

# Dynamic Imperfections

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# Introduction

- A large number of dynamic imperfections exist
  - e.g. ground motion, RF phase and amplitude jitter, element transverse jitter, magnet strength jitter, . . .
- They can have quite different time-scales
  - from intra-pulse to days
- These imperfections need to be addressed across the whole machine
  - but can start looking at individual areas, e.g. main linac
- Imperfection can lead to direct luminosity reduction
  - e.g. quadrupole transverse jitter in main linac
- They can lead to indirect luminosity loss
  - the required feedback impacts the beam
  - impact on static alignment and tuning procedures

# CLIC Example of Fast Imperfection Tolerances

- Many sources exist

Source	Luminosity budget	Tolerance
Damping ring extraction jitter	1%	
Magnetic field variations	?%	
Bunch compressor jitter	1%	
Quadrupole jitter in main linac	1%	$\Delta\epsilon_y = 0.4 \text{ nm}$ $\sigma_{jitter} \approx 1.8 \text{ nm}$
Structure pos. jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04 \text{ nm}$ $\sigma_{jitter} \approx 800 \text{ nm}$
Structure angle jitter in main linac	0.1%	$\Delta\epsilon_y = 0.04 \text{ nm}$ $\sigma_{jitter} \approx 400 \text{ nradian}$
RF jitter in main linac	1%	
Crab cavity phase jitter	1%	$\sigma_\phi \approx 0.01^\circ$
Final doublet quadrupole jitter	1%	$\sigma_{jitter} \approx 0.1 \text{ nm}$
Other quadrupole jitter in BDS	1%	
...	?%	

# Typical Time Dependence of Imperfections

- Neglect the potential spatial correlation
- $\gamma$  is a Gaussian random number
- Independent jitter (white noise)

$$y_{i+1,j} = \gamma_{i+1,j}$$

the element jitters around a fixed position

- Random walk (attention, also called drift)

$$y_{i+1,j} = y_{i,j} + \gamma_{i+1,j}$$

the element moves around the new position

- Systematic drift

$$y_{i+1,j} = y_{i,j} + \delta_j$$

the element moves systematically in one direction

# What is Needed to Characterise the Imperfection?

- Example of ground motion
- We need full model of imperfections
  - ground motion
  - transfer through girder and elements
  - active stabilisation feedback (CLIC)

# A Simple Ground Motion Model

- For times of the order of seconds ground motion can be approximated by the ATL model
  - the relative RMS motion of two points separated by  $L$ , after the time  $T$  is given by

$$\langle (\Delta y)^2 \rangle = ATL$$

where  $A$  is a site dependent parameter

- The ATL-law represents a relative motion of points as a random walk in time and space
  - it can be simulated as

$$y_{i+1,j+1} = y_{i,j+1} + y_{i+1,j} - y_{i,j} + \sqrt{A\Delta t(s_{j+1} - s_j)}\gamma_{i+1,j+1}$$

# A More Complete Ground Motion Model

- Especially for short times the motion of different points can be correlated
- This can be modelled as waves of ground motion, which are described by by mode spectrum  $C(\omega, \lambda)$

- This can be modelled as

$$y(s, t) = \sum_{k,l}^{N_k, N_l} C_{kl} [\sin(\omega_k t) \sin(k_l s + \phi_{kl}) + (\cos(\omega_k t) - 1) \sin(k_l s + \psi_{kl})]$$

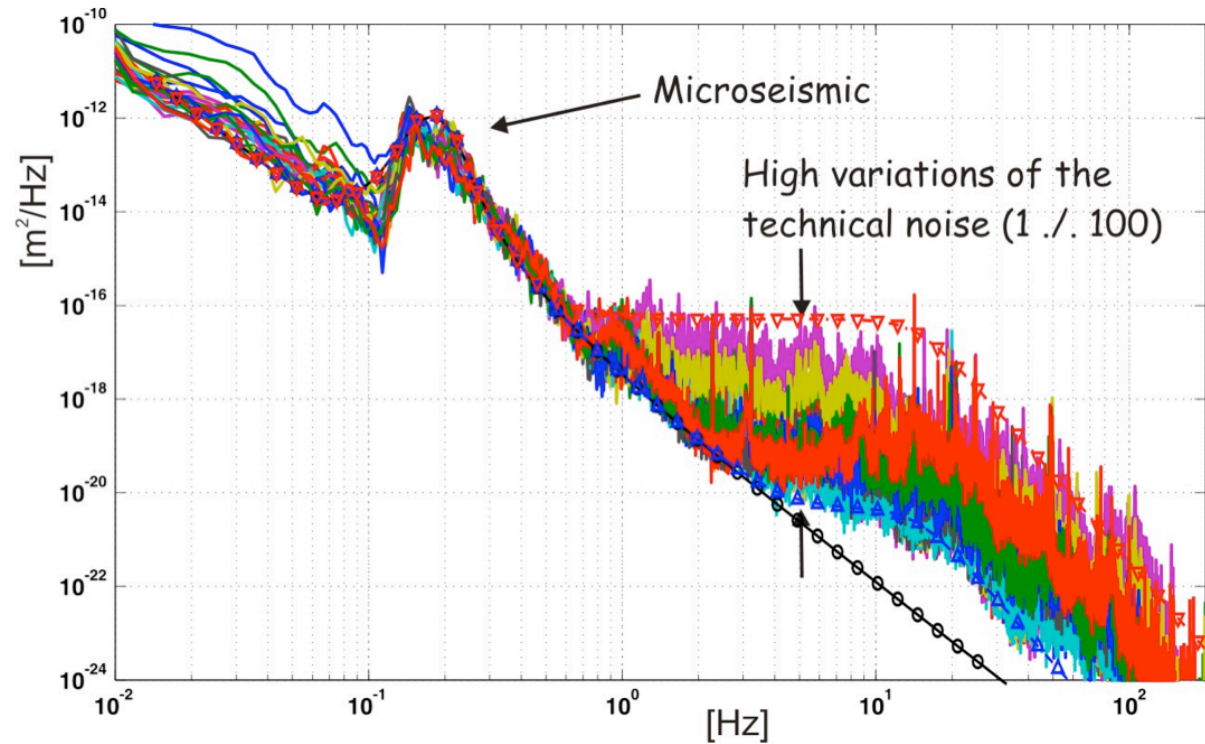
- This can be simulated, some tricks are useful to improve the efficiency of the calculation

# Example of Technical Noise

- Measurements in this example can be well approximated by

$$a(\omega) = \frac{a_0}{1 + \left(\frac{\omega}{\omega_0}\right)^6}$$

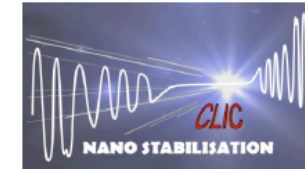
- That means technical noise looks like random pulse to pulse jitter





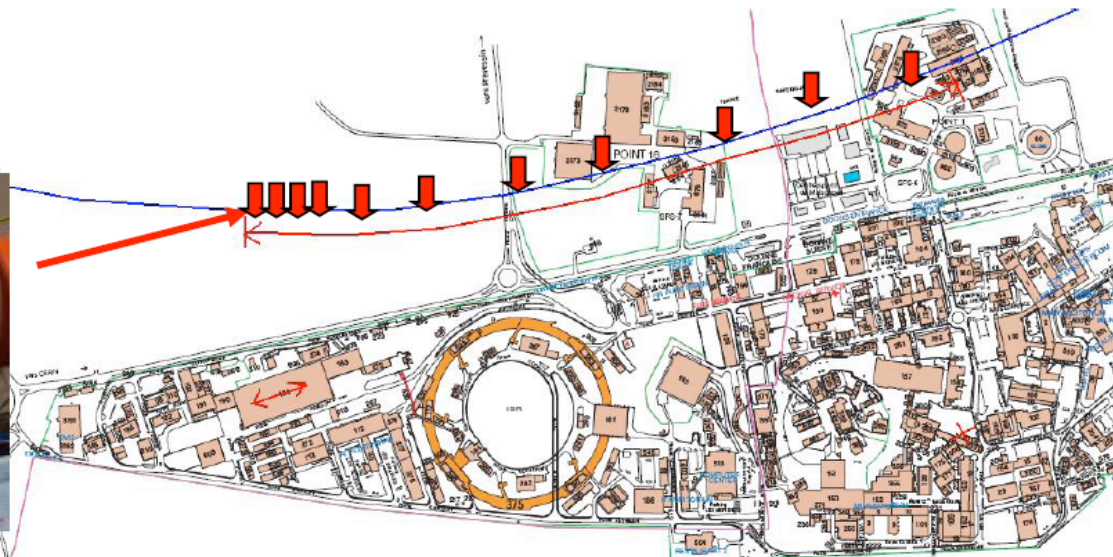
# Ground Motion Correlations

K. Artoos and M. Guinchard, CLIC Workshop (16 October 2008)



## LHC Measurements

LHC DCUM 1000  
~ 80 m under ground



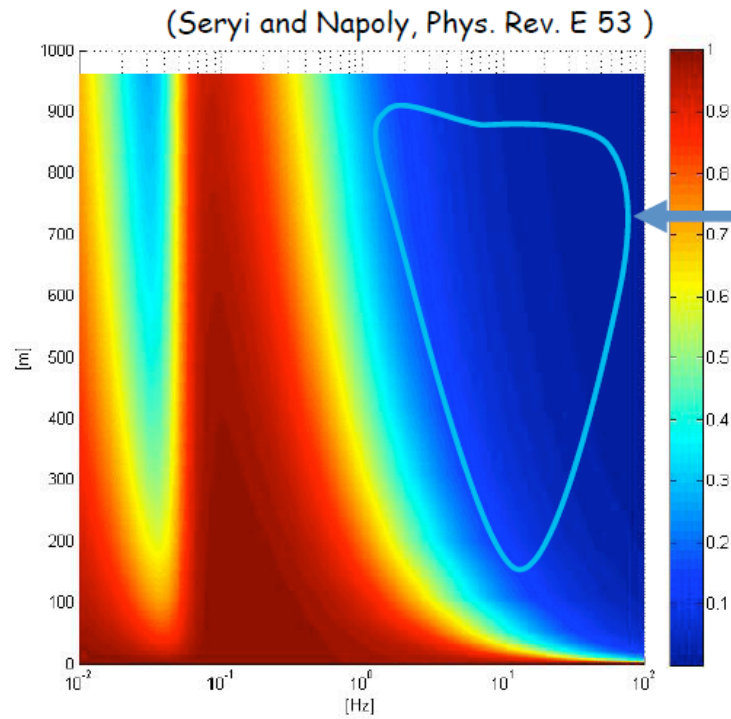
Measurements: 0 1 2 3 4 5 6 7 8 9 10 12 20 30 38 54 108 198 306 412 509 604 706 960 (m)

