Results from Betatron Phase Measurements in RHIC during the Sextant Test

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Abstract

The Sextant Test of the Relativistic Heavy Ion Collider (RHIC) was an important step towards its completion. One sixth of the two RHIC accelerators was fully commissioned. Gold ion beam was injected and transported through one sextant of one of the two rings. The betatron phase advance per cell was measured by recording differences in the horizontal and vertical positions of the beam at the end of the sextant due to a sequence of correction dipole kicks along the beam line. Measurement results show excellent agreement with predicted values, confirming that production measurements of the integral functions of the quadrupoles were very accurate, and that the polarity of all elements (correction dipoles, quadrupoles, dipoles et.) was correct.[1]

1 INTRODUCTION

RHIC will accelerate heavy ions (nominally fully stripped gold) up to an energy of 100 GeV per nucleon. It can also accelerate two polarized proton beams to 250 GeV, or even collide heavy ions with protons. The two superconducting rings will accelerate (up to 100 GeV/nucleon) and collide even or different heavy ion species (up the the fully stripped gold) as well as two 250 Gev polarized proton beams. There are six interaction regions (IR) with a *telescope* made of quadrupole triplets and three FODO cells on each side of the beam interaction points (IP). In between IRs there are six arcs made of twelve FODO cells. RHIC commissioning is expected in early 1999. RHIC includes two large detectors (PHENIX and STAR), and other smaller experiments (like BRAMS and PHOBOS).
The sextant test of one of the two rings of the Relativistic Heavy Ion Collider (RHIC) was performed at the beginning of 1997. The gold ion beam was successfully transported through the sixth of one *yellow* of the two rings. During the sextant test almost all RHIC systems were tested: the cryogenic-system and the large liquid helium refrigerator, the vacuum system, power supplies and wave form generators, control system, beam-permit link, beam position monitors, loss monitors, injection kicker and the *Lambertson* septum magnet, beam profile monitors, current monitors, correction dipoles, and the personnel safety system.
This report describes a betatron phase measurement which relied on:

- Magnetic field measurements, including integral functions.
- Electric and polarity measurements.
- Magnetic center and roll production surveying measurements.
- Beam position monitor (BPM) survey measurements with respect to the center of the quads

2 BETATRON PHASE MEASUREMENTS USING DIPOLE CORRECTOR MAGNETS

The measurements described were performed within the FODO cells of one of the twelve RHIC arcs. The magnets were first cooled down to 4.2K. Each quadrupole is in the center of a cryostat assembly (the *CQS package*), together with a sextupole and a BPM on one side, and a corrector on the other.

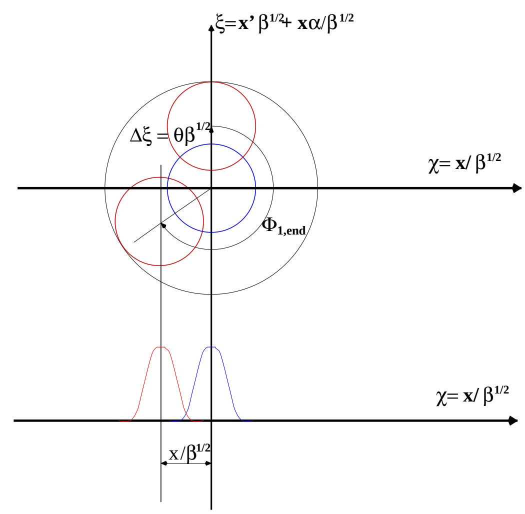

Figure 1: Beam profiles and dipole kicks presented in normalized phase space.

Beam profile monitors (*flags*) [1] were installed along the beam injection line and at the end of the sextant. In circulating beam operation ionization profile monitors will be used. The beam was successfully transported, first through the beam line from the Alternating Gradient Synchrotron (AGS) to the beam line dump. Gold ions, with $2 \cdot 10^8$ ions per bunch, reached the end of the sextant without using any of the dipole corrector magnets. Nominal values of the dipole current and of the of the quadrupole currents were applied to the three main buss lines. One bus is for the dipoles. The focusing *QF* and defocusing *QD* quadrupole busses are powered by a single quad power supply with a *trim* quad buss supply to provide the difference. The defocusing quadrupoles were connected to the *main* power supply while the current through the focusing quadrupoles was equal to the sum of *main* bus with the *trim* power sup-

