Linear Modeling 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 fast and precise approach for identifying and rectifying errors in implementing a desired lattice in CESR (Cornell Electron Storage Ring). One key advantage of betatron phase measurement over β measurement is its sensitivity to phase variations between widely separated points. This methodology has been successfully implemented for the Recycler NOvA Ring at Fermilab, with the adoption of TAO (Tool for Accelerator Optics) developed by Cornell University. By employing this technique, a linear model of the Recycler NOvA ring is established, enabling the correction of quadrupole errors.

INTRODUCTION

• The Recycler ring, 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, were 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 NUMI target by Main Injector. The upgrade included the installation of modified end-shims 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 second phase trombone [3] to add flexibility in tune compensations. With cycle time of only 1.13 seconds, for slip stacking 12 proton batches, 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 TBT data to sine functions, phase and amplitude at each BPM can be determined. In addition, this program utilized 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 Recycler ring is to construct a predictive model that can accurately represent machine behaviour. At CESR (Cornell Electron Storage Ring) [6] utilizing the measurement of coherent betaron oscillation phase has emerged 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 customized TAO program for Recycler Ring, we were able to turn measured phases and beta functions into quadrupole errors from design lattice. The adaptations of TAO program for the Recycler Ring are presented in this paper.

ADOPTING AND BENCHMARK 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 Fortran 95, 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 Recycler 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:

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

A special device was installed at CESR and Program TAO was used to locate isolated errors from the measurement data with the betatron phase analysis [6].

- In the Recycler ring at Fermilab, we could only ping the beam with one-shot kicker, and taking the TBT data using console application program R92. For the Recycler ring a gap clearance kicker is as a horizontal pinger, and in summer shutdown of 2018 a vertical pinger was installed specifically for this purpose, which facilitated the collection of vertial plane TBT data.
- Program R92 does the analysis and gives the phase advance as well as the beta functions at BPMs (104 in Horizonal and 104 in vertical plane) as follows: (1) The BPM data, which records the betatron oscillation, is fitted to obtain beam parameters（x, x', y, y'）and $\Delta p/p$, using beam line transfer matrix based on the existing lattice model. (2) The resulted TBT beam parameters (x, x') or (y, y') are fitted to ellipses to obtain the lattice function β, α, and the emittance associated with the betatron oscillation. The tune of the machine can be calculated from the phase space angles of the successive turns, in the normalized phase space. (3) Output phase and amplitude data, as well as the lattice functions obtained by R92 to TAO

•By default TAO program comes with a dummy customization subroutine. To be able to read data output from R92 program this subroutine was modified locally to allowed measured phases and beta functions to be used by TAO for fitting, and the results benchmarked for better use and plot [9]. From the TBT data to the interaction between R92 console program and TAO program can be visualized in Fig. 1.

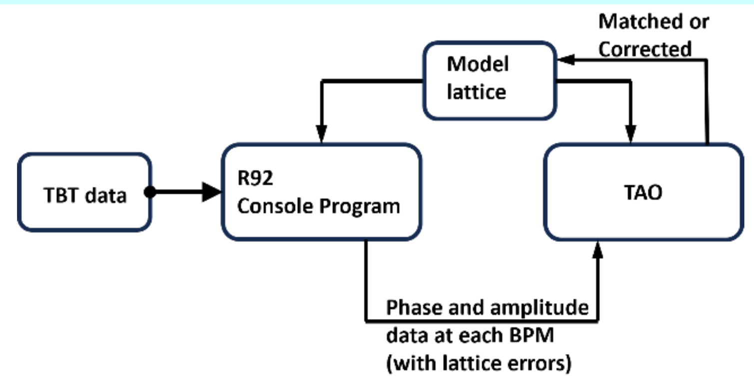


Figure 1: Flowchart from the TBT data to the interaction between R92 console program and the TAO.

