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## DETERMINATION AND CORRECTION OF THE LINEAR LATTICE OF THE AFS STORAGE RING\*

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**Abstract**  
The AFS storage ring is a very complicated machine consisting of quadrupoles and 200 magnets, each powered separately. The quadrupole calibration errors affect energy through the dispersion. The linear lattice of the AFS storage ring has been determined only through a very rough method. This method is not accurate and used a correct the  $\beta$ -function fitting around the ring. This correction is usually required for the linear lattice to improve efficiency for the low-emittance beam. The energy spread of the machine was the nominal value 1.0% 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

Finally, beginning of the AFS storage ring operation, there was a substantial difference between the linear lattice and the data during the first year. We had to do the optical correction to the whole machine to get the linear lattice correct. This was a difficult job when taking the machine to low energy conditions, such as the low-emittance lattice. That is why we decided to develop a method for linear lattice calibration using other response matrices. There are several other problems that can be solved through response matrix fit method:

- Lattice measurements around the ring
- BPM gain calibration. There are more than 200 beam position monitors (BPMs) around the ring and many of them have substantial gain errors. Right now there is no reasonable way to calibrate them all.
- Local linear coupling measurement and correction.

The other response matrix is the change in the orbit of the BPMs and the linear lattice design method corrects the response matrix is defined by the linear lattice of the machine. Therefore it can be used to calibrate the linear lattice in a storage ring. Modern storage rings have a large number of magnets and precise BPMs, so measurement of the response matrix requires a very large array of precise measurements.

The main idea of the analysis is to adjust the quadrupole gradient of a computer model of the storage ring until the model response matrix best fits the measured response matrix. The method was first suggested by the author's knowledge by Corbett, Lee,

and Zisman in SLAC [1]. A very careful analysis of the response matrix was done in the NSLS 3-GeV ring [2] and in the AFS [3]. There are a number of errors in the present work. The authors are grateful to the staff of the Fermilab Accelerator Science Department for their helpful comments and discussions.

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

$$M(x) - M_{\text{model}}(x) = 0, \quad (1)$$

which can be solved by Newton's method:

$$x_{i+1} = x_i - \frac{M(x_i) - M_{\text{model}}(x_i)}{J(x_i)}, \quad (2)$$

where  $J$  corresponds to the Jacobian matrix. 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 use Newton's method. The matrix  $J$  is usually a sparse matrix.

The most obvious independent variables are focusing centers (quadrupole calibration errors or orbit errors in symmetrically corrected lattices), and BPM gain errors. Another obvious but less important set of variables is the energy shift associated with the changing of each component. These are the variables that are used for the response matrix fit described in the paper. The discussion on other variables is not included in this paper. We do not think of the particular form of the fit, but only generally for response matrix calibration.

### 2 APPLICATION TO AFS

**2.1 Dipole error model line and degeneracy**  
Typically, the most comprehensive analysis of the response matrix has been done in the NSLS 3-GeV ring and in the AFS. These two storage rings are similar to the AFS. In case of the AFS, if we would fit to all 200 correctors and BPMs, there would be 2340 variables to vary and that 500000 elements in  $J$ . The size of the response matrix derivative would be 9 Gb and is much larger than the memory size of a single computer. In addition, the computation time would be very large.

There are two sources of model degeneracy in the storage ring fit that the other methods might miss. First, the variable range can differ in some of the beam without the computer program. This allows them to acquire two kinds of gradient errors: quadrupole imperfections and orbit errors in symmetric. Second, the average between

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