Beam Based Feedback Systems at SLAC

Linda Hendrickson
SLAC

August 9, 2005
Overview

SLC Feedback System:
• Generalized, distributed feedback system. Database-driven.
• Expanded from original 8 loops, to over 50 control loops.
• Third generation (first 2 generations were prototypes, without full interface and diagnostic capabilities).
• Accessible to large number of users: operators, machine physicists, engineers, etc.
• A large multi-person, multi-year project.

PEPII B Factory Feedback System:
• Beam-based feedback systems for injector and ring were extension of SLC system.
• Additional lessons learned.

Future Linear Collider Studies
• Beam testing using SLAC linac, to test improved strategies.
• Simulations for NLC/TESLA/CLIC -> ILC.
WHY IS FEEDBACK NEEDED

• Compensates for slow environmental changes
  Temperature drifts
  Laser intensity

• Fast response to step changes
  Klystrons cycling

• Speeds recovery from downtime

• Improves operating efficiency
  Feedbacks don’t get tired or distracted

• Frees operators to study subtle problems

• Decouples systems for non-invasive tuning
  Tune Linac emittance and matching
  while delivering luminosity

• Powerful monitor of machine performance

At the SLC
if you can describe it
put a Feedback on it

Nan Phinney,
SLC Program Coordinator
Some operational goals:
Fast response to step functions, help operator tuning, recover after rate limiting/outages
Flatten the orbit throughout the linac
Minimize RMS of orbit vs time at end of the linac
Minimize RMS of orbit vs time at IP
Minimize backgrounds on the detector
Feedback Integrated with Control System

- Uses BPMs, correctors, and CPUs from control system, without dedicated hardware. Dedicated point-point communications system used for 120-hz, but 1-hz feedback uses communications backbone of control system.
- Integrates with machine physics application software.

Example 1: In correlation plots, move anything and sample anything else. Move feedback setpoints, sample feedback measured and calculated variables.

Example 2: To phase klystrons, use energy feedback setpoint to move the energy, and feedback energy calculation.

Example 3: Emittance bumps. Optimize linac setpoint to minimize emittance.

- Attach feedback setpoint to physical knob in control room, use feedback for tuning (keeps beam stable while moving only position, for example).
- Save/restore configurations of feedback setpoints, measurement references, etc.
- Feedback calculations, measurements, control changes available in long-term history plots.
- Feedback problems can generate alarms, annunciators, etc. Logging system for diagnostics (when did they turn the loop on? were actuators at limits? etc).
**SCP (SLAC Control Program)**

- Select region of interest (LINAC)
- Select feedback loop (local control calculation)
- Acquire buffered data, examine plots, adjust gain factors, turn on/off loop, etc...

---

### Feedback Panel

<table>
<thead>
<tr>
<th>Magnet Panels</th>
<th>Feedback Panel</th>
<th>HELP</th>
<th>RETURN</th>
<th>INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Select GUN</td>
<td>Select INJECT</td>
<td></td>
<td>NEXT Page</td>
<td></td>
</tr>
<tr>
<td>LI03 FBCK LOOP</td>
<td>LI04 FBCK LOOP</td>
<td></td>
<td>PRINT</td>
<td>Display MCCPRINT</td>
</tr>
<tr>
<td>LI06 FBCK LOOP</td>
<td>LI09 SCAV LOOP</td>
<td></td>
<td>PRINT</td>
<td>Text Display MCCPRINT</td>
</tr>
<tr>
<td>LI09 SCAV LOOP</td>
<td>LI10 SPPS/FTFB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LI11 FBCK LOOP</td>
<td>LI12 FBCK LOOP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LI18 FBCK LOOP</td>
<td>LI23 FBCK LOOP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LI26 FBCK LOOP</td>
<td>LI29 FBCK LOOP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LI29 SPPS/FTFB</td>
<td>FB31 ENERGY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESA FB31 LOOP</td>
<td>CB00 ELEC LAUNCH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acquire Data</td>
<td>States E- Vs TIME</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summary Display</td>
<td>Setpnt Display</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loop Status Display</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PLOT XY1 ORBIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Display Vector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cold Start Loop</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>One Shot</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Change Loop HSTA FEEDBACK</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Typical Feedback Loop Structure

Actuators:
Upstream correctors

States:
Fitted position and angle at selected point.

Measurements:
Typical BPM readings. Multiple, redundant.

