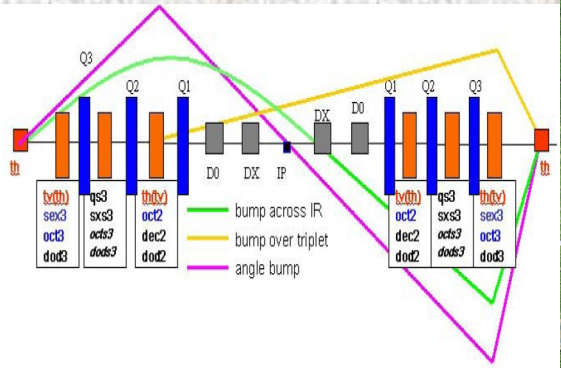
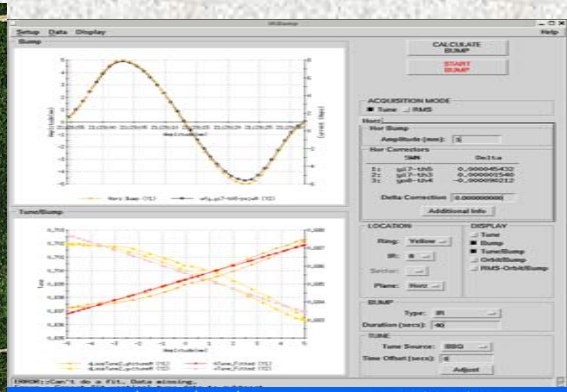
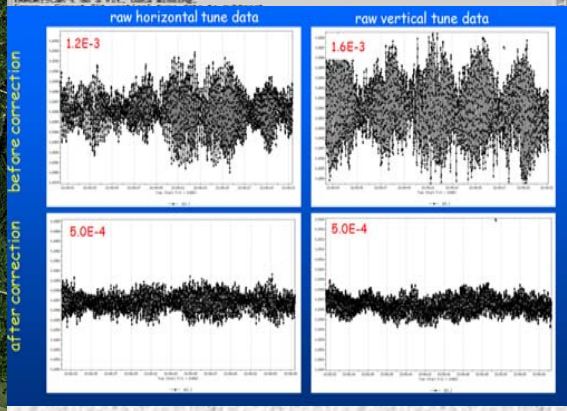
High Order Nonlinear Optics Correction Results







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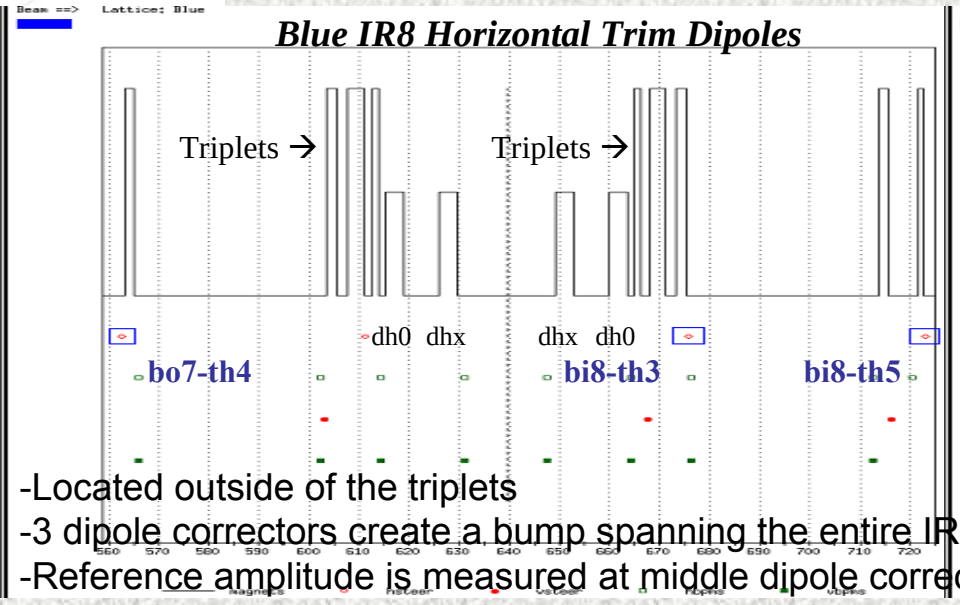
Summary

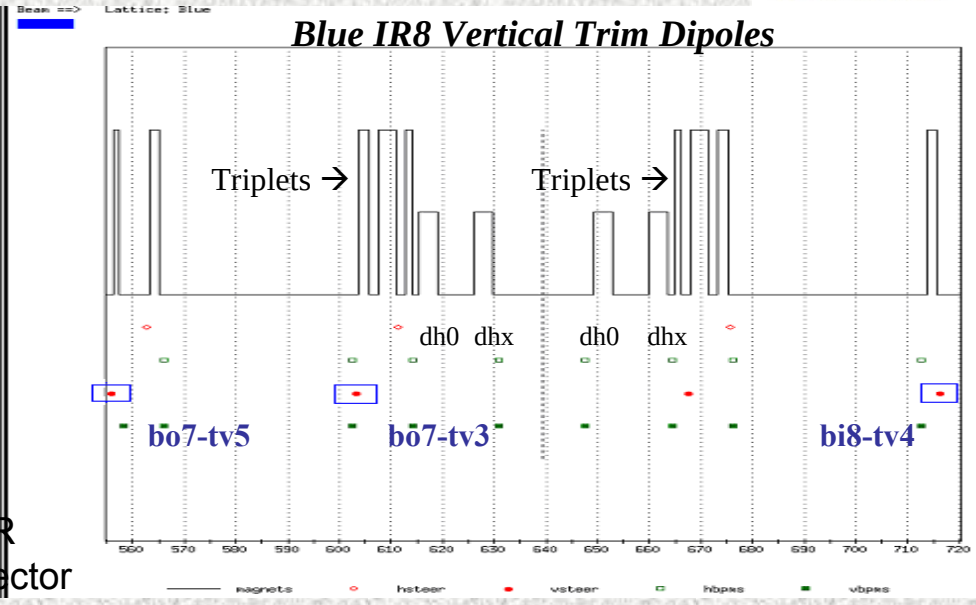
- Review of the method for nonlinear optics corrections in the interaction regions of RHIC
- Brief review of magnet locations
- Sextupole and skew sextupole correction highlights from run 10
- Octupole correction highlights from run 10
- Automation progress
- Conclusion

