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TUTORIAL ON BEAM-BASED FEEDBACK SYSTEMS FOR LINACS

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Abstract

A generalized fast feedback system stabilizes beams in the SLC. It performs measurements and modifies actuator settings to control beam states such as position, angle, energy and intensity on a pulse to pulse basis. An adaptive *cascade* feature allows communication between a series of linac loops, avoiding overcorrection problems. The system is based on the state space formalism of digital control theory. Due to the database-driven design, new loops are added without requiring software modifications. Recent enhancements support the monitoring and control of nonlinear states such as beam phase using excitation techniques. In over three years of operation, the feedback system has grown from its original eight loops to more than fifty loops, and it has been invaluable in stabilizing the machine.

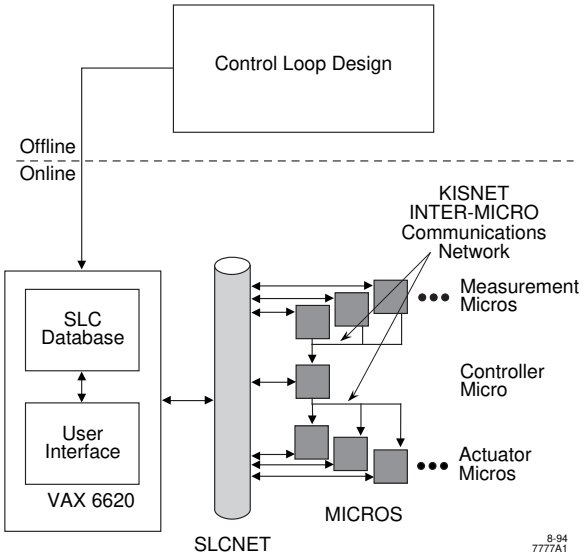

Figure 1: Feedback System Architecture

1 System Overview

The feedback system was originally designed to stabilize beam launch parameters in the SLC linac. The pulsed bunches of electrons and positrons are generated at 120 Hz, and the feedback control is typically applied at 20 Hz, although in a few cases it operates at the full beam rate. Each feedback loop controls a set of related beam parameters, such as beam launch (position and angle) at a specific linac location. The system takes input measurements such as Beam Position Monitor (BPM) readings and calculates fitted states such as beam position, angle and energy. The states are controlled by actuators, typically correctors. The major software components of the system are shown in Fig. 1.

The real time functions are performed on Intel 80386 and 80486 microcomputers (micros). In the SLC control system, the micros are distributed geographically, with each micro controlling devices in its own region. The feedback system is designed so that a single loop may include measurements and actuators in several micros. A controller task receives measurements, possibly from several sources. It performs the feedback calculations and determines actuator settings for the loop, sending them to the actuator tasks for implementation. Dedicated hardware is not needed for the feedback measurements and actuators, since pre-existing SLC control components are used. Intermicro communication is supported through a specialized high speed network, KISNet[2], which was adapted from the Advanced Light Source (ALS) project.

Through a touch panel interface, users may access an extensive selection of displays, diagnostics, and control functions[3]. These are supported on a VAX 6620 with VMS. The VAX communicates with the micros via the specialized network SLCNET. From the touch panels, users control the feedback performance, entering parameters such as gain factors, filtering cuts, and setpoints. Displays allow monitoring of the feedback performance and calculated beam parameters on a pulse-to-pulse basis and over long time periods. Alarm functions alert operators when feedback controls are not successful, such as when a corrector is at its limit. Displays and alarms for non-controlled beam parameters such as rms jitter and chi-squared values help operators and physicists to monitor changes in machine conditions.

