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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 280 magnets, each powered separately. The quadrupole calibration errors affect energy through the dispersion. The linear optics of the AFS storage ring has been comprehensively calibrated using a sophisticated data analysis. This method involves using a correct the  $\beta$ -function heating around the ring. This correction significantly improved the linear optics injection efficiency for the low-emittance beam. The energy dependence of the quadrupole was also investigated (1.8% 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 response.

### 1. INTRODUCTION

Finally, beginning of the AFS storage ring operation, there was a substantial difference between the beam size and the data storage ring. We can look at the typical correction factors of the quadrupoles, which are the main reason to get the beam size injection errors. This results in difficulties when trying to match the beam size conditions, such as the high emittance beam. That is why we decided to develop a method for these linear calibration using other response matrices. There are several other problems that can be solved through response matrix fit method:

- Linear optics 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 optics measurements and correction.

The other response matrix is the change in the orbit of the BPMs and the quadrupole dispersion matrix correction. The response matrix is defined by the linear optics 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 magnets and precise BPMs, so measurement of the response matrix requires a very large amount of practical 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 reported in the author's knowledge by Corbett, Lee,

and Zisman at SLAC [1]. A very careful analysis of the response matrix was done in the NCSX storage ring [2] and in the ALS [3]. There are a number of papers in the Particle Accelerator Science Program that describe certain model algorithms.

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:

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

which can be solved by Newton's method:

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

where  $J_M$  corresponds to the Jacobian matrix. In 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 solve for the values of the variables that satisfy equation (2).

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 corrector. These are the variables that are used for the response matrix fit described in the paper. The discussion on other variables is not reported in detail in the present form of the paper, but we have successfully fit response matrix calibration.

### 2. APPLICATION TO AFS

**2.1. Diagnostic model fit and degeneracy**  
Typically, the most comprehensive analysis of the response matrix has been done in the NCSX storage ring and in the ALS. These two storage rings are similar to the AFS. In case of the AFS, if we would fit to all correctors and BPMs, there would be 2340 variables to vary and then 500000 equations to fit. The size of the response matrix derivative would be 9 GB and it is much larger than the memory size of a storage computer. In addition, the computation time would be many days.

There are two sources of model degeneracy in the storage ring fit that the other configurations. First, the variable range can differ in some of the beam without the computer program. The data is then in response two kinds of gradient errors: quadrupole imperfections and orbit errors in symmetric. Second, the average between quadrupoles and quadrupoles in AFS is a rather

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