### Specific features :

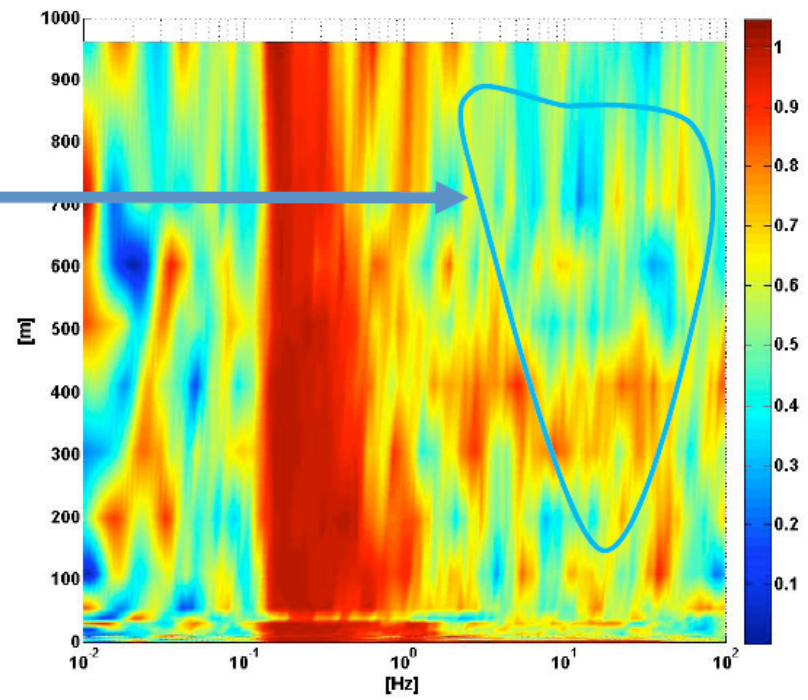
- Synchronous measurements
- LHC systems in operation, night time
- Multi-directional

# Ground Motion Correlations

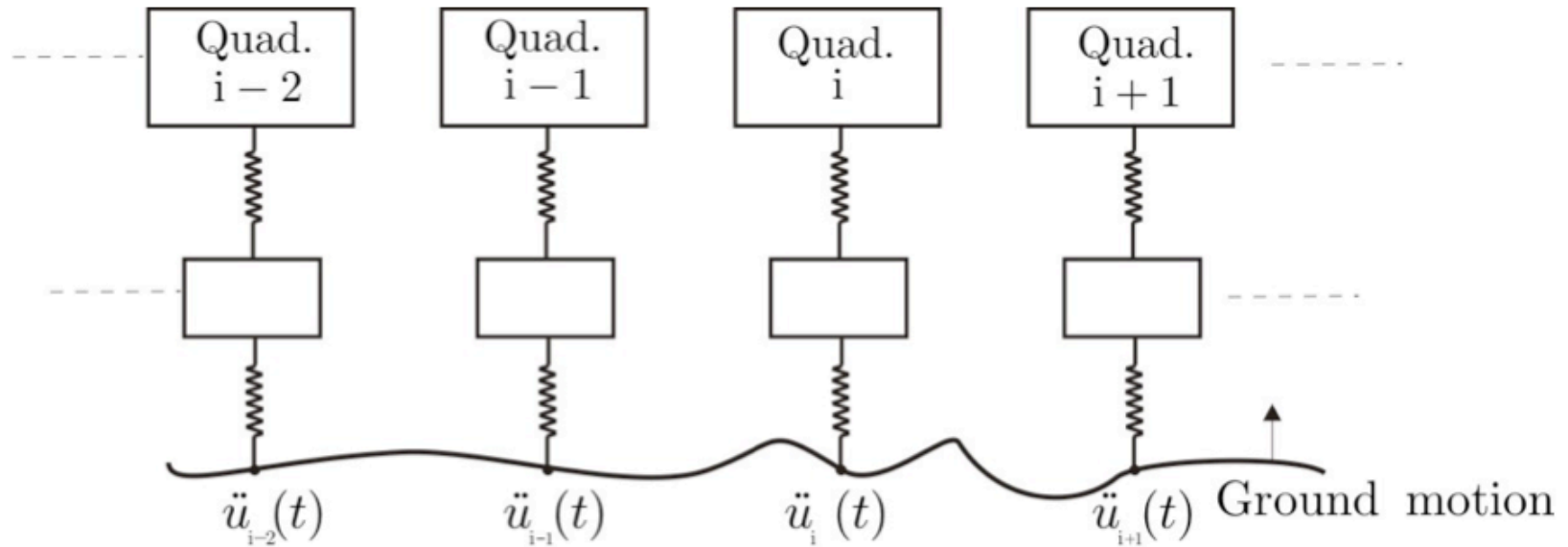
Coherence using a theoretical model



Calculated from measurement



# Impact of the Supporting Girder



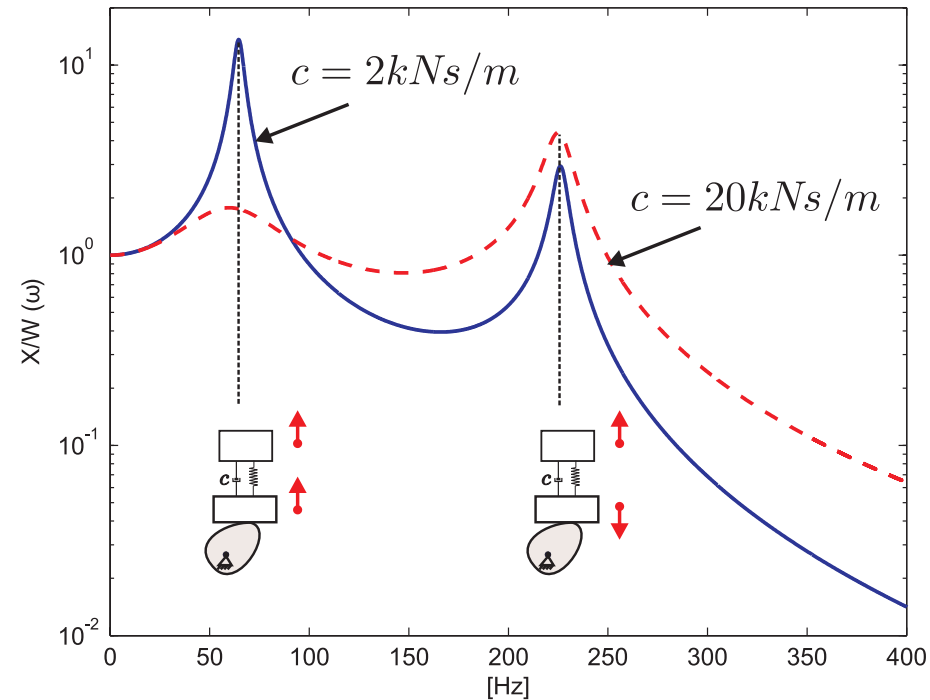
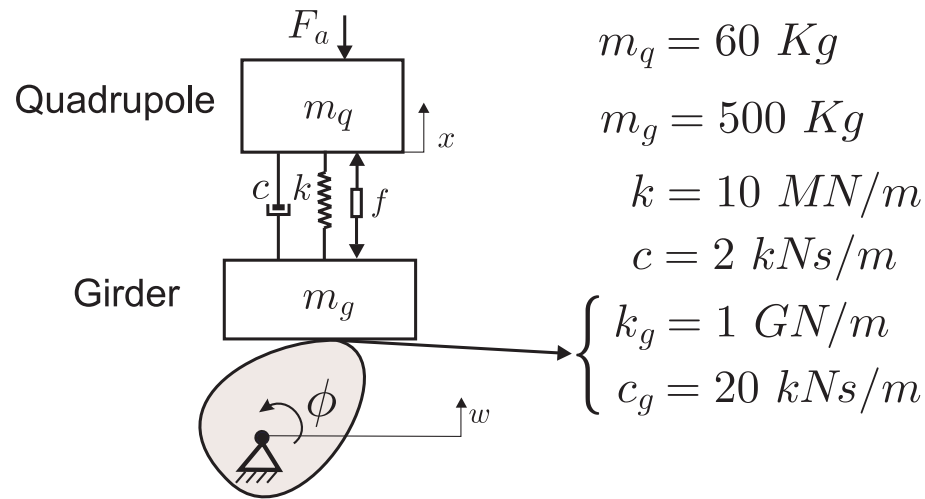
- The quadrupole
- The impact of the supporting girder can be characterised by the simple model

$$R(\omega) = r(\omega) \exp(i\phi(\omega))$$

original ground noise  $P_0$  becomes  $P$  at quadrupole

$$P(\omega) = R(\omega)P_0(\omega)$$

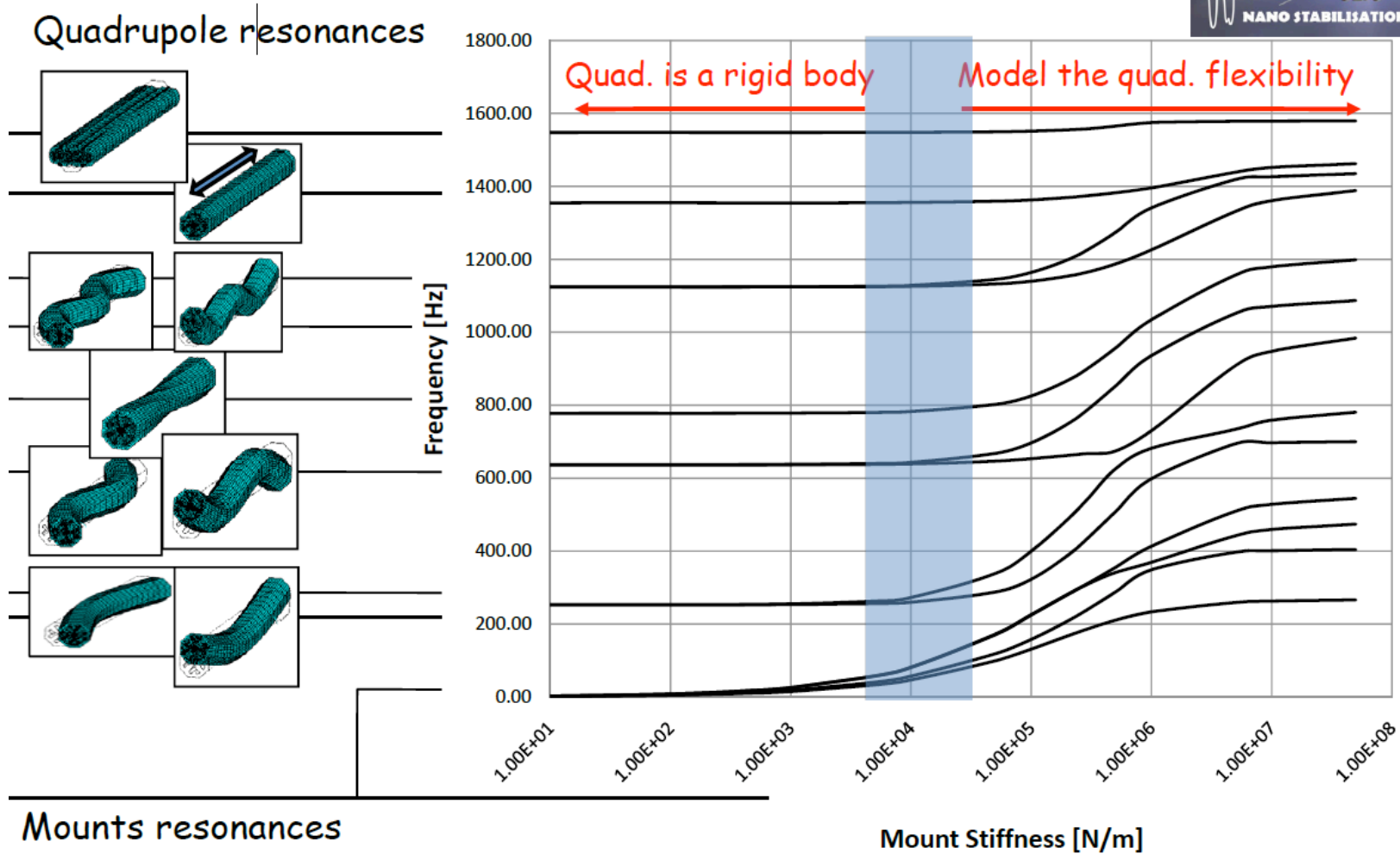
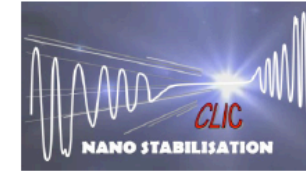
# Example Transfer Function



