Fast Digital Feedback System for Energy and Beam Position Stabilization

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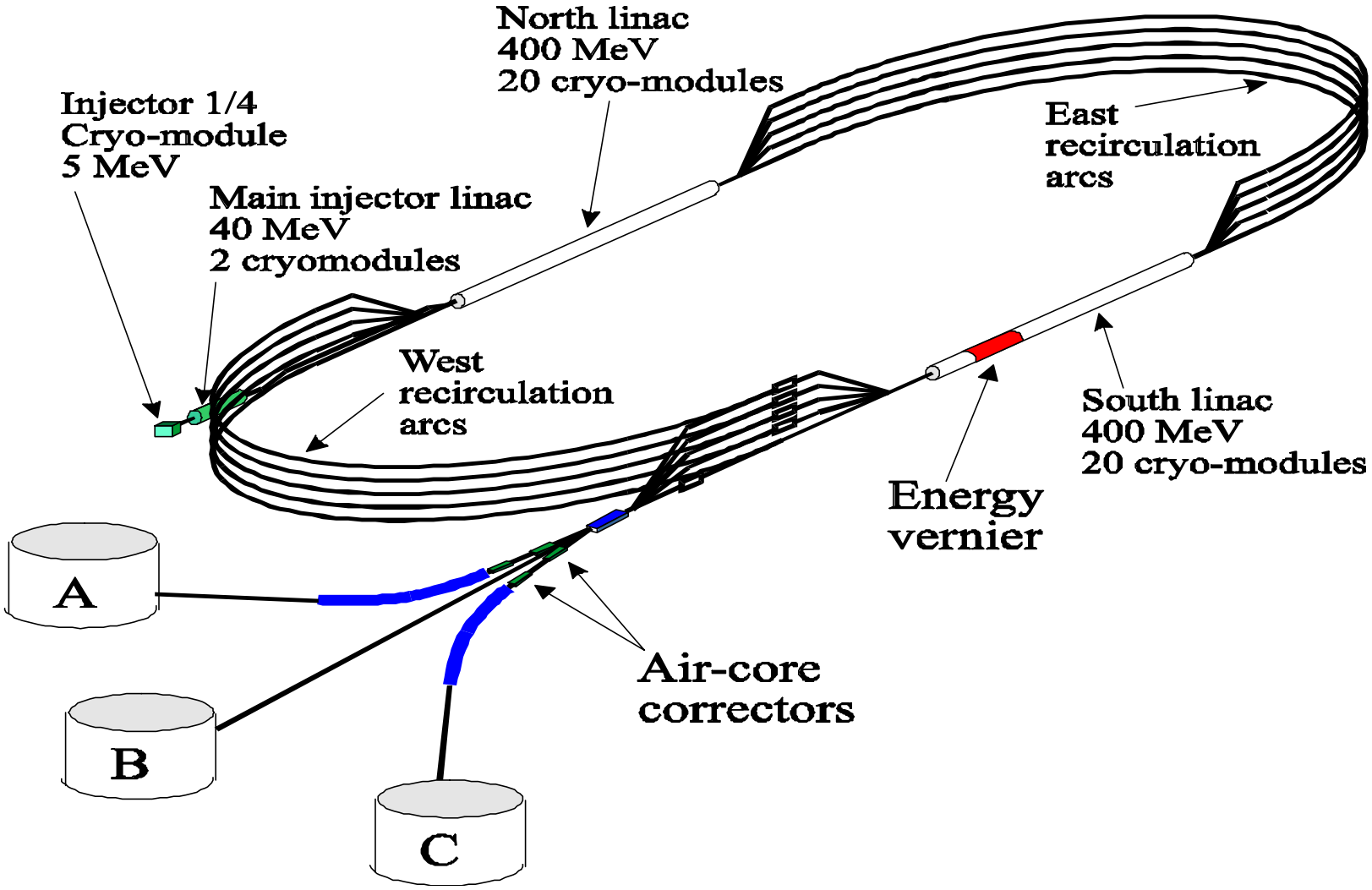
Jefferson Lab

CEBAF Accelerator

- Fixed target nuclear physics experiments
- Polarized electron beam (up to 75%)
- 5 pass recirculator
- 2 SC linacs (320 five cell SC cavities)
- Simultaneous 3 Hall operation

