Commissioning of a first-order matched transition jump at the Brookhaven Relativistic Heavy Ion Collider

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(Received 15 July 2003; published 15 January 2004)

When accelerating gold ions in the Relativistic Heavy Ion Collider (RHIC) the transition energy must be crossed. For this purpose, RHIC uses a set of correction quadrupoles and special power supplies which can reverse polarity in less than 40 ms. These quadrupoles are used to produce dispersion bumps which increase the transition energy as the beam approaches transition. The change of polarity will then jump the transition energy across the beam energy. This paper describes the commissioning of the RHIC first-order matched transition crossing system.

DOI: 10.1103/PhysRevSTAB.7.011001

PACS numbers: 29.20.Dh, 29.20.Lq, 29.27.Bd, 29.27.Eg

I. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) [1] consists of two superconducting storage rings, “BLUE” and “YELLOW,” capable of accelerating hadron beams to magnetic rigidities up to $B\rho = 840$ Tm. In order to keep the orbit length of both rings equal in spite of the fact that they are lying side by side, beams alternately travel in “inner” or “outer” rings around the sixfold symmetric machine; see Fig. 1. These beams are injected through a whole chain of preaccelerators. After generation in the appropriate ion source, beams other than protons are accelerated by a 15 MV Tandem-van-de-Graaf. In the next step, particles are accelerated to a magnetic rigidity of $B\rho = 3.7$ Tm in the booster, and transferred to the Alternating Gradient Synchrotron (AGS). The AGS further accelerates the beams up to a magnetic rigidity of $B\rho = 80$ Tm, which corresponds to a relativistic Lorentz factor of $\gamma = 10.5$ for gold ions, and injects them into the RHIC.

The RHIC is installed in a tunnel with circumference $C = 3833.845$ m and bending radius $R = 242$ m. If transition crossing in the RHIC were to be avoided, the lattice would have to be designed with a transition energy below the extraction energy of the AGS, i.e., with $\gamma_t = 10.0$. In a ring with a periodic FODO lattice, the momentum compaction factor $\alpha = \gamma_t^{-2}$ can be approximated as [2]

$$\alpha = \frac{1}{C} \oint \frac{D(s)}{\rho(s)} ds \approx \frac{2\pi l^2}{RC \sin^2 \frac{\mu}{2}}, \quad (1)$$

where $D(s)$ and $\rho(s)$ are the local dispersion and local bending radius along the ring, respectively, while l denotes the half cell length and μ the betatron phase advance per FODO cell. Solving Eq. (1) for l and using the geometrical constraints given above together with a betatron phase advance of $\mu = 90^\circ$ and a momentum compaction factor of $\alpha = \gamma_t^{-2} = 1/100$ yields a half cell length of $l = 27$ m. This results in a maximum β function of [2]

$$\hat{\beta} = 2l \frac{1 + \sin \frac{\mu}{2}}{\sin \mu} = 92 \text{ m}, \quad (2)$$

which requires large beam pipe radii to accommodate the beam with its design normalized 95% emittance of $\epsilon_n = 10\pi$ mmmrad at injection, which increases to $\epsilon_n = 40\pi$ mmmrad over the length of the store due to intra-beam scattering. It was therefore decided to design the RHIC so that the transition energy has to be crossed. It is also possible to avoid transition crossing altogether by designing a lattice with imaginary transition energy [3].

Transition crossing is characterized by two time scales: the nonadiabatic time T_c and the nonlinear time T_{nl} . The former, given by

$$T_c = \left(\frac{AE_T}{ZeV} \cdot \frac{\gamma_T^3}{h\gamma'} \cdot \frac{C}{4\pi c^2} \right)^{1/3}, \quad (3)$$

FIG. 1. (Color) Schematic view of the Relativistic Heavy Ion Collider with its two superconducting storage rings “BLUE” and “YELLOW,” intersecting at six locations around the ring circumference. During the 2002–2003 RHIC run, deuterons stored in the BLUE ring were colliding with fully stripped gold ions in the YELLOW ring.

TABLE I. RHIC parameters for fully stripped gold ions.

