IMPROVEMENTS TO THE FERMILAB MAIN RING

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ABSTRACT

In the process of converting Fermilab's Main Ring to operate in the capacity of an injector into the Tevatron and a source of protons for pbar stacking, a number of changes were made to it. These included the construction of overpasses to provide space for detectors in the nearby Tevatron, the change in the high field energy from 400 Gev to 150 Gev resulting in more destructive remanent fields at injection, and the insertion of a number of aperture restricting magnets used in the various transfers between Main Ring and other accelerators. Each of these changes has had a detrimental effect on the efficiency of Main Ring transmission at the injection energy of 8 GeV.

This paper describes the attempts to measure, simulate and rectify the problems which have been outlined above. Extensive tracking has been done in an attempt to understand the reduced 8 GeV lifetime. In doing so we have found that the systematic multipoles play an important role in particle stability.

Admittance measurements have verified the restricted aperture due to the overpasses. As a result the vertical dispersion originating from the overpasses has been reduced.

The effectiveness of these steps is discussed.

INTRODUCTION

The recent history of the Fermilab Main Ring has been documented elsewhere.[1] This paper reports on the continuation of the work reported on at that time. The focus of this work is to understand what is limiting the efficiency of the Main Ring at low energies with a goal of improving lifetimes, and preventing emittance growth.

8 GeV PERFORMANCE

In the last year Main Ring was equipped with a useful flying wire system which has enabled transverse emittance and momentum spread measurements. This has allowed better correlation between actual machine performance and the simulations.

	Incoming Beam			.1 Sec in MR			5 Sec in MR		
Turns	ϵH	ϵV	$\sigma p/p$	ϵH	ϵV	$\sigma p/p$	ϵH	ϵV	$\sigma p/p$
6	14π	14π	.95	12π	14π	.95	12π	13π	.83
5	11π	10π	.83	14π	15π	.8	14π	13π	.7
4	10π	9π	.8	12π	14π	.8	12π	13π	.75
3	9π	8π	.7	12π	14π	.68	13π	13π	.65
2	9π	6π	.6	10π	11π	.6	11π	12π	.6

		Lifetimes	
Turns	Incoming Intensity	.1 Sec τ	5 Sec τ
6	2.7 e10 ppb	<.5 sec	18 sec
5	2.3 e10 ppb	.5 sec	28 sec
4	1.8 e10 ppb	2.5 sec	29 sec
3	1.4 e10 ppb	9.0 sec	30 sec
2	.96 e10 ppb	33 sec	33 sec

Table 1

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

Table 1 shows the results of recent measurements done in the Main Ring during a studies period in which the machine was held at the injection energy of 8 GeV for 5 seconds. In the table emittances are in mm-mrad and include 95% of the beam. Momentum spreads are times 10^{-3} and the intensities are listed for protons per bunch. The principal means of controlling the intensity at the Fermilab accelerator complex is to vary the number of turns of H^- beam into the Booster from the Linac. The range utilized in operation is from 2 to 6 turns.

The results of these measurements indicate a number of things:

> The vertical acceptance seems to be limited at approximately 14π. This has been verified by other types of acceptance measurements as well.
>
> Smaller emittance beams in either plane, on the order of 11π, grow while circulating in the machine at 8 GeV. Scrapers have recently been installed in the 8 GeV transfer line into Main Ring in order to limit the beam size, but as of now studies with a smaller beam have not been done. This observation, though, indicates that any modeling of the machine must account for beam growth of particles with emittances of 11π and corresponding momentum spreads.
>
> The six turn data seem to indicate that once the momentum spread (sigma) reaches .1%, then this becomes the limiting parameter. The maximum obtainable emittances are confined to something smaller than what is observed when the momentum spread is smaller. Furthermore the momentum spread decreases while beam circulates. The sustainable dynamic momentum aperture seems to correspond to a momentum spread of .08%.

Based on these measurements the modeling has taken two approaches. Models incorporating beam growth and beam lifetimes from only beam-gas scattering have been reinvestigated. This provides a base line so that beam growth faster than what is predicted from this model can be attributed to effects relating to dynamic aperture. The second approach has been the particle tracking simulations. This simulation has been used to predict not only beam growth due to nonlinearities, but to investigate the nature of the beam loss due to the vertical dispersion.

