LATTICE FUNCTION MEASUREMENTS OF FERMILAB RECYCLER RING†

M.J. Yang‡, C.S. Mishra, A. Marchionni, Fermilab

Abstract

The Fermilab Recycler ring, designed and built as an 8-GeV anti-proton storage ring, is at the final stage of its commissioning. Once integrated into the accelerator complex it is expected to help achieve the luminosity goal of Run II at Fermilab. The Recycler Ring is made up mostly of combined function magnets with a substantial sextupole component. Any orbit error could cause higher order feed-down and potentially change the machine. Lattice function measurements had been done at various stages of the machine and the results is presented here.

INTRODUCTION

Several modifications to the Recycler were made during commissioning. The magnet end-shims[1] were replaced to correct for sextupole feed-down. Heater tapes around the ring, used for baking the beam pipe at high temperature, had to be replaced because they were found to be magnetic. A high beta straight section was replaced with one of medium beta when it was decided not to have Electron Cooling in transverse space [2]. Dipole corre c-tors were installed at every location to control closed orbit. Vertical re-alignment of gradient magnets was necessary to correct for a problem in the fiducial reference of the magnets. Any of these modifications could have significant impact on the machine.

Lattice function and dispersion function measurements had been taken throughout the commissioning and results will be presented here.

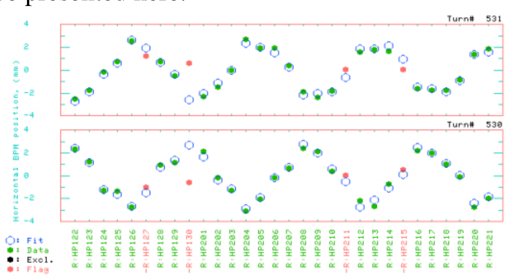

Figure 1. Two turns of BPM data from Recycler BPM house 20. Solid dots are data points and open circles are the calculated position based on the fitted x-x'.

DATA

The Recycler Ring Beam Position Monitor (BPM) system, in spite of its problems and limitations, has been used regularly to study the machine properties. First turn and circulating beam orbit data were used to extract phase advances. Beta function measurements from BPM orbit data, which are sensitive quadratically to calibration uncertainties, will not be presented. The dispersion function, also measured from orbit data, is instead sensitive to calibration only linearly.

The Turn-by-Turn (TBT) lattice function analysis [3], which is less sensitive to calibration error, is used for beta and alpha lattice function measurements. The Recycler BPM system precludes taking ring-wide TBT data simultaneously, instead data was taken over repeated injections. The injection reproducibility is likely a source of systematic error. Fig. 1 is an example of TBT BPM data in two consecutive turns. The TBT analysis also provides diagnostic information, such as RMS deviation which is used to gauge the quality of data.

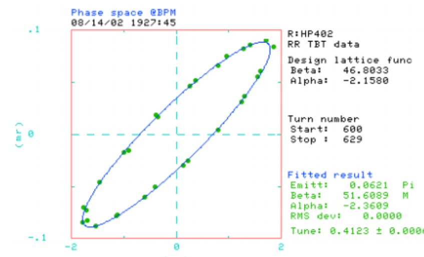

Figure 2. 30 turns of phase space points are plotted and fitted to an ellipse which gives lattice functions at the BPM location.

ANALYSIS

TBT lattice function analysis

The first step in TBT lattice analysis is to get the phase space coordinates, i.e. position and angle, at a reference location for every turn. Transfer matrices between the reference and the BPM locations, calculated based on known machine focusing properties, are used to fit for the coordinates which best match data from the selected number of BPMs. Fig. 1 shows BPM data with projected positions based on fitted coordinates at the reference location. Next step is to fit for an ellipse using the fitted phase space points over a number of turns (Fig. 2). The parameters of the ellipse give lattice functions β and α.

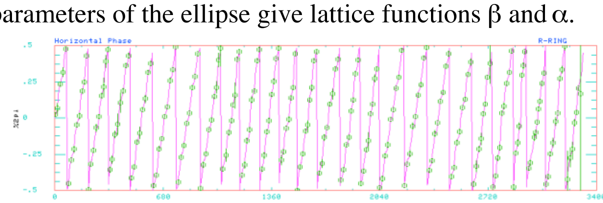

Figure 3. Horizontal phase advance measured from closed orbit and plotted in modulo of 2π. Data points are in green and model calculation is the magenta line. End-shim effects were included in the calculation and adjusted to match the data.

