

PHASING TOOLS FOR THE KLYSTRONS AT THE SLC*

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ABSTRACT

Modern large accelerators require the RF sources to be correctly phased to control emittance growth, and to preserve the energy and energy spread of the beam. Computer-based tools have been developed to aid in the phasing of the klystron RF sources at the SLC. Changes in hardware can result in different phase values for maximum energy gain; the hunting for the sources of these changes continues. Results and operational experience are presented.

1. INTRODUCTION

The SLAC 3-km linac¹ consists of approximately 960 3.05-m-long disk-loaded accelerating sections, powered by approximately 240 high-power klystron stations. The linac is further divided into 31 discrete sectors of klystrons, where each sector has a low-power subbooster klystron which provides RF drive for approximately 8 high-power accelerator klystrons.

Each klystron, and by necessity each sector of klystrons, must be phased correctly to control emittance growth, and for the preservation of the energy and energy spread of the beam. Phasing is accomplished using the beam as the primary reference. This insures that both the total energy gain, and the energy gain profile of the linac, correspond to the current operational requirements, and insures that there are no errors in the quadrupole focusing lattice.

2. CONTROLS

Each klystron and each subbooster driving a sector of klystrons is equipped with independent phase readback and control instrumentation,² which provides the operations staff of the accelerator with nearly 300 phase parameters to adjust for optimal machine operation. The RF controls and linac control system are designed to maintain the RF phase output of each klystron at the values in the on-line database, as compared to a local RF reference.^{3,4}

The control system maintains the phase of the machine, directly compensating for changes induced by weather, temperature, modulator voltage, and other factors not under our control. Even with such automatic stabilization tools, however, phasing of the accelerator is still periodically required to correct for changes which are not compensated for; for example, those caused by aging, thermal cycling, and the maintenance and replacement of individual components RF distribution systems.

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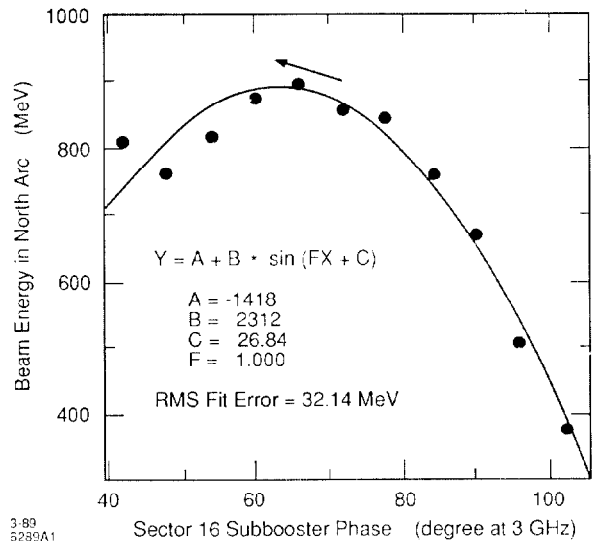


Fig. 1: Data from the phasing of a typical linac sector. Eleven samples were taken covering 60° of phase, and the beam energy was analyzed at each point. The data was fitted with a sine curve, and the phase offset term was used to determine the point of maximum energy gain. This example indicated a 8.5° phase error, with a RMS fitting error of 32 MeV.

Automated procedures have been developed to allow the phasing of the linac using the beam as the primary phase reference. Analysis is done using model driven analysis of the Beam Position Monitor data for determination of the observable beam parameters: X, X', Y, Y' position and angle, and dE energy error.⁵

2.1 Phasing Tools

One of the standard tools available through the SLC computer control system, the "correlation plot" ⁶ facility has proven a powerful tool for re-phasing RF devices. With it, it is possible to set up an automated data acquisition request where any controllable device can be stepped through a specified range of values, and at each step, a number of specified parameters can be acquired or analyzed and stored for later use.

This facility is used to optimize the phase of each individual klystron, or subbooster driving a sector of klystrons. The phase is stepped through a range of values, and for each sampled point, beam position data is acquired and automatically analyzed for beam energy error. The analysis package uses a linear least-squares fitting package, which determines both launch errors (angle and position offset) and energy offsets; effectively removing the effects of any linac RF steering from the sampled energy gain.

Figure 1 shows the results of a phase analysis, when done on a typical subbooster. The arrow indicates the difference between the current database "maximum energy gain" point, and the results of the analysis, and indicates an 8.5° (@3 GHz) error.

