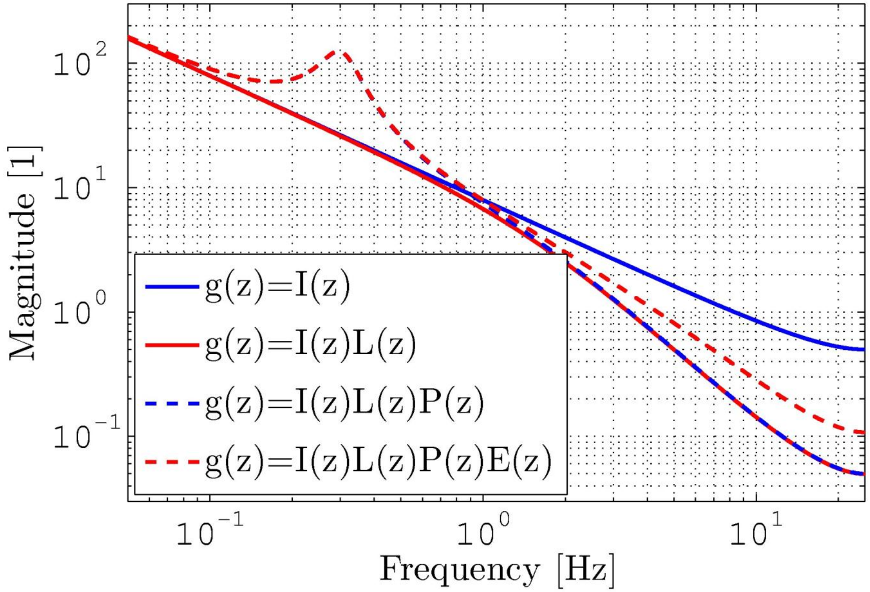
Ground-motion optimised orbit feedback design for CLIC

Jürgen Pfingstner

27th of September 2011

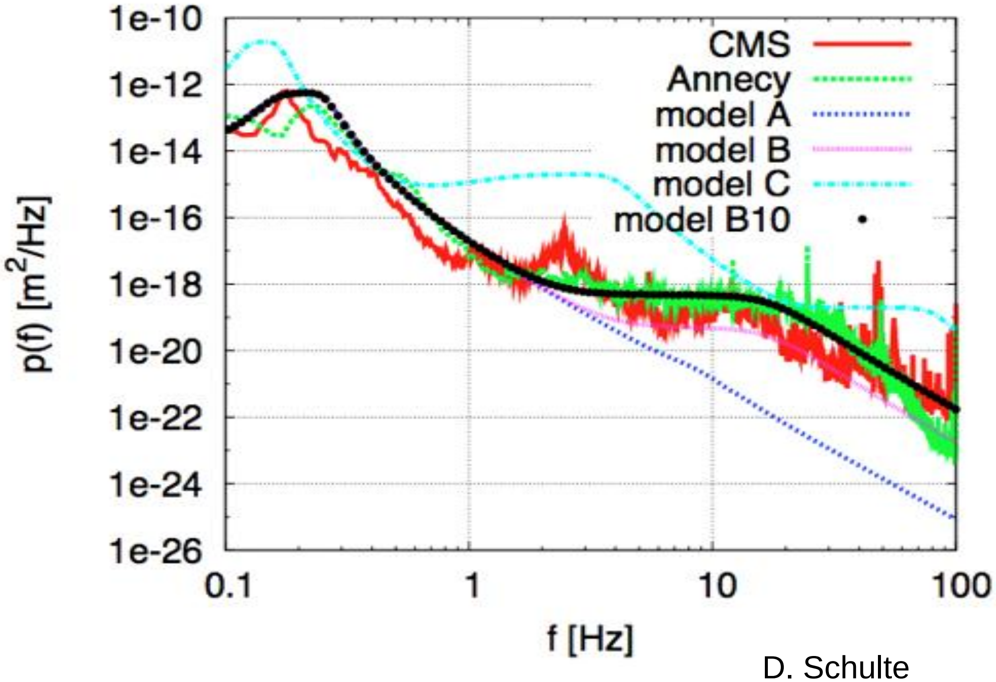
Content



1. The problem of ground motion and counter-measures
2. Orbit feedback design
   1. System description
   2. Decoupling
   3. Time-dependent feedback design
   4. Spatial feedback design
3. Results

1. The problem of ground motion and counter-measures

Ground motion



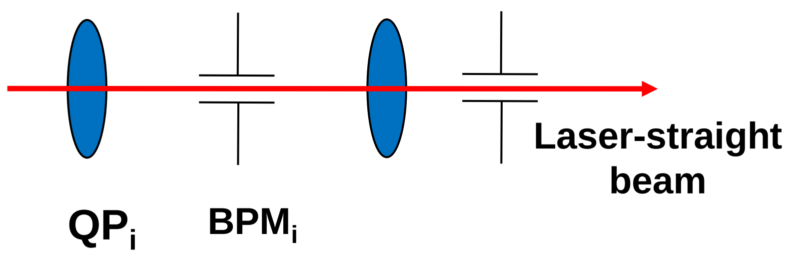
D. Schulte

- Ground motion is a stochastic process
- Description via the 2D-PSD (power spectral density) in frequency and wave length
- Characteristics of the 2D-PSD:
  - Diffusive motion (ATL law)
  - Microseismic peak
  - Cultural noise
- Out of many measurements the models A, B, B10 und C created

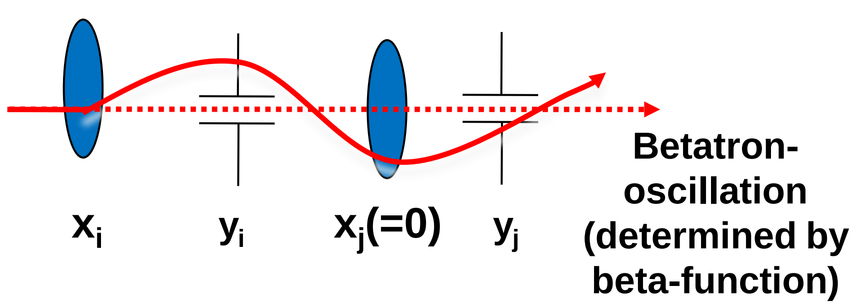
Problems due to ground motion

- Ground motion misaligns the quadrupole magnets (QPs) of CLIC
- This excites the beam to oscillations

