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THE STUDY ON COUPLING ISSUES IN THE RECYCLER AT FERMILAB*

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Abstract

We have been working and trying to answer the following questions: where are the coupling sources in the Recycler and is the existing correcting system working fine? In this paper, we report the analysis on the sources from both modeling and real machine. From the first turn flash orbit, we fit the off-plane orbits by third order polynomial, then separate 1st, 2nd and 3rd order coefficients to see different effects. We further develop a local3-bump method to make it possible to identify the source of coupling directly. On the other hand, we present the analysis from turn by turn data, which is to verify the phase of two skew quads families are more or less orthogonal, and to make sure the minimum tune split is small enough, and is consistent with the measurement.

INTRODUCTION

There are two skew quadrupole families in Recycler Ring, SQ408 and SQ410 in one family, SQ504 and SQ506 in another family. The linear coupling can be corrected to minimum tune split of less than 0.001. However, since September 2003, the best we can get was 0.0103. Presented in this report are the efforts we made to reduce the coupling in two aspects: one is to identify the coupling source, the other one is to verify if the existing skew quadrupole correcting system is working fine.

SINGLE TURN INJECTION STUDY

The machine studies were done by introducing orbit errors of trims dipoles at injection point from -2.5 A to 2.5 A in steps of 1/2 A. Orbit data of all the available BPMs (Beam Position Monitor) in both planes were acquired under the conditions that skew quads, trombone quads and chromaticity sextupoles are set to zero. There is no closed orbit change when we turned off elements.

We also simulated the single turn injection using code MAD[1], 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. BPMs data was extracted from MAD output files.

Both data from experiments and simulations are first fitted by 3rd order polynomial using beam line analysis program, and then their 1st, 2nd and 3rd order coefficients can be separated to see different effects. Figure 1 and figure 2 show the 1st order coefficients of the orbit in vertical plane and in horizontal plane, which indicates the coupling effect response to respectively to the horizontal kick at H328 and vertical kick at V329 with the kick strength of 1 Amp. The upper plot in each figure is from simulations and the bottom plot is from experiments. In the real machine, coupled orbit starts immediately from the injection points and get cancelled in some section, and then get stronger to the end. However, the results from the simulations show the coupling starts from section RR500, no cancellation through the ring. The phases of the oscillation are also different from those in the real machine. This implies that field errors and misalignment data used in the modeling do not reflect the real machine situation.

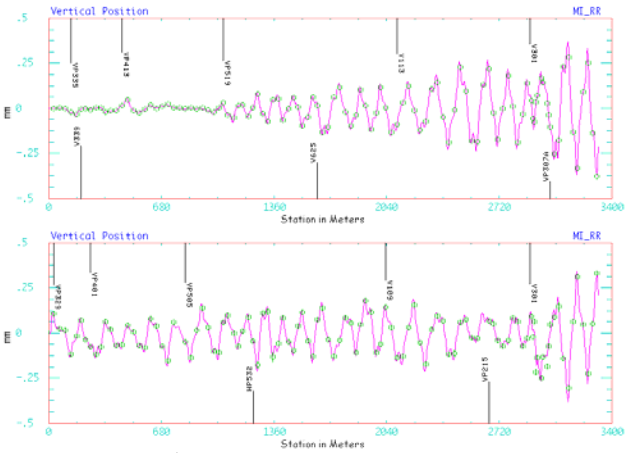

Fig. 1: the 1st order vertical orbits from simulations (upper) and from real machine (bottom).

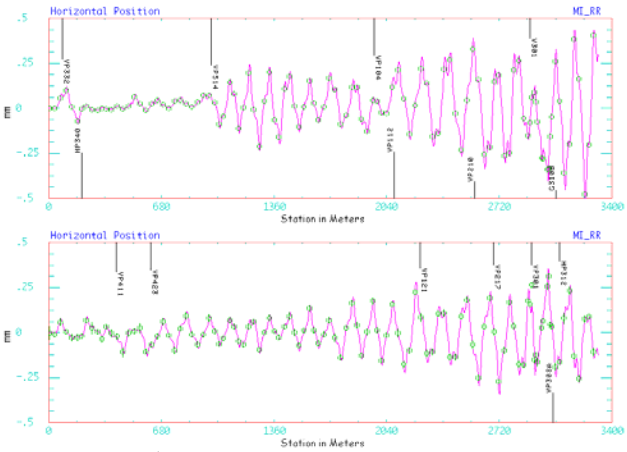

Fig. 2: the 1st order horizontal orbits from simulations (upper) and from real machine (bottom).

LOCAL 3-BUMP STUDY

To allocate the coupling sources directly, 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 off-plane coupled orbit. We used 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

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ring. The maximum bump size is ±8mm in horizontal plane and ±5mm in vertical plane.

