D

Beam-based Feedback: Theory and Implementation

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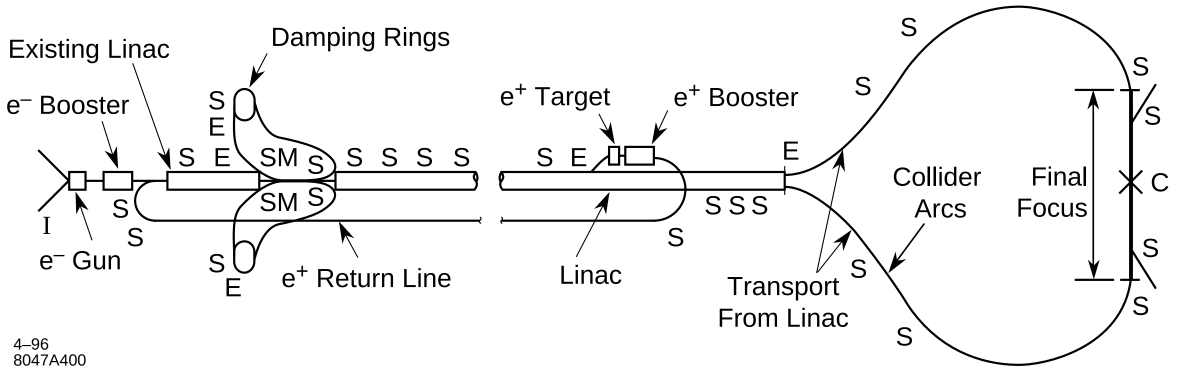

Figure D-1. *SLC schematic with feedback locations. S=steering; E=energy; I=intensity/gun; C=maintains beam collisions; M=minimization*

D.1 Introduction

In planning for feedbacks in the NLC, it is useful to study the existing SLC feedback system as a model. While the control system architecture for the NLC is likely to be different from the SLC, the basic feedback algorithms should be similar. The SLC feedback system is the first of its kind for accelerators. It is a generalized, database-driven system that applies linear closed-loop control. The mathematical design goal is to minimize the RMS of the beam jitter by applying state space techniques. In practice in the SLC, the feedback serves to stabilize the beam and decouple different areas of the machine, facilitating smoother startup after machine outages and easier machine tuning. This system has been essential to the operation of the SLC, and it is assumed that a similar system will be equally necessary for the NLC.

D.2 Planned NLC Feedbacks

For the NLC, feedback loops are planned for each major area of the machine, similar to the SLC feedbacks. At the guns, intensity and timing parameters will be controlled. In addition, feedback controls for each of the laser wire scanners are expected. Energy and steering (position and angle) parameters will be regulated for damping ring injection and extraction. For each linac, five diagnostic sections will each have energy and steering controls. For each final focus, feedbacks will stabilize the beam steering at two locations. Finally, an interaction-point feedback loop will regulate the beam-beam deflections to keep the beams in collision.

The feedbacks are planned to run at the full beam rate of 120 or 180 Hz. The steering loops control the average trajectory of the bunch train rather than individual bunches, so the “Q” BPMs are used, which measure the average of the train. Dipole corrector magnets are used, for which the feedback controls the magnetic field by setting a DAC (digital to analog converter) which alters the current from a power supply. Correctors and other actuators need to respond (to make 90 percent of a requested change) in a single 180-Hz period.

If SLC experience is taken as a model, many additional feedbacks are likely to be added to those originally planned. For the SLC, the original eight loops have been expanded to over 50 control loops, many of which are shown in Figure D-1.

D.3 Feedback System Design

The SLC feedback system is designed in a generalized, database-driven fashion, which contributes greatly to the flexibility of the system [Hendrickson 1995]. The system uses standard control-system hardware. As a result of this design, unplanned control loops can often be added with only database work, without requiring hardware or software changes. In addition to the beam position monitors and correctors used for steering control, the feedback system is capable of measuring and controlling a wide variety of devices. For example, it is equally trivial to add a steering loop in the linac as it is to stabilize the laser gun timing in the injector. Special-purpose extensions to the linear feedback system have been added to accommodate non-linear cases, such as optimization feedbacks in which the measurement responds parabolically to actuator movement. The system also provides built-in diagnostic and analysis capabilities, and the many sample-only monitoring loops provide a wealth of diagnostic information. These design features have been key to the success of the SLC system, and the NLC design should be equally flexible and extensible in order to support unplanned controls needs.

