RHIC PROTON BEAM LIFETIME INCREASE WITH 10- AND 12-POLE CORRECTORS*

W. Fischer†, J. Beebe-Wang, Y. Luo, and S. Nemesure, BNL, Upton, New York, USA
L. Rajulapati, Stony Brook University, New York, USA

Abstract

The RHIC beam lifetime in polarized proton operation is dominated by the beam-beam effect, parameter modulations, and nonlinear magnet errors in the interaction region magnets. Sextupole and skew sextupole errors have been corrected deterministically for a number of years based on tune shift measurements with orbit bumps in the triplets. During the most recent polarized proton run 10- and 12-pole correctors were set through an iterative procedure, and used for the first time operationally in one of the beams. We report on the procedure to set these high-order multipole correctors and estimate their effect on the integrated luminosity.

INTRODUCTION

The main effects affecting the proton beam lifetime in RHIC are the beam-beam interaction, nonlinear errors in the interaction region (IR) magnets, and parameter modulations like 10 Hz orbit variations stemming from mechanical triplet vibrations [1]. In 100 GeV polarized proton operation the reduction of β^* at the two experiments PHENIX and STAR from 1.0 m in 2008 to 0.7 m in 2009 [2], together with a reduction in the transverse emittance by 25% [3] lead to a significant reduction in the luminosity lifetime. The time dependent luminosity $\mathcal{L}(t)$ can be parameterized by

$$\mathcal{L}(t) = \mathcal{L}(0)\left[Ae^{-t/\tau_1} + (1-A)e^{-t/\tau_2}\right] \quad (1)$$

and the average of all physics stores, fitted over the first 3 h, is (A, τ_1, τ_2) = (12.1%, 0.39 h, 12.4 h) for 2008, and (17.9%, 0.46 h, 7.4 h) for 2009. The main parameters for 100 GeV polarized proton operation in 2009 are listed in Tab. 1.

In an effort to restore the luminosity lifetime 10- and 12-pole corrector settings in the Yellow beam were tested, in addition to the sextupole and skew sextupole settings already in use [4], and the correction of the nonlinear chromaticity [5]. While the interaction region sextupole and skew sextupole correctors can be set deterministically with measured tune changes due to orbit bumps in the triplets, the tune measurement resolution prevented such a technique for higher order multipole corrections in the past [4], and we chose an iterative approach based on direct observation of beam loss rates.

The triplets near the two experiments PHENIX and STAR are equipped with multipoles to correct the nonlinear magnetic errors of the IR magnets, namely the beam separation dipoles DX and D0, and triplet quadrupoles Q1, Q2 and Q3. Details of the layout can be found in Ref. [4]. Each triplet contains one 10-pole corrector (decapole), and two 12-pole correctors (dodecapoles).

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† Wolfram.Fischer@bnl.gov

Table 1: Parameters for RHIC polarized proton operation at 100 GeV in 2009.

quantity	unit	value
total energy E_p	GeV	100
$\beta^*_{x,y}$ at IP6, IP8	m	0.7
lattice tunes (Q_x, Q_y)	...	(.695,.685)
no of bunches	...	109
bunch intensity N_p, initial	10^{11}	1.35
rms emittance ϵ_n, initial	mm mrad	2.5
rms bunch length σ_s, initial	m	0.85
rms momentum spread*, $\delta p/p$	10^{-3}	0.4
hourglass factor F, initial	...	0.70
beam-beam parameter ξ/IP	...	0.007
number of beam-beam IPs	...	2

* For $V_{gap} = 300$ kV. During the run lower voltages were also used.

10- AND 12-POLE ERRORS

IR magnets are the DX and D0 dipoles and the triplet quadrupoles Q1, Q2 and Q3. 10-poles are the second allowed harmonic error in dipoles, and 12-poles are the first allowed harmonic in quadrupoles. During the magnet production the RHIC errors were reduced with shimming [6]. Table 2 shows a summary of the 10- and 12-poles (b_5 and b_6) as well as the next significant multipole errors.