1.) Perfectly aligned accelerator

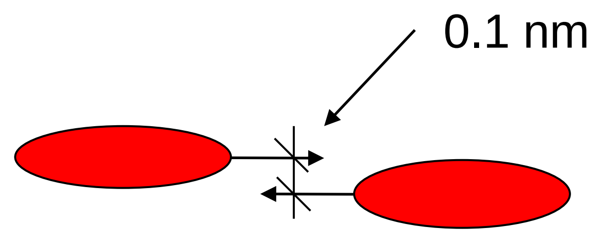


2.) One misaligned QP

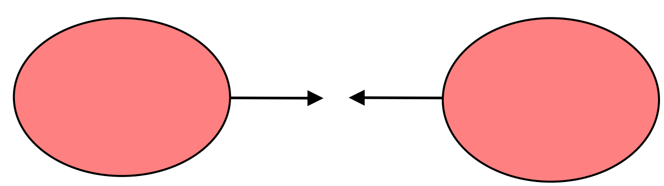


- **Two Problems due to ground motion**

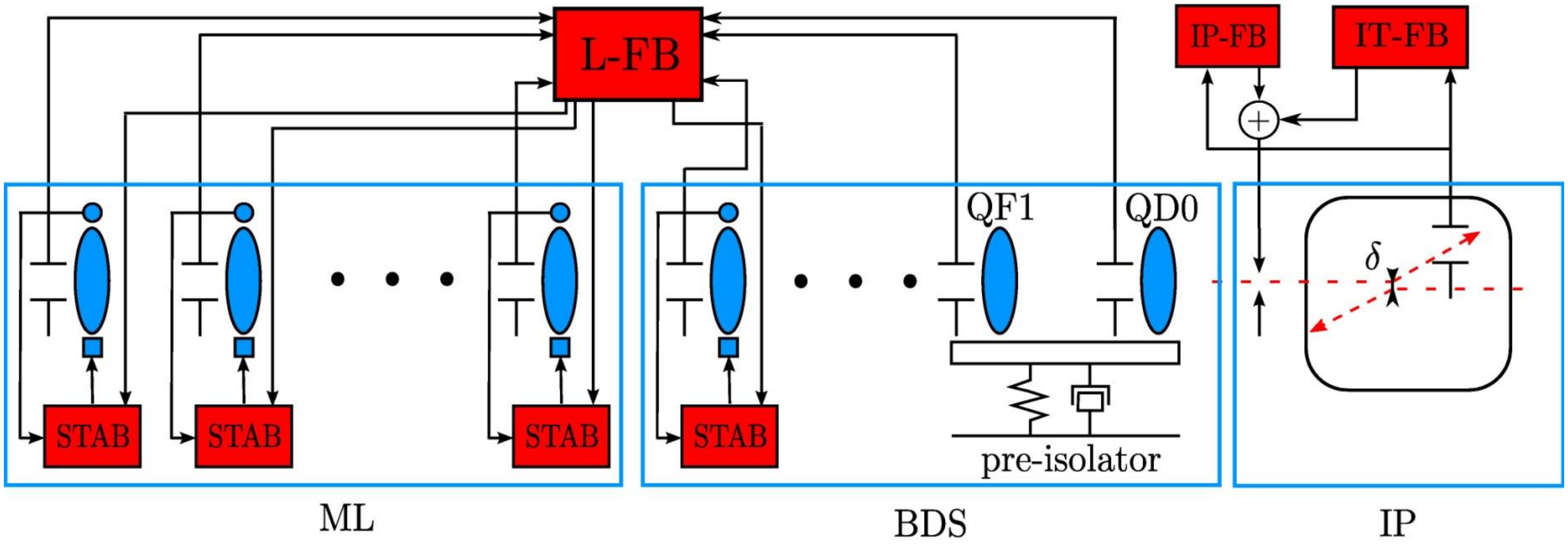
1.) Beam-beam offset



2.) Beam size growth



Counter-measures



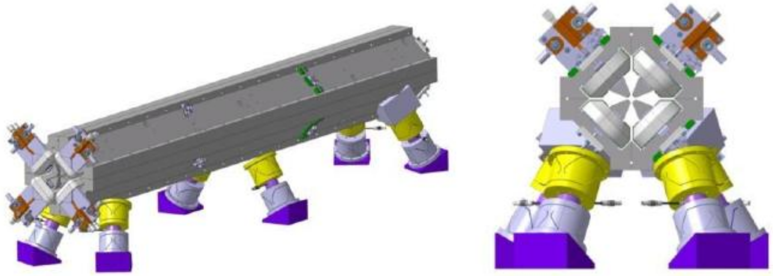
STAB	QP stabilisation	IP-FB	Interaction point FB	●	Seismometer
L-FB	Linac FB	IT-FB	Intra-train FB	■	Tripod
⊥ ⊤	BPM	↓ ↑	Dipole corrector	⬮	Quadrupole

Introduction to the orbit feedback

- **Purpose:**
  Reduction of beam oscillations in the main linac and BDS of CLIC

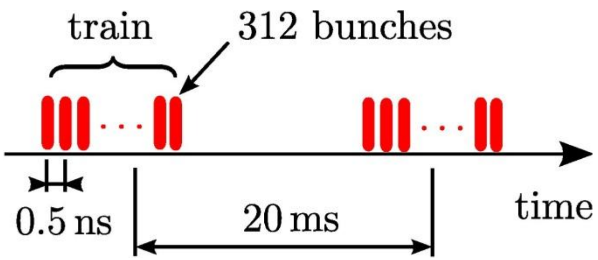
- **Sensors:** Beam position monitors (BPMs)

- **Actuators:** tripods



K. Artoos

- **Limitations:**
  ⇒ Sampling rate limited to 50Hz (beam structure), controller only efficient >1-4 Hz



