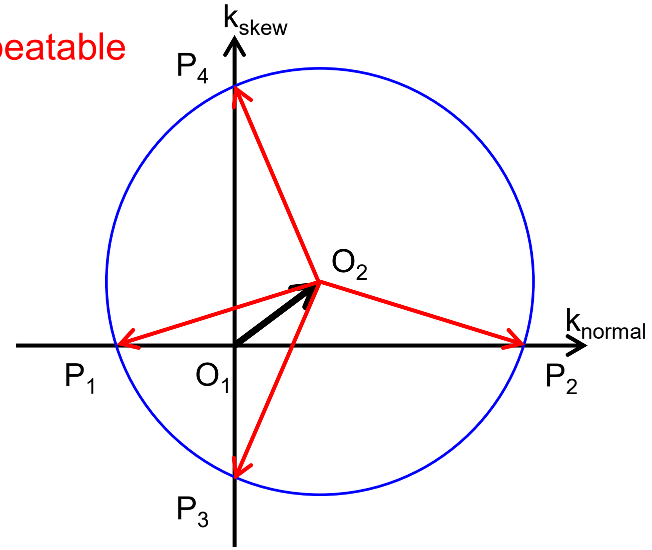
- A new method (cont'd)
  - Special cases like FLASH/XFEL injector
    - $\theta = 0$, i.e. a pure normal quad → $\langle xy \rangle = 0$
    - $\theta = \pi/4$, i.e. a pure skew quad

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

$$\sigma_x \neq \sigma_y$$

    - 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, <xy>=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

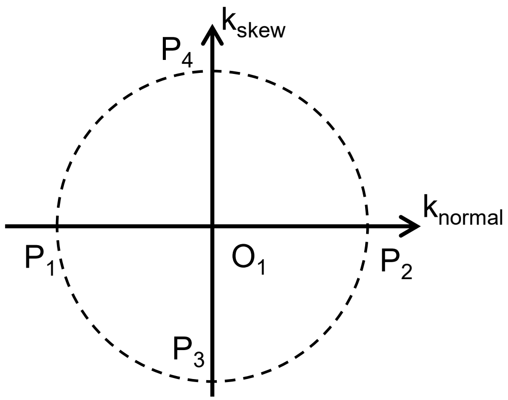
Simulations

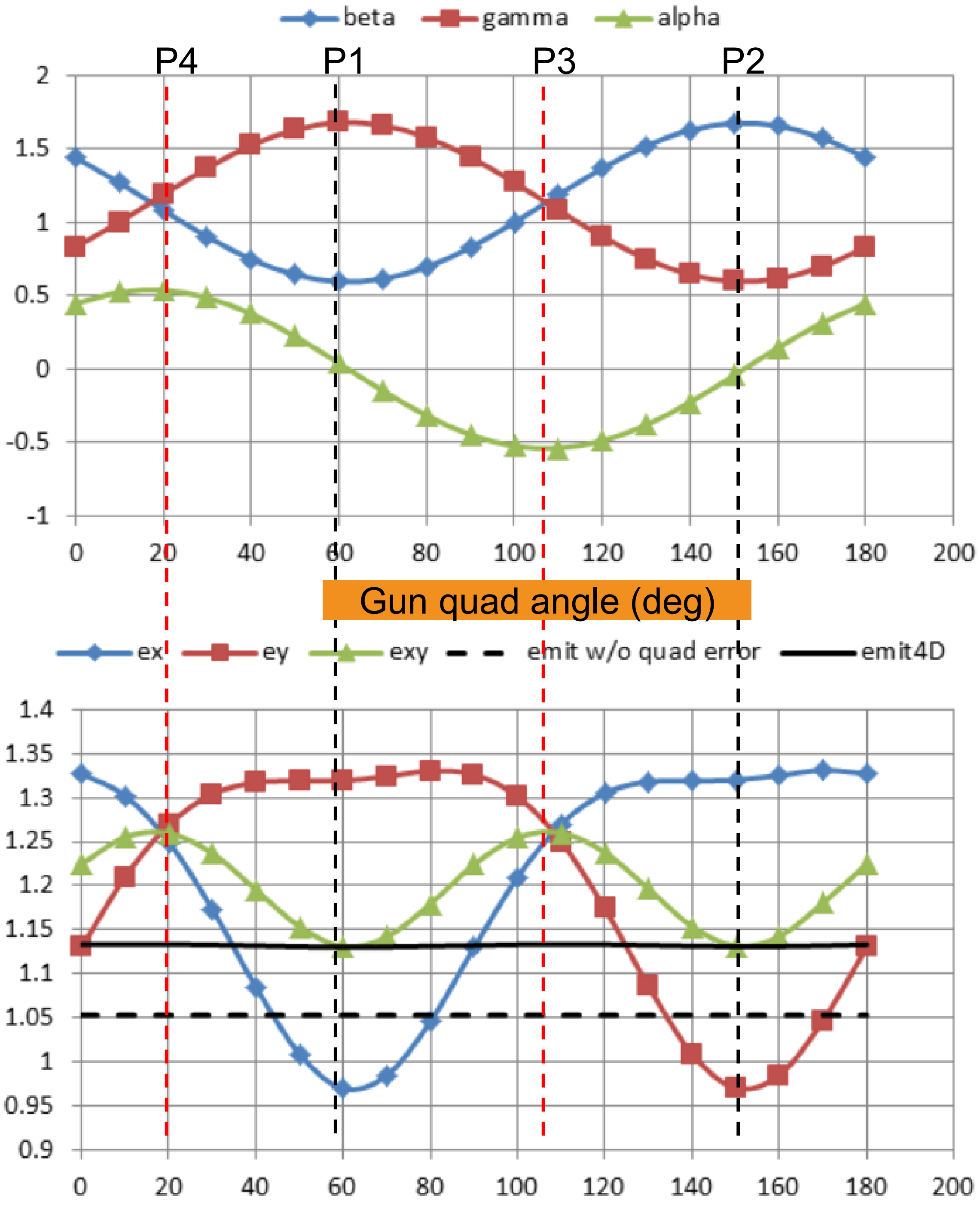
- Simulation setup
  - Laser, 6 ps FWHM, BSA1.3 mm, 500 pC (PITZ experiment optimizations)
  - PITZ setup, gun 6.3 MeV/c + booster
  - A distributed quadrupole error field like SLAC measurement
    - Using gun solenoid field map as a quad field map, inspired by the ANL study, quad angle can be configured in ASTRA
    - Quadrupole error strength assumption in simulation
      - Typical solenoid focusing strength k is ~3.5 m^{-1}
      - Integrated focusing strength k is ~0.01 m^{-1}, focal length ~100 m (typical range 50–100 m), roughly ~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

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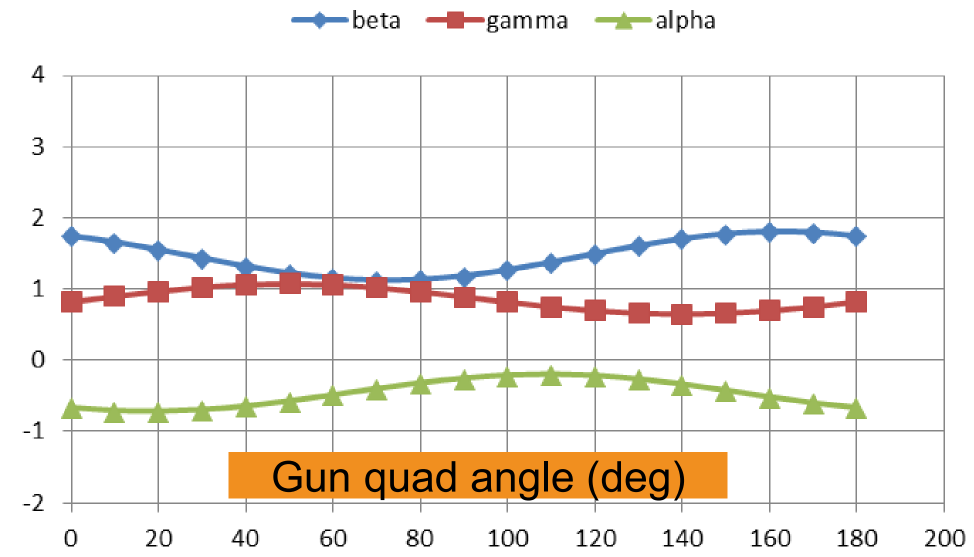
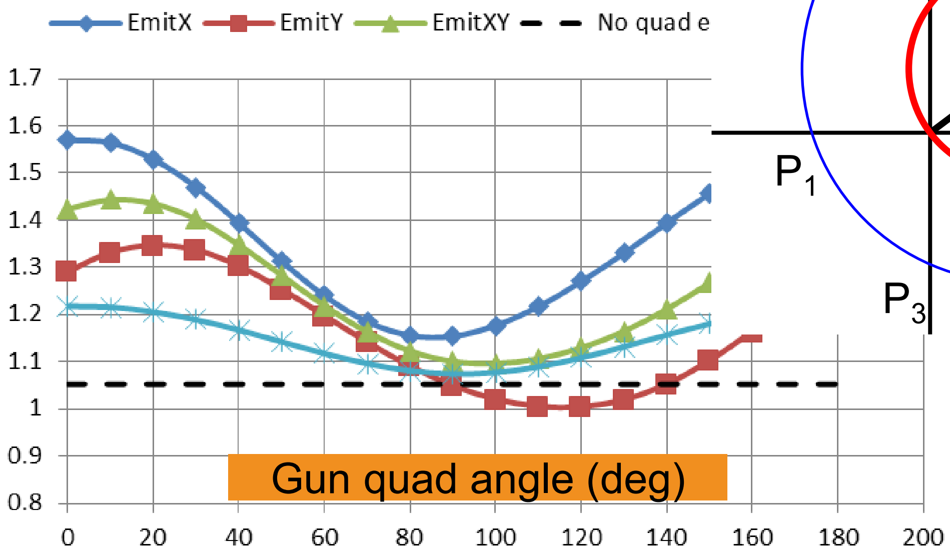
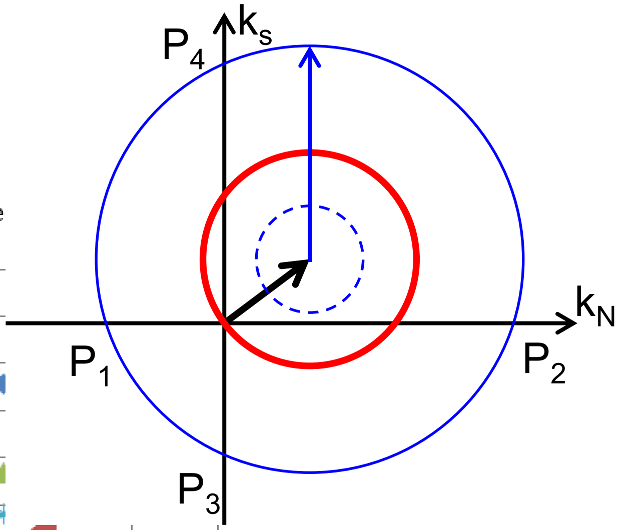
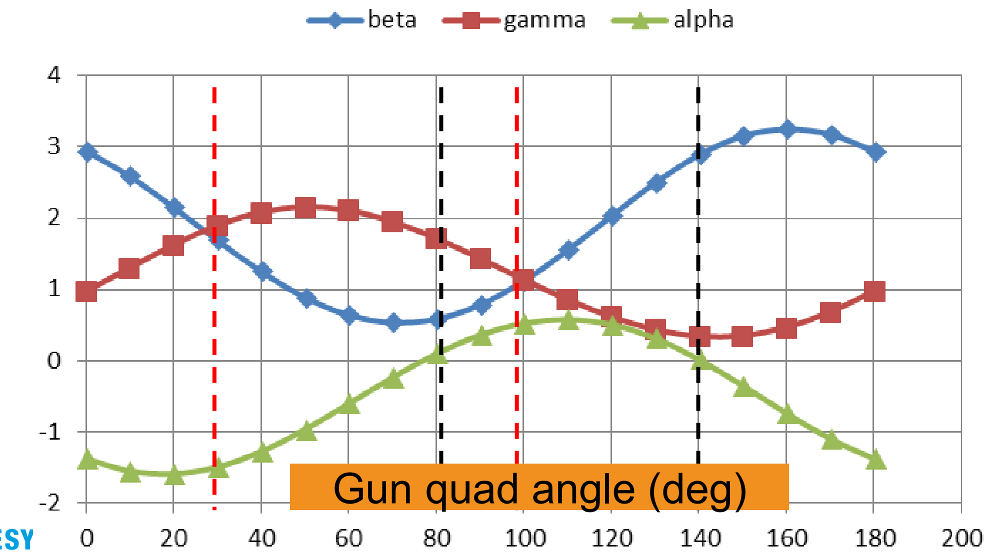
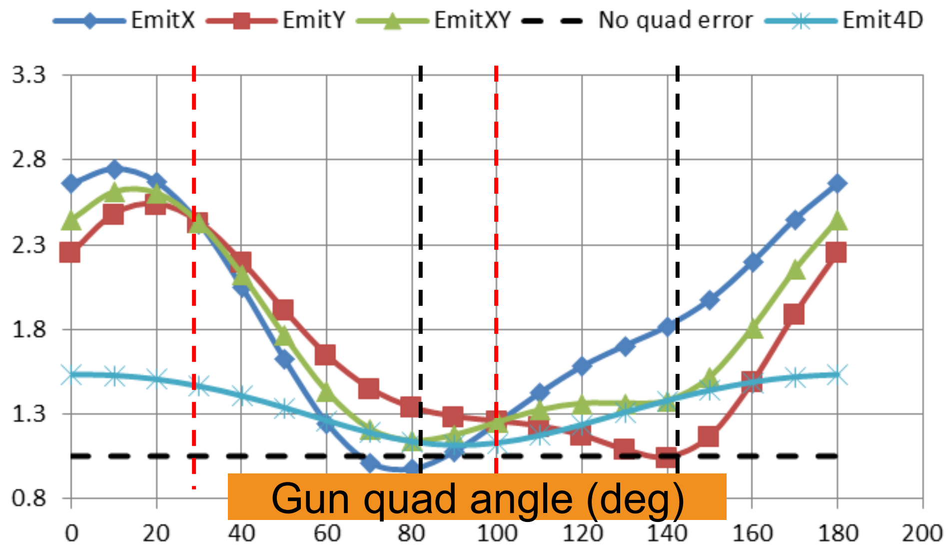