- A very simple model is that of a harmonic oscillator
  - the support is the spring
  - generally can calculate resonance frequencies but the damping is more difficult
- Generally:
  - full transmission for low frequencies
  - suppression of high frequencies
  - resonances in between

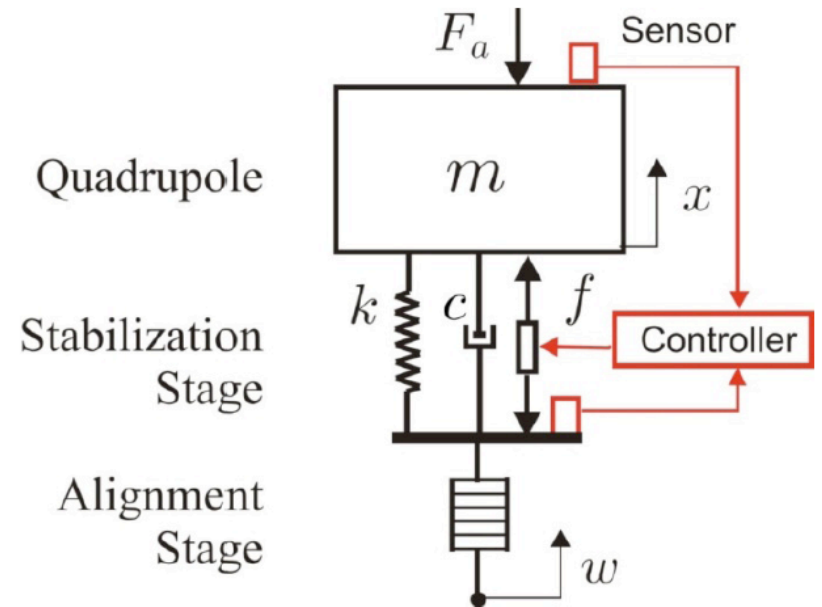
# Oscillation Modes

Modal analysis of the 2m long quad. with 6 mounts



# Active Stabilisation

- Need sensors and correctors
  - can measure acceleration
- ⇒ feedback works for high frequencies
- ⇒ but not for low frequencies



# Time Dependent Luminosity Loss/Emittance Growth

- Luminosity for first time step is  $\Delta\mathcal{L}_0$ , starting from static machine
- Luminosity loss/emittance growth are quadratic with the size of the imperfection (for small enough range)
- For the different dynamic imperfection types we find (in linear approximation)

- pulse-to-pulse jitter

$$\langle\Delta\mathcal{L}_n\rangle = \Delta\mathcal{L}_0$$

- ATL like motion

$$\langle\Delta\mathcal{L}_n\rangle = n\Delta\mathcal{L}_0$$

- slow drifts

$$\langle\Delta\mathcal{L}_n\rangle = n^2\Delta\mathcal{L}_0$$

- for mode model situations is somewhat complex
- feedback cannot help in the first case

# Quadrupole Jitter

- Want to estimate relative beam jitter at the end of the linac due to quadrupole jitter
- Calculate the normalised local kick

$$\frac{\Delta y'}{\sqrt{\frac{\epsilon_y}{\beta_y \gamma}}} = \frac{\Delta}{f} \frac{1}{\sqrt{\frac{\epsilon_y}{\beta_y \gamma}}}$$

- Summation over all quadrupoles leads to

$$\left\langle \frac{\Delta^2}{\sigma_y^2} \right\rangle = \sum_{i=0}^n \frac{\delta_i^2}{f_i^2} \frac{\beta_{y,i} \gamma_i}{\epsilon_y} \sin^2(\phi_f - \phi_i)$$

- To simplify, we approximate the sum over  $\sin^2$  with  $1/2$ , since

$$\frac{1}{2\pi} \int_0^{2\pi} \sin^2(x) dx = \frac{1}{2}$$



# Calculation of the Beta-Function

- Want to calculate the effective mean beta-function

$$\beta = \frac{1}{2} (\hat{\beta} + \check{\beta})$$

we use

$$\hat{\beta} = L \frac{\kappa(\kappa + 1)}{\sqrt{\kappa^2 - 1}} \quad \check{\beta} = L \frac{\kappa(\kappa - 1)}{\sqrt{\kappa^2 - 1}}$$

with  $\kappa = \frac{2f}{L}$ , which yields

$$\beta = L \frac{\kappa^2}{\sqrt{\kappa^2 - 1}}$$

# Application to CLIC

- We replace the sum with an integral for CLIC

$$f = f_0 \sqrt{\frac{E}{E_0}} \quad L = L_0 \sqrt{\frac{E}{E_0}}$$

with  $L_0 = 1.5$  m and  $f_0 = 1.3$  m

$$\left\langle \frac{\Delta^2}{\sigma_y^2} \right\rangle \approx \frac{\delta^2}{2\epsilon_y} \int_{E_0}^{E_f} L \frac{\frac{4f^2}{L^2}}{\sqrt{\frac{4f^2}{L^2} - 1}} \frac{\frac{E}{mc^2}}{f_0 \frac{E}{E_0}} \frac{1}{L} \frac{1}{\eta_{fill} e G} dE$$

$$\Rightarrow \left\langle \frac{\Delta^2}{\sigma_y^2} \right\rangle \approx \frac{\delta^2}{2\epsilon_y} \frac{1}{f_0^2 L_0} \frac{1}{\eta_{fill} e G} \frac{\frac{4f_0^2}{L_0^2}}{\sqrt{\frac{4f_0^2}{L_0^2} - 1}} \frac{E_0}{mc^2} \int_{E_0}^{E_f} dE$$

$$\Rightarrow \left\langle \frac{\Delta^2}{\sigma_y^2} \right\rangle \approx \frac{\delta^2}{2\epsilon_y} \frac{1}{f_0^2} \frac{E_0}{mc^2 \eta_{fill} e G} \frac{\frac{4f_0^2}{L_0^2}}{\sqrt{\frac{4f_0^2}{L_0^2} - 1}} (E_f - E_0)$$

$$\left\langle \frac{\Delta^2}{\sigma_y^2} \right\rangle \approx 0.025 \left( \frac{\delta}{\text{nm}} \right)^2$$

# Stability and Feedback

- Stability is required to avoid luminosity degradation of a tuned machine
  - beam-based feedback will be used for low-frequency motion
  - typical luminosity with feedback is loss

$$\Delta\mathcal{L}_{total} = \Delta\mathcal{L}_{uncorr}(g) + \Delta\mathcal{L}_{noise}(g) + \Delta\mathcal{L}_{residual}(t)$$

$\Delta\mathcal{L}_{uncorr}$  actual dynamic effect that is not yet corrected/amplified

How fast does the feedback need to be?

$\Delta\mathcal{L}_{noise}$  feedback tries to correct dynamic effect that is faked by diagnostics noise

How good does the feedback need to be?

$\Delta\mathcal{L}_{residual}$  local feedback cannot correct all global effects

For how long is the feedback sufficient?

# ILC and CLIC

- In ILC, the long bunch separation allows for intra-train feedback at the end of the main linac
  - ⇒ relevant measure is the emittance growth
  - ⇒ speed of convergence is also important
- In CLIC the train is too short
  - ⇒ relevant is the multi-pulse emittance
    - the projected emittance of subsequent pulses overlaid

# Most Simple Feedback Example

- Correct pulse to pulse
- Have a set of BPMs and a set of correctors
- Know the effect of changing the current in corrector  $i$  by  $\delta_i$  leads to beam trajectory change in BPM  $j$  of  $r_{j,i}$
- Unperturbed system prediction is then

$$\mathbf{y}_{i-1} - \mathbf{y}_i = R\delta_i$$

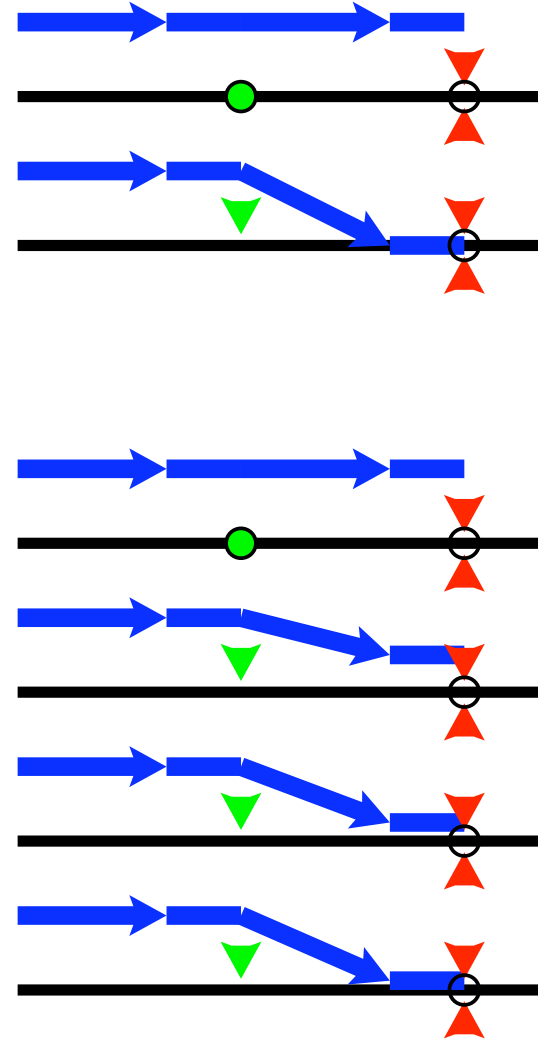
- Correction is calculated as

$$\delta_i = -gR^{-1}\mathbf{y}_i$$

$R^{-1}$  is the pseudo-inverse

- For simplification assume that  $R^{-1}$  is the inverse and is precisely known one finds

$$\mathbf{y}_{i+1} = \mathbf{y}_i + R\delta_i = \mathbf{y}_i - gRR^{-1}\mathbf{y}_i = \mathbf{y}_i - g\mathbf{y}_i$$