The effect of the multipoles was tested in dynamic aperture (DA) simulations. For this the DA of a lattice with all IR errors and the beam-beam interactions is compared to the DA of a lattice in which either the 10- or 12-pole errors are set to zero. The result is shown in Tab. 3. The beam-beam interaction was modeled as a single 4D kick. Switching off either the 10-poles or the 12-poles has only a small effect on the DA, consistent with earlier studies. In these it was also found that the DA is not dominated by a single multipole error order, and that the DA is a insensitive measure under conditions with significant beam-beam interactions. We expect therefore only limited guidance from the these simulations for beam lifetime observations.

CORRECTION METHOD AND RESULTS

A generic optimization scanner program that adjusts independent variables in order to optimize one or more dependent variables was used to determine optimal corrector strengths. The program takes a set of initial conditions that include magnet strength, step size, and delay. There are optional boundary conditions for the magnet current read back to prevent damage to power supplies. When the user

Table 2: Selected multipole errors in the RHIC IR magnets, quoted in units of 10^{-4} of the dipole field at the reference radius R and for 100 GeV proton energy [6]. Shown are 10- and 12-poles (b_5 and b_6) as well as the next significant errors.

magnet	multipole	mean	rms
DX ($R = 60$ mm)	b_3	-1.12	1.89
(6 magnets)	b_5	-3.06	0.46
	b_7	-1.84	0.10
	b_9	-1.09	0.07
	b_{11}	-1.13	0.02
D0 ($R = 31$ mm)	b_3	0.15	1.38
(24 magnets)	b_5	0.46	0.30
	b_7	0.22	0.07
Q1 ($R = 40$ mm)	b_4	-0.01	0.74
(26 magnets)	b_6	1.19	0.73
Q2 ($R = 40$ mm)	b_4	-0.61	0.36
(27 magnets)	b_6	-0.65	0.63
Q3 ($R = 40$ mm)	b_4	-1.55	1.04
(13 magnets)	b_6	0.08	0.29

Table 3: 10^6 turn DA with beam-beam interaction for 100 GeV protons and 5 different angles A_y/A_x.

case	15°	30°	45°	60°	60°	Min
all errors	4.4	4.9	4.9	4.9	6.5	4.4
no b3	5.6	5.5	5.5	4.9	6.1	4.9
no b5	4.6	4.9	4.8	4.5	5.6	4.6
no b6	4.4	4.5	4.8	4.9	5.7	4.4

initiates the optimization task, the program sets the initial magnet strength and sits at that value for a user defined time. The data collected during this time is averaged and graphically displayed along with a standard deviation before moving on to the next magnet strength defined by the step size (Fig. 1). Once the magnet has settled at the new set point the program collects more data. After data for the second point has been collected the program decides where to set the next current by comparing the data from the current average to the previous one. If the trend of the current read back is continuing in the optimized direction, the program continues to set the strength in the same direction. If the read back is less optimal the program will change the direction for the next magnet set point. This process continues until a locally optimized value has been found. The centrally optimized value along with the points collected to either side are then fit to a Gaussian. The peak of this Gaussian is determined to be the optimal magnet strength. If no optimal value is found before reaching a boundary condition, the boundary condition value will be used.

We used this application to scan 10- and 12-pole IR correctors in the Yellow ring of the two IRs with the PHENIX and STAR experiments, parasitic to physics operation. While such scans can be done manually in principal, the time required to complete a scan and the high probability of errors makes such a manual scan impractical. Figure 1 shows the user interface during a 12-pole scan that minimized the Yellow beam loss rate.

The correctors were always scanned in the same order, beginning with the 12-poles and followed by the 10-poles. The order of the correctors is the same as shown in Tab. 4.

