BPM Data Acquisition and Orbit Feedback at BNL

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Curious History of Orbit Corrections in RHIC

Orbit feedback was developed during the 11th year of RHIC running. It did not require modification of existing hardware. It has been used during every ramp and periodically during every store since. Before that, orbit corrections were only performed during dedicated time, scheduled after orbit deteriorated enough to start causing beam aborts.

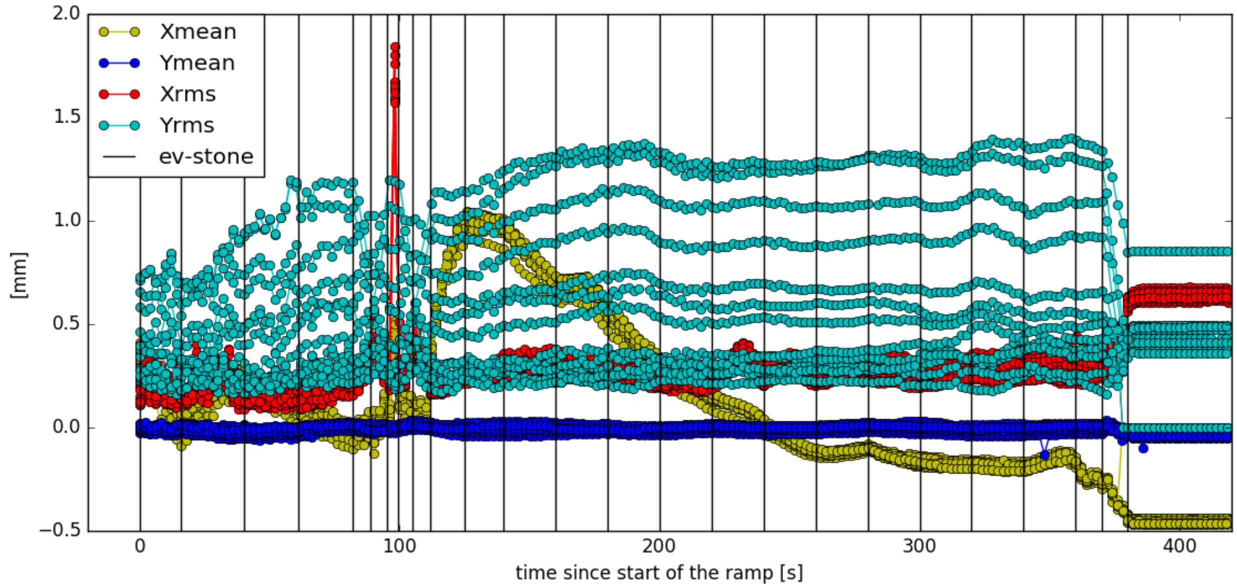

Figure 1: A weekend of orbits during 100 GeV Au-Au ramps in RHIC in 2010.

