RHIC Non-linear Chromaticity and IR Correction

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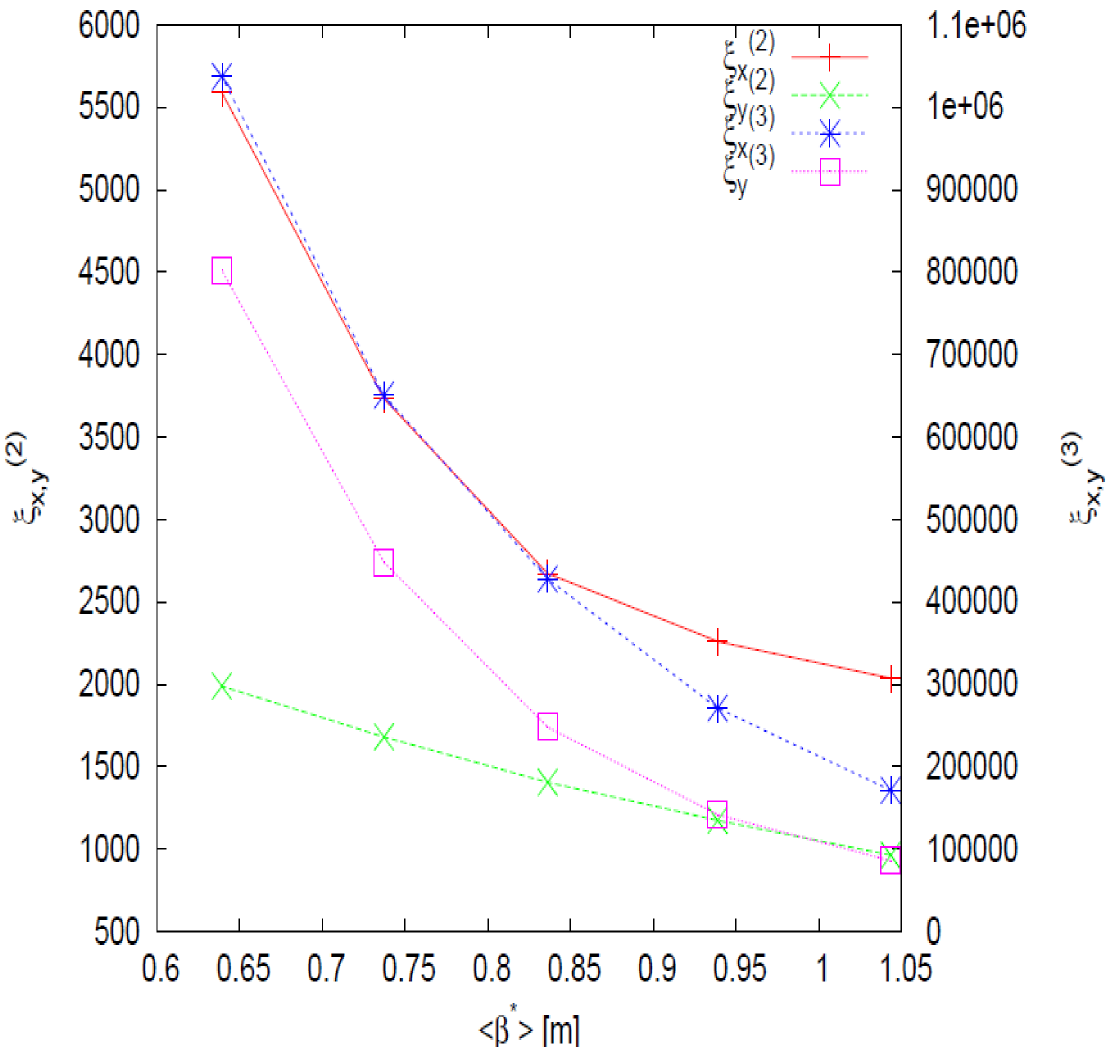
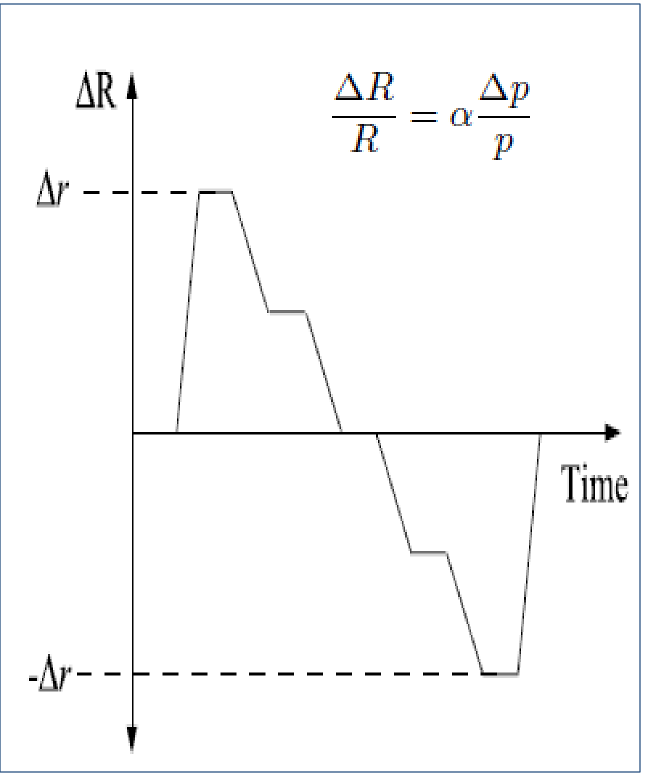
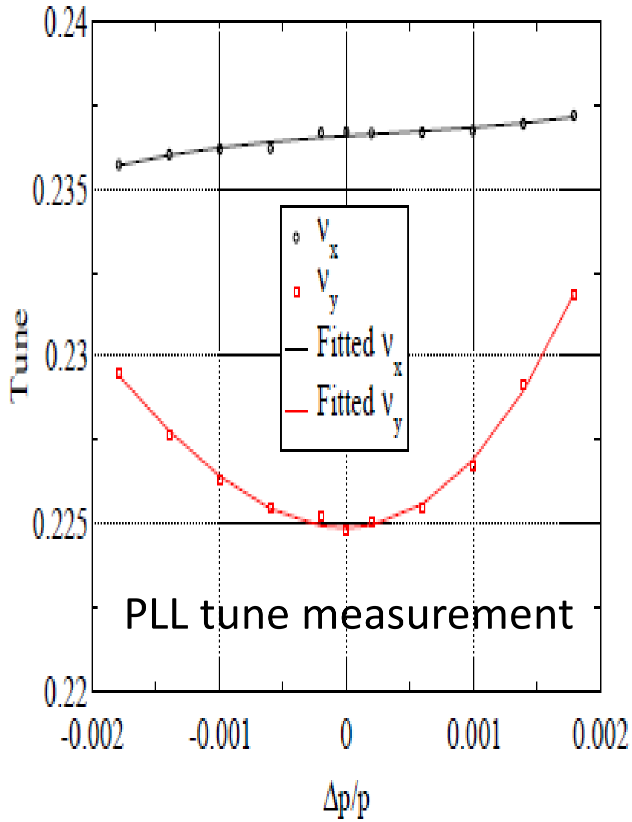
Motivation for non-linear chromaticity correction

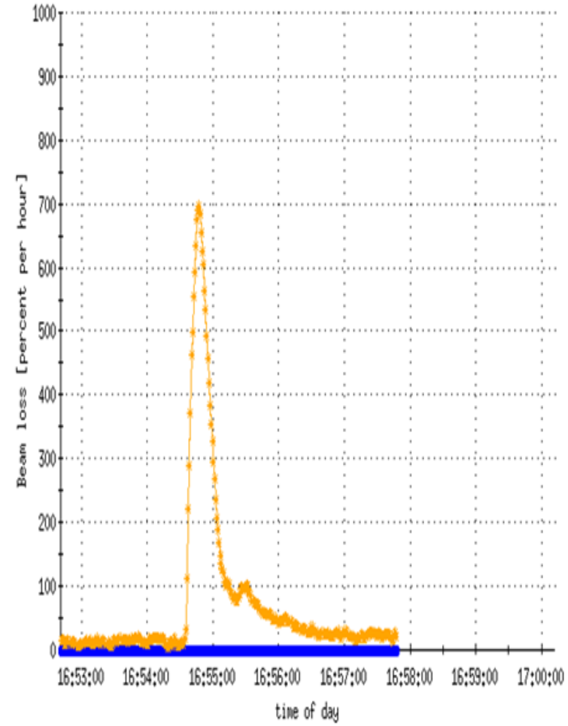


- Low β* lattice will give large off-momentum tune shifts and off-momentum β-beat.
- Currently β* = 0.7m for RHIC proton and heavy ion runs. We are marching to or even below β*=0.5m. Dynamic β* squeezing to 0.58m demonstrated with Stochastic cooling.
- In the heavy ion runs, RF re-bucketing requires a enough momentum aperture. Before re-bucketing, $(dp/p_0)_{max}$=0.0009. After re-bucketing , $(dp/p_0)_{max}$=0.0017 .