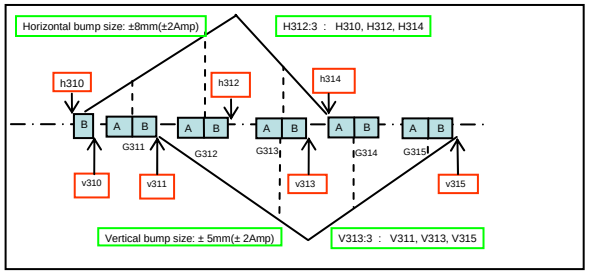

Fig.3: local 3-bumps at H312 (horizontal) and at V313 (vertical).

The 1st order off-plane orbit is taken and smoothed by a "Magnet Move" program which automatically places the proper kick errors inside the 3-bumps. If the kick error is from the magnet at the center of the 3-bump region, the source most likely are skew quadruples which may arises from rolled quads or gradient magnets. 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 itself) have roll, since the displacements at those locations are closed to 0. We also can identify the BPM rolls 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. In this way, we are able to find the roll angles [2] in 84 magnets totally among 416 magnets in the ring, given in figure 4. It is shown most of the roll angles are less than 1°. The most significant locations are lambertson 402 regions and RR620. We later found by survey that a magnet G620 had roll about 1.3°. Detailed analysis and results for LAM402 and other lambertson magnets are presented in [3]. We also found 20% of trim dipoles and BPMs have rolls up to 3 °, although they are not the sources of coupling.

SKEW QUADS CORRECTING SYSTEM

There are two skew quads families in the Recycler ring, with two quads in each family for coupling compensation. The phase advances of four skew quads in the lattice are as follows:

	ν_x	ν_y		ν_x	ν_y
SQ408M	2.632	2.549	SQ504M	5.708	5.414
SQ410M	2.866	2.776	SQ506M	5.958	5.629

What counts, when it comes to coupling resonance correction, is how the difference in the phase advances progresses. We have:

$$(\nu_x - \nu_y)_{(408)} - (\nu_x - \nu_y)_{(408)} = 0 \quad ==> \quad 0 \text{ deg}$$
$$(\nu_x - \nu_y)_{(410)} - (\nu_x - \nu_y)_{(408)} = 0.004 \quad ==> \quad 1 \text{ deg}$$
$$(\nu_x - \nu_y)_{(504)} - (\nu_x - \nu_y)_{(408)} = 0.208 \quad ==> \quad 75 \text{ deg}$$
$$(\nu_x - \nu_y)_{(506)} - (\nu_x - \nu_y)_{(408)} = 0.243 \quad ==> \quad 88 \text{ deg}$$

the first two skew quads (408,410) are "in phase", and the second set (504,506) are approx. 90 deg out of phase. Therefore the phases of two families in the lattice are more or less orthogonal.

