OVERVIEW OF RHIC BEAM INSTRUMENTATION AND FIRST EXPERIENCE FROM OPERATION *

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Abstract

A summary of the beam instrumentation tools in place during the year 2000 commissioning run is given including the technical layout and the appearance on the user level, here mainly the RHIC control room. Experience from first usage is reported as well as the lessons we have learned during RHIC operation so far. Upgrades and changes compared to the year 2000 systems are outlined. Described tools include beam position monitors (BPM), ionization profile monitors (IPM), beam loss monitors (BLM), bunch current measurements, luminosity monitors, tune meters and Schottky monitors.

1 INTRODUCTION

The **R**elativistic **H**eavy **I**on **C**ollider (RHIC) is the new accelerator flagship at Brookhaven National Laboratory on Long Island, NY (USA). The two super-conducting rings are built in the 3.8 km long tunnel originally constructed for the ISABELLE project. RHIC has 6 interaction regions where the two beams - “blue” circulating clockwise and “yellow” counter-clockwise - collide with zero crossing angle. Four are equipped with experiments. Table 1 summarizes some of the major collider parameters.

One of the major goals of the RHIC project is to discover and study the quark-gluon plasma, a very hot and dense state of matter believed to have existed a fraction of a second after the Big Bang. For this purpose, RHIC is designed to operate with various ions, from gold to lighter species such as copper, oxygen or silicon. In addition RHIC can accelerate polarized proton beams. The combination of polarization, luminosity, and beam energy to be found in RHIC will open exploration of a new and theoretically interesting regime in high energy spin physics.

RHIC instrumentation systems [1, 2] monitor diverse beams of up to 60(120) bunches in each of the two collider rings. Intensities range from low-intensity commissioning and pilot bunches to 10^{11} protons/bunch at 250 GeV and 10^9 Au^{+79} ions/bunch at 100 GeV/nucleon.

The major challenge to Instrumentation during the year 2000 commissioning run was to provide adequate diagnostic information during the acceleration ramp. While the main dipole and quad bus power supplies were well behaved, there were regulation problems in the shunt supplies (these problems grew out of late vendor deliveries, and are corrected for the year 2001 run) that caused tune and orbit to drift up the ramp. The effect of orbit drift at the beginning of the ramp was aggravated by poor sextupole power supply regulation at the extreme low currents required at injection, as well as by the compensation required for snapback. In addition, during acceleration of Gold the beam must pass thru transition. Transition crossing was complicated by the absence of power supplies for the gamma jump, which led to the use of a radial jump for transition crossing, and tune shifts proportionate to chromaticity. All of the above suffered the additional complication that the machine was not fully repeatable, that ramps with apparently identical initial conditions often produced radically different results. Despite these difficulties, but not without considerable effort, the machine was successfully commissioned and good experimental physics data was gathered.

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Parameter	Value	Unit
Circumference	3833.845	m
Beam energy (Au)	10.2 - 70 (100)	GeV/u
Beam energy (p)	28.3 - (250)	GeV
Revolution Frequency	78	kHz
Revolution Time	12.8	μs
RF frequency	28 (200)	MHz
# of filled buckets	60	
Bunch separation	220	ns
Luminosity	0.2 (2) 10^{26}	$cm^{-2}sec^{-1}$
Betatron tunes (x/y)	0.22/0.23 (0.19/0.18)	
horiz. ϵ_{nor} (*)	10-20	π mm mrad
vert. ϵ_{nor} (*)	10-15	π mm mrad
β^*	3,8 (1,10)	m
Number of ions/bunch	5 10^8 (1 10^9)	

Table 1: *Basic RHIC parameters during the year 2000 commissioning run. Design values, if different from commissioning run values, are added in brackets.((*): measured)*

2 BEAM POSITION MONITORS

The BPM electrode assemblies [3] operate at 4.2 K. The collider ring contains 480 BPM assemblies plus additional units for spin rotators, Siberian snakes, and beam dumps. Tight constraints on orbit relative to quadrupole centers are imposed during polarized proton acceleration, to minimize the strength of spin resonances. The relative locations of BPM electrical centers and quadrupole magnetic centers was measured for all BPMs with an estimated accuracy of approximately 100 μm RMS, and beam positions are corrected with this database.

