SIMULTANEOUS ORBIT, TUNE, COUPLING, AND CHROMATICITY FEEDBACK AT RHIC

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Abstract

All physics stores at the Relativistic Heavy Ion Collider are now established using simultaneous orbit, tune, coupling, and energy feedback during beam injection, acceleration to full beam energies, during the "beta-squeeze" for establishing small beam sizes at the interaction points, and during removal of separation bumps to establish collisions. In this report we describe the major changes made to enable these achievements. The proof-of-principle for additional chromaticity feedback will also be presented.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) consists of two independent superconducting accelerators designed to provide collisions at multiple experiments [1]. During a given running period, numerous operating scenarios with different particle species, beam energies and accelerator optics must be established in support of the physics programs. While initially developed to improve the efficiency of commissioning new optics, the successful application of these feedback loops has significantly improved the reproducibility of accelerator conditions and has additionally allowed for operation under more extreme conditions as beneficial for both higher luminosities and beam polarization.

TUNE/COUPLING FEEDBACK

The key developments leading to the first demonstration of simultaneous tune/coupling feedback [2] include high precision measurement of the betatron tunes using direct-diode detection [3], development of the methodology required for determination of the beam's coupling [4-6], and new measurements methods allowing to distinguish between the measured tunes and the eigentunes [6,7]. Since this proof-of-principle in run-06, tune/coupling feedback has been made fully operational with successful application during all ramp development periods in run-09, regular use by operations (ramp development only) in run-10, and for routine implementation (together with orbit feedback) for all ramps including those for physics stores in run-11.

In the intervening years, chromaticity measurement and control and the presence of strong 60 Hz harmonics proved to be an impediment for routine application of tune/coupling feedback [8]. Just prior to run-09, numerous hardware and software changes were made resulting in deterministic delivery of the tune measurements and an order-of-magnitude improvement in the resolution of the tune and coupling measurements [9,10] as demonstrated in Fig. 1 which compares measurements of coupling parameters made during run-08 and recently in run-11. Experience since these modifications were made has shown that chromaticity feedback is not a prerequisite for tune/coupling feedback and that the improved measurement accuracy has obviated the difficulties associated with the 60 Hz harmonics (which are still present).

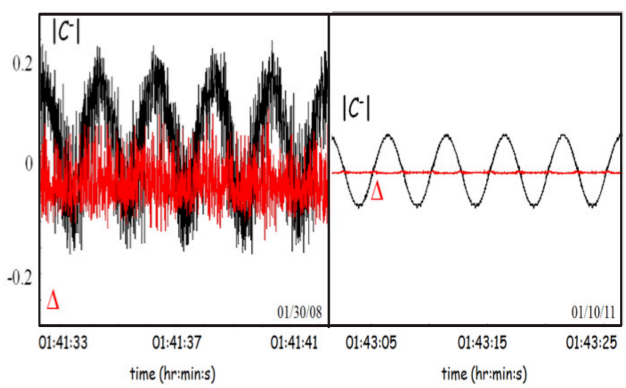

Figure 1: Comparison of coupling coefficient measurements (symbol definition given in Ref. [5]) before (left) and after (right) numerous modifications for improved integrity of the tune measurements.

In run-09, the time required to commission new optics was reduced from a few shifts to less than one through the use of tune/coupling feedback. However, these loops were implemented only during the commissioning of a new operating mode. For physics stores, tune/coupling feedback was not used (primarily due to suspected emittance degradation introduced by the measurement) and the previously recorded magnet strengths were fed-forward and applied without feedback ("replay mode"). Over the course of time, the accelerators were observed to drift as shown in Fig. 2 which shows significant deviations of the measured tunes from nominal with values approaching the dangerous 2/3 resonance.

In contrast, Fig. 3 shows the tunes and coupling from multiple ramps (superimposed) as measured with continuous application of tune/coupling (and orbit) feedback in run-11. The tunes and coupling are seen to be well controlled and the reproducibility is excellent.

