SIMULATIONS OF THE FERMILAB MAIN RING

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ABSTRACT

Tracking programs are routinely being used in the design of future accelerators. We report on the use of such a program in understanding an existing accelerator. The problems of obtaining useful magnetic measurements from an operational machine are first discussed, as well as alternative methods of specifying the fields if these measurements are not available. The simulation results are compared with measurements made on the Main Ring with particular emphasis on the sources and corrections of the driving terms for the third-integer resonance lines.

INTRODUCTION

The Fermilab Main Ring was originally intended to be used as the final stage of acceleration for a facility doing fixed target physics. At the present time its functions are different, and as a result many modifications have been made that influence its performance. During fixed target physics with Main Ring as the final machine, the intensity per booster batch delivered by Main Ring was better that 2.5 E12. At the present time it can do no better than 1.3 E12. Most of the beam is lost prior to transition at 17 GeV. The following items may be contributors to the reduced performance.

1. Aperture restricting Lambertson magnets have been installed at four locations in the ring. They are needed for; injection and extraction from/to the pbar source (F17), injection of protons into the Tevatron (D49), injection of pbars into the Tevatron (E11), and extraction of protons as a part of the single turn abort system (B49). The F17 Lambertson is at a location where both horizontal beta and the horizontal dispersion function are large. All of the Lambertsons require large horizontal displacements in the equilibrium orbit.

2. The installation of the Tevatron in the same tunnel. The influence of the Tevatron fringe field on the Main Ring 8 GeV beam has been observed and measured. The effect influences beam positions, tunes, and coupling.

3. The Main Ring magnets are no longer run into saturation. The 150 Gev cycles for injection into the Tevatron only require 6.7 kilogauss of field. This influences the remanent field which effects the beam at injection.

4. Two overpasses have been installed so that Main Ring bypasses the detectors installed to observe collisions in the Tevatron. The effects of the overpasses are numerous. Among them are; the resultant vertical dispersion, the additional power supplies which produce global effects when in error or when they ripple, and the vertically bending magnets which are horizontal aperture restrictions. These vertically bending dipoles impose a 3 inch horizontal aperture (rather than the normal 5 inch aperture) at locations where the horizontal beta and momentum dispersion are both large.

In addition to the changes mentioned above, it had been noted prior to the installation of the B0 overpass that the third integer resonance lines which have always been a problem for Main Ring during 8 GeV coasting time, seemed to be more persistant than they had been. The construction of the B0 overpass required removing about 30 dipoles from the ring. This was seen as an opportunity to utilize the techniques that had been developed in the measurements of the field contour of the Tevatron magnets, and do the same thing with the small sample of Main Ring magnets. At the same time a tracking program was prepared so that the results of the magnet measurements could be used. The remainder of this paper indicates what has been learned, both in the measurement of Main Ring magnets, and the attempts to simulate its performance.

MAGNETIC MEASUREMENTS

The magnetic measurements were done using a rotating coil to measure the deviation of the magnetic field shape from a perfect dipole (or quadrupole). The signal produced by the rotating probe is Fourier analyzed to give the field error in terms of normal and skew harmonic multipoles.[1] These are normally quoted in units of 10^{-4} of the main field at one inch. There were two major problems with these measurements, both of which were related to the asymmetric aperture of the magnets (1.5" x 5" called B1 magnets or 2" x 4" called B2 magnets). The first problem was caused by an electrostatic pick-up between the rotating probe and the beam tube. This caused large apparent skew multipoles which were greatly suppressed by wrapping the probe with a thin aluminum layer. The second problem comes from the nature of the representation chosen. The multipole representation is most suitable for cylindrical geometry, whereas the magnet has a strongly rectangular geometry. This leads to a large number of multipoles (up through 18-pole) being needed to describe the field shape at the 400 gauss injection field level.

The validity of the magnetic measurements were cross checked against the behavior of beam in the machine in two ways. The first of these was the chromaticity. The modeling program was used to calculate chromaticity including higher order multipoles, and a comparison was made with measurements. The agreement was quite good. A second check can be made from machine measurements of the coupling. Even after the electrostatic shielding, the magnetic measurements indicated an average skew quad in the dipoles of one unit. The behavior of the beam appears to exclude anything over .1 units.

