ILC Feedback System Studies

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Outline

- Cascaded feedback control
- Adaptive Alignment feedback control
- Conclusions and plans

Multi-Cascaded Feedback control

- Proposed and realized at SLAC for SLC linac at 1990th

  Generalized Fast Feedback System in the SLC,
  L. Hendrickson et.al., SLAC-PUB-5683 (Nov.1991)

- NLC Feedback studies (~2000-2004)

- ILC feedback studies 2006 -2008

FEEDBACK CALCULATIONS

The feedback algorithm can be summarized equations which are based on the predictor-corrector formalism of digital control theory.

$$\hat{\mathbf{x}}_{\mathbf{k}+1} = \mathbf{\Phi}\hat{\mathbf{x}}_{\mathbf{k}} + \mathbf{\Gamma u} + \mathbf{L}(\mathbf{y} - \mathbf{H}\hat{\mathbf{x}}_{\mathbf{k}})$$

Est. values of states, associated with FB loop, based on the previous state, actuator settings, and meas.

$$\tilde{\mathbf{u}}_{k+1} = \mathbf{K}\hat{\mathbf{x}}_{k+1} + \mathbf{N}\mathbf{r}_{k}$$

Calc. actuator settings based on the estim. state vector

$\mathbf{x}_{\mathbf{k}}$ estimate of the state vector on the kth pulse.

Φ - system matrix and describes the dynamics of the accelerator model.

Γ - control input matrix. It describes how changes in the actuators should affect the state.

u - actuator vector. It contains the current actuator settings with reference values subtracted.

L - Kalman filter matrix. Given an error on the estimate of the sensor readings, it applies a correction term to the estimate of the state vector.

y - measurement vector. It contains the current meas. with reference values subtracted.

H - output matrix. It maps the state vector to the output vector. That is, given an estimate of the states, it gives an estimate of what the sensors should read.

K - gain matrix. It is derived in a manner similar to **L**. It is designed to minimize the RMS of selected state vector elements.

N - controller-reference-input matrix. It maps the reference vector to actuator settings and is directly derivable from the model of the accelerator.

r - reference vector which contains setpoints for the states controlled by the loop.

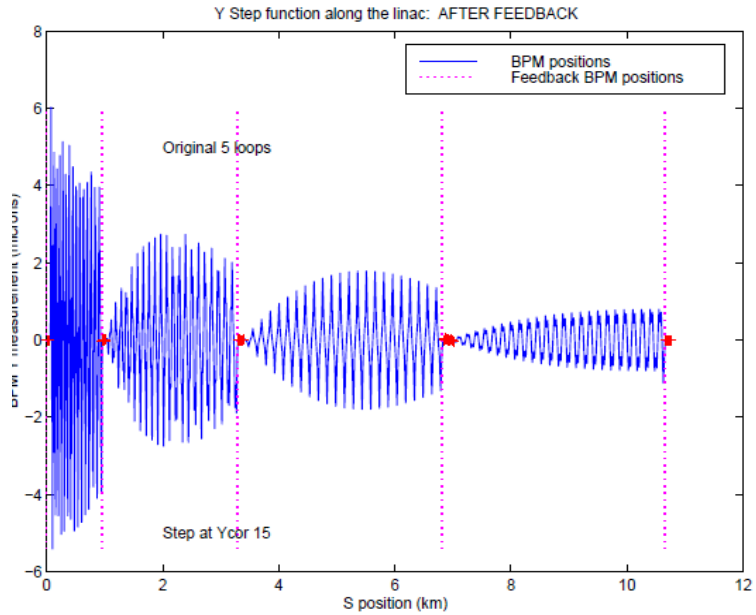
Cascaded Fast Feedback in NLC

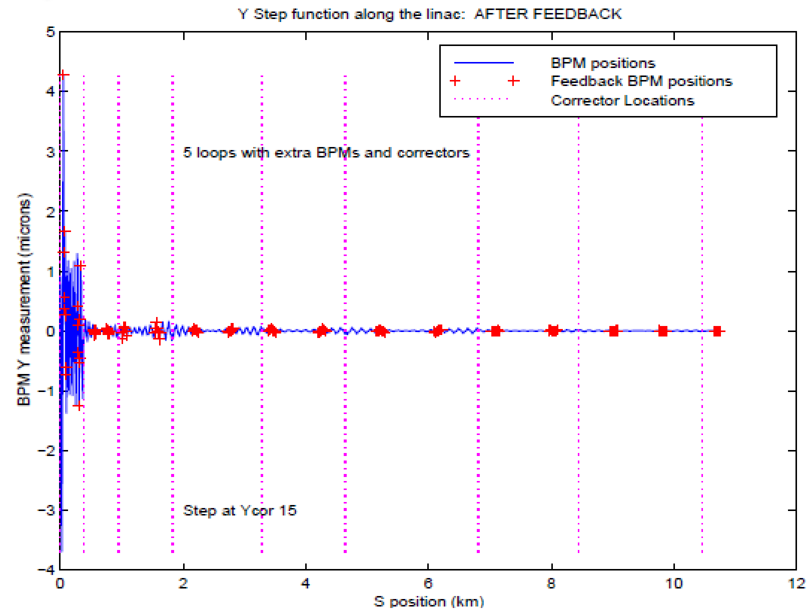
In the NLC multi-cascade scheme, each feedback receives information from all of the upstream loops. The beam transport is an overconstrained least squares fit matrix, which converts many upstream states to the fitted downstream location. The simulations used 30 minutes of ATL-like GM with a coefficient of 5.0e-7 µm2/m/sec, a typical value for the SLAC site. The BPM resolution was 0.1 µm and results from 100 random seeds were averaged.

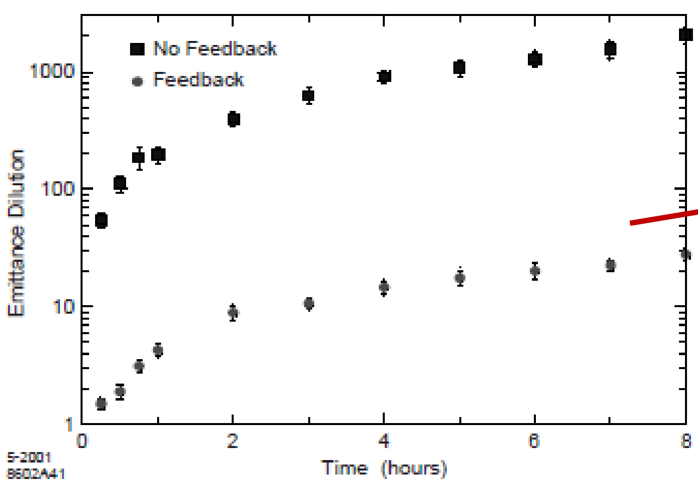
# Feedback Loops	# BPMs per loop	# Cors per loop per plane	Emittance Growth (%)
0 (off)	0	0	104
5	16	2	31
5	8	4	21
5	16	4	5.7

Beam-based Feedback Simulations for the NLC Linac*, (Sept.2000)
L. Hendrickson, N. Phinney, P. Raimondi, T. Raubenheimer, A. Seryi, P. Tenenbaum

NLC studies (cont.)







