Transverse Beam Stability and Feedback

D. Schulte for the beam physics team and stabilisation friends

LCWS 2010, Beijing March 2010

Sources of Transverse Beam Motion

- A number of sources for transverse beam motion exists
  - ground motion
  - technical noise
  - jitter amplification by mechanical supports
  - RF gradient and phase jitter and dispersion
  - beam jitter from upstream systems
  - dynamic magnetic field variations
  - temperature variations
  - . . .
- Not all are due to the technical installation

  $\Rightarrow$ beam stability is site dependent

  $\Rightarrow$ develop beam stabilisation techniques and use what a given site requires

Tools to Reduce Beam Motion

- Choose a quiet site
  - e.g. the LEP/LHC tunnel is relatively quiet
- Avoid technical noise
  - identify sources of noise and modify their design if possible
- Avoid amplification of vibrations through supports etc.
  - careful girder design
- Use mechanical feedback and feedforward
- Use motion sensor based feedforward on the beam
- Use beam-based feedback
  - mainly using BPM signals

Strategy to Evidence Beam Stability for CDR

- Perform integrated simulation of main linac, beam delivery system and collision including
  - RF phase and amplitude jitter
  - a realistic model of the ground motion and technical noise
  - realistic transfer through supports, including mechanical feedback
  - realistic sensitivity curves and noise for ground motion sensors for beam-based feedforward
  - a realistic concept of the beam-based feedback
- Have an integrated simulation of main linac, BDS and beam-beam interaction
  - PLACET, benchmarked with LIAR, MAD, Merlin, Lucretia, SLEPT etc., tested at CTF3
  - GUINEA-PIG, benchmarked with CAIN

Feedback

- Can use a simplified treatment for understanding
- Luminosity loss is given by

$$\Delta\mathcal{L} \approx \Delta\mathcal{L}_{uncorrected}(g) + \Delta\mathcal{L}_{noise}(g) + \Delta\mathcal{L}_{residual}(t)$$

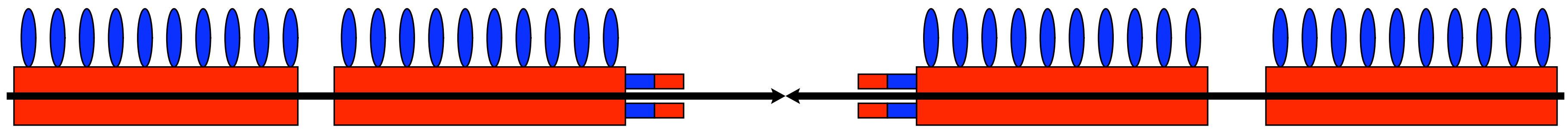
  $\Delta\mathcal{L}_{uncorrected}(g)$: loss not yet corrected due to feedback delay

  $\Delta\mathcal{L}_{noise}(g)$: loss due to noise introduced by feedback (e.g. BPM resolution)

  $\Delta\mathcal{L}_{uncorrected}(t)$: residual loss that the feedback does not correct by design

- We will eventually use a full model of the machine and feedback in the beam simulations

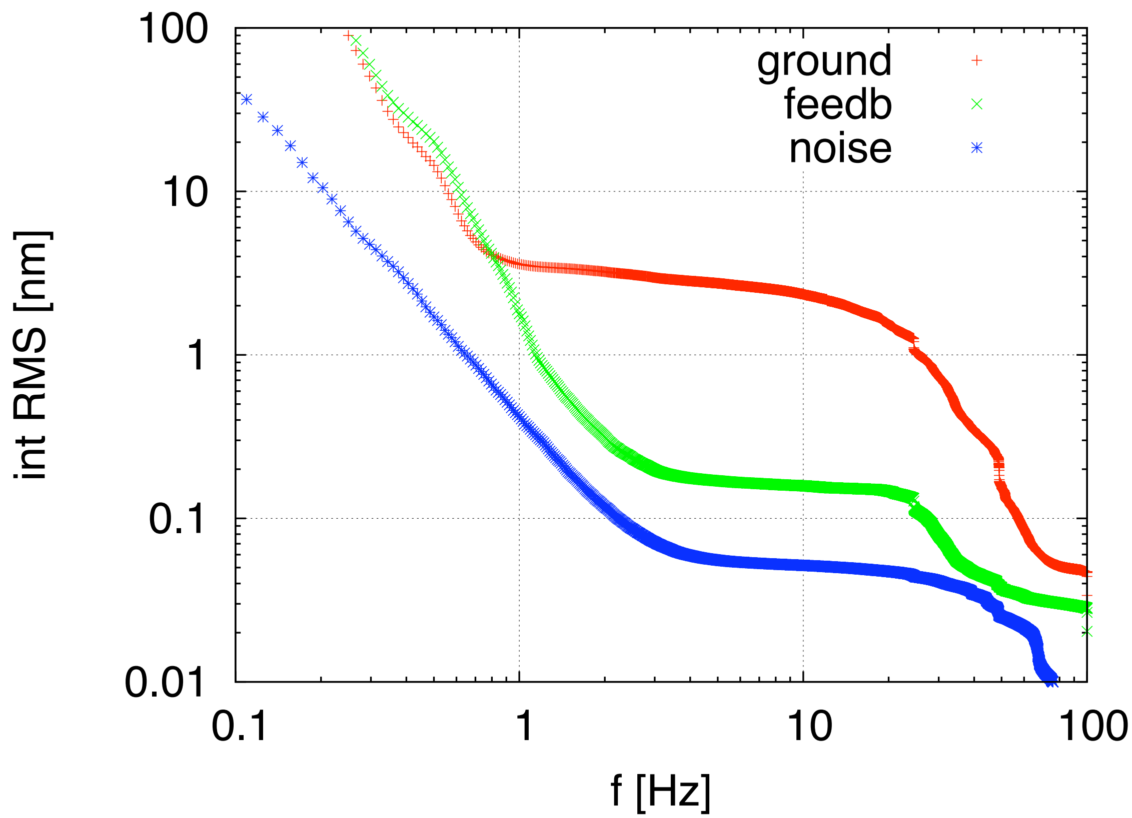
IP Feedback/Feedforward Conceptual Layout



- Currently the following feedback/feedforward systems are foreseen
  - a mechanical feedback for the quadrupoles (ground motion sensors on quadrupoles+actuators)
  - an intra-pulse beam-based feedback (BPMs+kickers)
  - a pulse-to-pulse beam-based feedback system (BPMs+kickers)
  - a feed-forward system based on ground motion sensors using the kickers to move the beam
- Beam-beam jitter tolerance $0.3\,\mathrm{nm}$ for 2% loss

Example of Mechanical Feedback and Noise

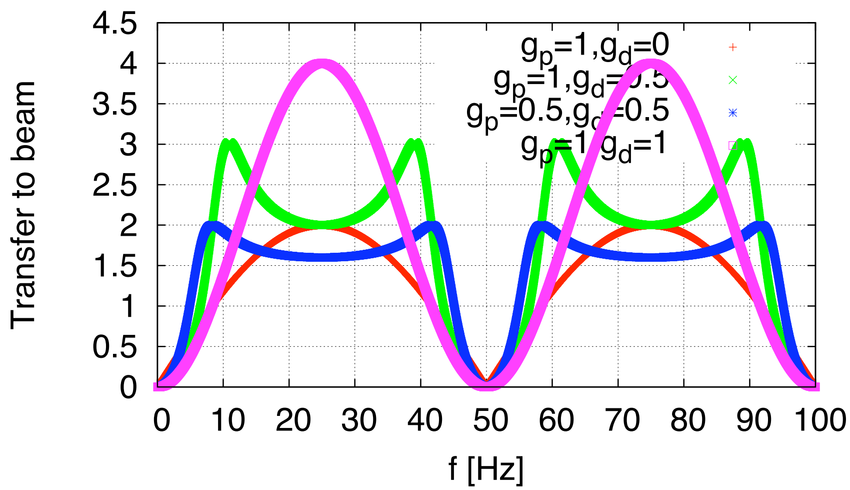
- A cantilever with feedback on the stabilisation table
  - not the real mechanical design
  - impact of magnetic field and radiation on sensors remains to be studied
  - used for illustration only
  - ground motion is Annecy

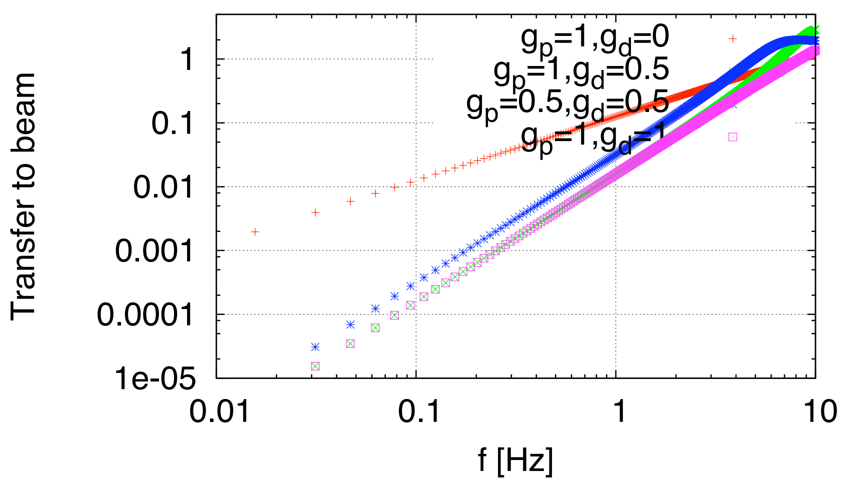


Data from B. Bolzon et al., noise assumed to be real-time measurement noise (A. Jeremie)

Simplified Model

- Ignore incoming beam jitter
- Four independent point-like quadrupoles studied
  - correlations will help, correlation expected strong for micro-seismic peak, will change controller design
  - assume that measured stability is stability of whole quadrupole
- Home-made controller
  - serious study of controler design started in Annecy (B. Caron, L. Brunetti)





