RHIC Instrumentation

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Abstract. The Relativistic Heavy Ion Collider (RHIC) consists of two 3.8 km circumference rings utilizing 396 superconducting dipoles and 492 superconducting quadrupoles. Each ring will accelerate approximately 60 bunches of 10^{11} protons to 250 GeV, or 10^{9} fully stripped gold ions to 100 GeV/nucleon. Commissioning is scheduled for early 1999 with detectors for some of the 6 intersection regions scheduled for initial operation later in the year. The injection line instrumentation includes: 52 beam position monitor (BPM) channels, 56 beam loss monitor (BLM) channels, 5 fast integrating current transformers and 12 video beam profile monitors. The collider ring instrumentation includes: 667 BPM channels, 400 BLM channels, wall current monitors, DC current transformers, ionization profile monitors (IPMs), transverse feedback systems, and resonant Schottky monitors. The use of superconducting magnets affected the beam instrumentation design. The BPM electrodes must function in a cryogenic environment and the BLM system must prevent magnet quenches from either fast or slow losses with widely different rates. RHIC is the first superconducting accelerator to cross transition, requiring close monitoring of beam parameters at this time. High space-charge due to the fully stripped gold ions required the IPM to collect magnetically guided electrons rather than the conventional ions. Since polarized beams will also be accelerated in RHIC, additional constraints were put on the instrumentation. The orbit must be well controlled to minimize depolarizing resonance strengths. Also, the position monitors must accommodate large orbit displacements within the Siberian snakes and spin rotators. The design of the instrumentation will be presented along with results obtained during bench tests, the injection line commissioning, and the first sextant test.

OVERVIEW OF RHIC

Upon completion in 1999, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory will accelerate and collide protons, polarized protons, and heavy ions (1) (2). Heavy ion collisions up to Gold on Gold at 100 GeV/u beam energies will produce extended nuclear matter with energy densities an order of magnitude greater than that of the nuclear ground state. This should result in temperatures and matter densities that prevailed a few microseconds after the origin of the universe. It is also believed that these extreme conditions could produce a phase transition to a quark-gluon plasma. The Spin Physics program at RHIC will utilize polarized protons at up to 250 GeV and 70% polarization. The primary goal is to study the spin structure function of the proton.

The collider consists of two rings separated horizontally by 90 cm in a tunnel 3.834 km in circumference. Collision points are provided in six insertion regions that are connected by six arcs. The total complement of magnets for both rings include 288 arc dipoles, 276 arc quadrupoles, 108 insertion dipoles, and 216 insertion quadrupoles. Additional magnets include 72 trim quadrupoles, 288 sextupoles, and 492 correctors. All ring magnets are superconducting.

The Alternating Gradient Synchrotron (AGS) complex is the injector to RHIC. Beam is extracted through the H-10 septum magnet into the AGS-to-RHIC (AtR) transfer line as single bunches during a flat-top of the AGS magnet cycle. The AGS cycle is repeated until each of the two RHIC rings are filled. The 1900-foot-long AtR line consists of several sections, starting as the "U-line", becoming the "W-line," the branch into the "V-line" to the g-2 experiment. A switch magnet at the end of the W-line directs beam into either the "X-line" or "Y-line" to the counter-rotating RHIC rings.

RHIC construction officially began in 1991. In the Fall of 1995, the first part of the AtR line was commissioned up through the W line. In February, 1997, beam was transported to a temporary dump at the end of the first sextant. Collider commissioning will begin in early 1999 with project completion scheduled for June of that year. Relevant parameters are listed in Table 1.

TABLE 1. RHIC Parameters

Parameter	**Value**
Kinetic Energy, Injection-Top (each beam)	Gold: 10.8 – 100 GeV/u Protons: 28.3 – 250 GeV
Luminosity, Au-Au at 100 GeV/u	$2 \cdot 10^{26}$ cm^{-2} s^{-2}
Operational lifetime, Gold	10 hours
No. of bunches/ring	60
No. of particles/bunch	Gold: 10^9 (at times, a few 10^7) Protons: 10^{11} (upgrade, $3 \cdot 10^{11}$)
Bunch length	from 20 ns down to 1 ns
Normalized Emittance, gold	Injection: 10π mm mrad After 10 hr: 40π mm mrad
Filling mode	Bunch to bucket, 30 Hz peak rate
Filling time	1 min, each ring
Acceleration time	75 s
Revolution frequency	About 78 kHz
rf harmonic number	Acceleration system: h = 360 Storage system: h = 2520
Beta at crossing, H,V	During injection: 10 m Low beta insertion: 2 m
Transition energy	$\gamma_T = 22.89$
Circumference	3833.845 m
Beam tube i.d. in arcs	69 mm
Vacuum, warm beam tube sections	$7 \cdot 10^{-10}$ mbar
Operating temp., helium refrigerant	< 4.6 K

INSTRUMENTATION

A list of the major instrumentation systems is provided in Table 2. Most of the transfer line systems have already been installed and tested during the 1995 AtR commissioning and the 1997 Sextant Test (3) (4) (5). All of the listed systems are expected to be available for collider commissioning in 1999, although some will provide only a subset of potential functionality.

TABLE 2. Table of Instrumentation

System	Quantity
Position monitors	52 measurement planes in transfer line 667 planes total in collider rings
Ionization profile monitors	One horizontal and one vertical per ring
Wall current monitors	One per ring
Transverse feedback	Two kicker units per ring (each provides horizontal and vertical deflection)
Schottky cavities	One per ring (each provides horizontal, vertical and longitudinal signals)
Transfer line intensity monitors	Five integrating current transformers
Loss monitors	120 ion chambers in the transfer line 400 ion chambers in the collider tunnel
Collider ring current monitor	One DCCT per ring

ATR BEAM PROFILE MONITORS

Video Profile Monitors (VPMs) are used in the AtR line (6). A total of 12 VPMs were installed, any four of which can be viewed on a single transfer via a 4×16 video multiplexer. Low mass phosphor screens minimize scattering and allow four profiles to be acquired on a single bunch for an emittance measurement. VME-based image processing electronics are used to acquire and process the data.

