

RHIC BBA Measurement, Analysis & Related Issues

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BBA Measurement Status (at Q1, Q3 & tQ4)

During RHIC run12

| | bh1 | bv1 | bh3 | bv3 | bh4 | bv4 | | bh1 | bv1 | bh3 | bv3 | bh4 | bv4 |
|-------|---------|---------|---------|---------|---------|---------|-------|---------|---------|---------|---------|---------|---------|
| bi1- | 6/13/12 | 6/13/12 | 6/13/12 | 6/13/12 | | | yo1- | 5/30/12 | 5/30/12 | 6/13/12 | 5/30/12 | 6/13/12 | 6/13/12 |
| bo2- | 6/13/12 | 6/13/12 | 6/13/12 | 6/13/12 | | | yi2- | 5/30/12 | 5/30/12 | 5/30/12 | 6/13/12 | 6/13/12 | 6/13/12 |
| bo3- | 6/13/12 | 6/13/12 | 6/13/12 | 6/13/12 | | | yi3- | 6/13/12 | 6/13/12 | 5/30/12 | 6/13/12 | | |
| bi4- | 6/13/12 | 6/13/12 | 6/13/12 | 6/13/12 | | | yo4- | 6/13/12 | 6/13/12 | 6/13/12 | 6/13/12 | | |
| bi5- | 5/2/12 | 5/2/12 | 5/30/12 | 5/30/12 | 5/2/12 | 6/13/12 | yo5- | 5/16/12 | 5/16/12 | 5/16/12 | 5/16/12 | 5/16/12 | 5/16/12 |
| bo6- | 5/2/12 | 5/2/12 | 5/2/12 | 5/2/12 | 5/2/12 | 5/2/12 | yi6- | 5/16/12 | 5/16/12 | 5/16/12 | 5/16/12 | 5/16/12 | 5/16/12 |
| bo7- | 5/30/12 | 5/30/12 | 5/30/12 | 6/13/12 | 6/13/12 | 6/13/12 | yi7- | 5/16/12 | 5/16/12 | 5/16/12 | 5/16/12 | 6/13/12 | 5/17/12 |
| bi8- | 5/30/12 | 5/30/12 | 6/13/12 | 5/30/12 | 6/13/12 | 6/13/12 | yo8- | 5/30/12 | 5/30/12 | 6/13/12 | 5/17/12 | 5/17/12 | 6/13/12 |
| bi9- | 5/30/12 | 5/30/12 | 6/13/12 | 6/13/12 | | | yo9- | 5/17/12 | 6/13/12 | 6/13/12 | 5/30/12 | 6/13/12 | 6/13/12 |
| bo10- | 6/13/12 | 6/13/12 | 6/13/12 | 5/30/12 | | | yi10- | 5/17/12 | 5/30/12 | 6/13/12 | 6/13/12 | 6/13/12 | 6/13/12 |
| bo11- | 5/30/12 | 5/30/12 | 5/30/12 | 6/13/12 | 6/13/12 | 6/13/12 | yi11- | 6/13/12 | 6/13/12 | 5/30/12 | 5/30/12 | 6/13/12 | 6/13/12 |
| bi12- | 5/30/12 | 5/30/12 | 5/30/12 | 6/13/12 | 6/13/12 | 6/13/12 | yo12- | 5/30/12 | 5/30/12 | 6/13/12 | 5/30/12 | 6/13/12 | 6/13/12 |

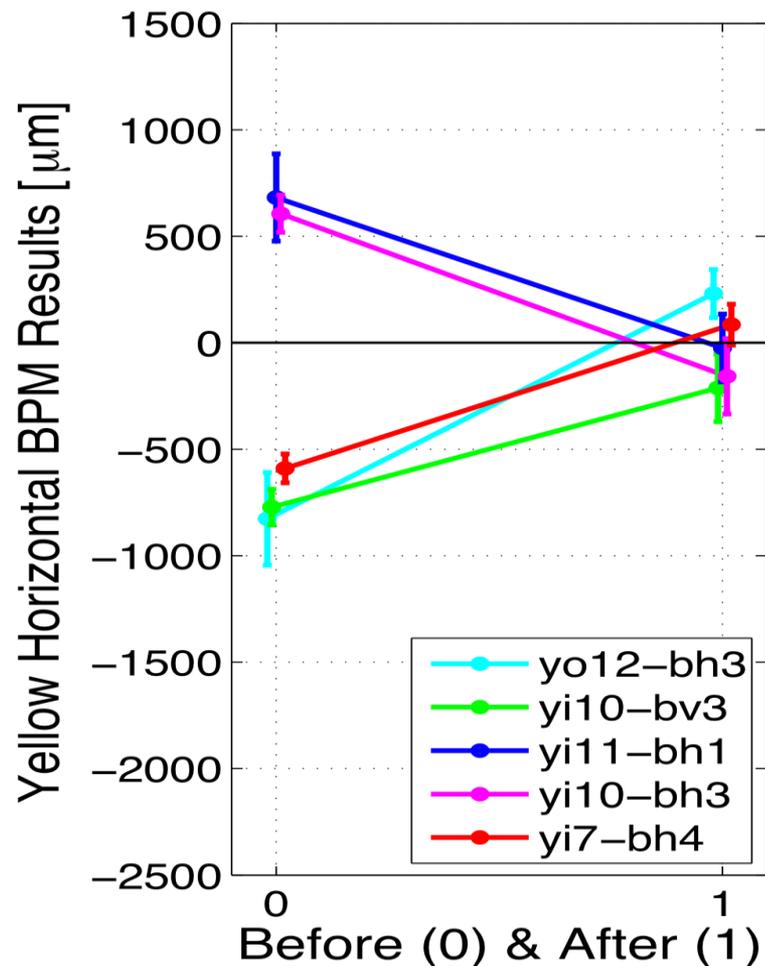
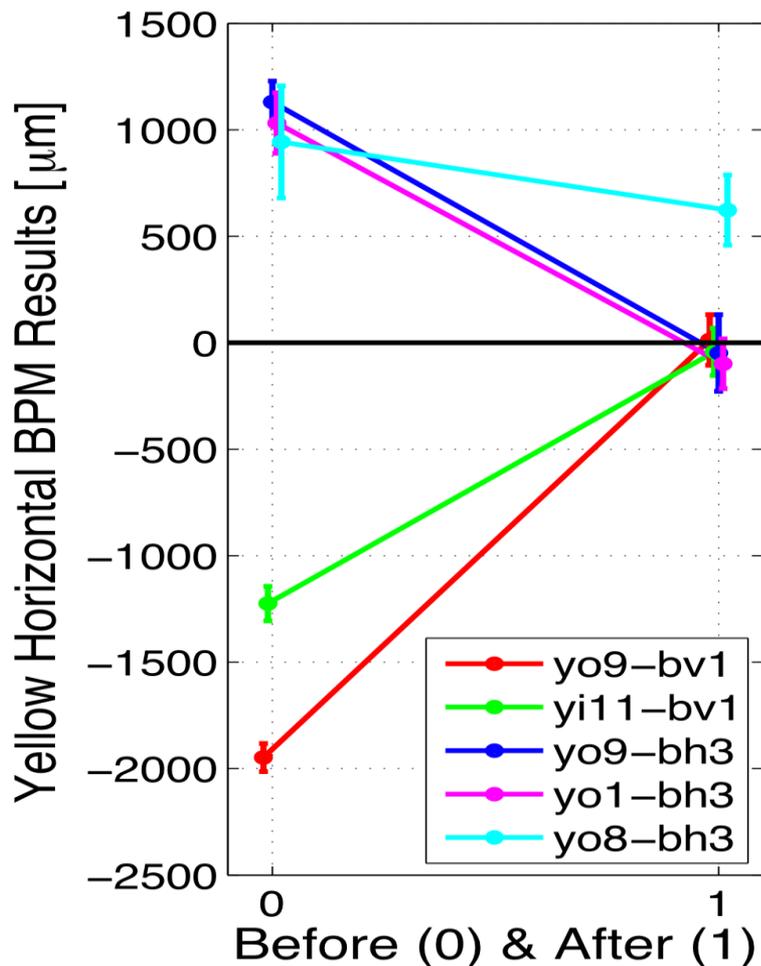
BBA Measurements During APEX 6/13/2012

