Space charge effects based on measured lattice

K. Ohmi (KEK)

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Y. Sato, J. Takano

Status of J-PARC MR

- MR Beam Power is 200-220kW at 30GeV for Fast eXtrac.
- Limitation of bunching factor (~0.2) due to leakage (extra kick) of injection kicker.
- Tune shift is ~0.2, for the beam size ε(1σ)=4-5π μm at 3GeV.
- $Np=1.3x10^{13}x8$ bunches

Aperture: ~70 π μm

- Operating point, 22.4,20.75
- Instability has been observed. Feedback and chromaticity suppress basically.

- Linac upgrade 180MeV to 400 MeV in 2014.
- Quality and quantity(>2x) of RCS beam is improved.
- High power operation toward the design power (750kW) becomes real mission.

Introduction

- One turn map is determined by nonlinear force itself and linear optics at the nonlinear force elements.
- Linear optics parameters are measurable.
- Nonlinear space charge dynamics based on measured optics.
- My stand point: we understand nonlinear components (including space charge) of an accelerator, but do not understand the linear optics at the nonlinear components.

One turn map for nonlinearity lattice

$$\mathcal{M}(s) = \prod_{i=0}^{N_I - 1} M_0(s_{i+1}, s_i) e^{-:H_I(s_i):}$$

Transfer matrix from s_i to s_{i+1}

Nonlinear transformation at s_i

$$e^{-:H_I(s_i):}\boldsymbol{p} = \boldsymbol{p} - \frac{\partial H_I(s_i)}{\partial \boldsymbol{x}}$$

$$H_I(s_i) = \frac{K_2(s_i)}{6}(x^3 - 3xy^2) \qquad K_2 = \frac{eB"}{p_0}$$

ex. Sextupole magnet

$$H_I = \Phi(x, y, s)$$

ex.2 space charge potential given by solving Poisson equation with the beam distribution.

Integration step: $\Delta s < \beta_{xy}$

$$\Delta\phi_{x,y} = \frac{\Delta s}{\beta_{x,y}}$$

Linear dynamics

- Linear Motion is represented by symplectic matrix transformation of the dynamic variables x.

$$\boldsymbol{x}(s) = (x, p_x, y, p_y, z, \delta)^t \qquad z = v(t_0 - t) \quad \delta = \frac{\Delta p}{p_0}$$

- Revolution matrix, M(s).

$$\boldsymbol{x}(s+C) = M_0(s)\boldsymbol{x}(s)$$

- Diagonalize 2x2 blockwisely

$$V_0(s)M_0(s)V_0(s)^{-1} = \begin{pmatrix} U_X & 0 & 0 \\ 0 & U_Y & 0 \\ 0 & 0 & U_Z \end{pmatrix} \equiv U_0 \qquad U_i \equiv \begin{pmatrix} \cos\mu_i & \sin\mu_i \\ -\sin\mu_i & \cos\mu_i \end{pmatrix}$$

$$i = X, Y, Z$$

- Split into three modes (X,Y,Z), with tunes $\mu_i = 2\pi\nu_i$

- Transfer matrix and betatron phase

$$M_0(s_2, s_2) = V_0(s_2)^{-1} U_{21} V_0(s_1)$$

measurable

$$U_{21} \equiv \begin{pmatrix} U_{u,21} & 0 & 0 \\ 0 & U_{v,21} & 0 \\ 0 & 0 & U_{w,21} \end{pmatrix}$$

$$U_{i,21} \equiv \begin{pmatrix} \cos(\phi_i(s_2) - \phi_i(s_1)) & \sin(\phi_i(s_2) - \phi_i(s_1)) \\ -\sin(\phi_i(s_2) - \phi_i(s_1)) & \cos(\phi_i(s_2) - \phi_i(s_1)) \end{pmatrix}$$

Twiss parameter and normal mode

- Diagonalizing (eigenvector) matrix, V_0, is parametrized

$$V_0(s) = B_0(s)R_0(s)H_0(s)$$

$$R = \begin{pmatrix} r_0 & 0 & -r_4 & r_2 & 0 & 0 \\ 0 & r_0 & r_3 & -r_1 & 0 & 0 \\ r_1 & r_2 & r_0 & 0 & 0 & 0 \\ r_3 & r_4 & 0 & r_0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \qquad H = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & -\eta_x \\ 0 & 1 & 0 & 0 & 0 & -\eta'_x \\ 0 & 0 & 1 & 0 & 0 & -\eta_y \\ 0 & 0 & 0 & 1 & 0 & -\eta'_y \\ \eta'_x & -\eta_x & \eta'_y & \eta_y & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$B = \begin{pmatrix} B_X & 0 & 0 \\ 0 & B_Y & 0 \\ 0 & 0 & B_Z \end{pmatrix} \qquad B_i = \begin{pmatrix} \frac{1}{\sqrt{\beta_i}} & 0 \\ \frac{\alpha_x}{\sqrt{\beta_i}} & \sqrt{\beta_i} \end{pmatrix} \qquad i = X, Y, Z$$

- $V_0=B_0R_0H_0$ is represented by Extended Twiss parameters (α,β,r_1-r_4,η).

$$r_0 = \sqrt{1 - r_1 r_4 + r_2 r_3}$$

- Normal coordinates **X** are defined by V,

$$\boldsymbol{X}(s) = B_0(s)R_0(s)H_0(s)\boldsymbol{x}(s) = V_0(s)\boldsymbol{x}(s) \qquad \boldsymbol{X}(s+C) = U_0\boldsymbol{X}(s)$$

$$\boldsymbol{X} = (X, P_X, Y, P_Y, Z, P_Z)^t \qquad J_X = \frac{X^2 + P_X^2}{2}$$

Betatron motion and Extended Twiss parameters

- Linear optics parameters, B, R, H and betatron (synchrotron) phases are measurable.
- Betatron oscillation (4x4 formalism, omit 5,6 components)

$$\delta(\boldsymbol{x}^T A_X^R \boldsymbol{x} - W_X)\delta(\boldsymbol{x}^T A_Y^R \boldsymbol{x} - W_Y)$$

- Courant-Snyder invariant

$$W_{X,Y} = 2J_{X,Y} = \boldsymbol{x}^T A_{X,Y}^R \boldsymbol{x}$$

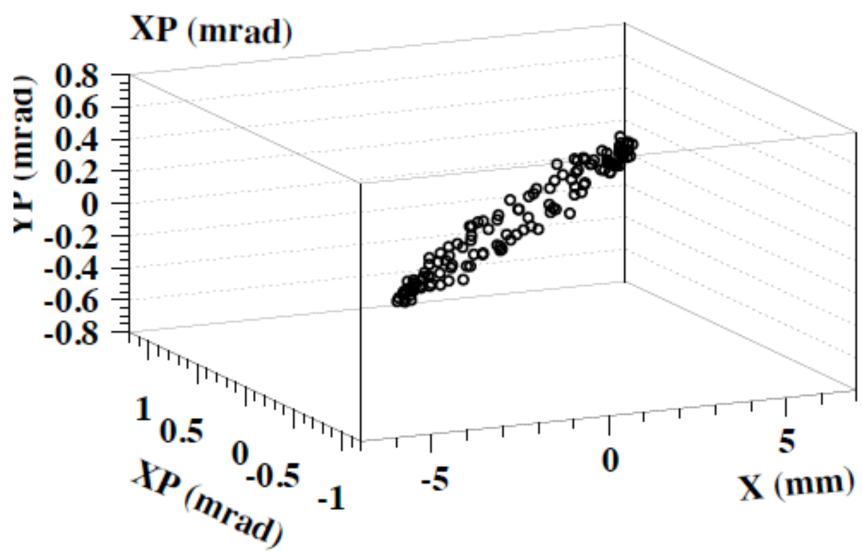
$$A_i^R \equiv R S_4 A_i R^{-1} \qquad S_4 = \begin{pmatrix} S_2 & 0 \\ 0 & S_2 \end{pmatrix} \quad S_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$A_X = \left(\begin{array}{cc|c} \gamma_X & \alpha_X & 0 \\ \alpha_X & \beta_X & \\ \hline \multicolumn{2}{c|}{0} & 0 \end{array}\right) \qquad A_Y = \left(\begin{array}{c|cc} 0 & \multicolumn{2}{c}{0} \\ \hline 0 & \gamma_Y & \alpha_Y \\ & \alpha_Y & \beta_Y \end{array}\right)$$

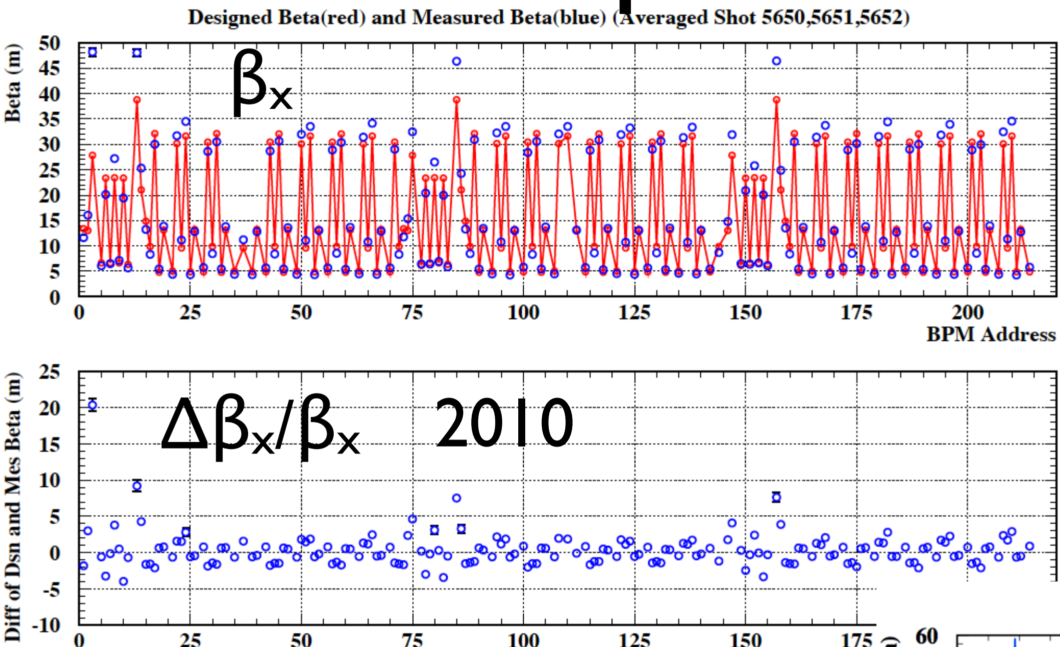
Measurement of E-Twiss parameters

- X mode is induced by x injection error. $X \sim x$, $W_Y \sim 0$
- Elliptical trajectory in 4 dimensional phase space (x, p_x, y, p_y). $\delta(\boldsymbol{x}^T A_X^R \boldsymbol{x} - W_X)$
- The phase space trajectory is reconstructed by turn-by-turn monitor
- α, β, Φ, R are given by $A^R{}_X$.