Typical loop spans limited region, such as 1 linac sector.
Sometimes using “cascade” to coordinate multiple loops

09Aug2005 LHendrickson
Status display shows status for all loops in a region. Can see at a glance which are on/off, which are sick, etc. Example: LI12 loop has correctors out of limits (RED).
Database-driven plots for items of interest. FFTs, histograms, etc. Can set user scaling. (Yes, a modern interface would use a GUI for scaling, but this control system is ~20 year old!)
Buffered data plots are shown for 4 correctors, following a momentary beam perturbation. Feedback rates range from 1 Hz to 120 Hz. Buffers typically hold the last 1000-2000 sampled pulses.
Feedback calibration/Modeling

Feedback matrices are designed offline through automated program which is currently implemented in matlab m-files using control toolbox and signal processing toolbox. User can choose to generate matrices using online model, or calibration (measured matrices). Choice between linear calibration (scan) and dither-style calibration (move back and forth and fit a line to 2 points).
Measurement Panel

Users can enter measurement limits, filtering criteria, residual cuts, etc. Time history plots available. Similar interface available for actuators and states.
Feedback Design Issues

“The feedback software is easy, the exception handling is 90% of the work.” - T. Himel

14 years later, it is still not finished!

- **Bad measurements.** Is it a broken BPM, a flaky BPM, an errant beam pulse, or has the beam really moved? Measurement limits, filtering, chi-squared calculations, etc.

- **Broken corrector power supplies.** Broken hardware or database error (SLC)? Or a normal, large failure rate (PEPII)?

- **Broken communication links, CPUs unavailable, etc.** -> “cascade” system, can turn off problematic loops and leave rest of the system functional.

- Steering Feedback in Dispersive Regions

- Energy Feedback, and other non-linear feedbacks (linearize it, with pseudo-actuators).
Handling of Bad Measurements

Assumes we have extra (redundant) BPM measurements.
Calculate expected measurements, based on time-averaged state estimates which include actuator motion. Use expected value if a measurement has bad status.

- Pseudo-Median Filtering: If measurement far from expected and not between 2 previous, then filter (originally just one measurement, later for all together).

- Measurement limits.

- Chi-squared residual limits (PEPII). When residuals are large, try to guess which BPM is unreasonable, by excluding each measurement in turn, then mark the worst one SUSPECT.

Problem: chi-squared gets worse with time, esp if steering within range of feedback. Expected value is not same as measurement, so state jumps when measurement goes bad.

Partial Solution: Recalculate matrix taking meas -> states, excluding bad meas. (Doesn’t help for intermittent bad status, though).

Other solution: Save measurement references often. (But PEPII fears drifting orbit).

 Beam Test: set a single BPM limit so that it is alternating between good and bad status.
Feedback Response without Cascade

We choose to have multiple feedback loops in the linac for operational convenience: can decouple areas of the machine, turn off some loops, etc. Useful in the case of broken correctors, broken communications links, etc.

With a global feedback this is more difficult. But with multiple loops and without ‘cascade’ system, feedback loops overshoot and ring, even with low gain factors.

**Measured response of 7 SLC loops, gains=0.05, 5 Hz**

**Simulated response of 7 perfect NLC loops, gains=0.05, 120 Hz**
Cascade – the “Ant Accelerator”

On pulse 1: perturb the position up by 1 unit, all loops see position=1.

Assume single-phase, position only.
no quads, all transport matrices are 1.0. Apply feedback on second pulse, designed to fix entire perturbation in the next pulse.

Without cascade, each loop fixes its own value completely, but since upstream loops also fix it, we have overcorrection.

With cascade, each loop subtracts the adjacent loop’s transported states from its own state, and corrects the difference. With simple linear transport, perfect results!
Successful Cascade Test in the SLC LINAC

Note limitations were seen in initial SLC linac cascade. At higher intensity, wakefield effects were significant, and multiple-source cascade was needed (i.e. sent from all upstream loops). Tested successfully after SLC was finished.

Another limitation was that the transport matrices between feedback loops were calculated adaptively using SER method. Mathematical flaw in algorithm, when BPM resolution is significant compared to beam noise -> magnitudes of transport matrix are systematically too small. Tested solution: Calibrate transport by moving correctors: successful.

Without cascade, overshoot and ringing from the series of 5 feedback loops

Initial beam test of the cascade system gives a good result. Perturbation is fixed without overshoot.
What about Steering Feedback in Regions with Dispersion?