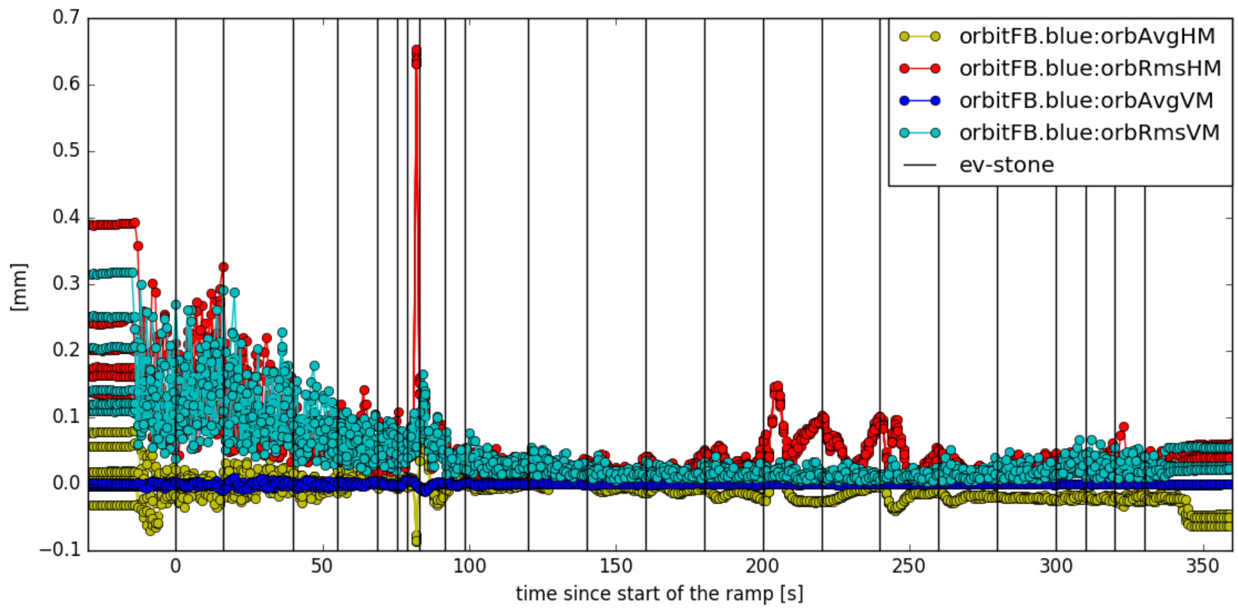

Figure 2: A weekend of orbits during 100 GeV Au-Au ramps in RHIC in 2014.

Figure 1 shows mean and RMS of horizontal and vertical orbits in arcs during 100 GeV Au-Au ramps performed over one weekend in 2010. It shows that vertical orbits were changing greatly from ramp to ramp and that both mean of horizontal orbit and RMS of horizontal and vertical orbits were far from goal (which was zero).

In 2010, I described the situation with orbit control thusly:
"In the strictest sense, RHIC is not reproducible during the same day, the ramp which is good in the morning, can be lost in the evening due to orbit change. To avoid that, we have the rule when to preform orbit correction and when not to." Those corrections would frequently not work, i.e. they would make orbit worse and / or cause beam abort. Generally speaking control of RHIC at that time was very manual.

Figure 2 shows mean and RMS of the differences between goal and measured beam positions during 100 GeV Au-Au ramps performed over one weekend in 2014 during which orbit feedback was active. It shows that feedback made orbits much better and stable. At injection RMS values were ~0.2 mm and then they became smaller as ramps progressed. That effect was due to insufficient number of bits in digital-to-analog converters of power supply controllers. RMS of orbit differences at store after corrections would reach ~40 μm, but would immediately start drifting upwards.

About BPMs and Correctors in RHIC

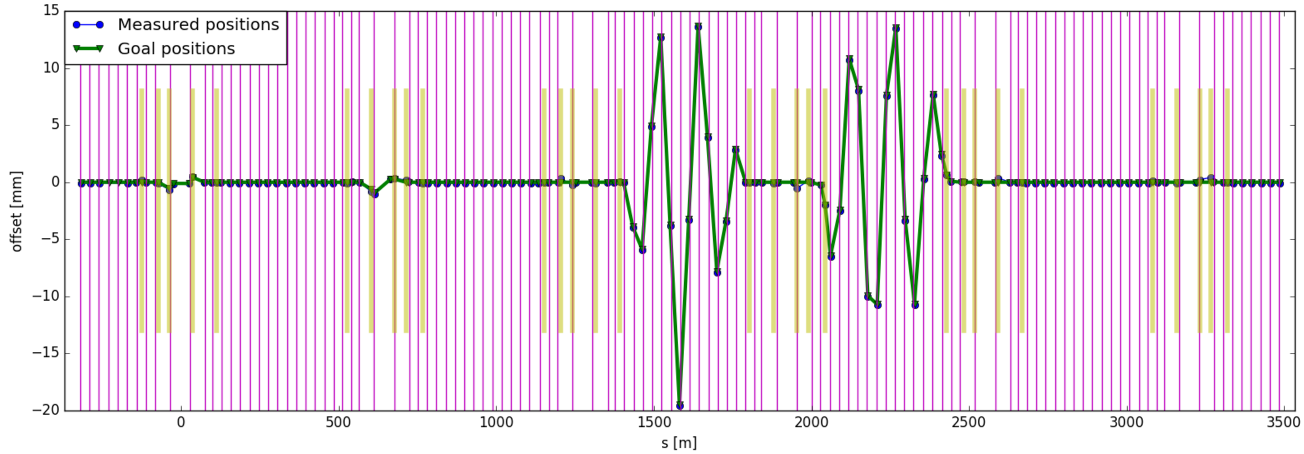

Figure 3: Measured vs. goal horizontal orbit after end of store Au-Au ramp.