Main machine parameters

Total beam energy	4 GeV (5.5 GeV)
Injector energy	45 MeV
Beam current	200 μA
Beam power	1 MW
Total transport length	~ 6 km
Number of power supplies for magnets and correctors	~ 1700
Normalized beam emittance	1 - 2 mm mrad



Layout of the CEBAF recirculator

Beam position and energy stabilization

Requirements

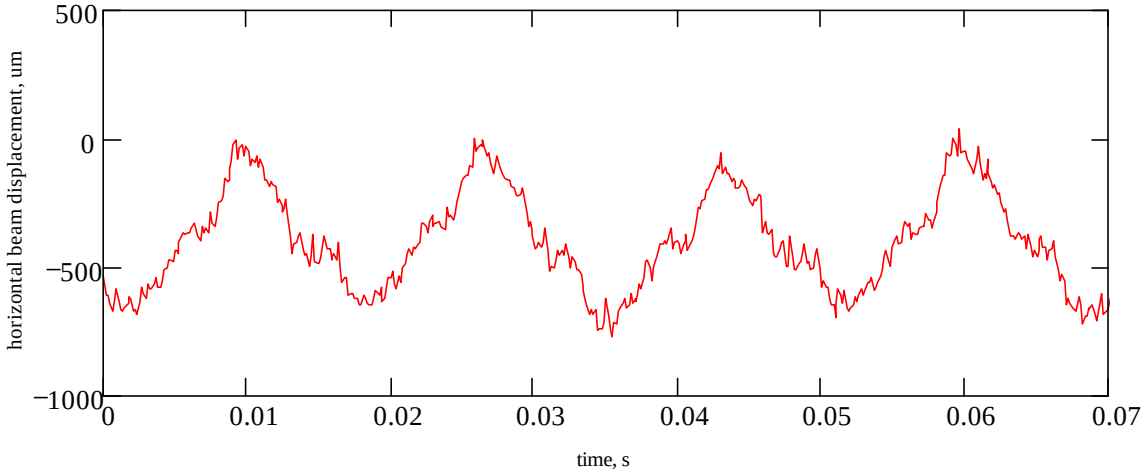
- Stabilization better than the beam size for $I_b > 3$ μA
  - ➢ $\Delta x < 20$ μm
  - ➢ $\Delta p/p < 10^{-5}$
- Beam energy spread $\Delta p/p \sim (1\text{-}2)10^{-5}$
  - ➢ RF phase stabilization better than 0.2 deg
- Two-hall operation (common SC linacs)
  - ➢ Only one hall stabilizes energy
  - ➢ Halls A & C - (1 - 100) μA

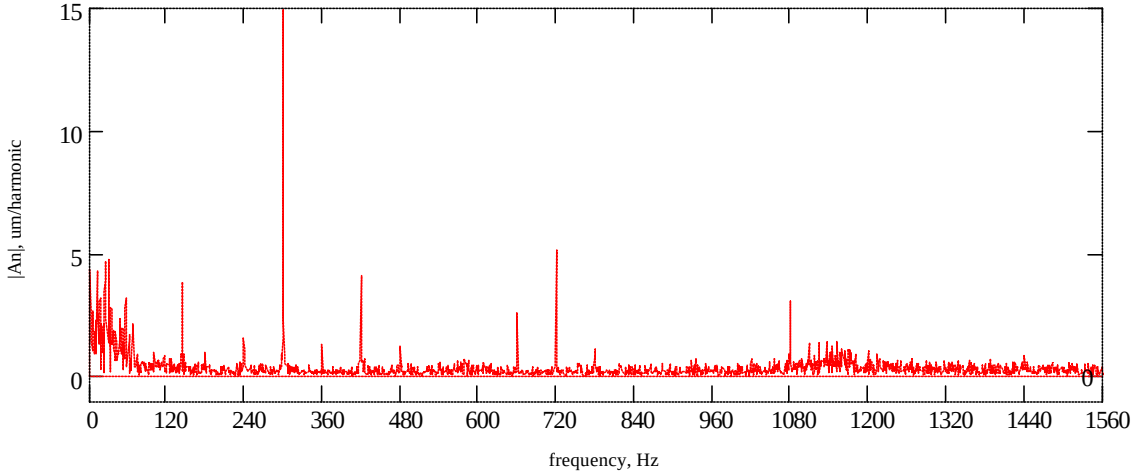
Six dimensional phase space

- Fast feedback system for beam position and energy stabilization
- Measurements and stabilization of SC linacs RF gang phase
  - ➢ M. Tiefenback
    "High-precision non-invasive beam-RF relative phase monitoring at Jefferson Lab"