2.1 BPM Electronics

Each channel of BPM electronics employs a broadband sampler [4]. The basic design is depicted in Figure 1. All measurement planes are treated independently; dual-plane assemblies are connected to two independent electronic channels. Two channels are contained within each BPM integrated front-end (IFE) module. Channels in the ring insertion regions, injection area, and dump area are cabled to accessible equipment buildings in up to 150-meter runs. All other ring modules are located in cryogenic areas of the tunnel and cabled to the appropriate electrodes with shorter, 2-meter cables. The low vacuum minimizes beam-gas scattering and the resulting radiation field at the electronics.

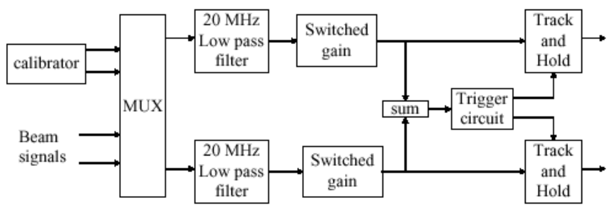

Figure 1: BPM electronics sampler design

Variable gain of 0, 20 or 40 dB is available. A high-impedance sum circuit provides the input to a self-trigger circuit. The trigger threshold is adjustable and self-trigger can be completely disabled to allow external clocking. In RHIC a selected bunch is sampled turn-by-turn at the revolution frequency of 78 kHz. There is no provision for simultaneous multi-bunch acquisition with a single BPM plane. Each sampler resides on a circuit board that also contains an FPGA-based timing decoder, DSP-based signal processing, and IEEE-1394 interface. [5]. The control system communicates with the channels via shared memory in a VME/Firewire [6] interface board. Up to 12 channels are connected to each interface board. The channels can operate in different modes. During injection, a turn-by-turn record of 128 turns for each injected bunch was collected. For the rest of the collider cycle, the channels periodically sent a turn-by-turn record for a particular bunch, and simultaneously streamed 10-kiloturn averaged and RMS position data at 0.25 Hz. For the next run the turn-by-turn record is upgraded to 1024 turns. Depending on gain setting and beam intensity, the BPM single measurements with a resolution of $1\mu m$ yield an accuracy of $20 - 50\mu m$ while the average orbit accuracy is of the order of $5\mu m$.

Among other things, data from the BPM system was used to accomplish remarkably good measurements of betatron functions[7], and in and in the orbit correction system[8].

3 BEAM LOSS MONITORS

3.1 Ion Chambers

The primary function of the RHIC ring BLM system[9, 10] is to prevent a beam loss induced quench of the superconducting magnets. BLMs also provide quantitative loss data for tuning and loss history in the event of a beam abort[11]. Due to the various magnet quench scenarios, RHIC BLMs have to cope with 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. This results in a dynamic range of 8 decades in detector current. The amplified signal is continuously compared to programmable fast and slow loss levels that can cause a beam abort, when data acquisition is halted to provide 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 BLMs are modified Tevatron ion chambers [12] with improved radiation hardness. The ion chamber [13] consists of a 113-cc glass bulb filled with argon. Half of the ion chambers are mounted between the two RHIC rings on the quadrupole cryostats. 96 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. In 1999 the BLM system could successfully be used to locate aperture limits (such as broken bellows shield fingers).

Electronics and Data Acquisition The electronics are located in service buildings, allowing access during beam storage. Since the ring BLM system is used for quench prevention, redundancy is provided by separate HV power supplies. In addition the power supplies are monitored by the RHIC alarm system. Readings can be taken at additional times as required for specific applications. Different gain settings compensate for the increased magnet quench sensitivity with current. Signals are directed to respective fast or slow loss comparators with independent programmable references. 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. A micro-controller [14] allows the BLM system to continue to provide beam loss quench protection even in the event of a controls failure.

3.2 PIN Diodes

A total of 16 PIN diodes [15, 16] are employed as fast, sensitive, cheap and easy to install loss monitors in the vicinity of the collimators in both rings. Arrays of 4 diodes surrounding the beampipe are installed downstream of the blue and yellow beam scrapers. In the yellow ring an additional array of 8 diodes is installed upstream of the scrapers, approximately 5m downstream of the crystal collimator. All diodes are readout by VME based scaler boards situated outside the ring.

4 BEAM INTENSITY MONITORS

4.1 DCCT

A DCCT for each ring was purchased from Bergoz. The unit has remotely switchable 50 and 500 mA maximum current ranges. 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, or when the wide-band output is integrated over 30 msec or more, but higher frequency measurements are affected. Because the modulation is regular, the high oversampling makes it possible to digitally filter much of this noise. The BCMs are located in the warm region of the 2 o'clock sector, which will be baked to 130 C. The BCM housing has been designed to insulate the transformer core from the heated beam pipe and prevent it from exceeding 60 C. Thermocouples on the detector are used to interlock the heater blanket. The outer shell of the housing provides the bypass path for the wall current around the transformer. Beam intensity information is used in a number of ways which set different requirements on the data.

