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A BEAM ENERGY ANALYSIS AND MONITORING SYSTEM FOR LINEAR ACCELERATORS*

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Abstract

A model-based beam orbit simulation program has been used successfully to analyze the beam energy errors at the two-mile linear accelerator during commissioning of the SLC system. This simulation program has also been used to develop a nondestructive beam energy error monitoring system. The method of analysis, the simulation program, and a beam energy analysis and monitoring system using expert systems techniques will be described.

Introduction

We have developed a Trajectory Analysis Program (TAP) to find beam energy errors in the SLC LINAC. TAP has found actual beam energy gain errors that have caused the Automatic Beam Steering Program to function poorly. Its development is based on our experience in using the "GOLD" method[1] to identify magnet focus strength and alignment errors.[2] We have demonstrated that it is possible to use the same two-step method to find beam energy errors.

Since one of the more probable causes of a beam energy error is the RF phase error, we have also developed a Phase Wobbling Method (PWM) to check the RF phase relative to the beam without deflecting the beam off axis into a spectrometer as in the conventional method. Numerous cases have been successfully analyzed to find actual energy errors during commissioning of the LINAC. In this paper, we will discuss our experience using TAP to find energy errors and using PWM to check RF phase errors. It is possible to monitor the change in the beam energy on-line by combining these two methods. Some salient features of this combined system will be described.

The Modeling Parameters

The LINAC beam line consists of 29 sectors (Sector 2 to Sector 30); each sector is powered by eight klystrons with one klystron suppling RF power to a module consisting of four accelerator sections; a quadrupole magnet is located at the end of a module (in Sector 3 to 30) or located at the end of an accelerator section (Sector 2). There is one BPM and one corrector (per plane) at every quadrupole magnet. The model of the beam line is represented by the machine functions calculated from the lattice code COMFORT.[3]

The control system for the SLC LINAC uses model-based application programs to change beam parameter values (e.g., beam trajectory). The performance of these programs (e.g., the Automatic Beam Steering Program) depends on the accuracy of the values of the modeling parameters (e.g., beam energy gain) as well as the algorithm. In particular, in order to utilize the Automatic Beam Steering Program more reliably, it is necessary that the values of the beam energy gain in the model correspond to the actual values in the machine.

Modeling parameters such as quadrupole strength, beam energy gain and klystron phase are stored in the database of the SLC control system. The actual beam energy gain at each accelerator section is assumed to be the "no-load" (maximum) value stored in the database multiplied by the cosine of the klystron phase. The control system can be used to change the values of the quadrupole strengths and the klystron phases to any desired values. The klystron phase is normally zero corresponding to the maximum energy gain condition. The energy profile is defined as the value of the beam energy at the end of each beam line element.

Effects of the Modeling Errors

It has been observed that actual parameter values could change from the modeling parameter values in the database without our knowledge. For example, due to the instability in the drive line that delivers the signal to the sub-booster klystron in each sector, the RF phase value (relative to the beam) could change by a modest amount. When this happens, the actual beam energy profile downstream of this sector will be different from the profile derived from the database.

The conventional method to check the phase of a klystron requires deflecting the beam into a spectrometer and is sensitive to RF steering (kicks on the beam due to transverse error fields in the accelerator sections). We have seen that in the early sectors where the RF steer effects are large, the normal phasing method does not work very well. Thus, it is necessary to find a method that does not disrupt the beam trajectory appreciably and is not sensitive to the RF beam steering.

The GOLD Method

TAP is based on the GOLD method which was used during the commissioning of the SLC to find relatively large isolated errors in magnet strength and element alignment. The GOLD method is not effective for finding small and distributed errors, but these are correctable using any conventional methods. The GOLD method consists of two steps: (1) to identify the error-free regions; (2) to find possible locations of element errors outside of the error-free regions. We define the difference trajectory as the change in the trajectory induced by a dipole corrector kick. The GOLD method uses a simulation program to produce simulated difference trajectories induced by hypothetical dipole corrector kicks.