BEAM-GAS SCATTERING

The beam-gas scattering evaluation done at this time focused on measurable quantities. Thus the conclusions predict both emittance growth and anticipated lifetimes at 8 GeV. The model and complete results are reported elsewhere.[2] The model predicts that at 8 GeV and at vacuum levels which are obtainable in Main Ring, an emittance growth of 10% can be expected over the 4 seconds during which the measurements were taken. Only the two turn data actually show an emittance growth, and these data (Figure 1) are well fit by the model. The results of the lifetime calculations of the beam-gas scattering model are used to predict the behavior of the larger beam which already occupies the acceptance of the machine upon injection. In this case the average aperture is used as a limit for the diffusion process. The results are shown in Figure 2.

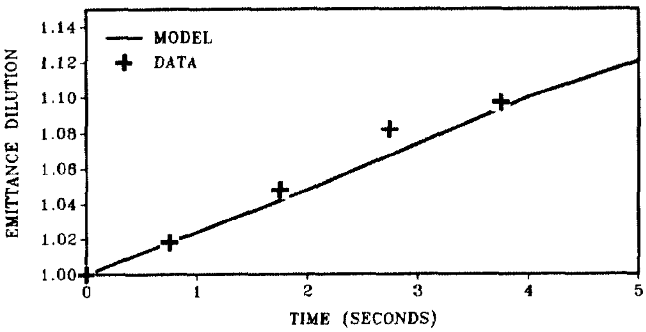

Figure 1

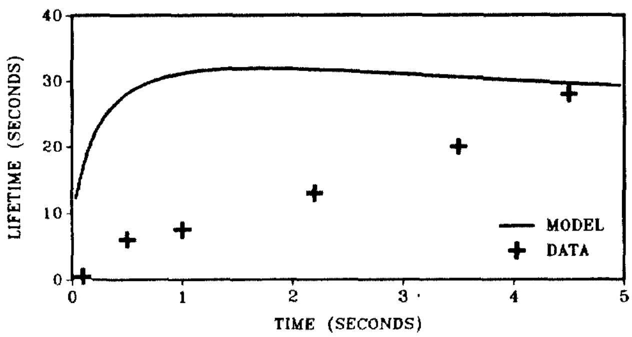

Figure 2

The fit of these data to the model indicates that the performance of Main Ring with intensities and emittance corresponding to two turns is well represented by the Beam-Gas Scattering model. Beams at higher intensities and larger emittances show beam loss which is greater than what is predicted by the Beam-Gas Scattering model. In an attempt to quantify the mechanism behind this a tracking simulation is used.

TRACKING SIMULATIONS

The tracking was done with a modified version of Tevlat, the program written to do tracking in Fermilab's Tevatron. The code was executed on a FPS-164 with 64 bits per floating point word. 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 rolled dipoles. The lattice which was input into the program includes the dipoles and quadrupoles as well as the correction element packages. The correction element packages can be tuned in much the same manner as their real counterparts in Main Ring are tuned. Thus the intentional orbit distortions introduced into Main Ring to avoid the Lambertson septa can be included in this model.

Based on the results of the Beam-Gas Scattering Model and the 8 GeV measurements, the tracking studies address the rapid loss associated with the very short lifetime during the first few second after injection. Due to the operational consideration that beam is only held at 8 GeV for at most .75 seconds, and to reduce computer time the tracking is limited to 35,000 turns. This number was chosen because it corresponds to .75 seconds in the Main Ring.

Recently our attention has been focused on the higher order systematic multipoles. The empirical observations of limited momentum aperture and the highly nonlinear chromaticity observed in Main Ring reinforced the notion that the large systematic high order (decapole and higher) multipoles found in the early magnetic measurements should be investigated by tracking. Initial investigations into this revealed that indeed single particle emittance growth is observed in a machine with essentially no random errors, but significant (and realistic) high order systematics. The authors are aware of no analytic theory explaining the growth and subsequent beam loss. The initial tracking studies exploring this phenomena were done using a simple planar machine. In all of the studies synchrotron motion was included and deemed to be necessary to see the effect at realistic emittances and field specifications. Increasing the random content of any multipole enhances the effect although it is important to note that this was not necessary in order to observe emittance growth. The inclusion of the overpasses enhanced the effect as did the inclusion of the realistic closed orbit which has large 20 mm bumps around Lambertsons. In each of these cases the machine aperture was at infinity and the criterion was the smallest initial emittance which would eventually 'ever increasingly' grow. The time scales for this effect are also different from the emittance growth associated with purely resonant behavior. In this case the particle could be well behaved for many thousands (greater than 33,000 in some cases) of turns before exhibiting rapid emittance growth.