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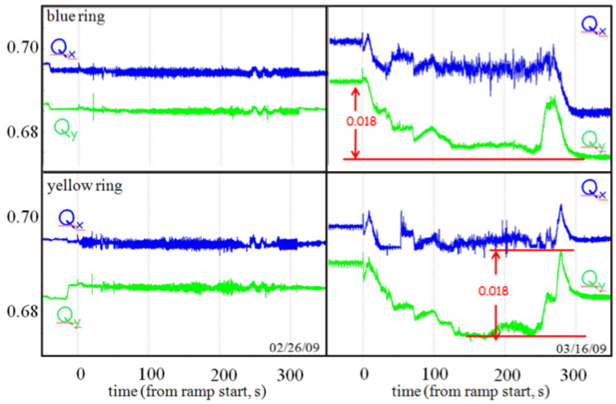

Figure 2: Horizontal (Q_x) and vertical (Q_y) betatron tunes measured with (left) and without (right) tune/coupling feedback in run-09.

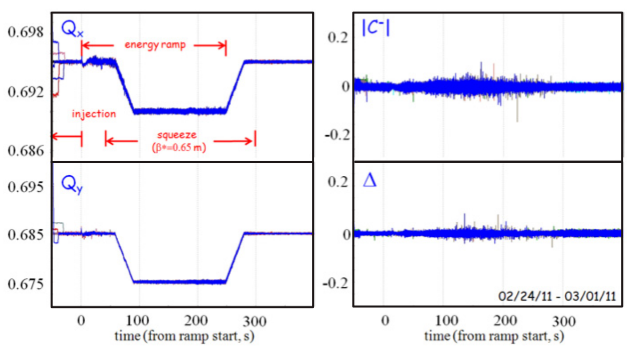

Figure 3: Superposition of measurements from multiple ramps of the betatron tunes (left) and coupling (right) measured with tune/coupling feedback in run-11.

ORBIT FEEDBACK

From the commissioning of 14 different operating modes in support of the physics program in run-09 is histogrammed in Fig. 4 the reasons for "failed ramps" (those which did not end with files suitable for use in replay mode). The leading cause was identified as poor orbit control. Before run-10 an ambitious program to develop global orbit feedback was initiated. Developed entirely within the framework of existing infrastructure, the new systems were successfully demonstrated [11,12] only four months later. Key to precision orbit control was an improvement of about a factor of 10 in the resolution of the measured average orbit [13]. Shown in Fig. 5 are average orbit measurements made with and without implementation of an IIR filter to effectively average out predominantly ~10 Hz variations of the closed orbit.

A figure of merit for evaluating the orbit stability is the root mean square (rms) value of all arc BPMs in a given plan at any given instant in time. Shown in Fig. 6 are the superposition of multiple orbit rms values acquired during the last week of 250 GeV polarized proton operations in run-09 and during a week of steady operations (also 250 GeV protons) in run-11.

Orbit feedback is now used routinely together with tune and coupling feedback. The reproducibility of the orbits is excellent and well below the 300 micron tolerance [14].

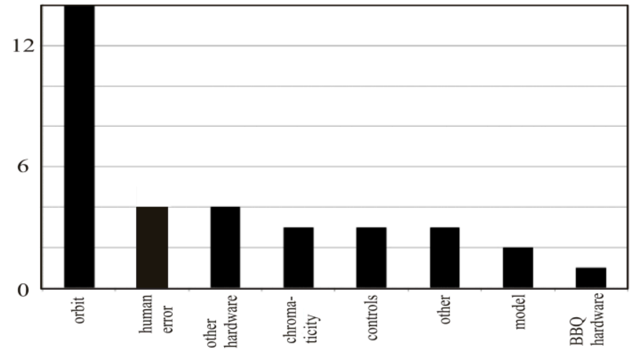

Figure 4: Histogram of ramp failures during 14 different commissioning periods of run-09.