In the first step, given a measured difference trajectory (produced by an intentional dipole corrector kick), the GOLD method finds error-free regions by finding the simulated difference trajectory that best matches the measured difference trajectory. This procedure is independent of RF steering. TAP uses the same methodology but additionally includes energy effects.

In the second step, all accelerator sections located between two adjacent error-free regions are considered to possibly contain energy gain errors. Again, TAP generates a number of hypothetical trajectories by simulating the effects of each possible accelerator section error. It then finds the simulated trajectory that best matches the measured trajectory to determine the "most likely" location and value of the error.

Application of TAP

Our first experience in applying TAP to find actual beam energy errors in the LINAC was to determine why the Automatic Beam Steering Program was not working properly. Since large energy gain errors were suspected in the first few sectors, we measured the difference trajectory induced by a dipole corrector kick at the beginning of Sector 2. A plot of the difference trajectory measured at the BPMs in Sectors 2 to 5 is shown in Fig. 1. The solid line is the measured data and the dotted line is the best simulated difference trajectory. The mismatch between the solid and dotted lines shows possible energy gain errors in the on-line database (model).

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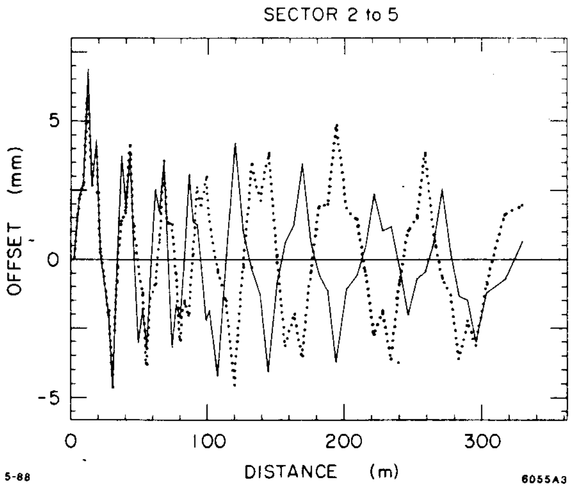

Fig. 1. A plot of the measured difference trajectory (solid line) induced by a dipole corrector kick at the beginning of Sector 2. The dotted line is a plot of the difference trajectory based on the energy gain values in the database. The large mismatch between the solid and dotted lines indicates the presence of energy errors.

We used TAP to analyze the measured data (solid line in Fig. 1) to find the first error-free region downstream of the kick. The value of the discrepancy (the difference between the best simulated difference trajectory and the measured difference trajectory) obtained from TAP is plotted in Fig. 2. From this plot it can be seen that the first error-free region is between BPM 11 and BPM 19 (Distance 21 to 45 m). The energy and the slope of the trajectory (the launch condition) were adjusted at the launch point (BPM 11) to match the measured data.

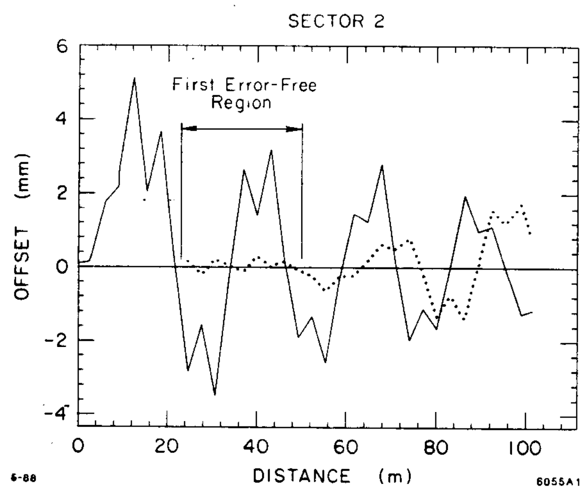

Fig. 2. The result of using TAP to find the first error-free region by analyzing the measured difference trajectory (solid line). The dotted line is the discrepancy between the best simulated difference trajectory and the measured difference trajectory.

