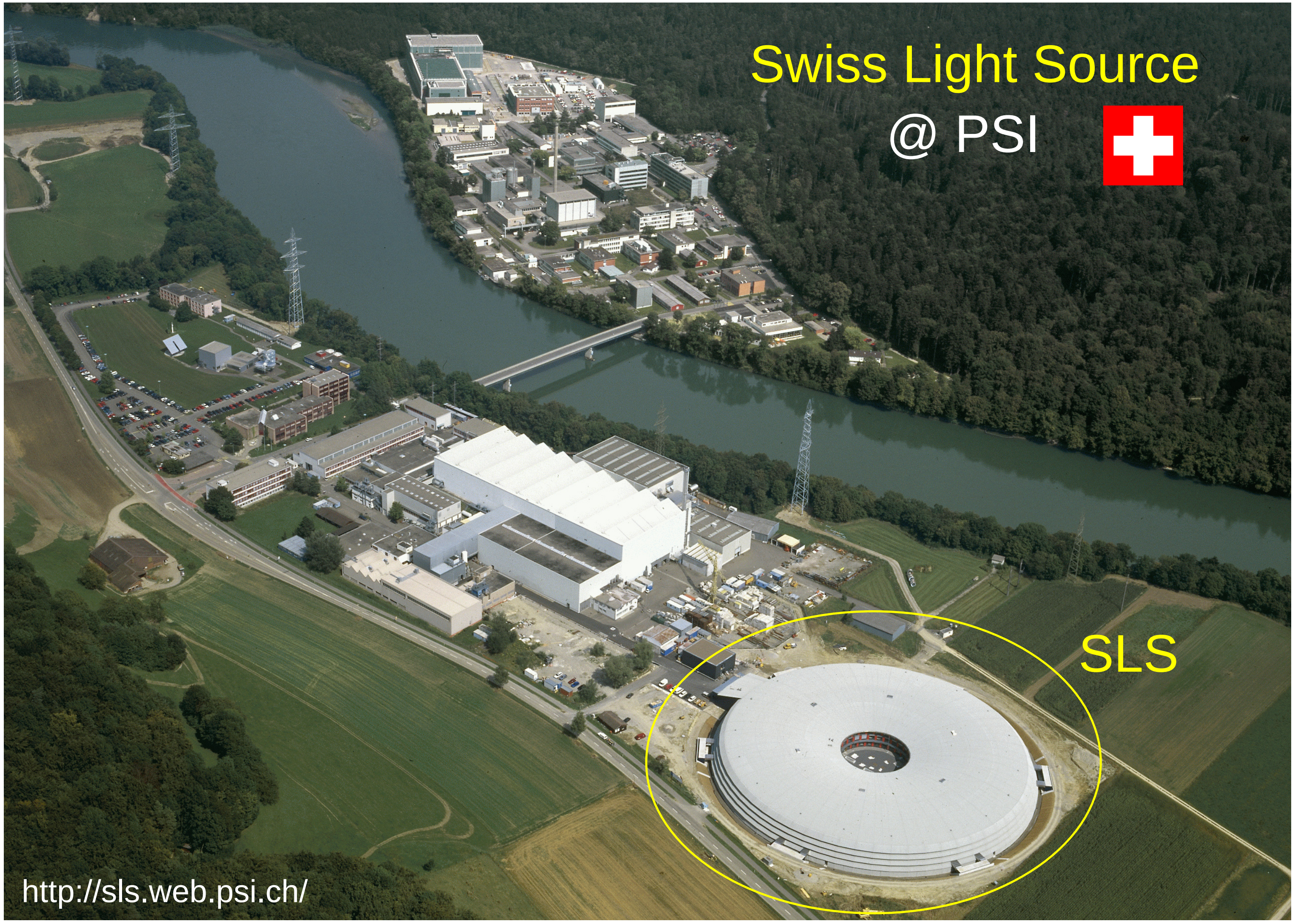
SLS at the Paul Scherrer Institute (PSI), Villigen, Switzerland

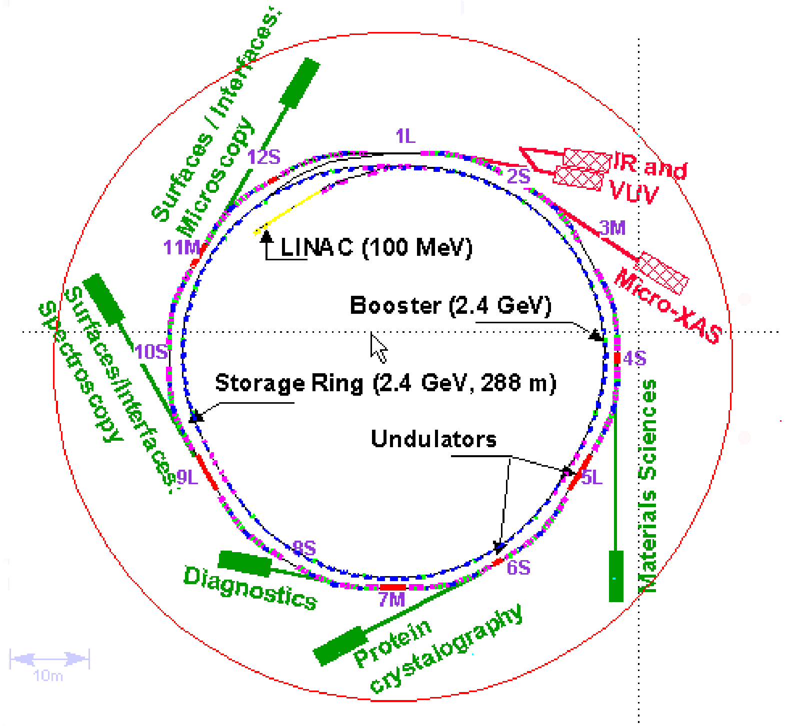


Outline

- Introduction
  - SLS Layout
  - Storage Ring Design
  - BPM/Corrector Layout
- Motivation
  - Stability - Ground Noise
  - Stability - Worst Case Stability Estimate
- Theory & Simulations (T&S)
  - Orbit Correction Schemes
  - Response Matrices
  - Path Length Correction
  - Model for a Closed Orbit Feedback
- Fast Orbit Feedback (FOFB)
  - Digital BPM System
  - Digital Power Supplies
- Slow Orbit Feedback (SOFB)
  - Golden Orbit
  - Schematic View
  - RMS/Mean Orbit, Path Length
  - RF changes vs. Temperature
  - Long Term Stability - BPMS
  - Stability - Top-up
  - Stability - Position Monitoring System (POMS)
- Fast Orbit Feedback (FOFB)
  - From Manual Correction to FOFB
  - Power Spectral Densities
  - Vertical Transfer Functions
- Conclusions

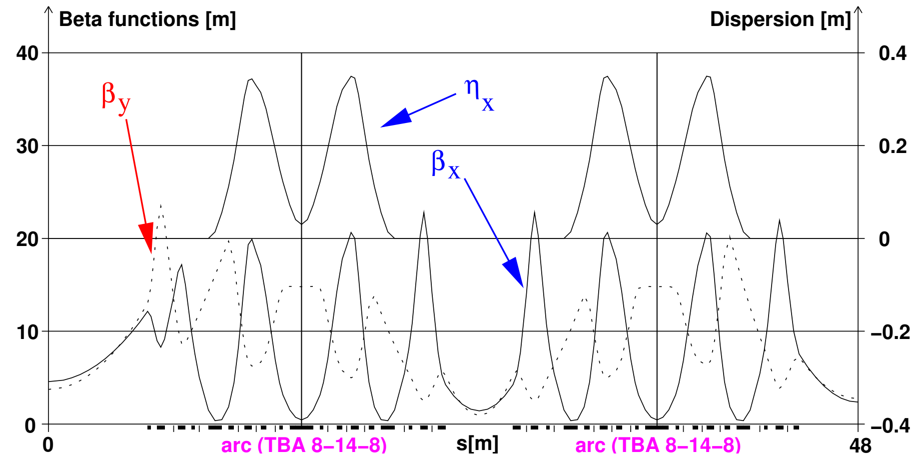
Introduction - SLS Layout

- Pre-Injector Linac
  - 100 MeV
- Booster Synchrotron
  - 100 MeV to 2.7 GeV @ 3 Hz
  - ϵ_x = 9 nm rad
- Storage Ring
  - 2.4 (2.7) GeV, 400 mA
  - ϵ_x = 5 nm rad
- Initial Four Beamlines:
  MS – 4S, PX – 6S,
  SIS – 9L, SIM – 11M



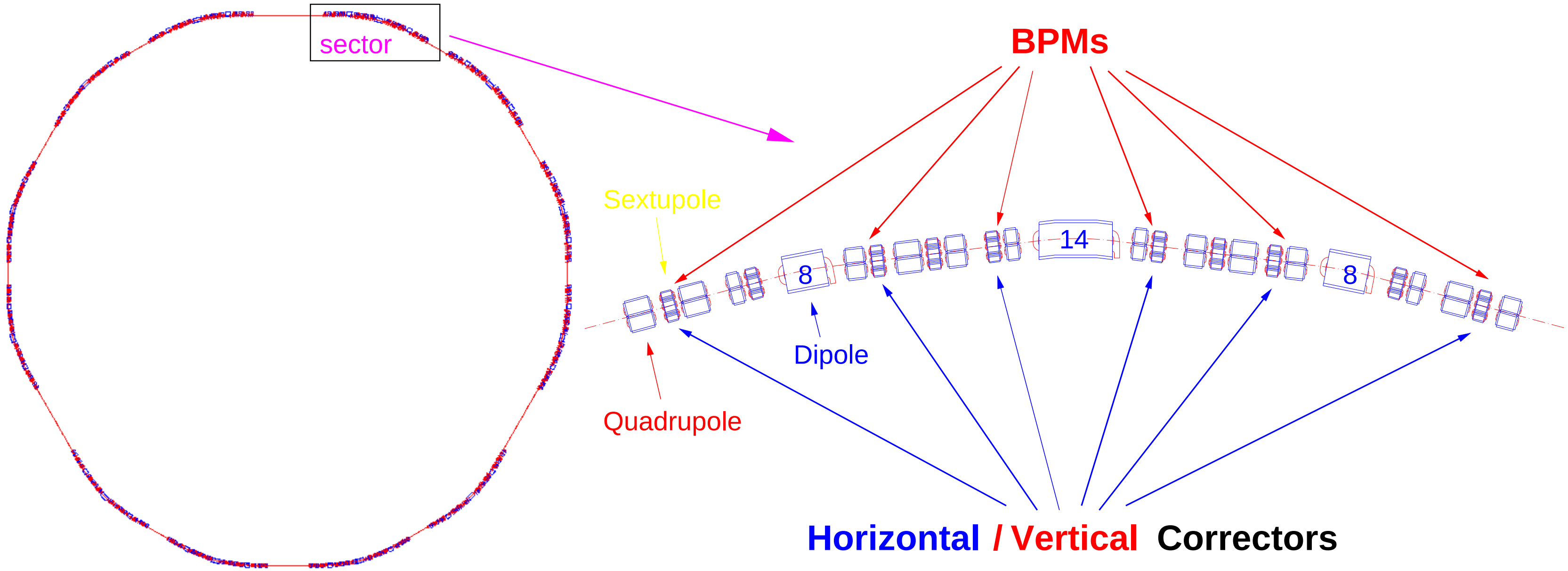
Introduction - Storage Ring Design

- 12 TBA: 8° / 14° /8 °
- 12 Straight Sections:
  - 3 × 11 m (n**L**)
    - ∗ **Injection, U212**
  - 3 × 7 m (n**M**)
    - ∗ **UE56**
  - 6 × 4 m (n**S**)
    - ∗ 2× **RF, W61, U24**
- Energy: 2.4 GeV (2.7 GeV)
- ϵ_x: 5 nm rad
- Current: 400 mA
- Circumference: 288 m
- Tune: 20.42) / 8.17)
- Chromaticity: -66 / -21



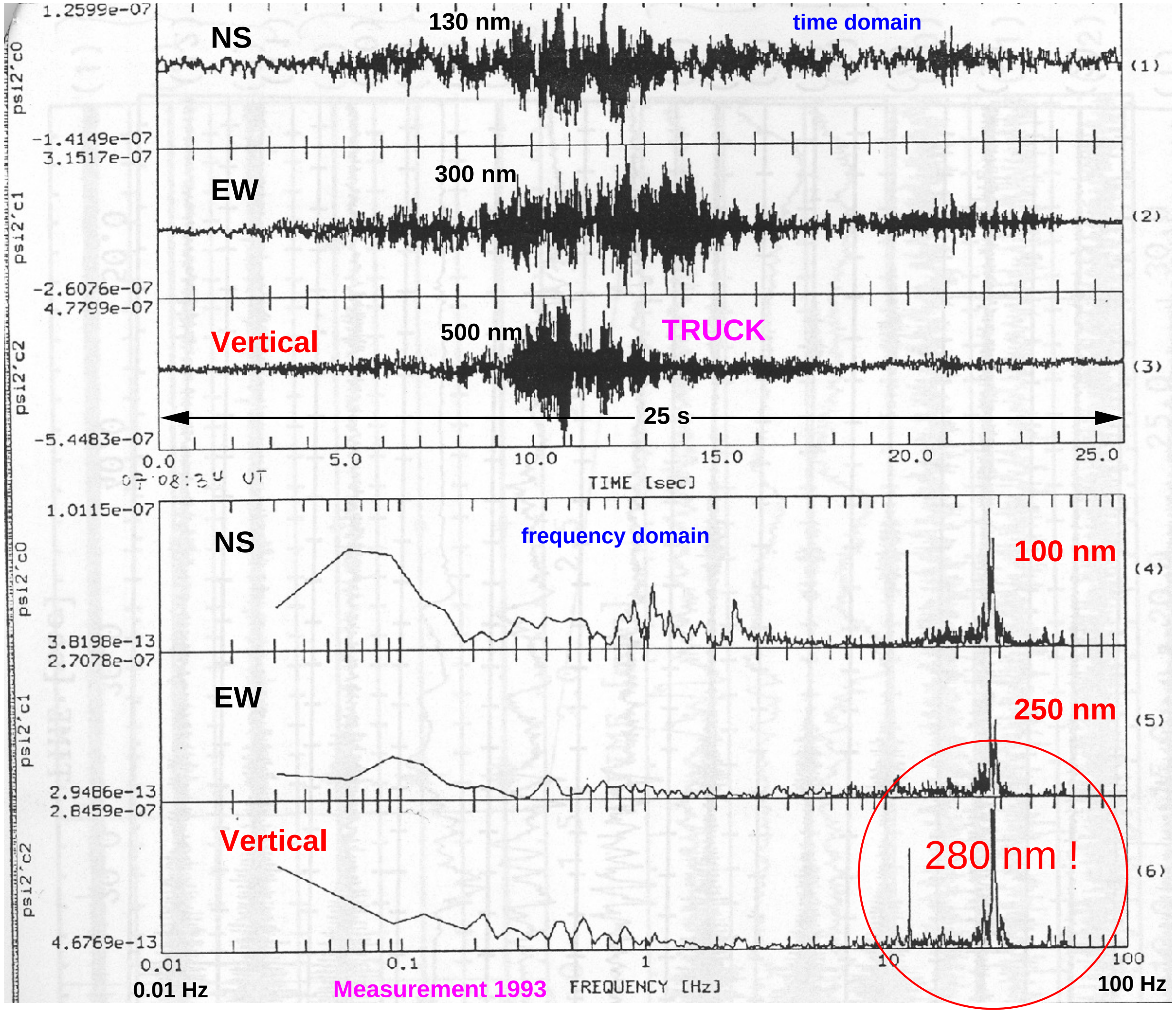
Energy	[GeV]	2.4 (2.7)
Circumference	[m]	288
RF frequency	[MHz]	500
Harmonic number		(2^5x3x5 =) 480
Peak RF voltage	[MV]	2.6
Current	[mA]	400
Single bunch current	[mA]	≤ 10
Tunes		20.38 / 8.16
Natural chromaticity		−66 / −21
Momentum compaction		0.00065
Critical photon energy	[keV]	5.4
Natural emittance	[nm rad]	5.0
Radiation loss per turn	[keV]	512
Energy spread	[10^{-3}]	0.9
Damping times (h/v/l)	[ms]	9 / 9 / 4.5
Bunch length	[mm]	3.5