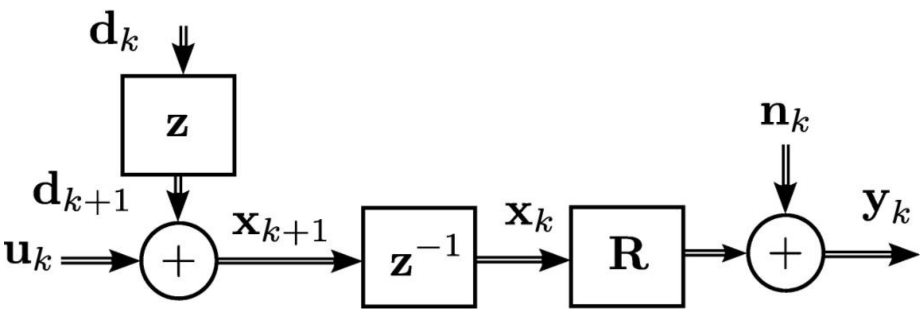
  ⇒ Bode‘s sensitivity integral (for the system in this work)

$$\int_0^\infty \log |S(e^{j\omega T_d})|\, d\omega = 0$$

2. Orbit feedback design (Linac feedback)

2.1 System description

Accelerator system

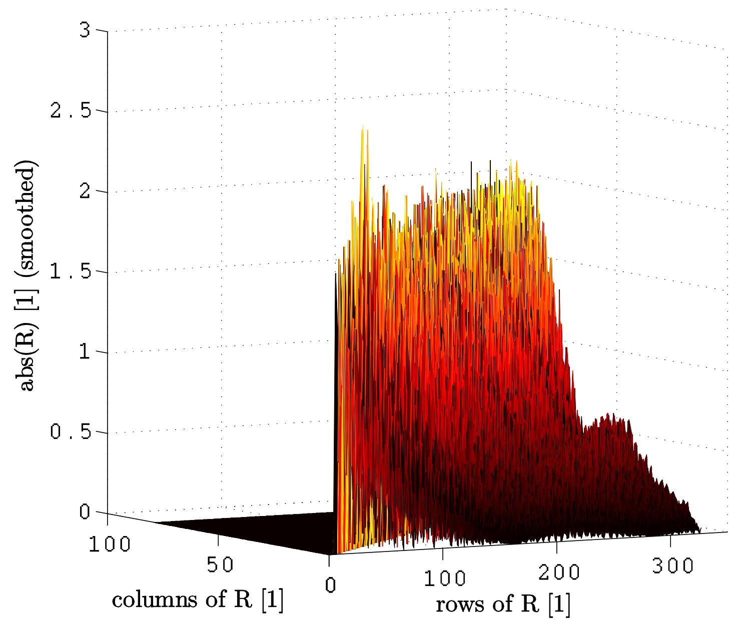


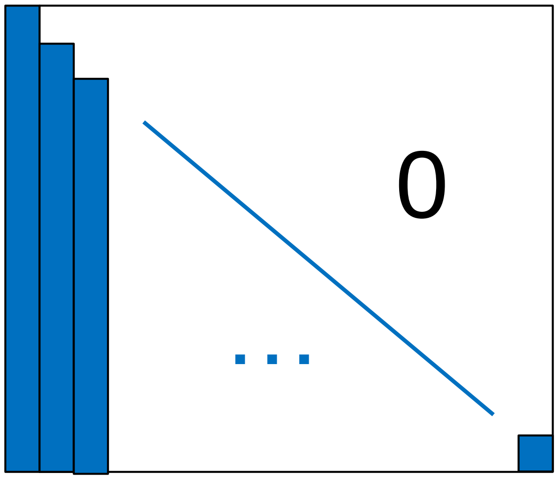
k … Time index
$\boldsymbol{d}_k$ … Ground motion
$\boldsymbol{u}_k$ … Settings of the actuators
$\boldsymbol{x}_k$ … Position of the QPs
z … Unit-shift operator of the *Z*-transform
$\boldsymbol{R}$ … Orbit response matrix
$\boldsymbol{y}_k$ … Measurements
$\boldsymbol{n}_k$ … Measurement noise

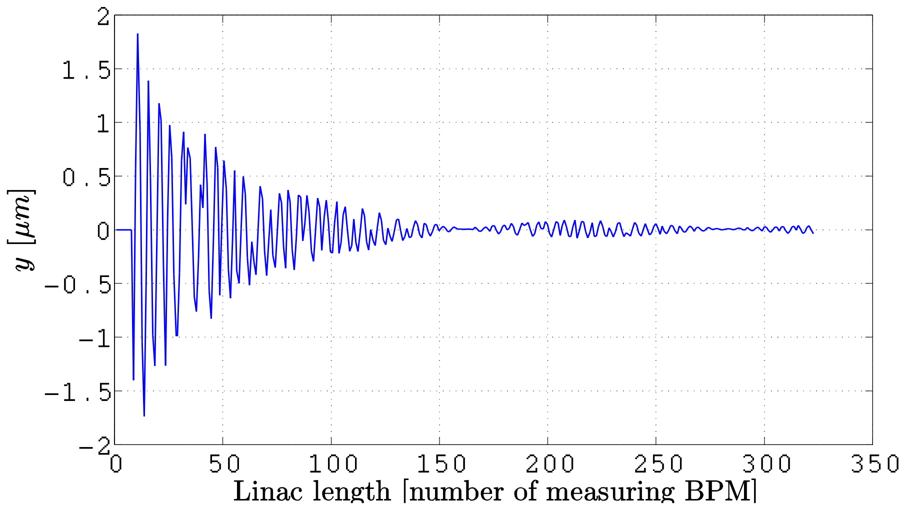
- Large, discrete, linear MIMO-System: 2104 in- and 2122 outputs
- System is controllable and observable
- Simple dynamic structure (no internal back coupling): FIR system (finite impulse response)

The matrix *R*

- The i[th] column corresponds to the measured beam motion in the linac, caused by a misalignment of the i[th] QP.
- The motion is determined by the lattice design of the linac an the beam properties.
- ***R*** is a triangular matrix. The elements close to the main diagonal have the largest values.







2.2 Decoupling

Principle of decoupling

- Accelerator system is very large => Simplifications necessary
- Possibility: Simplification via decoupling of the in- and outputs

- Decoupling can be achieved with the singular value decomposition (SVD) of the matrix ***R***

$$\boldsymbol{R} = \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^T \qquad \boldsymbol{\Sigma} = \mathrm{diag}(s_i)$$

