SLAC-PUB-8236
August 1999

Beam Based Solenoid Compensation for the PEP-II*

Yunhai Cai
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Abstract

Commissioning the compensation system of the solenoid in the BaBar detector presents a challenging problem due to the complexity of the system, which uses twelve normal quadrupoles and twelve skew quadrupoles in each ring. The setting of these skew quadrupoles needs to be readjusted according to the machine optical parameters since the machines always have some unknown errors. In this paper, we will describe a beam based method to match the coupling and optics in the interaction region to compensate for the optical effects due to the solenoid. The method has been successfully used to find the wrong polarities and the wrong scaling factor of the skew quadrupoles in the early stage of the commissioning. It is being refined to set the skew quadrupoles in the machines in order to reduce the beam size at the interaction point and improve the luminosity of PEP-II.

Submitted to *e+e- Factories'99*,
September 21th - 24th 1999, KEK, Tsukuba, Japan.

*Work supported by the Department of Energy under Contract No. DE-AC03-76SF00515.

Beam Based Solenoid Compensation for the PEP-II*

Yunhai Cai, Stanford Linear Accelerator Center, USA

Abstract

Commissioning the compensation system of the solenoid in the BaBar detector presents a challenging problem due to the complexity of the system, which uses twelve normal quadrupoles and twelve skew quadrupoles in each ring. The setting of these skew quadrupoles needs to be readjusted according to the machine optical parameters since the machines always have some unknown errors. In this paper, we will describe a beam based method to match the coupling and optics in the interaction region to compensate for the optical effects due to the solenoid. The method has been successfully used to find the wrong polarities and the wrong scaling factor of the skew quadrupoles in the early stage of the commissioning. It is being refined to set the skew quadrupoles in the machines in order to reduce the beam size at the interaction point and improve the luminosity of PEP-II.

1 INTRODUCTION

The BaBar detector is surrounded by a strong solenoidal field of 1.5 Tesla and 6 meter in length. This solenoid has very strong optical effects on the accelerators of PEP-II, especially the Low Energy Ring(LER) which has a beam energy of 3.1 Gev, a factor of three lower than the High Energy Ring(HER). For example, the positron beam is rotated 17^0 after it passes through the solenoid in the LER.

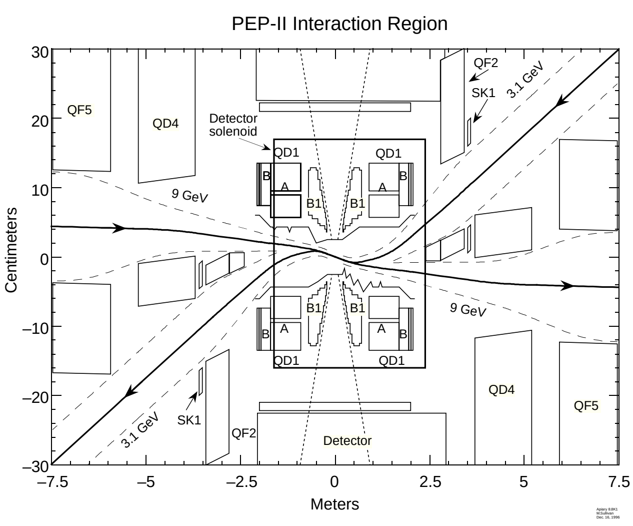

Figure 1: *Top view of the PEP-II magnets and detector solenoid near the IP.*

The compensation scheme of the solenoid [1] uses twelve normal quadrupoles and twelve skew quadrupoles in the interaction region(IR) and the two neighboring arcs. As shown in Fig.1, the orbits inside the solenoid are bent away from the centers of the permanent dipole(B1) and quadrupole(QD1). Even in the ideal design, the nested magnets with the off-centered orbits make the model in the region of the solenoid much more complicated than in any other regions. In the real machines, the situation is further complicated by the fact that the strength of the permanent magnets was reduced about 2% by the magnetic field of the solenoid of 1.5 Tesla. The uncertainty in the setting of the permanent magnets, including the final focusing quadrupoles, causes a large uncertainty in the model of the accelerators. All of these complexities make the commissioning of the solenoid compensation system very difficult and challenging.

To handle the complicated model of the accelerators, we have developed an object-oriented class library: LEGO[2] since the end of the lattice design. The class library provides a flexible environment in which we write application software to solve many problems encountered during the commissioning of PEP-II given short notice. This work is one of the successful examples of using the library.

2 METHOD

The region of interest is the straight section where the BaBar detector and the system of solenoid compensation reside. In order to match the optics and coupling we need to extend the region of observation and measurement into the two arcs adjacent to the IR.