**SLC Experience:**
When steering in dispersive region, always find fit point (effective position and angle calculation point) with zero dispersion.
Example: In SLC ARCs, no convenient fit point with zero dispersion. But we chose an artificial fit point at end of linac, which the model thinks has zero dispersion. Then the feedback uses ARC BPMs (all with dispersion) to calculate the following states, back-transported to the end of the linac:
X position, Y position, X angle, Y angle, energy.
The feedback controls the positions and angles, but calculates the energy. Correctors in the ARC are calibrated to calculate the effect on the calculated state. It worked fine!

**ILC Simulations:**
Currently using calibration from BPMs in BDS to BDS correctors. Measure energy at reference point, and on every pulse. Measure dispersion at each BPM and subtract effect of energy changes on BPMs before applying feedback. It works, but not very robust.
Fast Feedback Architecture

Control Loop Design

Offline

Online

SLC Database
Control Program
VAX 8800

SLCNET

MICROS

KISNET
INTER-MICRO
Communications
Network

Measurement
Micros

Controller
Micro

Actuator
Micros

09Aug2005 LHendrickson
Fast Feedback Architecture, cont’d
LQG Feedback algorithms (Linear Quadratic Gaussian): Optimal (Modern) Control Theory.
State-space formalism, Kalman filter, Predictor-corrector.

What does this mean to us?

- Optimal controller: minimizes RMS of signal, given inputs of noise spectrum and plant response.
- Predictor-corrector theory: Feedback knows about its own actuator movement, so it does not repeatedly try to fix the same error (overcorrection). Feedback responds to UNEXPECTED changes.
Control Design (FDESIGN) Inputs:

- **Plant noise model:**
  Low-pass, white, harmonic oscillator, bandpass, etc.
  (harmonic oscillator dangerous in simulation)

- **Actuator Response Model:**
  Time delay (N pulses or feedback iterations.)
  or  Exponential Response (dangerous!)

- **Sensor Noise**

- **Plant Transport Matrices:**
  States => Measurements
  Actuators => States

But: In practice in the SLC, always use same basic design.
Exponential response with selected speed, usually 6 pulses.
State-Space Feedback Model

Output from accelerator with added measurement noise -> feedback measurements (y), input to feedback system

Control input to accelerator is output from the feedback system (u vector)

Feedback’s estimated state vector $x(n)$ is time-averaged. Inputs are measurements (with references subtracted), previous state estimate, and actuator movement.
LQG control design (now using Matlab control toolbox) designs optimal controller for expected noise spectrum. Typical SLC feedback design includes a combination of low-pass noise, and white noise. Note we can design systems which strongly damp noise in narrow frequency bands, but these systems are less robust to modeling errors.
Typical SLC feedback design included a static 2 pulse delay. But actual response is a ramp of about 1/10 second. With 120-hz feedback, this is not a good model. Problem with LQG: If we use the low-pass filter model, it wants to create a controller which overshoots the controller output from feedback (the actuator vector), in order to obtain the ideal noise response. But this is operationally dangerous! Solution: Pollute the LQG matrices so that feedback expects a long delay, but without the overshoot. This “safer” feedback design works, but isn’t elegant…
Luminosity Optimization in the SLC

Dithering techniques were applied for 10 orthogonal final focus parameters including waists, eta, etc. Beamstrahlung monitor was used. Many 120-hz pulses were averaged to get good resolution. Typical tuning cycle every 30-40 minutes.

Estimated 20-40% of SLC luminosity was lost due to bad resolution on parabolic optimization scans. ~3% luminosity spent on dithering, with improved resolution.

Resolution of dithering technique (+), compared to parabolic scan method (o).
New Challenges with PEPII:
2 colliding rings, HER and LER. 8 IP correctors for each ring.
Different linear combinations of the same correctors, closed bumps to control:
X position, Y position, X angle, Y angle.
Cannot keep beams in collision using BPMs: need to maximize luminosity.

For example, combined HER/LER IP X position (controlling absolute position of collision point) is a separate and independent control than HER or LER alone (collides the beams).

We have multiple feedback loops, running at different rates, using the same correctors.
**HER ORBIT, LER ORBIT:** BPM-based, semi-global feedback control.
**IP:** dithering techniques keep beams in collision, maximizing luminosity with HER X position, HER Y position and HER Y angle.
While above feedback controls are on, user needs to manually control:
HER X angle, HER/LER Y angle, LER X angle, HER/LER X position, HER/LER Y position
Maintaining collisions during a fill:

The IP feedback loop alternates between dither cycles for X, Y and Y angle. Each plane perturbs the beam in turn, and fits a parabola to maximize luminosity.
8 HER Correctors are used. Different linear combinations of same cors for X,Y,YANGLE. We cycle through 4 dither settings (nominal, above nominal, nominal, and below nominal), and then calculate a parabolic offset. This is fixed on each iteration, if the statistical error is small and if the proposed move is less than the dither size.
PEPII B Factory Beam-based Feedback

(Lesson: Better to plan for feedback in advance.)

