OPERATIONAL EXPERIENCES DURING RHIC COMMISSIONING: FY2000

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Abstract
During the period between December 1999 and August 2000, the Relativistic Heavy Ion Collider or **RHIC** was brought on line for the first time. RHIC is designed to accelerate Au ions to a momentum of 100 GeV/c per nucleon in two counter-rotating rings with six (6) intersection/collision regions (IRs). The following will describe Operation's experiences by during this period. Topics will include: special methods for independent ring power supply management and control, Operational techniques for utilisation of superconducting (SC) trim and corrector magnets, techniques for crossing transition in an SC collider, techniques for steering in the (IRs) and methods for management of cryogenic and quench protection systems.

1. INTRODUCTION

The RHIC accelerator complex consists of the following components:

- **Injectors:**

Tandem van de Graff, which accelerates Au^{ions} to a momentum of 40 MeV/c per nucleon.

During RHIC operation in FY 2000 it delivered a beam pulse width of 700 µsec and a current is 12 µAmps or approximately 1.5×10^9 Total Au ions per pulse.

AGS Booster, which has a radius ρ of 32 m (104 ft). It collects and accelerates Au^{+32} to a momentum of 430 MeV/c per nucleon. The average intensity was $\cong 1 \times 10^9$ ions per cycle in FY 2000.

The Alternating Gradient Synchrotron or AGS (which is nearly identical to the PS at CERN) has a radius ρ of 128 m (419 ft) collects and accelerates Au^{+77} ions in 4 bunches to 11.24 GeV/c per nucleon. Typical intensity in the AGS was 2×10^9 ions per cycle.

- **Transport lines:**

Tandem to Booster (TTB) line: An 853 m (2800 ft) transport line. Au^{+12} extracted from the Tandem is stripped to Au^{+32} for Booster injection in this line.

Booster to AGS (BTA) transports beam between synchrotrons. It is 61 m (200 ft) long and has a stripping foil, which creates Au^{+77} for injection into the AGS.

The AGS to RHIC (ATR) line transports beam to the X and Y arcs. It has a switching magnet that when commanded to a positive value sends beam down the X arc for Blue ring injection and when negative transports beam to the Yellow ring. There is also a stripping foil, which removes the final electrons from the Au ions for injection into RHIC.

- **ARCs**

The X and Y arcs transport beam from the end of the ATR line into the two RHIC rings. The X arc transports to Blue and the Y to Yellow.

- **RHIC**

A 3.8 km (2.4 mile) circumference accelerator comprised of 2 (two) rings, Blue and Yellow, which accelerates Au^{+79} beam to a momentum of 100 GeV/c per nucleon and collides the two beams at 4 active experimental sites.

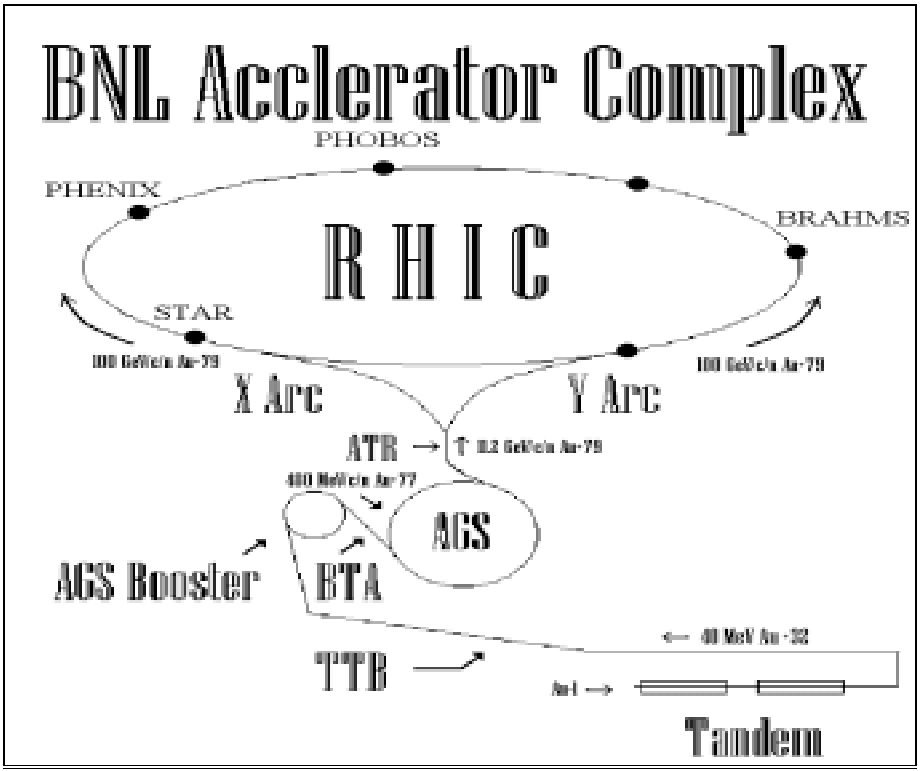

Fig. 1: Representation of Collider Accelerator Complex (not to scale)

During the previous RHIC runs, sextant test and engineering runs, Operations' main concern was with AGS experiments. The main contribution to these runs was to keep the injector on for the RHIC Physicists, while they ran RHIC itself.

During the effort to commission RHIC, Operations was charged with gaining as much hands on experience as possible. To help achieve this, Operations personnel were utilised as 'hands' for commissioning Physicists as much as possible. In doing so, Operators became familiar with nearly all aspects of everyday operation the collider.

2. EARLY COMMISSIONING

During the early stages of the commissioning effort, Operations worked with RHIC Accelerator Physicists and set up the injectors and ATR transport line.

2.1 AGS extraction

AGS extraction was set up such that beam could be delivered to the desired RHIC ring on demand. This required the use of several triggers for AGS extraction equipment. The Blue ring and Yellow ring triggers where set up as on demand, manually activated triggers. A third trigger called *'green'* was used for much ATR commissioning. This triggers extraction every AGS cycle. The AGS has one cycle approximately ever four (4) seconds. When triggering with the green trigger, the beam is transported to a beam dump at the end of ATR, upstream of the arcs.

2.2 ATR setup

Prior to injecting into RHIC, the transport line was set up and studied. Utilising the ATR dump, beam was extracted continuously from the AGS and ATR studied. The first objective was to re-establish transport to the dump (Fig. 2). This had been done previously during the sextant test and engineering run.

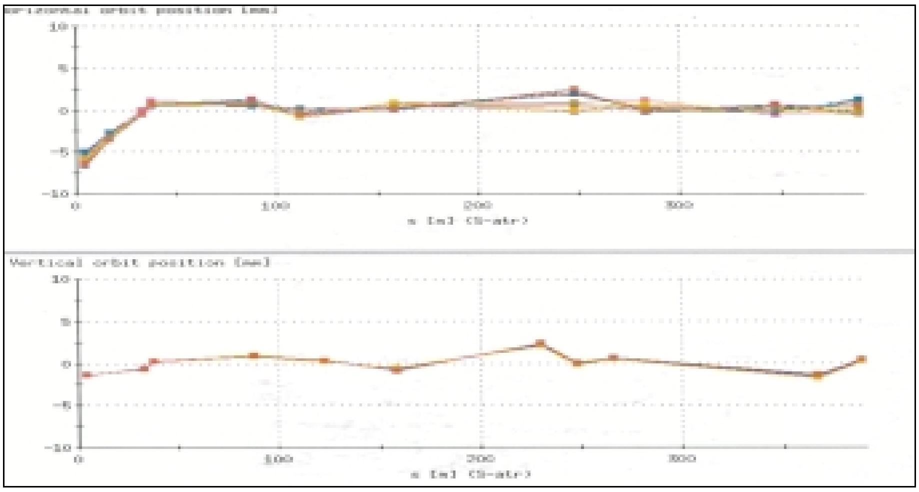

Fig. 2: Beam to AtR dump

Once transported to the dump, beam losses were minimised. Studies dedicated to cross-calibrate Beam Position Monitors (BPMs) to quad centres followed. Operators systematically varied the current for quadrupoles in the line just upstream of each BPM. This exercise was completed for a range of transverse positions incident to the quad. After several sets of data, optical centre was determined and BPM offsets were incorporated into the model for the line. Figure 3 shows a plot of ATR and the Y arc as the arc current was varied, which changes both the dipole and quadrupole strength. Moving a quadrupole in the ATR line produced similar plots.

