Resonance Corrections at J-PARC MR

US-Japan Workshop on Accelerators and Beam Equipment for High-Intensity Neutrino Beams
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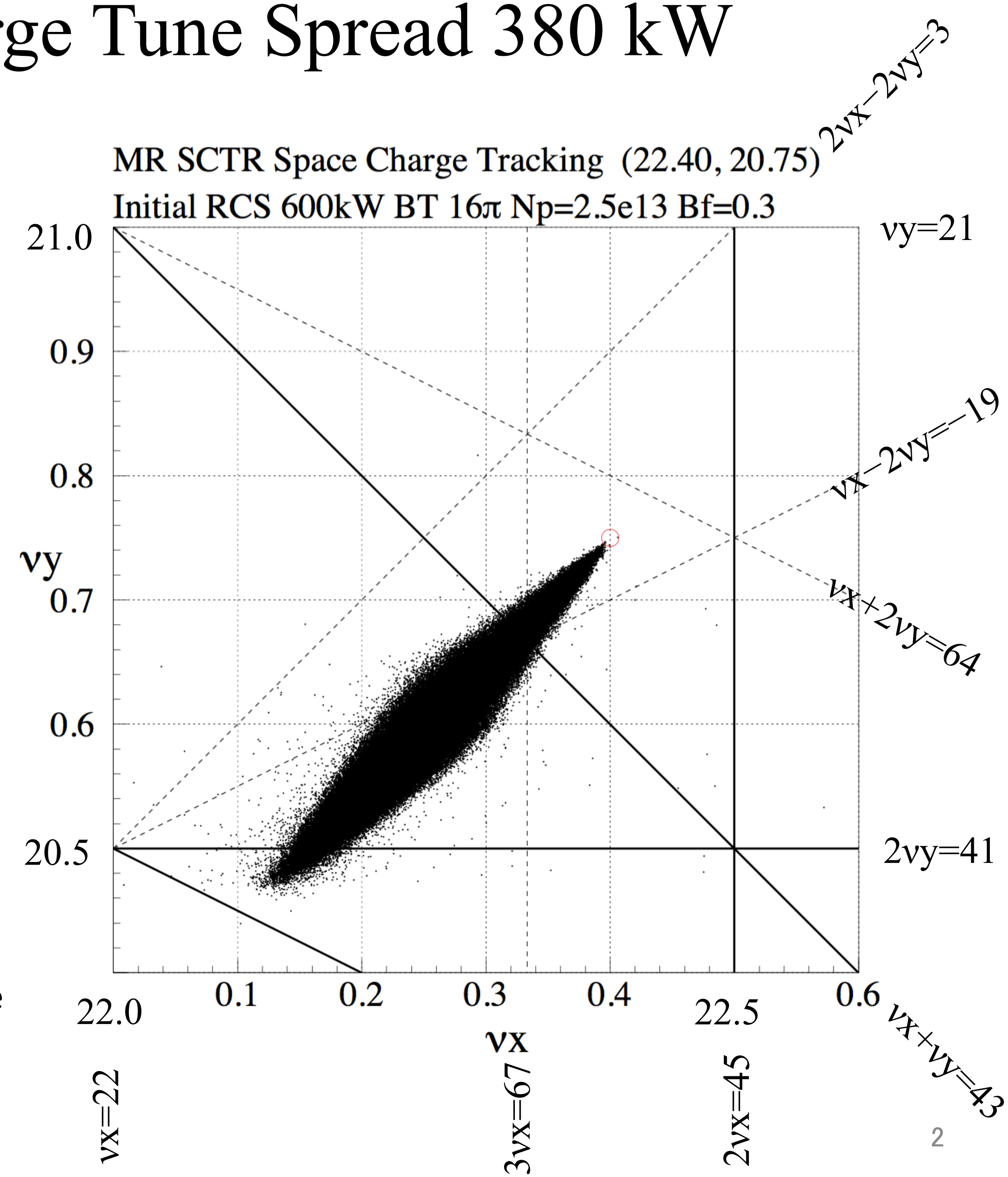
Space Charge Tune Spread 380 kW

- MR Power 380 kW
- MR Cycle: 2.48 s
- Number of protons: 2.5e13 ppb
- Transverse Emittance: 16π mmmrad
- Bunching Factor: 0.3
- Space Charge Tune Shift: 0.33

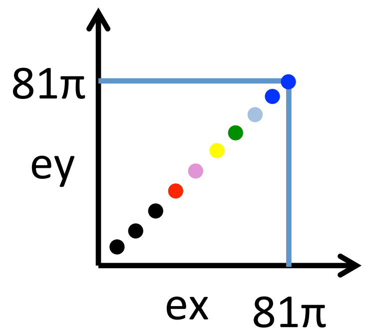
$$\Delta\nu = \frac{2\pi R N r_0}{4\pi\sigma^2/\beta(v/c)^2\gamma^3 B_f} = 0.33$$

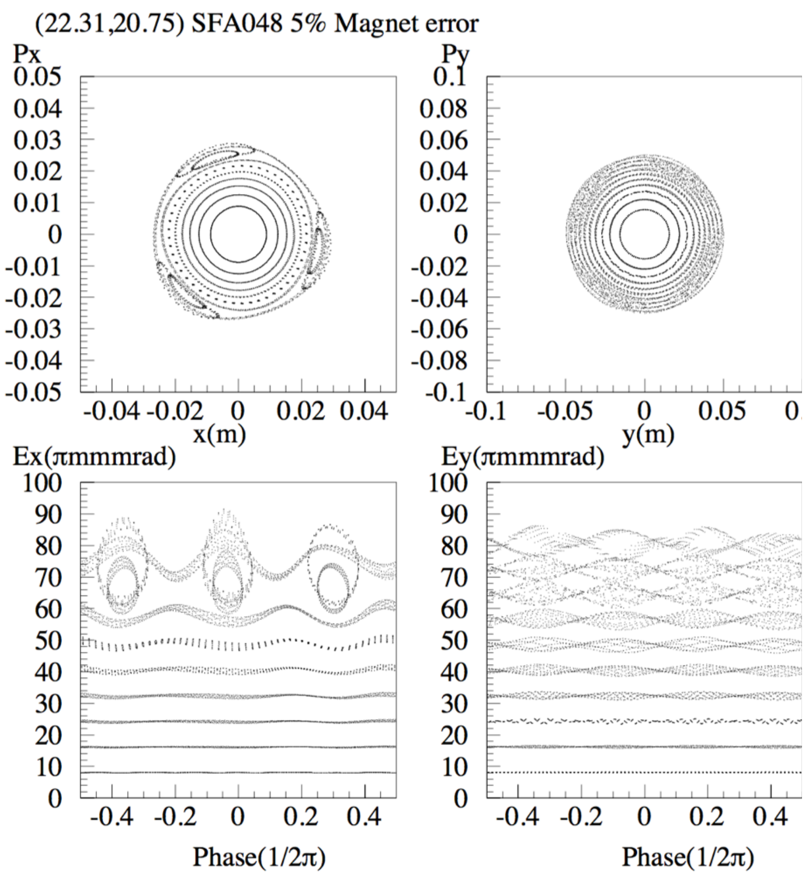
- E = 3 GeV
- $(v/c)^2\gamma^3$=69.751
- $2\pi RN = 2.5\times10^{13}\times9$: Intensity
- $4\pi\sigma^2/\beta$ = 16π mmmrad : Emittance
- B_f = 0.3 : Bunching factor