Phase advance

Phase advance at the BPM is calculated from orbit displacements using two correctors, approximately 90° apart in phase advance [4]. Fig. 3 shows a closed orbit data e x-ample. All other phase advance results presented will be from first turn orbit data. Sources of systematic errors include corrector strengths, beta functions at the correc-

† Work supported by the US Department of Energy under contract DE-AC02-76CH00300.
‡ E-mail: YANG@FNAL.GOV

tors, and phase advance between them. This analysis is inherently insensitive to BPM calibration.

Dispersion function

The dispersion function is measured by observing position changes as a function of Δp/p. Likely systematic errors are the calculated Δp/p, based on the phase slip factor, and BPM positions which are sensitive to calibration errors.

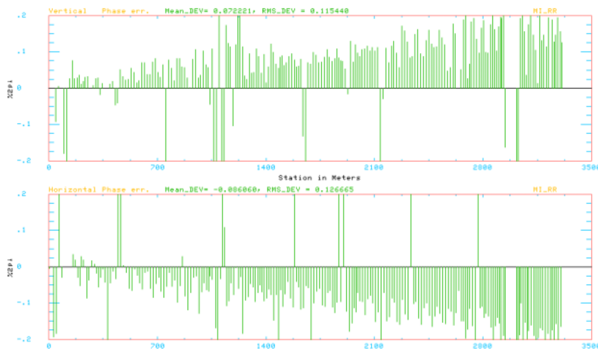

Figure 4. The phase advance errors as measured before the end-shim replacement using first turn orbit data. The cumulated phase advance error is about +0.15 in the vertical plane (top plot) and -0.18 for horizontal plane, in units of 2π.

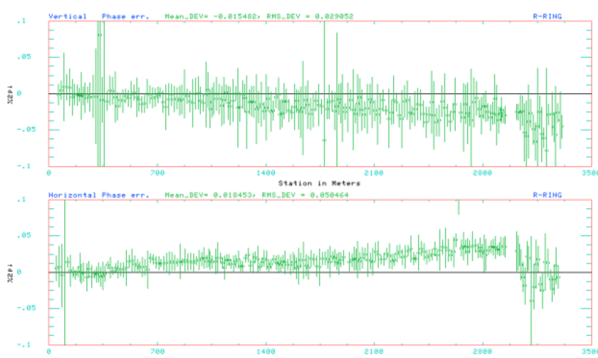

Figure 5. Phase advance error after end-shim and heater tape replacement.

LATTICE RESULTS

The results are shown with reference to specific issues during the commissioning and in chronological order.

End-shim feed-down

Each permanent gradient dipole installed in the Recycler Ring has two end-shims to correct for magnetic errors. With a large fraction of the body sextupole component being corrected at the end and with a sagitta offset of about 7.5 mm, the feed-down from sextupole is significant. Fig. 4 shows the deviations of the measured phase advances from that calculated from the machine model. The deviations are consistent with tune measurements using Schottky detectors. A quadrupole component was added to the end-shims to cancel the feed-down during the January 2000 shut-down. The heater tapes, made of magnetic stainless steel, were also replaced.

Recycler with high beta straight section

The new end-shims had over corrected the phase advance by about 10% or so. Fig. 5 shows the horizontal phase advance going faster and the vertical slower than expected, opposite of Fig. 4. The errors are well within the range of the phase trombone for tune adjustment.

At the 3000 m location in Fig. 5, after the high beta straight, a drop in phase advance error is seen. This is consistent with high beta quadrupole gradients being -1% off from design. This deviation predicts beta functions that compare well with beta functions measured with TBT lattice analysis (see Fig. 6 and 7, where the solid green line is the design lattice calculation and the dashed cyan line includes the -1% gradient error in the calculation).

