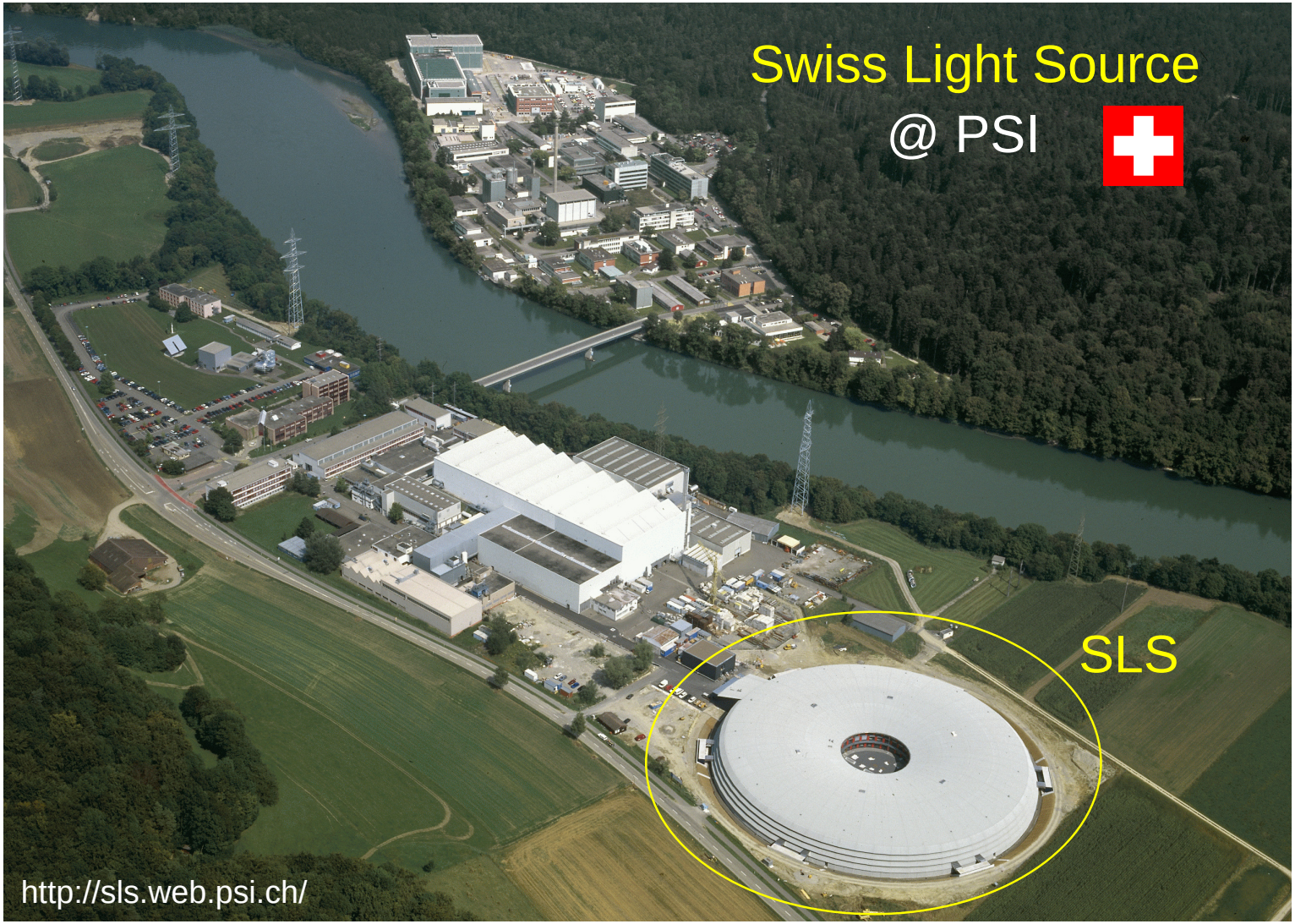
SLS at the Paul Scherrer Institute (PSI), Villigen, Switzerland



Outline

- Introduction
  - SLS Layout
  - Booster Design
  - Storage Ring (SR) Design
  - SR BPM/Corrector Layout
  - SR Lattice Errors
  - SR Lattice Calibration
- Fast Orbit Feedback (FOFB) Motivation
  - Ground Noise Measurement in 1993
  - User Requirements & Worst Case Estimate
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  - Orbit Correction Schemes
  - Response Matrices
  - Path Length Correction
  - Model for a Closed Orbit Feedback
- FOFB Subsystems
  - Digital BPM System
  - **PO**sition **M**onitoring **S**ystem
  - Digital Power Supplies (PS)
  - Hardware Layout
  - System Integration
- FOFB Operation
  - BBA & Golden Orbit
  - Transition from Slow (SOFB) →Fast Orbit Feedback
  - Closed Loop Performance
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  - Effect of Top-up Operation
  - X-BPM & Bunch Pattern Feedback
  - Long Term Stability
- FOFB Outlook
  - Limitations & Upgrades

Introduction - SLS Layout

- Pre-Injector Linac
  - 100 MeV
- Booster Synchrotron
  - 100 MeV – 2.4 (.7) GeV @ 3 Hz
  - ϵ_x = 9 nm rad
- Storage Ring
  - 2.4 (.7) GeV, 400 mA
  - ϵ_x = 5.1(7.3) nm rad (FEMTO)
- Ten Beamlines:

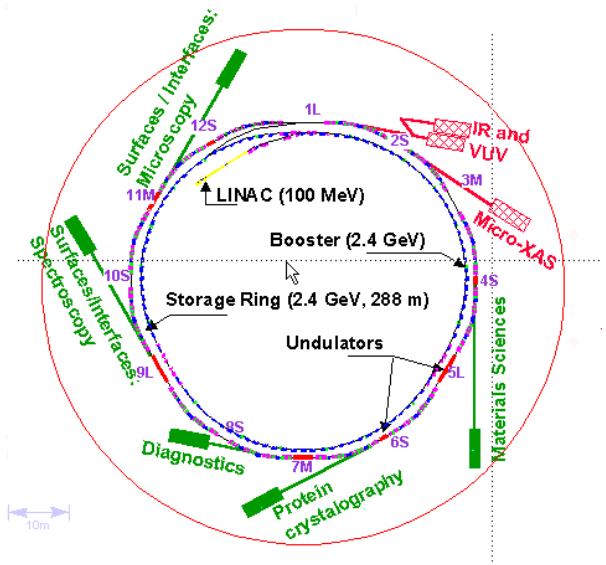
  MS – 4S, μXAS / FEMTO – 5L,

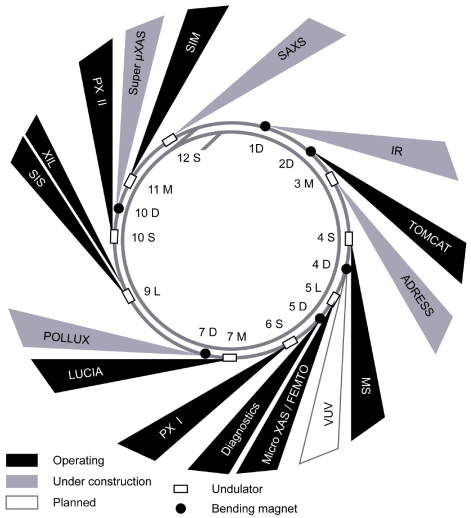
  DIAG – 5D, PX – 6S,

  LUCIA – 7M, SIS – 9L,

  PXII – 10S, SIM – 11M,

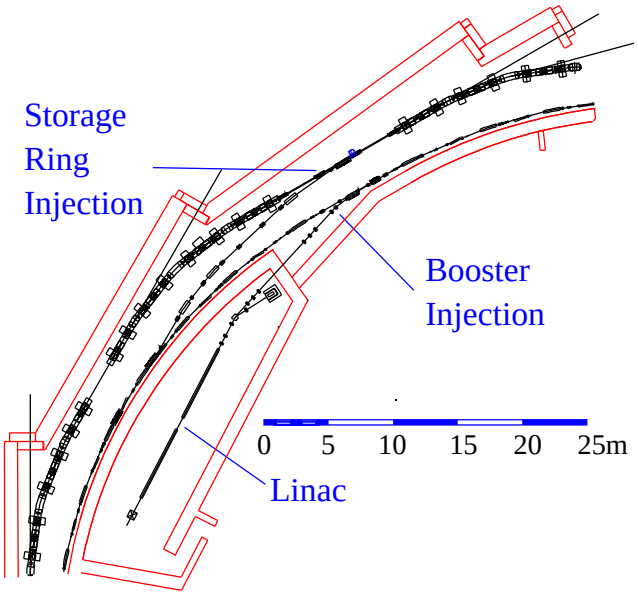
  TOMCAT – 2DA, POLLUX — 7DA





Introduction - Booster Design

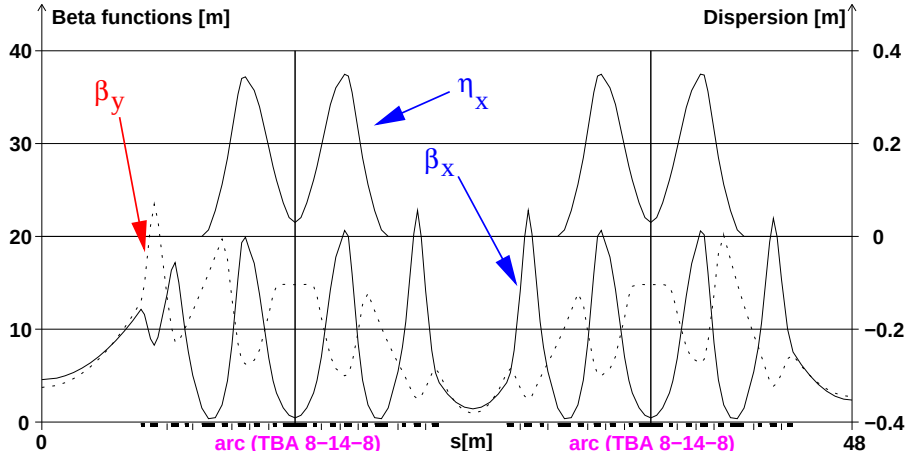
– 3 FODO arcs with 48 BD (+SD) 6.4410 °and 45 BF (+SF) 1.1296 °
– 3 × 6 Quadrupoles for Tuning, 54 BPMs, 2 × 54 Correctors
– ± 15 mm × ± 10 mm Vacuum Chamber
– Energy: 100 MeV → 2.7 GeV, Repetition Rate: 3 Hz, Circumference: 270 m
– Magnet Power: 205 kW, ϵ_x @ 2.4 GeV: 9 nm rad



Maximum Energy	GeV	2.7
Circumference	m	270
Lattice		FODO with 3 straights of 8.68 m
Harmonic number		(15x30=) 450
RF frequency	MHz	500
Peak RF voltage	MV	0.5
Maximum current	mA	12
Maximum rep. Rate	Hz	3
Tunes		12.39 / 8.35
Chromaticities		−1 / −1
Momentum compaction		0.005
Equilibrium values at 2.4 GeV		
Emittance	nm rad	9
Radiation loss	keV/turn	233
Energy spread, rms		0.075 %
Partition numbers (x,y, ε)		(1.7, 1, 1.3)
Damping times (x,y,ε)	ms	(11, 19, 14)

Introduction - Storage Ring (SR) Design

- 12 TBA: 8° / 14° /8 °
- 12 Straight Sections:
  - 3 × 11 m (n**L**)
    - **Injection**,2×**UE212**,**W128**,**U19**
  - 3 × 7 m (n**M**)
    - 2×**UE56**, **UE54**
  - 6 × 4 m (n**S**)
    - 2× **RF**, **W61**, 2×**U19**
- Energy: 2.4 (.7) GeV
- ϵ_x: 5.1 (7.3) nm rad (with **W128**)
- Current: 350 mA (400 mA)
- Circumference: 288 m
- Tune: 20.43 / 8.73 (FEMTO Optics)
- Natural 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 - SR Lattice Errors - Error Specifications & Dynamic Acceptance

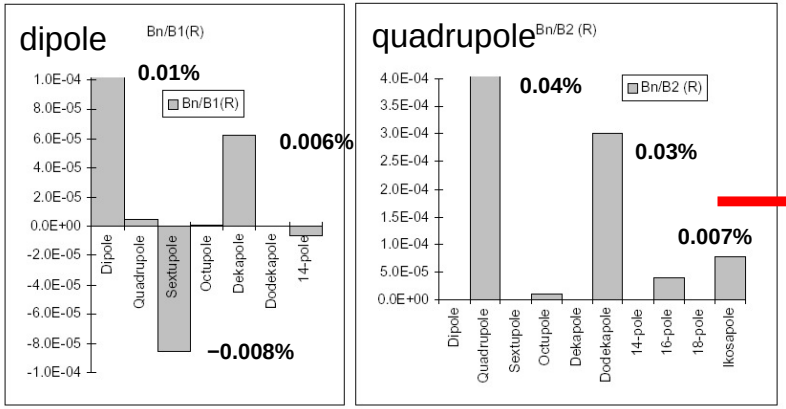
Dipole (2.4 GeV, 1.4 T)
R = 20 mm

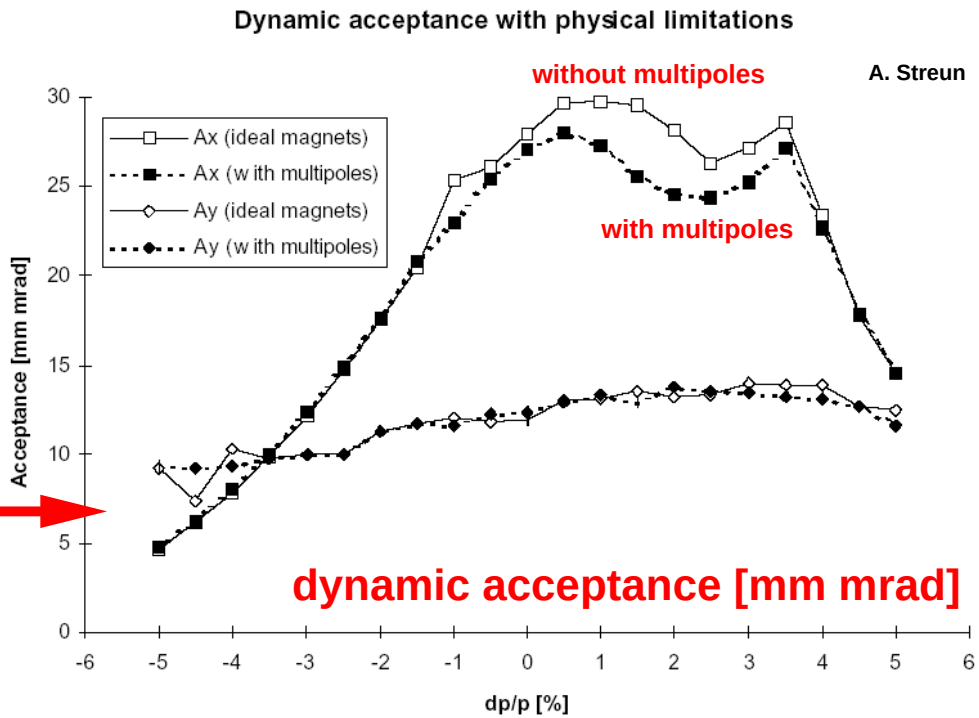
Multipole	n	B_n (R) [T]	B_n/B_1 (R)	b_n/b_1 [m^{1-n}]
Dipole	1	1.39797	1	1
Quadrupole	2	5.77E-06	4.13E-06	2.06E-04
Sextupole	3	-1.20E-04	-8.57E-05	-2.14E-01
Octupole	4	1.02E-06	7.30E-07	9.12E-02
Dekapole	5	8.64E-05	6.18E-05	3.86E+02
Dodekapole	6	0	0.00E+00	0.00E+00
14-pole	7	-8.25E-06	-5.90E-06	-9.22E+04

Quadrupole (max. gradient)
R = 30 mm

Multipole	n	B_n/B_2 (R)	b_n/b_2 [m^{2-n}]
Dipole	1	0	0
Quadrupole	2	1	1
Sextupole	3	0	0
Octupole	4	1.00E-05	1.11E-02
Dekapole	5	0	0
Dodekapole	6	3.00E-04	3.70E+02
14-pole	7	0	0
16-pole	8	4.00E-05	5.49E+04
18-pole	9	0	0
Ikosapole	10	8.00E-05	1.22E+08