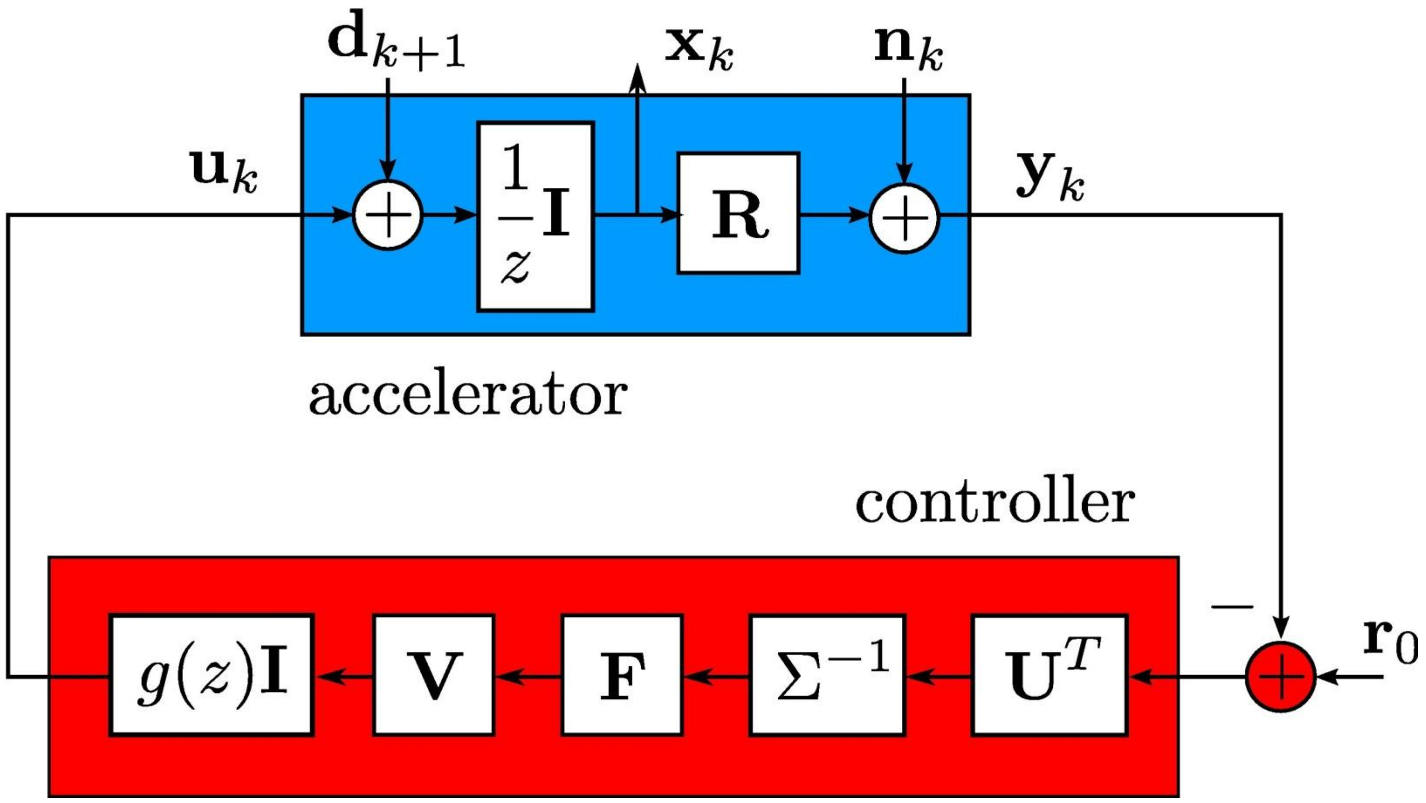
$$\boldsymbol{V}\boldsymbol{V}^T = \boldsymbol{I} \qquad \boldsymbol{U}\boldsymbol{U}^T = \boldsymbol{I}$$

- ***U*** and ***V*** are orthonormal matrices, and the s_i are the singular values of ***R***
- If the system is pre-multiplied with ***V*** and post-multiplied with $\boldsymbol{U}^T$, the combined system is diagonal and hence decoupled.

$$\boldsymbol{U}^T\boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^T z^{-1}\boldsymbol{I}\boldsymbol{V} = z^{-1}\boldsymbol{\Sigma}$$

- For the accelerator system, the decoupling achieved for all frequencies!!!

Structure of the control loop



r_0 … Reference trajectory

$R^{-1} = V\Sigma^{-1}U^T$

2.3 Time-dependent feedback design

Control engineering basics

- Definitions:

$H(z)$ … Accelerator transfer function
$C(z)$ … Controller transfer function
T_d ... Sampling time
$H(z = e^{j\omega T_d})$ … frequency response of the transfer function *H(z)*
$O(e^{j\omega T_d}) = H(e^{j\omega T_d})C(e^{j\omega T_d})$ … open loop frequency response
f_c … cut-through frequency; frequency for which $|O(e^{j\omega T_d})| = 1$
$\varphi_M = 2\pi - \arg\{O(e^{j2\pi f_c T_d})\}$ … phase margin

- Nyquist's theorem (simplified version for the current application => open loop stable system with only one pole on the unit circle):

The closed loop system of the assumed form is stable $\Leftrightarrow$ $\varphi_M > 0$

Design of *g(z)*

The filter *g(z)* is used by all decoupled channels and is designed with the loop-shaping method:

$$g(z) = I(z)L(z)P(z)E(z)$$

$$I(z)$$

- Integrator: base element of the controller
- Motivated physically: ATL-law
- If *g(z)=I(z)* and f_i=1
  => Dead-beat controller

$$L(z)$$

- Low pass to demagnify high frequencies
- Improvement of the controller behaviour for measurement noise and high frequent ground motion
- Design based on a continuous low pass which is transformed to a discrete system

