10.6 Beam-based Feedback Systems

10.6.1 Overview

Beam-based dynamical feedback control is essential for meeting the high performance and luminosity needs of the ILC accelerator.

Beam based feedback systems will stabilize the electron and positron orbits in the damping rings and trajectories throughout the machine. It will also be used to correct for emittance variations, and for measurement & correction of dispersion in the Main Linac.

Detailed requirements for several of the beam-based feedback systems are included in other sections of the overall BCD, with only a brief synopsis of physics requirements being provided in this section.

Only beam-based feedback systems are discussed in this section, all of which employ instrumentation such as beam position monitors (bpms) and fast kickers. Other (non-beam based) feedback systems, such as cavity temperature control are considered out of scope for this section

A summary of anticipated beam-based feedback loops follows…

10.6.1.1 Damping Ring: Injection trajectory control

- Purpose: maintain injection efficiency close to 100%
- Monitors: injection orbit via bpms
- Actuators: setpoints for injection kicker and septum.
- Correction plane: horizontal
- Correction sampling rate: 5Hz

10.6.1.2 Damping Ring: Dynamic orbit control

- Purpose: compensate for drift and low frequency disturbances to keep beam through center of the multipoles
- Monitors: closed orbit via NN bpms.
- Actuators: MM correctors.
- Correction plane: horizontal and vertical
- Correction sampling rate: 10-20KHz.

10.6.1.3 Damping Ring: Bunch-by-bunch transverse feedback

- Purpose: reduce coupled-bunch instabilities.
- Monitors: single wide-bandwidth bpm to provide bunch-by-bunch signals.
- Actuators: fast deflecting cavity or striplines.
- Correction plane: horizontal and vertical
- Correction rate: full bunch rate (500/650MHz)

10.6.1.4 Damping Ring: Extraction orbit control

- Purpose: preserve emittance through extraction septum
- Monitors: emittance of extracted beam from RTML
- Actuators: correctors in damping ring.
- Correction plane: horizontal and vertical
- Correction sampling rate: 5Hz

10.6.1.5 Ring to Main Linac: Pre-Turnaround emittance correction.

- Purpose: reduce emittance growth
- Monitors: emittance measurement.
- Actuators: 4 skew quads
- Correction sampling rate: 5Hz

10.6.1.6 Ring to Main Linac: Turnaround trajectory feed-forward

- Purpose: correct for extraction kicker jitter.
- Monitors: beam trajectory measured upstream via bpms.
- Actuators: 2 fast correctors per plane.
- Correction plane: horizontal and vertical
- Correction sampling rate: bunch spacing (~3MHz)

10.6.1.7 Ring to Main Linac: Post-Turnaround emittance correction

- Purpose: minimize emittance growth.
- Monitors: emittance measurement.
- Actuators: 4 skew quads
- Correction sampling rate: 5Hz

10.6.1.8 Main Linac: Trajectory Feedback (several cascaded loops)

- Purpose: compensate for drift and low frequency disturbances to keep beam through center of multipoles and RF cavities.
- Monitors: multiple bpms in each large section.
- Actuators: nominally 4 horizontal and 4 vertical correctors per section.
- Correction plane: horizontal and vertical.
- Correction sampling rate: 5Hz.

10.6.1.9 Main Linac: Dispersion measurement and control

- Purpose: provide means to measure dispersion; provide means to apply local dispersion correction.
- Monitors: dispersion measurement, laser wire.
- Actuators: use local RF amplitude control to generate local dispersion ‘bumps’ (Dispersion free steering).
- Correction sampling rate: ??

10.6.1.10 Main Linac: Local RF phase and amplitude control

- Purpose: stabilize RF cavity phase/amplitude for each klystron

- Monitors: RF phase/power monitoring
- Actuators: LLRF phase/amplitude control
- Correction sampling rate: LLRF rate (1MHz)

10.6.1.11 Beam Delivery System: Trajectory feedback from pulse to pulse

- Purpose: compensate for drift and low frequency disturbances to keep beams directed towards the interaction point.
- Monitors: nominally 9 bpms per plane.
- Actuators: nominally 9 correctors per plane.
- Correction plane: horizontal and vertical.
- Correction sampling rate: 5Hz

10.6.1.12 Interaction Point: Trajectory feedback from pulse to pulse

- Purpose: maximize average cross-section of colliding beams
- Monitors: post-IP measurement of beam trajectory.
- Actuators: nominally one corrector per plane.
- Correction plane: horizontal and vertical
- Correction sampling rate: 5Hz