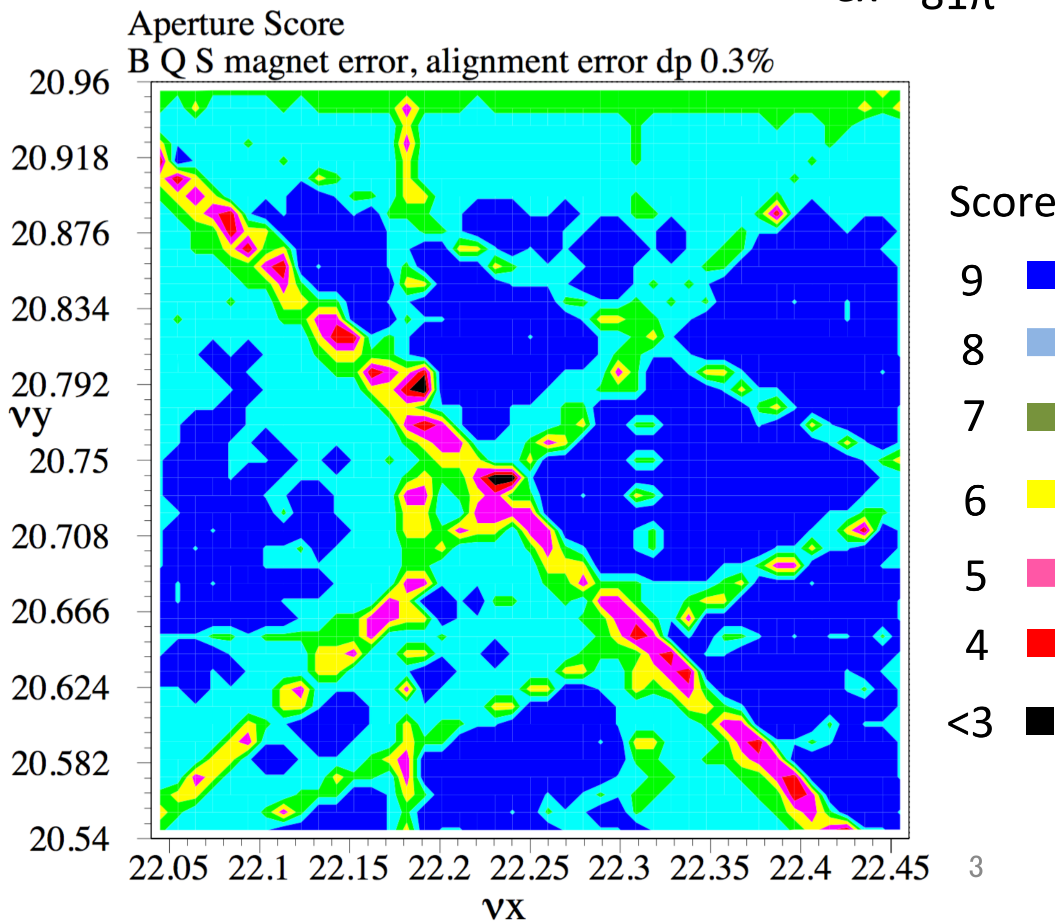


Dynamic Aperture

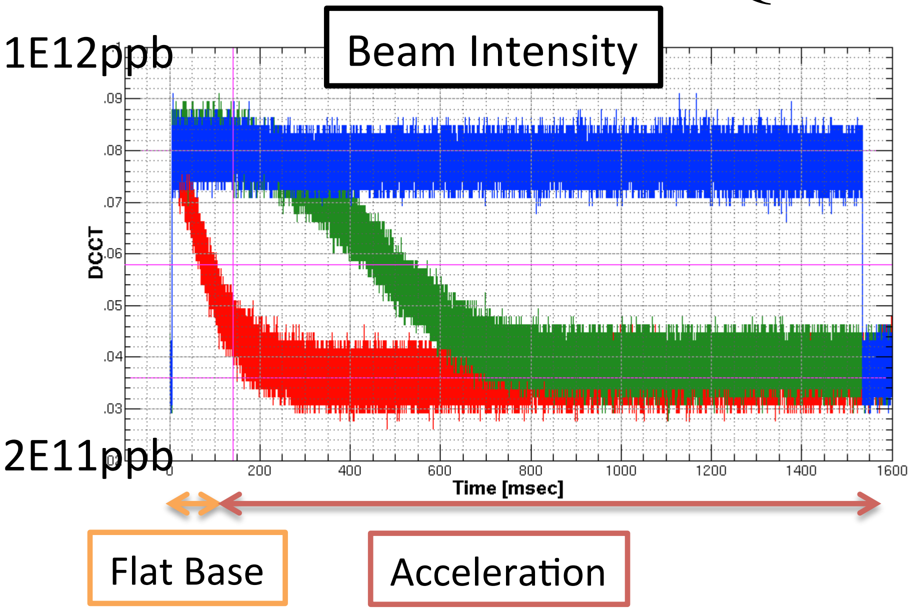
- J-PARC MR has a three fold symmetry.
- Non structure resonances would be caused by magnet errors.
- SAD simulation with magnet errors, multipole components and alignment errors.
- Track 10 test particles for 1000 turns and count the number of particles within the aperture of 81π mmmrad for each set of tune.







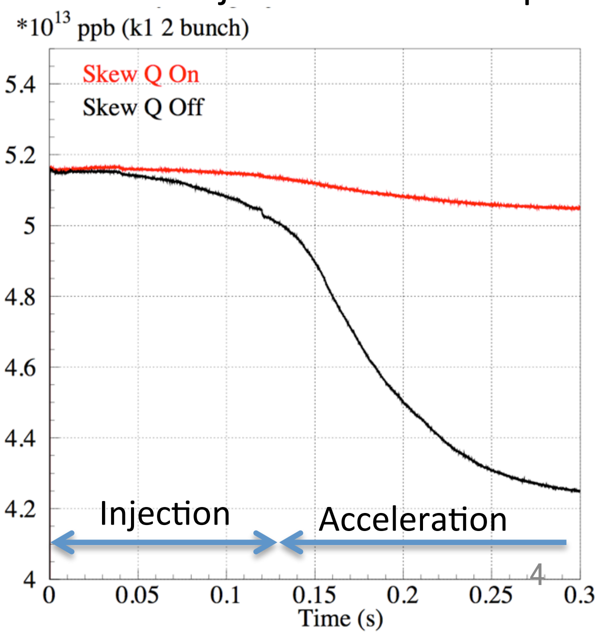
Linear Coupling Resonance Correction with Skew Quadrupole Magnets