Gadolinium Oxy-sulfide doped with Terbium (Gd_2O_2S:Tb) phosphor was chosen because it has low mass and can be deposited in a thin (0.002") coating. In order to see individual profiles on successive transfers the light had to decay fully in 33 ms. Chromium doped aluminum oxide (Chromox) has too long a decay time and is not available in such thin sheets. Tests have shown Gd_2O_2S:Tb to fully decay faster than the 30 Hz camera frame rate. The screen is mounted at 45^o and pneumatically inserted. The drive, viewing window and two lamp ports are on the same 8" conflat flange, simplifying alignment. A 45^o first-surface mirror transfers the image to the camera over a typical 300 cm path length. Screen durability has not been established but none have been damaged in the low-intensity gold beam runs. Aluminum oxide screens are used at the two upstream locations where intense proton beams are transported to the g-2 experiment.

Pulnix TM-7cn CCD cameras are used in all locations except in the AGS ring tunnel. Because typical CCD camera lifetime is 100 to 700 Rad, a Cidtek (3710D) charge injection device (CID) camera, rated at 20 kRad, was used there, but failed after one week. The dose was estimated to be consistent with the expected life. Other alternatives are to use an MRad version of the Cidtek camera or a Dage radiation hardened vidicon camera. At most locations in the transfer line the cameras are mounted in 14" diameter tubing inserted into the tunnel wall to provide gamma shielding. Since the light lasts only a millisecond, the camera must either acquire the full frame at once (Cidtek) or have an overlap period in which the odd and even fields are both sensitive (Pulnix). The camera must be synchronized with the beam in this way or every other line on the vertical display will be blank. More than 3 decades of light intensity is expected, but a typical lens will only adjust over a 150:1 range. Lenses with a graded neutral-density center spot can cover 3 decades but are very expensive and require a motor drive interface. A simple device using solenoids to insert up to four neutral density filters between the camera and the lens, providing a 20,000:1 range has worked well. A 500 mm f/5.6 reflector lens is used at most locations, but 1000 mm f/8 reflector lens and 300 and 400 mm f/5.6 refractors are also used. About half of the cameras were rotated 90° to best match the beam aspect ratio with the orientation re-established in the computer-generated display. The lens, camera, and filter array are aligned on an optical rail using commercial optical mounting hardware. The rail sits on a sliding tray which uses tapered pins for precision location, allowing rapid replacement. An inexpensive "leveling" laser substituted for the camera and lens was used to align the optics.

Phosphor screen grain size, air waves and mechanical motion are not significant limitations on resolution for the AtR beam sizes, which range from several mm to several cm at 2.5 sigma. With the screen at 45°, depth of field is a factor which can be significant if the beam is well off center or vertically large. Camera resolution is limited by the number of pixels and transmission and electronics bandwidths. Wideband (6 MHz) analog fiber-optic links are used to preserve resolution over the longest (1700 ft) run to the centrally located VME-based image processing electronics. The resolution was calculated to be better than 0.25 mm using measurements and manufacturer's data for the cameras and lenses. Measurements of the fine fiducial marks were consistent with the estimate.

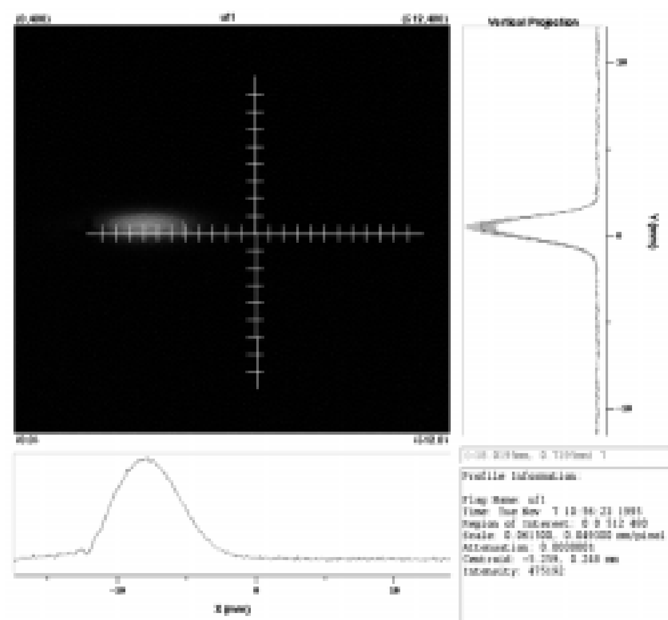

FIGURE 1. Video Profile Monitor display.

The acquisition and processing of the video data uses Imaging Technology Inc. VME modules running under VxWorks. These include four IMA-VME-4.0 boards with 4 AMVS-HS acquisition modules, 2 CMCLU-HS Convolver arithmetic modules, and 2 CMHF-H histogram/feature extractor modules. Forty-eight 512×512 frames, plus base frames for background subtraction, and computational results can be stored on-board. A 128×128 subset of the full frame can be generated either from a 4×4 convolution or a region of interest (ROI), which can be pre-selected or dynamically determined by a threshold setting. The full RHIC fill can be stored for these reduced data sets and later sent over the LAN for higher level processing. On-line real-time computations available include: pixel-by-pixel base frame subtraction of full frame data, centroid of the full frame, H and V projections, and sum of all pixels. So far, only the full 512×512 frame data has been used. High-level code was written to control and display the beam profiles and calculate emittance. Figure 1 shows a typical profile display.

