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

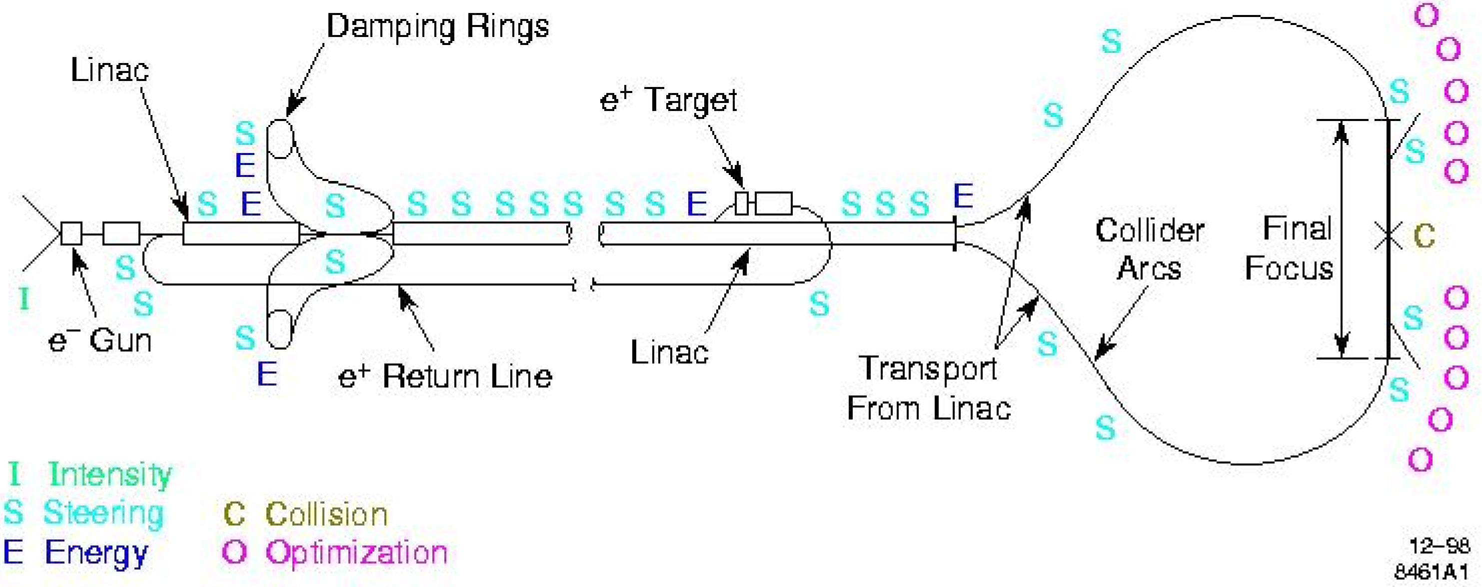
- Decouples systems for non-invasive tuning
  Tune Linac emittance and matching
  while delivering luminosity

- Powerful monitor of machine performance

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

Nan Phinney,
SLC Program
Coordinator

SLC Feedback Diagram



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.

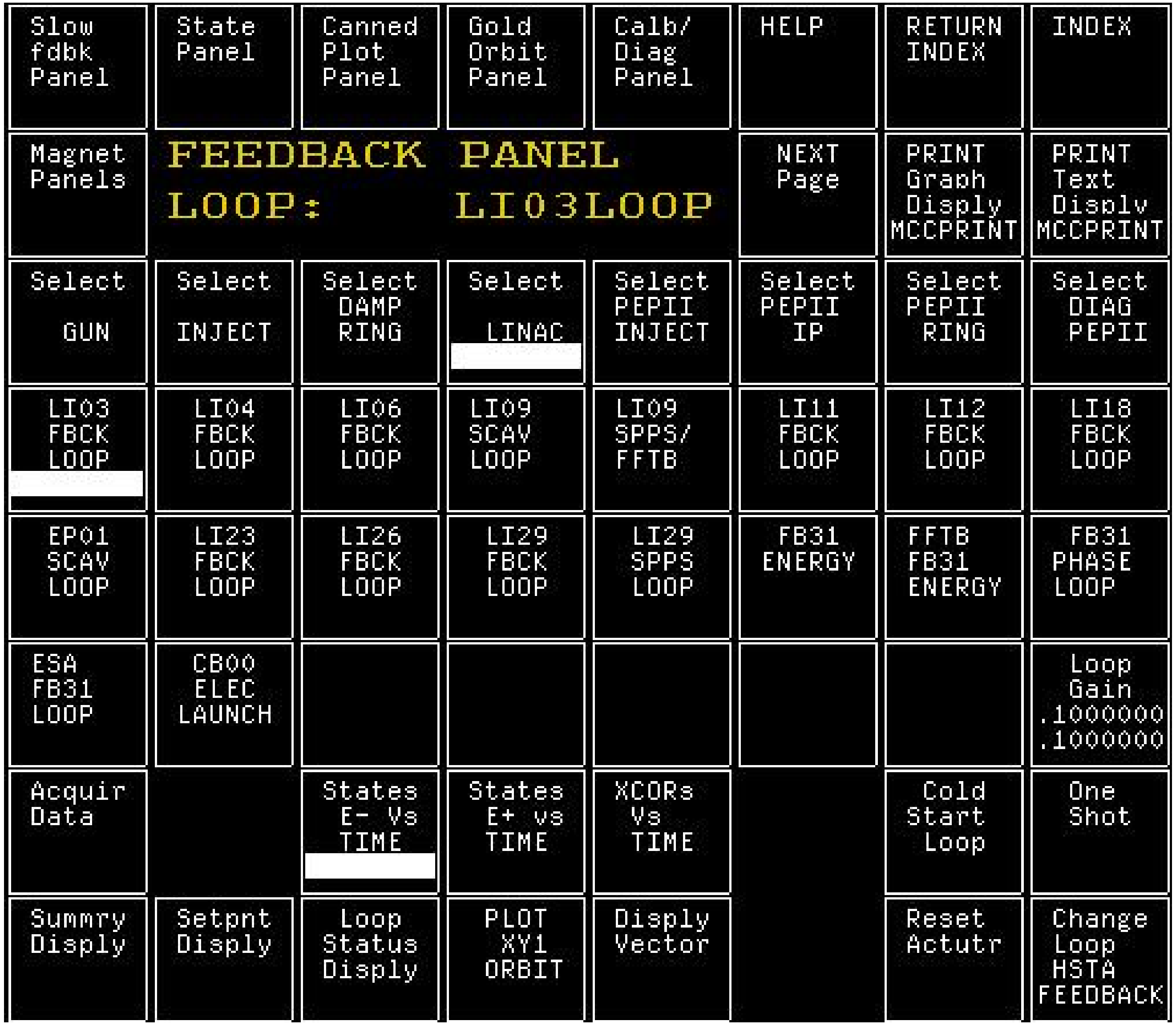
Example 2: to phase klystrons, use energy feedback setpoint to move the energy, and feedback energy calculation.

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...



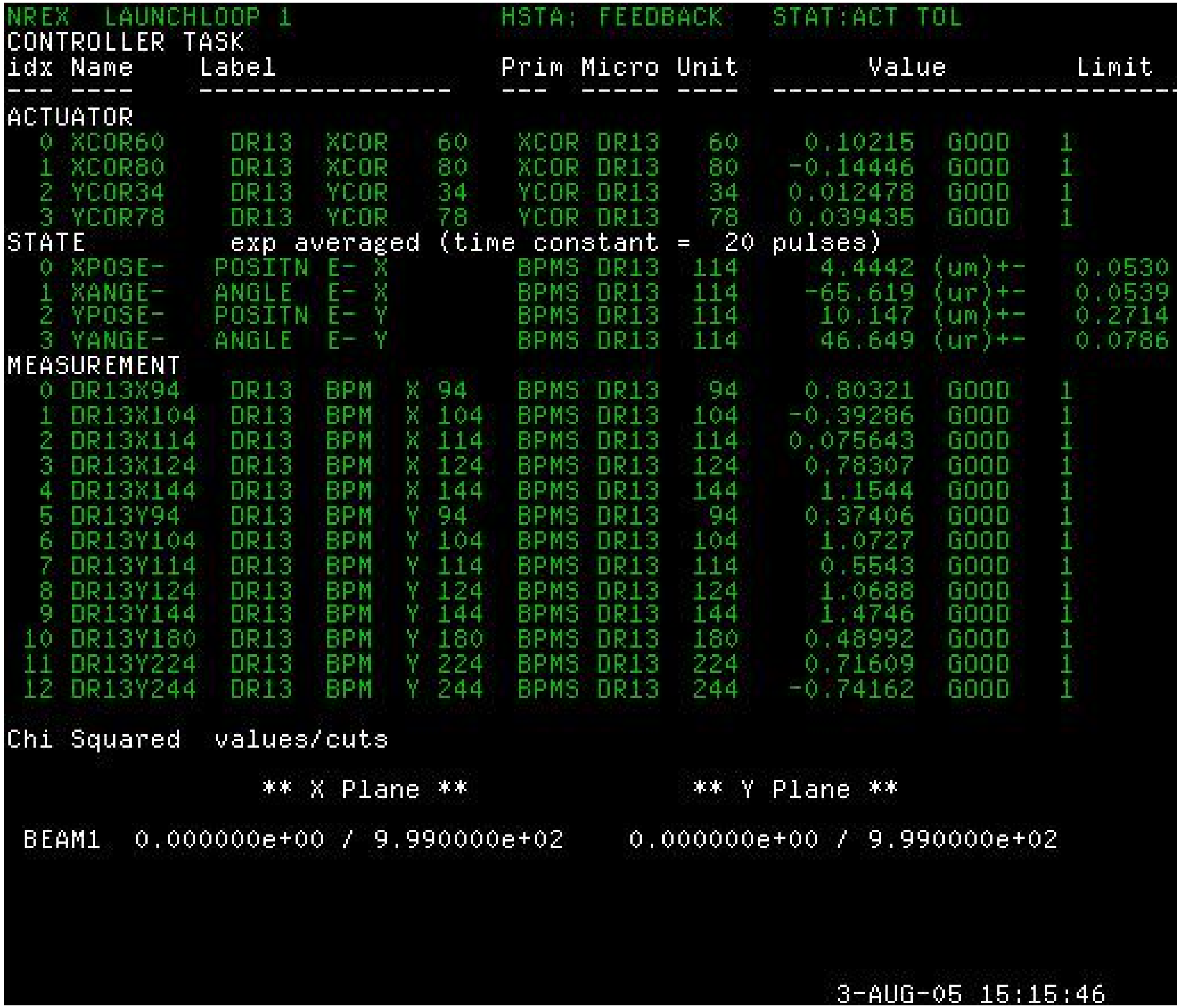
Typical Feedback Loop Structure

Actuators:
Upstream correctors

States:
Fitted position and angle at selected point.

Measurements:
Typical BPM readings. Multiple, redundant.

