

EXPERIMENTAL VERIFICATION OF DIPOLE EDGE FOCUSING IN LINEAR MODEL BY OPERATING IN THE WEAK FOCUSING REGIME AT THE LOS ALAMOS PROTON STORAGE RING*

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Abstract

Linear optics models are important for the operation of circular accelerators because of their ability to predict the linear lattice functions, primarily betatron amplitude functions and betatron tunes. The accuracy of the linear model's prediction is dependent on how well the real machine's focusing lattice is known and represented. While quadrupoles may be mapped magnetically and their focusing properties well understood, the focusing effect due to dipole edge fields is less certain. For rings with rectangular dipoles like the Proton Storage Ring (PSR) at Los Alamos National Laboratory, the dipole edge focusing can be a significant contributor to the vertical focusing. Most accelerator modeling codes, like MAD and AT (Accelerator Toolbox), use the K. Brown formulation[1], but this approach can lead to errors $\sim 10\%$ in the models betatron tune prediction[2]. Here we discuss particle tracking through simulated dipole fields, including edge effects, with TOSCA 3D to obtain the focal lengths of the edge focusing. We verify model and focal lengths by operating the PSR in the weak focusing regime (without vertically focusing quadrupoles) and show that the model predicts the betatron amplitude functions and tunes even in this unusual operating condition.

INTRODUCTION

The PSR is a 90 m circumference circular accelerator with broken ten-fold FODO cell symmetry, which occurs in the injection section (top of Fig. 1). While most cells have a 36° dipole magnet (SRBM), the injection section starts with a SRBM-type dipole that is shunted by 100 A (SRBM01) to allow room for RIBM09, which merges H-beam with the circulating H+ beam for charge-exchange injection. The dipole at the beginning of the next cell is replaced with two large gapped C-magnets (SRBM11 and SRBM12) accommodating a dump line. Relevant parameters for the five PSR dipoles types are listed in Tab. 1.

All PSR dipoles are rectangular, so including a good representation of the edge focusing is very important for the PSR linear model. There are three parameters in the edge focusing model: gap width, edge angle, and the fringe field integral (FINT) defined by

$$\kappa = \int_{-\infty}^{\infty} \frac{B_0 B_y(s) - B_y^2(s)}{g B_0^2} ds \quad (1)$$

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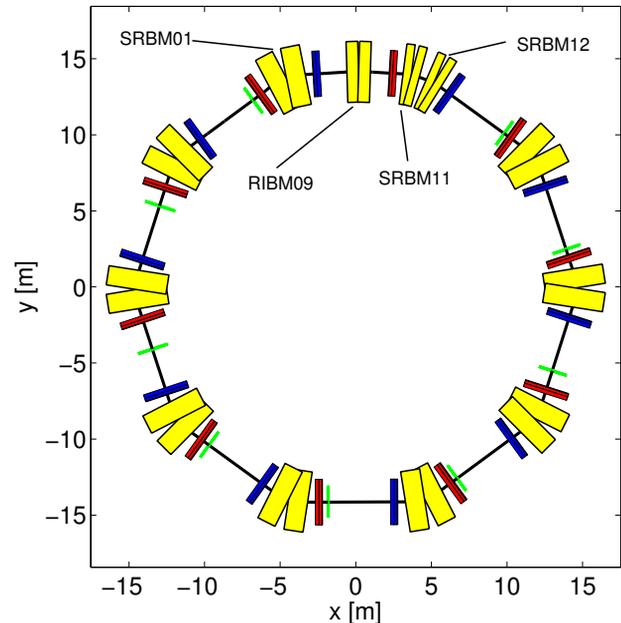


Figure 1: (Color) PSR model: dipoles (yellow) split into two model elements, focusing and defocusing quads (blue and red respectively), and vertical steering magnets (green).

Type	l [m]	θ°	$\theta/2^\circ$	g [cm]
SRBM	2.550	36	18	10.478
RIBM09	1.553	6.8	3.4	12.852
SRBM01	2.542	32.8	11.9	10.478
SRBM11	1.095	16.2	8.1	18.059
SRBM12	1.080	16.2	8.1	12.852

Table 1: Five types of PSR rectangular dipoles.

and related to the edge focusing focal length by

$$\frac{1}{f} = \frac{1}{\rho} \tan \left(\frac{\theta}{2} - \psi \right), \quad (2)$$

where

$$\psi = \frac{g\kappa}{\rho} \sec \left(\frac{\theta}{2} \right) \left(1 + \sin^2 \frac{\theta}{2} \right). \quad (3)$$

The initial (or baseline) PSR model uses gap width and edge angles from physical measurements and FINT based on applying Eq. (1) to results of a TOSCA 3D magnet field

	Measured	Baseline	Improved
Horizontal	$3.2266 \pm 9 \times 10^{-4}$	3.2216	3.2251
Vertical	$2.2192 \pm 4 \times 10^{-4}$	2.2642	2.2154

Table 2: Betatron tunes from baseline and improved models and measurement.