(34 in Blue, 30 in Yellow, Incomplete list)

| BPM | QUAD | DATE & TIME | Result [mm] | Adjusted Result | Error [μm] | BPM | QUAD | DATE & TIME | Result [mm] | Adjusted Result | Error [μm] |
|----------|----------|--------------------|---------------|-----------------|------------|----------|----------|--------------------|---------------|-----------------|------------|
| bi9-bh3 | bi9-qf3 | 6/13/2012 22:21:46 | <u>0.428</u> | -1.263 | 131 | yo9-bv1 | yo9-qd1 | 6/13/2012 22:05:44 | <u>0.013</u> | -0.703 | 119 |
| bo10-bv1 | bo10-qd1 | 6/13/2012 22:24:28 | <u>0.817</u> | 0.120 | 100 | yil1-bv1 | yil1-qf1 | 6/13/2012 22:08:40 | <u>-0.043</u> | -0.810 | 111 |
| bo11-bv3 | bo11-qd3 | 6/13/2012 22:27:43 | <u>0.054</u> | 0.721 | 62 | yo9-bh3 | yo9-qd3 | 6/13/2012 22:12:10 | <u>-0.048</u> | 1.153 | 180 |
| bo7-bv3 | bo7-qd3 | 6/13/2012 22:30:29 | <u>0.062</u> | 0.920 | 127 | yo1-bh3 | yo1-qd3 | 6/13/2012 22:16:30 | <u>-0.099</u> | 0.626 | 117 |
| bo10-bh3 | bo10-qd3 | 6/13/2012 22:33:26 | <u>0.082</u> | 0.290 | 132 | yo8-bh3 | yo8-qd3 | 6/13/2012 22:19:33 | <u>0.623</u> | 0.486 | 165 |
| bi9-bv3 | bi9-qf3 | 6/13/2012 22:37:23 | <u>0.317</u> | 1.412 | 93 | yi2-bv3 | yi2-qf3 | 6/13/2012 21:53:14 | <u>-0.341</u> | 1.117 | 482 |
| bi8-bh3 | bi8-qf3 | 6/13/2012 23:01:36 | <u>-0.220</u> | -0.760 | 74 | yo12-bh3 | yo12-qd3 | 6/13/2012 22:22:57 | <u>0.231</u> | -0.957 | 113 |
| bo10-bh1 | bo10-qd1 | 6/13/2012 22:52:38 | <u>0.065</u> | 1.209 | 110 | yil0-bv3 | yil0-qf3 | 6/13/2012 22:26:06 | <u>-0.212</u> | 0.103 | 159 |
| bi5-bv4 | bi5-tq4 | 6/13/2012 22:55:24 | <u>-0.044</u> | 0.035 | 71 | yil1-bh1 | yil1-qf1 | 6/13/2012 22:57:11 | <u>-0.024</u> | -0.023 | 159 |
| bil2-bv3 | bil2-qf3 | 6/13/2012 21:21:45 | <u>0.361</u> | 1.195 | 111 | yil0-bh3 | yil0-qf3 | 6/13/2012 13:00:08 | <u>-0.158</u> | 0.976 | 177 |
| bil-bh1 | bil-qf1 | 6/13/2012 21:24:38 | <u>0.335</u> | 0.278 | 190 | yi7-bh4 | yi7-tq4 | 6/13/2012 23:03:45 | <u>0.085</u> | -0.223 | 96 |
| bil-bv1 | bil-qf1 | 6/13/2012 21:27:43 | <u>-0.317</u> | -0.594 | 196 | | | | | | |

Results from the BBA Analysis

10 BPMs re-measured 6/13/2012

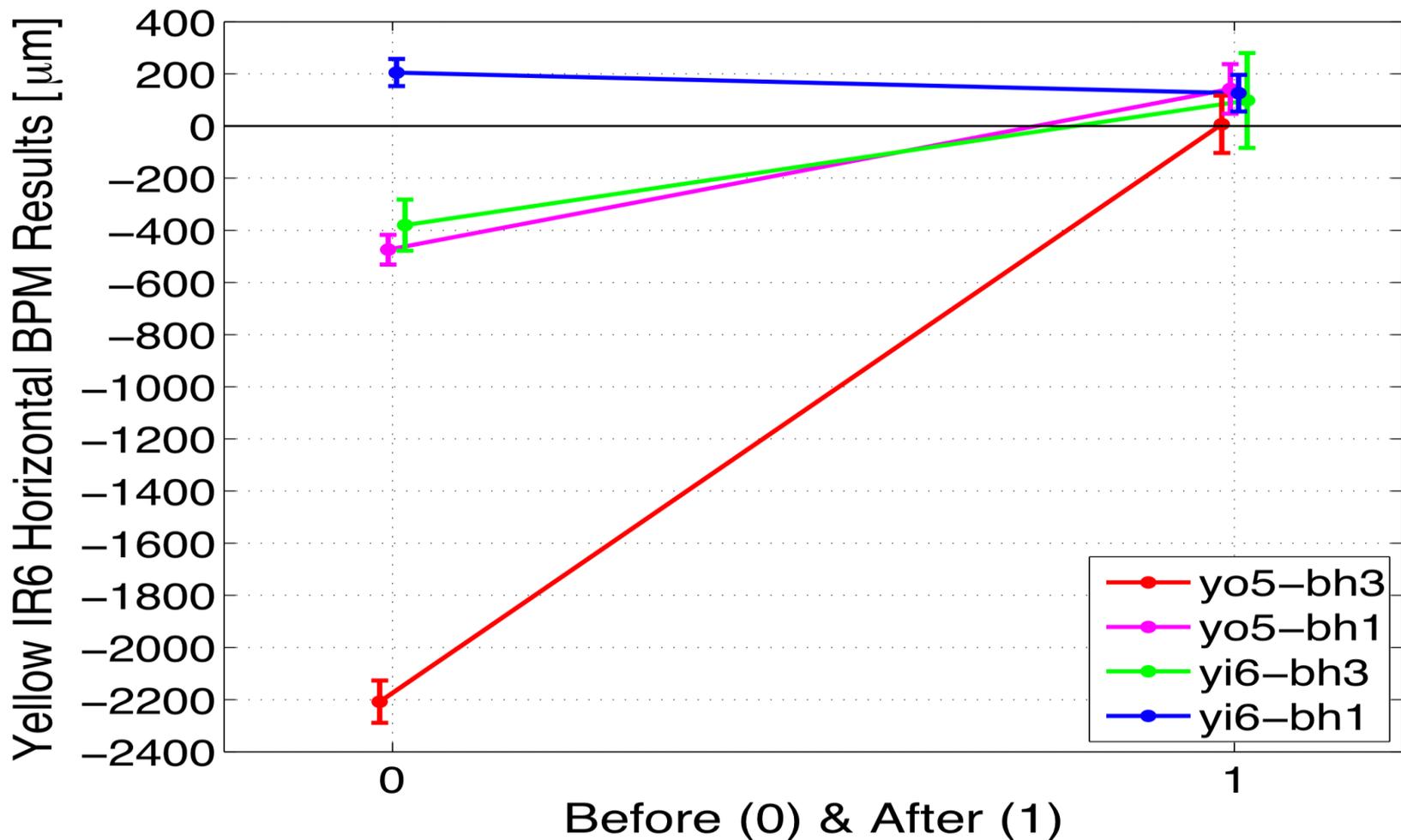


Summary

1. Q1 & Q3 Completed in both ring (48 BPMs in each ring).
2. tQ4 in IR 6, 8, 12 in both ring (24 BPMs in each ring).
3. Confirmed some of large offsets.
Results are generally good.
4. Script ready and tested.