# Simple Feedback Transfer Function

- The simplest feedback is to use

$$y_{n+1} = y_n - g \times y_n + \gamma_n$$

- In our linear case the feedback can be described by its transfer function

$$p(\omega) = p_0(\omega)R(\omega)$$

$p$  noise with feedback

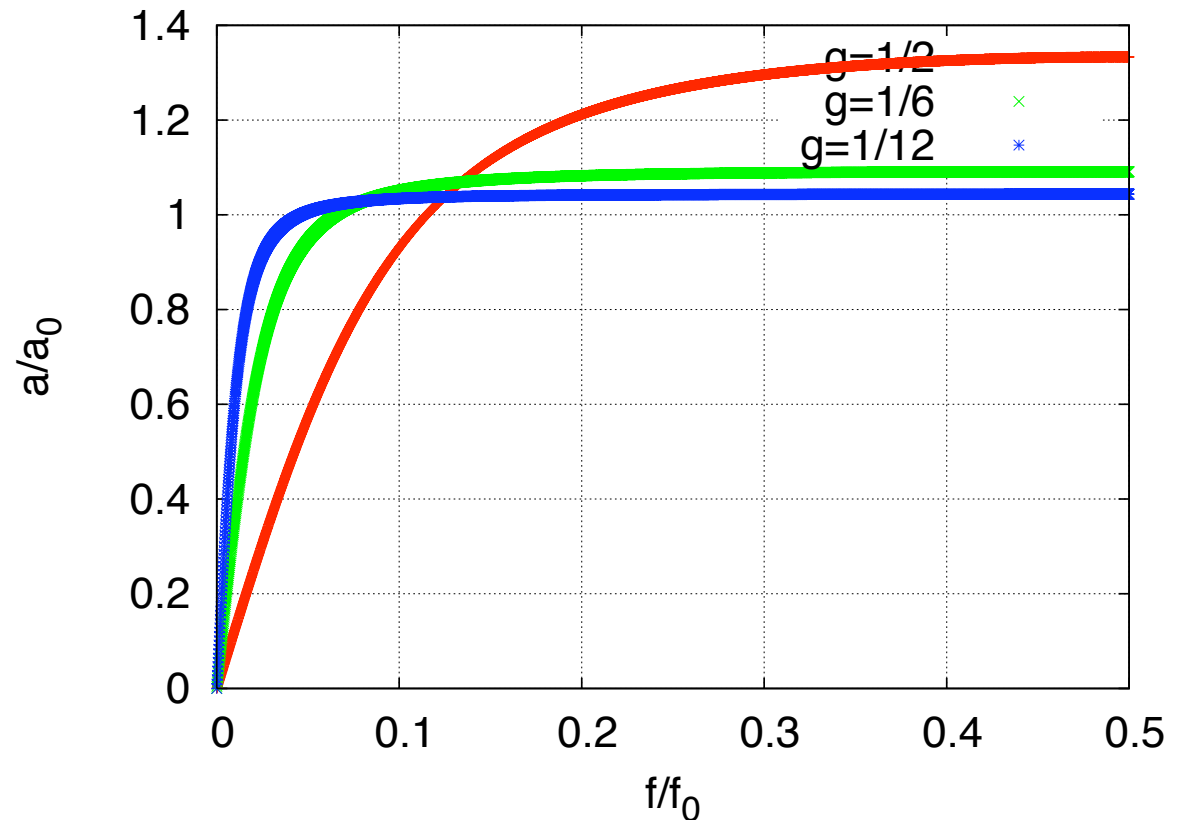
$p_0$  noise without feedback

$R$  feedback transfer function

- Noise added by the feedback can also be written in this form

$$p(\omega) = p_0(\omega)R(\omega) + p_1(\omega)$$

$p_1$  noise added by feedback, e.g. BPM noise



# Simple Feedback Transfer Function Calculated

- The impact of a feedback can usually be described by the transfer function  $R$  in frequency domain

$$\tilde{X}(t) = R(\omega)\tilde{x}(\omega)$$

$x$  is the motion with no feed back,  $X$  is the motion with feedback

- For our simple feedback we calculate  $R(\omega)$   
Difference equation for our system is

$$X_{n+1} - X_n = (x_{n+1} - x_n) - gre(X_n)$$

for motion only at the frequency  $\omega$  we exploit  $X_{n+1} = X_n \exp(-i\omega\Delta t)$  and  $x_{n+1} = x_n \exp(-i\omega\Delta t)$

$$\Rightarrow (\exp(-i\omega\Delta t) - 1)X_n = (\exp(-i\omega\Delta t) - 1)x_n - gre(X_n)$$

$$\Rightarrow (\exp(-i\omega\Delta t) - 1)R(\omega)x_n = (\exp(-i\omega\Delta t) - 1)x_n - gre(R(\omega)x_n)$$

to simplify our life we chose the moment where  $R(\omega)x_n$  is real

$$\Rightarrow (\exp(-i\omega\Delta t) - 1)R(\omega) = (\exp(-i\omega\Delta t) - 1) - gR(\omega)$$

$$\Rightarrow R(\omega) = (\exp(-i\omega\Delta t) - 1)/(\exp(-i\omega\Delta t) - 1 + g)$$

- Test  $g = 0$

$$R(\omega) = 1$$

- Test  $\omega\Delta t \rightarrow 0, g \neq 0$

$$R(\omega) = 0$$

# Examples for Simple Models

- The feedback will change the required stability

- look at  $\Delta L_{uncorr}(g)$  first

- The simplest feedback is to use

$$\Delta y_{n+1} = \Delta y_n - g \times y_n$$

- For the different noise types we find

- pulse-to-pulse jitter

$$\Delta L(n) = \Delta L_0 \quad \rightarrow \quad \Delta L_{uncorr} = \Delta L_0 \frac{2}{2-g}$$

- ATL like motion

$$\Delta L(n) = n\Delta L_0 \quad \rightarrow \quad \Delta L_{uncorr} = \Delta L_0 \frac{1}{g(2-g)}$$

- slow drifts

$$\Delta L(n) = n^2\Delta L_0 \quad \rightarrow \quad \Delta L_{uncorr} = \Delta L_0 \frac{1}{g^2}$$



# Not Yet Corrected Growth Calculated

- Random walk

RMS offset is given by

$$\langle \Delta x^2 \rangle = \sum_{i=0}^{\infty} \gamma_i^2 \sigma^2 (1-g)^{2i}$$
$$\Rightarrow \langle \Delta x^2 \rangle = \sigma^2 \frac{1}{g(2-g)}$$

- White noise

RMS offset is given by

$$\langle \Delta x^2 \rangle = \gamma_0^2 \sigma^2 + g^2 \sum_{i=1}^{\infty} \gamma_i^2 \sigma^2 (1-g)^{2(i-1)}$$
$$\Rightarrow \langle \Delta x^2 \rangle = \sigma^2 \frac{2}{2-g}$$

- Systematic motion

$$\langle \Delta x^2 \rangle = (\Delta x_0)^2 \left( \sum_{i=0}^{\infty} (1-g)^i \right)^2$$
$$\Rightarrow \langle \Delta x^2 \rangle = \sigma^2 \frac{1}{g^2}$$

# Another Feedback Transfer Function

- Summation feedback

$$\mathbf{a}_n = \frac{1}{m} \times \mathbf{y}_n + \left(1 - \frac{1}{m}\right) \times \mathbf{a}_{n-1}$$