Nonlinear IR Corrections Review

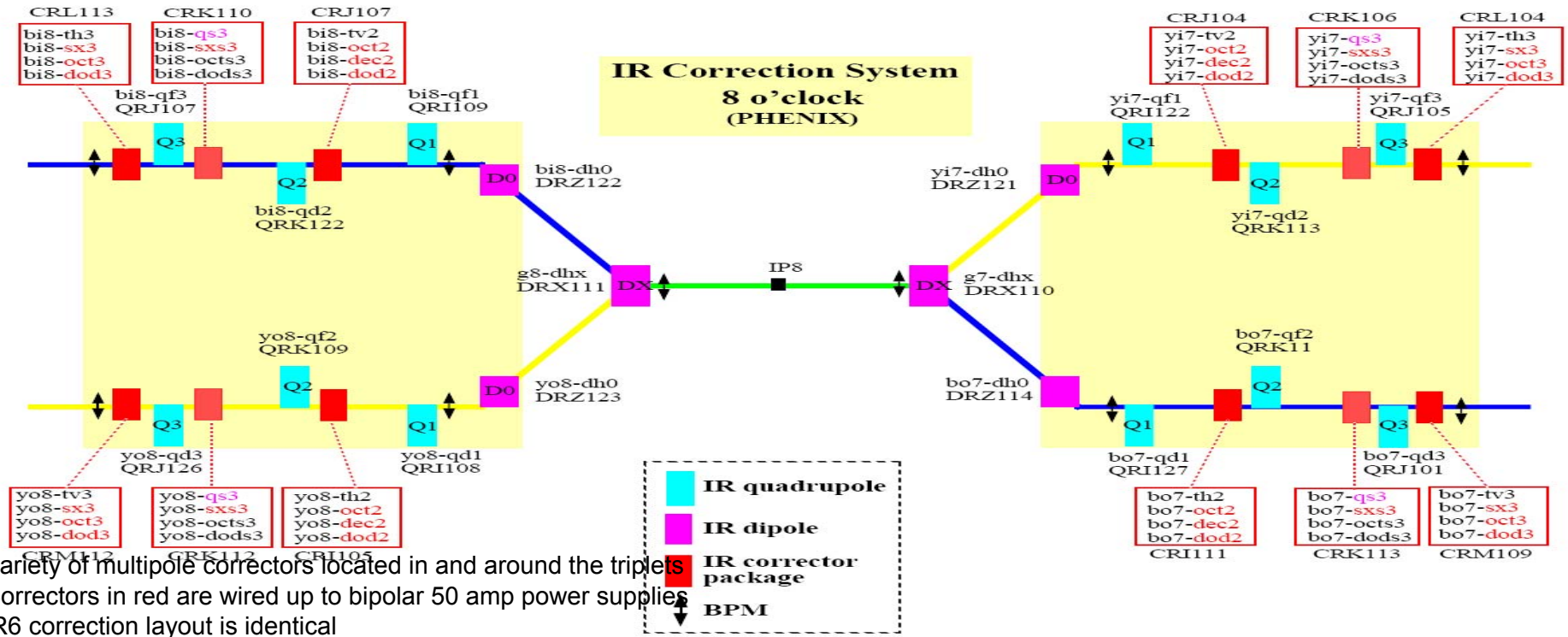
- Dedicated 12x12 ramps used for measurements/adjustments
- Some setup necessary. Beams are anti-cogged, orbit is corrected throughout the rings and centered through the IR's, machine is de-coupled and the tunes are separated > 0.012 to further reduce coupling effects
- Apply a continuously-changing closed orbit three-bump, which creates an orbital excursion through the entire IR (maximum amplitude of 5mm or 10mm)
- This orbital excursion through regions with non-linear fields (IR magnets) generates feed-down effects to lower order field harmonics => gives a measurable tune shift
- Exploit this tune shift in order to compensate for these nonlinear errors
- Compensate by adjusting dedicated multipole corrector magnets until the tune shift for a given bump is minimized
- Horizontal bump used to produce tune shift from normal sextupole fields, vertical bump used to produce tune shift from skew sextupole fields
- Horizontal and vertical bumps produce tune shifts due to octupole fields
- One normal and one skew sextupole corrector for each set of triplets (two of each for a given IR/ring for a total of 8 per IR)
- 2 octupole correctors for each set of triplets (total of 8 per IR)
- Purposefully located near the triplets → areas with relatively large β values
- Use the correctors at locations of higher β_x to correct the horizontal tune shift, similarly the correctors at locations of higher β_y are used to correct the vertical tune shift
- Normal sextupole and skew sextupole correction settings for the IR6 and IR8 magnets experimentally determined during the set-up phase as a standard practice
- Octupole correction shown to be operationally feasible at end of run 9. Run-10 marks the first run with partial octupole correction settings in place for IR6+IR8