10.6.1.13 Interaction Point: Trajectory feedback within bunch-train

- Purpose: maximize bunch-to-bunch cross-section of colliding beams.
- Monitors: bunch-by-bunch bpms.
- Actuators: 2 fast kickers per plane.
- Correction plane: horizontal and vertical
- Correction sampling rate: bunch spacing (~3MHz)

▪ Key parameters that influence beam-based feedback

Performance metrics for the beam-based feedback systems are entirely derived from the physics requirements of the ILC, specifically beam quality and beam stability at the IP. Derivative requirements will come from the physics requirements of each upstream machine (gun, damping ring, compressor, linac, beam delivery system).

10.6.2 Baseline Configuration

The following subsections provide more description of specific feedback loop requirements, and discuss overall architecture and infrastructure for implementing feedback loops.

10.6.2.1 Damping Ring: Dynamic orbit control

Real-time dynamical orbit feedback will be used to stabilize the electron orbit both against long-term drift and against dynamic disturbances such as ground motion.

Damping ring orbit stability requirements are likely to be similar to those for existing 3rd-generation synchrotron light sources

The orbit will be corrected using the response matrix method that takes orbit measurements from multiple bpms around the ring, and corrects the orbit using multiple correctors, also distributed around the ring. Algorithms and technology are well established in the synchrotron light sources, and usually revolve around solving a response matrix using least-squares or SVD (singular value decomposition). Sufficient phase advance is required between the bpms to properly sample the lattice phase response, similarly the correctors. It is typical to use a similar number of bpms as correctors in the algorithm. A larger number of bpms provides more robust measurement of orbit disturbances, while a increasing the number of bpms and correctors allows orbit corrections to be more localized.

To provide good feedback loop gain for ground motion and other sources of dynamic orbit motion in the 10's or 100's of hertz, a feedback loop sample rate of several kilohertz is required. For a 17km damping ring, it would be feasible to implement orbit correction turn-by-turn (ie at 17.6 kHz), but this would be considerably more challenging for a 6km ring.

Local processing will convert raw bpm button signals into x and y position information at the full turn-by-turn rate (or faster). These x and y positions will be pushed onto a fast synchronous network dedicated for real-time orbit correction. A reflective memory network would be the choice for this network today.

Similarly, local processing for the corrector magnet power supplies will receive newly updated setpoints for each corrector at the orbit correction sampling rate.

At one location in the network, a dedicated real-time processing crate will implement the orbit correction algorithm, receiving real-time bpm values from the reflective memory network, and synchronously pushing new corrector setpoints onto the network. The choice of a single local processing crate (over the distributed processing used in many systems today) has the advantage of increased flexibility of algorithms, and increased convenience for servicing, lower overall cost, and easier high availability implementation. Although this potentially creates an I/O bottleneck to the processors, rapid advances in digital processing technology mean it is likely this would be a non-issue by the time the ILC is built.

10.6.2.2 Trajectory Feedback Control

All transfer lines and the Main Linac will require trajectory feedback control. With the exception of the damping ring trajectory feed-forward system described below, all trajectory control systems will comprise the same basic elements use the same algorithm, and will use similar or identical hardware.

Implementation will be similar to that in the damping ring, with the trajectory control algorithm being developed from response matrices. A minimum of two bpms and two correctors are required to correct trajectory position and angle. The two bpms must be separated by sufficient phase advance (preferably 90 degrees), and similarly the correctors. A response matrix couples the corrector responses and bpm measurements. Bpms must be placed downstream of the correctors if closed-loop correction of the trajectory is required.

Unlike the damping ring, however, most of the trajectory correction loops will operate synchronously at the 5Hz ILC pulse rate. Bpm measurements taken at every bunch will be averaged locally, producing an average beam position for each pulse. These will be pushed onto the controls network, taking advantage of the middle-ware layer of the controls infrastructure. The trajectory control algorithm (implemented as middle-ware in the controls architecture) will synchronously calculate corrector magnet settings for the subsequent ILC pulse, distributing the corrector setpoints synchronously using the controls network.

Given the pulsed nature of the ILC beam that results in beam trajectory measurements at only 5Hz, the trajectory control system bandwidth will be restricted to a fraction of a hertz, making it effective only for long-term drift effects rather than for dynamical beam disturbances that will be corrected by the damping ring orbit correction system.