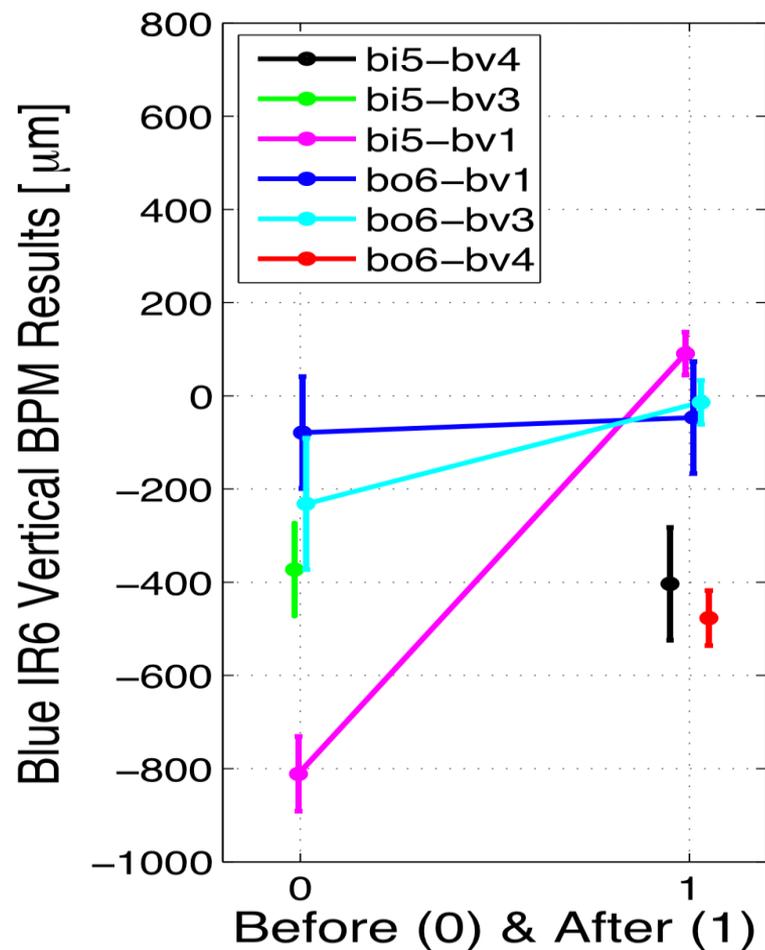
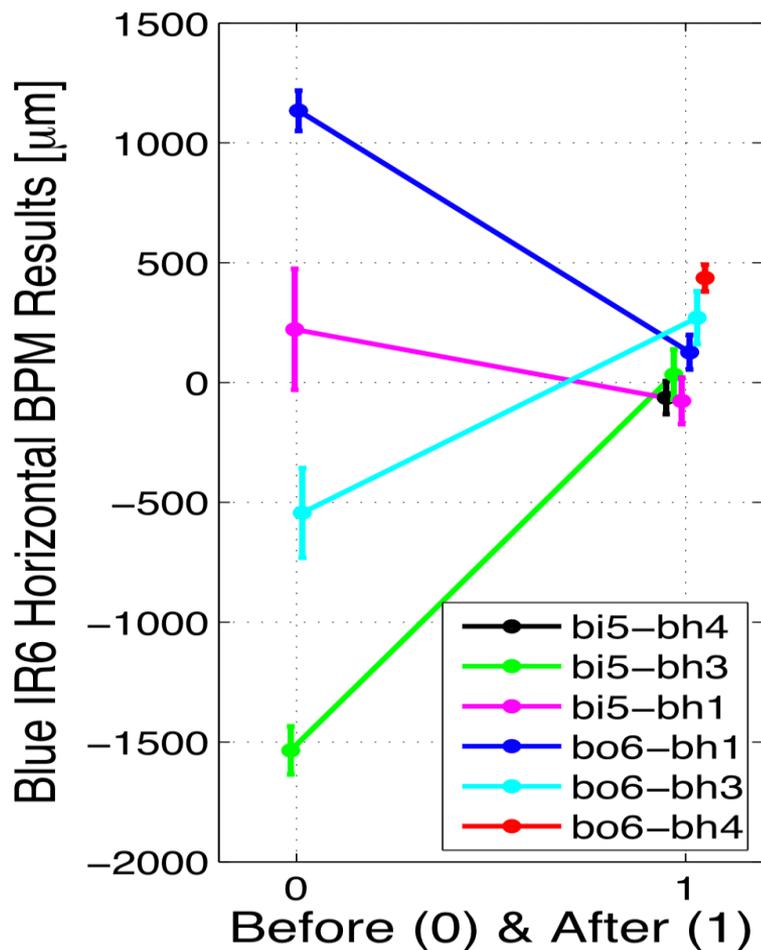
Results from the BBA Analysis

Yellow IR6, measured 5/2/2012, installed 5/7/2012, re-measured 5/16/2012



Results from the BBA Analysis

Blue IR6 BPM results (APEX 5/2/2012, bi5-bv3 not working)



Goal of this BBA Session

1. Verify the BBA results from the previous measurements (last APEX and/or last two years);
2. Obtain BBA measurements on other BPMs;
3. Test a possibly more thorough BBA measurement procedure and compare the results to that of previous BBA measurement. The procedure is to do BBA systematically on all the measurable quad/BPM in IR one-by-one from upstream to downstream: (a) Starting BBA measurement from Q4trim/BPM4 pair upstream of IP; (b) use 3 correctors to put the beam through the center of Q4trim found through step (a); (c) move on to BBA measurement on Q3/BPM3 and Q1/BPM1; (d) move the beam to the center of Q1 before moving on to the Q1/BPM1 on the other side of IP...
4. Test possible strategy for beam alignment (optimum beam path) through IR (Q4-Q3-Q2-Q1-Q1-Q2-Q3-Q4) by iteration through the following steps: (a) BBA measurements in the section (6 BPMs, horizontal and vertical) and find the correction to BPMs; (b) include the BPM corrections into a target orbit; (c) apply orbit feedback to move the beam as close to the targeted orbit as possible. Then repeat (a) to (c) to see if the result converges.

Procedure of this BBA Session

The BBA results in ROUND 0:

- (a) Install the offsets based on the best results from previous BBA sessions.
- (b) Use liveFeedback to send the orbit at all BPMs in IR6 to zero mm (or, as close as Feedback could make it) before starting Round 1.

For each measurement in ROUND 1:

- (a) Took a BBA measurement on the 1st quad upstream of IR;
- (b) installed the offset into the BPM;
- (c) run liveFeedback for ~10 seconds to re-zero beam on those BPMs using the newly installed orbPositionOffsetS value;
- (d) On the next BPM downstream, repeat steps (a) to (c).