Magnet Locations



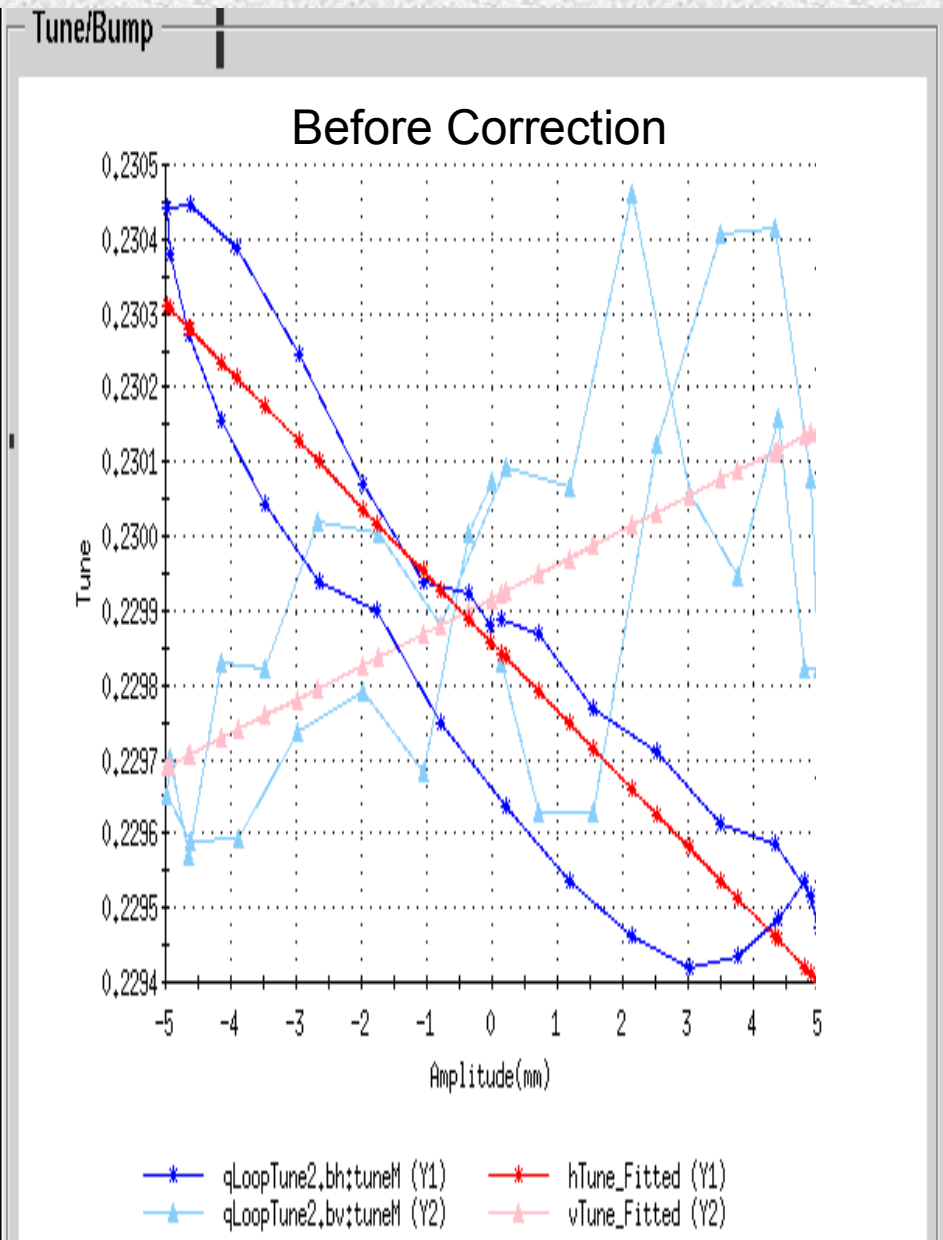


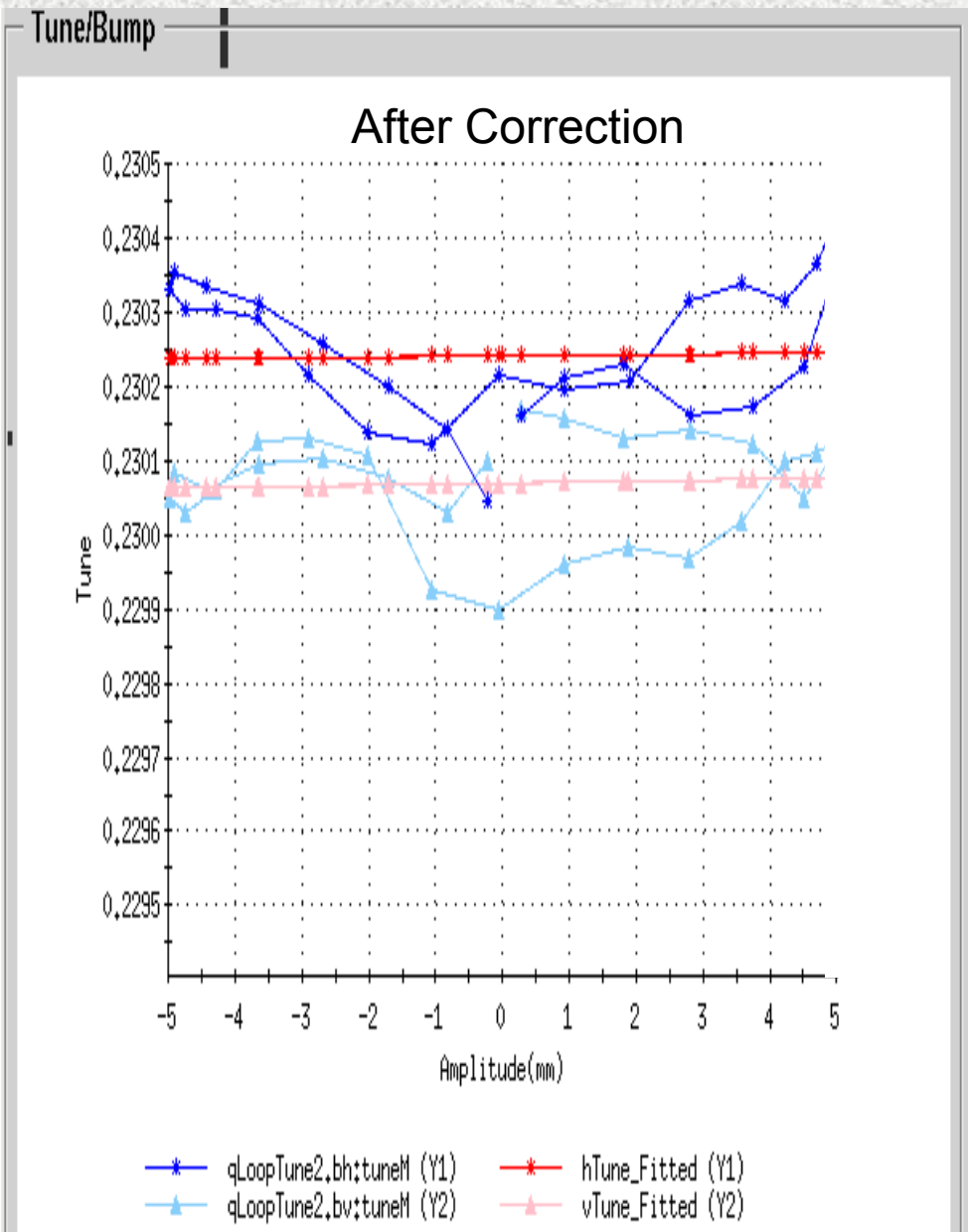
-Located outside of the triplets
-3 dipole correctors create a bump spanning the entire IR
-Reference amplitude is measured at middle dipole corrector