Introduction - BPM/Corrector Layout



- 12 sectors
- 6 BPMs and 6 Horizontal/Vertical Correctors per sector
- Correctors in Sextupoles, BPMs adjacent to Quadrupoles

Motivation - Stability - Ground Noise



Motivation - Stability - Worst Case Estimate

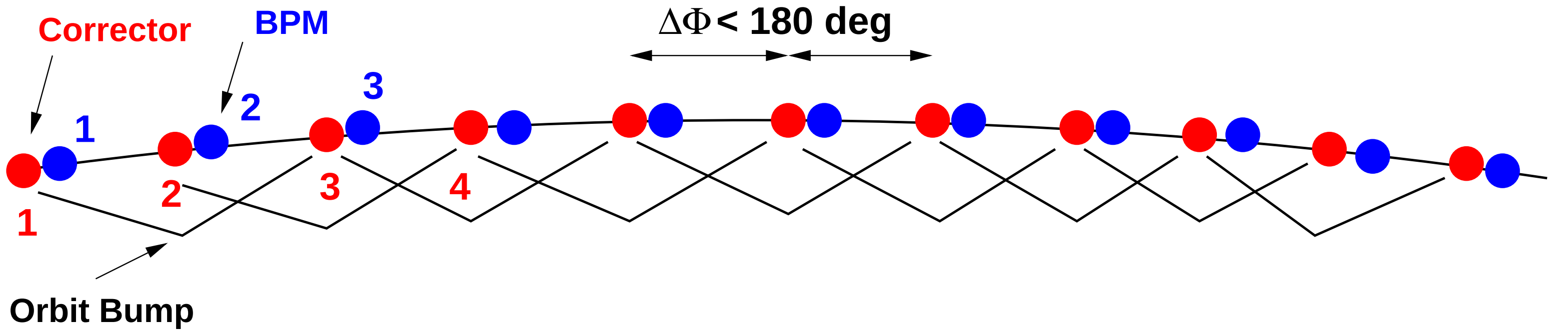
- β_x = 1.4 m, β_y = 0.9 m at **ID** position of section n**S** $\rightarrow$
  σ_x = 84 μm, σ_y = 7 μm assuming emittance coupling ϵ_y/ϵ_x = 1 %
- With stability requirement $\Delta\sigma = 0.1 \times \sigma$ $\rightarrow$

Requirement: Orbit jitter < 1 µm at insertion devices

	Worst case Noise estimate	30	60	Hz
	Seismic measurements	300	30	nm
	Damping by hall's concrete slab	neglected		
	Girder resonance max amplification	< 10	< 10	
	Closed orbit amplification hor./vert.	8/5	25/5	
$\rightarrow$	Maximum Orbit jitter hor./vert	24/15	7.5/1.5	µm
	Attenuation by orbit feedback	−55	−35	dB
$\rightarrow$	**Maximum Orbit jitter hor. /vert.**	**40/30**	**130/30**	**nm**

T&S - Orbit Correction Schemes

- **Sliding Bump** - Phase advances between Correctors $0° < \Delta\phi < 180°$, Correctors 1,2,3 allow to zero the orbit in BPM 2 near Corrector 2. 1 opens "Orbit Bump", 2 provides kick for 3 to close it again. Continue ("Slide") with 2,3,4 to zero orbit in BPM 3 ... iterate until orbit is minimized in all BPMs !

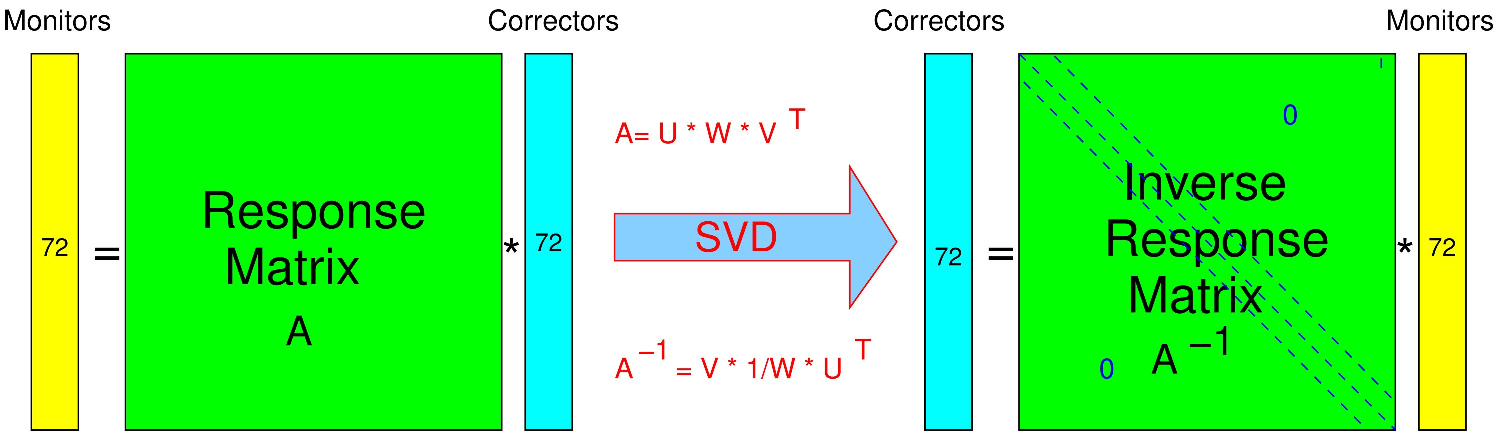


- **MICADO** - Finds a set of "Most Effective Correctors", which minimize the RMS orbit in all BPMs at a minimum ("most effective") RMS Corrector kick by means of the SIMPLEX algorithm. The number of Correctors (= iterations) is selectable.

- **Singular Value Decomposition (SVD)** - Decomposes the "Response Matrix" $A_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \cos\left[\pi\nu - |\phi_i - \phi_j|\right]$ containing the orbit "response" in BPM i to a change of Corrector j into matrices U,W,V with $A = U * W * V^T$. W is a diagonal matrix containing the sorted Eigenvalues of A. The "inverse" correction matrix is given by $A^{-1} = V * 1/W * U^T$. SVD makes the other presented schemes obsolete !-)

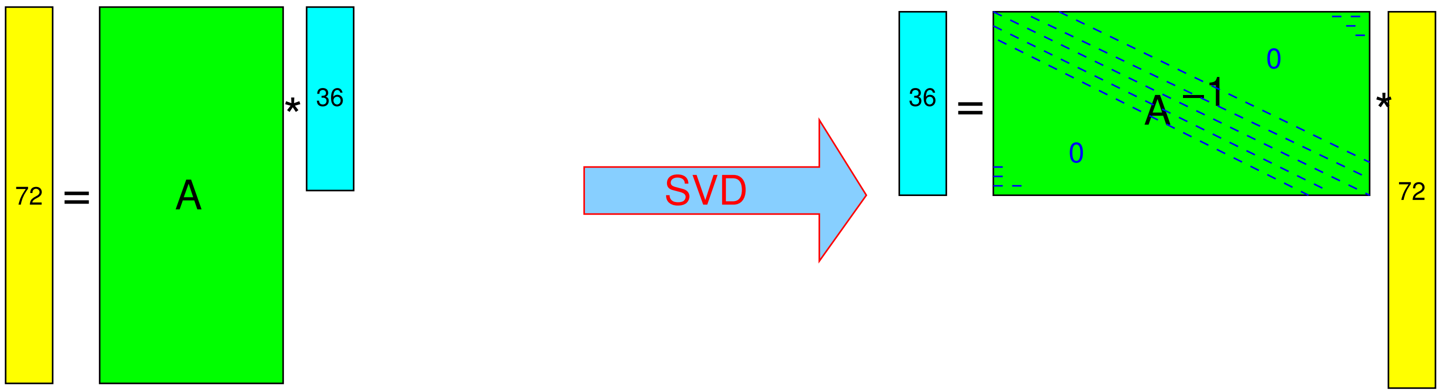
T&S - What SVD does

72 monitors / 72 correctors



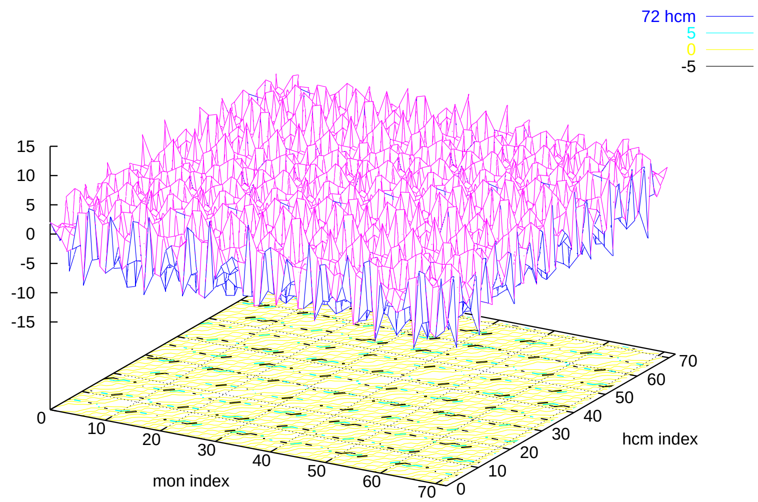
=> Minimization of the RMS orbit (=0 in case of "Matrix Inversion" using all Eigenvalues)

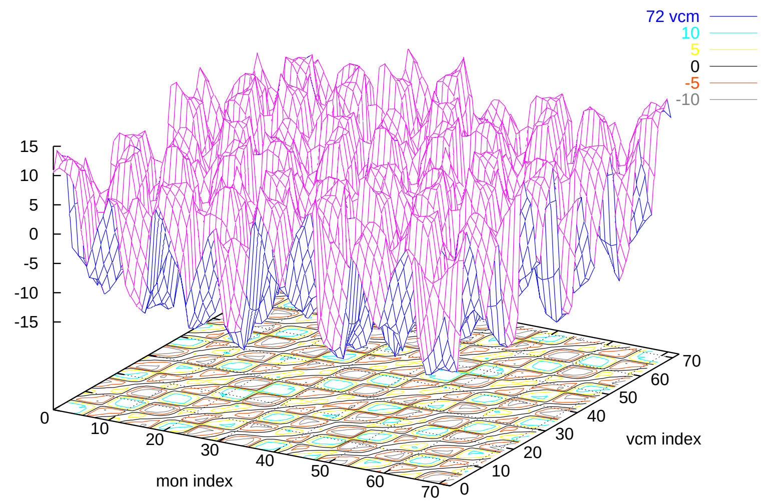
72 monitors / 36 correctors



=> Minimization of the RMS orbit (monitor averaging)

T&S - Response Matrices

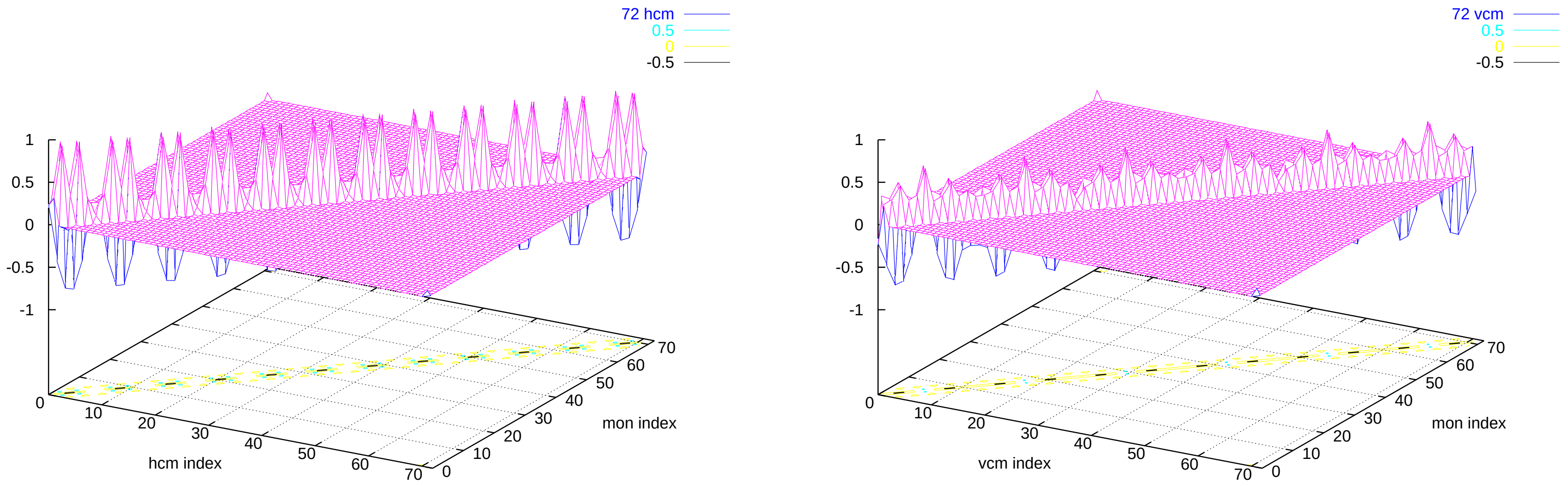




$$A_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2\sin\pi\nu}\cos\left[\pi\nu - |\phi_i - \phi_j|\right] = (U * W * V^T)_{ij}$$

- ν_x = 20.42 (≈3 BPMs/Correctors per unit phase, $\phi = 360°$)
- ν_y = 8.17 (≈9 BPMs/correctors per unit phase)

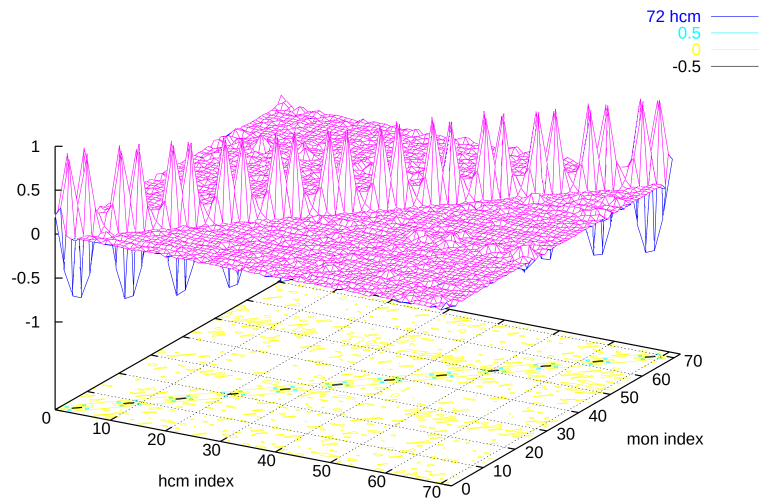
T&S - Inverse Response Matrices

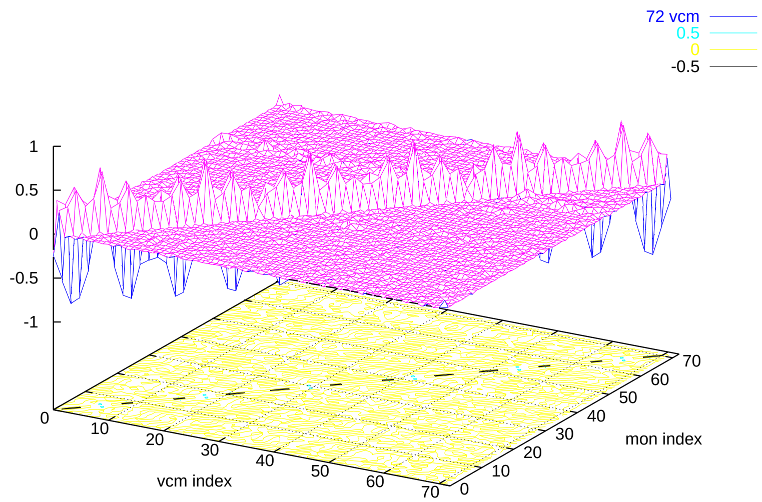


$$A_{ij}^{-1} = (V * 1/W * U^T)_{ij}$$

- A_{ij}^{-1} is a sparse "*tridiagonal*" matrix (3 large (+1 small) adjacent coefficients are nonzero since BPM and Corrector positions are slightly different)
  →"Sliding Bump Scheme" iteratively inverts A
- A_{ij}^{-1} contains *global* information although it is a "*tridiagonal*" matrix !
  → Implementation of a Fast Orbit Feedback (FOFB)