The acquired data is fit with a cosine function of fixed frequency, and with energy offset E_0 , energy gain E_{gain} and phase offset ϕ_0 as free parameters:

$$f(\phi) = E_0 + E_{gain} \cdot \cos(\phi + \phi_0)$$

When fitting data to any function, it is always important to understand the affects any errors in the sampled data will have on the analysis results. In this application, any random or non-systematic error in the sampled energy gain will alias as errors in all three free variables, notably including the phase offset. Systematic errors in either energy offset, or a systematic error in the analysis energy gain, show up in both the offset and amplitude terms, and not in the phase offset term.

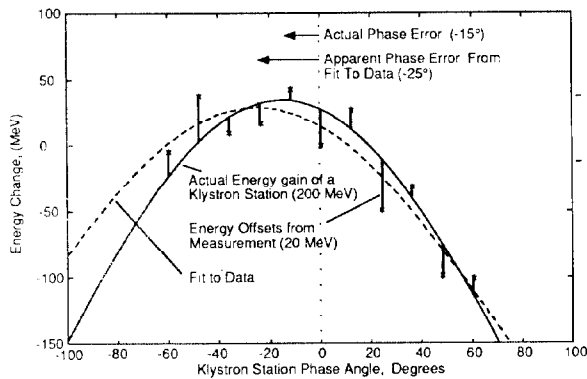


Fig. 2: In this study of phase offsets, a random error was introduced on each of 11 data points. Shown is the energy gain of the actual device, the "energy measurements", and the fit to the noisy data. Note the error in the phase of the fit.

Figure 2 shows the effect that random errors in the sampled beam energy have on the energy gain function. In this simulation, the energy output of a misphased klystron is sampled with an error of 20 MeV/point (normal distribution) added to the prototypical klystron's energy gain (errors in analyzing the beam's energy of 20% are common). In this study, the resultant fitted function is incorrect in all three free parameters, including a phase offset which is reported at -25° , 10° greater than the introduced offset. It is shown later that the predicted error in determining the phase offset is around 4° (sigma). Point to point errors or 20° are larger than typically achieved, and the actual error typically around 2° .

Optimally, a phase sweep of $\pm 90^\circ$, covering a range of 180° , is desired. This will generate an energy offset at least as great as the nominal energy gain of the device being studied; which for the SLAC linac can be a energy change of around 200 MeV out of 47 GeV, or 0.5% for single klystrons; or one sector out of 30, or 2% for entire sectors of klystrons. When phasing subboosters, the phase is typically swept over a smaller range of 60° for subboosters, at some sacrifice of accuracy, since an energy change of 2%

exceeds the energy acceptance of our available analyzing areas.

It is possible to predict the accuracy obtained in phasing a linac in the presence of "noise." Note that when trying to understand the effects of essentially random sampling noise, the only figure of merit is the ratio of the measurement noise to the energy gain of the device (or set of devices) being phased. Since the larger errors are related to BPM measurement noise, the performance can be improved by increasing the number of energy measurement points. The beam energy at the analyzer only appears indirectly, as the absolute noise figure is usually strongly correlated with the beam's energy.

Figure 3 shows the expected accuracy of phase nulling studies on a device which is correctly phased when measurement noise is introduced. The predictions are the "best case" prediction, since the error generally increases as the actual phase offset increases. Plotted is the error in the phase offset (sigma) as a function of both phase range and fractional energy error per point, with eleven cases of no error in analyzing the beam's energy, where the error in the estimated phase offset is identically zero.

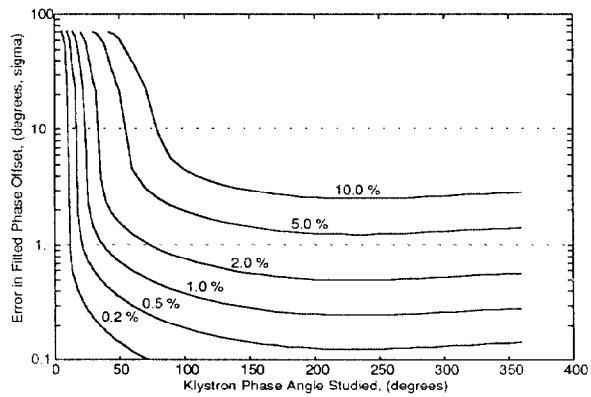


Fig. 3: Predictions of error in phase offset analysis results when data is subject to random or nonsystematic noise. Error is a function of both noise magnitude normalized to energy gain of the device under study, and the phase angle studied. Note that the energy acceptance of the analyzer must be greater as larger phase angles are studied.