10.6.2.3 Ring to Main Linac: Turnaround trajectory feed-forward

Individual bunches are extracted from the damping ring by a fast extraction kicker magnet. Shot-to-shot fluctuations in the kicker amplitude translate to bunch-to-bunch trajectory errors of the extracted beam.

A turnaround section has been included in the Ring to Main Linac (RTML) section to allow bunch-by-bunch trajectory measurements immediately after the damping ring to be fed forward over a shorter path length to a Trajectory Correction section comprising two fast correctors/kickers per plane, separated by 90 degree phase advance.

Processing time is critical for this success of the correction system, with a turnaround section length of 170m, giving less than 0.5 microseconds to measure, process, and apply the kick angle correction.

Further details of the machine requirements of this system are described in the RTML section of the BCD.

10.6.2.4 Main Linac: Dispersion measurement and control

Mitigation of emittance growth in the Main Linac includes a scheme for measuring dispersion by locally changing beam energy for low current pilot bunches sent down the linac. This is known as Dispersion Free Steering. A variant of this algorithm is to create small dispersion "bumps" to cancel others.

Alternative methods of correcting unwanted dispersion involve changing corrector settings or moving quadrupoles, so do not involve beam-based feedback. If the dispersion can not be measured sufficiently accurately, we will have to optimize dipole corrector or quad settings based on emittance measurements. Thus, it not only the BPM data that we will need, but also the laser wire data.

10.6.2.5 Beam Delivery System: Trajectory feedback from pulse to pulse

We plan a 5Hz orbit feedback system that may be cascaded with the linac 5Hz systems, and/or augmented with feed-forward information from upstream in the machine (i.e. from the linacs and/or the damping rings). In addition a 5Hz interaction-point (IP) feedback system will similarly be implemented. All of these systems will use similar hardware: BPMs, digital feedback processors and kickers. Corrections will be made to both x and y trajectories, as well as to x' and y'.

10.6.2.6 Interaction Point: Trajectory feedback within bunch-train

Integrated simulations of the linac and BDS trajectory feedback systems show that, for noisy sites (eg. ground motion models 'C' and 'K'), these systems recover only of order 20% of the nominal design luminosity. Via one-to-one steering, relative motion of the final quadrupoles on opposite sides of the IP leads to relative offsets of the electron and positron beams at the IP and the degradation in instantaneous (and hence integrated) luminosity. The problem is most serious in y where the beam is of order 5 nanometres in size.

For collision optimization, and luminosity stabilization, an intra-train (bunch-to-bunch) feedback system will be implemented in the interaction region. The BPM sensor will be placed several metres downstream of the IP to record the trajectory of the outgoing bunches, and the correcting kicker will be placed several metres upstream of the IP to correct the trajectory of the incoming bunches. Such a system can 'lock in' within the first 100 bunch crossings to achieve roughly 80% of luminosity attainable if the beams were in perfect collision. Duplicate systems, one for each beam, are planned to allow redundancy of control, and several BPMs at different locations would provide robustness with respect to potentially large electromagnetic backgrounds for the BPM sensors. Additional upstream BPM-kicker sets would be used to provide angle correction.

Additional benefit can be provided by an intra-train position/angle scan(s) based on optimization of a bunch-by-bunch luminosity signal from the 'beam calorimeter'. After a further 1-2 hundred bunch crossings for the scan(s) it is possible to achieve a total of roughly 90% of the nominal luminosity attainable if the beams were in perfect collision.

Inputs to the feedbacks from additional diagnostics such as beam charge, transverse size, and bunch length monitors would allow adaptive gain control as collision conditions change. Inclusion of feed-forward information from the upstream trajectory feedbacks is desirable.

10.6.2.7 Architecture for 5Hz feedback systems

The relatively low correction rates and the distributed nature of many of the monitors and actuators make it appealing to consider using the integrated controls infrastructure for the 5Hz feedback systems. The controls network would be used to distribute monitor readbacks and actuator setpoints without requiring dedicated hardware and interfaces. The feedback algorithms themselves would be implemented in the Middleware layer of the control system, using dedicated processor units.

Implementing a feedback infrastructure into the integrated control system offers many advantages, such as:

- Simpler implementation, since dedicated interfaces are not required for equipment involved in feedback loops.
- Higher equipment reliability, since there are fewer components and interfaces.
- Greater flexibility, since all equipment would inherently be available for feedback control, rather than limiting functionality to pre-defined equipment.
- Offers the ability to develop ad-hoc or un-anticipated feedback loops with the same inherent functionality and tools. This could significantly enhance the commissioning process and operation of the ILC.