ATR BEAM INTENSITY MONITORS

Beam intensity is monitored at five junction points in the AtR line using Integrating Current Transformers (ICT) and electronics manufactured by Bergoz (7). For the RHIC sextant test, an ICT from the left injection arc was moved to the end of the string of superconducting magnets. The design of the ICT provides passive pre-integration of a fast current pulse, reducing the effect of core losses. The slower risetime signal is then integrated and held for acquisition by the RHIC MADC (8). Initially noise from the AGS extraction kicker, which is coincident with the beam, interfered with the signal, but passing multiple turns of the tri-axial signal cable through a ferrite core significantly reduced the pick up. Reliable signals were then obtained even for 10^7 gold ions.

ATR BEAM LOSS MONITORS

The Beam Loss Monitors (BLMs) are ion chambers mounted on the vacuum flanges downstream of each magnet. To limit the number of electronic channels while providing complete coverage, signals from the 120 detectors were grouped into 56 channels. The electronics were located in four equipment houses. The BLMs, designed to be sensitive one decade below the nominal 10^9 gold ion intensity, were able to monitor the losses for beam intensities from 10^6 to 2×10^7 Au79 ions.

The BLMs are Tevatron ion chambers (9) modified by using an isolated BNC to break the ground loop formed by the signal and HV cable shields. Rexolite is used rather than PTFE for the insulators in the BNC and SHV connectors to improve the radiation hardness. The ion chamber (10) consists of a 113 cc glass bulb filled with argon to about 725 mTorr. Each chamber is calibrated using a cesium-137 source. The mean sensitivity in the middle of the plateau (1450 V) is 19.6 pA/R/h, with 95% within (1.5 pA/R/hr of the mean. Where multiple detectors were used on a single channel, they were grouped by calibration with the average value used for the group.

The ionization current from the detector is fed to a low-leakage (less than 10 pA), gated integrator and read out using the standard RHIC MADC. The integrator input pre-integrates the electron signal with a millisecond time constant (comparable to the ion collection time), greatly reducing noise from the kicker magnets which are time coincident with the beam. To take full advantage of the pico-Amp sensitivity of the detector and electronics, it was necessary to use non-tribo-electric cable (Belden 9054) to reduce noise caused by mechanical motion. These features resulted in the noise level of about 10 pA observed during the AtR commissioning.

POSITION MONITORS

Position Monitor Electrodes

The beam position monitor (BPM) electrode assemblies for the collider ring and the AtR line share a common mechanical design (11). Nearly all of the collider assemblies operate at 4.2 Kelvin while the all of the AtR assemblies operate at room temperature. They contain 23 cm long, shorted striplines with a carefully controlled 50-ohm impedance. These large striplines couple enough power to allow accurate measurement of low-intensity pilot bunches. The shorted design requires electronics with a low return loss in order to control beam coupling impedance, but the static cryogenic load is reduced by a factor of two over the more expensive back-terminated designs. The assemblies are constructed of 316L stainless steel and are copper brazed in a hydrogen reducing atmosphere. The resulting assembly is fully annealed and therefore mechanically stable under extreme temperature variations. The feedthrough is a coaxial, glass-ceramic design supplied by Kaman Instrumentation. Unlike conventional ceramic-kovar feedthroughs, these units can be reliably thermally cycled from a 300-degree Celsius bakeout temperature down to a 4.2-Kelvin operating temperature while providing excellent microwave performance. Over 1400 feedthroughs have been tested and installed with no insulator failures. The cryogenic installation requires a special cable to bring the signal to room temperature feedthroughs mounted on the cryostat. These .141" diameter cables have a Tefzel insulator that provides increased radiation hardness over the standard Teflon. To optimize thermal performance, the jacket is made of stainless steel instead of copper and the central portion of the cable is thermally stationed at the 55-Kelvin heat shield.

Most of the assemblies contain two opposing striplines and are oriented horizontally or vertically such that the position measurement is made in the plane having the larger beta function. These are designated Type 1 monitors; a cutaway view of one is shown in Figure 2. In critical areas, particularly in the insertion regions, the monitors allow simultaneous measurement of horizontal and vertical position by including four striplines. In order to match the expected beam size, they are constructed with either large (Type 3) or small (Type 2) apertures. The collider ring contains 480 electrode assemblies plus additional units for the spin rotators, Siberian snakes, and the beam dumps. The AtR line contains 39 assemblies.

FIGURE 2. Position monitor electrode assembly.

For ease of commissioning, the offset between electrical centers of the position monitors and the magnetic centers of the quadrupoles must be accurately characterized. Even tighter constraints are imposed during polarized proton acceleration, which requires accurate orbit control in order to avoid depolarizing spin resonances. Because the main arc quadrupoles do not have individual trim supplies, the position monitor offset characterization cannot be easily performed online. Therefore, this offset was surveyed during magnet assembly by performing the following procedure (12):

1. The magnet center is measured relative to cryostat fiducials. For early units, this measurement was made with a magneto-optical technique (13). For later units, a measurement coil was used.
2. An antenna is inserted into the electrode assembly. The position of the antenna is optically surveyed relative to the cryostat fiducials.
3. An rf signal is injected into this antenna and the signal amplitudes at the position monitor ports are measured. This provides a measurement of the offset between the electrical center and the antenna.
1. The offset between the position monitor electrical center and the magnet's center is calculated. The estimated tolerance of the offset measurement is about 100 μm rms.

Position Monitor Electronics

Analog Sampler

Each channel of position monitor electronics employs a broadband sampler (14) depicted in Figure 3. This circuit has evolved since publication of the 1995 reference, but the basic design remains. All measurement planes are treated independently. Therefore, dual-plane electrode assemblies (Type 2 and Type 3) are connected to two independent electronic channels. Two channels are contained within the beam position monitor module that will be described in the next section. As shown in Table 2, the AtR line requires 52 channels and the collider rings require a total of 667 channels. All AtR electronics are rack mounted in equipment buildings that are accessible during operations. These signals are transported on 3/8-inch, solid, shielded coax between the tunnel and the equipment building. Where possible, the collider ring channels are cabled in a similar manner with 1/4-inch coax. Channels in the insertion regions, injection area, and dump area are all cabled this way with up to 150-meter-long runs. All other modules are located in the tunnel and cabled to the appropriate electrodes with shorter, 2-meter-long cables. These channels are all in cryogenic regions. The low vacuum should minimize beam-gas scattering and the resulting radiation field at the electronics. In all cases, the signal first passes through an attenuator and a coaxial, 135 MHz low-pass filter before reaching the analog sampler. The filter rejects high-frequency, high-voltage signals from short bunches while the attenuator provides improved return loss. An upgrade to higher cost diplexers will be considered if required in the future.