As reported,[1] attempts have been made to measure a few of the main dipoles for multipole components. This is difficult because the vertical height of the aperture will not allow a large probe to be inserted, and therefore only a small portion of the horizontal aperture can be sampled. This leads to multiple probe samplings at different horizontal offsets and the resulting problem of recombining the data from the measurements. Detailed studies were done with a set of multipoles that were derived from the three rotation magnet measurement data and modified slightly to produce a chromaticity curve which more closely follows the chromaticity measured in Main Ring.

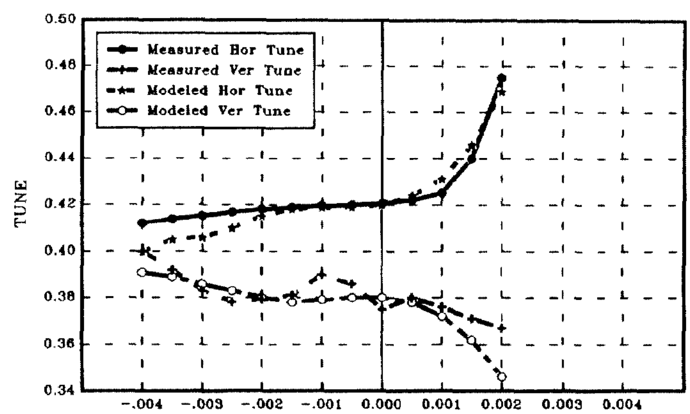

Figure 3

Figure 3 indicates the chromaticity derived from the model as compared to the chromaticity measured in Main Ring.

The actual multipole coefficients used are shown in the following table. The systematic octupole includes 1 unit which is actually attributed to the main quadrupoles. Multipoles above 16-pole were not used. In the future the 18-pole may be included.

Normal multipoles:	B1 magnets	B2 magnets
4-pole	0.0 +/- 1.00	0.0 +/- 1.00
6-pole	-7.28 +/- 0.88	-4.62 +/- 0.83
8-pole	0.3 +/- 0.75	1.0 +/- 0.75
10-pole	2.3 +/- 0.75	0.75 +/- 0.35
12-pole	1.3 +/- 0.5	-0.05 +/- 0.15

	B1 magnets	B2 magnets
14-pole	-0.3 +/- 0.15	.003 +/- 0.08
16-pole	-0.06 +/- 0.1	.007 +/- 0.03
Skew multipoles:	**B1 magnets**	**B2 magnets**
4-pole	0.0 +/- 3.00	0.0 +/- 3.00
6-pole	0.04 +/- 0.19	0.12 +/- 0.40
8-pole	-0.28 +/- 0.40	0.11 +/- 0.50
10-pole	-0.08 +/- 0.11	0.03 +/- 0.16
12-pole	0.23 +/- 0.28	0.07 +/- 0.22
14-pole	0.02 +/- 0.04	.004 +/- 0.03
16-pole	-0.05 +/- 0.06	- .02 +/- 0.04

The table entries are the field error at 1 inch, and are to be multiplied by 10^{-4}.

Table 2

Under these conditions a particle with initial single particle emittances of 9π mm-mr and a momentum error of .1% was lost within 35,000 turns 11 out of 12 times. If the momentum error is increased to .15% the emittances must be reduced to 6π to stay in the machine.

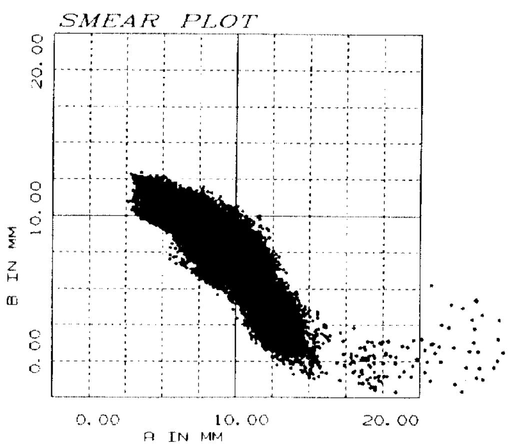

Figure 4

A display of tracking results is shown in Figure 4. The Courant-Snyder invariant for horizontal motion is plotted along the abscissa, and the vertical invariant is plotted along the ordinate. Linear, uncoupled behavior would result in a point when plotted for many turns. In this case the particle survived for for 33,000 turns before exhibiting rapid horizontal emittance growth. Growth in the horizontal plane is much more common than growth vertically.