First we want to know what are the differences between the machine and the design in terms of the optical and coupling parameters in the IR. We then want to learn what are the causes of these differences by varying the model until it matches the machine. Based on the changed variables in the model, we determine either to fix the problems of hardware or software directly or to change the configuration of the machine to correct the machine back toward the design.

The data analyzed was a set of closed orbits at the locations of the Beam Position Monitors(BPM) excited by the dipole correctors outside of the fitting region which contains the IR and the two adjacent arcs. To sample all phases of betatron motion, we usually choose two correctors which are 90^0 apart in betatron phase in each plane to generate the oscillations. In additional to the oscillation data, we often take the orbits with different energies for dispersion.

It is very important to ensure high quality of the data. Before taking any data, the BPMS are calibrated at the beam current at which the data will be taken. Redundant

* Work supported by the Department of Energy under Contract No. DE-AC03-76SF00515

data is always helpful for checking the repeatability of the measurements and the noise of the BPMs. Finally, we always remove "dead" and "bad" BPMs from the data before any analysis.

For the problem of optics and coupling, we analyze only the difference orbits. These difference orbits are treated as single-pass beamline in the fitting region. This treatment is valid for the difference of two closed orbits in a storage ring provided that the kick is outside the region. That is the reason why we always select the correctors outside the region. Usage of the closed orbits allowed us to take an average of the readings and hence make the data more accurate than the direct single-pass measurement.

The first step of the analysis is to use the arc before the IR as a good region to fix the orbit trajectories including x, p_x, y, p_y, δ. Then we project the fixed trajectories into the IR and the arc after. If the machine is as perfect as the design, the projected orbits should match the readings of the BPMs in the region both in the horizontal and vertical planes. When there was a problem of coupling, we should see mismatches of the orbits in the "coupling plane", the plane which is not excited directly by the betatron oscillation. Of course, if there is an optical problem, we should see the difference mainly in the oscillating plane.

When the machine and the design disagree, we choose a set of parameters, including usually the setting and alignment of the magnets in the model, to fit the machine. The changes in the parameters give us a clue that could lead to the discovery of the error in the machine, such as wrong polarities of the skew quadrupoles and large misalignment of sextupoles.

The success of the method depends largely upon the selection of the fitting parameters. The selection is partially based on the location where the projected trajectories start to deviate from the readings of the BPM in the machine. The information from the operation of the machine, the knowledge of the design, and understanding of the accelerator physics play crucial roles in making the right choice. Finally, there is always some luck and intelligent guessing.

3 THE HIGH ENERGY RING

The optical and coupling effects due to the solenoid in the HER is much less than the ones in the LER due to the difference in the beam energies. The simplicity of the low-beta optics is also very helpful for the commissioning of the compensation system. For these reasons, we expected that the only thing we needed to do was to set normal quadrupoles and skew quadrupoles to their design values and to place the sextupoles at the calculated positions as the field of the solenoid was ramped up.

3.1 A scaling factor

After the solenoid was turned on to its full field, the luminosity was much lower than we achieved without the solenoid at comparable beam currents. The beam size measured as $\Sigma_y = \sqrt{\sigma_{y+}^2 + \sigma_{y-}^2}$ from the beam-beam scan was as large as 27 microns compared with the design value 7 of microns.

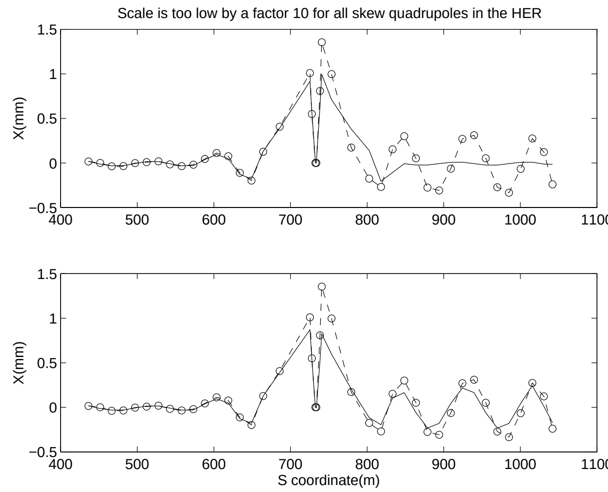

Figure 2: *A trajectory analyzed in the coupling plane. The symbol "o" presents the measured data and solid lines are the model trajectories. The upper plot is the projection into the IR and the arc 3 without any changes in the model. The lower plot is the projection after turning off all skew quadrupoles in the model.*

The oscillation data was taken on June 9 and was analyzed. The result, shown in Fig.2, indicated strongly that all skew quadrupoles were too weak in the machine. The subsequent measurement of the magnetic field in the skew quadrupoles confirmed this finding. Finally the error of a factor 10 was traced to the polynomial used to set the current for the required magnetic field. The factor of 10 is the difference between kilo-Gauss(KG) used in the control system and Tesla used in the magnetic measurements.