Integration with Mechanical and Beam-Based Feedback

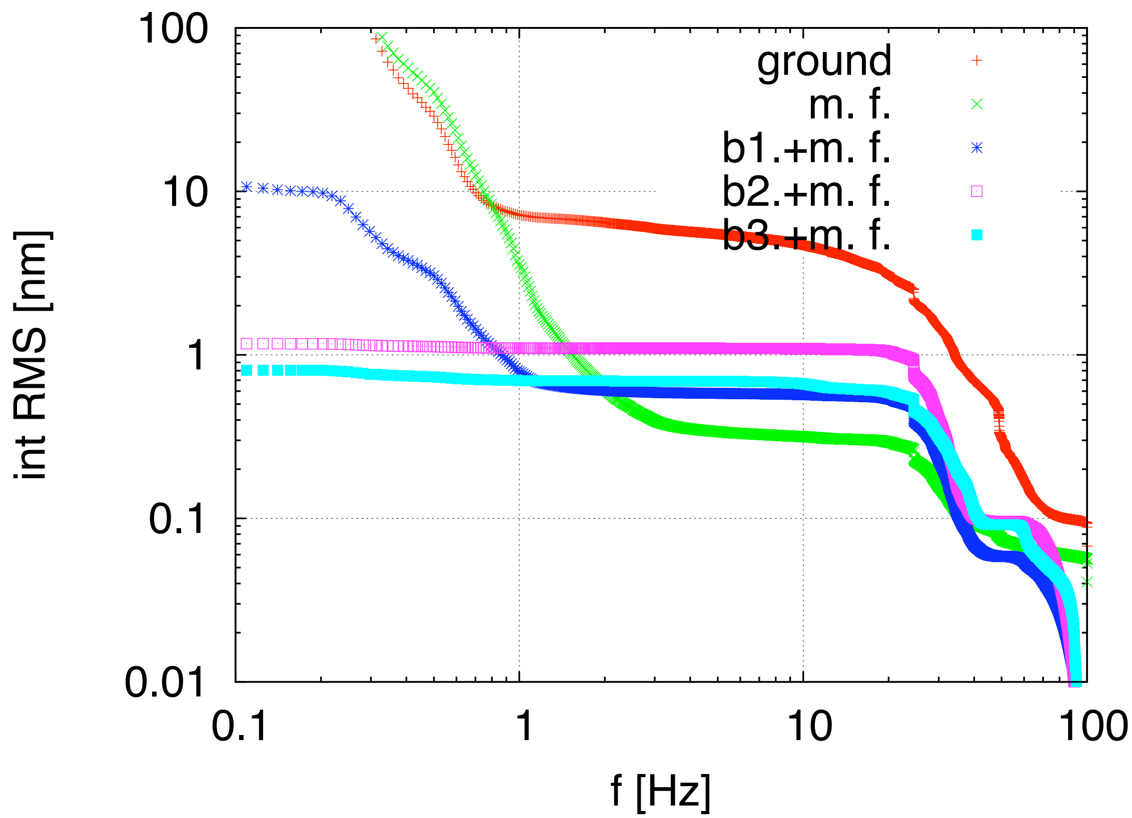
Three controllers shown

Note: For Seryi model did not need differential term since low frequency motion is correlated

$p_Q(\omega)$ power spectrum of beam-beam motion with mechanical feedback

$T_B(\omega)$ transfer function of beam-beam feedback

$p_N(\omega)$ noise spectrum of beam-beam feedback

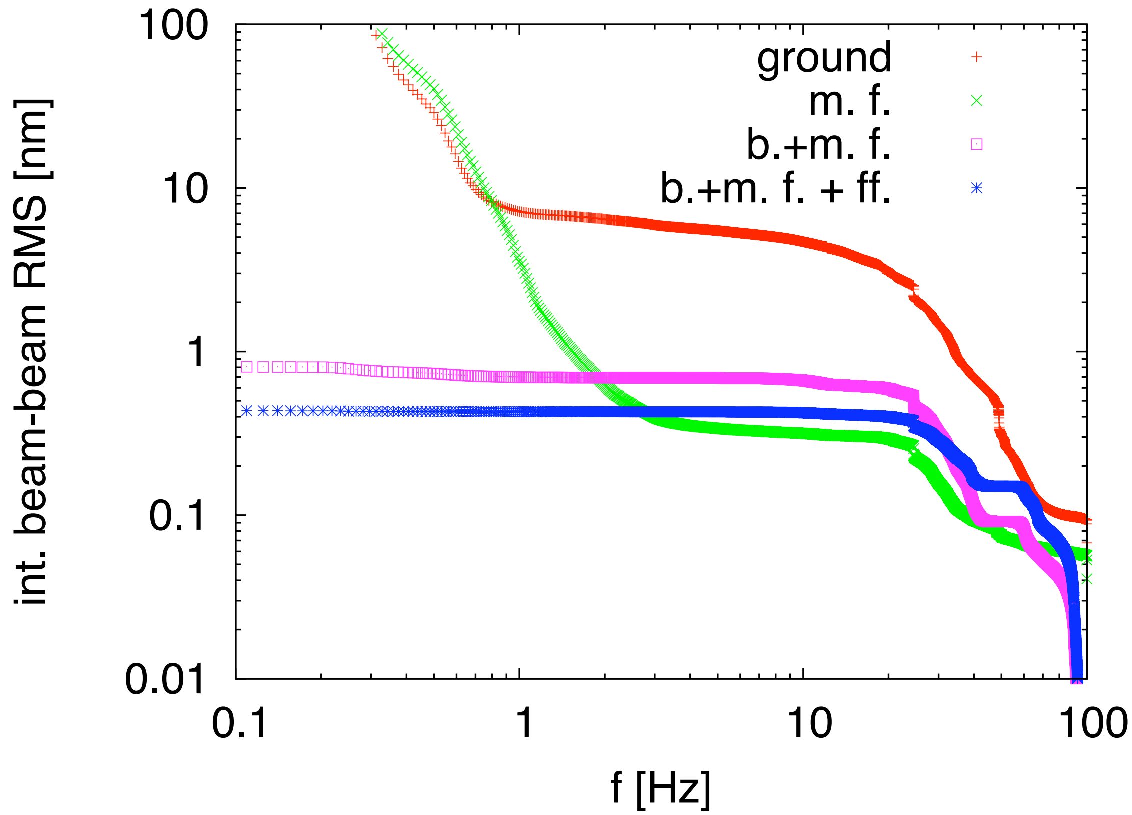


- Expectation for beam-beam offset can be calculated as

$$\langle y^2 \rangle = \int_0^\infty T_B(\omega)^2 p_Q(\omega) + p_N(\omega) d\omega$$

Addition of Feedforward

- Geophone sensitivity function and noise used as example
  - but problematic in magnetic field
- Best controller shown, need to do more detailed analysis of sensor (will reduce performance)



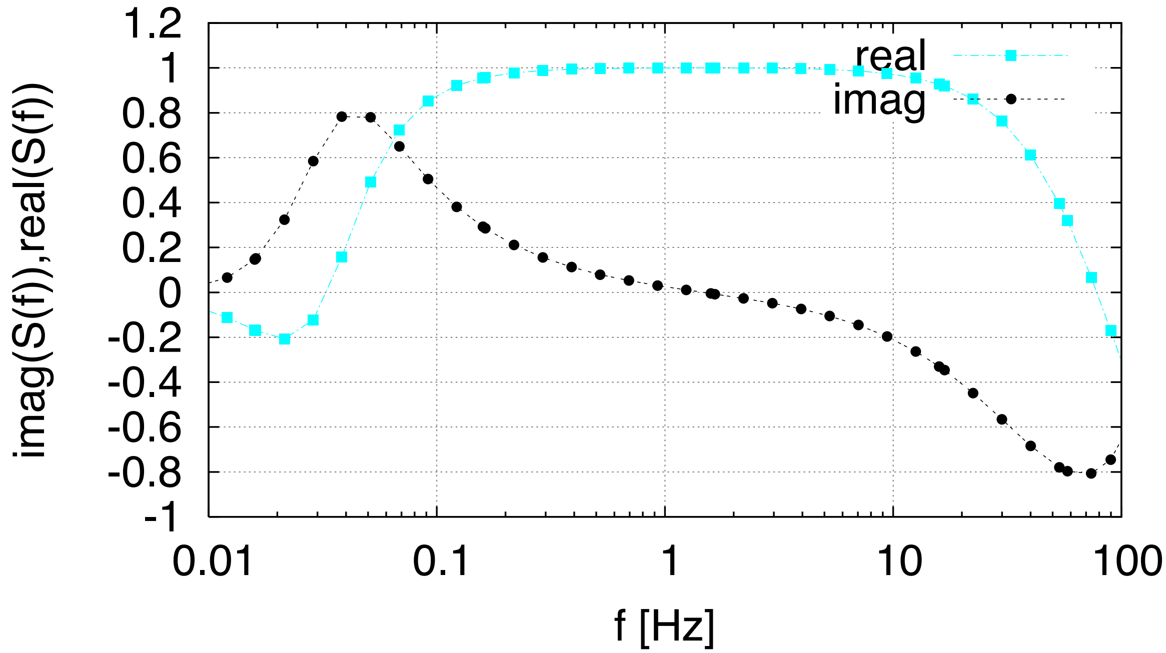
$$\langle y^2 \rangle = \int_0^\infty \; T_B(\omega)^2 \left(T_{FF}(\omega)^2 p_Q(\omega) + p_{FF}(\omega) \right) + p_N(\omega) d\omega$$

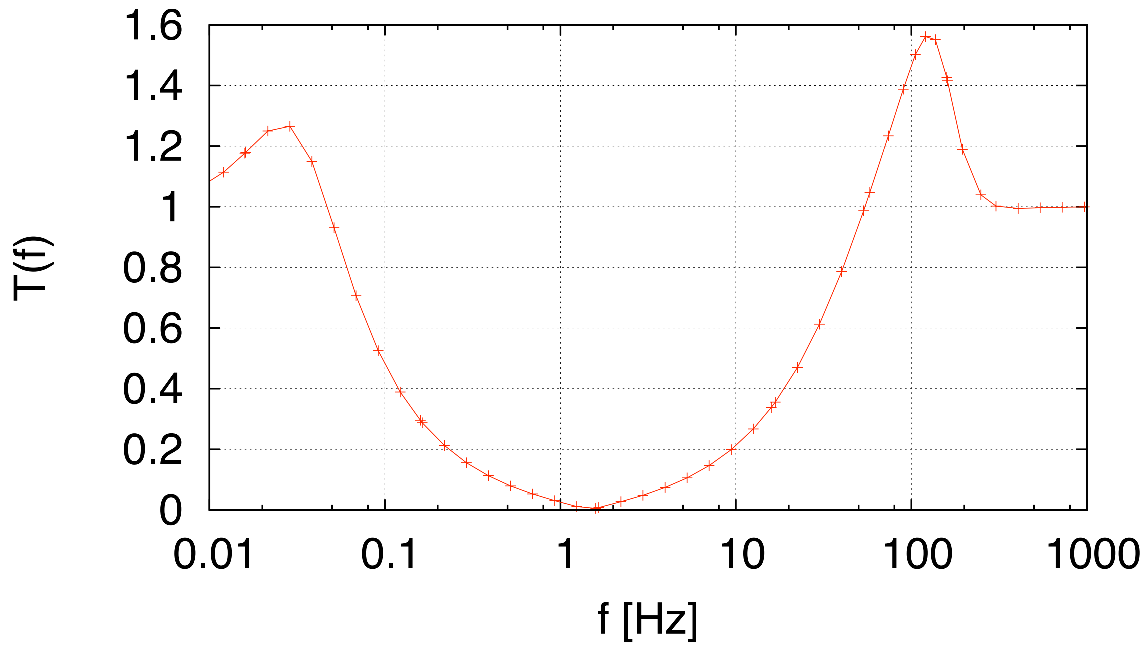
Example Sensor: Geophone

- Relevant is real-time measurement

$$T_{FF} = (1 - S(\omega))$$

- This sensor will need to be protected from magnetic field or need to design new sensor
- If sensitivity function were $S(\omega) = 1$ would reduce beam-beam offset by factor 2



