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SUPPRESSION OF BEAM MOTION IN CEBAF

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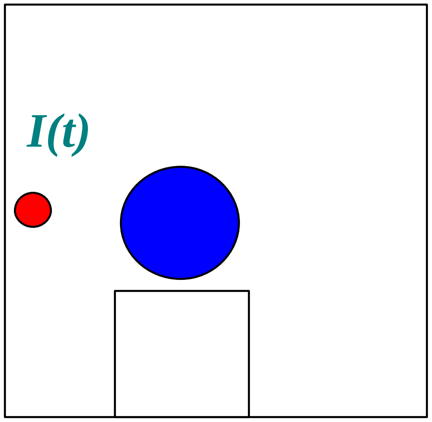
1. Introduction

Sources of the Beam Motion



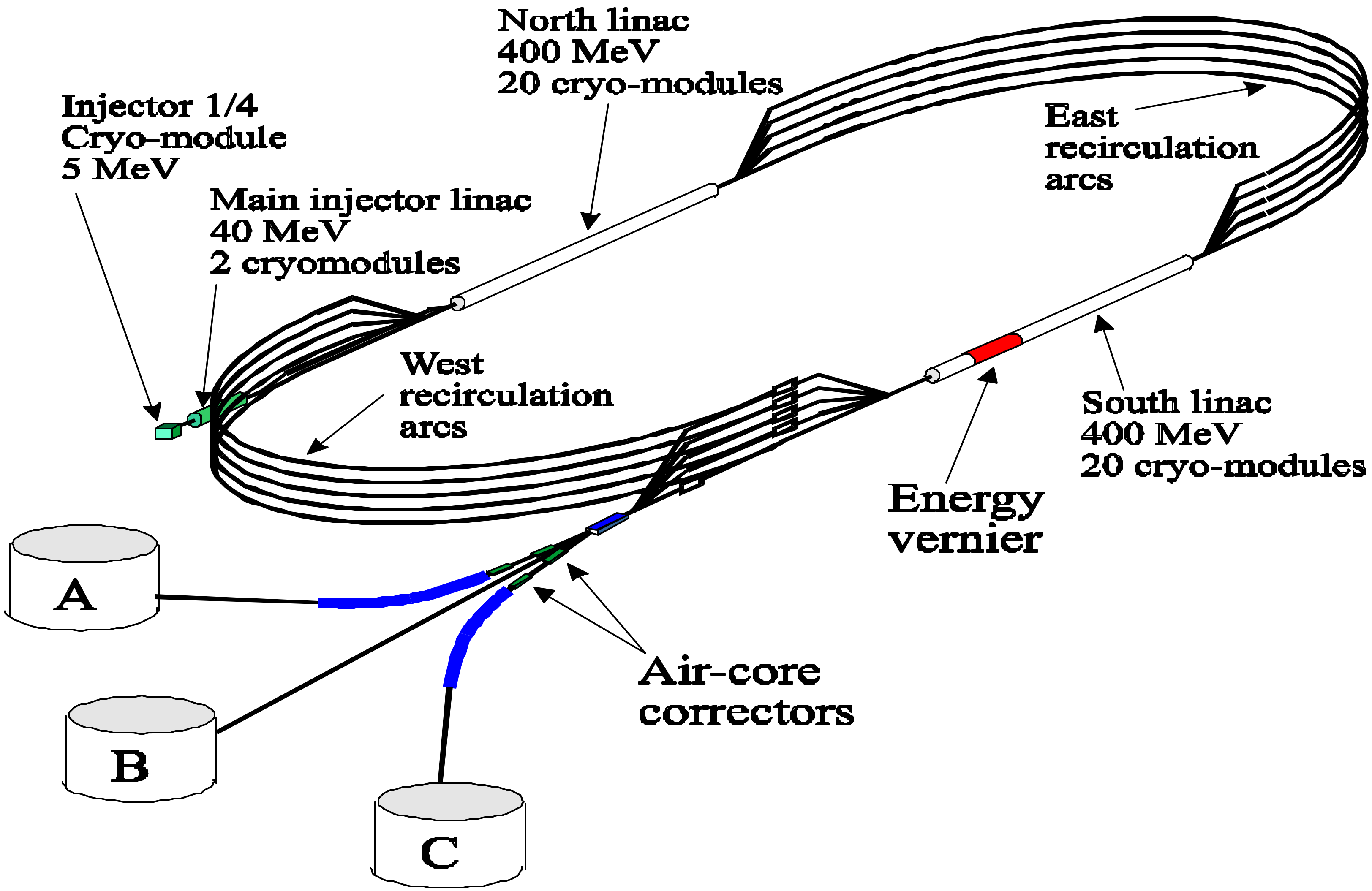
- Transverse beam motion
  - Drift, ripple and noise in power supplies of magnets
  - Ground current loops
  - Uncontrolled changes of remnant field in dipoles
  - Quad motion due to ground motion
    - Microseism
    - Technogen noise (pumps, helium liquefiers, powerful engines, etc.)
    - Moon tides
    - Temperature drifts
- Longitudinal/energy variations
  - Microphonics in cavities
  - Temperature induced RF phase shifts
  - MO noise and drifts

General attitude to noise suppression

- Study possible noise sources at design and try to mitigate their effects
- Design machine to be less sensitive to errors and noises
- Pay attention to the noise sources at commissioning
  - Try to suppress effect of major offenders
  - Do not expect to identify and suppress all the sources
- Suppress beam/energy motion using beam-based feedback system
  - It is the most cost effective way