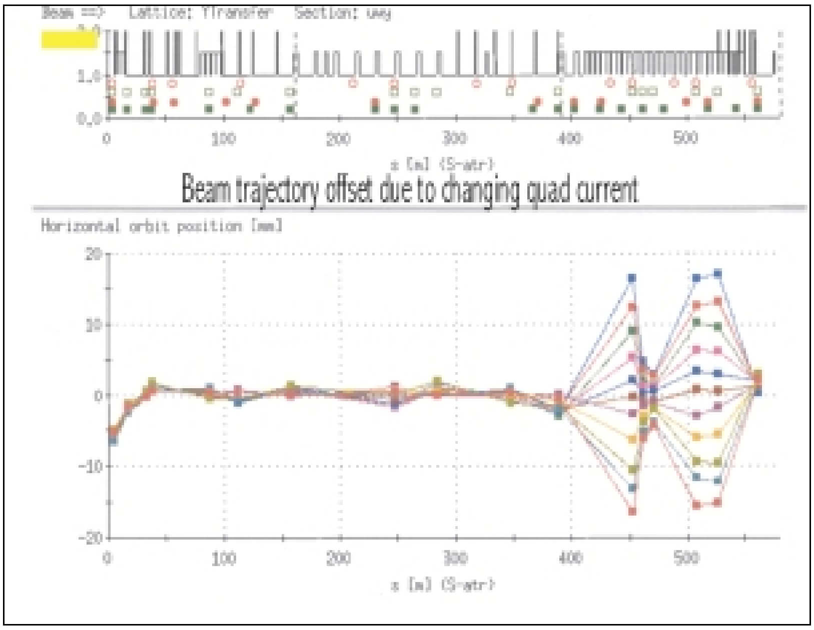

Fig. 3: Trajectory effect of changing the Y arc current

2.3 First RHIC injection

Beam was injected into one ring at a time, first the Blue then Yellow. Since beam has a downward trajectory at the end of the injection arc, it must be kicked upward onto the equilibrium orbit. The first injections were single turn only and done using a corrector dipole to deliver the required diversion. The first turn trajectory was measured and corrected using several methods. The first of these was by 'hand'. This method had an operator measuring the beam trajectory then changing individual orbit corrector magnets to minimise the divergence from the centre of the beam pipe. Although instructive, this proved to be very tedious and hard to reproduce. In order to close the orbit and circulate the beam, the injection kicker had to be set up. Figure 4 shows the current pulses for three of the four injection kicker modules for the Blue Ring as well as the beam signature on a nearby BPM.

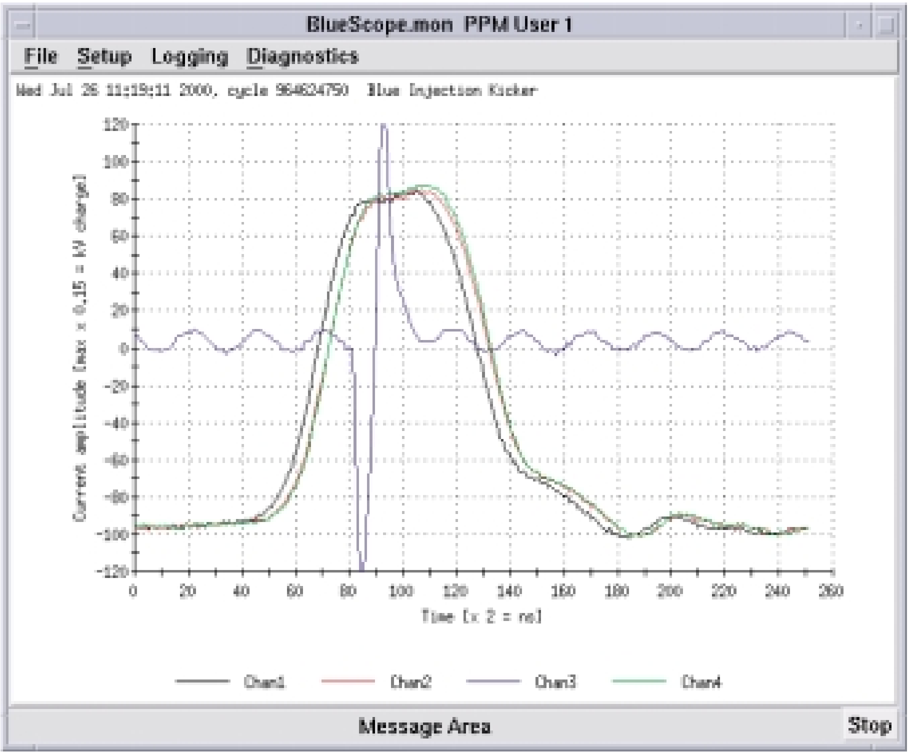

Fig. 4: Injection kicker and beam signals

Once injection with the injection kickers was established, The magnetic field for injection was adjusted to centre the beam on the ring BMPs. The next objective was to smooth the orbit. The controls for orbit correction allow the choice of any section (local) or the whole accelerator ring (global) for correction. The 'local' control was later used to steer the beams onto each other at the Intersections Regions (IRs). Figure 5 top, shows the measured orbit (red) and the corrected orbit (green) for a section of the Yellow ring. Figure 5, bottom shows a detailed view, which could be used for IR steering.

When the orbit correction application produced unexpected results, polarity checks were made on the correctors and several were found to be in the wrong polarity. Several BPM were also wired backwards. Both of these problems were compensated for in the software.

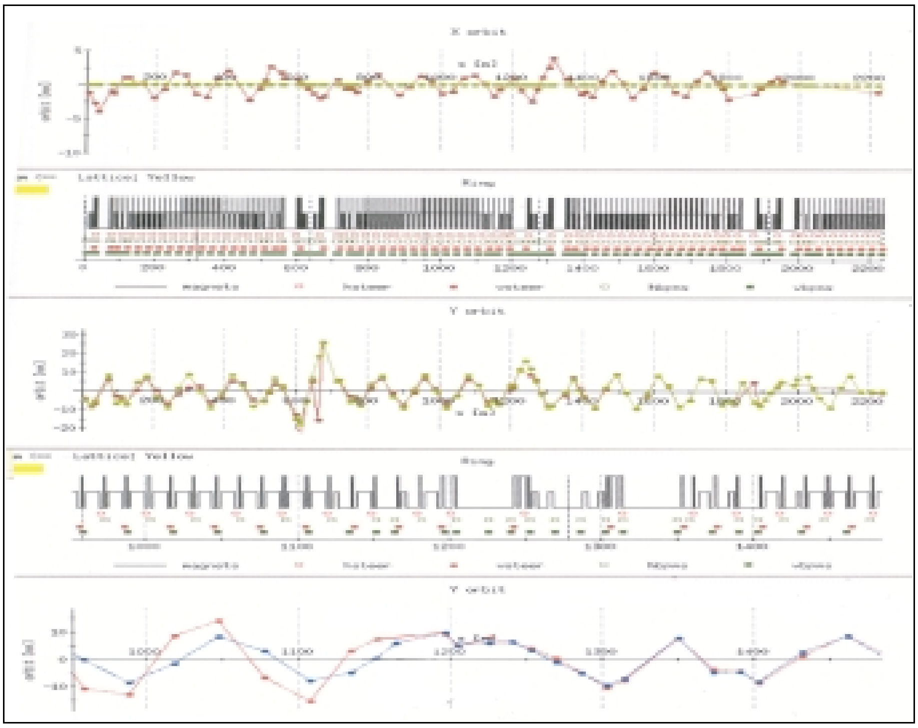

Fig. 5: Orbits

3. CAPTURE AND STORAGE AT INJECTION ENERGY

With beam parameters defined and survival for several seconds achieved, the RF system was brought on and set up. RF experts synchronised the RF systems in the AGS and RHIC so that bunches from the AGS were injected into specific bunches in RHIC. At first, one AGS bunch was injected and stored in each ring. Later 4 bunches were injected then finally 56. Table 1 displays RF harmonics and beam bunches during commissioning period. 4 Booster cycles of 6 bunches each were injected into the AGS. The beam was then de-bunched and adiabatically re-bunched into 4 bunches utilising a specialised RF cavity in the AGS. At extraction in the AGS, bunches are in every 3rd of 12 bunches and extracted into four buckets in RHIC. Bunches are in every 6th bucket in RHIC. Once in routine operation RHIC was filled with 56 bunches (i.e. 14 AGS cycles).

