CALCULATION OF THE ORBIT LENGTH CHANGE OF THE RECYCLER DUE TO MAIN INJECTOR RAMP*

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Abstract

Orbit length of a beam in the Recycler changes during the Main Injector ramps. Unknown kicks from the effects generated by a stray field distribute around the ring. Particularly we observed additional effects from the MI lambertsons and the C-magnets during their ramps for a beam transfer. To estimate the changes, simulated virtual kicks are created in the Recycler lattice. The difference of the orbit lengths is calculated by comparing the horizontal closed orbit of the beam with a reference orbit. Calculation results show that strong effect came from the buses. In this report, we describe the calculation methods. Also presented are the analysis including the calculation of the orbit length changes and the strength of the simulated kicks before and after we shield the buses.

INTRODUCTION

Fermilab Recycler Ring (RR) locates on top of the Main Injector (MI) Ring. They are in the same tunnel. The Main Injector (MI) is a multi-purpose machine, in which there are various MI ramp cycles or events. The MI main dipole magnets perturb the stored beam in the Recycler. A set of RR dipole corrector magnets and a global dipole corrector loop magnets were designed to keep the orbit stable transversely. However, we observed additional effects from the MI lambertsons and the C-magnets during their ramps for beam transfers. Beam studies show that the orbit changes differently with and without the lambertsons ramps. The buses, which connect the power supply to the lambertson magnets and the C-magnets, run at 2,500 Ampere and they are 25 meters long, they may be one of the sources.

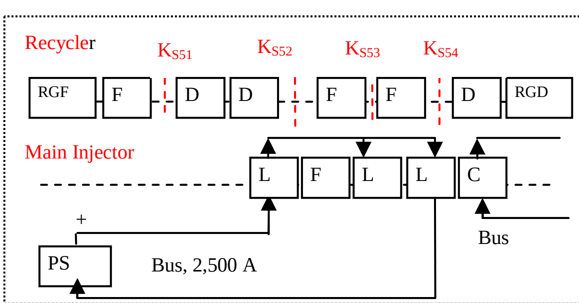

Figure 1: The lattice in Recycler ring around one of the Main injector Lambertson (L) and C-magnet (C). RGF and RGD represent the gradient magnets, F and D represent focusing and defocusing quadrupoles. PS is Power Supply. K_{s51}, K_{s52}, K_{s53} and K_{s54} (in red) are simulated virtual kicks.

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Figure 1 gives the part of the Recycler lattice around one of the MI lambertson magnets LAM52 and C-magnet V701, as well as their buses. k_{s51} and k_{s52} shown in Figure 1 are simulated for bus effect, k_{s53} and k_{s54} are simulated respectively for the effects of lambertson magnets and C-magnet. A BPM system distributed throughout the Recycler lattice in both horizontal and vertical planes are used to take the closed orbit measurement during the ramps. The orbit lengths difference is calculated by comparing the horizontal closed orbit of the beam with a reference orbit.

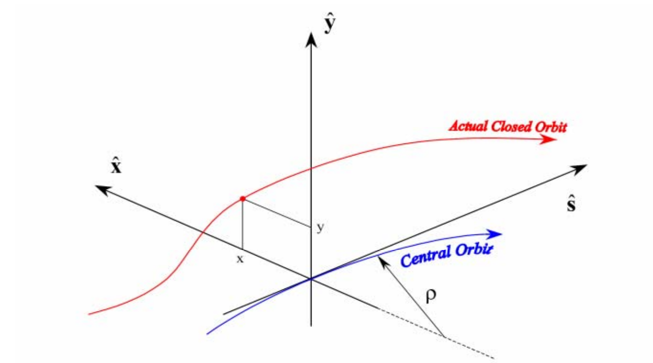

Figure 2: Coordinate system used to describe the motion of the beam in an accelerator.

FIRST ORDER CALCULATION OF ΔL

Figure 2 gives the curvature coordinate system used for the specification of the closed orbit in the Recycler. The infinitesimal element of the path length, *dL*, along any orbit in this system is given by:

$$dL^2 = dx^2 + dy^2 + (1 + k_x x + k_y y)^2 ds^2 \qquad (1)$$

k_x and k_y specify the curvature ($1/\rho$) in the *x-s* and *y-s* planes respectively. There is no significant vertical curvature in the Recycler, therefore, the $k_y y$ term will be dropped in the calculations that follow. The length of an orbit is calculated by integrating *dL* in equation one full term around the Recycler,

$$L = \oint \sqrt{1 + 2k_x x + (k_x x)^2 + x'^2 + y'^2}\, ds \qquad (2)$$

x' and y' denote the longitudinal derivatives of x and y .