Spectral Density of beam motion

Amplitude at 60 Hz, μm	236
Amplitude at 120 Hz, μm	24
Amplitude at 180 Hz, μm	54
Residual rms beam motion at other power line harmonics, μm	25



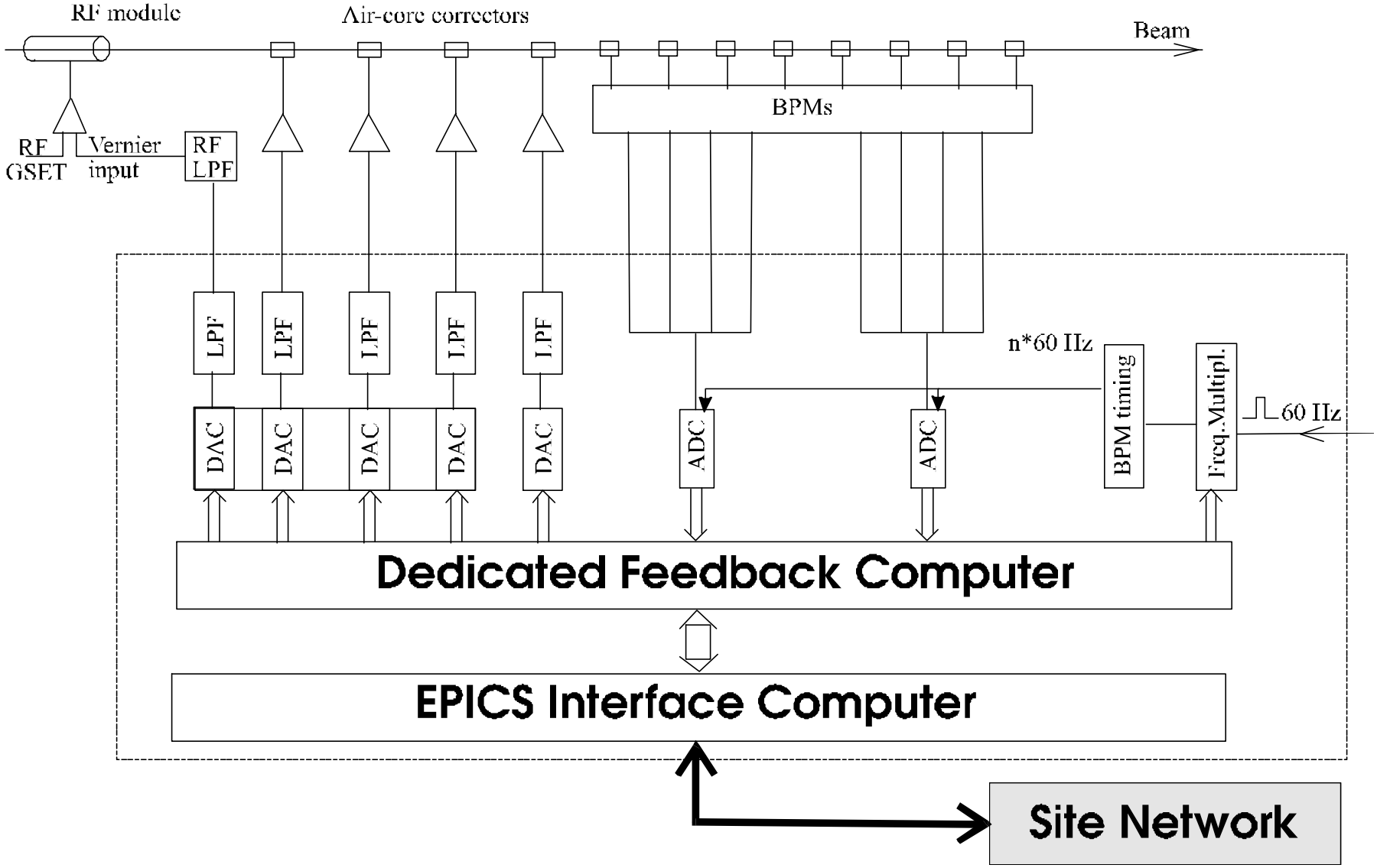


Beam motion at IPM3C12:

Top - measured signal

Bottom - spectrum without first three harmonics

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



Fast Feedback System Schematic

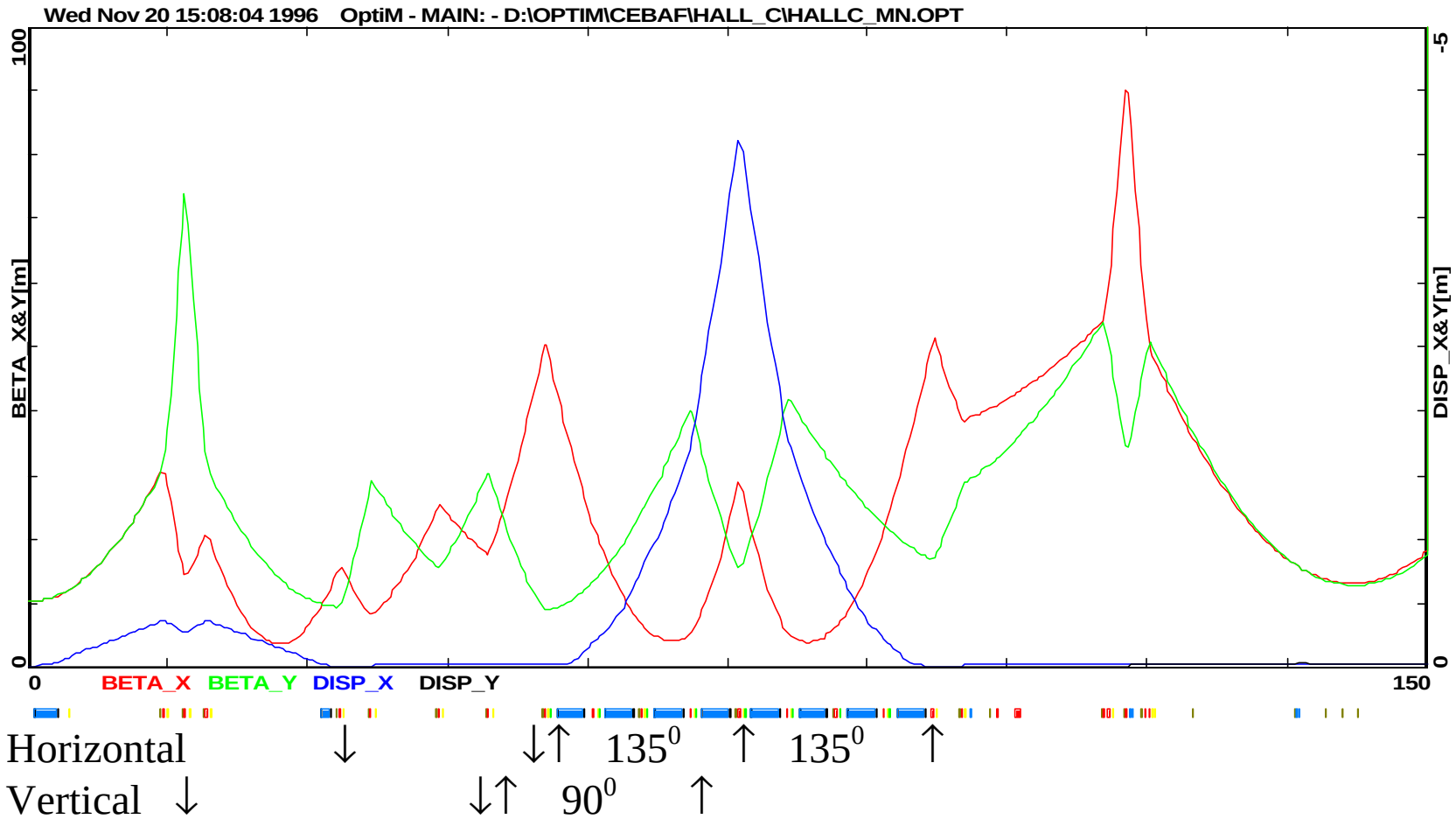
System implementation

- All digital hardware in one VME crate
  - Two CPUs
    - ⇒ A dedicated CPU (PowerPC) runs the feedback process
    - ⇒ Second computer with EPICS supports an operator interface
  - Communication between two computers through a VME memory card
  - 8 BPMs
  - DACs
  - Programmable fourth order Bessel analog filters

- Wind River Systems VxWorks operating system
  - DMA for fast data acquisition from BPMs