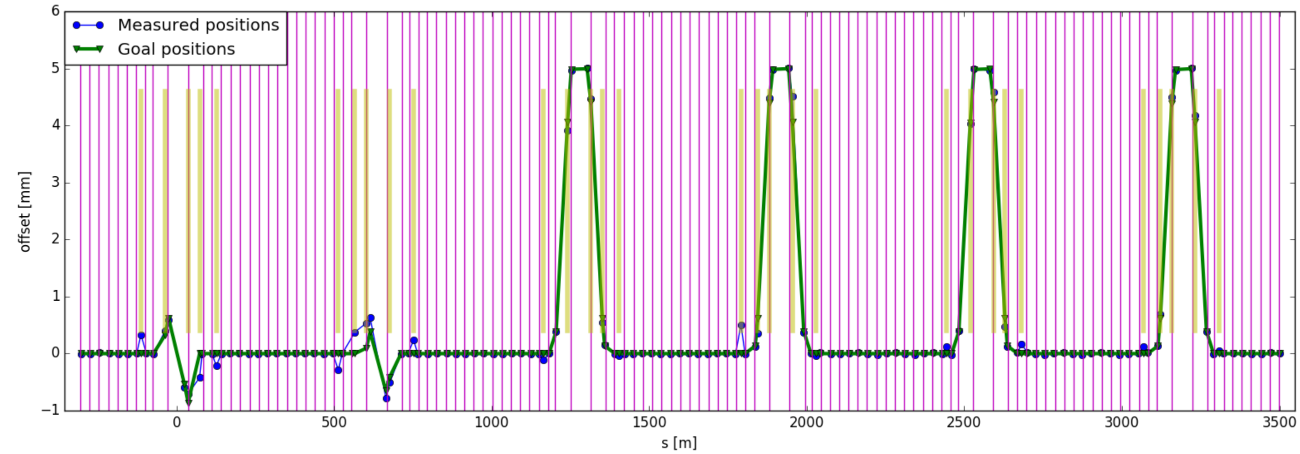

Figure 4: Measured vs. goal vertical orbit after end of store Au-Au ramp.

By design there are 167 BPMs per plane in RHIC, but at most 117 are used to correct orbit; 20 of the unused BPMs are snake, rotator, dump and DX BPMs (beams from both rings pass through DX BPMs), and 30 are redundant, i.e. beam positions at their locations are not independent of beam positions at locations of neighboring BPMs. DX and redundant BPMs can be included in orbit correction if that is desired. Of 167 BPMs per plane, 87 are single plane and are included in correction, the rest are dual plane or both dual plane and dual beam (DX BPMs). All the BPMs in arcs are single plane. Figure 3 shows achieved and goal horizontal orbits and figure 4 shows achieved and goal vertical orbits after end of store Au-Au ramp. Thin vertical lines indicate the locations of dipole correctors and thick vertical lines indicate the locations of redundant BPMs.

BPMs in RHIC can measure the position of a selected bunch (normally the first bunch in a ring) at every turn, which for RHIC means ~78000 times per second, but can only deliver average beam positions at most once per second and 1K, 2K or 4K beam positions on demand, but only 1K and 2K can be delivered as frequently as once per second.

Devices for processing signals from BPMs are connected to 20 FECs with Firewire which in turn are connected to 100 Mb or 1 Gb Ethernet network.

117 dipole correctors per plane are used to correct the orbit. Distances between neighboring correctors and BPMs range between ~0.5 m and ~3.5 m, but they are most commonly 2.763 m (that is the distance between BPMs and correctors in arcs). These 117 x 4 correctors are controlled by 18 x 2 PS FECs.

Feedback Procedure

The programs for performing orbit corrections in RHIC are called Orbit Correction (OC) managers, and there is one for each ring. They receive beam positions and send corrections using the same network as other devices in RHIC.