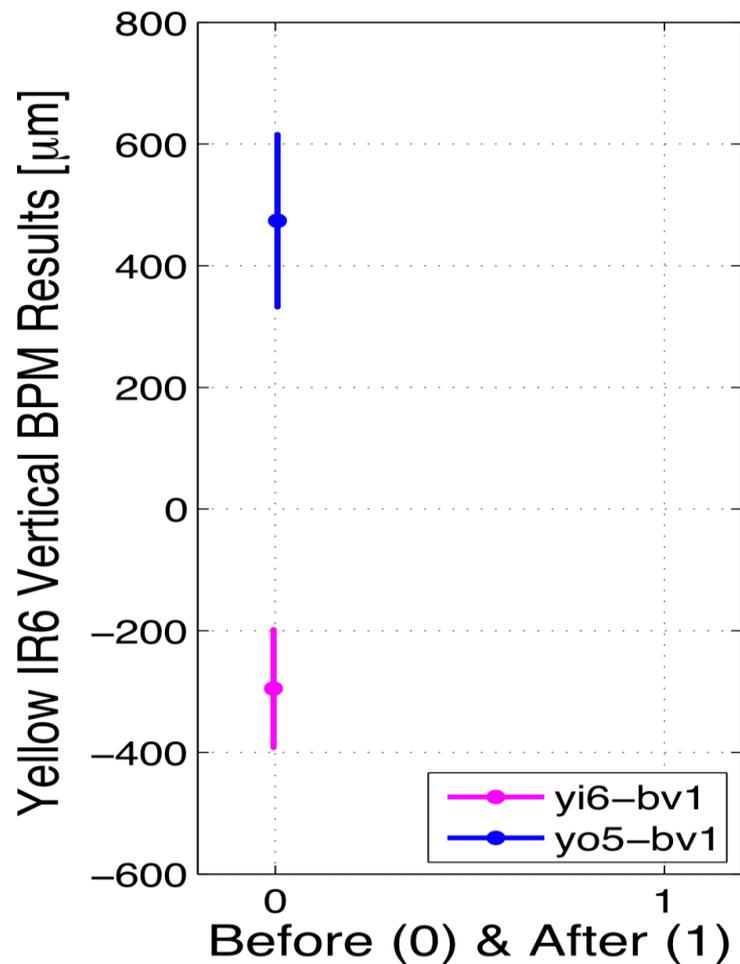
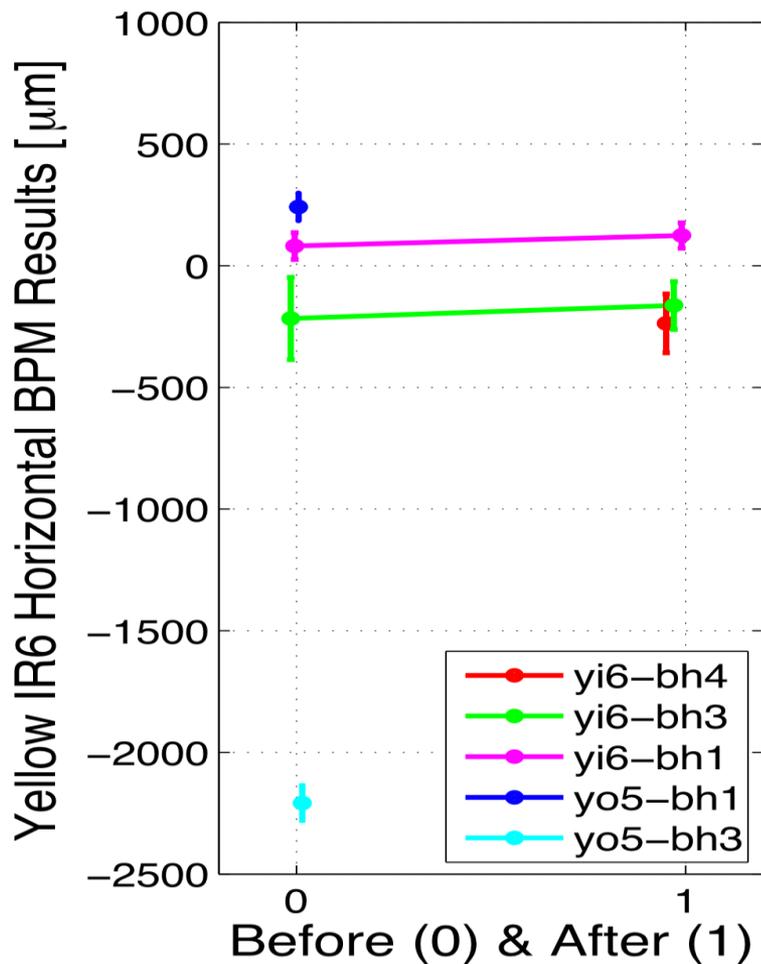
Results from the BBA Analysis

Complete list of the BBA measurements during APEX 5/2/2012

| BPM | QUAD | DATE and TIME | Res. [mm] | Err [μ m] |
|---------|---------|-------------------|----------------|----------------|
| bi5-bh4 | bi5-tq4 | 5/2/2012 10:12:07 | <u>-0.0306</u> | 65 |
| bi5-bh4 | bi5-tq4 | 5/2/2012 10:37:48 | <u>-0.0632</u> | 69 |
| bi5-bh3 | bi5-qb3 | 5/2/2012 10:42:44 | <u>0.0331</u> | 105 |
| yi6-bh4 | yi6-tq4 | 5/2/2012 10:52:29 | <u>-0.2369</u> | 121 |
| yi6-bh3 | yi6-qb3 | 5/2/2012 10:58:24 | <u>-0.1636</u> | 98 |
| yi6-bh1 | yi6-qb1 | 5/2/2012 11:03:53 | <u>0.1242</u> | 52 |
| bi5-bh1 | bi5-qb1 | 5/2/2012 11:04:18 | <u>-0.0765</u> | 97 |
| bo6-bh1 | bo6-qb1 | 5/2/2012 11:14:33 | <u>0.1264</u> | 72 |
| bo6-bh3 | bo6-qb3 | 5/2/2012 11:19:48 | <u>0.2704</u> | 110 |
| bo6-bh4 | bo6-tq4 | 5/2/2012 11:25:09 | <u>0.436</u> | 56 |
| bi5-bv4 | bi5-tq4 | 5/2/2012 11:30:23 | <u>-0.4035</u> | 121 |
| bi5-bv1 | bi5-qb1 | 5/2/2012 11:42:34 | <u>0.0905</u> | 46 |
| bo6-bv1 | bo6-qb1 | 5/2/2012 11:48:26 | <u>-0.0466</u> | 120 |
| bo6-bv3 | bo6-qb3 | 5/2/2012 11:53:23 | <u>-0.0139</u> | 47 |
| bo6-bv4 | bo6-tq4 | 5/2/2012 11:57:59 | <u>-0.477</u> | 59 |

Results from the BBA Analysis

Yellow IR6 BPM results (APEX 5/2/2012, three measurements)



Results from the BBA Analysis

BPM yo5-bh3 (10 sets of measurements in 2 years)

| BBA measurement run-time data file names | center [μm] | error [μm] |
|--|-----------------------------|----------------------------|
| yo5-bh3_log_Wed_Mar__3_08:55:10_2010 | -1996 | 377 |
| yo5-bh3_log_Tue_Mar__9_23:21:13_2010 | -2081 | 408 |
| yo5-bh3_logQ1_Wed_Mar_21_19:03:46_2012 | -2208 | 81 |
| yo5-bh3_logQ1_Sun_Apr_22_09:50:07_2012 | -2150 | 118 |
| yo5-bh3_logQ1_Sun_Apr_22_09:56:57_2012 | -1997 | 119 |
| yo5-bh3_logQ1_Sun_Apr_22_10:00:26_2012 | -2265 | 173 |
| yo5-bh3_logQ1_Sun_Apr_22_10:04:24_2012 | -1863 | 197 |
| yo5-bh3_logQ1_Sun_Apr_22_11:56:37_2012 | -2152 | 91 |
| yo5-bh3_logQ1_Sun_Apr_22_12:01:54_2012 | -2211 | 207 |
| yo5-bh3_logQ1_Sun_Apr_22_12:06:47_2012 | -2316 | 149 |
| Average | -2124 | 192 |
| Standard deviation | 140 | 114 |

Conclusion

1. BBA on RHIC produce reliable results now.
2. There are some room for improvement
 - (a) Systematic measurement
 - (b) Iteration through measure-align-measure-align
3. Accuracy limitation: ~ 0.1 mm
 - (a) Quads physical misalignment relative to each other
 - (b) Limited correctors
 - (c) repeatability under same machine settings

Results from the BBA Analysis

from 1Hz BPM reading of all BPMs in all arcs

| | 3/21/12 | | 3/3/10 | | 3/9/10 | | 3/27/11 | |
|---------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| BPM | Offset | Error | Offset | Error | Offset | Error | Offset | Error |
| | (μm) |
| yo5-bh1 | 242 | 57 | 220 | 180 | 135 | 229 | -125 | 240 |
| | | | 318 | 225 | | | -206 | 230 |
| yo5-bh3 | -2208 | 81 | -1996 | 377 | -1866 | 264 | | |
| yi6-bh1 | 81 | 55 | 200 | 484 | 350 | 304 | | |
| yi7-bh1 | -240 | 93 | -269 | 74 | -264 | 385 | | |
| yo8-bh1 | 268 | 123 | -137 | 74 | -268 | 875 | | |
| yo8-bh3 | 652 | 68 | 457 | 116 | 416 | 251 | | |

Principle of BBA measurement

If the closed orbit of beam relative to the magnet center of the i^{th} quadrupole located at s_i is $x(s_i)$, deflection angle is:

$$\theta_i = k_i L_i x(s_i)$$

Changing the quad strength k_i by Δk_i or change $x(s_i)$ by $\Delta x(s_i)$ gives additional deflection angle $\Delta\theta_i$.