T&S - Inverse Measured Response Matrices

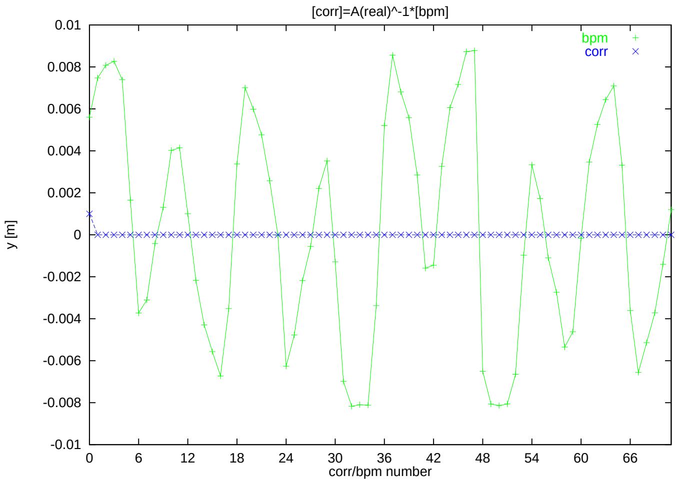


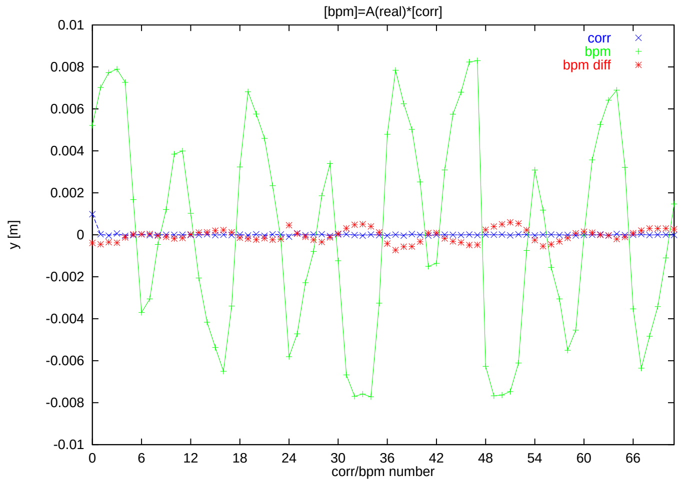


- Horizontal β Beat: $\approx$ 4 %
- Vertical β Beat: $\approx$ 3 %

$\rightarrow A(real)_{ij}^{-1}$ is still a sparse "*tridiagonal*" matrix plus some noise

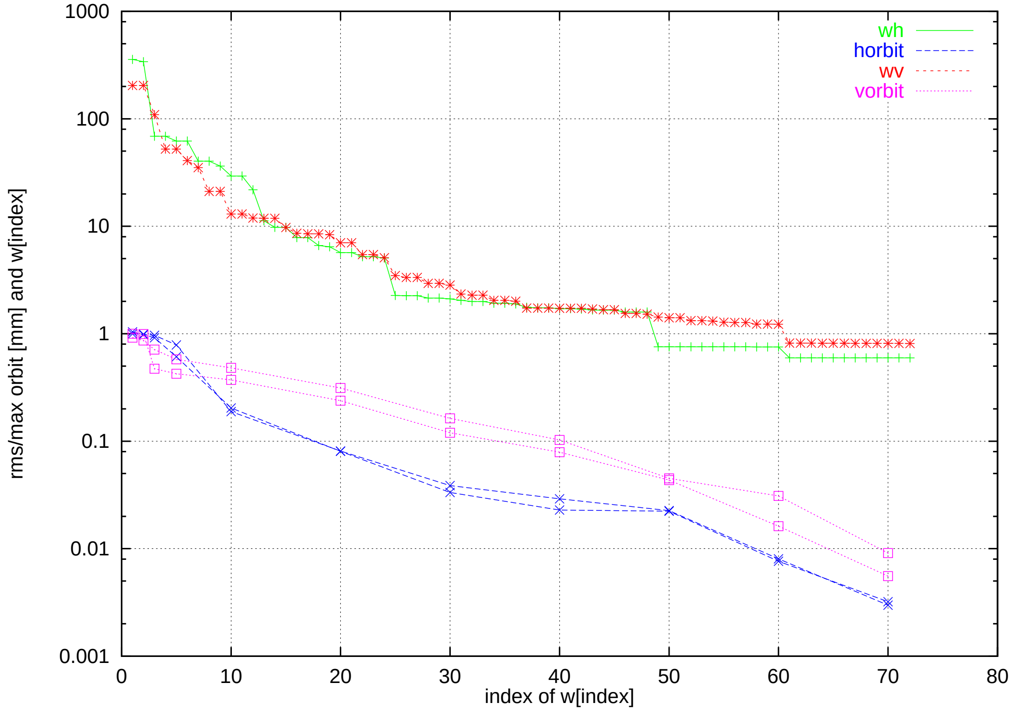
T&S - Single Corrector Example





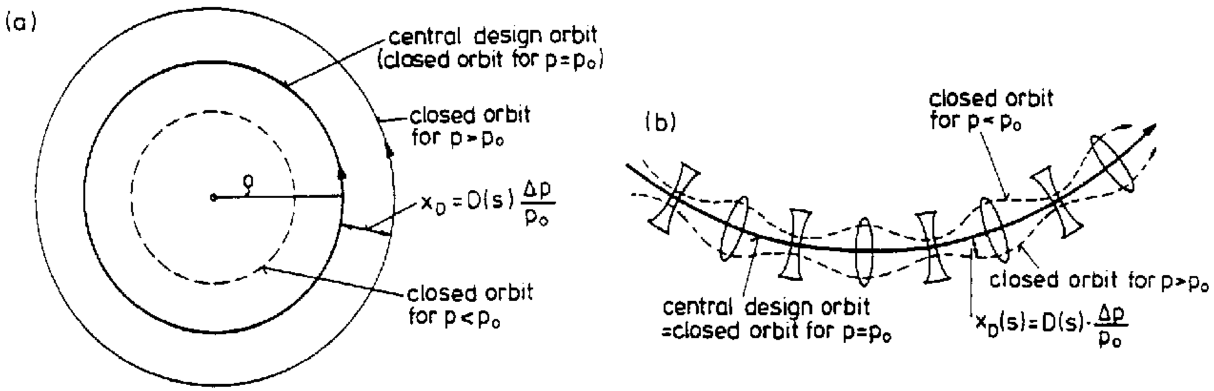
- Vertical βtron oscillation in a machine with distortions
- The measured $A(real)_{ij}^{-1}$ would predict *one* corrector
- $A(ideal)_{ij}^{-1}$ for the ideal machine predicts *one* corrector plus some noise on the other correctors
- Residual βtron oscillation after the correction

T&S - SVD Eigenvalues



- Range of Eigenvalues $0.5 < W < 500$
- Eigenvalue Cutoff @ i_0 ($W_i = 0$ for $i > i_0$) determines the minimum achievable RMS Orbit and Corrector Strength after Correction → "MICADO" like: the largest Eigenvalues correspond to the "Most Effective Corrector" patterns
- No Cutoff corresponds to "Matrix Inversion". The RMS Orbit after Correction is Zero !

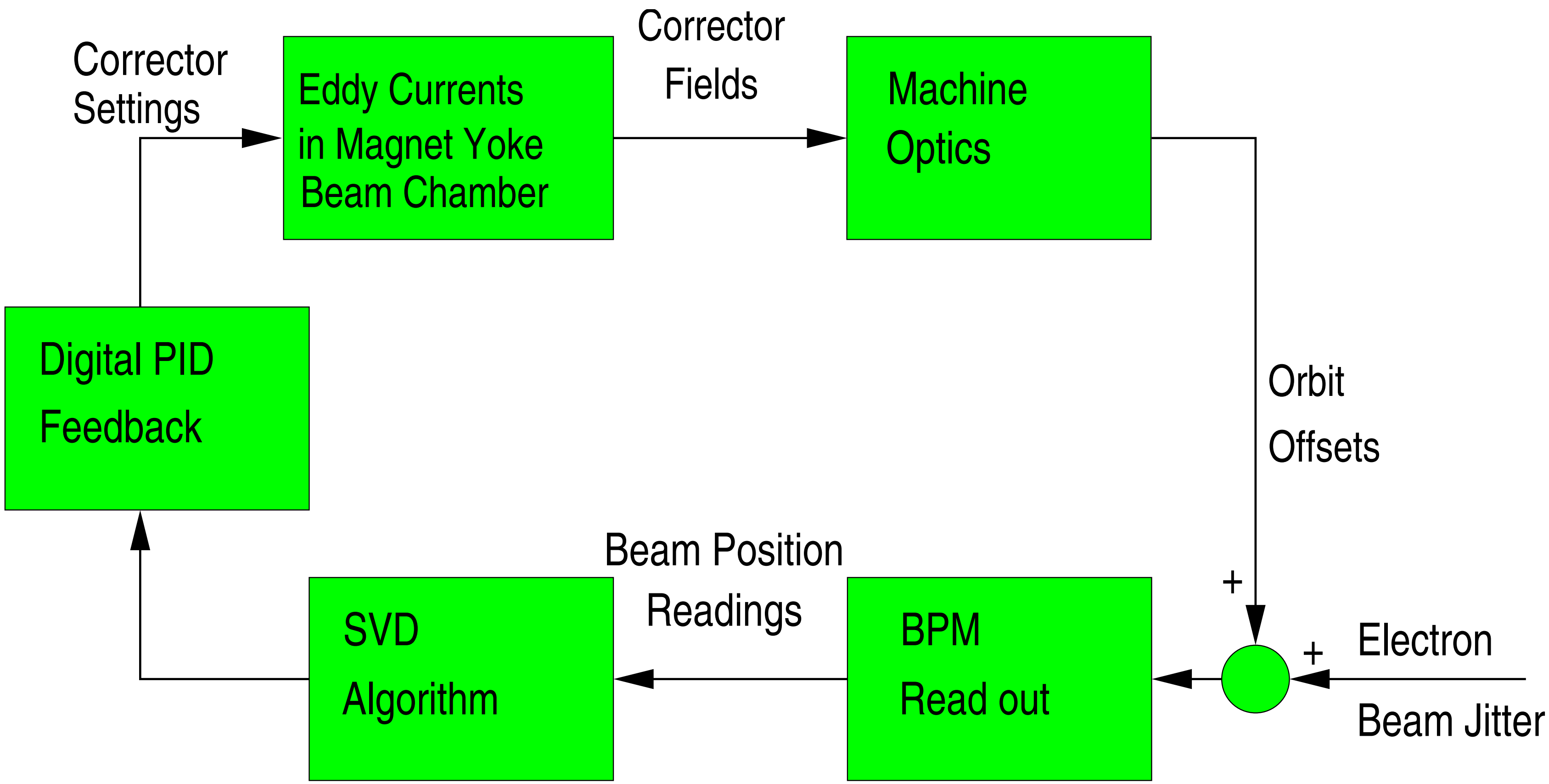
T&S - Path Length Correction



- In a homogeneous magnetic field (a) the radius of the Closed Orbit is proportional to the Energy p (shown are $p < p_0$, $p = p_0$ und $p < p_0$). The Orbit gets shorter or longer ("Path Length" change $\Delta L/L_0$)
- In the case of "strong focussing" (b) the Orbit Deviation @ a location s is given by $x_0(s) = D(s)\Delta p/p_0$ with $\Delta p = p - p_0$, $D(s)$ denotes the Dispersion. $\Delta L/L_0 = \alpha_c \Delta p/p_0$ with the momentum compaction factor $\alpha_c = 1/L_0 \int_0^{L_0} D(s)/\rho(s)ds$ ($\approx\ 6 \cdot 10^{-4}$)
- p variations due to "Path Length" (thermal or modelling effects) changes have to be corrected by means of the RF Frequency f with $\Delta f/f = -\alpha_c \Delta p/p_0$ and NOT by the Orbit Correctors !

$\rightarrow$ Fit $\Delta p/p_0$ part of the Orbit using SVD on a 1 column response matrix containing dispersion values D_{i0} @ the BPMs and change the RF frequency by $-\Delta f$ to correct for $\Delta p/p_0$!

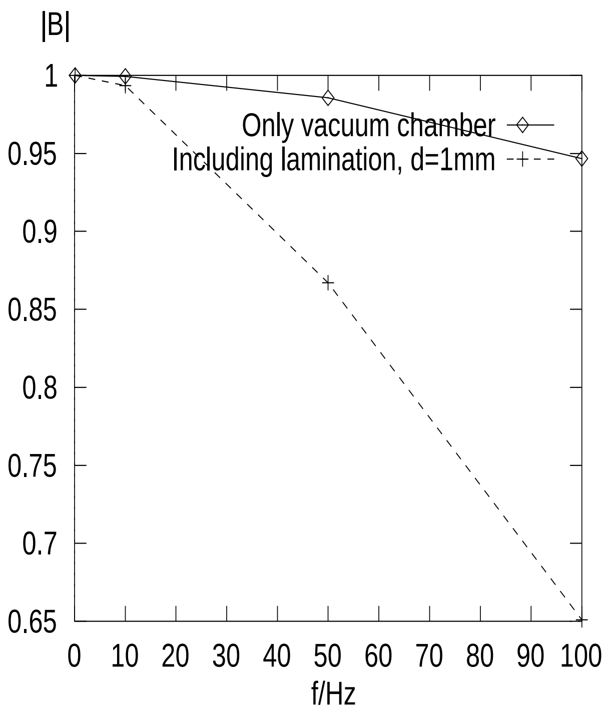
T&S - Model for a Closed Orbit Feedback



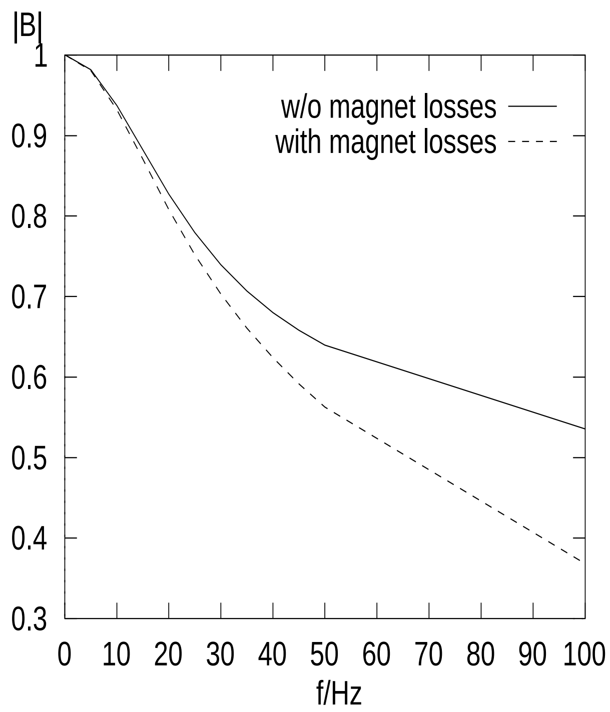
T&S - Calculated Corrector Transfer Functions $|B|$

- MAFIA estimated Eddy Current Effects induced by the Vacuum Chamber (3 mm Stainless Steal) and the Laminated Iron of the Sextupoles:

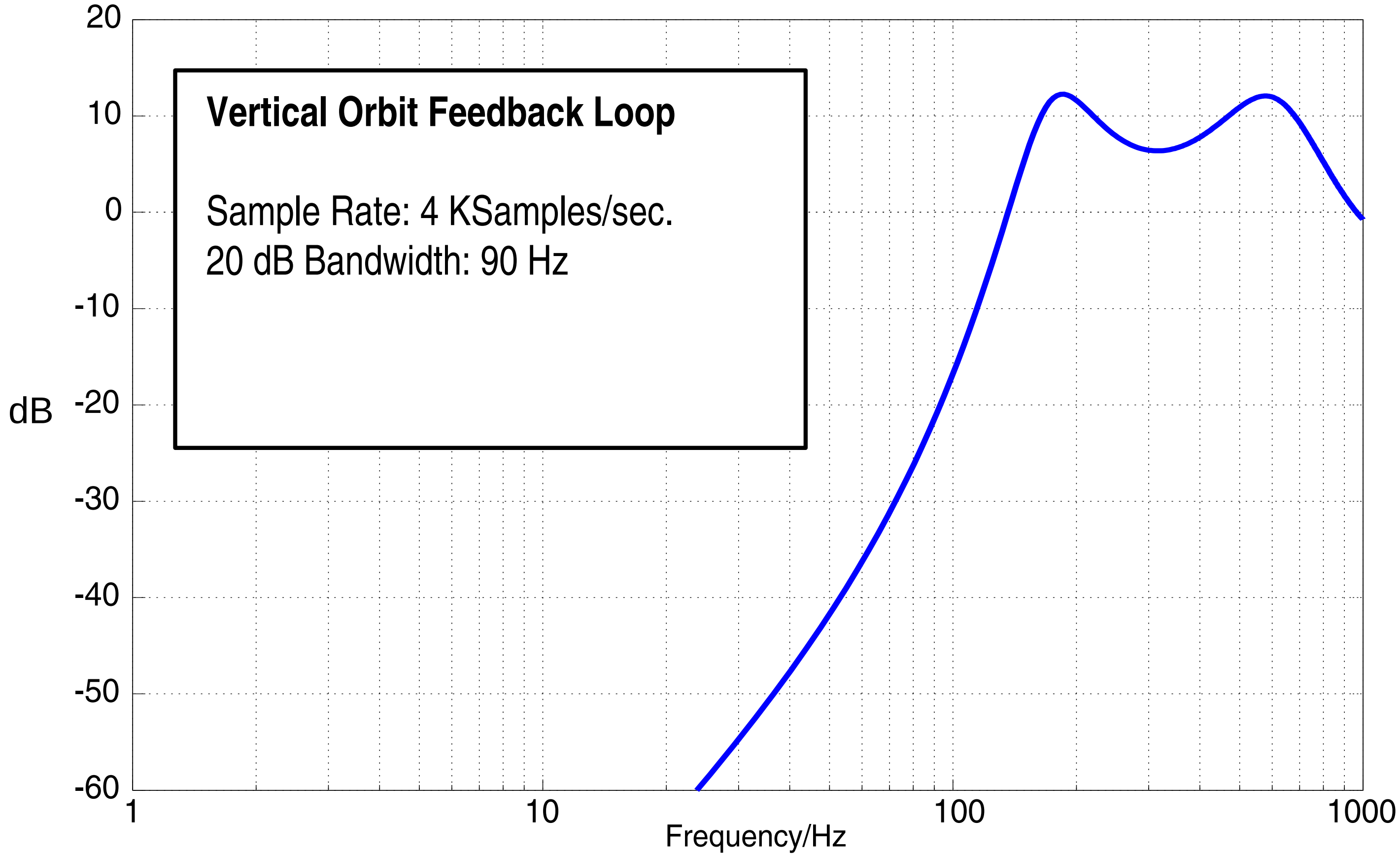
Horizontal Polarization



Vertical Polarization



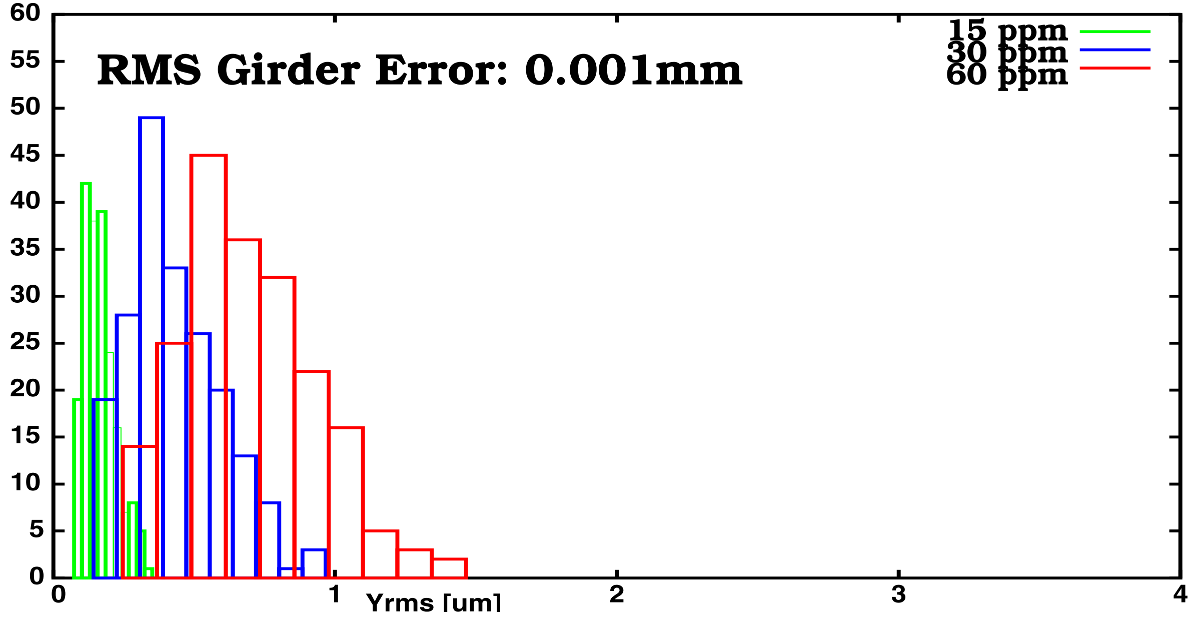
T&S - Simulated Attenuation of Orbit Noise



- 4 KHz Sampling Rate needed in order to have a gain ≈20 dB @ 90 Hz

T&S - Power Supply Resolution and RMS Orbit Distortion

TRACY estimated Residual Vertical RMS Orbit after Orbit Correction as seen by the BPMs (histograms for 200 seeds introducing RMS girder misalignment of 1μm):

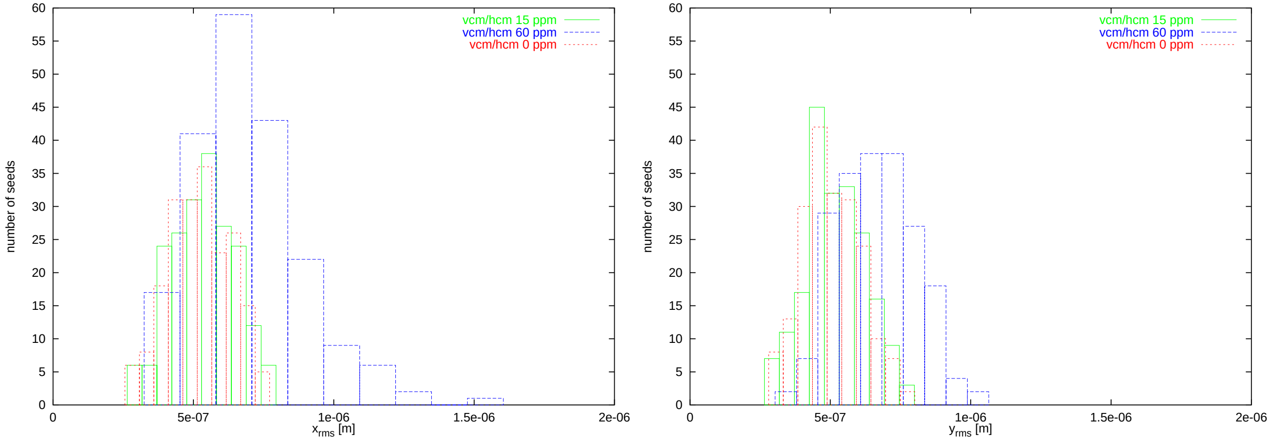


- 1 ppm in amplitude corresponds to a resolution of 10^{-6} at a maximum Current of 7 A ($\approx$ 860 μrad in the vertical plane)
- 60 ppm: y_{rms} = 0.75μm, 30 ppm: y_{rms} = 0.5μm, 15 ppm: y_{rms} = 0.25μm

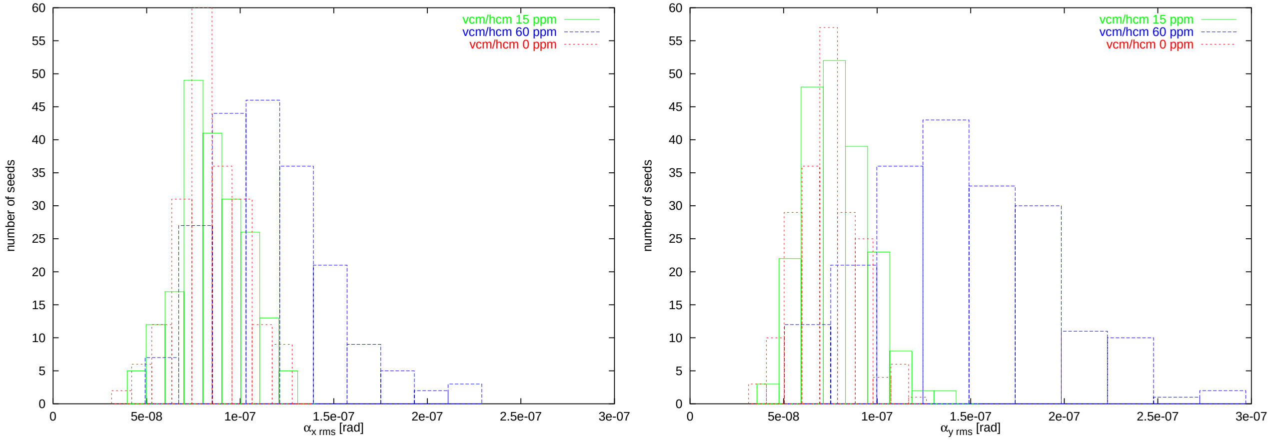
$\longrightarrow$ 15 ppm ($\approx$ 10 nrad or 100 μA) sufficient

T&S - Power Supply Resolution and RMS Position/Angle @ IDs

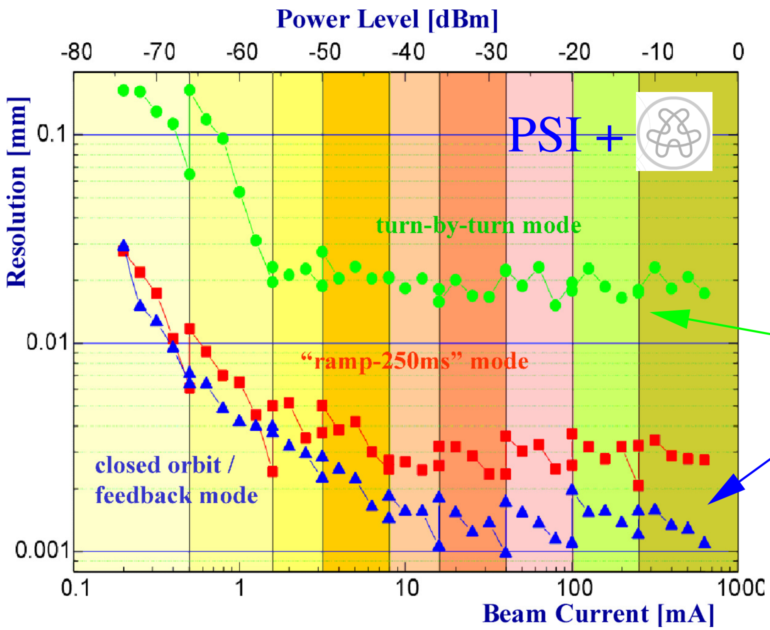
RMS Position @ Insertion Devices with $\beta_x \approx 1.4$m,$\beta_y \approx 0.9$m (x/y_{rms}= 0.5μm for 15 ppm):



RMS Angle at the Insertion Devices ($\alpha_{x/yrms}$= 0.08μrad for 15 ppm):



FOFB - Digital BPM System

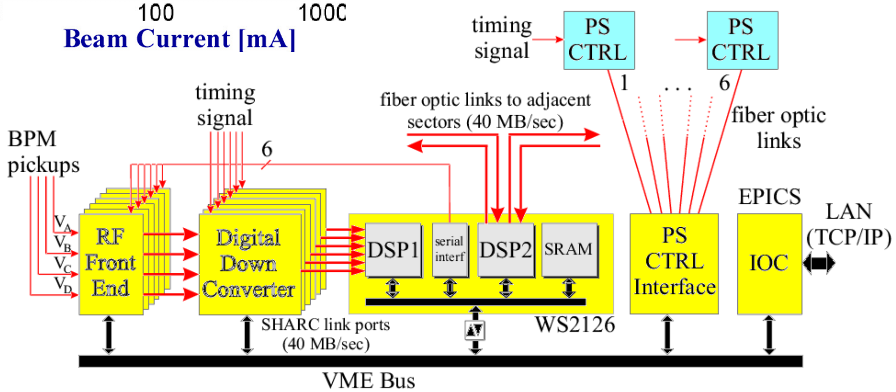


Only One BPM System in Different Operation Mode for All Machines

Turn–by–Turn:
1 MSample/s, <20 μ m

Closed Orbit:
4 KSample/s, <1.2 μ m

Turn–by–Turn:
Vital for Commissioning

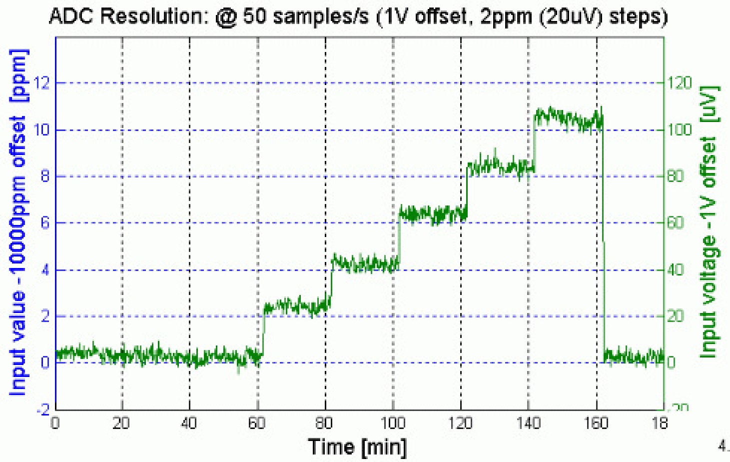


Closed Orbit Mode –> Fast Orbit Feedback

FOFB - Digital Power Supplies

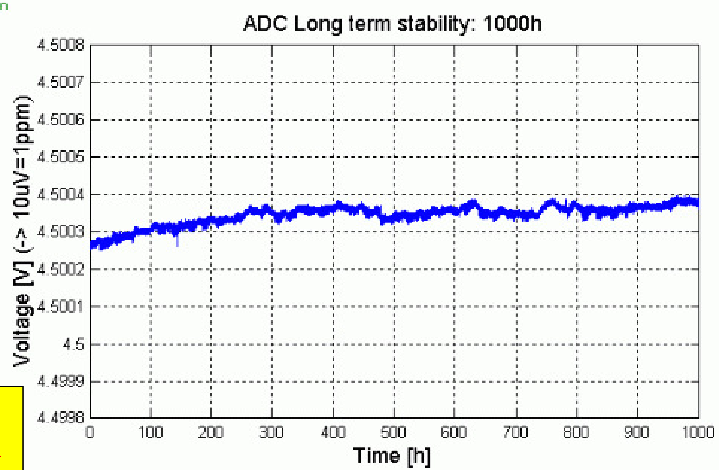
One Digital Control Unit for ~600 power supplies of the SLS