OC managers are provided with the expected values of optics functions at the location of every BPM and corrector for every second of the ramp. They are also given goal positions at different times in ramp. The goal position at the location of every BPM is zero, unless it is specified as non zero. Using that information, OC managers generate the goal orbits for every second in the ramping cycle. That makes it possible for operators to request “fixing” of orbit at any time. Orbit feedback in RHIC can be started moments after a bunch has been injected. In RHIC, tune / coupling feedback works in a similar way.

OC managers also accept live changes of goal positions at injection and store. That makes it possible to use OC managers to make bumps which are used only during injection of the beam, or for various scans. Standard 3-bumps or combinations of 3 bumps can be also created on demand by another manager (called bump manager). These capabilities make it easy to create simple python scripts for performing various measurements.

Orbit feedback procedure is as follows:

1. On the second, BPMs start delivering average position data to OC managers. It takes ~0.04 s on average (and at most 0.2 s because of the limit on orbit acquisition duration) for OC managers to receive the data.
2. To calculate dipole correctors strengths needed to transform measured vertical orbit into goal orbit, OC managers use the singular-value decomposition (SVD).
3. In order to prevent changing of the beam radius, the procedure to correct horizontal orbit is more involved. First, to ensure that correction does not correct dispersive orbit, OC manager adds a scaled dispersion to goal orbit to make its radius the same as the radius of measured orbit. Then it calculates dipole correctors strengths using that modified goal orbit. Second, to keep the sum of correctors strengths at zero, it adds the scaled strengths which are the solutions for dispersive orbit to previously calculated strengths.
4. SVD procedures mentioned above can be setup to exclude some physical solutions by applying cut on singular values, but to ensure that orbit is closest to the goal, OC managers are always setup to include all physical solutions.
5. If power supplies (PS) are at injection or ramping, 40% of the calculated correctors strengths are sent to correctors, while at store only 10% are. It takes 0.5 seconds after BPM data have been requested for all correctors strengths to reach PS controllers which upon receiving them, start linearly adding them to existing strengths, finishing one second after receiving them. At injection and store feedbacks stop when RMS goals are reached. At injection those goals are 0.18 mm and at store are 0.07 mm in horizontal and 0.05 mm in vertical plane.
6. To keep beam radius at zero, simple PI loop sends frequency correction requests to RF every second. In RHIC, beams of two rings are phase locked. Therefore, to achieve zero beam radius in both rings, the strengths of arc dipoles in the ring not considered primary by RF have to be adjusted. But that procedure does not ensure zero radius of non-primary beam at transition. Another feedback, called dipole transition feedback, which modifies strength of arc dipoles tries to achieve that. Radius feedback (called Xmean feedback) runs only during ramps.
7. After first successful ramp, the correction strengths used during ramp are fed-forward to trim ramp settings in order to reduce the strengths applied by feedback during subsequent ramps. Correction strengths are also supposed to be fed-forward when they become too large. Figure 5 shows typical correction strengths

and Figure 6 shows correction strengths during ramp with the failed magnet protection diode.