The table below indicates the results.

Normal multipoles:	B1 magnets	B2 magnets
4-pole	1.68 +/- 1.12	0.86 +/- 1.37
6-pole	-8.50 +/- 0.94	-4.83 +/- 1.16
8-pole	-1.63 +/- 0.75	0.03 +/- 0.23
10-pole	4.53 +/- 1.80	0.64 +/- 0.32
12-pole	2.37 +/- 0.98	0.04 +/- 0.10

Skew multipoles:	B1 magnets	B2 magnets
4-pole	3.85 +/- 0.53	4.31 +/- 0.66
6-pole	0.15 +/- 0.19	0.11 +/- 0.32
8-pole	-0.78 +/- 0.25	0.04 +/- 0.52
10-pole	-0.42 +/- 0.62	0.05 +/- 0.30
12-pole	1.47 +/- 0.54	0.09 +/- 0.24

*Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy

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THE SIMULATION

The tracking was done with a modified version of Tevlat, the program written to do tracking in Fermilab's Tevatron. Tevlat allows a linear or nonlinear kick to be applied to the beam in the center of any element. Tevlat was modified to accommodate the overpasses through the insertion of arbitrarily rolled dipoles. The lattice which was input into the program includes the dipoles and quadrupoles as well as the correction element packages. Multipoles were turned on in the main dipoles but not in the main quadrupoles. The correction element packages can be tuned in much the same manner as their real counterparts in Main Ring are tuned.

Also introduced into the program was the capability to calculate driving terms for all of the second and third integer resonance lines. This allows comparison between the tracking results and the analytic expressions, and also provides a relationship between the correction element settings and the distribution of multipoles in the main dipoles.

Aperture restrictions can be introduced at any point in the lattice, and with various shapes (i.e., Lambertsons).

ATTEMPTS TO SIMULATE RESONANCE LINES

Since the development of the simulation was well ahead of the magnet measurements, the decision was made to go ahead and obtain some numbers to use for the distribution of sextupole in the ring. Many save files of the settings of the trim sextupoles which correct the third integer resonances are available, and all were analyzed and driving terms for the four lines were calculated and plotted as a function of time over the past ten years. The assumption was made that the driving term for the third integer resonance lines is similar and opposite to the size of the driving term of the correction. A statistical distribution of sextupole multipoles can then be put into the main dipoles.

The next problem to be dealt with was a way to simulate the sort of resonance scans that are typically done in the Main Ring. These scans are done by varying the tune along a line $\nu_x = \nu_y + .04$ through the resonance lines and plotting the 8 GeV efficiency. See Figure 1. for an example. Simulating the tune variation is straightforward, but a parameter needed to be derived from the single particle tracking which would be analogous to efficiency in the Main Ring. In the simulation, particles are always launched along a line (in physical horizontal-vertical space) that runs in from the corner of the Main Ring aperture toward the center. The numbers used for aperture limitations were 50mm for the horizontal aperture and 20mm for the vertical aperture. From the starting coordinates, the Courrant-Snyder invarient was calculated for both the horizontal and vertical planes. These were then combined in quadrature to obtain something resembling a two dimensional amplitude. Tracking was then done until a particle was found which survived a predetermined number of turns (usually around 512). The two dimensional amplitude of this boundary particle was then plotted as a function of tune and compared to the tune vs. efficiency plots taken from Main Ring data. Some of the two dimensional resonance lines act differently depending on the starting coordinates. In this case several paths were taken in launching the particle, and the boundary particle with the smallest initial amplitude was used in the data.

The first experiment was to introduce third integer driving terms similar to those we had been correcting for, and to do the scan. The driving term was introduced through a distribution of sextupole errors in all of the main dipoles. The skew sextupoles were not turned on. The results are shown in Figure 2. The correctors were then set to compensate and the scan was done again. Total correction was obtained as expected. Secondly, similar driving terms were introduced, but in this case by only one sextupole. This situation would occur in the real Main Ring if one of the chromaticity correcting sextupoles were hooked up backwards. Again the correctors were set to compensate the driving term and the scan was done. No sign of the resonances was observed, however the overall acceptance of the simulated machine was significantly reduced. This was due to the fact that one large sextupole produces significant coupling, and the horizontal amplitude quickly couples into the vertical amplitude. The reduced aperture would not have been observed if the horizontal and vertical aperture limitations were equal or if the launching amplitudes had been equal.