Although it is difficult to measure the displacement of an orbit relative to the central orbit, the Recycler BPM system is capable of accurately measuring the difference between any two closed orbits. In particular, if one of those orbits is the reference orbit, then we can define a Δx and Δy such that:

$$\begin{aligned} \Delta x &= x - x_r \\ \Delta y &= y - y_r \end{aligned} \qquad (3)$$

x_r and y_r are the horizontal and vertical displacements of the reference orbit relative to the central orbit.

It is shown that the difference of the closed orbit length to the first order is given by

$$\Delta L = \oint k_x \Delta x ds. \quad (4)$$

It depends only on the horizontal displacement from the reference orbit. In this approximation, distortion of the vertical orbit does not affect the orbit length.

CLOSED ORBIT DISTORTION MODEL

The model used for the orbit length calculation assumes that the distortion of the closed orbit from the reference orbit can be written as a superposition of dipole kicks from all of the possible sources of such a kick [1]. The model also allows for a beam momentum error (i.e. an error that causes the beam to be radically off-center in the arcs). This superposition of kicks is written as:

$$\Delta x(s) = \frac{\sqrt{\beta(s)}}{2\sin \pi\nu_x} \sum_i \sqrt{\beta}\theta_i \cos\left(\pi\nu_x - \left|\mu(s) - \mu_i\right|\right) + D(s)\frac{\Delta p}{p} \quad (5)$$

where

$\beta(s)$ = Horizontal beta functionat longitudinal positions;

β_i = Horizontal beta functionat at the i^{th} kicker;

$\mu(s)$ = Horizontal betatron phase at s;

μ_i = Horizontal betatron phase at the i^{th} kicker;

$D(s)$ = Horizontal dispersion at s;

ν_x = Horizontal betatron tune;

θ_i = Dipole kick from the i^{th} kicker;

$\Delta p/p$ = momentum error.

Determination of the kicks θi and $\Delta p/p$ is accomplished by substituting the BPM measurement of $\Delta x(s)$ in equation at each horizontal BPM, and solving for the kicks. The lattice parameters are obtained from MAD output. The equation to be solved for θi and $\Delta p/p$ is

$$\mathbf{b} = \left([\mathbf{M_{bk}}][\mathbf{D_b}]\right)\cdot\begin{pmatrix}[\boldsymbol{\theta}_\mathbf{k}] \\ \frac{\mathbf{\Delta p}}{\mathbf{p}}\end{pmatrix} = \mathbf{M_b}\cdot\boldsymbol{\theta} \quad (6)$$

b: a vector of length N_b - N_b is the number of horizontal BPMs, containing the BPM readout of the difference between the orbit of the interest and the reference orbit.

$\mathbf{D_b}$: a vector of length N_b containing the value of the horizontal dispersion function at each horizontal BPM.

$\boldsymbol{\theta}_\mathbf{k}$**:** a vector of length N_k containing the kicks from the kick elements

$\mathbf{M_{bk}}$: the N_b X N_k matrix that connects the kicks from the kick elements to an orbit displacement at the horizontal BPMs.

This is a least squares problem. It can be solved by manipulating the Singular Value Decomposition (SVD) of $\mathbf{M_b}$ [2]. Once equation (6) has been solved for **θ,** the displacement of the orbit relative to the reference orbit can be calculated elsewhere in the Recycler lattice. In particular, we are now in a position to calculate $\Delta x(s)$ in the arcs so that the integral in equation (4) can be evaluated. The difference of the closed orbit length is

$$\Delta L = \sum_{i=1}^{N_d}\int_{s_i}^{s_i+L_i} k_x[\Delta x_d(s)]_i ds = \sum_{i=1}^{N_d}\int_{s_i}^{s_i+L_i} k_x[\mathbf{M_d}(s)\cdot\boldsymbol{\theta}]_i ds \quad (7)$$

$\mathbf{M_d}$ is a N_d X N_k dimensional matrix, where N_d is the number of horizontal main bending dipoles. it connects the kicks to horizontal distortion of the closed orbit in the main bending dipoles.

ANALYSIS

A program in Mathcad was written for the calculation of orbit length changes in Recycler during MI ramps. The data taken as input for this analysis consist of closed orbits before and after the LAM52 and V701 magnet buss work. Both the data before and after buss work consist of three different closed orbit measurements, with MI at 8 GeV and at 150 GeV with and without LAM52 and V701 ramping. For each of these measurements, all of the 110 horizontal BPMs in the Recycler were used, except those from RR-302 to RR-308 are masked due to their higher uncertainty.

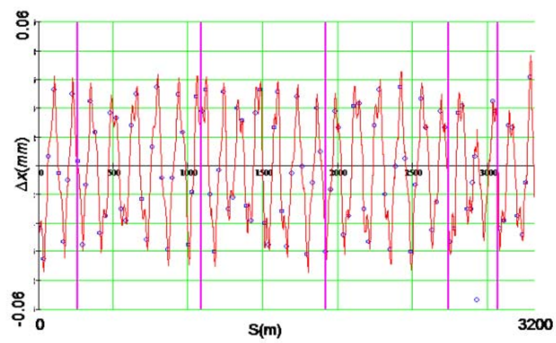

Figure 3: Orbit difference between MI at 150 GeV with LAM52 and V701 ramping and MI at 8 GeV before the LAM52 and V701 magnet bus work. Blue circles are measured values, red line is the fitted value. BPMs from RR-302 to RR-308 are masked. Noted here most measured values of those BPMs are out of range.