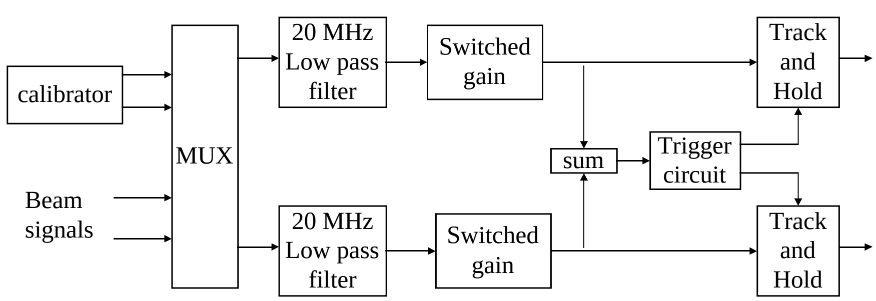

FIGURE 3. Block diagram of the BPM analog sampler.

Referring again to Figure 3, a multiplexer (MUX) at the input to the sampler selects between beam signals and an on-board calibration pulser. This MUX can also swap the input signals to allow observation of imbalance in the following electronics. Signals then pass through matched 20 MHz, lowpass filters. These are Bessel filters with good transient response. A high impedance sum circuit provides the input to a self-trigger circuit. The trigger threshold is adjustable and the self trigger can be completely disabled to allow external clocking. When the self trigger is enabled, an external gate is applied to select a particular bunch. Independent delays are adjusted to assure that each signal is sampled precisely at the peak. Track-and-holds with 14-bit linearity are used to sample the signals. The output is digitized by a 16-bit ADC. In the AtR line every transported bunch is sampled. This leads to a maximum acquisition rate of 30 Hz. In the collider ring modules, a selected bunch is sampled turn by turn at the revolution frequency of about 78 kHz.

Data Acquisition

Each analog sampler resides on a circuit board that also contains the data acquisition hardware. Each board includes two 16-bit digitizers, a fixed point digital signal processor (DSP) subsystem, an in-system programmable gate array, a beam synchronous timing interface, and an IEEE1394 Serial Bus (Firewire) interface (15). Two boards are packaged together in each module, but each board functions as a completely independent position channel. The control system communicates with the channels via shared memory in a VME/Firewire interface board. As shown in Figure 4, up to 12 channels are connected to each interface board via the Firewire Serial Bus. In the AtR line, a data record containing all the positions of all transported bunches is sent to the shared memory on every AGS cycle. In the collider rings, the channels can operate in different modes. During injection, a turn-by-turn record for each injected bunch is written to shared memory. For the rest of the collider cycle, the channels will periodically send a turn-by-turn record for a particular bunch and simultaneously stream signal averaged position data at 10 Hz.

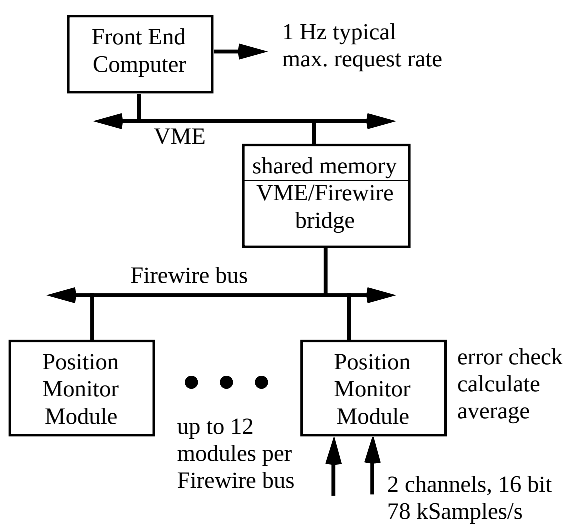

FIGURE 4. Data flow from the BPM system.

Test results

Results from several tests are summarized in Table 3. To ease comparison, all position amplitudes are normalized to the nominal 69 mm aperture of the RHIC arcs. The bench tests were made on production prototypes of the final modules. All beam tests were performed with similar but earlier prototype samplers.

TABLE 3. Summary of Position Sampler Tests

Test	Result	Comment
Minimum measurable bunch intensity	$5 \bullet 10^8$ charges	Bench measurement
Maximum measurable bunch intensity	10^{12} charges	Bench measurement
Noise in turn by turn measurement	2 × µm rms	Bench measurement, max. intensity
	1 mm rms	Bench measurement, min. intensity
	<10 µm rms	Measured proton bunch in Tevatron during store
Accuracy	±100 µm	Bench measurement,
		$5 \bullet 10^8 <$ bunch intensity $< 10^{12}$
	< 1 mm	Orbit correction results from AtR test. Includes other error sources.
Scatter in single pass, single bunch measurement	20 µm rms	Vertical scatter of bunches extracted from AGS
Drift over 5 hours	±5 µm	Calibration pulse injected into channel during AGS extraction
	±25 µm	Measured vertical orbit of bunches extracted from AGS

RING BLM SYSTEM

BLM System Design

The primary function of the RHIC Ring BLM system is to prevent a beam-loss quench of the super-conducting magnets. It will also provide quantitative loss data for tuning and loss history in the event of a beam abort. The system uses 400 AtR style ion chambers, but since the AtR is single pass, different electronics are employed. It has been estimated that the RHIC superconducting magnets will quench for a fast (single turn) loss > 2 mJ/g or a slow (100 ms) loss > 8 mW/g. This is equivalent to 78.3 krad/s at injection (49.3 krad/s at 100 GeV/c) for uniform loss over a single turn and 4.07 rad/s at injection (0.25 rad/s at 100 GeV/c) for slow losses. This will yield a range of signal currents from 5.5 mA for the injection fast loss level to 17.6 nA for a slow loss quench at full energy. Allowing for studies results in a dynamic range of 8 decades in detector current. The amplified signal is digitized at 720 Hz and continually compared to programmable fast and slow loss levels which can cause a beam abort. This will halt data acquisition, providing a 10-second history of the pre-abort losses. BLM parameters are adjusted during injection, magnet ramp and storage phases to set gains, fast and slow loss thresholds, and abort mask bits on specific RHIC Event Codes.