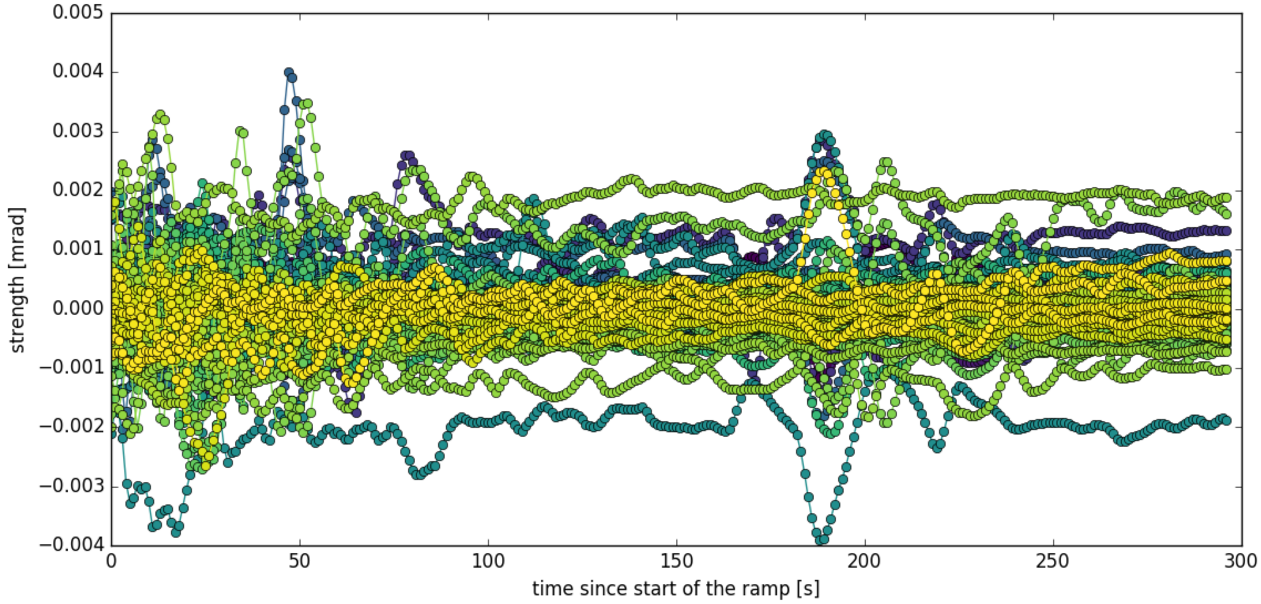

Figure 5: Yellow horizontal orbit corrections before breaking magnet protection diode.

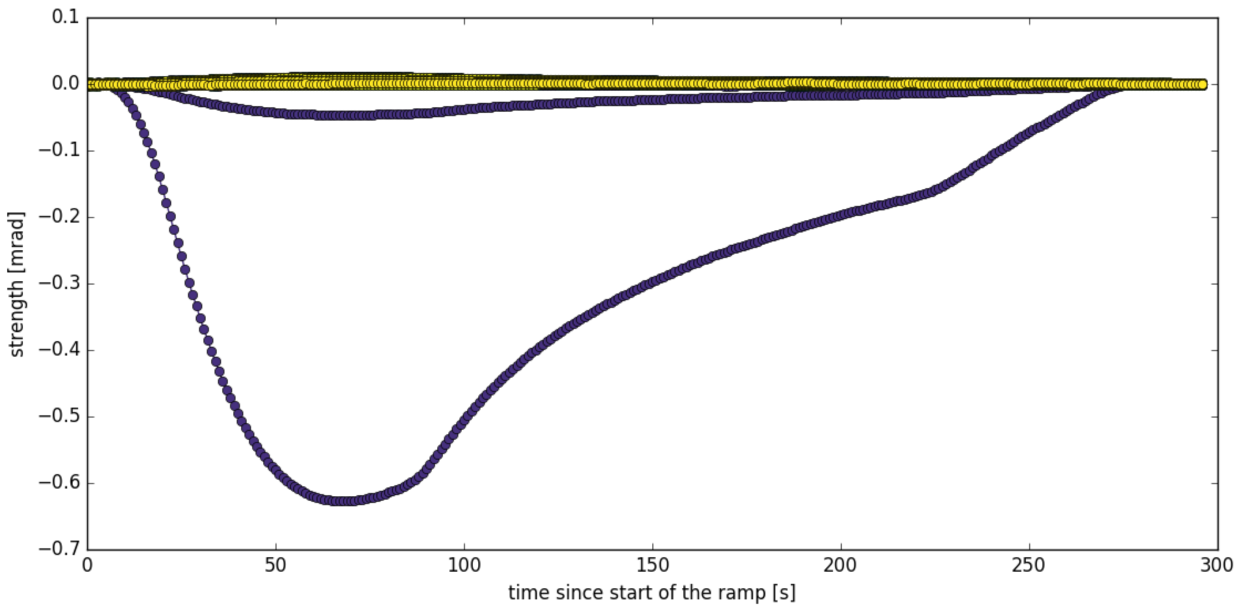

Figure 6: Yellow horizontal orbit corrections after breaking magnet protection diode.

Orbit feedback generates very reproducible orbits. That can be seen from Figure 7 which shows coincidence rates at beginning of stores being affected by the procedure which offsets beam in one and then the other direction, first in vertical and then horizontal plane, in order to ascertain that current beam positions maximize coincidence rates. Sometimes positions which maximize coincidence rates are not changed for months.