Table 1: RF Harmonics

Machine	**Booster**	**AGS**	**RHIC**
Harmonic	6	12	360
Bunches	6	4	4 (56)

Figure 6 shows the ‘Supercycle’, which defines configuration of the injectors. The graphic shows five (5) Booster Main Magnet current cycles (four (4) with beam and 1 dummy cycle) for every AGS cycle. Each RHIC ring takes as many as 14 Supercycles to fill.

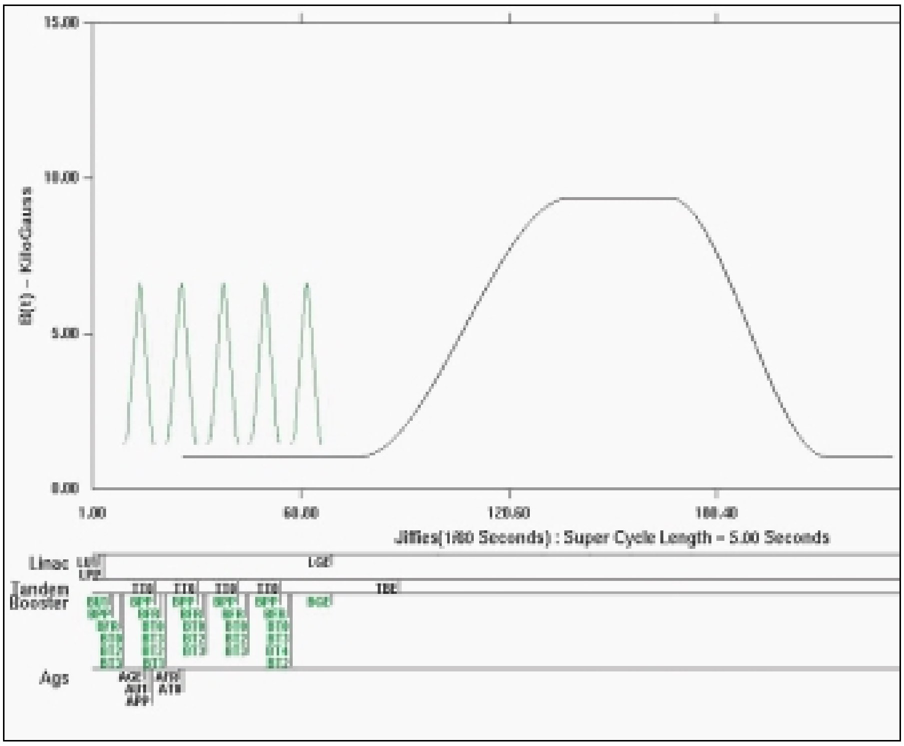

Fig. 6: Depiction of the injectors' Supercycle

4. ACCELERATION

With beam routinely stored at injection energy, attempts to accelerate the beam were made. The first of these was done with the main magnets ramping to 20 GeV/c/n or just below transition energy (22.9 GeV/c/n). Stopping the ramps at lower energy was done to save time, since a hysteresis correction cycle was necessary after each unsuccessful acceleration attempt. Early in commissioning, resetting the magnets took several minutes (see section on magnet control).

Initial attempts to accelerate were unsuccessful. After observing that the machine was strongly coupled at injection, attempts to adjust the tune produced unexpected results. Upon investigation, a systematic wiring error was found. Several quadrupole shunt supplies were wired backwards. This was corrected, but unfortunately, acceleration continued to elude commissioners. Further investigation and debate prompted commissioning Physicists to suspect that the some of the Chromaticity Sextupoles might also be wired wrong. Investigation proved this suspicion to be correct. Beam was accelerated shortly after this wiring error was corrected.

Later, a system for executing steps necessary to accelerate routinely was developed. It was eventually formalised and incorporated into the 'Sequencer'. The sequencer is an application designed to sequentially execute commands to control hardware and software. Steps included performing a hysterisis reset, filling the rings, activating RF beam control and activating, acceleration ramp and dumping the beam at the end of a cycle or store. The sequencer proved to be a valuable tool and is presently being expanded upon for use in FY 2001.

Figure 7 Top shows the beam current transformer profiles for the Yellow and Blue rings during an early attempt at acceleration. Beam current for the Yellow and Blue rings are orange and blue respectively. Beam Lifetimes are yellow and green. The bottom shows the radial pick up electrode signals (Blue on the top trace and Yellow on the bottom) as the beam crashed to the inside of the rings. Beam was surviving to $\gamma \cong 12$ at this point.

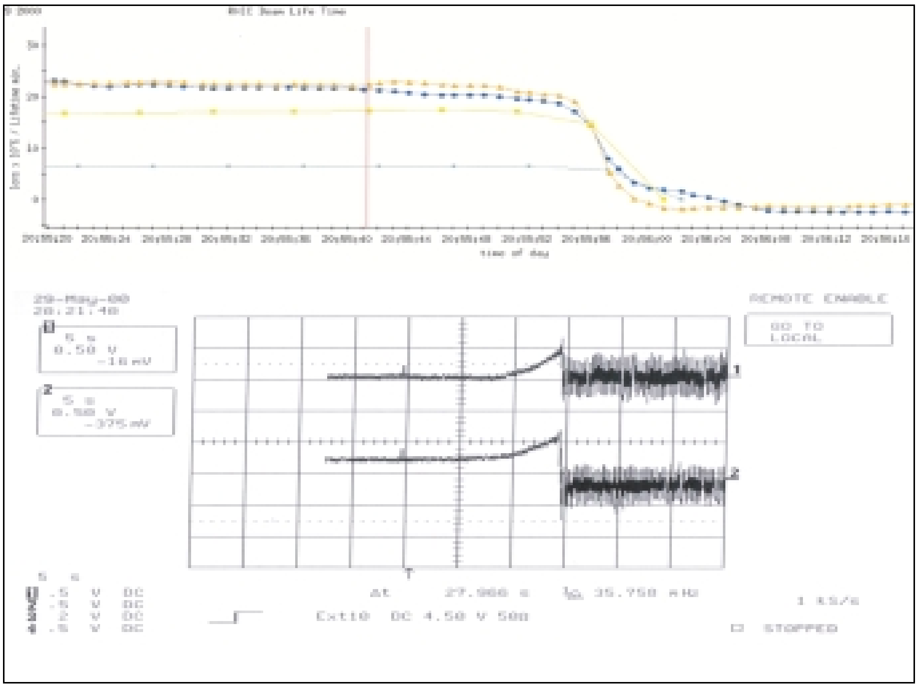

Fig. 7: Early attempt at acceleration

The machines were tuned until acceleration to transition was reproducible when the challenge became crossing a transition with a superconducting machine. This had not been done in a slow ramping superconducting machine before. Since beam is unstable at transition energy, it is desirable to cross through it as quickly as possible. This can be achieved a number of ways. One way is to gradually change the optics of the accelerator for a brief period just prior to transition, and then quickly reverse the distortion, moving the machines through transition as the distortion is removed. This is the preferred method and is achieved utilising a separate set of quadrupoles in the rings specifically designed for this task called ‘gamma jump quads’. During the commissioning efforts, the gamma jump was not available and an alternate method had to be employed. It was dubbed the ‘poor man’s jump’ due to the fact that no specialised (expensive) equipment was needed to create it. Using the poor man’s jump, the energy of the beam is changed rapidly using the RF radial control. The disadvantages of this method include that it is slower than the gamma jump, increasing the time the beam spends at transition and thus beam blow up, and that it utilises much of the beam pipe aperture, increasing the potential for losses. Figure 8 illustrates the gamma jump. The ‘poor man’s jump’ in on the left, the gamma jump on the right.

