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LINEAR MODELLING FROM BETATRON PHASE MEASUREMENTS AT THE FERMILAB RECYCLER NOvA RING*

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Abstract

Utilizing the measurement of coherent betatron oscillation phase has emerged as a fast and precise approach for identifying and rectifying errors in achieving a desired lattice in CESR (Cornell Electron Storage Ring), using TAO analysis program and BMAD subroutines. One key advantage of betatron phase measurement over β measurement is its sensitivity to phase variations between detectors. This software package has been successfully implemented for the Recycler Ring at Fermilab, with the adaptation of different hardware installations. By employing this technique, a linear model of the bare Recycler ring was established, enabling the correction of quadrupole errors.

INTRODUCTION

The Recycler Ring (RR), located at Fermilab, is an 8 GeV permanent magnet storage ring specifically designed for antiproton storage with electron cooling during the Tevatron Era [1] to improve luminosity. A phase trombone, located in RR60 straight section, is used to adjust phase advances, i.e., tunes in the ring [2]. In 2012 the ring was converted to a proton storage ring to stack 12 batches of beam from Booster, to be injected into Main Injector in one single transfer. This is necessary for delivering over 900kW of beam power to the NUMI target by Main Injector. The upgrade included the installation of modified endshims to change focussing of ARC gradient dipole magnets and the replacement of e-cool high beta straight section at RR30 with regular straight section lattice, and with a second phase trombone [3] to add flexibility in tune compensations. With cycle time of only 1.13 seconds, for slip stacking 12 proton batches, the closed orbit response using LOCO (Linear Optics from Closed orbit) [4] technique is no longer suitable. Instead, the console application program R92 for lattice measurement [5] has been used. By fitting Turn-By-Turn (TBT) data to sine functions, phase and amplitude at each BPM can be determined. In addition, this program utilizes TBT orbit to fit beam phase space coordinates. By tracking TBT phase space coordinates the beta function can be calculated.

The objective of lattice measurement for the RR is to construct a predictive model that can accurately represent machine behaviour. At CESR (Cornell Electron Storage Ring) [6] utilizing the measurement of coherent betatron oscillation phase has been used as a fast and precise approach for identifying and rectifying errors. For this analysis TAO (Tool for Accelerator Optics) was developed at Cornel University [7]. The same software package has been successfully implemented for the present Recycler ring at Fermilab with adaptations. With the customized TAO program for the RR, we were able to turn measured phases and beta functions into quadrupole errors from design lattice. The adaptations of TAO program for the RR are presented in this paper.

ADAPTING AND BENCHMARKING TAO

TAO is a general purposed program for simulating high energy particle beams in accelerators and storage rings. The simulation engine that TAO uses is the Bmad software library [8]. Bmad subroutine library were written in FORTRAN95, for relativistic charged–particle and X-Ray simulations in high energy accelerators and storage ring. It was developed at Cornell University's Laboratory for Elementary Particle Physics and has been in use since 1996. Both TAO program and Bmad subroutines were compiled using FORTRAN 95 compiler and installed here at Fermilab. The input lattice for Bmad was converted from a MAD8 RR lattice.

The technique utilized at CESR is to shake the beam at betatron sideband and then measure the phase of the oscillations at the beam position detectors around the ring. This yields the betatron phases $\phi_{x,y}$ at the detectors which can then be related to the beta function via:

$$\frac{1}{\beta_{h,v}} = \frac{d\phi_{h,v}}{ds} \quad (1)$$

An AC-dipole was used as shaker at CESR and Program TAO was used to locate isolated errors from the measured data by analysing the betatron phases [6]. In the Recycler ring at Fermilab, we could only ping the beam with one-shot kicker, and record the TBT orbit oscillation data. In the RR a gap clearing kicker was programmed to also work as horizontal pinger, and during summer shutdown of 2018 a vertical pinger was installed to facilitate collection of vertical plane TBT data. Program R92, after collecting TBT data from all BPM systems, does two independent analyses. The first is to perform sinusoidal fit to each individual BPM TBT data (104 in Horizonal and 104 in vertical plane). This gives betatron phases and oscillation amplitudes at BPM detectors. The second analysis is to: (1) use each turn of TBT data to construct TBT orbit data. (2) use beam line transfer matrix calculated based on lattice model, each turn orbit data is fitted to obtain TBT beam phase space coordinates (x, x') and (y, y'), as well as $\Delta p/p$. (3) resulted TBT coordinates, (x, x') or (y, y'), will exhibit betatron oscillation and populate the phase space around an elliptical trace. By fitting for the parameters of this elliptical trace we obtain the lattice function β, α, and the emittance associated with the betatron oscillation. (4) export phase and amplitude data, as well as the lattice functions. The output will then be available as input to TAO program for analysis.