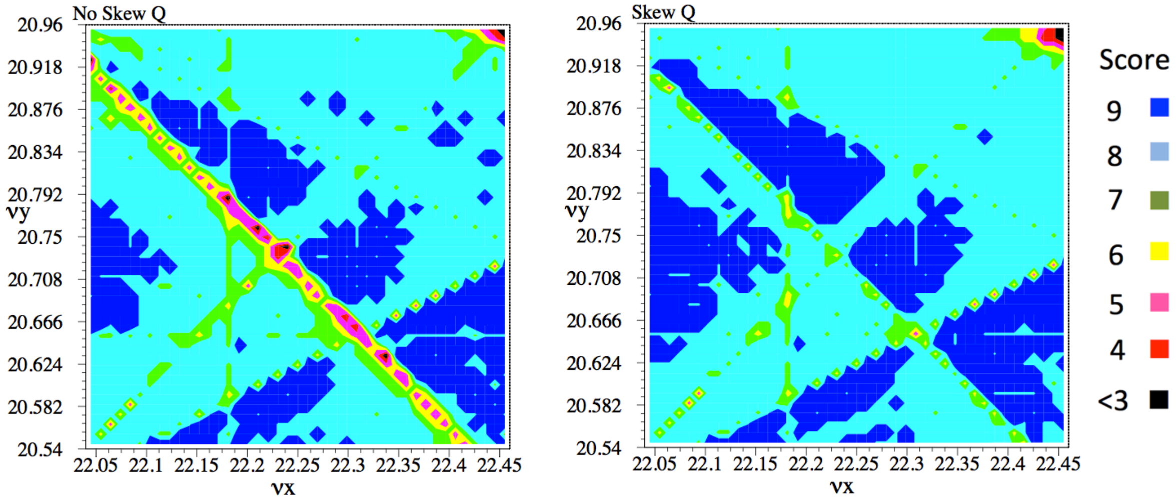
Measured beam survival
on LCR (22.28, 20.71)
w changing Skew Q
No correction
Corrected with 3 GeV DC
Corrected from 3 to 30 GeV

Skew Q setting reduces beam loss in high intensity operation and is used for the user operation.

2 bunch injection 380 kW equiv.

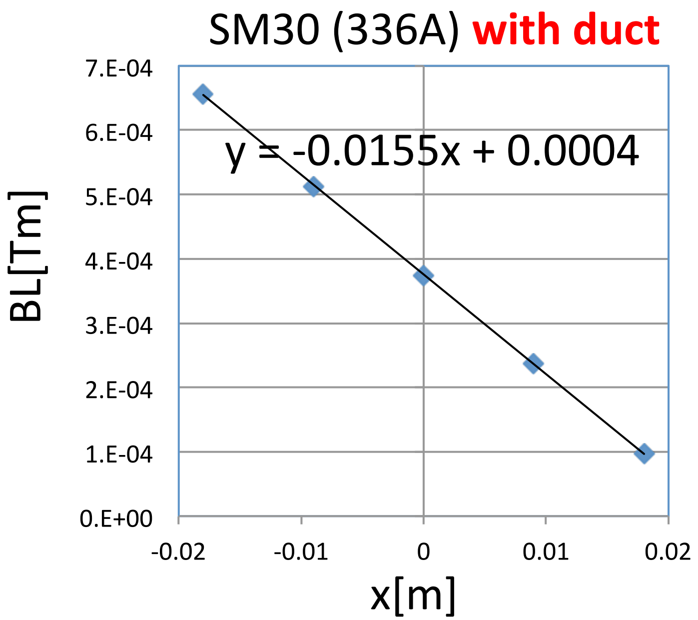


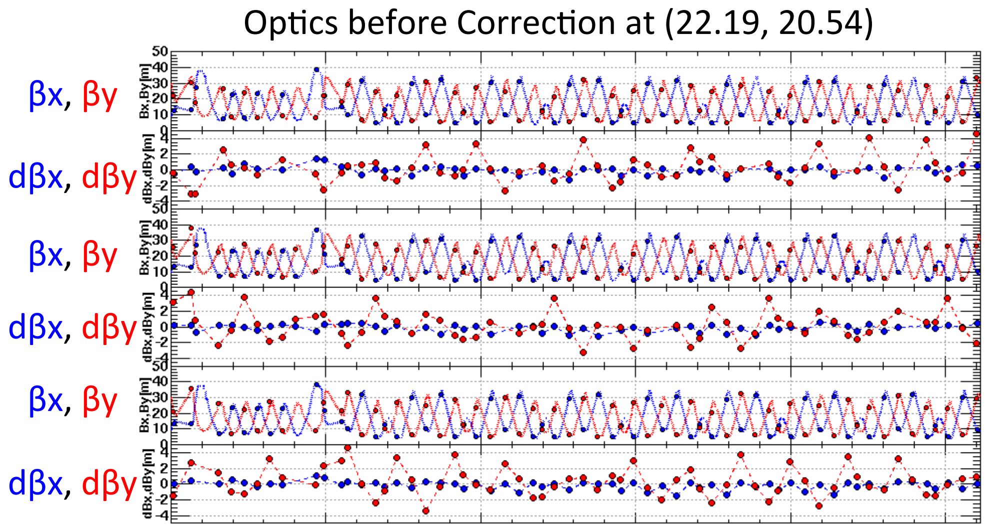
Simulation for tune survey for aperture w/o Skew Q, with Skew Q

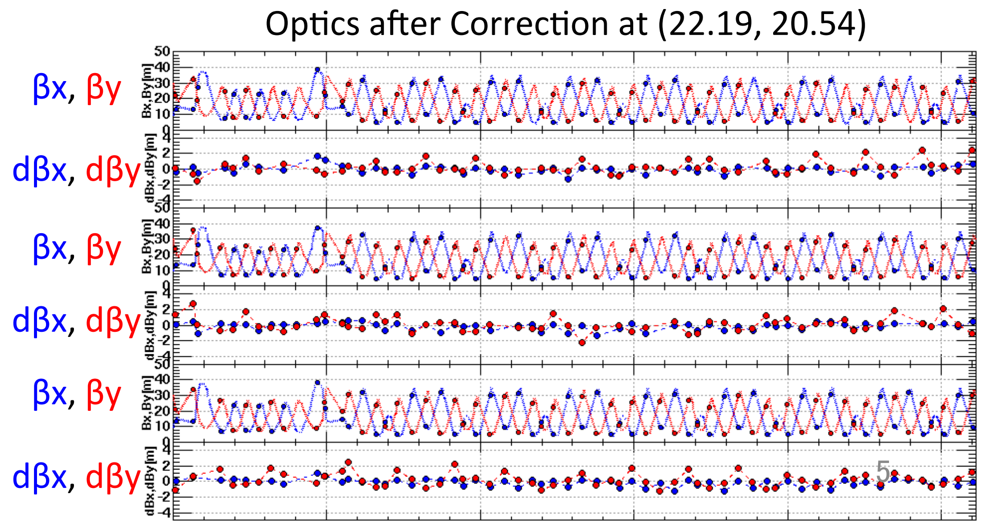


FX Septum Leak Field

- FX septum magnets makes undesirable Q fields for circulating beam with the leak fields.
- Leak field of 8 FX septum magnets corresponds to ~3% of K1 of the main Q magnet.
- Trim coils of 3 Q magnets have been used to correct the leak field of FX septum magnets.