The Detectors

The detectors and cable are as in the AtR line. Half of the ion chambers (198) are mounted between the two RHIC Rings on the quadrupole cryostats using stainless steel "belly bands." This will not provide equal sensitivity to losses from each ring, but if more precision is required a second detector can be added on the outer ring and either the outputs of the two BLMs connected in parallel or the number of channels doubled. Ninety-six BLMs are placed at insertion region quads. In the warm regions, 68 detectors are mounted on the beam pipe at expected sensitive loss points. In addition, 38 BLMs are available as movable monitors. Since the Ring BLM system is used for quench prevention, redundancy is provided by separate HV power supplies for the two cables which provide the bias voltage to alternate detectors. Further redundancy is not required since the system is not to be used for personnel protection.

Electronics

The analog circuitry is packaged in an 8-channel module. A micro-controller module manages up to 8 analog boards independent of the crate front-end computer (FEC), once the write list values have been set through high level code. This insulates the real-time operations from the control system I/O, allowing the BLM system to operate during a controls link failure. Commercial digital I/O and DAC modules are used to control the HV power supplies. The electronics will be located in service buildings at 2,4,5,7,8,10 and 12 o'clock, allowing access during beam storage. Standard VME crates were modified for the special needs of the BLM electronics. Tests indicated that the standard ±12 V switcher power supplies were too noisy for the high sensitivity analog circuitry. While DC-DC converters might have been used, due to limited real estate for the converters and filters and the possibility of oscillator noise, it was decided incorporate a separate linear ±15 V supply into the crate. A piggy-back board across the last nine P2 connectors provided a dedicated bus between the micro-controller module and the 8 analog modules and a means of supplying the ±15 V.

The Analog Module

Figure 5 shows a simplified schematic of the analog section for one of the eight channels on the Analog Module. An input low-pass RC filter, matched to the magnet thermal time constant, integrates the fast loss impulse, greatly reducing the dynamic range while providing a sufficiently fast rising signal to protect against a single turn loss quench. Back-biased, matched, low-leakage diodes (DPAD-5) protect the amplifier input from high voltage spikes. The low-current amplifier (OPA627AU) is rolled off to a 10 μs rise time. To allow for BLM shielding differences, jumpers can set two alternate gains. The front-end op-amp output is applied to a second amplifier with programmable gains of 1 or 10 prior to signal acquisition. The data is read at 720 Hz by a RHIC VME MADC configured for ±10 V, 13 bits and stored in a 1 Mbyte on-board memory. An optional off-board 360 Hz anti-aliasing filter is available. Readings can be taken at additional times as required for specific applications. For the nominal jumper setting and a buffer gain of 10, one LSB represents 12.5 pA, comparable to the noise observed in beam tests. Offsets, typically a few LSBs, are not adjustable since these can be removed in the higher level processing.

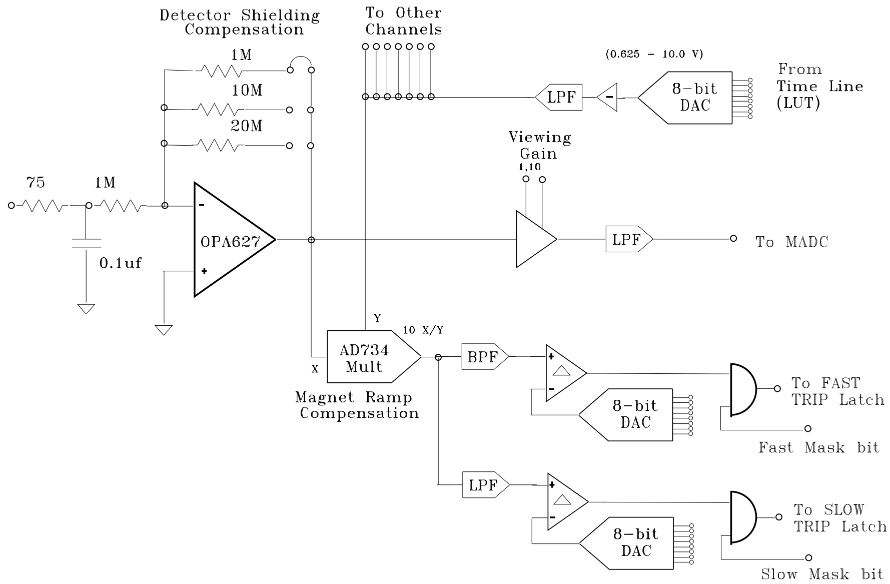

FIGURE 5. Schematic of a typical channel of the BLM Analog Module.

The front-end op-amp output also goes to an AD734BN analog multiplier which provides a gain to compensate for the increased magnet quench sensitivity with current. An 8-bit DAC sets the gain for all multipliers on a board. A high-pass (100 µs) and low-pass (20 ms) filter direct the signal to respective fast- or slow-loss comparators with independent programmable references. The 8-bit reference DACs are sufficient due to the magnet current compensation provided by the analog multiplier. Each comparator can be masked to prevent a bad BLM from inhibiting the beam or to allow special conditions. The gains, mask bits and trip levels may be changed by Events on the RHIC Event Link. Any trip latches the states allowing the location to be determined. An Altera 7128 chip performs all logic functions and communication with the BLM Micro-controller module via the dedicated bus on the VME P2 backplane.

