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FAST FEEDBACK FOR LINEAR COLLIDERS

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ABSTRACT

A fast feedback system provides beam stabilization for the SLC. As the SLC is in some sense a prototype for future linear colliders, this system may be a prototype for future feedbacks. The SLC provides a good base of experience for feedback requirements and capabilities as well as a testing ground for performance characteristics. The feedback system controls a wide variety of machine parameters throughout the SLC and associated experiments, including regulation of beam position, angle, energy, intensity and timing parameters. The design and applications of the system are described, in addition to results of recent performance studies.

INTRODUCTION

In four years of operation, the SLC feedback system has expanded from an originally-planned eight linac launch loops to nearly 50 control loops in every major area of the SLC as well as special experiments and diagnostic loops. Due to the database-driven design, new control loops are easily implemented usually without requiring software changes. The system, described more fully elsewhere[1], is generalized and supports the use of existing control system elements, usually without requiring the addition of dedicated hardware. The control algorithm is based on the state space formalism of digital control theory [6].

The pulsed electron and positron bunches in the SLC are generated at 120 Hertz. While some of the feedback loops operate at the full beam rate, others run at lower rates (typically 20 Hertz) mainly due to CPU and beam position monitor (BPM) limitations. The real-time functions run on Intel 80386 and 80486 microcomputers (micros) which are distributed geographically. In the SLC control system, the micros do not ordinarily communicate with each other; to facilitate intermicro communication for the feedback system, a specialized point-to-point network was added[3].

The design is based on linear control, although some special-purpose nonlinear capabilities have been added. Matrices used by the real-time software are calculated offline in advance, usually incorporating data from the accelerator model with a design noise spectrum. The typical design corrects a step function with an exponential time-constant of 6 feedback iterations. The control algorithm does not include online adaption to changes in the machine response or noise spectrum. A "cascade" capability was added to the feedback system as a later enhancement; it is designed to eliminate overcorrection from a series of linac launch loops using adaptively calculated transport matrices.

The user interface to the feedback system provides a rich variety of control, diagnostic and analysis capabilities. Displays summarize the status of all feedback loops in selected geographical areas of the machine as well as details of specified loops. Calculated parameters may be studied on a pulse to pulse basis and over longer periods. Diagnostics such as beam jitter estimates and goodness-of-fit calculations enable operators and physicists to study long-term changes in the machine. From touch panels, users enter control parameters such as setpoints, gain factors, limits and filtering cuts.

APPLICATIONS

Applications of the system have far exceeded those originally planned. Figure 1 provides an overview of the types and locations of controls for the SLC. In addition there are control loops for special projects such as the Final Focus Test Beam, fixed target experiments and the polarized gun lab, as well as many diagnostic compute-only loops. Several more loops are planned for the new laser wire beam size monitor and for the PEP-II project.

Launch loops stabilize the beam positions and angles in the linac, injector, damping rings, positron return line,

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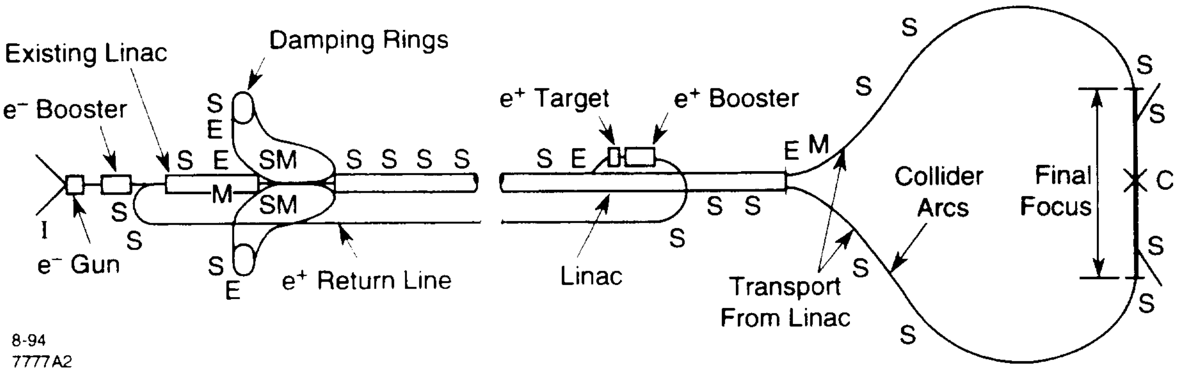

Figure 1: SLC schematic with fast feedback locations shown. S = steering loop; E = energy control; I= intensity/gun control; C = special purpose loop to maintain beam collisions; M= minimization

collider ARCs and final focus areas using BPM measurements and corrector magnet control. While the system was originally designed for this purpose, it was generalized in order to support a wide variety of measurement and control devices, including measurements of gated ADCs, and actuators such as amplitude controls, klystron phases and timing delays. With the addition of the polarized gun to the SLC, several feedback loops were added to control intensity of the YAG and Ti Sapphire lasers, gun extraction timing, and monitoring of gun-related parameters such as the polarization asymmetry.