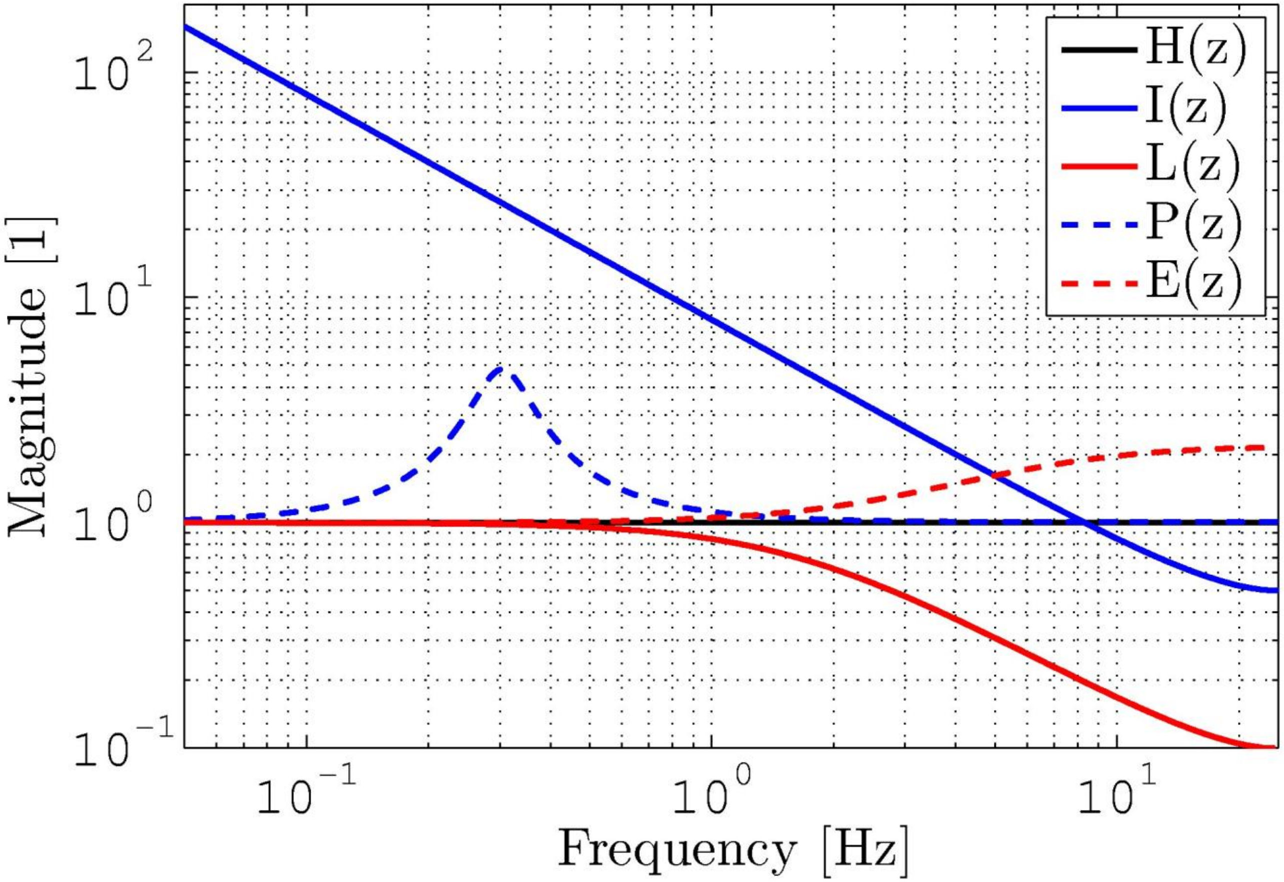
$$P(z)$$

- Amplification around 0.3 Hz
- QP- and “final doublet”-stabilisation have different frequency responses
- Mismatch has to be counteracted by a better correction of the L-FB around 0.3 Hz

$$E(z)$$

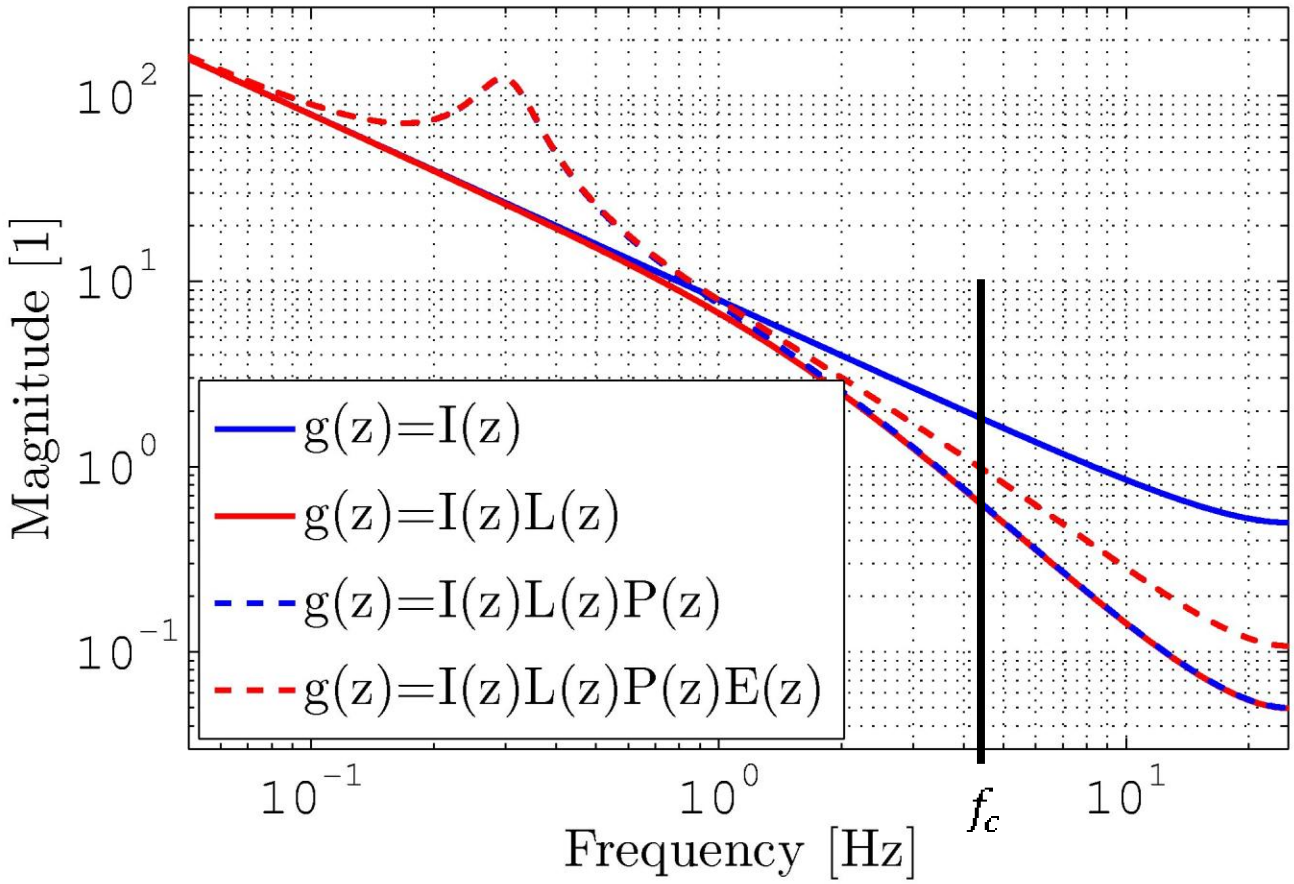
- Phase margin, due to I(z), L(z) and P(z) insufficient.
- Phase lift element: Phase margin is lifted at the cut-through frequency f_c = 4.4 Hz to 36.3º