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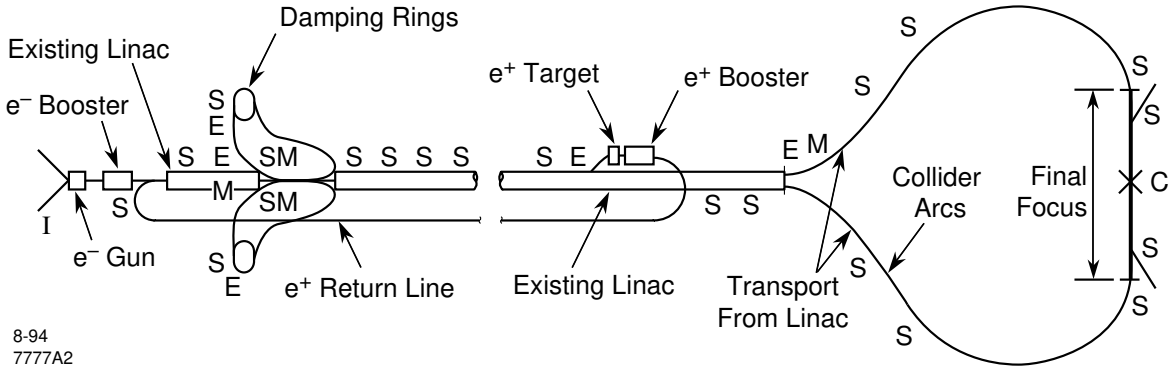

Figure 2. Layout of the SLC with fast feedback loops shown. **S** = steering loop; **E** = energy control; **I** = intensity/gun control; **C** = special-purpose loop to maintain beam collisions; **M** = minimization

2 SLC Applications

The system is database-driven so that when a new feedback control loop is added, ordinarily only database and hardware work is required. The system is generalized to support a variety of measurement and actuator types. This design is the main reason for the large expansion in the number of SLC feedback loops. Figure 2 shows the SLC machine with feedback locations. In addition to the original linac loops, launch control loops have been added to the damping rings, collider ARCs, and final focus sections. The beam energy is controlled in five locations, in some cases requiring special non-linear phase kink calculations which have been added as an extension to the linear feedback control. In order to provide independent control of the positron and electron beam energies in the linac, the feedback was recently extended to control the timing of the 261 linac klystrons and subboosters, in addition to two phase shifters. At the interaction point, the beam deflection angles are controlled to keep the electron and positron beams in collision. In addition, the SLC feedback controls ten parameters associated with intensity and timing for the polarized gun. For these feedbacks, the measurements are taken from gated ADCs, and the actuators are amplitude controls and timing delay settings. Several minimization-type loops, described later in this paper, are currently being commissioned.

In addition to supporting standard SLC running, several feedback loops control beamlines for special projects such as end station fixed-target experiments, the Final Focus Test Beam, and a polarized gun lab. For one fixed-target experiment, a feature was added so that in addition to controlling the beam position on the target, the feedback system rastered the beam in a pattern distributed across the circular target in order to minimize depolarization.

3 Feedback Algorithm

The matrices which are used for the real-time control are calculated off-line in advance, using the SLC model or calibrated beam data as input. The control calculations are based on the predictor-corrector formalism of digital control theory[1]. The off-line design and simulation program[4] is based on the MatrixX package from Integrated Sytems Incorporated. The matrices are designed to minimize the rms jitter of the controlled parameters in addition to providing a good response to step functions. The feedback response characteristics may be tuned by adjusting the expected noise spectrum of the accelerator, although most of the SLC feedback loops have a common setup. The SLC feedback loops are typically designed to correct a step disturbance in six pulses. A knowledge of the corrector speeds can be built into the feedback so that, for example, if it takes two pulses for a newly calculated actuator setting to be implemented, the feedback does not overcorrect.

The calculations performed by the real time feedback controller are based upon the following equations, also described elsewhere[4] in further detail. The first controller equation estimates the values of states which are associated with the feedback loop based on the previous state estimate, currently implemented actuator settings, and measurements:

$$\hat{\mathbf{x}}_{k+1} = \mathbf{\Phi}\hat{\mathbf{x}}_k + \mathbf{\Gamma}\mathbf{u} + \mathbf{L}(\mathbf{y} - \mathbf{H}\hat{\mathbf{x}}_k),$$