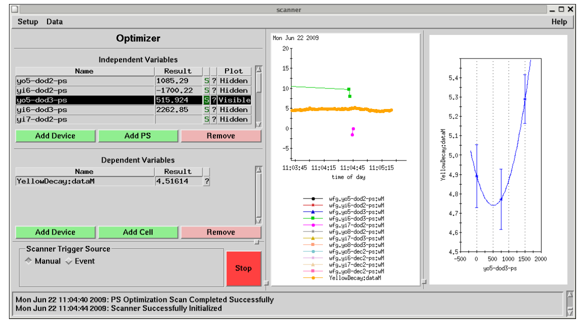

Figure 1: User interface of a general scanner program used to minimizes the beam loss rate with changes in 10- and 12-pole interaction region correctors.

The step size was chosen so that a clear change in the beam loss rate could be observed. After three iterations the 10-pole corrector strength did not change significantly any more and an average of the previous scans was used in the following 12-pole scans. Four of the 12-pole correctors were not scanned any further after another iteration, using again an average of previous scans as the final value. For the remaining 12-poles three more iterations were done. The results of all scans are shown in Tab. 4.

In fill 10968 an 8-pole scan was done in addition to the 10- and 12-pole scan but did not result in a measurable reduction in the beam loss rate. The reported beam loss rate in the Blue ring was more noisy and a scan of all 10- and 12-poles in IR6 and IR8, which took about an hour in the Yellow ring, would have required about twice as much time in the Blue ring. The RHIC run came to an end before the Blue ring could be scanned.

EFFECT ON INTEGRATED LUMINOSITY

The effect of the 10- and 12-pole settings was tested in 3 stores by setting all corrector strengths to zero and comparing the beam loss rate with and without the 10- and 12-pole correctors. The results are shown in Tab. 5. Figure 2 shows the change in the Yellow beam loss rated at the beginning of fill 10998, when the effect was largest.

Table 5: Increase in the Yellow beam loss rate due to turning off of the 10- and 12-pole correctors.

date	fill no	rate change	comment
06/22/09	10968	$4 \rightarrow 5$%/h	3 h into store
06/26/09	10995	$2.7 \rightarrow 3.5$%/h	5 h into store
06/26/09	10998	$9 \rightarrow 11$%/h	1/2 h into store

Similar to Eq. (1) we parameterize the Yellow time dependent intensity as

$$N_Y(t) = N_Y(0)\left[Ae^{-t/\tau_1} + (1-A)e^{-t/\tau_2}\right]. \quad (2)$$

The average of all 2009 physics stores, fitted over the first 3 h, is (A, τ_1, τ_2) = (8.9%, 0.43 h, 26.1 h). The increase in the time dependent beam loss rate $R(t) = (1/N_Y(t))(dN_Y(t)/dt)$ with the measured values in Tab. 5 can be parameterized with the set $(A, \tau_1, \tau_2)_\Delta$ = (10.4%,

Table 4: Summary of 10- and 12-pole corrector scans in the Yellow ring with 100 GeV proton beam in 2009.

date	06/20/09	06/21/09	06/21/09	06/22/09	06/22/09	06/23/09	06/25/09
fill no	10961	10963	10964	10968	10969	10972	10986
start values	arbitrary	10961 result	10963 result	10964 result	10968 result	10969 result	10972 result
12-pole correctors (step size: 750 m^{-5})							
corrector	[m^{-5}]	[m^{-5}]	[m^{-5}]	[m^{-5}]	[m^{-5}]	[m^{-5}]	[m^{-5}]
yo5-dod2	+1479	+678	+226	+985/+1932/+1085*	-214	-86/-523/-347*	+480
yi6-dod2	+3750	+183	-1251	-1700	-3012	-3750/-3750*	-3012
yo5-dod3	-117	+342	+894	+516	no further scan, used +584 →		
yi6-dod3	+1083	+1106	+1855	+2262	+2680	+2784	+2982
yi7-dod2	-513	-416	-545	-495	no further scan, used -485 →		
yo8-dod2	-769	+1564	+1231	+2176	+2545	+1351	+2502
yi7-dod3	-3750	-3336	-2393*	-2269	no further scan, used -2666 →		
yo8-dod3	-769	-659	-443	-424	no further scan, used -509 →		
10-pole correctors (step size: 5 m^{-4})							
corrector	[m^{-4}]	[m^{-4}]	[m^{-4}]				
yo5-dec2	+3.4	+4.3	+5.5/ +1.5* +6.1	no further scan, used +4.4 →			
yi6-dec2	+12.2	+16.4	+16.9/+15.2* +15.1	no further scan, used +15.9 →			
yi7-dec2	+25.0	+25.0	+25.0 +25.0	no further scan, used +32.2† →			
yo8-dec2	+3.0	+0.2	+1.0 +0.8	no further scan, used +0.7 →			