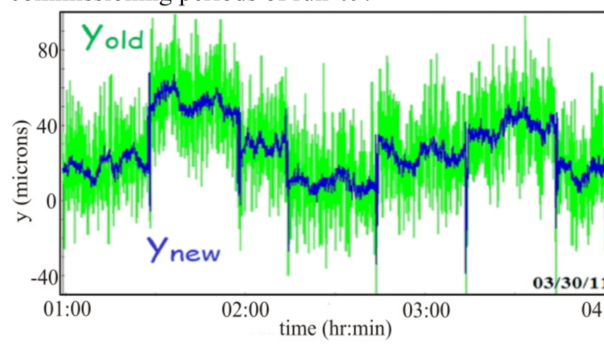

Figure 5: Average orbit measurements (vertical plane) with and without improved data processing algorithm.

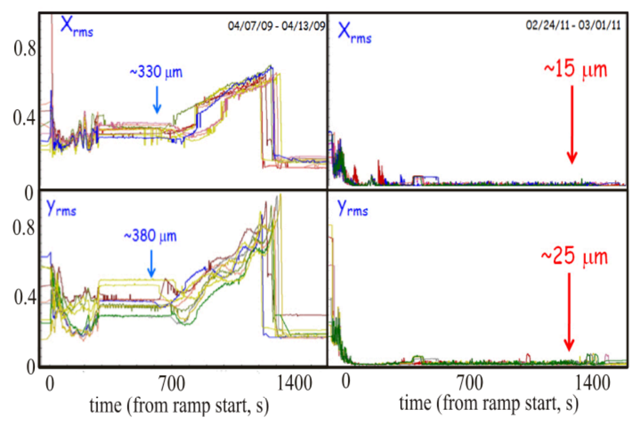

Figure 6: Superposition of measurements from multiple ramps of horizontal (x) and vertical (y) orbit rms measured without (left, run-09) and with (right, run-11) orbit feedback.

RADIUS FEEDBACK

In the past, the rf frequency was adjusted based on the energy deviation derived from two dedicated BPMs located in a dispersive region separated by ~180 degree phase advance. In run-11 the energy deviation is now derived from the mean of all horizontal BPMs located in the arcs. Figure 7 shows the benefit of the higher precision estimate of the energy deviation and the improved stability at injection energy due to application of orbit feedback.

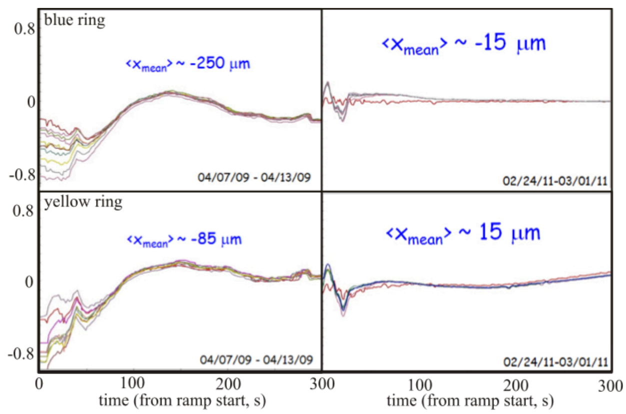

Figure 7: Superposition of measurements from multiple energy ramps of the mean horizontal position deviations derived from BPMs located in the arcs measured without (left, run-09) and with (right, run-11) radial feedback.