Feedback system choice

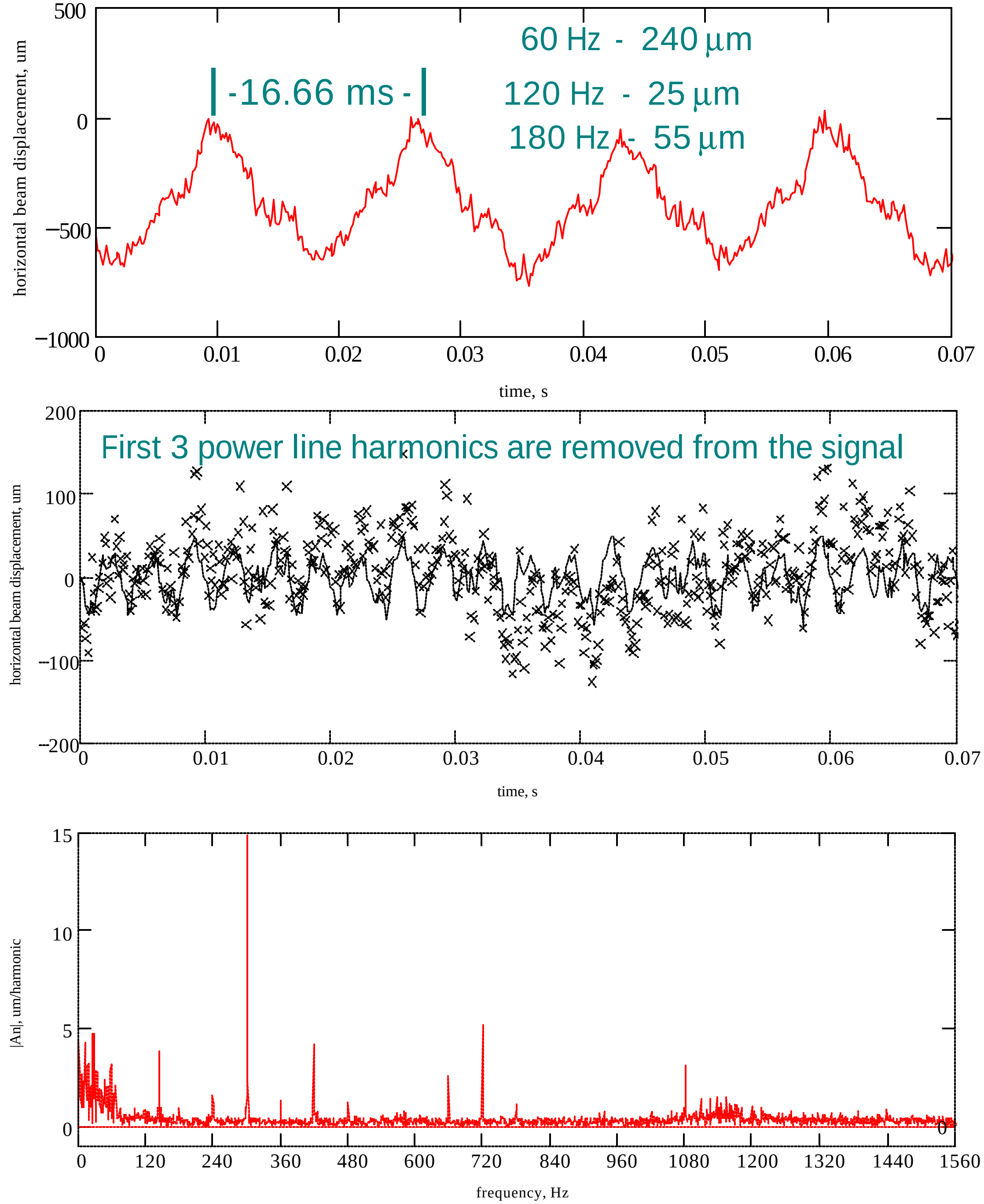
- Beam based
- Design is determined by the task
- Digital system is preferable (f < 10 - 100 kHz)
  - Combination of feedforward and feedback can make better suppression
  - Redundant sensors are useful



Layout of the CEBAF recirculator

2. Experimental measurements of beam motion

a) b) c)



CEBAF experience (transverse beam motion)

Beam motion at IPM3C12

October 24, 1996

a) meas. signal, 7.1 ksample/s

b) meas. signal without first three harmonics - ×, and an estimate of the beam displacement due to higher power line harmonics - solid line.

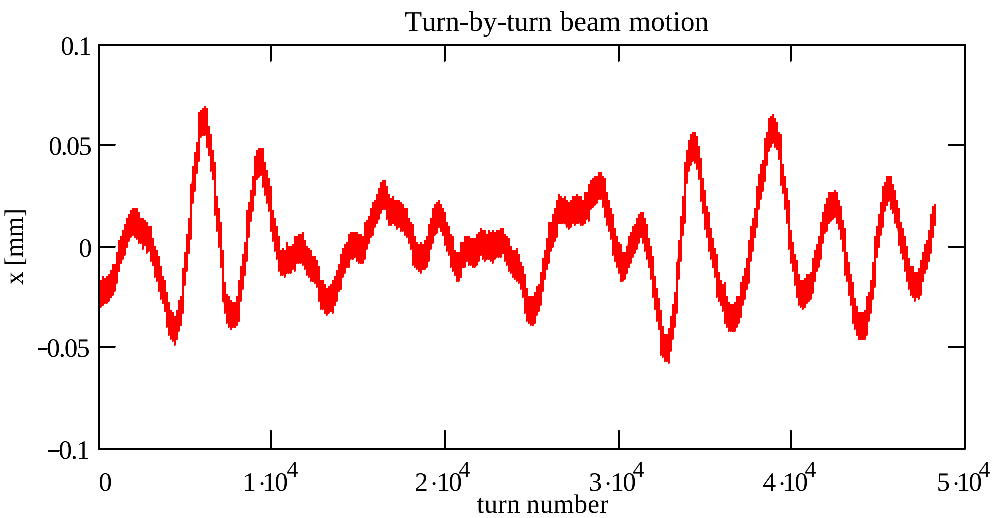
c) spectrum without first three harmonics, 6 s data set is used for FFT

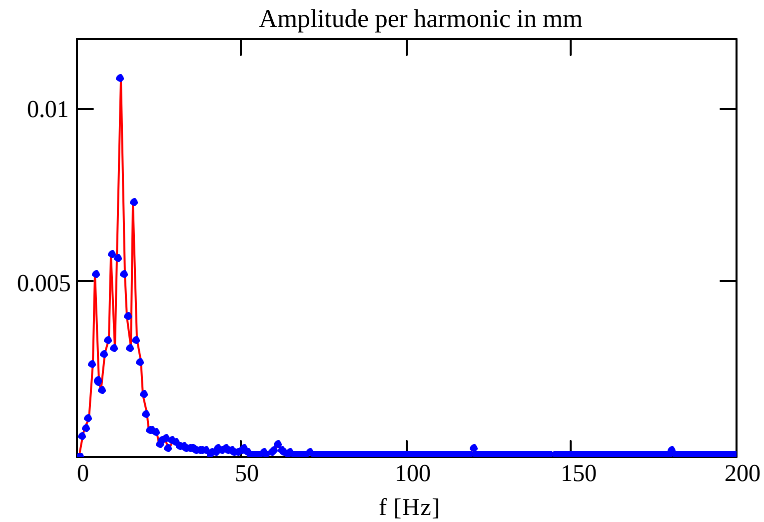
Beam current is equal to 38 μA, and the beam energy is 3.245 GeV.