The Micro-Controller Module

The RHIC Control System talks to the BLM micro-controller (16) which controls the BLM analog module. This was necessary due to the large number of set-point changes, particularly during injection, acceleration and transition. The micro-controller, once in possession of the write-list, completely controls the BLM analog module, freeing the FEC and allowing the BLM system to continue to provide beam loss quench protection even in the event of a controls failure. A Microchip PIC16C64 micro-controller services the 256 byte registers on the BLM analog modules. A 64k ˘ 16 bit memory holds the write-lists for 256 RHIC Event codes each associated with up to 255 address/data values. On detection of a specific Event, the corresponding write-list is sequentially executed with the data (gain, fast/slow trip level...) going to a particular register. Altera 9320 and 7128 gate arrays are used on the board.

BLM Test Results

Figures 6a and 6b show the losses from an 8 bunch transfer at 30 Hz for 2 ˘ 10^{12} protons, 20 times RHIC intensity. The top trace is the analog output showing the signal rising rapidly due to the loss from each bunch transfer. The signal then decays with the 100 ms front-end filter time constant. The middle trace of Figure 6a is the slow-loss filter output with the fast losses rejected. The bottom trace is the comparator output for a 2 V reference. The middle trace of Figure 6b is the fast loss filter output, showing only the electron component of the signal. The bunches did not have equal losses so the comparator does not trip for every transfer. It is clear that the circuit has the ability to discriminate between fast and slow losses.

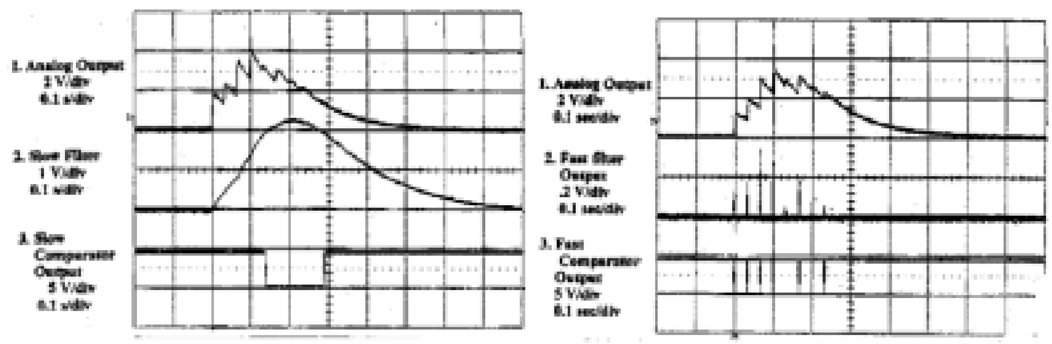

FIGURE 6. Eight bunch 2 ˘ 10^{12} proton transfer. a) Slow filter and comparator output. b) Fast filter and comparator.

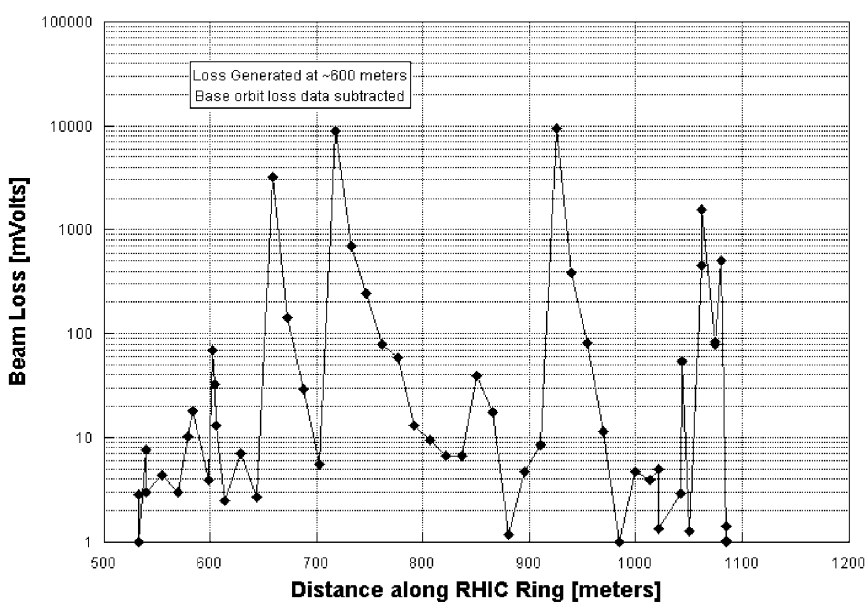

FIGURE 7. Loss data from the Sextant Test.

In January 1997, an Au^{+79} beam was injected into one ring of the first sextant of superconducting magnets. BLMs were installed at their final locations, which for these tests were on the inside of the Ring carrying the beam. Since the beam was single pass and sufficient Ring electronics were not yet available, AtR electronics (integrators) were used. The results of an average of two runs normalized to 10^8 ions is shown in Figure 7. A large loss was purposely created at 600. With the BLMs located at the quads (about 15-meter interval) there is sufficient spatial resolution and dynamic range to determine the direction of the beam causing the loss. In other runs, larger losses were purposely generated requiring the integrator gain to be lowered and gate width to be reduced. The observed integrator noise and offsets, of the order of a few LSBs, are similar to that observed with the prototype Ring BLM electronics installed in the AtR line. These tests indicted that the BLM system will have sufficient range to meet the design requirements.