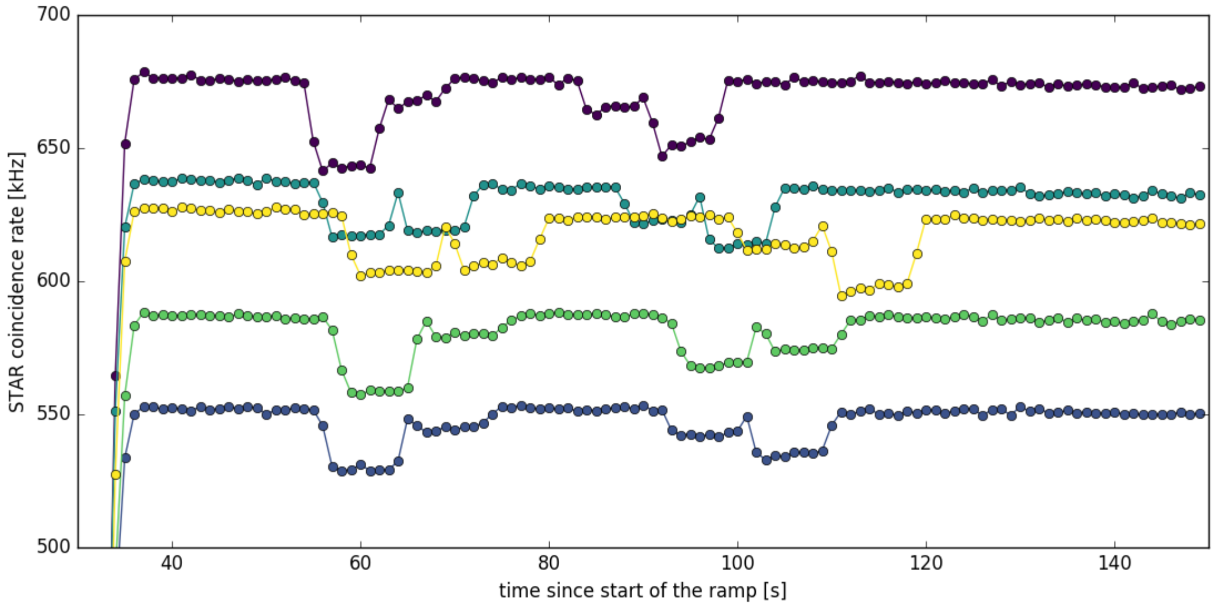

Figure 7: Coincidence rates at start of the stores during one weekend.

On absolute precision of beam measurements

Only at some locations in RHIC there exist quad – BPM – dipole corrector configuration required for Beam Based Alignment (BBA) method which provides independent measurement / confirmation of beam positions relative to neighboring quadrupoles, for example in RHIC we can check the alignments of b1 and b3 BPMs (BPMs closest to interaction regions) using BBA. Results of these measurements are used to adjust offsets applied to BPM measurements. Figure 8 shows one such measurement.