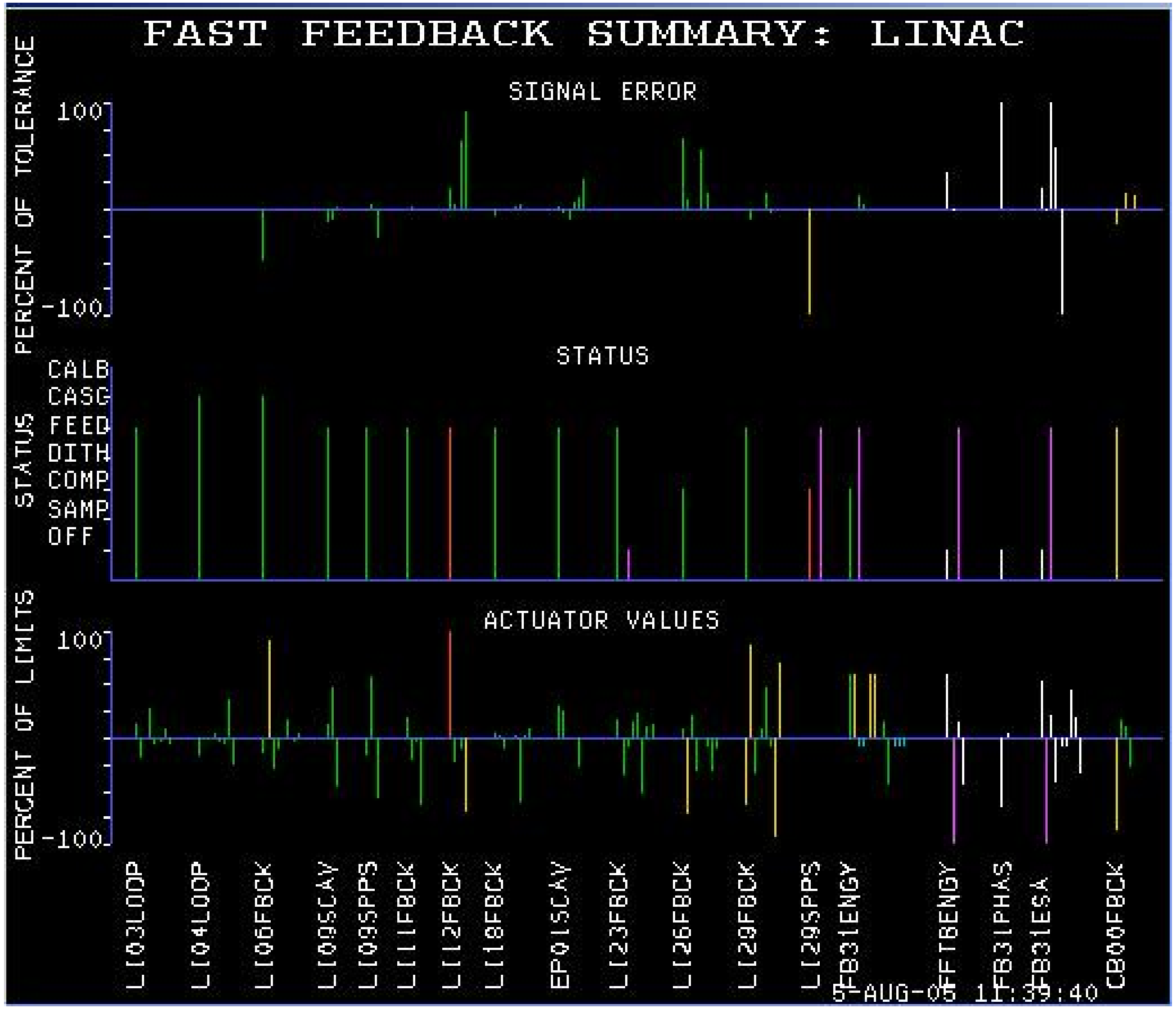
Typical loop spans limited region, such as 1 linac sector. Sometimes using "cascade" to coordinate multiple loops



```
NREX  LAUNCHLOOP 1             HSTA: FEEDBACK   STAT:ACT TOL
CONTROLLER TASK
idx Name    Label              Prim Micro Unit        Value        Limit
--- ----    ----------------   ---  ----- ----  --------------------------
ACTUATOR
  0 XCOR60    DR13  XCOR   60   XCOR DR13   60     0.10215 GOOD    1
  1 XCOR80    DR13  XCOR   80   XCOR DR13   80    -0.14446 GOOD    1
  2 YCOR34    DR13  YCOR   34   YCOR DR13   34    0.012478 GOOD    1
  3 YCOR78    DR13  YCOR   78   YCOR DR13   78    0.039435 GOOD    1
STATE         exp averaged (time constant =  20 pulses)
  0 XPOSE-   POSITN E- X        BPMS DR13  114      4.4442 (um)+-   0.0530
  1 XANGE-   ANGLE  E- X        BPMS DR13  114     -65.619 (ur)+-   0.0539
  2 YPOSE-   POSITN E- Y        BPMS DR13  114      10.147 (um)+-   0.2714
  3 YANGE-   ANGLE  E- Y        BPMS DR13  114      46.649 (ur)+-   0.0786
MEASUREMENT
  0 DR13X94   DR13  BPM  X 94   BPMS DR13   94     0.80321 GOOD    1
  1 DR13X104  DR13  BPM  X 104  BPMS DR13  104    -0.39286 GOOD    1
  2 DR13X114  DR13  BPM  X 114  BPMS DR13  114    0.075643 GOOD    1
  3 DR13X124  DR13  BPM  X 124  BPMS DR13  124     0.78307 GOOD    1
  4 DR13X144  DR13  BPM  X 144  BPMS DR13  144      1.1544 GOOD    1
  5 DR13Y94   DR13  BPM  Y 94   BPMS DR13   94     0.37406 GOOD    1
  6 DR13Y104  DR13  BPM  Y 104  BPMS DR13  104      1.0727 GOOD    1
  7 DR13Y114  DR13  BPM  Y 114  BPMS DR13  114      0.5543 GOOD    1
  8 DR13Y124  DR13  BPM  Y 124  BPMS DR13  124      1.0688 GOOD    1
  9 DR13Y144  DR13  BPM  Y 144  BPMS DR13  144      1.4746 GOOD    1
 10 DR13Y180  DR13  BPM  Y 180  BPMS DR13  180     0.48992 GOOD    1
 11 DR13Y224  DR13  BPM  Y 224  BPMS DR13  224     0.71609 GOOD    1
 12 DR13Y244  DR13  BPM  Y 244  BPMS DR13  244    -0.74162 GOOD    1

Chi Squared  values/cuts

                ** X Plane **              ** Y Plane **

 BEAM1  0.000000e+00 / 9.990000e+02    0.000000e+00 / 9.990000e+02



                                                    3-AUG-05 15:15:46
```

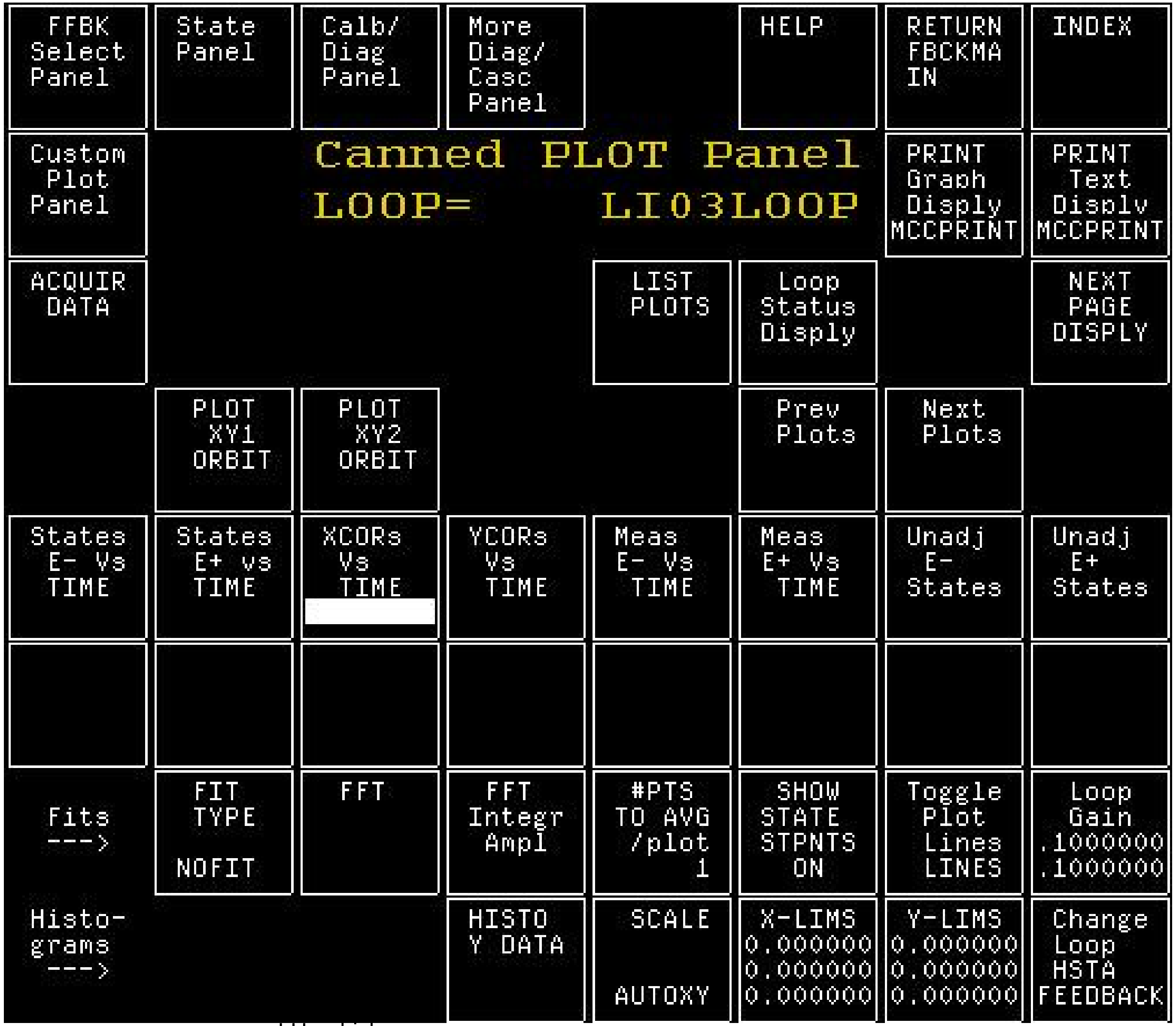
SCP Feedback Status Display

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).



SCP Plot Panel

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!)

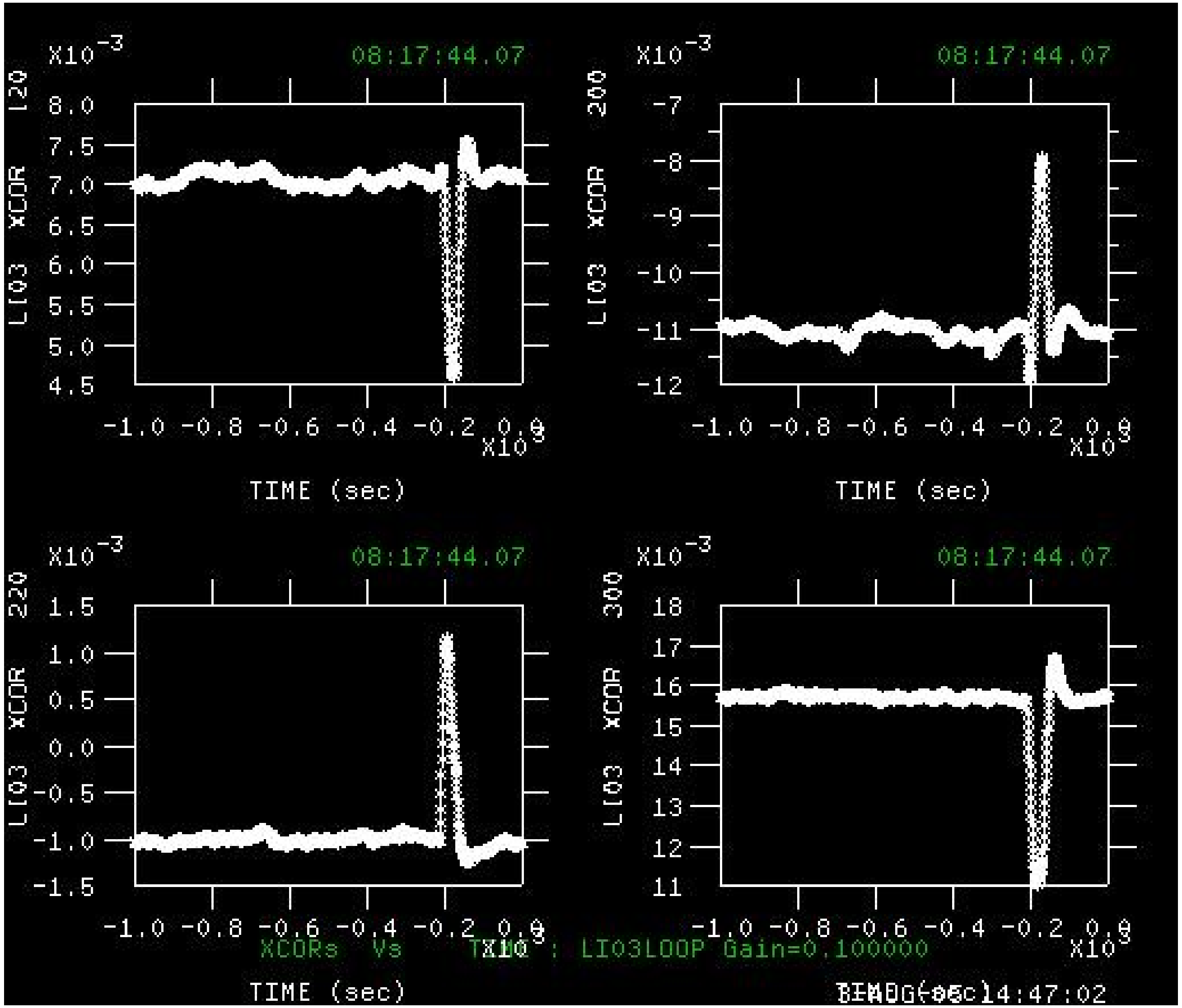


Canned PLOT Panel

LOOP= LI03LOOP

Typical SCP Feedback Plot

Buffered data plots are shown for 4 correctors, following a momentary beam perturbation. Feedback rates ranges from 1 Hz to 120 Hz. Buffers typically hold the last 1000-2000 sampled pulses.