where $\hat{\mathbf{x}}_k$ is the estimate of the state vector on the k^{th} pulse; $\mathbf{\Phi}$ is the system matrix and describes the dynamics of the accelerator model, including any implementation delay for actuators; $\mathbf{\Gamma}$ is the control input matrix, which defines how changes in the actuators should affect the state; and $\mathbf{u}$ is the actuator vector. It contains the current actuator settings with reference values subtracted. The Kalman filter matrix is denoted by $\mathbf{L}$. Given an error on the estimate of the sensor readings, it applies a correction term to the estimate of the state vector. This matrix is responsible for the typical 6-pulse time for feedback loops to correct for a step function. It is designed (via the Linear Quadratic Gaussian method) to minimize the rms error on the estimate of the state. The measurement vector $\mathbf{y}$ contains the current measurements with reference values subtracted; and $\mathbf{H}$ is the output matrix. Given an estimate of the states, it gives an estimate of what the sensors should read. The matrices $\mathbf{\Gamma}$ and $\mathbf{H}$ are usually obtained from the model of the accelerator. In some cases, the

$\mathbf{\Gamma}$ matrix is determined from measured beam calibration data. For special loops such as gun intensity control, $\mathbf{\Gamma}$ and $\mathbf{H}$ are calculated by physicists and input manually into the system.

The second controller equation calculates the actuator settings based on the estimated state vector:

$$\mathbf{u}_{k+1} = \mathbf{K}\hat{\mathbf{x}}_{k+1} + \mathbf{N}\mathbf{r},$$

where $\mathbf{K}$ is the gain matrix. It is derived in a manner similar to $\mathbf{L}$ and is designed to minimize the rms of selected state vector elements. The controller-reference-input matrix is $\mathbf{N}$. It maps the state setpoints to actuator settings and is directly derivable from the model of the accelerator or from calibrated results. And $\mathbf{r}$ is the reference vector which contains user-entered setpoints for the states controlled by the loop.

The real-time controller modifies these calculations in several ways in order to improve user control over the feedback process and to provide added stability. A user-entered gain factor scales actuator changes. A software filter is applied to the measurements, so that anomalous BPM readings and beam pulses are rejected. On each pulse, if any measurement is more than a user-specified amount away from its expected value, and if it is not between the last two measurements, it is rejected. If too many measurements are bad, the feedback control is not applied for that pulse. The cascade system described below also requires modification of the basic feedback calculations for some loops.

4 Cascaded Fast Feedback

As shown in Fig. 2, steering in the SLC linac is controlled by a string of several 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 corrects only the perturbations initiated immediately upstream of it. Figure 3 shows the response for the chain of feedback loops when a step disturbance is introduced. Part (a) shows the ringing introduced when the cascade corrections are disabled. In part (b), with the cascade corrections working, the system responds as a single feedback loop and virtually no overcorrection is seen. Figure 4 shows the results of the cascade corrections on the movement of a single feedback corrector. In the first portion of the display, with the cascade correction disabled, the corrector is moved to

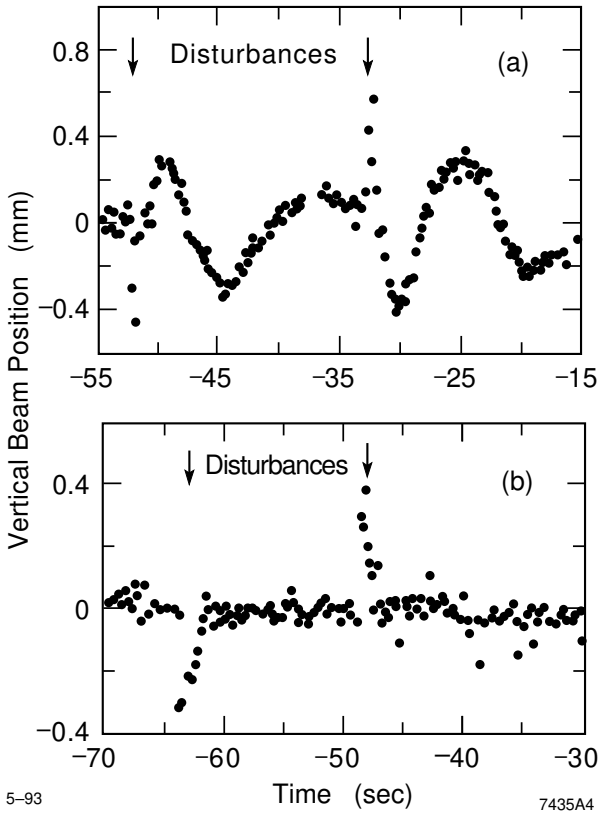

Figure 3: Feedback response to a step disturbance, showing ringing without cascade (a) and good response with cascade (b).