The feedback algorithm is based on linear matrix calculations, but in some cases there is a need to control actuators which are not linear with the controlled states. This is accomplished by designing matrices to control an imaginary device which responds linearly. In the real-time software, the matrix equations determine a setting for the imaginary actuator and estimate its effect on the states. Given a requested setting for the imaginary actuator, the special purpose software then calculates what is needed for the real, nonlinear actuators in order to accomplish the required control. Control of the beam energy is provided in five SLC locations, some of which require nonlinear actuator calculations. For example, the energy control for the electron bunch which is extracted from the linac to make positrons, is accomplished with an interface to a hardware-based feedforward system. The feedforward controls the klystron phases for two linac sectors and is designed to compensate the energy for intensity variations detected in the damping ring. The feedback system controls the energy indirectly by varying amplitude controllers which are part of the feedforward. These amplitudes represent quadratic fit coefficients for energy versus klystron phase.

Energy control for the electron and positron beams in the linac requires nonlinear control of the klystron phases for two sectors. In order to provide independent energy control for the two beams, this was recently extended to control the timing of the 261 linac klystrons and subboosters, called the PSK time. The calculated PSK time is broadcast over a specialized network, received by all of the linac micros, and added to the nominal trigger timing for each klystron and subbooster.

At the interaction point, the beam deflection angles are controlled to keep the beams in collision. The beam behaviour is characterized by an S-shaped deflection curve. The slope of the linear portion of the curve (corresponding to small beam-beam separations), along with measurements of the beam deflections and intensities, is used in the special-purpose feedback calculations. Since the slope changes with beam size it is periodically determined by an external process which scans one beam across the other before downloading updated parameters to the feedback system. For small separations, the feedback controls optimally, within the central linear portion of the curve. In those cases where large disturbances bring the beam-beam separation out to the nonlinear portions of the curve, the feedback response is slower, but it controls correctly and collisions are successfully maintained.

MINIMIZATION

Minimization is an extension to the feedback system which applies where measurements respond parabolically with actuator movement. In these cases, given a single raw measurement such as a BPM reading, there is not enough information for a feedback to tell which way to move the actuator, because it may be on either side of the parabola. One way to obtain this information is to move the actuator and observe the measurement change. For the SLC optimization packages, the actuator is scanned through a range of values and a parabolic fit is performed; but this is an invasive procedure. An alternate method implemented in the feedback system is called "dithering" [5]. This involves perturbing the actuator by a tiny amount above and below its nominal setting while taking synchronous beam measurements. After many pulses, an average slope is calculated for the measurement versus the actuator change. The slope of the parabola is linear with the actuator, so the linear feedback calculation is formulated with the calculated slope as a measurement. Minimization is accomplished by keeping the slope set at zero, but the feedback system is generalized so that the slope can be kept to any requested setpoint. In the SLC, generalized capability for dithering and minimization has been developed and demonstrated. The system has been able to perform dithering and control the beam to a stable point on the parabola. Unfortunately, use of the dithering system has proven to be invasive; the smallest dithering bit sizes cause unacceptable beam disturbances.

However, a noninvasive minimization feedback has been implemented and commissioned. The kicker timing feedback loop relies on the natural jitter of the ring extraction kick time (measured with a TDC) to produce slope calculations of BPM measurements versus kick time; dithering is not needed. In order to provide a reasonable slope estimate, 10,000 pulses of data are averaged; at a BPM measurement rate of 60 Hertz, it takes almost 3 minutes to produce a single calculation. Commissioned only a few days before the end of the last SLC run, the loop has already been shown to improve machine performance.

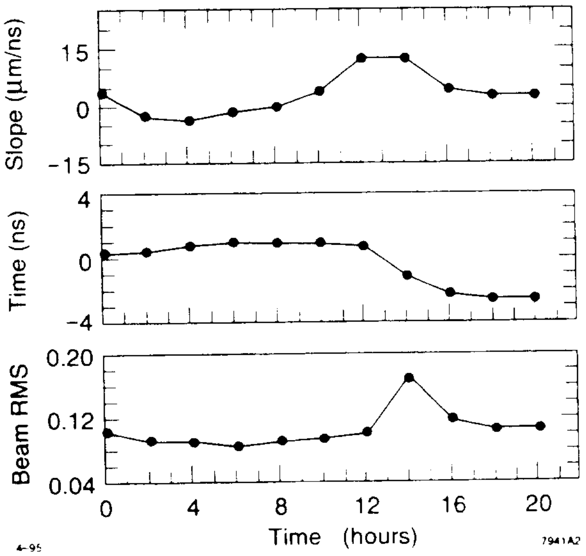

FIGURE 2: Minimization kicker timing feedback improves the RMS beam jitter

Figure 2 shows the feedback response to changing ring extraction conditions; the RMS beam jitter (calculated by a downstream feedback loop) increases until the feedback corrects the kicker timing, which reduces the jitter to its normal value. Note that the feedback response is slow due to an intentionally conservative initial design.