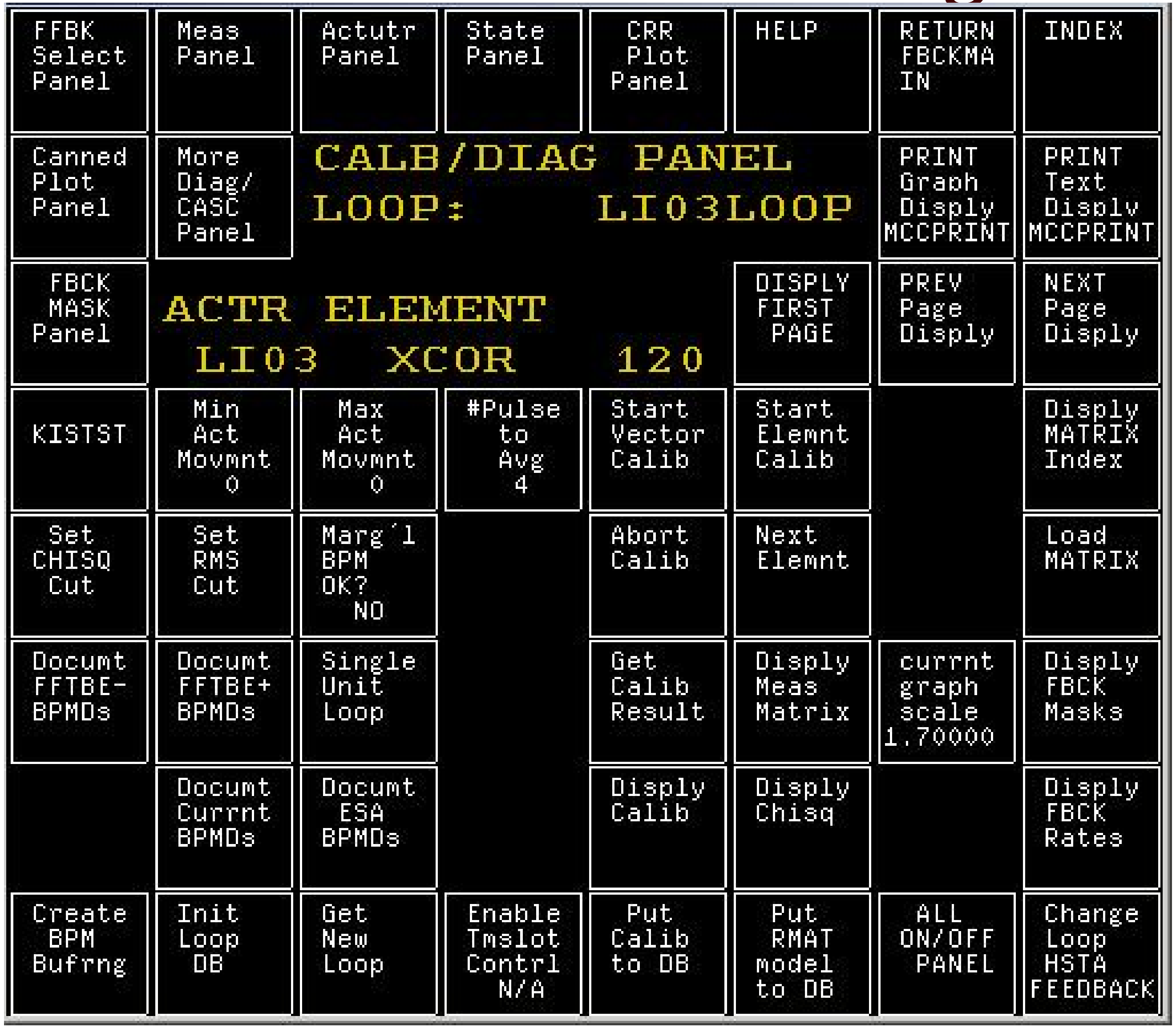


Feedback Calibration/Modeling

Feedback matrices are designed offline through automated program which is currently implemented in matlab m-files using control toolbox and signal processing toolbox.

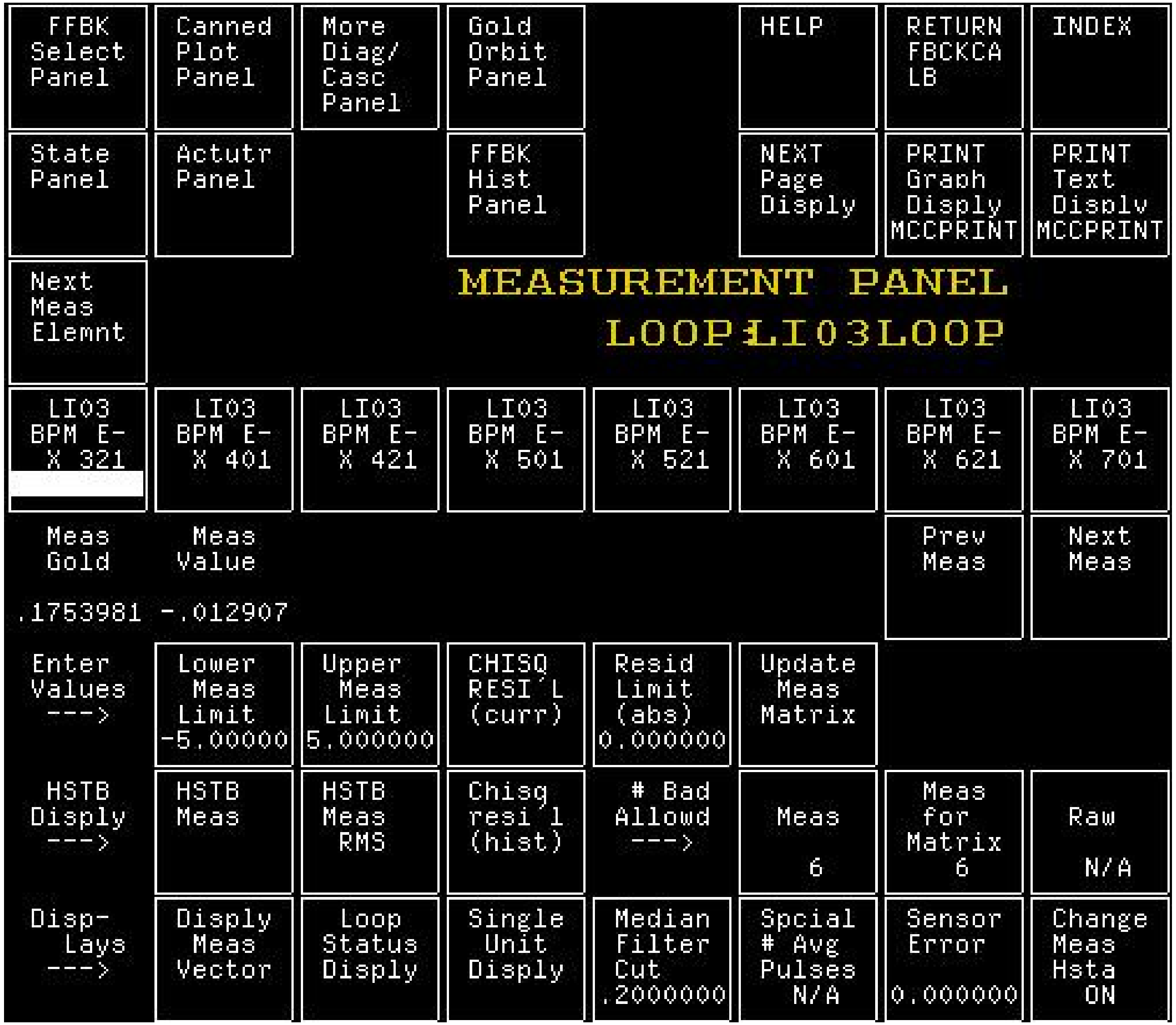
User can choose to generate matrices using online model, or calibration (measured matrices).

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.



Meas Gold .1753981
Meas Value -.012907
Lower Meas Limit -5.00000
Upper Meas Limit 5.000000
CHISQ RESI´L (curr)
Resid Limit (abs) 0.000000
Meas 6
Meas for Matrix 6
Raw N/A
Median Filter Cut .2000000
Spcial # Avg Pulses N/A
Sensor Error 0.000000
Change Meas Hsta ON

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.

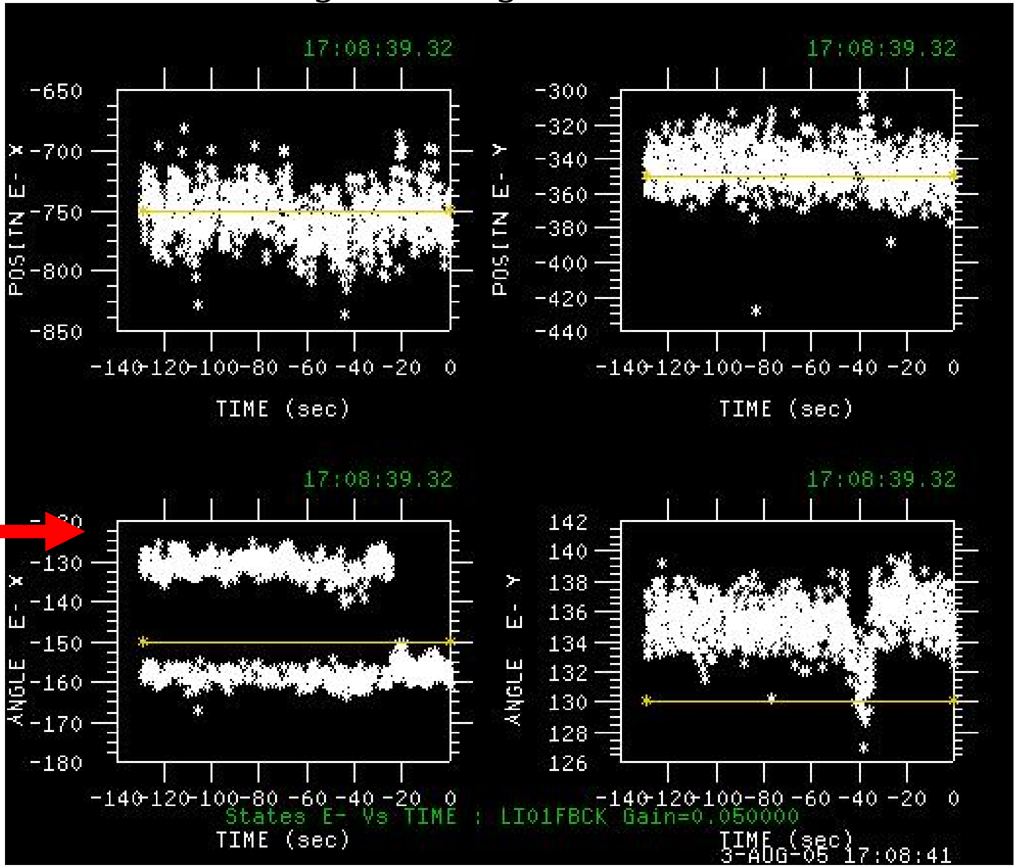
- Pseudo-Median Filtering: If measurement far from expected and not between 2 previous, then filter (originally just one measurement, later for all together).
- Measurement limits.
- Chi-squared residual limits (PEPII). When residuals are large, try to guess which BPM is unreasonable, by excluding each 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.