multipole errors

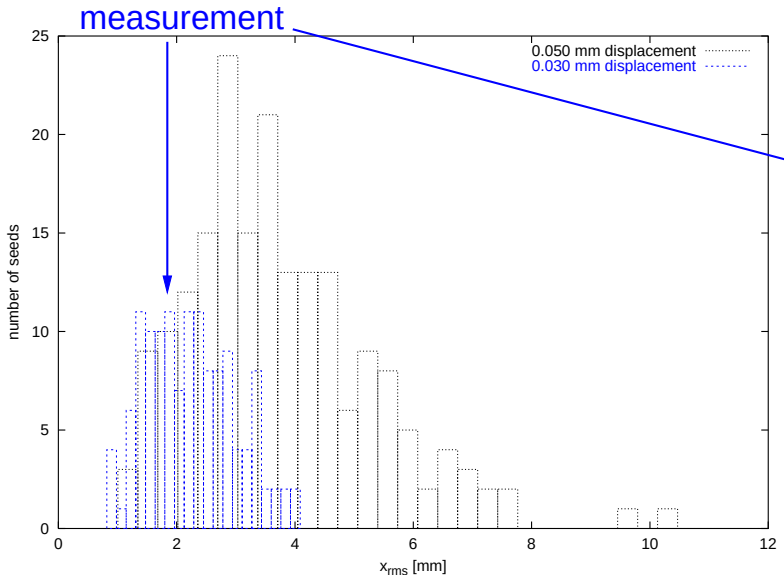


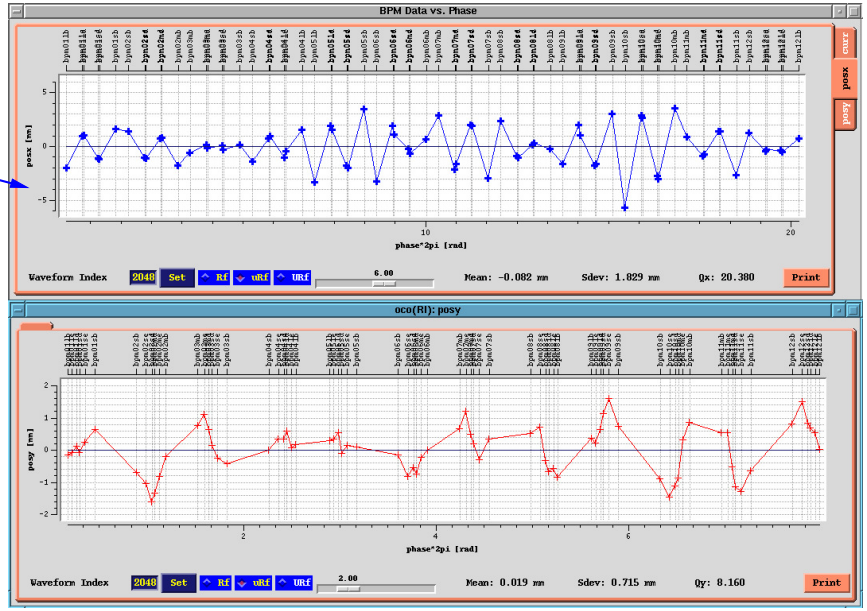


Specified alignment tolerances (RMS, Gaussian with cut @2 σ):

- Girders: **300** μm (**100** μrad), Girder joints: **100** μm (girder to girder)
- Magnets on girders: **30** μm (**25** μrad) (with respect to magnetic center)

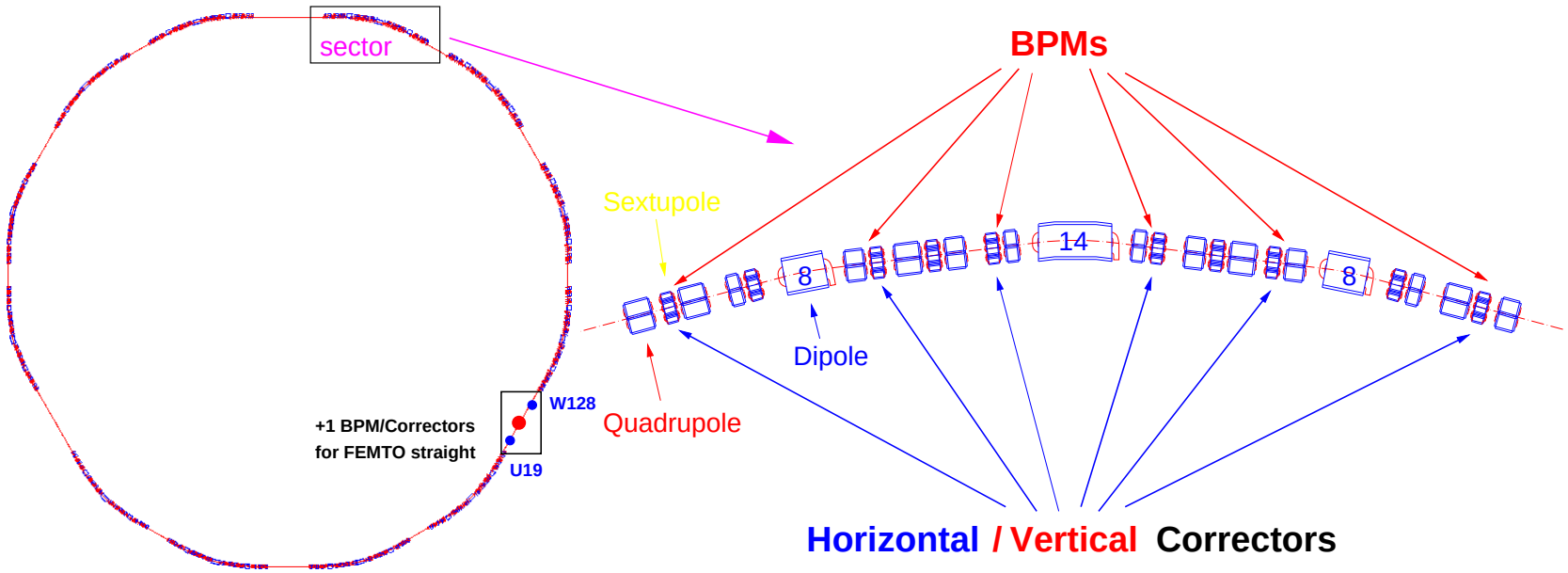
Introduction - SR Lattice Errors - “Bare Orbit”





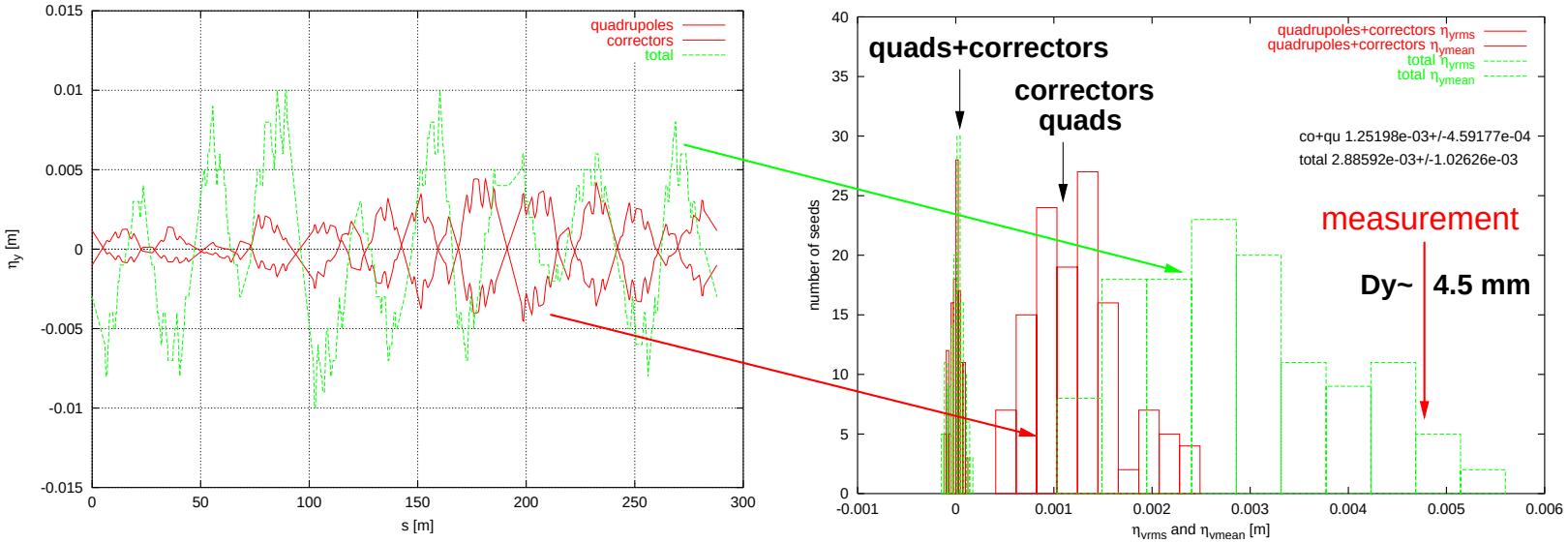
- Right/Top: Horizontal Orbit: x_{RMS}= 1.8 mm
- Right/Bottom: Vertical Orbit: y_{RMS}= 0.7 mm
- Left: Consistent with quadrupole displacements of 30 μm RMS (simulation for 200 seeds)