Precision of the AD converter card



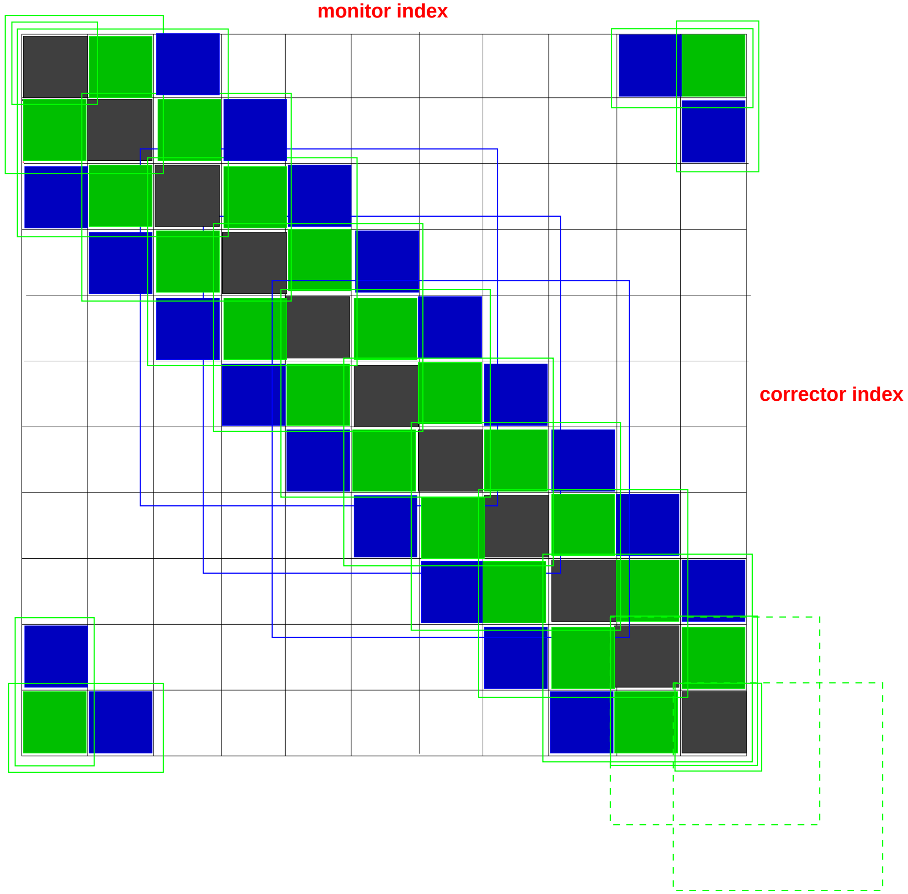
- Long- term stability (1000h) better than 30ppm
- Reproducibility better than 30ppm

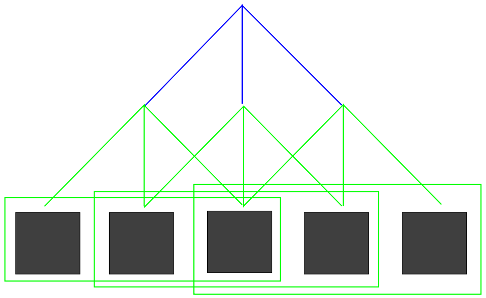
- Resolution up to **1ppm**
- Short- term stability (<60s) better than 10ppm

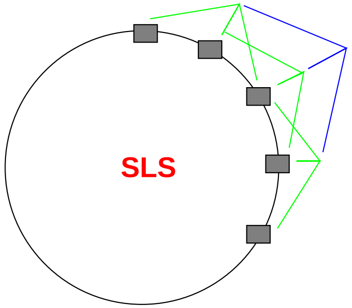


Short/Long–term: <10/30 ppm

FOFB - Inverse Response Matrix

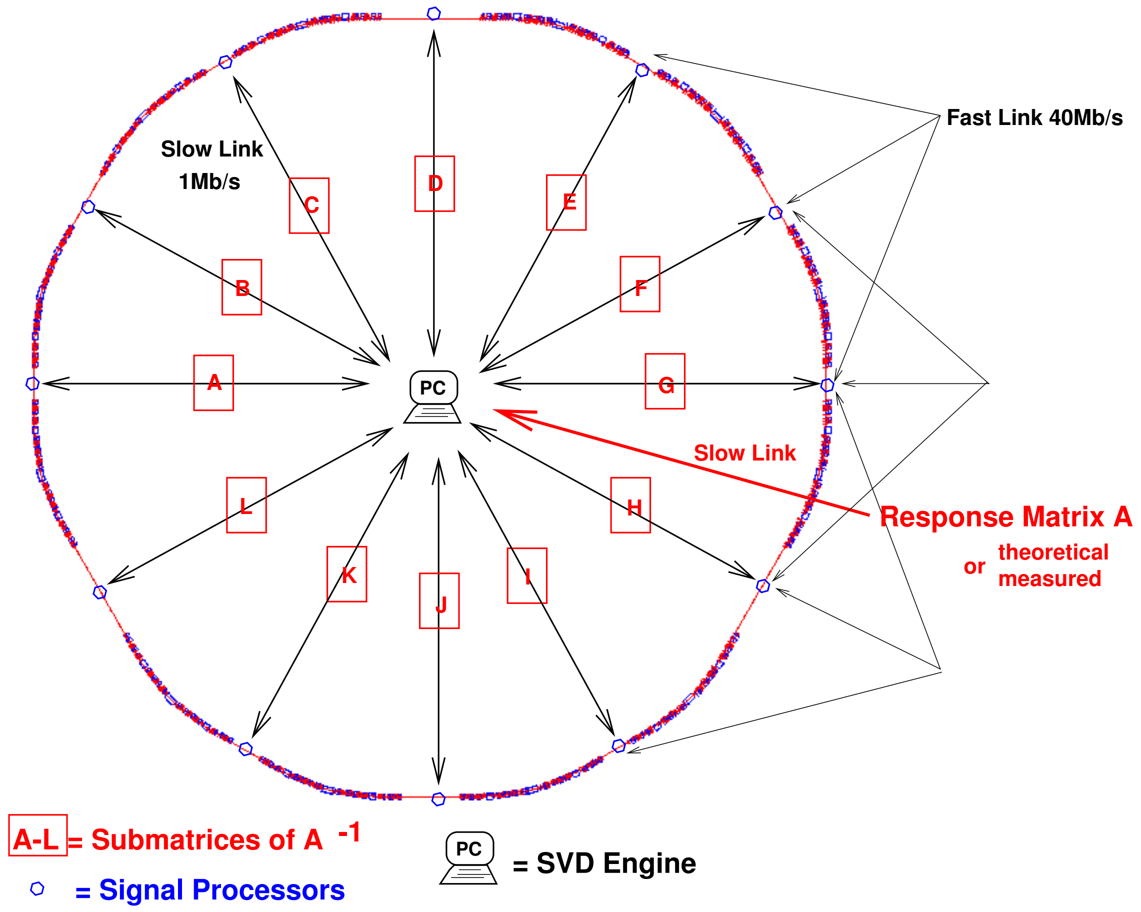






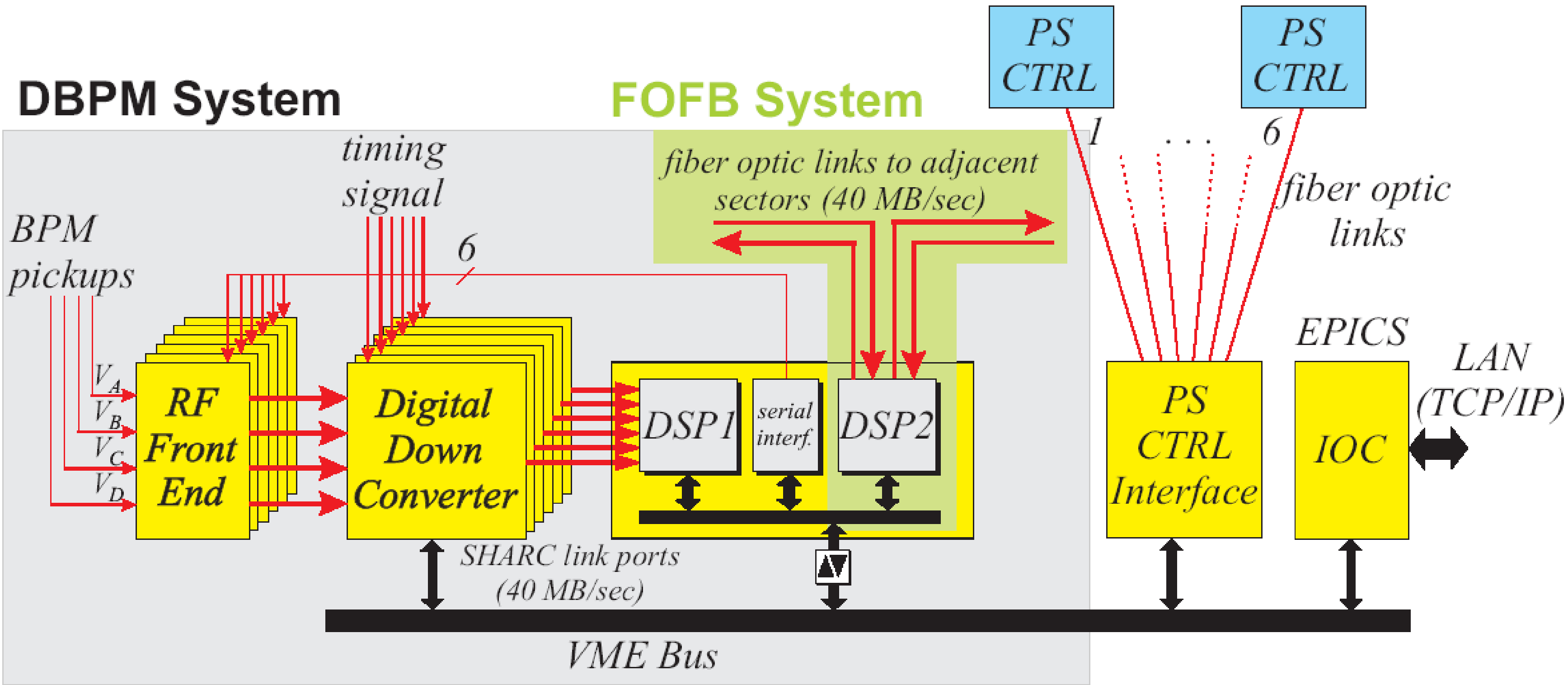
- 12 sectors
- 6 BPMs and 6 Horizontal/Vertical Correctors per sector

FOFB - Schematic View

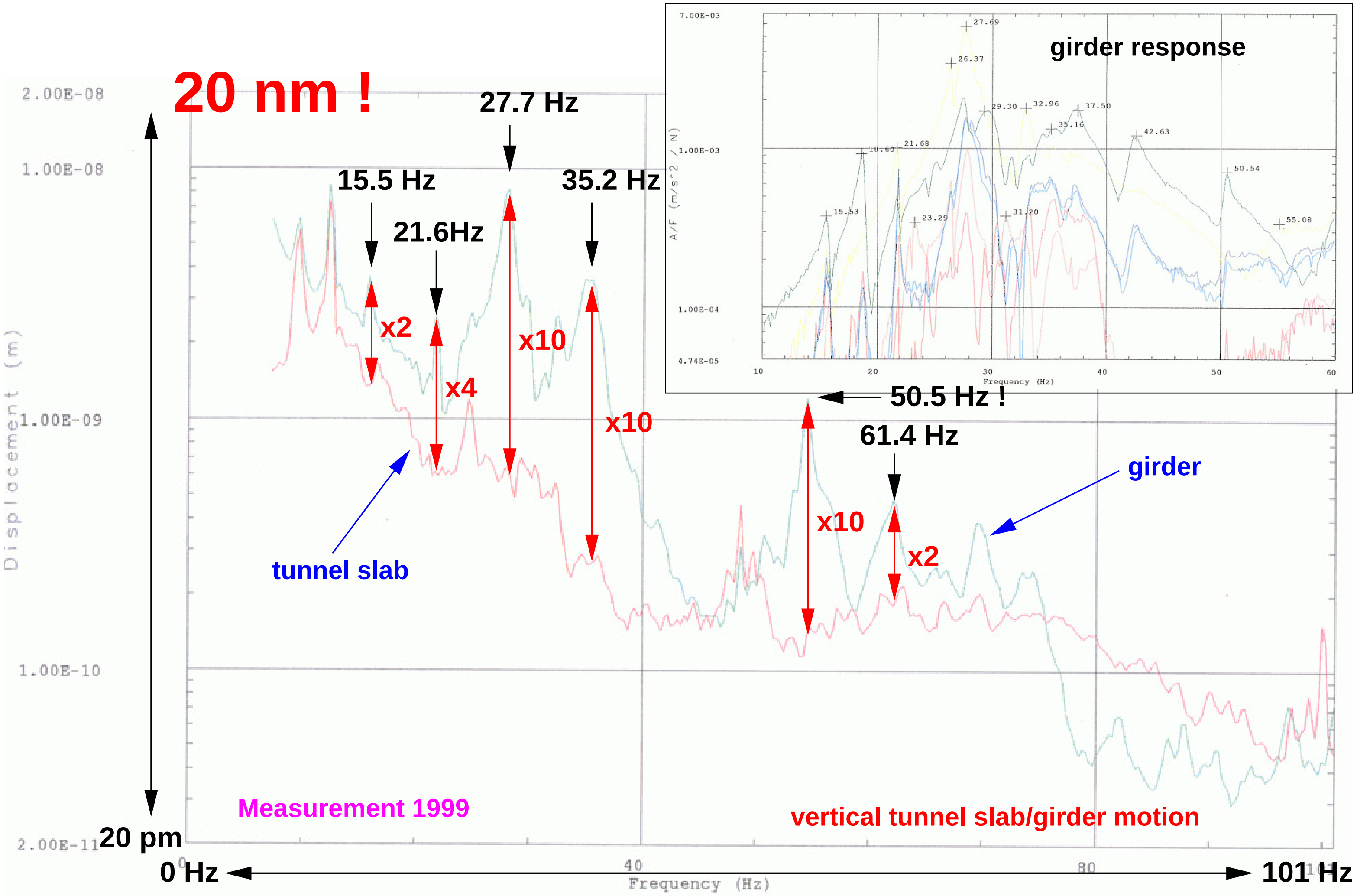


- Dedicated Signal Processors perform Matrix Multiplications in parallel !

