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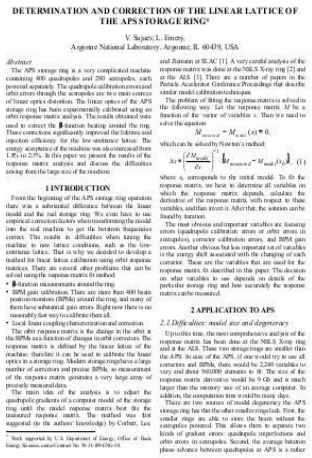

DETERMINATION AND CORRECTION OF THE LINEAR LATTICE OF THE APS STORAGE RING*

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Abstract

The APS storage ring is a very complicated machine containing 400 quadrupoles and 280 sextupoles, each powered separately. The quadrupole calibration errors and orbit errors through the sextupoles are two main sources of linear optics distortion. The linear optics of the APS storage ring has been experimentally calibrated using an orbit response matrix analysis. The results obtained were used to correct the β-function beating around the ring. These corrections significantly improved the lifetime and injection efficiency for the low-emittance lattice. The energy acceptance of the machine was also increased from 1.4% to 2.5%. In this paper we present the results of the response matrix analysis and discuss the difficulties arising from the large size of the machine.

1 INTRODUCTION

From the beginning of the APS storage ring operation there was a substantial difference between the linear model and the real storage ring. We even have to use empirical correction factors when transforming the model into the real machine to get the betatron frequencies correct. This results in difficulties when tuning the machine to new lattice conditions, such as the low-emittance lattice. That is why we decided to develop a method for linear lattice calibration using orbit response matrices. There are several other problems that can be solved using the response matrix fit method:

- β-function measurements around the ring.
- BPM gain calibration. There are more than 400 beam position monitors (BPMs) around the ring, and many of them have substantial gain errors. Right now there is no reasonably fast way to calibrate them all.
- Local linear coupling characterization and correction.

The orbit response matrix is the change in the orbit at the BPMs as a function of changes in orbit correctors. The response matrix is defined by the linear lattice of the machine; therefore it can be used to calibrate the linear optics in a storage ring. Modern storage rings have a large number of correctors and precise BPMs, so measurement of the response matrix generates a very large array of precisely measured data.

The main idea of the analysis is to adjust the quadrupole gradients of a computer model of the storage ring until the model response matrix best fits the measured response matrix. The method was first suggested (to the authors' knowledge) by Corbett, Lee and Zisman at SLAC [1]. A very careful analysis of the response matrix was done at the NSLS X-ray ring [2] and at the ALS [3]. There are a number of papers in the Particle Accelerator Conference Proceedings that describe similar model calibration techniques.

The problem of fitting the response matrix is solved in the following way. Let the response matrix M be a function of the vector of variables x. Then we need to solve the equation

$$M_{measured} - M_{model}(x) = 0,$$

which can be solved by Newton's method:

$$\Delta x = \left(\frac{\partial M_{model}}{\partial x}\right)^{-1}\left(M_{measured} - M_{model}(x_0)\right), \quad (1)$$

where x_0 corresponds to the initial model. To fit the response matrix, we have to determine all variables on which the response matrix depends, calculate the derivative of the response matrix with respect to these variables, and then invert it. After that, the solution can be found by iteration.

The most obvious and important variables are focusing errors (quadrupole calibration errors or orbit errors in sextupoles), corrector calibration errors, and BPM gain errors. Another obvious but less important set of variables is the energy shift associated with the changing of each corrector. These are the variables that are used for the response matrix fit described in this paper. The decision on what variables to use depends on details of the particular storage ring and how accurately the response matrix can be measured.

2 APPLICATION TO APS

2.1 Difficulties: model size and degeneracy

Up to this time, the most comprehensive analysis of the response matrix has been done at the NSLS X-ray ring and at the ALS. These two storage rings are smaller than the APS. In case of the APS, if one would try to use all correctors and BPMs, there would be 2,240 variables to vary and about 560,000 elements to fit. The size of the response matrix derivative would be 9 Gb and is much larger than the memory size of an average computer. In addition, the computation time would be many days.

There are two sources of model degeneracy the APS storage ring has that the other smaller rings lack. First, the smaller rings are able to zero the beam without the sextupoles powered. This allows them to separate two kinds of gradient errors: quadrupole imperfections and orbit errors in sextupoles. Second, the average betatron phase advance between quadrupoles at APS is a rather

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