Figure 9 shows the Yellow ring beam current (blue trace) and a Main Magnet function with a maximum field at $\gamma = 30$. The Black is dipole current and the red the quadrupole current.

In FY 2000 beam final acceleration was $\gamma = 70$. RHIC is scheduled to run at design energy in FY 2001 ($\gamma = 100$).

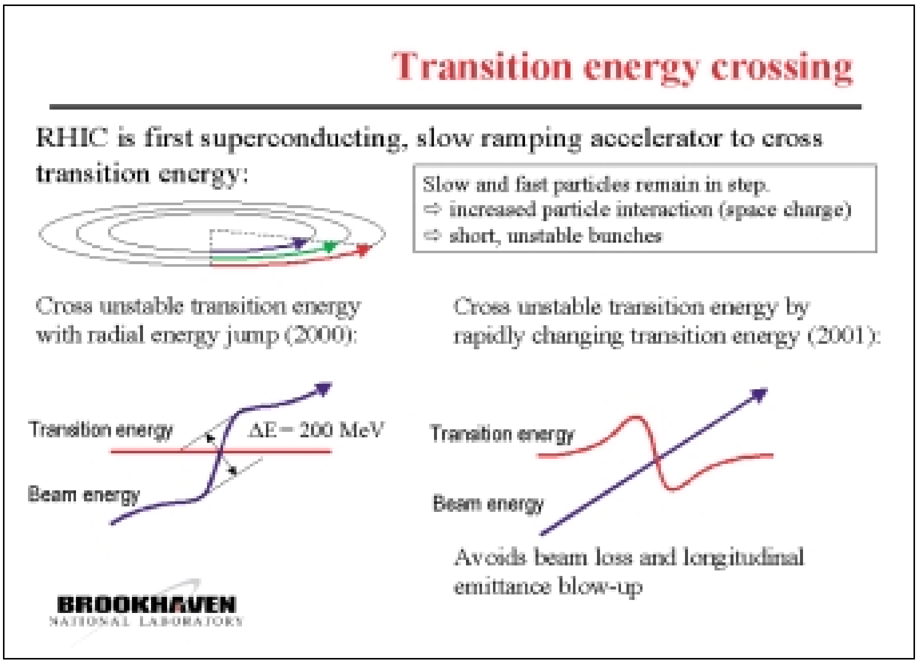

Fig. 8: Methods for crossing transition

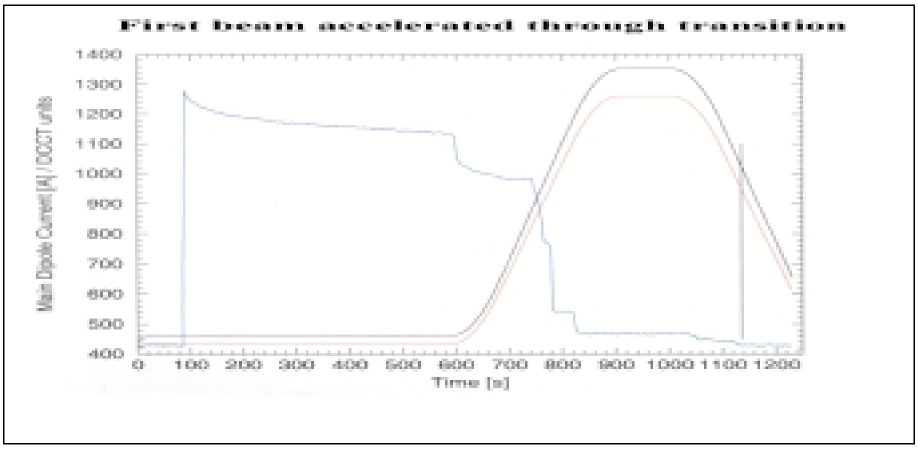

Fig. 9: First beam through transition in Yellow ring

5. COLLISIONS

After accelerated beam was established and stored in both rings simultaneously, the emphasis shifted to establishing collisions. In each IR, the Yellow and Blue beams must change position from the inside ring to the outside or ring RHIC (or visa versa). This is done using specialised dipole magnets, called DX magnets. These magnets are in series with the Blue main dipole bus and bend both beams, causing them to cross. During acceleration, the beams are not coincident transversely or longitudinally. When collisions are desired, i.e. at storage energy, they must be. This is done using the DX and corrector magnets for the transverse planes and by manipulating the RF longitudinally.

RHIC was designed with a Wall Current Monitor (WCM) physically located at the Intersection Point at 4 o'clock. Since the particle bunches have the same charge, they will induce opposite polarity signals on the WCM. Longitudinal bunch alignment can therefore be confirmed by observing that the two WCM cancel (i.e. if both machines have the same current, the signals will be zero). This process was completed in two steps. The first step was to synchronise the RF systems by locking them to the same frequency. In FY 2000, both rings were locked to the Yellow Ring's frequency. By doing this, the respective bunches 'stand still' relative to one another. The second step was to change the relative phase between Yellow and Blue bunches in small steps until they are on top of each other.

Figure 10 shows the process by which the beams were 'synched and cogged'.

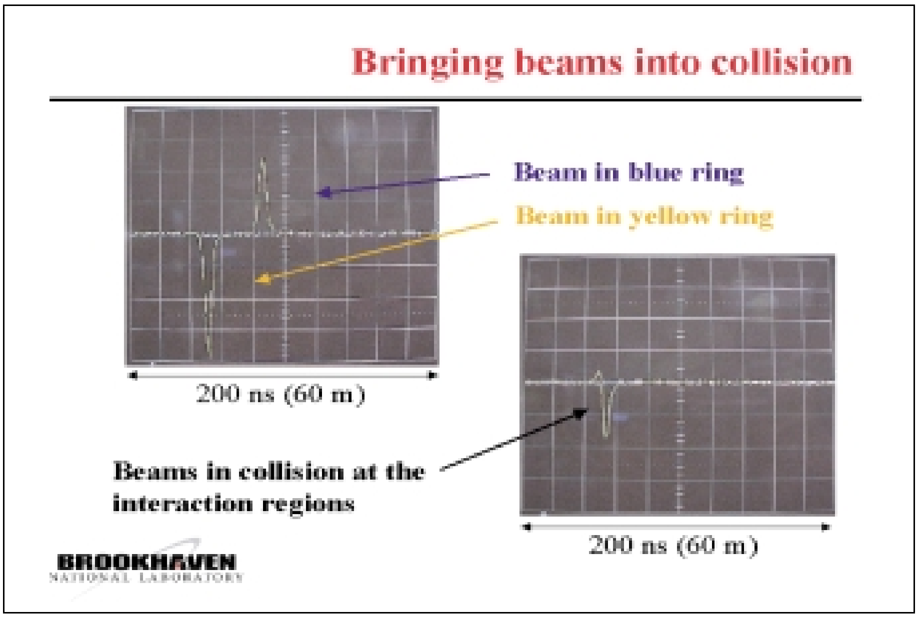

Fig. 10: Left: two bunches, one Blue one Yellow. Right: 'cogged'

With beam cogged and synched, the final step towards collisions was to steer the beams onto each other transversely. There are special BPMs located around the IPs specifically designed for this task. These have both horizontal and vertical plates where as other Ring BMPs are either vertical or horizontal. As previously mentioned, there is a specialised routine in the orbit control application designed specifically for steering the beams in the IRs. Figure 11 shows a sample display of the specialised BPM outputs during tuning for collisions.