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A TAO customization subroutine was originally created by D. Sagan to read only phase data. It was later modified here at Fermilab to read more types of data output from R92 program, as well as output of TAO internal parameters such as focussing errors. The results of TAO program were benchmarked by using simulated data with and without artificial errors [9].

The process of optimization in TAO involves minimization of a Merit Function. The merit function M, which is a measure of how well the data as calculated from the model, fits the measured data. Tao uses a merit function of the form:

$$M \equiv \sum_i w_i[\delta D_i]^2 + \sum_j w_j[\delta V_j]^2 \qquad (2)$$

where

$$\delta D = data_{Model} - data_{meas} \qquad \delta V = var_{model} - var_{meas} \qquad (3)$$

$data_{model}$ is the data as calculated from the model and $data_{meas}$ is the measured data. var_{model} is the value of a variable in the model and var_{meas} is the value as measured at the time the data was taken. The sum j runs over all variables that are allowed to be varied to minimize M. The second term in the merit function prevents degeneracies (or near degeneracies) in the problem which would allow TAO to find solutions where $data_{model}$ matches $data_{meas}$ with the var_{model} having "unphysical" values (values far from var_{meas}). The weights w_i and w_j need to be set depending upon how accurate the measured data is relative to how accurate the calibrations for measuring the var_{meas} as values are.

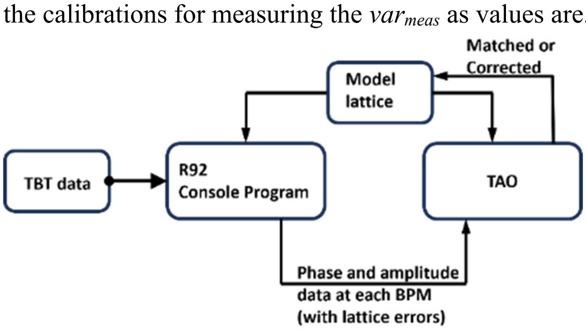
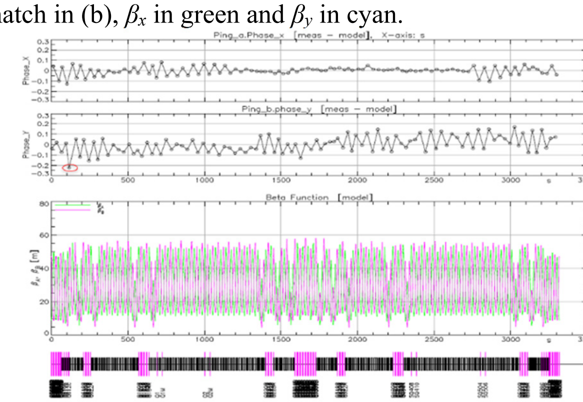


Figure 1: Flowchart from TBT data to the interaction between R92 console program and TAO.

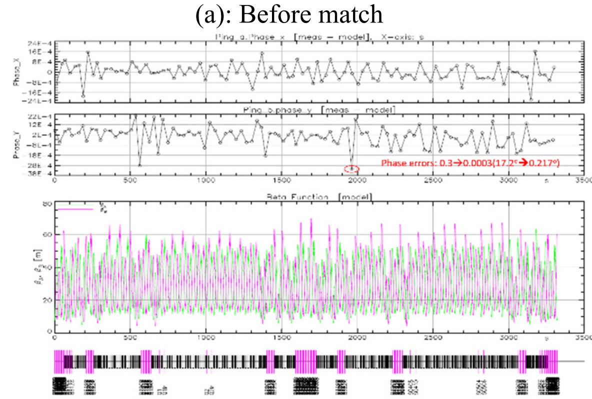
Three types of main magnets are used in Recycler ring, i.e., quadrupole, dispersion suppressor dipole, and arc dipole. Dispersion suppressor dipoles are gradient dipole magnet without sextupole component. Arc dipoles are gradient dipole magnets with built-in sextupole component. Each arc dipole is also equipped with two end-shims for harmonic compensation. There are two dipole magnets at each of the 108 horizontally focussing locations and the 108 defocussing locations. To set TAO up with variables at every location it was decided that for quadrupole component k_1 of main quadrupole magnets, body k_1 of dispersion suppressor magnets, and downstream end-shim of ARC magnets would be used as variables. The k_1 of Trim quadrupoles in RR30 and RR60 straight section are reserved for the lattice corrections. Total number of the variables is 460. The flowchart from the TBT data to the interaction between R92 console program and TAO program can be visualized in Fig. 1.