Evolution of the emittance at the end of the NLC main linac under the influence GM *("ATL" coeff = 5.10^{-7}m^{2}/m/sec)*

A set of 9 FB loops are sufficient to maintain the desired emittance for several hours.

After ~ 8hrs, even with the FB loops unacceptable emittance dilution is observed.

Feedback Systems for Linear Colliders,
L. Hendrickson *et al.* PAC99

Developments in beam-based Alignment and Steering of the NLC Main Linac, SLAC-Pub 8933, 2001
P. Tenenbaum, L. Hendrickson, T.O. Raubenheimer

Ground motion models

A.Seryi et.al., " Recent developments of LIAR Simulation Code", EPAC 2002

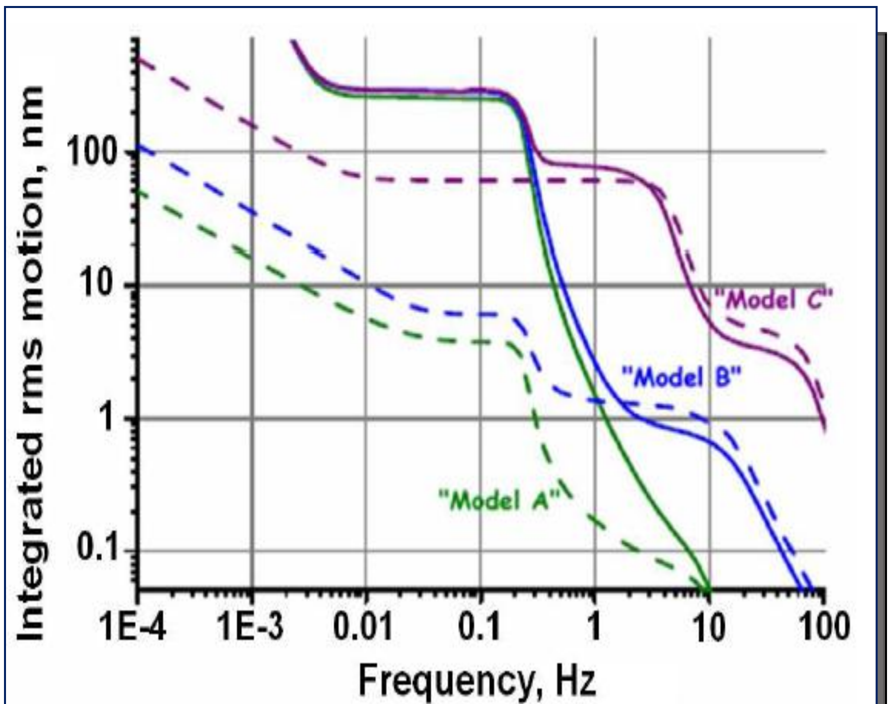
GM is Modeled with a 2-D Power Spectrum P(w,k)

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

Diffusive corrected "ATL" — Isotropic plane wave motion

$$U_i = \begin{cases} \frac{2}{\sqrt{(\omega/v_i)^2}}, & |k| \geq \frac{\omega}{v_i}, \\ 0, & |k| > \frac{\omega}{v_i}, \end{cases}$$

$$D_i = \frac{a_i}{1 + [d_i(\omega - \omega_i)/\omega_i]^4}$$



Different GM Models in LIAR/Lucretia

Parameter	A Model	B Model	C Model	KEK (4AM)	KEK (10AM)
A (m/s)	1E-19	5E-19	1E-17	1E-17	1E-17
B (m^2/s^3)	5E-19	1E-18	5E-18	5E-18	5E-18
Resonances Freq. (Hz) ω_i	0.001 0.2 5	0.001 0.2 4.5	0.14 2.5 50	0.012 0.22 0.5 3.0 10.0 20.0	0.012 0.22 1.1 2.0 3.0 10.0 20.0
Amplitude (m^2 s) a_i	1E-9 3.5E-13 1E-21	1E-9 3.5E-13 2.5E-20	1E-11 1E-15 1E-19	1E-10 1E-11 5E-15 5E-16 1.5E-18 1.3E-20	3E-10 1.5E-13 2.0E-15 1.5E-15 5.0E-15 1.8E-17 5.0E-19
"d" (~1/width) d_i	1.0 3.5 1.3	1.0 3.5 0.35	5 1.5 1.5	1.0 5.5 2.0 8.5 3.5 3.0	0.7 6.5 7.0 3.0 8.0 5.5 4.0

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

ISSUES OF STABILITY AND GROUND MOTION IN ILC

A. Seryi, L.Hendrickson, G.White, SLAC (SLAC-PUB-11661, Jan. 2006)

Assumptions:

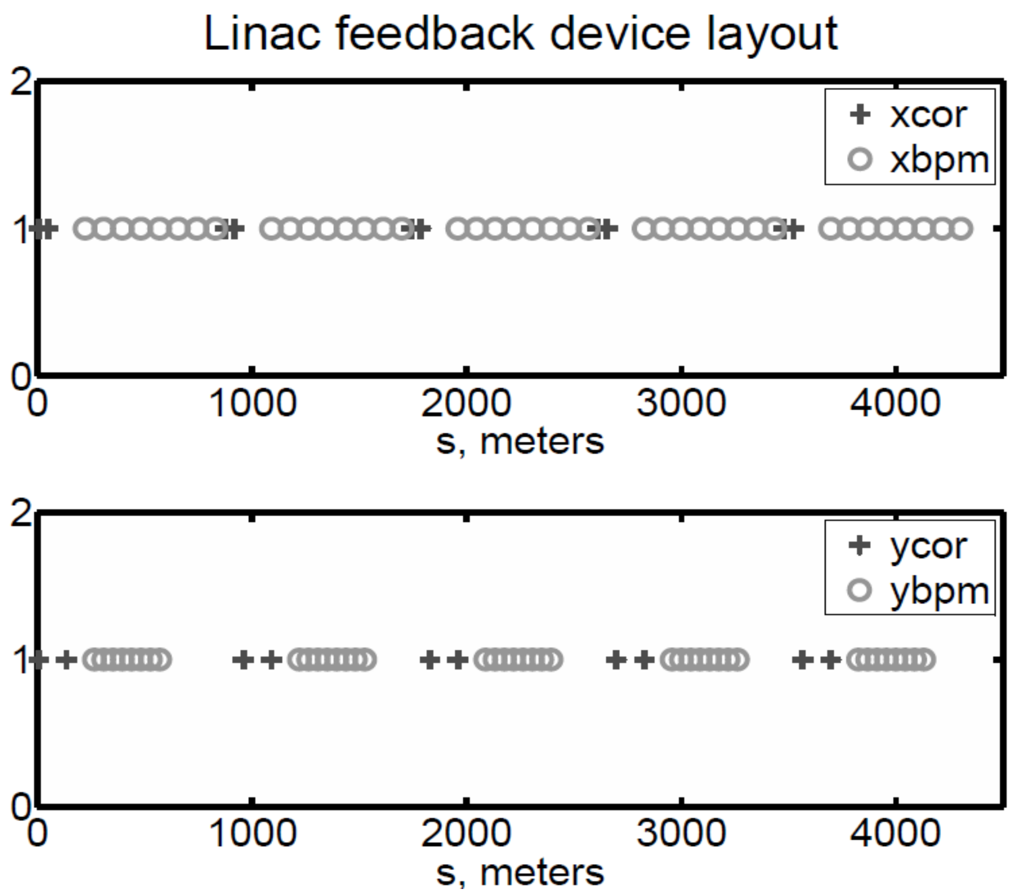
- Integrated simulations of ILC, from linac entry to the IP were set up with 5Hz feedback and idealized IP feedback. GM models: B, C and K
- ML: 5 distributed 5Hz FB loops in (each with 4X and 4Y dipole corr. and 8 BPMs) were cascaded and have exp. response of 36 pulses.
- In BDS there was one loop, with 9 BPMs and 9 dipole correctors.
- The IP deflection (X&Y) in 5Hz loop was not cascaded and has 6 pulse exponential response.
- Additional component jitter of up to 25 nm in BDS and 50 nm in ML.
- DR: extraction jitter 10% of beam sigma. The beam current jitter 5%.
- RF jitter: 0.5%,2°uncorr. ampl./phase on each klystron; 0.5°corr. phase
- The BPM resolution was assumed to be 100 nm.
- Beam jitter at the end of ML ≤50% of beam size