The feedback control algorithm is based on state space formalism, with an LQG (Linear Quadratic Gaussian) controller. Matrices are designed and calculated offline in advance, with inputs including a model of the beam transport and the expected beam and BPM noise characteristics. The mathematical design minimizes the rms of the beam states over time, given the noise inputs [Himel 1991]. By modifying the input beam noise design assumptions, it is possible to tune the feedback performance response characteristics. The initially-proposed feedback algorithm does not adapt to modeling or noise spectrum changes, consistent with the current SLC design. In the future, adaptive methods may provide improved performance. The beam transport characteristics within a single loop may either be obtained from the accelerator model, or be measured by an invasive online beam-based calibration procedure.

An extension to the basic feedback system, "cascade" is designed to allow multiple linac loops to communicate with each other, avoiding overcorrection problems when a perturbation is induced upstream of the chain of feedback loops. With cascade, each feedback loop receives the calculated positions and angles from the next upstream loop, mathematically transports them to the downstream location, and subtracts them from the states calculated using the local BPMs. The resulting adjusted states are then used for the local feedback corrections, so that each loop should correct only perturbations which were not seen by an upstream loop.

D.4 Performance Questions

There are a variety of performance questions which have been investigated in the SLC system, in particular with the chain of linac steering loops. These include concerns about the stability of the SLC model, speed of the steering magnets, and functions of the cascade system. In the SLC, gain factors can be used to slow the feedback response and reduce sensitivity to suspected feedback imperfections. Several types of imperfections are discussed in the following sections. Where quicker feedback response is not needed, the lower gain factors have been successful in improving the stability of the feedback system.

D.5 Adaptive Cascade

Problems were observed with the cascade system, which is intended to allow each of a string of feedback loops to correct only the perturbations initiated immediately upstream of it. The cascade system relies on a linear beam transport which is independent of the source of the perturbation. The adaptive feature of the cascade system enables each feedback loop to learn the transport from the upstream loop, using the beam jitter to calculate the beam transport. The adaptation has the assumption that perturbations immediately upstream of a feedback loop are uncorrelated with upstream perturbations. In the current SLC cascade design, each loop obtains beam information only from the adjacent upstream loop; the assumption is that if the loop upstream saw a perturbation, either it or any loops further upstream will eventually fix it.

In several tests, it was observed that the linac loops did not exhibit perfect cascade response. In particular, the feedback response to perturbations induced in the middle of the linac is different from the response to perturbations from the beginning of the linac. The SLC design assumes that the beam transport is independent of the source of a perturbation. At high currents this is not valid because of the effect of transverse wakefields which cause oscillations to propagate differently depending on their source. This is a fundamental problem with the SLC architecture, but for the low currents of the NLC, this effect should be less significant. If wakefield effects are expected to be a problem for the NLC, an alternate cascade design should be developed to provide downstream feedback loops access to beam information from all upstream loops instead of just the single nearest upstream neighbor. This would require more complicated algorithms and more communications paths than those available in the present SLC system.

Tests of cascade performance during low-current operation uncovered additional information. A test was done to confirm that the cascade system responds well when the transport is invasively measured (instead of adaptively calculated), and the resulting cascade response was between 95 and 100% effective (nearly perfect). A design flaw in the adaptive beam transport calculation, associated with exception handling for broken BPMs, was found and fixed. In the most recent test, large betatron jitter was induced upstream of the chain of linac feedback loops. The feedbacks adapted to the induced beam noise, and the resulting cascade response was between 90 and 100% effective. However, without either measurement or induced noise, the performance was much poorer. This may be explained by an additional design flaw, in which poor BPM resolution during low-current SLC running results in incorrect adaptive transport calculations. It is hoped that when this design flaw is fixed or better BPMs are available, low-current cascade adaption performance will be improved.

Further concerns include questions about the nature of the incoming beam jitter, which is the source of the adaptive transport calculations. If the incoming jitter is not dominated by betatron jitter, adaptive transport calculations would get the wrong answer. For the NLC, a conservative initial plan is to omit the cascade adaption to calculate the interloop beam transport matrices, and instead measure the transport semi-invasively by stealing beam pulses and perturbing the beam once an hour. With this method, the cascade should be able to work well at low intensities.

D.6 Rate Considerations, and Corrector Speeds

Ideally, feedbacks should operate at the full repetition rate of the machine. At the SLC, where the rate for many loops is limited to 20 Hz by CPU and other hardware constraints, aliasing problems associated with the partial sampling rate have been observed. Full-rate operation requires sufficient processing power and hardware response time.

A source of poor performance which was investigated at the SLC is the sensitivity to corrector speeds. Feedback simulations showed that, when the corrector speeds are slower than expected, the feedback performance is degraded. In particular, performance is extremely sensitive to the relative speeds of correctors within a single loop. If some correctors are slow, it is better to have them all the same speed as the slowest one. This effect is exaggerated when there are modeling errors or other imperfections in the loop design.