* The automatic scan was interrupted.

† At limit in previous scans. 32.3 m^{-4} is the result of 3 separate scans with increased limit in fill 10968.

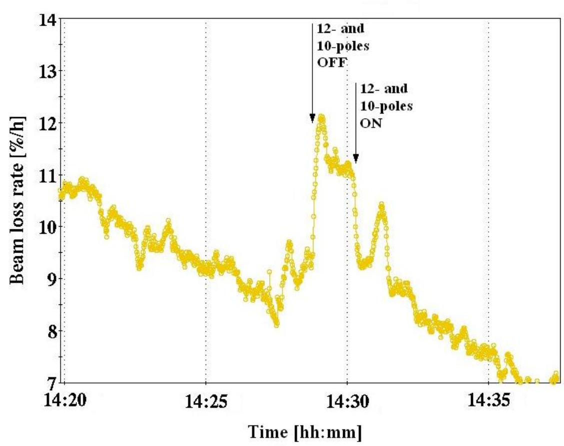

Figure 2: Yellow beam loss rate with and without 12- and 10-pole correctors at the beginning of a polarized proton store (10998).

0.40 h, 21.1 h). The time dependent beam loss rate for both parameter sets (A, τ_1, τ_2) over the average store length of $T_{store} = 6.1$ h is shown in Fig. 3.

Since the luminosity is proportional to the Yellow intensity, we now estimate the effect of the 10- and 12-pole correctors on the integrated luminosity L as

$$\frac{\Delta L}{L} = \frac{\int_0^{T_{store}} [N_Y(t) - N_{Y\Delta}(t)]\, dt}{\int_0^{T_{store}} N_{Y\Delta}(t) dt} \approx 4.3\% \qquad (3)$$

where $N_Y(t)$ denotes the run-averaged time dependent Yellow intensity with parameters (A, τ_1, τ_2), and $N_{Y\Delta}(t)$ with parameters $(A, \tau_1, \tau_2)_\Delta$.

SUMMARY

During the 100 GeV RHIC polarized proton run in 2009 10- and 12-pole interaction region correctors were used operationally for the first time. The correctors were set with an automatic scanning procedure during physics stores that

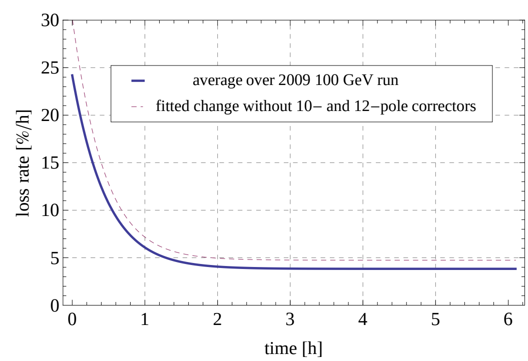

Figure 3: Time dependent Yellow beam loss rate in the 2009 GeV polarized proton run, averaged over all physics stores and fitted change due to turning off of 10- and 12-pole correctors.

adjusted the strengths according to the observed the beam loss rate. The process converged after a few scans of all correctors and the reduction of the beam loss rate in one of the two beams increased the integrated luminosity per store by about 4%.

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