Summary of ILC stability goals:

1. ML: Up to gm "C" with additional component jitter ≤ 30nm
2. BDS: Up to gm "C/3" (or "B*3") and component jitter ≤10nm
3. GM and component jitter contribute to lumi degradation equally

FNAL activity in cascaded FB studies

- In 2008 Linda Hendrickson algorithms was implemented and used with Lucretia code. Continue SLAC ILC studies for ML and RTML.



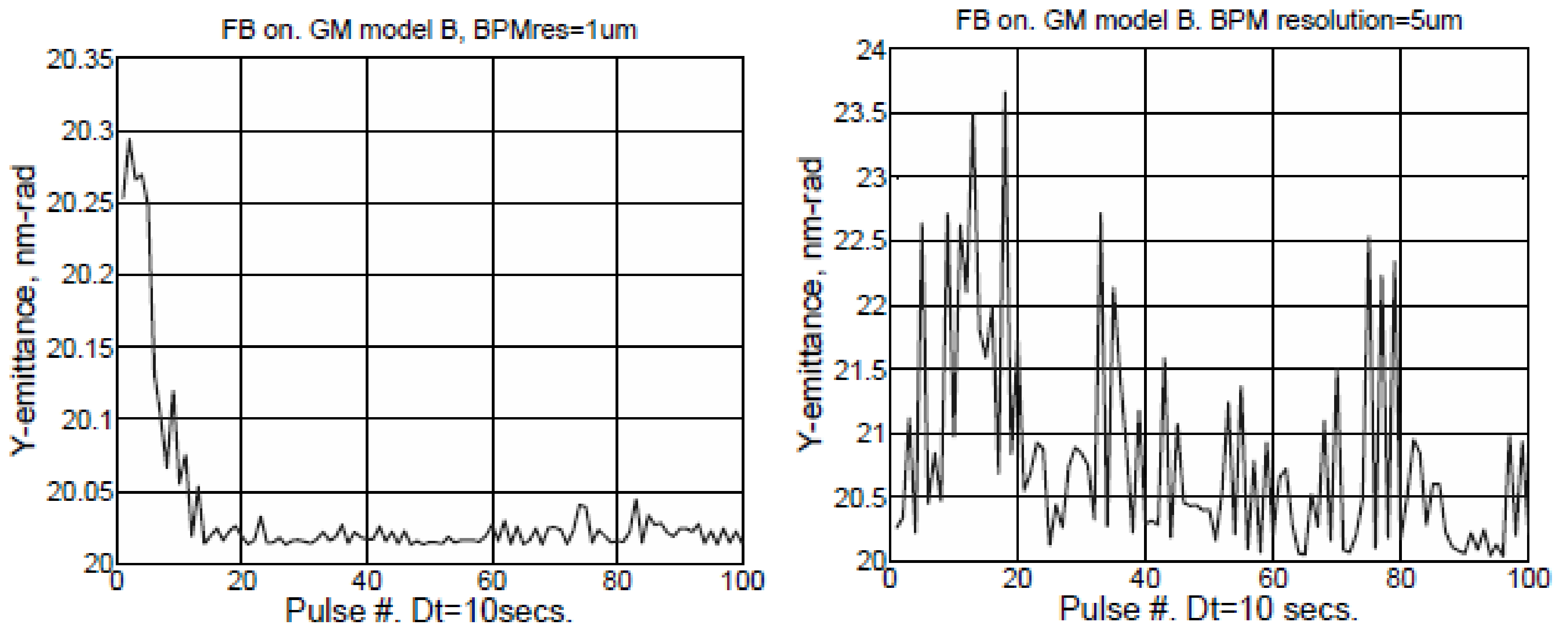
Studies of FB efficiency vs. number of model parameters

- Gain parameter
- Frequency response
- BPM resolution
- GM models

V.Ivanov, N.Solyak

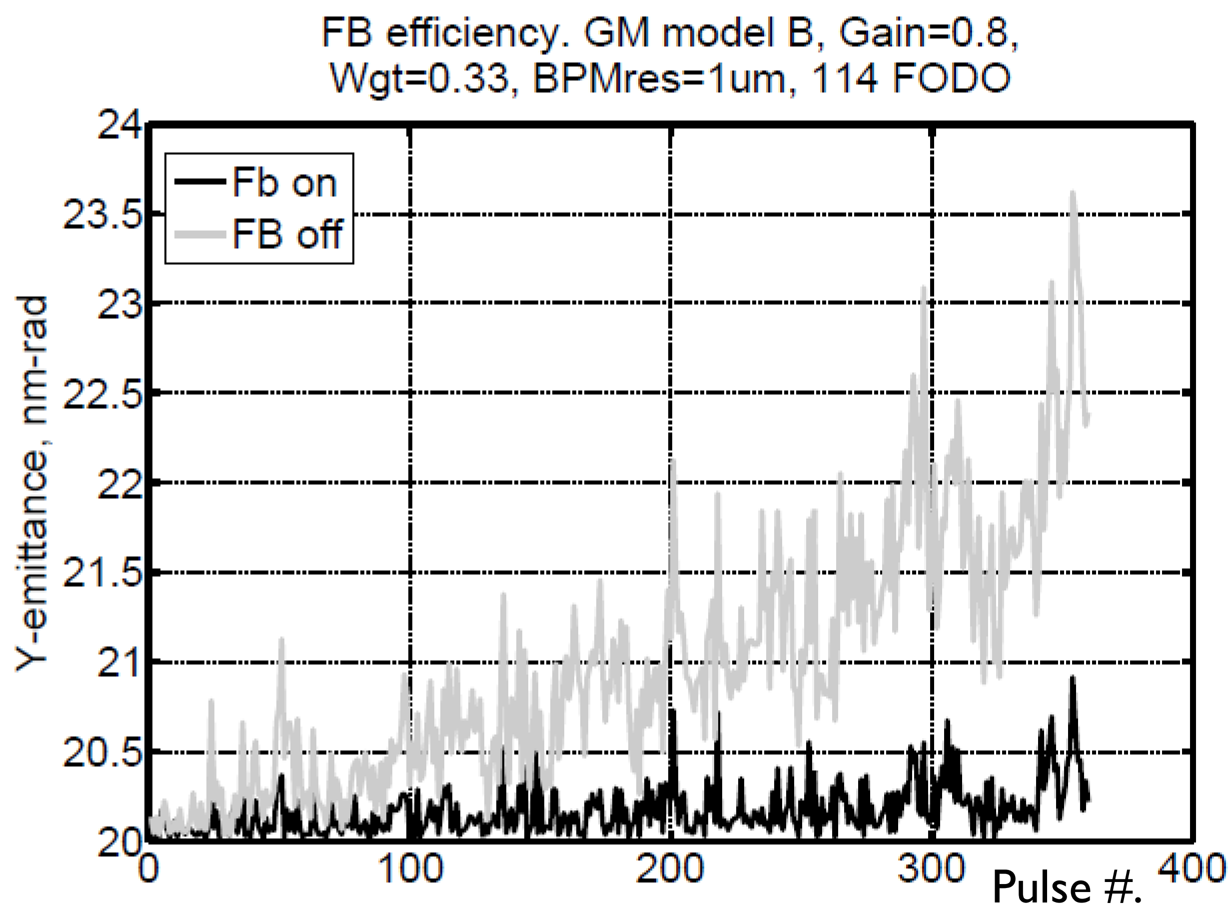
ML like lattice layout: 5 FB loops of 2 correctors, 8 BPMs in each plane