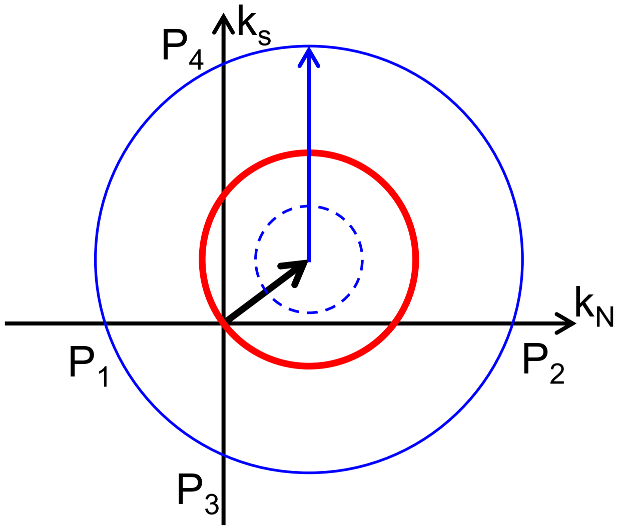




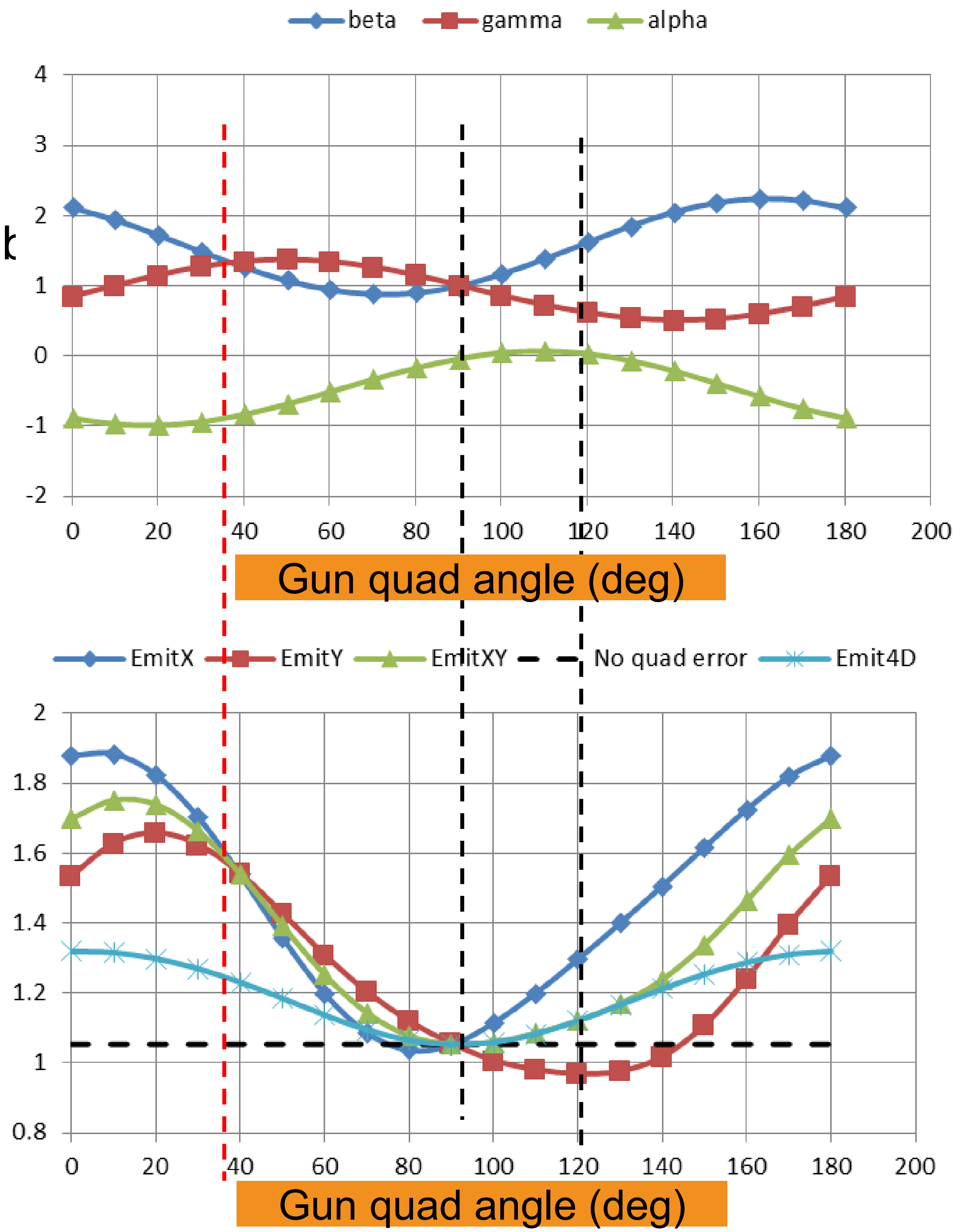
Quadrupole error study

Quad error + quad corrector

- Corrector amplitude matches error amplitude by mannual 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