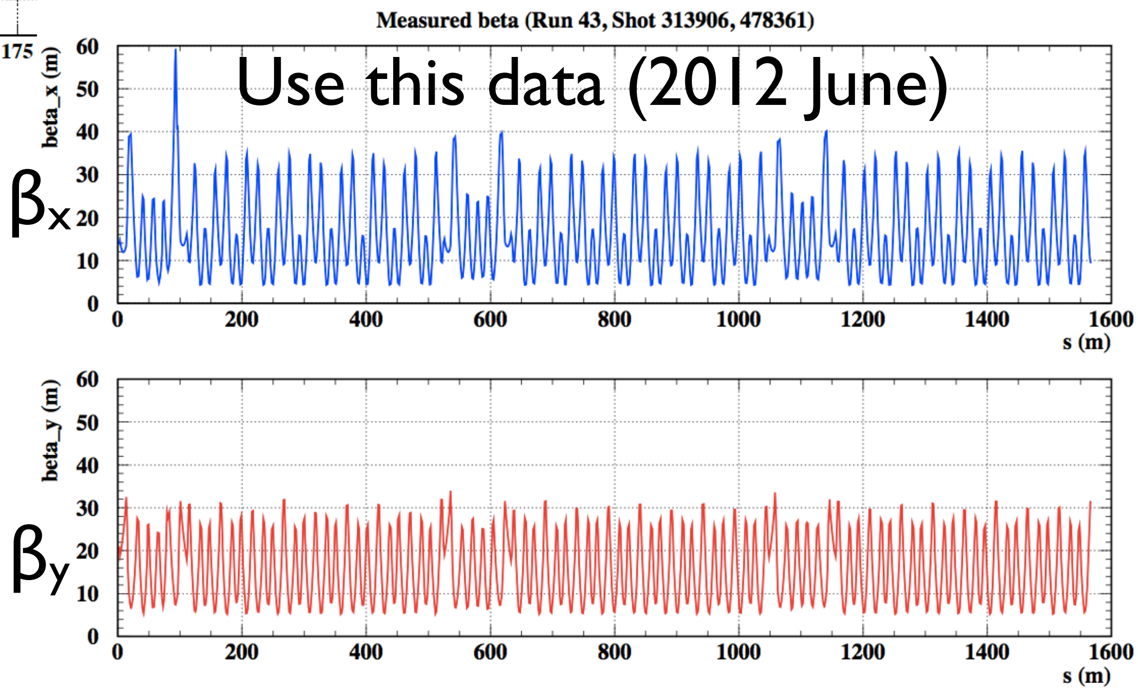
Projection on 3 dim space (x, p_x, p_y)



Example of measurement beta function

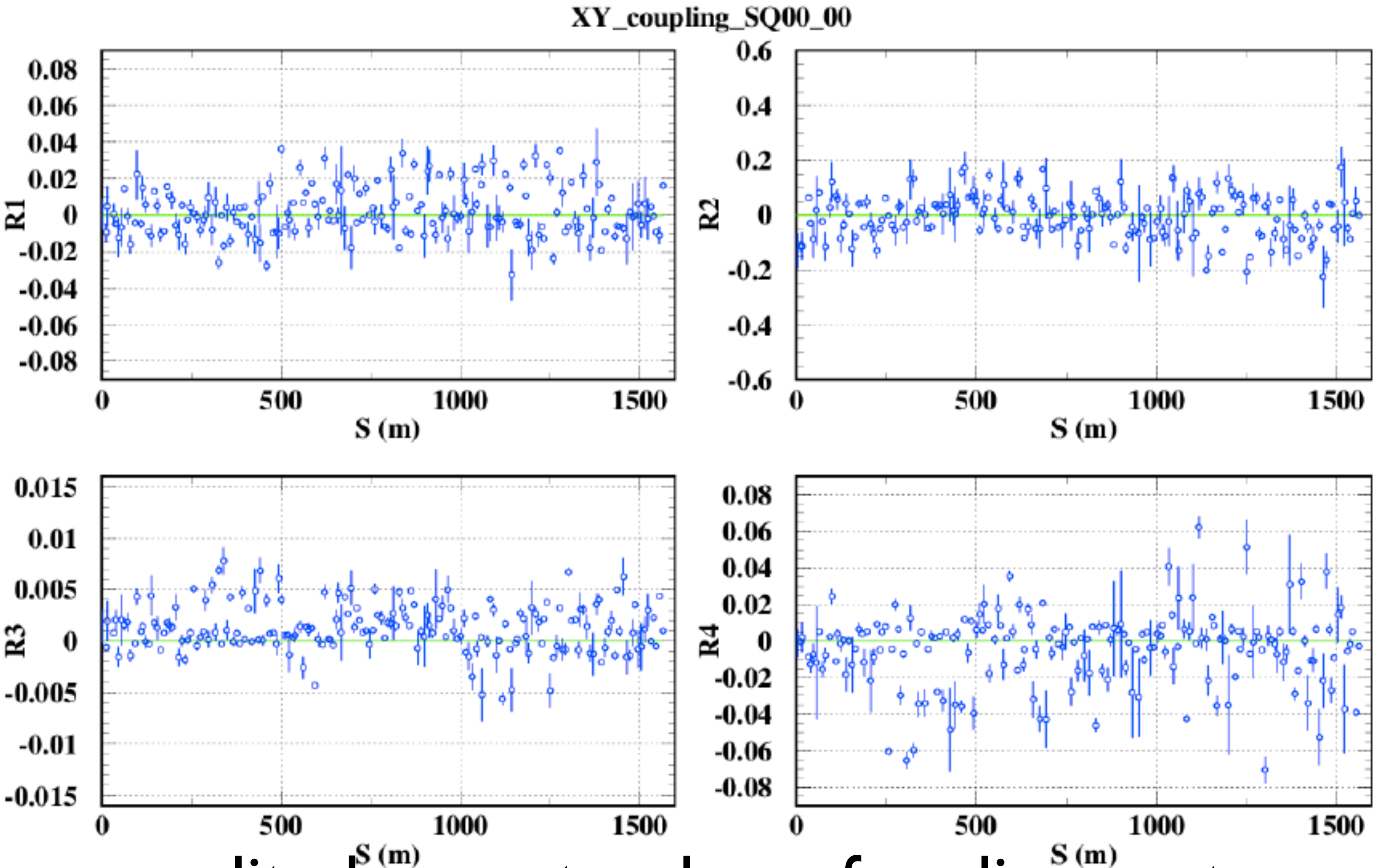


- Beta function deviate ~5% from design.



Example of measurement

r_1-r_4. x mode excitation



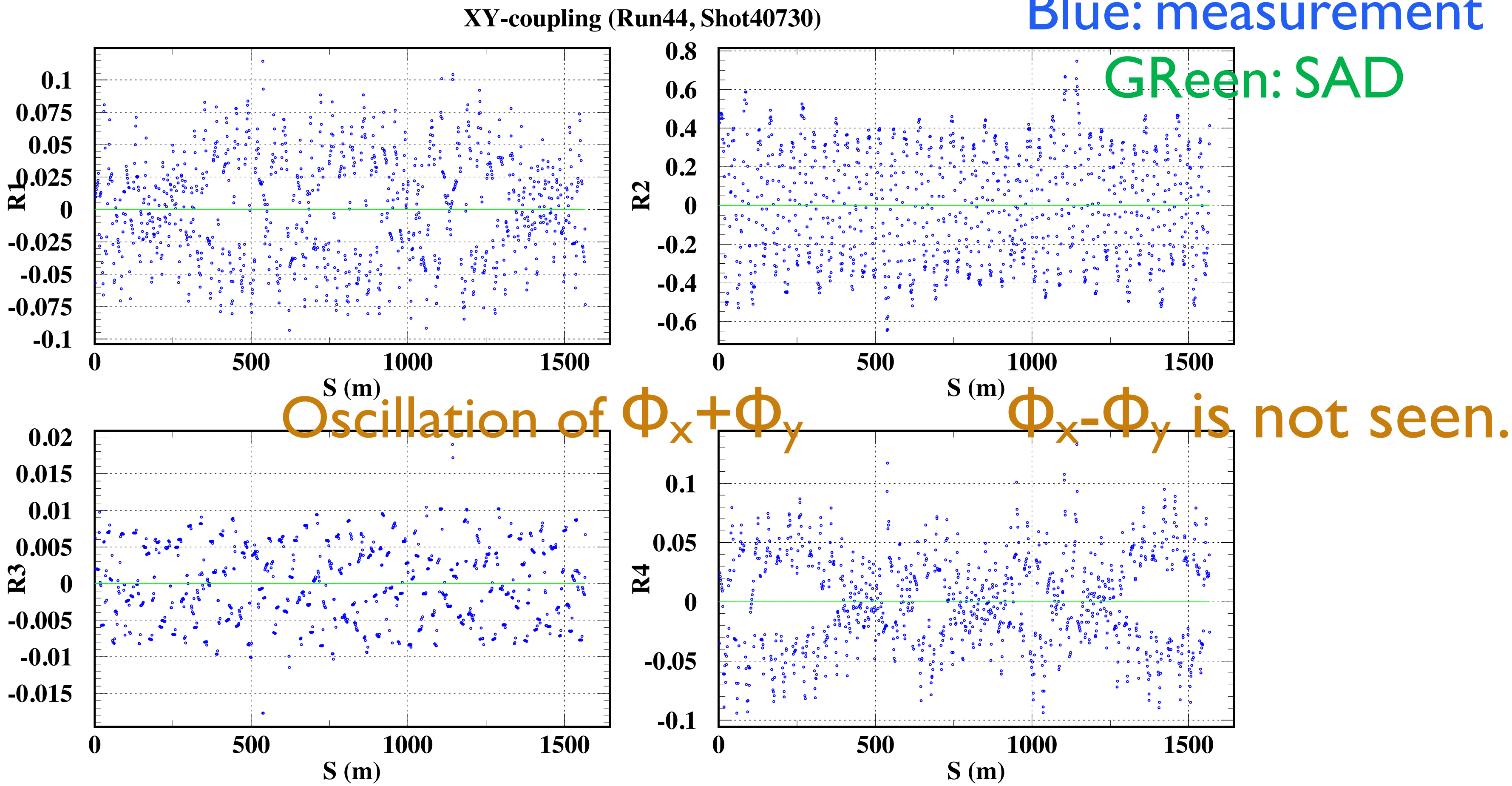
These amplitudes are too large for alignment errors.