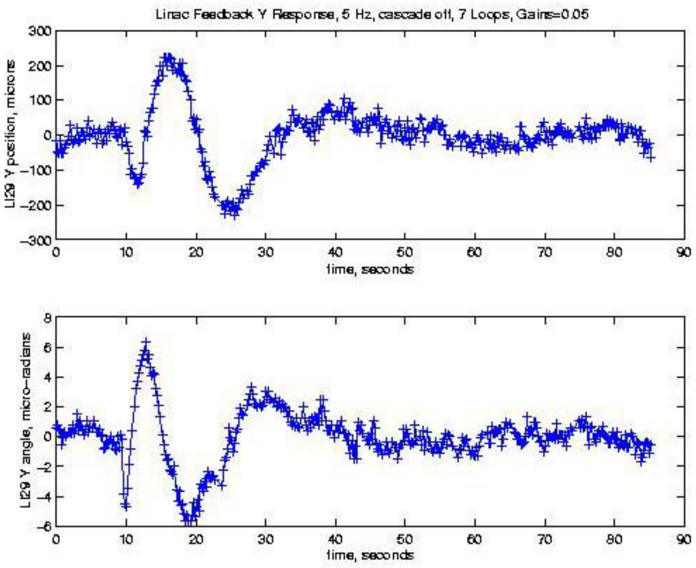
Feedback Response without Cascade

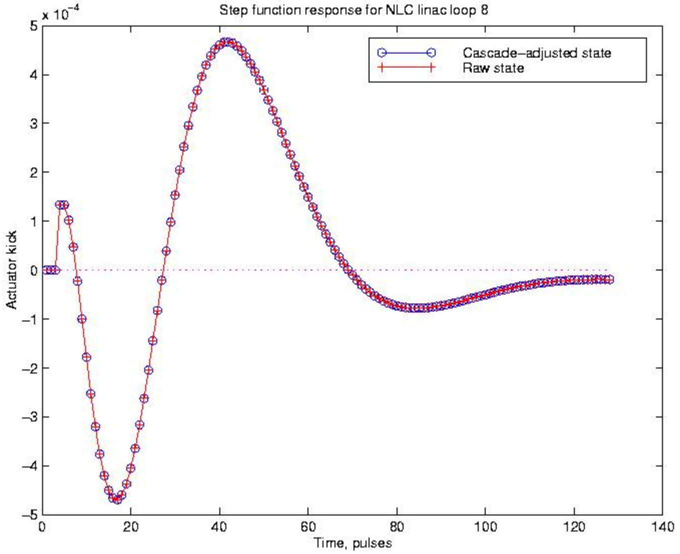
We choose to have multiple feedback loops in the linac for operational convenience: can decouple areas of the machine, turn off some loops, etc. Useful in the case of broken correctors, broken communications links, etc.

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

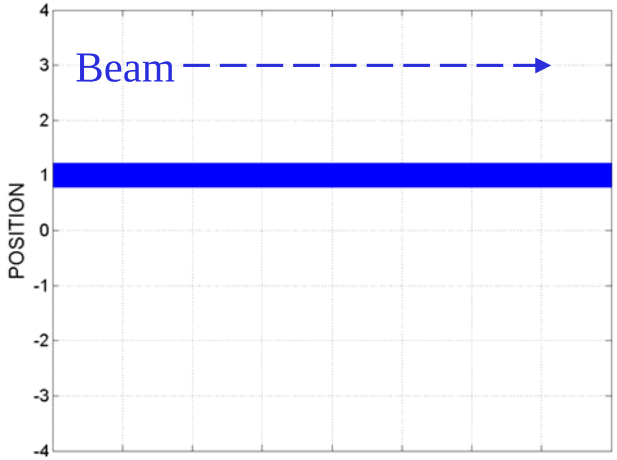


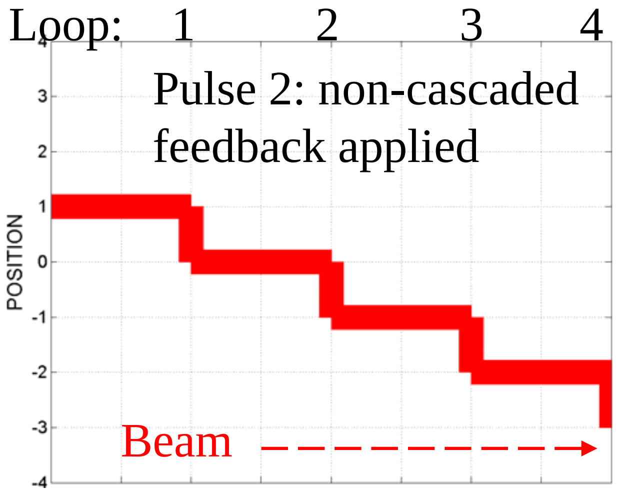


rickson

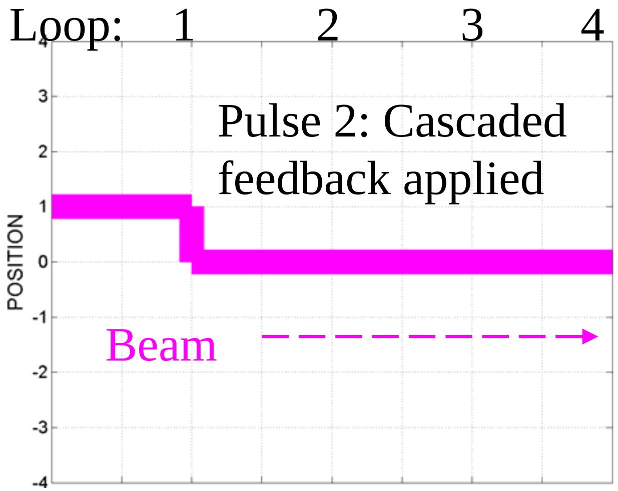
Cascade – the "Ant Accelerator"

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





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



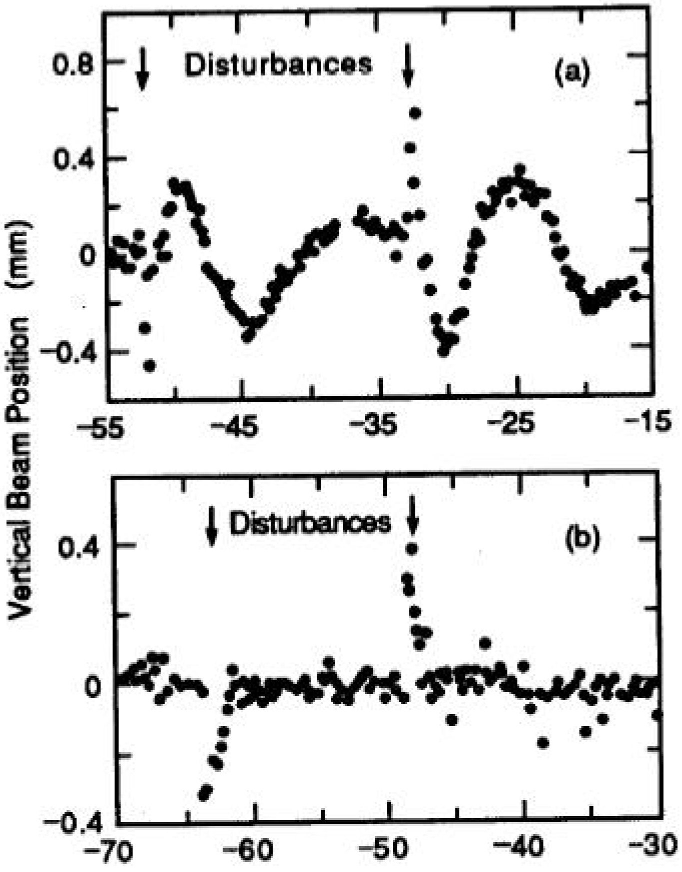
With cascade, each loop subtracts the adjacent loop's transported states from its own state, and corrects the difference. With simple linear transport, perfect results!

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.

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:

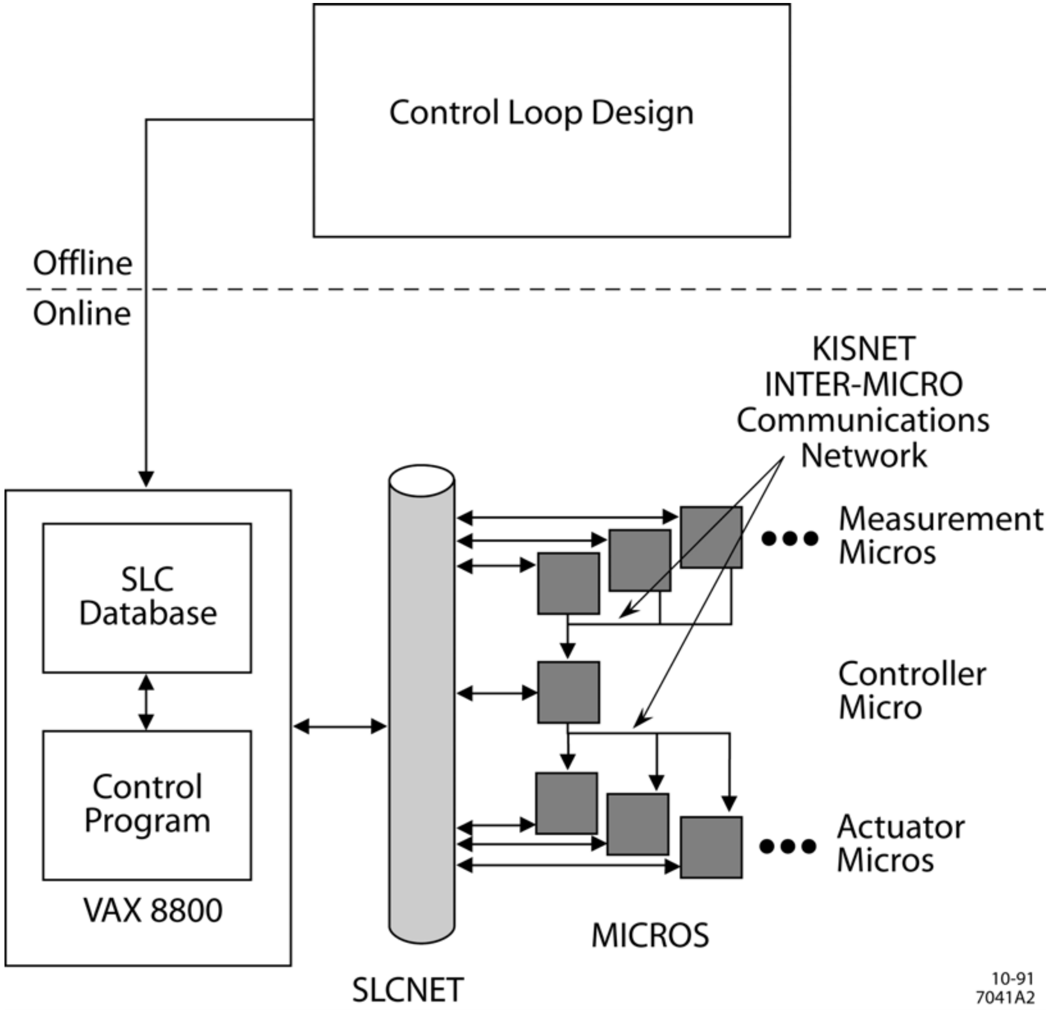
X position, Y position, X angle, Y angle, energy.

