STUDY OF COUPLING ISSUES IN THE RECYCLER AT FERMILAB*

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Abstract

To maximize the tune space due to momentum spread, an operating point close to the coupling resonance line is desirable. This requires a knowledge of all the coupling sources in the Recycler and a correction system capable of global decoupling to the desired level. We report on the efforts to identify major sources of coupling and verification of the integrity of the powered skew quad circuits used for global decoupling

INTRODUCTION

Sources of coupling in the Recycler include: the skew quad component in the gradient magnets, rolled gradient magnets and quads, the electron cooling solenoid, and the vertical orbit through the sextupole in gradient magnet and chromaticity correcting sextupoles. The desired minimum tune split is less than 0.001. Since September 2003, the linear coupling could only be corrected to a minimum tune split of 0.01, a factor of 5 greater than previously attained using the skew quad circuits.

Two techniques were employed to look for sources of coupling. The first utilized single turn off-plane BPM response to an excitation at the injection point. The second analyses again looked at off-plane orbits induced by local 3-bumps. Both analysis used "Harmonic Decomposition" of orbit data [1] to generate the 1st order differential orbit for analysis.

SINGLE TURN INJECTION STUDY

Trim dipoles at the injection point were set from -2.5 to 2.5 Amps in steps on ½ Amps to introduce an orbit distortion in a single plane. Orbit data of all the available BPMs (Beam Position Monitor) in both planes were acquired under the conditions that the skew quads, phase trombone quads and chromaticity sextupoles are set to zero, i.e. the "bare machine". We also simulated single turn injection using the code MAD [2], based on the nonlinear lattice which consists of design lattice and field errors, as well as the misalignment of all the magnets. Lambertson bumps, counter wave and injection off-set are also included in the simulation. BPM data was extracted from MAD output files for further analysis.

BPM response data (position vs current) from both machine experiments and simulations are fit by a polynomial using an accelerator controls on-line beamline analysis program [3]. Figures 1 and 2 show a differential orbit in the vertical and horizontal plane, respectively, constructed from the 1st order coefficients of response polynomial. We utilize 1st order to filter out any effects from higher order multipoles to limit off-plane response to linear coupling. Circles (in blue) represent the results from simulations (upper) or measurement (lower), which can be fitted (solid line, in pink) by placing kick errors in the beam line. Kick errors are found at the locations which are marked by BPMs (in black). Subsequent to data taking, it was found that the correctors and BPM had roll errors of upwards of a few degrees, which complicates the analysis. By comparing the upper and lower differential orbits, it is clear that there are multiple sources of distortion (due to coupling or corrector/BPM roll) as evidenced by oscillation amplitude changes and phase differences between the machine data and simulation. This implies that field errors and misalignment data used in the modeling do not yet reflect the real machine situation.

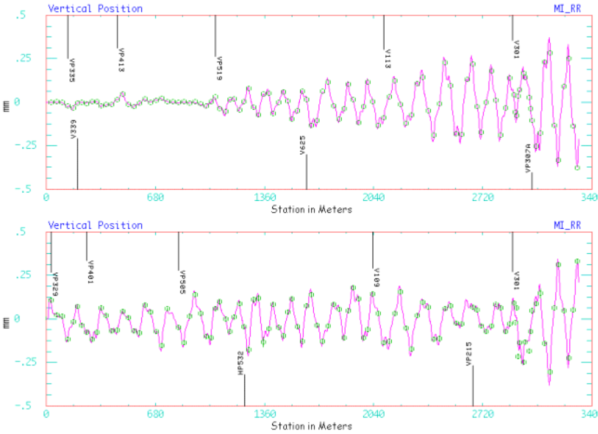

Figure 1: The 1st order differential vertical orbits from simulations (upper) and from measurement (bottom) due to horizontal excitation at injection point H328.

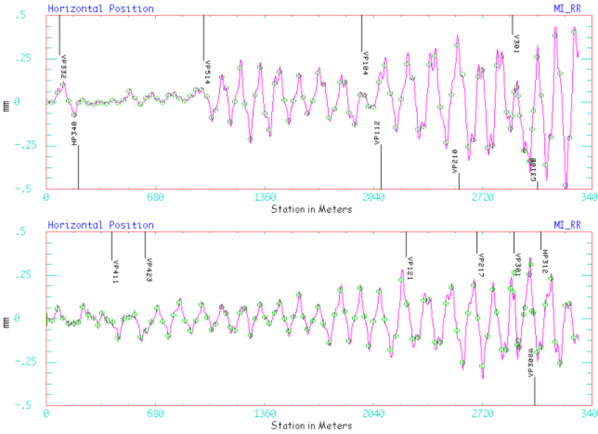

Figure 2: The 1st order differential horizontal orbits from simulations (upper) and from real machine (bottom) due to vertical excitation at injection point V329.