Introduction - SR BPM/Corrector Layout



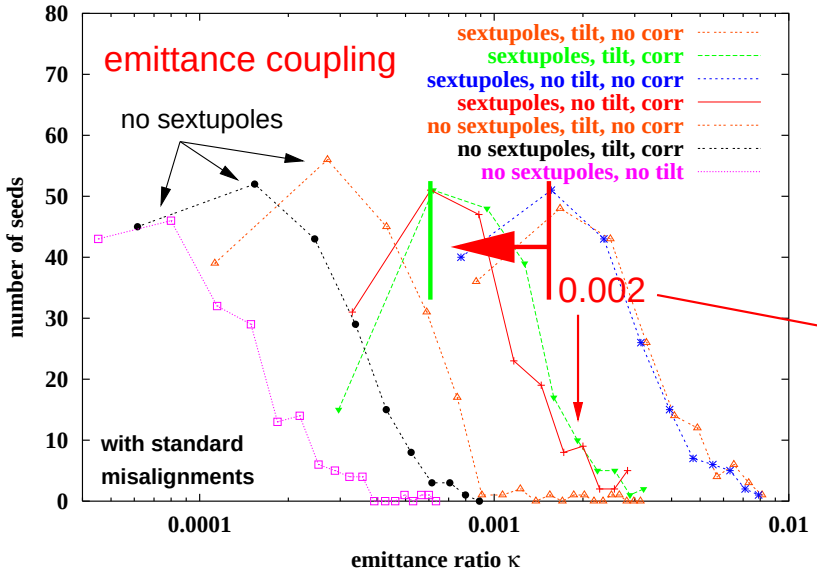
- 12 sectors
- 6 BPMs and 6 Horizontal/Vertical Correctors per sector
- Correctors in Sextupoles, BPMs adjacent to Quadrupoles
- +1 BPM/Correctors set for 5L (FEMTO) straight

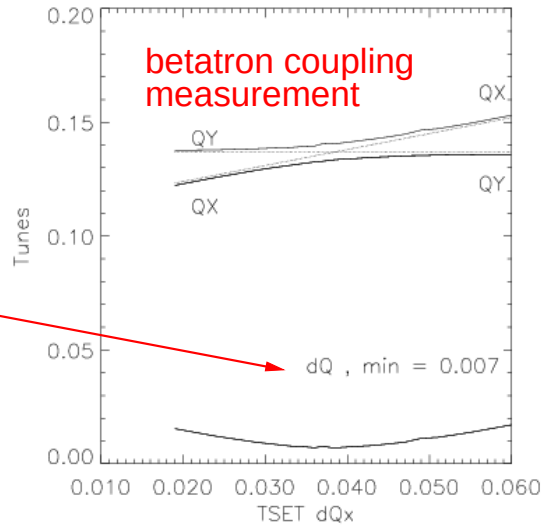
Introduction - SR Lattice Errors - Sources of Vertical Dispersion



- Left: Dispersion waves from quadrupoles and correctors in antiphase if BPM-quadrupole errors are small (<50 μm RMS) ($\rightarrow$ Beam-Based Alignment) after correction to quad centers
- Main contribution to dispersion from sextupoles through betatron coupling (simulation for 200 seeds)

Introduction - SR Lattice Errors - Betatron Coupling





- Betatron coupling: dQ=0.007
  - Emittance coupling in absence of spurious vertical dispersion: 0.2% (Guignard)
- Left: Emittance coupling after betatron coupling correction with skew quadrupoles $\approx 0.1\%$ (simulation for 200 seeds)

Introduction - SR Lattice Calibration - Beta Functions

174 Quadrupoles with Individual PS

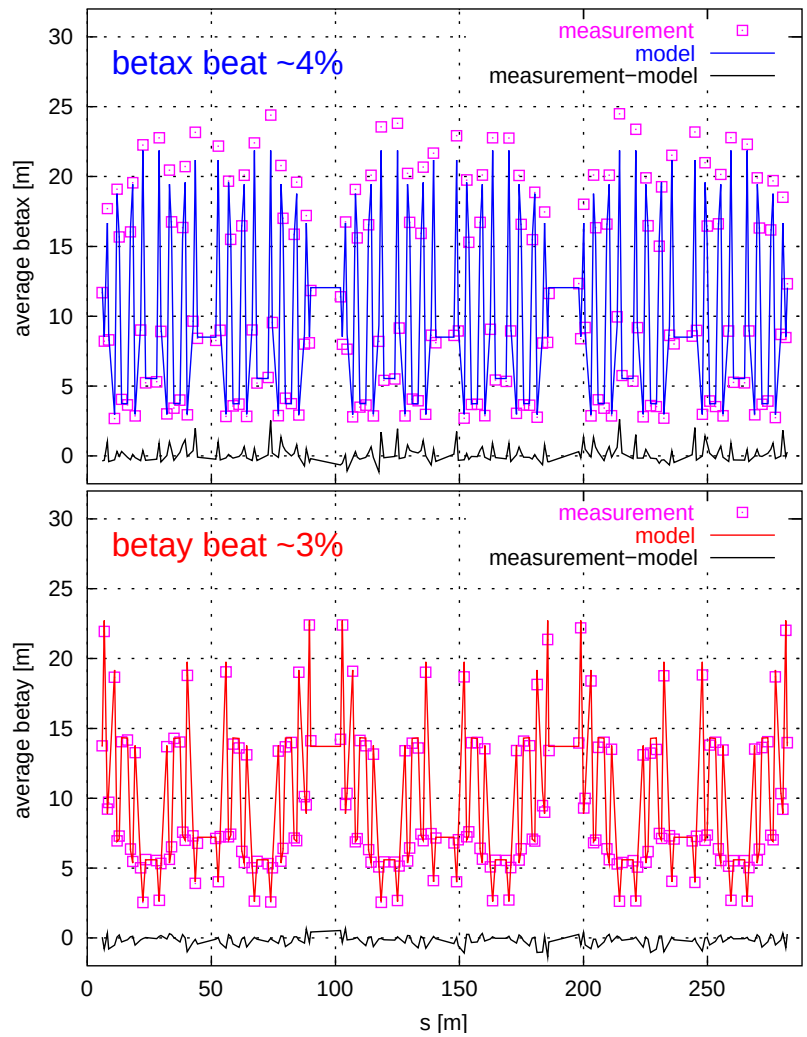
$\longrightarrow\longrightarrow$

Gradient Correction:

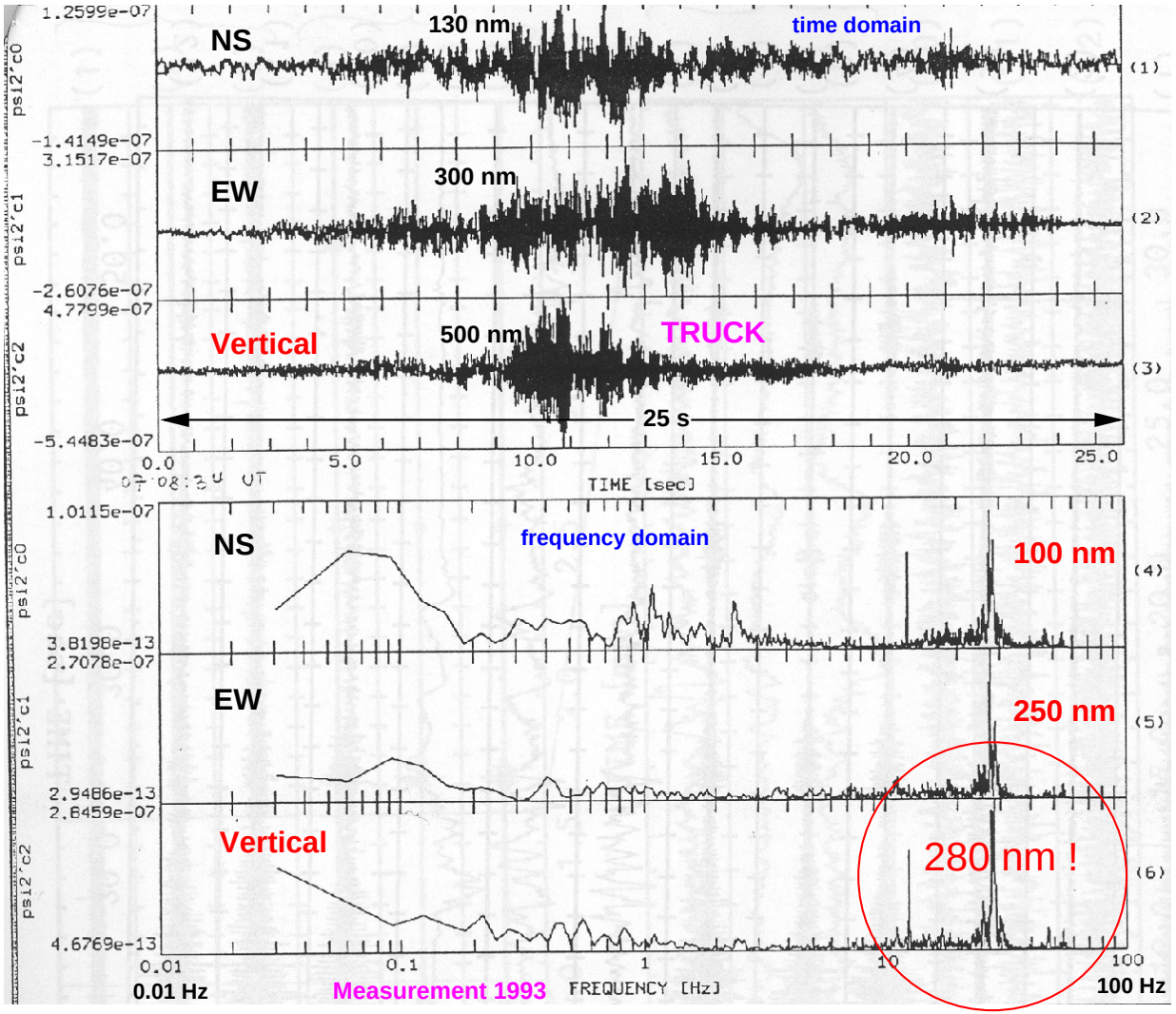
- Procedure:
  1. Measure $<\beta_i>$ for i=1..174