The transverse orbit displacement at position s due to deflection θ_i is:

$$\Delta x(s) = \frac{\sqrt{\beta(s)}}{2 \sin(\pi\nu)} \sum_{i=1}^N \theta_i \sqrt{\beta(s_i)} \cos(|\phi(s) - \phi(s_i)| - \pi\nu)$$

The objective of BBA is to measure the beam offset $x(s_i)$ by steering the beam and minimizing the measured orbit shift associated with changing the quad strength. Then $x(s_i)$ is used to zero the reading of the BPM near by the quadrupole.

Using $\Delta k_i = 2 \times 10^{-3} \text{ m}^{-2}$ to avoid large optics, tune, and beam lifetime changes. This is 1.7–2.5% of a typical IR quadrupole strength at RHIC injection.

Why is BBA Measurement Difficult in RHIC

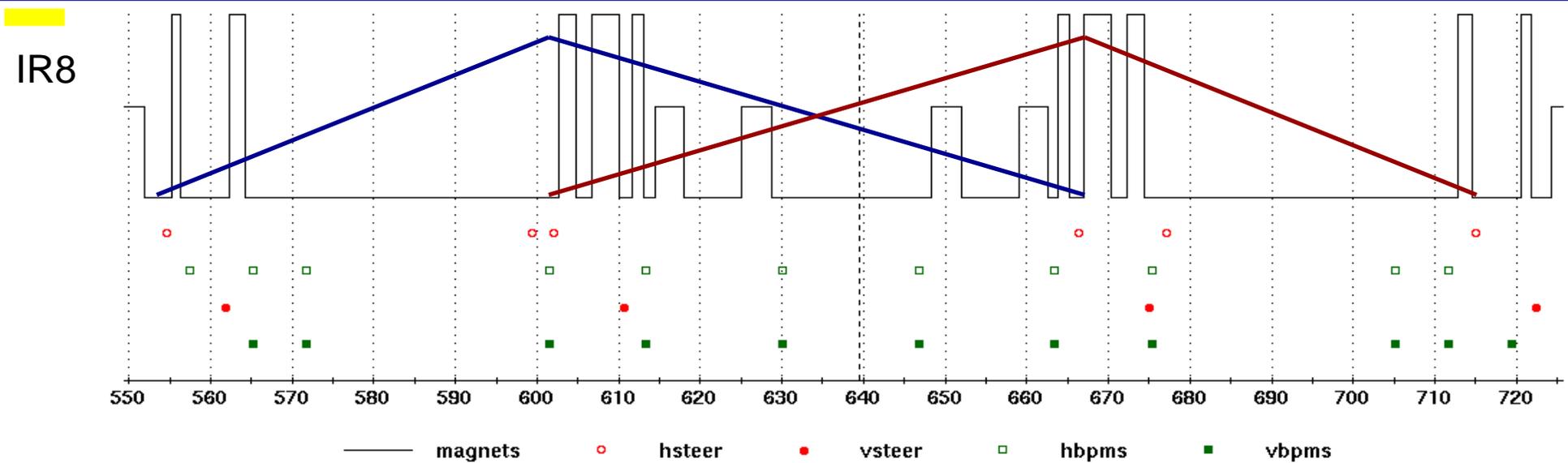
Why is BBA Measurement Difficult in RHIC:

1. Limited dipole correctors. In each 3-corrector bump there are 6-7 quads, 2 DXs, 2 D0s
2. Can't decouple the effects of Q1, Q2, Q3 and they are equally strong
3. Unknown magnet alignment errors
4. Unknown beam positions and angles at the first corrector (beam angle at triplet)
5. Very large ring. When all the BPMs in all arcs are used, some BPMs contribute to noise more than to signal.
6. Signal/Noise ratio is low.

Possible Solutions:

1. Try to treat the triplet as one unit. Minimize total deflection angle in the section
2. Minimize the frequency of quadrupole change. (Procedure with 1-Q-Move)
3. Chose subgroup (or single) of BPMs
4. Step-by-step (faster easier procedure, using of 1kHz BPM signals)

Three-corrector-bumps in BBA Measurements



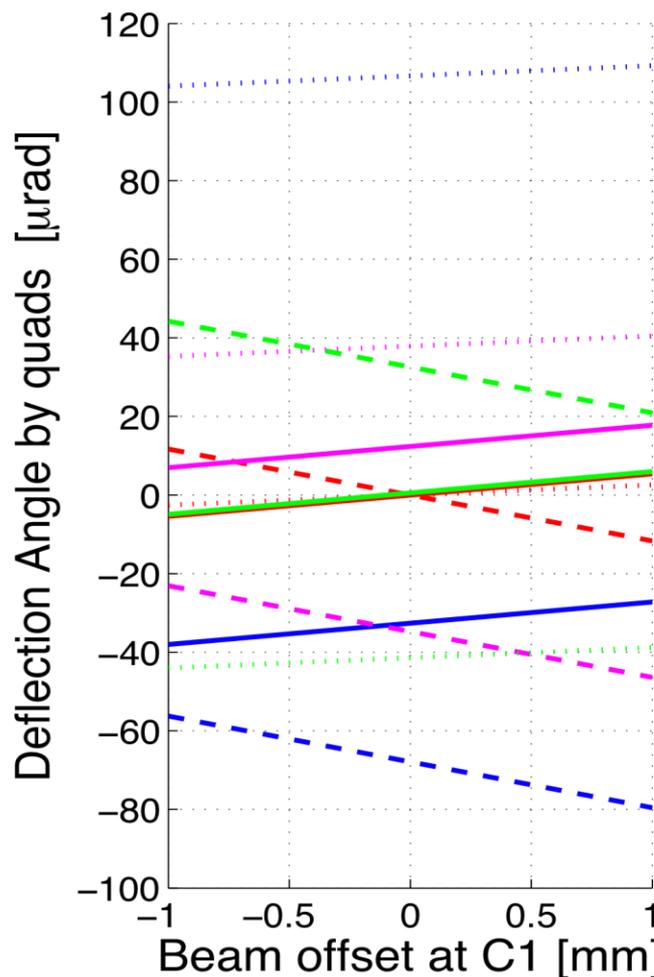
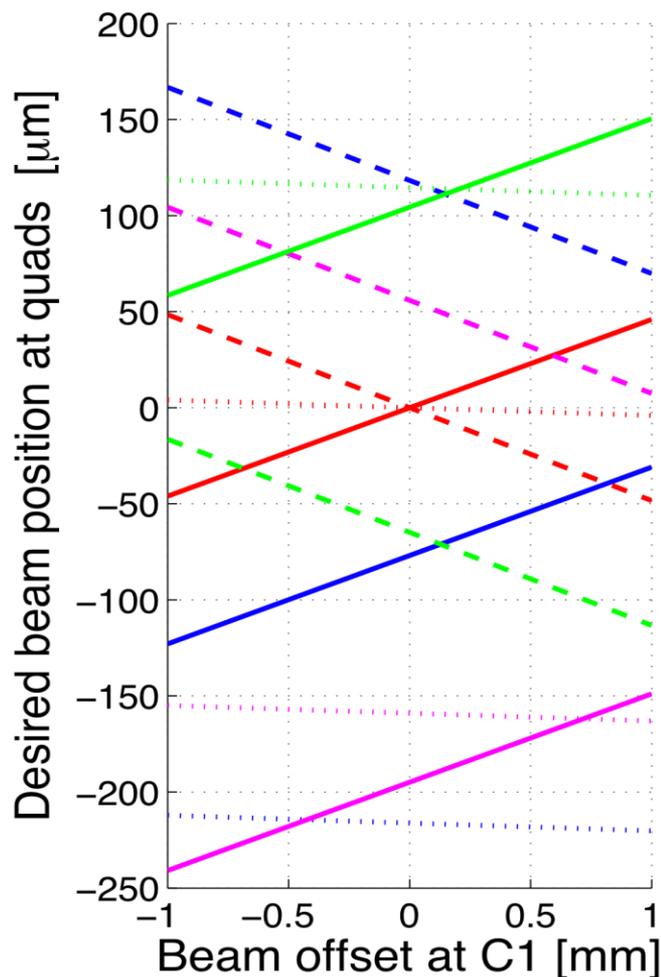
Quad Settings During BBA Measurements