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!

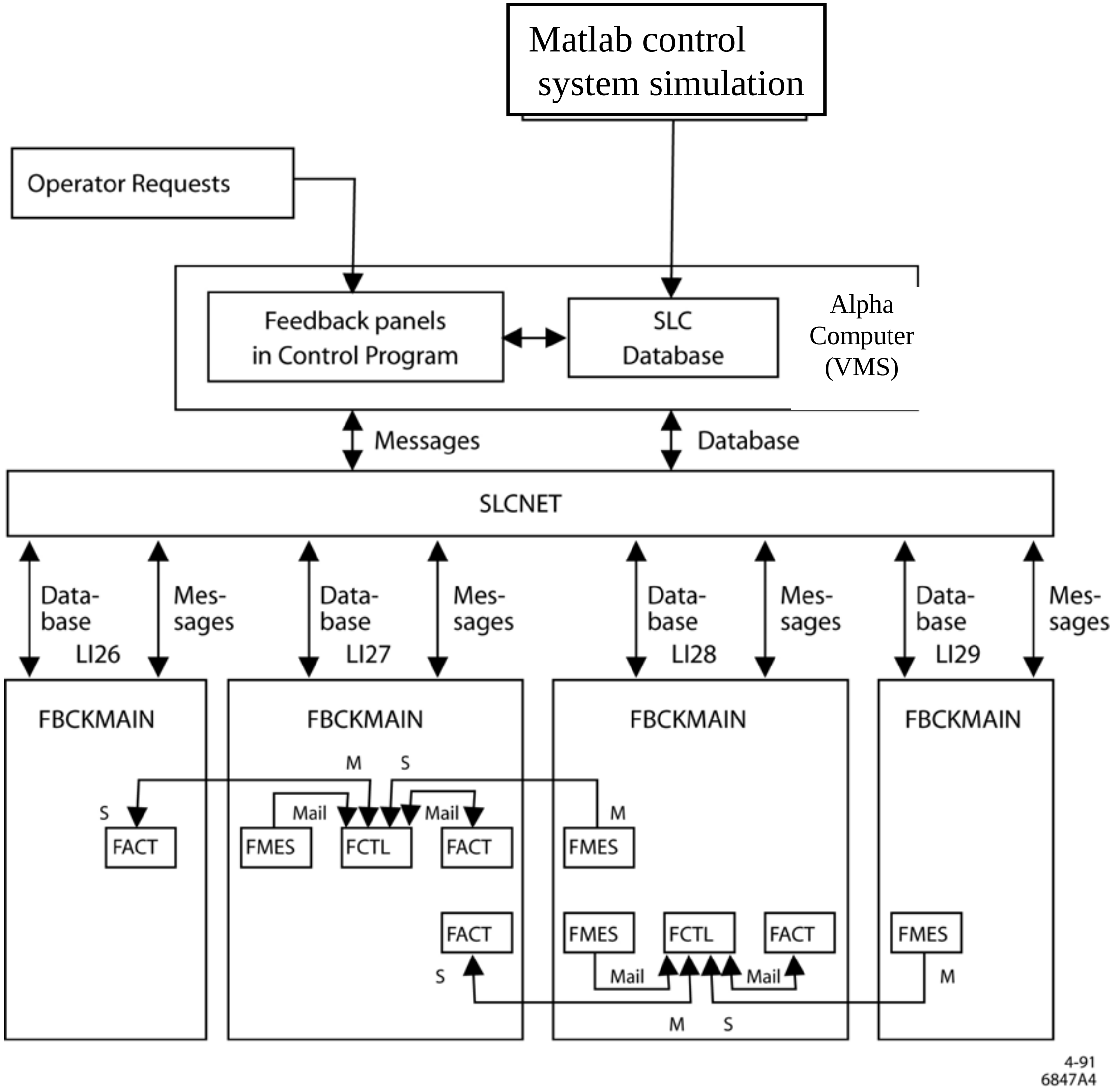
ILC Simulations:

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



Fast Feedback Architecture, cont'd



SLC Feedback Algorithms (Himel)

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.

SLC Feedback Algorithms, cont'd

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:**

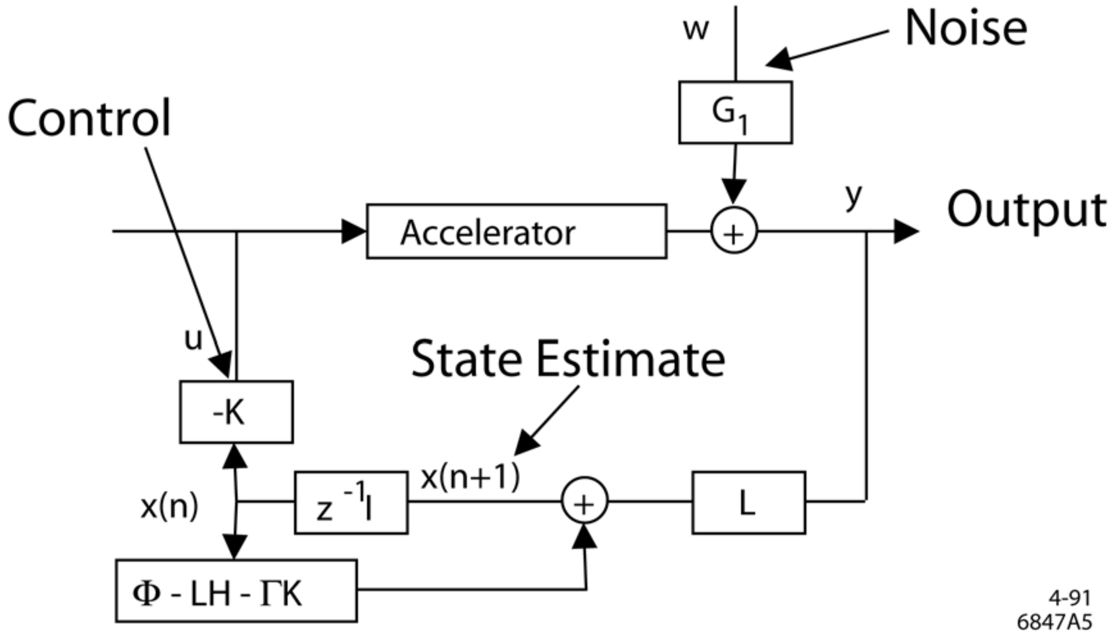
  States => Measurements

  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

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

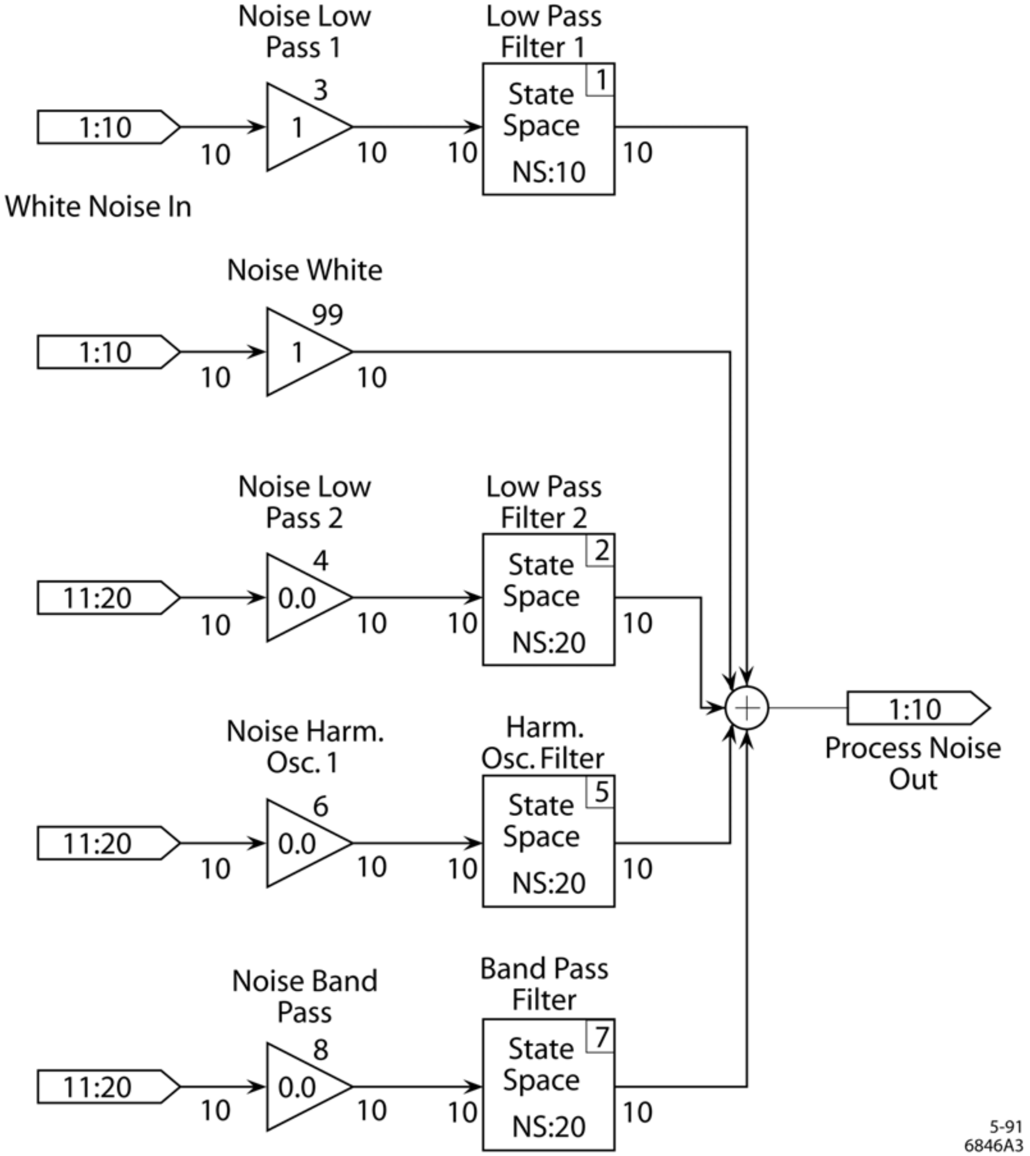


Output from accelerator with added measurement noise -> feedback measurements (y), input to feedback system

Feedback's estimated state vector x(n) is time-averaged. Inputs are measurements (with references subtracted), previous state estimate, and actuator movement.

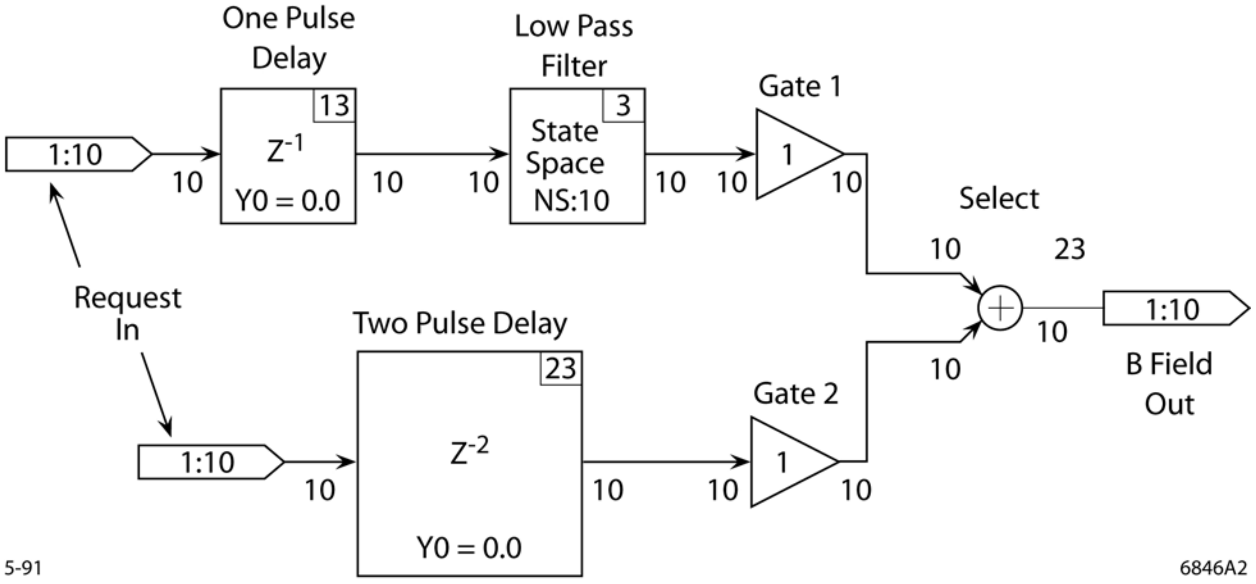
Feedback Noise Model Options

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.