While observing the beam position on BPMs, instruments at the IPs were monitored to determine the existence of collisions. These instruments, called 'Zero Degree Calorimeters' (ZDCs) are tungsten sample calorimeters and are positioned at equal distances from and at zero degrees to each experimental IP. With this geometry, incidental events on either detector due to interaction with residual gasses or other obstructions can be excluded and actual collisions detected.

Figure 12 shows the ZDC coincidence rate for STAR, PHENIX, BRAHMS and PHOBOS shortly after the first collisions.

Although the steering algorithm is designed for independent control in the IRs, in practice, when steering for one IR, others were somewhat affected. Operators were careful to record collision rates and BPM positions at all IRs prior to steering anywhere. Once the desired steering was completed, an iterative process of steering and re-steering restored all of the rates.

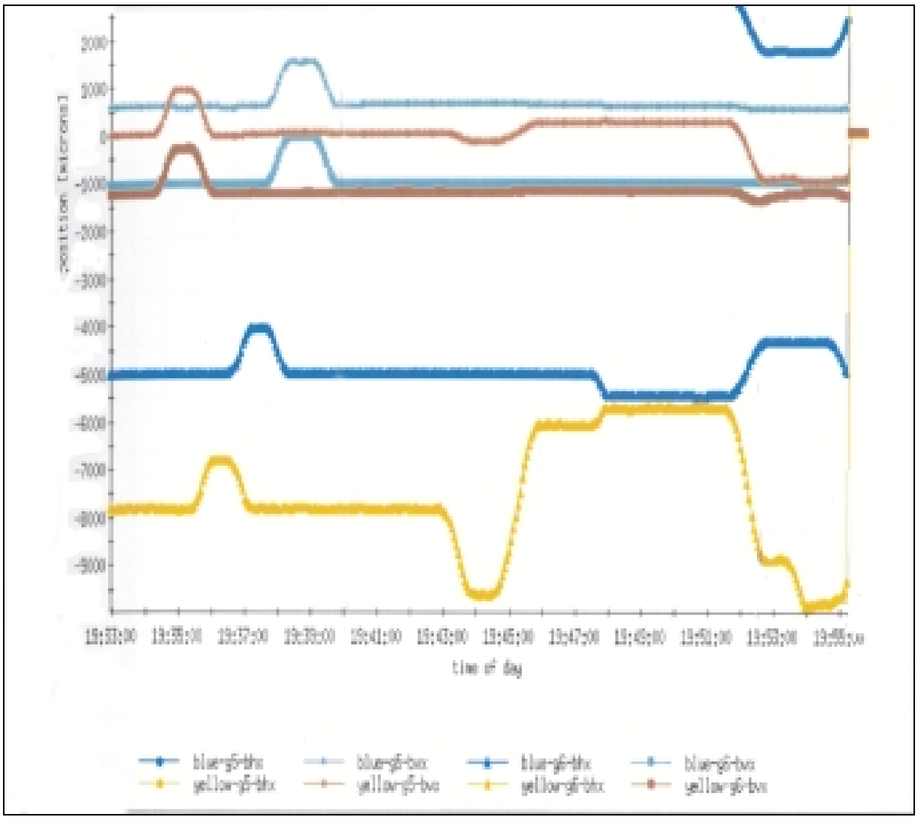

Fig. 11: Steering around the IR at 6 o'clock

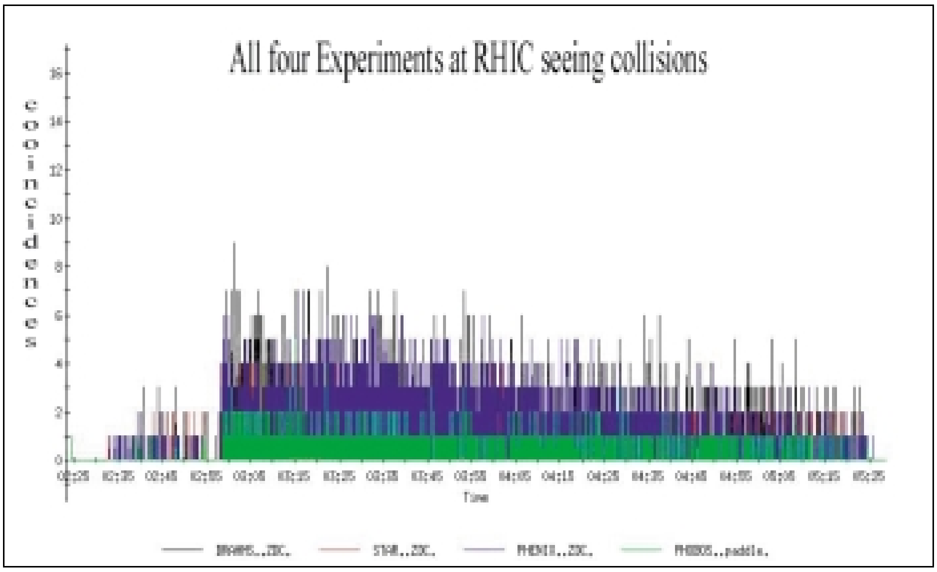

Fig. 12: Collisions with 4 bunches in each RHIC ring

6. MAGNET CONTROL

As mentioned, the RHIC ring is comprised of several different systems of magnets. Each of the systems are controlled and protected in various ways. The main ring magnets are controlled primarily by two applications, one called 'Ramp Editor' and one called 'Ramp Manager'.

Ramp Editor is used to create and load driving functions for the magnet power supplies. The user can define desired characteristics for the ramp and the application then calculates magnet currents using the accelerator model. When designing a ramp, the user can define the machine optics at various values for γ. Each of these segments called ‘Stones’ has editable inputs for all of the magnetic subsystems called ‘Pebbles’. Each Stone is a complete description of the machine. Stones for energies throughout the RHIC cycle are combined and fitted to create a time dependent ramp function. By employing this method the user has the option of either propagating a new setting throughout part, or all of a ramp or of having a change remain in effect for a particular Stone only. An example of a correction that might be propagated throughout a ramp is an orbit correction made at the Stone at injection. Examples of those that it may not be desirable to propagate are IR steering on the Last stone or modified tunes for Stone at transition. Figure 13 shows a sample ramp. Each horizontal line represents a Stone. The stones are fitted together to form a smooth ramp function.

Acceleration Ramp Table

	Time	γ	Stone#	muX.Blue	muX.Yellow	muY.Blue	muY.Yellow	chromX.Blue	chromX.Yellow	chromY.Blue
0	0.0	10.25	stone4	28.41	28.48	29.28	29.185	15.2079	17.2079	-7.64003
1	1.84808	10.336	stone17	28.4	28.48	29.28	29.188	20.0	20.0	-8.0
2	2.77815	10.86	snapback	28.4	28.47	29.27	29.175	23.6663	9.99996	-11.8249
3	4.79825	12.68	stone20	28.403	28.46	29.278	29.17	17.6663	18.0	-8.83487
4	6.19472	13.3	stone9	28.375	28.433	29.28	29.175	3.99997	4.00003	-5.58886
5	14.4338	22.4	stone10	28.305	28.367	29.308	29.185	-11.0	-11.0	19.0
6	15.5151	23.6	stone11	28.305	28.38	29.313	29.17	-11.0	-11.0	19.0001
7	21.2881	30.0	stone12	28.275	28.335	29.358	29.215	-15.0	-15.0	32.9999
8	38.3418	50.0	stone22	28.275	28.33	29.308	29.21	-15.0	-15.0	15.0
9	68.9311	70.0	stone27	28.255	28.298	29.277	29.184	-35.0	-15.0	15.0

Fig. 13: Stones and Pebbles making up a Ramp

Once a ramp is defined and loaded an application called ‘Ramp Manager’ is used to execute it. The Ramp Manager defines where to ramp to and how fast to ramp. This turned out to be critical since the rate of ramp must be such that the difference between the measured and expected main ring currents must be within tight tolerances or the Quench Protection System will shut the main ring power supplies down. Early in the commissioning effort, this rate was as slow as 2 amps per second, making a ramp to $\gamma = 70$ take 1600 seconds or 26 minutes! Ramp times were significantly reduced by the end of the commissioning period. A ramp presently takes approximately 2 minutes.