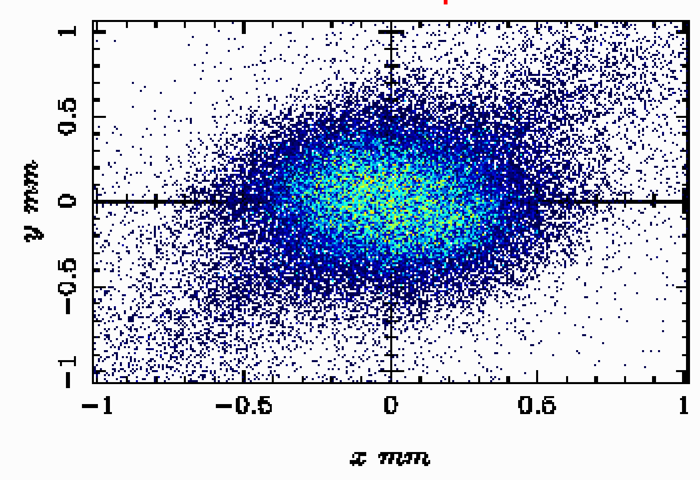
- b

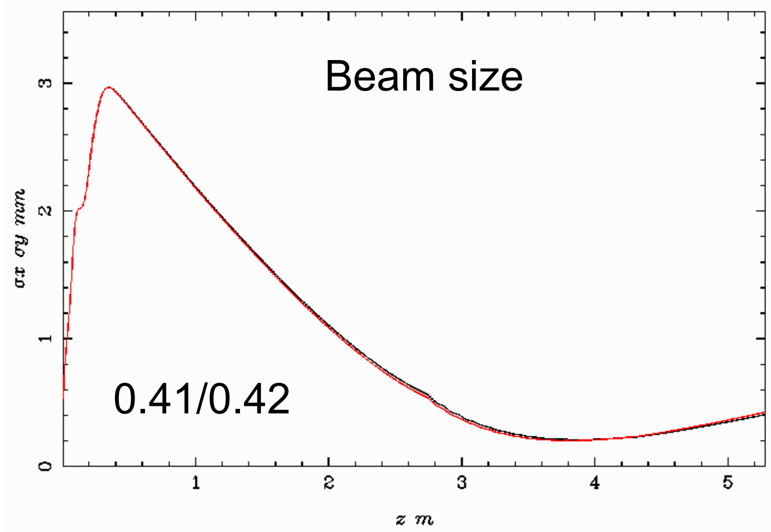


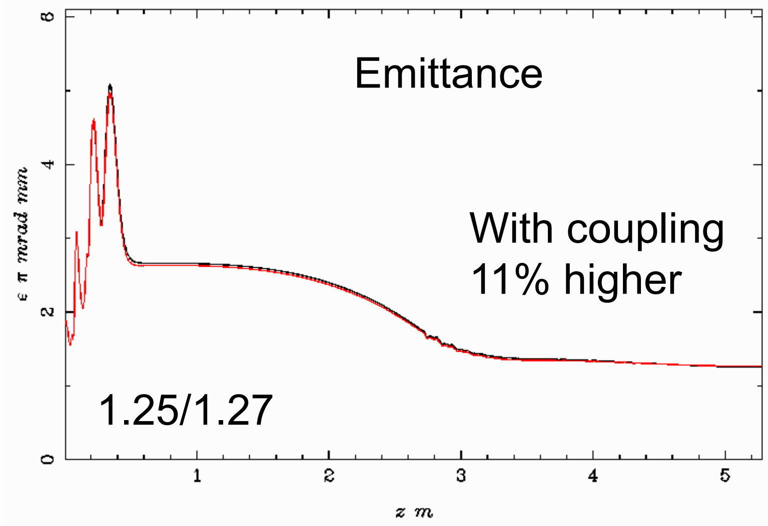
Before correction

- H1.scr1

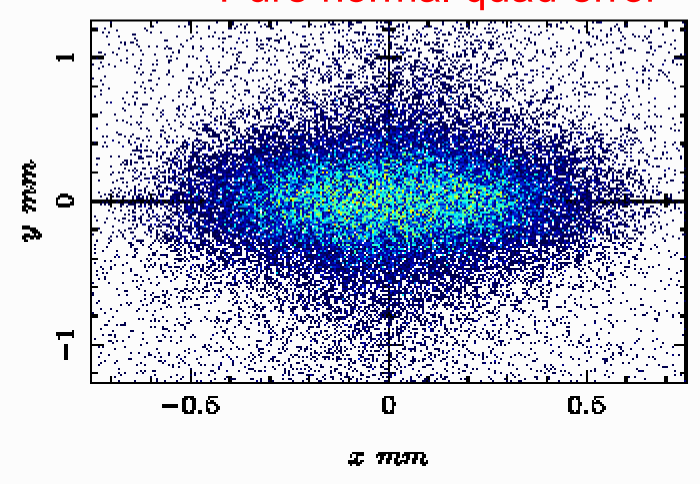
Pure skew quad error

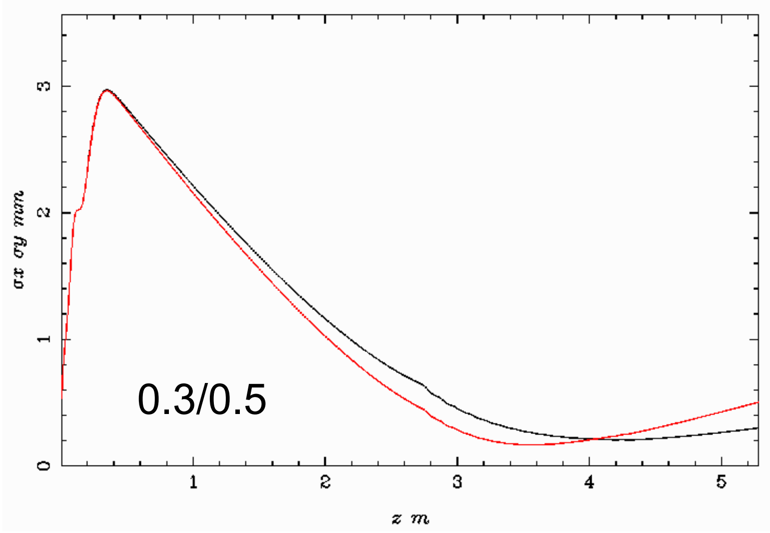


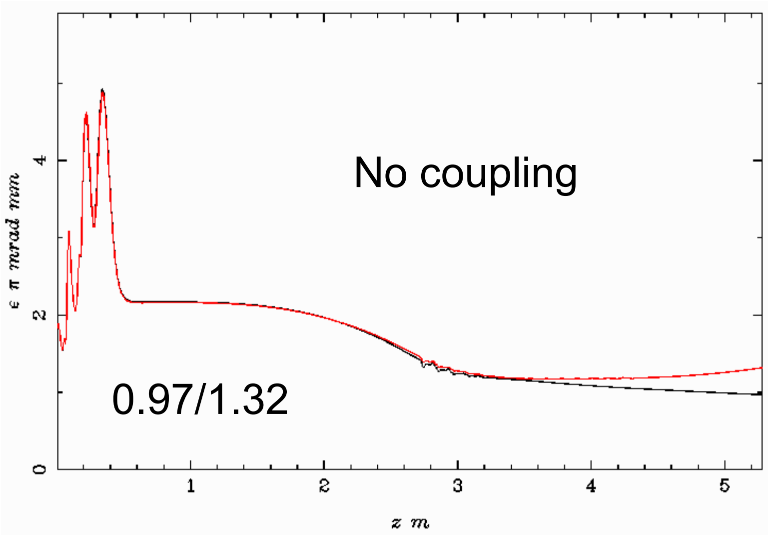




Pure normal quad error

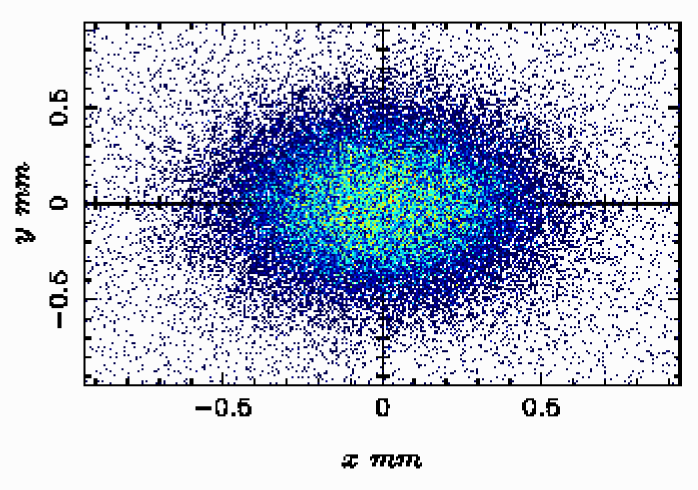


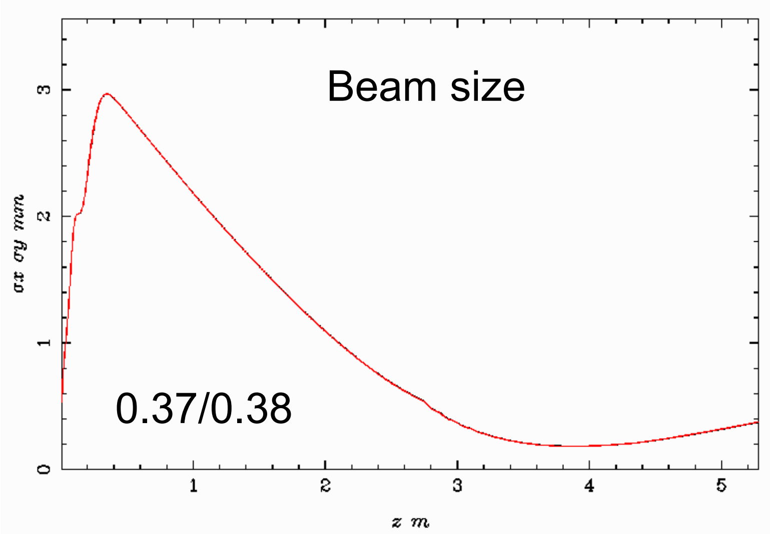


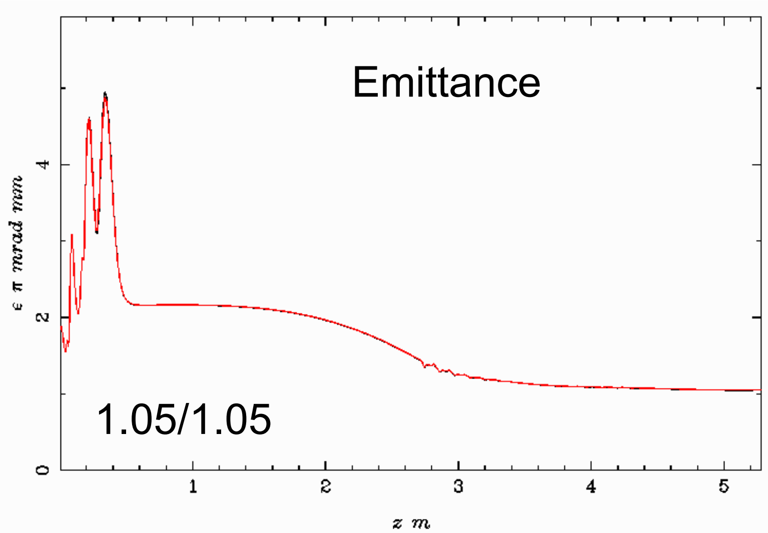


After correction

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



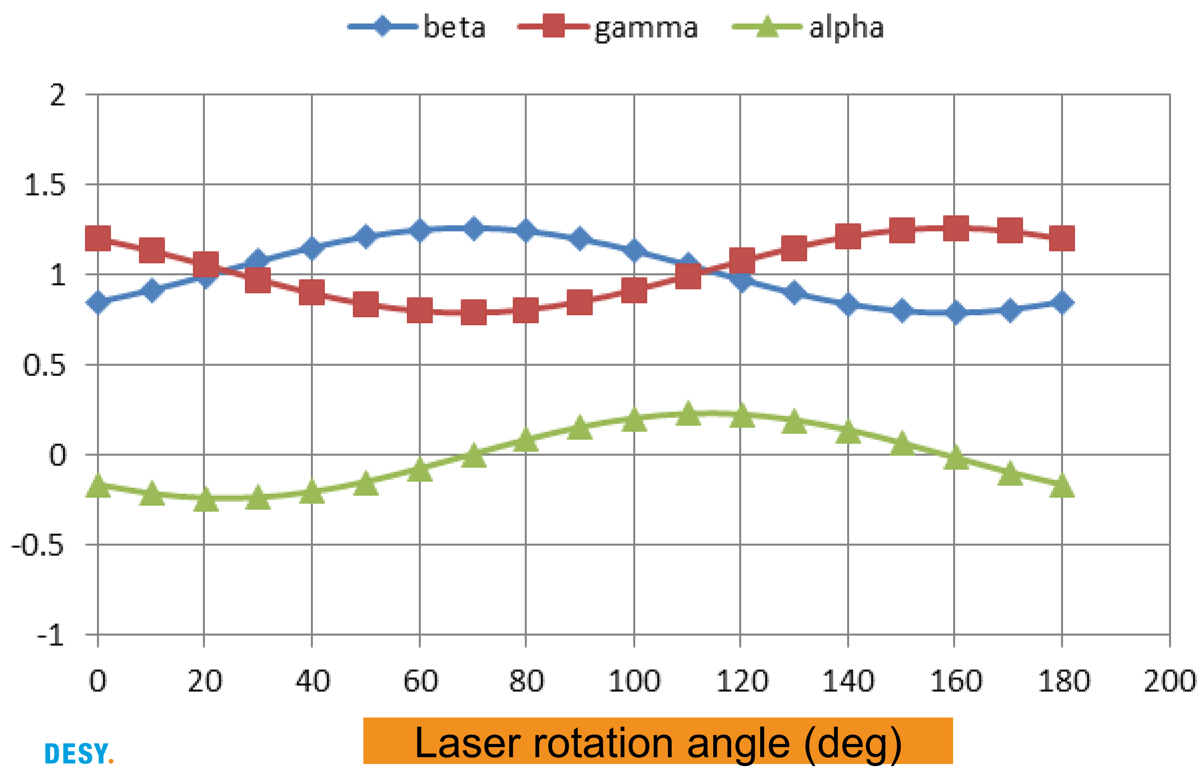


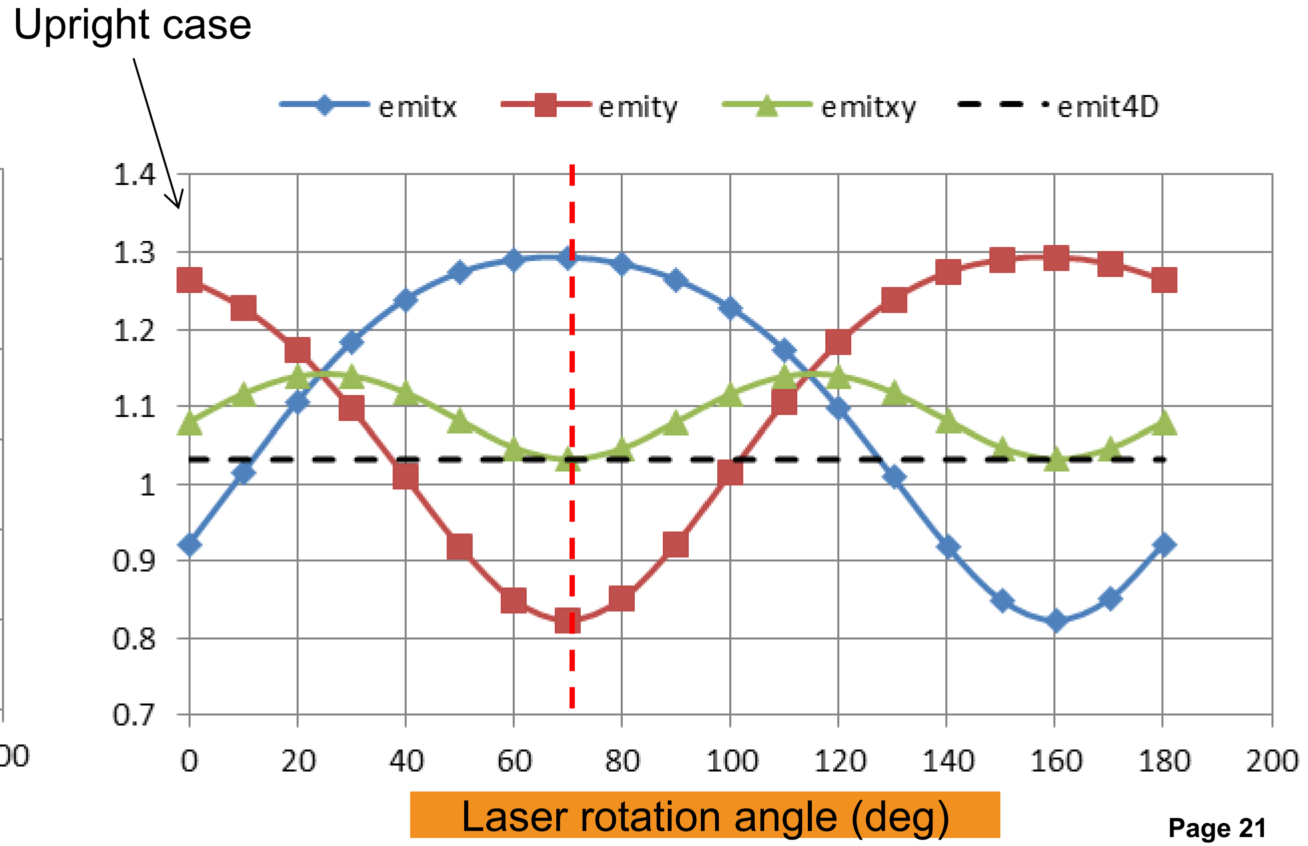


Laser asymmetry 10% p-p

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





Laser asymmetry 10% p-p

w/ quad corrector

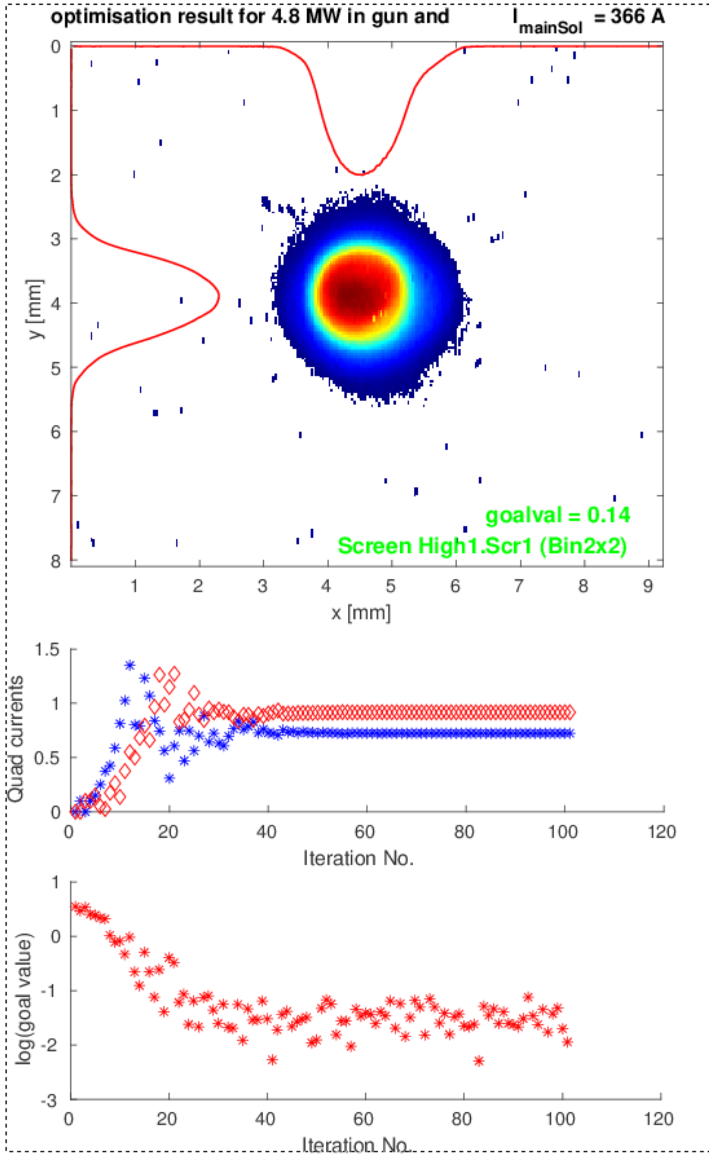
- Formula prediction
  - 35.3 G/m, -46 degree for upright laser asymmetry