Measurement of linear & non-linear chromaticity



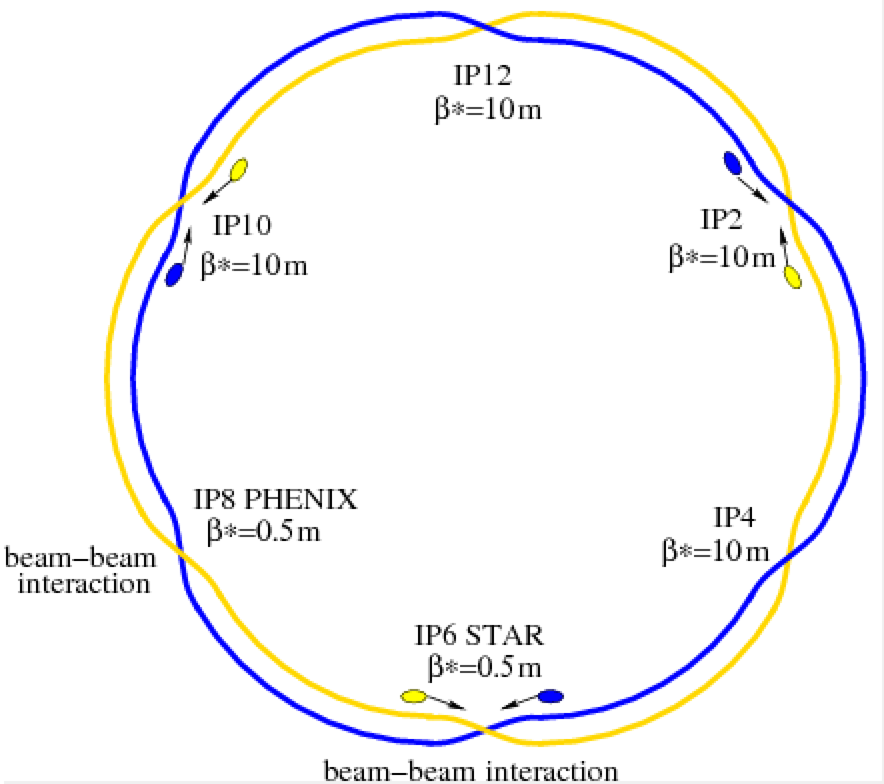


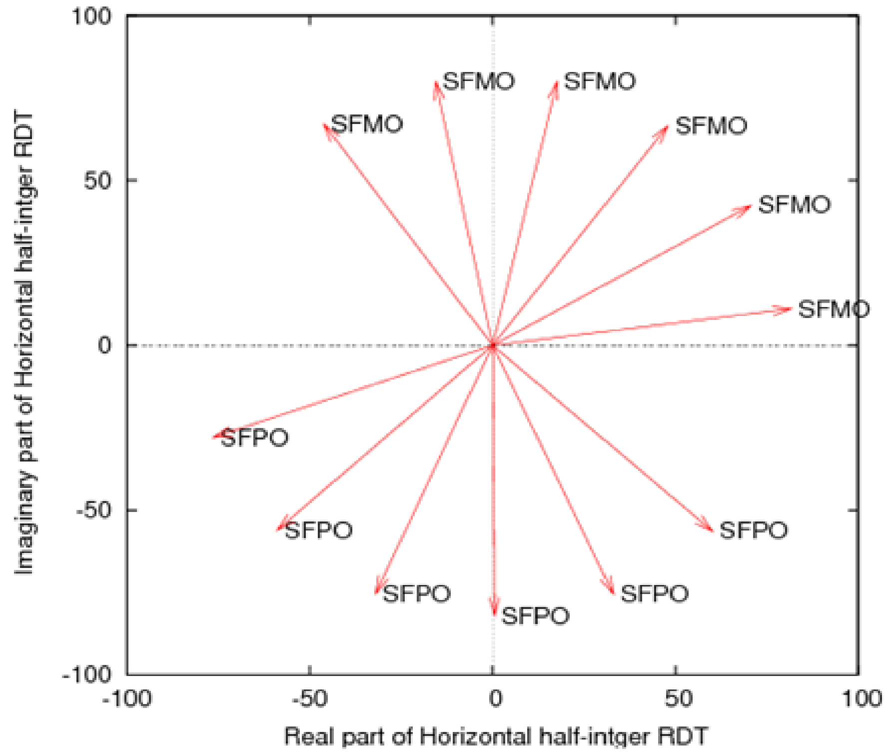


- Off-momentum tunes are measured with PLL and fitted up to 3rd order.
- Reliable measurement is very important for correction and modeling.
- Beam decay in this measurement is a good indicator of momentum aperture.

(S. Tepikian, et al, PAC'05)

RHIC arc chromatic sextupoles





- There are 144 arc sextupoles in 6 arcs. Before 2007, 2-family scheme was used for chromaticity correction. After 2007, the number of arc sextupole power supplies was doubled.
- The betatron phase advance per FODO cell is about 83degree. We split the SFs and SDs into two sub-families in each arc. There are totally 24 sub-families .

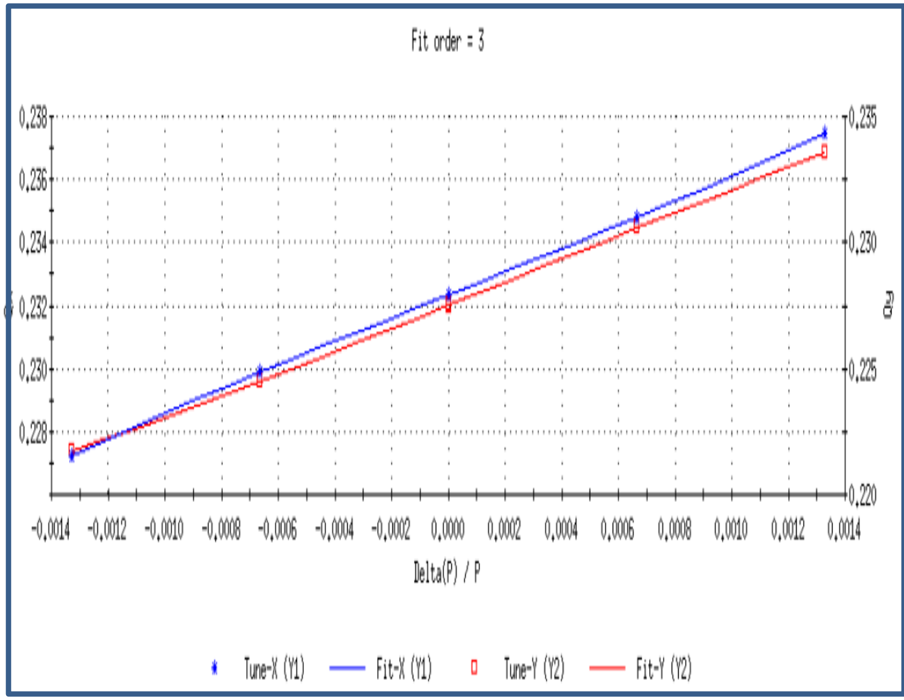
(Y. Luo, et al., PAC’07)

Lattice model based correction

Table 4: Blue store: linear chromaticity measurement and modeling.

	Tunes (Q_x, Q_y)	Chromaticities (Q'_x, Q'_y)	Chromatic sextupole strengths $(K_2$
Case 5:			SF: 0.3310m^{-3} SD: -0.6575m^{-3}
Measurements	(28.228, 29.215)	(4.0, 4.3)	-
Modeling with $(K_2L)_{dipole,mean} = 0\text{m}^{-2}$	-	(0.8, 8.2)	-
Modeling with $(K_2L)_{dipole,mean} = 0.0095\text{m}^{-2}$	-	(4.0, 5.1)	-
Case 6:			SF: 0.3202m^{-3} SD: -0.6348m^{-3}
Measurements	(28.232, 29.227)	(1.5, 1.6)	-
Modeling with $(K_2L)_{dipole,mean} = 0\text{m}^{-2}$	-	(-1.2, 5.1)	-
Modeling with $(K_2L)_{dipole,mean} = 0.0095\text{m}^{-2}$	-	(1.9, 2.0)	-