PERFORMANCE ISSUES

In the past year, progress has been made in identifying and analyzing SLC feedback performance issues[4]. Of particular interest is the response in the linac. There was concern that imperfections in the feedback modeling and the large number of loops may result in amplification of beam noise for some frequencies. However, with the finite sampling rate used in the feedback system, even ideal conditions would result in noise amplification for some frequencies. Techniques were developed to analyze the feedback response for both single loops and for the linac system as a whole. Several sources of feedback imperfection were identified and studied.

The matrices for a launch loop incorporate a transport model for that area of the accelerator, including transport elements between BPM readings, beam positions and angles, and corrector settings. In some cases, the online model does not accurately reflect the accelerator response, so feedback calibration is needed. This is accomplished by moving each corrector one at a time through a range of values and measuring the fitted beam positions and angles for each setting. The slopes of these states versus the corrector settings are incorporated into new feedback matrices. Recent software improvements have made the calibration system easier to use, but it remains an invasive procedure for which it is difficult to get sufficient beam time. In a few areas of the machine, the model is so poor that the feedback cannot be used without calibration. In marginal cases, imperfect modeling simply degrades the feedback performance.

Another performance consideration is the time response of the correctors. The design for linac loops assumes that corrector changes are implemented with a delay of three feedback iterations; one iteration is allowed for calculations and communication, with two additional iterations for the magnetic field to change. Recent measurements indicate that typical linac correctors can move from 10 to 90% of a requested change within about 9 120-Hertz pulses. For most of the linac loops, which run at 20 Hertz, the response is close enough to that used in the feedback design. However, for the last loop in the linac, which was upgraded to run at 60 Hertz, the corrector response is relatively slow and not adequately modeled. Simulations for the standard feedback design, shown in figure 3, indicate that when corrector response is slow compared to the design feedback control of 6 pulses, there is performance degradation. Furthermore, the response becomes more sensitive to other factors such as imperfect modeling. Near the end of the last SLC run, attempts were made to design matrices with a better model of the slow corrector response. Tests of the new design showed improved feedback response, but other problems made it operationally unacceptable. Additional work is needed.

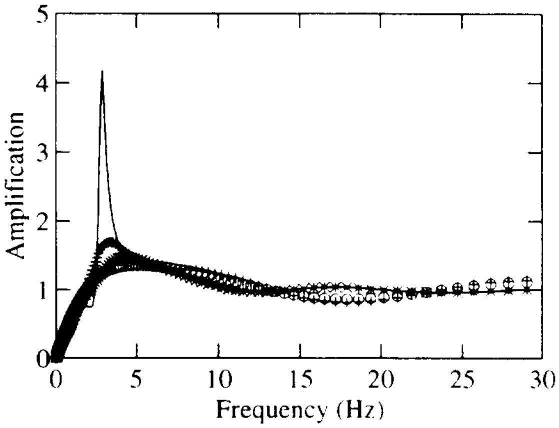

Figure 3: Simulations of feedback response with slow corrector speeds and imperfect calibrations. Plots shown are for the ideal case (o), slow correctors (*), poor modeling (+), and the combination of slow correctors with poor modeling (-).

Figure 4 shows estimates of feedback response for the series of linac launch loops. The response is measured by inducing a step function upstream of the linac, first with the feedbacks on and then with the feedbacks off. Fitted beam position data for both cases is acquired for several hundred consecutive pulses. The FFTs for both data sets are calculated and the ratio is plotted. Unfortunately this measurement is noisy. An alternate technique involves inducing sine waves over a range of known frequencies and measuring the resulting amplitudes with feedback on and off. The sine wave technique produces cleaner results less invasively, but it is more time-consuming. Also shown in figure 4 are simulations for feedback performance. Note that the "ideal" simulation assumes that the accelerator model is perfect, correctors are as fast as modeled, that all of the loops are operating with gain factors of 1.0 and that the cascade system is working perfectly. This is identical to the ideal simulation for a single loop. An initial attempt at a more realistic simulation includes effects of imperfect modeling, low gain factors and imperfect cascade performance. More work needs to be done to measure, simulate and hopefully to optimize the performance of the linac loops as a system.