pp12b-v2 at injection

| Magnet Names | Length [m] | k [m ⁻²] | kL [m ⁻¹] |
|-----------------|---------------|-------------------------|--------------------------|
| Q1 | 1.44 | 0.0818 | 0.1178 |
| Q2 | 3.4 | -0.1887 | -0.6416 |
| Q3 | 2.1 | 0.1148 | 0.2411 |
| tQ4 | 0.75 | 0.0378 | 0.0284 |
| Q4 | 1.83 | -0.1637 | -0.2996 |
| tQ5 | 0.75 | 0.0135 | 0.0101 |
| tQ6 | 0.75 | -0.0134 | -0.01 |
| Q7 | 0.95 | 0.0834 | 0.0792 |
| Q8 | 1.13 | -0.091 | -0.1028 |
| Q9 | 1.13 | 0.0891 | 0.1007 |

Effects of unknown position & angle at C1

bi8 triplet with a range of assumed misalignments in Q1, Q2 & Q3



XQ1 = 0.0

XQ2 = 0.0

XQ3 = 0.0

XQ1 = 200 μm

XQ2 = -50 μm

XQ3 = 400 μm

XQ1 = -300 μm

XQ2 = -100 μm

XQ3 = 200 μm

XQ1 = 100 μm

XQ2 = 50 μm

XQ3 = -200 μm

$|\theta_{C1}| < 20 \mu\text{rad}$

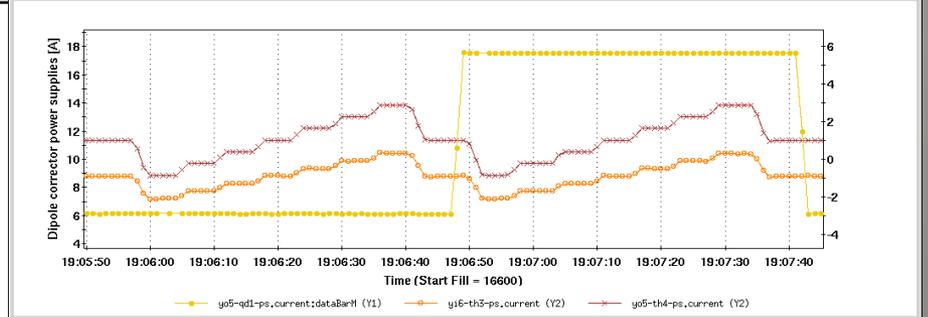
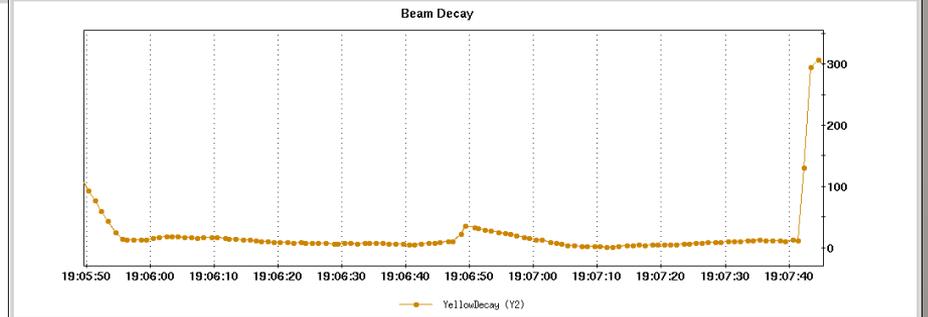
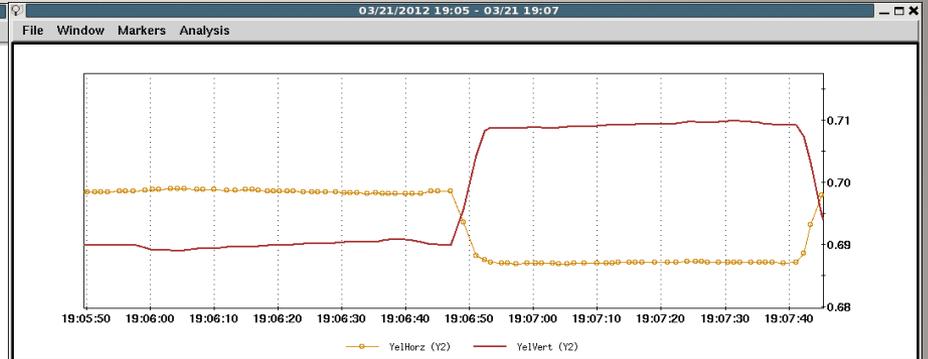
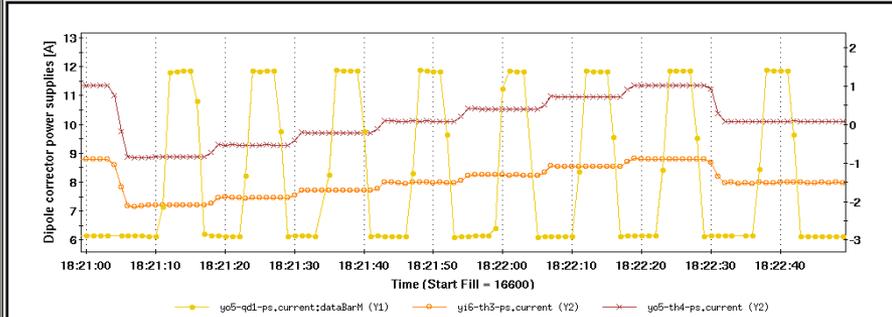
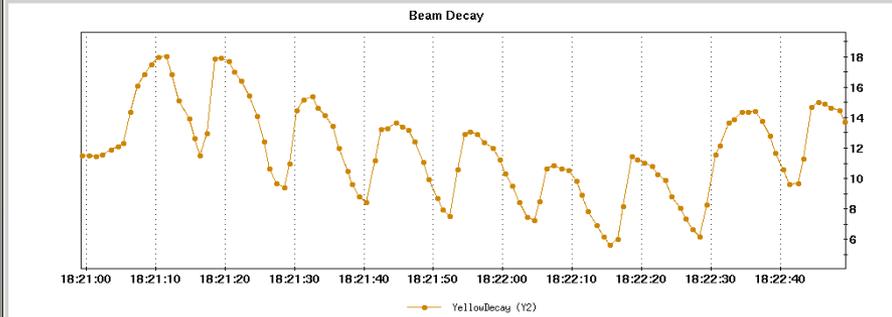
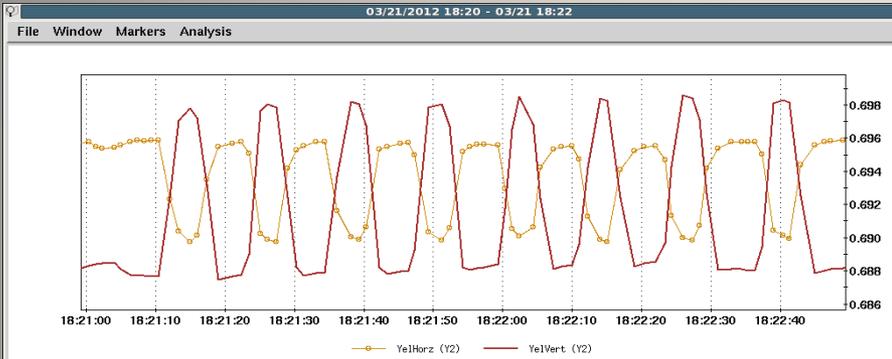
$|\theta_{Q1}| < 40 \mu\text{rad}$