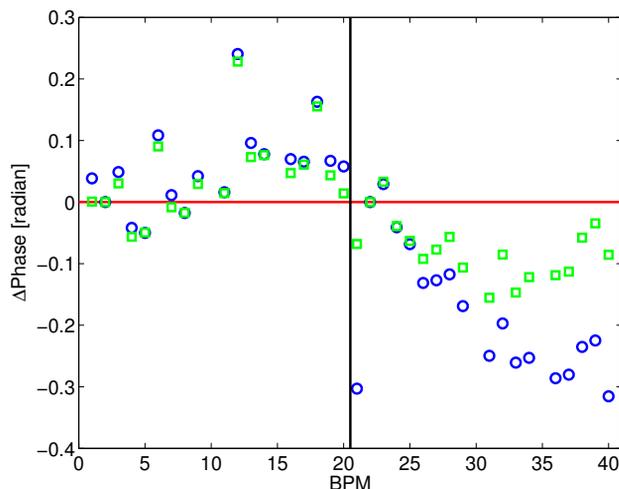


Figure 2: (Color) Difference between measured and baseline (blue) and improved (green) model phase advance from the first BPM after injection (2 and 22). ORM BPM indexing convention is used: horizontal BPMs (1-20), vertical BPMs (21-40) such that BPM 2 and 22 are the horizontal and vertical planes of first BPM after injection.

simulation to determine the dipole edge focusing. The resulting betatron tunes from the baseline model are compared with measurement in Tab. 2. We note that the vertical tune difference between baseline model and measurement is not good, 0.05. To understand the origin of the vertical tune difference between baseline model and measurement, we plot the difference between measured and baseline model phase advance in Fig. 2. Note the vertical phase demonstrates a systematically increasing phase difference between baseline model and measurement. We conclude that the baseline model systematically over focuses vertically. Since the baseline model horizontal tune result is good, we concentrate our model improvement efforts on the only model element that effects vertical and not horizontal focusing: the rectangular dipole edge focusing.

RAY TRACING THROUGH THE FRINGE FIELDS

Ultimately, the most important part in considering fringe fields from rectangular dipoles is obtaining the edge focusing focal length. To determine the edge focusing focal length, we traced on-momentum parallel rays through 3D magnetic field from TOSCA simulations of the PSR dipoles. The parallel rays were initially positioned on a 4×4 cm transverse grid with a ray every centimeter at

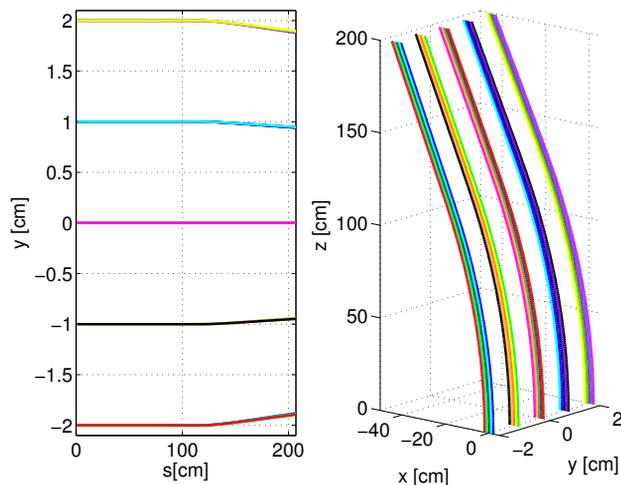


Figure 3: (Color) (Left) Rays' vertical position as a function of longitudinal coordinate, which encounter edge focusing $s \simeq 120$ cm. (Right) Ray position in the magnet-based coordinate system.

Magnet	Focal Length [m]		Fringe Field Integral	
	Baseline	Improved	Baseline	Improved
SRBM	13.208	13.733	.54150	.90291
SRBM01	13.208	13.733	.54150	1.2908
SRBM11	32.186	32.389	.44940	.46491
SRBM12	30.823	30.889	.51930	.52685
RIBM09	234.17	238.96	.35790	.47085

Table 3: The edge focusing focal length and FINT for each type of PSR horizontal bender from the baseline and improved models.

the longitudinal center of the dipole and traced through the downstream half of the PSR dipoles, Fig. 3. The fringe field focal length can be calculated from the ray tracing data for each of the PSR rectangular dipole types.

We can reverse engineer the K. Brown model of edge focusing, Eqs. (1) to (3), to produce the focal length calculated from the ray tracing data. We choose to modify the FINT parameter because the gap width and edge angle are physical parameters. In Tab. 3, we compare the edge focusing focal length and FINT from ray tracing, which we will call improved model, explained later, and the baseline model. Note that the baseline model edge focusing focal lengths are systematically smaller than from ray tracing with the largest fractional difference in the SRBM and SRBM01 type dipoles. This is the cause of the vertical over focusing in the baseline model.

We construct an improved model using the FINT parameter determined by the ray tracing data and compare it with measurement in Tab. 2 and Fig. 2. Note the improved model has a much better prediction of the vertical tune and little systematic phase advance difference.