[1]Work performed under the auspices of the U.S. Department of Energy

ply. Nominal values were derived from data recorded during the test bench measurements and stored in a SYBASE database. The betatron phase advances per FODO cell were obtained by measuring the movement in beam position at the end of the sextant produced by single dipole corrector excitations along the sextant arc. Successive dipoles were excited by the same value of ± 1 A to produce kicks of $\pm 59.94\ :\ \mu rad$. The beam position was recorded at the beam profile monitor *flag* at the end of the sextant. The gold ion beam distribution is presented in normalized phase space ($\chi = x/\sqrt{\beta}$ and $\xi = x'\sqrt{\beta} + x\alpha/\sqrt{\beta}$) in Fig. 1. The central circle at the origin represents the beam position at the dipole corrector before the kick. After the kick the beam moves upward along the ξ axis by $\theta\sqrt{\beta}$. The position of the circle at the end of the sextant depends on the phase difference between dipole corrector and the position of the *flag* according to:

$$x_{flag} = \theta\sqrt{\beta_c \beta_{flag}}\ \ \sin(\phi_{flag} - \phi_c) + x_{co}, \qquad (1)$$

where β_c and β_{flag} are the betatron functions at the corrector and the *flag*, ϕ_{flag} and ϕ_c are the betatron phases and x_{co} is the offset of the closed orbit from the design orbit. Because the vertical and horizontal corrector magnets are located within the *CQS packages* they follow the periodicity of the lattice. Vertical or horizontal dipole correctors are attached to the vertical or horizontal focusing quadrupoles, respectively. The distance between two consecutive vertical corrector dipoles is equal to the FODO cell length $L_{FODO} = 29.657m$ (the same is valid for the horizontal correctors). Beam offsets at the end of the sextant are labeled as x_n, where *n* corresponds to the *n*th corrector. Sixteen horizontal and fifteen vertical correctors were used in the phase measurements. If the phase difference between the last (*n*=*N*) corrector and the *flag* is labeled as ϕ_{NF}, than the previous equation can be written as:

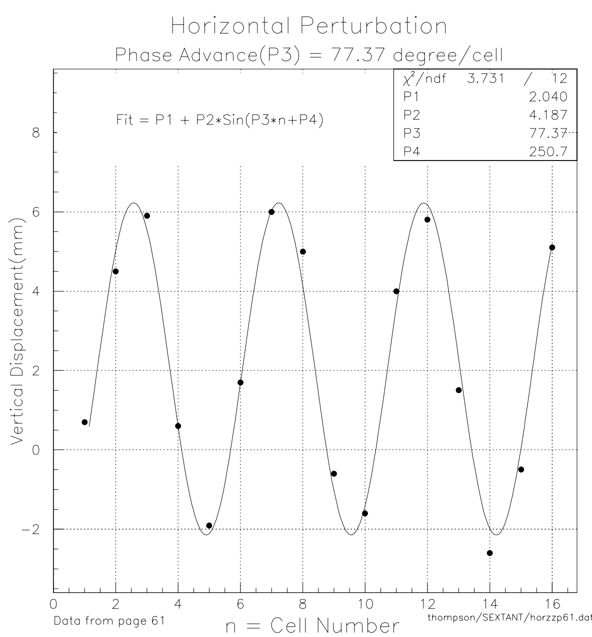

Figure 2: Measurement results of the FODO cell horizontal phase advance.

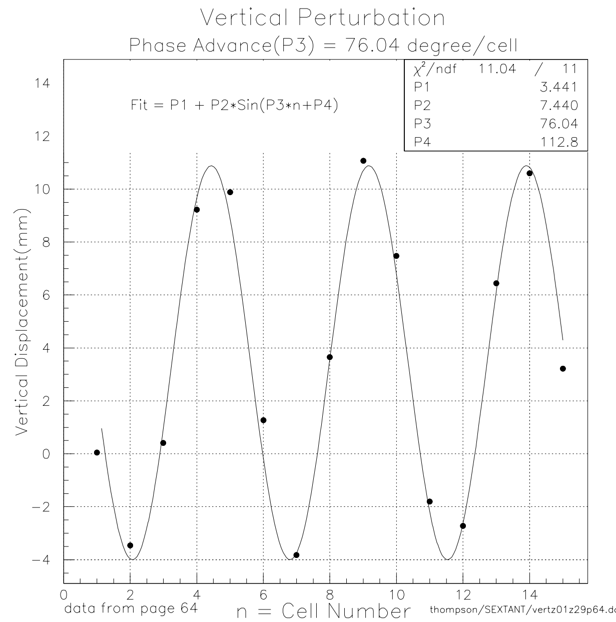

Figure 3: Measurement results of the FODO cell vertical phase advance.

$$x_n = \theta\sqrt{\beta_c \beta_{flag}}\ \sin((n-1)\phi_{FODO} + \phi_{NF}) + x_{co}. \quad (2)$$

A sinusoidal curve was fitted through the 16 (15) experimental points and the horizontal (vertical) phase advance per FODO cell was obtained. Fig. 2 and 3 represent a typical measurement result, for one of the measurement sets.