$|\theta_{Q2}| < 110 \mu\text{rad}$

$|\theta_{Q3}| < 80 \mu\text{rad}$

BBA Measurements (03/21/2012)

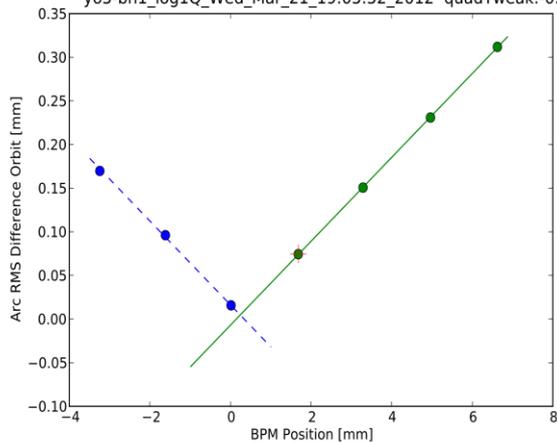
traditional procedure vs. 1-Q-move procedure



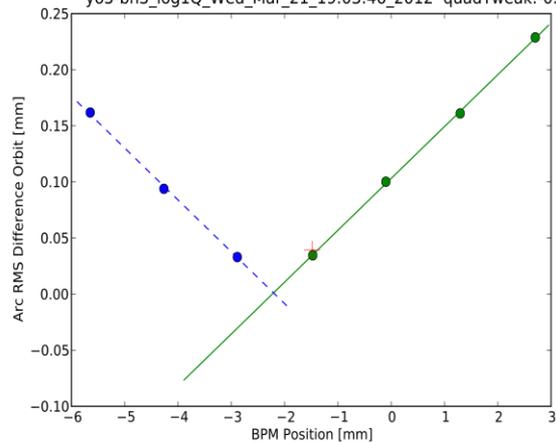
BBA Analysis of Beam Experiment (03/21/2012)

from 1Hz (all arc) BPM reading

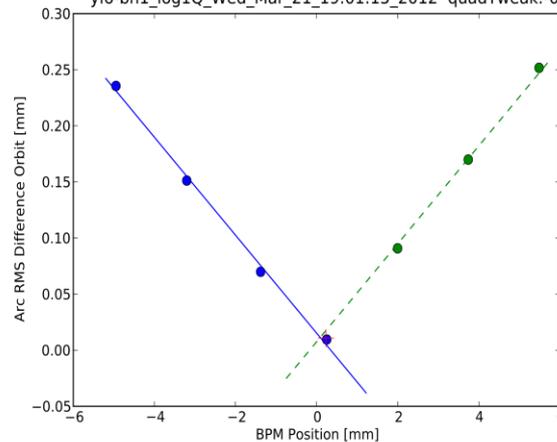
BPM:yo5-bh1 Quad:yo5-qd1 intersect:0.2417mm +/- 0.0414mm
left fit: m=-0.0481, b=0.0162 right fit: m=0.0481, b=-0.0070
yo5-bh1_log1Q_Wed_Mar_21_19:05:52_2012 quadTweak:-0.002



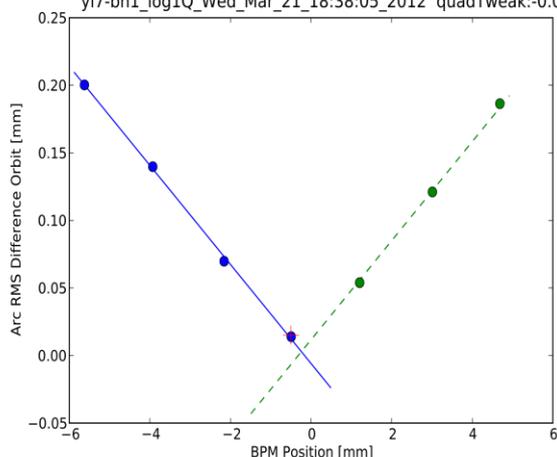
BPM:yo5-bh3 Quad:yo5-qd3 intersect:2.2079mm +/- 0.1140mm
left fit: m=-0.0462, b=-0.1010 right fit: m=0.0462, b=0.103
yo5-bh3_log1Q_Wed_Mar_21_19:03:46_2012 quadTweak:-0.002



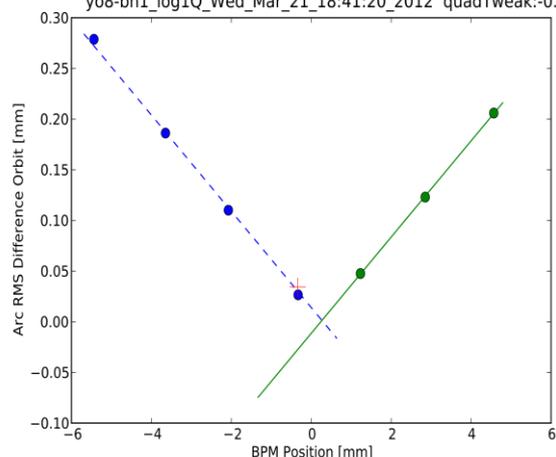
BPM:yi6-bh1 Quad:yi6-qf1 intersect:0.0889mm +/- 0.1391mm
left fit: m=-0.0436, b=0.0153 right fit: m=0.0436, b=-0.0075
yi6-bh1_log1Q_Wed_Mar_21_19:01:15_2012 quadTweak:-0.002



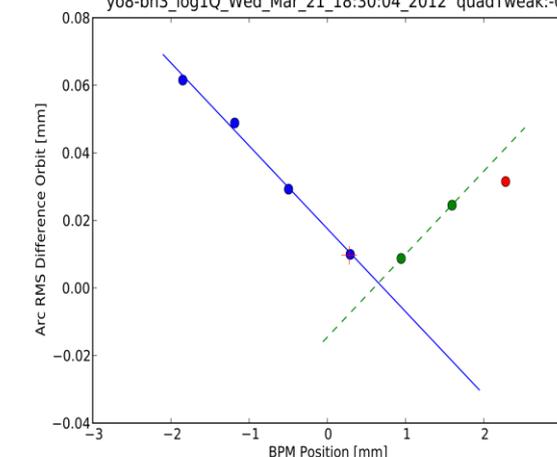
BPM:yi7-bh1 Quad:yi7-qf1 intersect:-0.2397mm +/- 0.0883mm
left fit: m=-0.0367, b=-0.0059 right fit: m=0.0367, b=0.0117
yi7-bh1_log1Q_Wed_Mar_21_18:38:05_2012 quadTweak:-0.0015



BPM:yo8-bh1 Quad:yo8-qd1 intersect:0.2675mm +/- 0.1823mm
left fit: m=-0.0475, b=0.0140 right fit: m=0.0475, b=-0.0114
yo8-bh1_log1Q_Wed_Mar_21_18:41:20_2012 quadTweak:-0.002