Lack of accuracy perhaps.

SQ scan near resonance

SQ 0A

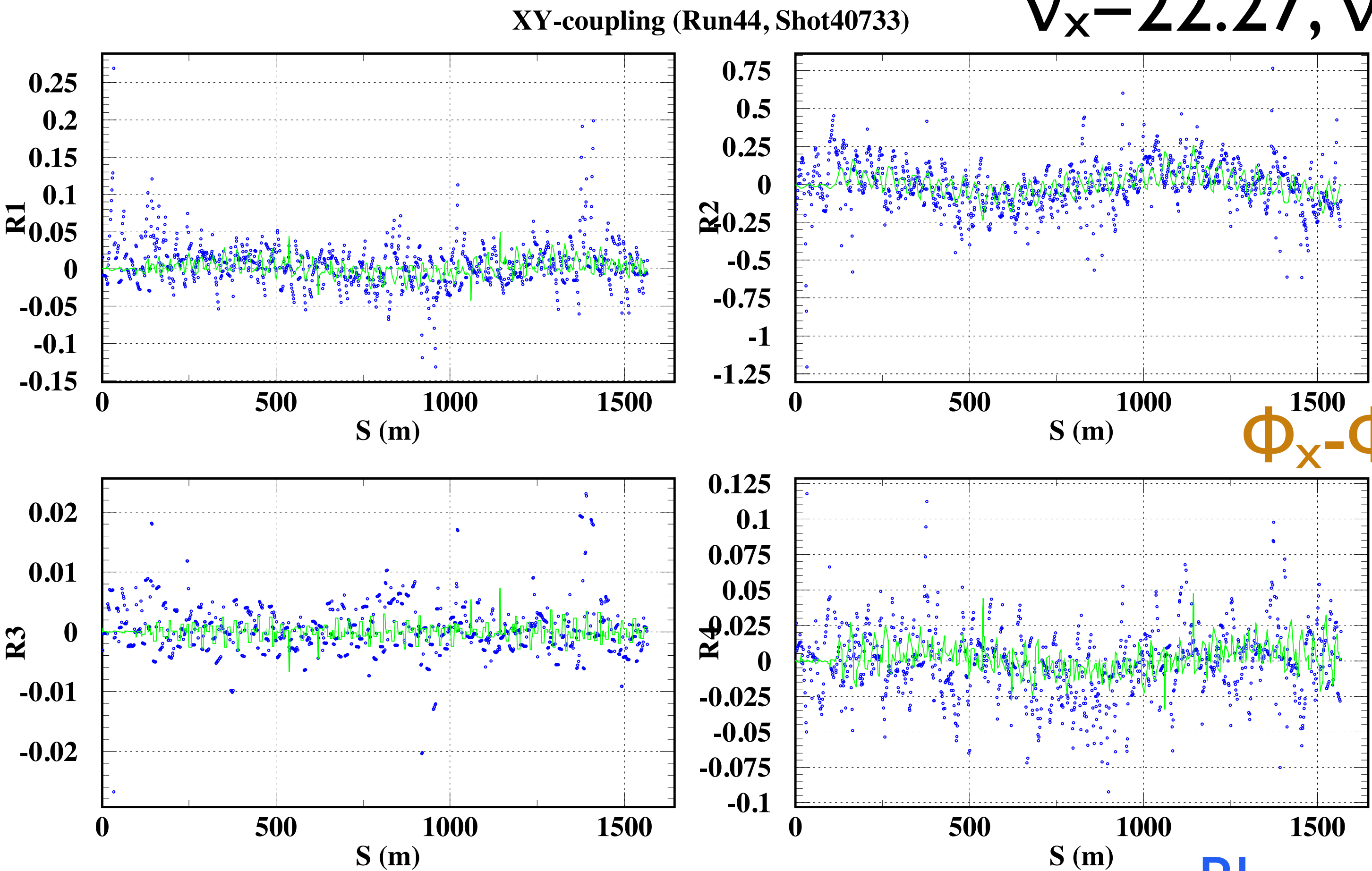
ν_x=22.27, ν_y=20.69



- Amplitude increases for closer $\nu_x+\nu_y$=43
- Reasonable behavior. Sufficient accuracy near the resonance.

SQ 1.7A, 0.2A

ν_x=22.27, ν_y=20.69



Φ_x-Φ_y is seen.

Blue: measurement

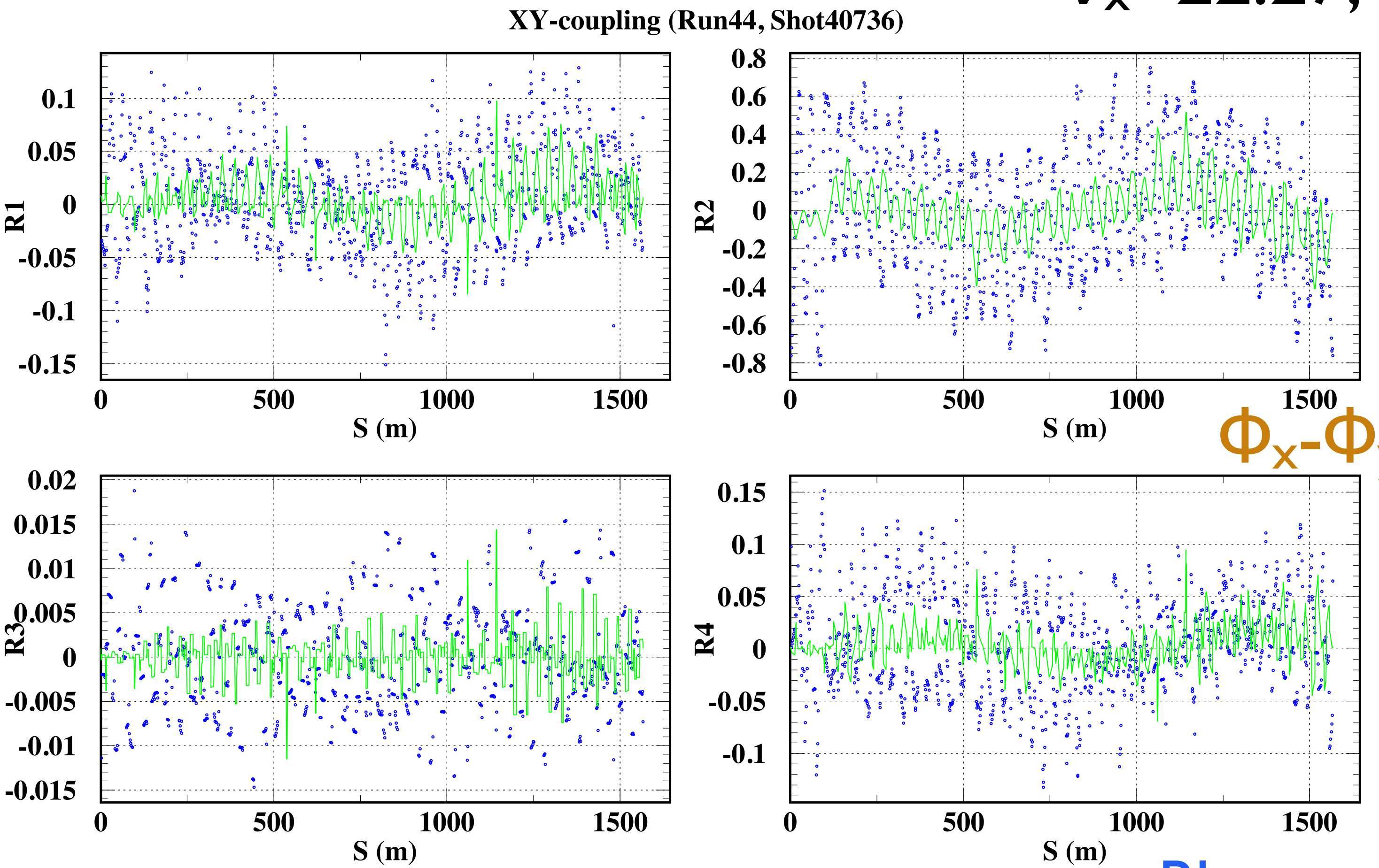
GReen: SAD

- Fast oscillation component is small

Φ_x+Φ_y

SQ 3.4A, 1.0A

ν_x=22.27, ν_y=20.69



Φ_x-Φ_y is seen.