- Partial correction
  - 0.36/0.36 mm
  - 0.95/1.17 mm.mrad

Experiment 1 (2020/0312N)

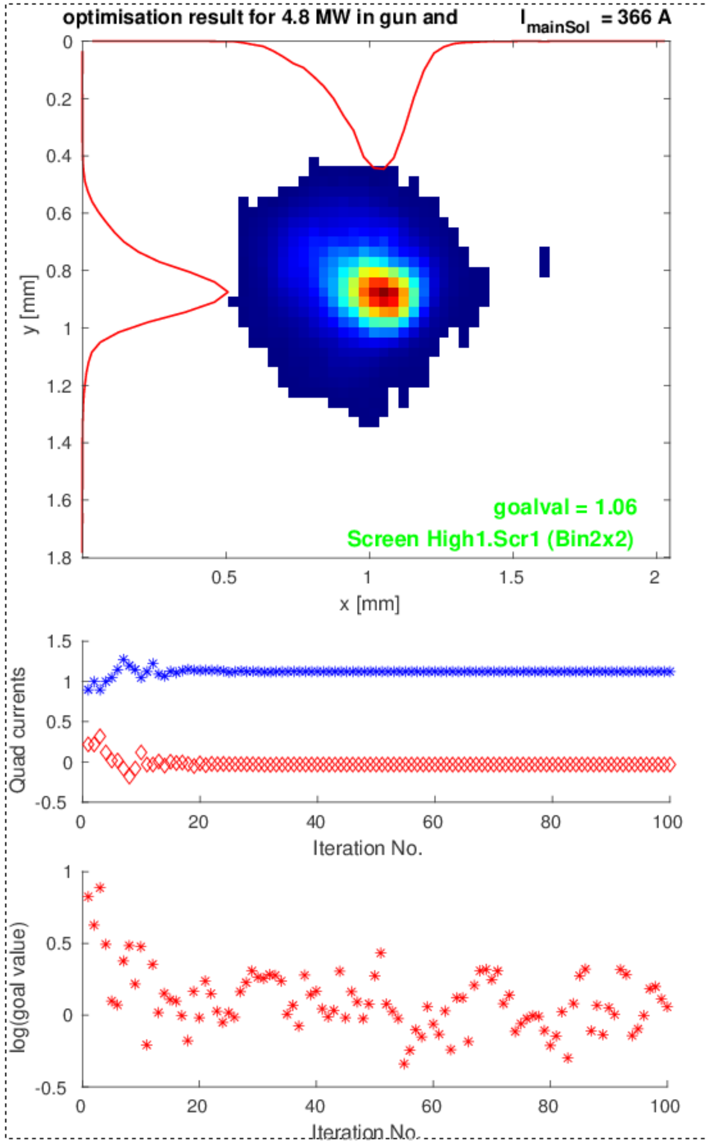
Gun quad rotation vs optimizer, vs charge

- 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
  - Iq1 = 0.724 A, Iq2 = 0.917 A
  - Amp: 1.17 A, angle: 25.8°
- 300 pC gun quad optimizer
  - Iq1 = 1.122 A, Iq2 = -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



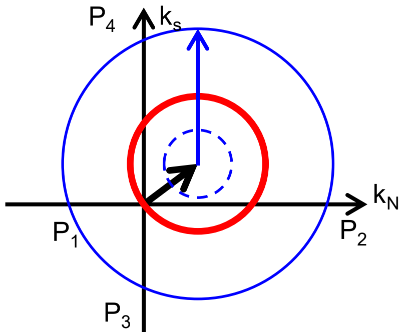
300 pC with EMSY1 YAG



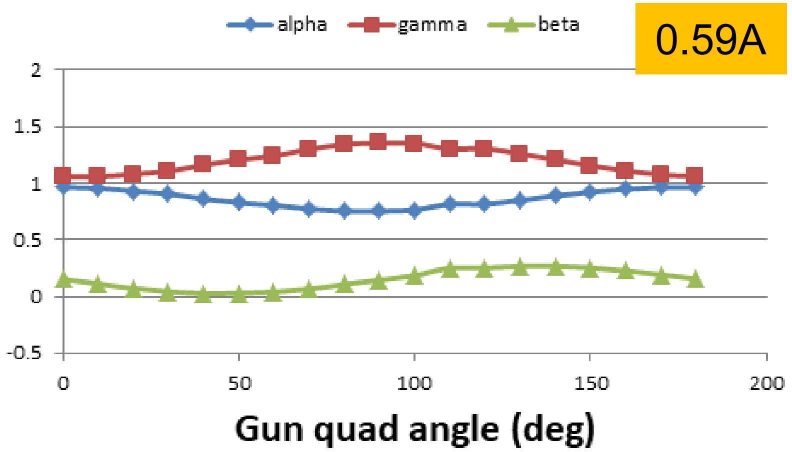
Experiment 1 (2020/0312N)

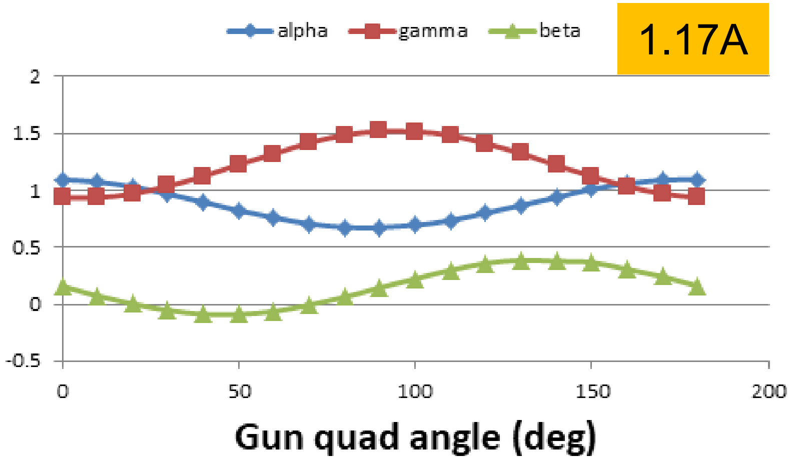
Gun quad rotation vs optimizer, vs charge

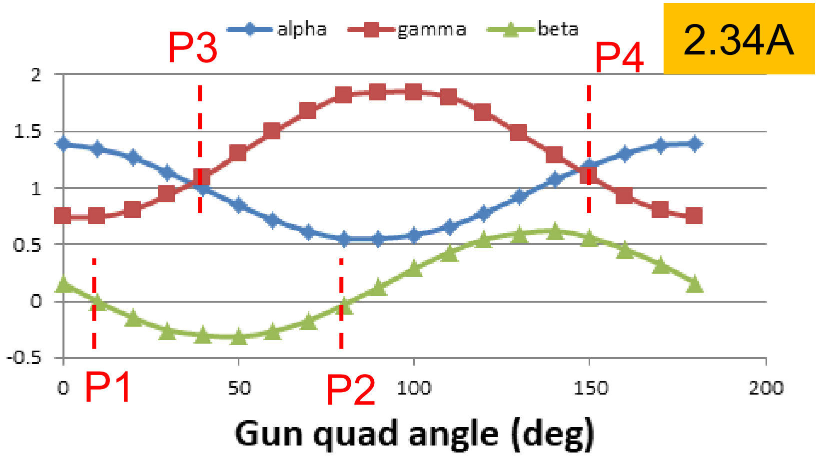
$$I_c = \frac{1}{2} I_0 \sum_{n=1}^{4} e^{i2\alpha_n}$$



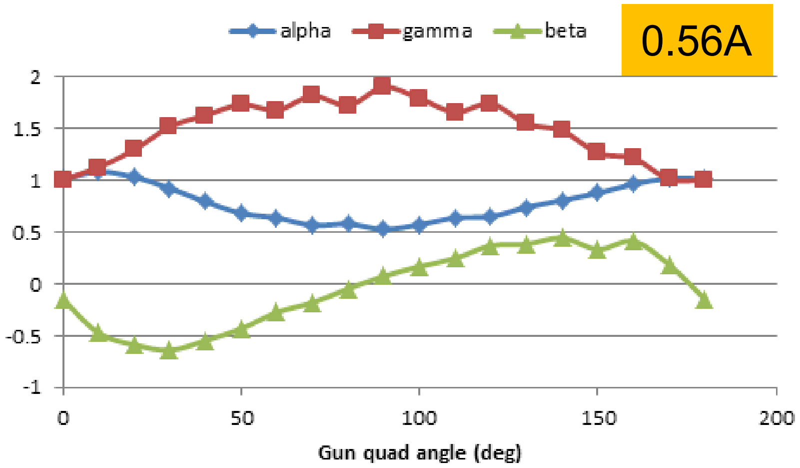
- 30 pC (sum of pixel during rotation, ~1% rms variation, EMSY1 lyso screen)