Effect of BPM resolution



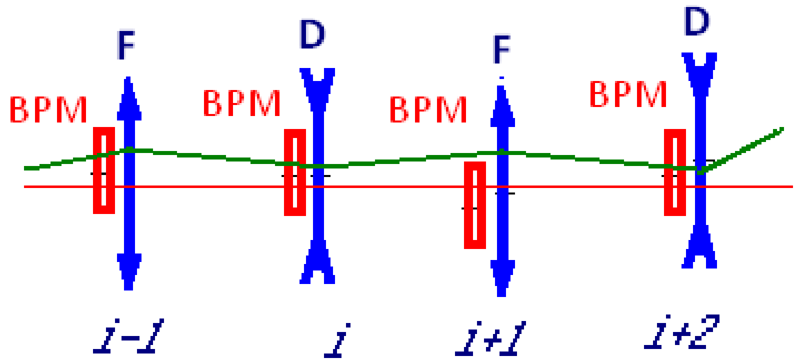
Dynamics of vertical emittance for BPM resolution 1 μm (left) and 5 mμ (right)
Ground motion model B

Efficiency of Feedback control



The effect of FB control for entire initially aligned linac . Period of simulation T=10 hours. Control signals applied to the correctors with an interval of 100 s.

Adaptive Alignment (AA) – Basic Principle



Proposed by V. Balakin (1991) for VLEPP project

"local" method: BPM readings (Ai) of only 3 (or more) neighboring quads are used to determine the shifting of the central quad (Δy_i).

$$\Delta y_i = cnvg \cdot (a_{i-1} + a_{i+1} - a_i(2 - K_i L \cdot (1 - \frac{\delta E}{2E_i}))$$

cnvg : Convergence parameter (< 0.3)
a_i : BPM reading
K_i : Quad strength
L : Distance between successive quads
δ**E** : Energy gain between successive quads
E : Beam Energy at central quad
The procedure is iteratively repeated

New position of quad & BPM:

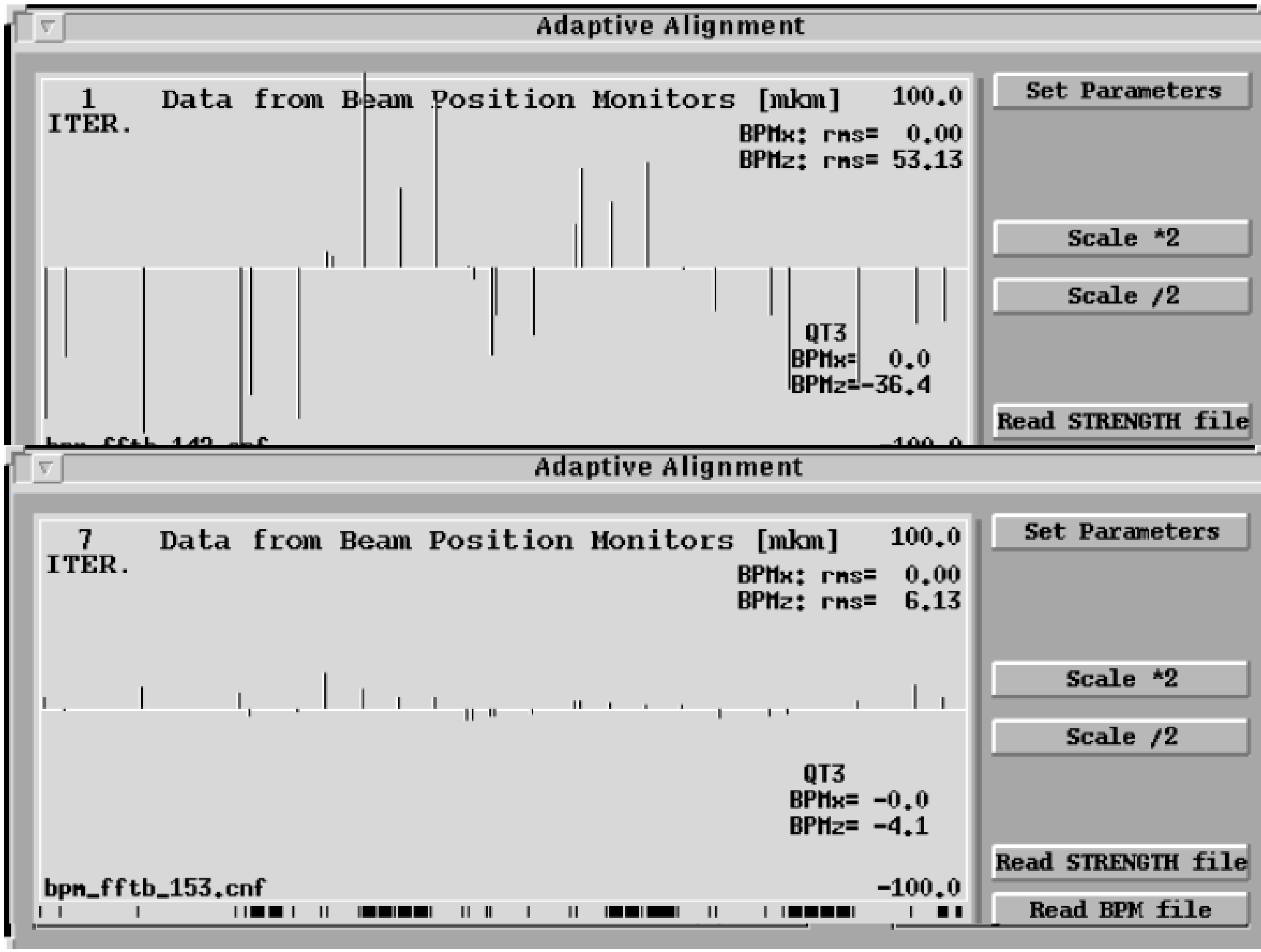
$$y_i^{new} = y_i^{old} - \Delta y_i$$

More general case:

$$\Delta X_i = \left(B_{i+1}\frac{a_{i+1}}{L2} + B_{i-1}\frac{a_{i-1}}{L1} - B_i \cdot a_i \cdot \left(\frac{1}{L1} + \frac{1}{L2} - K_i \cdot \left(1 - \frac{1}{2}\cdot\frac{\delta E}{E} \right) \right) \right) \cdot \frac{L1 \cdot L2}{(L1+L2)} \cdot Cnvg$$

$$B_i = 1 - \frac{K_i \cdot s}{4}$$ *s - quad length*

AA test at SLAC, 1996



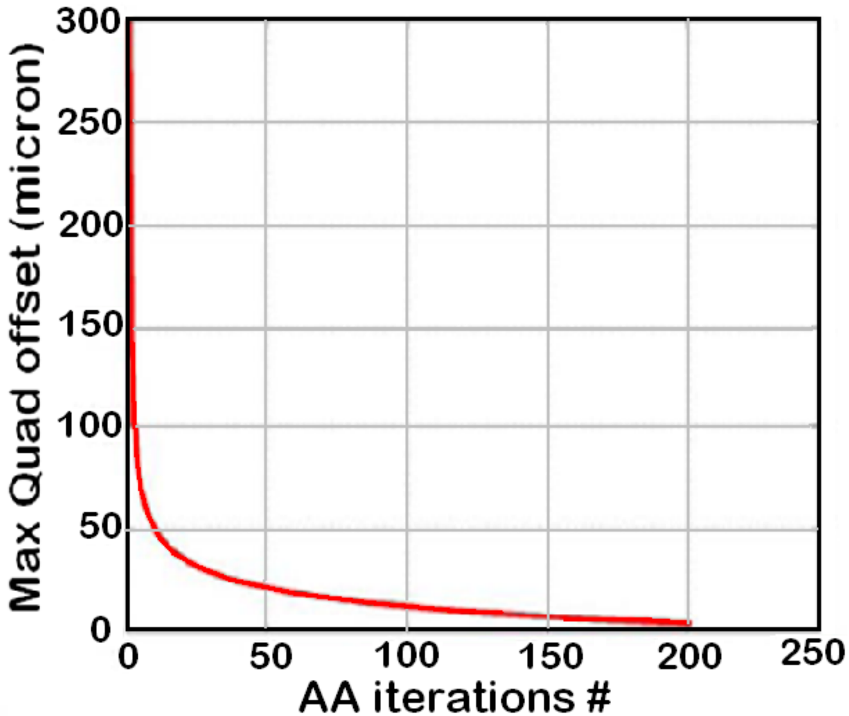
Experimental Test of the Adaptive Alignment of the Magnetic Elements of Linear Collider, V.Balakin et. al; Linac 1996.

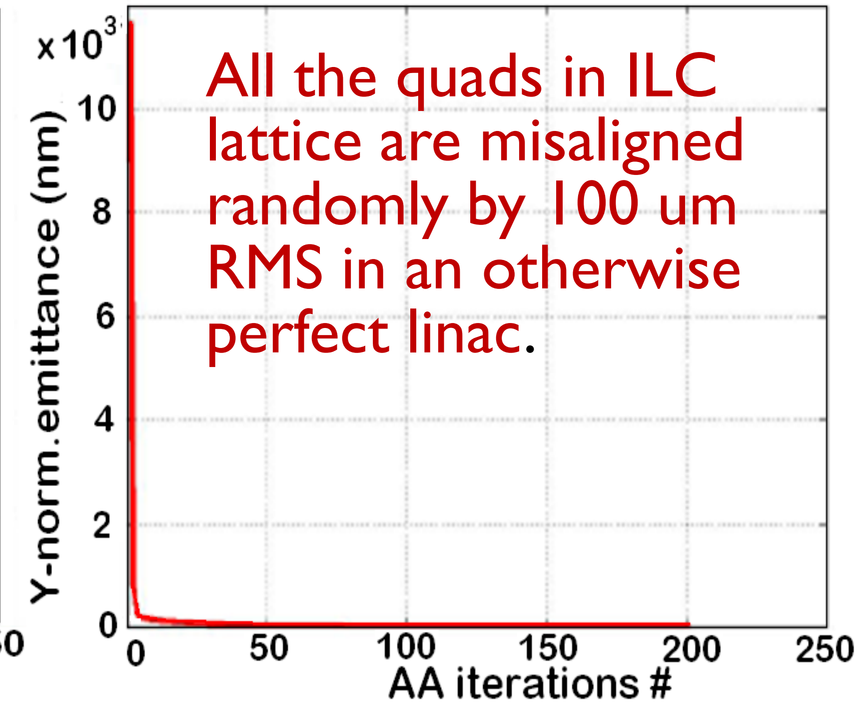
ILC ML parameters, initial misalignments:

- Bunch length = 300 μm;
- Norm. vertical emittance = 20 nm;
- Norm. horizontal emittance = 800 nm;
- ML budget for vert. emittance = 8 nm;
- FODO lattice: μ= 75°/60° in x/y plane.