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LOCAL 3-BUMP STUDY

To better identify the coupling sources, closed local 3-bumps are used. Figure 3 shows the horizontal 3-bump at H312 and vertical 3-bump at V313. We know that the coupling can only come from the elements inside the local 3-bump region if we see an off-plane orbit. We used a circulating proton beam to take closed orbit data with 64 turns averaging, and typically took 8 different bump sizes (from -2 A to 2 A, 0.5 A/step) per location for the whole ring. The maximum bump size is ±8mm in horizontal plane and ±5mm in vertical plane.

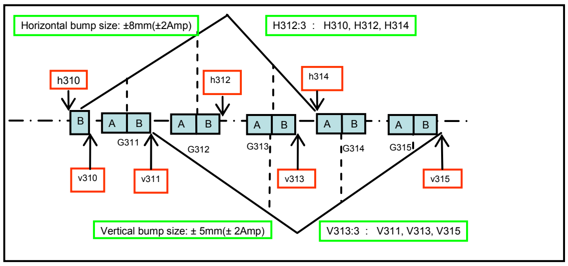

Figure3: local 3-bumps at H312 (horizontal) and at V313 (vertical).

The 1st order off-plane differential orbit is smoothed by a "Magnet Move" program which automatically places the proper kick errors inside the 3-bumps. If the kick error comes from the magnets at the ends of the 3-bump region, for example G310B and G314A in Figure 3, it implies that trim dipoles (H310 or H314) have roll, since the displacements at those locations are closed to 0. If the kick error originates from the center of the 3-bump region, this indicates the coupling source could be a skew quad term from a rolled quad or gradient magnet, a skew multipole, or a rolled trim magnet used in the local 3-bump.We also can identify if the BPM itself is rolled or not by looking at the off-plane orbit, usually the displacement in off-plane near the center of the kick is twice or three times larger than those in the rest of the ring. Suspected magnet rolls were found in 84 out of 416 magnets in the ring. Although the installation tolerance for roll is less than 0.03°, most of the roll angles as shown in Figure 4 are less than 1°, except at the skew quad correctors, the three Lambertson regions and the quads at 607 and 620. We later found by survey that a magnet, Q620B, had roll about 1.3°. Detailed analysis and results of local 3-bump studies are presented in [4].

COUPLING CORRECTION SYSTEM

There are two skew quad families in the Recycler ring, with two quads in each family for global coupling compensation. What counts, when it comes to coupling resonance correction, is how the difference in the phase advances progresses. Table 1 shows the difference in *x-y* phase advance for each of the skew quad circuits relative to the SQ408 element. Measured results were obtained by the interpolation of the phase advances between two BPMs, which were extracted from turn-by-turn data [5].

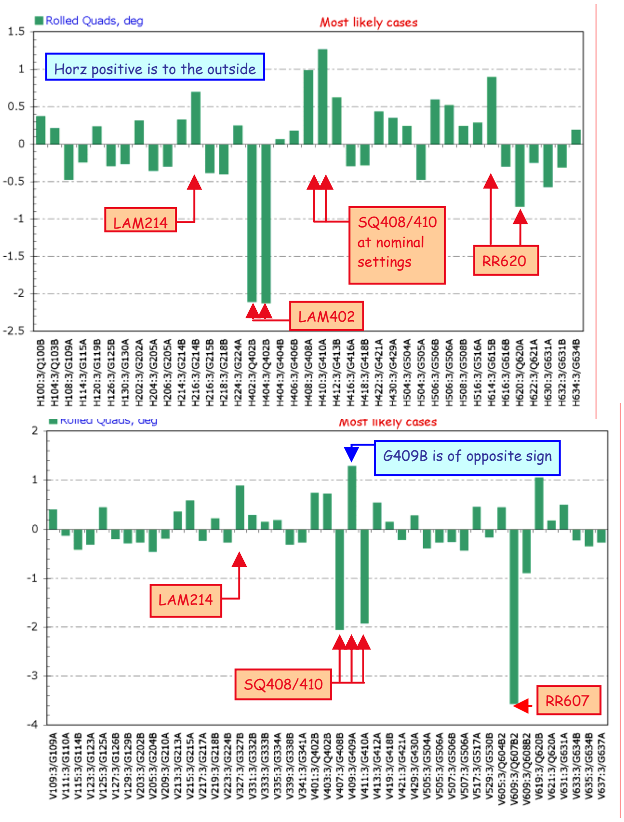

Figure 4: Magnet rolls found by horizontal and vertical local 3-bumps

Turn-by-turn data was acquired for every BPM by introducing a small injection error for lattice function measurement. Figure 5 shows the differences between measured and design phase advances in each plane. Note that in Table 1 the first two skew quads (408,410) (cos like, shown in red) are "in phase", and the second set (504,506) (sin like, shown in blue) are approx. 90 deg out of phase. The two skew quads families in the machine are orthogonal in phase.

Table 1: *x-y* Phase advance difference between skew quads calculated from model and extracted from phase advance measurements.