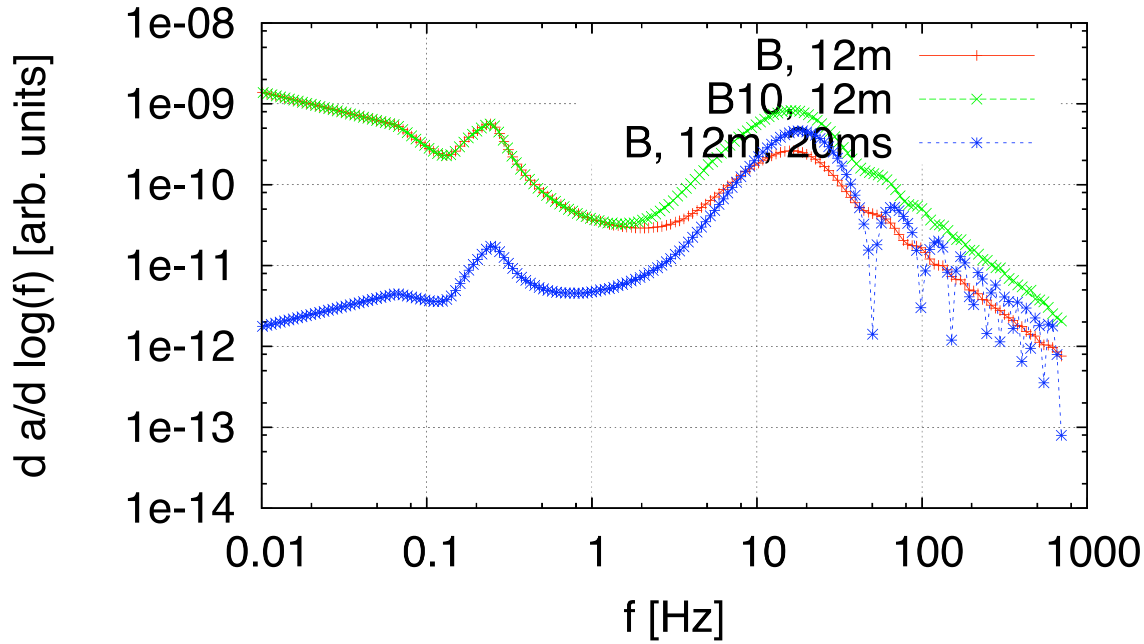


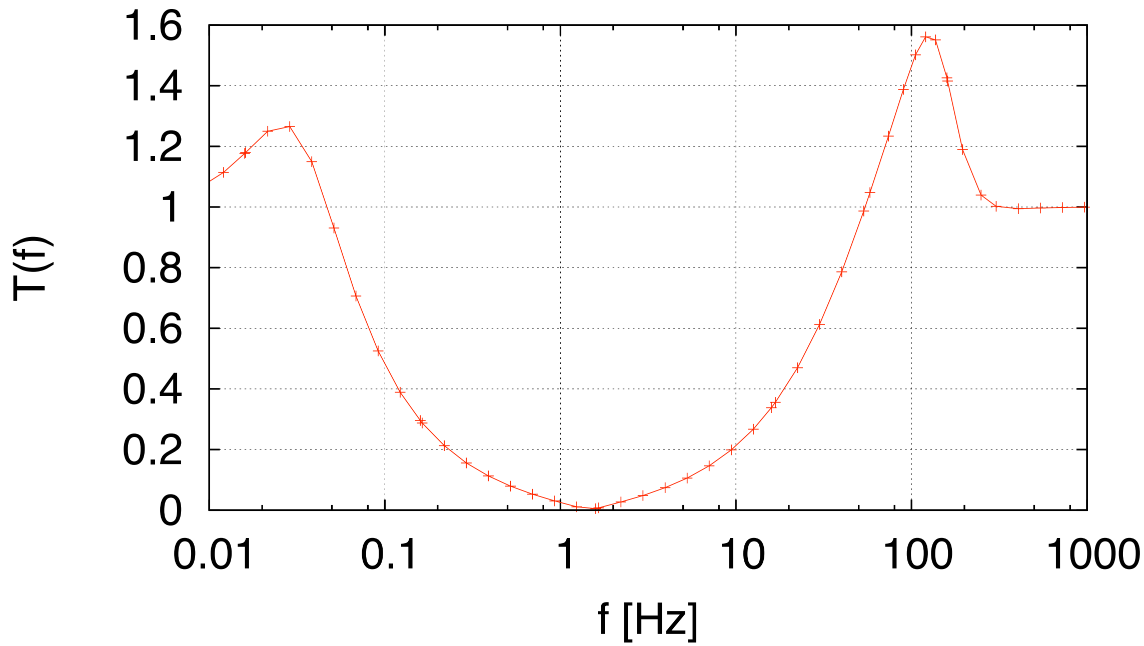
Sensor Frequency Choice

- Sensor choice is important to match motion spectrum
- Spectrum of relative motion is shown (over $12\,\mathrm{m}$)

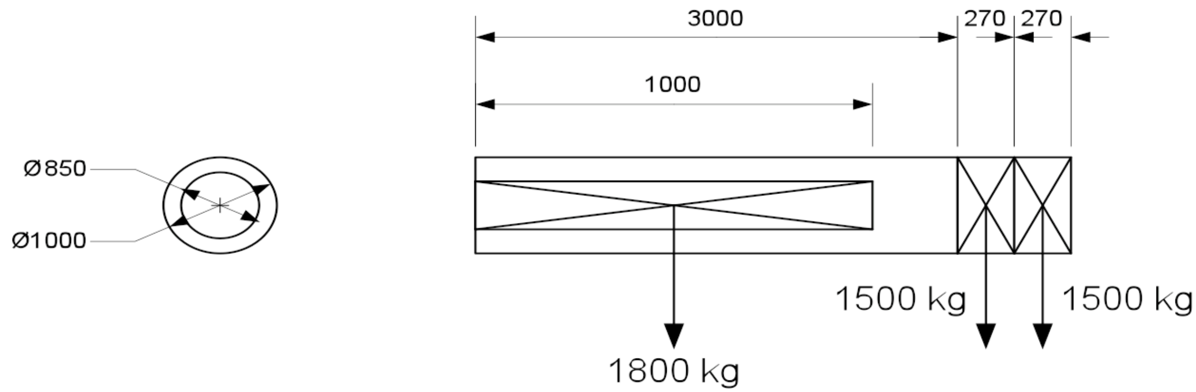
  - also motion at $50\,\mathrm{Hz}$

$\Rightarrow$ Geophone has not an optimum frequency response for ground motion model B

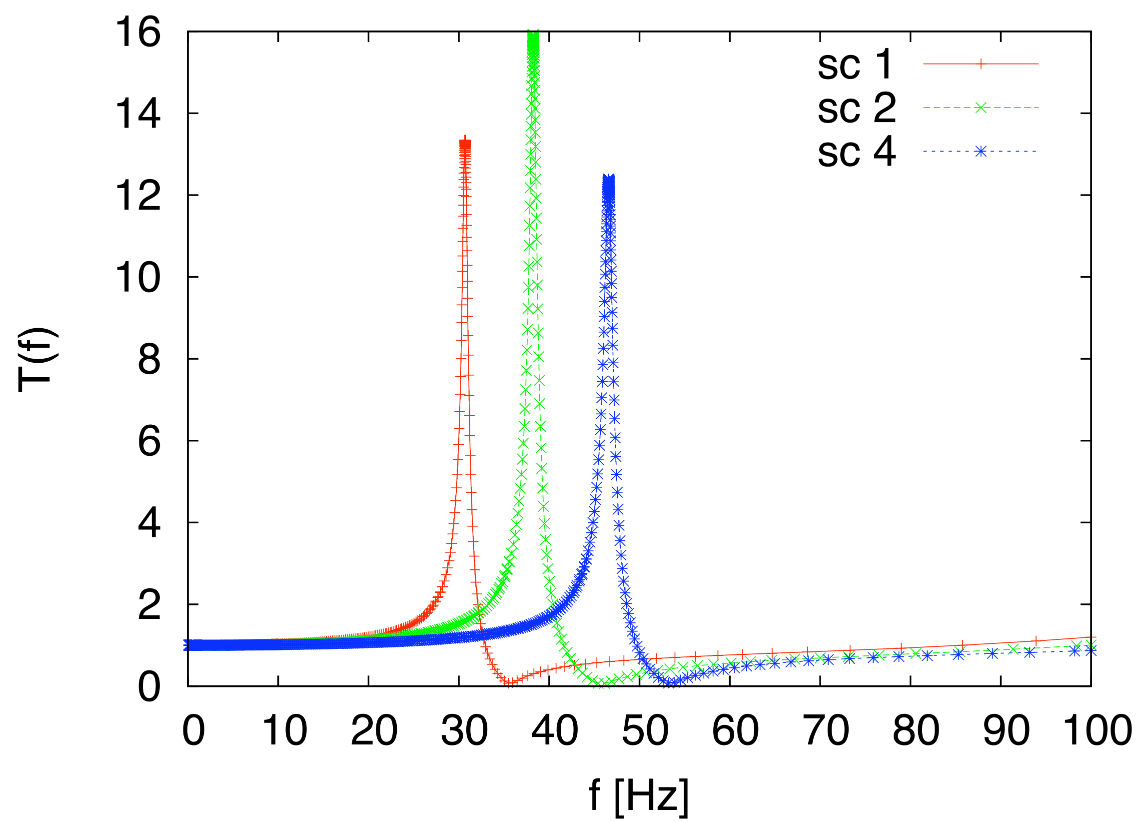




Cantilever Designs



- Designs and transfer functions from Hubert Gerwig, Alain Herve and Fernando Duarte Ramos
- Different designs not tuned for specific frequency
- Scenario 4 is shown