$$\Delta y_{n+1} = \Delta y_n - a_n$$

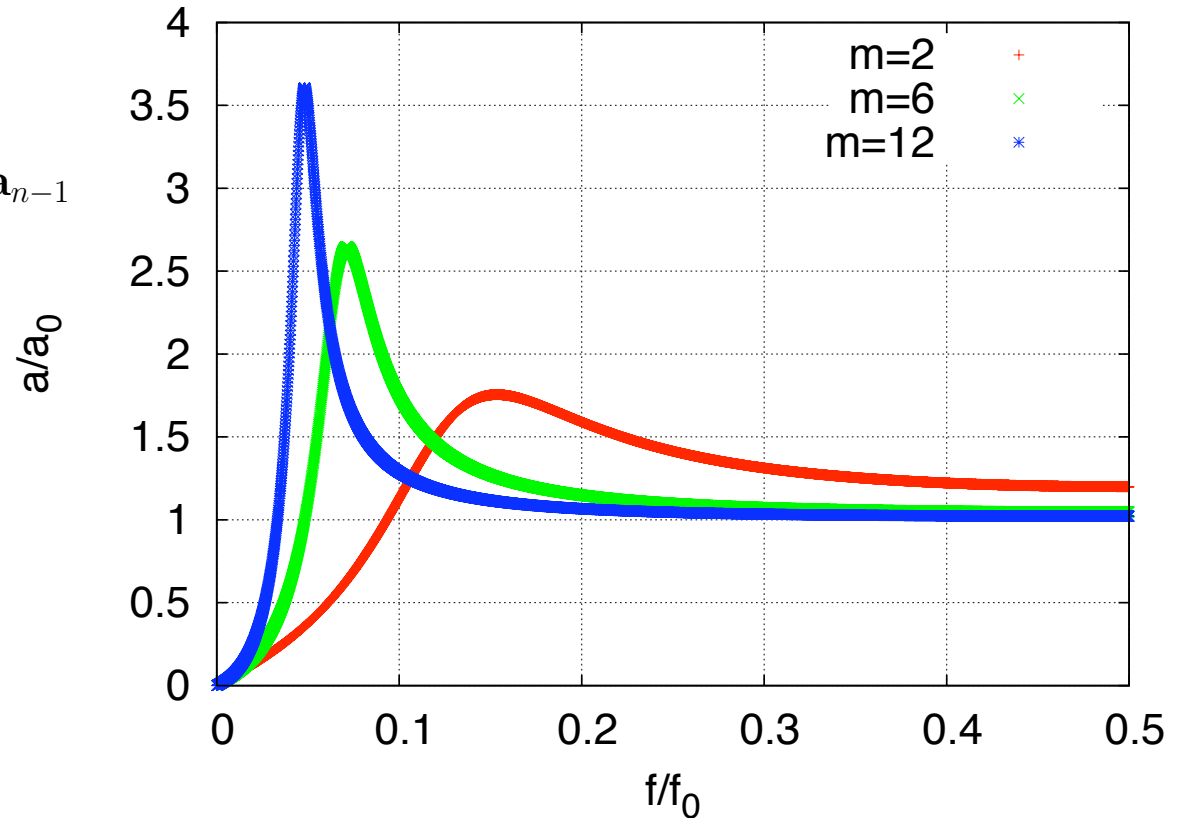
- For slow drifts

$$\Delta \mathcal{L}_{uncorr} = \Delta \mathcal{L}_0$$

⇒ good low frequency behaviour

- For jitter for large  $m$

$$\Delta \mathcal{L}_{uncorr} \approx 1.5 \Delta \mathcal{L}_0$$



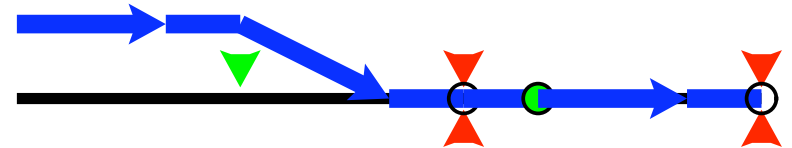
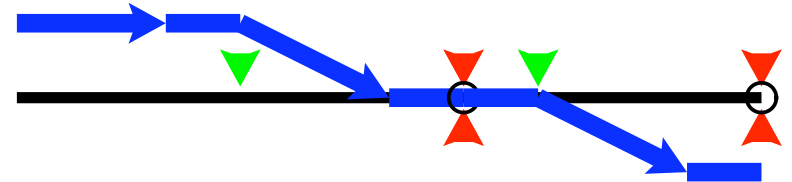
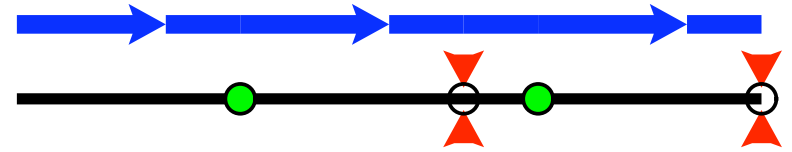
- For CLIC at 1 Hz amplification is 0.27 (m=12), 0.16 (m=6), 0.13 (m=2)
- At 4 Hz m=2 is marginal
- Will have to fold with ground motion/transfer function

# Main Linac Feedback Strategy

- Stabilisation of elements using local mechanical feedback (CLIC only)
- Information from survey system is only recorded, not used directly (CLIC only)
- Intra-pulse beam feedback
  - only possible in ILC (at CLIC at the interaction point)
- Pulse-to-pulse feedback
  - main linac orbit feedback, RF phase and amplitude feedback
- Re-tuning
  - slow process in the main linac
- Complex beam-based alignment and tuning
  - not in normal running conditions
- Other feedback systems exist (e.g. RF feedback)
- Independent feedbacks on the same property will have to share the overall feedback bandwidth
  - ⇒ try to combine as much as possible
    - but need to know response

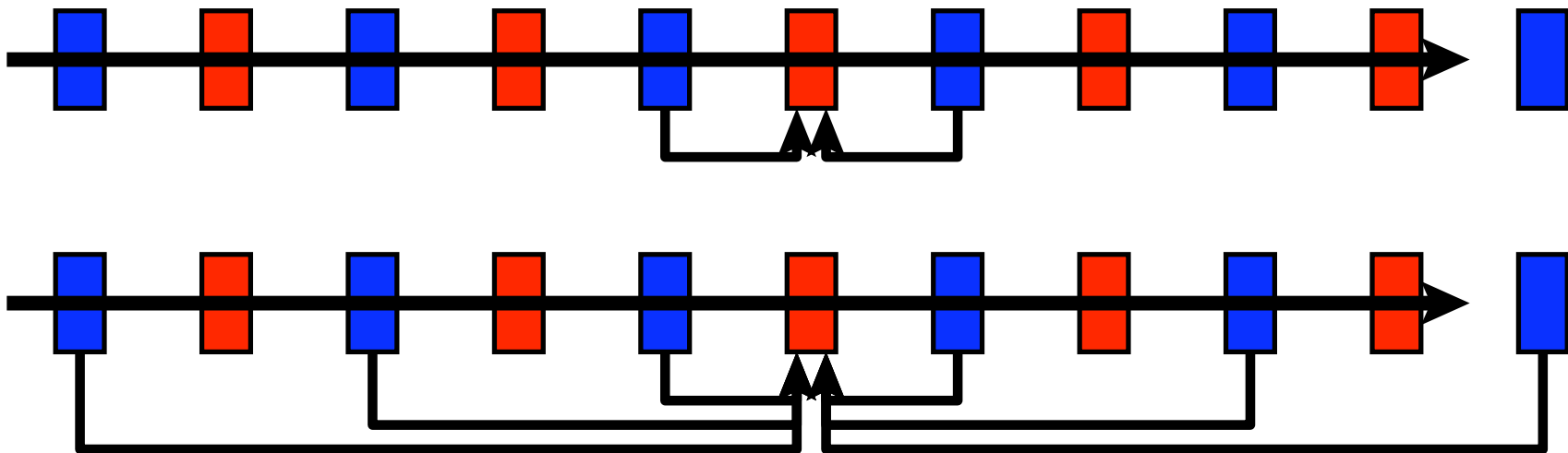
# Single vs Multiple Feedback Loops

- If independent feedback loops correct the same thing the system can become unstable
  - ⇒ need to share bandwidth
  - ⇒ correction becomes small



# Overall Fast Beam Feedback Design

- Main basis will be a fast BPM-based orbit feedback
  - ⇒ feedback on same beam property at different locations
- Three alternatives considered
  - chain of independent MIMOs, have to share bandwidth, slow
  - chain of decoupled MIMOs, but no perfect decoupling (CLIC)
  - single MIMO, model error needs to be studied
- Except for collision point beam position and angle will be corrected by each feed-back



# Main Linac Feedback (CLIC)

- Comparison of decoupled feedback and MIMO

- $N_f = 40$  feedback stations
- some quadrupole misalignment, then feedback on stable machine
- perfect knowledge of response assumed

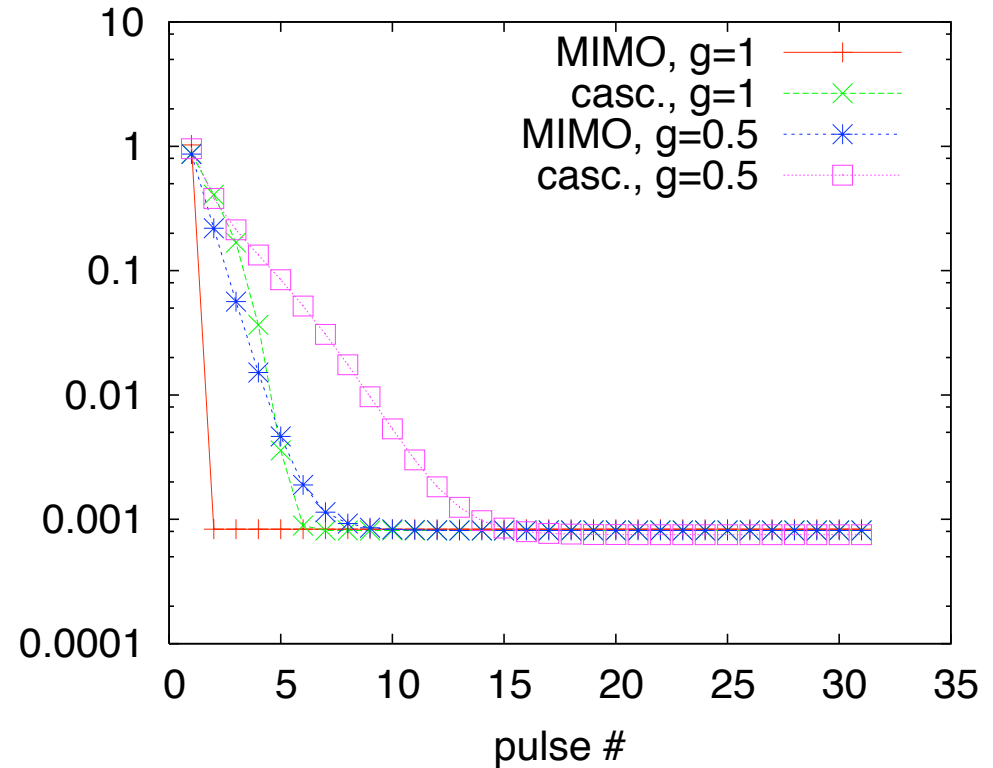
- Corrector step size for feedback is 5 nm with 2 nm precision

- to avoid emittance growth due corrector noise

- Independent feedback loops slow convergence down

⇒ MIMO controller is better

- but system knowledge is important (also for decoupled feedback)



# Main Linac BPM Resolution

- The BPM resolution will limit the feedback bandwidth
- Assume pulse-to-pulse uncorrelated BPM readout jitter
- Emittance growth (corresponding to  $\Delta\mathcal{L}_{noise}$ ) can be estimated as function of gain  $g$  by

$$\Delta\epsilon = \Delta\epsilon_0 \left( g^2 \sum_{i=0}^{\infty} (1-g)^{2i} \right)$$
$$\Delta\epsilon = \Delta\epsilon_0 \left( \frac{g}{2-g} \right)$$

- For 100 nm resolution, the emittance growth is  $\Delta\epsilon_0 \approx 0.3$  nm
- ⇒ Even for large gains  $g \leq 1/2$  the emittance growth should be small
- BPM resolution is determined by need to see beam jitter
    - beam jitter is measured in vertically focusing quadrupoles
    - beam is smallest at the end of the linac
    - with  $\beta_y \approx 65$  m and  $\epsilon_y \approx 10$  nm we find  $\sigma_y \approx 465$  nm
- ⇒ require BPM resolution of about 50 nm

# Impact of Corrector Step Error

- The steps performed by the correctors may not be predictable
  - will lead to additional emittance growth
- A random error in the corrector step can be regarded as quadrupole jitter
- A simple estimate of allowed error is given by

$$\sigma_{step} \approx \sigma_{jitter} \sqrt{\frac{N_{quad}}{N_{corrector}}}$$

$N_{corrector}$  is the number of correctors used

- To be negligible for  $N_{corrector} = 80$  we require  $\sigma_{step} < 5 \text{ nm}$
- ⇒ Should use minimum step size of  $\Delta = 5 \text{ nm}$  to reduce impact of step size to much less than quadrupole jitter
- Typical movements are some  $100 \text{ nm}$  (but site dependent)
    - we require convergence between pulses
    - stabilisation during correction with piezo movers is not obvious