RMS BPM resolution ~20 μm

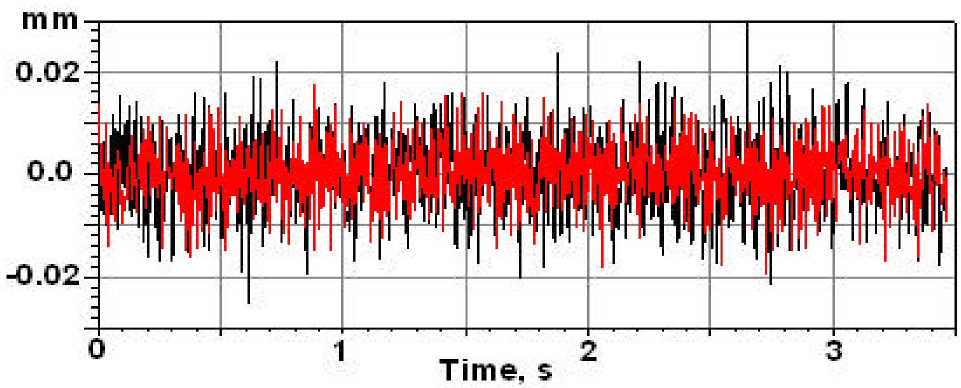
FNAL experience

Tevatron

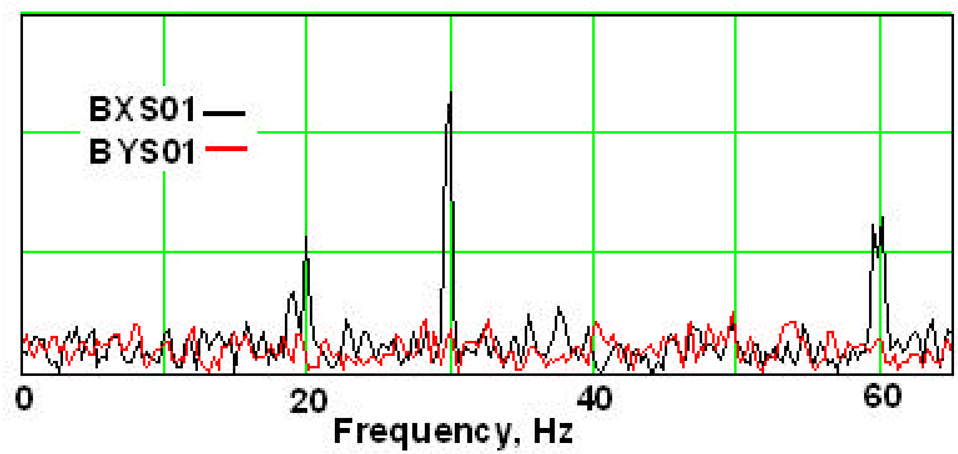




Electron cooler



Deviations of the beam centroid in X (black) and Y (red) directions in mm measured in the supply section during the sampling.



FFT transformation of signals from BXS01 and BYS01 BPMs

3. CEBAF Feedback Systems

- Slow locks
  - Correct beam position at the beginning of every arc
  - Correct energy gain of Injection and North linacs
- RF phase correction (MO modulation system)
  - Correct gang phase of every linac
  - Minimizes energy spread of the beam.
    - The energy spread can be monitored on the OTR monitor
    - But its correction is not trivial without MO modulation system
- Fast feedback system
  - Final energy and position stabilization of the beam on target

Slow locks

- Simple digital feedback systems
  - 13 asynchronous, independent syst.
    - 3 Energy locks (Injection, NL, SL)
    - 10 position locks (Inj., 9 arcs)
- Supported by a UNIX process
  - Sampling rate ~1 Hz
- Algorithm

$$\begin{cases} \mathbf{y}_n = \mathbf{M}(\mathbf{x}_n + \mathbf{c}_n) \\ 0 = \mathbf{y}_{n+1} = \mathbf{M}(\mathbf{x}_n + \mathbf{c}_n + ?\mathbf{c}_n) \end{cases}$$

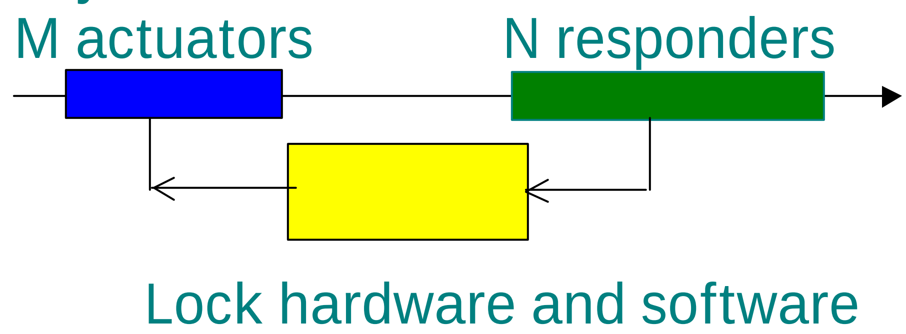
$$\Rightarrow \begin{cases} ?\mathbf{c}_n = -g\mathbf{M}_{\text{inv}}\mathbf{y}_n \\ \mathbf{M}_{\text{inv}} = \left(\mathbf{M}^T\mathbf{M}\right)^{-1}\mathbf{M}^T \end{cases}$$

where: g ∈ [0, 1] – gain of the system

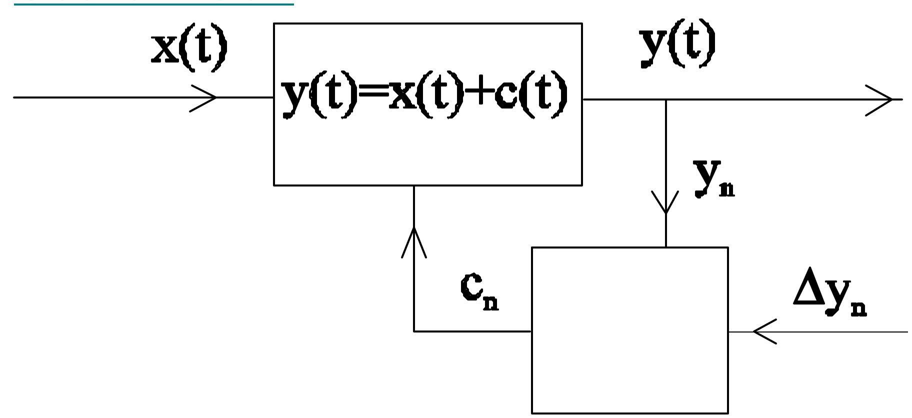
$\mathbf{y}=y_i$ - position vector: $I = 1, N$ – number of sensors (BPMs)

$\mathbf{x}=x_j$ - state vector $j = 1, M$ – number of actuators (correctors) (M≤N)

Layout



Scalar lock



Vector lock

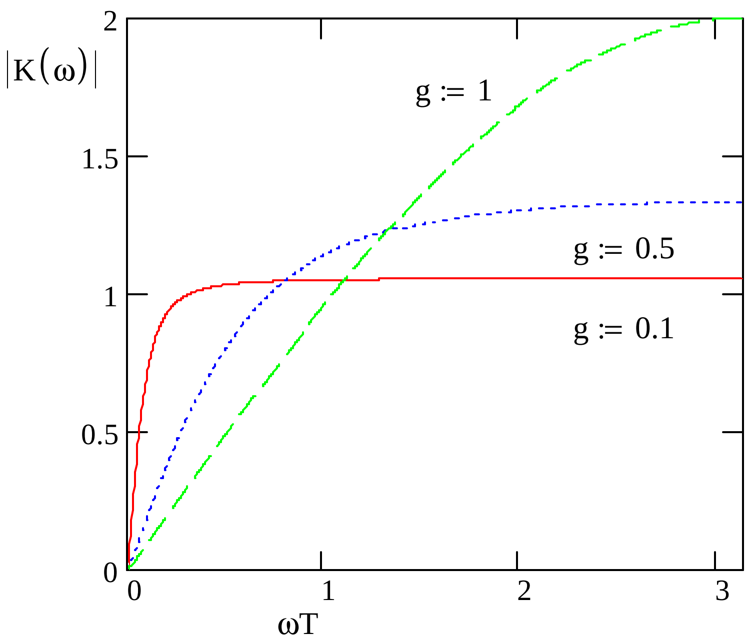
$$\mathbf{y}(t) = \mathbf{M}\big(\mathbf{x}(t) + \mathbf{c}(t)\big) + ?\mathbf{y}(t)$$