TYPICAL STORE SETUP

Shown in Fig. 8 are an overlay of both beam's betatron tunes (top), an overlay of the rms orbits for both beams (middle) and collision rates measured at the two interaction points (bottom) from which the sequence of engaging and disengaging feedback loops can be seen. Presently after the beams are injected the tune/coupling feedback is engaged followed in rapid succession by closing of the orbit then the energy (radial) feedback loop. At time t=0 the energy ramp starts. To avoid a depolarizing snake resonance at tune Q_y= 7/10 (with strength increasing with beam energy), the betatron tunes are intentionally lowered for the majority of the energy ramp. At the end of the energy ramp the betatron tunes are brought back to nominal. At RHIC the beta-squeeze (to 0.65 m in run-11 at two interaction points) is implemented continuously starting partially into the energy ramp and ending after the final tune swing. For a short period of time thereafter (~ 120 s, variable) the orbit, energy, and tune/coupling loops are disengaged to allow the beam to be captured into a higher harmonic rf system to shorten the bunches and (optionally) to allow for polarization measurements. All feedback loops are then again engaged for the long (~900 second) "rotator ramp" during which time spin rotators around each interaction point are slowly turned on to precess the vertical polarization into the longitudinal plane at the interaction points.

At the end of this process (t~1400 s in Fig. 8) the nominally longitudinally aligned beams are then brought transversely into collision. Shown in Fig. 9 (top) are 8 orbits acquired with 5 second spacing showing the removal of the vertical separation bumps in one of the accelerators at the physics experiments, STAR and PHENIX (the time evolution of the orbits in the other accelerator is mirror symmetric about the horizontal axis). The removal is achieved by changing the reference trajectories used by orbit feedback. At the same time the beams are brought to nominal positions at the jet polarimeter. An expanded view is shown in Fig. 9 (bottom) demonstrating peak-to-peak deviations (consistent with the ~20 micron rms shown previously). Earlier in run-11 tune/coupling feedback remained engaged during separation bump removal. Recently due to an isolated but real complication from coherent modes, the tune/coupling feedback is now disengaged shortly before removal of the separation bumps. After the beams have been brought into collision, the orbit and radial loops are then disengaged.

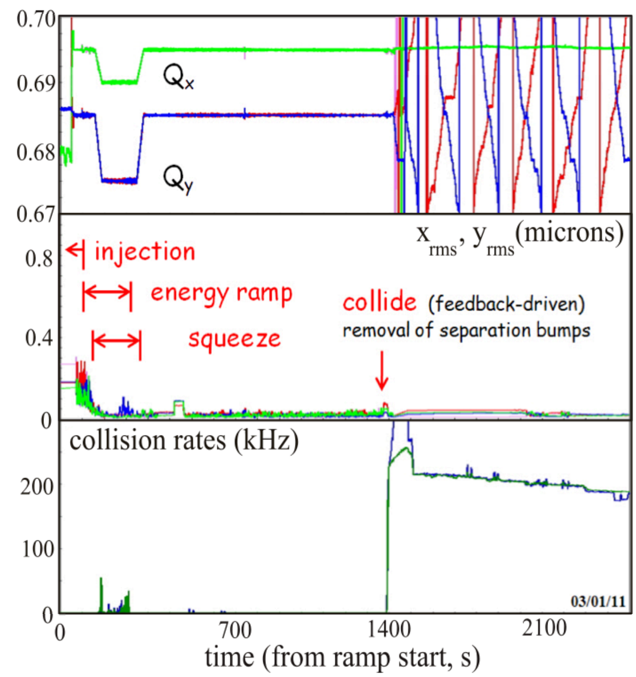

Figure 8: Betatron tunes (top), orbit rms's (middle) and collision rates (bottom) highlighting the sequence of events (see text) for setup of a typical physics store during run-11.

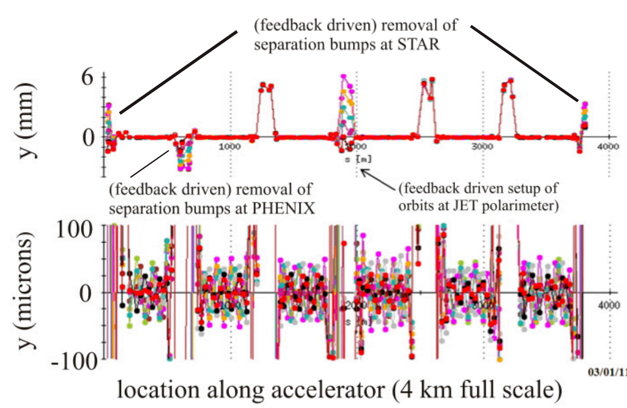

Figure 9: Orbit measurements as beams are brought into collision by removal of the vertical separation bumps.