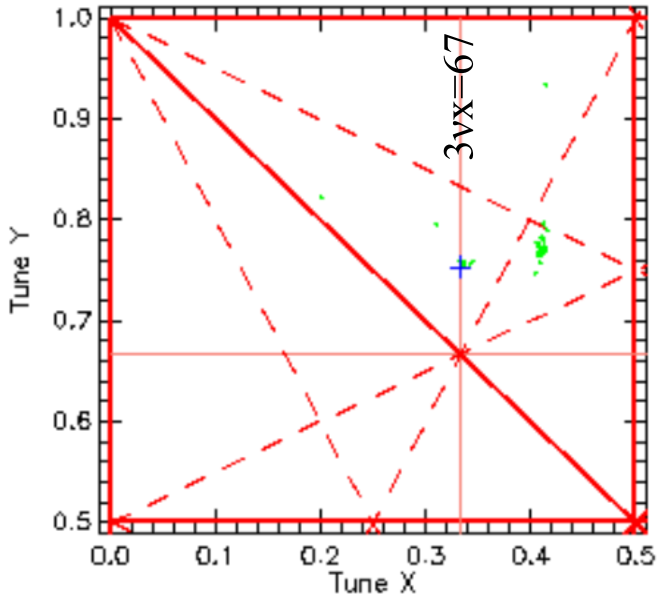




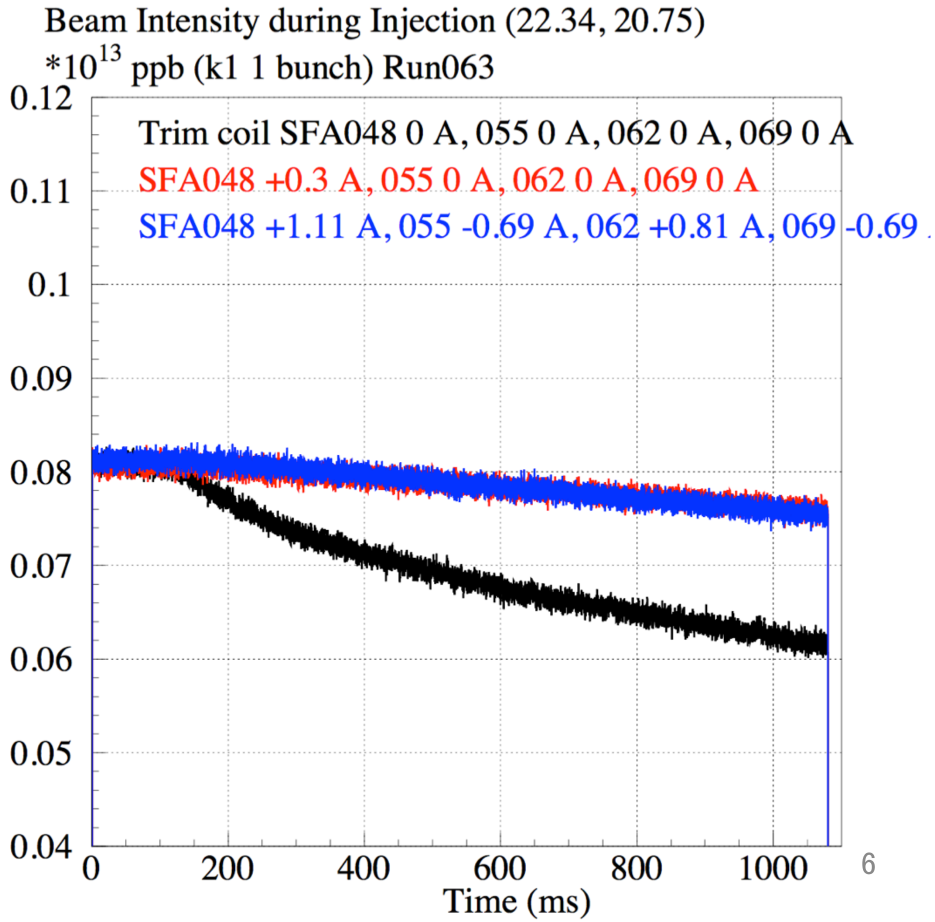


Correction of the Resonance $3\nu_x = 67$

- Search the tune around (22.34, 20.75) for the condition of worse beam survival.
- Low intensity beam of 8E11ppp
- 3 GeV DC mode
- Search the trim coil current setting for the recovery of beam survival. SFA048 +0.3 A、SFA055 0 A.
- The beam survival recovered with the trim coil current setting for the correction of both $3\nu x = 67$ and $\nu x+2\nu y = 64$ (SFA048 +1.11 A, 055 -0.69 A, 062 +0.81 A, 069 -069 A).

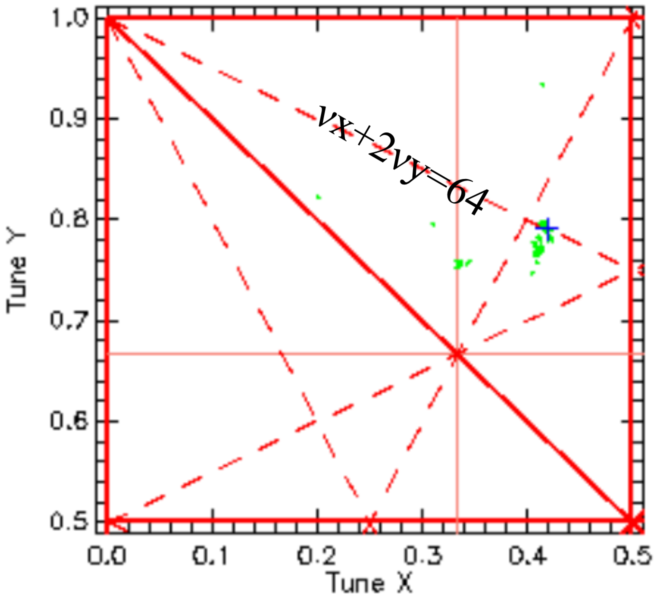


$$\left|G_{3,0,64}\right| = \left|\frac{\sqrt{2}}{24\pi}\beta_x^{3/2}k_2\exp[i(3\phi_x)]\right| = 0.033$$

