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ENERGY MEASUREMENTS FROM BETATRON OSCILLATIONS*

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ABSTRACT

In the Stanford Linear Collider the electron beam is accelerated from 1–50 GeV in a distance of 3 km. The energy is measured and corrected at the end with an energy feedback loop. There are no bends within the linear accelerator itself, so no intermediate energy measurements are made. Errors in the energy profile due to mis-phasing of the RF, or due to calibration errors in the klystrons' RF outputs are difficult to detect. As the total betatron phase advance down the accelerator is about $30 \times 2\pi$, an energy error of a few percent can cause a large error in the total phase advance. This in turn degrades the performance of auto-steering programs. We have developed a diagnostic program which generates and measures several betatron oscillations in the accelerator. It then analyzes this oscillation, looking for frequency changes which indicate energy errors. One can then compensate for or correct these energy errors.

1. INTRODUCTION

At the Stanford Linear Collider (SLC) there are several systems which depend critically on an accurate knowledge of the accelerator lattice to function properly. Chief among these are feedback,[1,2] and auto–steering.[3,4] They both use the transfer matrix elements (R12's) from a corrector to downstream beam position monitors (BPM's) in their calculations. If these R12's are not accurate, then these systems do not work well. The R12's are calculated with an online model, COMFORT,[5] based on our knowledge of the quadrupole strengths and the beam energy. Errors in this knowledge cause errors in the calculated lattice which then make steering and feedback perform poorly.

A particularly tough case occurs in the linac, where our knowledge of the energy profile (energy as a function of distance along the linac) is rather limited. We estimate it from our knowledge of klystron power outputs. These estimates have errors. In addition, sometimes the phase of a klystron changes a large amount without our knowledge, thus changing the energy it contributes to the beam. Also, the main drive line which propagates the phase reference signal down the 3-km length of the linac is not completely stable which causes changes in the energy profile. Note that there is an energy feedback loop which stabilizes the energy at the end of the linac, but the energy at other places in the linac will vary. These energy errors cause errors in the focusing strengths of the quadrupoles and thus cause errors in the lattice. The total betatron phase advance in the linac is about $30 \times 2\pi$ so it only takes a few percent energy error to generate an error of more than π in the phase advance, which corresponds to a sign error in the R12's.

For the above reasons, it is in fact quite common to have energy errors of several percent and errors in phase advance of several π. Because of this we cannot auto–steer the whole linac at once. We are forced to steer it in about 10 short pieces; each piece is short enough so the cumulative lattice errors are not significant. This is much slower than steering the whole linac at once. These lattice errors also exacerbate another problem. Beta is not properly matched coming into the linac; as a result, there are beta beats. As energy errors change, causing the total phase advance to change, these beta beats move. It is possible to fix the beta mismatch in the Final Focus System (FFS) optics, but it is a time-consuming procedure and can't be repeated frequently. Hence, due to the beta mismatch, changing linac energy errors cause the beam size to change in the FFS, which causes problems affecting both luminosity and detector backgrounds.

2. THE LATTICE DIAGNOSTIC

To attack this problem of lattice errors in the linac, we have developed a new online lattice diagnostic program. This program uses a corrector to purposely induce a betatron oscillation, which it then records by reading the BPM's. It can display this measured betatron oscillation on top of the prediction of the online model. The operator can look to see if they agree; if they don't, the measurements can be saved to disk so that offline programs[6] can be used to look for discrete lattice errors, such as incorrect quadrupole strengths or quadrupole fringe fields on dipole magnets.

One can also run an online fitting program which measures the energy profile, since the frequency of a betatron oscillation depends on the energy. The measured oscillation is compared to that predicted by the model. The energy profile in the model is varied until its prediction fits the data. This fitted energy profile is then compared to the nominal one, and displayed for the user who can either try to fix the error (by adjusting phases) or update the model with the fitted energies. Note that this measurement method is not very sensitive to exactly where an energy error occurs (*e.g.*, it won't be able to tell whether an error is in the first or second klystron of sector 6). However, it is good-enough so that by using the fitted energy values the transfer matrices all the way down the linac will be well determined. That is, it determines the phase advance quite well, which is all that is really needed to cure the two problems above. The program will also identify BPM's which don't properly lie on the betatron oscillation and thus are probably broken.

One might ask why we fit the energy errors rather than just directly measuring the R12's with the two betatron oscillations. After all, it is really only the R12's one needs to know. The answer to this is two fold. First of all, there are about 1200 independent R12's. If we evaluate them directly, there is no redundancy, and a bad BPM will end up with a bad R12 rather than being flagged as bad. In fitting the energy there are only about 30 free parameters, so the fit is greatly over-constrained and will be much more robust against errors in the data. Second, by fitting the energy errors, we get an answer which has an easily interpretable physical meaning which can lead to finding the cause of the error (*e.g.*, a poorly phased klystron). Finding the physical reason why 1200 R12's are different from the model is more difficult.