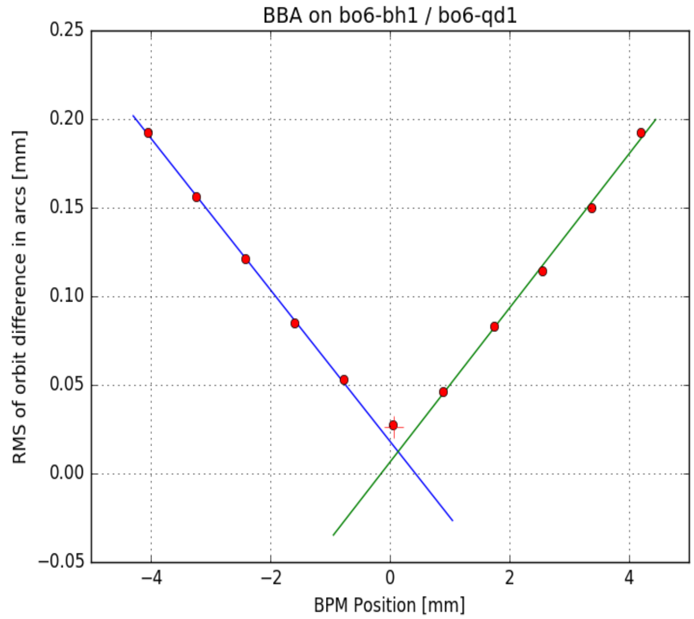

Figure 8: Results of doing BBA on bo6-bh1 BPM

According to RHIC design manual “Beam Position Monitor - Reference Orbit” tolerances were supposed to be Δx = Δy = 0.25 mm rms and “Quadrupole - Beam Position Monitor” tolerances were supposed to be Δx = Δy = 0.25 mm rms where these last tolerances refer to the magnetic center of the quadrupole relative to the center of the BPM, all along the axis of the quadrupole. The actual offsets of BPMs at time of magnet installation were measured and they were used as the initial values for BPM offsets. RMS of those offsets were ~0.5 mm, but RMS of current offsets are slightly larger due to changes after BBA procedures: currently the only offsets greater than 1.5 mm are the offsets modified after BBA measurements.

Unfortunately, the estimates of BPM accuracy have to take into account the fact that after BPM calibration procedure, reported BPM positions change by up to 1 mm, therefore it really can not be said that the accuracy of BPM in RHIC is much better than 1 mm.

Summary

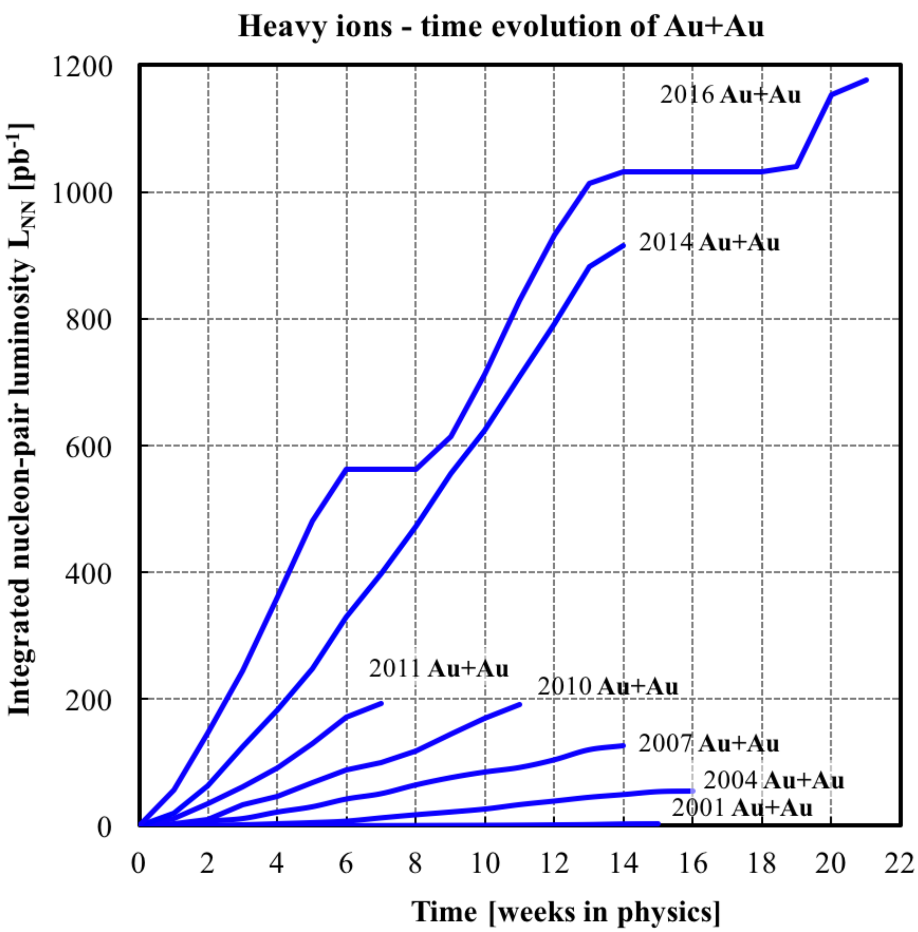

Figure 9: Integrated luminosity of Au-Au runs.