Ramp Manager was utilised to complete a hysteresis reset. It was determined that the injection field could be reproduced by ramping the magnet from near zero to a value at or above the maximum current for the next cycle, then back to near zero and finally to injection field. At first, this process was quite tedious due to slow ramp rates, but once regular stores were achieved and ramp rates increased, it became less of an issue. Figure 14 illustrates a hysteresis reset. Pilot bunches were utilised to determine if the field was in fact correct. If these pilot bunches, which are low intensity, showed that this was not the case, adjustments were made prior to full injection.

Blue ring was commissioned first because the Intersection Region magnets, which are common to both rings, are controlled by the Blue ring power supply. Because of this, the Blue ring can accelerate beam independently but the Yellow cannot. There were two ‘Ramp Managers’ early in the commissioning effort, one for Yellow and one for Blue magnet control. This allowed one group to work on the magnet power supplies while another could work with beam in the other ring. The two were combined later to form the present Ramp Manager.

Other means of power supply control are available and useful for specific tasks. All of the magnet power supply controls are available via a spreadsheet application called ‘pet’. Control via spreadsheet is most useful when an individual or small group of supplies needs to be manipulated. In practice this was very useful after power supply interlocks. All of the ATR magnets are controlled in this way. Two features designed into the spreadsheet control became useful for performing hysteresis resets for the (warm) magnets in ATR. The first of these features is that, for a given set of parameters, the user is able to associate a value for γ. An operator can change all of the ATR magnets simultaneously by changing the value for γ. When performing the hysteresis reset in ATR, operators would vary γ to complete a cycle similar to that of Fig. 14. Another feature was the use of Stones. To bring supplies on and reset hysteresis, operators had the option of changing ATR to a special Stone that has all zero commands. The method of changing to the 'zero Stone' in ATR was also adopted to expedite personnel access into controlled areas of ATR and RHIC. Since critical devices must to be secured prior to entry and the preferred method of turning off the power supplies is to do it with zero current command, the use of the zero Stone was a nice option.

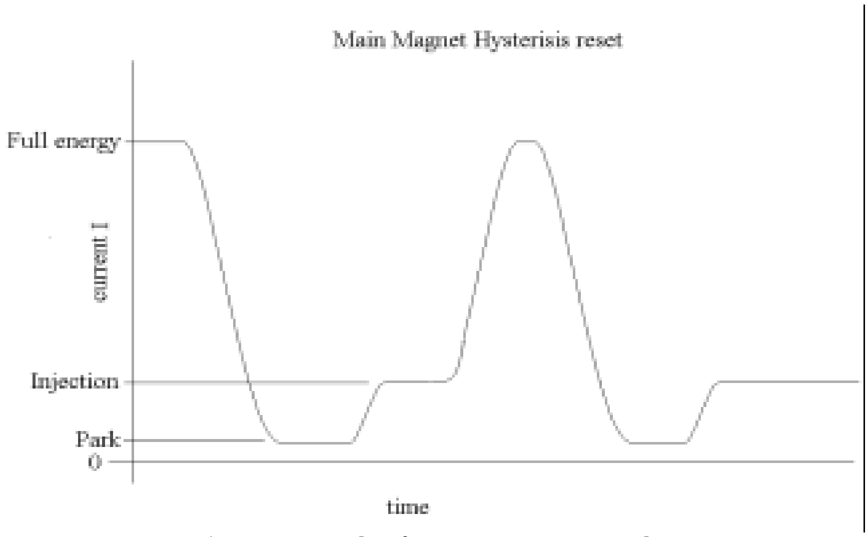

Fig. 14: Example of a Hysteresis reset cycle

In addition to interlock trips, other less obvious modes of failure were encountered. A tool called the Post Mortem Viewer was developed and proved very valuable for diagnosing such failures. It was designed to record magnet functions during each ramp. In the event of Quench Link Interlock, the data is saved into a file for later viewing. Otherwise, the data was overwritten during the next ramp. Figure 15 shows a sample output for the Post Mortem. A full output is comprised of over a thousand plots.

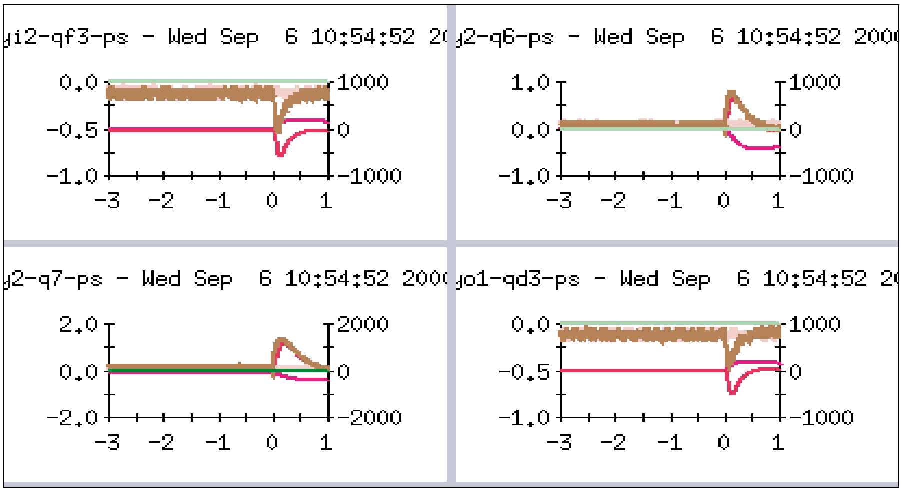

Fig. 15: Post Mortem View Sample graph

Another application called 'PSALL' was available for use. It was similar to the 'pet' version in that the user has control of specific devices. It was arranged so as to be very useful for recovering from quench link interlocks and was widely used in the field by power supply engineers.

7. QUENCH PROTETCTION

During the commissioning run, a major effort was put forth into setting up and understanding the Quench Protection System (QPS). As designed, the QPS monitors the magnets in the RHIC ring, all of which are super-conducting. Cryogen reserve level and flow, magnet voltage, current and temperature are monitored and must be within tight tolerances of predicted values. Early in the commissioning effort, interlocks from the QPS were very frequent, as many as 30 a day. These interlocks were almost exclusively *not* from actual Quenches. Many factors contributed to these interlocks.

An additional set of interlocks was actually implemented during the commissioning effort. Following a corrector magnet failure that was determined to be due to lack of coolant, lead flow indication for these and the ring sextupole magnets was incorporated in the QPS. Interlocks due to low lead flow for these magnets were separated from a main quench interlock system. They would not cause a beam abort or interlock the main ring supply (i.e. pull the Quench Link). A corrector-lead flow interlock would interlock only the supplies affected by the lead indicating low flow. Supplies with common interlocks also share common power supply alcoves in the RHIC ring enclosure. Following the recovery of flow in the lead in question, power supply recovery from a corrector-lead flow interlock was relatively simple. Affected supplies could be reset and brought up individually or in small groups via ‘pet’ or ‘PSALL’ then ramped to the desired value. Effect on the beam due to these trips varied from negligible to drastic depending on the devices that were interlocked.

Unfortunately, the majority of quench link interlocks did cause the beam to be aborted and the Main Ring Power Supply to interlock. The beam would be dumped and the main magnet supply interlocked when any one link in system of permit links (i.e. the Quench Link) failed.

N*early all of the Quench Link failures were NOT due to actual quenches.*

Several items related to the control of the magnets were found to cause interlocks. One of these was related to the Real Time Data Link (RTDL), which contains magnet command and read back information, and runs at 720 Hz. Occasionally, a bad data point on the RTDL would cause the quench link to be pulled. Power supply engineers added additional hardware and software to the systems affected by the RTDL to preserve magnet protection while keeping a single bad data point from causing the link to go down. A second source came from the Wave Form Generators (WFGs), which drive the magnet supplies. Differences between WFG command and WFG read back values often caused the Quench Link to go down. To minimise this problem, WFG software configuration was modified and power supply engineers cleaned up noise on the power supply read back outputs. All of the afore mentioned problems were static, i.e. they were independent of the ramp rate. Others were not.