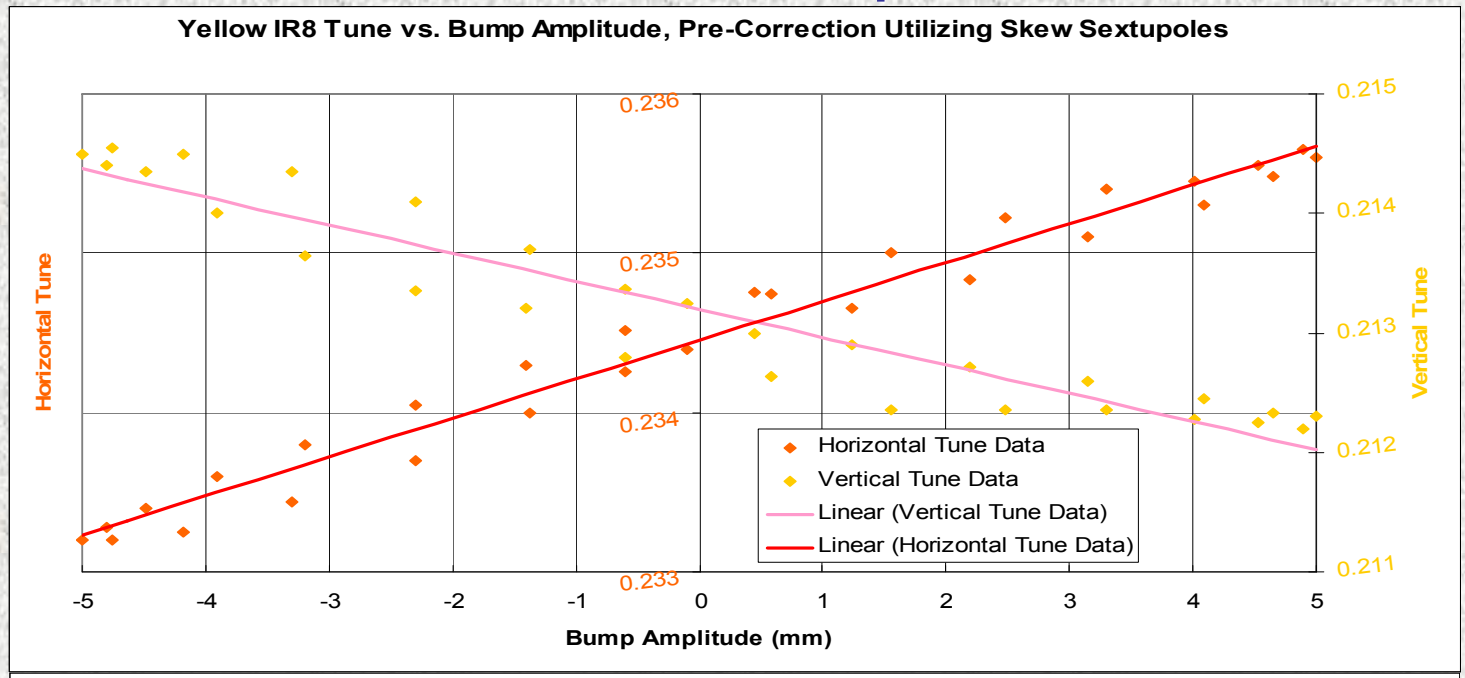
-Variety of multipole correctors located in and around the triplets
-Correctors in red are wired up to bipolar 50 amp power supplies
-IR6 correction layout is identical