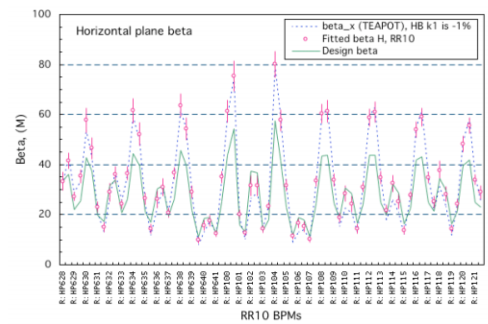

Figure 6. Measured horizontal beta function of RR10 BPMs.

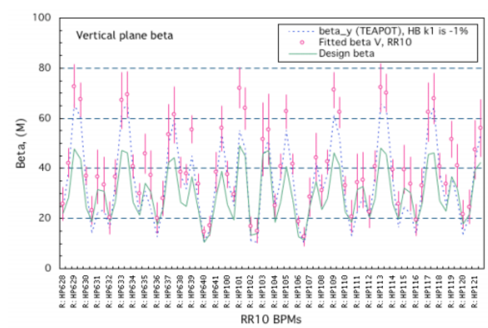

Figure 7. Measured vertical beta function of RR10 BPMs.

With medium beta straight section

With the medium beta straight, installed in July 2001 shut-down, the measured phase advance error (shown in Fig. 8) was consistent with expectations.

The measured lattice functions compared to calculations are shown in Fig. 9 and Fig. 10, which shows the error for the whole ring. While the vertical beta appears to be in good agreement with the model, the horizontal beta function does not.

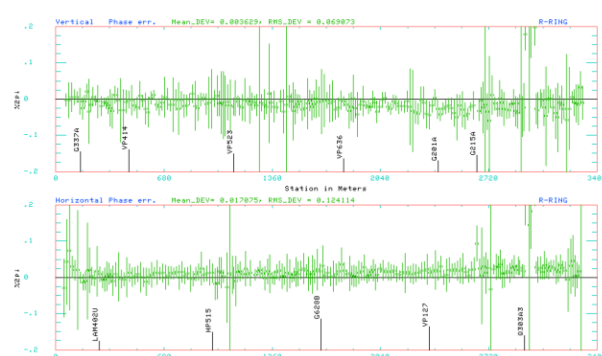

Figure 8. Measured horizontal and vertical plane phase advance error with the medium beta straight in place.

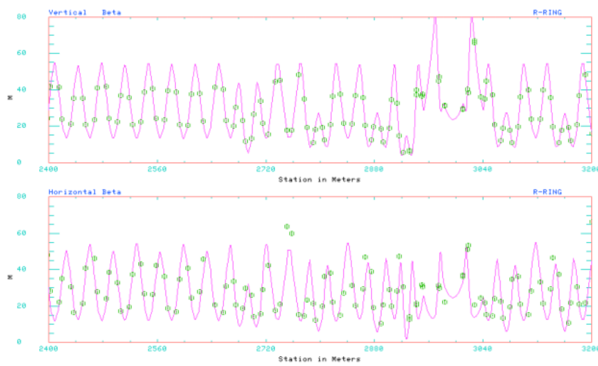

Figure 9. Measured horizontal and vertical beta functions compared with model calculations over a stretch of 800 m, including the medium beta straight region.

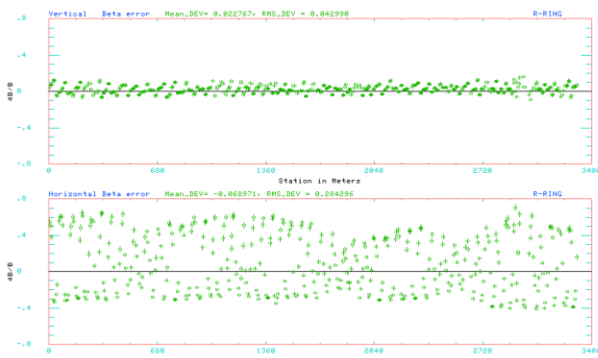

Figure 10. Plots of ring-wide $\Delta\beta/\beta$ for horizontal and vertical planes. As in Fig. 9 the horizontal beta error was substantial.