Φ_x+Φ_y

Blue: measurement

GReen: SAD

Simulation with the measured linear optics

$$\mathcal{M}(s) = \prod_{i=0}^{N_I-1} M_0(s_{i+1}, s_i) e^{-:H_I(s_i):}$$

$$M_0(s_{i+1}, s_i) = V_0^{-1}(s_{i+1}) U_{i+1,i} V_0(s_i)$$

- Design transfer matrix M_0 is replaced by measured transfer matrix M.

$$\mathcal{M}(s) = \prod_{i=0}^{N-1} M(s_{i+1}, s_i) e^{-:H_I(s_i):}$$

Actual coding

V: measured optics
V_0: design optics
ΔU: phase difference

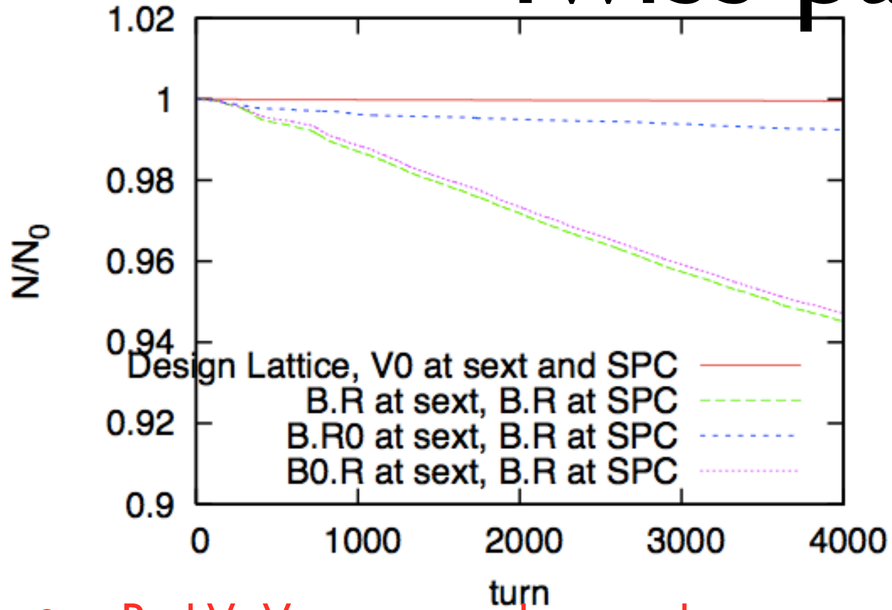
$$M(s_{i+1}, s_i) = V^{-1}(s_{i+1}) U_{i+1,i} \Delta U_i V(s_i)$$

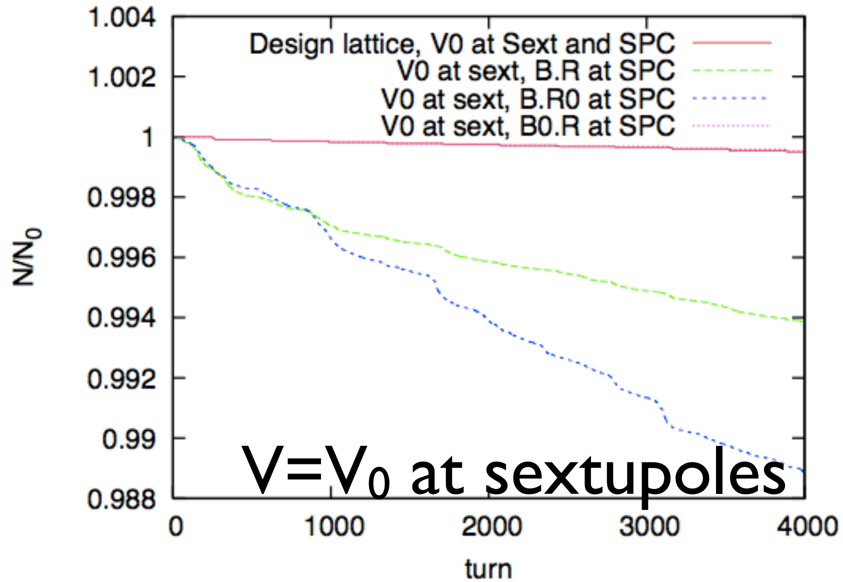
$$= V^{-1}(s_{i+1}) V_0(s_{i+1}) M_0(s_{i+1}, s_i) V_0^{-1}(s_i) \Delta U_i V(s_i)$$

$$e^{-:H_I:} \Rightarrow \boxed{V_0^{-1}(s_i) \Delta U_i V(s_i)} e^{-:H_I:} \boxed{V^{-1}(s_i) V_0(s_i)}$$

insert these transformation, tilt sext, tilt space charge

Simulation results using measured Twiss parameters





- Red: $V=V_0$ at sext and space charge
- Green: $V=V_{meas}$ at sext and space charge
- Blue: $V=B_{meas}R_0$ at sext and : $V=V_{meas}$ at spc
- Magenta: $V=B_0R_{meas}$ at sext and : $V=V_{meas}$ at spc

- Red: $V=V_0$ at sext and space charge
- Green: $V=V_{meas}$ at space charge
- Blue: $V=B_{meas}R_0$ at spc
- Magenta: $V=B_0R_{meas}$ at spc

Coupling at Sextupoles is main source of the beam loss.

β deviation does not affect in this case.

Non-resonant space charge model

- Space charge force gives only tune spread.
- Space charge force does not give any resonance term.
- Emittance growth related to resonances is caused by the lattice resonance and space charge tune spread.

$$H = \boldsymbol{\mu} \cdot \boldsymbol{J} + \boxed{\cancel{H_{00}(\boldsymbol{J})} + \sum_{\boldsymbol{m}=1} G_{\boldsymbol{m}}(\boldsymbol{J}) \exp(-i\boldsymbol{m} \cdot \boldsymbol{\phi})} + \boxed{U(J_x, J_y)}$$

Lattice nonlinearity
based on measured optics

Space charge

Estimate lattice resonance term

- One turn map is represented by Polynomials.
- Polynomial expression of Hamiltonian
- Expression using J,Φ. $H_n(\boldsymbol{X}) \Rightarrow H_n(\boldsymbol{J},\boldsymbol{\phi})$

$$X = \sqrt{2J_x}\cos\phi_x \quad P_X = \sqrt{2J_x}\sin\phi_x$$

$$H_n(\boldsymbol{J},\boldsymbol{\phi}) = H_{00}(\boldsymbol{J}) + \sum_{\boldsymbol{m}=1} G_{\boldsymbol{m}}(\boldsymbol{J})\exp(-i\boldsymbol{m}\cdot\boldsymbol{\phi})$$

up to 12-th order

$$\begin{aligned} H_{00}(\boldsymbol{J}) &= 3.43103\times10^{14}J_x^6 + 7.36914\times10^{14}J_x^5J_y + 7.17029\times10^{11}J_x^5 + 2.34124\times10^{15}J_x^4J_y^2 \\ &+ 1.70991\times10^{12}J_x^4J_y + 1.43961\times10^{8}J_x^4 + 4.48931\times10^{15}J_x^3J_y^3 + 2.20917\times10^{12}J_x^3J_y^2 \\ &+ 2.50211\times10^{8}J_x^3J_y + 613899.J_x^3 + 3.33998\times10^{15}J_x^2J_y^4 + 1.79716\times10^{12}J_x^2J_y^3 \\ &+ 7.07531\times10^{8}J_x^2J_y^2 + 809323.J_x^2J_y + 1095.71J_x^2 + 7.58773\times10^{14}J_xJ_y^5 \\ &+ 5.7438\times10^{11}J_xJ_y^4 + 4.55828\times10^{8}J_xJ_y^3 + 650655.J_xJ_y^2 + 2096.06J_xJ_y \\ &+ 4.11283\times10^{13}J_y^6 + 4.00294\times10^{10}J_y^5 + 5.3027\times10^{7}J_y^4 + 79924.4J_y^3 + 1106.98J_y^2 \end{aligned}$$

Characteristics of the resonances

- Slope of tune in ***J*** space breaks the resonance condition for ***J*** deviation.
- G_m characterizes strength of the resonance.
- Expand U near $\boldsymbol{J}_R$.

$$U(\boldsymbol{J}) = U(\boldsymbol{J}_R) + \left.\frac{\partial U}{\partial \boldsymbol{J}}\right|_{J_R} (\boldsymbol{J} - \boldsymbol{J}_R) + (\boldsymbol{J} - \boldsymbol{J}_R)\frac{1}{2}\left.\frac{\partial^2 U}{\partial \boldsymbol{J}\partial \boldsymbol{J}}\right|_{J_R} (\boldsymbol{J} - \boldsymbol{J}_R)$$

$$\left.\frac{\partial \nu_i}{\partial J_j}\right|_{J_R} = \left.\frac{\partial \nu_j}{\partial J_i}\right|_{J_R} = \left.\frac{\partial^2 U}{\partial J_i \partial J_j}\right|_{J_R}$$

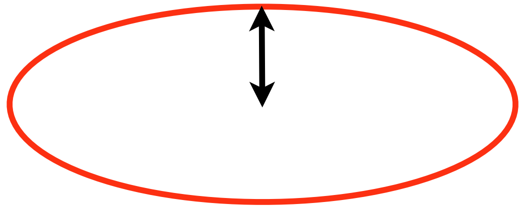
Tune slope near $\boldsymbol{J}_R$.