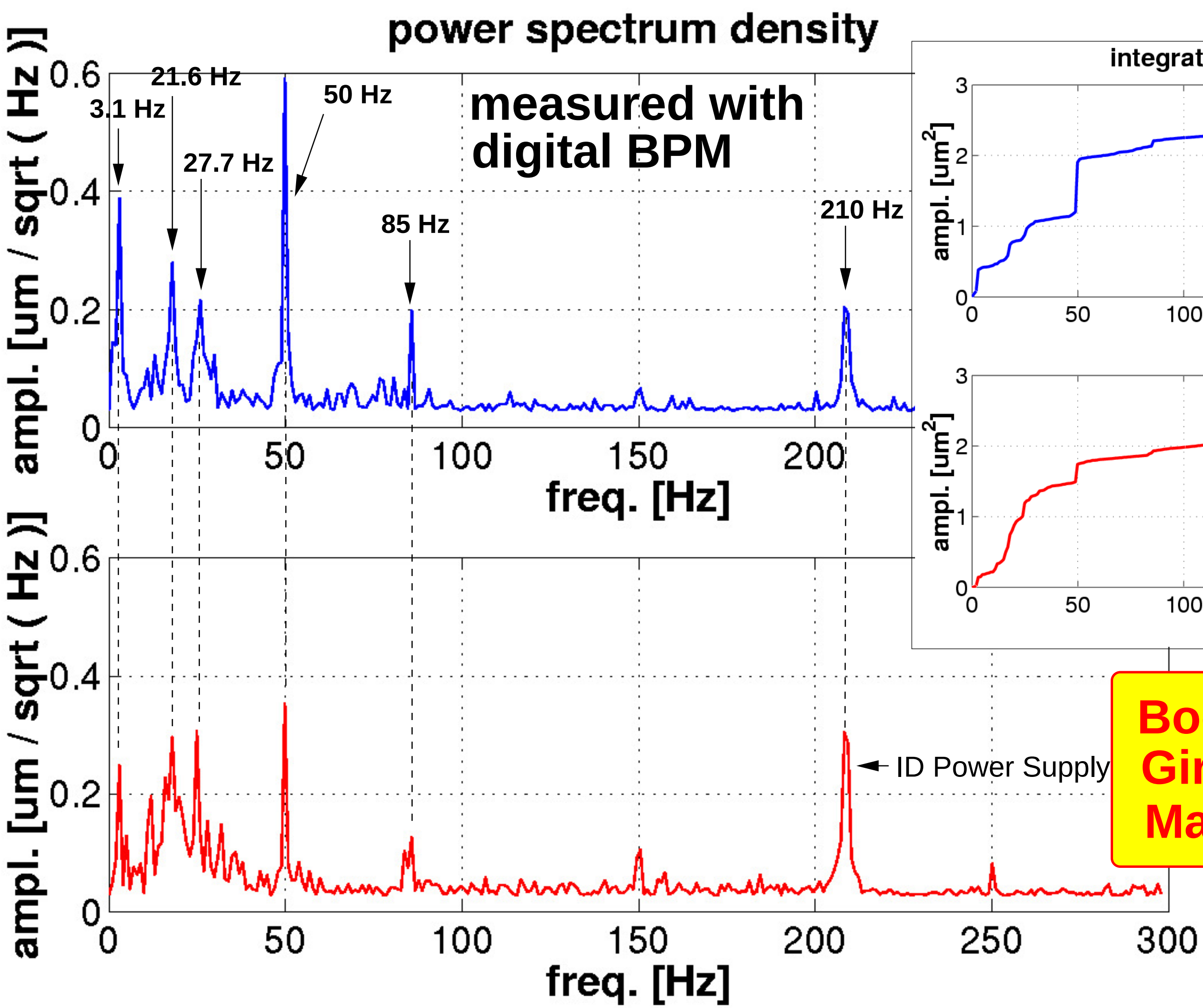
FOFB - Hardware Layout

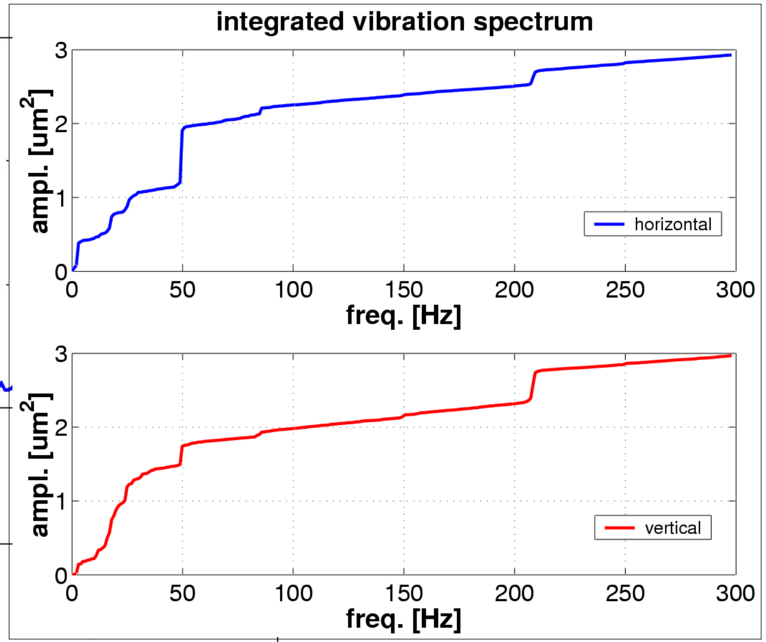


SOFB - Stability - Girder Response



SOFB - Stability - Power Spectral Densities



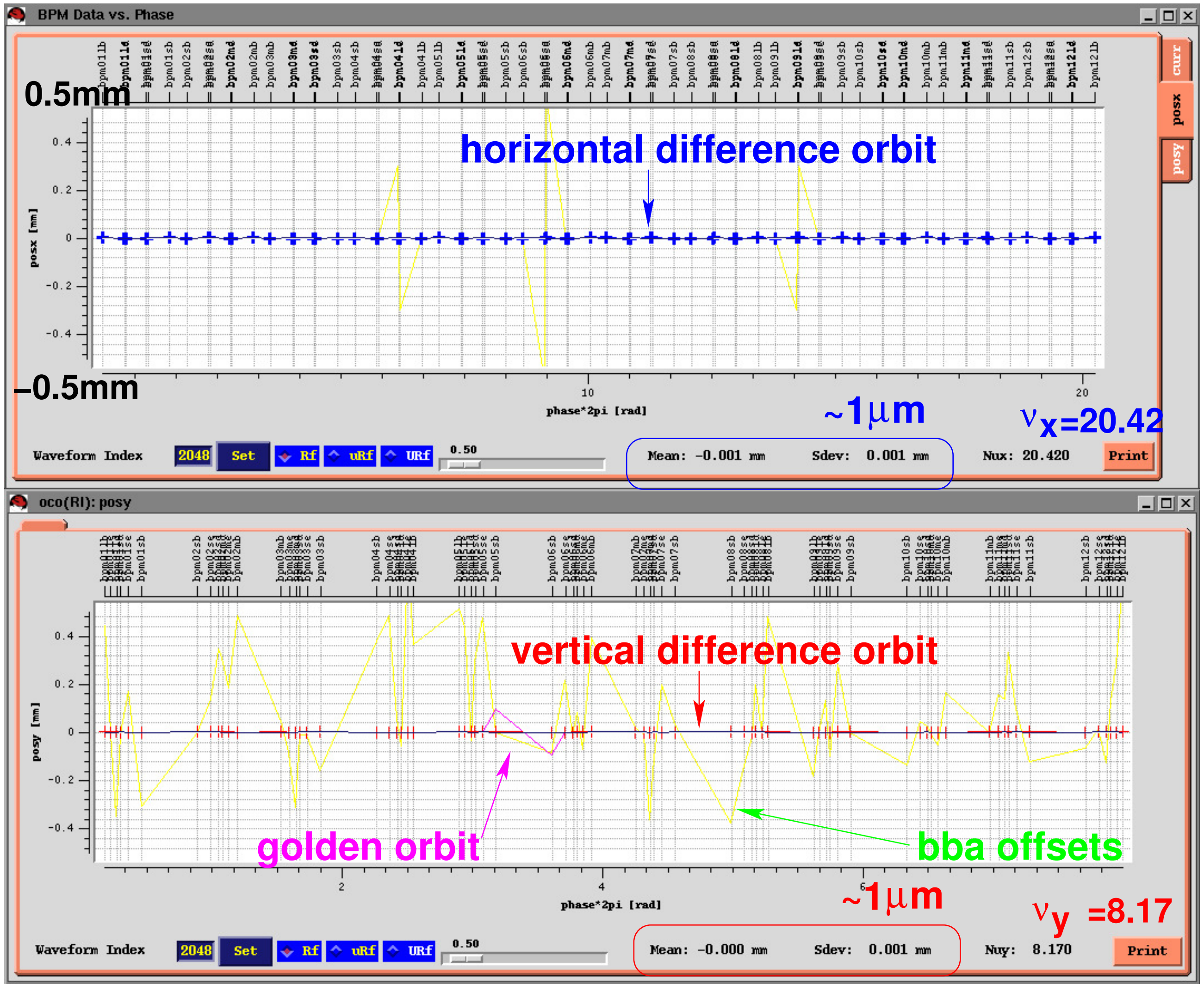


Booster: 3.1 Hz
Girders: 21.6, 27.7Hz
Mains: 50 Hz

β_x=11m<β_x>=10m

β_y=18m<β_y>=11m

SOFB - Golden Orbit

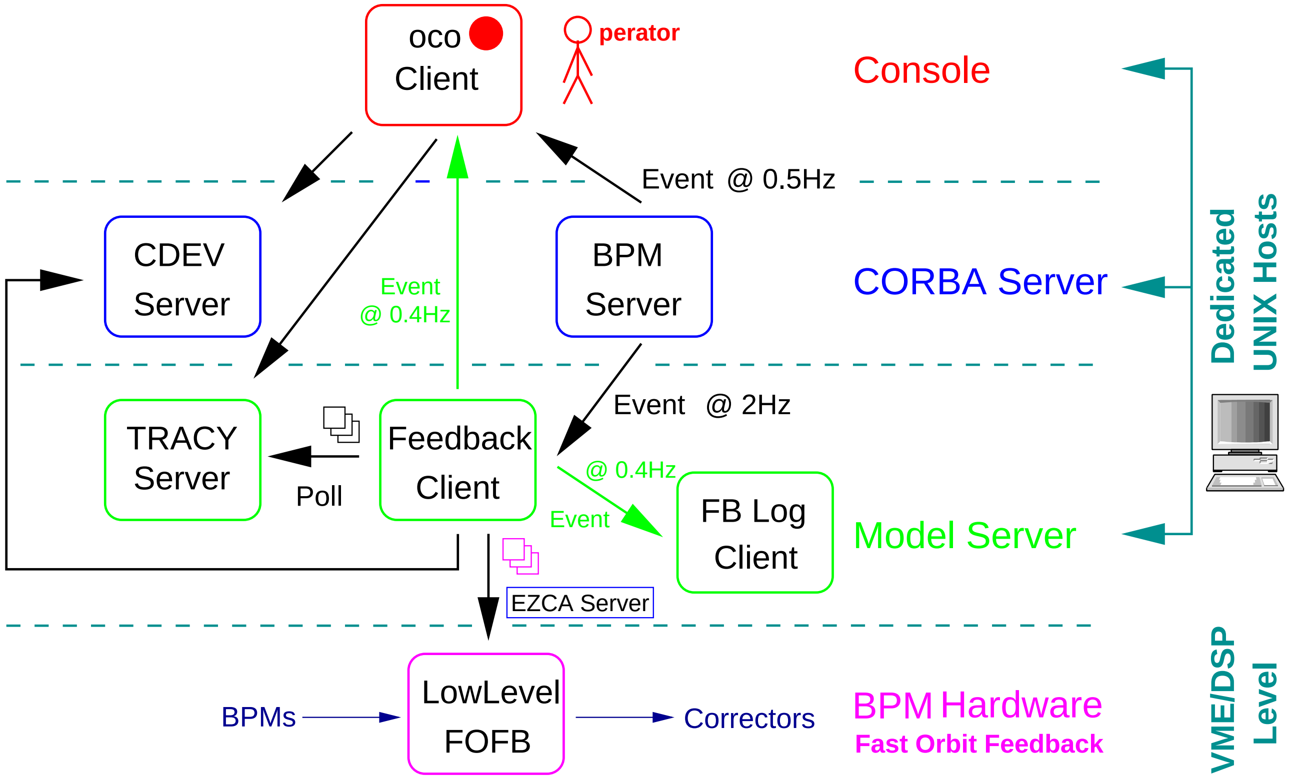


72 BPMs
72 corrs
/plane

0.5 Hz (3 Hz) refreshrate

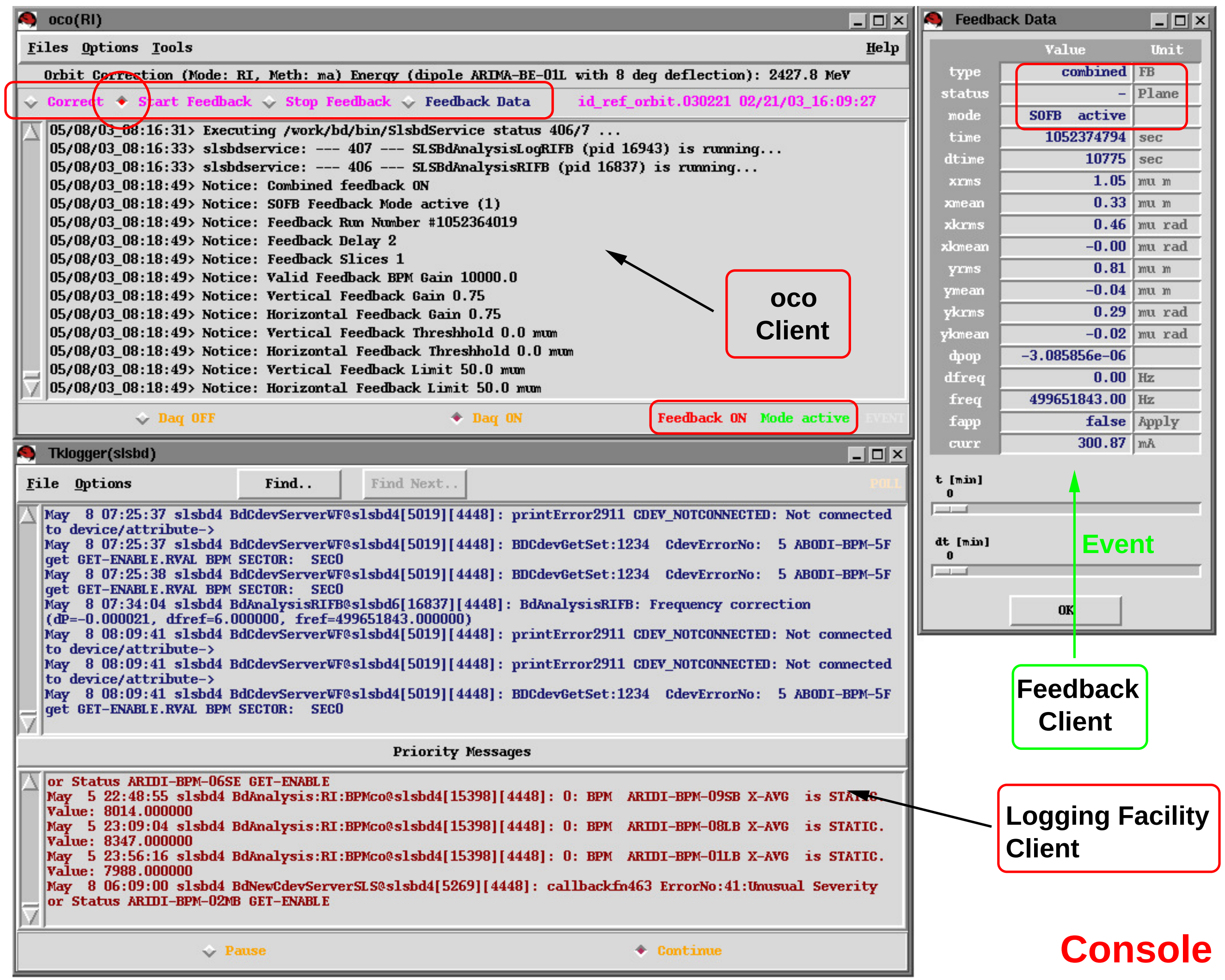
~0.3µm precision of BPMs

SOFB - Schematic View

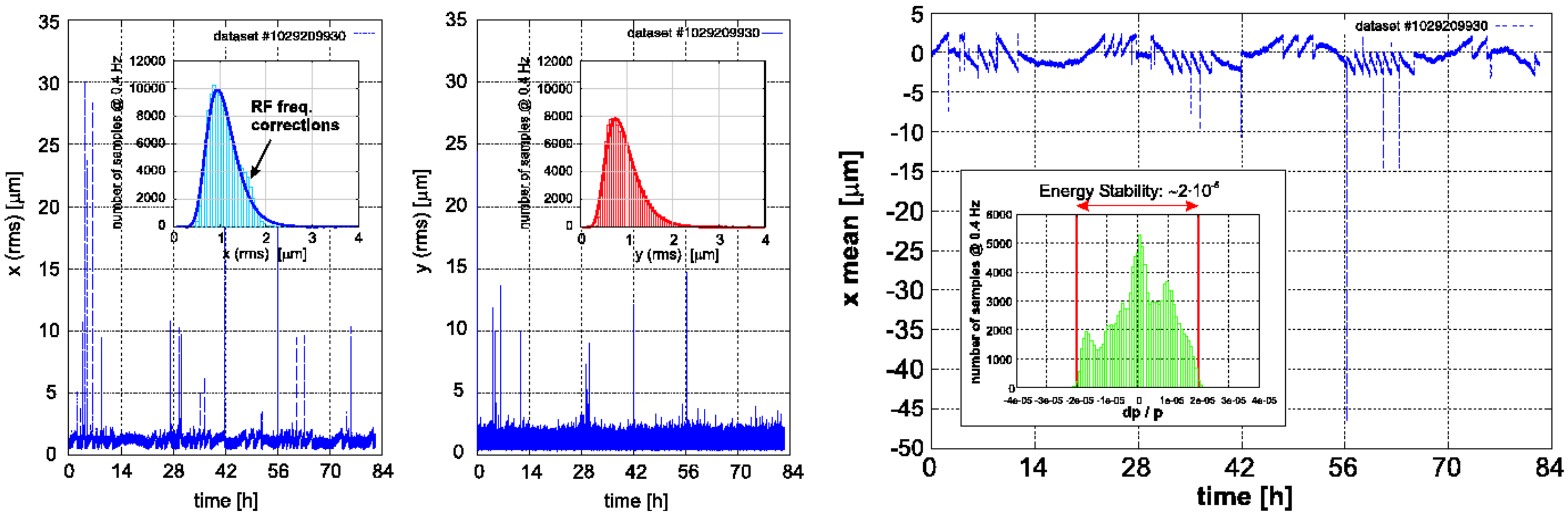


- Development within a Client-Server (Common Object Request Broker CORBA) environment
- Hard Correction ("Matrix Inversion" on the Model based Response Matrix using SVD)
- BPM Datasets @ 2 Hz, average over 3 successive Datasets => ≈ 0.4 Hz correction rate (toggle between x/y plane => 5 s for full cycle)