THE RHIC RING BCM SYSTEM

System Requirements

The ring beam current monitor (BCM) must cover the range shown in Table 4. Because studies intensities may be an order of magnitude lower, the intensity may range from 1×10^9 to 1.2×10^{13} charges or 12.5 μA to 150 mA. RHIC is a storage accelerator so the BCM must be able to measure DC current yet be able to observe bunch-stacking at 30 Hz. Since the beam in RHIC will cross transition, the BCM bandwidth must allow intensity changes over several turns to be observed, although at lower resolution. Stability should be ±10 μA over the 10-hour storage time.

TABLE 4. RHIC Intensity and Current

Number of Bunches	Gold (+79) [Intensity current]	Protons [Intensity current]	Pilot protons [Intensity current]
1	7.9×10^{10} 0.99 mA	1×10^{11} 1.25 mA	1×10^{10} 0.125 mA
57 (Nominal)	4.5×10^{12} 56.2 mA	5.7×10^{12}/ 71.1 mA	5.7×10^{11} 7.11 mA
120	9.5×10^{12} 118 mA	1.2×10^{13} 150 mA	1.2×10^{12} 15.0 mA

The Beam Current Monitor

A DCCT for each ring was purchased from Bergoz (17). The unit has remotely switchable 50 and 500 mA maximum current ranges. Modulator noise is less than 1 μA when integrated over 30 ms. The long term stability has not yet been measured, but sensitivity to temperature is consistent with the 5 μA/ °C quoted by the vendor. An RTD mounted on the sensor will be used to correct for this effect. The unit was specified with 75-meter-long cables to allow front-end electronics to be removed from the RHIC tunnel. However, preliminary tests indicate that the modulator noise is more than an order of magnitude greater than with the standard 3-meter cables. This noise is not a problem when viewed on the electronics low-pass output (~4 kHz high-order filter), or when the wide-band output is integrated over 30 ms or more, but higher frequency measurements will be affected. Because the modulation is regular, the high over-sampling makes it is possible to digitally filter much of this noise. Certainly the result will be better with the shorter cables which may be used for the RHIC commissioning.

The BCMs will be located in the warm region of the 2 o'clock sector, which will be baked to 150^{o} C. The BCM housing has been designed to insulate the transformer core from the heated beam pipe and prevent it from exceeding 60^{o} C. Thermocouples on the detector will be used to interlock the heater blanket. The outer shell of the housing will provide the bypass path for the wall current around the transformer.

BCM Data Requirements

Beam intensity information will be used in a number of ways which set different requirements on the data as summarized in Table 5.

TABLE 5. BCM Data Requirements

Measurement	Read Rate	Resolution	Data
High Resolution (Decay Rate)	1 Hz	20 bits	Display each reading Display 1000 point sliding avg
Medium Resolution	78 kHz	16 bits	Non real-time digital filtering Display 1000 point sliding avg
Low Resolution (Tuning)	720 Hz	13 bits	Average of last 72 readings With 10 Hz display
Low Resolution (Logging)	720 Hz	13 bits	Each reading recorded In 10-second sliding memory
Injection	30 Hz	16 bits	Average over 33.3 ms All bunch display

The long term beam decay rate will be monitored by a very high resolution, slow update digital multimeter (DMM) for each Ring. Since loss rates of less than 10 µA must be detected, acquisition of 1 µA or better will be needed. This 20-bit resolution will be provided by a Keithley Model 2000 with a IEEE-488 interface, which can be programmed to provide a rolling average, lessening the load on the FEC. Measurement of the intensity at injection or around transition will require a faster acquisition at medium resolution. A 16-bit, 16-channel, 100 kS/s/channel ADC with 4 Mbytes on-board memory will be used to read at the 78 kHz revolution frequency. This data, suitably averaged, will also be used at injection to track the bunch stacking. The modulation noise on the signal is highly periodic and amenable to digital filtering to obtain sub-millisecond non real-time intensity information. A standard RHIC MADC will provide the 720 Hz low-resolution (13-bits plus sign). The low-pass output BCM signals will be stored in a 10-second deep memory which will be available in the event of a beam abort. An average of 72 MADC readings will be used to provide a display at 10 Hz for tactile feel tuning.

WALL CURRENT MONITOR

The wall current monitor system incorporates ferrite loaded pickups based on the design by Weber (18). One pickup is installed in each ring. The ferrite has been selected to attain a flat frequency response down to 3 kHz with a transfer impedance of 1 ohm. The response extends to 6 GHz, which is well above pipe cutoff. Interfering modes will be attenuated by microwave absorber installed on either side of the pickup. A calibration port has been included.

The signal from the pickup will be digitized by a LeCroy LC584AL oscilloscope. This scope has bandwidth of 1 GHz and will digitize in 8 Gsa/s bursts at a trigger rate of up to 30 kHz. The scope is controlled and read out over GPIB by a computer running LabVIEW. This software is based on a similar application developed at Fermilab by Barsotti (19). The RHIC control system communicates with this application via shared memory on a VME/MXI interface board. The entire system is event driven and synchronized by the RHIC beam synchronous event system. Functions provided by the system are summarized in Table 6.

TABLE 6. Wall Current Monitor Functions

Function	Features
Injection and acceleration bucket fill pattern	Reports integrated charge within each of the 360 buckets, and total charge
Store bucket fill pattern	Reports integrated charge within each of the 2520 buckets, and total charge
Bunch profile and beam centroid	Mountain Ranges
Calculated bunch parameters	length, peak current, area...
Spectral waterfall	Time resolved frequency domain view

IONIZATION PROFILE MONITORS

The ionization profile monitors (IPM) collect electrons that are produced as a result of beam-gas interactions (20). Two monitors will be installed in each ring, one horizontal and one vertical. Because the dispersion is non-zero at the location of the horizontal IPM, the measured beam width will be affected by both the transverse emittance and the momentum spread. A desirable future upgrade will be the addition of a horizontal monitor in an area of high dispersion.