Fixing the scale factor reduced the Σ_y from 27 to 19 microns. Also the luminosity increased to a reasonable level of $10^{32} cm^{-2} s^{-1}$.

3.2 Correction

Given the success of the method, more oscillation data was taken on July 30 to understand the residual coupling in the HER. There were ten difference orbits used for the analysis. The parameters were fit to all trajectories in both the oscillating and coupling planes. In Fig.3, we show one of the typical trajectories in the coupling plane before and after fitting.

There are sixteen variables used in the fitting. Among them, eight are the setting of the skew quadrupoles and four are the vertical alignment of the sextupoles. These twelve parameters are for the compensation of the coupling due to the solenoid. The additional four variables are the horizontal alignment of the sextupoles used to adjust the phases between the skew quadrupoles. The result of the fitting is tabulated in the Table 1.

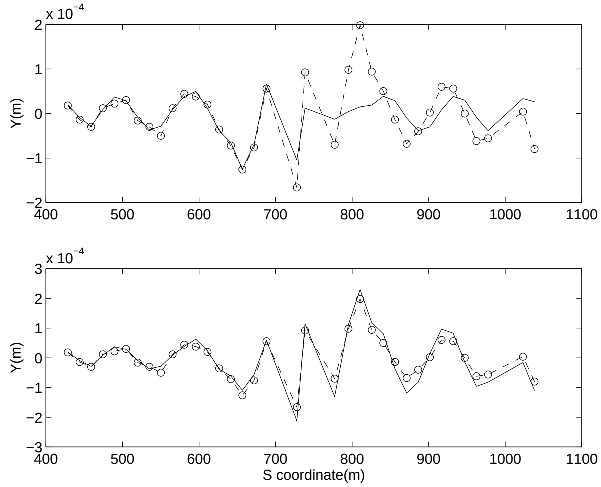

Figure 3: *A trajectory analyzed in the coupling plane. The symbol "o" are the measured data and solid lines are the model trajectories. The upper plot is the projection into the IR and the arc 3. The lower plot is the projection of the fitted model.*

Magnets	Model	Fitted Model
Skew Quad.	K1L(KG)	K1L(KG)
SQ1L	-0.42057	-0.60099
SQ1R	1.30700	1.12925
SQ2L	0.50517	0.92345
SQ2R	-1.15130	-0.93370
SQ3L	0.03603	0.24194
SQ3R	-0.09516	0.03511
SQ4L	-0.06507	0.10886
SQ4R	-0.40202	-0.36664
Sextupole	Ysxt(mm)	Ysxt(mm)
SD4A2(SQ5L)	-2.981	-2.208
SD2A1(SQ5R)	6.724	6.347
SD4A1(SQ6L)	-3.194	-2.429
SD2A2(SQ6R)	0.907	0.137
	Xsxt(mm)	Xsxt(mm)
SD4A2(SQ5L)	3.500	4.950
SD2A1(SQ5R)	7.000	7.461
SD4A1(SQ6L)	3.500	4.826
SD2A2(SQ6R)	0.000	3.339

Table 1: The solution of the model to fit the HER based on the analysis of the oscillation data taken July 30, 1999.

Note that the changes needed to match the model to the machine are rather large, sometime more than 50%, indicating that the unknown coupling errors in the IR are still quite large. Given the machine errors are not known, we would like to use the solution to tune the machine back to the design model. To do that, the new setting of the skew quadrupoles should be

$$K1L_{new} = K1L_{mach.} - (K1L_{fitted} - K1L_{model}), \quad (1)$$

where $K1L_{mach.}$ is the setting of the skew quadrupoles when the data was taken. The minus sign in front of the bracket in the Eqn.1 says that if the setting is too high in the fitted model(matched to the current machine), then the setting in the machine should be lower. Since the coupling problem is basically a linear problem, the relationship is linear as well.