Thus the problem which was initially addressed, why the 3rd integer resonance lines continue to be seen in Main Ring after correction is attempted, is not understood in the light of this simple sextupole model. As magnet measurements became available, the random sextupole numbers appeared to be smaller than what is suggested by the correction element save files. Work has begun in pursuing other sources of driving terms for the 3rd integer resonance lines. In particular the random decapole is being considered. The magnet measurements indicate a greater distribution of random decapole than anticipated. Calculation of the driving terms of the third integer resonance lines from the distribution of decapole (as measured for the Main Ring magnets at 8 GeV) indicates that the resonance line widths from this source will be greater than from the sextupole distribution. The decapole driven third integer resonance lines will be wider than the decapole driven fifth integer resonance lines. This has been considered by tracking and the results are shown in Figure 3. In this case the normal (as opposed to skew) systematic sextupole in the main dipoles was turned on but not the random. Both systematic and random normal decapole were turned on according to the magnet measurements. The correction sextupoles were turned on to correct chromaticity only. The two dimensional third integer line, $\nu_x+2\nu_y=58$ is larger than the two, two dimensional fifth integer lines, $3\nu_x+2\nu_y=97$ and $\nu_x+4\nu_y=97$. The single dimension third integer resonance line, $3\nu_x=58$ is larger than the fifth integer single dimension line which is scarcely visible.

In Main Ring the fifth integer resonance lines can be seen only if the the scans are done with the rf turned off. They are not an operational concern. The tracking shows that for one statistical distribution of decapoles the third integer lines are more serious. The magnet measurements also indicate that the random sextupoles will produce third integer resonance lines of similar widths to those shown in the Figure. Since the magnet measurement data has been presented in a statistical manner, it is not known whether the distributions of sextupole and decapole are related in each magnet so that the combined resonance behavior adds or cancels. It is known that a third integer resonance line driven by decapoles but corrected by a sextupole correction system will only be effective at one amplitude. Thus, this could account for the inability in correcting these resonance lines.

IMPROVED COMPENSATION TECHNIQUES

During the study of previous correction element save files and the analysis of the driving terms which are generated by the correctors, it became obvious that the method that had been used to compensate the driving terms was contributing to the problem. The technique involved moving the tunes so that the beam behavior was influenced primarily by the resonance in question. Then a set of correction elements was varied in a manner that changed the cosine or sin component of the driving term. The problem was that these adjustments were not orthogonal. The adjustment for $3\nu_x=58$ also changed the driving term for the $\nu_x+2\nu_y=58$ resonance. This had been understood, and attempts had been made to iterate on these resonance lines, however we had not realized the extent to which the compensation interacted. A new console applications program was written which not only provides completely orthogonal compensation, but also continuously updates a plot showing the driving term vectors. (See Figure 4.) This program has now been in use during the last running period. It has made the process of compensating resonance lines much easier and aided in our understanding of the compensations. However the failure to completely compensate the driving terms still exists, and therefore the lack of orthogonality of the previous technique is not the only culprit.

CONCLUSION

The problem of simulating Main Ring transverse behavior is part of a program to understand the limitations on Main Ring intensity and performance. The simulation efforts are still in early stages and have not yet addressed all of the issues mentioned in the introduction. The focus to this point in time has been the modeling of third integer resonance behavior, and attempts to understand why compensation of these lines has not been successful. A possible explanation has been put forth, relating a distribution in the decapole multipoles to these resonances. Other explanations have been contemplated (feed-down of octupole, an incorrectly wired correction sextupole), but these have been either ruled out, or not yet modeled.

ACKNOWLEDGEMENT

The authors wish to thank Don Edwards for many enlightening discussions.