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

Example of AA, no GM

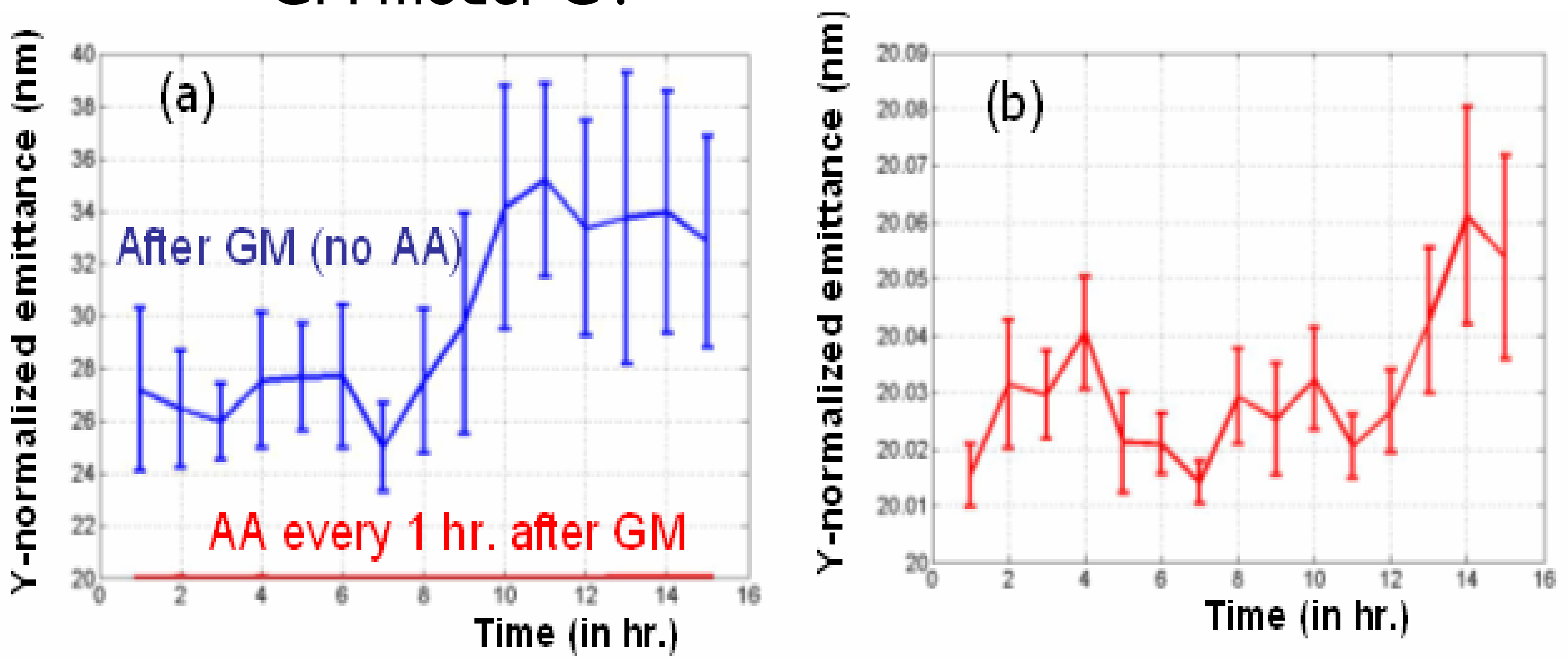




- AA procedure smoothes out the beam thrusts, and decreases the emittance growth significantly from ~12000nm to ~20nm (initial). Gain=0.2
- Sensitive to BPM-Q offset and BPM resolution

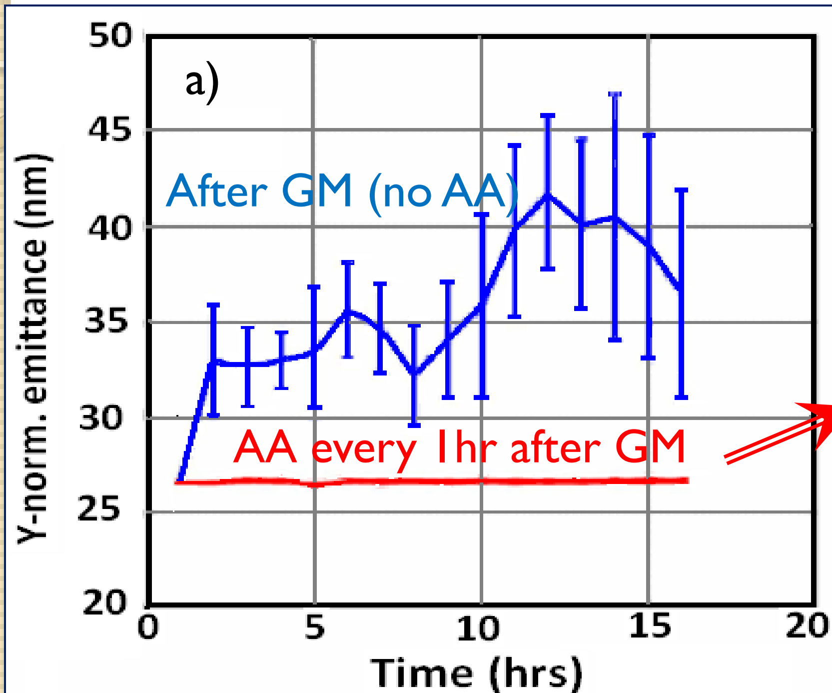
Effect of GM in perfectly aligned linac

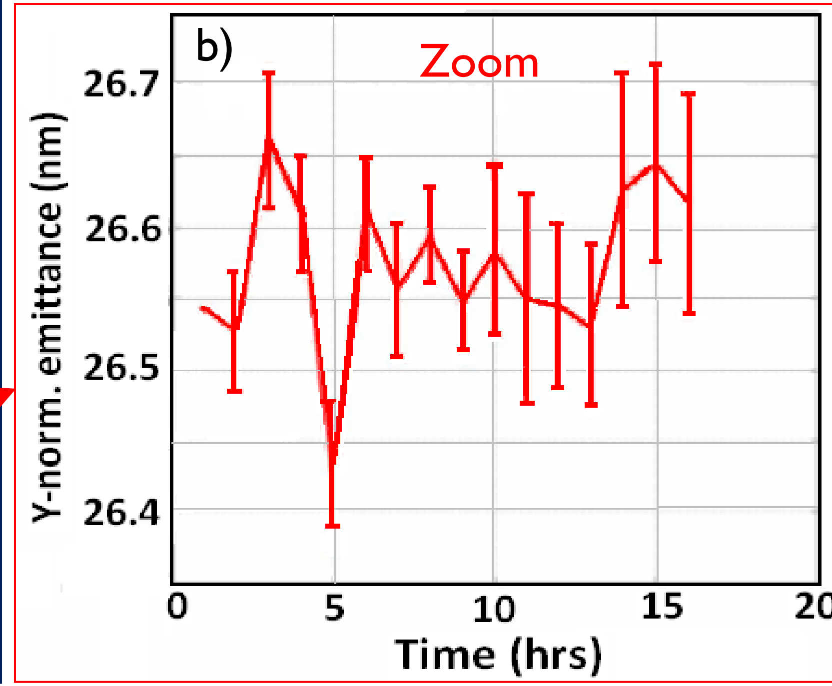
GM model 'C'.



(a) Normalized vertical emittance vs. time in a perfectly aligned linac. AA of 100 iterations and 0.3 convergence factor is implemented after every one hour of GM model 'C'. (b) A blown-up portion of the plot after Adaptive Alignment. AA is implemented after intervals of 1 hour after GM.