4.2 Wall Current Monitor

The wall current monitor system [17]incorporates ferrite-loaded pickups based on the design by Weber [23]. One pickup is installed in each ring. The ferrite has been selected to attain flat frequency response down to 3 kHz with a transfer impedance of 1 Ω. The response extends to 6 GHz, which is well above pipe cutoff. Microwave absorber installed on either side of the pickup attenuates interfering modes. A LeCroy scope with a bandwidth of 1 GHz digitizes in 8 Gsa/s bursts with trigger rates up to 30 kHz. The scope is controlled and read out over GPIB by a computer running LabVIEW. 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 synch clock. The two basic functions provided by the WCM are bunch fill pattern and bunch profile. In fill pattern mode the WCM delivers integrated charge per bucket (360 buckets at injection, 2520 at store) and total charge. In bunch profile mode it delivers longitudinal profile of a single bunch as well as centroid relative to the bucket, typically in a waterfall display with 3 turn minimum interval, and calculated parameters such as bunch length and peak current. Since the WCM is sensitive to bunched beam only while the DCCT monitors the total circulating current, the difference between the two devices is used to detect and monitor debunched beam currents in RHIC.

The DCCT and WCM were useful for measurements of beam lifetime and emittance growth [18, 20], intra-beam scattering [19], and non-linear momentum compaction [21]. The WCM was particularly useful for transition studies.

5 IONIZATION PROFILE MONITORS

The ionization profile monitors (IPM) collect electrons that are produced as a result of beam-gas interactions [24]. Two monitors are installed in each ring, one horizontal and one vertical.

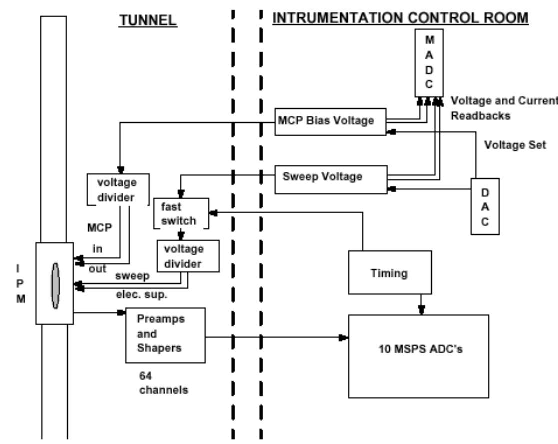

Figure 2: Block diagram of the IPM system

With 10^9 Au^{+79} ions/bunch, beam width measurements were expected to be accurate to 3%, and with a single bunch in RHIC good profiles were obtained. However, ringing caused by image current effects made the IPMs practically useless for operations. The addition of shielding and modified grounding should remedy this problem for the year 2001 run [22].

The system block diagram is shown in Figure 2. 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.

Data gathered by the IPM was used for injection matching and in emittance growth measurements [18, 20]

6 TUNE METER

6.1 ARTUS

At RHIC the first generation tune measurement device, ARTUS [25, 26], consists of a fast horizontal and vertical kicker magnet and one dual-plane BPM per ring. To measure the machine tunes, betatron oscillations are excited with a fast transverse kicker magnet [27] and transverse beam positions are recorded from the BPM. The fractional tunes are extracted from the position data by performing a FFT analysis. The capability of multiple turn-by-turn kicks ensures decent signal amplitude at all beam energy settings. The readout electronic developed for the dedicated BPM and the control system is installed in a VME crate outside the ring.

The Transverse Kicker Each ring has two kicker modules with four 2-m stainless steel striplines, allowing both horizontal and vertical kicks. The two kickers are connected in series to provide 4 m of stripline kickers. Each stripline subtends an angle of 70°at an aperture of 7 cm. Single pulses can power each of the four planes independently. The kick pulses are generated by fast FET switches [28] producing an approximately 140 ns long pulse. Single bunch excitation is possible with even up to 120 bunches per ring. All switches for all striplines in both rings are charged by one 5kV/2A power supply.