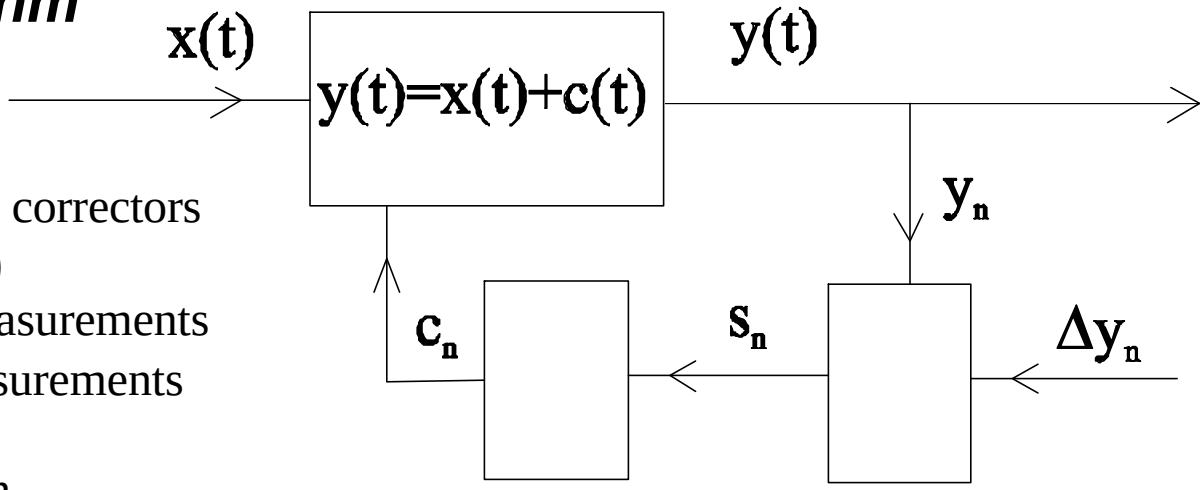
Optics Modifications

- Achromatic
- Large dispersion
- 90^0 betatron phase advances for optimum betatron motion detection



Dispersion and beta-functions for a hall beam line

Numerical algorithm



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

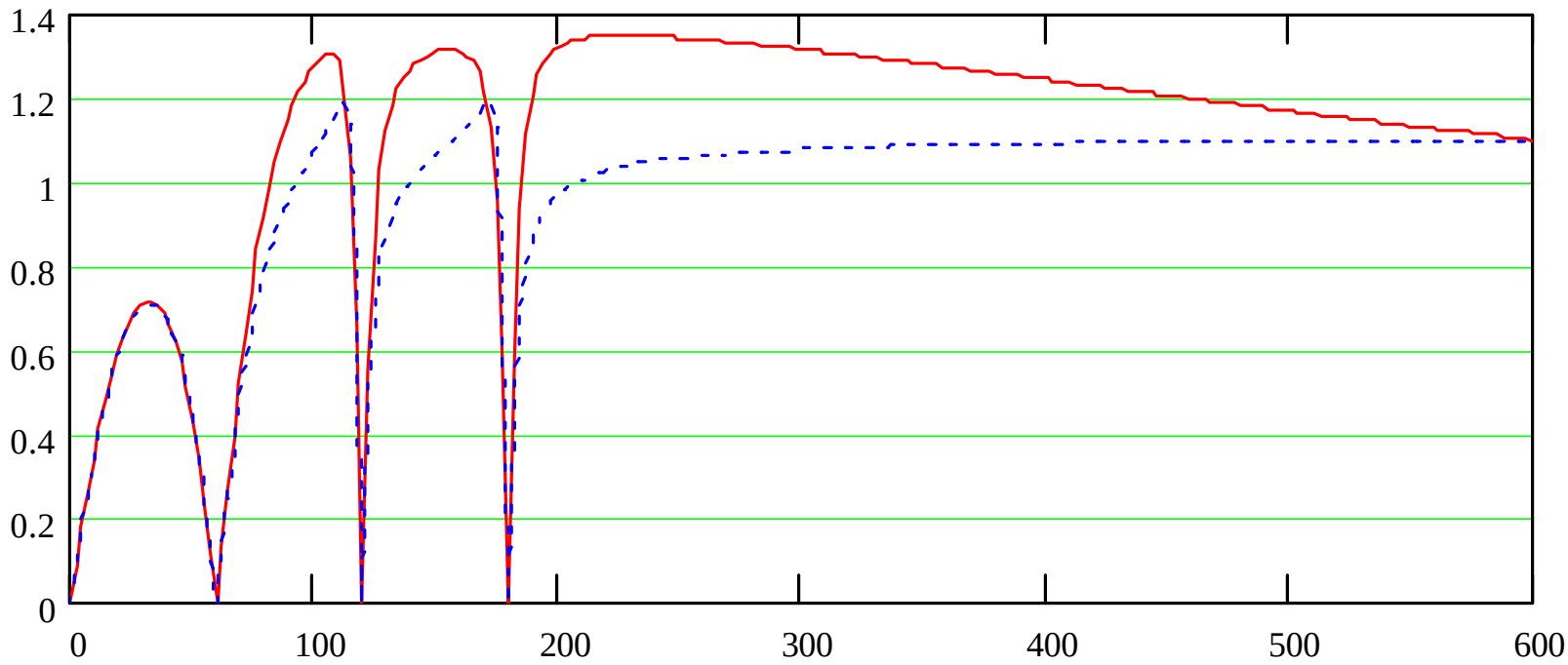
$$\mathbf{c}_n = \mathbf{B}\mathbf{y}_n \quad , \quad \textit{where} \quad \mathbf{B} = \left(\mathbf{M}^T\mathbf{M}\right)^{-1}\mathbf{M}^T$$