AA with GM after static alignment (1-2-1, DFS and bumps)



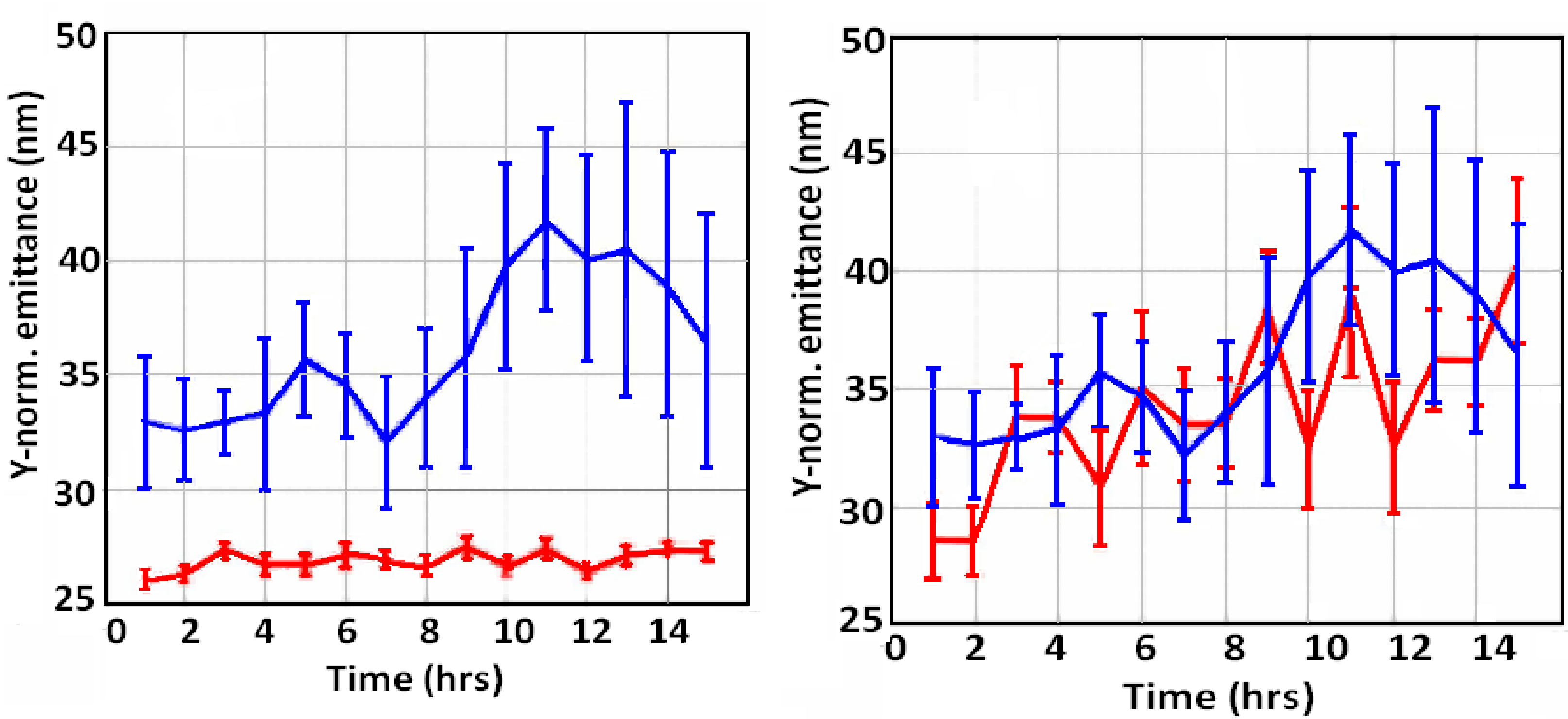


(a) Normalized vertical projected emittance vs. time in a dispersion-free steered linac. AA is implemented after every hour of GM model 'C'.

(b) A blown-up portion of the red plot after 100 AA iterations, gain=0.3.

Orbit after DFS is used as a reference, in this case AA is not sensitive to BMP-to-Quad offsets

Effect of BPM resolution

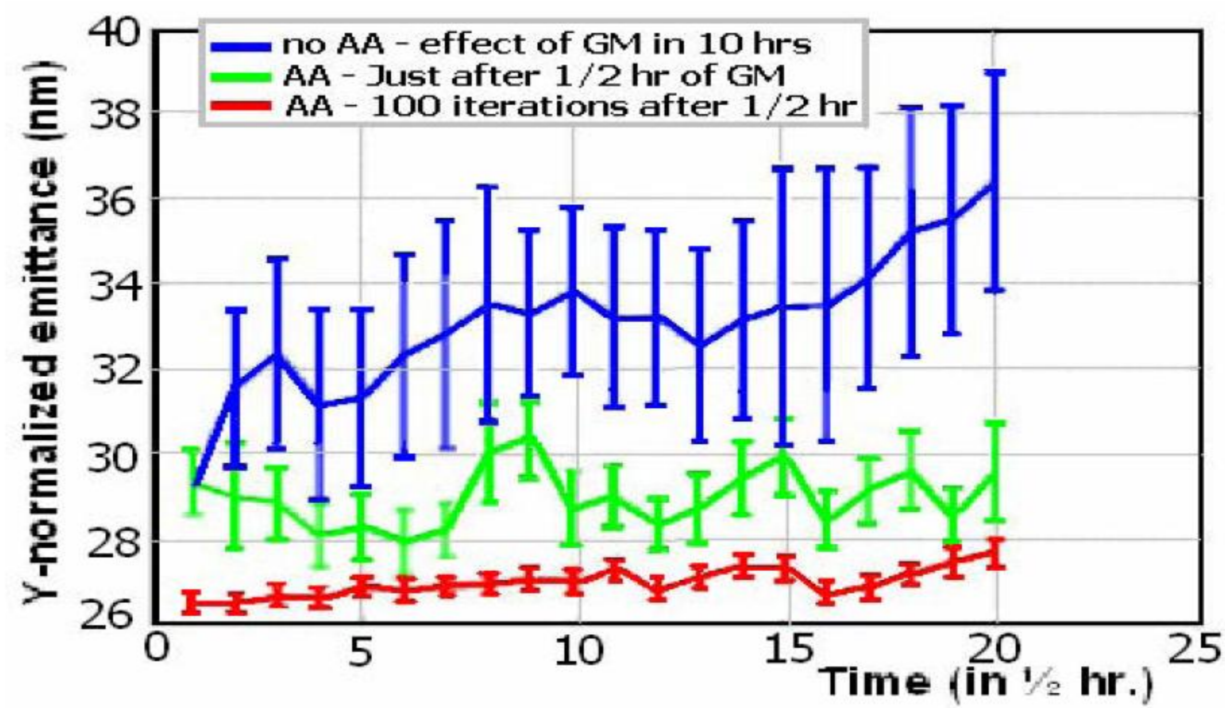


Normalized vertical emittance as a function of time in a dispersion-free steered linac. AA of 100 iterations and 0.3 convergence factor is implemented after every one hour of ground motion of model 'C' for (a) BPM resolution of 0.2 μm and (b) for BPM resolution of 1 μm.