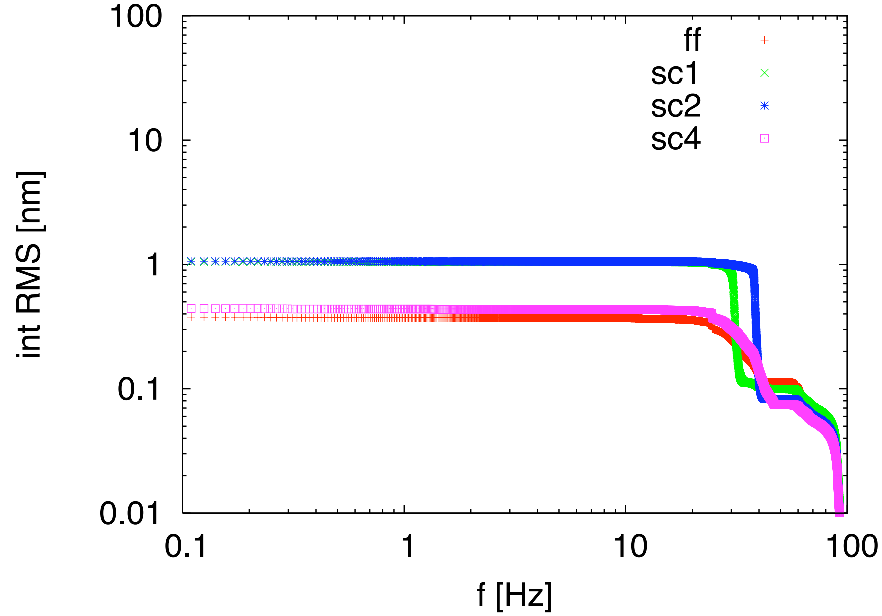
Impact of Cantilever

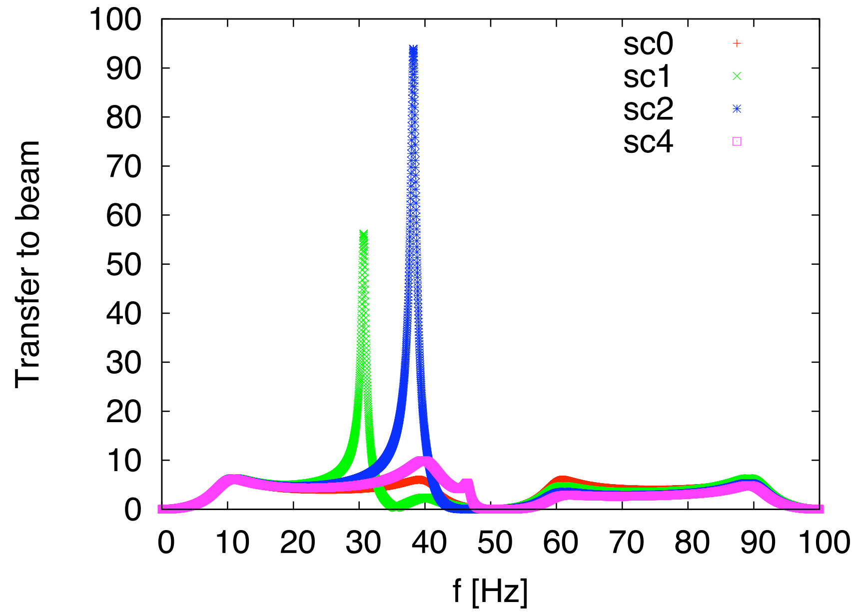
- Combination of ground motion, mechanical stabilisation, beam feed-forward (simplified), beam-beam feedback and cantilever is shown

- Note: based on earlier calculations update for new ones planed

⇒ The cantilver increases the quadrupole motion

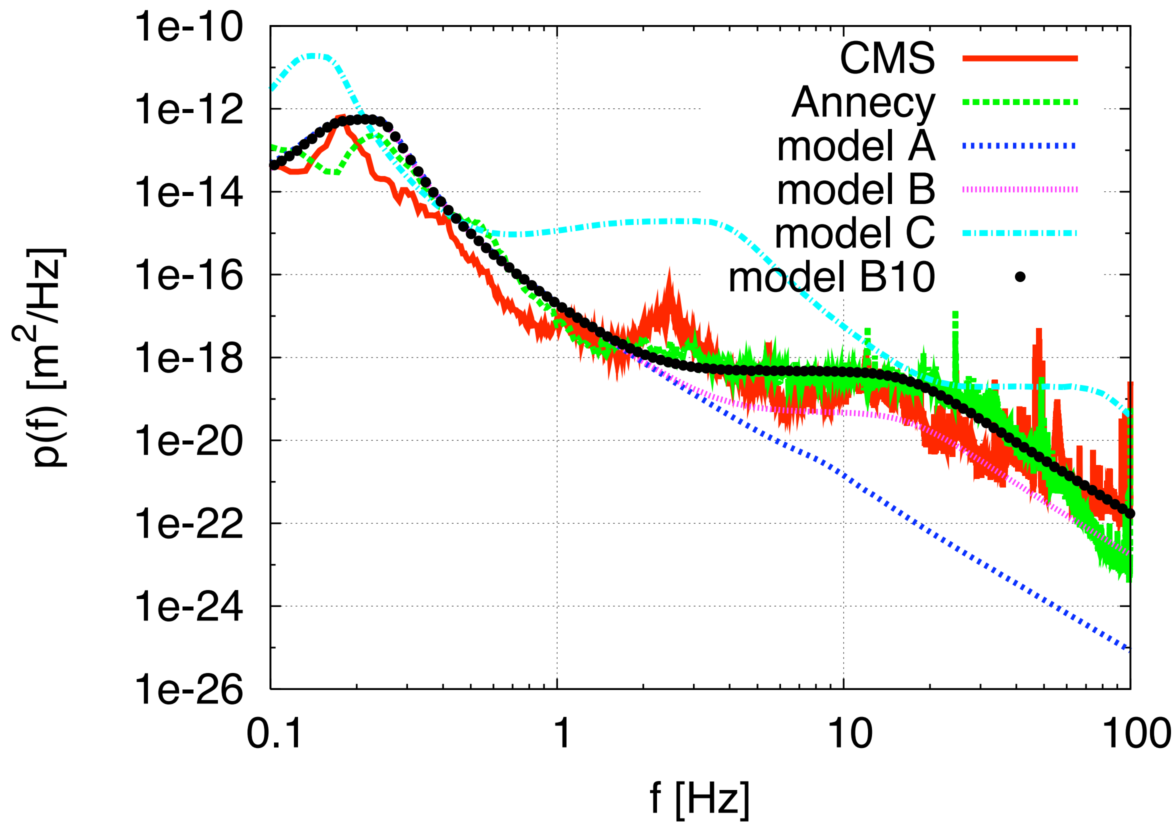
  - but not very much if resonance freqeuncy is good





Ground Motion Models

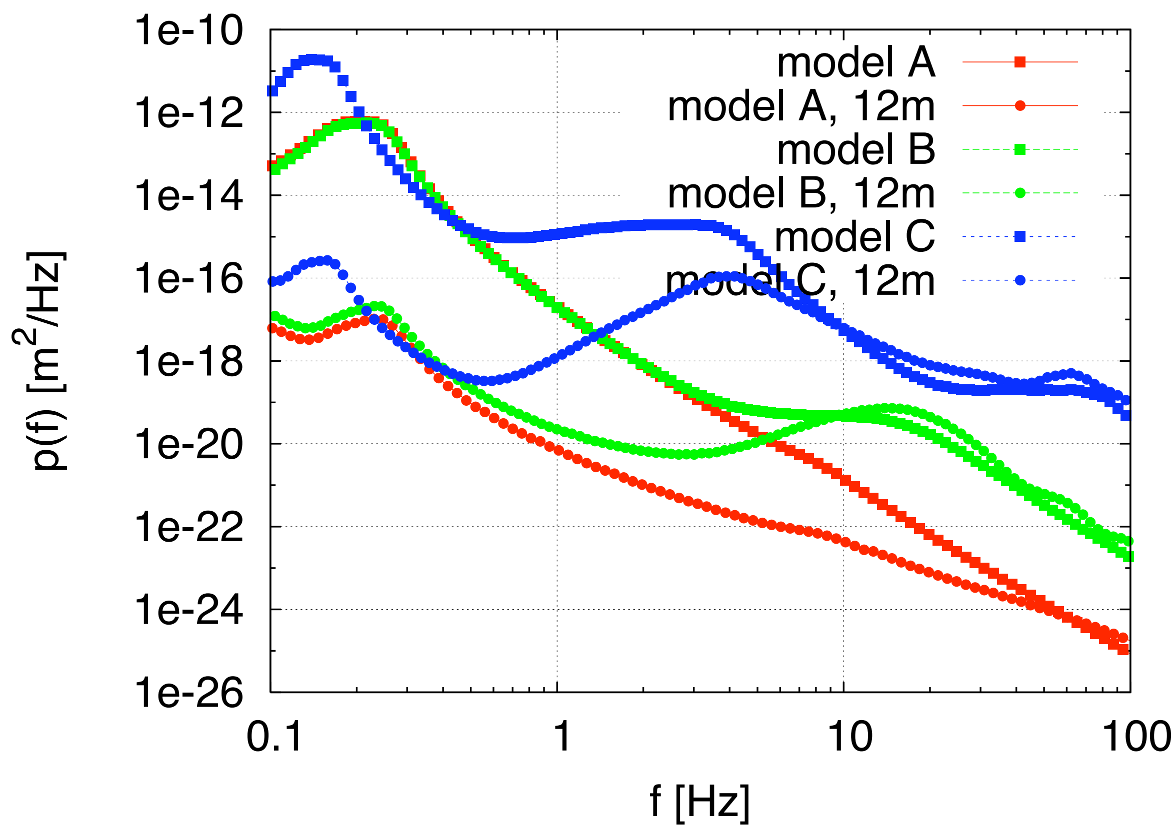
- Some examples are shown
  - Annecy and CMS hall floor
  - models based on Andrei Seryi's measurements
- LEP/LHC tunnel is relatively quiet
- Model B has similar shape as Annecy or CMS hall floor
  - B10 if we amplify one peak by factor 10 agrees even better



Ground Motion Correlation

- Ground motion is correlated
- Correlation has an impact on the luminosity performance
  - e.g. relative offsets of final quadrupoles is important (relevant distance $\approx 12\,\mathrm{m}$)