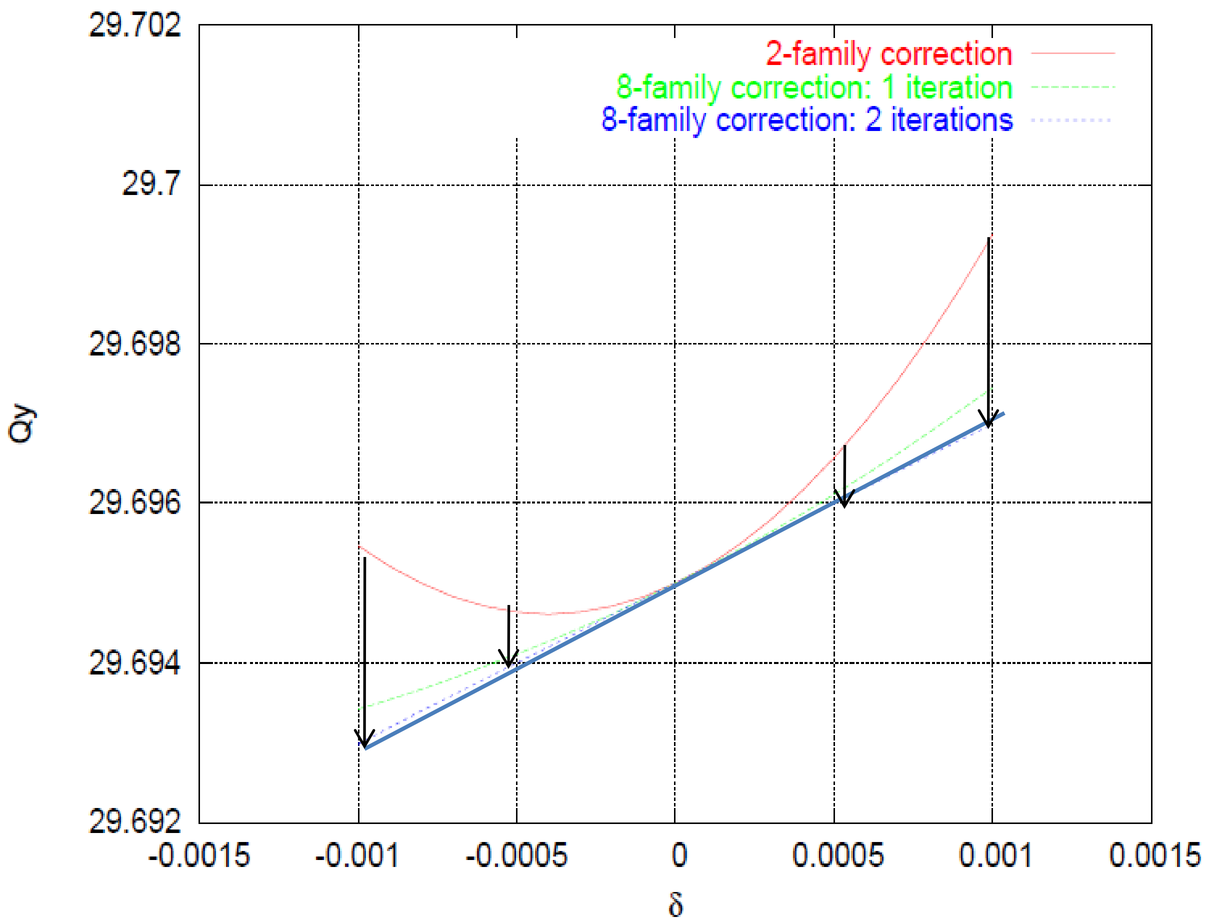
ΔQ'x,y ~ 4 at store.



- ➢Non-linear chromaticity can be easily corrected if the optics model reflects real machine.
- ➢One difficulty is discrepancy in Q' from machine and prediction. We model <b2> in arc dipoles from Q' split. On top of it, we applied model based correction.
- ➢This method worked very well just by typing the correction strengths for the Blue ring in 2007 Au-Au run when β* = 0.8m.

(Y. Luo, et al., BNL C-AD/AP/Note-276, 2007)

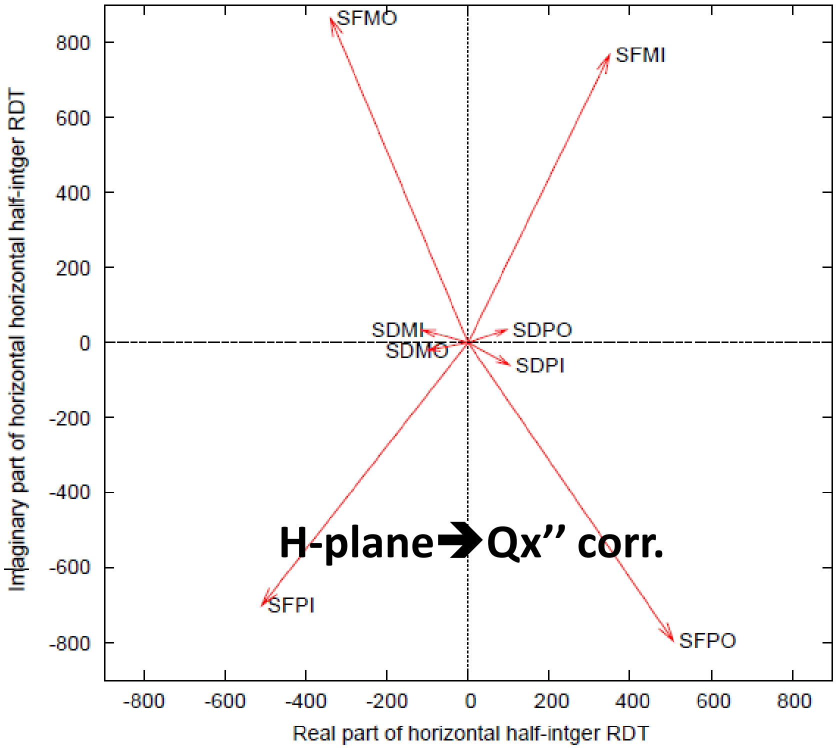
Response Matrix based on-line correction

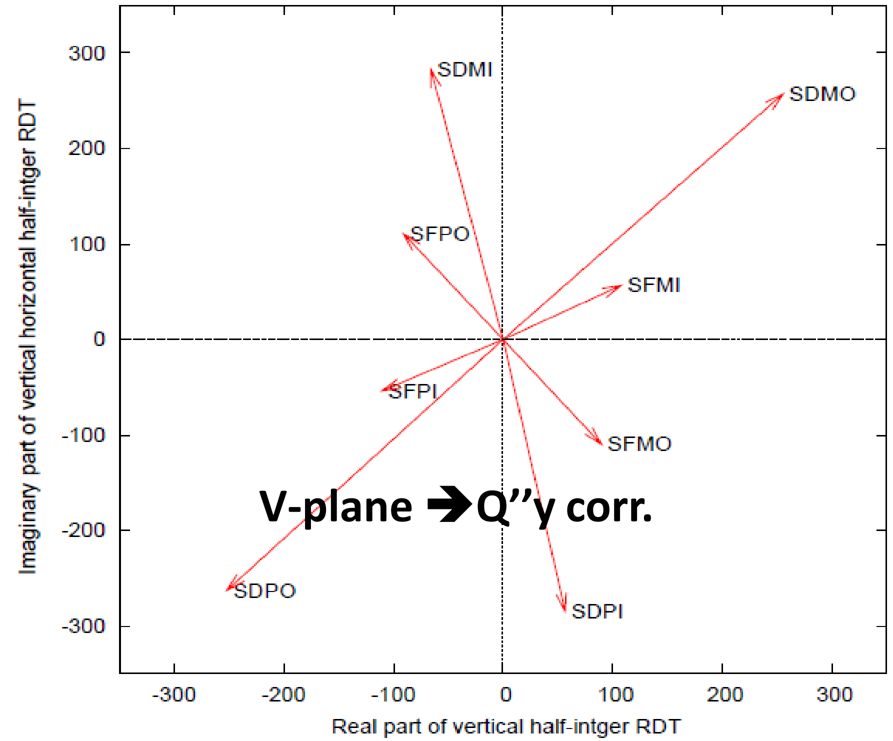


(Y. Luo, et al. PAC'07.)

- Using the response matrix of off-momentum tunes w.r.t. the strengths of sextupole families to push the off-momentum tunes onto the projected off-momentum tunes by the linear chromaticity.
- This method corrects all order of non-linear chromaticities.
- This method was tested and didn't work very well due to SVD over-shooting and change of linear chromaticity with correction (c.o.d. in sexts).

4-Knobs for on-line correction





- According to their contribution to half-integer resonance driving terms, 144 arc chromatic sextupoles are sorted into four families (4-knobs) to minimize the second order chromaticities.
- This method avoids sextupole polarity reversal and unbalanced sextupole correction strengths. The correction will not change the first order chromaticity at least in principle.
- It was proved to be very effective to correct second order chromaticites and was Implemented in RHIC control system.

(Y. Luo, et al., IPAC 2010)

Measurement vs. model calculation

Table 1: Second order chromaticity comparison

Run#	Ring	Δr [mm]	X [meas]	X [model]	Y [meas]	Y [model]
4207	Yellow	2.0	12 ± 26	137	1332 ± 28	1141
			-13 ± 44		1661 ± 119	
			94 ± 27		1563 ± 32	
			448 ± 33		1452 ± 25	
4454	Blue	2.0	410 ± 19	844	855 ± 24	940
			346 ± 27		838 ± 62	
			365 ± 17		924 ± 48	
			292 ± 31		871 ± 21	
Averaging measured values for a comparison						
4207	Yellow		134 ± 179	137	1460 ± 105	1141
4454	Blue		361 ± 40	844	870 ± 26	940