Magnitude of the individual frequency responses

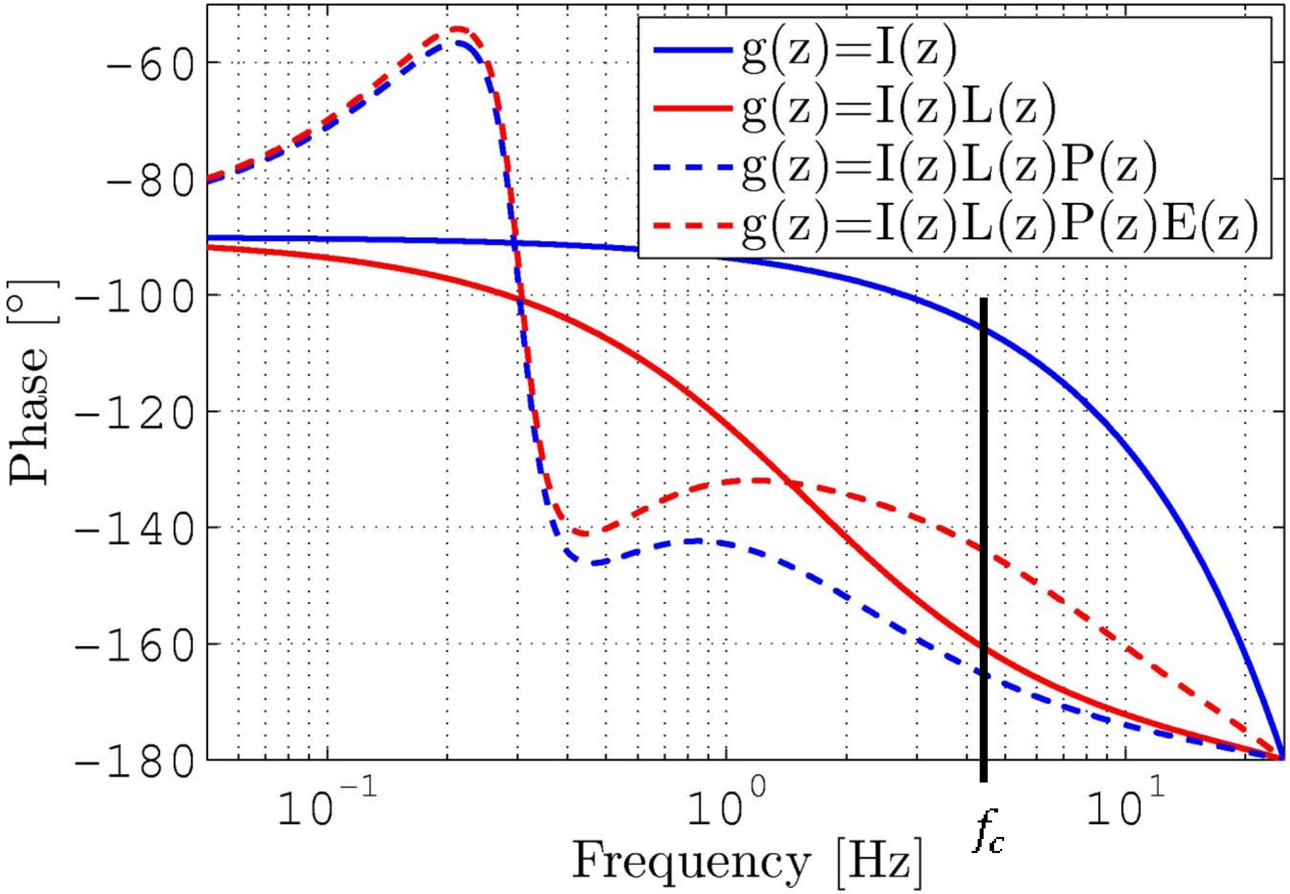


$H(z)=z^{-1}$ is the transfer function of the accelerator if $s_i=1$.

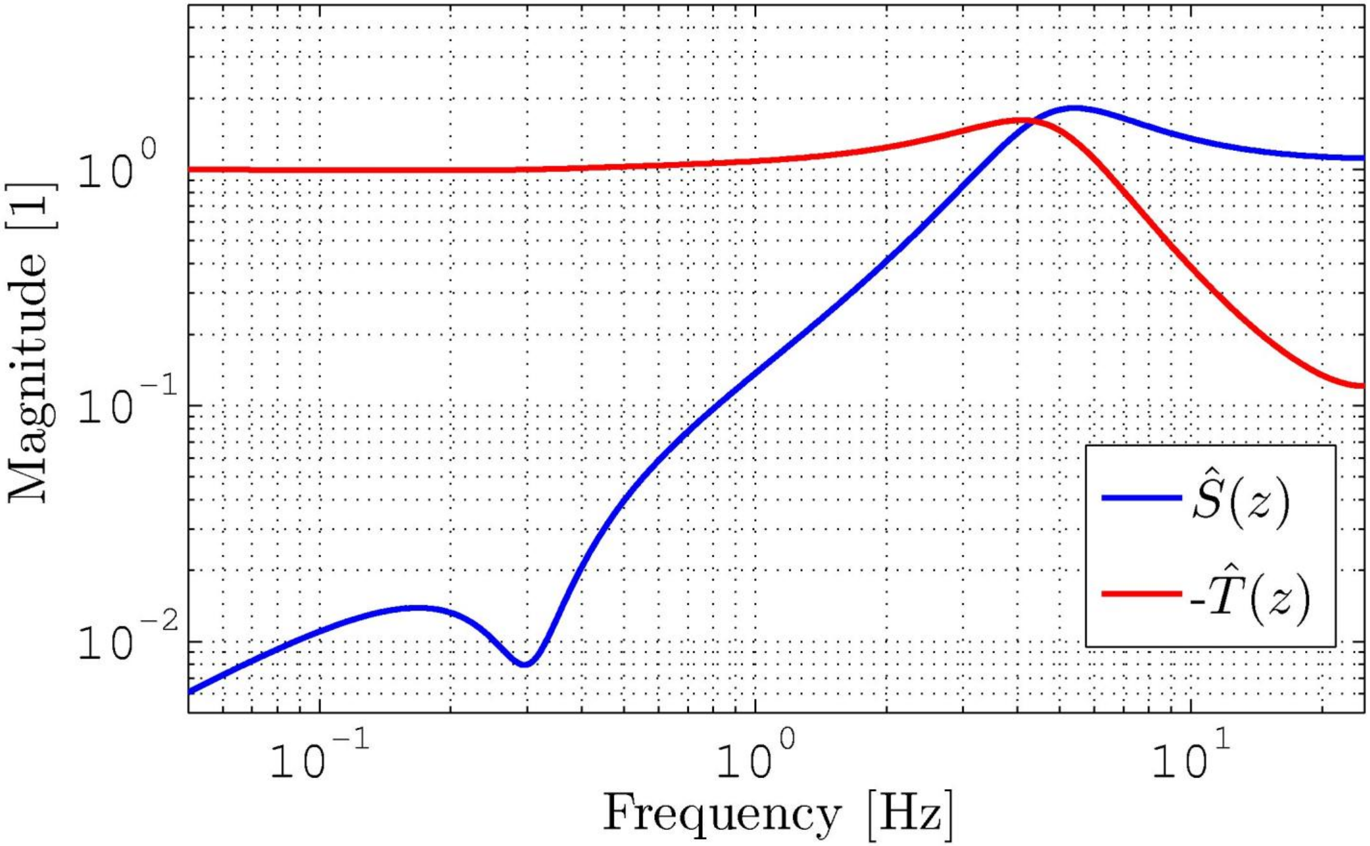
Magnitude of the open control loop (for f_i=1)