VERTICAL DISPERSION

In order to allow for the detectors in the Fermilab Tevatron, two overpasses have been installed in the Main Ring. The first overpass to be built was for the detector at D0 and raises the Main Ring 1.42 meters above the plane the rest of Main Ring lies in. This was chosen so that no tunnel construction would be necessary. The second overpass was built for the B0 detector and this overpass, requiring a new tunnel, raises Main Ring 5.76 meters. Although the D0 overpass is more modest, the constraints to stay within the tunnel led to a placement of vertically bending magnets which result in a large (1.7 meters peak) vertical dispersion wave around the entire ring. The B0 overpass was designed such that the vertical dispersion wave around the ring is quite small (.4 meters peak), but has large values (up to 5.0 meters) within the overpass. The combination of the two overpasses was such that between B0 and D0 (one third of the ring) the vertical dispersion waves add and in the rest of the ring they subtract. As the intensity in Main Ring was pushed up it became clear that the limitations were at points of large vertical dispersion in normal vertical aperture.

Tracking studies were done with the vertical aperture set at the real machine aperture and in this case the particle was always lost at the location of largest vertical dispersion. The loss occured without emittance growth, but often was delayed many thousands of turns. Evidently the right combination of betatron phases, momentum phases, and coupling are required and in some runs this did not occur for more than 20,000 turns. Therefore reducing the vertical dispersion may increase lifetimes during the full .75 seconds at 8 GeV.

The vertical dispersion leads to other problems as well, namely the increase in vertical emittance as beam is injected from the Main Ring into the Tevatron via a transfer that is not dispersion matched. For primarily this reason it was decided to modify the D0 overpass. The goal in doing so was to eliminate the residual vertical dispersion wave, and to match the transfer into the Tevatron. The low energy performance of the machine should benefit as well. The technique used was to install shoulders on the overpass which are themselves sources of dispersion, but cancel the dispersion from the D0 overpass itself outside the region of the overpass. Figure 5 depicts a schematic of the old and modified overpasses showing the vertical dipoles.

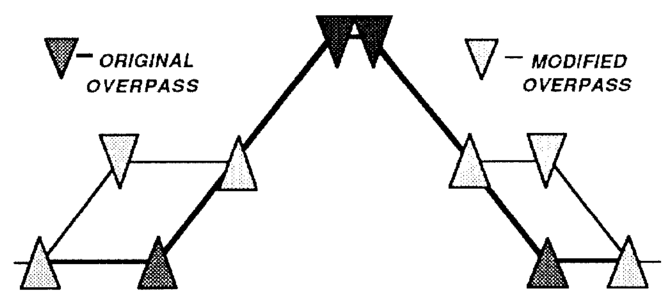

Figure 5

A solution was found which completely eliminates the dispersion wave, and keeps the accelerator in the tunnel. This solution was modified slightly so that the D0 overpass produces a slight wave which in critical locations reduces the dispersion generated by the B0 overpass. The large vertical dispersion in Main Ring is now limited to several locations within the B0 overpass and at these locations the vertical aperture is enlarged.

CONCLUSIONS

The new overpass is in the process of commissioning. It is hoped that improvements in the low energy performance of the machine will be realized as a result. Based on the tracking results a smoothed orbit around transfer Lambertsons will be attempted. Removing these orbit distortions from the model increased the dynamic aperture from 9π to 16π. If these corrections do not yield the needed lifetimes, correctors of decapole order or higher will have to be considered.

1. R. Gerig, S. Pruss, F. Turkot, "Simulations of the Fermilab Main Ring," Proceedings of the 1987 IEEE Particle Accelerator Conference, 1987, pp. 1123-1125

2. Beam-Gas Scattering Lifetimes in the Fermilab Main Ring, M. J. Syphers, Fermilab FN-484