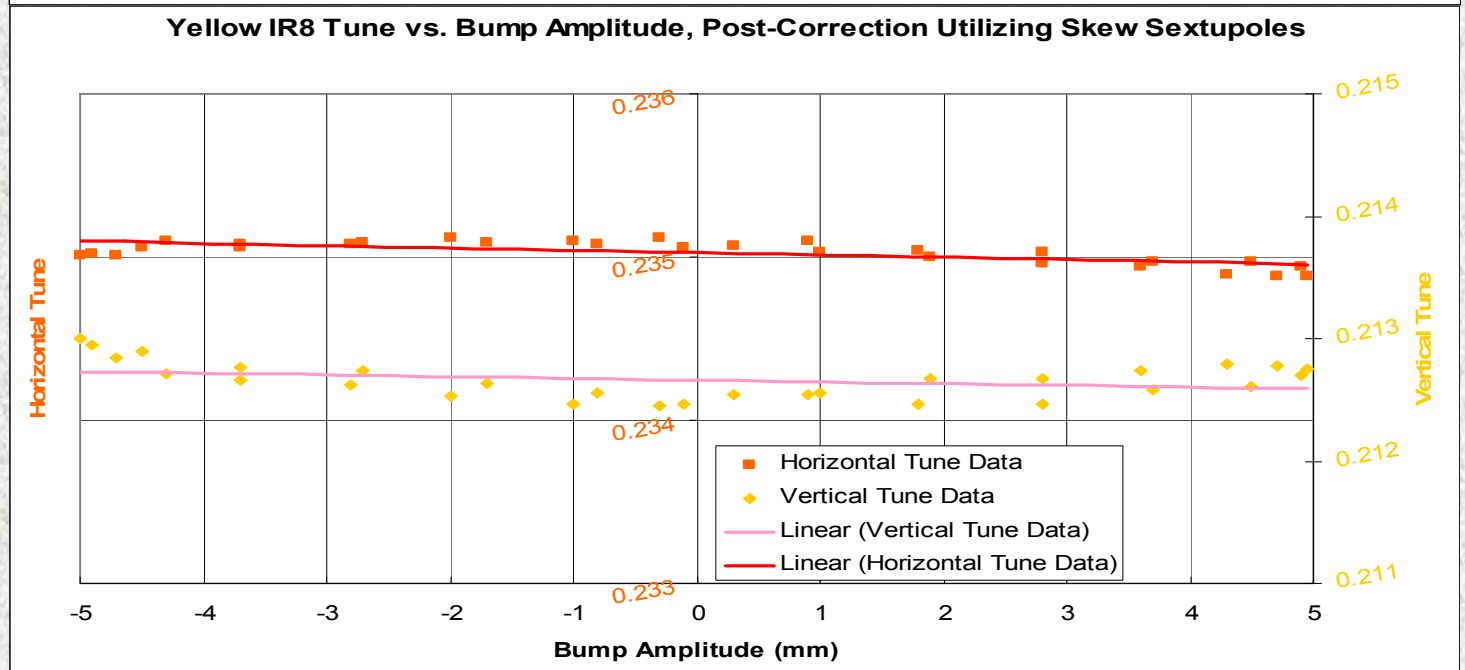
Blue IR8 Sextupole Correction



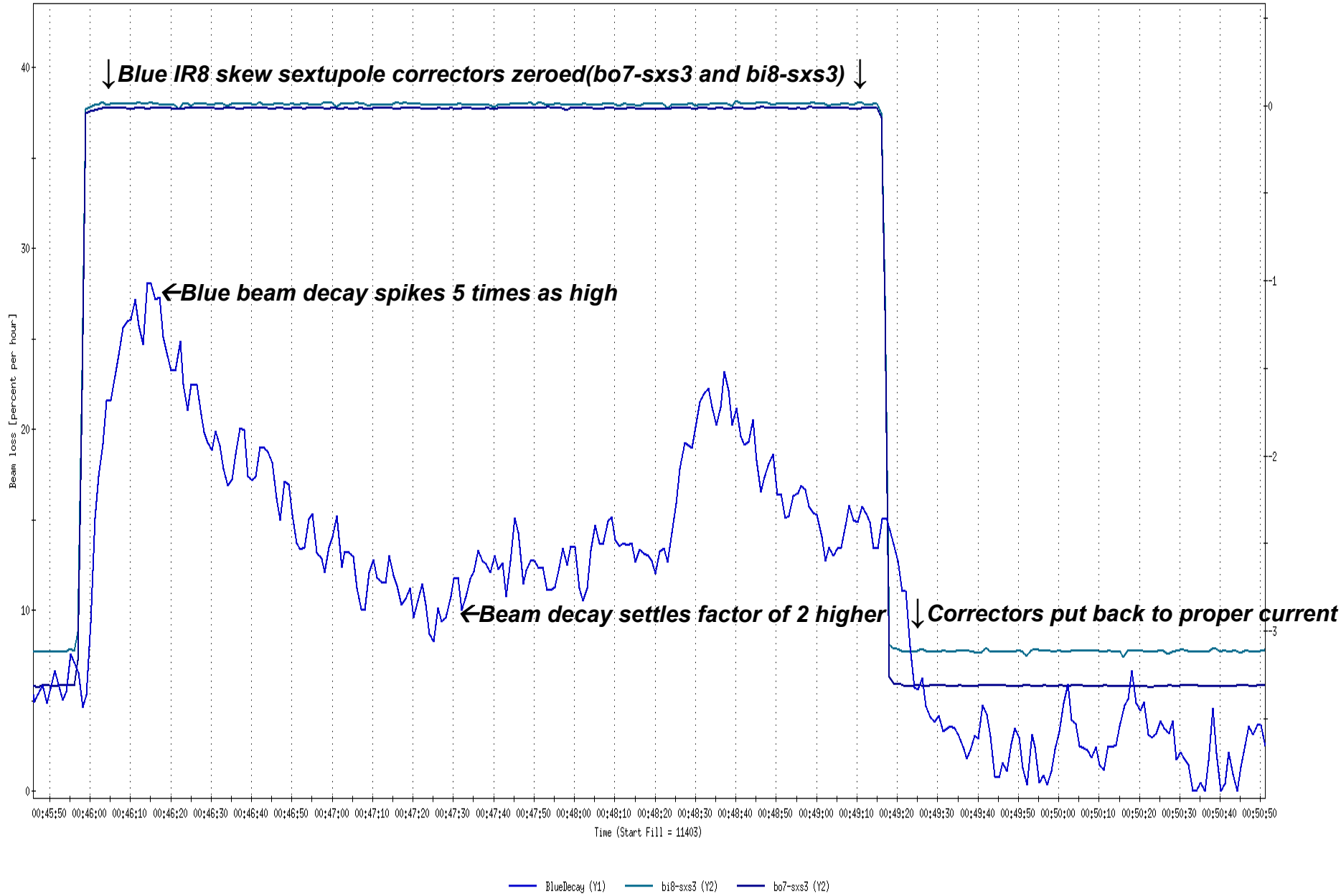


Yellow IR8 Skew Sextupole Correction



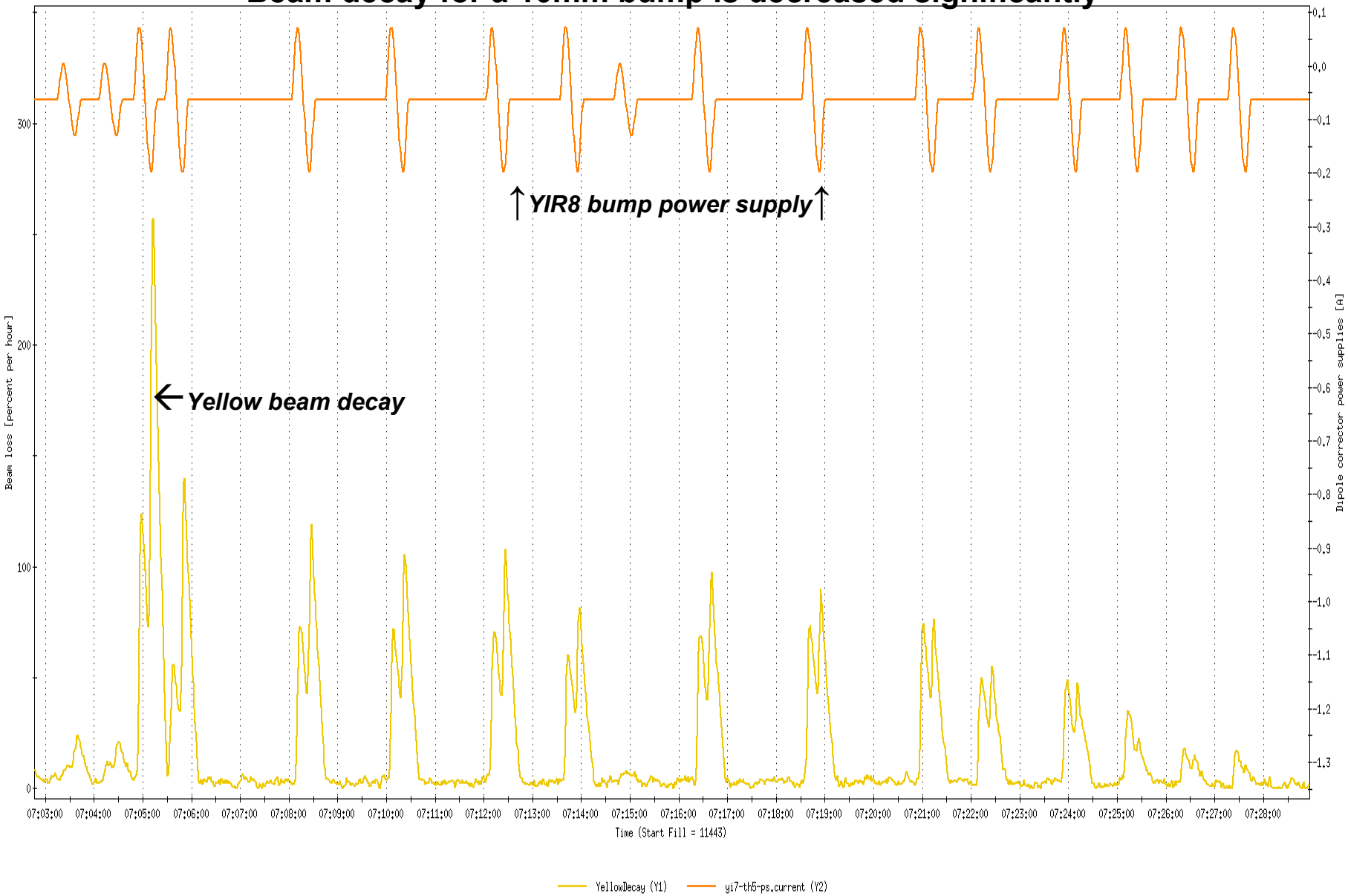


Effect of Removing Skew Sextupole Correctors (BIR8)



