A FAST AND ACCURATE PHASING ALGORITHM FOR THE RF ACCELERATING VOLTAGES OF THE SLAC LINAC*

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Abstract

The RF phases, defined as the phases between the crests of the RF accelerating voltages and the accelerated beam, must be controlled within a few degrees in the linac of the SLAC Linear Collider (SLC). Changes in the RF phases not only affect the available acceleration but more importantly modify the dynamics of the accelerated beam, e.g. the beam optics. Precision phase control is therefore crucial for maintaining high beam quality. We present a fast and accurate algorithm to determine the effective RF phase for groups of eight klystrons in the linac, the so-called subbooster phase. The new phasing method was implemented in 1997 and it was used to routinely determine all linac subbooster phases in about 2 minutes with a typical accuracy of 2 degrees. Using this algorithm a day-night variation of the linac master phase reference that was indicated by beam measurements in 1996 was directly confirmed and the online compensation verified.

1 INTRODUCTION

This paper presents a novel and fast method for measuring the effective RF phases in the SLAC linac. For this purpose we define the RF phase as the phase between the particle beam in the linac and the accelerating radio-frequency (RF) voltage in the accelerator structures (compare Fig. 1). In our convention the RF phase is zero for maximum beam acceleration. The SLAC linac contains about 240 klystrons, with groups of eight klystrons powered by a single "subbooster" drive unit. For optimal performance, each individual klystron phase must be determined and set to the proper value. Because the procedure is time-consuming, these are typically checked only every few months. Small random phase errors which accumulate in the intervening time tend to average out and do not seriously impact performance. Errors in the subbooster phases can be more important because they affect eight klystrons coherently.

Beam measurements made in 1996 indicated that the dominant source of RF phase errors is variations in the phase length of the cable which distributes the phase information to the klystrons. This cable, the ("Main Drive Line") [2], has a phase velocity slightly different from that of the beam, which travels at the speed of light. Any change in the velocity of this cable results in phasing errors which grow linearly along the 3 km length of the linac. Although the cable is temperature-stabilized, the phase velocity is affected by changes in atmospheric temperature and pressure. To compensate for these variations, an interferometer monitors the phase length of the cable and the information is used to automatically adjust the subbooster phases. In spite of this correction, residual phase errors of up to 20 degrees were measured which varied linearly along the length of the linac and appeared correlated to temperature. This was partially eliminated by adding an empirical correction, proportional to temperature, to the length as measured by the interferometer. In order to further improve this compensation, a fast and accurate method of determining the subbooster phases was developed. The new method replaced an older procedure which had poorer resolution and was too slow to apply on a regular basis.

To deliver high current, small emittance beams for the SLC [1], it is crucial that the RF phases be set and maintained within a few degrees. Proper phasing is necessary to produce the gradient required to accelerate the beams to about 46 Gev. In addition, the phase of the early klystrons is offset from nominal to introduce a correlated energy spread in the beam for BNS damping [4] which reduces the amplitude of incoming oscillations. Precise knowledge of the energy profile is necessary to match the lattice to the beam. The SLC also uses closed betatron oscillations to cancel residual wakefields. This type of global cancellation does not remain stable if the optics varies due to unknown energy errors. [3]. Accurate knowledge of the RF phases is critical to achieving high performance from the accelerator.

The following describes the new phasing procedure, its application, and conclusions drawn from monitoring of the RF phases in the SLAC linac.

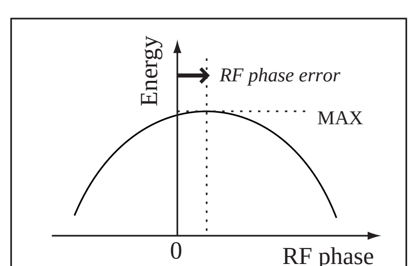

Figure 1: The definition of the RF phase in the SLAC linac.

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2 MEASUREMENT OF THE RF-PHASES

To get a good estimate of the RF phase errors in the SLAC linac it suffices to monitor the effective RF phases for just the 29 subboosters. The measurement principle is quite straightforward. The RF phase of each subbooster is varied, one at a time, and the final beam energy measured. The point of maximum beam energy defines the zero location of the effective subbooster phase. We now describe the phasing method in more detail.