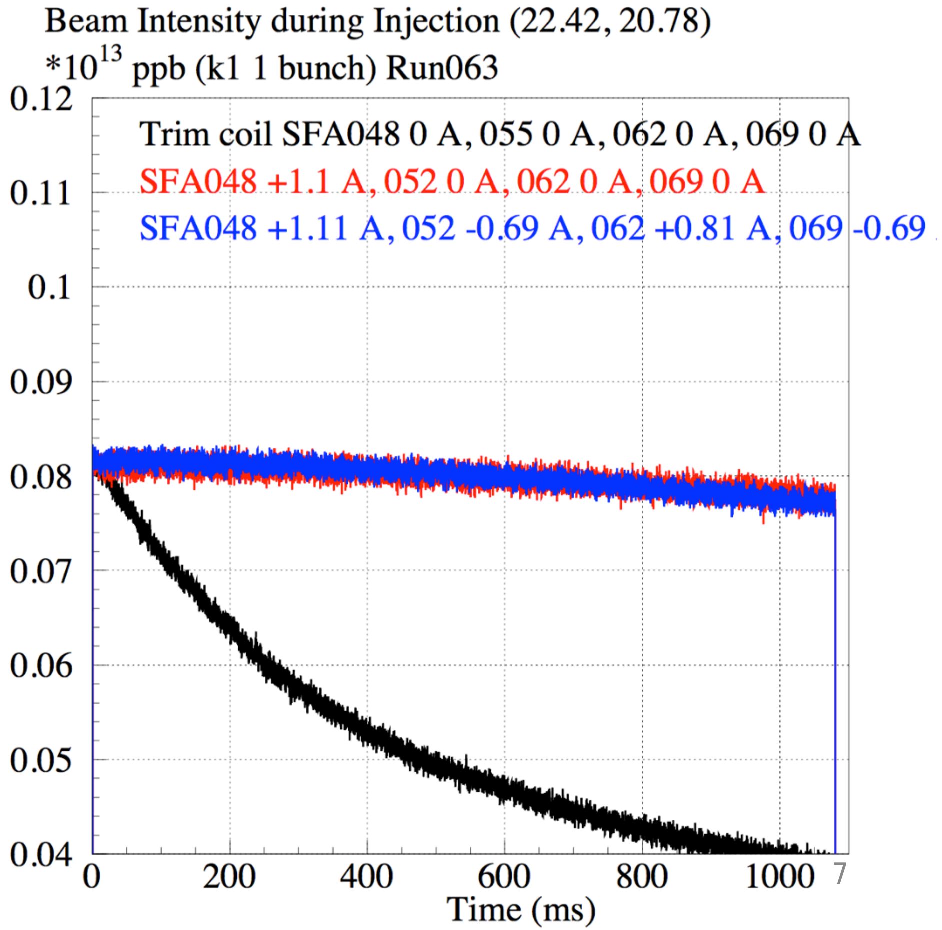


Correction of the Resonance $\nu_x+2\nu_x=64$

- Search the tune around (22.34, 20.75) for the condition of worse beam survival.
- Low intensity beam of 8E11ppp
- 3 GeV DC mode
- Search the trim coil current setting for the recovery of beam survival. SFA048 +1.1 A、SFA055 0 A.
- The beam survival recovered with the trim coil current setting for the correction of both 3νx = 67 and νx+2νy = 64 (SFA048 +1.11 A, 055 -0.69 A, 062 +0.81 A, 069 -069 A).



$$\left|G_{1,2,64}\right| = \left|\frac{\sqrt{2}}{8\pi}\beta_x^{1/2}\beta_y k_2 \exp[i(\phi_x+2\phi_y)]\right| = 0.17$$



Correction of the 3rd Order Resonances of both νx+2νy = 64 and 3νx = 67

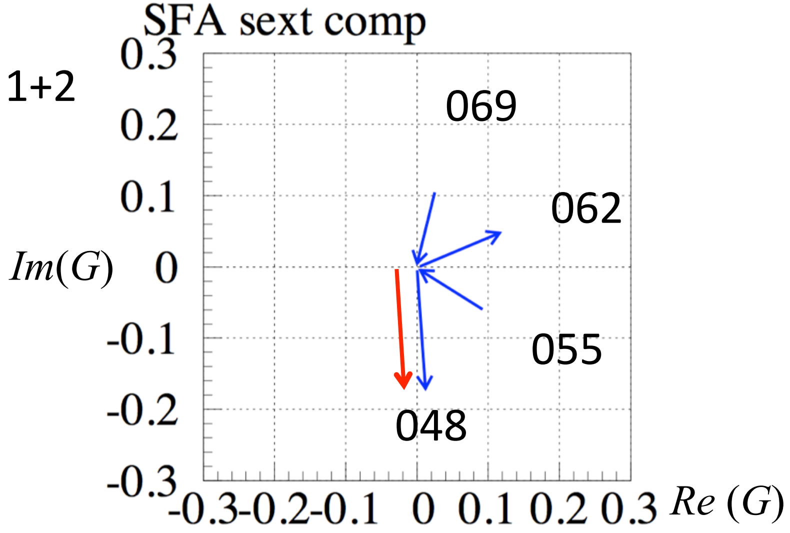
- Equations for canceling both resonances, for $k_2(1)$, $k_2(2)$, $k_2(3)$, $k_2(4)$.
- 1 = SFA048, 2 = SFA055, 3 = SFA062, 4 = SFA069

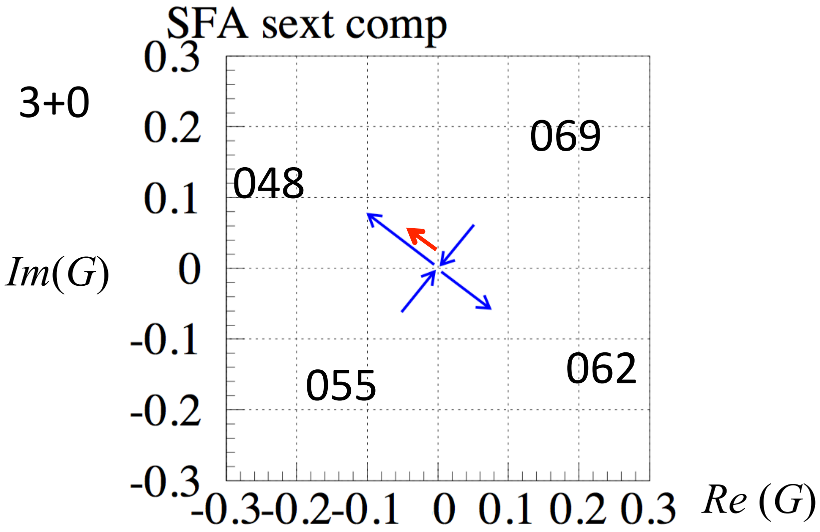
$$\sum_{j=1}^{4} \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(j)\ k_2(j) \cos[3\phi_x(j)] = \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(1)\ k_2(1) \cos[3\phi_x(1)]$$

$$\sum_{j=1}^{4} \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(j)\ k_2(j) \sin[3\phi_x(j)] = \frac{\sqrt{2}}{24\pi} \beta_x^{3/2}(1)\ k_2(1) \sin[3\phi_x(1)]$$

$$\sum_{j=1}^{4} \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(j)\beta_y(j)\ k_2(j) \cos[\phi_x(j)+2\phi_y(j)] = \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(1)\beta_y(1)\ k_2(1) \cos[\phi_x(1)+2\phi_y(1)]$$

$$\sum_{j=1}^{4} \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(j)\beta_y(j)\ k_2(j) \sin[\phi_x(j)+2\phi_y(j)] = \frac{\sqrt{2}}{8\pi} \beta_x^{1/2}(1)\beta_y(1)\ k_2(1) \sin[\phi_x(1)+2\phi_y(1)]$$