Transition Lorentz factor	γ_T	22.8
Acceleration rate	$d\gamma/dt = \gamma'$	0.5
Maximum off-momentum parameter	$\delta_{\max}$	0.0043
Circumference	C	3833.845 m
Atomic number	Z	79
Atomic weight	A	197
Transition energy per nucleon	E_T	21.4 GeV
Peak rf voltage	V	300 kV
Harmonic number	h	360
Nonlinear momentum compaction parameter	α_1	-0.54

represents the time during which description of the longitudinal motion of the synchronous particle by a slowly varying Hamiltonian is inappropriate [4]. Here, e denotes the electron charge, while c is the speed of light. The other symbols are defined in Table I. Using RHIC parameters given in Table I, the nonadiabatic time is

$$T_c = 0.053 \text{ s.} \quad (4)$$

The nonlinear time

$$T_{\text{nl}} = \frac{|(\alpha_1 + \frac{3}{2}\beta_T^2)\delta_{\max}\gamma_T|}{\gamma'} = 0.188 \text{ s} \quad (5)$$

parametrizes the Johnsen effect, representing the fact that particles with different momenta cross transition at different times [5,6]. For a particle at the edge of the beam, i.e., at $\delta = \pm\delta_{\max}$, transition crossing is delayed or advanced by $\pm T_{\text{nl}}$. In the case of the RHIC, the nonlinear time T_{nl} is much longer than the nonadiabatic time T_c due to the slow ramp rate $\gamma' = 0.5$ of the superconducting magnets. Therefore, special care has to be taken during transition crossing to reduce particle losses and longitudinal emittance growth to reasonable values.

For this purpose, a dedicated γ_T jump system, consisting of correction quadrupoles and corresponding fast pulsed power supplies, has been implemented. In order to maximize the resulting γ_T jump height while simultaneously minimizing the associated tune and optics change, a so-called first-order matched transition jump scheme has been chosen [7,8]. “First order” describes the fact that the change in γ_T is proportional to the current in the associated γ_T quadrupoles, while “matched” reflects

the minimization of optics distortions. The RHIC is the first machine where such a scheme has been implemented and is the only superconducting accelerator that crosses transition.

Since commissioning results in the two almost identical RHIC rings turned out to be very similar, we report in most parts of this paper only those obtained in the BLUE ring.

II. OPTICS CONSIDERATIONS

Each arc of the sixfold symmetric RHIC lattice is equipped with eight γ_T quadrupoles connected in two families. One family of four magnets, located in the periodic FODO structure of each arc where a nonzero dispersion function exists, provides the actual transition jump. These quadrupoles are therefore referred to as “G.” The related tune shift is compensated by the other family (“Q”), consisting of four magnets located in pairs of two at the end of each arc where the dispersion is approximately zero. Assuming equal β functions in all eight γ_T quadrupoles, as well as identical dispersion in all four G quadrupoles, the maximum jump height together with a zero tune change can be achieved by connecting all eight γ_T quadrupoles to a single power supply. However, a perfect tune compensation in both planes (horizontal and vertical) can be achieved only if the betatron phase advance within each group of magnets is 90° , as schematically shown in Fig. 2. In this case, the quadrupole pairs G1–G3 and G2–G4 form two 180° closed dispersion

FIG. 2. Arrangement of two γ_T quadrupole families in one of the six RHIC sextants for a first-order transition jump [9].

FIG. 3. (Color) Horizontal (black) and vertical (red) β functions in one-third of the BLUE RHIC ring, before transition (top panel) and after (middle panel), for a γ_t jump height of $\Delta\gamma_t = \pm 0.5$ and a β function of $\beta_{x,y}^* = 5$ m at all interaction points. The plot at the bottom depicts the regular situation with the γ_t quadrupoles off.

bumps, while the tunes remain unchanged by a polarity change in these quadrupoles if the Q quadrupoles change sign simultaneously. Since a β beat is driven with twice the phase advance, adjacent quadrupoles cancel each other in this respect.