While investigating possible sources for frequent quench link interlocks, power supply engineers discovered that the main ring sextupoles’ monitoring circuitry was different from the other elements. The voltage for the sextupoles is monitored on the (warm) power supply side of the cables, rather than the (cold) ring side, as is the case for the dipoles and quadrupoles. The calculation used for expected voltage did not take this into account. Modifying the algorithm for the sextupoles eliminated these interlocks.

Another source of trips came when attempts were made to ramp the magnets too fast. The algorithm for main monitoring the magnet was originally set up (or tuned) for a slow ramp rate. Elements to this algorithm needed to be changed (re-tuned) in order to ramp faster.

As each bug became evident and was corrected, quench events went from as many as 20 a day to about one a week. The ramp rate was also increased by more than 10 times. Figure 16 shows the pet page for the Quench Link Summary. A failure of any of these inputs will cause the link to go down.

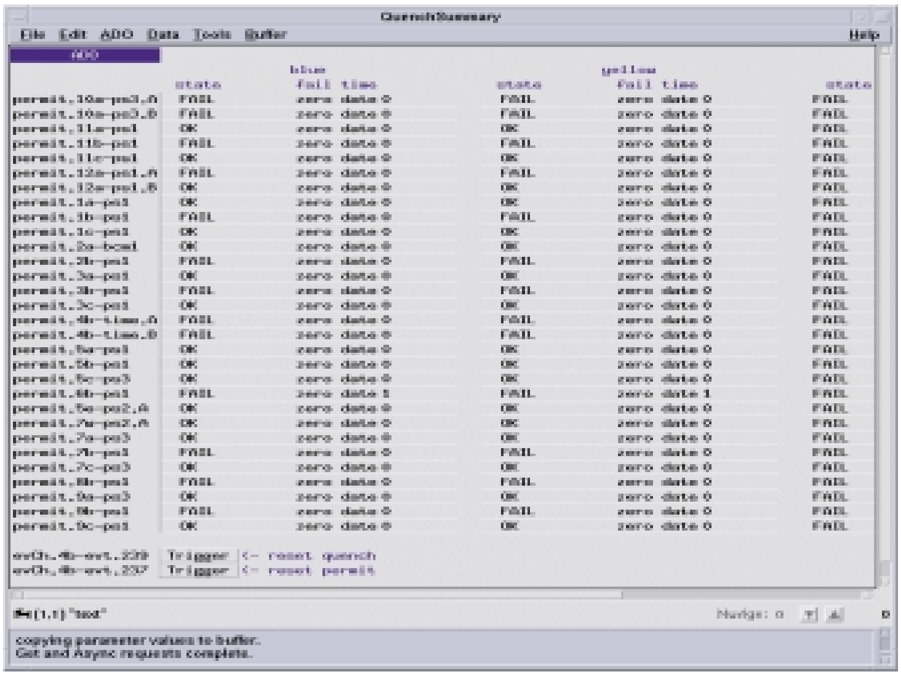

Fig. 16: Quench Link Summary page

8. RUNNING PHYSICS

By the end of the run, RHIC was routinely running for physics at all four experiments in the ring. Stores of many hours were common, some as long as 12 hours. Operations had taken over nearly all of the tasks involved in everyday running of the machine. For example, during the Sextant test, 4 RHIC Physicists were on 3 shifts a day and Operations spent most of the time working with injectors only. By the end of the commissioning run, One RHIC physicist was on during the day and evening, while Operations ran through each night. Figures 17–21 show various parameters for the FY 2000 run.