Remanent Field of Resonance Sextupole Magnet for Slow Extraction

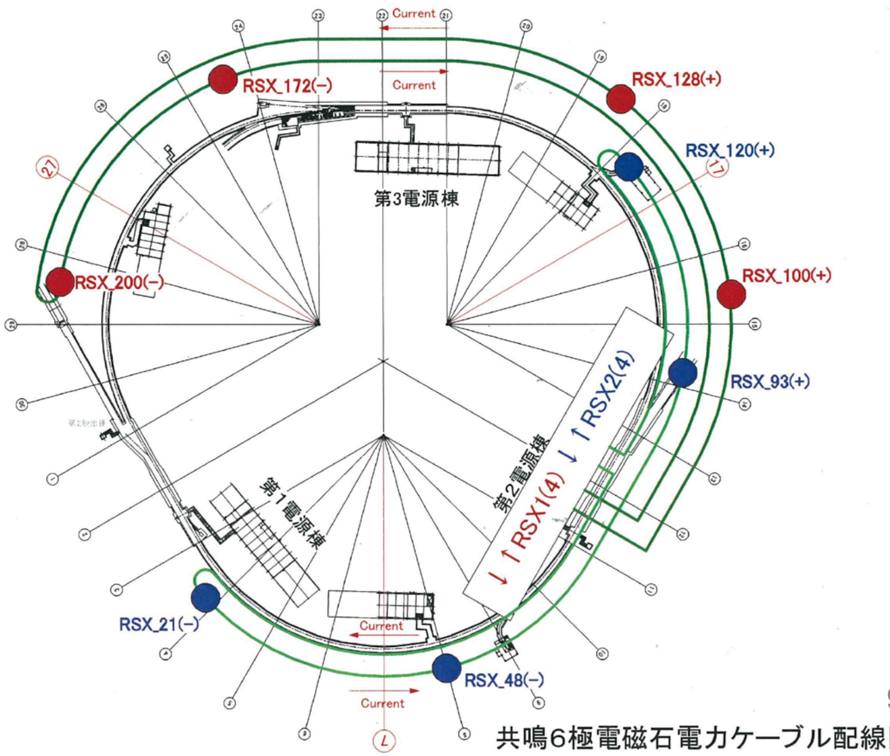
- Eight magnets are used for the slow extraction.
- Remanent field was measured at the pole tip to be 5.2 gauss.
- K2 = 0.0123 m-2
- We degaussed the RSX magnets before the FX operation.

$$B = B_2 x^2$$

$$B_2 L = \frac{B}{x^2} L = \frac{5.2 \times 10^{-4}}{(0.068)^2} \times 0.7$$

$$K2 = \frac{1}{B\rho} \frac{d^2 B}{dx^2} L = \frac{0.156 Tm^{-1}}{12.75 Tm} = 0.0123 m^{-2}$$

RSX magnet	Remnant Field (gauss)
021	-5.0
049	-5.0
093	+4.8
100	+5.0
121	+5.0
128	+6.0
172	-5.0
200	-5.5



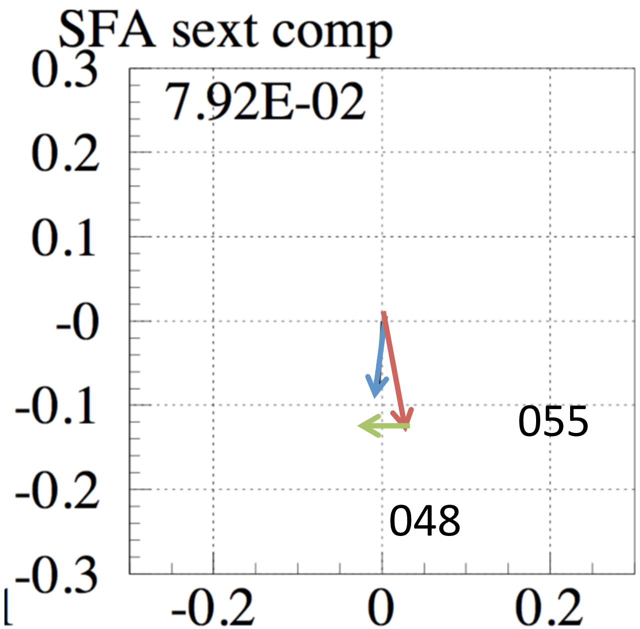
共鳴6極電磁石電力ケーブル配線図

Resonance Amplitude of 3νx = 67 and νx+2νy = 64 before and after the degaussing of RSX

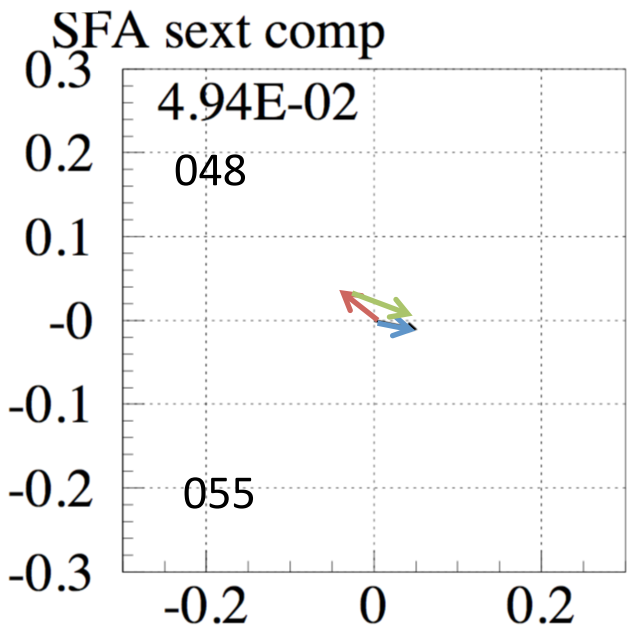
- Resonance Amplitude
- G3,0,67 = 0.033 (Before Degaussing)
  − 0.069 (Remanent of RSX)
  = 0.049 (After Degaussing)
- G1,2,64 = 0.139 (Before Degaussing)
  − 0.058 (Remanent of RSX)
  = 0.079 (After Degaussing)

- For the correction of both 3νx = 67 and νx+2νy = 64
- SFA048 +0.64 A
- SFA055 −1.05 A
- SFA062 +1.04 A
- SFA069 −0.85 A