# Time Dependent Residual Emittance Growth

- The residual emittance growth determines for how long the feedback is sufficient
- Use simple feedback

$$\Delta y_{n+1} = \Delta y_n - g \times \Delta y_n + \gamma_n$$

- For the different dynamic imperfection types we find
  - pulse-to-pulse jitter

$$\Delta \mathcal{L}_{resid,n} = 0$$

- ATL like motion

$$\Delta \mathcal{L}_{resid,n} \approx a \times n \Delta \mathcal{L}_0$$

- slow drifts

$$\Delta \mathcal{L}_{resid,n} \approx a \times n^2 \Delta \mathcal{L}_0$$

- Luminosity loss per timestep is  $\Delta \mathcal{L}_0$
- Feedback reduces emittance growth per time step by factor  $a$

# Number of Feedback Stations and Emittance Growth

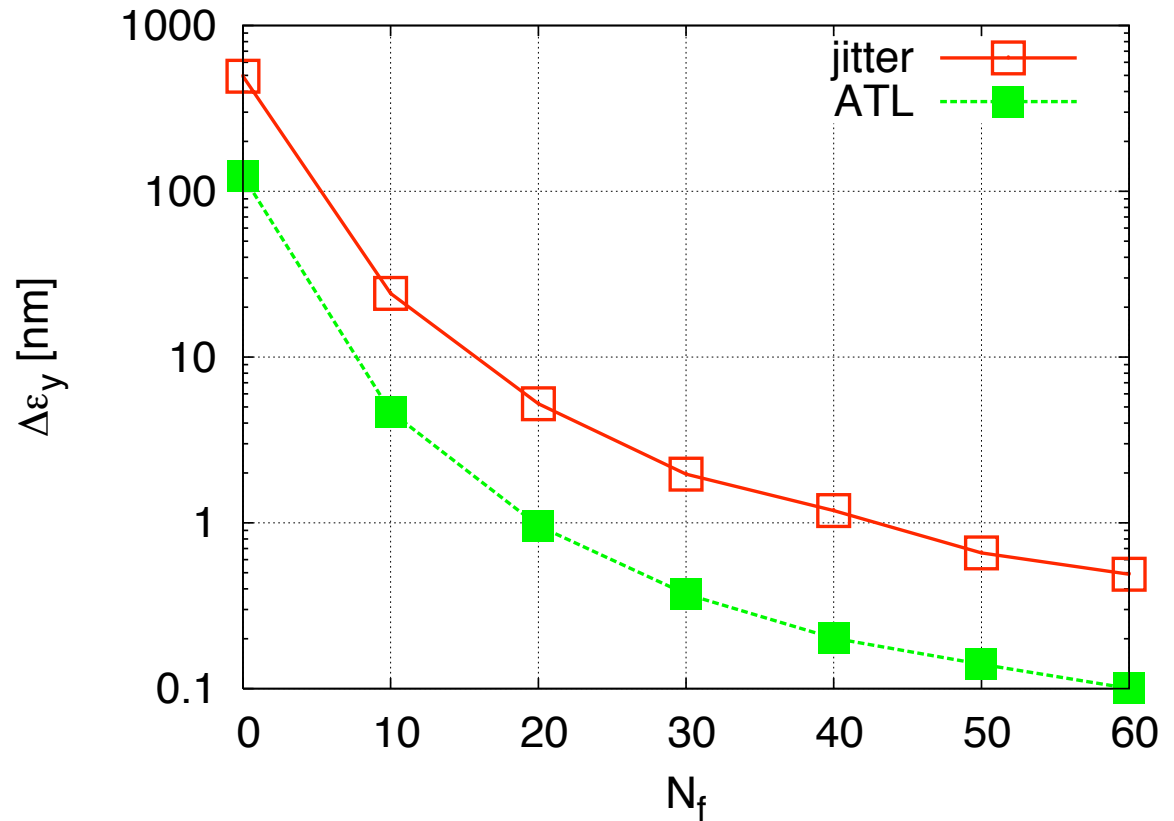
- The residual emittance growth is roughly

$$\Delta\mathcal{L}_r \propto \frac{1}{N_f^2}$$

- For ATL motion and  $N_f = 40$

$$\Delta\mathcal{L}_r \approx 0.2 \times 10^{-3} \text{ nm/s}$$

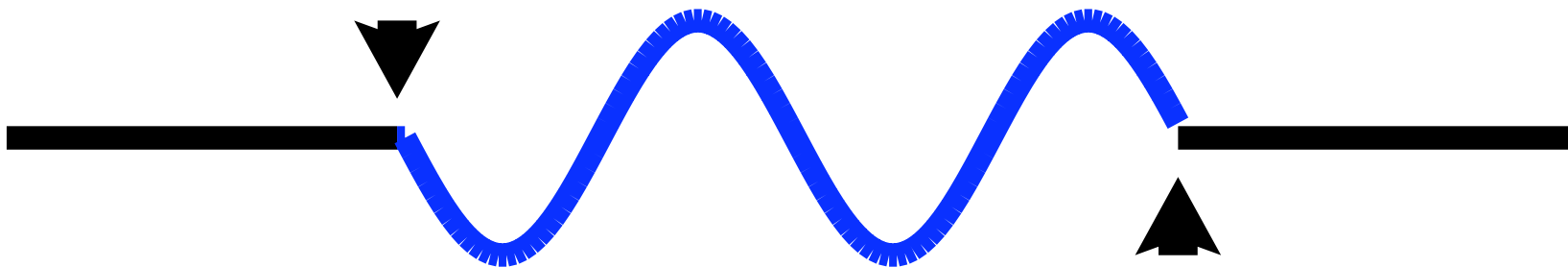
⇒ can run for some 1000 s



- A final feedback to re-steer to the original orbit is always included

# Determination of Response Matrix

- A correct response matrix is important for an efficient MIMO
  - Can be determined by a dedicated measurement
    - takes time
    - machine might slowly drift away from measured response
  - Solution is to introduce noise on purpose
    - kick a beam at location  $s_1$
    - apply another kick at  $s_2$  that should remove the beam oscillation
- ⇒ allows to measure response in this sector



# Some Results for ILC

# The Banana Effect

At large disruption, correlated offsets in the beam can lead to instability

The emittance growth in the beam leads to correlation of the mean  $y$  position to  $z$

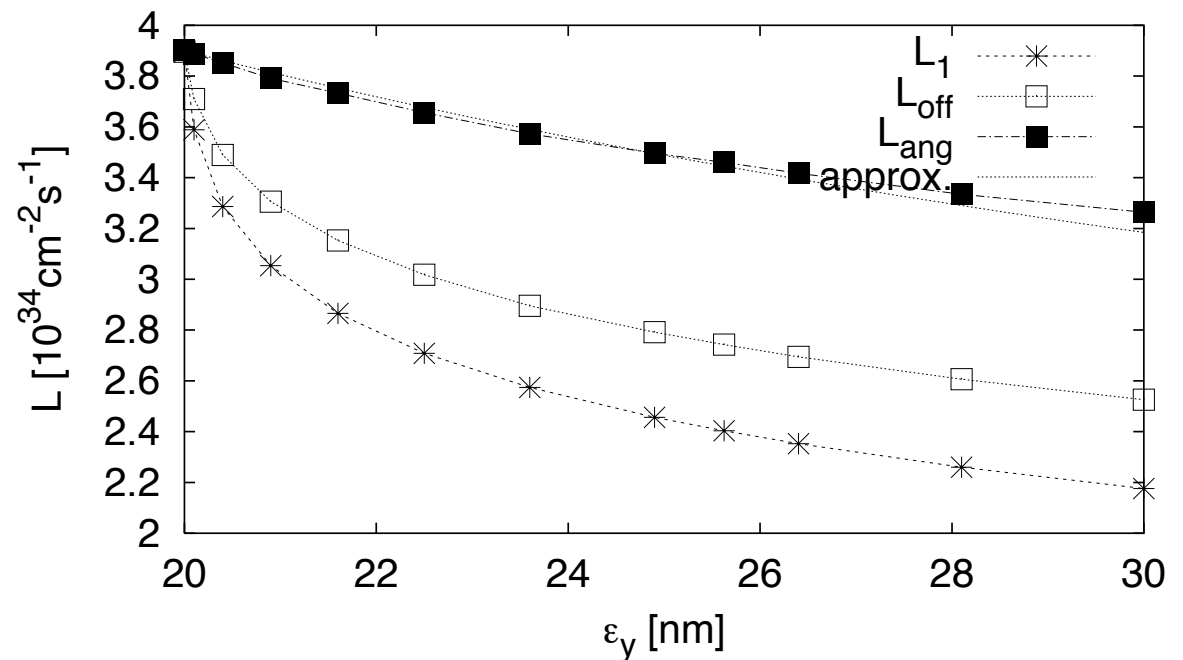
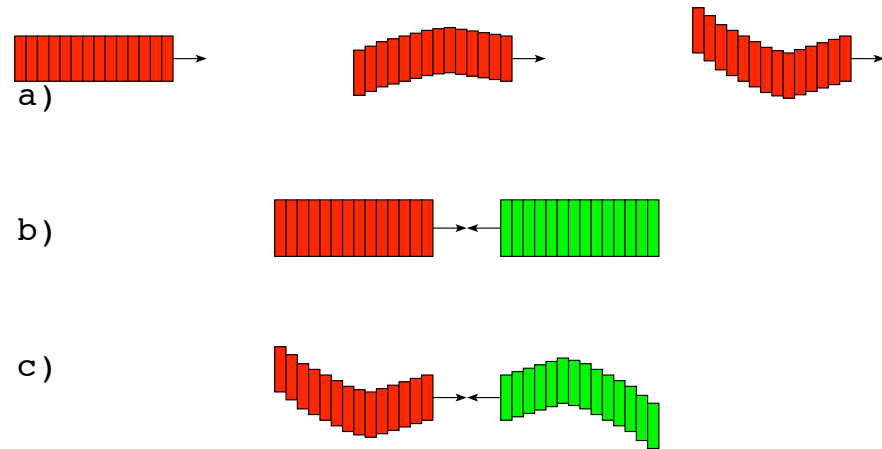
a) shows development of beam in the main linac