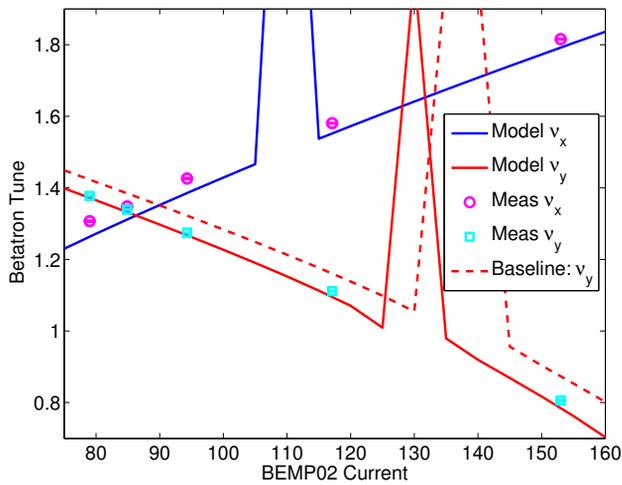


Figure 4: (Color) Model and measured tunes as a function of horizontal focusing quadrupole current: measured tunes (horizontal: magenta circles and vertical: cyan squares), model tunes (horizontal: blue line, and vertical baseline: dashed red line, vertical improved: solid red line).

OPERATING THE PSR IN THE WEAK FOCUSING REGIME

The improved model uses an engineered FINT to produce the edge focusing focal lengths calculated from the ray tracing data. The edge focal length was not actually measured. Can we make a more direct, physical measurement? To isolate the edge focusing in a beam-based measurement, we operate the PSR with the vertically focusing quadrupoles at 0 A. To provide stable beam with this set up, the horizontally focusing quadrupole current (BEMPO2) needs to be dramatically reduced so as to not overcome the edge focusing in the vertical. The improved model indicates that there are several regions of transverse stability, Fig. 4.

We measured the betatron tune at several stable points with reduced horizontally focusing quadrupole current and compared them with predictions from the improved model, Fig. 4. Note that even with the vertically focusing quadrupoles turned off, the improved model does a decent job at reproducing the measured vertical tunes, much better than the baseline model. Of course, we would like the model to yield closer results. Also note the greater discrepancy between the measured and model horizontal tune, as much as 0.03. This may be an indication that the current to gradient length conversions used in the model for the horizontally focusing quadrupoles do not work well due to a lack of magnet mapping data for such low currents and that we need to add the residual field effect in the vertically focusing quadrupoles.

Figure 5 compares the measured and model phase for horizontally focusing quadrupole current 89.4 A. Note in the vertical, both the phase advance from the first BPM after injection and the BPM-to-BPM phase advance de-

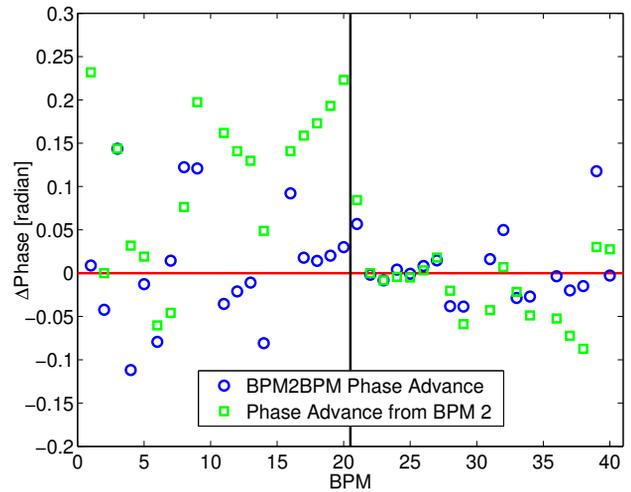


Figure 5: (Color) Difference in phase advance from the first BPM after injection (BPM 2 and 22, green) and the difference in BPM-to-BPM phase advance (blue) between measured and improved model at focusing quadrupole current 89.4 A. ORM BPM indexing convention is used as described in Fig. 2.

viation between the improved model and measurement is much smaller than in the horizontal.

We need to refine the improved model horizontal tune and phase predictions prior to fitting the edge focusing in the vertical. In continuing studies, we intend to fit the horizontally focusing quadrupole strengths to the measured horizontal tunes and then fit the FINT for each of the five PSR rectangular dipole types to match the measured vertical phase advance. Because the improved model performs well for normal operating conditions, we expect only a few percent adjustment to refine the improved model FINT.

CONCLUSIONS

We corrected the PSR linear model by engineering the FINT to yield the same focal length as found by tracing parallel rays through 3D magnetic fields resulting from TOSCA simulations. We compared linear lattice functions predicted by the improved model with measurement, in particular the betatron tune and phase advance. Although the improved model is better than the baseline model, we realize that we did not directly measure the FINT. To isolate the edge focusing in measurement, we operate the PSR without vertically focusing quadrupoles. We compare improved model predictions with measurements of the tune and find the model reproduces the measured vertical tunes well but not the horizontal. We need to correct the horizontal model before we can reliably fit the FINT.

REFERENCES

- [1] K.L. Brown, SLAC-75 (1967).
- [2] J. Kolski, Ph.D. thesis, unpublished (Indiana University 2010).