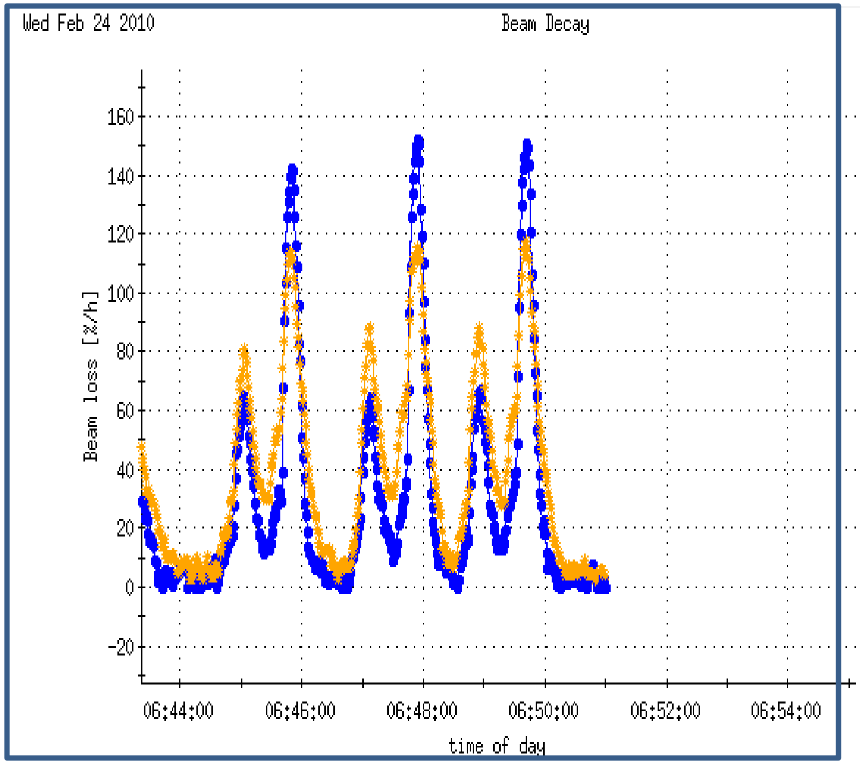
β^*=1.0 m lattice

(Ref: S. Tepikian, et al, PAC'05)

- Measurement of second order chromaticity agreed with the model prediction very well before 2007 with $\beta^* > 0.8$m lattices.
- Large discrepancies were observed with $\beta^* < 0.7$m lattices.

Errors in the chromaticity measurement

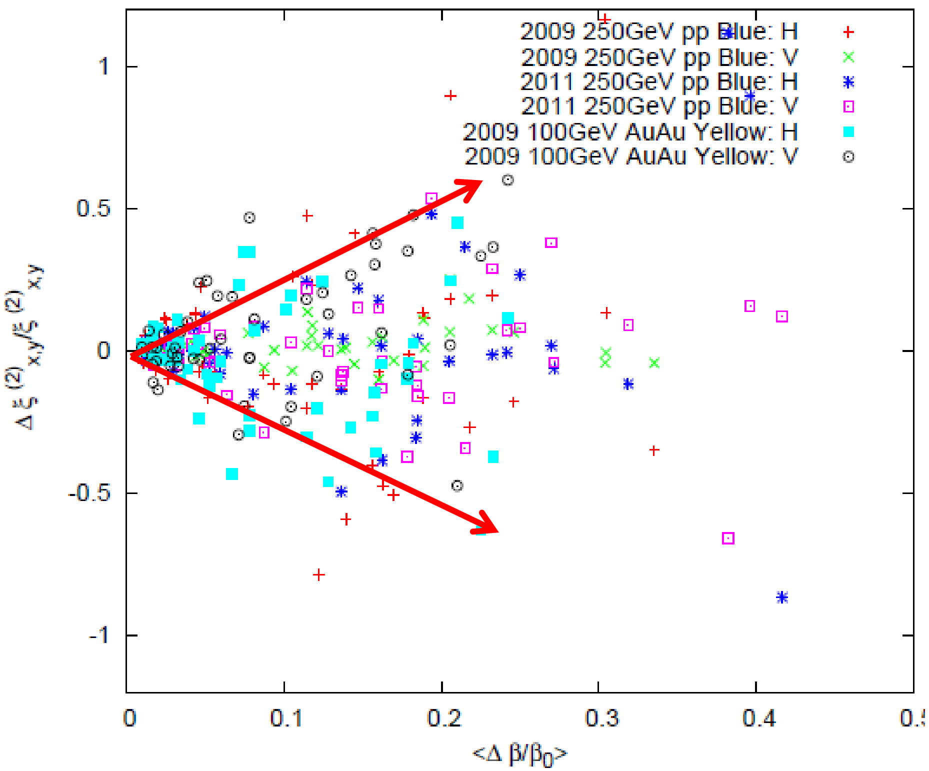
Radial (mm)	Q''x/2	Qy''/2
0.5	1089	-1645
	1112	-942
	1053	-1156
	870	-1201
	852	-1039
	779	-1377
Model	3077	4728

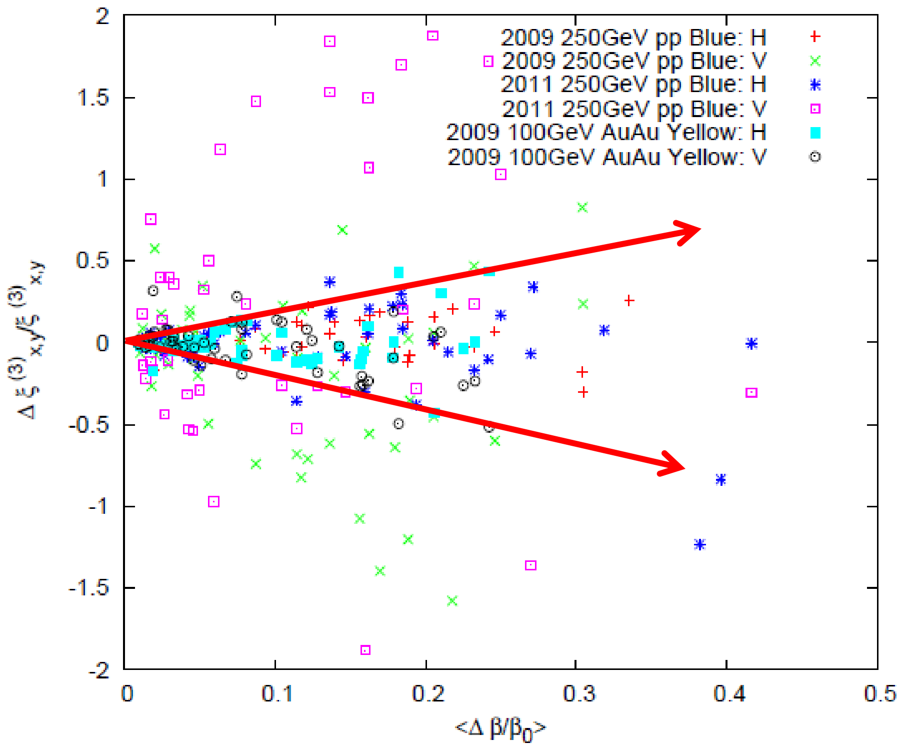


(Yellow 2010 Au-Au run, β*=0.7 m)

- Measurement tunes and fitted chromaticities didn't repeat very well.
- Small momentum aperture prevented large (dp/p_0) scan.
- Un-balanced beam decay with positive and negative (dp/p_0) in this example.

Non-linear chromaticity and on-momentum β-beat





➢ Simulation shows that more than 10% on-momentum beta-beat will introduce 30% second order chromaticity uncertainty (1200 units here).

(Y. Luo, et al., BNL C-AD/AP/418, 2011)

Source of non-linear chromaticities

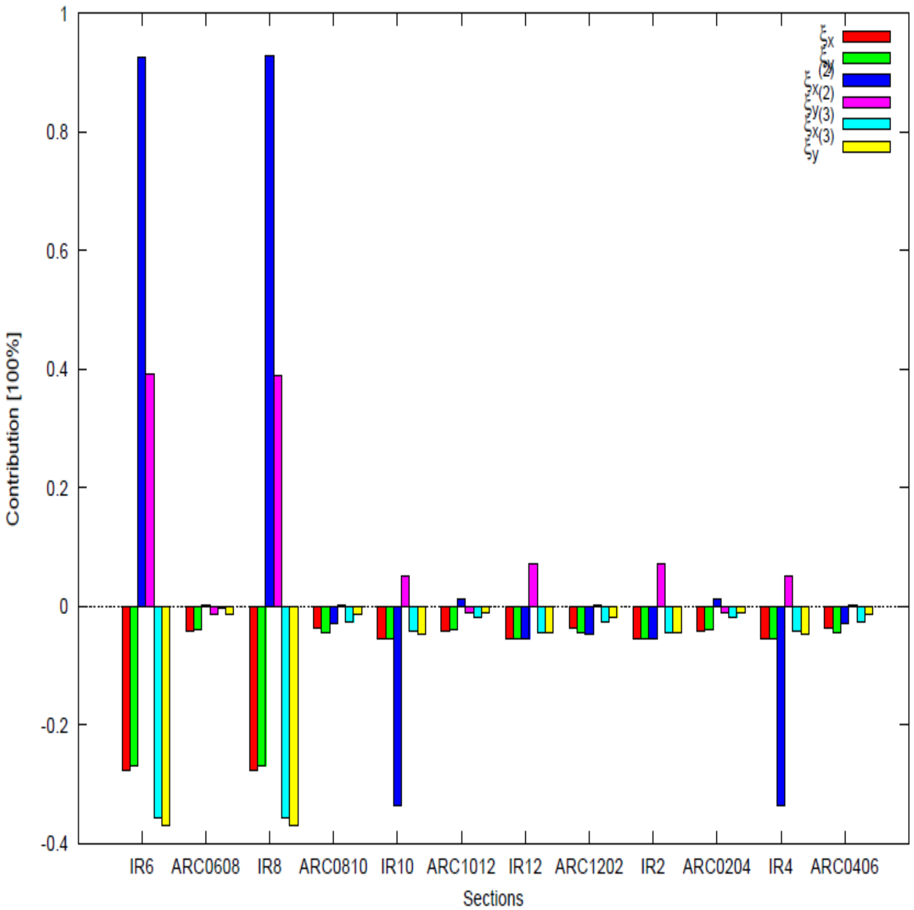


Table 4: Contributions to the linear and nonlinear chromaticities

Sections	$\xi_x^{(1)}$	$\xi_y^{(1)}$	$\xi_x^{(2)}$	$\xi_y^{(2)}$	$\xi_x^{(3)}$	$\xi_y^{(3)}$
2009-pp-Blue:						
IR6 and IR8	-0.55	-0.53	1.85	0.78	-0.71	-0.73
Other IRs	-0.21	-0.21	-0.77	0.24	-0.17	-0.18
Arcs	-0.22	-0.24	-0.07	-0.02	-0.11	-0.081
2011-pp-Blue:						
IR6 and IR8	-0.58	-0.57	1.20	0.84	-0.74	-0.78
Other IRs	-0.20	-0.20	-0.20	0.17	-0.15	-0.16
Arcs	-0.21	-0.22	0.00	-0.02	-0.10	-0.05
2010-AuAu-Yellow:						
IR6 and IR8	-0.47	-0.50	0.34	1.15	-0.74	-0.86
Other IRs	-0.26	-0.24	0.71	-0.20	-0.17	-0.03
Arcs	-0.25	-0.25	-0.06	0.04	-0.08	-0.10