2.2 Phasing System Performance

The SLAC linac is rephased at periodic intervals. A quick rephasing is done by optimizing the subboosters, and less frequently, rephasing of the entire linac is done. RF distribution systems at SLAC are vulnerable to long-term drifts, a situation which is largely due to the 3-km length of the linac and the drive system.⁵ The phase of individual klystrons within any given sector is observed to be comparatively stable, being primarily dependent on a much shorter (100 m) and electrically simpler phase reference system.

Rephasing of the individual sectors of the linac is done by optimizing the energy gain of the linac while changing the phase of the drive to the subbooster RF drive klystron. Phase angles are usually studied over a 60° range, and energy errors are typically between 10-20 MeV. Energy

errors are identified as the RMS residuals of the sampled datum and the fitted cosine wave. The fractional energy error is between 0.5-5%, resulting in an expected measurement phase error of less than 5°.

The phasing of all the individual klystrons of the linac at SLAC is a much more protracted operation, and is done several times a year. Since fractional energy errors of 5-10% are typical when phasing single klystrons (due primarily to the small energy contribution of individual stations), phase angles are typically studied over an extended range of 120°. With this the expected error is quite small, of the order of several degrees per station.

Studying the long term phase stability of both individual klystrons and sectors of klystrons is an ongoing project. The comparatively large phase errors associated with our primary RF distribution system, however, make detailed phase stability studies difficult.

Figure 4 shows the state of the linac in February 1989 following a protracted down time. The linac was previously phased in December, 1988, and the points represent the phase change which has occurred in the last six months. Omitted from the results are three sectors where significant RF hardware development occurred, and several sectors where data was not available. The general linear term in the phase offset is probably related to work done in the area of the master RF source, which adversely affected the offset of the main drive line's interferometer. Feedback loops exist in the main control computer which use the interferometer data in removing the effect barometric pressure and ambient temperature have on the electrical length of our primary RF reference line.

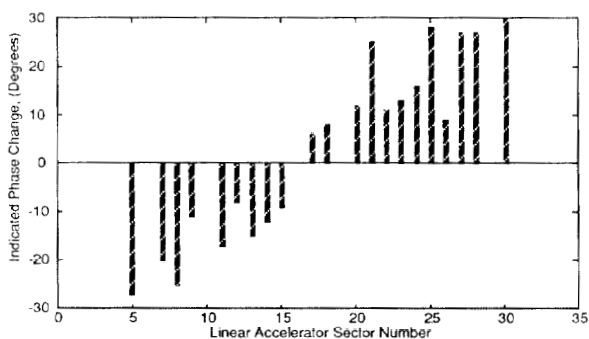


Fig. 4: Phase errors of 21 individual sectors of klystrons (out of 31) at the SLAC linac. Phasing of the linac had been done two months earlier, prior to a protracted down time. The general slope in the offset data is probably due to work which adversely effected the interferometer's reference.

3. BEAM ANALYSIS

Data from approximately 10 beam position monitors are used to determine the launch and error into a dispersive beam transport. An online model driven analysis package compares the actual orbit against a "golden" standard reference orbit, and computes both launch parameters and beam energy offset. For phasing studies, only the energy offset term is used.

Beam analysis tools for the linac exist at the entrance to the Damping Ring (1.1 GeV), at the "ten sector point" (16 GeV), and at the end of the linac (50 GeV). Different analyzers are used to allow the optimization of energy acceptance and resolution. The choice of an analyzer is often determined by the machine program currently scheduled.

Since beam losses upstream of the final beam position monitor are often the result of energy-dependent losses which change the energy spread of the beam, analyzers are chosen and used with some deliberate care.

Additional problems occur when attempting to phase very early sectors in the 3-km linac; where changes in the energy generate large energy errors for the focusing lattice. The beam is transported down the line, and these errors often result in unacceptably high losses, or orbit distortions which exceed the dynamic range of the model-based analysis tools.

4. CONCLUSIONS

Automated phasing procedures for large linear accelerators are practical, and indeed critical for modern linacs. Procedures involve using the beam as a primary reference, and as such care must be exercised to optimize energy gain, while remaining insensitive to systematic errors induced by RF steering and lattice errors.

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