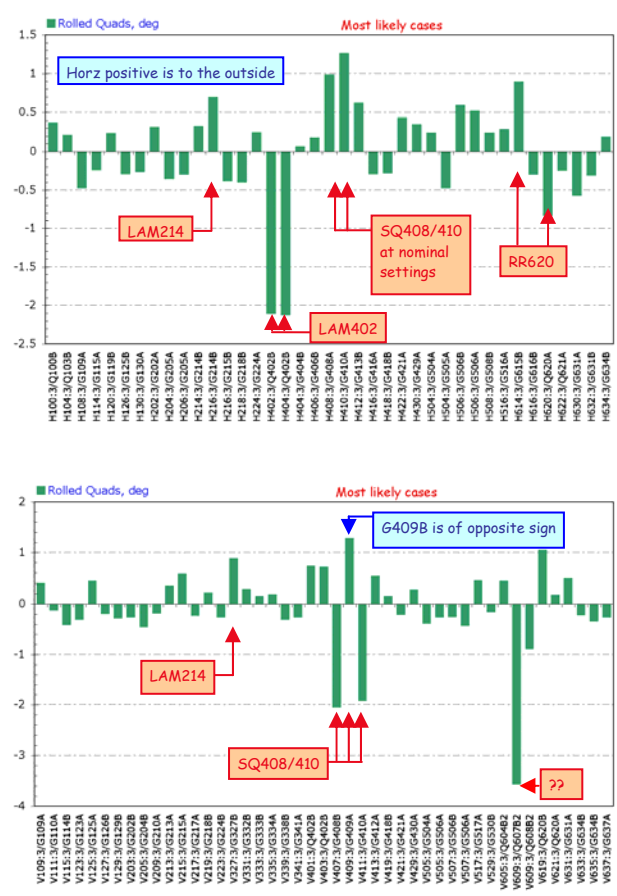

Figure 4: magnet rolls found by horizontal and vertical local 3-bumps

Based on designed lattice, the contributions in tunes of each skew quadrupole to coupling correction per 1 Ampere current were calculated [4] and listed in Table 1. The real part and imaginary part of complex forms of C- represent the contributions in horizontal plane and vertical plane respectively. The tunes changes due to each skew quadrupole contribution in the machine were measured using Recycler Spectrum Analyzer, seen in Table 2. Opposite sign of the tune changes in *x*- and *y*- plane indicates that the tunes in two planes will be brought together. Note that the contributions are reasonably closed to what we calculated, except for SQ408, which seems no effect on coupling correction. We later found that its power supply circuit had been broken. With this problem fixed, the minimum tune split was reduced to 0.003.

Phase advances were calculated from turn-by-turn data in Recycler taken before and after SQ408 power supply problem. Shown in figure 5 are the differences of measured phase advances from designed phase advances. The deviations of measured phase advances from those in design lattice at SQ408 & SQ410 and SQ504 & Q506 are within ±0.02 rad (6°) in horizontal plane and 0.01 rad (3°)

in vertical plane. This result verifies that the phases of two families in the machine are more or less orthogonal too.

By extracting coupling generating functions around the ring and computing the coupling coefficients, the minimum tune split can also be calculated from turn by turn data [4], listed in Table 3 are complex form of C- for two cases. The real and imaginary parts give the residual tunes needed to be corrected in horizontal plane and vertical planes respectively. This result is agreed with direct minimum tune split measurement with Schottky.

Table 1: skew quads contribution from lattice (per 1 A)

Skew quads	C-
SQ408	0.00104292-0.00010216i
SQ410	0.00108263-2.9E-6i
SQ504	-0.00026328 -0.00103626i
SQ506	-0.00020395-0.00104664i

Table 2: skew quads contributions from measurement

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

Table 3: Residual tunes before and after SQ408 fixed

Conditions	C-
Before SQ408 fixed	0.0090+0.0001i
After SQ408 fixed	0.0003+0.0023i

Beam studies show that the current of SQ408 & SQ410 family reaches its upper limits while the minimum tune split can only be corrected to 0.003. Taking into account that solenoids contributions of the future Electron Cooling Section in the Recycler Ring are 0.003 in phase with SQ408 & SQ410 family and -0.003 in phase with SQ504 & SQ506 family, we decided to install one more skew quads in the family of SQ408 & SQ410. Several locations in the ring are $\pm 5^{o}$ in phase with SQ408, but only 404 area is dispersion free and available in space. We finally installed SQ404 in the ring during the 2004 shutdown of Fermilab accelerator complex. The minimum tune split was significantly 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 make us possible to identify the coupling source directly. Significant coupling sources were found in three lambertson locations and RR620. On the other hand, the problem of SQ408 power supply was found by the measurement of the skew quads contributions. We also found the existing correcting system is not strong enough to completely compensate the coupling sources. One new skew quads SQ404 was installed, and the minimum tune split in the Recycler Ring now is reduced to less than 0.001.

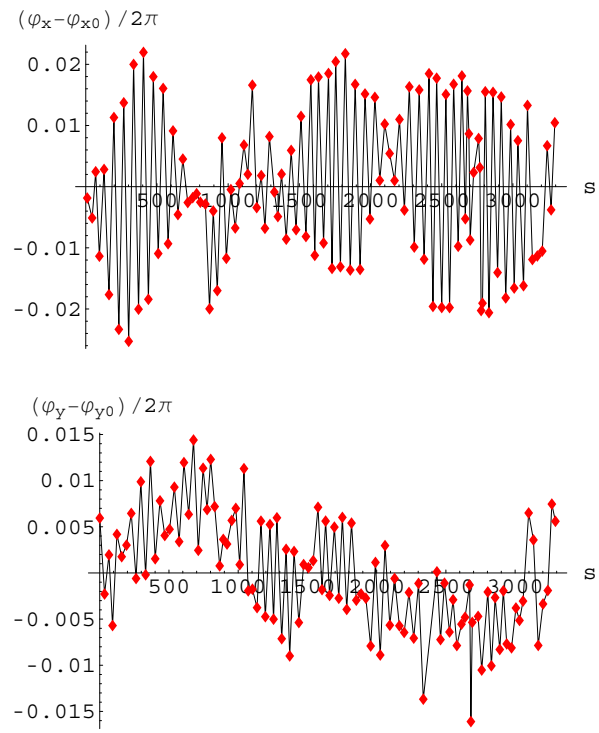

Fig. 5: the differences of measured phase advances from designed phase advance in horizontal plane (upper) and vertical plane (bottom).

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