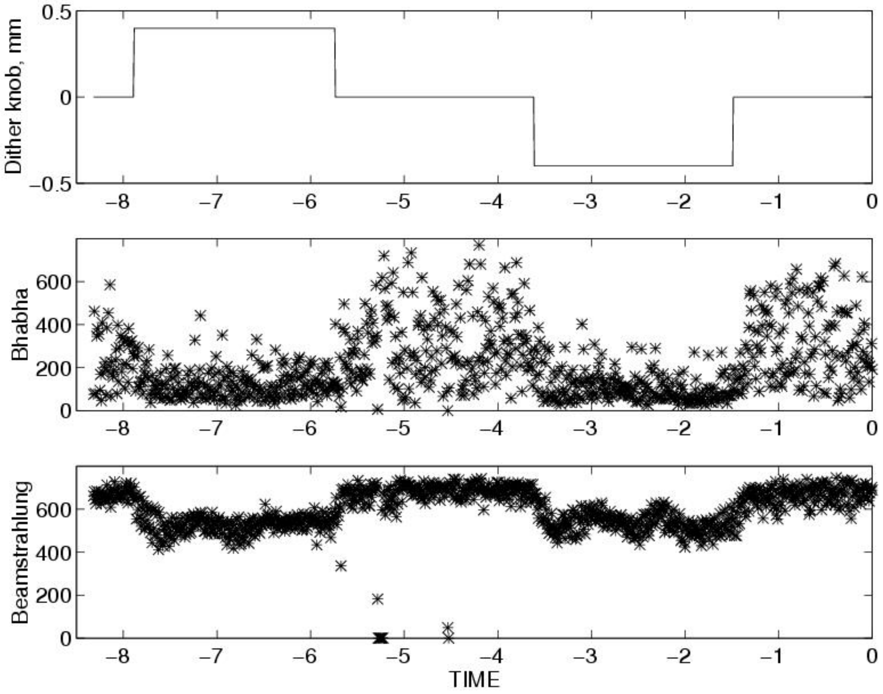


Feedback Actuator Model

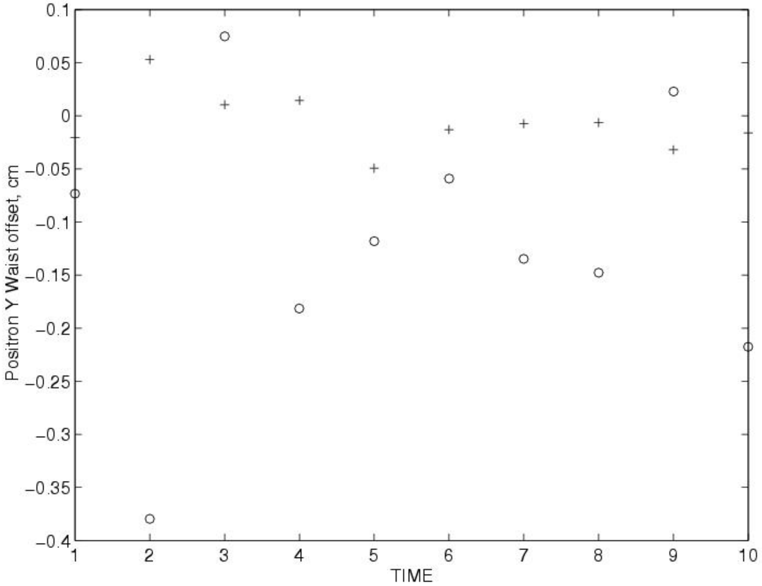
Typical SLC feedback design included a static 2 pulse delay. But actual response is a ramp of about 1/10 second. With 120-hz feedback, this is not a good model. Problem with LQG: If we use the low-pass filter model, it wants to create a controller which overshoots the controller output from feedback (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.



Resolution of dithering technique (+), compared to parabolic scan method (o).

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

PEPII B Factory Beam-based Feedback

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.

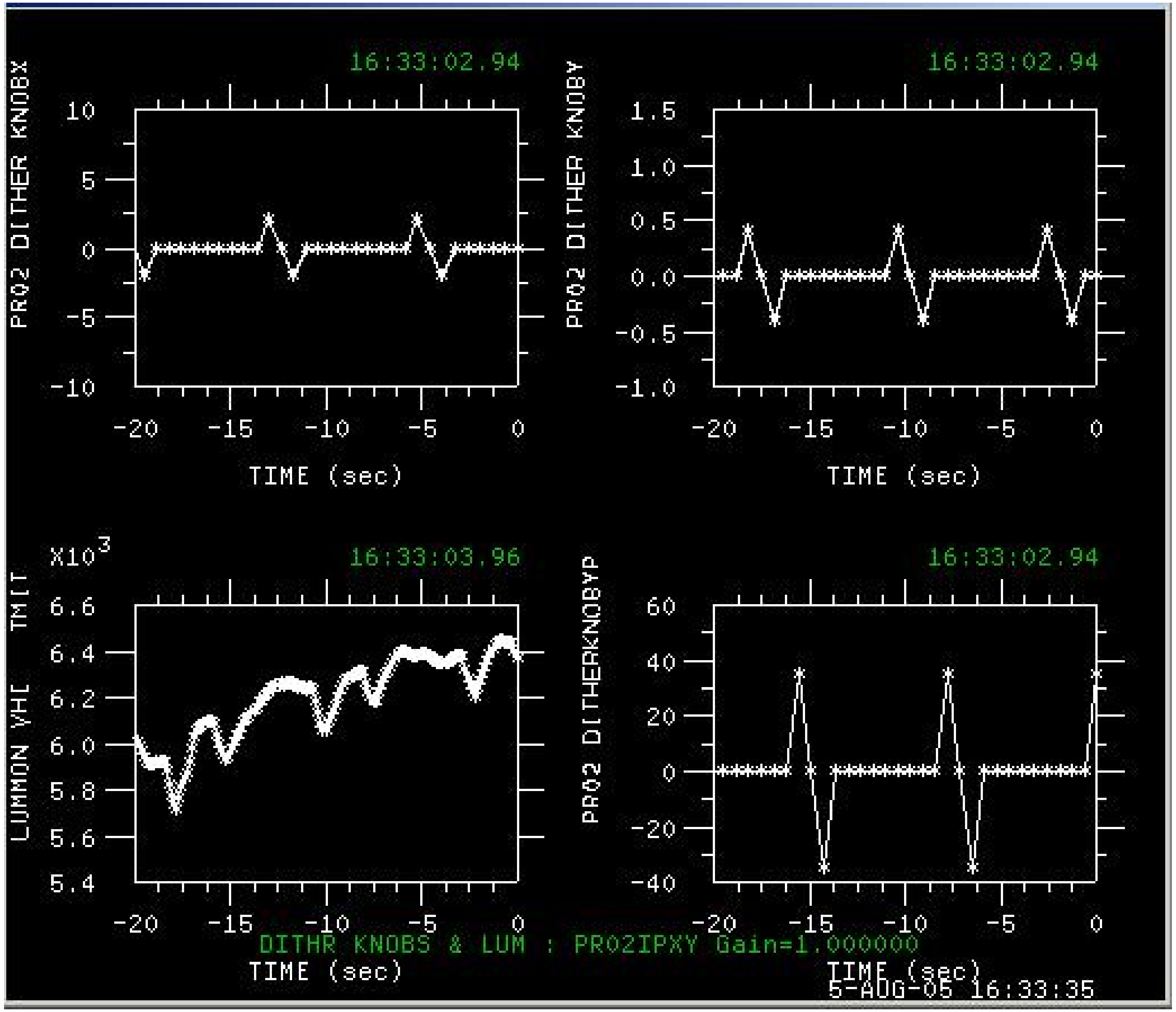
For example, combined HER/LER IP X position (controlling absolute position of collision point) is a separate and independent control than HER or LER alone (collides the beams).

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

PEPII – Dithering to Maintain Collisions

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.