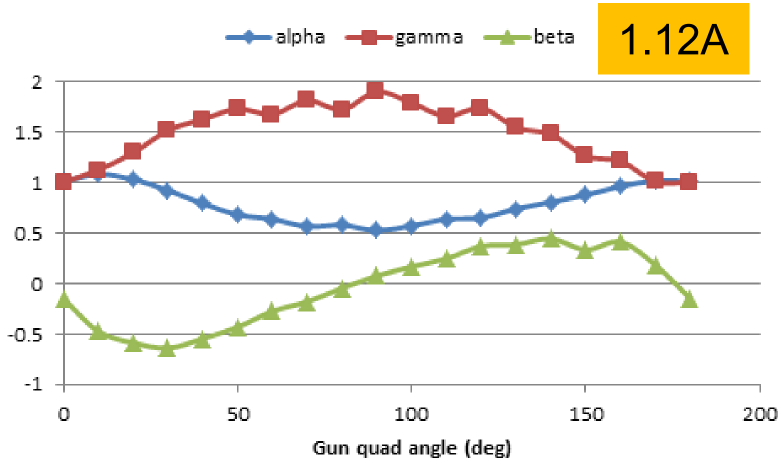


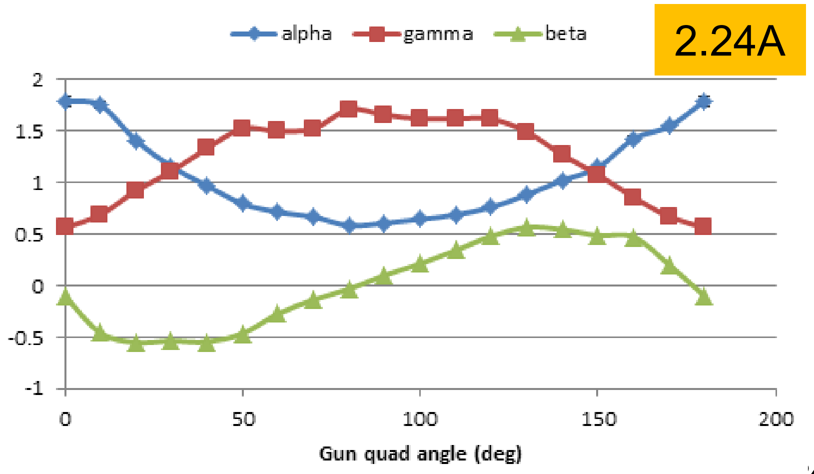




- 300 pC (sum of pixel during rotation, ~8% rms variation, EMSY1 YAG screen)







Experiment 1(2020/0312N)

Gun quad rotation vs optimizer, vs charge

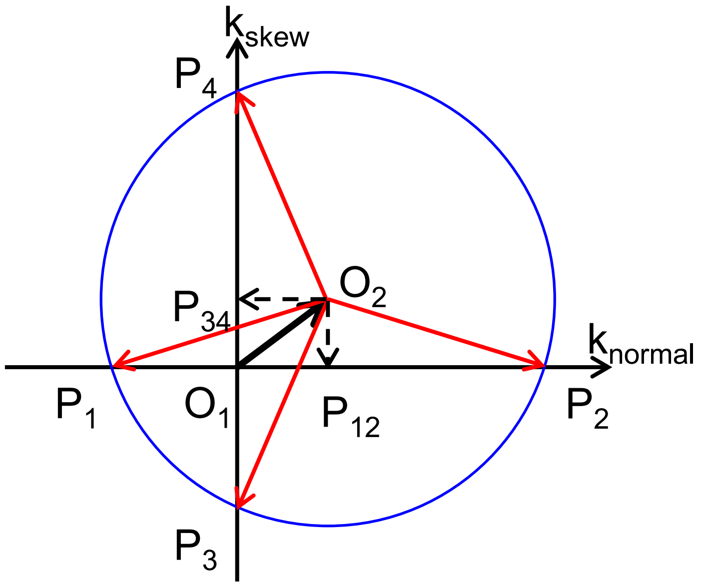
- 30 pC (sum of pixel during rotation, ~1% rms)
  - Based on scan with 1x amp: 1.11 A, 22.4°
  - Based on scan with 2x amp: 1.10 A, 22.3°
  - Gun quad optimizer: 1.17 A, 25.8°
- 300 pC (sum of pixel during rotation, ~8% rms)
  - Based on scan with 1x amp: 1.06 A, 0.8°
  - Based on scan with 2x amp: 1.05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

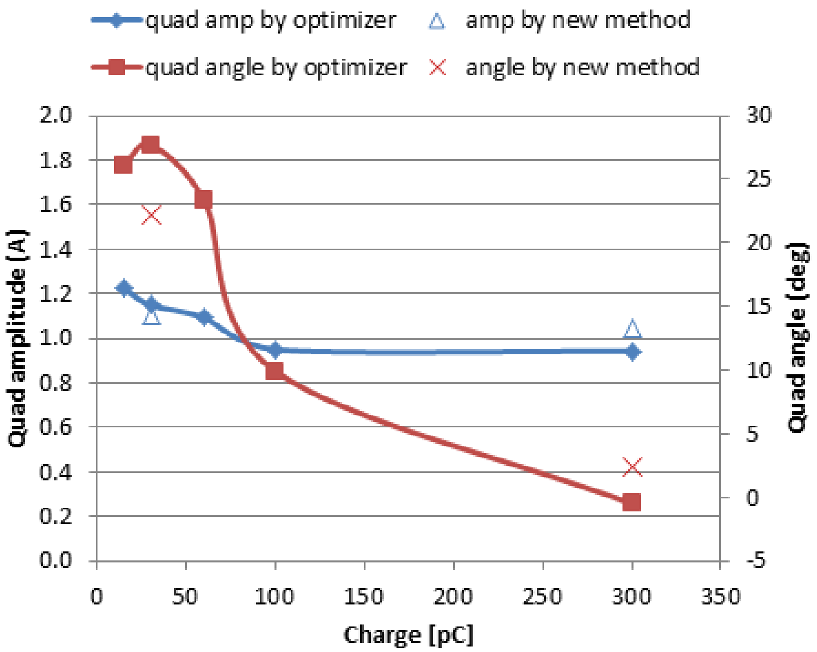
charge	Q1	Q2	pulses	Amp	phase
15	0.749	0.967	10	1.22	26.1
30	0.653	0.946	8	1.15	27.7
60	0.75	0.795	3	1.09	23.3
100	0.894	0.322	10	0.95	9.9
300	0.942	-0.016	3	0.94	-0.5

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

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

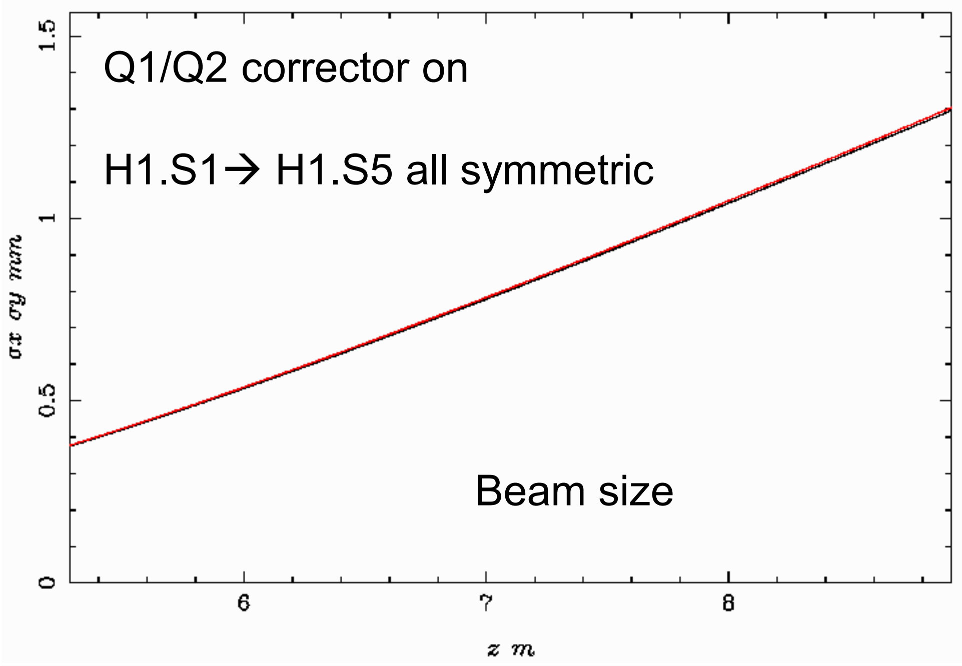
P34 ~90x2 deg
Gun Q1 happens to be normal axis

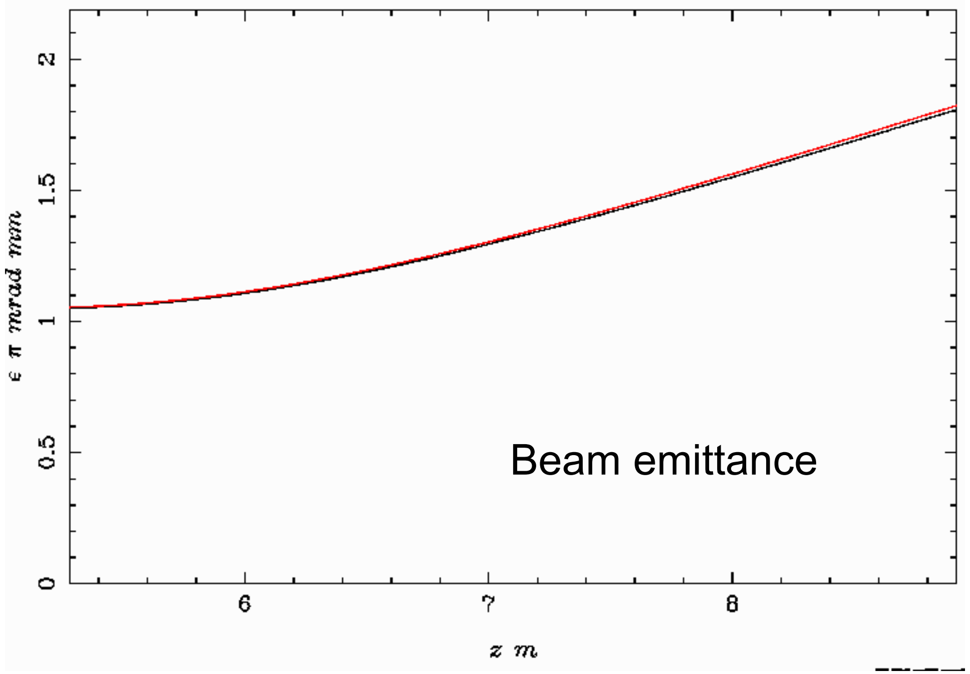
Integrated quad error O1O2
~0 deg around 250pC, pure normal quad, no coupling, only breaks beam symmetry

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



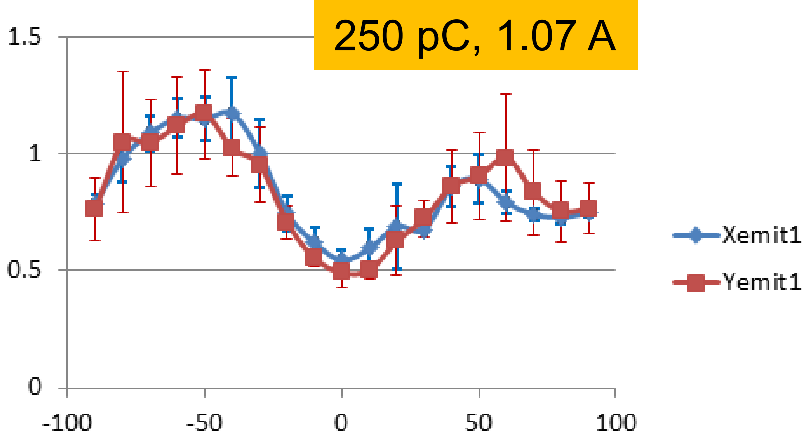


Experiment 3

Emittance vs gun quad angle

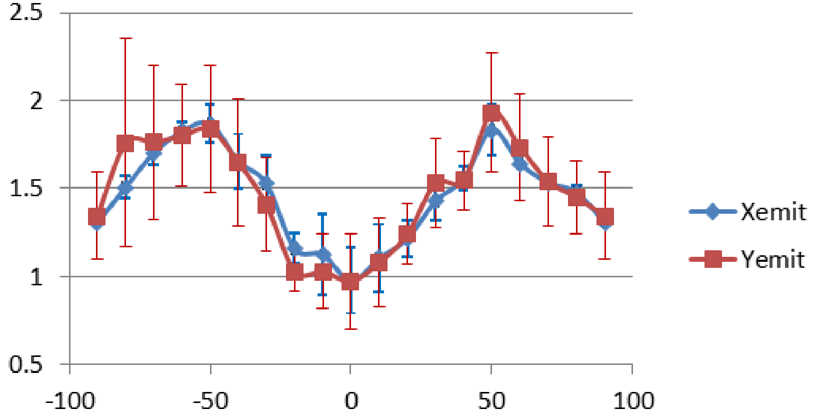
Effective quad error for both charges happens to be a pure normal quad error.
(because best angle is almost same as normal aixs).
That's why emittance improvement is only ~7%.