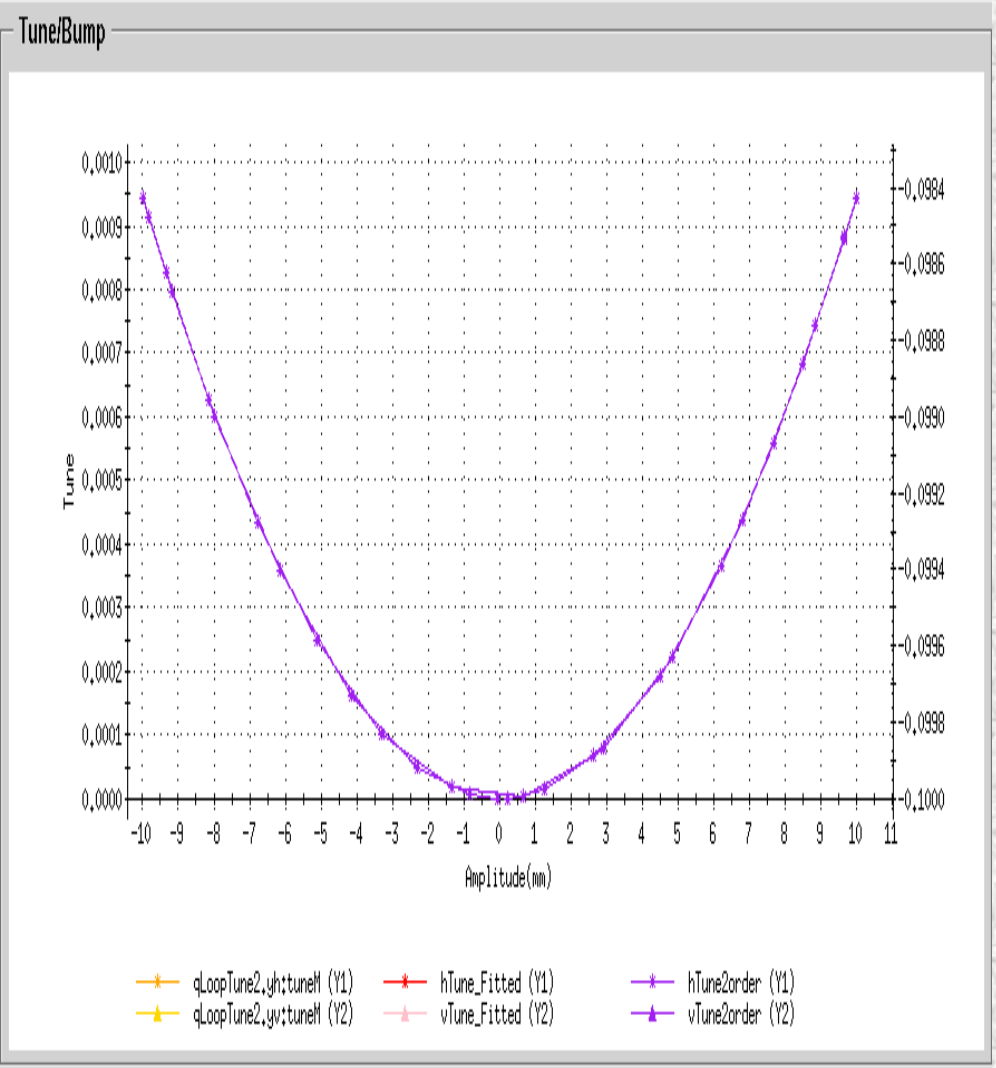
Yellow IR8 Octupole Correction

Beam decay for a 10mm bump is decreased significantly

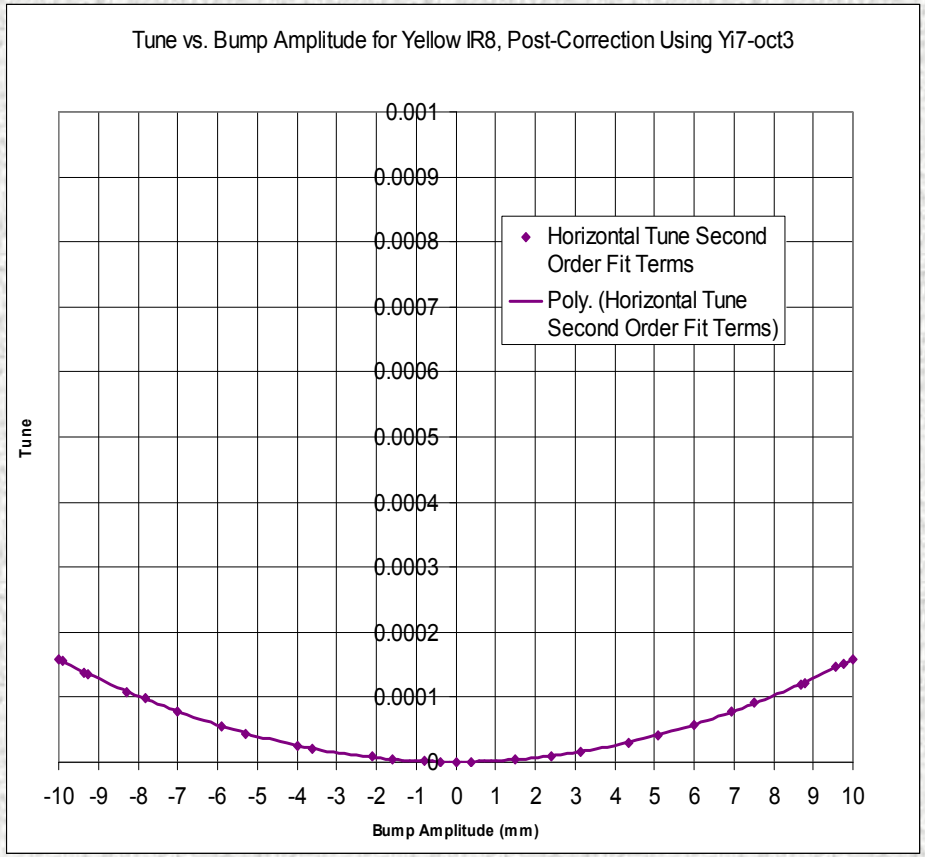


Yellow IR8 Octupole Correction (using yi7-oct3)