However, for this to be possible, the controls infrastructure must provide synchronous network activities and time-slicing of the network traffic, which in turn would require that all network attached devices comply with the time-slicing rules. The fact that the entire control system must in some way be synchronized to the 5Hz ILC pulse repetition rate means that to some degree, such requirements will be implicit in the control system implementation.

Details of the integrated control system architecture are provided in the control system section of the BCD.

An alternative, but less desirable solution, is to implement dedicated networks for all equipment associated with the feedback systems, perhaps using the same architecture and hierarchy as implemented for the integrated control system.

Additional functionality and versatility will be provided by integrating high level applications such as Matlab into the feedback system infrastructure, simplifying the task of developing and implementing feedback control algorithms.

10.6.2.8 Architecture for intra-bunch feedback systems

Dedicated local systems will be required for intra-bunch feedback systems that must operate at the bunch rate of ~3MHz, such as the RTML turnaround trajectory feed-forward control, and intra-bunch trajectory control at the IP.

In addition, a fast synchronous infrastructure will allow implementation of delayed bunch-to-bunch feedback/feed-forward along the length of the linac.

Local input/output processors will acquire beam position, cavity fields, beam current, and other local beam parameters at the full 3MHz bunch rate, and distribute that information to a fast synchronous network that runs the length of the linac. Local interconnections with the low-level RF systems provide opportunities for local feedback loops at the full 3MHz bunch rate. Distributing the bunch-by-bunch information on a dedicated network allows dedicated external processors to perform dynamical feedback control within the 1mS ILC pulse.

Dedicated processing crates will provide both dedicated real-time bunch-to-bunch control, such as RF cavity fields, dispersion free steering, etc, while additional uncommitted crates will provide feedback systems to be implemented as required by operations and for physics studies. High level applications such as Matlab and Simulink will simplify the process of implementing such algorithms.

10.6.2.9 Hardware Implementation

Most of the feedback processing requirements described in this section can be met using commercial hardware, including the 5Hz feedback loops and dynamic orbit control in the damping ring.

Custom hardware solutions will be required in cases where low latency or unique capabilities are required, such as for the RTML turnaround trajectory feed-forward and the IP intra-bunch trajectory feedback.

High Availability solutions will be implemented as appropriate, using the same standards and approach as for other instrumentation and control system equipment.

10.6.3 Present State of the art

Present third-generation synchrotron light sources have refined orbit correction systems to the level likely required for the ILC damping ring. Ongoing advances in digital processor performance and fast high performance analog to digital conversion chips has allowed the conversion from the analog to digital domains to be performed much earlier in the signal chain. Most challenging are systematic effects in beam position monitoring when required resolutions are at or below the few micron level.

Fast intra-bunch trajectory control systems for the IP presently being developed under the FONT and FEATHER collaborations, with the latest implementation ("FONT-4") aiming to demonstrate feedback with 100nS latency in the electronics and stabilization at um level.

10.6.4 Path to Specification

1. Identify stability and bandwidth issues for damping ring orbit correction.
2. Identify beam position monitoring resolution and stability requirements.
3. Identify trajectory stability requirements for the linac pre-IP, and for the beam delivery system.
4. Identify bunch compressor feedback loop requirements.
5. Identify any additional beam-based control loops required from gun to IP.

10.6.5 Required R&D

1. The most difficult challenges surround the bunch-by-bunch trajectory feedback system in the beam delivery system. High precision measurement at 3MHz bunch rate, fast (low latency) processing, and fast kicker systems all require development.

2. Development of fast highly stable kicker magnets is required for the intra-bunch feedback in the beam delivery system and turnaround section of the RTML.

3. Depending on beam stability and measurement bandwidth requirements, substantial development may be required for beam position monitors and associated electronics. , so their experience can be drawn upon. unique requirements will likely drive specific development needs.

10.6.6 References:

1. P. Burrows, Beam Based Feedback Systems, Snowmass 2005.
2. G. Decker, Beam Stability in Synchrotron Light Sources, DIPAC 2005
3. Beam-based Feedback: Theory and Implementation, NLC Zeroth Order Design Report,

10.6.7 Cost Model

A bottom-up system cost model will be produced following cost estimating rules of the GDE.

10.6.8 Alternate Configuration

No alternates under active consideration at this time.