By applying the same procedure downstream, we found the next error-free region. The result is shown in Fig. 3, from which it can be seen that the second error-free region extends from BPM 28 to BPM 49 (Distance 70 to 175 m). Based on these results we proceeded to find the energy gain error between BPM 19 and BPM 28. To find this error each accelerator section between BPM 19 and BPM 28 was considered suspect. For each candidate, we used NPSLAC[4] to minimize the discrepancy between the simulated and measured difference trajectories over

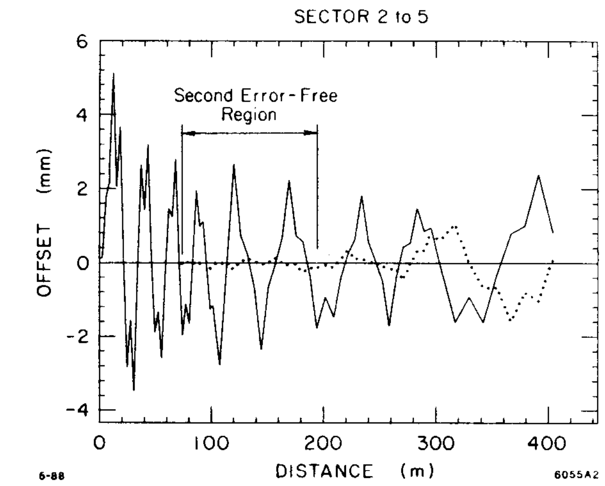

Fig. 3. The result of using TAP to find the second error-free region by analyzing the measured difference trajectory (solid line). The dotted line is the discrepancy between the best simulated difference trajectory and the measured difference trajectory.

all of the BPM's in both the first and second error-free regions. The lowest discrepancy corresponds to an energy error in accelerator section 4 of Sector 2. The predicted results including this energy gain error is shown in Fig. 4.

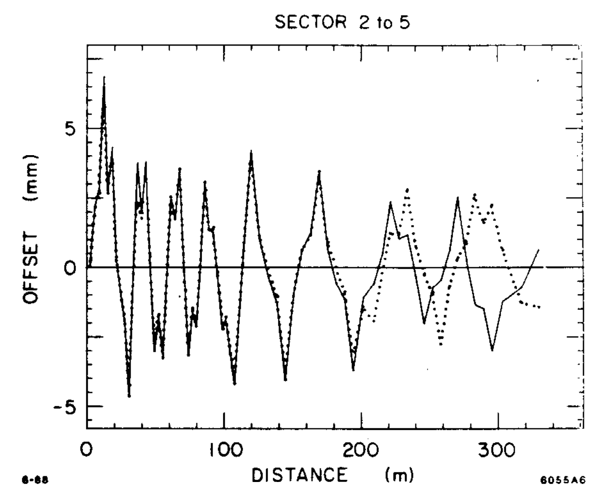

Fig. 4. A plot of the measured difference trajectory (solid line) and the best simulated difference trajectory including the predicted energy gain error at accelerator section 4 in Sector 2 (dotted line).

This procedure was repeated until the end of Sector 5. We found a total of four error-free regions and, thus, three accelerator sections with energy gain errors. The locations and values of these errors are presented in Table 1. Because of the limited resolution of the GOLD method, these results should be interpreted as probable error locations and equivalent error values (since there may be more than one isolated error within each subregion).

Based on the results presented in Table 1, the klystrons in the vicinity of these three most probable error locations were re-phased by deflecting the beam off axis into a spectrometer. The Automatic Beam Steering Program subsequently functioned properly.

Table 1. Klystron energy check.