IR6 and IR8 contributes most of non-linear chromaticities than the other sections.

(Y. Luo, et al., BNL C-AD/AP/Note-418)

Phase advances between IP6 and IP8

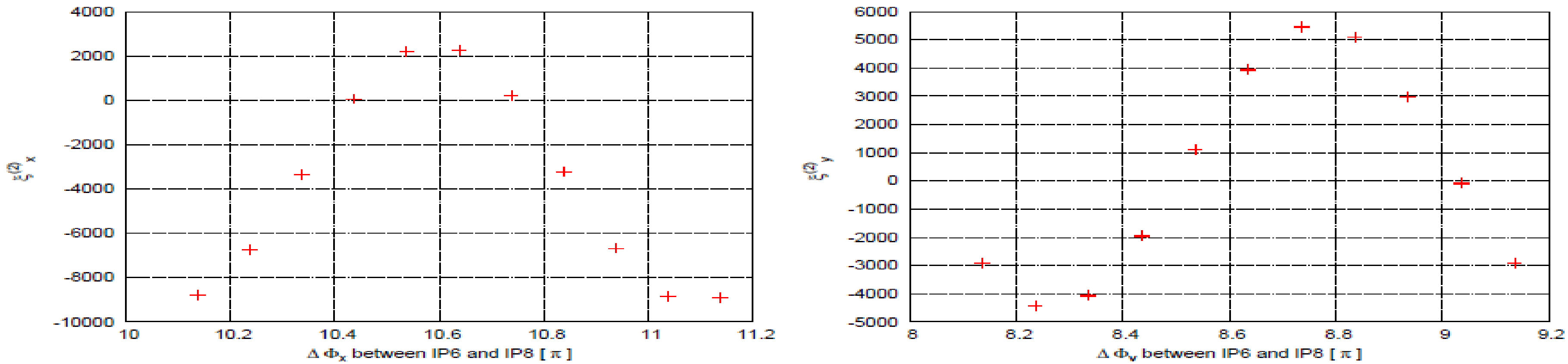
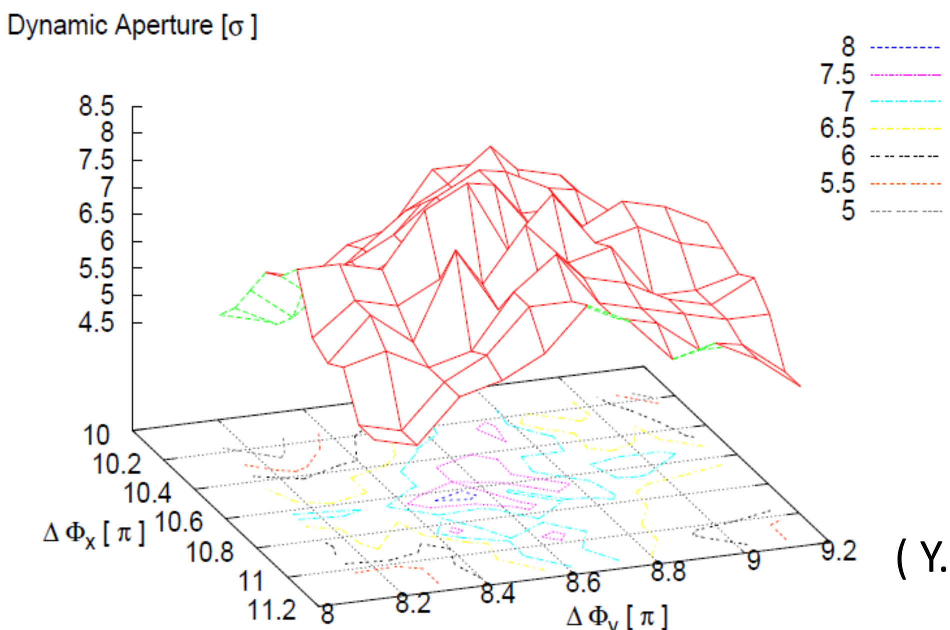


Figure 2: 2011pp-Blue: second order chromaticities versus phase advances between IP6 and IP8.

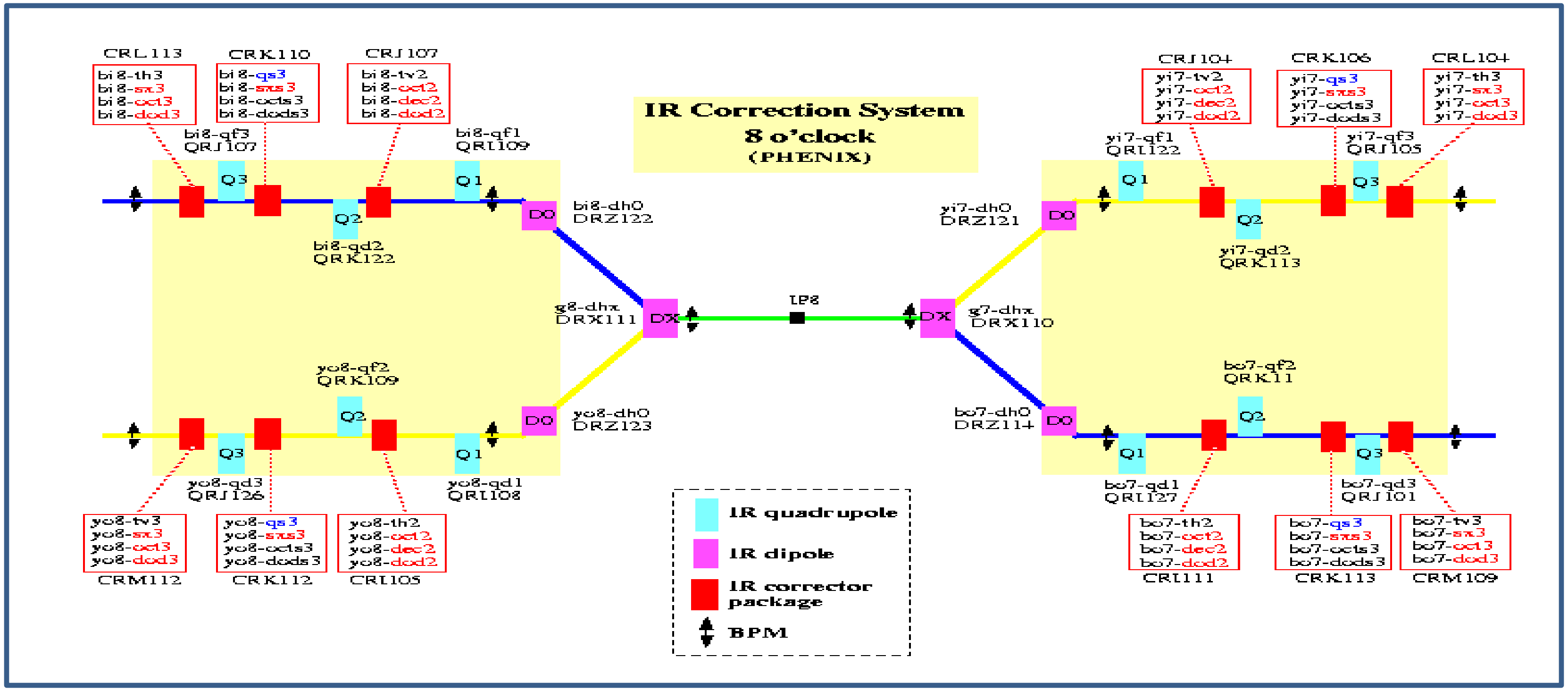


- ➢It is possible to adjust the phase advances between IP6 and IP8 to cancel their the contribution to the global chromatic effects from IR6 and IR8.
- ➢Unfortunately so far we have no enough arc quadrupole power supplies to do this job.

(Y. Luo, et al., BNL C-AD/AP/Note-426, 2011; Y. Luo, et al., PAC 2011.)

