International Journal of Modern Physics A
© World Scientific Publishing Company

BEAM-BASED FEEDBACK SYSTEM FOR INTERNATIONAL LINEAR COLLIDER

V. Ivanov

Muons, Inc., 522 N.Batavia Ave., Batavia, Illinois 60510, USA,
vivanov@fnal.gov

Received Received Day Month Day
Revised Day Month Day

The algorithms and computer codes for linac Feedback system were developed at SLAC during 1991–2004. The efficiency of that system have been demonstrated for the SLC, CLIC, TESLA and NLC projects. International Linear Collider (ILC) has its own features. Ground motion (GM) oscillations play a dominant role here. It forced to implement a new version of the code [6] based on the previous developments [7–12]. A set of benchmark tests and realistic simulations for the whole ILC structure have been performed. The effects of different GM models, BPM resolution, time intervals, initial misalignments, a dispersion-free steering (DFS), and a quad jitter have been studied.

Keywords: Feedback system; Kalman's filter; particle accelerator

PACS numbers: 29.27.Bd; 43.38.Ew

1. Introduction

Feedback systems are necessary elements of modern linear colliders, providing an effective method for relaxing tight tolerances of the design. For the ILC, extensive feedback systems control the beam parameters, such as beam position, energy, final focusing luminosity, etc., under ground motion and other sources of perturbation. This system should include a number of sensors (beam position monitors) and actuators (dipole magnets). It allows precision beam tuning and provides pulse-to-pulse diagnostics.

2. Beam dynamics under ground motion (GM) and technical noise

Typical requirements for the ILC design parameters are:

- Electron and positron linacs of 10.5 km length each;
- Accelerating gradient = 31.5 MV/m in 1.3 GHz cavities;
- Injection energy = 15 GeV;
- Extraction energy = 250 GeV;
- Initial energy spread = 150 MeV;
- Bunch charge = 2×10^{10};

- Bunch length = 300 μm;
- Normalized vertical emittance = 20 nm;
- Normalized horizontal emittance = 800 nm;
- Main linac (ML) budget for vertical emittance = 8 nm;
- Optics: FODO lattice with β phase advance of 75°/60° in x/y plane.

Each quad has a cavity-style beam position monitor (BPM) and a vertical corrector—dipole magnet. A set of nominal initial misalignments in main linac (ML) includes:

- Quad offset = 300 μm;
- Quad rotation = 300 μrad;
- BPM offset = 300 μm;
- BPM resolution = 1 μm;
- Cavity offset = 300 μm;
- Cavity pitch = 300 μrad;
- Cryostat offset = 200 μm;
- Cryostat pitch = 20 μrad.

The simulations show the growth of vertical emittance in such a linac is more than 10,000 nm rad, so a dynamic beam-based alignment should be provided continuously after a static alignment.

The main sources of an emittance dilution are:

- Dispersion from Misaligned Quads or Pitched cavities;
- Transverse SR Wake fields: Misaligned cavities and cryomodules (CM);
- XY-coupling from rotated Quads;
- Transverse Jitter.

The GM was modeled with a 2-D power spectrum [14], which include a diffusive corrected ATL term and a set of isotropic plane waves (Figure 1):

$$P(\omega,k) = \frac{A}{\omega^2 k^2}\left[1 - cos\left(\frac{kB}{A\omega^2}\right)\right] + \sum_i D_i U_i. \tag{1}$$

$$U_i = \begin{cases} \frac{2}{\sqrt{(\omega/v_i)^2}}, & |k| \geq \frac{\omega}{v_i}, \\ 0, & |k| > \frac{\omega}{v_i}, \end{cases} \quad D_i = \frac{a_i}{1 + [d_i(\omega - \omega_i)/\omega_i]^4}. \tag{2}$$

Here the coefficients A, B, ω_i, a_i, d_i are individual sets for different sites: a quiet model A, an intermediate model B and an aggressive model C.