BPM:yo8-bh3 Quad:yo8-qd3 intersect:0.6524mm +/- 0.0561mm
left fit: m=-0.0246, b=0.0175 right fit: m=0.0246, b=-0.0145
yo8-bh3_log1Q_Wed_Mar_21_18:30:04_2012 quadTweak:-0.001



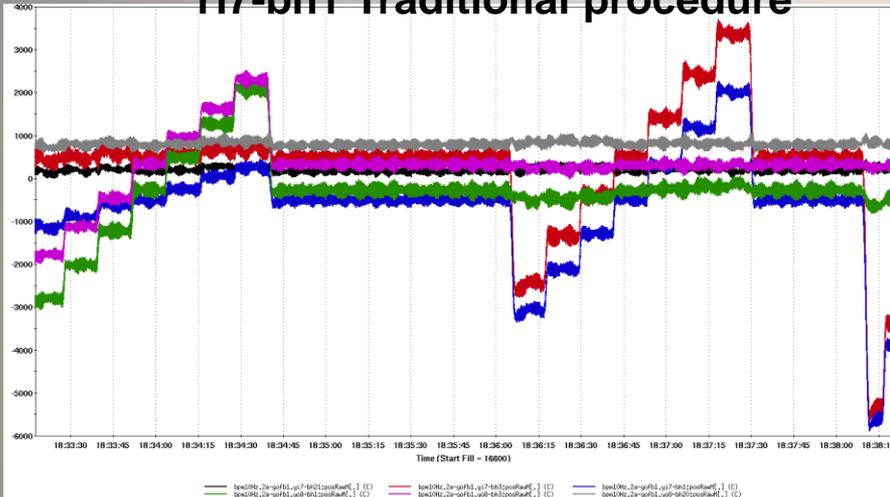
What we have learned from BBA measurement

- 1. Possible to develop nonconventional procedure to improve the accuracy/speed**
When the machine is reasonably stable BBA measurement can be performed by taking baselines (without changing the quad) for all beam-offset locations, then change quad once and take the measurement at the same set of offset locations. (It allows us to manipulate the offset in a nonconventional fashion in order to improve the accuracy/speed.)
- 2. A step towards streamline measurement: knowledge on measurement parameters**
A careful choice of beam-offset range and the amount of quad strength change in a given lattice can improve measurement accuracy without much sacrifice of beam lost. It was found the best beam-offset range is $[-4.0 \ 4.0]$ mm with quad strength change of -0.002 on Q1 or Q2 at injection.
- 3. A step towards automatic analysis: data requirement for reliable analysis**
Needs minimum 9 measurement points (4 on positive side and 4 on the negative side) to have confidence of good measurement since a line obtained from fitting 2 or 3 measurement points appears to be unreliable.
- 4. Knowledge on measurement accuracy vs. 1Hz BPM reading settle time**
The 3 seconds waiting time for the 1Hz BPM reading appears to be adequate. But the first/last measurement point (after a big step from/to the original setting) is bad in some of the measurements. The solution could be a 4-5 seconds waiting for the first and the last step.

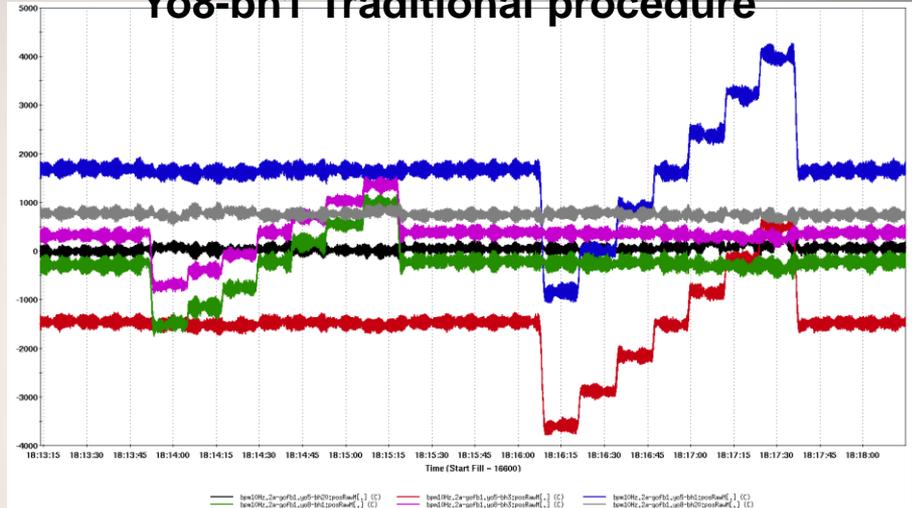
Beam Experiment (03/21/2012)

1kHz signals on BPM 1kHz signals on BPM in yi7 & yo8 during yi7-bh1 & yo8-bh1 measurement

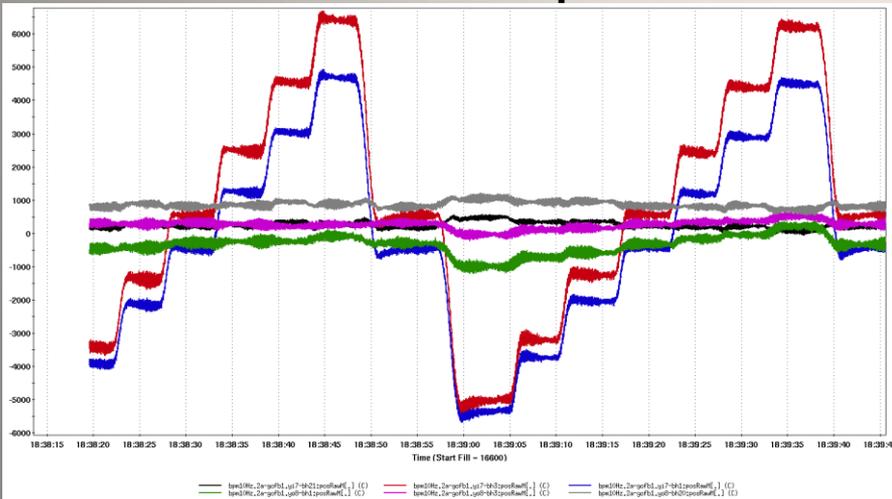
Yi7-bh1 Traditional procedure



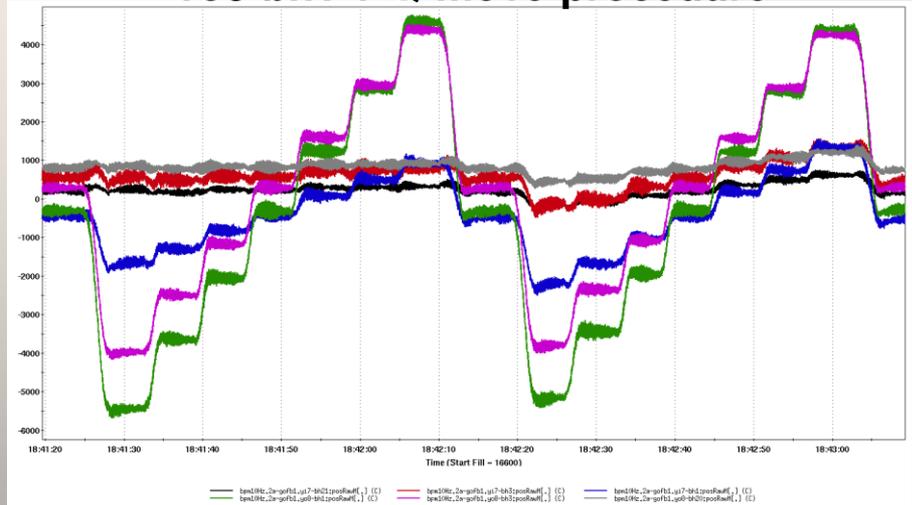
Yo8-bh1 Traditional procedure



Yi7-bh1 1-Q-move procedure



Yo8-bh1 1-Q-move procedure



BBA Measurements (03/21/2012)

during two measurements on BPM yo5-bh1