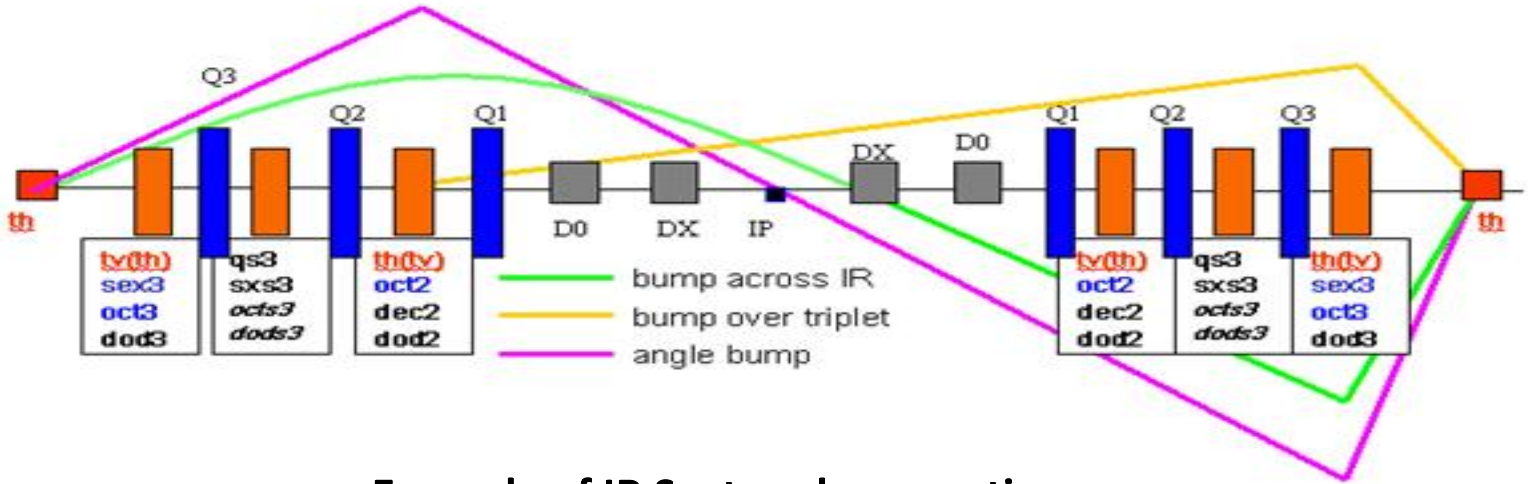
2011pp run:default phase advances between IPs: (10.65π, 8.64π)

IR Multipole Correction

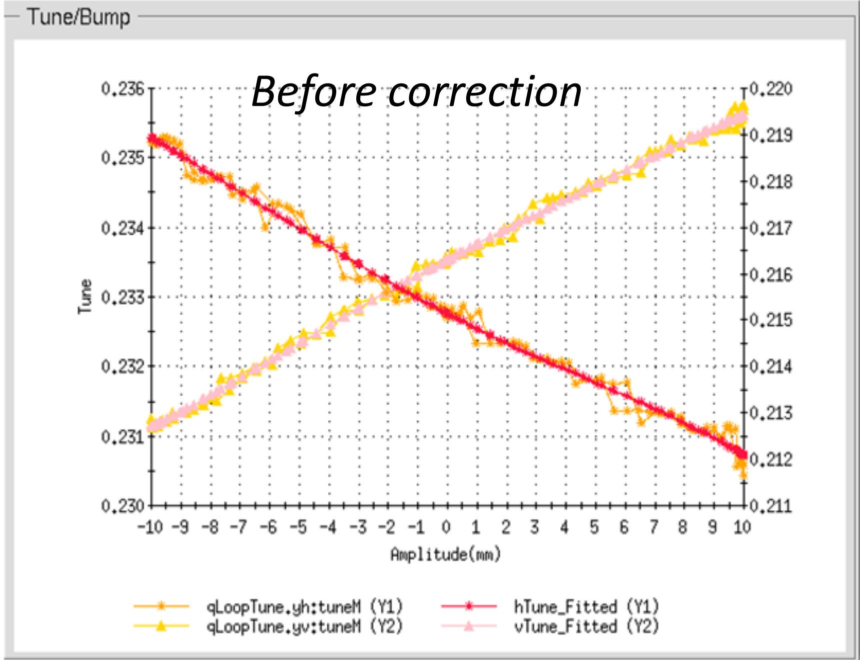


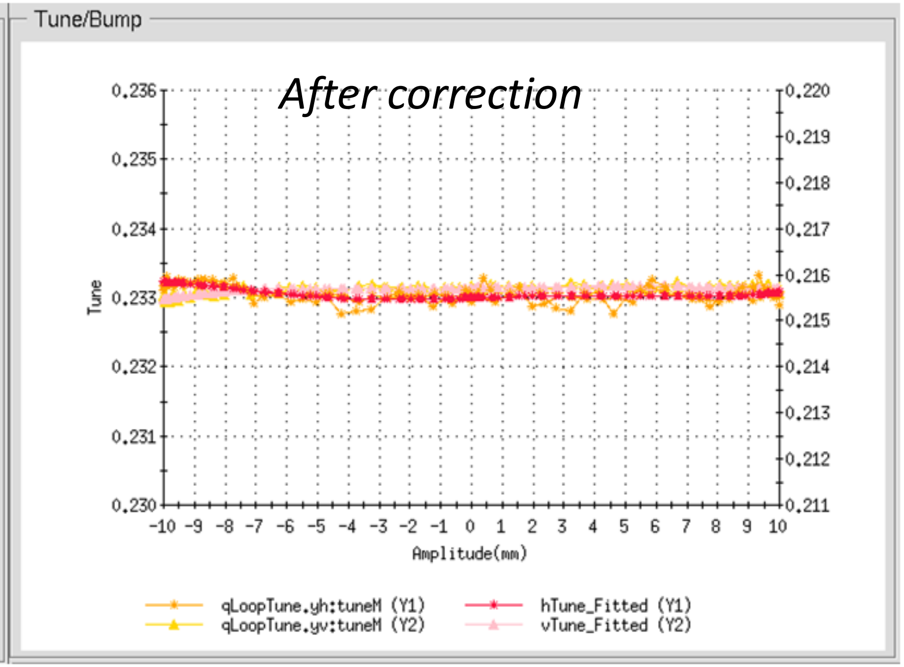
1) J. Wei, Particle Accelerators, Vol. 55, 1996 .-→Action-angle minimization
2) J-P. Koutchouk, F. Pilat, V. Ptitsyn, et al. In PAC 2001. →IR bump method
3) Y. Luo, et al., PAC 2005. →Compare different methods
4) F. Pilat, Y. Luo, et al., PAC 2005. →RHIC experiences with IR bump
5) W. Fischer, Y. Luo, et al., IPAC 2010. → 5th and 6th IR nonl-inear correction

On-line IR bump correction



Example of IR Sextupole correction

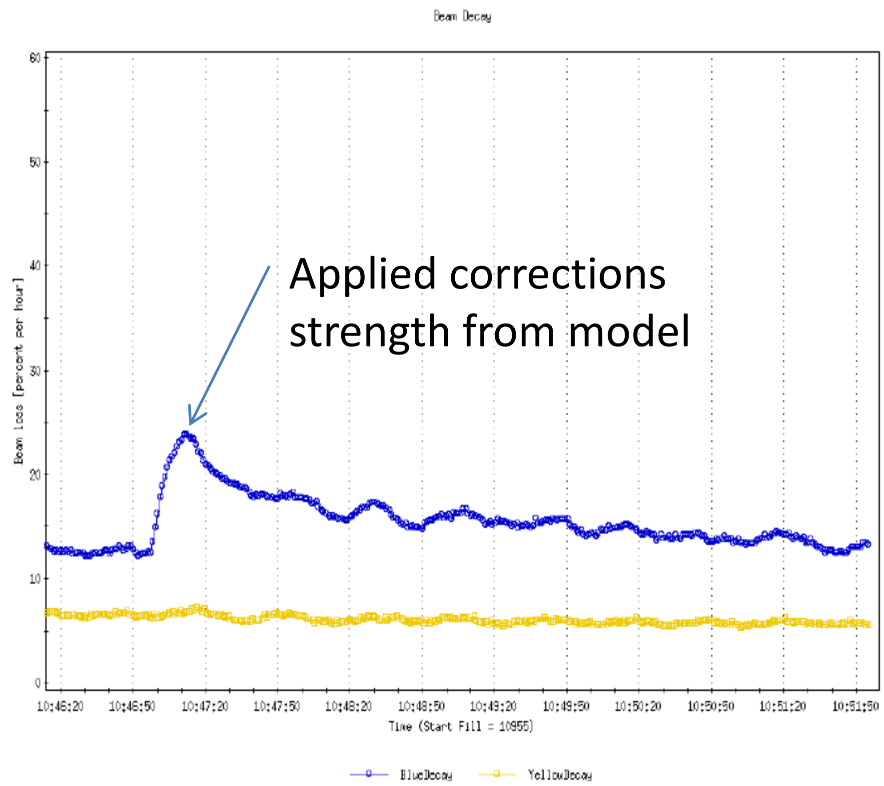




IR bump versus model correction

Blue ring:		
bi5-sx3	0.001439	-0.00040
bo6-sx3	-0.003861	-0.00050
bo7-sx3	-0.002804	-0.00400
bi8-sx3	0.001890	0.00180
Yellow ring:		
yo5-sx3	-0.000922	-0.00100
yi6-sx3	0.000288	0.00070
yi7-sx3	0.001679	0.00200
yo8-sx3	-0.003085	-0.00200
	↑ **Model**	↑ **IR-bump**

?