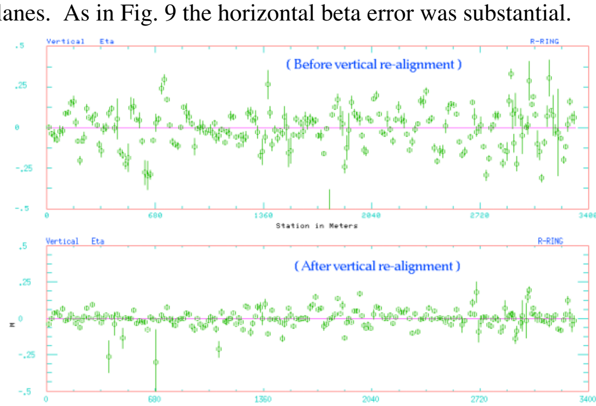

Figure 11. Ring-wide vertical dispersion function measured before (top) and after (bottom) vertical plane re-alignment.

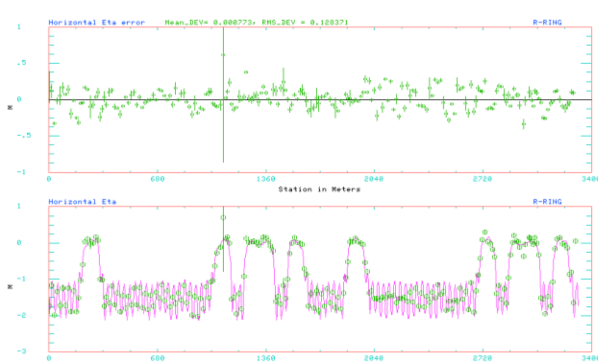

Figure 12. Measured ring-wide horizontal dispersion function. Bottom plot shows both data and calculation (cyan line), and the top plot their difference.

Vertical alignment and corrector installation

During the October 2001 shut-down Recycler was re-aligned to correct for the vertical fiducial problem. Dipole corrector were also installed at every location in the ring. A dramatic improvement was observed in the measured vertical dispersion function as shown in Fig. 11. For completeness the horizontal dispersion function is also shown in Fig. 12. The dispersion-free region is well preserved.

The measured beta functions after the re-alignment are shown in Fig. 13. The horizontal plane beta is close to design, to within 10%, while the vertical beta shows deviation up to 30%.

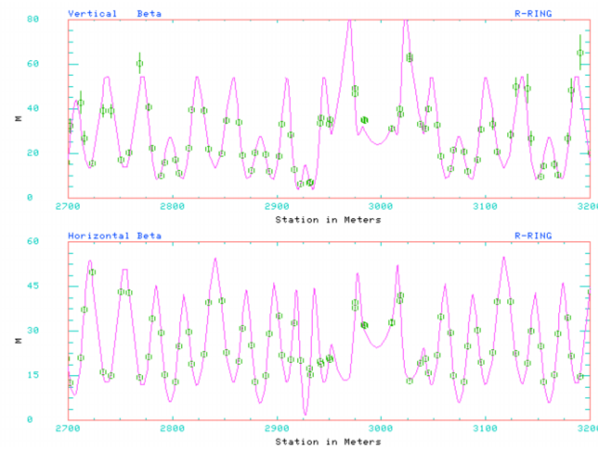

Figure 13. Up-to-date measured Recycler beta functions for a portion of the Recycler ring: bottom plot is the horizontal and top the vertical. Green circles are the measurements and magenta line is the model calculation.

CONCLUSION

Lattice measurement is an important tool to understand the machine. Disagreements between measurements and model calculations have been shown to point to problems which in some cases were independently known.

The reliability of Recycler BPMs has always been an issue. The system is in the process of being upgraded [5] to improve its stability and absolute calibration. A robust BPM system is critical in keeping track of the closed orbit which is important to the consistency and stability of the machine. Improvements to the accuracy of the lattice function measurements are expected.

REFERENCES

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[2] W. Wan et al, "Design and Implementation of the Medium Beta Insert for the Fermilab Recycler", Proc. PAC '01, p.2575.

[3] M.J. Yang, "Lattice Function Measurement with TBT BPM Data", Proc. PAC '95, p. 2500

[4] M.J. Yang, "A Beam Line Analysis Program for Main Injector Commissioning", Proc. PAC '99, p723.

[5] Fermilab document RR-BPM-0001.rev1.1