Temporal part

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

a_k, b_k - seven coefficients which determine system dynamics(N_{so}=2·NmbOfZeroes – 1=7)

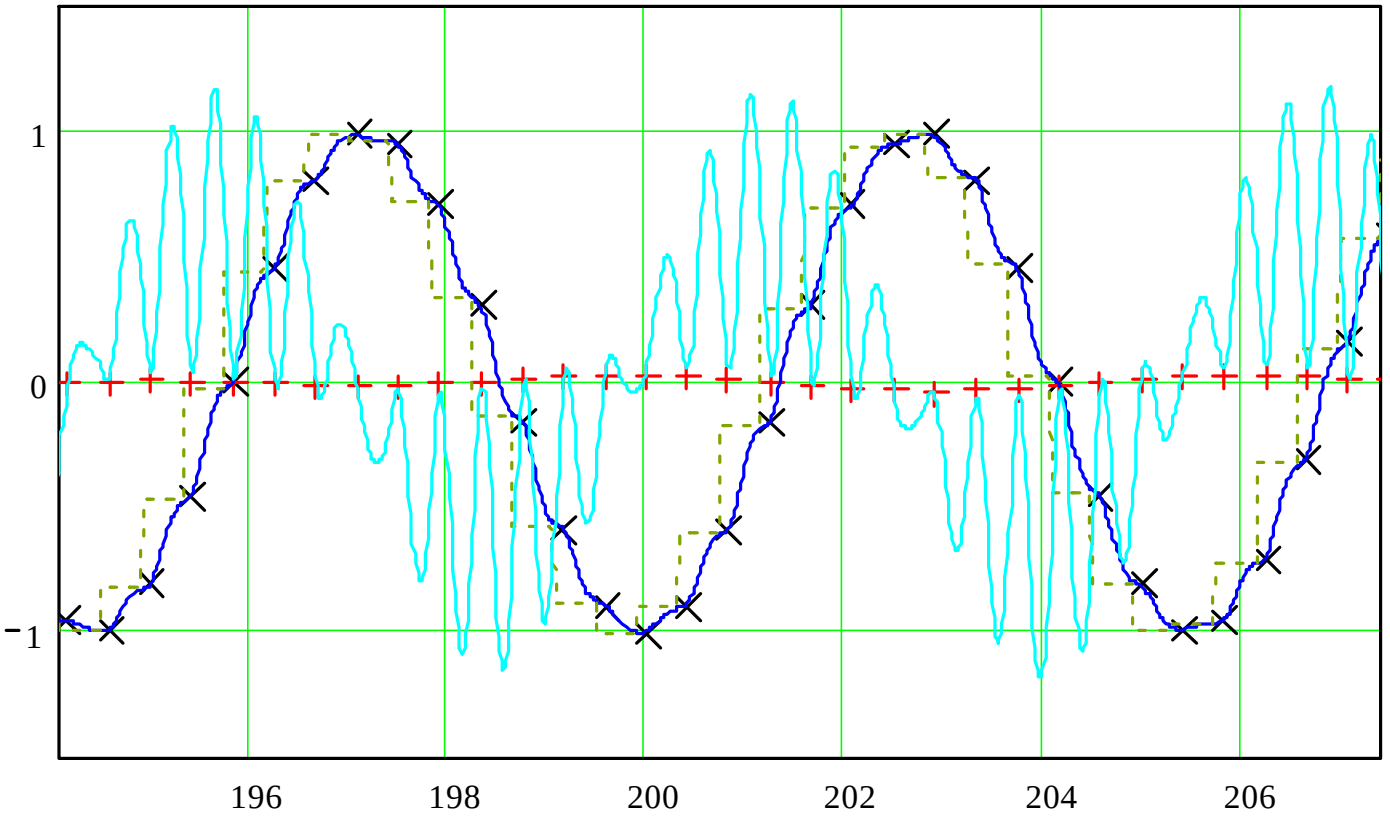
Frequency Domain



Suppression of harmonic signal, of K(f) as function of the frequency; Red - with analog filter, blue - without analog filter

- Seven system dynamic coefficients can be expressed through following parameters
  - 4 gains (near every zero of $K(f)$)