For the sextupoles, their positions are set according to the BPM nearby. The new reading of the BPM at the sextupole is given

$$Yb_{new} = Yb_{mach.} + (Ysxt_{fitted} - Ysxt_{model}), \quad (2)$$

where $Yb_{mach.}$ is the reading of the BPM in the the reference orbit which was subtracted from the orbits to make the difference orbits used in the analysis. Please note that the alignment change of sextupoles does not depend on the absolute reading of the BPM but rather the relative one. The plus sign before the bracket in Eqn.2 is due to the fact that the BPM reading implies to move the beam instead of the sextupole magnet.

Magnets	Machine	New Machine
Skew Quad.	K1L(KG)	K1L(KG)
SQ1L	-0.42057	-0.24014
SQ1R	1.30700	1.48475
SQ2L	0.50517	0.08689
SQ2R	-1.15130	-1.36889
SQ3L	0.03603	-0.16988
SQ3R	-0.09516	-0.22543
SQ4L	-0.06507	-0.23900
SQ4R	-0.40202	-0.43739
BPMS	Yb(mm)	Yb(mm)
SD4A2(SQ5L)	0.574	1.346
SD2A1(SQ5R)	-1.968	-2.344
SD4A1(SQ6L)	1.576	2.341
SD2A2(SQ6R)	-1.146	-1.916

Table 2: New setting of the skew quadrupoles and the position of sextupoles used in the HER based on the analysis of the oscillation data taken July 30, 1999.

The settings of the skew quadrupoles and the vertical alignments of the sextupoles were implemented in the HER. The horizontal alignments of the sextupoles were very difficult to set because the absence of the horizontal BPM near the sextupoles. Therefore, they were left untouched. After the implementation, the strength of the global skew quadrupoles decreased by a factor of two. The leak of the coupling outside the IR was reduced as well but there are still residual leakages of the coupling into the arcs. It seems that more iterations of the correction are required.

4 THE LOW ENERGY RING

The low-beta optics of the LER[3] is much more complicated than in the HER due to the vertical separation the rings and the local chromatic module in the IR. Similar data has been taken and analyzed. Partial solutions have been tried in the machine. The results are similar to those in the HER.

From the analysis, we found the strong local sextupoles near the IP in the region of the vertical separation were aligned away from their design positions by a few millimeters. As shown in Tab. 3, the finding agrees with the data obtained from the beam-based alignment(BBA) at the left side of the IR.

Sextupoles	PR02 BPM X	Target Reading	Reading(BBA)
SCX2	3102	3.968 mm	-0.021 mm
	3082	5.360 mm	1.298 mm
SCX1	3042	offline	offline
	3041	5.844 mm	1.807 mm
SCX1L	2185	8.704 mm	7.097 mm
	2182	7.762 mm	5.893 mm
SCX2L	2142	-3.762 mm	-3.962 mm
	2122	-2.716 mm	-2.798 mm

Table 3: Targeted the position of sextupoles in the LER based on the analysis of the oscillation data taken July 23, 1999.

For the LER, often the solutions of the analysis can not be applied to the machine because the needed strengths of the four skew quadrupoles near the four local sextupoles were too strong. This indicates that the vertical orbits at the sextupoles are not well controlled due to the absence of vertical BPMs in the region. Clearly we need to add more vertical BPMs and correctors to reduce the vertical orbits near the sextupoles.

5 DISCUSSION

As this paper is written, the settings of skew quadrupoles in the HER are very close to the values listed in the Table 2, and the settings of the skew quadrupoles in the LER was tweaked away from a fitting solution to minimize the vertical beam size at the interaction point. Σ_y was reduced to about 8.5 microns at the low beam currents and the peak luminosity reached $8 \times 10^{32} cm^{-2} s^{-1}$. One of the remaining problems is that the global coupling in the LER is still quite large. We are planning to try more iterations of the correction in the future.

6 ACKNOWLEDGMENTS

We would like to thank Martin Lee and Ron Ruth for many helpful discussions about the data analysis. We would also like to thank Tom Himel, Michiko Minty, Ina Reichel, and Mike Sullivan for taking oscillation data and John Seeman for his support and using the results of the analysis in the accelerators of PEP-II.

7 REFERENCES

[1] J. Y. Nosochkov, Y. Cai, J. Irwin, M. Sullivan and E. Forest, "Detector Solenoid Compensation in the PEP-II B-Factory", SLAC-PUB-95-6890, May 1995.

[2] Y. Cai, M. Donald, J. Irwin and Y. Yan, "LEGO: A Modular Accelerator Design Code," SLAC-PUB-7642, August 1997.

[3] Y. Cai *et al.* "Low Energy Ring Lattice of the PEP-II Asymmetric B-Factory," SLAC-PUB-95-6868, May 1995.