ORBIT CORRECTION IN THE RECYCLER PERMANENT MAGNET STORAGE RING

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Abstract

The Recycler Ring at Fermilab is a storage ring with the aim to store and cool the precious antiprotons for the Tevatron collider program. It is built from permanent magnets to keep the antiprotons even in the case of a power failure.
The initial orbit steering was done with a very limited set of powered correction elements. Eventually, all orbit correction will be done by realigning the gradient magnets and quadrupoles to obtain the desired closed orbit.
We will present the orbit correction software and the procedure to realign the magnets. The first results of the orbit correction and the present status will be shown.

1. INTRODUCTION

The purpose of the Fermilab Recycler Ring [1] is to augment the luminosity for the upcoming Tevatron collider run by increasing the number of antiprotons available for collisions. It stores cooled antiprotons from the antiproton source accumulator ring and allows more effective cooling there. It will also store and cool antiprotons that are left over from the previous Tevatron collider store. The Recycler has to be very reliable to avoid any accidental loss of the precious antiprotons.

The Recycler is a storage ring for antiprotons of fixed 8 GeV kinetic energy with a circumference of 3319 m. It is built from permanent magnets, which does not only greatly reduces the cost and construction efforts but also makes it nearly independent of electrical power and hence increases the reliability. To even lower the risk of accidental beam loss, the tune adjustment and orbit correction are foreseen to be independent of electrical power. This implies that the orbit correction has to be done by adjusting the transverse position of the permanent combined function gradient and quadrupole magnets. It was shown in simulations that already a limited number of magnet movements can achieve the desired orbit [2].

2. ORBIT CORRECTION

There are a total of 344 permanent gradient and 100 permanent quadrupole magnets in the Recycler Ring. They have been carefully aligned to a relative accuracy of ± 0.25 mm [3, 4].

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The orbit distortions generated from the residual misalignments and magnetic field errors have to be corrected. There is a very limited number of powered trim dipole magnets installed in the ring, 19 in the horizontal and 20 in the vertical plane. Yet, these correction elements are mainly located around locations of septum magnets and stochastic cooling devices to allow a precise steering there. For the initial conditioning of the machine, they still can be used for a global orbit correction while eventually all steering will be achieved by magnet movements.

2.1 Magnet Movement Calculation

The orbit correction with magnet movements has to be effective and in particular has to use the least number of magnets possible to minimize the effort of physically moving the magnets. For this reason, the MICADO algorithm [5] was chosen for the calculation. It finds the most effective correction for a given number of magnets. The MICADO algorithm solves a system of linear equations

$$r = A \cdot \theta + b. \tag{1}$$

$b = (b_i)$ is the vector of the beam position monitor (BPM) measurements, $\theta = (\theta_i)$ is the correction kick vector and $A = (a_{ij})$ the beam response matrix to a set of correction kicks given by

$$a_{ij} = \frac{\sqrt{\beta_i^{BPM} \beta_j^{kick}} \cos\left(|\mu_i^{BPM} - \mu_j^{kick}| - \pi Q\right)}{2\ \sin(\pi Q)}. \tag{2}$$

β_i^{BPM} and μ_i^{BPM} are the betatron function and phase at the BPM locations, β_j^{kick} and μ_j^{kick} at the kick locations, respectively, and Q is the betatron tune.

The algorithm iteratively minimizes the norm of the residual vector r using a least squares method. At each iteration, it finds the first best correction kick that yields the lowest residual r.m.s. BPM distortions. This correction kick is appended to the previously selected set, the residual distortion is reanalyzed and the next best correction kick selected. The strengths of all corrections from previous iterations are recalculated. This is repeated for up to a chosen number of corrections until the residual r.m.s. BPM distortions are as small as desired. The algorithm is fast and converges with a small number of correction kicks.

The MICADO algorithm used here is contained in the orbit correction package COCU (Closed Orbit Correction Utilities) [6] which was developed at CERN. The package calculates corrections of the closed orbit, a trajectory in a circular accelerator or transfer line, and orbit or trajectory correction over a short range without affecting the rest of the machine. It also does calculation of bumps and simulation of the effects of kicks on the orbit. Calculations are based on the Twiss parameters which can be taken from simulations like MAD [7].

The COCU package is implemented as a client server in the accelerator controls system at Fermilab. The existing source could be compiled with minor changes under SunOS and Linux. An application client program was written for the VAX control consoles. This program takes and filters the BPM data and allows the selection of orbit correction type, plane to correct, number of magnet movements, etc. The BPM data and the correction commands are sent via TCP/IP to the server running on the UNIX side. The server program performs the data input to the COCU program, runs it and sends the predicted orbit and calculated correction kicks back to the console program.