1+2

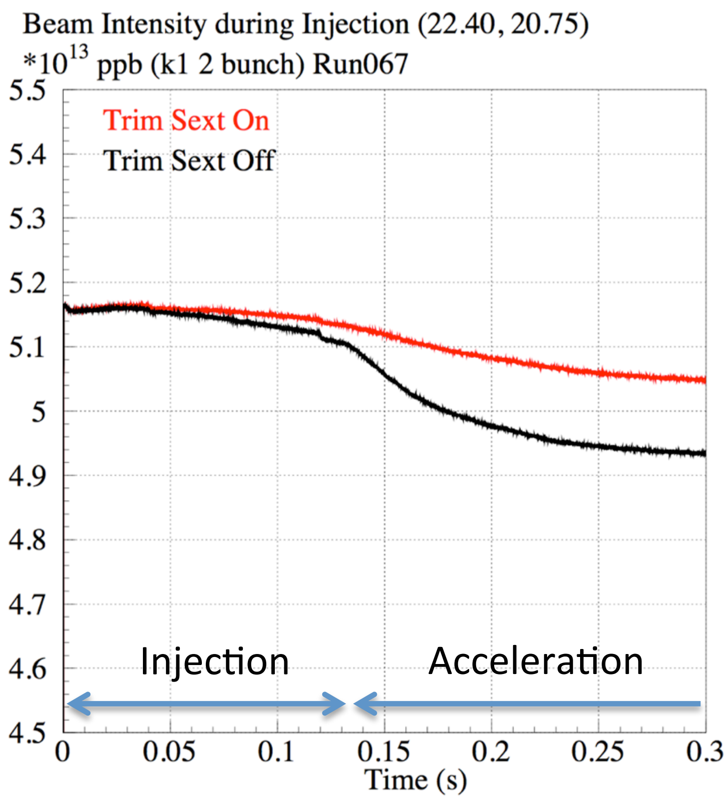


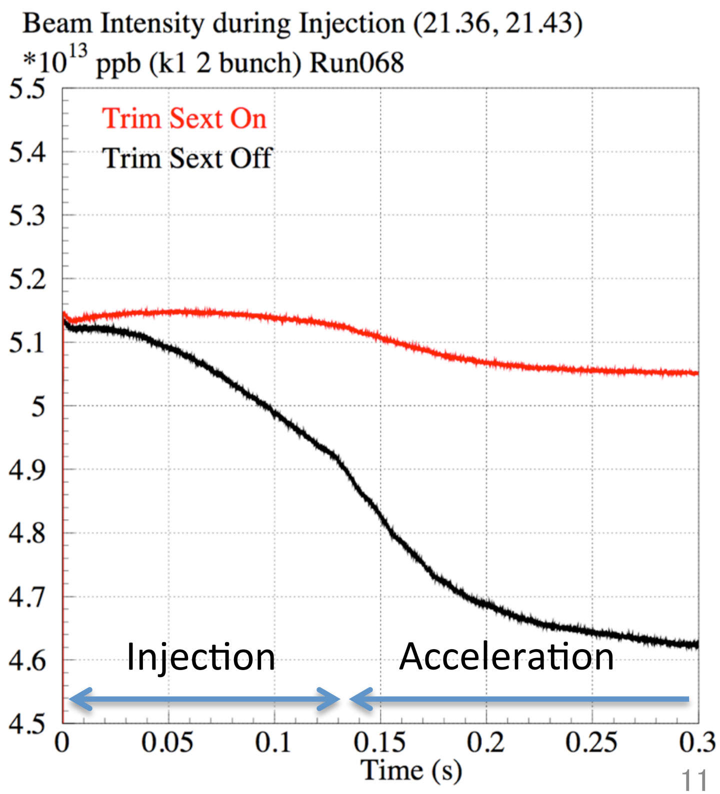
3+0



Correction of the 3rd Order Resonances of both νx+2νy = 64 and 3νx = 67 (or 64)

- Beam losses were reduced with the correction during injection and the beginning of acceleration for high intensity beam of 380 kW equivalent.
- Correction of both $\nu_x+2\nu_x=64$ and $3\nu_x=67$ for tune of (22.40, 20.75)
- Correction of both $\nu_x+2\nu_x=64$ and $3\nu_x=64$ for tune of (21.36, 21.43)



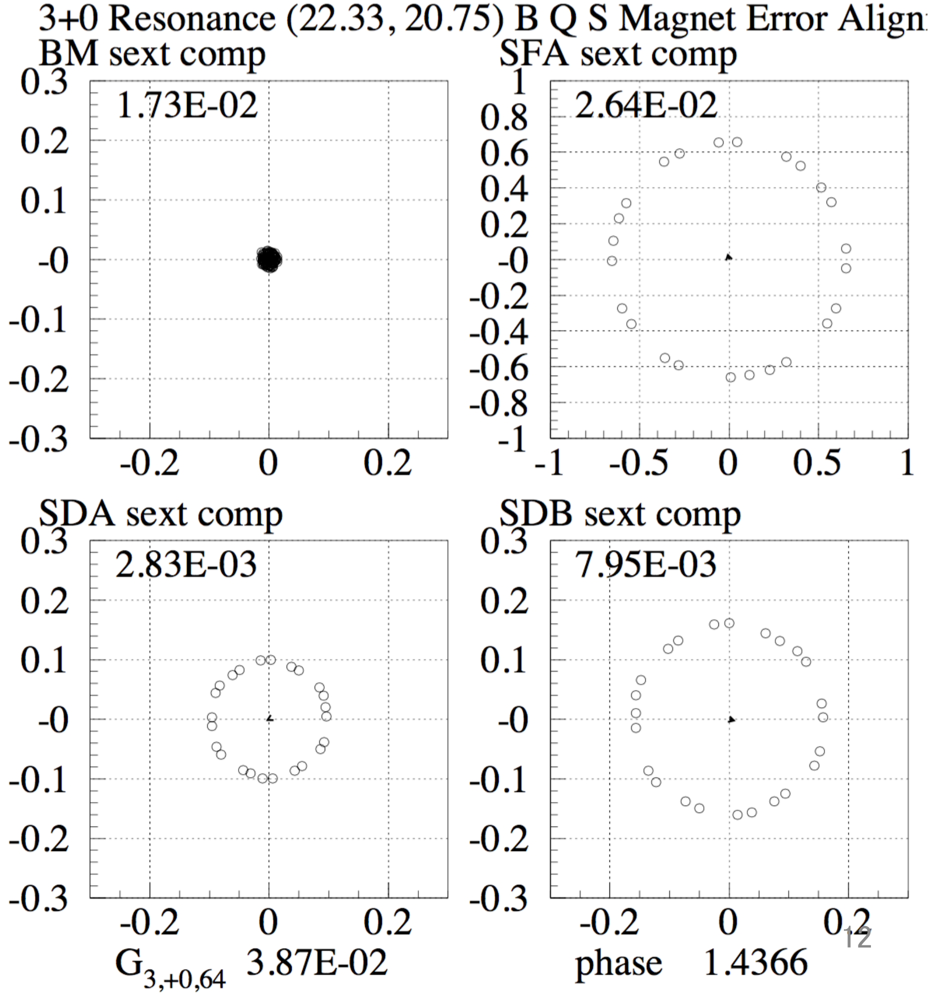


Estimate of Resonance Amplitudes with Magnet Errors of B Q S

- Variation of main components from field measurements
- Variation of multipole components from field measurements
- Alignment errors σ 0.14 mm
- Rotation errors σ 0.14 mrad