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



Gun quad angle w.r.t. right angle (deg)

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



Gun quad angle w.r.t. right angle (deg)

(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: 1.07 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

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

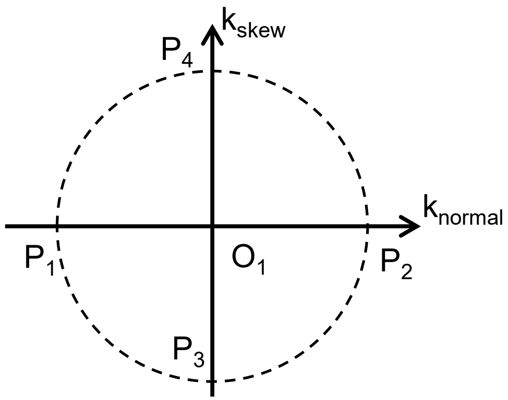
Best scale1: 0.98 mm.mrad (uniform laser)
Best scale2: 1.37mm.mrad
Xrms/Yrms=1.02, Xscale1/Yscale1=1.0, Xscale2/Yscale2=0.9

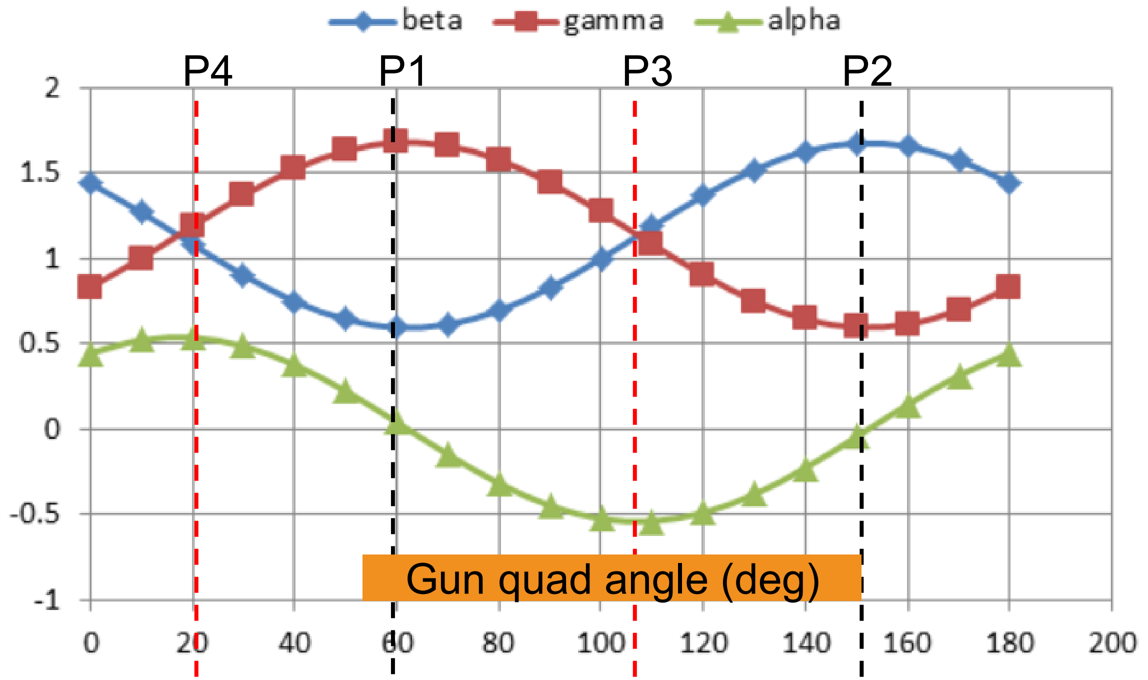
Worst emittance with wrong correction angle: 1.9 mm.mrad

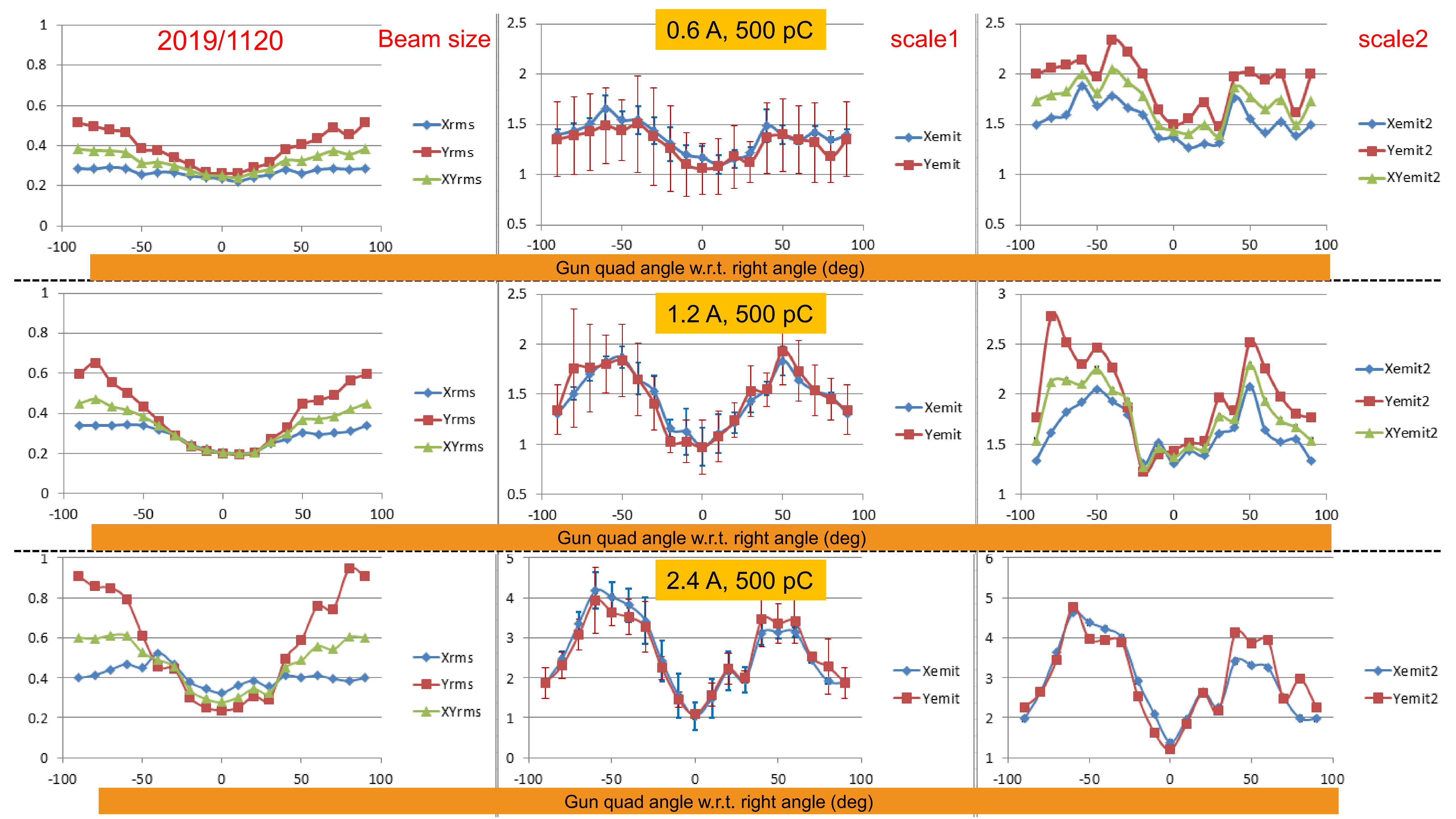
Quadrupole error study

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



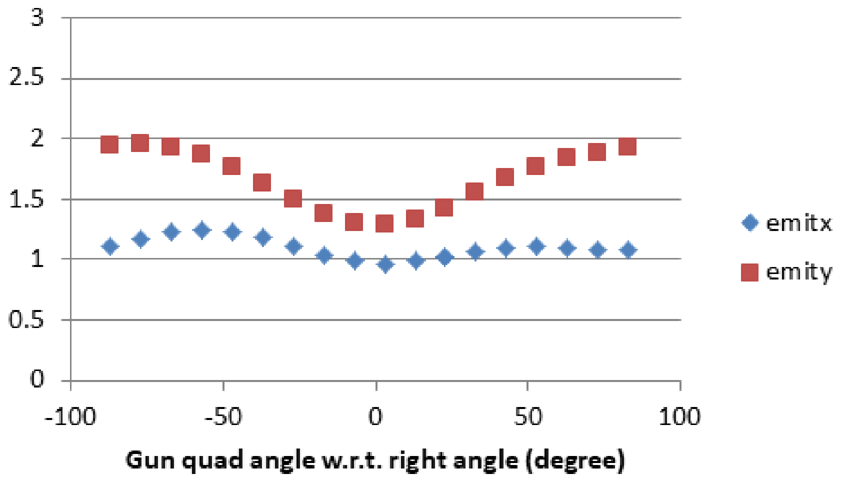


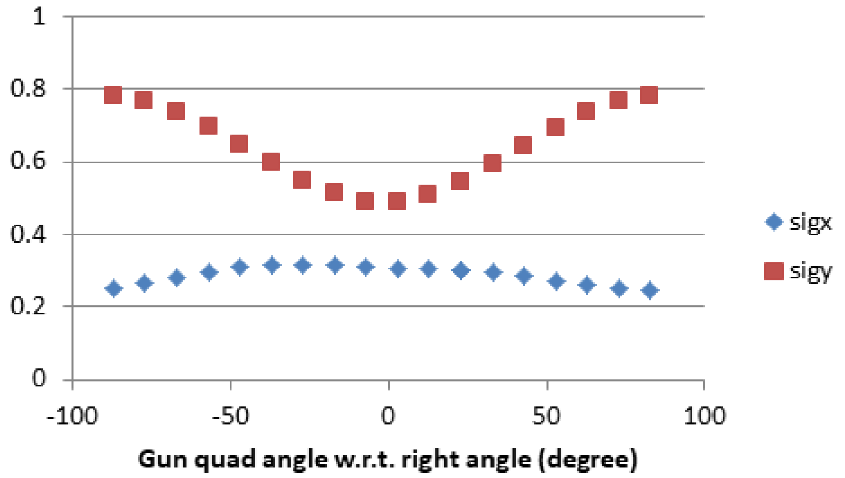

2019/1120
Beam size
0.6 A, 500 pC
scale1
scale2
Xrms
Yrms
XYrms
Xemit
Yemit
Xemit2
Yemit2
XYemit2
Gun quad angle w.r.t. right angle (deg)
1.2 A, 500 pC
Gun quad angle w.r.t. right angle (deg)
2.4 A, 500 pC
Gun quad angle w.r.t. right angle (deg)

Experiment 4 (2019/1120)

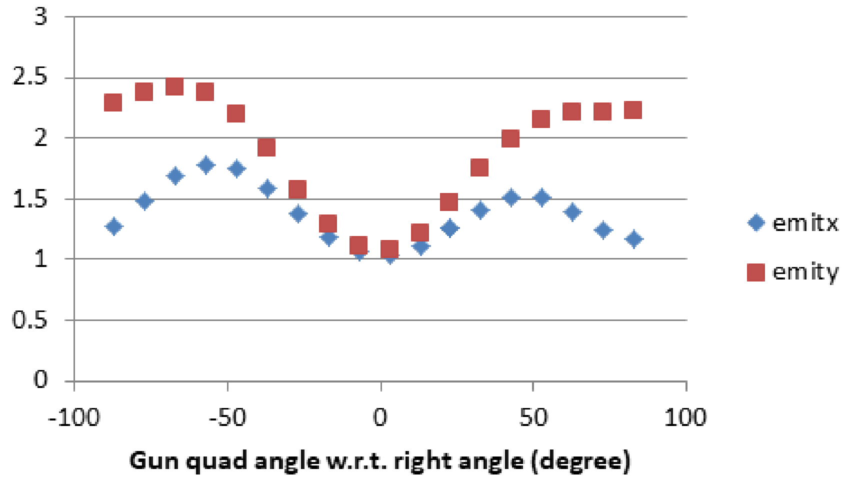
500 pC simulations (quad error increased by x1.7 compared to slide 15, angle rotated by 65°)