The console program shows the predicted orbit and calculated magnet movements. The magnet movements Δx_Q and Δy_Q are calculated from the correction kicks by the following formulae

$$\Delta x_Q = \frac{\theta_x}{k_1 L} \qquad\qquad \Delta y_Q = -\frac{\theta_y}{k_1 L}. \tag{3}$$

The code is not particularly accelerator specific and can easily be extended to other transfer lines and circular machines. It is also successfully used for the orbit correction with trim dipoles in the transfer lines between Booster and Main Injector [8], Main Injector and Recycler, as well as closed orbit correction in the Recycler Ring and for injection closure calculation.

In the case of the Recycler magnet movement calculation there are 207 horizontal BPMs, 206 vertical BPMs and 444 possible locations for magnet movements. So the system of equations is under-determined and the solution is not unique. The maximum correction kicks in COCU have been limited such that the movement is below 5 mm which is thought to be imposed by mechanical support and vacuum system.

3. MAGNET MOVEMENTS

A complete survey setup with common survey instruments for the magnet movements would be too time consuming. Therefore a simple setup with five dial indicators has been developed to displace the magnet by a specified amount. This setup is sketched in Fig. 1.

The dial indicators are fixed to the magnet hangers of the magnet to be moved, close to positions of the alignment screws. Two are mounted in the vertical, one in horizontal direction at one end of the magnet, one dial indicator per plane is at the other end (see Fig. 2 and 3). This placement of dial indicators allows both planes to be read simultaneously and monitors the movement in both transverse planes. The dial indicators have a range of 2.54 cm (1000 mil) with a resolution of 25 μm (1 mil). Prior to any changes being made to the magnet, all the indicators are zeroed. The magnitude of the move can be monitored on the dial indicators and the magnets can be set to the desired displacement.

This moving procedure was tested with additional dial indicators measuring the distance to the ceiling and the tunnel wall [9]. Magnets were moved over a range of $\pm$50 mils (1.27 mm). For both horizontal and vertical motion, the errors are limited to 0.5 mils.

4. PRESENT STATUS

During the initial commissioning, the orbit was corrected with the available powered trim dipoles. When the ring was only one third completed, the injected beam reached the temporary abort after steering only at the injection location. After complete installation of the ring, circulating beam with a lifetime of about 15 s could be achieved with the correction dipoles. The closed orbit established is shown in Fig. 4. An orbit with smaller excursions can be obtained with the trim dipoles at the expense of a shorter beam lifetime. This indicates that we do have some localized aperture restrictions.

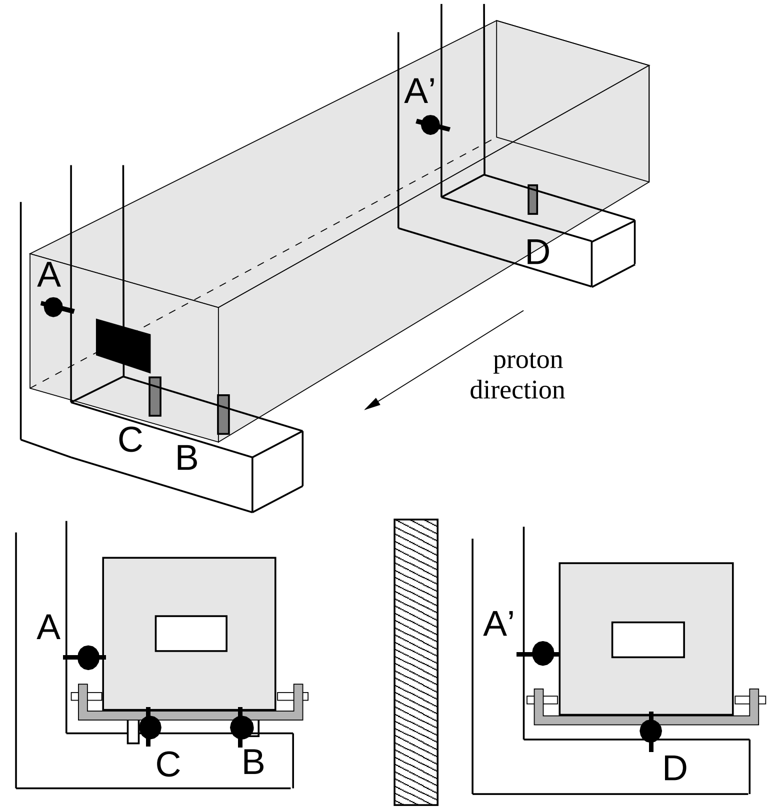

Figure 1: Setup for the adjustments (not to scale).

A magnet movement based on the actual measured orbit was not yet performed. We are presently still working on the determination of the lattice functions which have to correspond to the design before we want to alter the magnet positions. We are also investigating for the aperture restrictions mentioned above.

The magnet movement procedure was tried on magnets around an injection septum magnet to produce a closed orbit bump at this location. The amplitude of the movement was calculated from the desired design orbit change at the septum location. The dial indicator setup and magnet movement took about 15 minutes per magnet. The orbit change after the movement was as planned which confirms the functionality of the movement setup.