- for simplicity we choose the same state variables (for example energy or angle) and corrector variables (energy correction, angle correction). It does not limit the generality of consideration

Slow lock frequency response

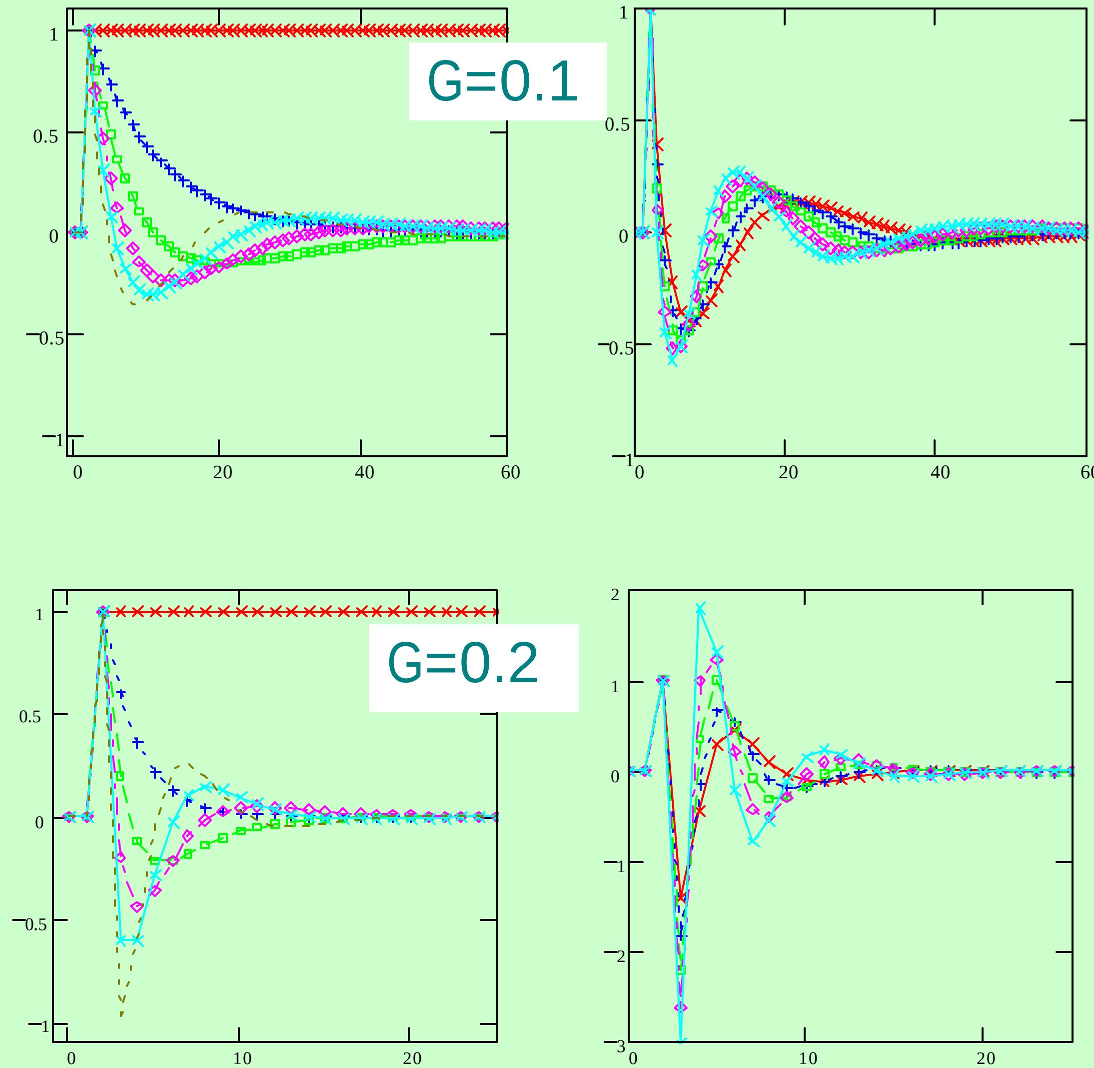
$$y_w = K(w)x_w$$

$$K(w) = \frac{1-e^{iwT}}{(1-g)-e^{iwT}}$$



Response of the 10 locks to the step function

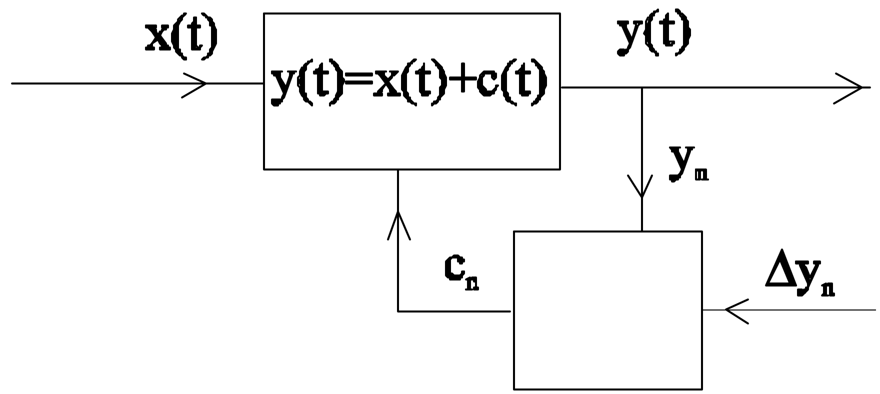
First five locks **Second 5 locks**



The beam displacements are normalized on its maximum value without locks.