     $\delta\nu = -\frac{1}{4\pi}\oint \beta(s)\delta k(s)ds$

     Precision: $\approx$ 1.5 / 1.0 %
  2. Fit Errors δk_i to $<\beta_i>$ (SVD)
  3. Correct $<\beta_i>$ with -δk_i
  4. Measure $<\beta_i>$ again
- Results:
  - Horizontal β Beat: $\approx$ 4 %
  - Vertical β Beat: $\approx$ 3 %



FOFB - Motivation - Ground Noise Measurement in 1993



FOFB - Motivation - User Requirements & Worst Case Estimate

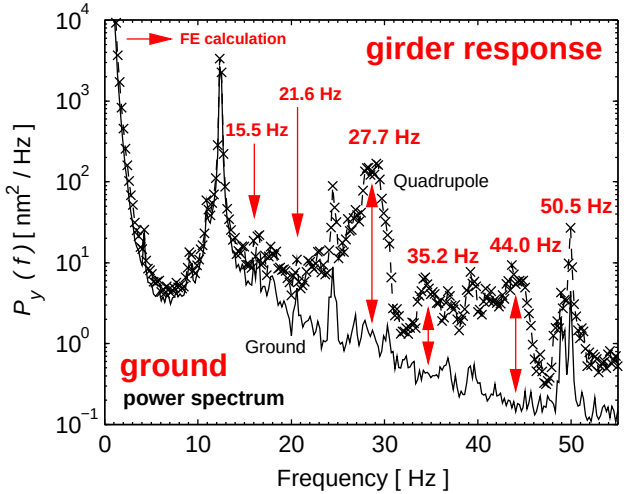
- β_x = 1.4 m, β_y = 0.9 m at **ID** position of section n**S** $\rightarrow$
  σ_x = 84 μm, σ_y = 7 μm assuming emittance coupling ϵ_y/ϵ_x = 1 %
- With stability requirement $\Delta\sigma = 0.1 \times \sigma \rightarrow$

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**

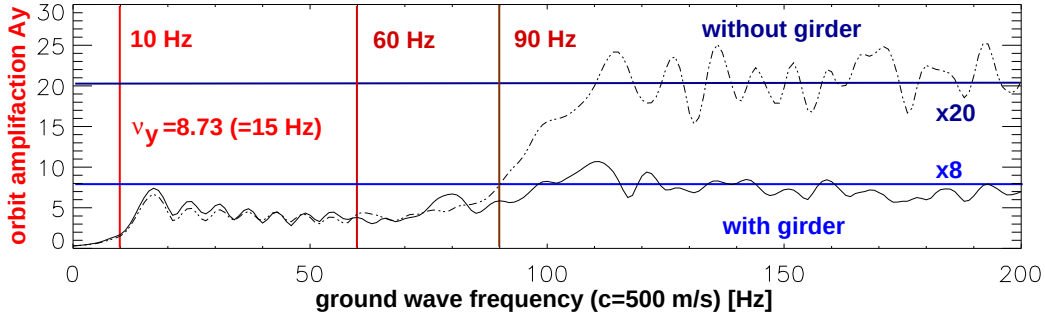
FOFB - Measured Short Term Noise Sources in 2004

f [Hz]	Noise Source
3	booster stray fields
12.4	helium-refrigerator
15-50	girder resonances
50	power supplies&pumps

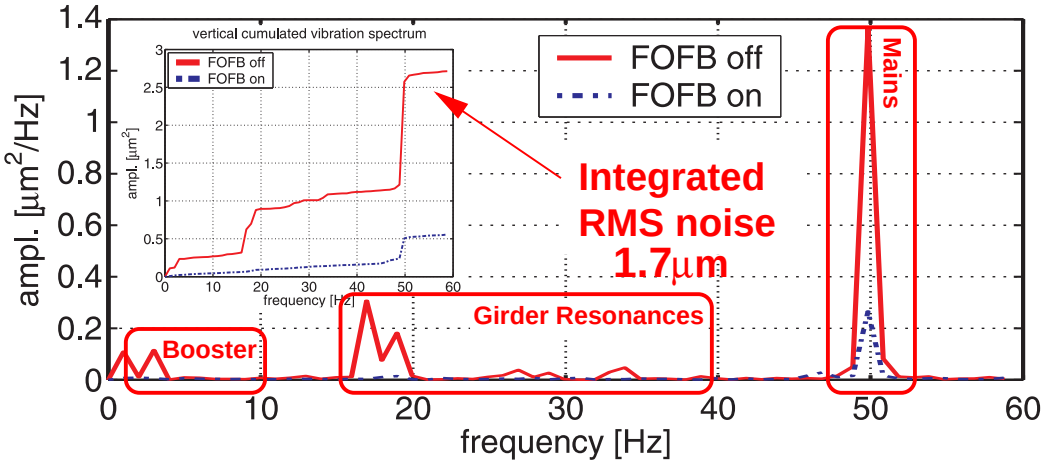


Vertical **vibration** PSD (1-55 Hz) measured on the slab and a girder (Redaelli et al.).

Vertical **orbit amplification factor** A_y for planar waves:



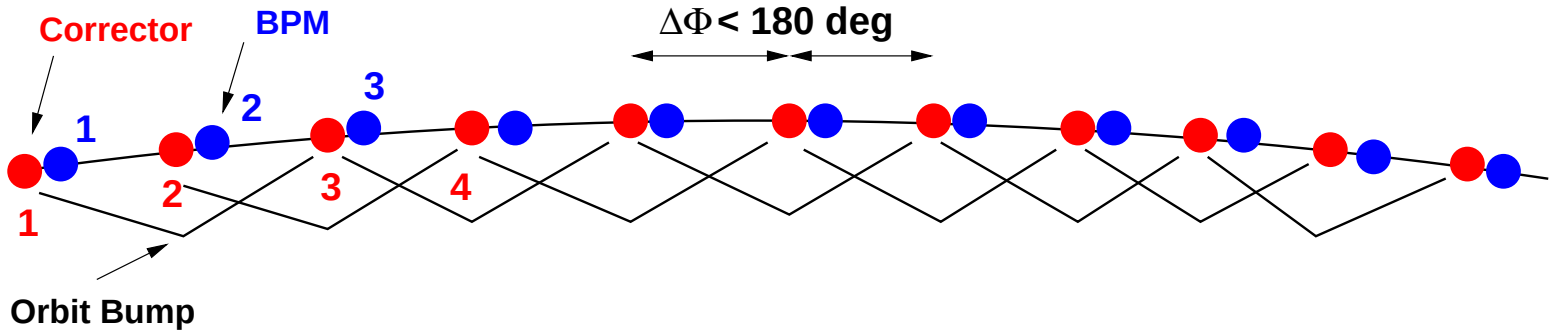
Vertical **orbit** PSD (1-60 Hz) without and with orbit feedback @ BPM (β_y=18 m):



→ **Integrated RMS motion σ_y only ≈0.4 μm $\cdot\sqrt{\beta_y}$!**

FOFB - T&S - Orbit Correction Schemes

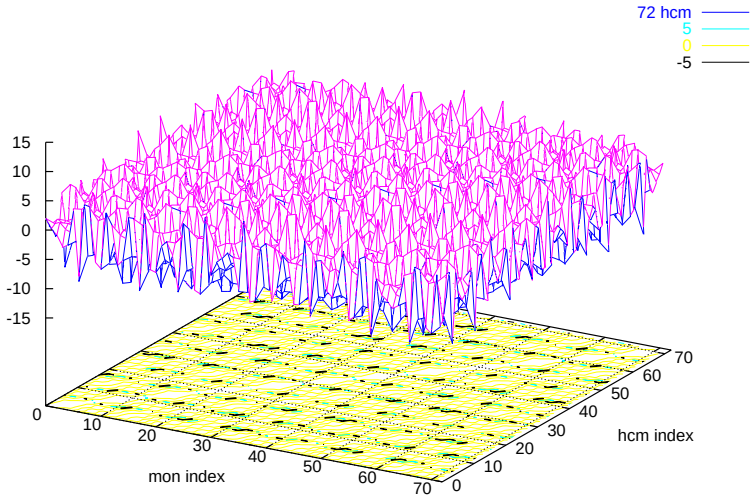
- **Sliding Bump** - Phase advances between Correctors $0° < \Delta\phi < 180°$, Correctors 1,2,3 allow to zero the orbit in BPM 2 near Corrector 2. 1 opens "Orbit Bump", 2 provides kick for 3 to close it again. Continue ("Slide") with 2,3,4 to zero orbit in BPM 3 ... iterate until orbit is minimized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