$\Rightarrow$ high frequency part is uncorrelated

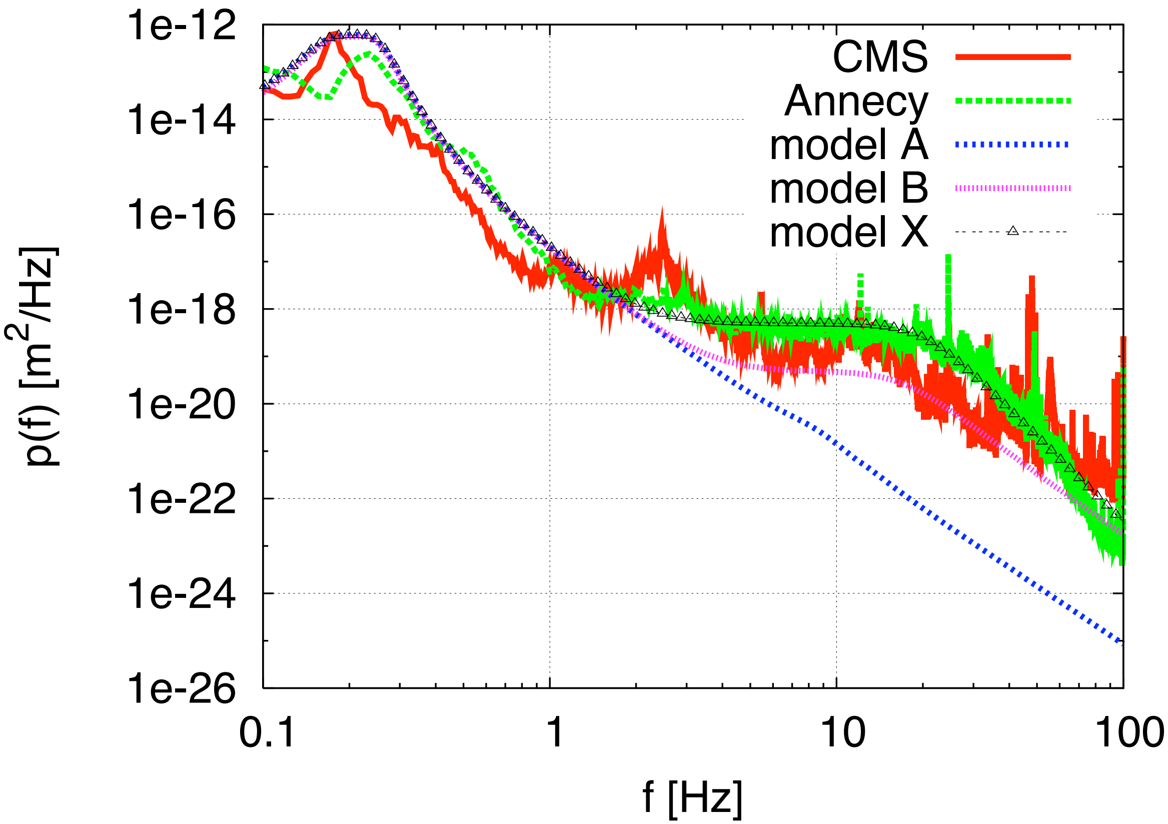


Another Model for CERN Site

- Consider ground motion as combination of
  - ground motion model A
  - technical noise modeled as (Ch. Collette)

$$P(\omega) = P_0 \frac{1}{1 + \left(\frac{\omega}{\omega_0}\right)^6}$$

- Parameters vary as function of position

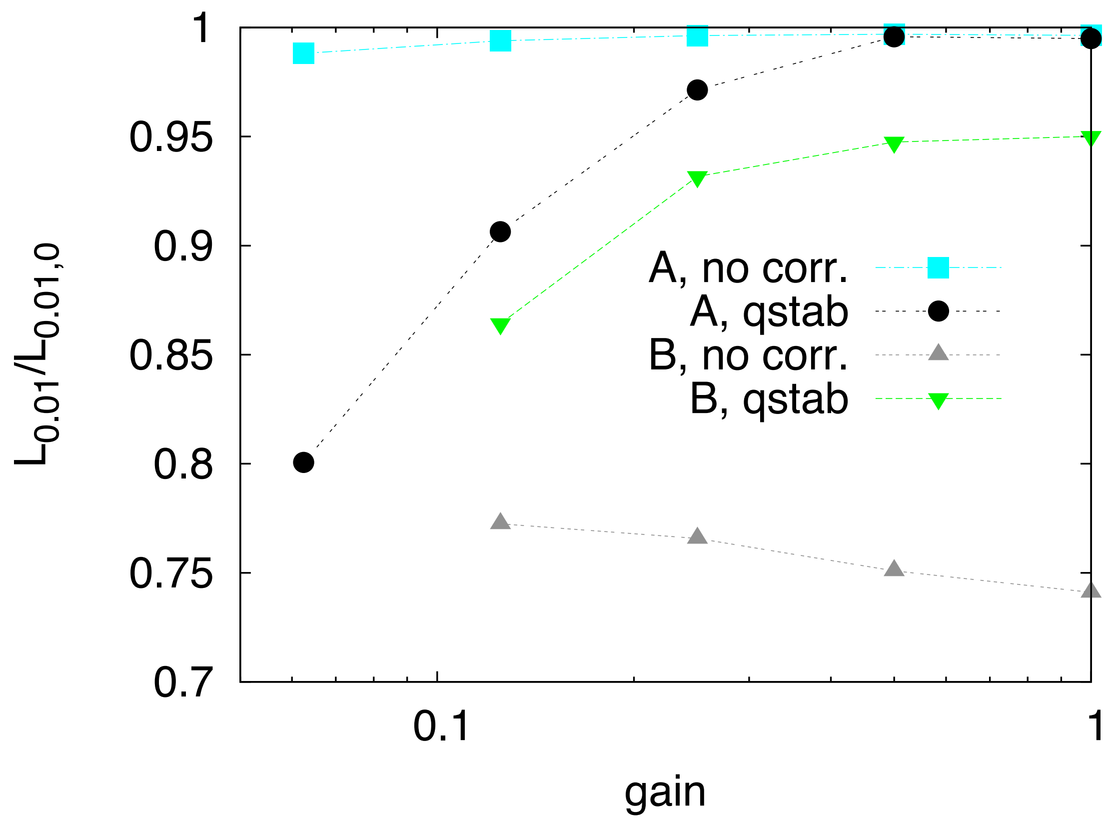


$\omega_0 = 40\pi$ and $P_0 = 0.5 \times 10^{-18}$ used

$\Rightarrow$ Should be able to choose representative model(s)

Impact of Ground Motion

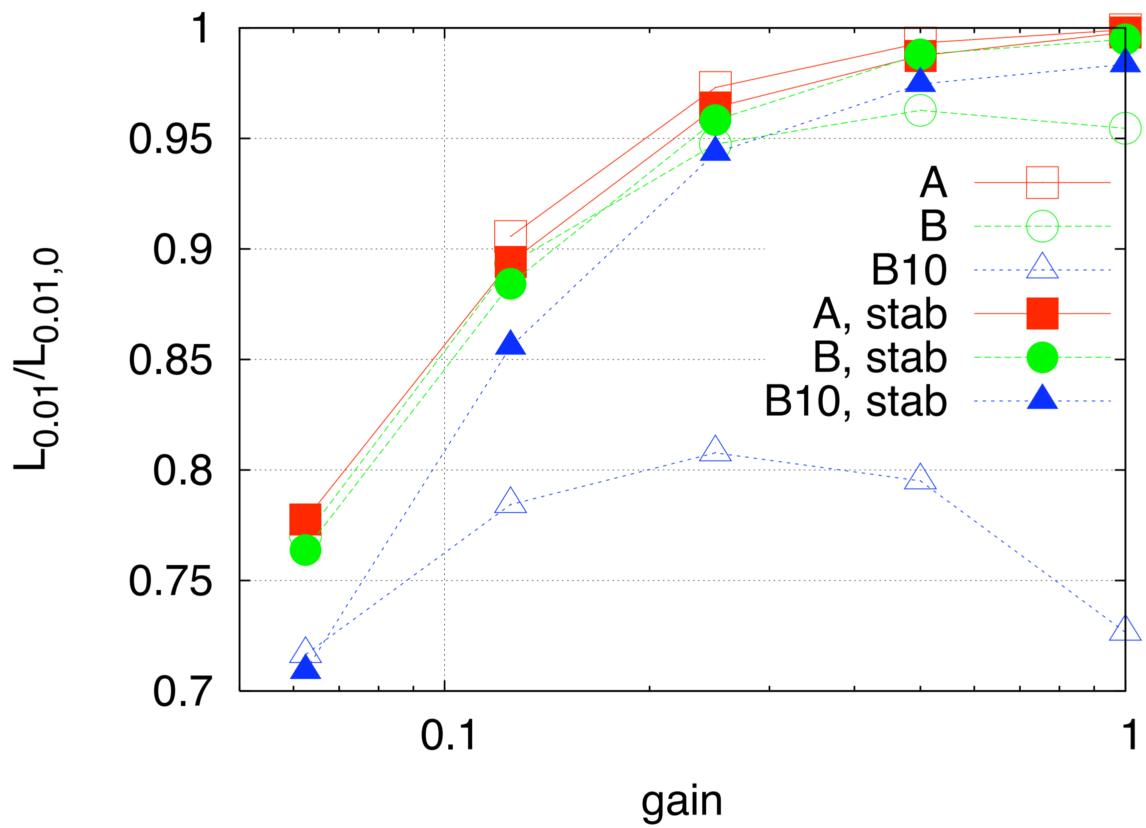
- Assumed a direct one-to-one transfer to beam line elements and simplified feedback
- Perfect stabilisation (air hook) is assumed at all frequencies
- Also multipoles in final doublet area are stabilised
- Note: in A stabilisation can increase luminosity loss as machine drifts away from stabilised magnets



⇒ A medium noisy site (B) is almost OK, if we stabilise the final doublets

Example: Impact of Quadrupole Stabilisation

- Assume stabilisation of all quadrupoles according to table in Annecy
  - for illustration only
- Need to replace the transfer function of that table more realistic model
  - iteration with stabilisation



Technical Noise

- Assume that technical noise has litte correlation

  $\Rightarrow$ jitter of each element around its nominal position

- Use previous fit

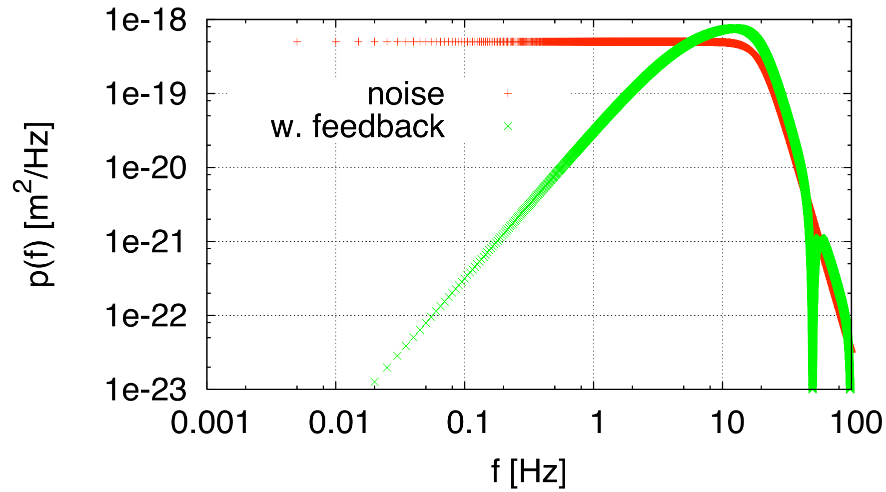
$$P(\omega) = \frac{0.5}{1+\left(\frac{\omega}{40\pi}\right)^6}\,\mathrm{nm}^2/\mathrm{Hz}$$