3. DETAILS OF THE ENERGY FIT

It is implicitly assumed when doing the energy fit that the dominant cause of the measured focusing errors is due to errors in the energy. The linac is divided into about 30 regions, where each region contributes the same fractional energy to the beam. Regions vary in length from 24 m at the beginning of the accelerator to 300 m at the end. The fit varies the energy gains in these regions, calculates the theoretical betatron oscillation, and compares it to the measured one. It continues doing this until it has minimized the chisquared of the difference. This is a 30-parameter, nonlinear fit which we want to execute online in under one minute on a VAX 8800. The idea is straightforward. The challenge was to make it fast enough.

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Our online modeling program takes about 30 seconds to calculate all the transfer matrices from one element to the next in the linac. Note that there are about 300 each of BPM's, quadrupoles, and X and Y correctors. Hence, it is impractical to run the modeling program for each iteration of the fit which has a different guess for the energy gains. Instead, the model is run once and the transfer matrices from one BPM to the next, and their derivatives with respect to energy are saved to disk. Now the calculation of the theoretical betatron oscillation for a given set of energy errors only involves adding and multiplying 300 2×2 matrices, which is much faster. In fact, the whole 30-parameter fit to 1200 data points (300 BPM's times 2 for x and y times 2 for two betatron oscillations generated 90° out of phase) takes just one to two minutes.

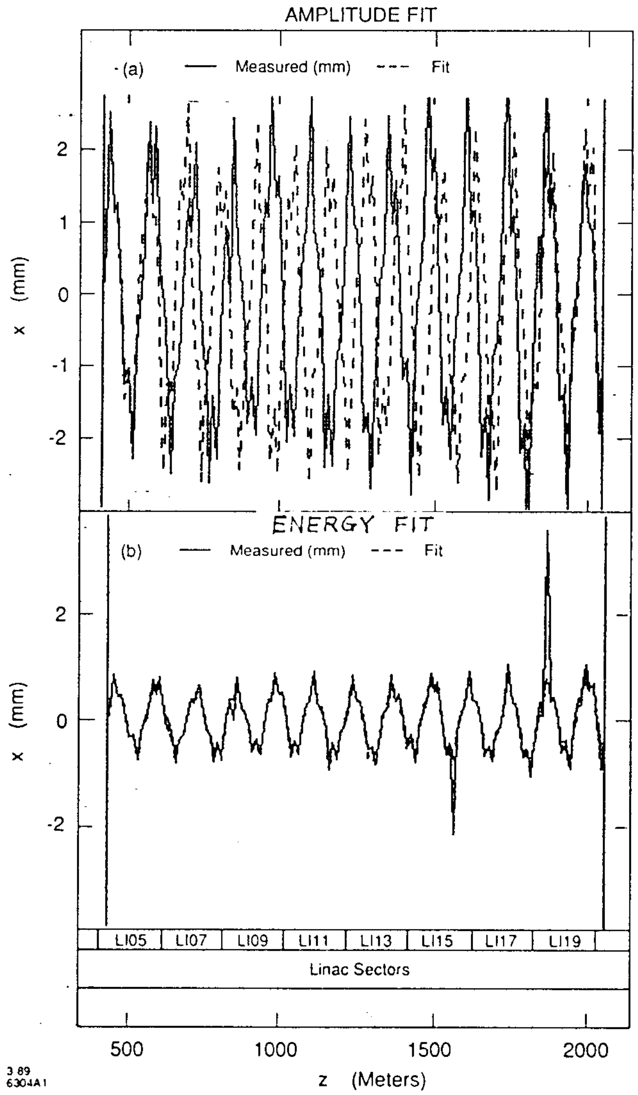

Fig. 1. Graphic output from the lattice diagnostic program. The solid line shows the measured betatron oscillation: (a) the dashed line shows the prediction of the model. Note the frequency is wrong causing a 2π error in the total phase advance; (b) the dashed line showing the energy fit lies almost exactly on top of the data.

4. OPERATING EXPERIENCE

We now have six months' experience using this lattice diagnostic at the SLC. In its simple form where it generates and measures a betatron oscillation and compares the measurement to the model, it has become a standard tool used in all parts of the SLC, not just the linac. With a minimum of setup time, one can check the lattice for focusing errors. When errors are seen, the results are saved to disk and offline analysis is used to try to localize the error.

The special energy fit for the linac has not been as successful. Figure 1(a) shows the comparison of the data and the model without the energy fit as produced by the program. There is an obvious frequency difference. Figure 1(b) shows the same data where the energy fit has been done. The chisquared is 474 for 234 degrees of freedom, and thus the fit is excellent. The online display is in color and shows that the two BPM's where the agreement is very poor were known to be defective. The problem is that the energy errors determined by the fit are not physically reasonable. It finds 20–30% energy errors, which are considerably larger than we believe them to be. On successive measurements, these errors reproduce with only a 1–2% variation. When we purposely cause an energy error by turning off a klystron, the program sees the change correctly. Our conclusion is that some systematic problem exists in the measurement or lattice which the fit is forced to interpret as energy errors. We are investigating the possibility that the quadrupoles have a few percent calibration error or that the BPM's have a random error in their gains of about 10%.

We expect that when we find and fix the systematic error, we will then have a tool which will allow us to rapidly localize energy errors in the linac, and then either fix them or compensate for them in the model.

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