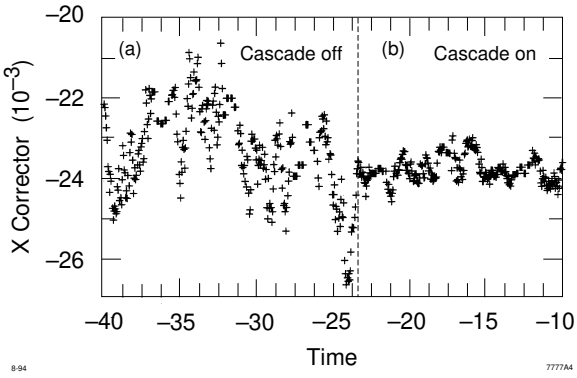

Figure 4: Feedback corrector movement, without cascade (a) and with cascade (b)

respond to each perturbation in the linac regardless of its origin. When cascade is enabled, the corrector is moved less because it only responds to perturbations which are generated immediately upstream of the loop.

The cascade corrections depend upon a reliable method for mathematically transporting the positions and angles at one point to the downstream location. This would be simple if the SLC model could be used, but some of the linac feedback loops are over a kilometer apart with many components in between. There are diurnal variations in the beam transport, presumably due to rf phase and

energy changes. Therefore adaptive methods are used to dynamically update the transport matrices. The adaption calculations are based upon the SEquential Regression (SER) algorithm[5], adapted for use in the SLC feedback system[6].

The algorithm, also described elsewhere[7], is as follows: On each pulse for which the transport matrix is to be updated the following is calculated:

$$\mathbf{S} = \mathbf{Q}(k-1)\mathbf{y_c}(k),$$

$$\gamma = \frac{\alpha}{1-\alpha} + \mathbf{y_c}^T(k)\mathbf{S},$$

$$\mathbf{Q}(k) = \frac{1}{\alpha}\left(\mathbf{Q}(k-1) - \frac{1}{\gamma}\mathbf{S}\mathbf{S}^T\right),$$

where $\mathbf{y_c}(k)$ = the state vector from the upstream loop with setpoints subtracted; k = beam pulse number; $\mathbf{Q}$ = estimate of the inverse of the covariance matrix of $\mathbf{y_c}$; $\mathbf{S}, \gamma$ = intermediate results; $\alpha = 2^{-1/\tau}$; and τ = number of pulses for covariance matrix—averaging, typically 50.

A large γ means the beam fluctuation has suddenly increased, which could cause the transport calculation to be unstable. Therefore the following equations which update the transport matrix are calculated only if γ is less than a cutoff value, typically 20:

$$\epsilon = (\text{raw state vector}) - (\text{raw state setpoints}) - \mathbf{T_c}(k)\mathbf{y_c}(k),$$

$$\mathbf{T}_i(k+1) = \mathbf{T_i}(k) + \eta\mathbf{Q}(k)\mathbf{y_c}(k)\epsilon_i.$$

The above equation must be evaluated for all i, that is for each row of the transport matrix. If there are changes to the physical model the $\mathbf{T}$ and $\mathbf{Q}$ matrices converge to new values within about 100 seconds:

$$\mathbf{T}_i = \text{estimate of the } i^{th} \text{ row of the transport matrix } \mathbf{T_c}$$

$$\eta = \text{learning rate or gain, typically 0.001.}$$

The adaptive cascade system has been remarkably stable. There have been no problems with divergence of the adaptive calculations. In addition to improving the feedback control, the adaptive beam transport calculations provides a useful diagnostic for accelerator physicists. Figure 5 shows diurnal variations of about 50° for the betatron phase advance between two of the linac loops.