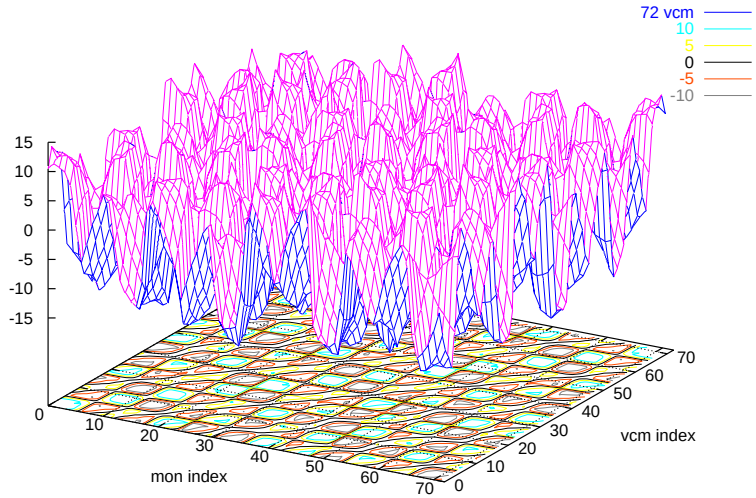


- **MICADO** - Finds a set of "Most Effective Correctors", which minimize the RMS orbit in all BPMs at a minimum ("most effective") RMS Corrector kick by means of the SIMPLEX algorithm. The number of Correctors (= iterations) is selectable.

- **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 !-)

FOFB - T&S - Response Matrices

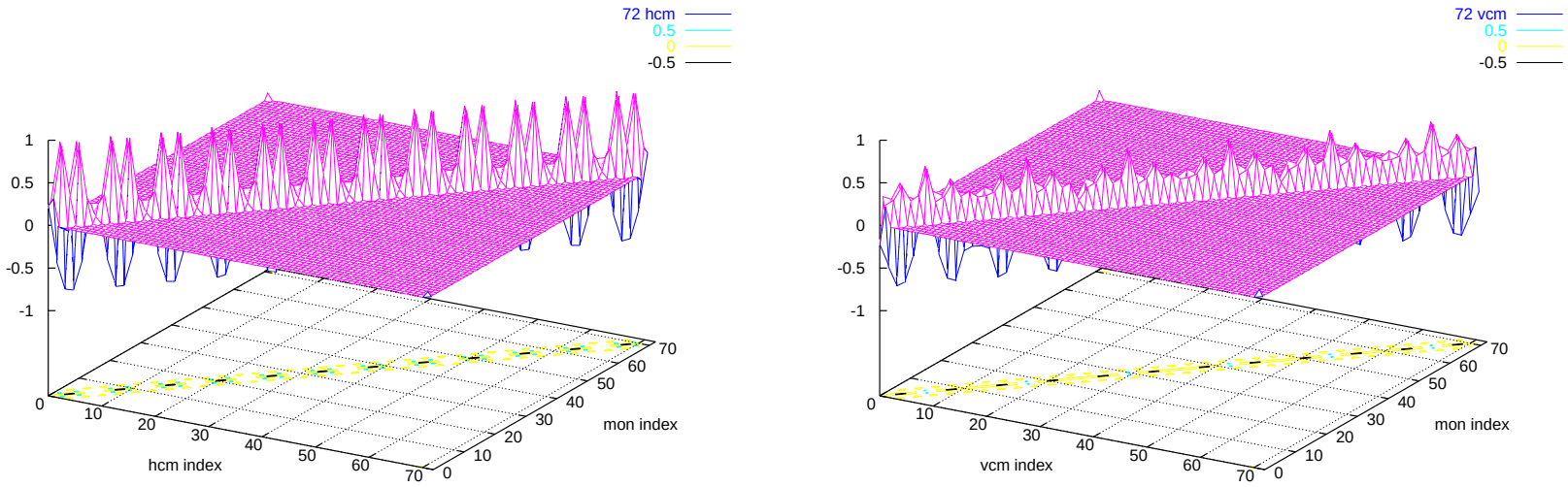




$$A_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \cos\left[\pi\nu - |\phi_i - \phi_j|\right] = (U * W * V^T)_{ij}$$

- ν_x = 20.43 (≈3 BPMs/Correctors per unit phase, $\phi = 360°$)
- ν_y = 8.73 (≈9 BPMs/correctors per unit phase)

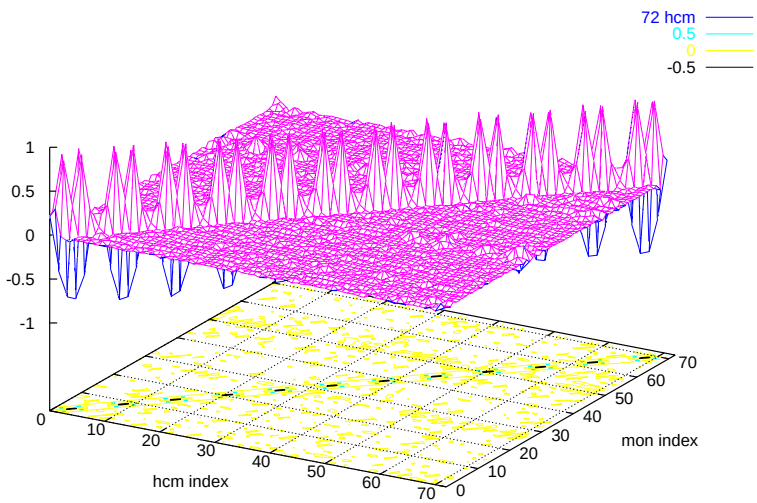
FOFB - T&S - Inverse Response Matrices

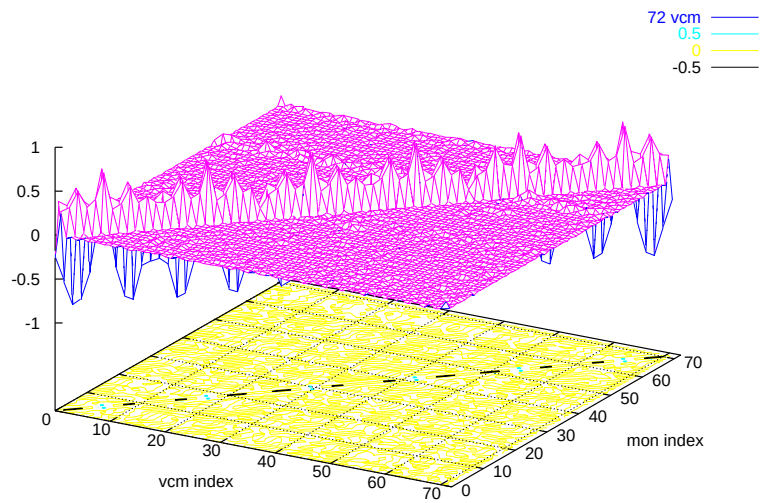


$$A_{ij}^{-1} = (V * 1/W * U^T)_{ij}$$

- 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)