Fast feedback system

Noise theorem:



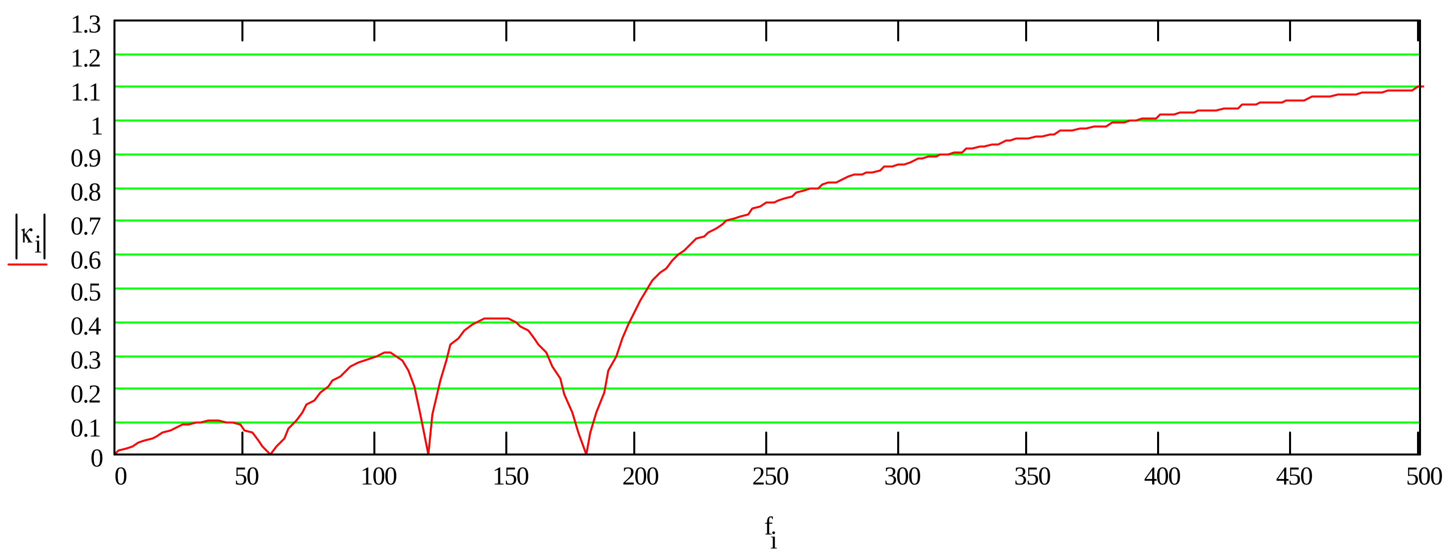
$$\overline{y^2} = \overline{\Delta y^2}\,\frac{T}{p}\int_0^{p/T}\left|K(w)-1\right|^2 dw$$

Better suppression results in an increased sensitivity to the BPM noise

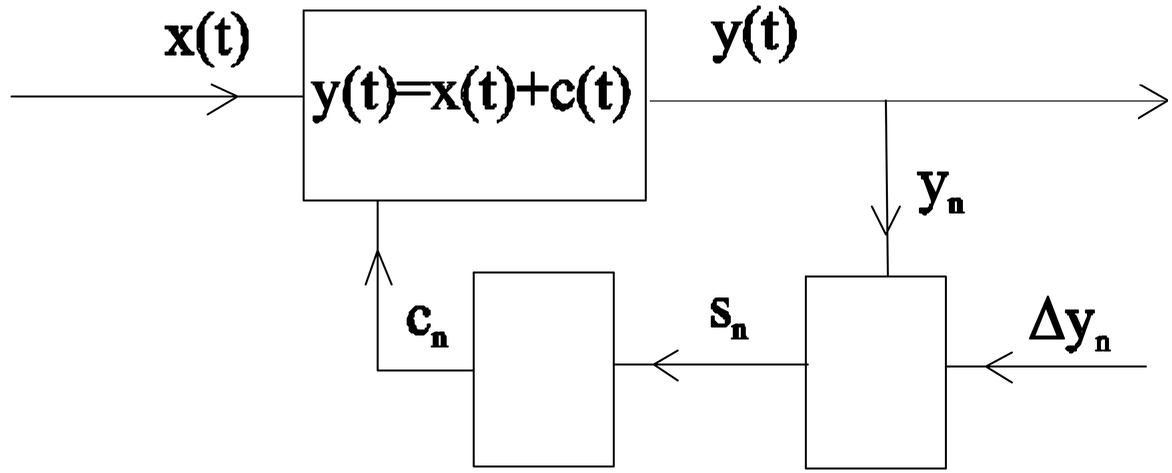
We choose desired frequency response function *K*(w):

$$K(w)=\frac{e^{iwT}-1}{e^{iwT}-(1-k_0)}\,\frac{e^{iwT}-e^{iw_0T}}{e^{iwT}-(1-k_1)e^{iw_0T}}\,\frac{e^{iwT}-e^{-iw_0T}}{e^{iwT}-(1-k_1)e^{-iw_0T}}\cdot\frac{e^{iwT}-e^{2iw_0T}}{e^{iwT}-(1-k_2)e^{2iw_0T}}$$

$$\frac{e^{iwT}-e^{-2iw_0T}}{e^{iwT}-(1-k_2)e^{-2iw_0T}}\,\frac{e^{iwT}-e^{3iw_0T}}{e^{iwT}-(1-k_3)e^{3iw_0T}}\,\frac{e^{iwT}-e^{-3iw_0T}}{e^{iwT}-(1-k_3)e^{-3iw_0T}}=\frac{\sum_{k=0}^{7}b_k\left(e^{iwT}\right)^k}{\sum_{k=0}^{7}a_k\left(e^{iwT}\right)^k}$$