3. Static & dynamic beam-based alignment

There are three main schemes for a static alignment:

- **One-to-One Steering**: Find BPM readings for which the beam should pass through the exact center of every quad, and use the correctors to steer

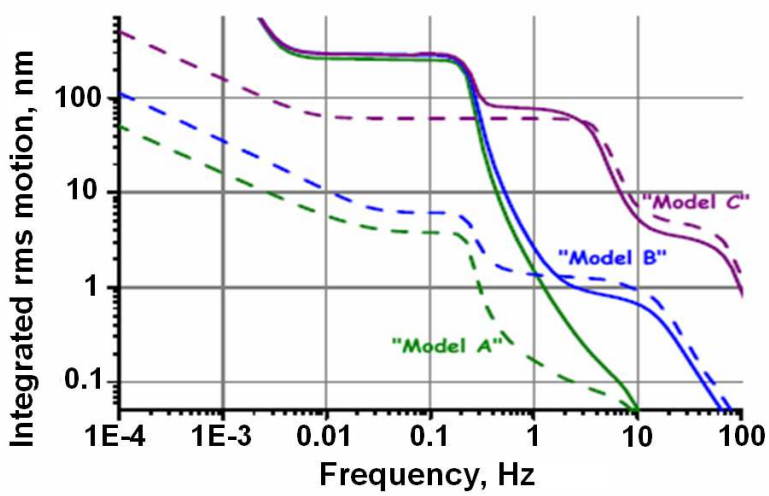

Fig. 1. The integrated absolute GM spectra (solid lines) and the integrated relative motion of 2 objects separated by 50 m distance (dashed lines).

the beam. The alignment generates a dispersion which contributes to the emittance dilution, and it is sensitive to the BPM-to-Quad offsets. Typically it reduces the emittance from ≈10,000 nm to ≈100 nm.

- **Dispersion Free Steering (DFS)**: Measure a dispersion via mismatching the beam energy to the lattice. Calculate the correction needed to zeroing the dispersion, and apply the correction. Make few iterations. This type of alignment can reduce the emittance growth to 5–7 nm.
- **Emittance (Dispersion & Wake) Bumps**: The goal is to minimize a beam size at the end of linac by varying the strength of the correctors. It can reduce the emittance growth to 2–3 nm.

The **Adaptive Alignment (AA) scheme** for a dynamic tuning [13] is a "local" method. It uses the BPM readings A_i of three (or more) neighboring quads to determine the correction for the central of them (Figure 2)

$$\Delta y_i = C\left\{A_{i+1} + A_{i-1} - A_i\left[2 + k_i L_i\left(1 - \frac{\Delta E}{2E}\right)\right]\right\}, \tag{3}$$

where C is a convergence factor, k_i is the inverse of i-th quad focusing length, L_i is the distance between successive quads, ΔE is the energy gain between successive quads, E is the beam energy at central quad.

The new position for the quad and BPM is $y_i^{new} = y_i^{old} - \Delta y_i$, and the procedure is repeated until the convergence is reached.

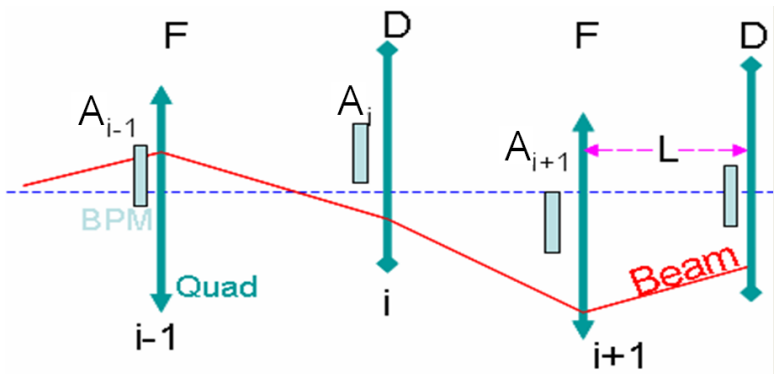

Fig. 2. Adaptive alignment scheme.

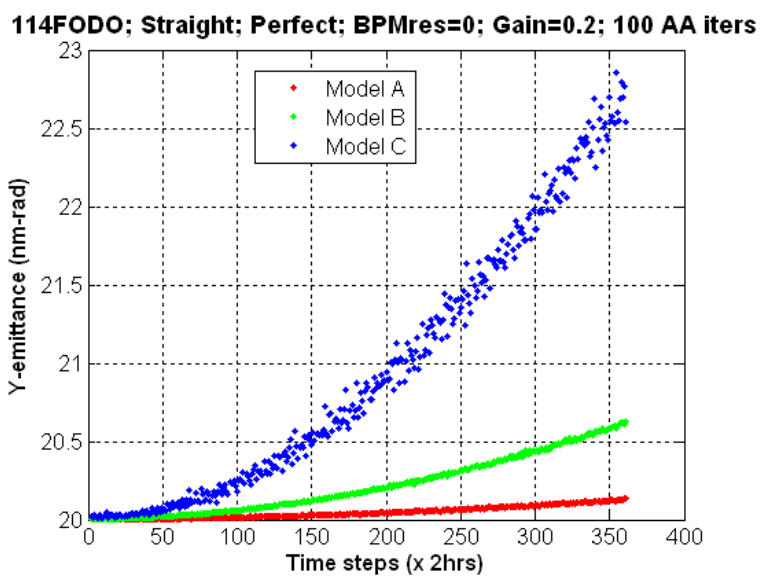

Fig. 3. Vertical emittance growth for the models A, B and C.