Standard model and Resonance width

$$H = \frac{\Lambda}{2} P_1^2 + G(\boldsymbol{J}_R)\cos(i\psi_1)$$

$$\Delta P_1 = 2\sqrt{\frac{G_{m_x,m_y}}{\Lambda}}$$

Half width of the resonance island



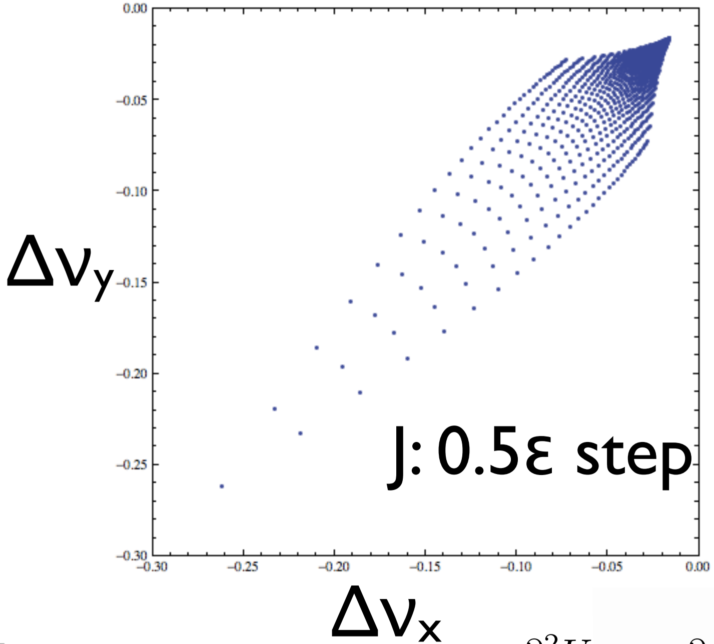
$$\Delta J_x = 2m_x\sqrt{\frac{G_{m_x,m_y}}{\Lambda}}$$

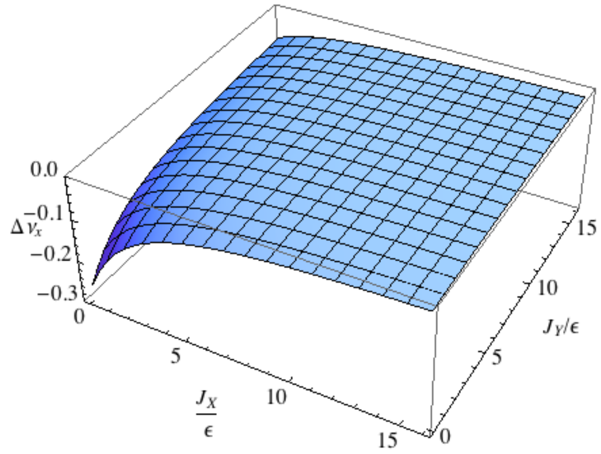
$$\Lambda = m_x^2 \frac{\partial^2 U}{\partial J_x^2} + m_x m_y \frac{\partial^2 U}{\partial J_x \partial J_y} + m_y^2 \frac{\partial^2 U}{\partial J_y^2}\bigg|_{J=J_R}.$$

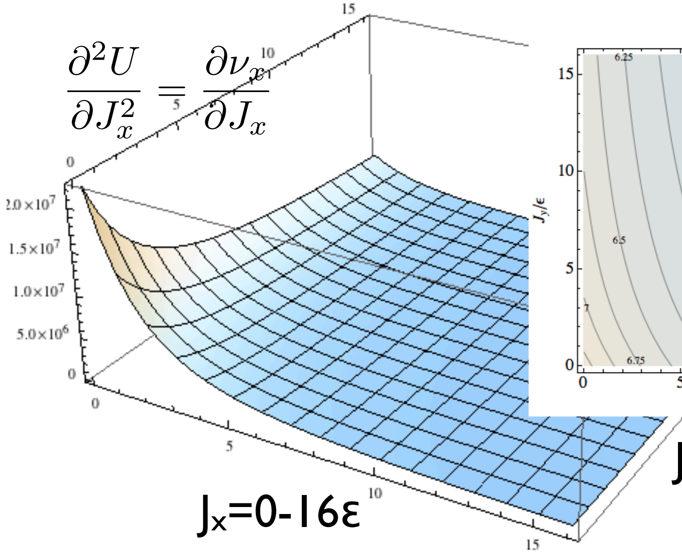
- Resonance width is sqrt of the ratio of the resonance strength (G) and the tune slope (Λ)

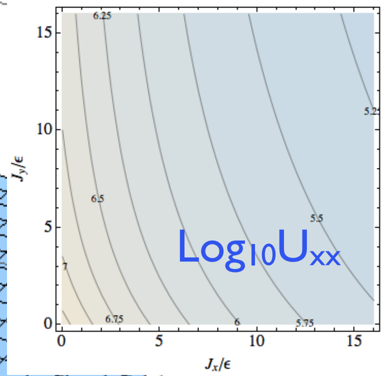
Tune shift & spread for the space charge force of round beam (analytic)

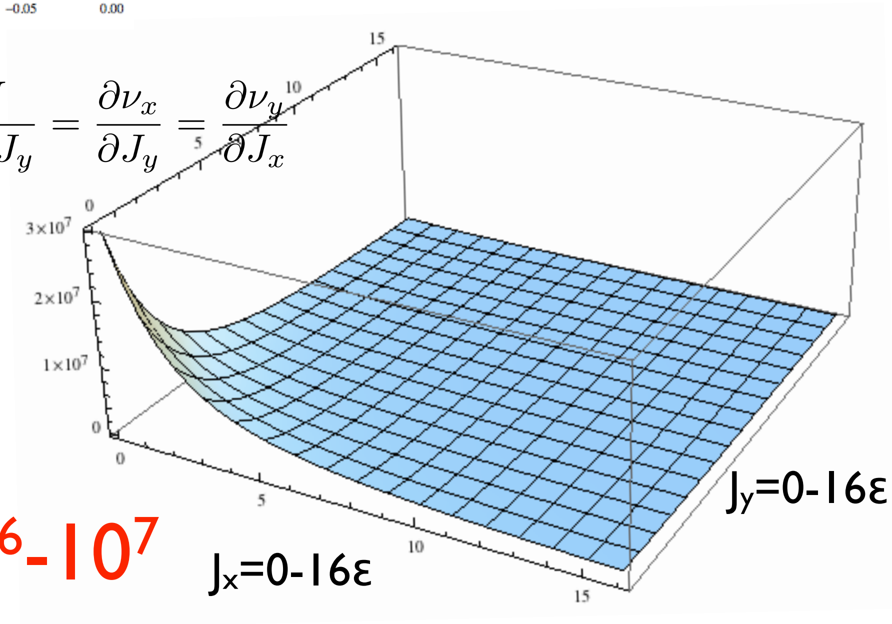
- 0-4 σ
- J=0-16ε
- ε=4x10^{-6}m



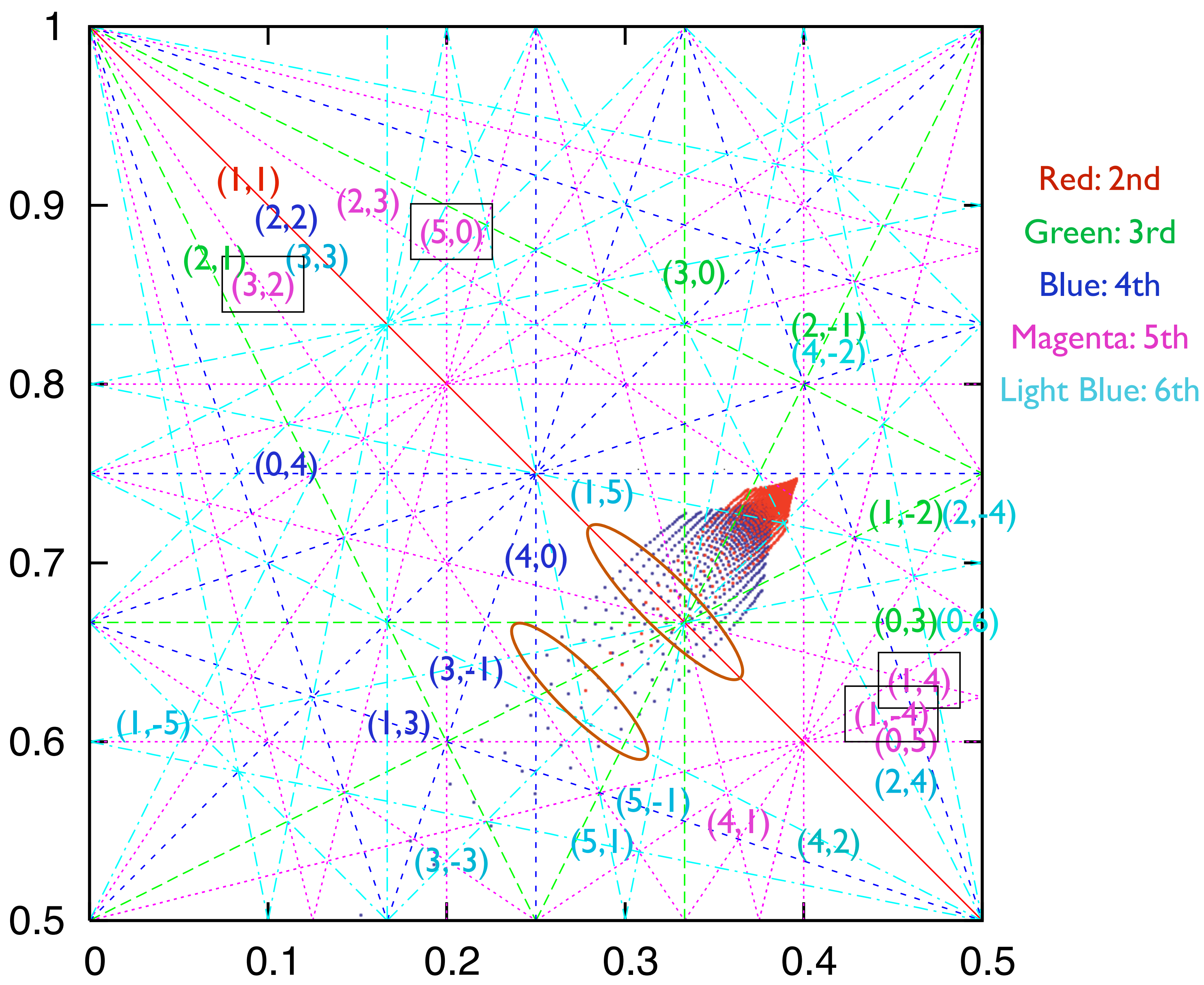








U_{xx}~10^6-10^7



1
0.9
0.8
0.7
0.6
0.5
0
0.1
0.2
0.3
0.4
0.5
(1,1)
(2,3)
(2,2)
(5,0)
(2,1)
(3,3)
(3,2)
(3,0)
(2,-1)
(4,-2)
(0,4)
(1,5)
(1,-2)(2,-4)
(4,0)
(0,3)(0,6)
(3,-1)
(1,4)
(1,-4)
(1,-5)
(1,3)
(0,5)
(2,4)
(5,-1)
(4,1)
(5,1)
(4,2)
(3,-3)
Red: 2nd
Green: 3rd
Blue: 4th
Magenta: 5th
Light Blue: 6th