BARE LATTICE MODEL

To measure bare lattice the TBT data was taken with all trim quads in RR30 and RR60, skew quads and trim sextupoles in the Recycler ring set to 0. The model built from the analysis result of this TBT measurement is called "Bare lattice model". TAO adapted here at Fermilab does the following: (1) read the phase advances and amplitude data, as well as the lattice functions (model-dependent) obtained by R92; (2) calculate the difference of phase and amplitude from the designed lattice, and then minimize the difference to match to the design lattice, shown in the upper part in Fig. 2. The bottom part of Fig. 2 is the beta-functions of the designed lattice before match in (a), and Bare lattice after match in (b), β_x in green and β_y in cyan.



(a): Before match



(b): After match

Figure 2: Phase errors between the measured and the calculated from designed lattice (upper), Beta-functions matched model (bottom - β_x in green, β_y in pink).

The maximum phase error between measured and the those from design lattice shown in RED circle in Figure 2 (a) is about 0.3 radian (17.2°), the phase errors after match are scaled and shown in Figure 2 (b). We can see the maximum phase error is now 0.0003 radian (0.217°).

With TAO outputs bare lattice model can be constructed and incorporated into operation control system. Figure 3 shows the comparison of analysis results of R92 based on design lattice and bare lattice. Notably, the predicted beta functions from bare lattice model are with differences less

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than 3% in both horizontal and vertical planes, which shows bare lattice model represents the real machine well.

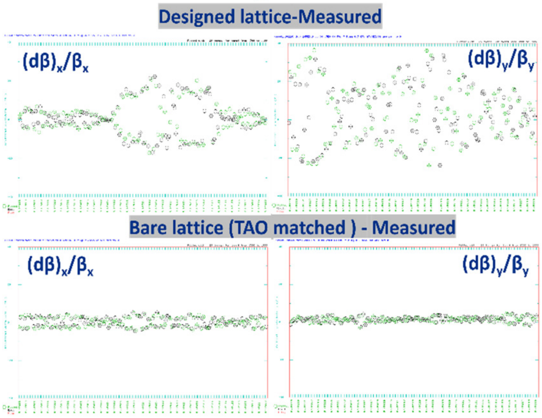
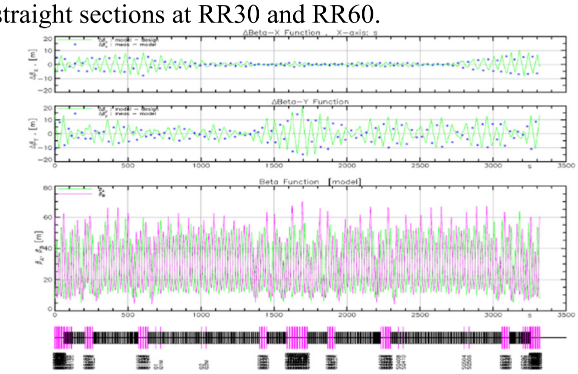


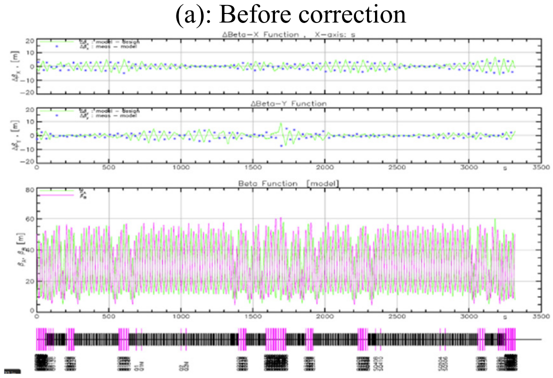
Figure 3: Comparison of TBT analysis based on design lattice and bare lattice model.