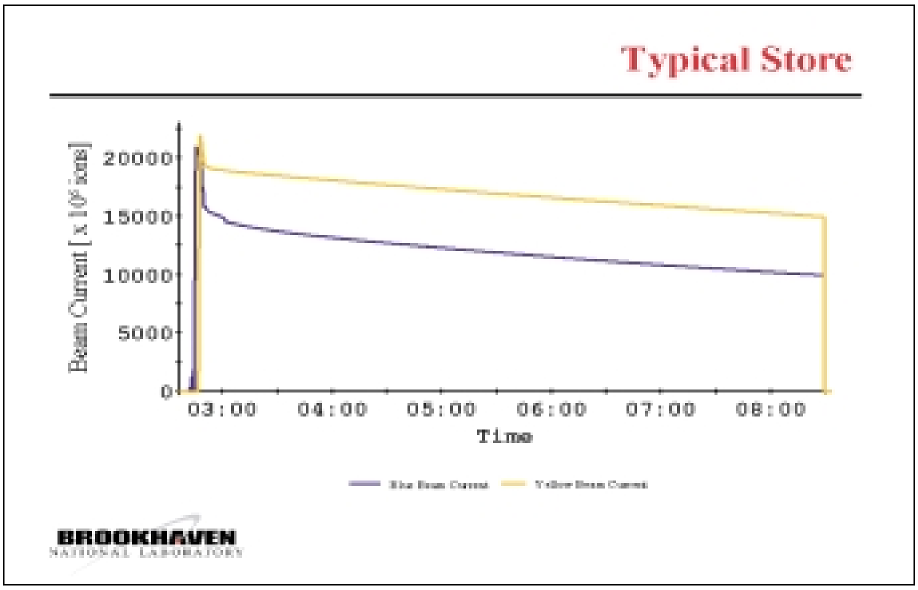

Fig. 17: Beam Current in Yellow and Blue during a typical store

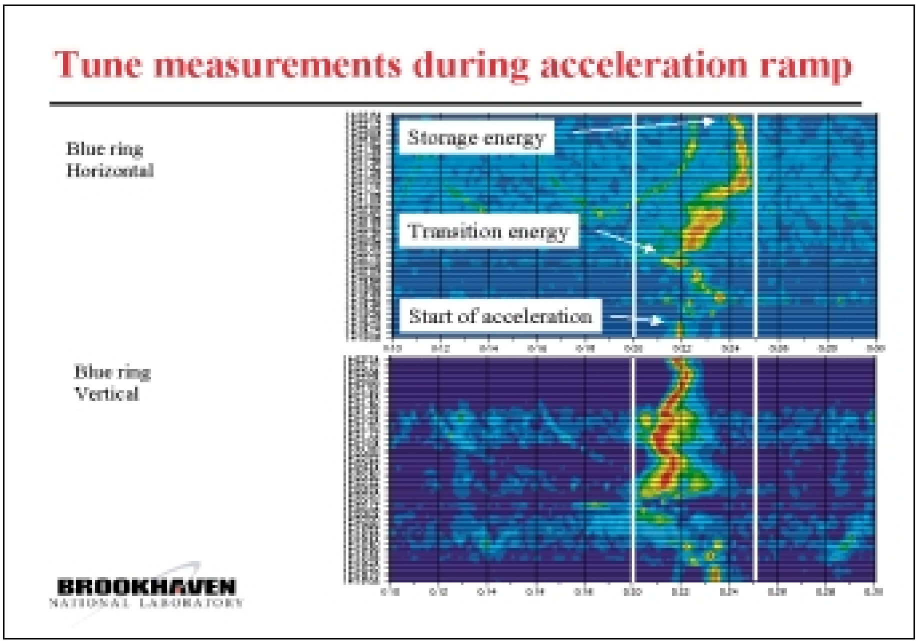

Fig. 18: Beam tunes during the acceleration ramp

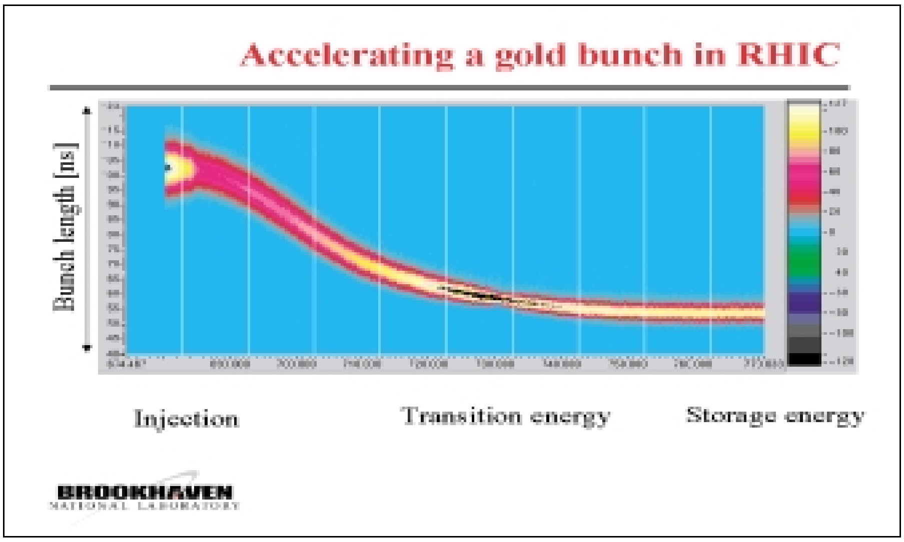

Fig. 19: FY2000 bunch lengths

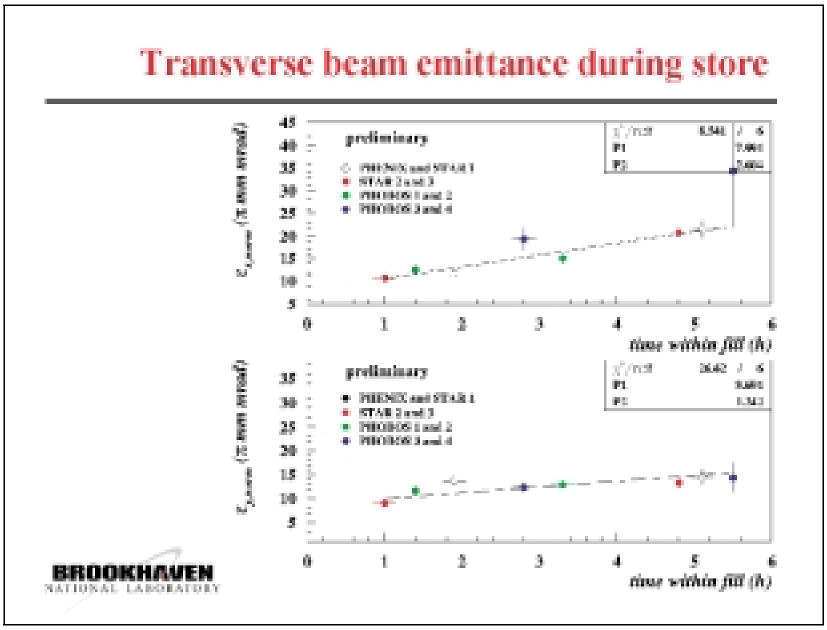

Fig. 20: Emittance vs. time in for a group of stores

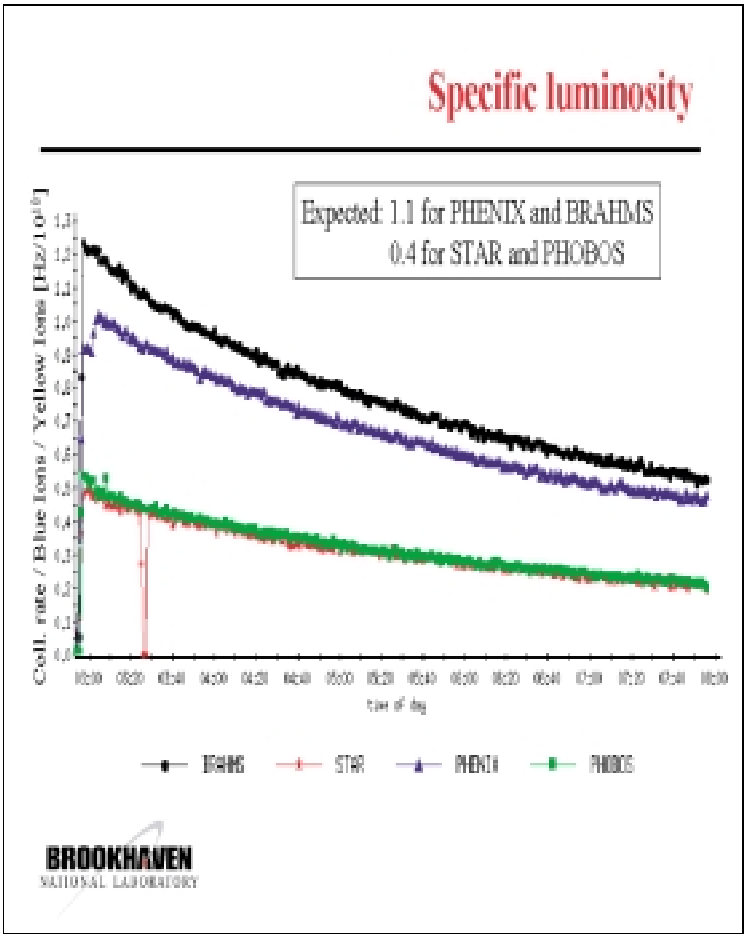

Fig. 21: Specific luminosity plot during a store

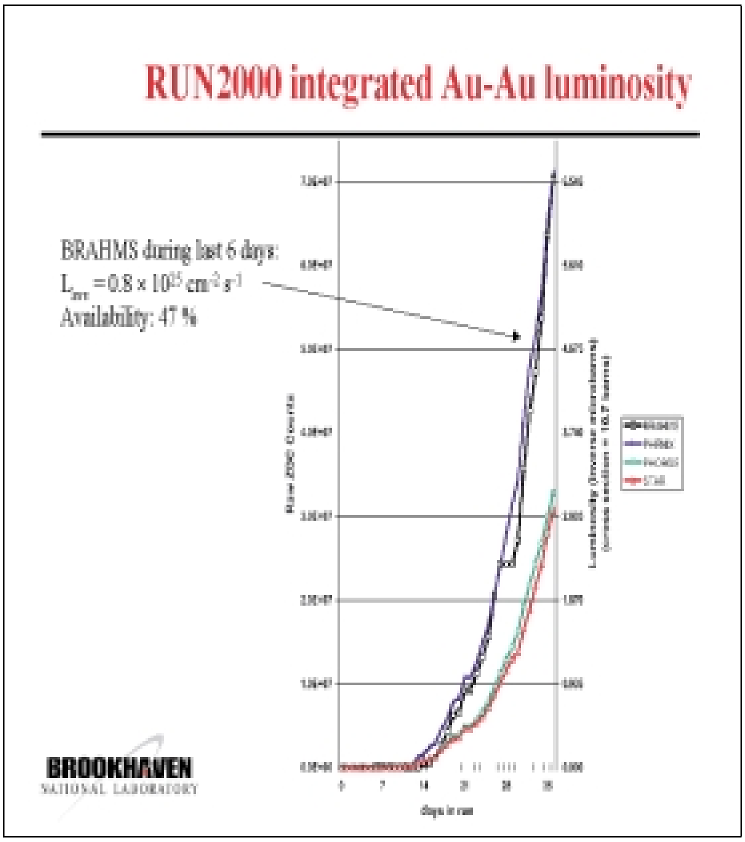

Fig. 22: Integrated luminosity for FY 2000 run

9. ACKNOWLEDGEMENTS

The following illustrations were taken from the RHIC logbooks for FY 2001: Figures 2, 3, 4, 5, 7, 9, 11, 12, and 13.

The following illustrations were adapted from a presentation for Quark Matter 2001 by *Dr. Thomas Roser,* Brookhaven National Laboratory: Figures 8, 10 and 17–21.