$G_m(J_R)$

$$
\begin{aligned}
G_{2,-1}(\boldsymbol{J}) &= (476.934 + 1826.57i)J_x^2\sqrt{J_y} - (84741. + 1.08066\times 10^6 i)J_x J_y^{5/2} \\
&- (653.179 - 398.496i)J_x J_y^{3/2} + (0.00557469 + 0.0610964i)J_x\sqrt{J_y} \\
&+ (6.07124\times 10^{12} + 1.94221\times 10^{13} i)J_x^5\sqrt{J_y} - (1.80699\times 10^{13} - 6.48683\times 10^{13} i)J_x^4 J_y^{3/2} \\
&+ (1.26929\times 10^{10} - 8.72993\times 10^{9} i)J_x^4\sqrt{J_y} + (7.29356\times 10^{13} - 4.38153\times 10^{13} i)J_x^3 J_y^{5/2} \\
&+ (1.49887\times 10^{10} + 2.39589\times 10^{10} i)J_x^3 J_y^{3/2} + (4.24466\times 10^{6} + 435556.i)J_x^3\sqrt{J_y} \\
&- (3.32852\times 10^{12} + 2.78795\times 10^{13} i)J_x^2 J_y^{7/2} - (3.94261\times 10^{9} - 6.26479\times 10^{9} i)J_x^2 J_y^{5/2} \\
&- (1.00423\times 10^{6} + 4.1807\times 10^{6} i)J_x^2 J_y^{3/2} - (1.7948\times 10^{13} + 1.7958\times 10^{12} i)J_x J_y^{9/2} \\
&- (1.36817\times 10^{10} + 2.57963\times 10^{9} i)J_x J_y^{7/2}
\end{aligned}
$$

- Substitute $J=J_R$
- G is evaluated at $J_R=3^2\varepsilon$ (as a typical case);
- $J_x+J_y=3\times10^{-6}\times9=36\times10^{-6}$

$$\Delta J_x = 2m_x\sqrt{\frac{G_{m_x,m_y}}{\Lambda}} \qquad \Lambda \approx 10^6$$

shot 40722

No error　measured B,U　measured B,U & R

mx	my	Jx	Jy	|G| (B0)	|G| (B)	|G| (BR)
1	0	3.6E−05	0.0E+00	4.84E−08	1.88E−07	1.86E−07
2	0	3.6E−05	0.0E+00	2.47E−08	4.55E−08	4.66E−08
1	1	1.8E−05	1.8E−05	1.28E−25	1.67E−26	4.01E−09
0	2	0.0E+00	3.6E−05	5.55E−09	3.91E−09	2.69E−09
3	0	3.6E−05	0.0E+00	5.46E−08	1.29E−07	1.32E−07
2	1	1.8E−05	1.8E−05	2.09E−25	1.42E−26	1.42E−07
2	−1	1.8E−05	1.8E−05	2.16E−25	4.52E−27	7.96E−08
1	2	1.8E−05	1.8E−05	4.66E−08	1.78E−07	1.83E−07
1	−2	1.8E−05	1.8E−05	1.48E−07	2.72E−07	2.72E−07
0	3	0.0E+00	3.6E−05	1.42E−25	1.59E−26	1.10E−07
4	0	3.6E−05	0.0E+00	2.50E−07	2.51E−07	2.51E−07
3	1	1.8E−05	1.8E−05	1.93E−26	2.52E−27	6.80E−09
3	−1	1.8E−05	1.8E−05	1.61E−26	4.97E−27	7.04E−10
2	2	1.8E−05	1.8E−05	2.49E−08	5.90E−09	5.58E−09
2	−2	1.8E−05	1.8E−05	1.27E−08	8.40E−09	8.03E−09
1	3	1.8E−05	1.8E−05	2.52E−26	5.66E−27	3.56E−09
1	−3	1.8E−05	1.8E−05	1.63E−26	1.10E−26	8.42E−10
0	4	0.0E+00	3.6E−05	1.20E−08	1.45E−08	1.42E−08

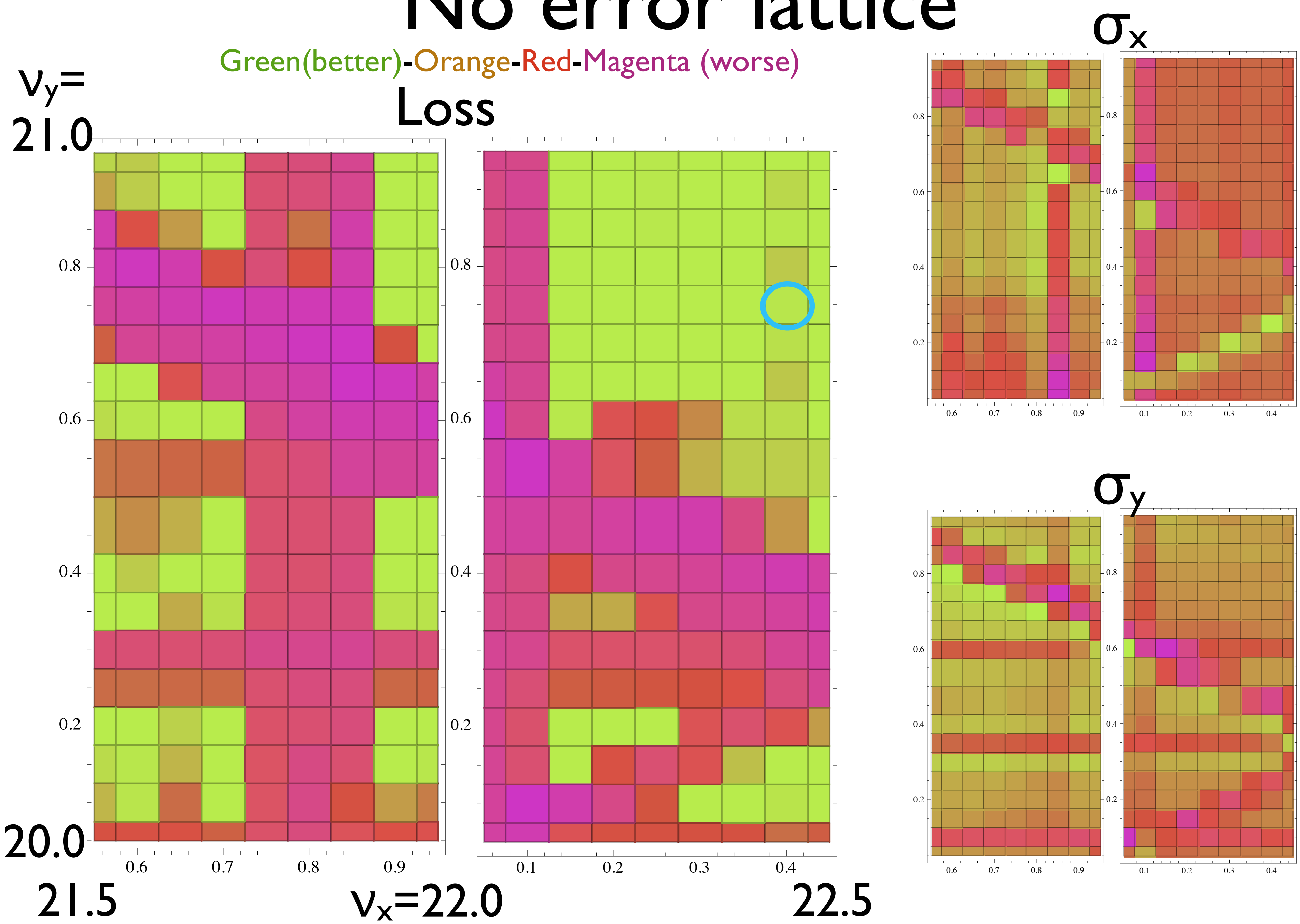
mx	my	Jx	Jy	|G| (B0)	|G| (B)	|G| (BR)
5	0	3.6E−05	0.0E+00	4.03E−09	3.07E−09	3.08E−09
4	1	1.8E−05	1.8E−05	7.11E−27	1.22E−28	6.63E−10
4	−1	1.8E−05	1.8E−05	7.09E−27	1.79E−28	1.63E−10
3	2	1.8E−05	1.8E−05	1.21E−09	1.62E−09	1.68E−09
3	−2	1.8E−05	1.8E−05	1.16E−09	2.20E−09	2.24E−09
2	3	1.8E−05	1.8E−05	2.69E−27	6.82E−28	3.93E−10
2	−3	1.8E−05	1.8E−05	1.08E−27	1.59E−27	2.35E−10
1	4	1.8E−05	1.8E−05	7.77E−11	5.31E−10	5.55E−10
1	−4	1.8E−05	1.8E−05	2.09E−10	3.49E−10	3.70E−10
0	5	0.0E+00	3.6E−05	1.37E−26	5.48E−27	9.37E−11
6	0	3.6E−05	0.0E+00	2.24E−09	1.65E−09	1.64E−09
5	1	1.8E−05	1.8E−05	2.74E−28	4.68E−29	6.53E−11
5	−1	1.8E−05	1.8E−05	2.35E−28	8.57E−29	2.08E−11
4	2	1.8E−05	1.8E−05	1.49E−10	1.63E−10	1.66E−10
4	−2	1.8E−05	1.8E−05	4.80E−11	1.06E−10	1.07E−10
3	3	1.8E−05	1.8E−05	5.55E−28	1.78E−28	8.94E−11
3	−3	1.8E−05	1.8E−05	7.28E−28	1.02E−28	1.96E−11
2	4	1.8E−05	1.8E−05	6.74E−11	8.74E−11	8.47E−11
2	−4	1.8E−05	1.8E−05	3.62E−11	1.22E−11	9.02E−12
1	5	1.8E−05	1.8E−05	1.16E−27	4.70E−28	5.52E−12
1	−5	1.8E−05	1.8E−05	5.13E−28	9.87E−28	8.16E−12
0	6	0.0E+00	3.6E−05	6.07E−13	1.52E−11	9.43E−12

Tune scan simulation focus on x-y coupling

- N_p=2.5x10^{13}, BF=0.2, ε=40 μm (parabolic)
- $21.5<\nu_x<22.5$, $20.0<\nu_y<21.0$, $\Delta\nu=0.01$
- Frozen potential at 1st turn.
- Loss and beam size evolution during 5000 turn. Injection time ~25,000 turn.