Trigger and Data Acquisition The FET switches are triggered by a TTL pulse of 200 ns width from a numerically-controlled oscillator (NCO) board. The two opposing kicker striplines for each plane are driven by one NCO channel. Thus both striplines are fired in accordance with the set frequency resulting in kicks with positive and negative signs. By selecting a NCO frequency close to the horizontal and vertical betatron frequency the beam is kicked resonantly enhancing the effect on the beam significantly if compared with a single kick. The enhancement factor was estimated to be of the order of 10 for a limited number of kick pulses. However, a set point equal or very close to the betatron frequency was shown to kick the beam out of the ring if the number of turns was too high. Tune measurements with ARTUS along the ramp have been successfully used as a feed forward correction to compensate for the large tune swings in RHIC.

6.2 Phase Locked Loop

During the year 2000 run a prototype Phase Locked Loop tune measurement system was operated. During beam store tune was continuously tracked with a precision of a few parts in 10^{-4}. The beam was excited with about 50 microwatts of power driving the tune kicker mentioned above. Emittance was monitored with good sensitivity by observing the power in the transverse Schottky signal. There was no observable emittance growth. The pickup was a movable BPM [29]resonated in difference mode with a Q of about 100 at a frequency of 230MHz. Schottky signals were also observable with this pickup. Using a resonant pickup above the coherent spectrum (acceleration RF is 28MHz) permits the low kicker power, and removes the beam-synchronous timing requirement. This system is evolving from prototype to operational status. It is hoped that after the PLL is operational the measured tunes can be used to drive the RHIC quadrupole buses [30], keeping the tunes at desired values all the way up the ramp.

7 LUMINOSITY MONITORS

Luminosity is monitored using a sampling Zero Degree Calorimeter (ZDC) [31] with two arms, one on either side of IR2, IR6, IR8 and IR10. The calorimeters are designed to measure neutrons emitted from nuclear fragments from Au+Au collisions that missed the actual interaction zone. The inclusive correlated emission in each beam direction is used to suppress many kinds of backgrounds and corresponds to a large cross section in the order of 10 b [32, 33].

The ZDC with a total length of about 0.7 m consists of alternating absorber and Cerenkov fiber layers. Crossing particles within a limited angular cone produce Cerenkov radiation which is channeled in the fiber ribbons to a photo multiplier tube (PMT). The detector arms are located at about +/- 18 m from each of the four equipped interaction points subtending an angle of about 2.5 mrad of the forward direction. The warm section between the DX and D0 magnets allows the installation of the ZDC modules between the two beampipes limiting the transverse size of the calorimeter to about 11 cm. The detector location is illustrated in Fig. 3.

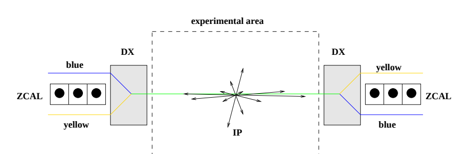

Figure 3: Geometry of the interaction region showing the beam splitting dipoles (DX) and the ZDC position.

At RHIC the ZDCs are both, monitors of the the collision rates at the four IRs and part of the experimental detectors, mainly the trigger system. Having the same design in each experiment the ZDCs are especially well suited to give comparable results everywhere. To guarantee comparability the readout electronics is identical in all IRs and split into two paths: one is leading to RHIC control system, the other is input to the experimental trigger.

8 SCHOTTKY

With the 17dB advantage in signal-to-noise ratio enjoyed with Au beams relative to protons, the Schottky spectrum is an extremely valuable source of information at RHIC. Two high-frequency cavities from Lawrence Berkeley National Laboratory [34] are used to detect longitudinal and transverse Schottky signals from both beams. The transverse modes of interest are the TM210 and the TM120 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 are down-converted to 2 MHz and amplified in the tunnel, then transported on 7/8" solid shield coax to a 10 MHz bandwidth FFT analyzer outside the ring.

Data is provided to the control system through LabVIEW communicating with the FFT analyzer via TCP, as well as through a remote Xterm scope application. During the year 2000 run this was primarily a specialist system. Considerable effort is being devoted to making the system more operator accessible, and to improving the interface to the control system.

During the beam run the Schottky system was useful for measuring tune and chromaticity up the ramp, and particularly at transition. In addition, non-linear momentum compaction was calculated [21] from the measurement of small variations in the frequency of synchrotron satellites near transition. Despite the comparatively poor S/N ratio relative to Au, during polarized proton running the Schottky system provided stripchart displays of tune, chromaticity, momentum spread, and transverse emittance during beam stores. [35]

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