# RHIC BPM SYSTEM PERFORMANCE, UPGRADES, AND TOOLS *

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*Abstract*

During the RHIC 2001–2 run, the beam position monitor (BPM) system provided independent average orbit and turn-by-turn (TBT) position measurements at 162 locations in each measurement plane and RHIC ring. TBT acquisition was successfully upgraded from 128 turns to 1024 turns per trigger, including injection. Closed orbits were acquired and automatically archived every two seconds through each acceleration ramp for orbit analysis and feed-forward orbit correction. This paper presents the overall system performance during this run, including precision, reproducibility, radiation damage, and analysis tools. We also summarize future plans, including million-turn TBT acquisition for nonlinear dynamics studies.

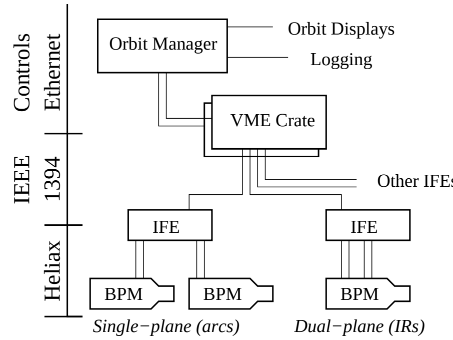


Figure 1: Architecture of the RHIC BPM system

## 1 SYSTEM ARCHITECTURE

RHIC consists of two three-fold symmetric rings, with lattices alternating between six regular FODO-cell arcs and six interaction regions (IRs). There are 160 BPM 23-cm cryogenically-stable electrode pairs (EPs) per plane per ring: 72 dual-plane BPMs distributed through the IRs, and 176 single-plane BPMs distributed at each arc $\beta_{\max}$. Each EP produces one position measurement. EPs are cabled through 6 dB reflection attenuators and 20 MHz lowpass filters to analog/digital integrated front ends (IFEs). Each IFE contains electronics for two measurement planes, including active 20 and 40 dB gain stages, 16-bit digitizers for 1$\mu$mresolution over a $\pm$32 mm measurment range, and Motorola 56301 fixed-point digital signal processors (DSPs) for data reduction and acquisition control. Arc IFEs are located in the tunnel, 2 m above the cryostat; IR IFEs are located in equipment buildings.

Each IFE calculates digitizer status, digitized raw signals, and beam position once per turn for a single selectable RHIC bunch, with position resolution of 1 $\mu$m. Upon receipt of a beam-synchronous trigger, up to 1024 turns are streamed to a local DSP buffer, then passed along IEEE1394 to VME memory and the RHIC control system. Upon receipt of a separate trigger, TBT positions are averaged over 10 kturns to provide a closed orbit (CO) measurement. Each IFE can acquire simultaneous TBT and CO information, and 1024-turn TBT records were acquired for most of the run. Details of RHIC BPM electrodes and acquisition electronics are available elsewhere [1, 2].

There are 20 dedicated BPM VME crates and controls front-end computers (FECs) distributed around the RHIC rings. A console-level server, the RHIC Orbit Manager, collects and correlates TBT and CO data from all BPMs, and handles both orbit logging and orbit delivery to application programs. This “centralized server” architecture reduces connection management and bandwidth requirements on BPM FECs. A schematic of overall the system architecture is presented in Fig. 1.

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## 2 SYSTEM PERFORMANCE

### 2.1 Short–Term Performance

TBT BPM channel performance was measured by triggering 20 1024-turn TBT acquisitions early in a typical physics store, over a period of 10 minutes with no applied beam excitation. These showed a typical RMS white noise fluctuation of 200$\mu$m , after a 100 Hz high-pass filter was applied to remove known systematic 8-15 Hz beam motion from IR triplet vibration [3].

Short-term individual BPM channel CO performance cannot be determined from analysis of logged orbits, since store-by-store orbit variations are smaller than expected systematics. Beam steering for collisions during every store, as well as beam studies to measure triplet multipole fields [4], demonstrate that successive CO measurements by this system over a one hour timescale with stable beam conditions are reproducible to 5–10 $\mu$m, near the system resolution. This result includes reproducibility of three-bump orbit control, and is consistent with 20–40$\times$ noise reduction over the single-turn measurement.