The strong space charge field of the RHIC beam affects the both the ions and electrons that are produced from the residual gas interactions. However, the electrons are easily confined to a small Larmor radius by a weak magnetic field. Therefore, a permanent magnet dipole is installed over the vacuum chamber. The confined electrons are swept out of the beam in a few nanoseconds by an applied electric field. Meanwhile, the ions are slowly accelerated in the opposite direction where they pass through an electron suppression grid near the opposite wall. The extracted electrons are amplified by a two stage chevron microchannel plate. The resulting charge is collected on 64 striplines that are spaced 0.6 mm center to center. Special preamplifier hybrids designed by the BNL Instrumentation Division are used to integrate, shape and buffer the signal before transmitting it out of the tunnel.

Gold beams will give single-bunch profiles, while proton beam profiles will be generated by integrating the signals from all bunches for several turns. With 10^9 gold ions/bunch, beam width measurement will be accurate to ±3%. To keep the MCP from saturating with gold beams (signal from proton beams is too small to saturate MCP), the sweep field will be turned on only during data collection. There will be two measurement modes:

1. The profile of a single bunch will be measured on every turn. The sweep field will be off during the passage of all other bunches.
2. Every bunch will be measured for one complete turn. The sweep field will be left off for 100-1000 turns for the MCP to recover.

The system block diagram is shown in Figure 8. All timing is controlled by the beam synchronous event system. The 10 Msample/s, 12 bit ADCs consist of 8 channel VME boards with 128 ksamples of memory behind each channel. These digitizer boards and the timing board reside in the control system front end computer.

A prototype IPM was successfully tested during the 1997 sextant test. Single-pass profile measurements of bunches containing 10^8 Gold ions were made. Beam widths agreed at the few percent level with those measured by the VPM system.

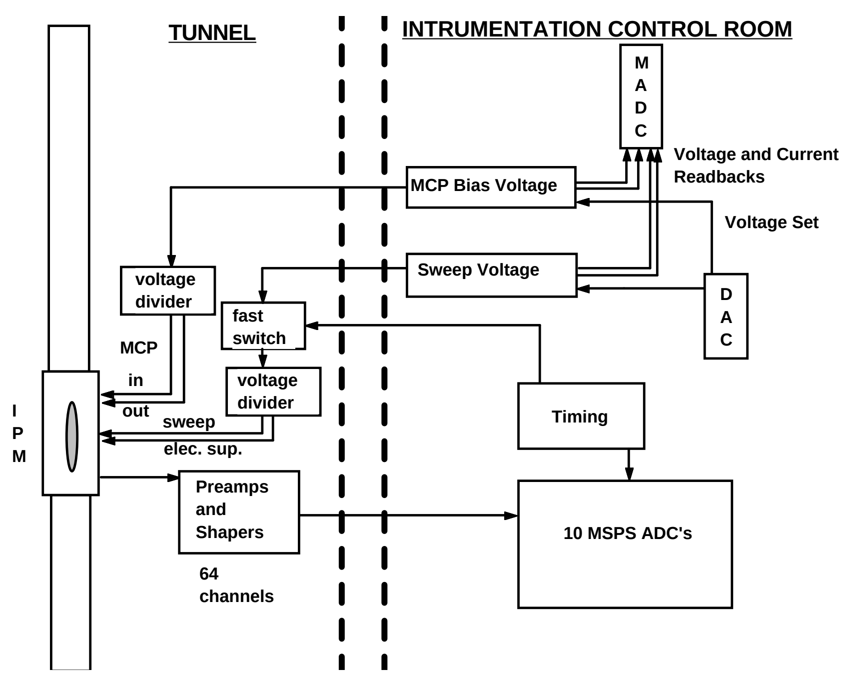

FIGURE 8. Block diagram of the Ionization Profile Monitor system.

TRANSVERSE FEEDBACK SYSTEM

The transverse feedback system will provide the following functions.

- Excitation of coherent betatron motion for diagnostics using one of the following modes:
  1. Single kick (50 μm amplitude at storage energy, expected decoherence time of a few hundred turns)
  2. Random sequence of kicks (larger betatron line, more emittance growth)
  3. Swept frequency
- Phase Lock Loop tune tracking
- Damping of injection errors
- Damping of transverse instabilities

The single kick and random kick modes will be provided for tune measurement during commissioning. All other functionality will be developed as experience is gained during operations.

The kicker system employs 50-ohm stripline kickers. Each unit is 2 m long and has four electrodes thus providing both horizontal and vertical deflection. Each ring has two units that will be wired in series for early operations. To provide large deflections at reasonable cost, the kickers are driven by solid state, switched pulsers capable of delivering up to 3 kV, 50 ns pulses at the revolution frequency of 78 kHz. Therefore, a selected bunch can be kicked turn by turn. After operational experience is gained, wideband linear amplifiers may be employed to drive one kicker unit per ring. This will allow development of a phase lock loop tune tracker and bunch by bunch feedback for damping potential instabilities.

The digital electronics consists of a Motorola VME based processor board and a Technobox PMC module for digital I/O. The VME board contains a 300 MHz PowerPC that will process the of 78 ksample/s turn by turn data stream while the PMC module contains an Altera gate array that will handle the 9.4 Msample/s bunch by bunch data stream. For tune measurements during early operations, turn by turn data from the standard position monitor channels will be used. Later, dedicated position monitor electronics will provide low noise, bunch by bunch measurements.

SCHOTTKY SYSTEM

A high frequency cavity from Lawrence Berkeley National Laboratory will be used to detect high frequency Schottky signals. Although somewhat harder to interpret than signals at lower revolution harmonics, these high-frequency signals suffer less contamination from coherent power (21). The cavity's transverse modes of interest are the TM_{210} and the TM_{120} at about 2.1 GHz. These two modes have a measured Q of about 4700 and are separated by 4 MHz. A longitudinal mode is at 2.7 GHz.

The signals will be carried from the tunnel on 7/8" solid shield coax to a digital signal analyzer located in the instrumentation control room. This analyzer has a 10 MHz bandwidth. During commissioning, the system will be locally operated. As certain data proves useful, it will be made available to the control system through a shared memory interface.

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