Figure 3 shows the emittance growth averaged over 20 GM random seeds after 100 AA iterations for initially perfectly aligned linac. The AA corrections have been applied each two-hour period after the GM. The total period of GM simulation is one month.

4. The Kalman filter model and the optimal control

The optimal control system is illustrated in Figure 4. Here the actuator vector $\vec{u}$ includes as a corrector signal as a measurement noise due to a limited BPM resolution. It affects on the control system via the state vector $\vec{X}$. Then the measurement

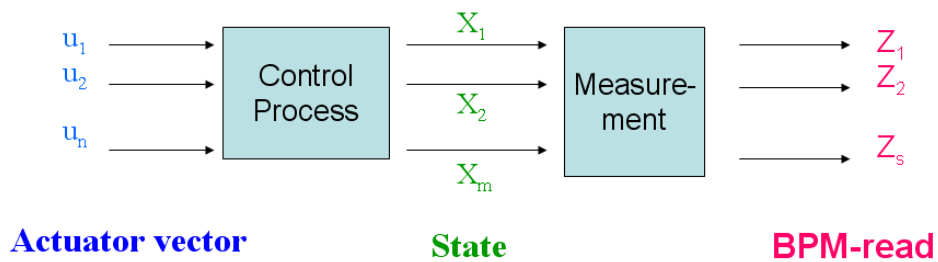

Fig. 4. Generalized scheme for the accelerator feedback system.

system produces the BPM-read vector $\vec{Z}$, which is used to update the new state vector.

In that way, the control procedure consists of two steps [16]. Step 1 **Prediction** evaluates the state ahead

$$X_k = \hat{A}X_{k-1} + \hat{B}u_k + w_k, \tag{4}$$

and projects the error covariance ahead

$$P_k = \hat{A}P_{k-1}\hat{A}^T + Q_{k-1}. \tag{5}$$

Here w_k is the process noise which is assumed to be drawn from a zero mean multivariate normal distribution with covariance Q_k.

Step 2 **Correction** computes the optimal Kalman gain

$$K_k = P_k\hat{H}^T(\hat{H}P_k\hat{H}^T + R)^-1, \tag{6}$$

updates the estimation with a measurement Z_k

$$X_k = X_K + K_k(Z_k - \hat{H}X_k), \tag{7}$$

and updates the error covariance

$$P_k = (\hat{I} - K_k\hat{H})P_k. \tag{8}$$

5. General feedback (FB) model in the "Linac Feedback System Code" (LFSC)

The computer program LFSC (Linac Feedback Simulation Code) is a numerical tool for simulation of beam based feedback in high performance linacs. The code LFSC is based on the earlier version developed by a group of authors at SLAC [7–12] during 1990–2005. Later work [17] studied the beam jitter in ILC also. That code was successively used in simulation of SLC, TESLA, CLIC and NLC projects. It can simulate pulse-to-pulse feedback on timescale corresponding to 5–100 Hz, as well as slower feedbacks operating in the 0.1–1 Hz range in the Main Linac and Beam Delivery System.

The FB model is described by the following system of equations

$$\begin{aligned} X_{k+1} &= \Phi X_k + \Gamma u_k + L(y - HX_k), \\ \tilde{u_k} &= -KX_{k+1} + Nr_k, \\ u_{k+1} &= +g(\tilde{u_k} - u_k). \end{aligned} \tag{9}$$

Here Φ is a system matrix for the dynamics of accelerator model; Γ is a control input matrix; L is a Kalman filter; H is an output matrix; K is a gain matrix; N is a controller-reference-input matrix; r is a vector of system set points; g is a gain factor.