Numerical algorithm



$\mathbf{x}(t)$ - input state vector , correctors $(x, x`, y, y`, \Delta p/p)$

$\mathbf{y}_n$ - vector of BPM measurements

$D\mathbf{y}_n$ - noise of BPM measurements

$\mathbf{s}_n$ - state vector

$\mathbf{c}_n$ - vector of correction

Space part

Relation between the vector of BPM measurements and the state vector

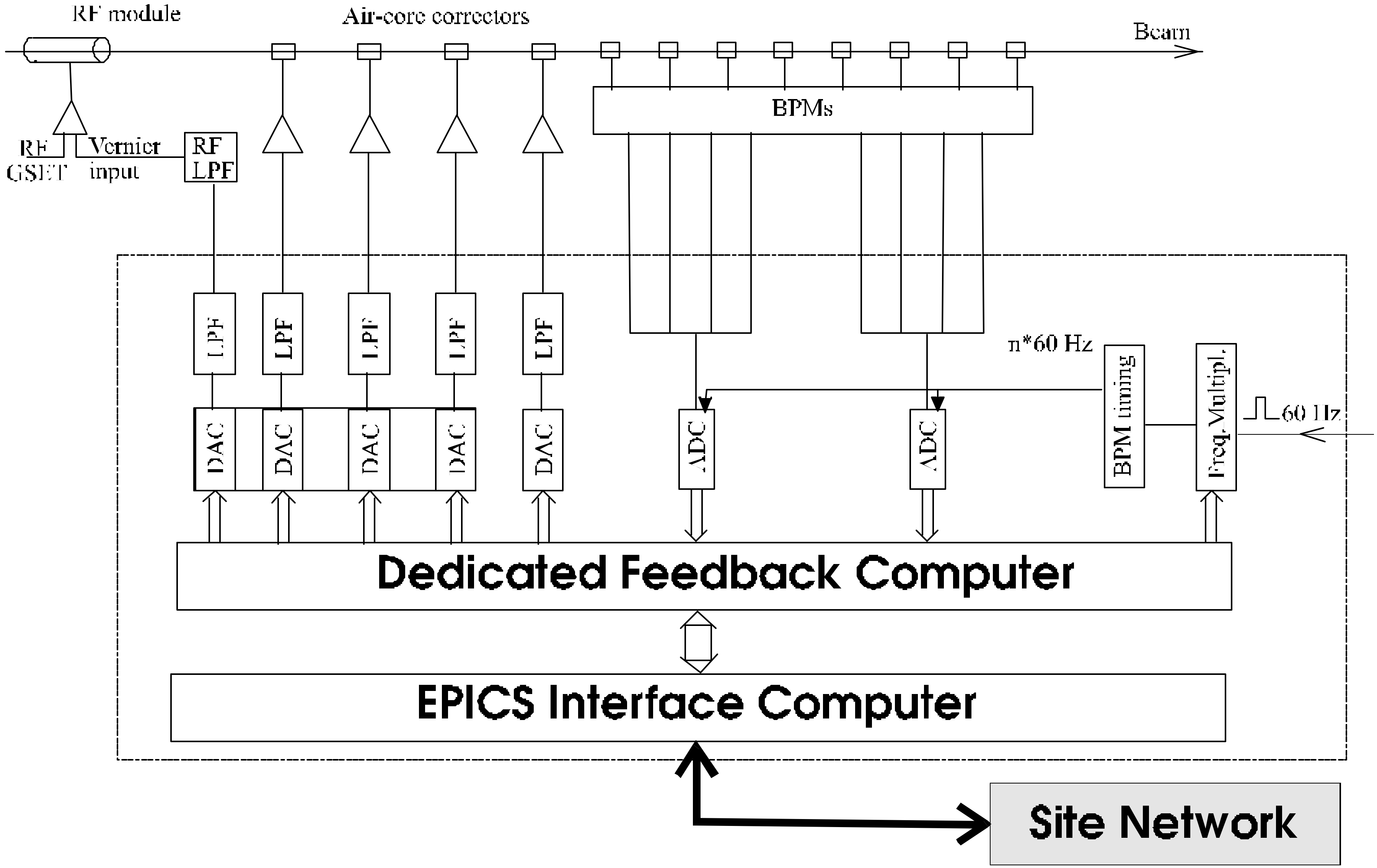
$$\mathbf{y}(t) = \mathbf{M}\mathbf{x}(t) \quad , \quad \xrightarrow{\text{SVD algorithm}} \quad \mathbf{x}_{opt} = \left(\mathbf{M}^T\mathbf{M}\right)^{-1}\mathbf{M}^T\mathbf{y}(t)$$

Representation in the algorithm

$$\tilde{\mathbf{y}}_n = \mathbf{B}\mathbf{y}_n \quad , \quad where \quad \mathbf{B} = \left(\mathbf{M}^T\mathbf{M}\right)^{-1}\mathbf{M}^T$$

Temporal part

$$\mathbf{c}_{n+1} = \sum_{k=0}^{N_{so}-1}\left(a_k\tilde{\mathbf{y}}_{n-k} + b_k\mathbf{c}_{n-k}\right) \quad .$$



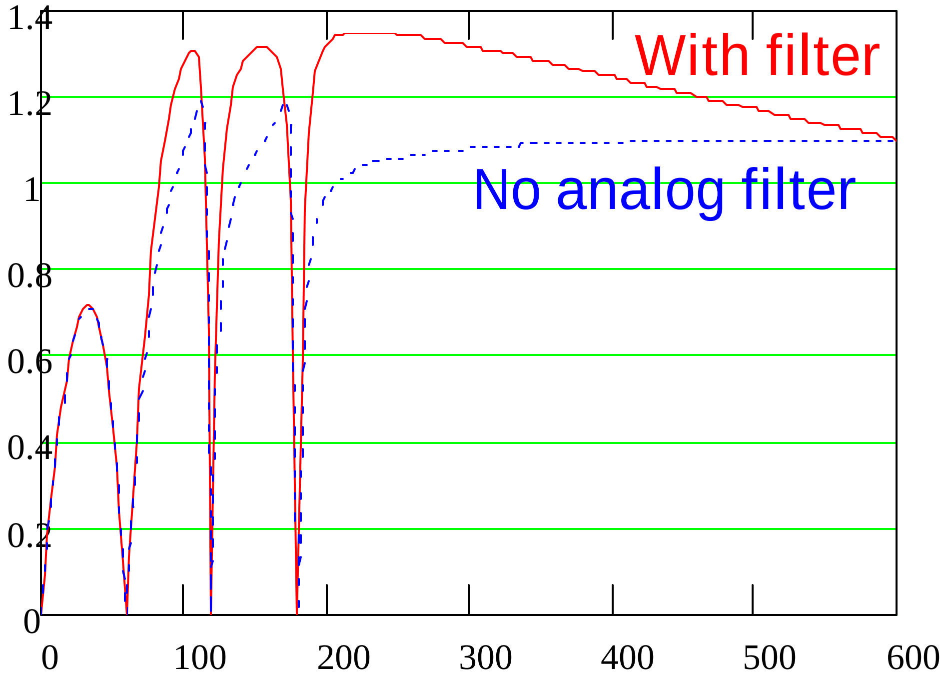
Fast Feedback System Schematic

Real system simulation

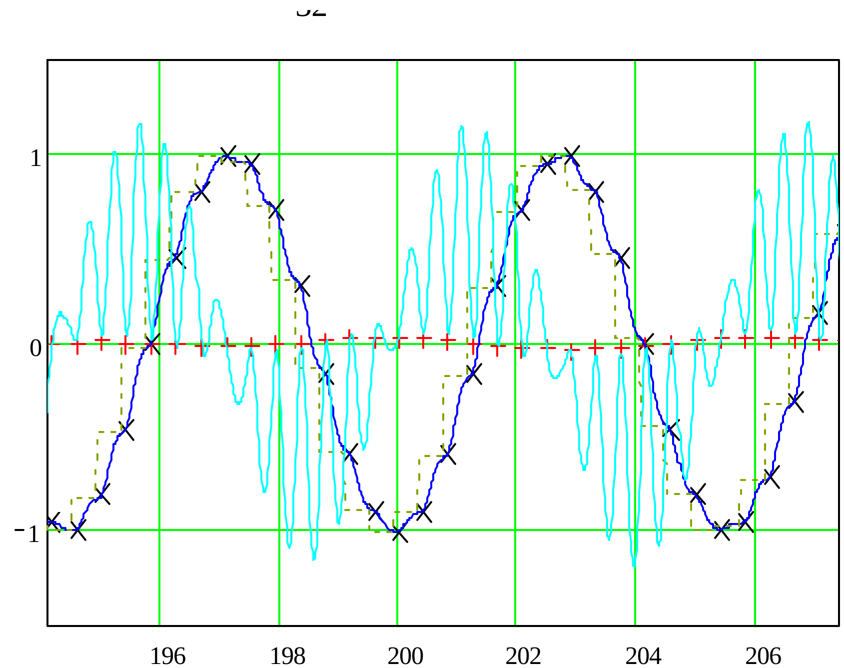
Sampling rate of 2.4 kHz and the analog 4-th order Bessel filter bandwidth of 1.5 kHz