Phase of the open control loop (for f_i=1)



Magnitude of the sensitivity and noise frequency response of *S(z)* and –*T(z)* of the closed control loop (for f_i=1)



2.1 Spatial feedback design

Calculation of the parameters f_i

- Complete controller of the i^th decoupled control loop has the form

$$g(z)s_i^{-1}f_i$$

- **Idea:** f_i is chosen such that the output signal *y[k,i]* is minimise
- PSD of *y[k,i]*

$$Y(\omega,i) = \left|z\hat{H}(e^{j\omega T_d})\hat{S}(e^{j\omega T_d})\right|^2 P(\omega,i) + \left|\hat{T}(e^{j\omega T_d})\right|^2 N(\omega,i)$$

$z\hat{H}(e^{j\omega T_d})\hat{S}(e^{j\omega T_d})$ … Controller frequency response to ground motion

$P(\omega, i)$ .... PSD of the ground motion

$-\hat{T}(e^{j\omega T_d})$ .... Controller frequency response to BPM noise

$N(\omega, i)$ .... PSD of the PBM noise

- $P(\omega, i)$ and $N(\omega, i)$ can be determined analytically or numerically.
- Minimisation performed in the frequency domain (Parseval's Theorem)

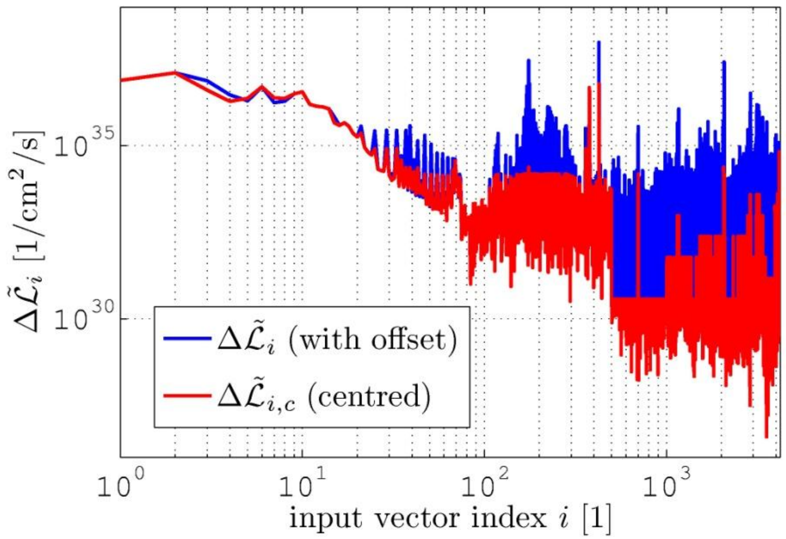
$$\min_{f_i} \|y(k,i,f_i)\|_{l^2} = \int_{-\infty}^{+\infty} Y(\omega, f_i)\, d\omega$$

Luminosity optimisation

- Result can be improved by using a different target function
- **Idea:** Minimise a signal prop. to the luminosity loss (and not the beam oscillations)

- Two components of the lumi. loss
  1. **Beam size growth**
     $\propto Y(\omega, i)$
  2. **Beam-beam offset**
     $\propto \left|S_{IP}(e^{j\omega T_d})\right|^2 Y(\omega, i)$