- 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:

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

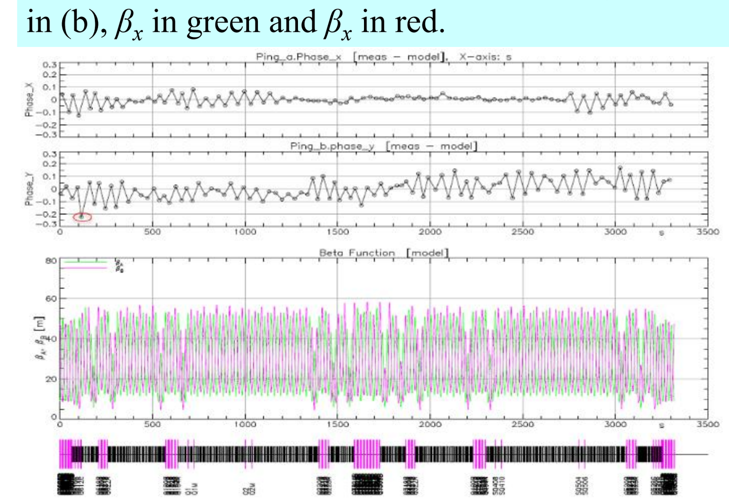
Where

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

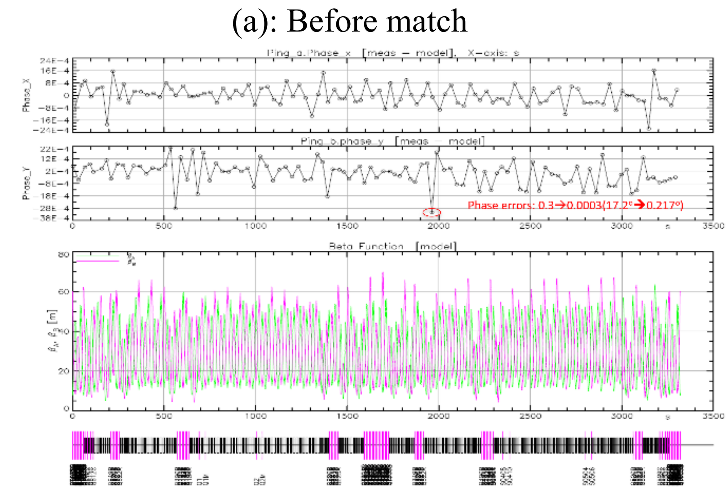
- $data_{model}$ is the data as calculated from the model and $data_{meas}$ is the measured data. var_{model} is the value of a variable in the model and var_{meas} is the value as measured at the time the data was taken , and the sum j runs over all variables that are allowed to be varied to minimize 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.
- Three major types of magnets are used in Recycler ring, i.e., quadrupole, dispersion suppressor dipole, and arc dipole. Dipoles are gradient magnets. Two dipole magnets are installed at each of the 108 horizontally focussing locations and the 108 defocussing locations. For ARC gradient magnets, 2 types of the end-shim are used to correct the feeddown effect from the body sixtupole components. Upstream end-shim is standard, the same for all the arc gradient dipoles, but downstream end-shim is customized, specifically for each gradient dipole.
- To set TAO up with variables to correct at every location it was decided that quadrupole component k_1 of downstream end-shim is used for gradient ARC dipole, while body k_1 of magnets will be used for the dispersion dipoles and quads in the straight sections. k_1 of Trim quadrupoles in RR30 and RR60 straight section are chosen for the lattice corrections. Total number of the variables is 460.

BARE LATTICE MODEL

The first step we do is to take TBT measurement with all the trim quads in RR30 and RR60, skew quads and trim sextupoles in the Recycler ring set to 0. The model built from the analysis of this TBT measurement is call "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, 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 in (b), β_x in green and β_x in red.



(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).