As shown in studies the effective BPM resolution can be significantly reduced by averaging over a few bunches (all bunches in train)

Effect of tuning intervals

In a real machine the Adaptive Alignment feedback control is working pulse by pulse (5Hz). In each pulse the information from all ***N*** previous pulses is used for calculation of correction. In simulation we are using correction ones per time interval (~0.5 hrs for ~1 month of dynamis with GM)

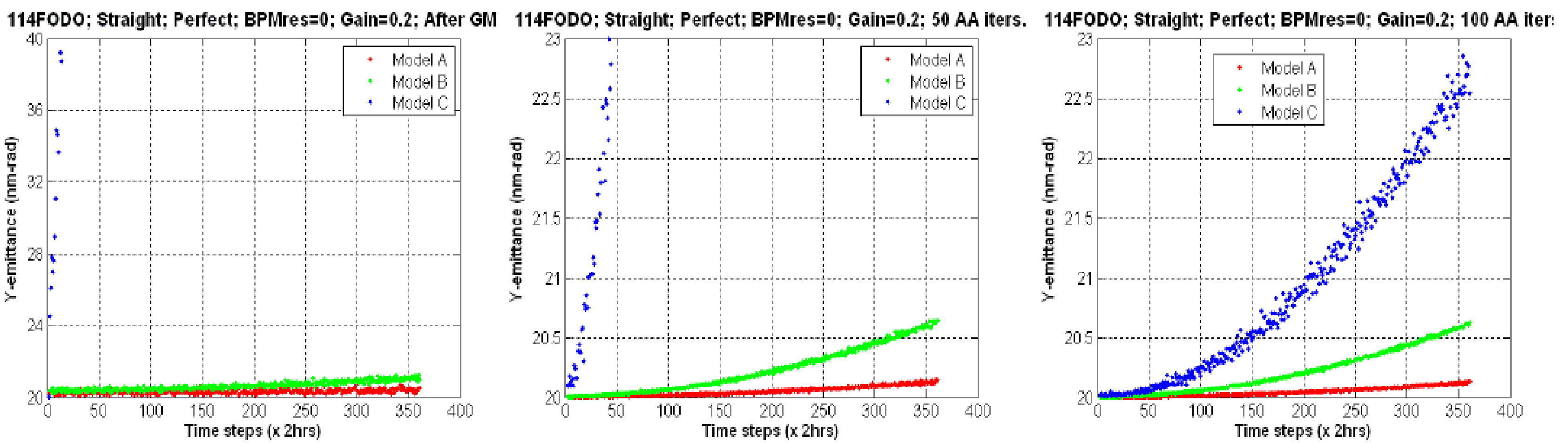


Normalized vertical emittance vs. time in a DFS linac. AA of 100 iterations and convergence factor 0.2 is implemented every half hour of GM of model 'C'.

Effect of N of iterations

- Perfectly aligned lattice – ILC BCD Like Straight Lattice (114 FODO cells)
- 20 different GM seeds (GM – Models ‘A’ , ‘B’ and ‘C’)
- GM of 30 days in step of 2 hr.
- When AA incorporated: AA of 100 iterations after every 2 hrs. (perfect BPMs, Gain = 0.2, no GM during AA iterations)

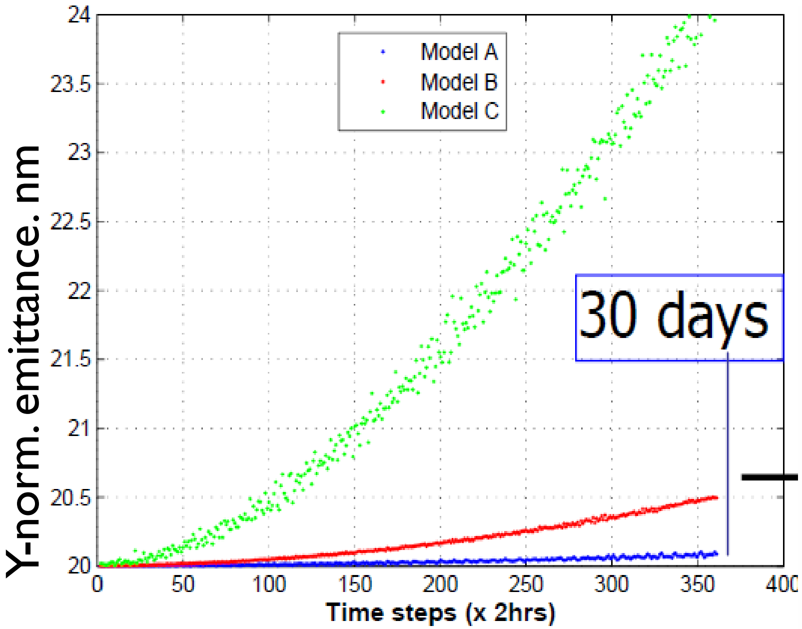
After GM | After 50 AA iterations | After 100 AA iterations

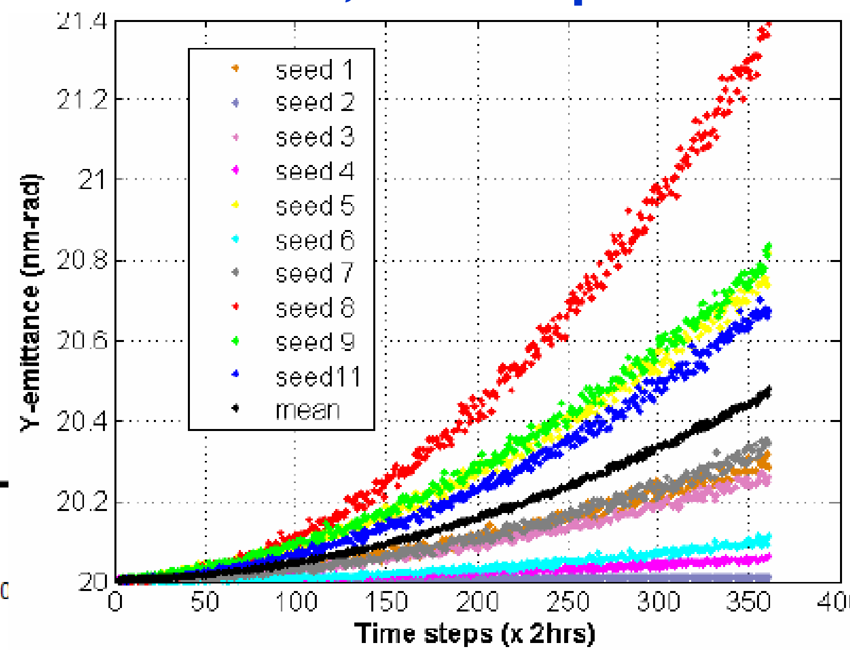


Time steps (x 2 hrs.)

AA FB control for one month of GM.

Y norm. emitt. at the ML exit after 100 AA iterations for GM models A, B, C. Total period one month, time step 2 hrs.





Average of 10 GM seeds for each model . Convergence (gain) = 0.2;

Individual GM seeds for model B.

Individual variation for different seeds & GM models can affect substantially on beam emittance

Summary of AA studies

- In the absence of dynamic steering the Ground Motion and jitter can severely limit machine performance (emittance dilution);
- Adaptive Alignment algorithm can be helpful as a dynamic tuning technique to stabilize the emittance performance in statically Steered linac for ~months time scale (site dependant).
- We expect to implement this algorithm every few pulses; however, a time interval of more than half hour between iterations can cause significant growth in emittance, particularly in GM model 'C'.

Plans for future studies

- Dynamics studies in ILC linac was slowed down due to luck of people.
- Plan to continue this studies in 2011
  - Open Post-doc and Associated scientist position at Fermilab (ILC and Project X beam dynamics studies).
- ILC-CLIC collaboration is essential.