6. Simple benchmarks (static and dynamic response)

The test problem we studied with LFSC was a perfectly aligned main linac of 114 FODO cells with 5 Hz repetition rate. The vertical offset for a Quad #50 varies as $dy_{50} = y_0 \cos(2\pi Ft)$, where amplitude $y_0 = 80\mu m$, and the frequency F varies in the range 0–0.5 Hz. The lattice with the only control loop is shown in Figure 5.

The efficiency of the control for static perturbation $F = 0$ is shown in Figure 6. The picture demonstrates the rate of decreasing of initial misalignment with time.

Dynamic response of the Kalman filter model is presented in Figure 7. One can see that initial misalignment can be effectively compensated for the perturbation frequencies ≤ 0.05 Hz.

7. FB system for ILC—main linac of 114 FODO cells

The lattice layout for entire main linac is presented in Figure 8. It includes 5 control loops. Two correctors of each loop have phase shift of 90° to make the efficiency of correction independent from their positions in the lattice. Eight BPMs in each loop are used for averaging of BPM-read to reduce the effect of limited BPM resolution.

Figure 9 demonstrates the efficiency of FB control for total period of simulation T=10 hours. Control signals applied to the correctors with an interval of 100 s.

8. Effects of BPM resolution, time interval and initial misalignment

There are many factors which determine the efficiency of a FB control system. The results presented in Figure 10 show that the BPM-read errors are negligible when the resolution is less the 1 μm.

Figure 11 shows the effect of time interval can preserve the vertical emittance for less than 10 hours of GM between corrections.

Beam position in the perfect aligned linac is shown in Figure 12 (left) for initial time moment and after 5 hours of FB control. Right picture shows the dynamics of vertical emittance for that case.

Figure 13 shows the beam position for random initial misalignments at different time moments.

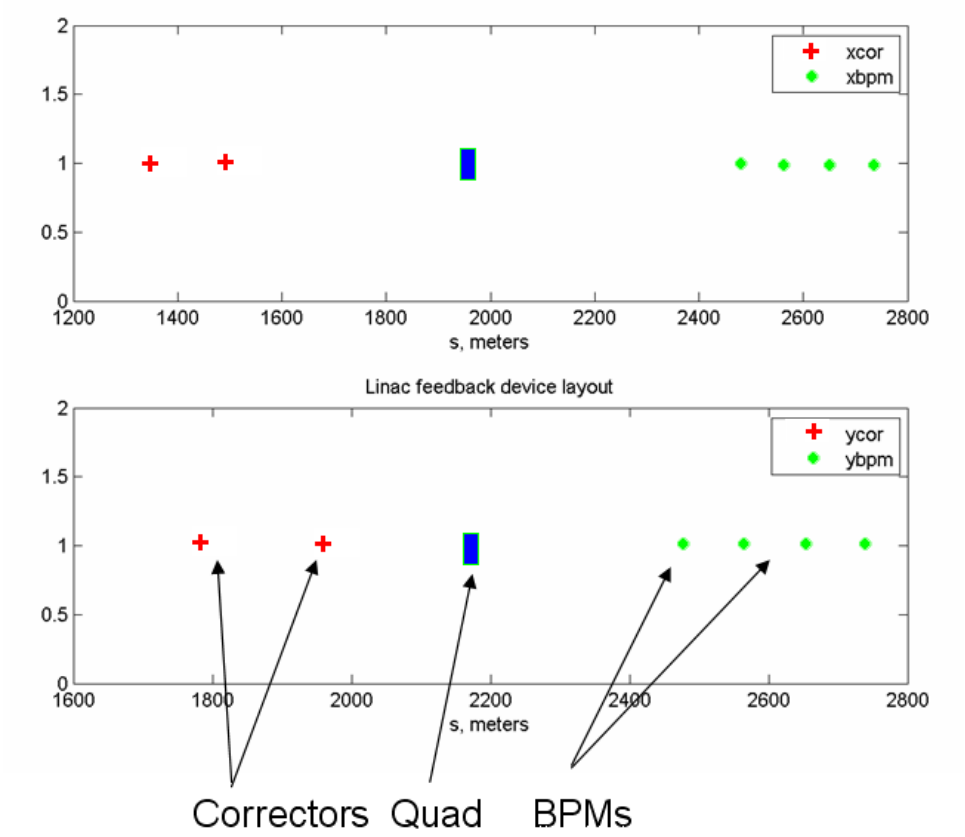

Fig. 5. Lattice layout: one FB loop of 2 correctors, 4 BPMs in each direction.