FOFB - T&S - Inverse Measured Response Matrices

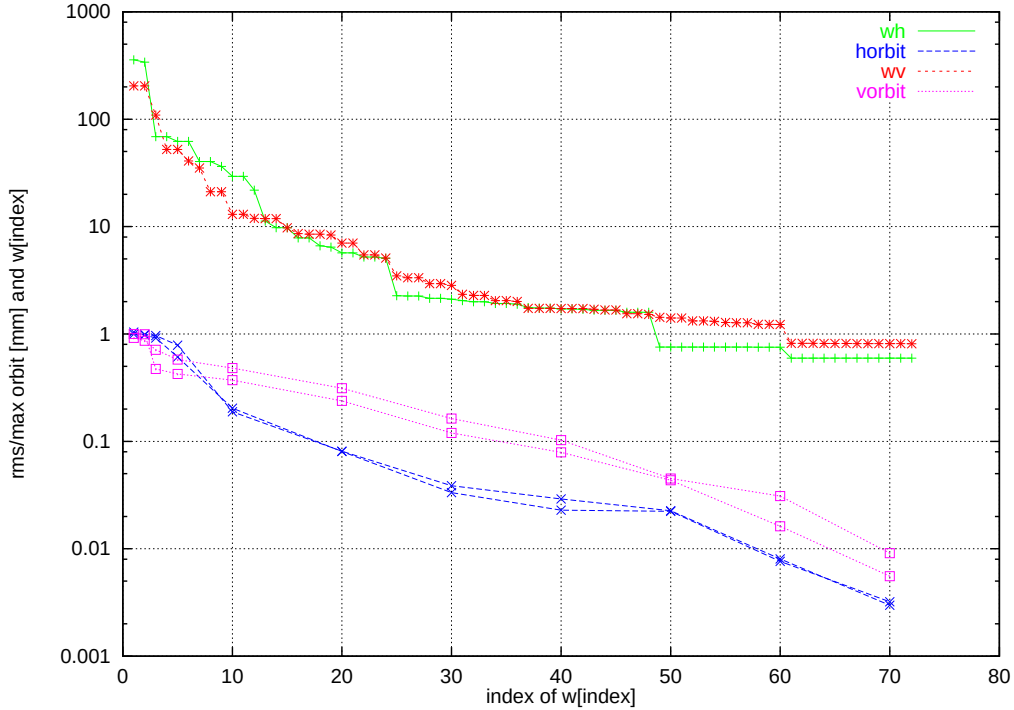




- Horizontal β Beat: $\approx$ 4 %
- Vertical β Beat: $\approx$ 3 %

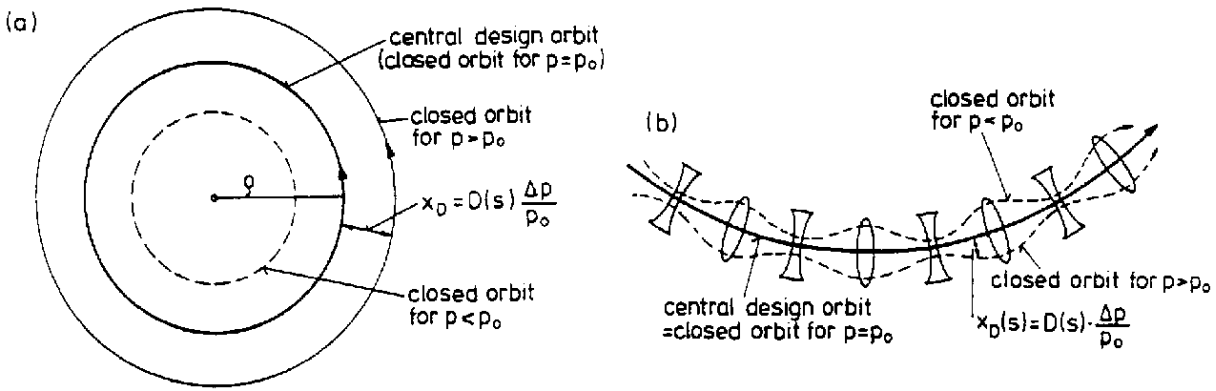
$\rightarrow$ $A(real)^{-1}_{ij}$ is still a sparse "*tridiagonal*" matrix plus some noise

FOFB - 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 $\rightarrow$ "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 !

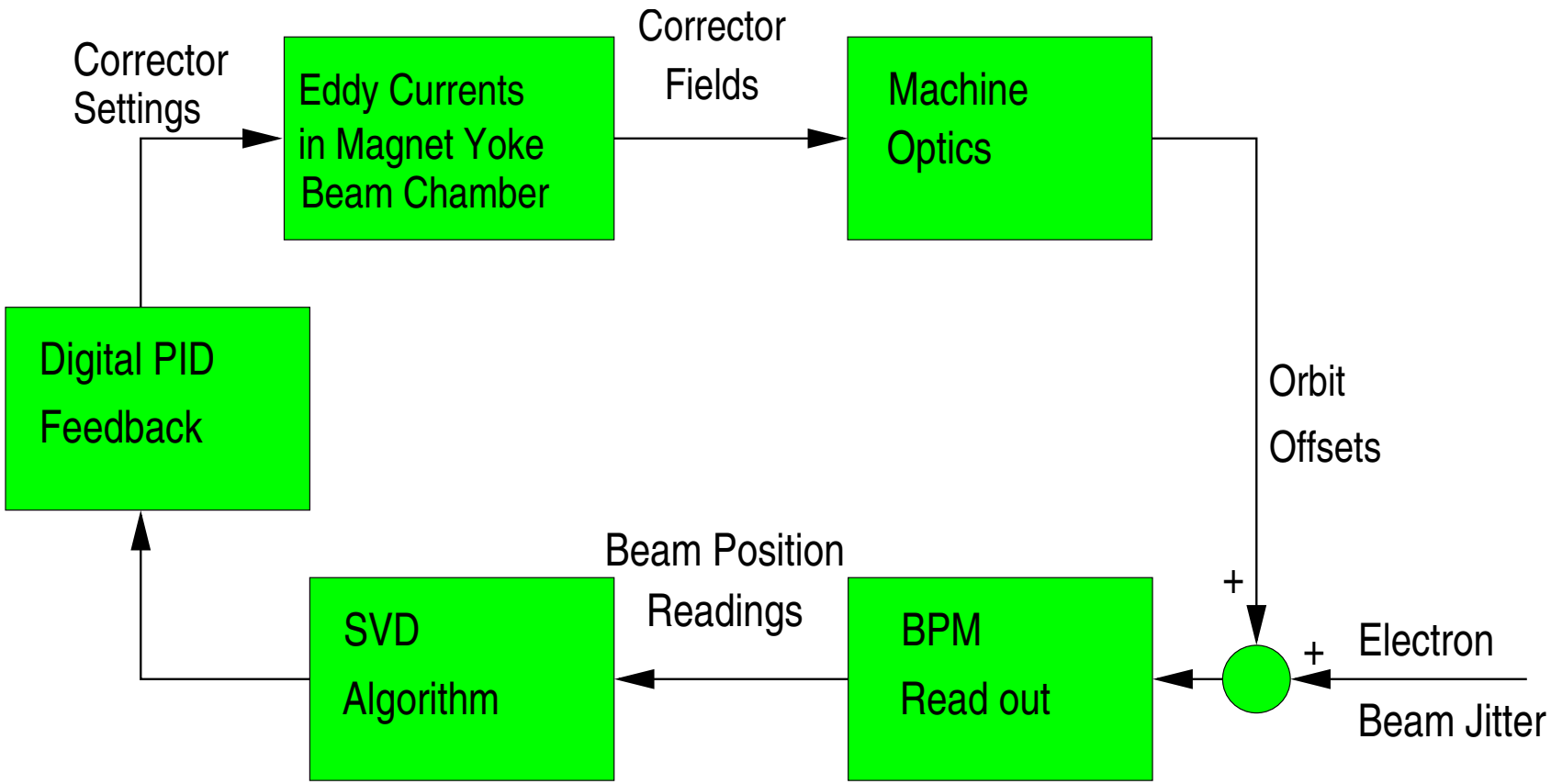
FOFB - T&S - Path Length Correction



- 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 $\Delta p/p_0$!

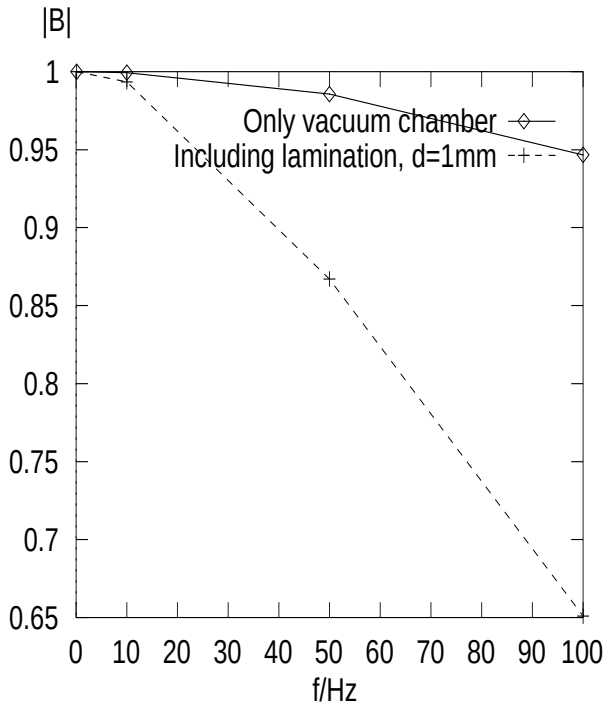
FOFB - T&S - Model for a Fast Closed Orbit Feedback



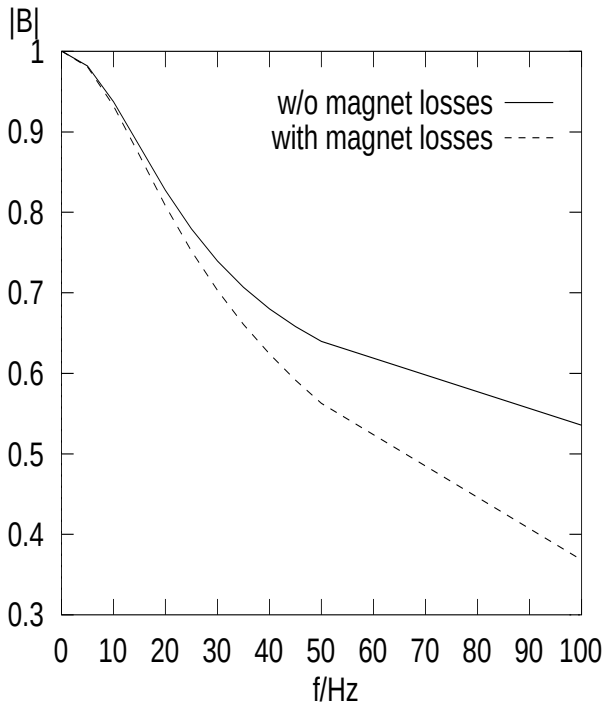
FOFB - T&S - Calculated Corrector Transfer Functions