LATTICE CORRECTION

To correct Recycler lattice back to as design we use TAO program again, to find the best trim quadruples to use. As mentioned above, trim quads are only in the trombone straight sections at RR30 and RR60.



(a): Before correction



(b): After correction

Figure 4: Beta-functions errors between the bare lattice and the lattice corrected by the trim quads in RR30 (upper), Beta-functions (bottom - β_x in green, β_y in pink).

As seen in Fig. 3, the beta-function errors in the horizontal plane are around 25% relative to the design lattice in the horizontal plane, and around 35% in the vertical plane. We tried to use either the variables in the RR30 trombone or in the RR60 trombone, it turns out trim quads in RR30 trombone worked better for the correction. TAO plots the differences of the beta-functions before correction, shown in Fig. 4 (a), and the differences after correction, shown in Fig 4 (b). Figure 5 gives a comparison of the relative β function error before and after correction. Significant improvement is observed in the vertical plane. Now the the beta-function errors in the horizontal plane are around 10% relative to the design lattice in the horizontal plane, and around 5% in the vertical plane.

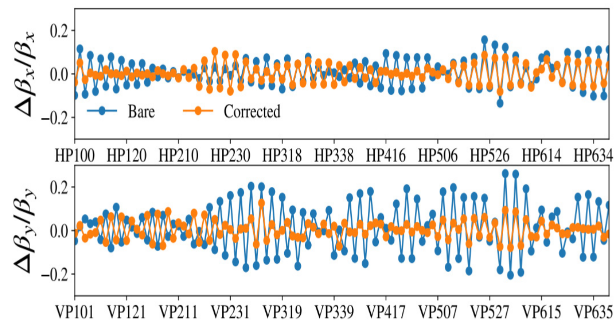


Figure 5: The relative beta-function errors between measured and design β functions before and after corrections.

CONCLUSION

We have successfully established a reliable model of the Recycler ring through TAO analysis. The corrected trim quads current in the RR30 straight section are applied in the operation routinely at the beginning of each year after machine Summer Shutdown.

The coefficients of trombone quads in RR30 and RR60 are updated for the tune and chromaticity program R2. 3-bumps table for the Recycler Ring is also updated based on the corrected lattice.

TAO, combined with the TBT analysis program R92, has proven to be a valuable tool for lattice measurements and corrections in the Recycler Ring at Fermilab. This combination facilitates lattice diagnostics and has the potential for broader applications beyond this specific machine.

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REFERENCES

[1] Gerry Jackson, "The Fermilab Recycler Ring Technical Design Report", FNAL, Batavia, IL, USA, Rep. Fermilab-TM-1991, November 1996.

[2] M. Xiao, "Phase Trombone Program Migration for the Recycler at Fermilab", in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper MPPE051, pp. 3135-3137.

[3] M. Xiao, "Recycler Chromaticities and End Shims for NOvA at Fermilab", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper TUPPR085, pp. 2023-2025.

[4] M. Xiao, "Measurements and Corrections of the Recycler Lattice at Fermilab", in *Proc. HB'08*, Nashville, TN, USA, Aug. 2008, paper WGA13, pp. 82-84.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP30

[5] M. J. Yang, "Lattice Function Measurement with TBT BPM Data", in *Proc. PAC'95*, Dallas, TX, USA, May 1995, paper MPQ20, pp. 2500-2502.

[6] D. Sagan, "Betatron phase and coupling correction at the Cornell Electron/Positron Storage Ring", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 3, p. 102801, 2000. doi:10.1103/PhysRevSTAB.3.102801

[7] D. Sagan, "The TAO Manual", Revision:16.7. March 2, 2019, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 558, pp 356-359, 2006. doi:10.1016/j.nima.2005.11.001

[8] D. Sagan, "Bmad: A Relativistic Charged Particle Simulation Library", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 558, pp. 356-359, 2006. doi:10.1016/j.nima.2005.11.001

The Bmad Manual can be obtained at: www.classe.cornell.edu/bmad

[9] Ming-Jen Yang, "Benchmarking TAO with simulation from R90 console program", Internal communication.