References

1. V.Ivanov. Dynamic Alignment in Presence of Ground Motion & Technical Noise, The 9th International Workshop on Accelerator Alignment, Sept. 25-29, 2006, SLAC, Stanford, CA, USA.
2. K.Ranjan, N.Solyak, V.Ivanov. Adaptive Alignment and Ground Motion. European Linear Collider Workshop, Daresbury Lab., Jan. 8-11, 2007, Daresbury, Great Britain.
3. K.Ranjan, N.Solyak, V.Ivanov. Dynamic simulations of Ground Motion & Adaptive Alignment. May.13 - June 3, Hamburg, 2007 Int. Linear Collider Workshop, Hamburg, Germany.
4. K.Ranjan, N.Solyak, V.Ivanov, S.Mishra. Study of Adaptive Alignment as Beam Based Alignment in ILC Main Linac in the Presence of Ground Motion, June 25-28, Albuquerque, PAC-2007, USA.
5. V.Ivanov, N.Solyak. Adaptive alignment for Main Linac. LET Beam Dynamics Workshop at SLAC, Dec. 11-12, 2007, SLAC, Stanford, CA, USA.
6. V.Ivanov. LFSC - Linac Feedback Simulation Code, User's Guide. Fermilab-TM-2409-CD, 2008.
7. T.Himel, L.Hendrickson et al., Use of Digital Control Theory State Space

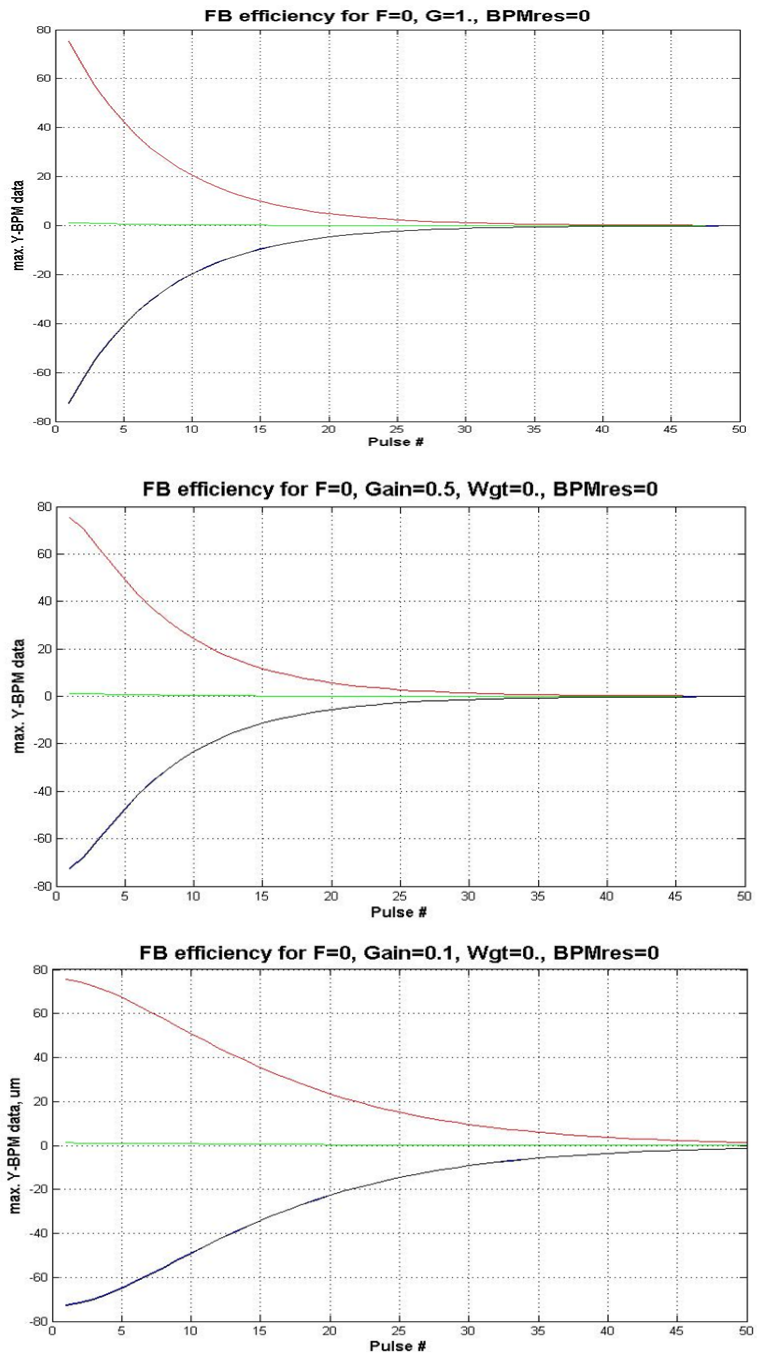

Fig. 6. Static response vs. gain g=1 (top), g=0.5 (middle) and g=0.1 (bottom). Different lines correspond to different BPMs.