- Signals are weighted with their relevance for the luminosity loss

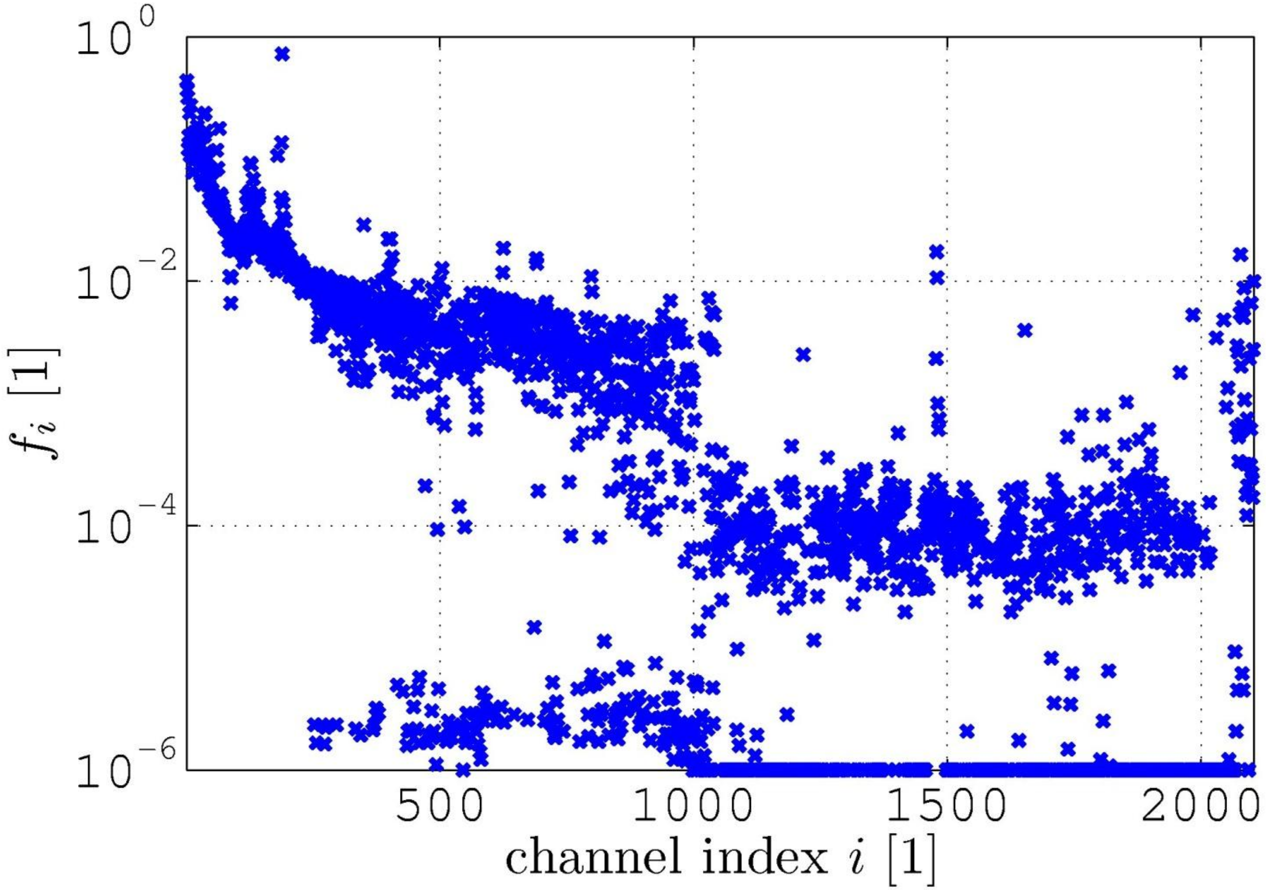


$S_{IP}(e^{j\omega T_d})$ … ground motion frequency response of the IP-FB

- Luminosity optimised minimisation problem

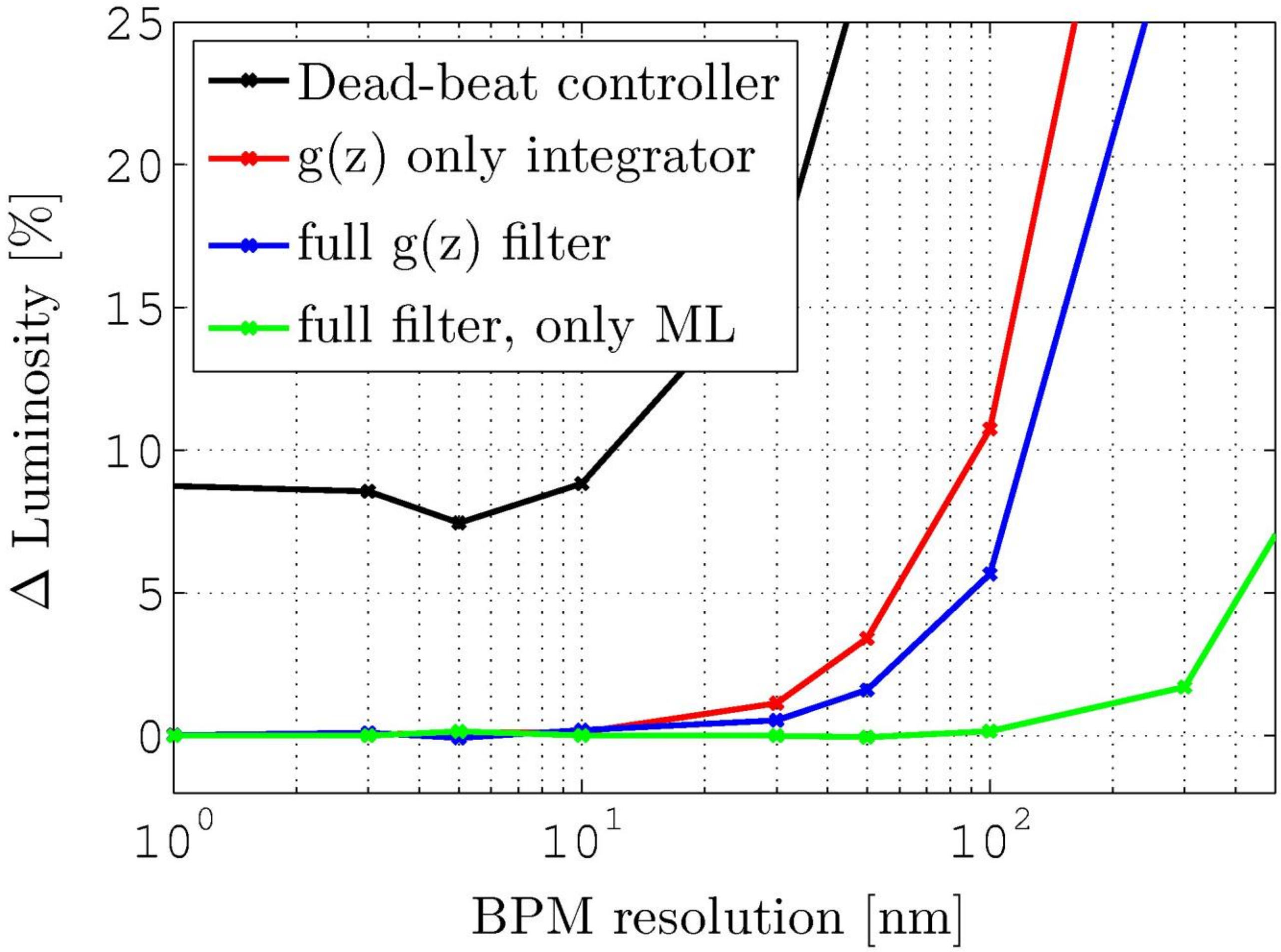
$$\min_{f_i} \int_{-\infty}^{+\infty} \left[\frac{\mathcal{L}_{i,c}}{\mathcal{L}_i} Y(\omega, i f_i) + \frac{\mathcal{L}_i - \mathcal{L}_{i,c}}{\mathcal{L}_i} \left|S_{IP}(e^{j\omega T_d})\right|^2 Y(i\omega, f_i)\right] d\omega$$

Calculated parameters f_i



3. Results

Influence of the BPM resolution



Advantages of the new design method

1. The method can easily be applied to other accelerators.
2. Models of ground motion and BPM noise can be incorporated in the design.
3. Different target parameters can be optimised: luminosity, beam oscillations, ...
4. By the choice of *g(z),* the user has the possibility to employ expert knowledge.
5. The user is relieved from the tedious task of designing each individual decoupled loop (2104 in the case of CLIC).
6. The semi-automatic procedure reduces the design time drastically.
7. Since the controller is base on the SVD decoupling, it stays clear and important insights are not lost.

Future work

- Further robustness analysis

  => problem: complete system is very large

Thank you for your attention!