b) simplified beam-beam calculation using projected emittances

c) beam-beam calculation with full correlation

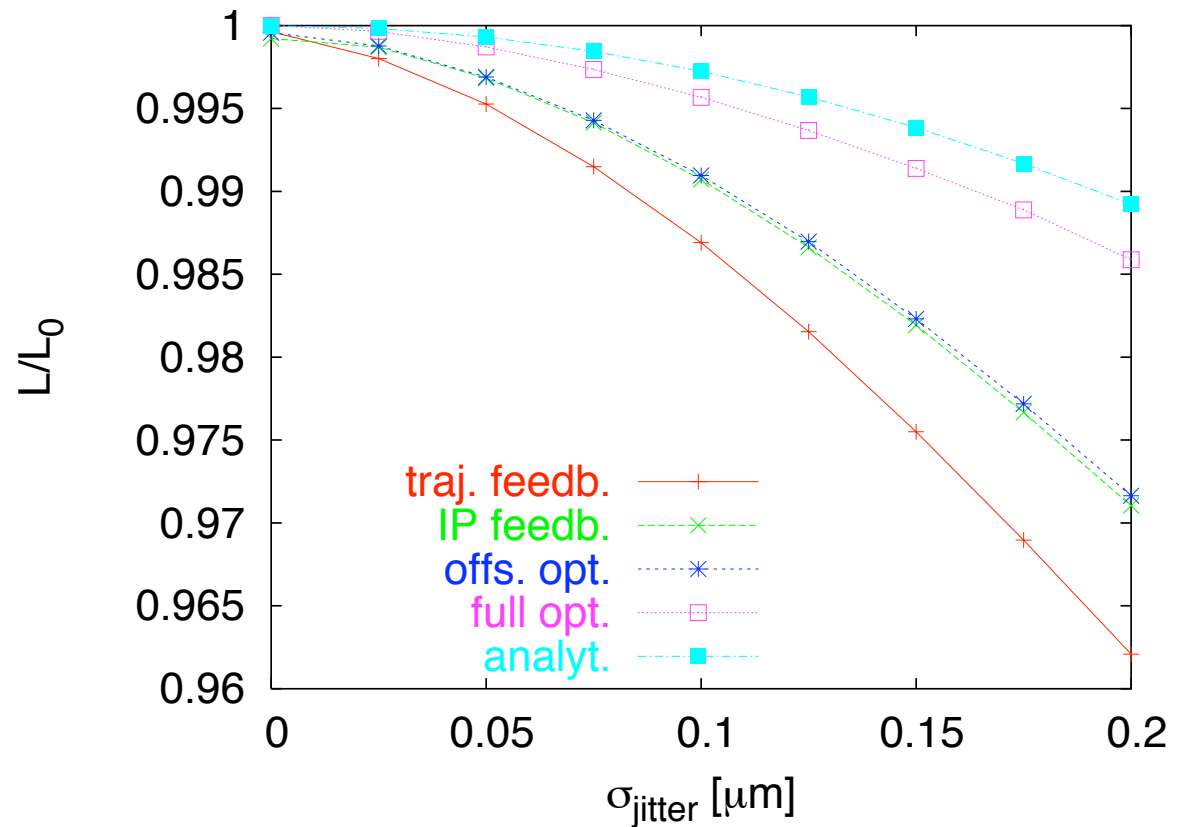
⇒ Luminosity loss increased

⇒ Cure exists



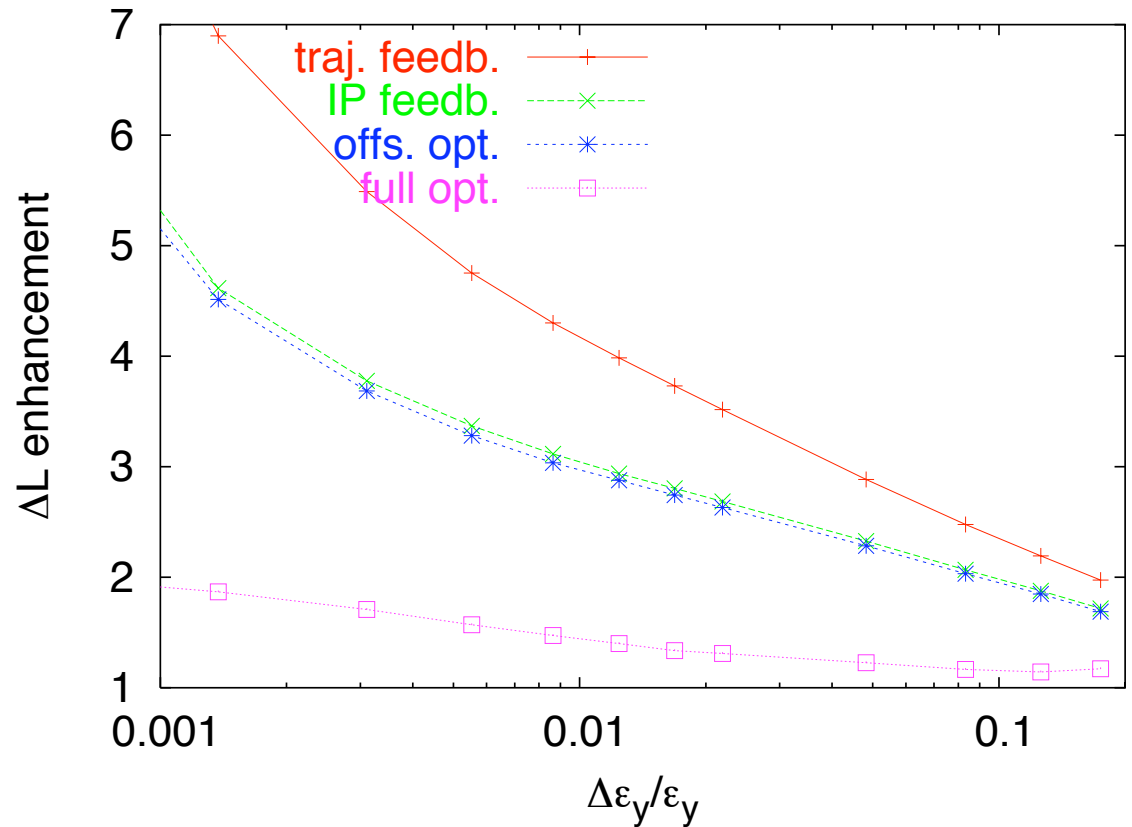
# Simplified Simulations of ILC Main Linac Quadrupole Jitter

- Simplified main linac lattice with 32 cavities per quadrupole  
 $\Rightarrow$  now 24 cavities per quadrupole
- Simulation procedure
  - emittance growth in main linac with PLACET
  - simplified trajectory feedback at end of ML
  - simple transfer matrix to IP
  - beam-beam with GUINEA-PIG



# Luminosity Loss Enhancement

- ⇒ Luminosity loss is enhanced with respect to expectation from emittance growth
- ⇒ Offset optimisation does not improve beam-beam feedback a lot
- ⇒ But angle optimisation does
- ⇒ For larger emittance growth loss enhancement is reduced



# Dynamic Effects During Alignment



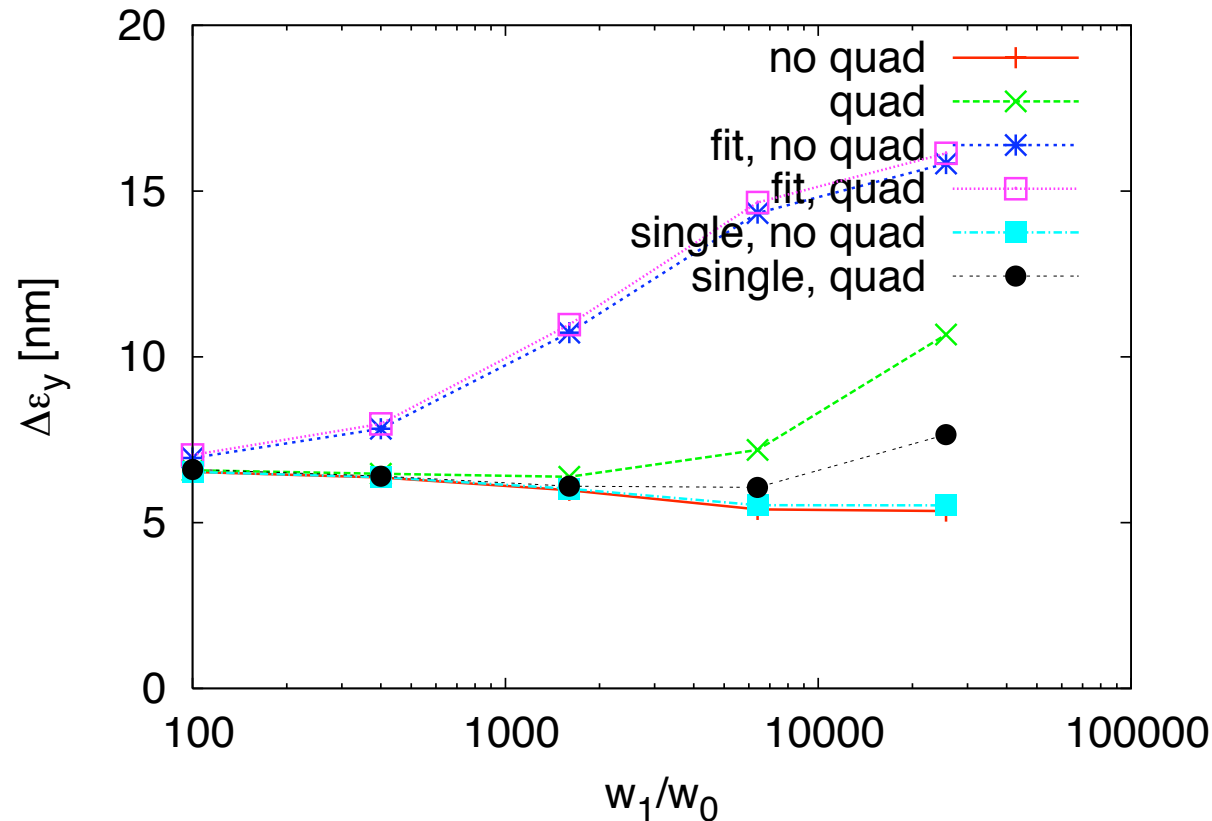
# Introduction

- Dispersion free steering uses beams at different energies to align quadrupoles
- They can be obtained using different gradients or bunch compressor settings
- Beam jitter during alignment fakes dispersion
  - either accept
  - or try to fit incoming beam trajectory
  - or use different energies within single pulse
- Simulations done using simplified ILC lattice
- Nominal misalignments are used
  - 1.5% RMS gradient jitter from RF unit to RF unit
  - 5% RMS random scale error of BPMs
- Similar results for CLIC
- Small energy difference used
  - gradient difference 1%
  - first two units are off

⇒ alignment of first six quadrupoles not treated

# Quadrupole Jitter

- Very large quadrupole jitter of 500nm added
- ⇒ Procedure with no fit suffers most
- ⇒ Fit of incoming beam helps a bit
- ⇒ Use of different energies in single pulse is best
- ⇒ But could try better fit
- ⇒ Recommend to use energy difference within a single pulse