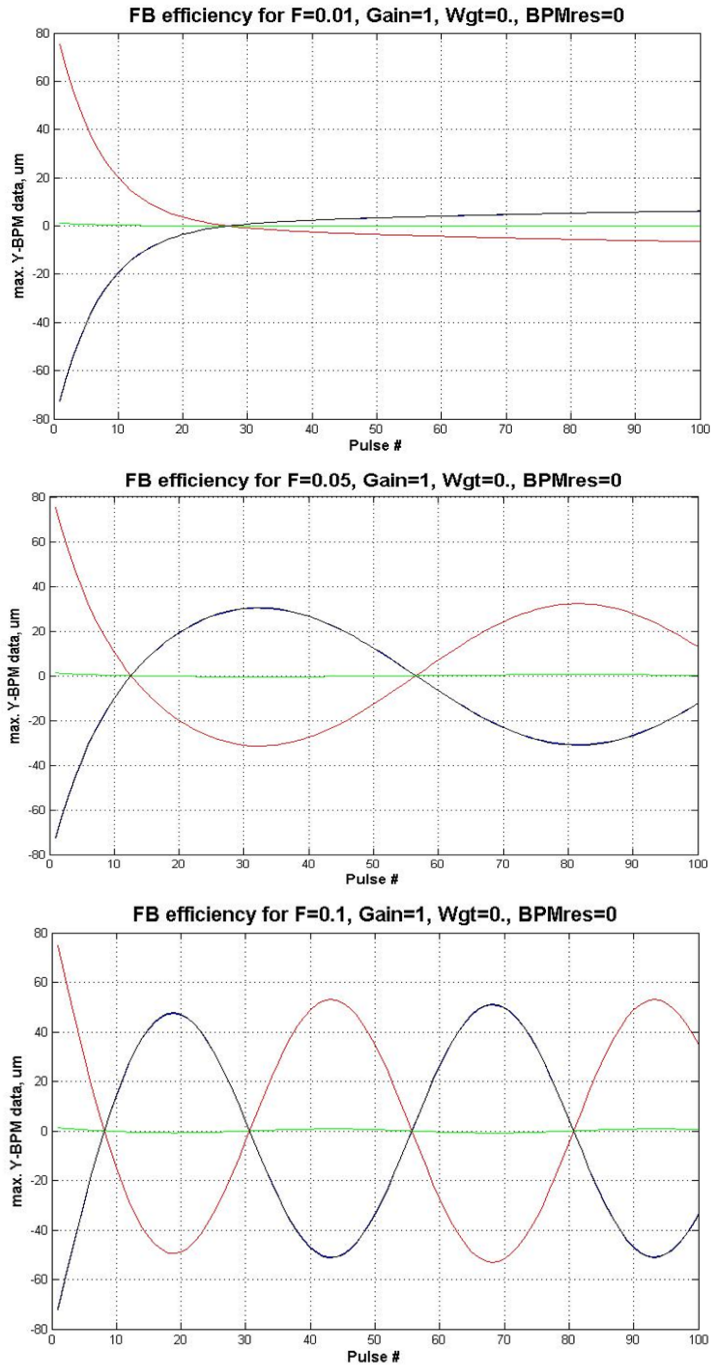

Fig. 7. Dynamic response for a varying frequency of perturbation; F=0.01 Hz (top), F=0.05 Hz (middle) and F=0.1 Hz (bottom).