No error lattice

Green(better)-Orange-Red-Magenta (worse)

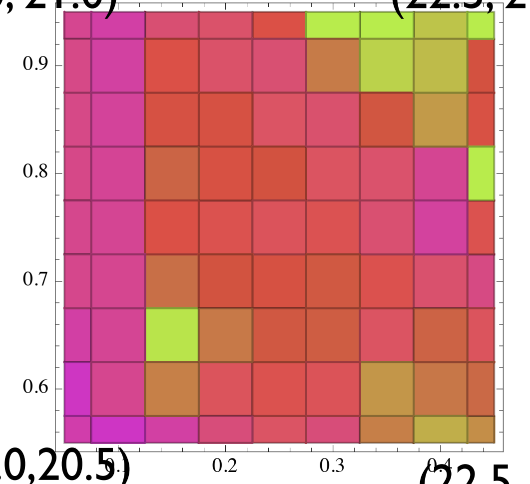


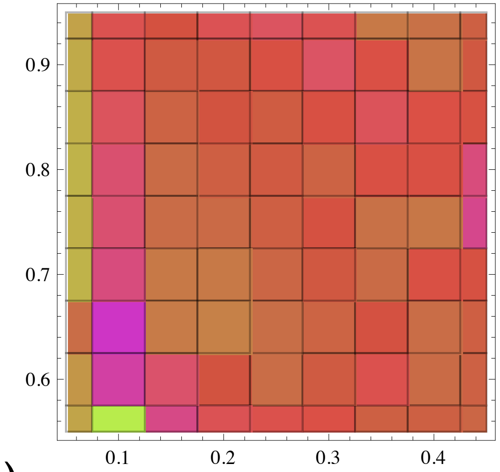
Measured x-y coupling

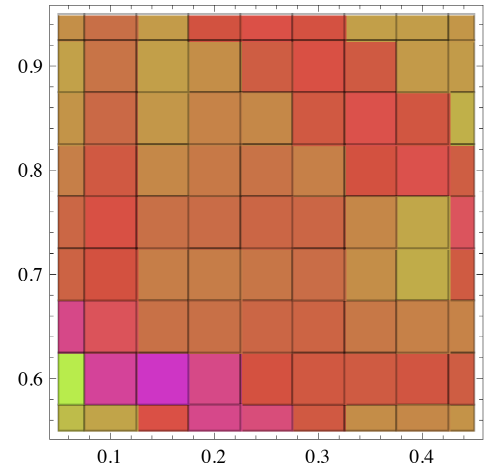
- R only at sextpoles

overestimate due to the measurement inaccuracy?

$$e^{-:H_I:} \Rightarrow V_0^{-1}(s_i)\Delta U_i V(s_i) e^{-:H_I:} V^{-1}(s_i) V_0(s_i)$$



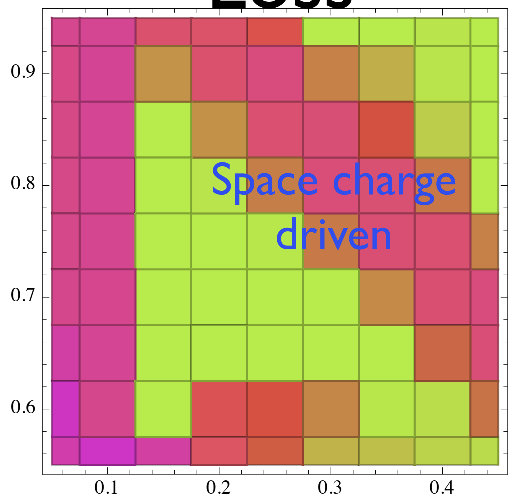




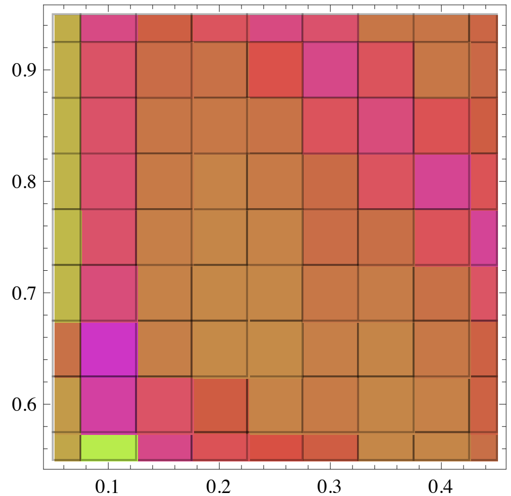
- R only space charge force

$$e^{-:H_I:} \Rightarrow V_0^{-1}(s_i)\Delta U_i V(s_i) e^{-:H_I:} V^{-1}(s_i) V_0(s_i)$$

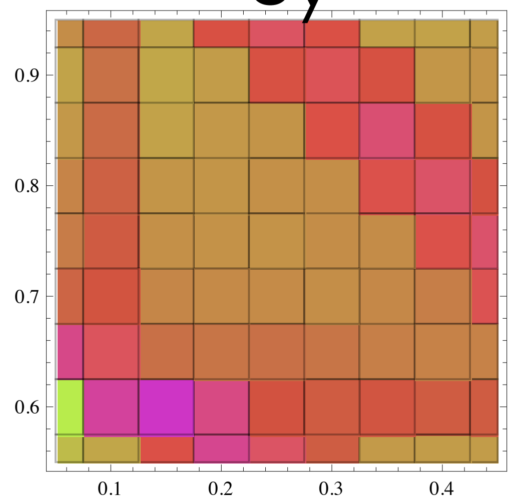
Loss



σ_x



σ_y

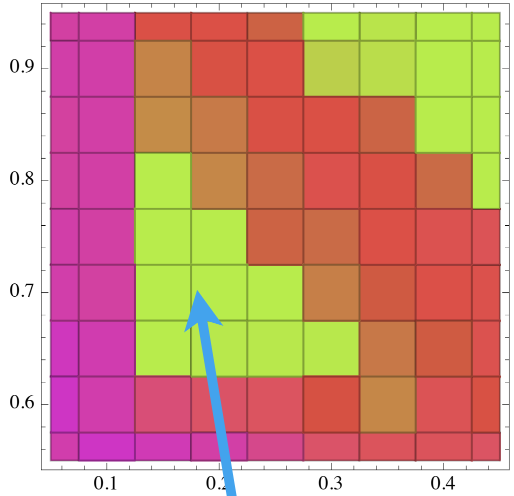


R is kept in the tune scan, though it is not realistic.

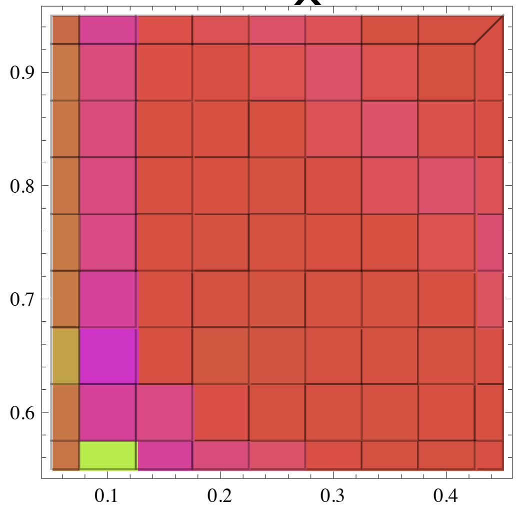
Use alignment error

not measured optics

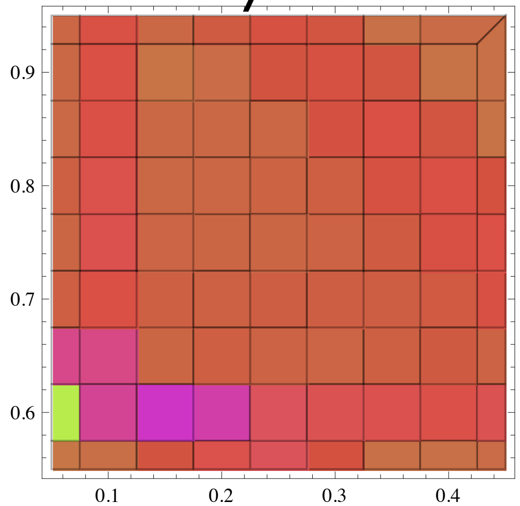
(22.0, 21.0) Loss (22.5, 21.0)



σ_x

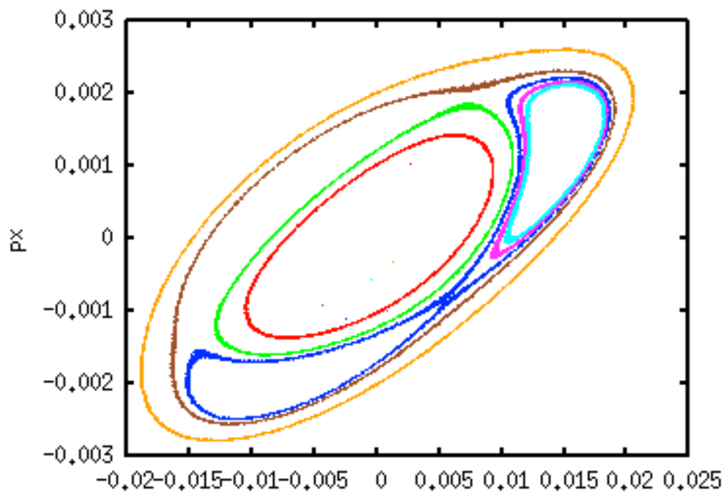


σ_y



(22.0, 20.5) (22.5, 20.5)

- Tune spread in this area crosses integer/half integer resonance.