- ➢In June 2009, we compared the correction strengths from IR non-linear model and that from IR-bump.
- ➢Experiment showed that the corrections from IR-bump method gave a better beam lifetime.

3Qx Resonance Correction

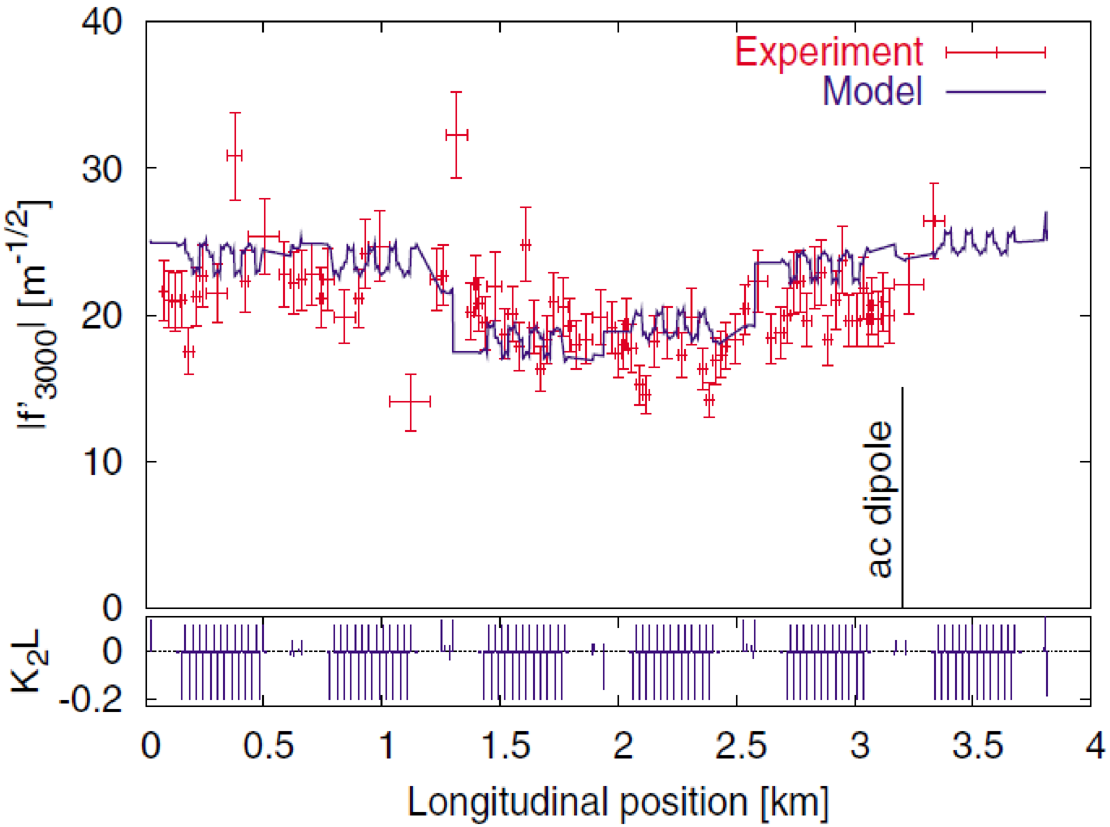
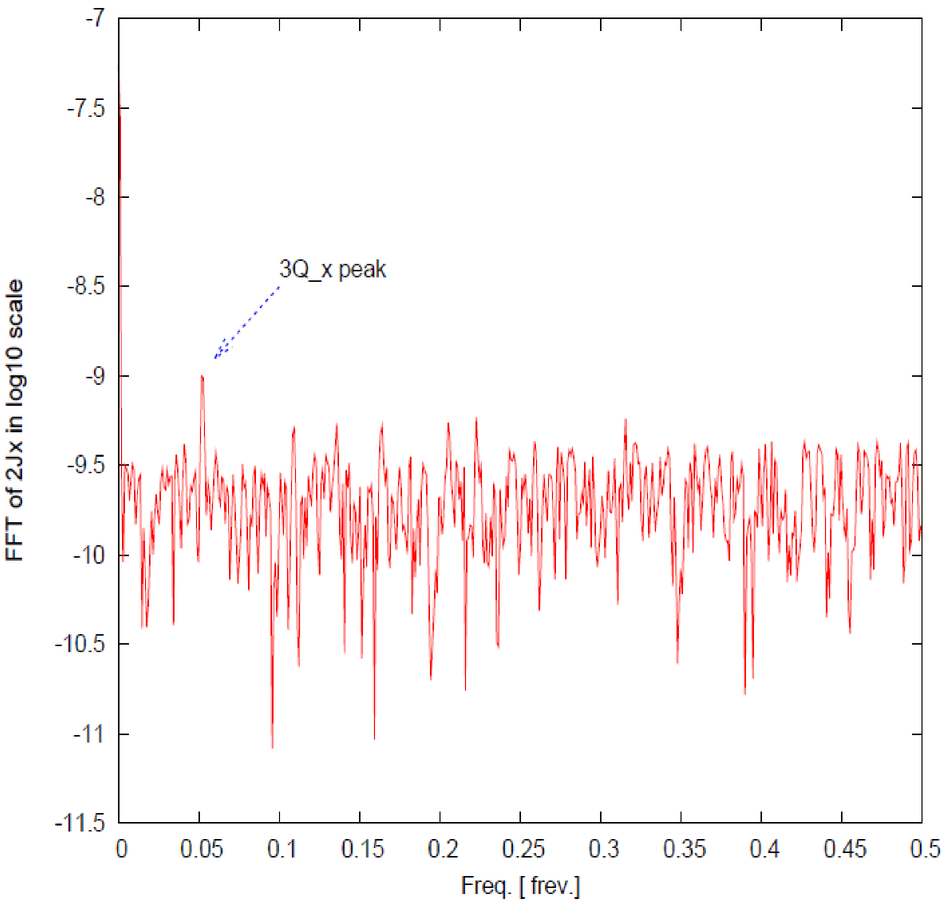


FIG. 4. (Color) Measurement of $|f'_{3000}|$ with an ac dipole. The bottom plot shows the sextupolar components of the ring.

- 3Qx resonance driving terms were measured with the TBT BPM data generated by AC dipole.
- Two methods to obtain the driving terms were tried in RHIC.
- This year the global correction of 3Qx was proposed but was not implemented due to tight machine time.

1) R. Tomas, et al., Phys. Rev. ST Accel. Beams 8, 024001 (2005).
2) R. Bartolini and F. Schmidt, Part. Aceel. 59, 93(1998).

Extract h3000 from FFT of Jx



$$
\begin{aligned}
J_x(N) &= J_x + \frac{A_{21000}(2J_x)^{3/2}}{\sin(\pi\nu_x)}\cos\left(\hat{\phi}_{21000} + \phi_x + N2\pi\nu_x\right) \\
&+ \frac{A_{10110}\sqrt{2J_x}2J_y}{\sin(\pi\nu_x)}\cos\left(\hat{\phi}_{10110} + \phi_x + N2\pi\nu_x\right) \\
&+ \frac{3A_{30000}(2J_x)^{3/2}}{\sin(3\pi\nu_x)}\cos\left[\hat{\phi}_{30000} + 3\left(\phi_x + N2\pi\nu_x\right)\right] \\
&+ \frac{A_{10020}\sqrt{2J_x}2J_y}{\sin\left[\pi\left(\nu_x - 2\nu_y\right)\right]}\cos\left[\hat{\phi}_{10020} + \phi_x - 2\phi_y + N2\pi\left(\nu_x - 2\nu_y\right)\right] \\
&+ \frac{A_{10200}\sqrt{2J_x}2J_y}{\sin\left[\pi\left(\nu_x + 2\nu_y\right)\right]}\cos\left[\hat{\phi}_{10200} + \phi_x + 2\phi_y + N2\pi\left(\nu_x + 2\nu_y\right)\right] \\
&+ O\left(b_3^2\right), \\
J_y(N) &= J_y - \frac{2A_{10020}\sqrt{2J_x}2J_y}{\sin\left[\pi\left(\nu_x - 2\nu_y\right)\right]}\cos\left[\hat{\phi}_{10020} + \phi_x - 2\phi_y + N2\pi\left(\nu_x - 2\nu_y\right)\right] \\
&+ \frac{2A_{10200}\sqrt{2J_x}2J_y}{\sin\left[\pi\left(\nu_x + 2\nu_y\right)\right]}\cos\left[\hat{\phi}_{10200} + \phi_x + 2\phi_y + N2\pi\left(\nu_x + 2\nu_y\right)\right] \\
&+ O\left(b_3^2\right) \qquad (156)
\end{aligned}
$$

1) Y. Luo, et al., in Proceedings of the 2007 PAC.
2) J. Bengtsson, SLS Note 9/97.