CHROMATICITY FEEDBACK

After identification and removal of a hardware limit identified late in run-09 and various corrections to the chromaticity algorithm, chromaticity feedback at RHIC was first successfully demonstrated during run-10 [15]. In the following we first describe the interaction of the chromaticity feedback with the other feedback loops, then present experimental data illustrating successful application of simultaneous orbit, tune, coupling, and chromaticity feedback.

Interaction with Orbit Feedback

The chromaticity measurement is based on the standard method of measuring the betatron tunes while a modulation is applied to the rf frequency. The modulation frequency is set to 0.5 Hz so that the BPMs are sampled at the zero crossing of the rf frequency modulation. The orbit and chromaticity feedback loops are therefore nominally decoupled however in practice there is a small degree of modulation observed in the BPM measurements due to the use of the improved algorithm mentioned earlier for determination of the average orbit.

Interaction with Tune/Coupling Feedback

Shown in Fig. 10 is a conceptual diagram of the tune and chromaticity feedback systems (the coupling feedback is not shown as skew chromaticity has not been addressed). Highlighted by the red oval are the error signals generated by the tune feedback loop, which are used as input to the chromaticity algorithm. The chromaticity feedback loop is therefore dependent on the gain and bandwidth of the tune feedback loop.

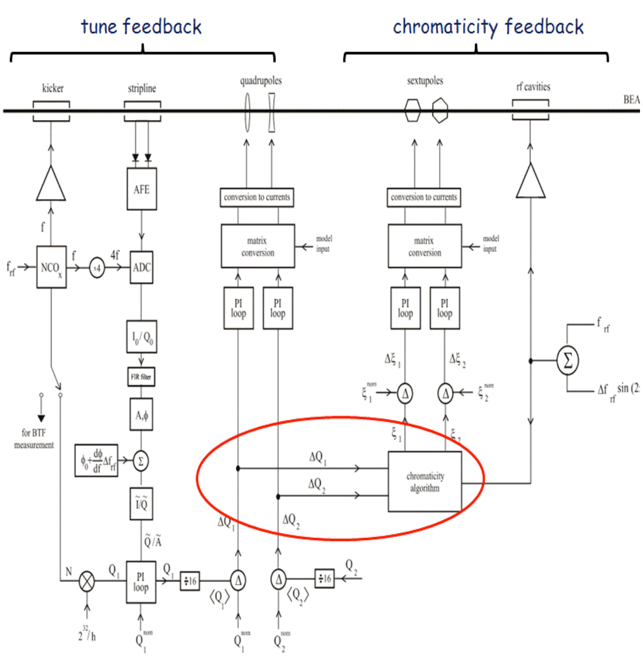

Figure 10: Conceptual sketch of the tune and chromaticity feedback systems highlighting the use of tune feedback for input to chromaticity feedback.

The chromaticity algorithm [16] is therefore calibrated with respect to tune feedback. The calibration is performed at injection energy. The bandwidth of the tune feedback loop produces a phase shift which is measured (see Fig. 11) by the difference in relative phase of the tune and rf frequency modulations acquired with tune/coupling feedback engaged. The gain of the tune feedback loop results in a scaling factor which is measured by comparing the chromaticity derived with and without tune/coupling feedback. Shown in Fig. 12 are tune and chromaticity measurements acquired with and without tune/coupling feedback after these calibrations have been implemented and applied during the energy ramp.