SOFB - oco Client



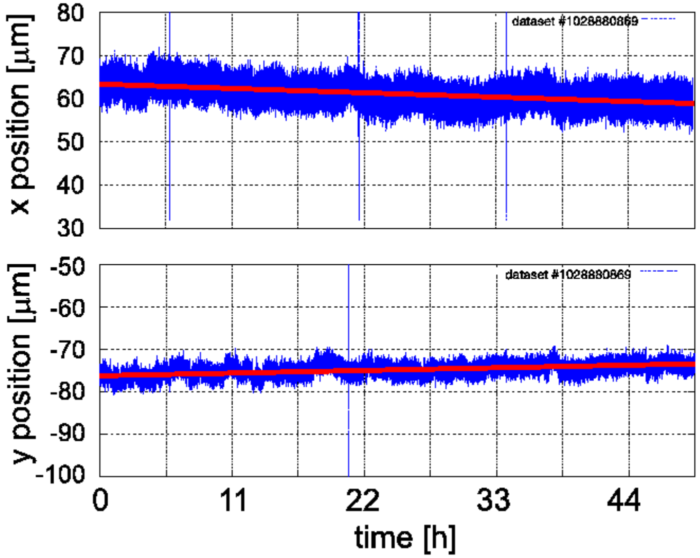
SOFB - RMS/Mean Orbit, Path Length

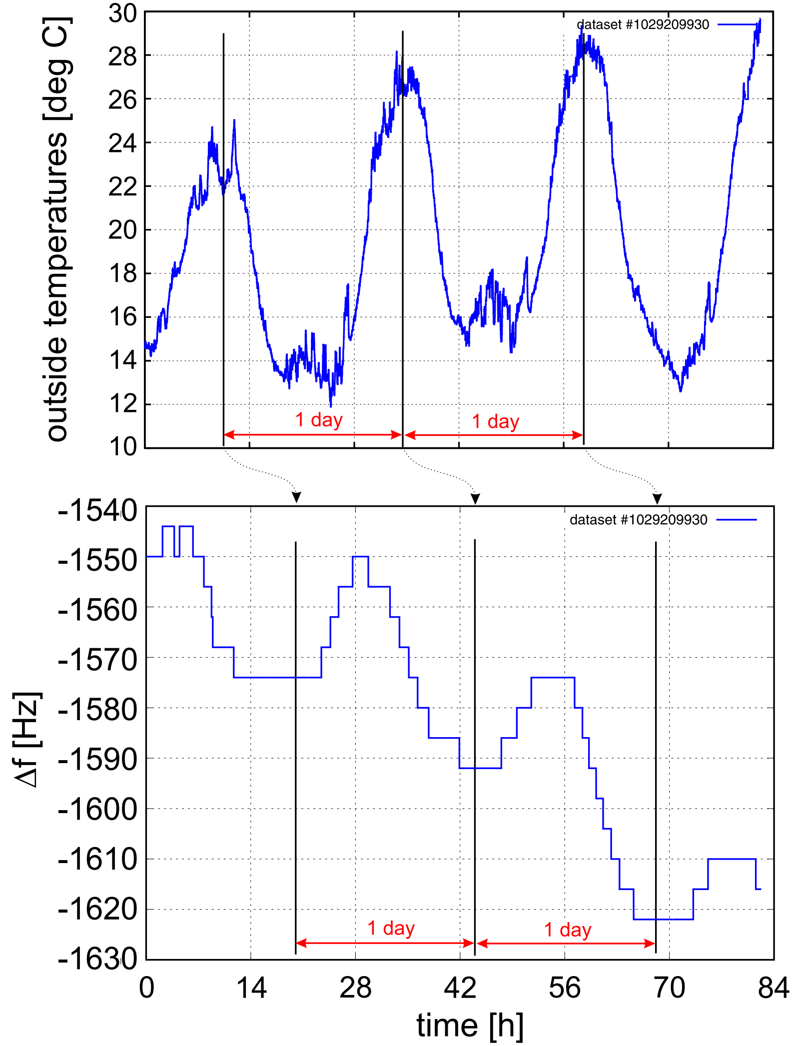


- Sample run Aug, 13-16 2002: x_{rms}, $y_{rms} \approx\ 1\ \mu m$ (see histograms)
- Off energy dp/p orbits fitted through SVD and subtracted before correction
- RF frequency changed by df whenever |df| exceeds 5 Hz (dp/p $\approx 2 \cdot 10^{-5}$) –> correction every $\approx$ 45 min (see "saw tooth")

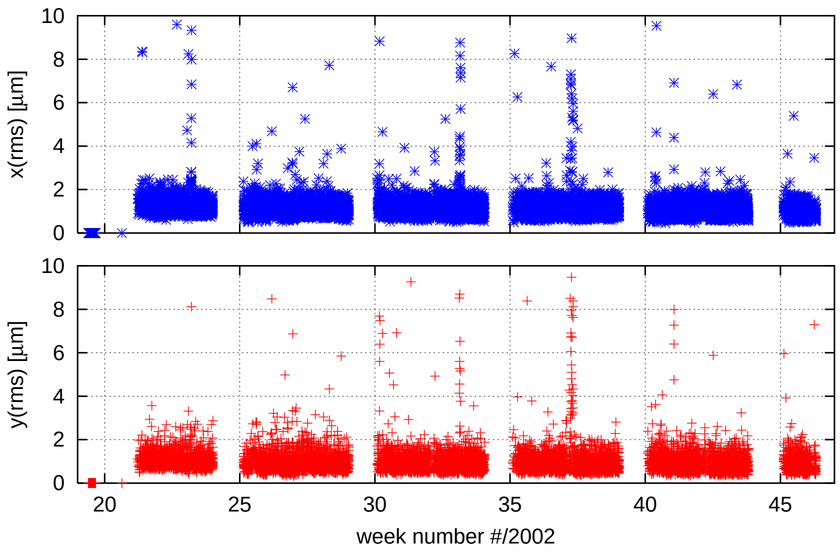
SOFB - RF changes vs. T, X-BPM Readings

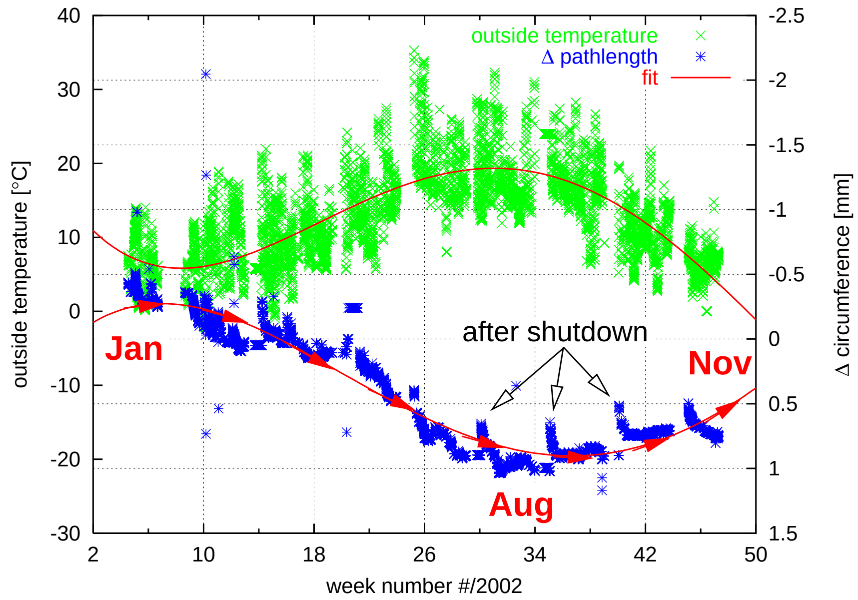
- Outside air temperature and RF frequency changes –>
- X-BPM @ **PX**
  $\approx$ 8.6 m from ID **U24**:
  σ_x = 2.7 μm (drift: 2.3 μm)
  σ_y = 1.5 μm (drift: 1.7 μm)
  $\sigma_{x'} < 0.31$ μrad @ source point !
  $\sigma_{y'} < 0.18$ μrad @ source point !





SOFB - Long Term Stability - BPMS

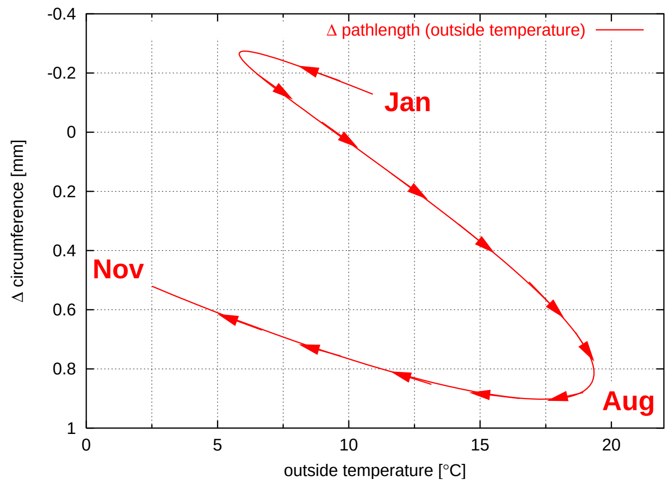




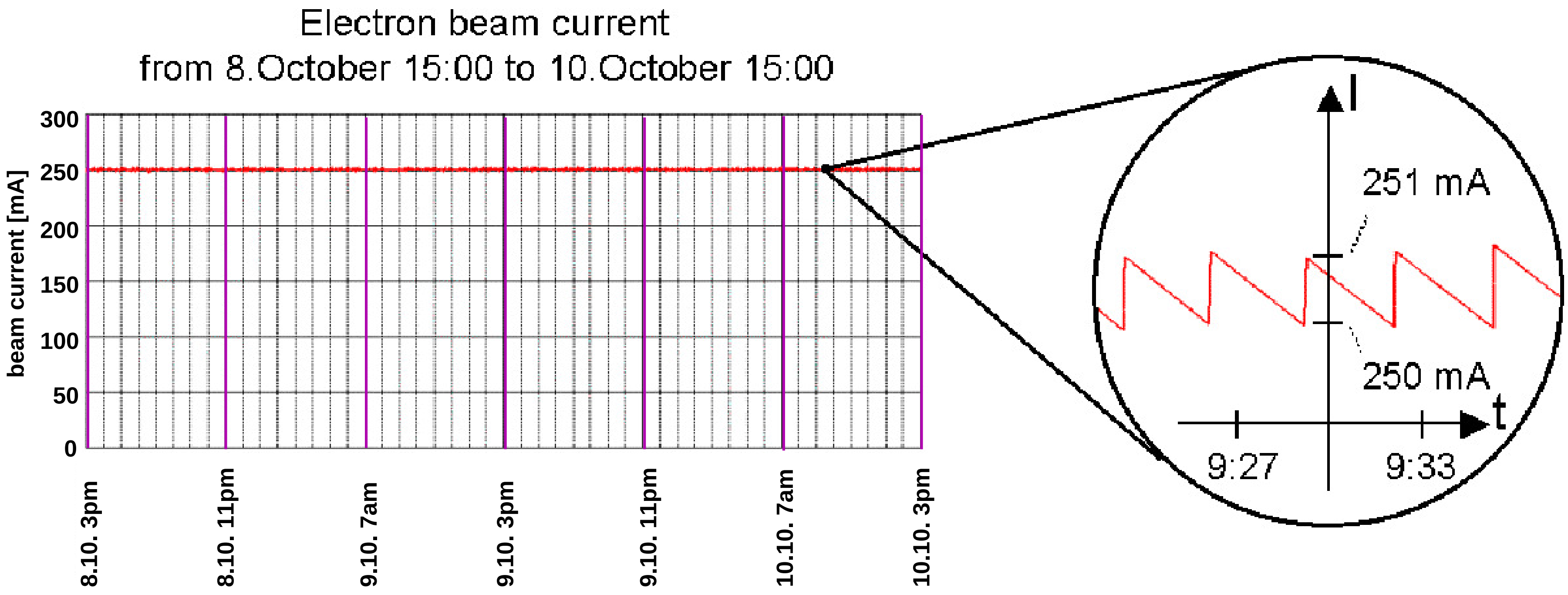
- x_{rms} and y_{rms} over 28 weeks ↑
- Outside air temperature and Δ circumference in 2002 →
- Δ circumference vs. outside air temperature in 2002 →

  Δ circumference ≈ 1.2 mm !

  Δ RF frequency ≈ 2000 Hz !