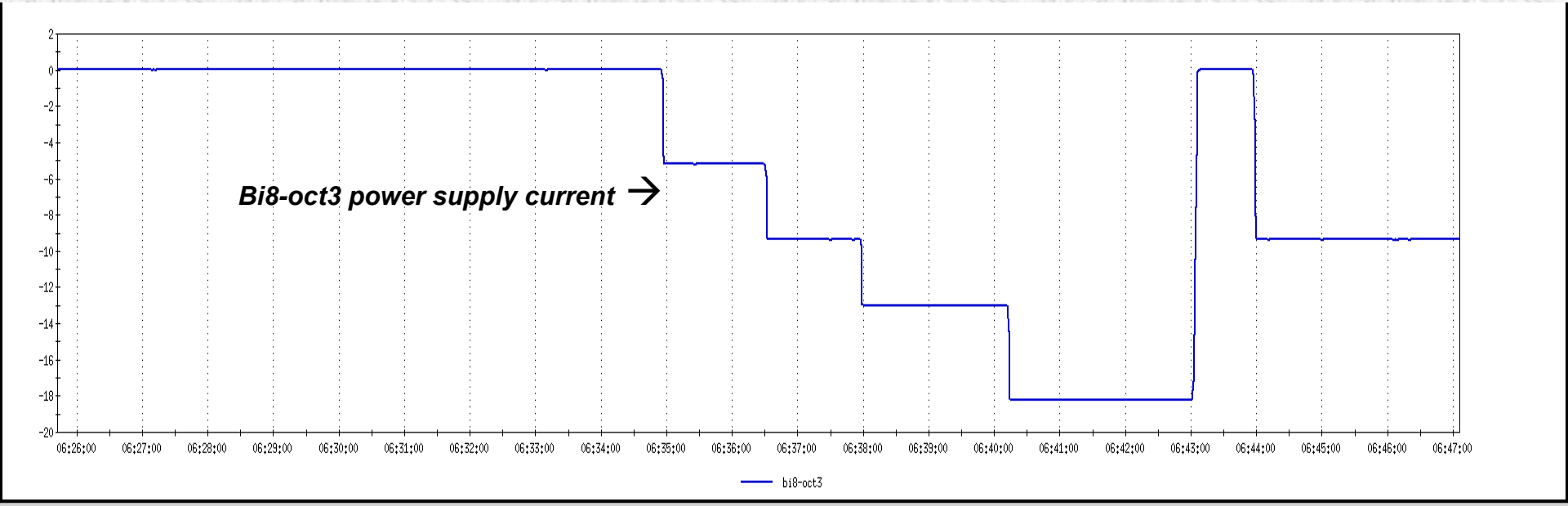
Pre-correction

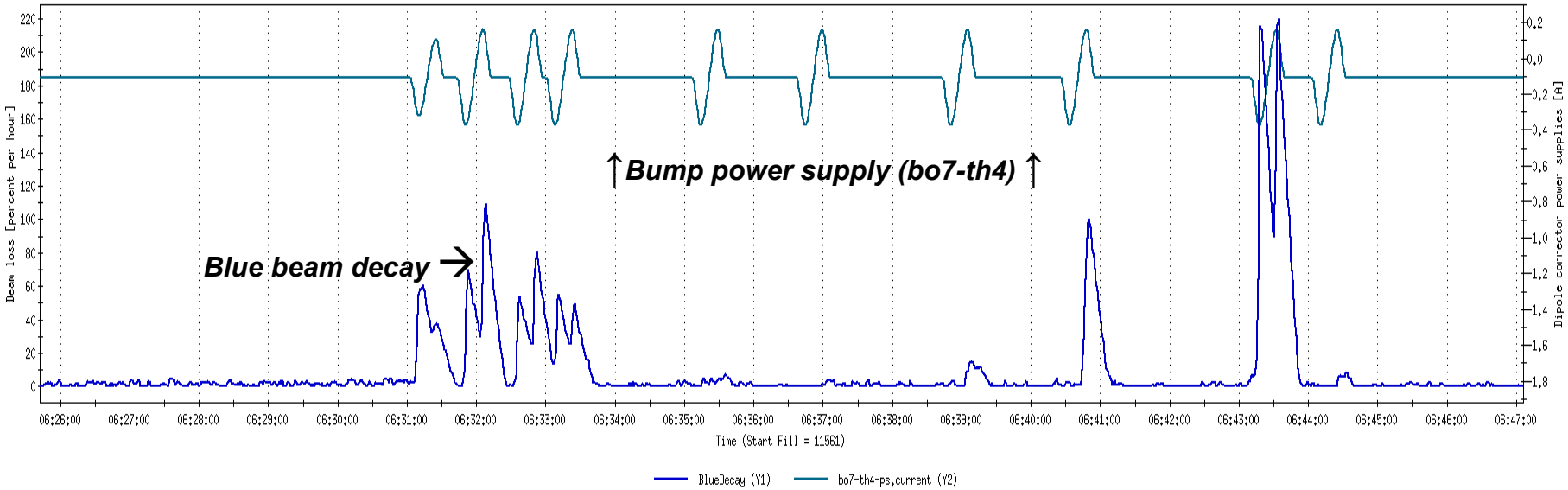


Post-correction

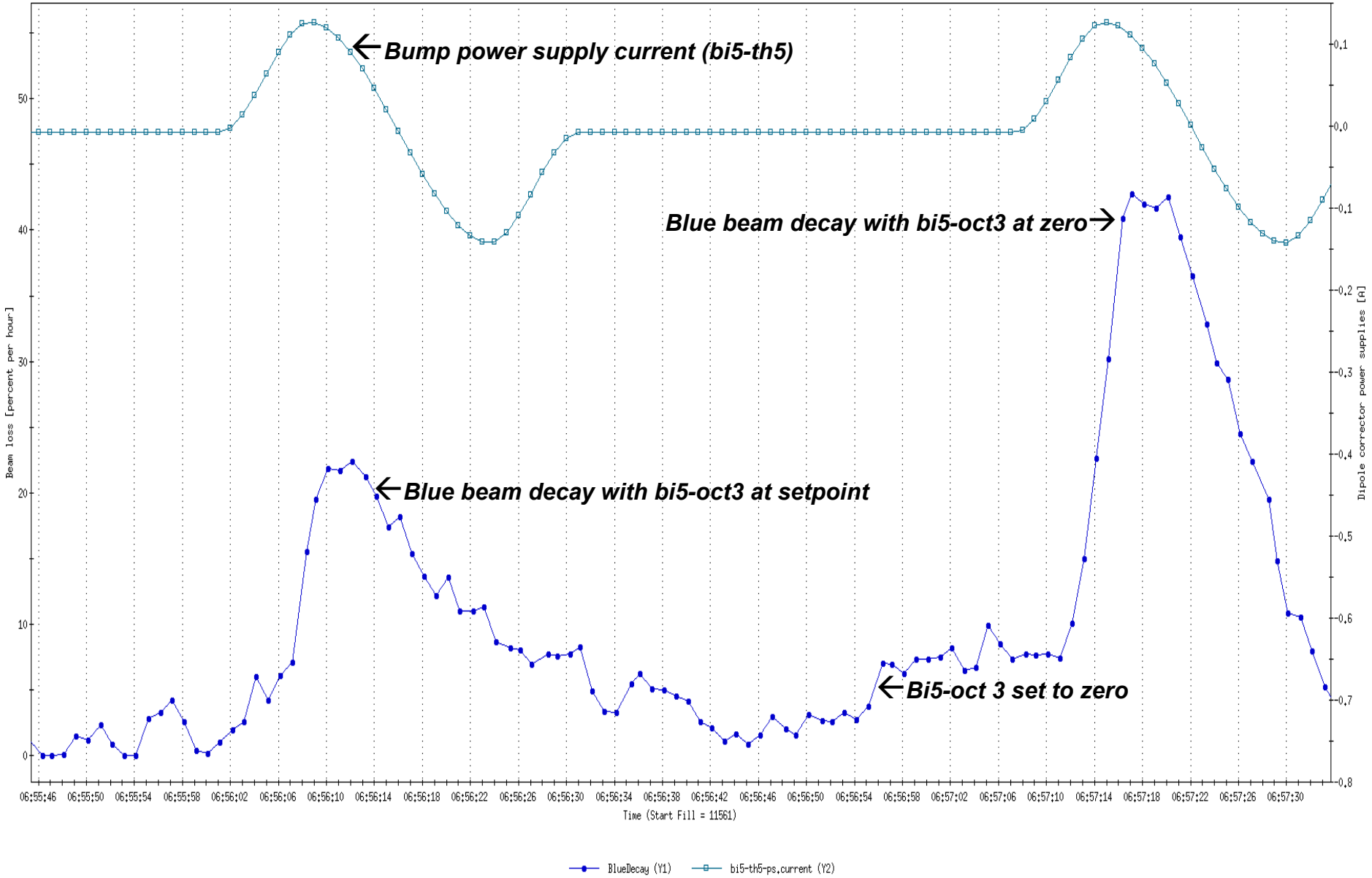


Blue IR8 Octupole Correction





Blue IR6 Octupole Test at End of Store



Sextupole Settings

IR Sextupole Corrector	Run 3: d-Au β^*=2m I(Q)=4500A	Run 3: PP β^*=1m I(Q)=2000A	Run 4: Au β^*=1m I(Q)=4500A	Run 4: PP β^*=1m I(Q)=2000A	Run 5: Cu β^*=1m I(Q)=4500A	Run 6: PP β^*=1m I(Q)=2000A	Run 7: Au β^*=.83m/ .77m (STAR/PHENIX) I(Q)=4500A	Run 8: d-Au β^*=.85m I(Q)=4500A	Run 8: PP β^*=1m I(Q)=2000A	Run 9: PP (250GeV) β^*=0.7m I(Q)=5000A	Run 9: PP (100GeV) β^*=0.7m I(Q)=2000A	Run 10: Au β^*=0.75m I(Q)=4500A
Yo5-sx3	-0.0014	-0.003	-0.006	-0.001	-0.007	-0.0022	-0.006	-0.006	-0.0025	-0.004	-0.001	-0.0055
Yi6-sx3	+0.004	0.0	+0.003	+0.001	+0.0035	+0.0008	+0.003	+0.003	+0.0015	+0.003	+0.0007	+0.0032
Yi7-sx3	+0.003	+0.007	+0.0005	+0.001	+0.003	+0.0072	+0.0005	+0.0005	+0.0035	-0.0001	+0.002	+0.0005
Yo8-sx3	-0.01	-0.038	0.0	-0.0012	-0.003	-0.0084	0.0	0.0	-0.0035	+0.0001	-0.002	-0.0003
Bi5-sx3	+0.0012	+0.001	+0.0011	-0.0022	+0.0025	+0.0008	+0.0011	+0.0011	-0.0008	-0.001	-0.0004	+0.0009
Bo6-sx3	-0.004	-0.003	-0.001	+0.001	-0.005	-0.0008	-0.001	-0.001	-0.0005	-0.0015	-0.0005	-0.004
Bo7-sx3	0.0	-0.003	0.0	-0.007	-0.005	-0.0012	0.0	0.0	-0.004	-0.0008	-0.004	-0.00019
Bi8-sx3	0.0	-0.0005	0.0	+0.002	+0.0025	+0.0005	0.0	0.0	+0.0018	+0.0003	+0.0018	+0.00096

-Smaller β^* correlates with smaller corrections as expected

-With the exception of a few outliers, signs and strengths are fairly consistent

Automation

- As of run 10 the application IRBump includes automatic nonlinear optics correction functionality
- These algorithms replicate the process handled by the system expert; specifically:
  1) Apply a closed bump and look at the ensuing tune shift
  2) Adjust corrector magnets in an attempt to null out the tune shift, then apply another bump
  3) Determine whether the tune shift is now better or worse and adjust accordingly
  4) Repeat these steps in a recursive manner (using the tune shift as a figure of merit) until no further improvement can be made
- Sextupole/skew sextupole algorithms seem to work properly
- Still trying to iron out strange behavior in the octupole algorithm. Difficult to troubleshoot as testing time is virtually nonexistent during RHIC operation
- Reliable automatic corrections within reach, but more testing is needed to verify that the algorithms will work efficiently and consistently

Conclusions

- Sextupole and skew sextupole corrections went smoothly last run, with all settings put in place during first correction attempt
- Run 10 marks the first run with octupole corrector magnet settings in place for operations
- Used ¼ of the available IR octupole correctors during run 10 to minimize the horizontal tune dependence on the horizontal bump amplitude
- Due to time constraints, explicit correction of the vertical tune shift from 10mm horizontal bumps and correction of tune shifts from 10mm vertical bumps is still largely unexplored
- Sextupole and skew sextupole correction is a fairly standard procedure at this point and run 11 should see quicker and less error-prone correction implementation than in years past, due to automation of these corrections