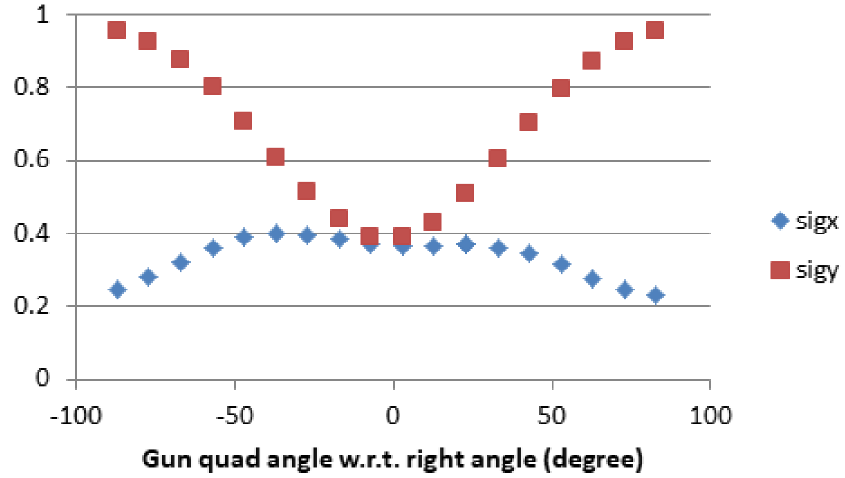
- Corrector amp=0.5x error amp



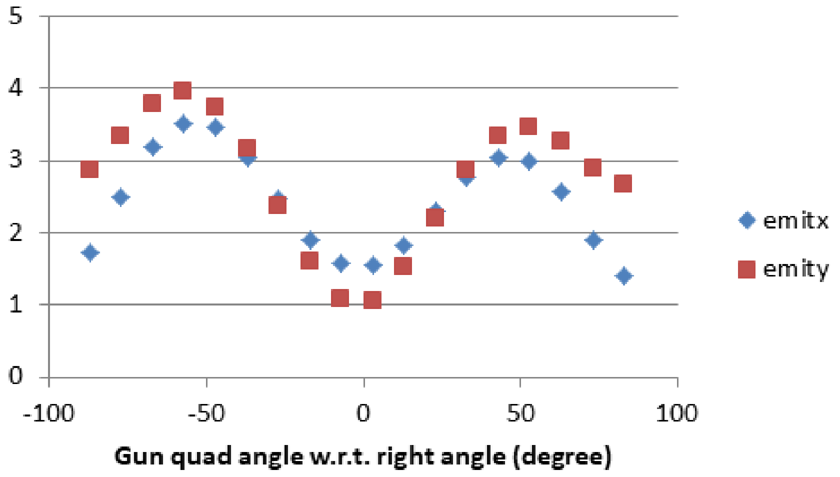


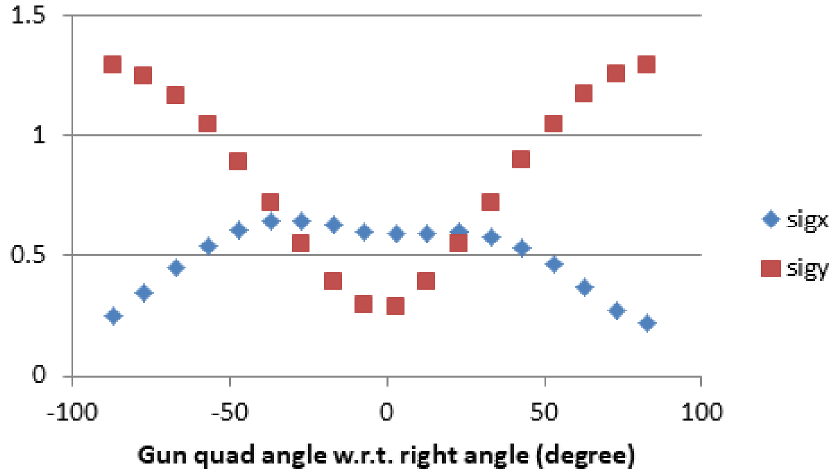
Corrector amp=1x error amp

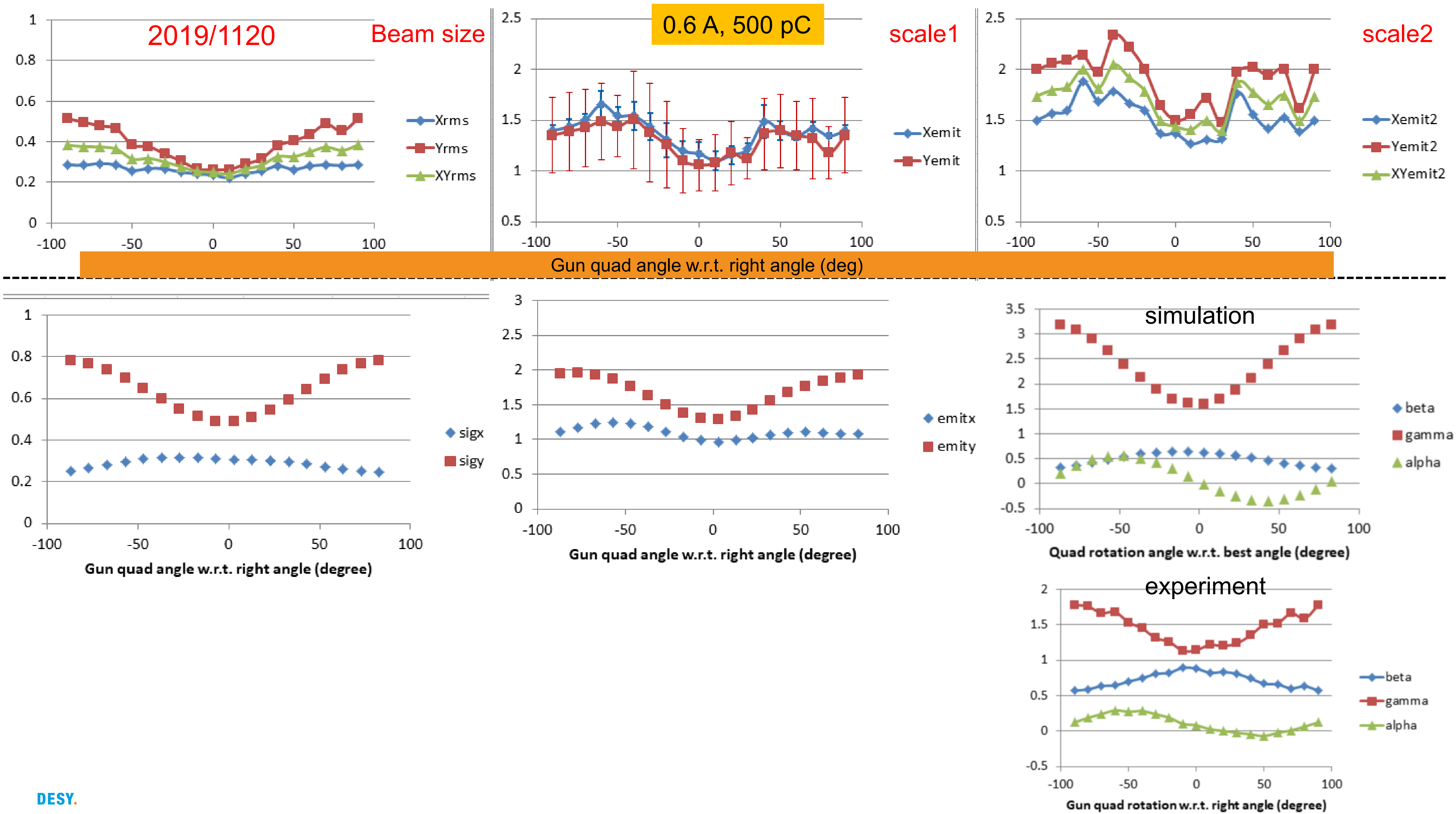




Corrector amp=2x error amp



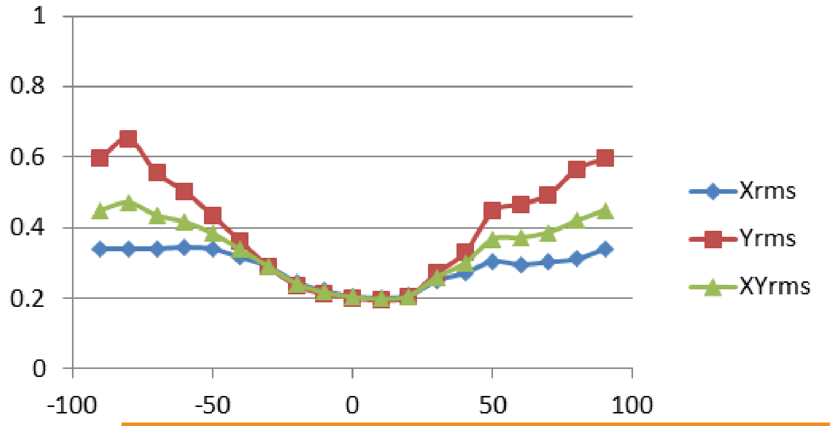


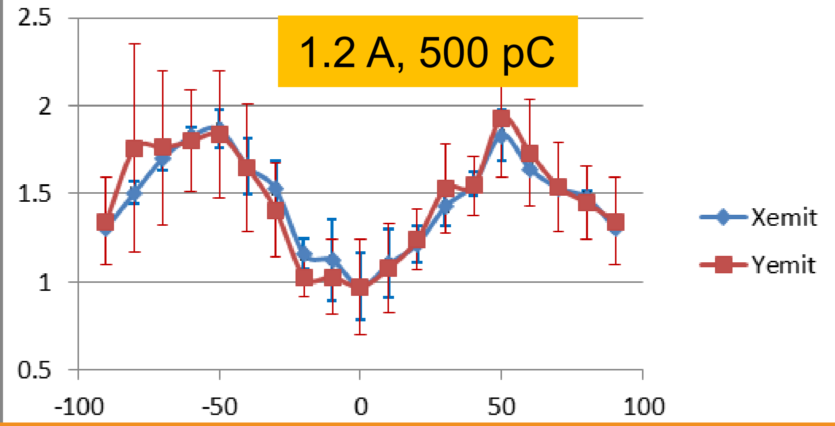

2019/1120
Beam size
0.6 A, 500 pC
scale1
scale2
Xrms
Yrms
XYrms
Xemit
Yemit
Xemit2
Yemit2
XYemit2
Gun quad angle w.r.t. right angle (deg)
sigx
sigy
Gun quad angle w.r.t. right angle (degree)
emitx
emity
Gun quad angle w.r.t. right angle (degree)
simulation
beta
gamma
alpha
Quad rotation angle w.r.t. best angle (degree)
experiment
beta
gamma
alpha
Gun quad rotation w.r.t. right angle (degree)