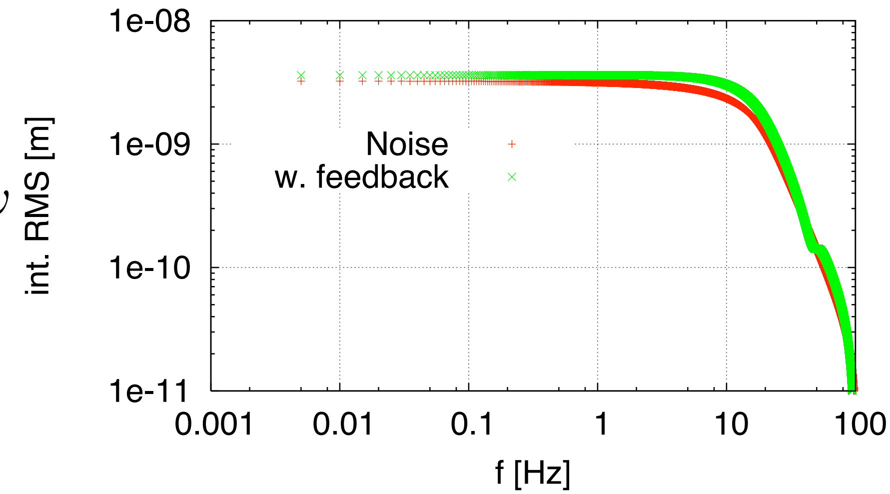
- RMS offset can be calculated as

  $\langle y^2\rangle = \int_0^\infty \left(P(\omega)T_S^2(\omega) + N_S(\omega)\right) T_B^2(\omega)d\omega$

  used no stabilisation for plots

$\Rightarrow$ Stabilisation needs to provide $T_S(\omega)$ and $N_S(\omega)$ to reduce $\sqrt{\langle y^2\rangle}$ to specification





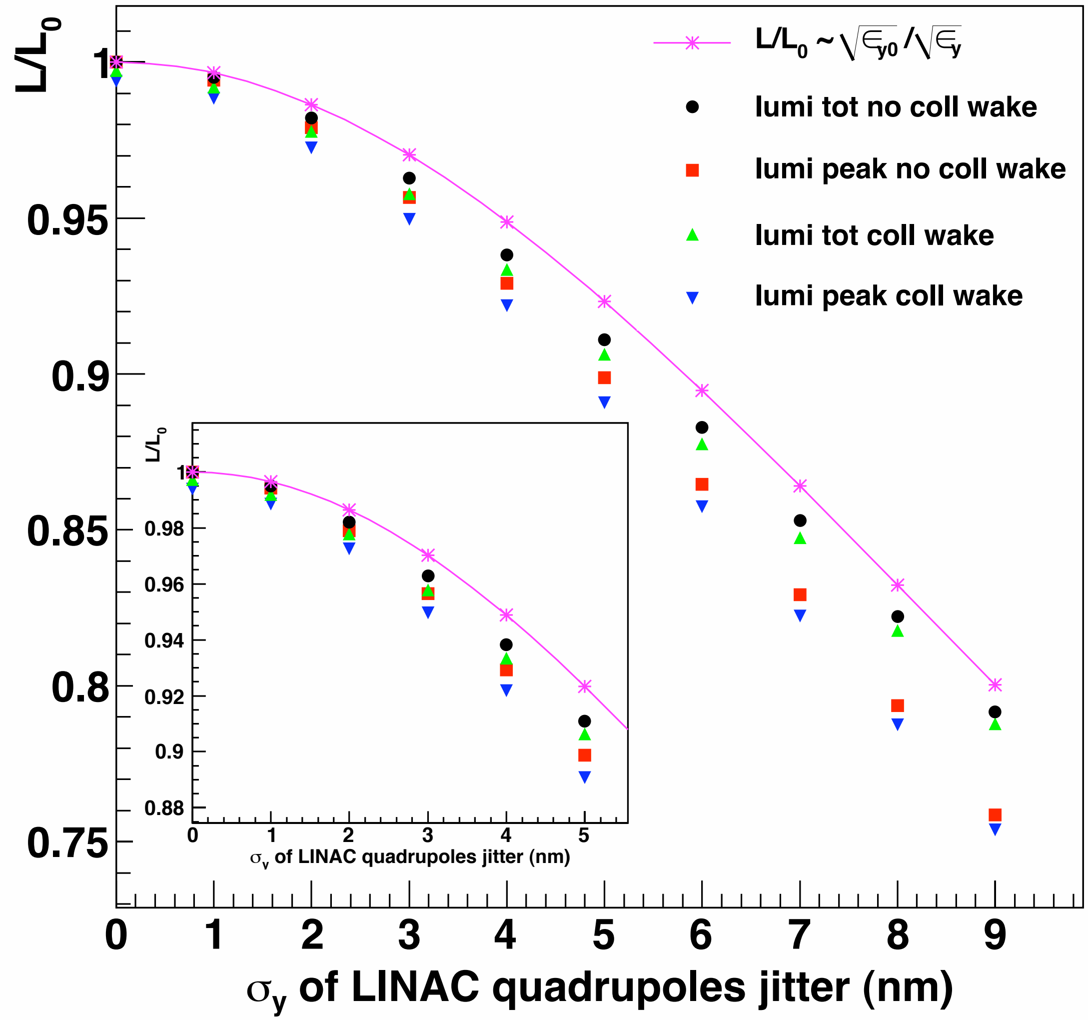
Main Linac Quadrupole Offset Tolerance

- Full simulation of main linac and BDS

⇒ The multi-pulse emittance is a good measure of the luminosity loss

⇒ The collimator wakefields add somewhat to the luminosity loss

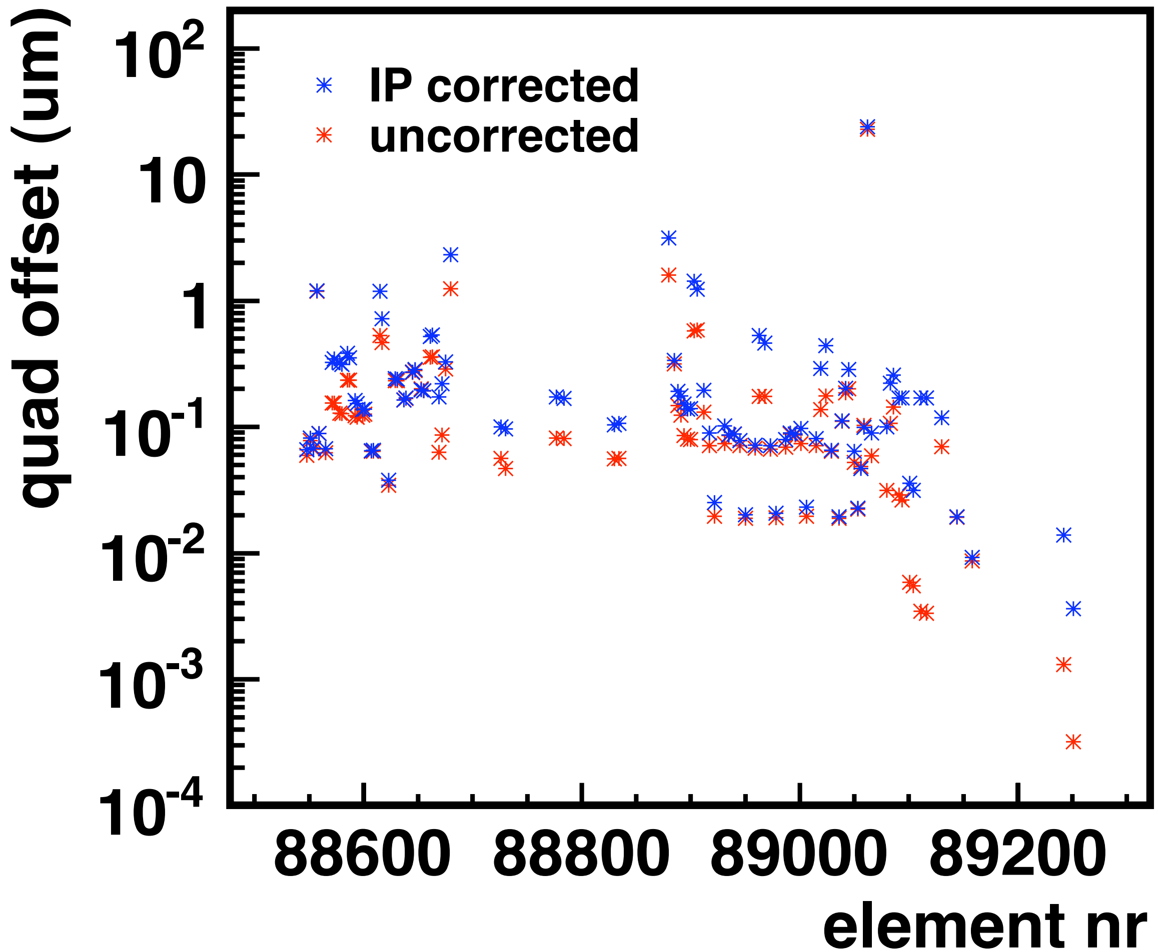
- Tolerance for $1\,\%$ dynamic luminosity loss is $\approx 1.3\,\mathrm{nm}$



B. Dalena

Beam Delivery System QuadrupoleOffset Tolerance

- Tolerance for 2% luminosity loss shown
  - no correction
  - optimisation of beam-beam offset