Theory (Extra Slide)

- The magnetic errors in an accelerator magnet can be described in terms of the multipole errors $\mathbf{a_n}$ and $\mathbf{b_n}$ defined as:

$$B_y + iB_x = B_N \sum_{n=0}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_r} \right)^n$$

- Here $\mathbf{B_N}$ represents the main field of some magnet measured at a reference radius $\mathbf{R_r}$. For a quadrupole, for example, $\mathbf{B_n/R_r}$ is the gradient. $\mathbf{b_n}$ and $\mathbf{a_n}$ are respectively the **normal** and **skew** harmonics of magnet errors
- An excursion of the local orbit through a region having non-linear fields generates feed-down effects to lower order field harmonics
- The most useful observable effects come from the feed-down to the zero and first order harmonics, which affect the beam closed orbit and betatron tunes respectively
- It is possible in theory to infer local non-linear effects both from the measure of residual RMS orbit and of tune shifts generated by a local orbit bump in the IR. Given existing limitations on the resolution of the orbit measurement and on the allowable bump amplitude at the triplets, **in practice we have used so far almost exclusively the measurement of tune shift as a function of bump amplitude for non-linear correction**
- The measured tune shifts arise from either the feed-down to the normal gradient or from the repelling effect of linear coupling
- The tune shift (**ΔQ**) and the linear coupling term (**Δc**) for different bump planes (H and V) and for different multipole errors (normal, skew, even and odd orders) can be expressed as follows (where c_n stands for either the a_n or b_n and z stands for x or y):

$$\Delta Q(H, norm) = g(b_n, x_{co}) \; ; \qquad \Delta Q(V, norm, odd) = -1^{(n-1)/2} g(b_n, y_{co})$$

$$\Delta Q(V, skew, even) = -1^{n/2} g(a_n, y_{co}) \; ; \qquad \Delta c(H, skew) = h(a_n, x_{co})$$

$$\Delta c(V, norm, even) = -1^{(n-1)/2} h(b_n, y_{co}) \; ; \qquad \Delta c(V, skew, odd) = -1^{(n+1)/2} h(a_n, y_{co})$$

Where the functions g and h are defined as:

$$g(c_n, z_{co}) = \frac{n}{4\pi} \frac{1}{B\rho} \int \beta_z B_N c_n \frac{z_{co}^{n-1}}{R^n} ds$$

$$h(c_n, z_{co}) = \frac{n}{2\pi} \frac{1}{B\rho} \int \sqrt{\beta_x \beta_y} B_N c_n \frac{z_{co}^{n-1}}{R^n} e^{i(\mu_x - \mu_y)} ds$$

- Whether the feed-down from a given multi-pole affects the normal gradient or the linear coupling depends on things such as the plane of the bump, on whether the multi-pole is normal or skew and on the parity of the multi-pole order n as summarized in this table:

Bump	b_2	a_2	b_3	a_3	b_4	a_4	b_5
H	ΔQ	Δc	ΔQ	Δc	ΔQ	Δc	ΔQ
V	Δc	ΔQ	ΔQ	Δc	Δc	ΔQ	ΔQ

- This table implies that for reasonable measurement of a tune shift due to I.R. magnetic field errors, the following bump types should be used to identify the relevant multipole: **horizontal for Sextupole**(b_2), **vertical for Skew Sextupole** (a_2), **horizontal and vertical for octupole** (b_3) etc. A **diagonal bump for skew octupole** is necessary; the mathematics are beyond the scope of this presentation