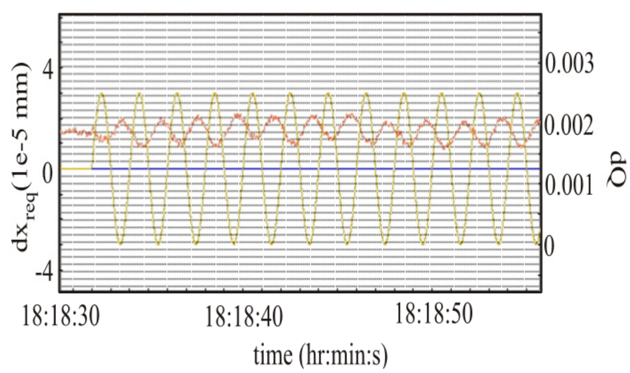

Figure 11: Measurement of the relative phase between measured betatron tune and requested rf modulation (specified in units of average horizontal position deviation).

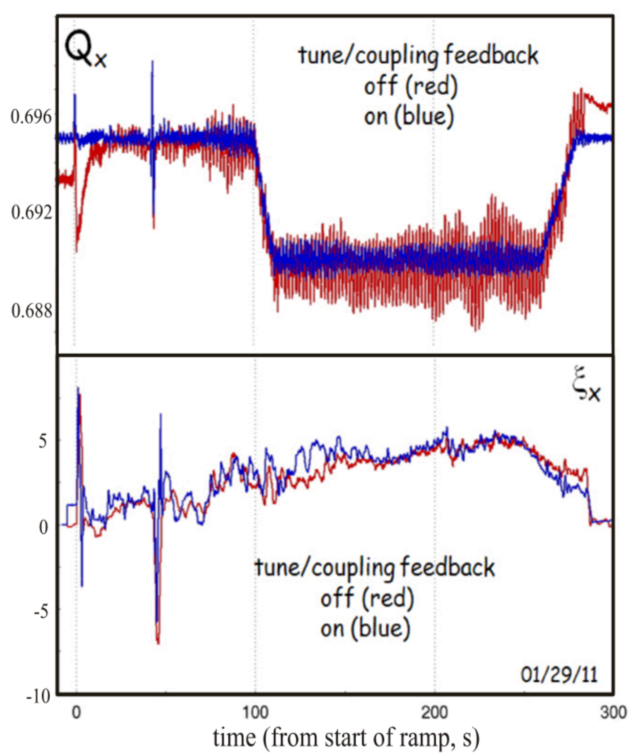

Figure 12: Measured betatron tunes (top) and chromaticity (bottom) with (blue) and without (red) tune/coupling feedback during the energy ramp and beta-squeeze.

SIMULTANEOUS ORBIT, TUNE, COUPLING AND CHROMATICITY FEEDBACK

The first demonstration of the simultaneous application of all feedback loops was demonstrated late in run-10 during setup of Au+Au collisions at 39 GeV/n. Shown in Fig. 13 are the measured betatron tunes and chromaticities for the four consecutive ramps used for this development. The first ramp with only 6 bunches per beam was immediately successful in accelerating both beams to full energy. However the pre-programmed setpoints of the sextupoles at t~100s (highlighted with red oval) along the energy ramp were in error with deviations too large for the chromaticity feedback loop to correct. In the second ramp these errors were corrected by hand and the energy ramp with 6 bunches succeeded with near 100% transmission efficiency of both beams. The third ramp was executed with rf frequency modulation intentionally turned off while the bunch number was increased. The final ramp, the basis for subsequent physics stores with replay, was executed with maximum bunch number and nominal bunch current. Highlighted in red however are systematic errors associated with the tune modulation sweeping across 60 Hz harmonics which resulted in ~3 unit errors in the chromaticity measurements.