5 Minimization and Dithering

A subtolerance excitation feature has recently been added to the feedback system[8]. It is used if measurements respond in a parabolic function when an associated actuator is moved. Examples are controlling beam phase and minimizing spot size. The system is designed to control the states to any setpoint on the parabola but because it is capable of moving to the minimum, it is referred to as a minimization system. In parabolic systems, a single measurement does not provide enough information for a feedback loop to determine which way

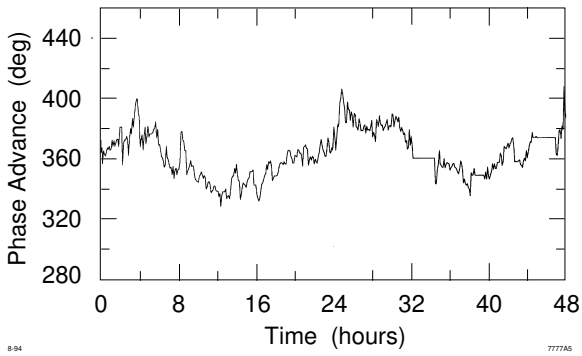

Figure 5: Betatron phase advance between two linac feedback loops, calculated by adaptive cascade system, plotted over two days

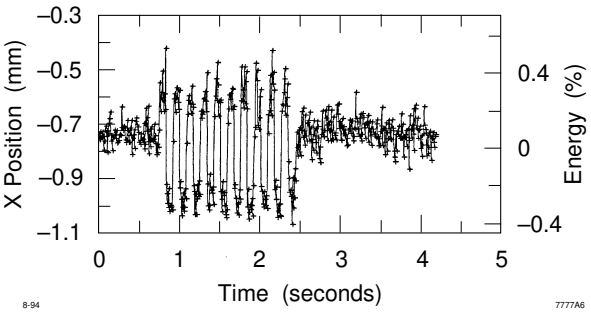

Figure 6: Beam energy measurements taken on 500 successive pulses showing the dithering technique. For this test, the dither size was increased to ten times the usual amount.

to move the actuator, since any measurement other than the minimum (or maximum) value might be on either side of the parabola. But if the actuator is moved a small amount and another measurement is taken, a slope can be calculated, and this slope responds linearly to actuator changes. Therefore the feedback system has been enhanced to move actuators up and down rapidly by small amounts, or *dithering*, while calculating the slope of raw measurements such as BPM readings with respect to the dithering movements. The dither size chosen is small enough so that there is minimal beam disturbance. In order to produce stable results, the calculated slopes must be averaged over many pulses, typically 10,000 for the SLC minimization loops. These calculated slopes are input as measurements to the feedback equations described previously.

There are four minimization feedback loops installed on the SLC. In the future, minimization of the spot size at the interaction point may be added. The ability to close the loops and hold the beam to a stable point on the parabola has been demonstrated, but due to operational and software issues the commissioning is not completed. Scale factor issues have been difficult to resolve, and careful scheduling of the dithering patterns has been necessary in some cases to avoid perturbation of the results by

the regular feedback loops. For example, if a standard feedback loop is allowed to control the beam energy while a minimization loop dithers the energy up and down, it has the effect of reducing the slope of the energy calculated by the minimization loop. Although the commissioning of this system has been a challenge, the dithering technique shows great promise both for the SLC and for future linear colliders.

6 Beam Experiences

The fast feedback system has been a remarkably successful addition to the SLC control system. Its usefulness is demonstrated by the expanding number of feedback loops, and also by the fact that it is now an essential system for successful SLC running. Some challenges remain. In recent months, numerical problems in generating the matrices have limited the usefulness of feedback's calibration system, and in some cases the SLC model is not good enough. As a result, some of the linac loops run with lower than optimal gain factors. Intermittant glitches in the fast intermicro communications network have often required attention. Finally, because new feedback loops and capabilities are frequently added, and because the feedback performance is closely intertwined with beam conditions and modeling which are often difficult to interpret, the feedback system requires a significant ongoing support effort. But the system has significantly improved the operation of the SLC. Efficiency was improved by a factor of 2 in the first year of feedback operation. Machine reproducibility is improved. With the feedback system, operators steer much less often, and there is a significant decrease in operator knobbing. This allows the operators time for more subtle tuning and contributes to increased luminosity.

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