Frequency Domain

Time domain



Frequency response function, K(f)



Suppression of 180 Hz signal

Brown dashed - DAC voltage

Blue - DAC voltage after analog filter

Red crosses - measured output signal times 10

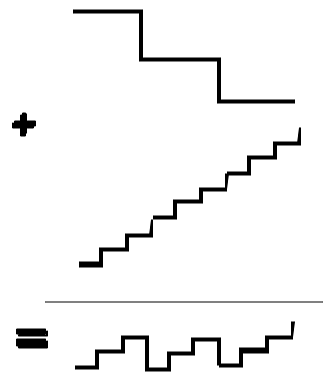
Light blue - output signal times 10

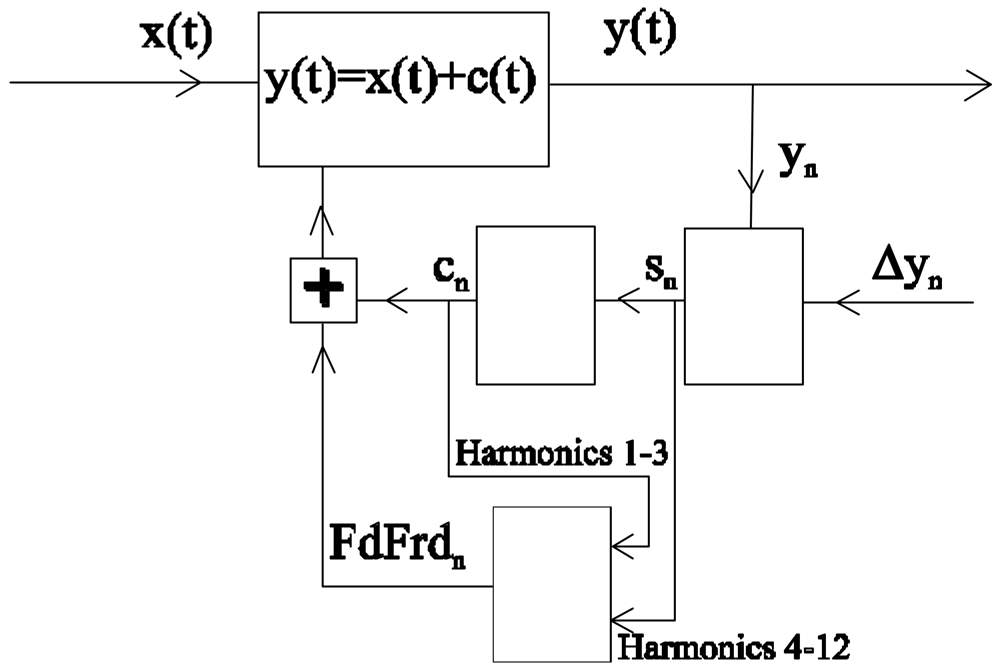
Feedforward

- BPM hardware limits sampling frequency to about 3 kHz
- DAC steps cannot be filtered out with sufficient accuracy
- Suppression of higher harmonics is highly desirable

Solution:

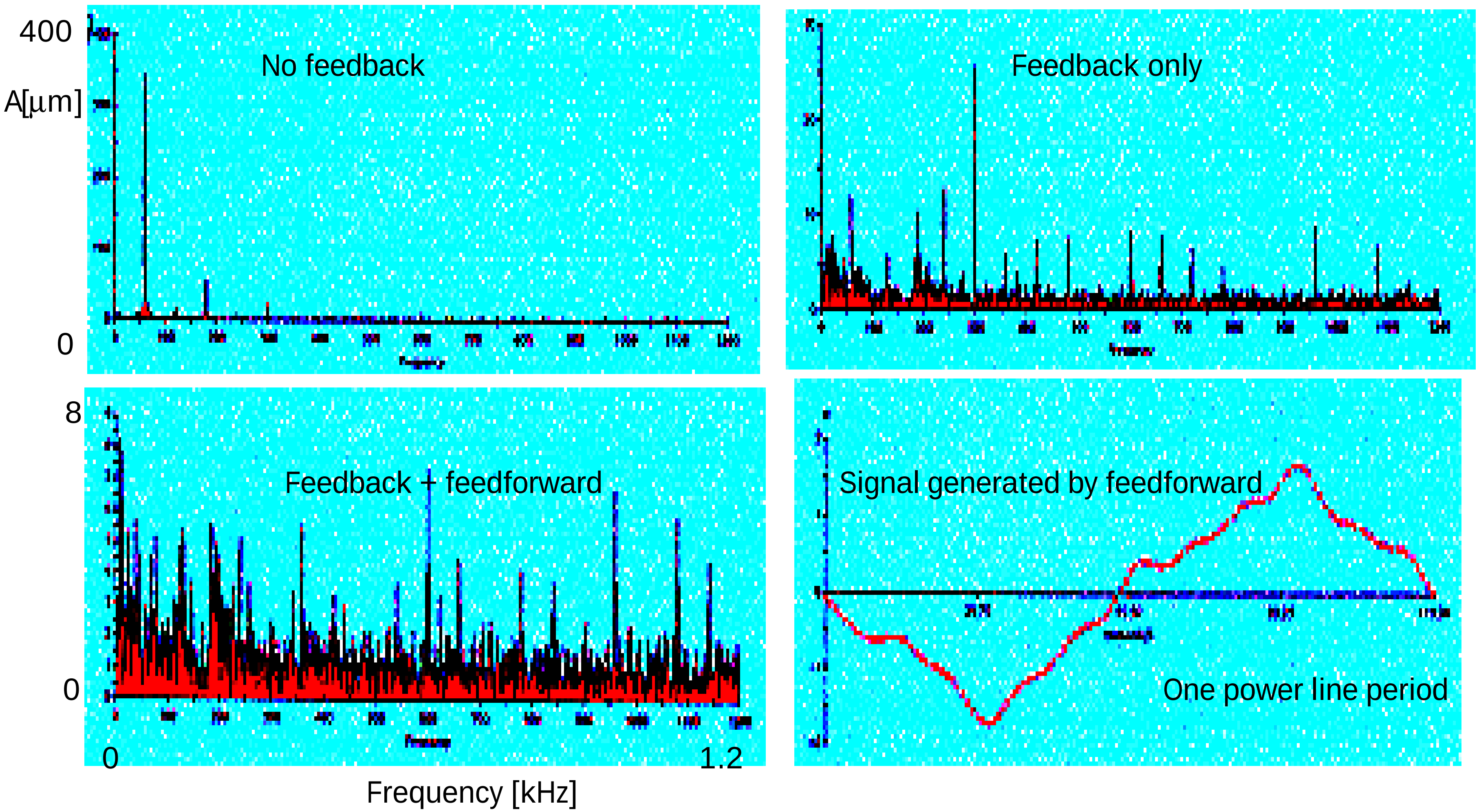
- Run DACs 3 times faster than ADCs
- Interpolate intermediate points for DACs using harmonic content of the signals