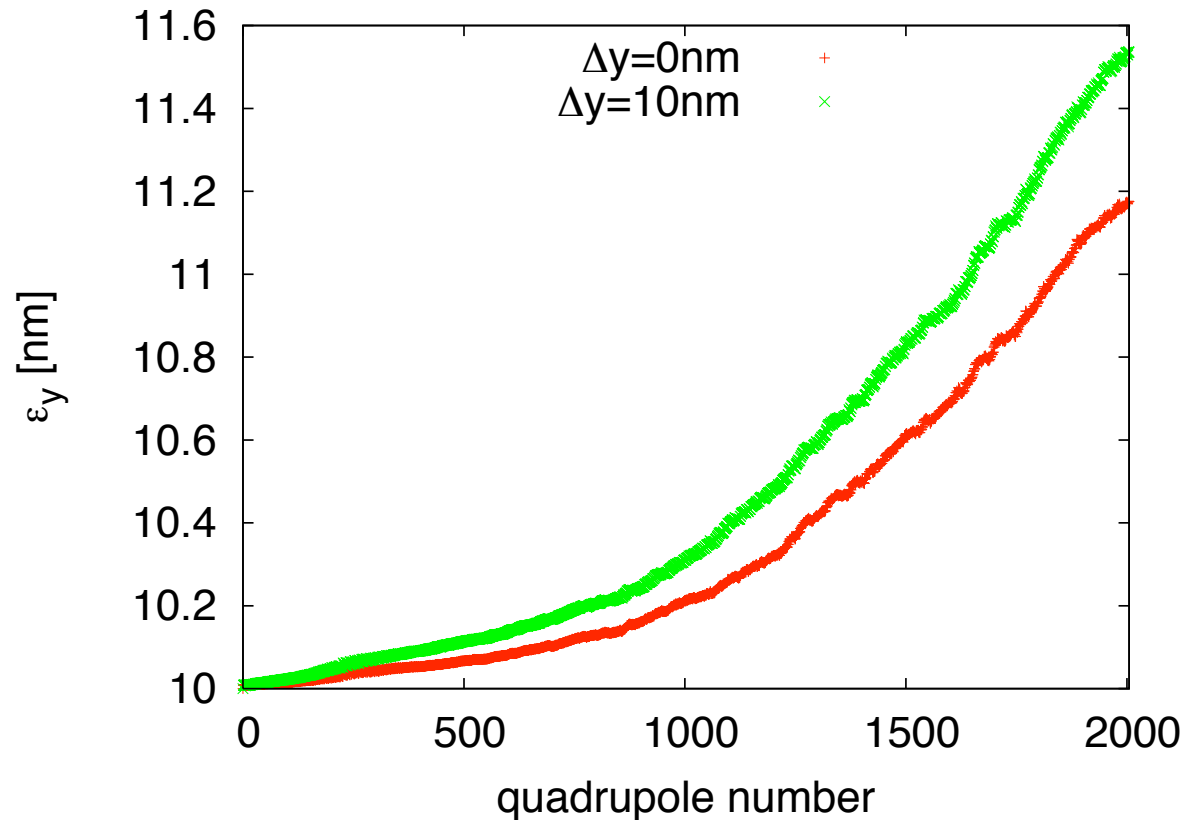


- correction can be performed with stable machine
- if spread can be reduced (better BPM resolution/averaging) or test bunches are used (after main pulse) one could align during luminosity operation

# Some Fun Stuff

# Main Linac Orbit Steering

- All quadrupoles could be stabilised
    - but in the long run they follow the ground motion
  - ATL-model used
    - ⇒ emittance growth is linear with time
    - one day simulated
  - All focusing quadrupoles used for steering in one-to-one correction
- ⇒ Emittance growth is  $\Delta\epsilon_{y,residual} = 1 \text{ nm per day}$
- Mover step size of 10 nm is noticeable in emittance

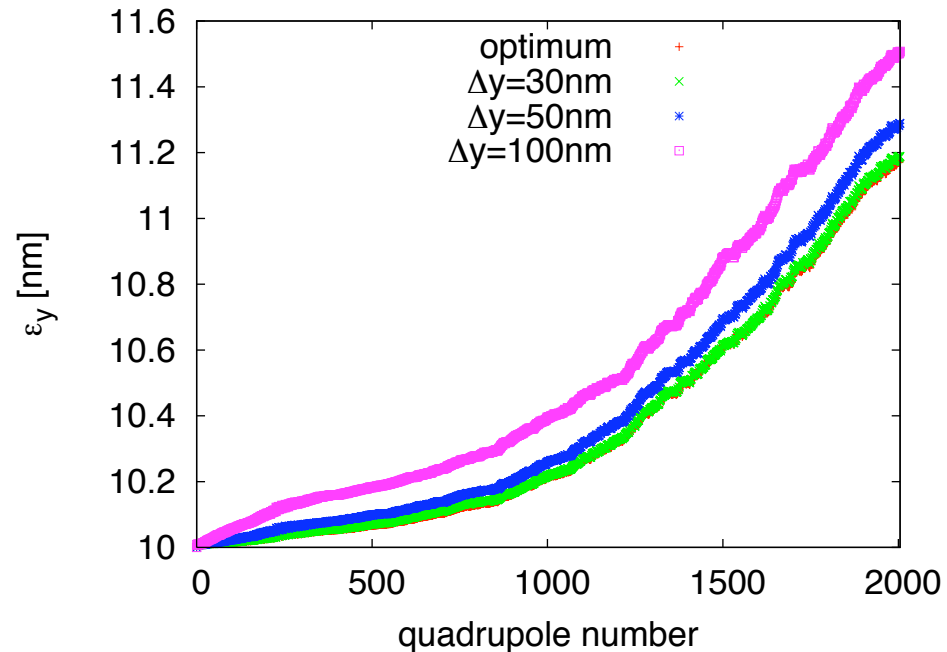


# Use of MICADO

- Try to find a small number  $m$  of most effective correctors
- Simulation performed using
  - one-to-one correction with given step size
  - then some iterations of MICADO

⇒ Significantly larger corrector step size are allowed

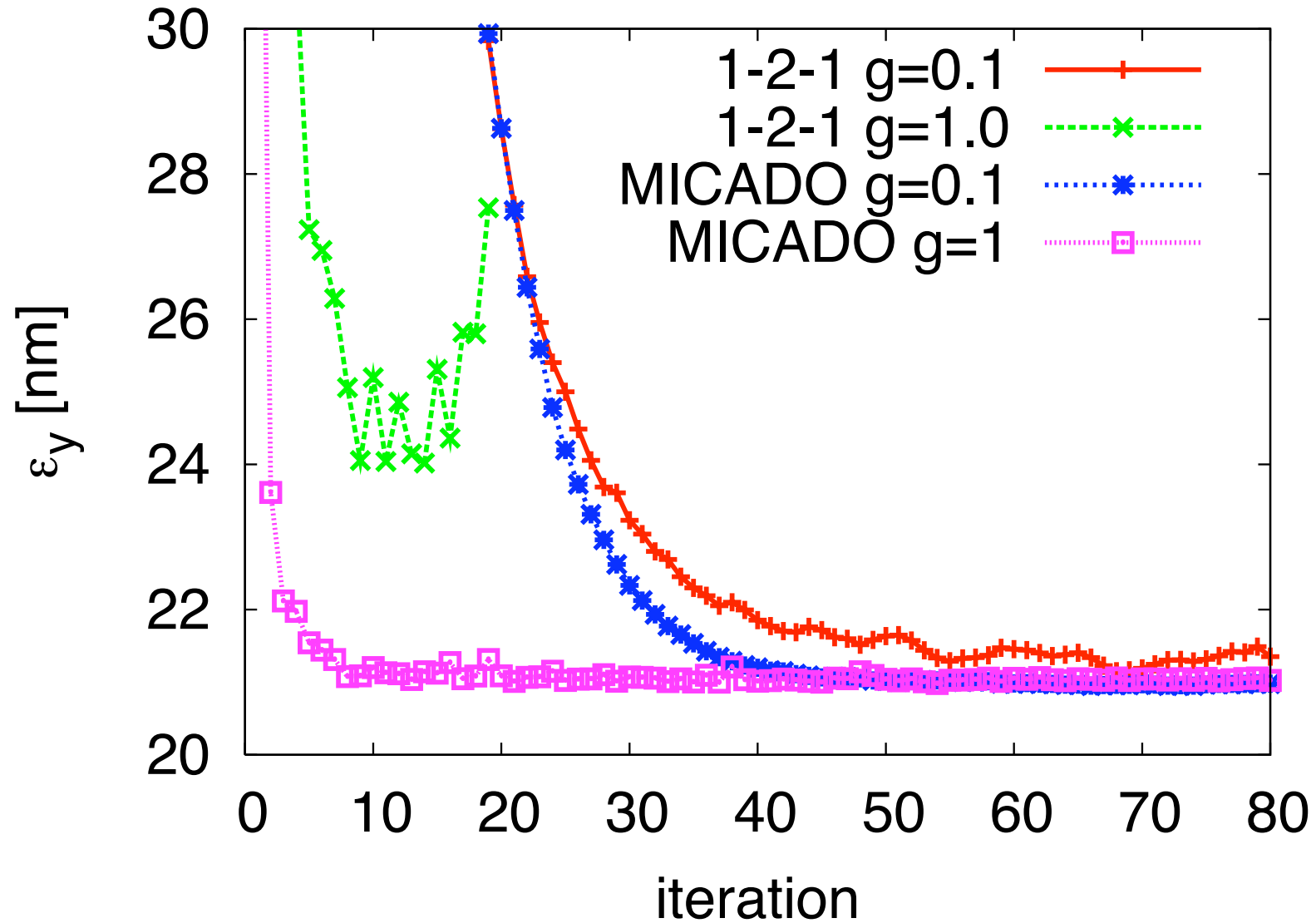
- In principle, MICADO can replace the one-to-one steering
  - speed of correction should be largely unaffected
- The main problem is to have an accurate enough model of the beam line
  - problem shared with other integrated feedback methods



# Some Simulation Procedure

- Assumed errors
  - $\sigma_K/K = 0.01$
  - $\sigma_{BPMscale} = 0.1$
  - $\sigma_{correctorscale} = 0.1$
  - $\Delta_{corrector} = 0.1\mu m$
  - $\sigma_{BPMres} = 1\mu m$
- ATL ground motion assumed for  $3 \times 10^6 s$  with  $A = 0.5 \times 10^{-6} \mu m/s/m$
- For MICADO 10 correctors are used
- For one-to-one correction all correctors are used (can be improved)

# Results



# One-To-One Results (BPM resolution $10\mu m$ )