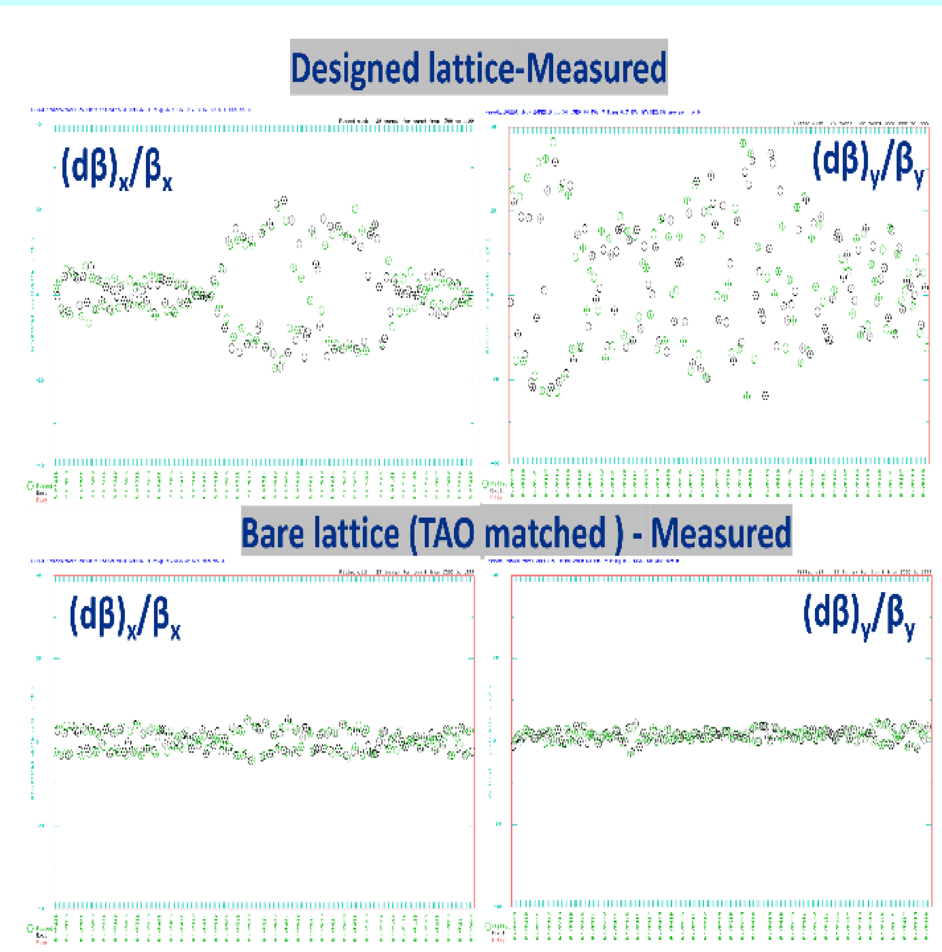


Figure 3: Comparison of TBT analysis based on Design lattice and Bare lattice model.

LATTICE CORRECTION

• 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 40% in the vertical plane. As mentioned above, only trim quads in the trombone straight section RR30 and RR60 can be adjusted and thus be used to correct the RR lattice. 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. Figure 4 shows a comparison of the β function error before and after correction. Significant improvement is observed in the vertical plane.

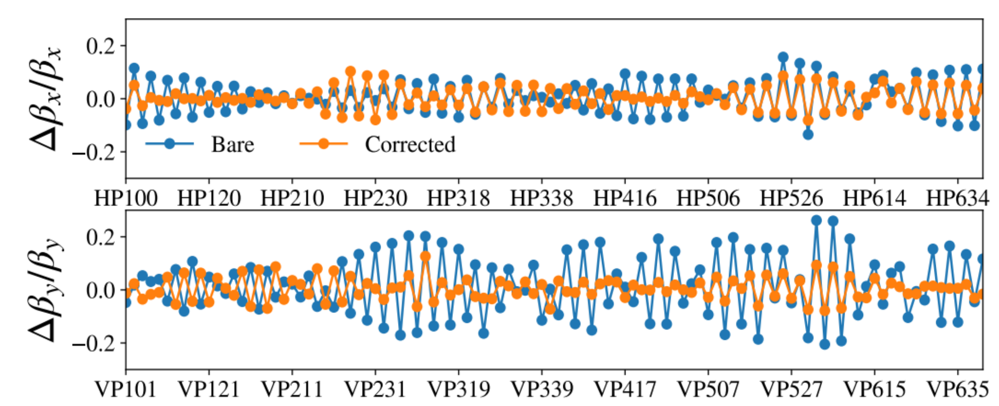


Figure 4: The difference between measured and design β functions before and after corrections

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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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