### 2.2 Trending and Stability

All BPM IFEs were self-calibrated with onboard calibration pulsers at the start of the run; modules were also calibrated when replaced due to failure. In the day to week timescale, BPM system stability is dominated by digitizer offset drift. Though this is a thermal effect and temperature readbacks area available from all IFEs, no effort made this

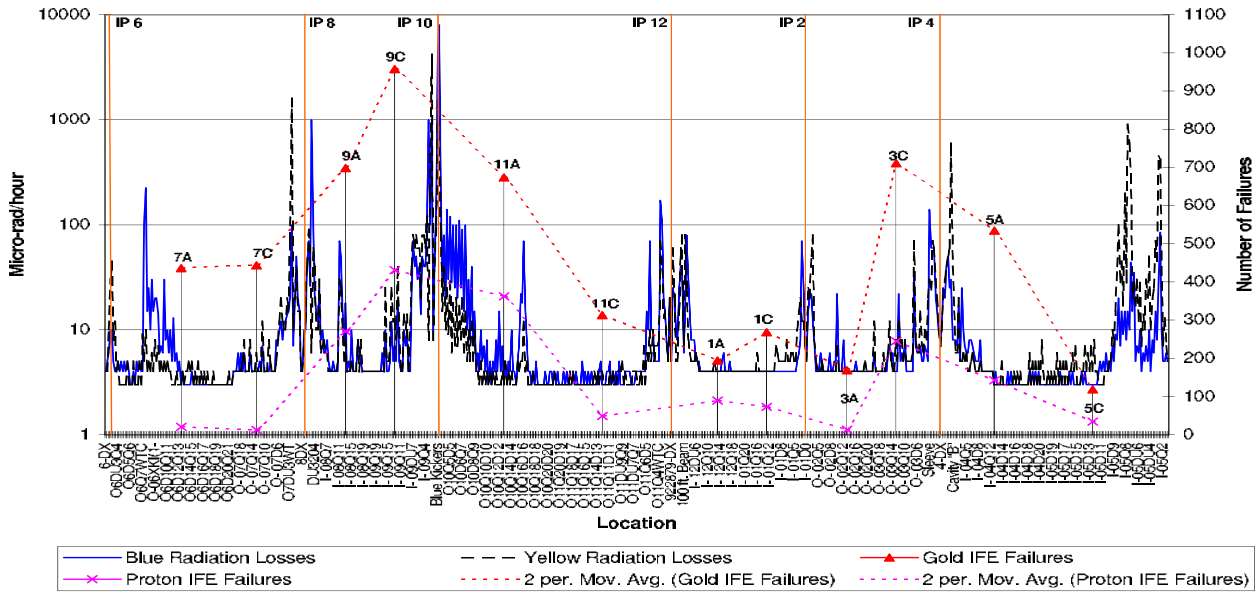


Figure 2: IFE failures and integrated beam losses in both RHIC rings for FY02–03 gold and polarized proton runs. Totals include both resettable and non-resettable failures. Labels such as 7A, 7C, etc. are RHIC tunnel alcove names where IFE signals feed into the RHIC control system. Clear correlations are visible in the region from IP8 to IP10 and around IP4. IP8 includes beam collimators; IP10 includes the beam dump.

run to correlate BPM positions with IFE temperature. We expect this effect to be negligible for arc IFEs, located in the RHIC tunnel. and we will investigate it for IR BPMs in equipment buildings before and during the next run.

An item of greater concern is an observed systematic variation of average orbit data with beam intensity during RHIC stores. During stores, CO data for all BPMs were archived at five minute increments, and a clear correlation was seen. Physical beam motion can be eliminated, as collision calorimetry is a very sensitive measure of CO beam motion at the level of 100 $\mu$m. Further studies are required to determine whether this trend is a dependence on peak intensity, bunch shape, timing variation, or some other unknown factor. Systematics of active gain balance also require further study.

## 2.3 *Data Acquisition and Storage*

The maximum orbit delivery rate for CO acquisition is 1/2 Hz, or approximately sixty CO measurements up the course of an acceleration ramp. This is adequate for the stringent orbit control requirements of polarized proton operations, where the closed orbit must be controlled to below 1 mm RMS to maintain polarization efficiency. This is also adequate for beam studies, where rapid successive changes and measurements improve study efficiency. The size of a single-ring CO data set, stored in SDDS binary format [5], is approximately 12 kilobytes.

The maximum orbit delivery rate for TBT acquisition was 1/5 Hz for 128-turn data and 1/15 Hz for 1024-turn data. This period is much longer than typical chromatic decoherence times, and is adequate for all but special-setup transverse impedance [6], ac dipole [7], and nonlinear dynamics studies. The size of a single-ring 1024-turn TBT data set in SDDS binary format is approximately 4.5 megabytes. Over 1200 TBT data sets were saved through both Au and polarized proton runs, split between injection conditions and kicked storage conditions for linear optics measurements [8].