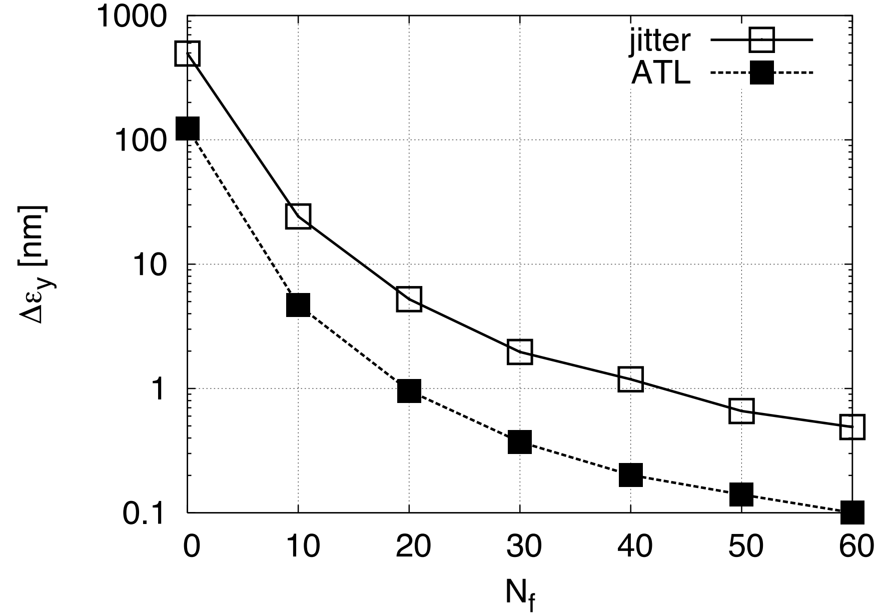


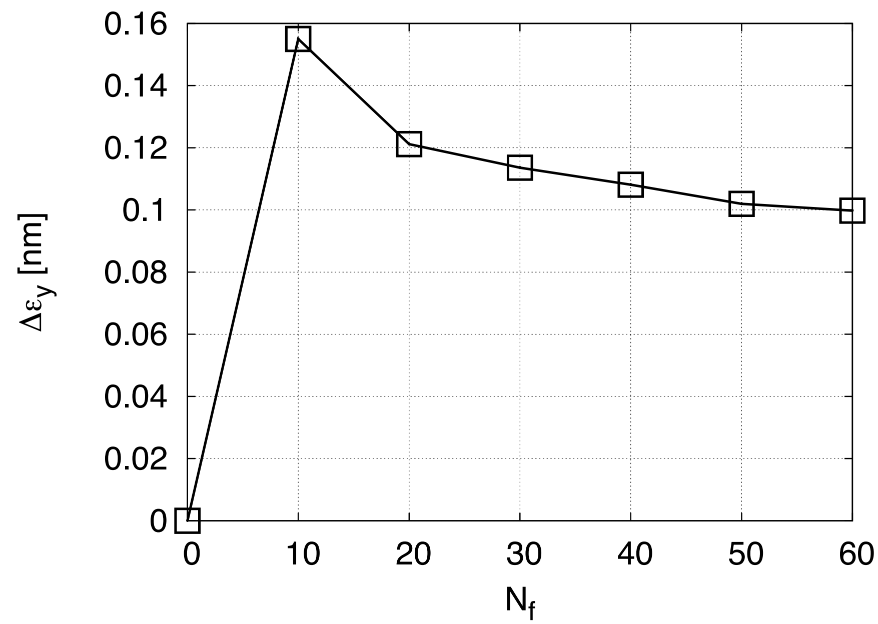
J. Snuverink

Main Linac Feedback Design

- Use 40 corrector pairs and 41 sets of eight BPMs
- Upper plot shows reduction of emittance bue to feedback
- Lower plot shows multi-pulse emittance induced by $100\,\mathrm{nm}$ BPM resolution

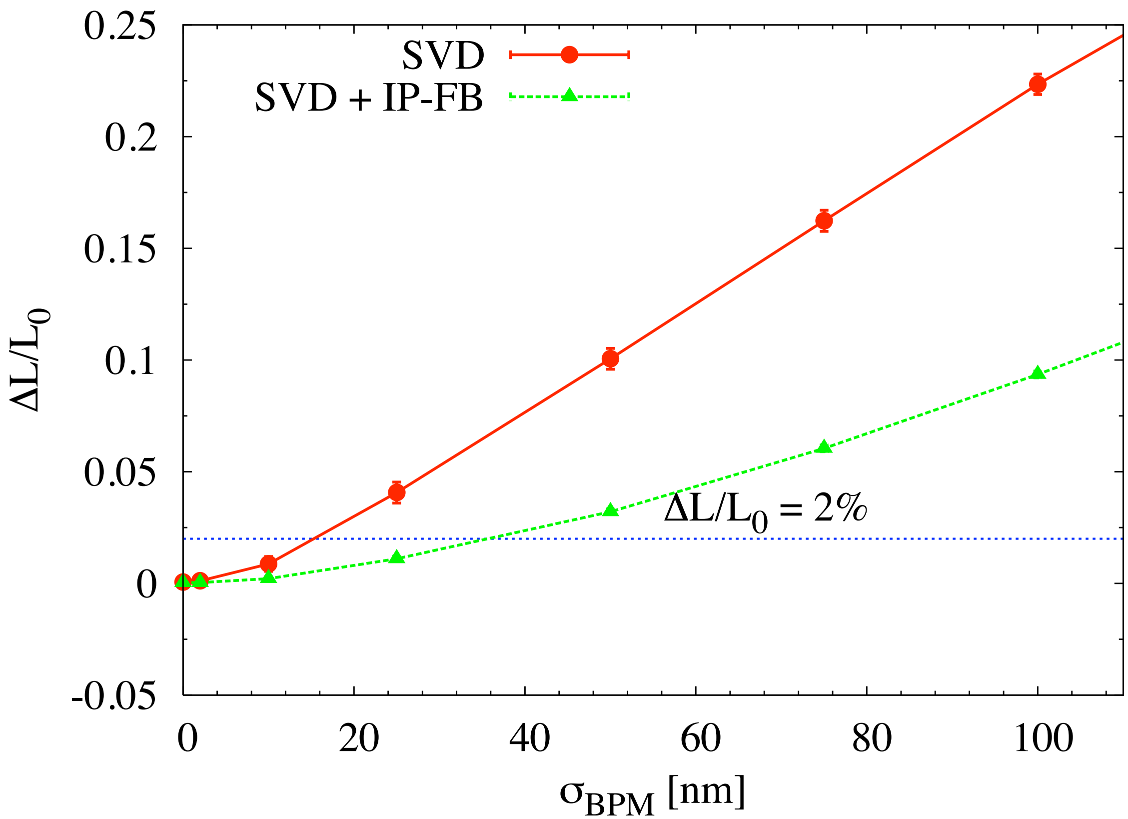
  $\Rightarrow$ can run with full proportional gain





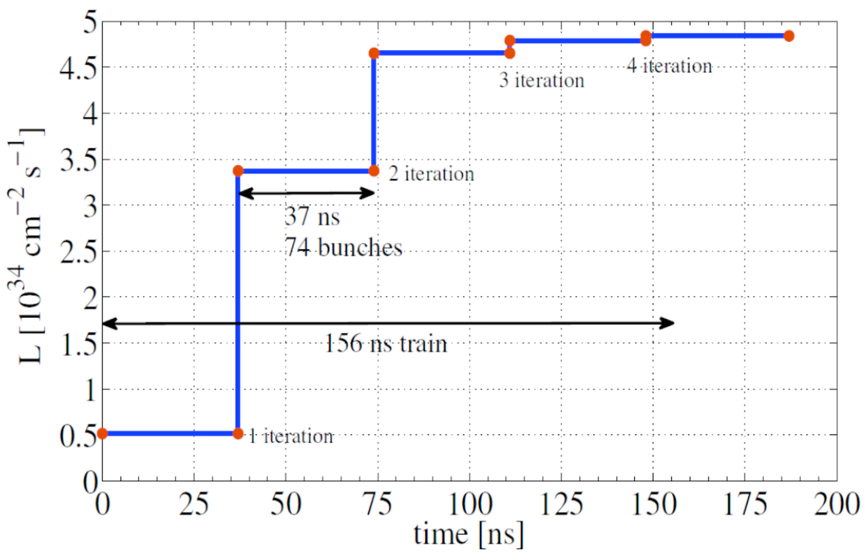
Beam Delivery System Feedback Design

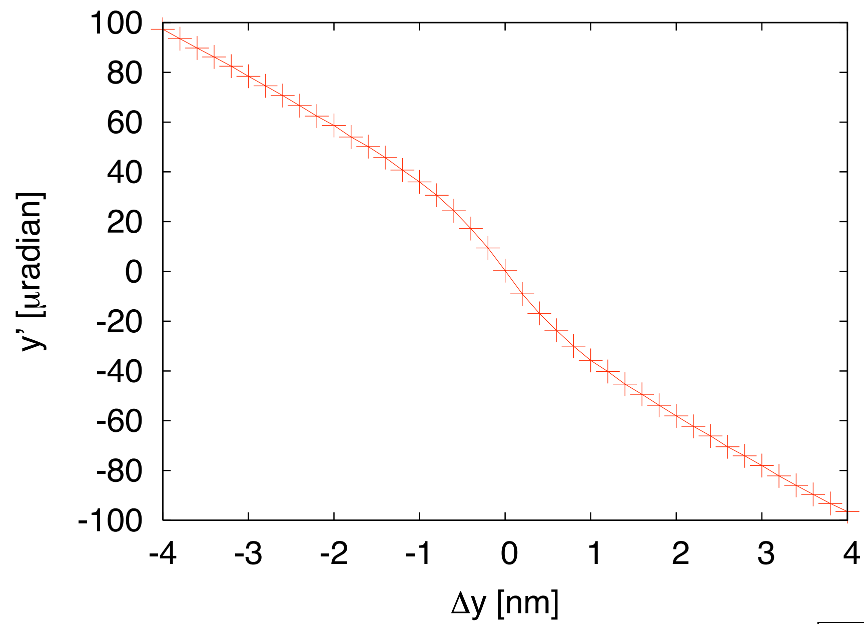
- Design is under development
- First results using a few-to-few correction show that BPM resolution should be better than $30\,\mathrm{nm}$ for fast feedback

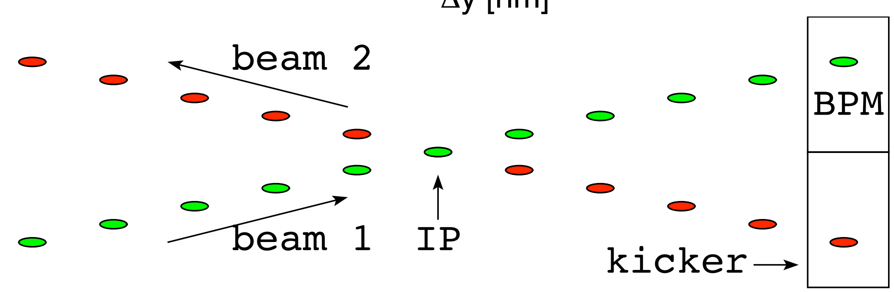


Intra-Pulse Interaction Point Feedback

- Simple beam-beam feedback based on deflection angle at IP
- Assuming 37 ns latency one can hope for factor 2 gain in tolerance
- Only cures offsets, μm BPM resolution is sufficient, but large aperture
- Collaboration with JAI







Thanks to Javier Resta Lopez

Main Linac and BDS Mechanical Feedback/Feed-Forward

- In the main linac and BDS ground motion sensor based beam feed-forward can be used
- Aim is to make the system cheaper
  - no mechanical feedback on quadrupoles
  - measurement of quadrupoles motion
  - correction by orbit correctors
- Requires is good system knowledge

  $\Rightarrow$ Juergen's thesis
- More challenging than the local mechanical stabilisation but could be less costly

  $\Rightarrow$ could be an alternative described in CDR

Conclusion

- Beam-based feedback design is under development
  - need to complete the BDS feedback
- Need more input from and interaction with the stabilisation group
  - noise sources
  - mechanical design and feedback
  - sensors
- Controler design started and needs continuation
  - integration of stabilisation and beam physics
- Integration is making progress
  - but quite a way to go
- Exploration of other beam jitter sources
  - e.g. stray fields study will start at CERN