Coupling correction

$$M(s)M_{SQ} = BU\begin{pmatrix} I_2 & P_{SQ} \\ S_2 P_{SQ}^t S_2 & I_2 \end{pmatrix}_0 B^{-1}M_{SQ} = BU\begin{pmatrix} I_2 & P_{SQ} \\ S_2 P_{SQ}^t S_2 & I_2 \end{pmatrix}_{cor} B^{-1}$$

- M_{SQ} is determined so that $P_{SQ,cor}$ has following form

$$P_{SQ,cor} = \begin{pmatrix} -S_- & -C_- \\ C_- & -S_- \end{pmatrix}$$

so-called sum resonance correction

Eliminate $\Phi_x+\Phi_y$ oscillation in R near s

- M_{SQ} is determined so that $P_{SQ,cor}=0$

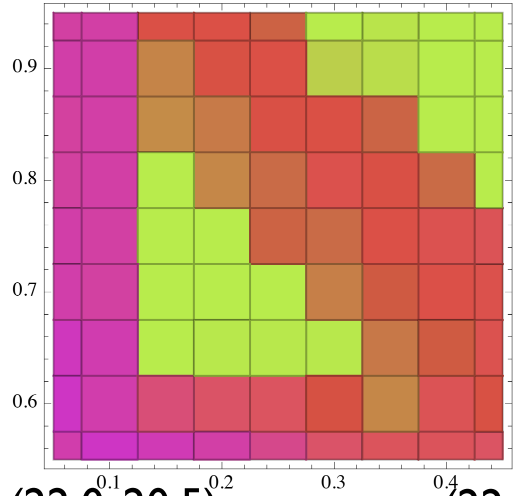
so-called sum and diff resonance correction

Eliminate $\Phi_x+\Phi_y$ and $\Phi_x-\Phi_y$ oscillation in R near s

not all s

Effect of sum resonance correction

- Before coupling correction

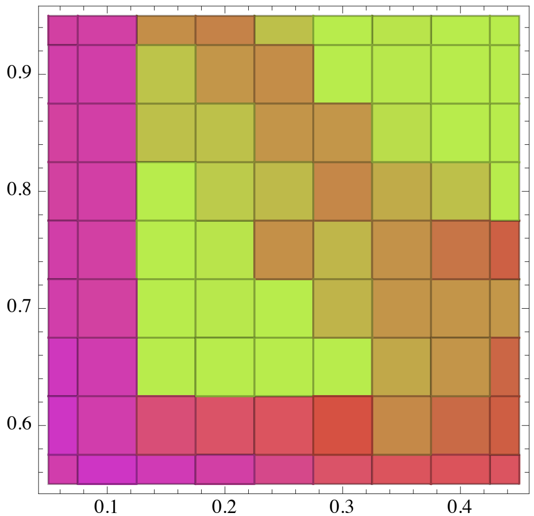


(22.0, 20.5) (22.5, 20.5)

$-\Delta N/N_0$

0.24172,	0.26387,	0.01219,	0.01266,	0.00271,	0.00000,	0.00002,	0.00000,	0.00000
0.28408,	0.28899,	0.00102,	0.00965,	0.01301,	0.00009,	0.00004,	0.00000,	0.00000
0.21697,	0.27194,	0.00083,	0.00132,	0.01038,	0.01133,	0.00249,	0.00000,	0.00000
0.22282,	0.26495,	0.00000,	0.00094,	0.00194,	0.01685,	0.01038,	0.00199,	0.00000
0.28455,	0.24889,	0.00000,	0.00000,	0.00264,	0.00193,	0.01384,	0.01884,	0.02295
0.30150,	0.23188,	0.00000,	0.00000,	0.00000,	0.00115,	0.00359,	0.01391,	0.01640
0.54120,	0.35528,	0.00000,	0.00001,	0.00001,	0.00001,	0.00138,	0.00344,	0.01792
0.65862,	0.32230,	0.06533,	0.03976,	0.03324,	0.00751,	0.00094,	0.02249,	0.00970
0.32307,	0.66829,	0.41992,	0.26686,	0.11868,	0.04130,	0.02884,	0.02768,	0.03626

- After coupling correction



$-\Delta N/N_0$

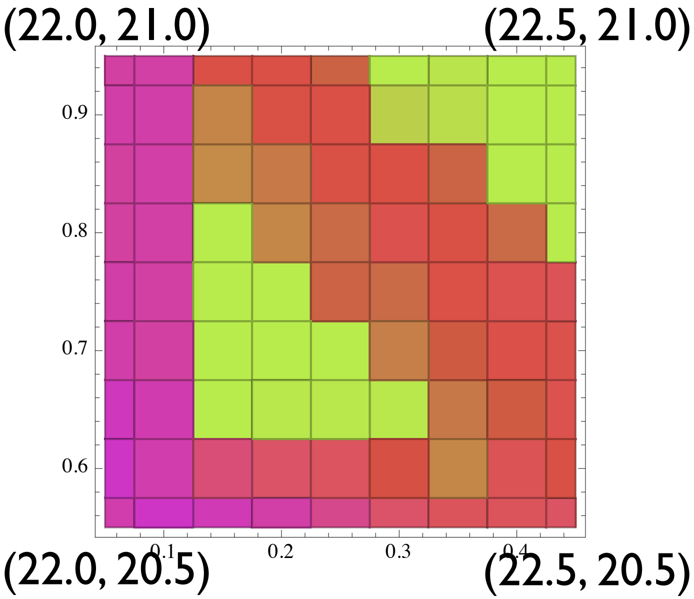
0.23896,	0.25142,	0.00079,	0.00107,	0.00018,	0.00000,	0.00002,	0.00000,	0.00000
0.28466,	0.28801,	0.00015,	0.00064,	0.00081,	0.00000,	0.00001,	0.00000,	0.00000
0.21712,	0.27178,	0.00017,	0.00017,	0.00065,	0.00063,	0.00004,	0.00000,	0.00000
0.22289,	0.26567,	0.00000,	0.00011,	0.00021,	0.00094,	0.00035,	0.00017,	0.00000
0.28478,	0.24939,	0.00000,	0.00002,	0.00075,	0.00025,	0.00070,	0.00148,	0.00286
0.30220,	0.23366,	0.00000,	0.00001,	0.00000,	0.00027,	0.00066,	0.00064,	0.00062
0.54129,	0.35556,	0.00000,	0.00000,	0.00000,	0.00000,	0.00038,	0.00066,	0.00237
0.65916,	0.32310,	0.06569,	0.04007,	0.03190,	0.00724,	0.00088,	0.00202,	0.00309
0.32262,	0.66829,	0.41987,	0.26457,	0.11726,	0.04163,	0.02907,	0.02751,	0.03282

Significant improvement 1/10

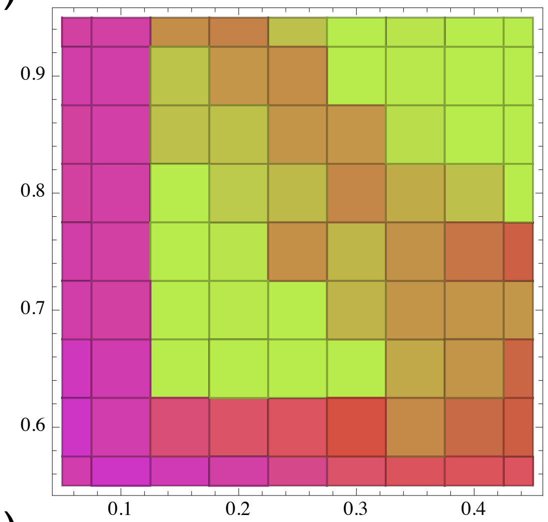
requirement <0.001

Further correction

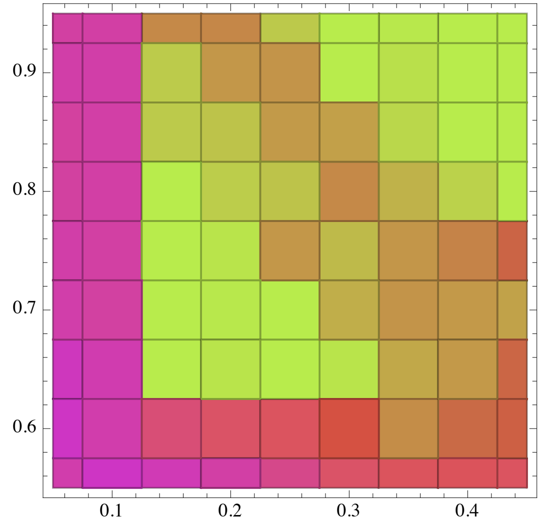
Alignment error



sum res. corr.



+diff. res. corr.



- No remarkable effect for the further correction.

0.23975,	0.25333,	0.00090,	0.00094,	0.00012,	0.00000,	0.00001,	0.00000,	0.00000
0.28440,	0.28698,	0.00011,	0.00061,	0.00066,	0.00000,	0.00003,	0.00000,	0.00000
0.21742,	0.27027,	0.00012,	0.00016,	0.00056,	0.00048,	0.00006,	0.00000,	0.00000
0.22233,	0.26460,	0.00000,	0.00010,	0.00015,	0.00090,	0.00028,	0.00008,	0.00000
0.28516,	0.24857,	0.00000,	0.00002,	0.00062,	0.00021,	0.00063,	0.00104,	0.00250
0.30219,	0.23224,	0.00000,	0.00001,	0.00000,	0.00031,	0.00067,	0.00058,	0.00046
0.54274,	0.35504,	0.00000,	0.00002,	0.00000,	0.00002,	0.00038,	0.00059,	0.00235
0.65841,	0.31872,	0.06361,	0.03943,	0.03149,	0.00701,	0.00081,	0.00203,	0.00294
0.32236,	0.66705,	0.41685,	0.26381,	0.11680,	0.04113,	0.02938,	0.02763,	0.03259

Summary

- Measurement of x-y coupling has been performed in J-PARC MR.
- β,α,Φ are reasonable, but R is not accurate.
- R is accurate near the coupling resonance.
- Space charge simulation SCTR(PIC) showed x-y coupling at sextupoles is dominant. Effect of β modulation is weak.
- Resonance width for measured optics was estimated. Not fruitful result at the present.
- Envelope theory with the x-y coupling is presented in HB2012.

Summary II

- Tune scan for space charge induced beam loss was performed.
- The present operating point of J-PARC MR is in good area.
- However x-y coupling pollutes the area upper right of the resonance line, $\nu_x+\nu_y=n$.
- Coupling correction recovers a certain amount.