2.1 Calibration of the Quadrupole Current

Phase advances were obtained under different quadrupole *main* and *trim* power supplies currents. The results showed confirmation of the previously measured values of the quadrupole integral transfer functions. The phase advance per FODO cell dependence on the quadrupole strength $k\ell = B'\ell/B\rho$ was compared to the results obtained by the MAD program [3]. A relationship between the quadrupole strength *k* and the quadrupole current was obtained by using the results from the quadrupole and dipole integral function measurements. Figure 4 show the experimental result on the FODO cell horizontal phase advance measurements dependence on the quad bus current. The integral transfer function is defined as a magnetic field strength over the whole quadrupole or dipole length per the excitation current through the coils. These measurements were performed at radius of the measuring coil of $R_o = 25$ mm radius. The bench dipole integral transfer function ($K \equiv \int_\ell B\delta l/I\ (Tm/kA)$ was measured for the RHIC injection conditions at two currents *K=6.66523 Tm/kA @ I=570 A* and *K=6.69117 Tm/kA @ I=660 A*. A nominal current through the dipole during the test was set to a value of 546.5 A. This allowed passage of the gold ion beam through the middle of the aperture. The integral dipole transfer

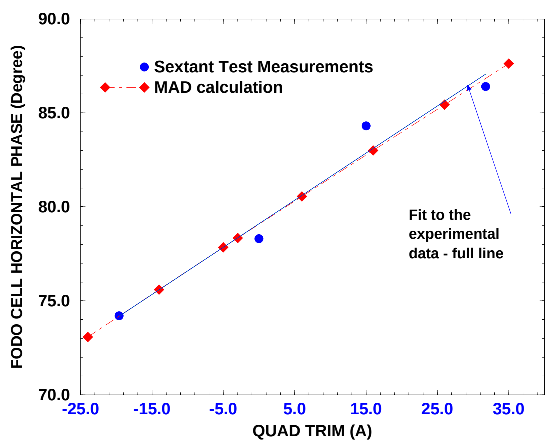

Figure 4: Dependence of horizontal phase advance per FODO cell on the quad *trim* current compared with the MAD results.

function of *K=6.6584856 Tm/kA @ I=546.6 A* is obtained by interpolation which provides $\int_l Bdl = 3.639528$ Tm. The *magnetic rigidity* is calculated as $B\rho = \theta \int_l Bdl = 93.5033839752\, Tm$ by using the FODO cell dipole bending angle ($\theta = 0.03892402676\, rad$).
The average values for the integral transfer functions of the RHIC quadrupoles, measured for the RHIC injection conditions, at two currents are $K = 0.41530Tm/kA@I = 570A$ and $K = 0.41566Tm/kA@I = 660A$. The *main* quadrupole power supply was powered between $I_{main} = 495$ A and $I_{main} = 510$ A, with a constant value of the *trim* current $I_{trim} = 7$ A. Corresponding defocusing quad strengths were $k_{QD-495A} = 0.08781$/m and $k_{QD-510A} = 0.0911$/m. The horizontal phase advance measurements were performed by scanning the *trim* quadrupole power supply values from $I_{trim} = -20A$ to $I_{trim} = +32$ A, while the *main* quadrupole power supply was set to be at a constant value of $I_{main} = 495$ A. The linear fitting through the experimental data produces a straight line exactly on the top of the MAD results. The standard deviation in the phase measurements was $\sigma = 0.57^o$. This allowed us to obtain the betatron functions in the FODO cell as presented in Table 1.

Table 1: Results for the Betatron Functions in the RHIC Sextant Measurements

$\hat{\beta}$ (m)	Measured	MAD
$\hat{\beta}_x(m)$	$48.9 \pm 0.29@\phi_x = 74.2^o$	48.844
$\hat{\beta}_x(m)$	$46.5 \pm 0.34@\phi_x = 86.4^o$	46.803
ϕ_{xFODO}	74.2 ± 0.57	74.091
ϕ_{xFODO}	86.4 ± 0.57	86.890

3 CONCLUSIONS

FODO cell phase advance measurements during the RHIC sextant test showed excellent agreement with the predicted values obtained from the quadrupole integral function measurements. The vertical and horizontal beam position dependence at the end of the sextant on dipole corrector excitations along the sextant beam line proved to be a very accurate method for the betatron phase measurements, with an estimated error of $\pm 0.67^o$. These measurements were useful in:

- Confirming the lattice design parameters.
- Gaining an important experience for the future operation of the RHIC collider.
- Confirming the high quality of the produced magnets and showing that a great care in the magnet preparation with respect to polarity check, electrical, magnetic, and surveying measurements was the main reason of the very successful test.

4 REFERENCES

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[2] E.D. Courant and H.S. Snyder, “Theory of Alternating Gradient Synchrotron”, Annals of Physics, Vol. 3, (1958), pp. 1-48.

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