Reserve

Dynamic Imperfections

- Luminosity loss is part of the emittance budget
- But limit luminosity fluctuation to less than 10%

  - total luminosity fluctuation is not straightforwad

Source	budget	tolerance
Damping ring extraction jitter	0.5%	kick reproducibility $0.1\sigma_x$
Transfer line stray fields	?%	data needed
Bunch compressor jitter	1%	
Quadrupole jitter in main linac	1%	$\sigma_{jitter} \approx 1.8\,\mathrm{nm}$
RF amplitude jitter in main linac	1%	0.075% coherent, 0.22% incoherent
RF phase jitter in main linac	1%	0.2° coherent, 0.8° incoherent
RF break down in main linac	1%	rate$< 3 \cdot 10^{-7}\,\mathrm{m}^{-1}\mathrm{pulse}^{-1}$
Structure pos. jitter in main linac	0.1%	$\sigma_{jitter} \approx 880\,\mathrm{nm}$
Structure angle jitter in main linac	0.1%	$\sigma_{jitter} \approx 440\,\mathrm{nradian}$
Crab cavity phase jitter	2%	$\sigma_\phi \approx 0.017^\circ$
Final doublet quadrupole jitter	2%	$\sigma_{jitter} \approx 0.17(0.34)\,\mathrm{nm}$–$0.85(1.7)\,\mathrm{nm}$
Other quadrupole jitter in BDS	1%	
...	?%	

$\Rightarrow$ Long list of small sources adds up

$\Rightarrow$ Impact of feedback system is important

Comment on Magnetic Field Stability

- The magnet has different oscillation modes
- The external vibration of each is not necessarily identical with the field vibration
- Feed-forward will help

  - can identify the modes with the sensors

  - can determine the correlation with beam motion experimentally in situ

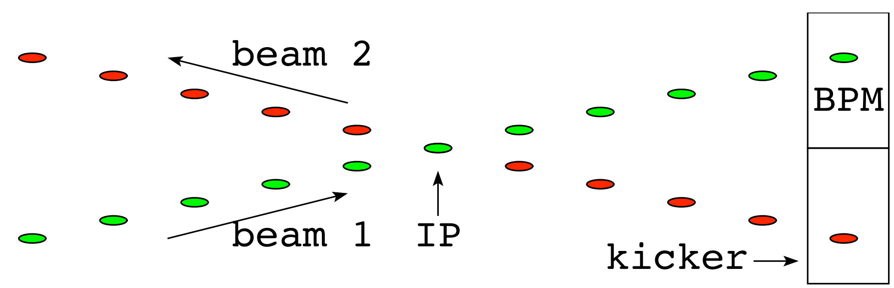
  - can use feed-forward to compensate additional magnetic motion
- Also would want to have the freedom to include feed-forward from direct ground measurement before mechanical feedback

Available Signals at Interaction Point

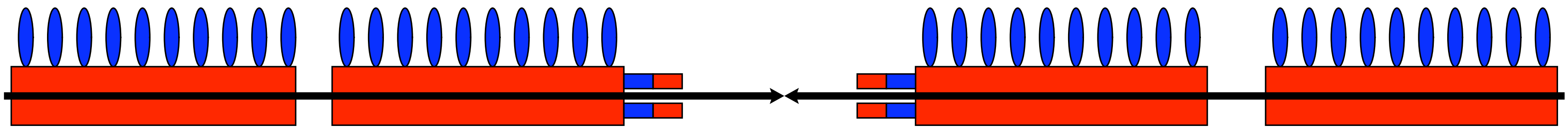
- The IP feedback/feed-forward system controls the beam-beam offset
- Available beam signals are for each beam pulse
  - the beam-beam deflection from the post-collision BPMs
  - the incoming beam jitter from the pre-collision BPMs
  - the incoming beam offset from the pre-collision BPMs
  - other beam-beam signals (energy loss, coherent and incoherent pairs, ...)
- Other available signals from ground motion sensors are the mechanical motion
  - of the ground from ground
  - of the quadrupole support
  - of the final quadrupoles

Interaction Point Feedback Design

- Currently the following feedback/feedforward systems are foreseen
  - a mechanical feedback for the quadrupoles (ground motion sensors on quadrupoles+actuators)
  - an intra-pulse beam-based feedback (BPMs+kickers)
  - a pulse-to-pulse beam-based feedback system (BPMs+kickers)
  - a feed-forward system based on ground motion sensors using the kickers to move the beam
- More complex systems need to be integrated but not on CDR timescale
  - etc. waist shift correction with beamstrahlung monitors
- Beam-beam jitter tolerance $0.3\,\mathrm{nm}$ for 2% loss



Proposed Conceptual Layout



- Sensors are used for mechanical feedback
- Feed-forward kicker does not need to be identical with intra-pulse feedback kicker
- Expected beam-beam offset due to quadrupole slice offsets δ_i and kicker strength k can be calculated via

$$\Delta y = -a(k_{ff} + k_b) + \sum_i b_i \delta_i$$

- Choose k_{ff} such that $\Delta y = 0$ is expected

  $\Rightarrow$ final beam motion is determined by sensor noise

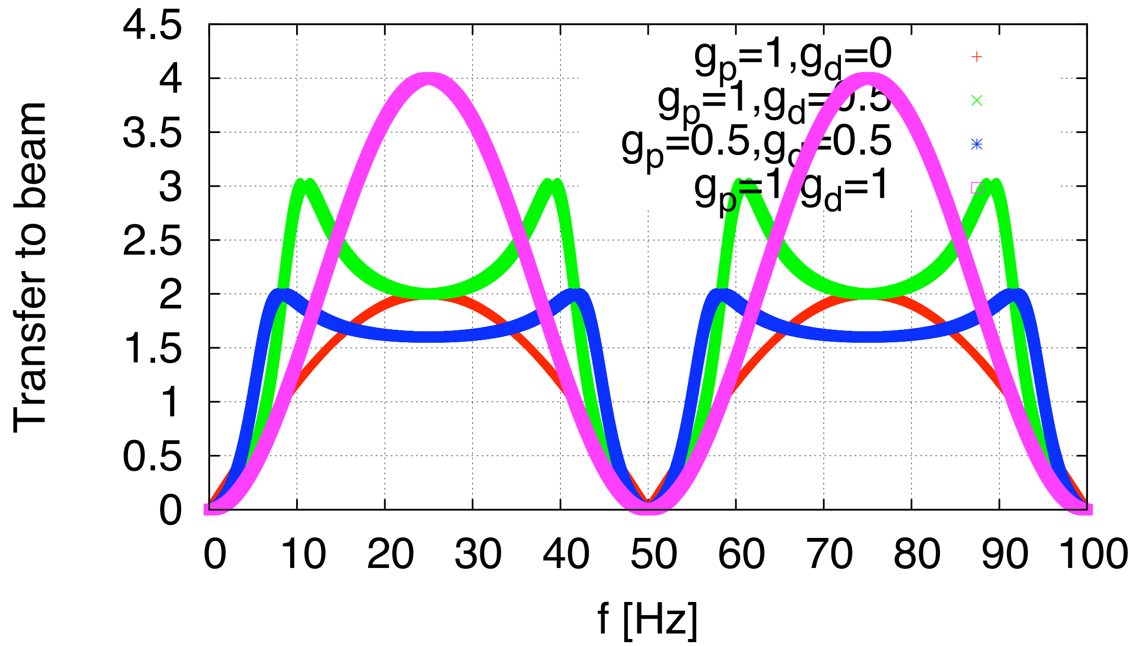
  - and imperfections in system knowledge

Simplified Model

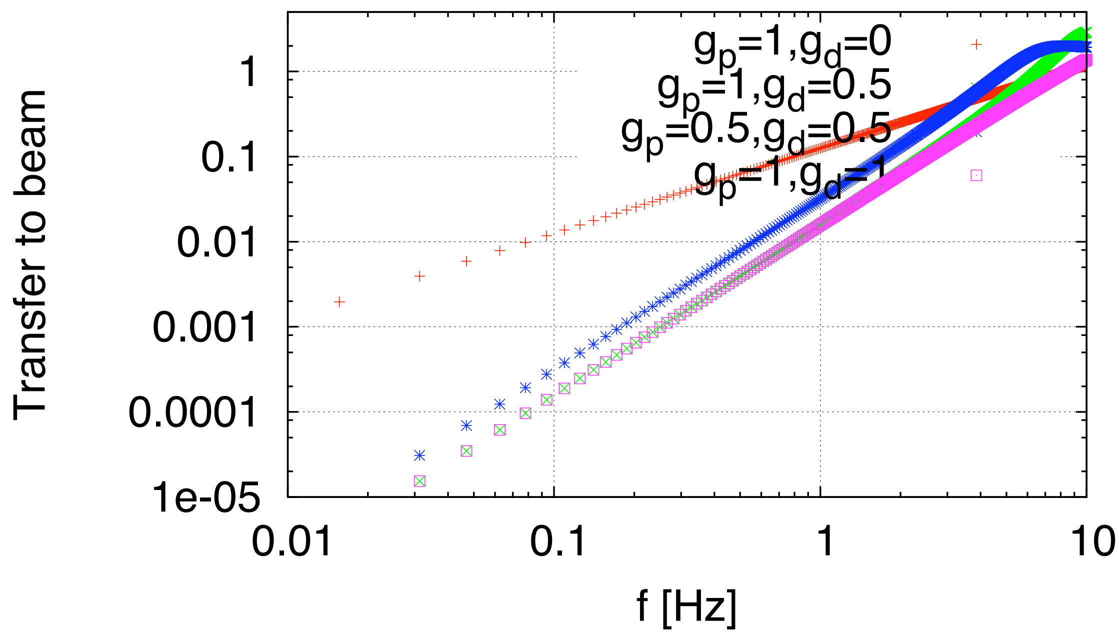
- Ignore incoming beam jitter
- Four independent point-like quadrupoles studied
  - correlations will help, correlation expected strong for micro-seismic peak, will change controller design
  - assume that measured stability is stability of whole quadrupole
- Quadrupole stabilisation feedback and beam feed-forward modelled by using sensor noise
- Beam-based feedback adds kicker strength k_b
- Simple home-made controller used:

$$\begin{aligned} k_b(n) &= g_i k_b(n-1) + g_p \frac{\Delta y(n-1)}{a} \\ &\quad + g_{d2}\left(k_b(n-1) - k_b(n-2)\right) + g_d \left(\frac{\Delta y(n-1)}{a} - \frac{\Delta y(n-2)}{a}\right) \end{aligned}$$

Beam Feedback Transfer Function



- Control on velocity cures low frequency perturbations better but causes more amplification at high frequencies
- Serious study of controler design started in Annecy (B. Caron, L. Brunetti)



Main Linac Feedback Performance

- The multi-pulse emittance growth as a function of the feedback gain is calculated
  - corresponds to

    $$\mathcal{L}_{uncorrected}(g)$$

  - primitiv controler used