**BPMs:**
- Sometimes periodically forget their firmware in presence of radiation.
- Not real-time response.
- Heavy BPM user acquisition can lock out feedback.

**Corrector Power Supply Controllers:**
- Multi-cpu intelligent controllers. Not real-time response. Periodically perform “long” status checks, locking out feedback system for seconds at a time. Some correctors move in closed bump and some fail, resulting in non-closed bump, luminosity dips and sometimes beam losses!
- Previous problems where power supply controller system froze, sometimes needed reset, requiring dumping the ring and refilling.

**CPU:**
Using TCPIP communications. Previous buggy TCPIP software would cause micro to freeze, requiring reboot.

These problems are worse for feedback system, because it is a frequent and taxing user of the control system, therefore often blamed for problems.
5-Hz ILC Integrated Feedback Simulations

- TESLA Linac, matched into NLC beam delivery section.
- **Linac feedback** distribution: 5 distributed loops per beam, each with 4 horizontal and 4 vertical dipole correctors, and 8 BPMs (X&Y). Based on SLC experience and NLC simulations.
- Linac and BDS feedbacks “Cascaded” system of 6 loops per beam: loops don’t overcompensate beam perturbations, but can be independently disabled for operational convenience. SLC-style “single cascade” (each loop communicates beam information to single adjacent downstream loop).
- Linac and BDS loops have **exponential response of 36 5-Hz pulses**. IP deflection (X&Y), not cascaded, **exponential 6 pulses** (like SLC).
- Matlab/liar/dimad/guinea-pig platform. Upgraded liar/dimad for energy and current jitter, and dispersion measurements.
- KEK-model ground motion (noisy site). Study effects of **component jitter, energy, current, kicker jitter**. Problems: BDS beamsize very sensitive; using dispersion compensation and perfect energy measurement.
Feedback Simulations, TESLA LINAC

Emittance growth in linac
~100% after 30 min “KEK”
ground motion + jitter for 10 seeds,
6% with feedback (3% with feedback
without jitter).

BPM readings after 30 minutes ground motion

5 distributed linac loops

1 BDS loop

IP loop
Feedback Simulations, TESLA LINAC

“Banana-bunch” shape is seen at end of LINAC after 30 minutes of “K” ground motion. Fixed with feedback.
Linac Beam Test of SLC Layout vs Distributed Layout

Response to an incoming X oscillation with SLC localized feedback compared with distributed feedback

Red arrows show location and length of feedback regions
Blue arrows show locations of BPMs, Green arrows correctors

SLC layout

Distributed layout
Single-beam studies of beamsize growth, with 5-hz feedback in LINAC and BDS.

Perfect initially, add 30 minutes “KEK” ground motion”, let feedback converge -> 5% beamsize growth (380% without feedback).

Increase energy spread for undulator (.15% end of linac; this effect needs more study!) -> 14%.

Add component jitter (25 nm BDS, 50 nm linac) -> 15%.

Add 5-Hz “KEK” ground motion -> 18%.

Add kicker jitter (.1 sigma), current jitter (5%), energy (.5% uncorrelated amplitude on each klystron, 2 degrees uncorrelated phase on each klystron, 0.5 degrees correlated phase on all klystrons, BPM resolution .1 um. -> 21%
ILC 2-beam Integrated Feedback Simulations

2 beams, 5-Hz linac, BDS and IP deflection feedback. Perfect initially, feedback turned on after 30 minutes of “KEK” ground motion. 5 Hz ground motion, added component jitter, kicker, energy, current jitter. No angle feedback, no intratrain feedback. For the first ~20 seconds, IP feedback cannot keep up with large BDS steering changes. After 20 seconds, beams kept in collision but luminosity is poor (~20% in preliminary simulations, ~79% with perfect intratrain IP feedback).

Beam-size jitter in steady-state.

Beam sizes decrease after feedback is turned on. (Note seed-dependent beamsize from ground motion; in this seed, e- becomes smaller).
Conclusions??

- For an experiment like the SLC, a powerful, generalized feedback system is essential to successful operation.
- For other experiments, feedback is a very useful tool, and the ability to easily configure feedback loops is good.
- A generalized system is a lot of work!
- It is important to plan for feedback systems in advance, and integrate with the control system, and plan for appropriate hardware and controls infrastructure.