2.1 Implementation

The old method of measuring subbooster or klystron phases scans through a wide range of phases monotonically, acquiring an energy value for each step. Typically a measurement of all devices, taking several hours, was done at the beginning of each many-month run. After that the procedure was primarily used for individual devices returning to online status after hardware repairs.

The new method of measuring subbooster phases makes use of fast phase shifters (available only on subboosters, not on klystrons) which can apply phase shifts of limited magnitude at 120 Hz, and the Dithered Buffered Data Acquisition facility within the SLC control system which allows synchronized pulse-to-pulse readout and control of several devices for a set of pulses. In order to measure the phase of a subbooster, a repeating pattern of phase shift requests is relayed to the microprocessor [5] controlling the subbooster. Requests are also made to this and other microprocessors controlling devices to be simultaneously read out, such as Beam Position Monitors (BPMs) in a dispersive region and the RF phase readback. Finally, a synchronizing signal, recognized by all participating microprocessors, is broadcast for the requisite number of pulses. The same synchronizing signal is used to fire a fast kicker which dumps the beam downsteam of the linac, since such off energy pulses tend to cause unacceptable backgrounds in the detector. Data from all pulses is analyzed at the host computer to find the orbit and energy of the beam for each pulse. Transverse orbit fluctuations are removed and then the energy versus phase data is fit with a cosine to find the maximum.

Many of the the parameters of the procedure are easily configurable, but most commonly 200 pulses are used to measure the phase of a subbooster by "dithering" the phase over a range of about 30 degrees at 9 different requested phases. The nominal phase of the subbooster is usually 10 to 20 degrees off peak for BNS damping. Hardware limitations unfortunately prohibit a significantly larger range or one which is centered about the peak, both of which would improve the fit. A plot of energy versus phase data plus fit as in Fig. 2 is displayed for each subbooster as soon as the measurement is complete, and is also recoverable from a file written at the time. To measure the phases of all 29 linac subboosters takes about two minutes; collisions in the detector are lost for less than 1 minute.

The rapidity of the procedure has advantages other than the obvious one of minimum interference with other uses of the beam. Because the whole procedure is completed so quickly, changes in the Main Drive Line due to temperature variation during the measurement are insignificant; the fits for all measured sectors belong to the same "snapshot." More important, for all but the first few sectors of the linac the procedure leaves the beams in essentially the same state they were in before the measurement. Errors of measurement due to drifts in beam parameters are thus minimized, and the procedure is transparent to the detector except for the lost pulses. In the earliest sectors a change in subbooster phase of 30 degrees corresponds to a large fractional change in energy, and the resulting beam is unstable, which degrades the measurement quality. (These same subbooster phases were essentially unmeasurable with the old, slow technique; only individual klystron phases could be measured.)

2.2 Fine Points

For the measurements to be useful, error estimates must be credible, and the errors themselves must be on the order of a degree or less. Care is taken in the fitting procedure to identify and discard anomalous points and to look for conditions, such as klystron dropout, which could invalidate the entire measurement.

Additional techniques are employed to lessen the effects of the measurement on the rest of the control system. The pattern of phases used to take the measurement is purposely "shuffled" to minimize the effect of slow changes in the beam parameters. Even so, the average energy (for example) of the measurement pulses is off nominal. An unexpected problem found in early tests of the procedure was a tendency for beam oscillations to accumulate as succes-

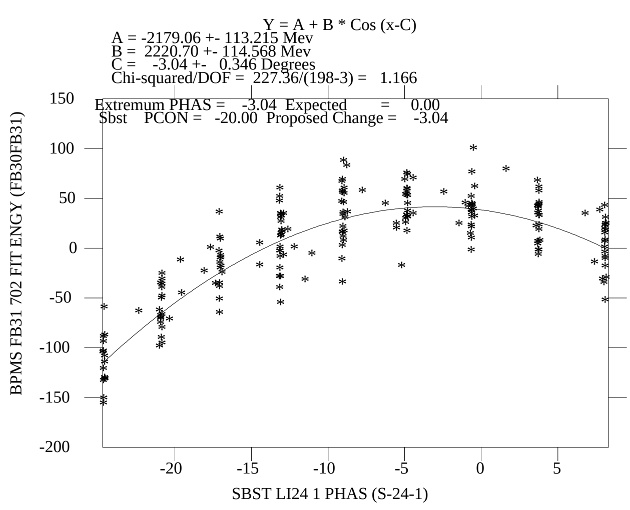

Figure 2: Computed energy versus RF phase, plus fit. The BPMs used in the orbit and energy calculation are located in a dispersive region. The points represent the measurements while the line shows the resulting fit.