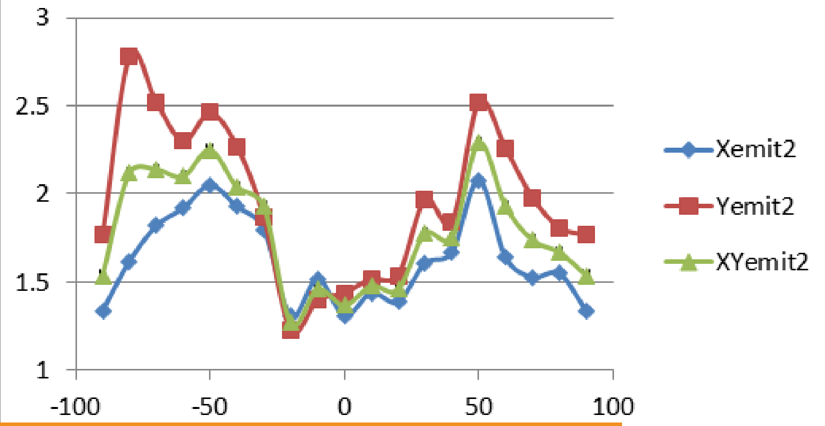
2019/1120 Beam size

scale1

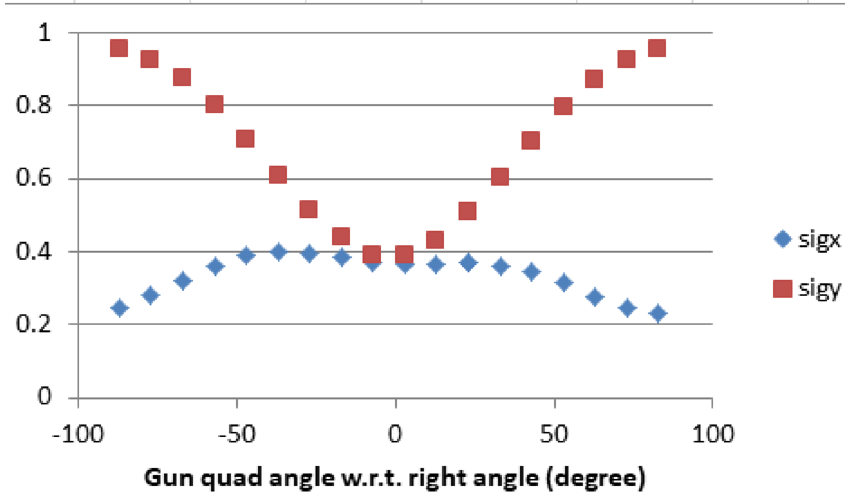
scale2

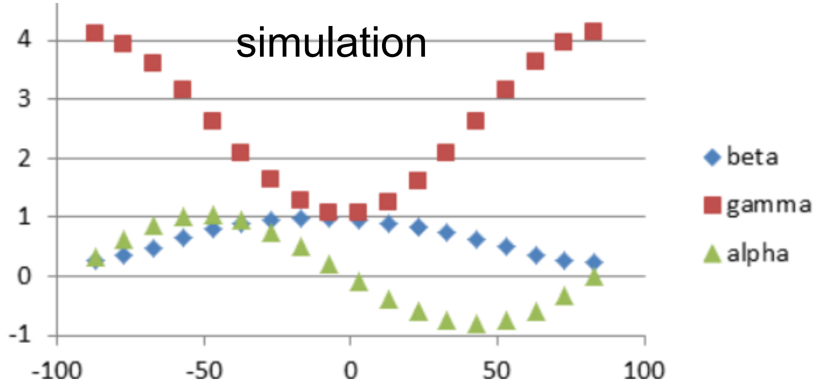


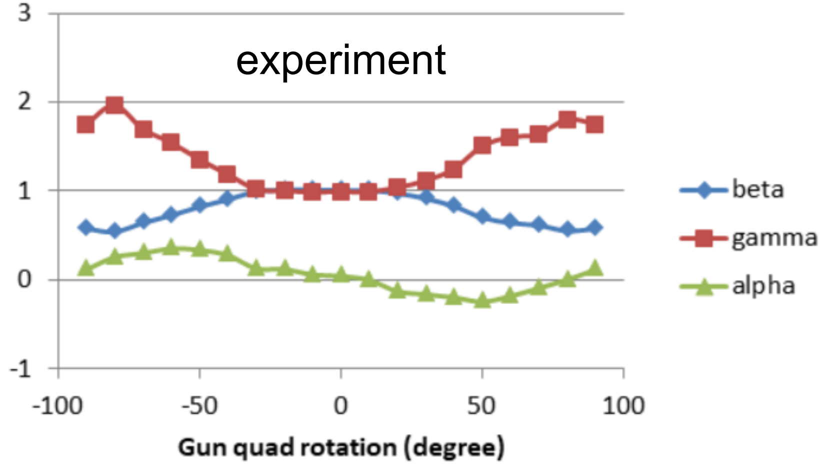




Gun quad angle w.r.t. right angle (deg)

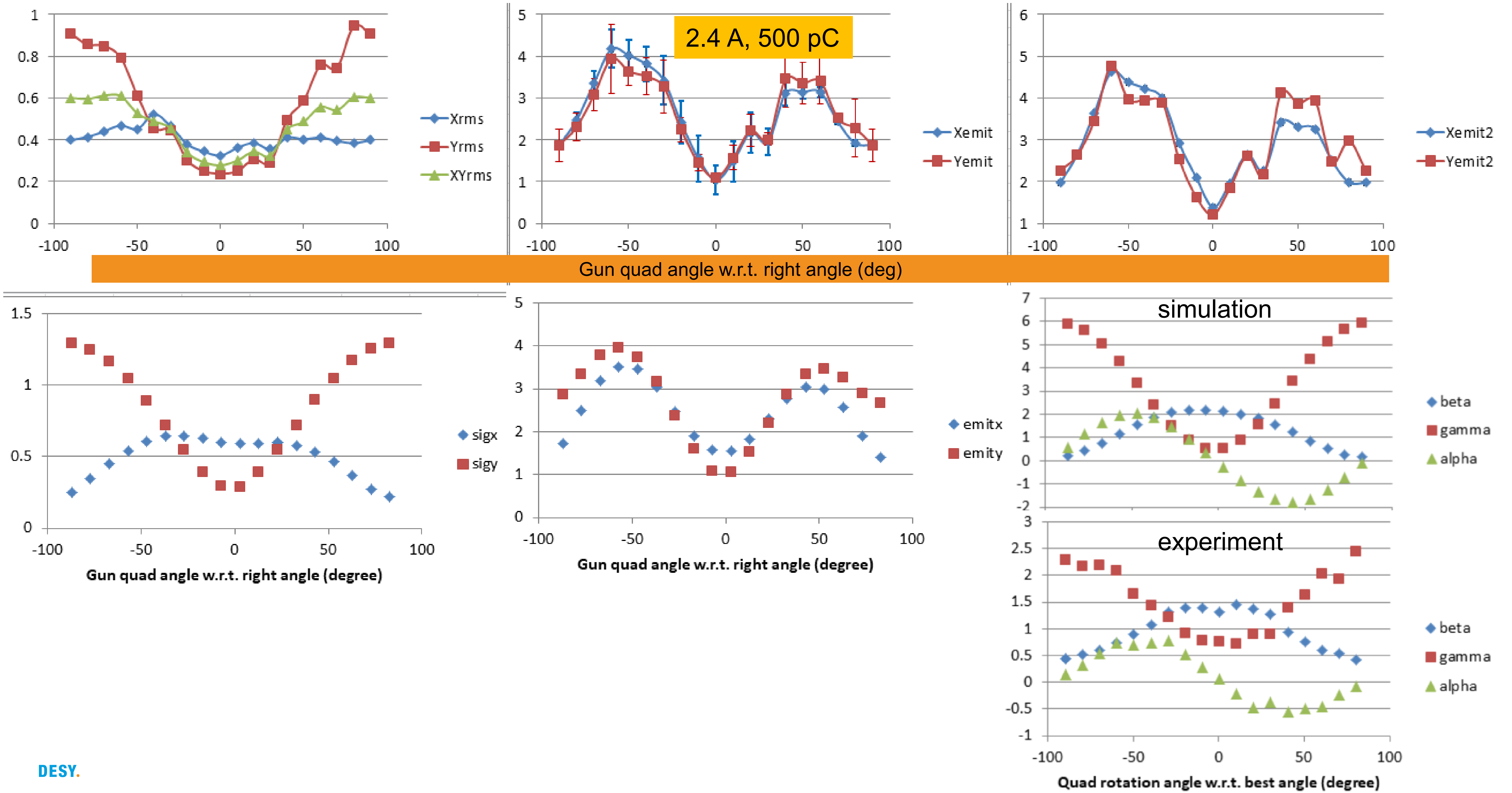






DESY.

2019/1120 Beam size scale1 scale2

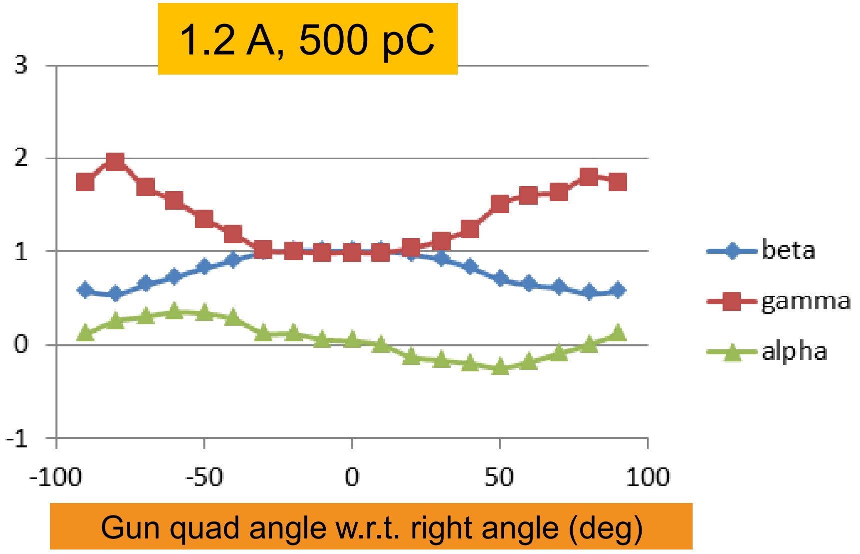


DESY.

Summary of 500/250 pC

- 250 pC, 2019/1019
  - 15% (rms), 69% (pp)
  - Optimizer: 1.07A, 1.8°
  - Quad rotation: 1.05A, 9.6°
    - Normal axis: 0.93/-0.6°
    - Skew axis:0.37/40.4°
- 500 pC, 2019/1120
  - Optimizer: 1.2A, -0.4°
  - Quad rotation: 1.08A, 10.2°
    - Normal axis: 0.98/0.5°
    - Skew axis:0.36/42.5°

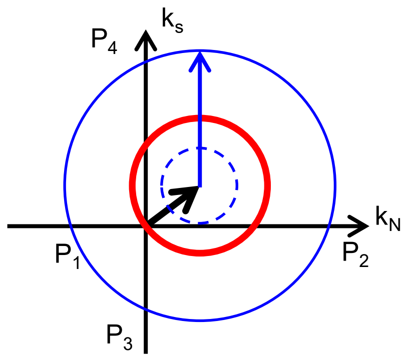
angle	beta	gamma	alpha	gamma/beta	Xemit	Yemit	XYemit
-90	0.578	1.755	0.117	3.038	1.308	1.346	1.327
-80	0.543	1.965	0.258	3.621	1.507	1.759	1.628
-70	0.642	1.698	0.302	2.644	1.702	1.763	1.732
-60	0.727	1.547	0.353	2.128	1.825	1.800	1.812
-50	0.822	1.357	0.339	1.650	1.869	1.837	1.853
-40	0.906	1.191	0.280	1.315	1.656	1.649	1.653
-30	0.994	1.024	0.132	1.031	1.528	1.407	1.466
-20	1.013	1.002	0.123	0.988	1.159	1.031	1.093
-10	1.015	0.989	0.062	0.974	1.126	1.030	1.077
0	1.008	0.994	**0.045**	**0.987**	0.977	0.974	**0.975**
10	1.007	0.993	**0.001**	**0.986**	1.104	1.079	**1.091**
20	0.975	1.042	-0.127	1.069	1.216	1.242	1.229
30	0.917	1.119	-0.160	1.220	1.429	1.532	1.479
40	0.830	1.251	-0.194	1.507	1.557	1.547	1.552
50	0.703	1.508	-0.243	2.146	1.833	1.932	1.882
60	0.643	1.607	-0.181	2.500	1.643	1.734	1.688
70	0.615	1.640	-0.090	2.669	1.534	1.542	1.538
80	0.553	1.808	0.004	3.267	1.480	1.451	1.465
90	0.578	1.755	0.117	3.038	1.308	1.346	1.327



Although rotation algorithm indicates best angle is ~10°, beam profile symmetry is also slightly better at 10°, but emittance is (6-12%) better at 0° for 250/500 pC than 10°.

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.
    - Worst emittance during scan similar as simulations
  - Major differences
    - No emittance (scale1) asymmetry in rotations with amplitudes of 0.6/1.2 A, as predicted by simulations, somehow vertical emittance measurement has large error bar due to large scaling factor, which maybe due to halos induced by couplings.
    - Beam size asymmetry pattern vs gun quad rotation is similar to simulation, but actual values are not.