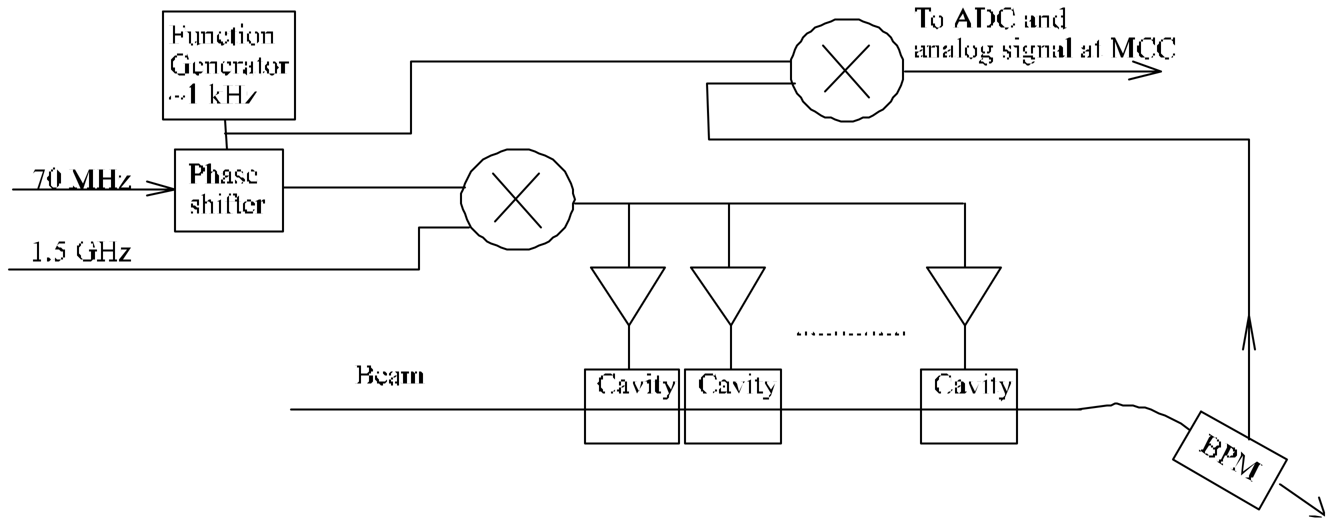


- Feedforward buffer signal is build from the first 12 power line harmonics
- Feedforward system is controlled by UNIX process, running at 0.2 Hz repetition rate
- Harmonic distortion ~ $(f_{DAC} / \Delta f_{filter})^4$
  $<$ 500 for the12th harmonic

Beam motion spectra with and without fast feedback system on



RF phase measurement and correction (MO modulation system)



Modulation of RF phase of the entire linac

$$\frac{\Delta E(t)}{E} = \cos\left(q_{err} + e_f \cos(\Omega t)\right) \approx \cos\left(q_{err}\right) - e_f \sin\left(q_{err}\right)\cos(\Omega t)$$

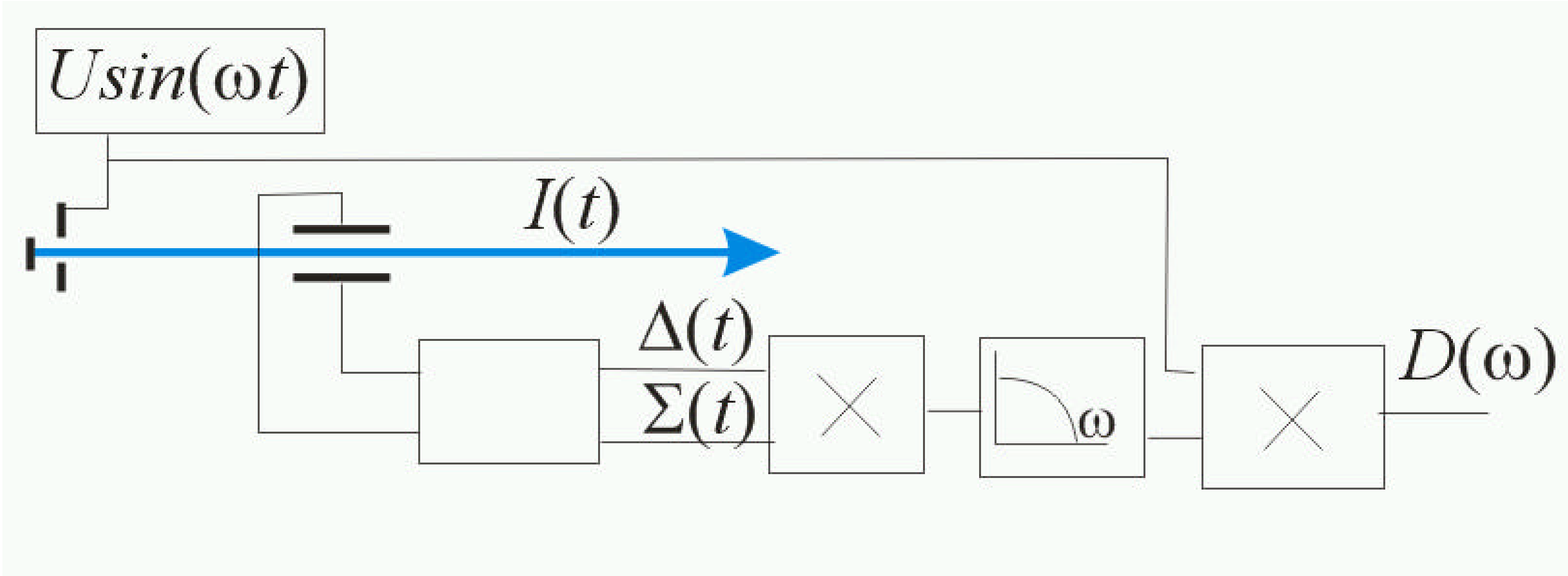
Phase error is obtained by synchronous detection of beam energy

Accuracy is about ~0.1 deg

Conclusions

- Beam position stabilization in large machine requires distributed set of local feedback systems: distribution in space and functionality are usually required
- Presently. Beam position stabilization to ~10 μm is routine task
- Digital feedback system presents more flexibility and better control of the system
- Unsolicited advice from operations: Do not build more systems than you need

Multi-pass BPM proposal



$$D(w) = \overline{\Delta(t)\cos wt} = \frac{1}{4}\overline{\left(e^{i(wt+y)} + e^{-i(wt+y)}\right)\sum_{n=1}^{N}\Delta_n\left(e^{iw(t+nT)} + e^{-iw(t+nT)}\right)}$$

$$= \sum_{n=1}^{N}\Delta_n \cos(nwT + y)$$

- 2N measurements in frequency band, f = [0, 1/T], yield N positions Δ_n and N phases y_n. More measurements yield better accuracy for each pass