The horizontal phase advance in the RHIC per FODO cell—and thus between adjacent γ_t quadrupoles—is only 81° , resulting in a significant β beat and therefore a non-negligible quadratic component in the tune-versus-

quadrupole strength function. Therefore, the two families per arc are provided with two independent power supplies, thus allowing the ratio between the magnet strengths of the two families to be optimized. Although the β beat due to each arc cannot be compensated completely, the effects of entire arcs partially cancel each other. Figure 3 shows the resulting optics in the BLUE RHIC ring for both polarities of the γ_t quadrupoles, for a γ_t jump of $\Delta\gamma_t = \pm 0.5$, together with the undisturbed case (γ_t quadrupoles off).

Since the associated tune change per quadrupole family for six arcs is about $\Delta Q_x \approx 0.3$ and $\Delta Q_y \approx 0.16$, exact tracking of the magnet currents in both families is very important. This is ensured by connecting the same number of identical quadrupoles, namely, four, to each power supply, thus providing an equal load to each of them. Furthermore, the exact duration of the actual polarity change can be fine-tuned independently for each individual power supply.

Figure 4 shows the equivalent circuit of the bipolar switching power supplies [10]. The excitation current ramps up slowly to a maximum value of ± 40 A over several seconds. When the solid state switches flip, the current in the magnet reverses polarity. Since the high inductance of the superconducting magnets ($L = 120$ mH) limits the current polarity jump time, a high voltage (HV) power supply is needed to increase the dI/dt rate while the magnet current switches direction. This is accomplished by a 600 V dc power supply charging a capacitor bank. A sufficiently high voltage is added across the inductance load while the current changes polarity. When the magnet current, which is measured using a dc current transformer, reaches its initial amplitude with reversed polarity, the high voltage power supply is disconnected and the magnet current is provided by the main current power supply. After the jump, the magnet current is slowly ramped down to zero. This scheme results in a γ_t jump of $\Delta\gamma_t \approx \pm 0.5$ within approximately 30 ms, maintaining a clearance of

$$|\gamma - \gamma_T| > 0.5 \approx 6 \cdot \gamma' T_{\text{m}}. \quad (6)$$

The corresponding transition crossing rate $d(\gamma -$

FIG. 4. Equivalent circuit of a transition jump quadrupole.

$\gamma_t)/dt = 33 \text{ s}^{-1}$ is approximately 60 times faster than without a jump.

III. COMMISSIONING RESULTS

The RHIC transition jump system has been fully commissioned during the 2002–2003 RHIC deuteron-gold run. The γ_t quadrupoles are ramped from zero to their design strength within 8 s, starting 10 s before the actual polarity change. This results in two intervals of 2 s duration each before and after the jump during which the machine optics remains unchanged while the beam energy increases. This ensures that relevant machine parameters such as tunes and chromaticities are stable during this period and can easily be monitored.

Before actual beam operations started, the jump duration of the various γ_t power supplies was adjusted. For this purpose, the power supplies were ramped to the same current as required for the transition jump. The high voltage on all power supplies was set to the maximum value. Then the polarity was flipped and the power supply currents were monitored. The exact duration of the jump for each individual power supply was adjusted by lowering the high voltage so that the resulting duration matched the slowest power supply, thus resulting in the fastest technically feasible jump. Figure 5 shows the resulting power supply currents during the polarity flip in the BLUE ring.

As a first step during beam operation, some tests were performed at injection. After initial polarity checks by observing tune changes as a function of magnet strength in single γ_t quadrupole families, all γ_t quadrupoles were set to their design strengths to measure the overall tune changes induced by the entire system. When all quadru-

FIG. 5. (Color) Measured magnet currents during the transition jump in the BLUE ring. The total jump duration is about 30 ms; the 12 involved power supplies track within 1 ms.

poles are set to a strength that corresponds to their setting just before the transition jump, the resulting tune changes in the BLUE ring are $\Delta Q_x = +0.008$ in the horizontal plane and $\Delta Q_y = -0.005$ in the vertical plane, while the changes in the YELLOW ring are $\Delta Q_x = +0.015$ horizontally and $\Delta Q_y = -0.001$ vertically. The corresponding design parameters are $\Delta Q_x = -0.003$ and $\Delta Q_y = -0.005$ (BLUE) and $\Delta Q_x = -0.000$ and $\Delta Q_y = -0.003$ (YELLOW). Given the fact that these tune changes are the differences of the tune shifts induced by the “G” and the “Q” families, which are about 0.3 horizontally and 0.16 vertically, this agreement is very good. The small discrepancies are most likely due to orbit changes in the RHIC sextupoles, caused by off-center beam positions in the changing γ_t quadrupoles. This explanation is consistent with the fact that during these tests the rms orbit in the YELLOW ring was about twice as large as in the BLUE.