Klystron	Database Energy	Predicted Energy	Energy Error
Sect2-Kly4	241.5 MeV	76.2 MeV	165.3 MeV
Sect3-Kly6	242.3 MeV	−89.7 MeV	332.0 MeV
Sect4-Kly2	242.7 MeV	−100.1 MeV	342.8 MeV

The Phase Wobbling Method

The difference trajectory downstream of an accelerator section depends on the cosine of the klystron phase. It is possible to determine whether a klystron is misphased since $\cos\phi$ is an even function of ϕ. A zero phase value will correspond to the symmetry point in the measured data. That is, if the measured difference trajectories at two phase values $\pm\delta\phi$ from the current operating phase are equal, then the klystron is correctly phased.

In practice, the optimal value for $\delta\phi$ is 90° because the phase wobbling method is most sensitive at this value. To find the magnitude of the misphasing, one assumes a phase offset and applies the "phase wobbling" test. If the two difference trajectories do not match, then we change the assumed phase offset and repeat until the two difference trajectories match. Since the phase wobbling test does not deflect the beam off axis, it can be performed without completely disrupting machine operation.

The phase wobbling method was used on-line during machine operation on several occasions and discovered phase errors of varying magnitudes which were subsequently corrected. Table 2 presents the results of such an occasion. The phase wobbling method has been very successful in the first several sectors of the LINAC and in the sub-booster klystrons (by wobbling the phase a few degrees). Figure 5 compares the difference trajectories (for $\pm\delta\phi$) for the final result using the phase wobbling method to correct the phase of the first klystron in Sector 2.

Table 2. Klystron phase check.

Klystron	Phase Before	Phase After	Phase Error
Sect2-Kly1	−31.0°	7.0°	38.0°
Sect2-Kly2	0.0°	23.0°	23.0°
Sect3-Kly2	15.0°	15.0°	0.0°

An On-line Energy Monitoring System

Lee, Kleban and Zambre have proposed to develop an on-line energy monitoring system for the LINAC by monitoring the change in trajectories continuously. This system can be used to deduce the "most likely" causes of trajectory deviations The GOLD method can be used to analyze these deviations to determine the error-free regions, the causes of errors, and the location and magnitudes of errors.

The techniques used in TAP can be automated to find beam energy gain errors by applying expert systems technology.[5] After the locations and values of the energy gain errors are found, the on-line system can automatically check the klystron phasing using the phase wobbling method. The advantage of this method is that the number of phase tests can be kept to a minimum.

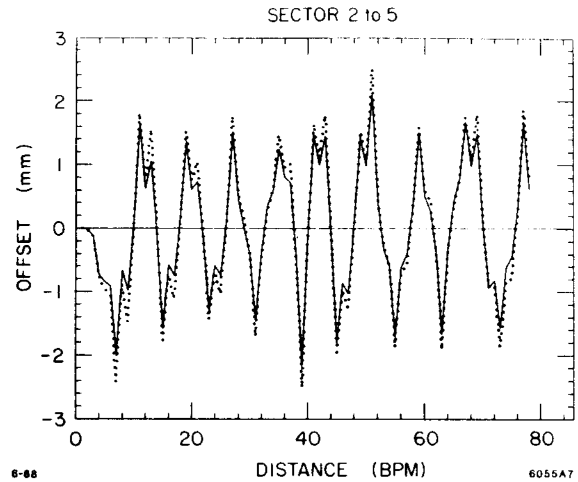

Fig. 5. A plot of the difference trajectory measured at ±50° from the corrected phased value (7°). The data for the − and + phase wobbled cases are shown as a dotted and solid lines respectively. Wobbling at ±90° is not possible at this early sector because of beam loss.

Summary

We have demonstrated that the method we used to find magnet strength and alignment errors can also be used to find beam energy gain errors in linear accelerators. Based on the results presented, these methods should be considered for accelerator control systems to monitor changes in the beam energy during machine operation. Since the output of the monitoring system will depend on the results of analyses and their interpretation, rules that distinguish between different types of errors must be developed. This paper presents a possible starting point for an automatic beam energy monitoring system.

Acknowledgements

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