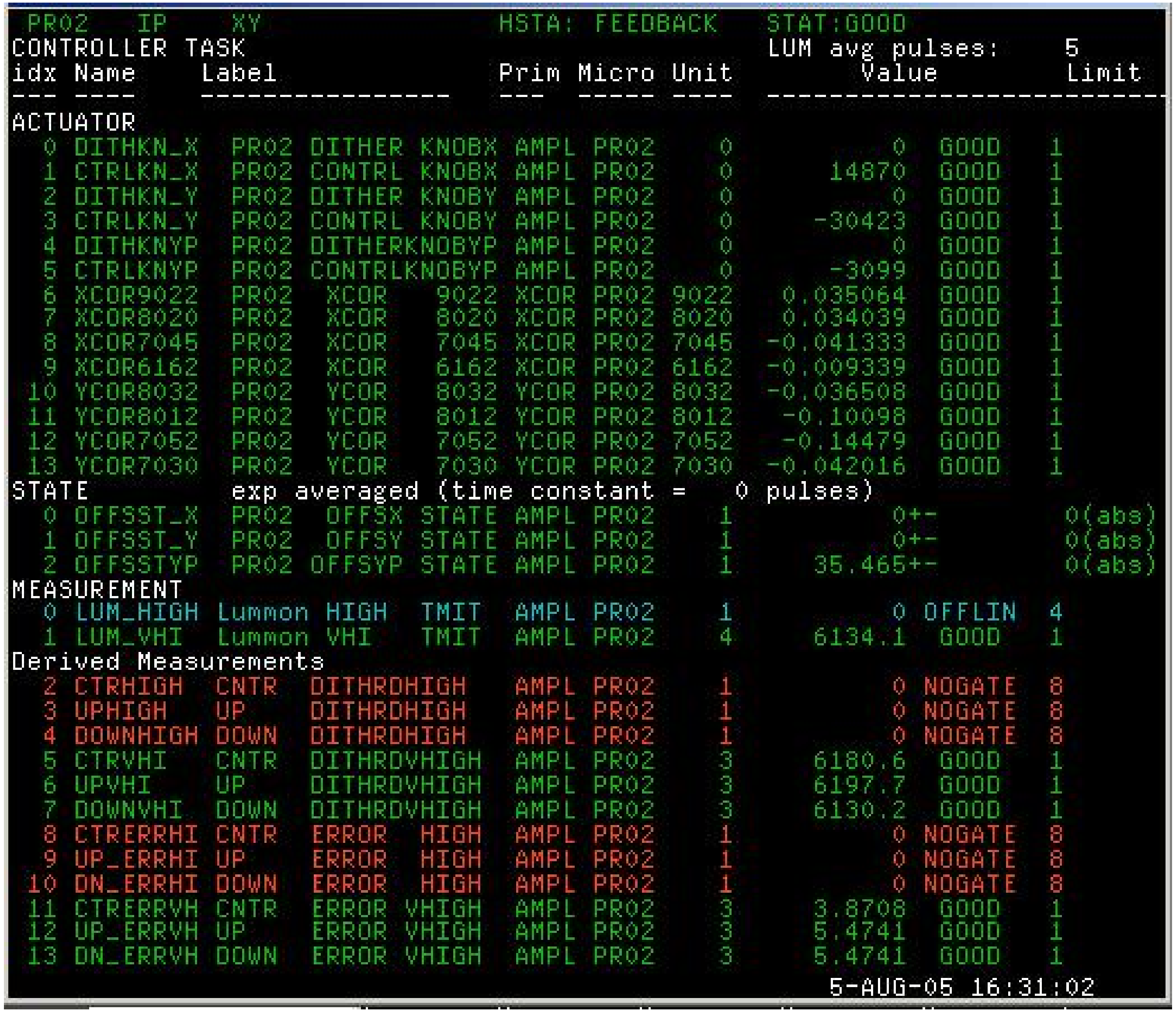


DITHR KNOBS & LUM : PR02IPXY Gain=1.000000

5-AUG-05 16:33:35

IP Collide Feedback Loop Structure

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.



```
 PRO2   IP    XY               HSTA: FEEDBACK   STAT:GOOD
CONTROLLER TASK                                 LUM avg pulses:    5
idx Name    Label              Prim Micro Unit        Value        Limit
--- ----    ----------------   ---  ----- ----  --------------------------
ACTUATOR
  0 DITHKN_X  PRO2 DITHER KNOBX AMPL PRO2    0          0  GOOD   1
  1 CTRLKN_X  PRO2 CONTRL KNOBX AMPL PRO2    0      14870  GOOD   1
  2 DITHKN_Y  PRO2 DITHER KNOBY AMPL PRO2    0          0  GOOD   1
  3 CTRLKN_Y  PRO2 CONTRL KNOBY AMPL PRO2    0     -30423  GOOD   1
  4 DITHKNYP  PRO2 DITHERKNOBYP AMPL PRO2    0          0  GOOD   1
  5 CTRLKNYP  PRO2 CONTRLKNOBYP AMPL PRO2    0      -3099  GOOD   1
  6 XCOR9022  PRO2  XCOR   9022 XCOR PRO2 9022   0.035064  GOOD   1
  7 XCOR8020  PRO2  XCOR   8020 XCOR PRO2 8020   0.034039  GOOD   1
  8 XCOR7045  PRO2  XCOR   7045 XCOR PRO2 7045  -0.041333  GOOD   1
  9 XCOR6162  PRO2  XCOR   6162 XCOR PRO2 6162  -0.009339  GOOD   1
 10 YCOR8032  PRO2  YCOR   8032 YCOR PRO2 8032  -0.036508  GOOD   1
 11 YCOR8012  PRO2  YCOR   8012 YCOR PRO2 8012   -0.10098  GOOD   1
 12 YCOR7052  PRO2  YCOR   7052 YCOR PRO2 7052   -0.14479  GOOD   1
 13 YCOR7030  PRO2  YCOR   7030 YCOR PRO2 7030  -0.042016  GOOD   1
STATE         exp averaged (time constant =   0 pulses)
  0 OFFSST_X  PRO2  OFFSX STATE AMPL PRO2    1          0+-        0(abs)
  1 OFFSST_Y  PRO2  OFFSY STATE AMPL PRO2    1          0+-        0(abs)
  2 OFFSSTYP  PRO2 OFFSYP STATE AMPL PRO2    1     35.465+-        0(abs)
MEASUREMENT
  0 LUM_HIGH Lummon HIGH  TMIT  AMPL PRO2    1          0 OFFLIN  4
  1 LUM_VHI  Lummon VHI   TMIT  AMPL PRO2    4     6134.1  GOOD   1
Derived Measurements
  2 CTRHIGH  CNTR  DITHRDHIGH   AMPL PRO2    1          0 NOGATE  8
  3 UPHIGH   UP    DITHRDHIGH   AMPL PRO2    1          0 NOGATE  8
  4 DOWNHIGH DOWN  DITHRDHIGH   AMPL PRO2    1          0 NOGATE  8
  5 CTRVHI   CNTR  DITHRDVHIGH  AMPL PRO2    3     6180.6  GOOD   1
  6 UPVHI    UP    DITHRDVHIGH  AMPL PRO2    3     6197.7  GOOD   1
  7 DOWNVHI  DOWN  DITHRDVHIGH  AMPL PRO2    3     6130.2  GOOD   1
  8 CTRERRHI CNTR  ERROR  HIGH  AMPL PRO2    1          0 NOGATE  8
  9 UP_ERRHI UP    ERROR  HIGH  AMPL PRO2    1          0 NOGATE  8
 10 DN_ERRHI DOWN  ERROR  HIGH  AMPL PRO2    1          0 NOGATE  8
 11 CTRERRVH CNTR  ERROR VHIGH  AMPL PRO2    3     3.8708  GOOD   1
 12 UP_ERRVH UP    ERROR VHIGH  AMPL PRO2    3     5.4741  GOOD   1
 13 DN_ERRVH DOWN  ERROR VHIGH  AMPL PRO2    3     5.4741  GOOD   1
                                                    5-AUG-05 16:31:02
```

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.

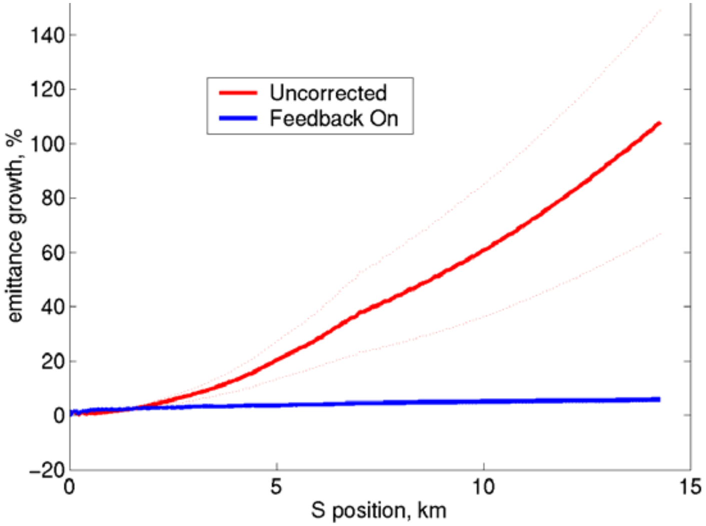
5-Hz ILC Integrated Feedback Simulations

- **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**.

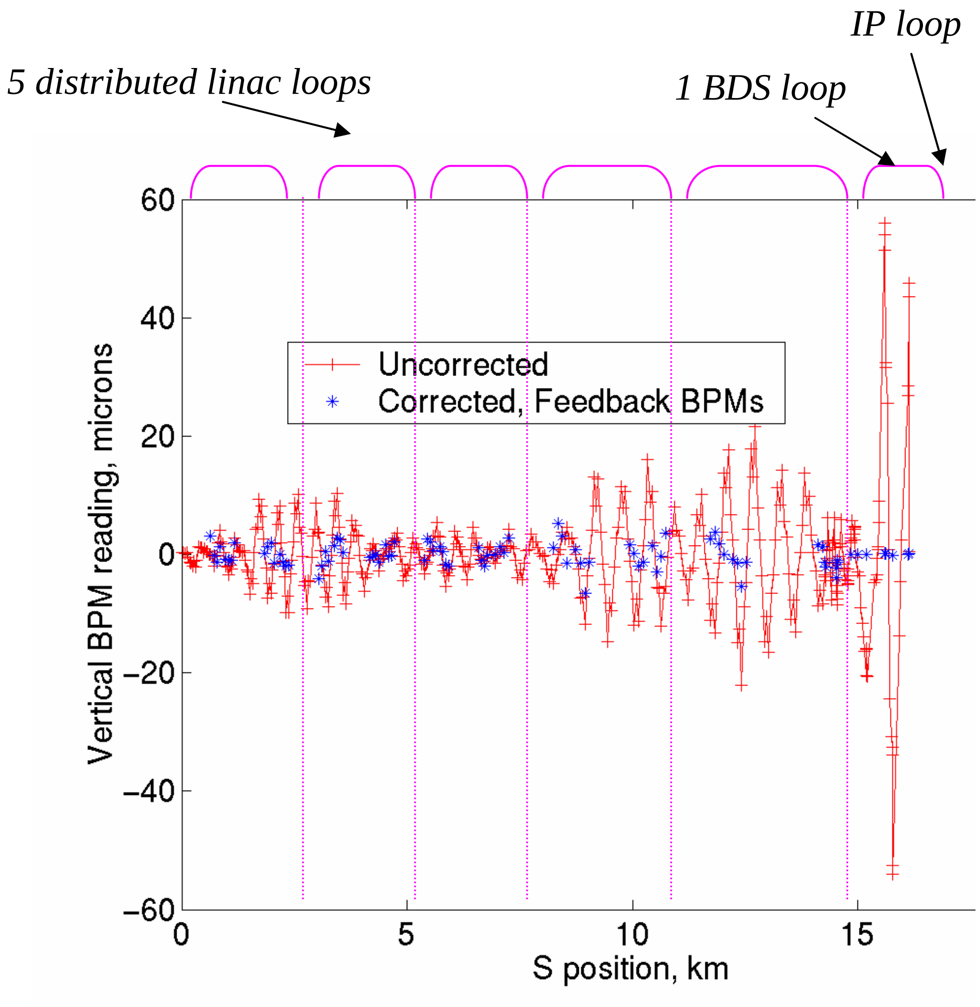
  IP deflection (X&Y), not cascaded, **exponential 6 pulses** (like SLC).
- **Matlab/liar/dimad/guinea-pig** platform. Upgraded liar/dimad for energy and current jitter, and dispersion measurements.
- **KEK-model ground** motion (noisy site). Study effects of **component jitter, energy, current, kicker 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).

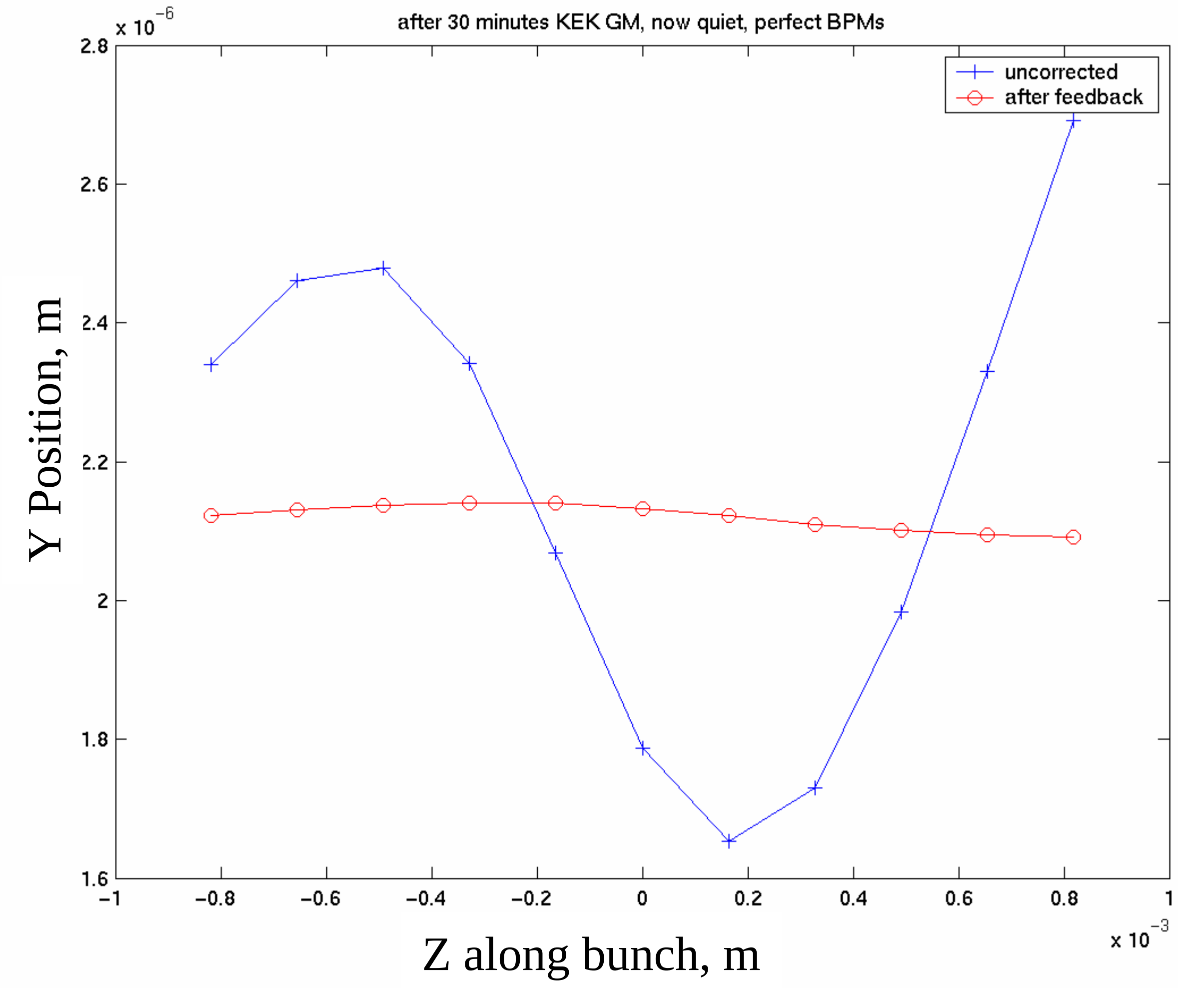


BPM readings after 30 minutes ground motion



Feedback Simulations, TESLA LINAC

"Banana-bunch" shape is seen at end of LINAC after 30 minutes of "K" ground motion. Fixed with feedback.