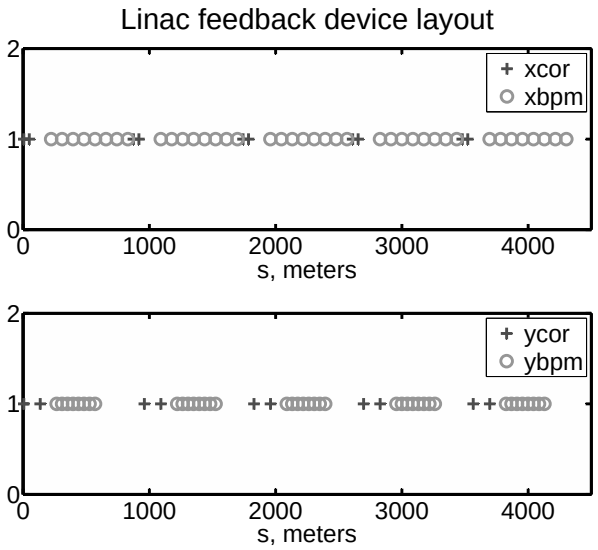

Fig. 8. Lattice layout: 5 FB loops of 2 correctors, 8 BPMs in each direction.

Formalism for Feedback at SLC, in Proc. of IEEE Part. Accel. Conf., SLAC-PUB-5470 (1991).

8. T.Himel et al., Adaptive Cascaded Beam-Based Feedback at the SLC, in Proc. of IEEE Part. Accel. Conf., SLAC-PUB-6125 (1993).
9. L.Hendrickson, S.Alison, T.Gromme et.al. Tutorial on beam-based Feedback systems for linacs, SLAC-PUB-6621, August 1994.
10. L.Hendrickson et.al. Feedback systems for linear colliders, SLAC-PUB-8055, April 1999.
11. P.N.Burrows et al., Nanosecond-timescale intra-bunch-train feedback for the linear collider, SLAC-PUB-11185, 2004.
12. L.Hendrickson et al., Beam-based Feedback for the NLC Linac, SLAC-PUB-10493, 2004.
13. V. Alexandrov, V. Balakin, A. Lunin, Experimental test of the adaptive alignment of the magnetic elements of linear collider, Proc. of XVIII International Linac Conference, 26-30 August 1996, Geneva, Switzerland.
14. A.Seryi et al., Recent developments of LIAR simulation code, EPAC'02, Paris, France.
15. P.Tenenbaum, Lucretia: A MATLAB-based toolbox for the modeling and simulation of single-pass electron beam transport systems, Proc. of 2005 Particle Accel. Conf., Knoxville, Tennessee.
16. http://en.wikipedia.org/wiki/Kalman_filter#The_Kalman_filter
17. A. Seryi, L. Hendrickson, G. White, Issues of stability and ground motion in ILC, SLAC-PUB-11661, January 2006.

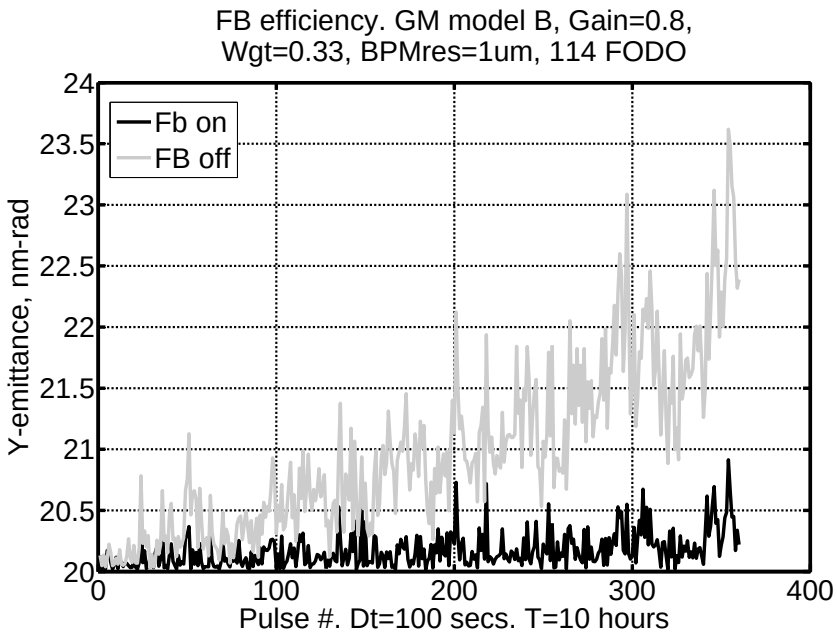

Fig. 9. The effect of FB control for entire linac; GM model B. BPM resolution = 1 μm.