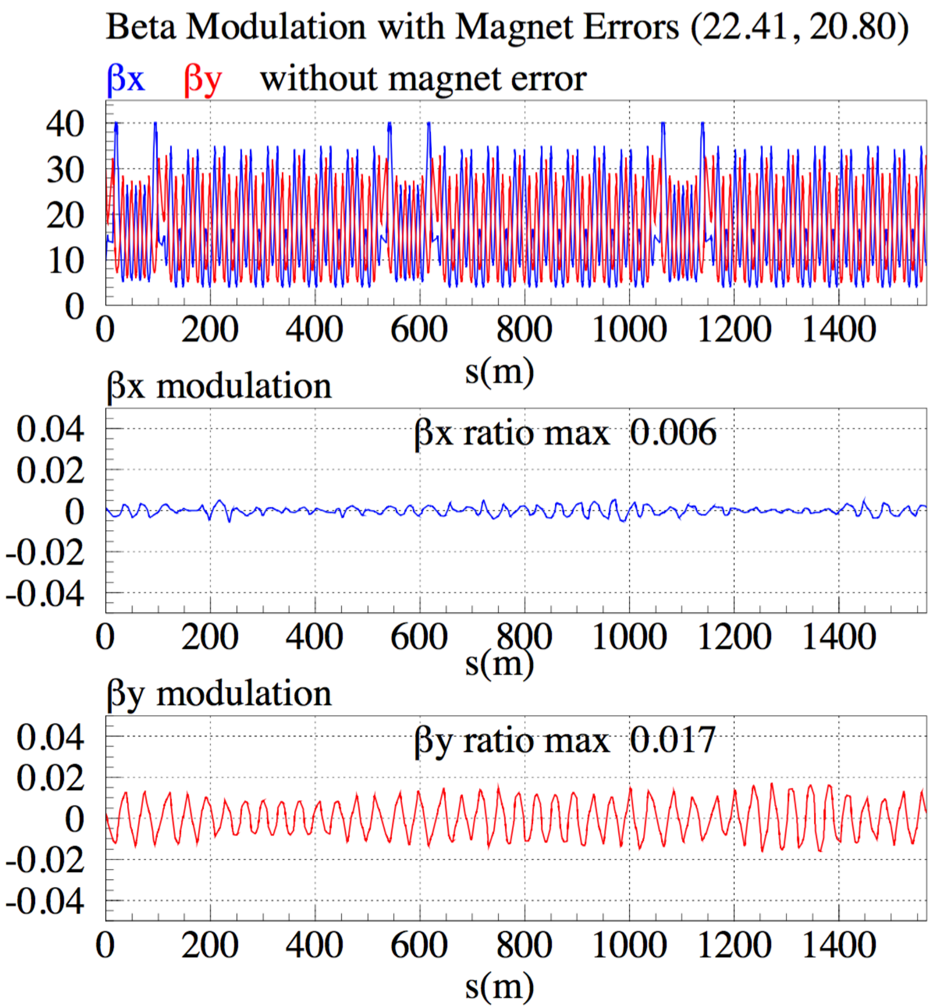
- SAD calculation
- Resonance Amplitude
- G3,+0,67 = 0.039 (calc.)
- G3,+0,67 = 0.049 (meas.)
- G1,+2,64 = 0.061 (calc.)
- G1,+2,64 = 0.079 (meas.)
- G1,−2,−19 = 0.053

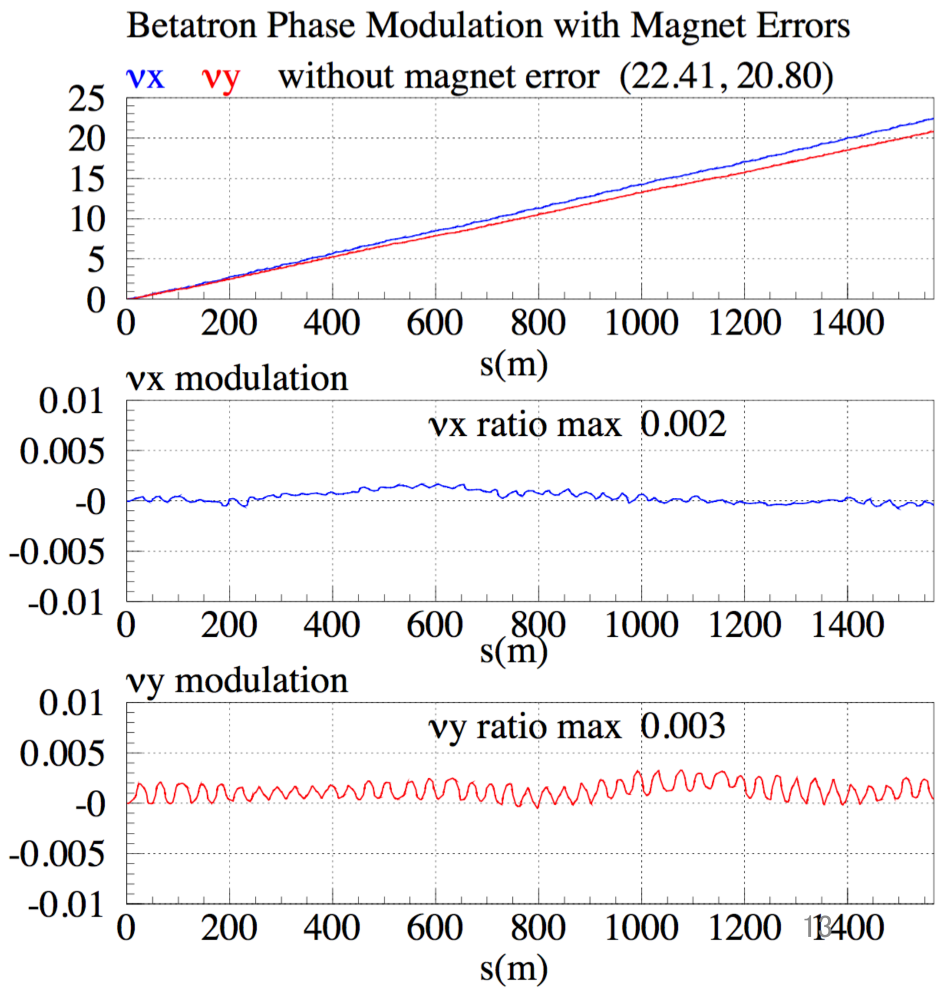
$$G_{3,0,64} = \frac{\sqrt{2}}{24\pi}\beta_x^{3/2}k_2\exp[i(3\phi_x)]$$



Resonance Amplitude with magnet errors of B Q S

- Beta and phase modulation from the variation of main magnets would cause the third order resonances.
- Variation of sextupole magnet itself is probably not the main cause.





Summary

- Magnet errors cause non-structure resonances and reduce the dynamic aperture.
- The linear coupling resonance was corrected with skew quadrupole mangets.
- The half integer resonance and beta modulation caused by the FX septum magnets were corrected with the excitation of the trim coils of quadrupole magnets.
- Third order resonances have been corrected with the excitation of the trim coils of sextupole magnets.
- The beam survival was improved with the resonance corrections.