## 2.4 *Radiation Damage*

In the course of the RHIC 2001–2 run, an unexpected number of IFE failures occurred. Though initially remotely resettable, these failures progressively deteriorated to unresettable failure over week-long timescales. 55 units required replacement and bench repair after this type of complete failure.

Investigation during and after the run demonstrated a clear geographic correlation between beam loss and IFE failure, as shown in Fig. 2. High levels of beam loss near IP8 (collimators) and IP10 (beam dumps) correlate with aperture restrictions in those regions. Both gold and polarized proton run statistics show elevated failures associated with radiation damage. In contrast, there were no IFE failures of this sort in ground-level equipment buildings.

IFE failure bench analysis showed that the consistent point of IFE failure was on-chip DSP memory. The process of procuring spare DSPs and surface-mount replacement, though feasible, is expensive and manpower-intensive. A more appropriate remediation is to move several alcoves of IFEs from locations above the cryostat to racks within the

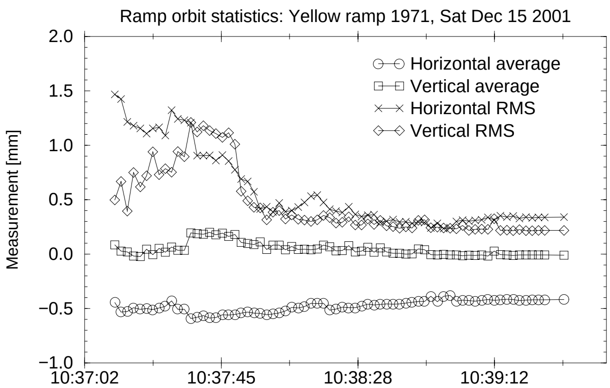


Figure 3: CO space-wise average and RMS in the RHIC blue ring through a RHIC polarized proton acceleration ramp, showing RMS orbit reduction after orbit correction on the ramp.

alcoves, as described in Section 4. It is important to note that self-correcting DSP code would defer but not eliminate failures, as the root cause is progressive irreversible silicon damage to DSP on-chip memory.

## 3 ORBIT ANALYSIS TOOLS

Besides routine closed orbit correction and IR steering to produce collisions[9], the primary tool for CO BPM orbit analysis is a tool `orbStat` that produces graphs of orbit statistics for every acceleration ramp, as shown in Fig. 3. Global orbit corrections were then applied, and global CO RMS values of less than 1 mm were routinely achieved. This level of orbit control is critical for good polarization transmission during RHIC polarized proton operations.

The primary tool for TBT BPM orbit analysis is a command-line tool, `RhicBpmAnalysis`. Options exist to print bad BPM reports (including type of failure), produce phase space plots, perform linear optics analysis (including betatron function and phase), and FFT tunes, including a tune FFT histogram for all BPMs through the ring. Many of these functions will be incorporated in the Orbit Display program for the next run, particularly tune and optics analysis, and phase space display.

Other online orbit tools, including ac dipole optics analysis and IR steering for collision setup, are described elsewhere [7, 9].

## 4 FUTURE PLANS

To limit radiation damage, BPM IFEs in sections 9A, 9C, and 11A of Fig. 2 are being moved from their locations above the RHIC cryostat to RHIC tunnel alcoves. Analog BPM signals will be carried from feed-throughs to alcove IFEs with low-loss 1/4" heliax. Software heartbeats and failure logging for all channels are also being implemented to correlate IFE failures with beam loss.

RHIC BPMs require careful setup of acquisition gate timing relative to beam-synchronous clocks. This is particularly important for DX BPMs, which see both beams in the collision region with a signal separation of 55 ns for 1–5 ns bunches. With these limitations, DX BPMs were not robust during this run, and retiming with beam at storage energy requires expert assistance for 30 minutes per IR. We are developing methods to automate BPM timing through the system, to make DX retiming routine at the start of every store. Automated timing setup will also make user-defined bunch selection feasible.

Eight BPMs (two per plane per ring) are being upgraded with 512 Mb SDRAM mezzanine connector cards to provide longer TBT recoreds, up to a maximum of approximately 50 million turns or 12 minutes of continuous TBT data. These will be used for nonlinear dynamics and AC dipole studies, as well as analysis and postmortem tools for transverse instabilities. 1024-turn data transfer blocks eliminates the need for a reconfiguration of existing 1394 memory map configurations.

Near-term RHIC operations scenarios include doubling the number of bunches from 55 to 110 in each ring. Existing BPM cable and attenuator heat loads and timing can handle this scenario with design intensity bunches[10].

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