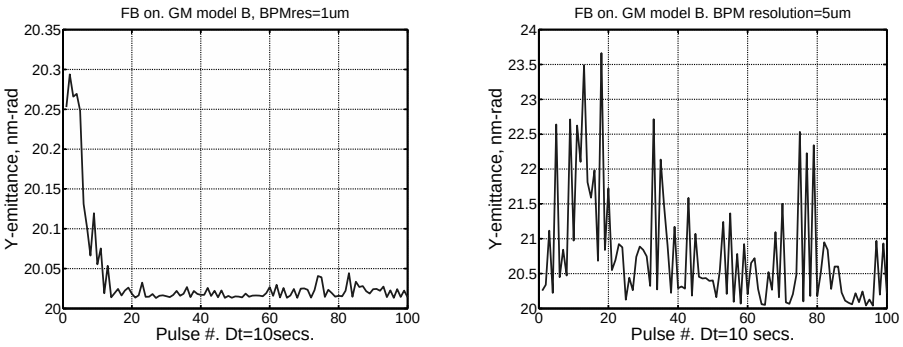

Fig. 10. Dynamics of vertical emittance for BPM resolution 1 μm (left) and 5 μm (right).

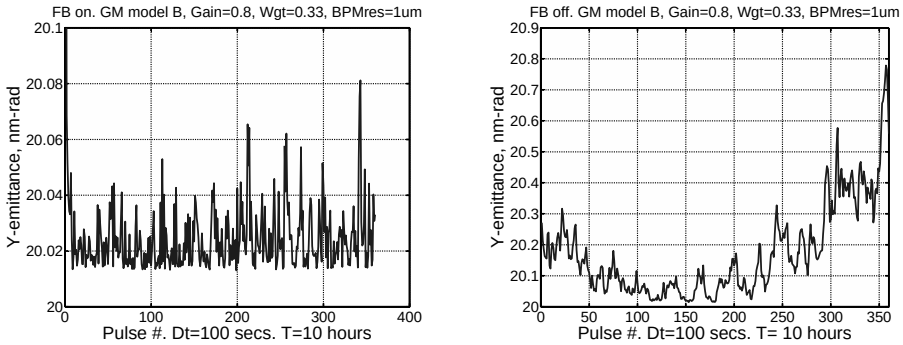

Fig. 11. Dynamics of vertical emittance for time interval of 1 hour (left) and and 10 hours (right) of GM between corrections.

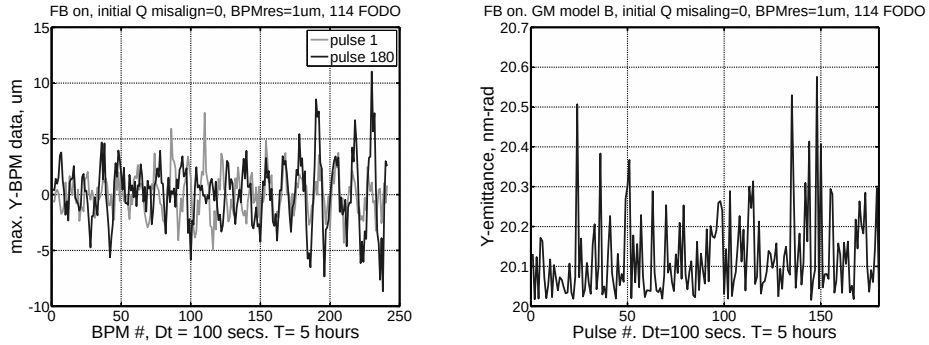

Fig. 12. Dynamics of a beam position (left) and vertical emittance (right) for perfect aligned linac.

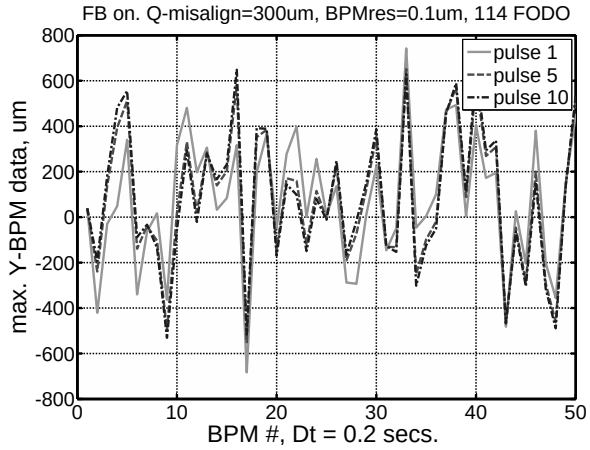

Fig. 13. Dynamics of a beam position for a random initial misalignment of 300 μm. Pulse 1—solid line, pulse 5—dashed line, pulse 10—dash-dotted line.