Circuits	Model	Measured
$(\nu_x - \nu_y)_{(408)} - (\nu_x - \nu_y)_{(408)}$	0	0
$(\nu_x - \nu_y)_{(410)} - (\nu_x - \nu_y)_{(408)}$	1	10
$(\nu_x - \nu_y)_{(504)} - (\nu_x - \nu_y)_{(408)}$	75	88
$(\nu_x - \nu_y)_{(506)} - (\nu_x - \nu_y)_{(408)}$	88	88

Based on the design lattice, contributions to the minimum tune split from each skew quad with an excitation of 1 Ampere were calculated, listed in Table 2. The real part and imaginary parts of complex form represent the contributions in horizontal plane and vertical plane respectively (primary contribution in color). To measure the action of each skew quad to the minimum tune split all the skew quads were first set to zero, producing a coupled lattice. Then, each skew quad was independently excited and the H/V tune shifts were measured and are listed in Table 3.

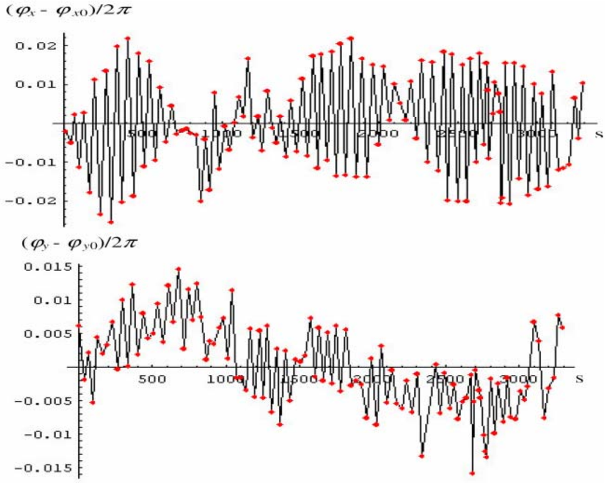

Figure 5: The differences of measured phase advances from designed phase advance in horizontal plane (upper) and vertical plane (bottom).

Comparisons between measured and calculated skew quad contributions to minimum tune split in Table 2 and 3 indicate that SQ410 contributions are reasonably close, SQ408 produced no observable tune changes, and SQ504 and SQ506 are within a factor of 2. We later found problems with SQ408 and SQ504/SQ506 power supplies. With these problems fixed, the minimum tune split was again reduced to ~0.003.

Table 2: Skew quads contribution from lattice (per 1 A)

Skew quads	Contribution to min tune split
SQ408	0.00104292 - 0.00010216i
SQ410	0.00108263 - 2.9E-6i
SQ504	-0.00026328 - 0.00103626i
SQ506	-0.00020395 - 0.00104664i

Table 3: Skew quad contributions from measurement

Skew quads	Current(A)	dQx	dQy	|Qx-Qy|
SQ408	10	0	0	0
	-10	.0007	0	0
SQ410	10(9.66)	.004	-.004	.008
	-10	-.0055	.0048	.0103
SQ504	-9.7(-8.7)	-.0028	.0023	.0051
SQ506	-9.2(-8.0)	-.0028	.0020	.0048

The minimum tune split can also be calculated from turn-by-turn data by extracting coupling generating functions around the ring and computing the coupling coefficients [5]. Table 4 lists the real and imaginary parts of the coupling coefficient and the expected minimum tune split calculated from TBT data taken before and after SQ408 circuit was fixed. The minimum tune split is in agreement with direct coupling measurements.

Table 4: Calculated residual tunes before and after SQ408 fixed

Conditions	Coupling coefficient	$\|Qx-Qy\|_{min}$
Before SQ408 fixed	0.0076+0.0001i	~.008
After SQ408 fixed	0.0003+0.0023i	~.002

Beam studies show that the current of SQ408 & SQ410 family reaches its upper current limits while the minimum tune split can only be corrected to 0.003. To reduce the current in the 408/410 family and reduce the minimum tune split further an additional skew quad was needed in the 408/410 family. Several locations in the ring were within ±5° in phase with SQ408, but only 404 is dispersion free with space available. We installed the skew quad, SQ404, (x3 stronger than existing skew quads) to replaced the SQ408 element in the 408/410 family during the 2004 shutdown of Fermilab accelerator complex. The minimum tune split was reduced to less than .001 with new SQ404.

CONCLUSION

Coupling issues have been studied in the Recycler Ring at Fermilab. Single turn injection studies show that field errors and misalignment data do not reflect the real machine situation. The model needs to be improved. Local 3-bump studies allowed identification of strong coupling sources directly. Significant coupling sources were found in the Lambertson magnets and several other locations (i.e. Q607 and Q620), some of which may be compensated through magnet alignment. The problem of SQ408 power supply was found by the measurement of the skew quad contributions. We also found the existing correcting system was not strong enough to completely compensate the coupling sources. Once new skew quad, SQ404, was installed, the minimum tune split in the Recycler Ring is now less than 0.001.

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