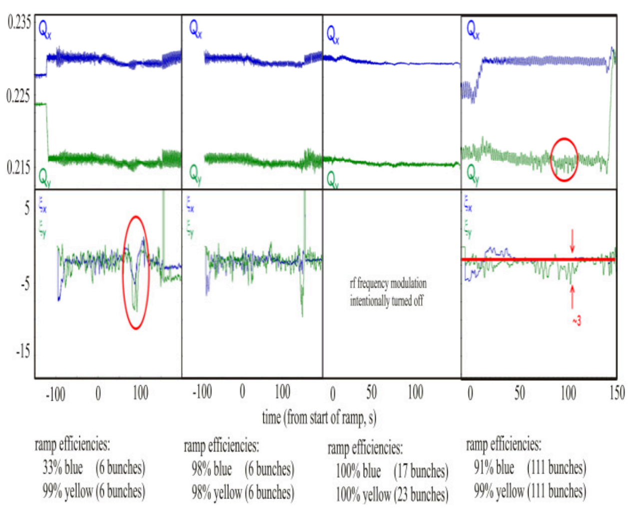

Figure 13: Measured tunes and chromaticities during the energy ramp with simultaneous orbit, tune, coupling, and chromaticity feedback.

SUMMARY

The stability achieved with and without the various feedback loops is summarized in Table 1. The factor of 10-100 improvement with feedback on was made possible by improved resolution of each feedback loop's input.

At RHIC the control of the magnets affecting beam properties during injection, acceleration, beta-squeeze, and establishing collisions has transitioned from being pre-programmed to based on measurements of the beam's properties. During the ongoing run-11 operating period all ramps, including those for physics, are now executed using orbit, tune, coupling, and energy feedback. Precision control of these parameters has expanded the parameter space accessible during acceleration; e.g. the depolarizing resonance at Q~7/10 is avoided by carefully positioning and controlling the betatron tunes precariously close to the dangerous orbital resonance at Q~2/3. Application of these feedback loops is now an integral part of RHIC operations.

Table 1: Summary of the stability achieved with and without various beam-based feedback at RHIC.

parameter	stability no feedback	stability with feedback	used in normal operations
ORBIT x_{rms} y_{rms}	~ 1 mm	~ 20 µm	YES
TUNE Q_x Q_y	~ 0.1	~ 0.001	YES
COUPLING $\|C-\|$ Δ	~ 0.1	~ 0.01	YES
CHROMATICITY ξ_x ξ_y	~ 10	~ 3 (with as yet limited experience)	NO

REFERENCES

[1] T. Roser, Proc. of EPAC08, p. 3723 (2008).
[2] P. Cameron *et al*, Phys. Rev. ST Accel. Beams **9**, 122801 (2006).
[3] M. Gasior and R. Jones *et al*, CERN-LHC-Project-Report 853 (2005).
[4] Y. Luo *et al*, Internal Report C-A/AP/#174 (2004).
[5] Y. Luo *et al.*, Phys. Rev. ST Accel. Beams **8**, 074002 (2005).
[6] R. Jones *et al*, Proc. of DIPAC05, p. 298 (2005).
[7] Y. Luo *et al.*, Phys. Rev. ST Accel. Beams **9**, 124001 (2006).
[8] P. Cameron *et al*, Proc. of PAC07, p. 886 (2007).
[9] M. Minty *et al*, Internal Report C-A/AP/#366 (2010).
[10] M. Wilinski *et al*, Proc. of BIW10, p. 333 (2010).
[11] V. Ptitsyn *et al*, Proc. BIW10, p. 469 (2010).
[12] M. Minty *et al*, Proc. of IPAC10, p. 519 (2010).
[13] R. Michnoff *et al*, Proc. of PAC09, p. 3468 (2009).
[14] Polarized Proton Collider at RHIC, BNL (1998). http://www.rhichome.bnl.gov/RHIC/spin/design
[15] A. Marusic *et al*, Proc. of IPAC10, p. 525 (2010).
[16] S. Tepikian *et al*, Proc. of EPAC02, p. 1983 (2002).