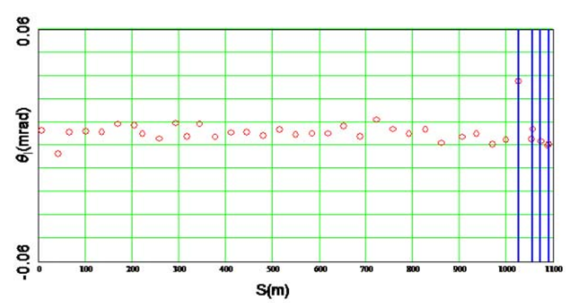

Figure 4: Kick strengths calculated from the orbit difference between MI at 150 GeV with LAM52 and V701 ramping and MI at 8 GeV before the LAM52 and V701 magnet bus work.. The blue lines indicate the location of simulated kicks.

Figure 3 gives the orbit difference between MI at 150 GeV with LAM52 and V701 ramping and MI at 8 GeV (before ramping). The orbit length difference is 0.41 mm over 3319.40 m. Figure 4 gives the kick strength calculated from the orbit difference above. We see that k_{s51} is 0.035 mrad, about 3 times larger than the other kicks(RR ramp correctors) in the Recycler ring. Note that most of the kicks are around +0.006 mrad, which indicates that the ramp effect was a little bit over corrected. This result shows that the effect from the buss was dominated, which verified our suspicion for the buss.

On Mar. 17, 2004 at the time Tevatron complex shut down, we disconnected the return loop of the buses. Instead, we use a cable, which mostly canceled the stray field generated by buss. We took the measurements again between MI at 150 GeV with LAM52 and V701 ramping and MI at 8 GeV(before ramping). Figure 5 and Figure 6 give the orbit difference and the kick strengths around the ring. We can see that the orbit difference now is much smaller than before. The orbit length difference is 0.22 mm. All the kicker strength are within ±0.012 mrad, k_{s51} is not dominated now.

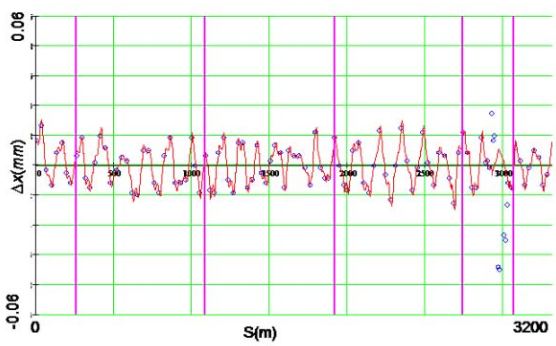

Figure 5: Orbit difference between MI at 150 GeV with LAM52 and V701 ramping and MI at 8 GeV after the LAM52 and V701 magnet bus work. Blue circles represent measured values, red line is the fitted value.

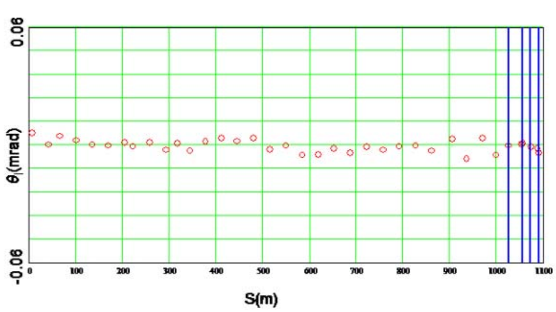

Figure 6: Kick strengths calculated from the orbit difference between MI at 150 GeV with LAM52 and V701 ramping and MI at 8 GeV after the LAM52 and V701 magnet bus work. The blue lines indicate the location of simulated kicks.

CONCLUSION

The methods and the program of the calculation for orbit length difference are developed, which can be used to compare any two cases. To investigate ramp effects of the Main Injector, the orbit length changes and the kick strengths in Recycler before and after LAM52 and V701 magnet bus work have been calculated. It helped to understand why the ramping of LAM52 and V701 magnet had larger effect on orbit change. Presently, the orbit length keeps varying by a few 10^{-7} (~mm over ~km radius). It means that the synchrotron frequency is not constant, it in turns causes longitudinal emittance growth. This orbit length variation can be measured by a phase detector, which was built later by comparing the phase of the beam stored in a r.f. barrier bucket or linear bucket to the phase of the r.f. wave form. A feedback system is installed to keep the variation small, and a feed-forward system is being developed to further compensate the ramp effects.

ACKNOWLEDGEMENTS

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