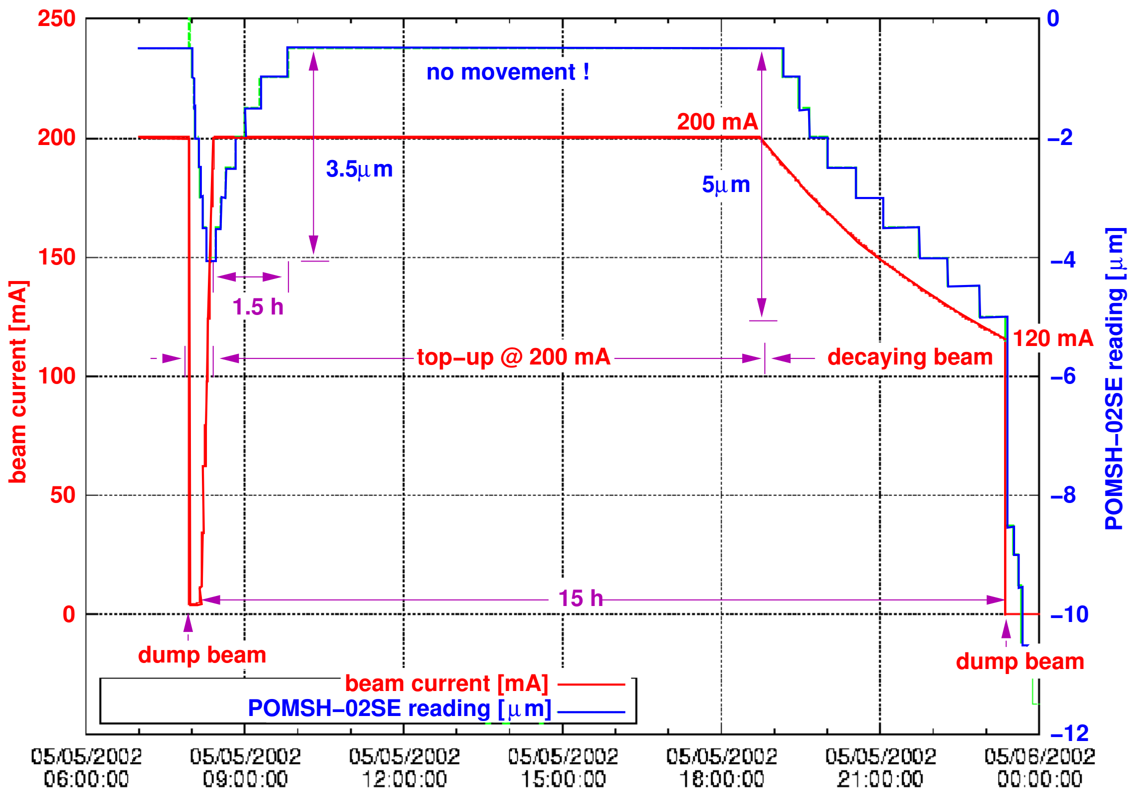


SOFB - Stability - Top-up



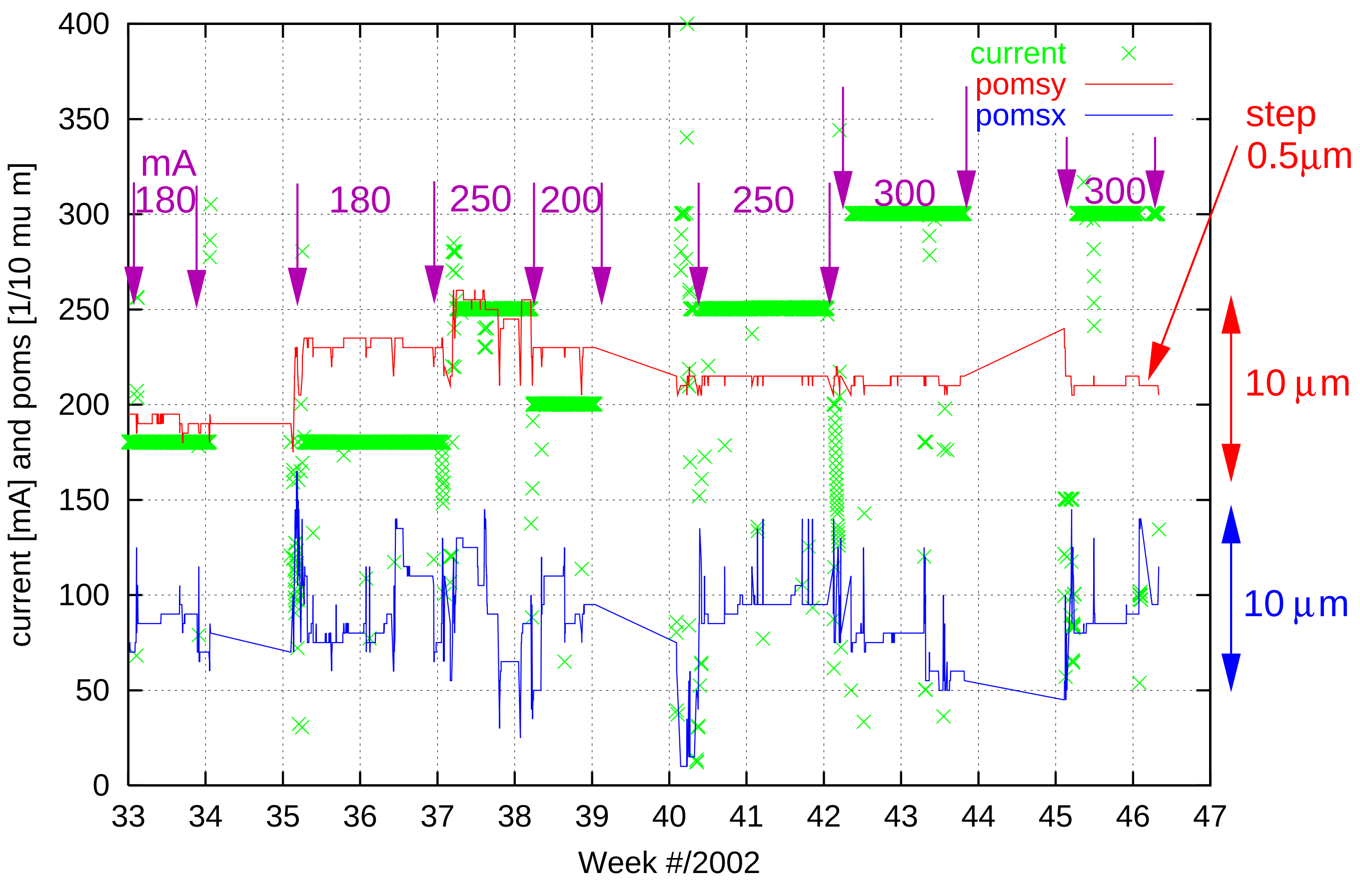
- 2 days run @ 250 mA with a deadband of 1 mA in October
- τ=12 h @ I=250 mA (I$\times\tau$=3 Ah)
- time between injections dt=3 min (≈960 injections in 48 h)
- **SR in thermal equilibrium !**

SOFB - Stability - POMS



- Top-up: Current is stabilized @ 200 mA (τ=12 h) with a deadband of 0.5 mA (injection every $\approx$ 2 min)
- **PO**sition **M**onitoring **S**ystem: linear encoders on all BPM stations measuring BPM/adjacent Quadrupole offsets (0.5 μm resolution) **–> no movement during Top-up !**

SOFB - Long Term Stability - POMS



- POMS Readings for ARIDI-BPM-05SB upstream of **U24**

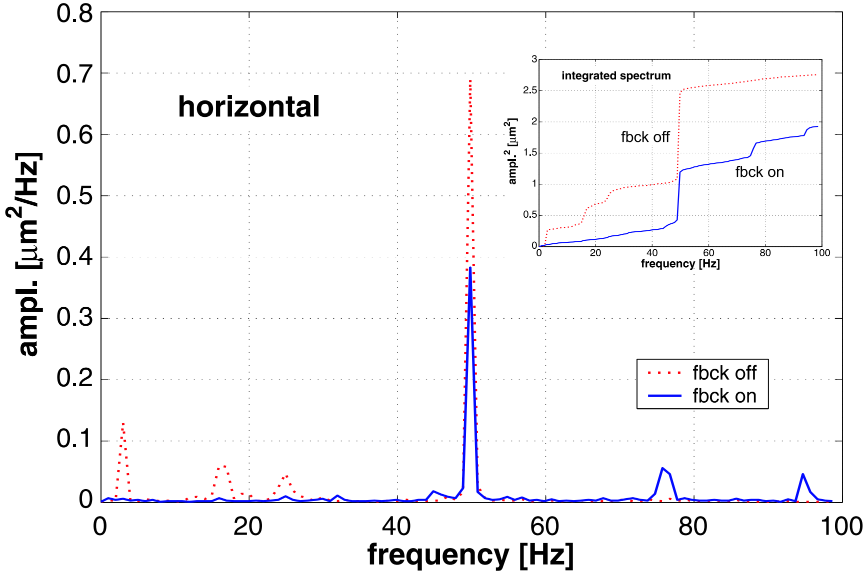
FOFB - From Manual Correction to FOFB

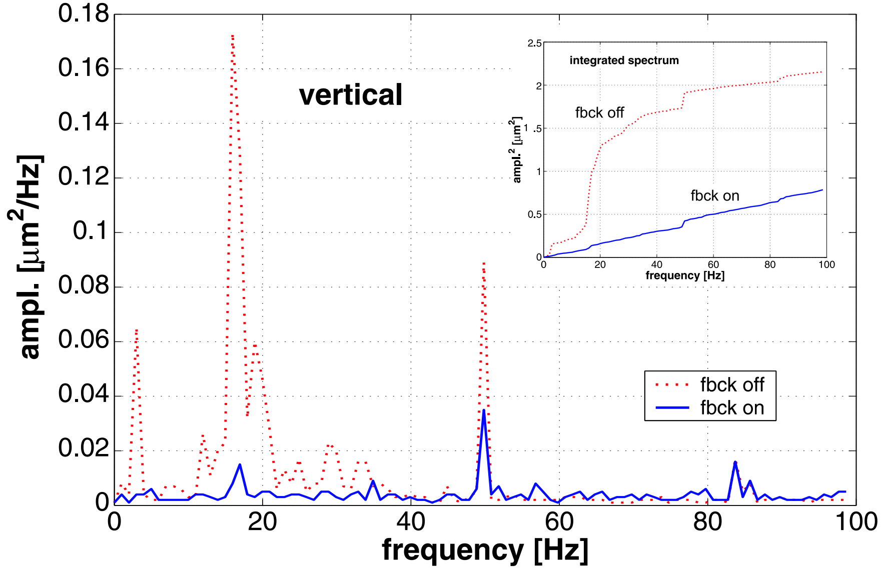
Stepwise Implementation of the Orbit Feedback:

1. Manual Orbit Correction, 0.5 Hz – **Operator** corrects Orbit using **oco Client**
2. Slow Orbit Feedback (**SOFB**), 2 Hz – **Operator** is replaced by **Feedback Client**
3. Fast Orbit Feedback (**FOFB**), 4 KHz – **Feedback Client**:
   - Corrects Orbit to $< 5\ \mu$m with respect to “Golden Orbit” using **SOFB**
   - Initializes **FOFB** (“Golden Orbit”, “Inverted” Response Matrices)
   - Starts/Stops **FOFB**
   - Runs in “Watchdog” like passive Mode supervising **FOFB**
   - Monitors BPM, Corrector Values (Faults, Saturation), Restarts FOFB with adapted settings

FOFB - Power Spectral Densities

- Snapshots of the horizontal and vertical power spectral densities measured with the digital BPM system at the location of the tune BPM ($\beta_x \simeq 11$ m, $\beta_y \simeq 18$ m):

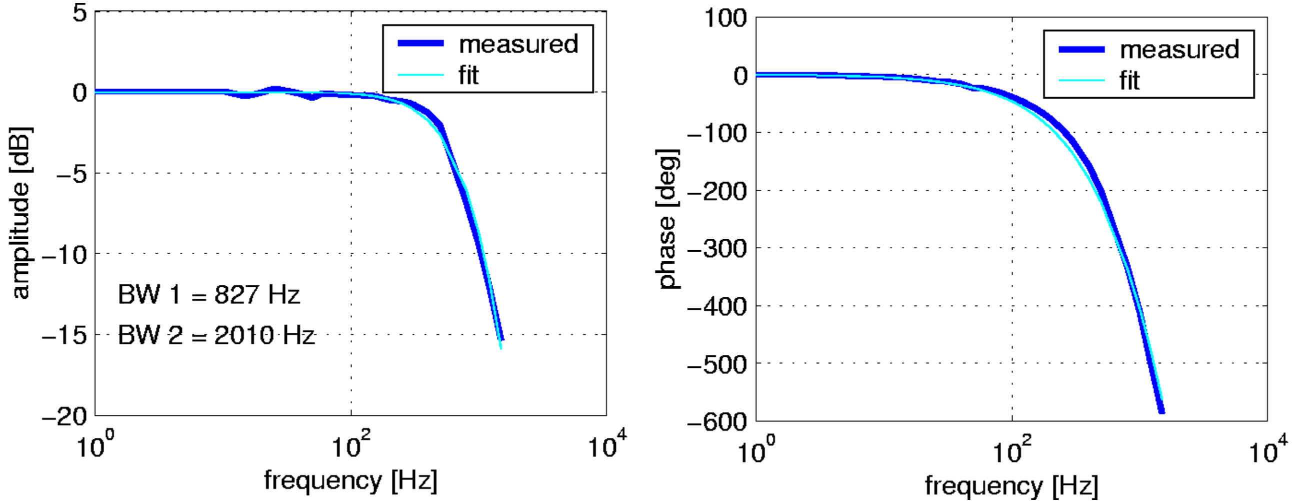




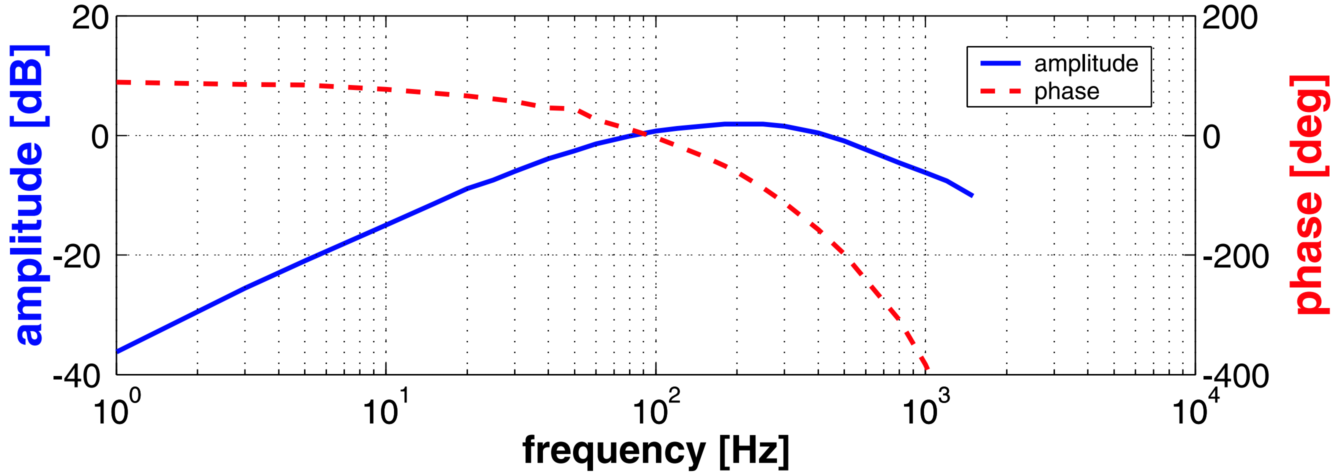
	horizontal		vertical	
FOFB	off	on	off	on
0.5-100 Hz	1.7 μm	1.4 μm	1.5 μm	0.9 μm
100-400 Hz	0.95 μm	1.1 μm	0.95 μm	1.2 μm

FOFB - Vertical Transfer Functions

Openloop Transfer Functions + Low Pass Filter Fit + Time Delay Fit

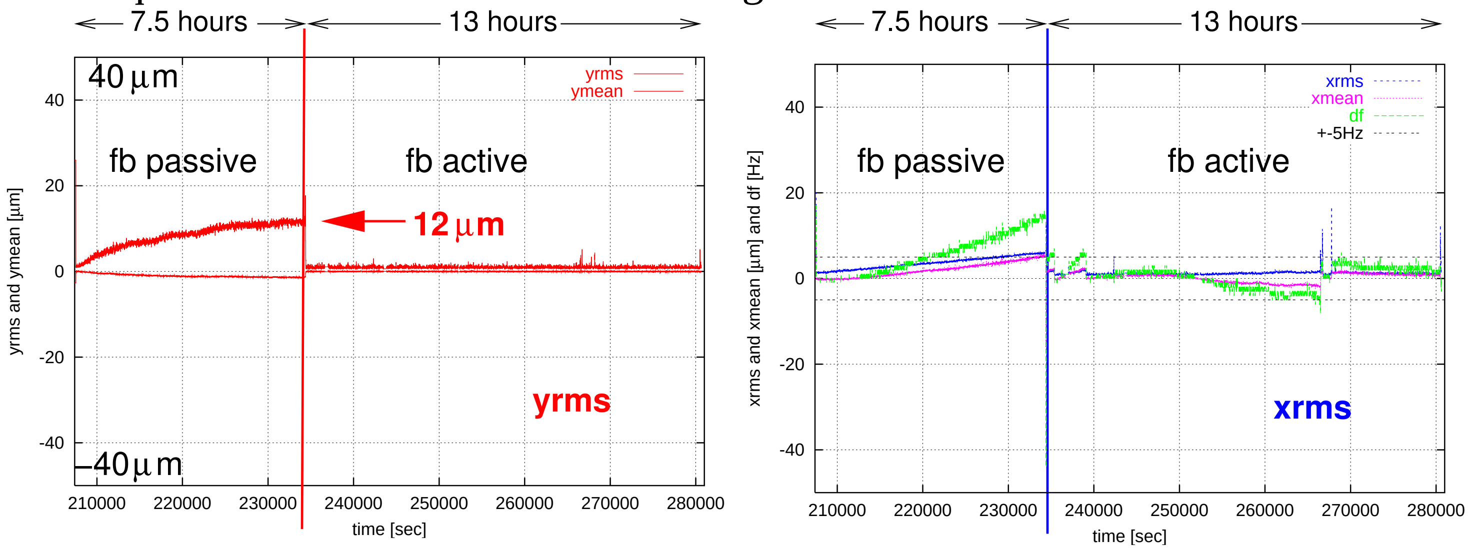


Closed Loop Transfer Function with Moderate PI Parameters



Conclusions

- For Frequencies >0.2 Hz: residual orbit noise ≈ 1 μm level
- For Frequencies <0.2 Hz: SOFB for "Long Term" Drifts:



- **ID** Operation induced Distortions (≈10 μm) corrected by SOFB
- Path Length changes corrected by means of the RF Frequency
- "Golden Orbit" established by SOFB
- Top-up Operation is vital for μm level stability !
- FOFB performs according to Design and will replace SOFB