Backup slides: Perturbation Theory

Definitions:

$$\xi^{(1)}_{x,y} = \frac{\partial Q_{x,y}}{\partial \delta} \tag{4}$$

$$\xi^{(2)}_{x,y} = \frac{1}{2}\frac{\partial Q^2_{x,y}}{\partial \delta^2} \tag{5}$$

$$\xi^{(3)}_{x,y} = \frac{1}{6}\frac{\partial Q^3_{x,y}}{\partial \delta^3}. \tag{6}$$

The first order chromaticities:

$$\xi^{(1)}_{x,y} = \frac{1}{4\pi}\oint \beta_{x,y}(s)[\mp K_1(s) \pm K_2(s) D_x(s)]ds. \tag{7}$$

The second order chromaticities:

$$\xi^{(2)}_{x,y} = -\frac{1}{2}\xi^{(1)}_{x,y} + \frac{1}{8\pi}\oint [\mp K_1 \pm K_2 D_x]\frac{\partial \beta_{x,y}}{\partial \delta}ds + \frac{1}{8\pi}\oint \pm K_2 \beta_{x,y} D^{(2)}_x ds \tag{8}$$

The third order chromaticities:

$$\begin{aligned}\xi^{(3)}_{x,y} \quad = \quad & -\tfrac{1}{3}\xi^{(2)}_{x,y} \\ & +\tfrac{1}{24\pi}\oint [\mp K_1 \pm K_2 D_x]\tfrac{\partial^2 \beta_{x,y}}{\partial \delta^2}ds + \tfrac{1}{24\pi}\oint [\pm K_1 \mp K_2 D_x]\tfrac{\partial \beta_{x,y}}{\partial \delta}ds \\ & +\tfrac{1}{24\pi}\oint [\pm K_2 D^{(2)}_x]\tfrac{\partial \beta_{x,y}}{\partial \delta}ds + \tfrac{1}{24\pi}\oint [\pm K_2 D^{(3)}_x]\beta_{x,y}ds \\ & +\tfrac{1}{24\pi}\oint [\mp K_2 D^{(2)}_x]\beta_{x,y}ds + \tfrac{1}{24\pi}\oint \pm K_2 D^{(2)}_x \tfrac{\partial \beta_{x,y}}{\partial \delta}ds.\end{aligned} \tag{9}$$

where $D_x = \frac{\partial x_{co}}{\partial \delta}$, $D^{(2)}_x = \frac{\partial x^2_{co}}{\partial \delta^2}$, and $D^{(3)}_x = \frac{\partial x^3_{co}}{\partial \delta^3}$.

(Y. Luo, et al., BNL C-AD/AP/Note-418)

Second order chromaticity, off-momentum β-beat and half-integer resonance driving terms

According to Ref. [2], the second order chromaticities are given by

$$\xi^{(2)}_{x,y} = -\frac{1}{2}\xi^{(1)}_{x,y} + \frac{1}{8\pi}\oint [\mp K_1 \pm K_2 D_x] \frac{\partial \beta_{x,y}}{\partial \delta} ds + \frac{1}{8\pi}\oint \pm K_2 \beta_{x,y} D^{(2)}_x ds, \tag{1}$$

where K_1 and K_2 are the strengths of quadrupoles and sextupoles. $\xi^{(1)}_{x,y}$ are the first order chromaticities. $\beta_{x,y}$ and $D^{(2)}_x$ are the betatron amplitude functions and horizontal dispersion. δ is the relative momentum deviation.

The second term in Eq. (1) is the dominant one which is determined by the off-momentum β-beat $\frac{\partial \beta_{x,y}}{\partial \delta}$. The relative off-momentum β-beat is

$$\frac{1}{\beta_{x,y}(s)} \frac{\partial \beta_{x,y}(s)}{\partial \delta} = \pm \frac{1}{2\sin(2\pi Q_{x,y})} \oint \beta_{x,y}(s')[\mp K_1(s') \pm K_2(s') D_x(s')] \cos(2|\phi_{x,y}(s) - \phi_{x,y}(s')| - 2\pi Q_{x,y}) ds'. \tag{2}$$

We define half integer resonance driving terms as

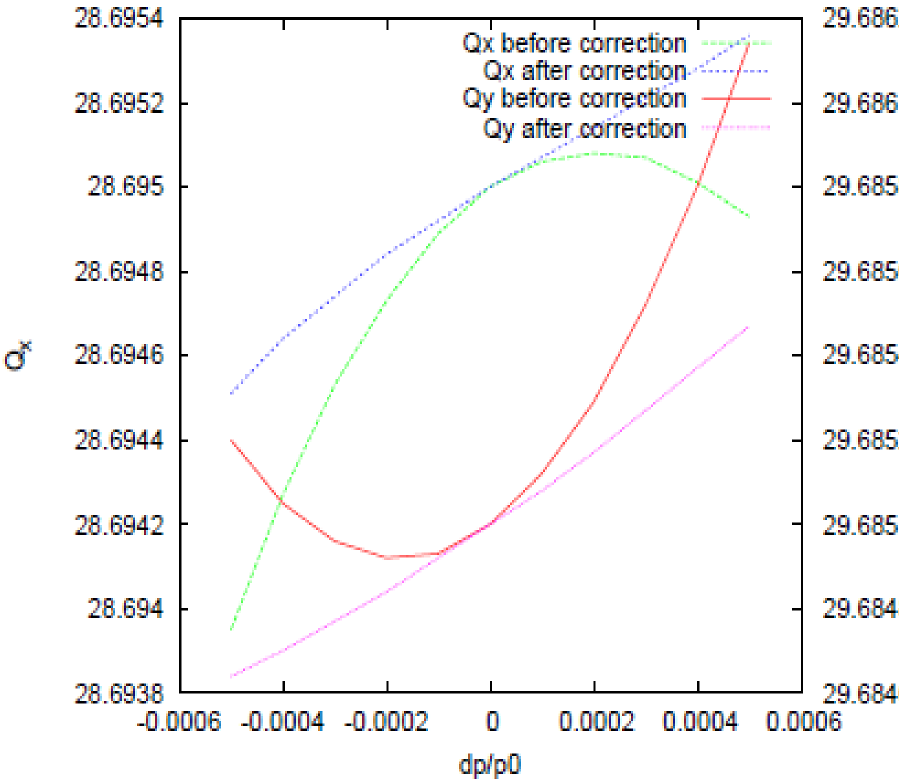
$$h_{20001} = \sum_i^N [-(K_1 L)_i + (K_2 D_x L)_i] \beta_{x,i} e^{-i2\phi_{x,i}}, \tag{3}$$

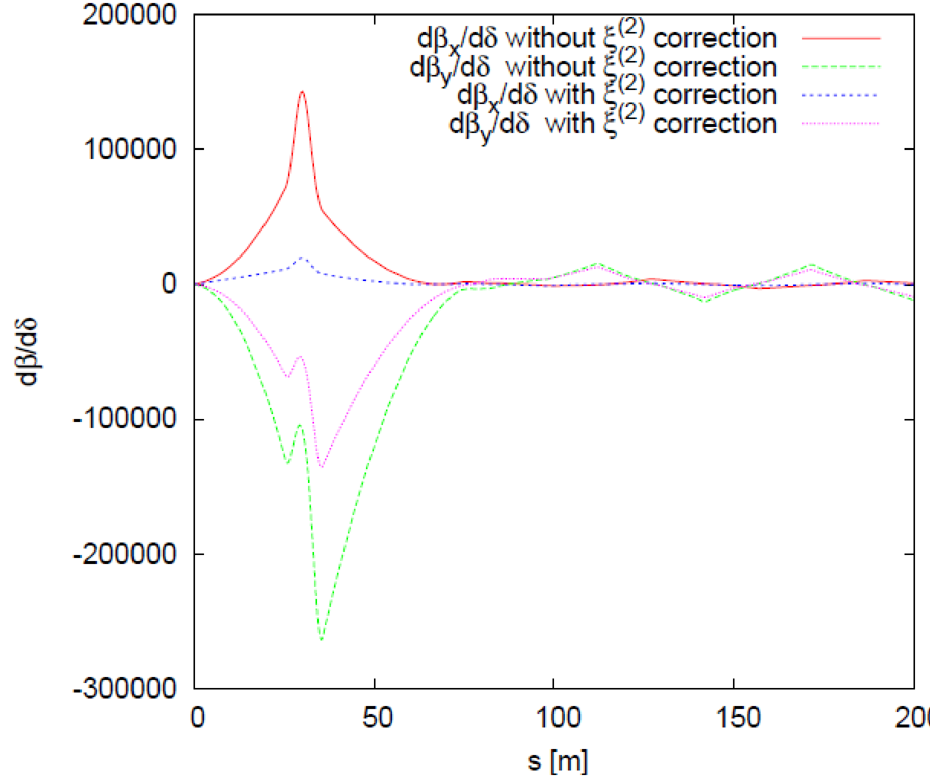
$$h_{00201} = \sum_i^N [+(K_1 L)_i - (K_2 D_x L)_i] \beta_{y,i} e^{-i2\phi_{y,i}}. \tag{4}$$

Here h_{20001} and h_{00201} are the horizontal and vertical half integer resonance driving terms. Comparing Eq. (2) to Eqs. (3)and (4), the relative off-momentum β-beat is governed by the half integer resonance driving terms.

(Y. Luo, et al., BNL C-AD/AP/Note-426, 2011; Y. Luo, et al., PAC 2011.)

An example: Off-momentum β-beat reduced after second order chromaticity correction





(Y. Luo, et al., BNL C-AD/AP/Note-348, 2007)