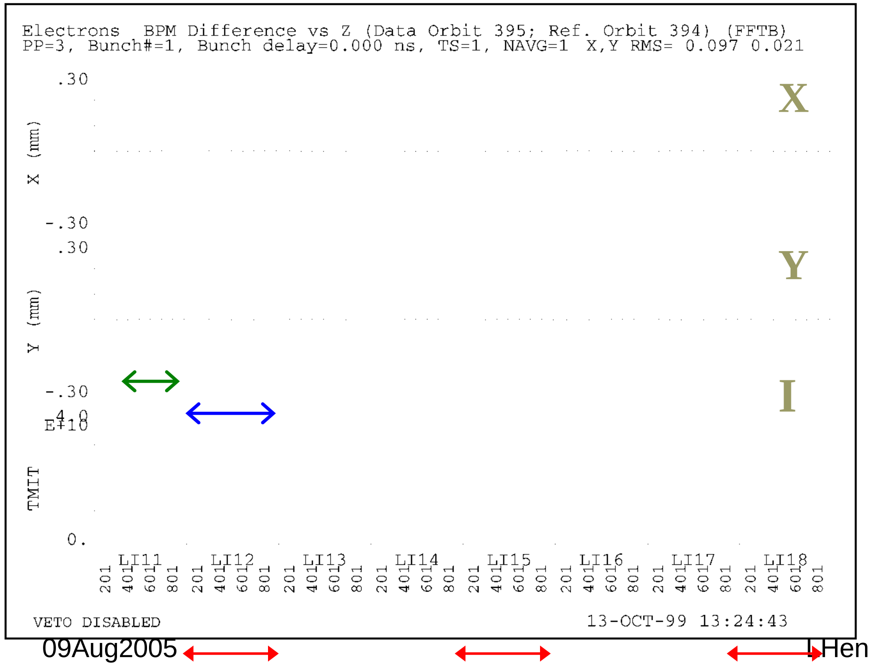
Linac Beam Test of SLC Layout vs Distributed Layout

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

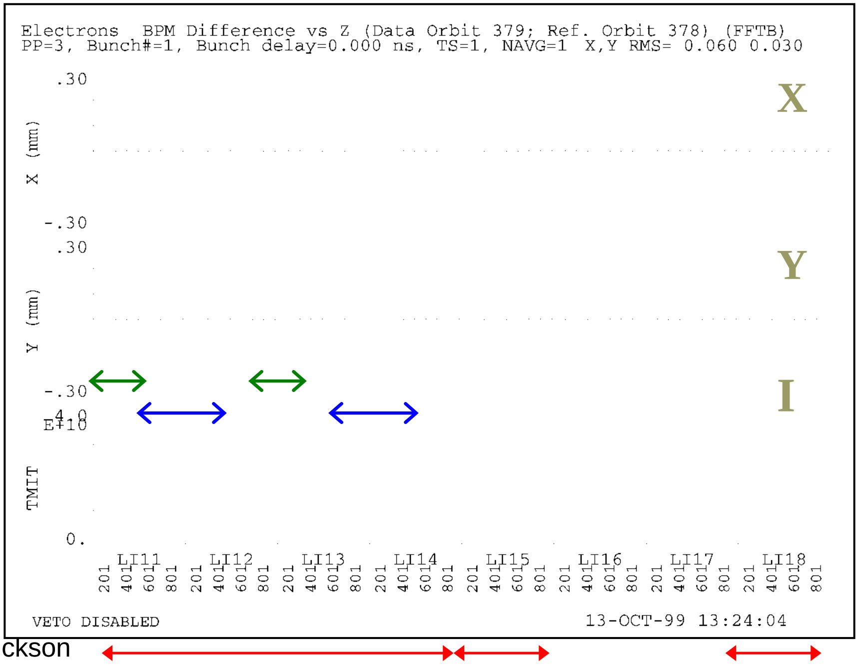
Red arrows show location and length of feedback regions

Blue arrows show locations of BPMs, Green arrows correctors

SLC layout



Distributed layout



ILC Beamsize growth effects, with feedback

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

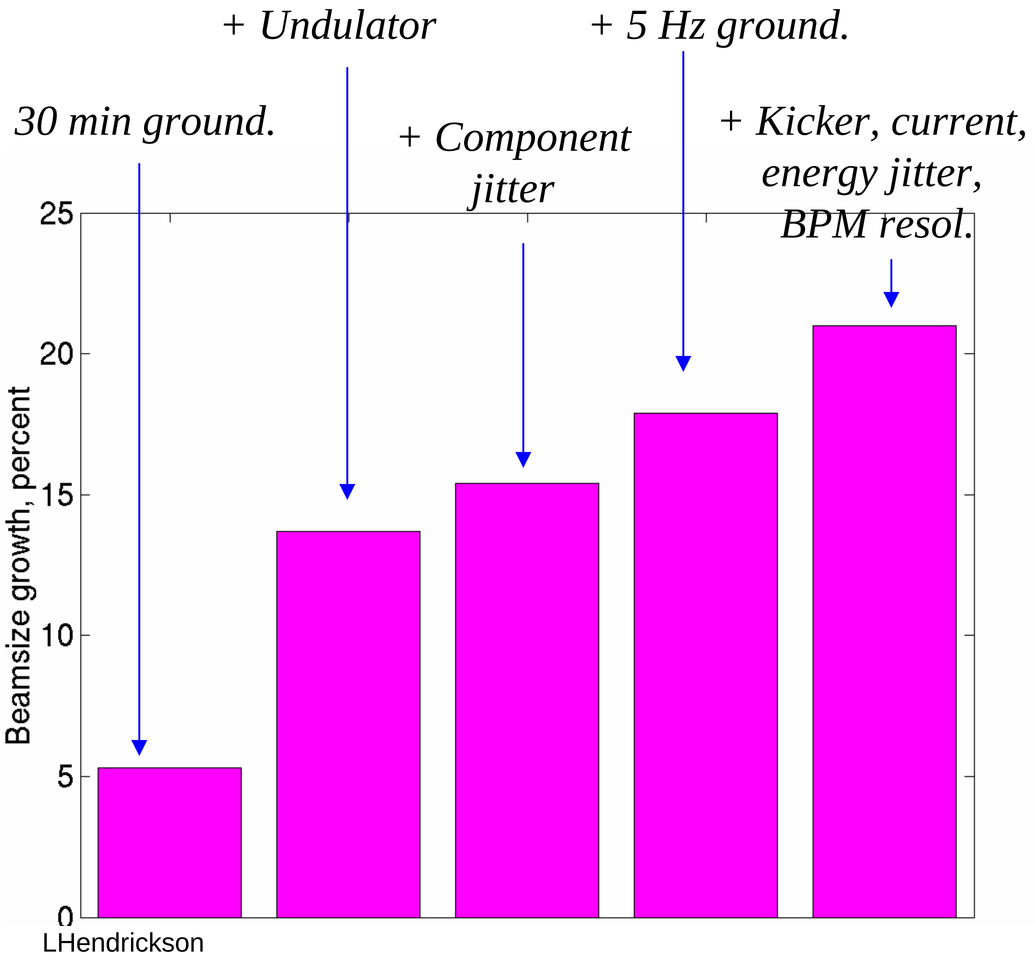
Perfect initially, add 30 minutes “KEK” ground motion”, let feedback converge -> 5% beamsize growth (380% without feedback).

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%.

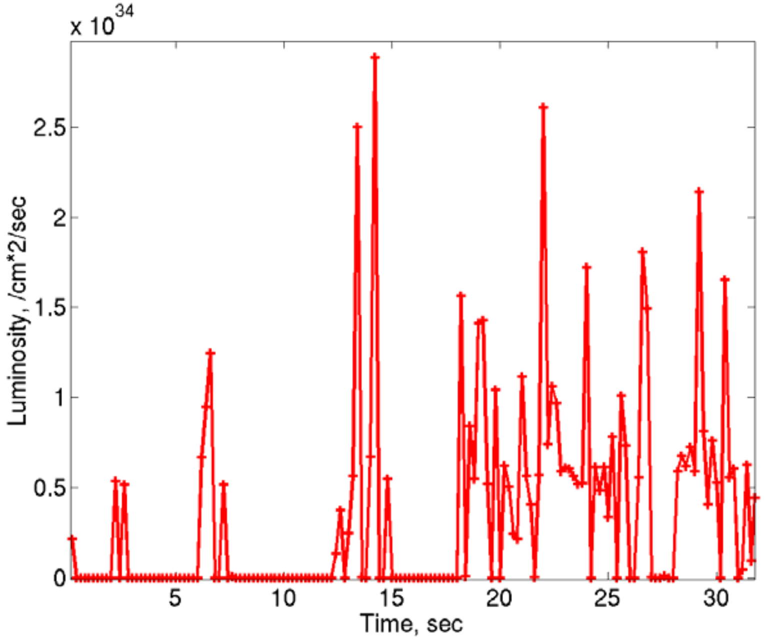
Add 5-Hz “KEK” ground motion -> 18%.

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

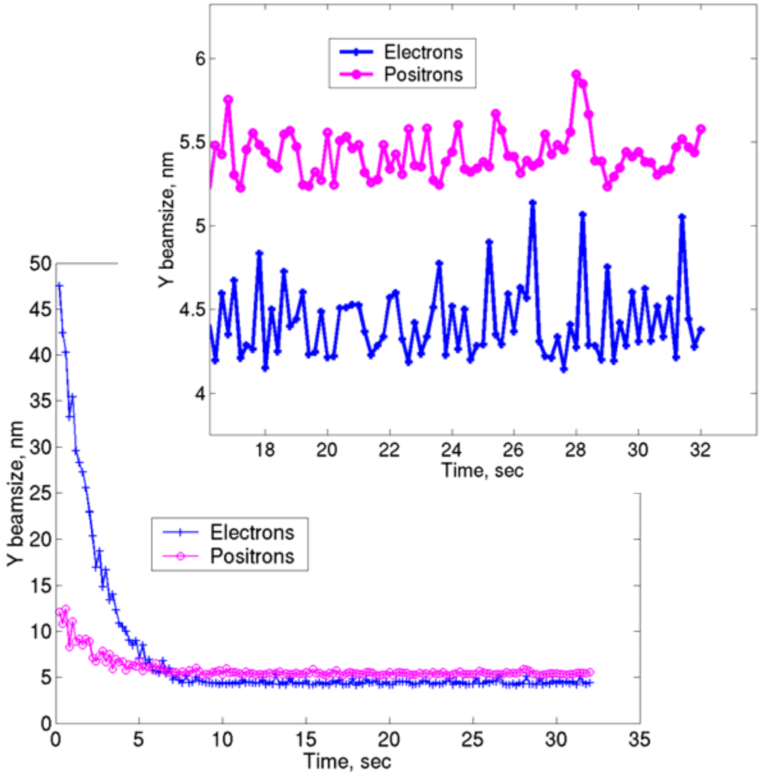


ILC 2-beam Integrated Feedback Simulations

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.