The correction system needs to be designed such that the response of the correctors is within one interpulse period, considering the speed of the power supply and the field propagation through the beam pipe. For the latest SLC run, a new feedback linac steering loop was implemented which is capable of 120 Hz response. This feedback loop has been commissioned and, under some noise conditions, has decreased the RMS of the beam jitter by up to 40%.

D.7 Calibrations and Modeling

The correct functioning of a feedback loop depends on knowledge of the model and transport between the steering magnets and position measuring devices. For the SLC, this transport is derived from the online machine model. A calibration procedure is provided to check and possibly update the transport matrices. Because such a procedure is invasive, it is rarely used. For the future, it may be desirable to use a fully adaptive feedback algorithm which is capable of responding online to machine changes. This extension of the state-space formalism is currently being developed at CEBAF, and may be useful for both the SLC and the NLC.

Recent SLC studies indicate that poor modeling is not currently as significant a problem for the linac feedbacks as are slow correctors and imperfect cascade performance. However, sensitivity to the model is exacerbated by incorrect modeling of the corrector response or other errors. Furthermore, simulations show that minor modeling imperfections can have disastrous results when combined with aggressive noise designs such as notch filters.

D.8 Global Performance Characterization

In addition to studies of specific sources of feedback imperfection, measurements and simulations were performed to study the global feedback response of a series of linac loops. For the SLC, measurements were taken, comparing the response of a step function with the series of linac loops off versus on. The FFT of both sets of data were calculated; the ratio of the FFTs with feedback on and off provides a measured amplification curve. Simulations reproduced the measured results, including the effects of measured imperfections. These measurements and simulations included effects of imperfect cascade correction, imperfect modeling, slow correctors, multiple loops running at low rates, and different gain factors. Reproducing the measured SLC performance improved confidence in our ability to simulate imperfections realistically. Given some assumptions about NLC conditions and imperfections, performance was evaluated for the series of NLC linac loops.

The NLC simulations evaluate a series of five linac loops, each running at the full beam rate of 120 Hz with relatively fast correctors that can control in one machine pulse. For the NLC, slow correctors should not be a problem. Imperfections in modeling and cascade response are assumed for the NLC. We assume that modeling/calibration imperfections are comparable to SLC conditions. We assume that cascade is 85% effective. While still imperfect, this is better than the current SLC performance; wakefield effects shouldn't be a significant problem, and we assume that the cascade transport for the NLC will be measured each hour. For the "SLC" noise design, which corrects a step function with an exponential time constant of six pulses, the results of the NLC simulation were very good. Response of the system to a step function is good and the system is able to damp very well at frequencies below 6 Hz. Above 6 Hz, beam noise is amplified somewhat, with a maximum amplification of 1.5. In order to damp more strongly at low frequencies, more aggressive noise designs were considered. While the more aggressive designs damp better at low frequencies and are able to damp noise up to 10 Hz, the jitter amplification at higher frequencies is increased, up to a factor of 4.5 for one design. Furthermore, when the imperfections are considered, the more aggressive designs have a poorer response to a step function. These studies indicate that with the more-conservative "SLC" noise design, modest imperfections have a minor effect on performance, but with a more aggressive design the same imperfections become significant. More work should be done to find an optimal design, but at this point the "SLC" noise design produces acceptable results while providing a robust system which is tolerant of minor imperfections.

D.9 Summary

Initial NLC simulations indicate that acceptable feedback performance can be obtained with an "SLC"-type noise design. More work should be done to characterize feedback performance and to study possibilities for improvements. Additional beam studies and simulations should be done at low current to insure that the cascade performance under NLC conditions will be acceptable. Also, more work should be done to determine an optimal noise design using the results of recent ground motion studies. Simulations show that any feedback system will amplify incoming jitter at some frequency, but in the design of the feedback system we have some control over the frequency and magnitude of the amplification. The goal would be a design which damps at high-jitter frequencies and minimizes amplification while providing a robust feedback system.

SLC experience has shown that operational considerations are just as important as noise response. Feedback systems which decouple different areas of the machine minimize the invasiveness of tuning procedures, allowing downstream programs to continue by automatically stabilizing the beam. Operators are freed from many routine responsibilities, allowing time for more subtle tuning. The generalized design of the feedback system has allowed extension to many unplanned applications. Feedbacks are integrated with optimization packages; for example, feedback set-points are controlled to minimize beam emittance. Finally, the system improves machine reproducibility, supporting easier startup after outages and improving machine efficiency.

References

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