  - 3 gain angles (gain distribution at right and left hand sides of zeroes of $K(f)$ except f=0)

Time Domain



Suppression of 180 Hz signal by fast feedback system running at 2.4 kHz and the analog 4-th order Bessel filter bandwidth of 1.5 kHz

Brown dashed - DAC voltage

Blue - DAC voltage after analog filter

Red crosses - measured output signal times 10

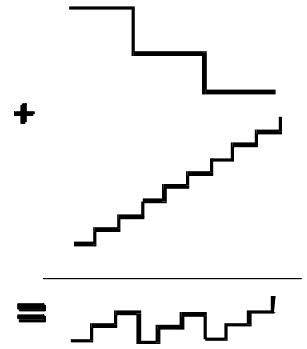
Light blue - output signal times 10

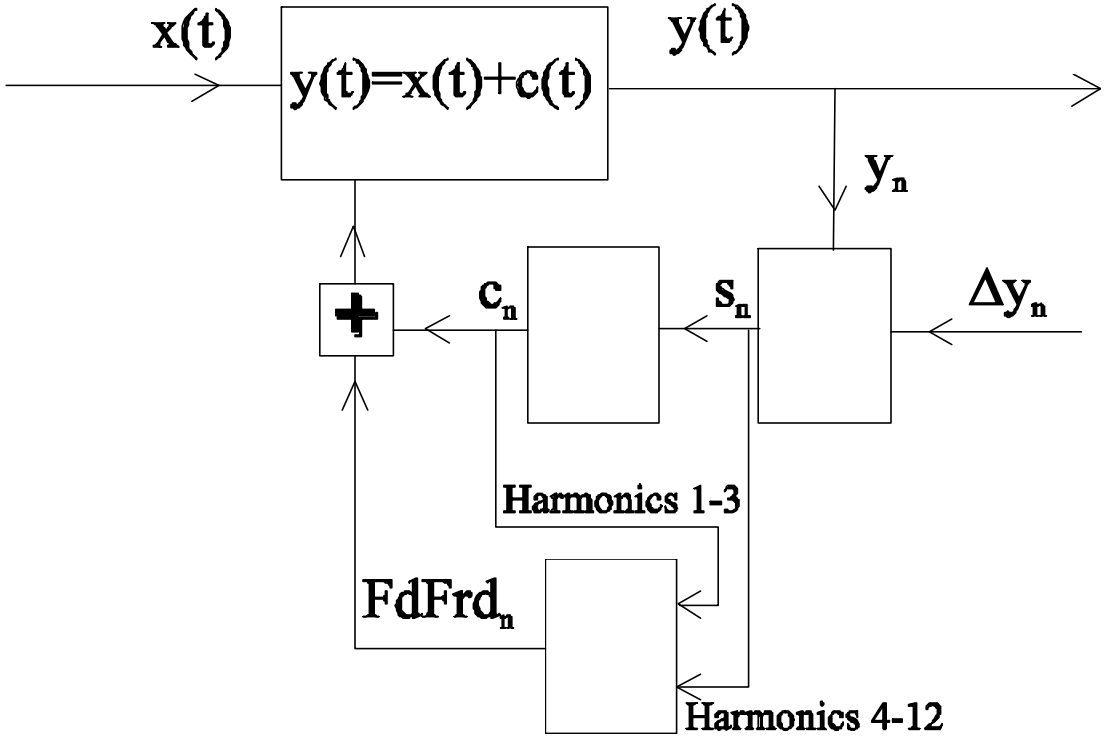
Feedforward

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

Solution:

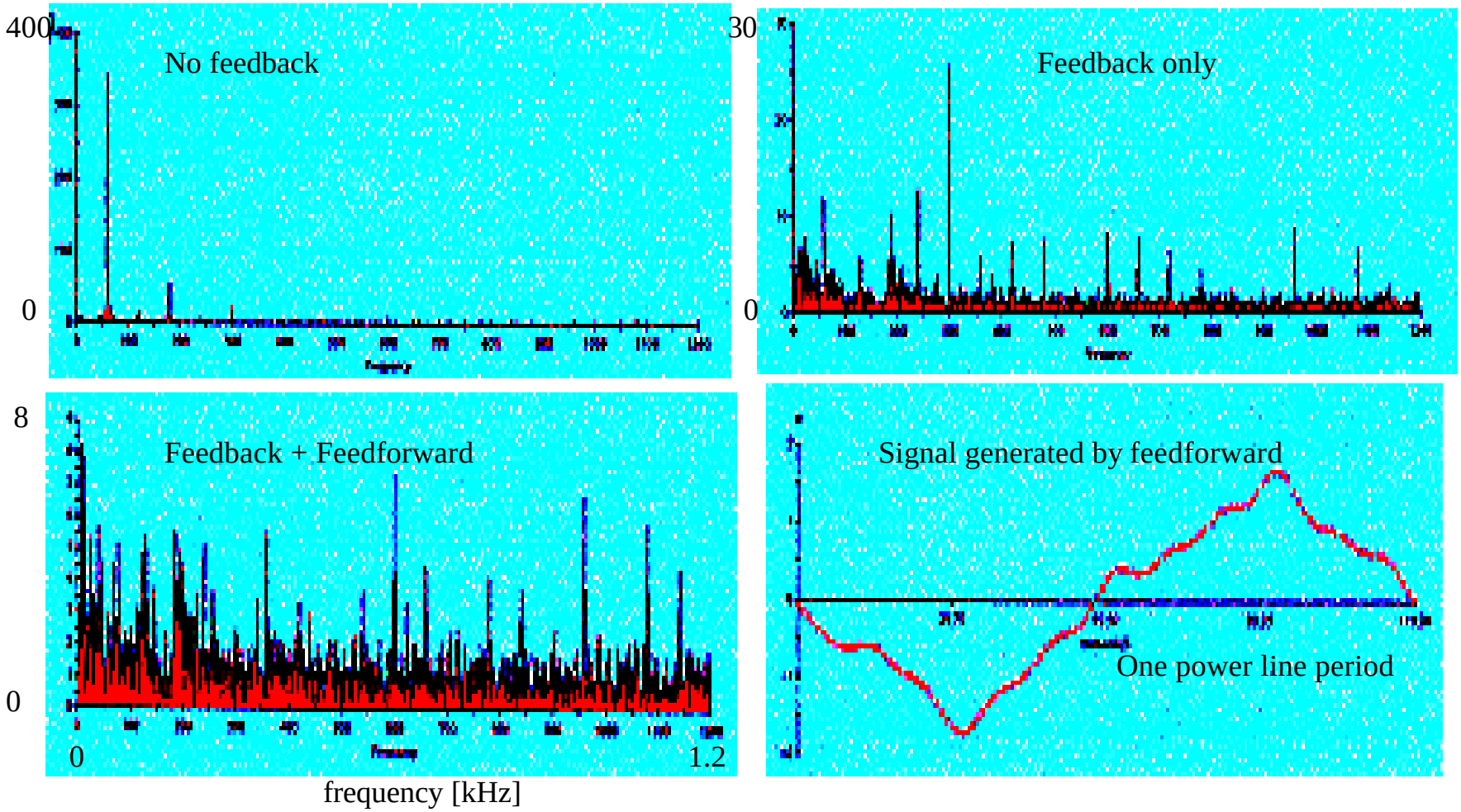
- Run DACs 3 times faster than ADCs





- 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 the 12^{th} harmonic

Beam motion spectra with and without fast feedback system on



Conclusions

- Total effort was about 2 man year (FTE)
- Reliable software, continuously used in operations
- EPICS interface consistent with the rest of control system
- The system suppresses the beam motion to less than about 30 μm and energy to better than 10^{-5} for beam current more than 20 μA
- Hall A system has been in use for about half year
- Hall C system has been recently installed