sive subboosters were measured. Under normal conditions, SLC is heavily dependent on feedback systems [6] to maintain proper trajectories and energy. These feedbacks were attempting to correct for the off-nominal conditions during measurement. A straightforward solution was to reconfigure the affected feedbacks to ignore the pulses used by the phasing procedure.

3 RF PHASE MONITORING FOR SLC

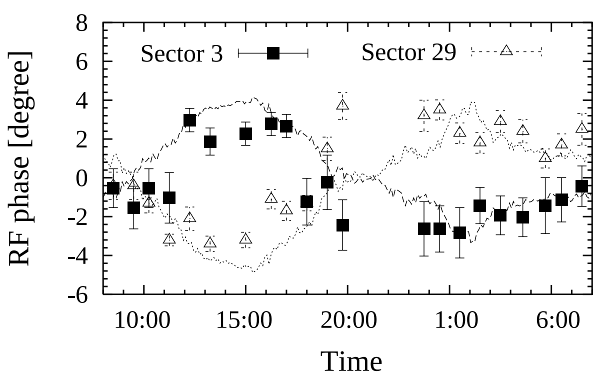

Figure 3: Measured variation of the RF phase error near the start (sector 3) and end (sector 29) of the linac over a 24 hour period. The dashed lines represent an empirical correction derived from the outside temperature and the location along the linac.

The new procedure was given its first serious trial in August of 1997 when measurements were taken every hour. These measurements confirmed the suspicion that phase errors in the machine had a diurnal, temperature-dependent component and also provided an excellent opportunity to commission the procedure. The measured diurnal variation of the RF phase in the beginning and the end of the linac is shown in Fig. 4. Note that the variation is of the same magnitude and opposite sign at the two ends of the linac. This is due to the fact that the final energy spread in the linac is maintained at a constant value which constrains the average phase error to be close to zero. The empirical correction that was established in 1996 [2] is shown as well. It is clear that the correction removes most of the diurnal variation in the RF phase. It is important to note that the phase measurement errors are consistently on the order of 1-2 degrees S-band.

Subsequently, the phases were measured daily at 3 PM and 3 AM and corrections recommended by the procedure were implemented when they were outside tolerance. As the run progressed through fall and into winter, with cooler weather and smaller diurnal temperature fluctuations, the residual diurnal RF phase variation became acceptably small. Most RF phase errors were caused by problems with single subboosters or klystrons. The goal was to keep the phases of all linac sectors within 3 degrees of nominal, but preferably within 2 degrees in the first two, most critical sectors. This could be achieved by measuring phases every few days.

4 CONCLUSION

The subbooster phasing package meets its design requirements: it provides a quick, accurate, unobtrusive way to measure phases in the SLAC linac. The paramount implementation issues were:

- Pulse-to-pulse synchronization of readout and control (subbooster phase stepping and BPM readout for this application). The speed and relative lack of undesirable side effects of the procedure all hinged on this facility.
- The fitting procedure. Attempts at pattern recognition of bad measurements paid off; more could be done along these lines. Accurate error estimates enabled operators to interpret the results of a measurement with confidence.
- Interaction with other elements of the SLC control system, such as feedback systems and automated procedures.

The new procedure provides fast measurements of the effective RF phase in the SLAC linac with an accuracy of about 1 degree S-band in about 2 minutes. By monitoring the RF phases hourly over 24 hours, it was possible to confirm and refine an empirical correction for temperature-driven RF phase variations. This successfully completed our understanding of a long-standing diurnal stability problem. The routine application of the new procedure allowed the RF phases to be held stable to within 3 degrees of their design values, contributing to the significant performance improvement during the 1997/98 SLC/SLD run.

5 REFERENCES

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