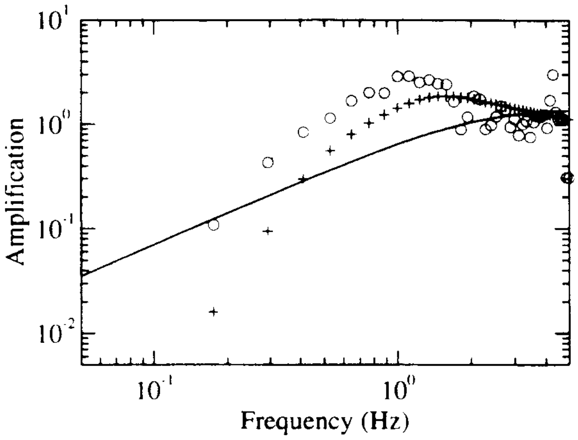

Figure 4: Measurement and simulations of feedback response (on/off) for the system of linac loops. Plots shown are for the ideal case (-), measured data taken from a ratio of FFTs (o), and an attempt at a realistic simulation (+).

"CASCADED" FAST FEEDBACK

As shown in figure 1, steering in the SLC linac is controlled by a series of feedback loops. In the original system, these loops were all controlling the same parameters; this resulted in problems with overcorrection of upstream perturbations and amplification of beam noise. This effect was predicted in the initial feedback design simulations and the cascade system was designed to correct this problem. Now, after receiving new measurements on each beam pulse, each linac loop sends its calculated states to the next downstream loop, and receives the current states from its upstream neighbor. The downstream loop performs corrections based on the differences between the states of the upstream and downstream loops. Therefore each loop should correct only the perturbations initiated immediately upstream of it. These corrections depend upon a reliable method for mathematically transporting the positions and angles at one point to the downstream location. The model is not good enough over these distances, so adaptive methods are used to dynamically update the transport matrices. The adaption calculations are based upon the SEquential Regression (SER) algorithm[7], adapted for use in the SLC feedback system[2].

Cascade performance can be characterized by rejection ratios. This is the fraction of an incoming perturbation which is seen and corrected by each feedback loop.

Ideally, for a loop immediately downstream of a perturbation, the rejection ratio should be one, and for the further-downstream loops the rejection ratio should be zero. Poor rejection ratios are an indication that the adaptively-calculated transport matrices do not perfectly model the actual beam transport.

Initially when the cascade system was commissioned, the rejection ratios for downstream loops indicated excellent response; typical downstream rejection ratios were 10%. In the past year, cascade performance has been revisited; recently the rejection ratios ranged from very good (10-25%) up to more than 50% for some cases. If all of the feedback loops ran with the full corrections, this would result in overshoot and ringing; as a result, the gain factors have been lowered so that each loop only performs a fraction of the required correction on each pulse.

Several possibilities were investigated in attempts to understand the cascade performance. If the machine were dominated by phase jitter instead of betatron jitter, this would produce incorrect transport, since the adaptive process relies on correlations of perturbations between loops. Furthermore, at recent SLC beam intensities, wakefields cause nonlinear transport effects which have been shown to be a significant problem for the cascade system. In one case, the transport magnitude from one feedback loop to the next varied by 50% for different perturbation source locations, both in simulation and from beam measurements. Finally, during low current studies, poorer BPM resolutions appeared to degrade the adaption results by introducing uncorrelated noise which pulls the adaptively-calculated transport magnitudes toward zero. Further study is needed in this area. However, analysis of the wakefield effect indicates that perfect cascade performance cannot be achieved with this architecture under current SLC conditions, since the beam transport is dependent on the source location of a perturbation and the implemented cascade design does not provide this information.

CONCLUSIONS

The fast feedback system has become essential for successful operation of the SLC. While its performance characteristics require further study and improvement, it provides many positive contributions for operations. The large number of feedback loops decouples the various areas of the SLC, supporting machine studies by allowing downstream loops to compensate for incoming disturbances. In the linac, beam emittance is optimized by moving feedback setpoints to produce closed orbit bumps. With the feedback system, machine reproducibility is improved and smoother startup after outages is seen. Efficiency was improved by a factor of two in the first year of feedback operation. Operators steer much less often and there is a significant decrease in operator adjustments. This allows the operators time for more subtle tuning and contributes to increased luminosity.

It is hoped that future colliders will benefit from the substantial base of beam experience with the SLC feedback system. Comparable or superior capabilities are likely to be required; realistic feedback performance estimates as well as designs for future systems should include consideration of the challenges faced in the SLC system.

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