5. CONCLUSIONS

The global orbit correction in the Recycler Storage Ring will be done by magnet movements. The software for the determination of the magnet moves is implemented and operational. A simple setup for the controlled displacement of the magnets has been developed. It was tested by changing the position of several magnets to produce a closed orbit bump at a septum magnet position and gave the desired result.

Figure 2: Setup for a magnet movement of a combined function gradient magnet.

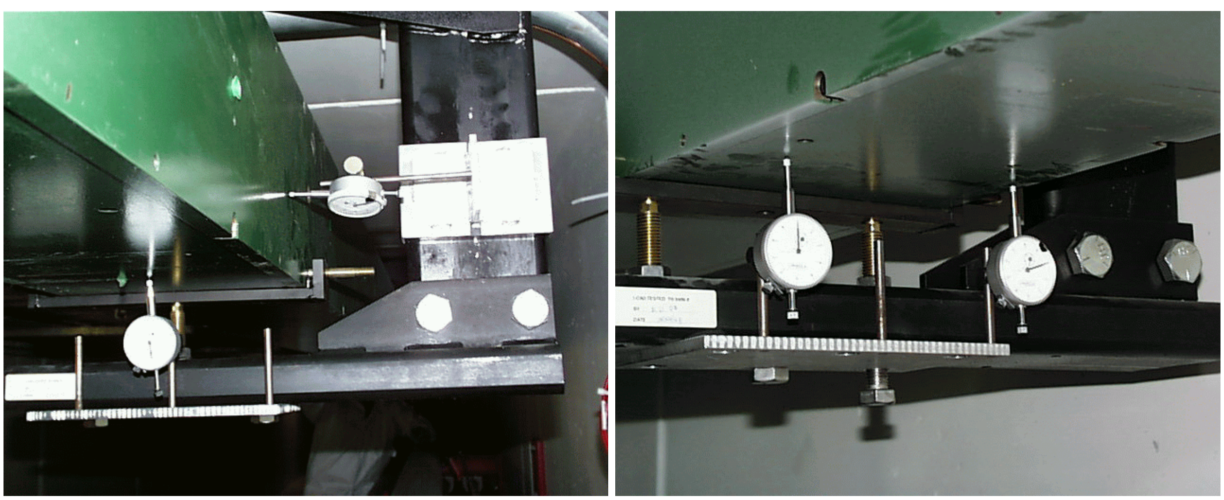

Figure 3: Dial indicator placement. One per plane is fixed to the proton upstream end of the magnet (left), two vertical and one horizontal (not shown) are mounted at the downstream end support (right).

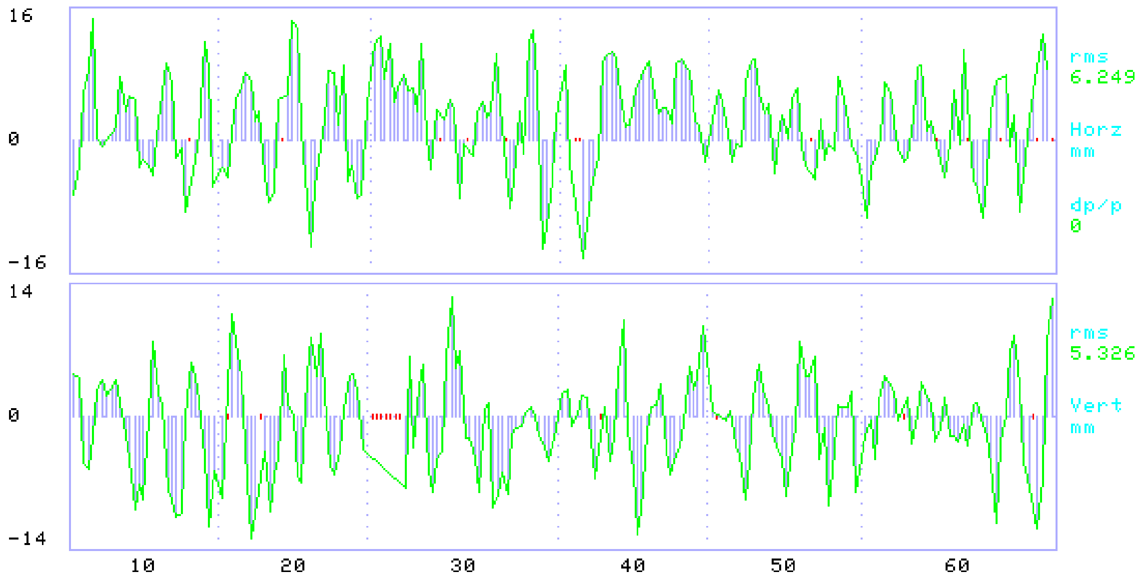

Figure 4: Present closed orbit in the Recycler Ring. The horizontal closed orbit is on the top, vertical on the bottom. BPMs with unphysically large readings are not shown.

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