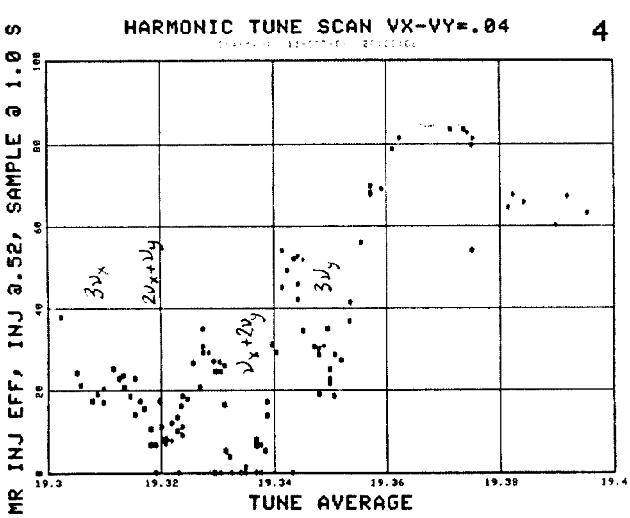

Figure 1

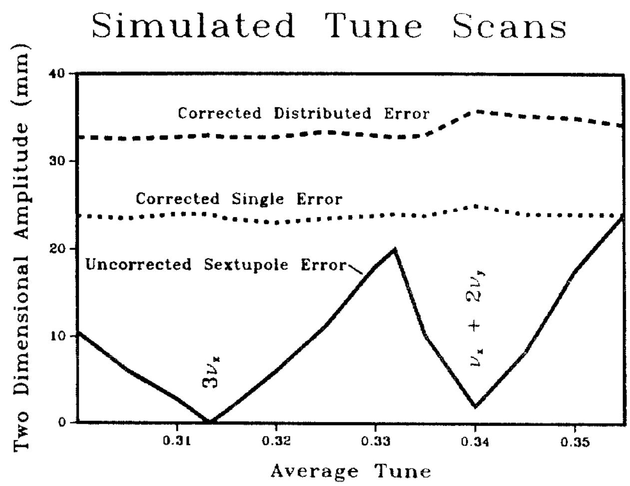

Figure 2

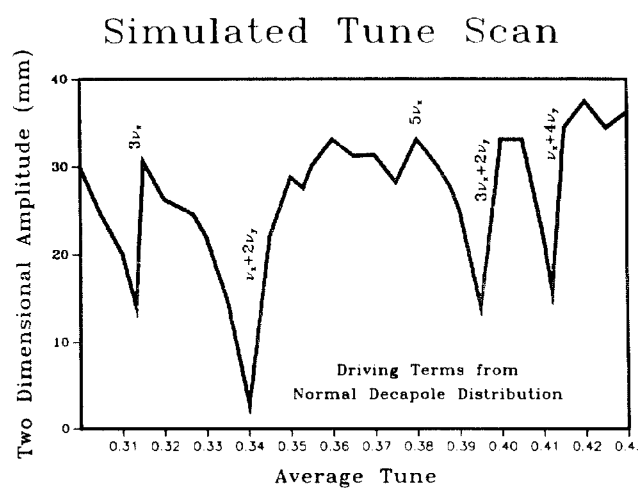

Figure 3

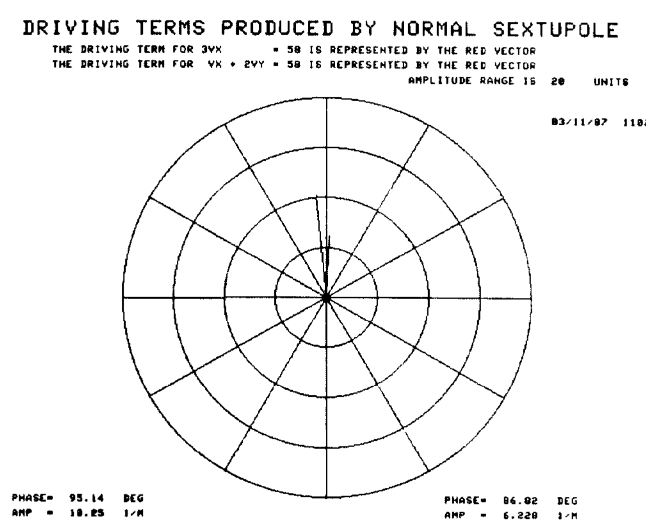

Figure 4

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1. B. C. Brown et. al. ,"A Data Acquisition System Design ...",IEEE Trans. on Nuclear Science,NS-32p.2050(1985).