To avoid unnecessarily large tune changes during the γ_t jump on the acceleration ramp, the orbit was centered in the γ_t quadrupoles. The magnetic center of those quadrupoles was determined at injection energy by a beam-based alignment technique, changing one quadrupole family in a single arc (four magnets) at a time. Treating each involved quadrupole as a dipole corrector, the magnetic center can thus be determined. After establishing a “golden orbit” through the centers of all γ_t quadrupoles, orbits on the acceleration ramp were corrected with respect to this ideal one.

Next, the exact timing for the γ_t jump was determined. Since the bunch length in the vicinity of γ_t varies proportional to the fourth root of the energy difference [11],

$$\sigma_s \propto |\gamma - \gamma_t|^{1/4}, \quad (7)$$

this was accomplished by plotting the fourth power of the bunch length versus time. Since the energy increases linearly with time, this translates directly into an energy difference $|\gamma - \gamma_t|$. Extrapolating the two resulting straight lines to the point where the bunch length equals zero thus gives the two times, or energies, when transition crossing would occur before and after the jump, respectively (see Fig. 6).

After finding the timing for the γ_t quadrupole polarity flip, the exact time of the associated rf phase flip was adjusted to minimize longitudinal quadrupole oscillations due to any kind of bucket mismatch after the jump. This adjustment was found to be sensitive on the level of 1 ms. The resulting performance is shown in Fig. 7.

IV. CONCLUSION

The RHIC transition jump system was successfully commissioned, resulting in nearly 100% transmission efficiency (see Fig. 8) together with zero bunch lengthening (Fig. 7). However, operational experience shows

FIG. 6. (Color) Measured rms bunch length σ_s (red line) and its fourth power σ_s^4 (blue line) around transition in the BLUE ring, fill 02684. The proper times for the case before and after the jump when $\gamma = \gamma_t$ can be found by extrapolating the measured σ_s^4 data to the points of zero bunch length. This is the case at -1.1 s and $+1.1$ s, respectively. Since the actual jump occurs at 0.0 s, this indicates a symmetric jump. Longitudinal quadrupole oscillations after the jump are due to mismatched timing of the rf phase flip with respect to the γ_t quadrupole polarity flip.

that the beam tends to become unstable when intensities are increased beyond a certain threshold. These phenomena can be categorized as two types of instabilities: a fast one which was cured by octupoles [12], and a slow one that was found to be critically dependent on the chroma-

FIG. 7. (Color) Measured rms bunch length σ_s (red line) and corresponding fourth power σ_s^4 (blue curve) after adjusting the timing of the rf phase flip with respect to the γ_t quadrupole jump. No longitudinal quadrupole oscillation is induced by the transition jump, indicating optimized timing.

FIG. 8. (Color) Total beam intensity during the ramp in both RHIC rings. Transition crossing is indicated by a dashed vertical line, as well as start and end of the ramp.

ticity, which has to change sign at or around transition. This sign change is provided by a chromaticity jump of about $+2$ units in both planes due to the polarity flip of the γ_t quadrupoles and the associated modification of the dispersion function. However, according to operational experience in the RHIC it is beneficial to change the sign of the chromaticity even a few seconds before the transition crossing. This sign change happens naturally rather slowly due to the slowly ramping sextupole magnets involved in the procedure, resulting in a timing that is not very well defined. In order to improve this situation, the installation of fast sextupole power supplies is potentially foreseen, providing a chromaticity jump of about five units in about 30 ms at or around transition [13,14].

ACKNOWLEDGMENTS

We would like to thank D. Trbojevic, J. Wei, and J. van Zeijts for helpful hints and discussions, as well as D. Bruno and G. Ganetis for maintaining the power supplies. We are also indebted to S. Peggs for reading the manuscript. This work was performed under the auspices of the U.S. Department of Energy.

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