- MAFIA estimated Eddy Current Effects induced by the Vacuum Chamber (3 mm Stainless Steal (finally reduced to 2 mm)) and the Laminated Iron of the Sextupoles:

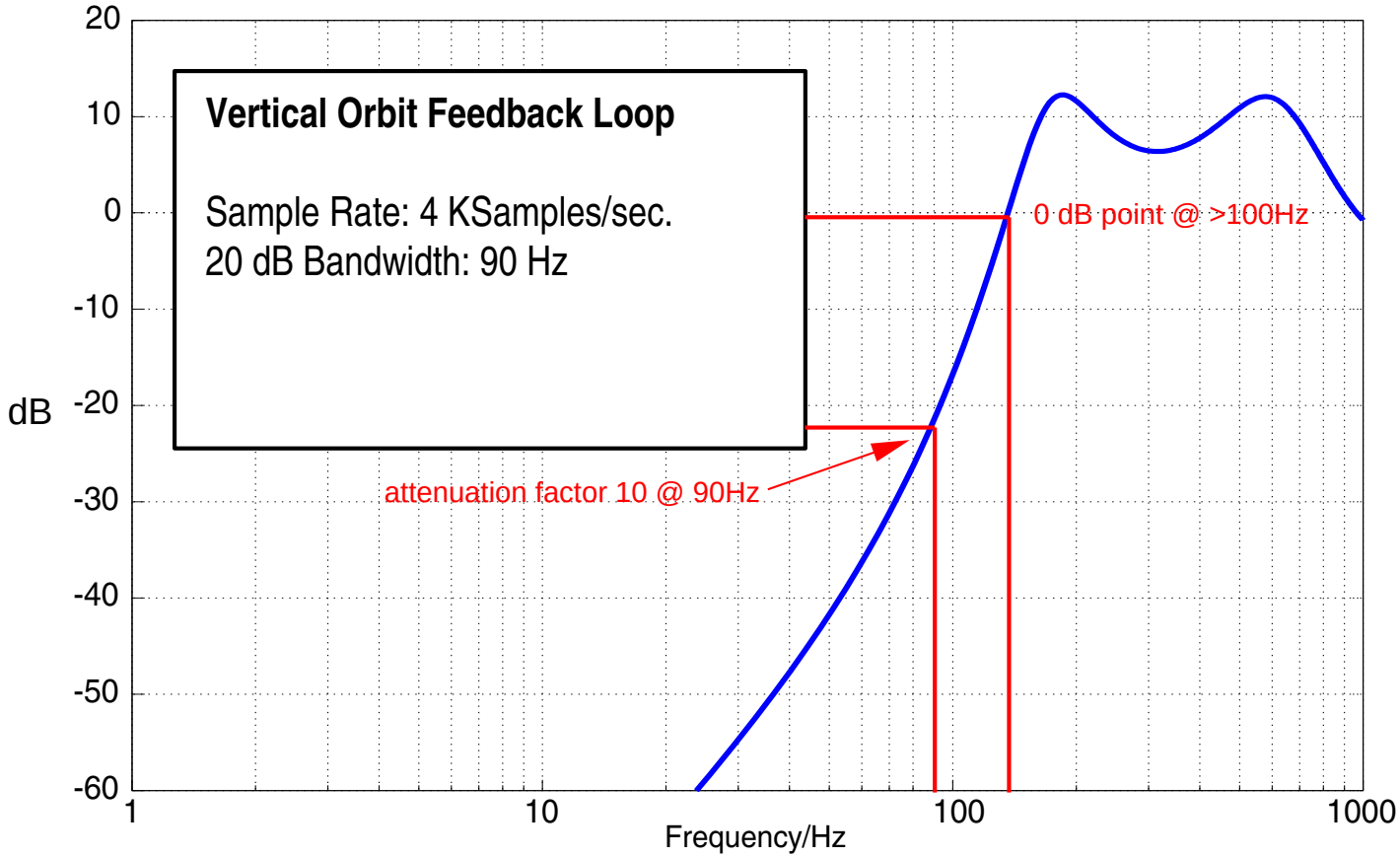
Horizontal Polarization



Vertical Polarization



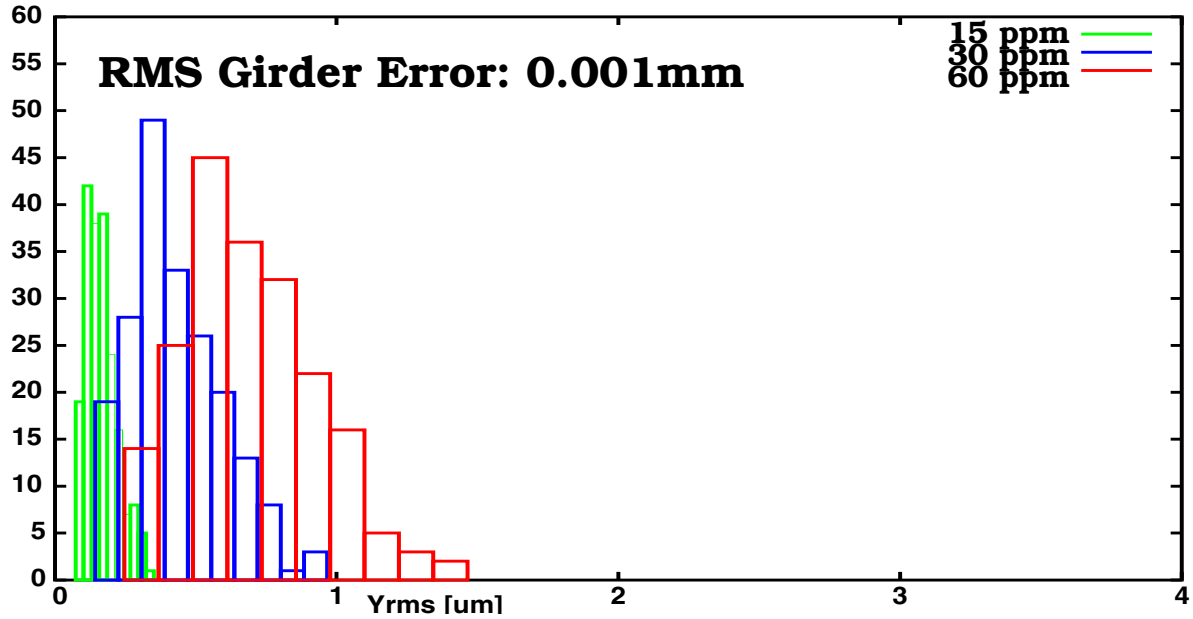
FOFB - T&S - Model based Orbit Noise Suppression



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

FOFB - T&S - PS Resolution & 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):

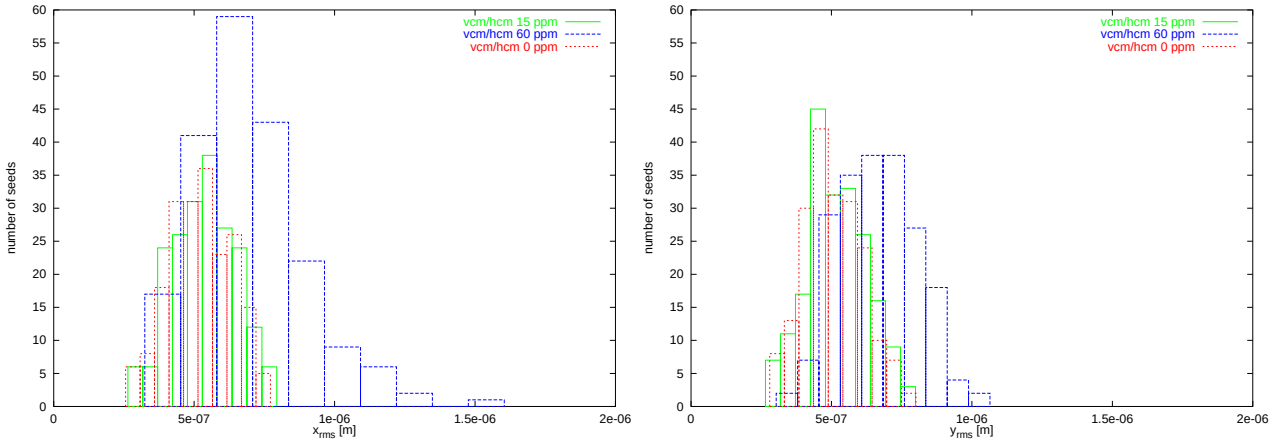


- 1 ppm in amplitude corresponds to a resolution of 10^{-6} at a maximum Current of 7 A ($\approx$ 860 μrad in the vertical plane)
- 60 ppm: y_{rms} = 0.75μm, 30 ppm: y_{rms} = 0.5μm, 15 ppm: y_{rms} = 0.25μm

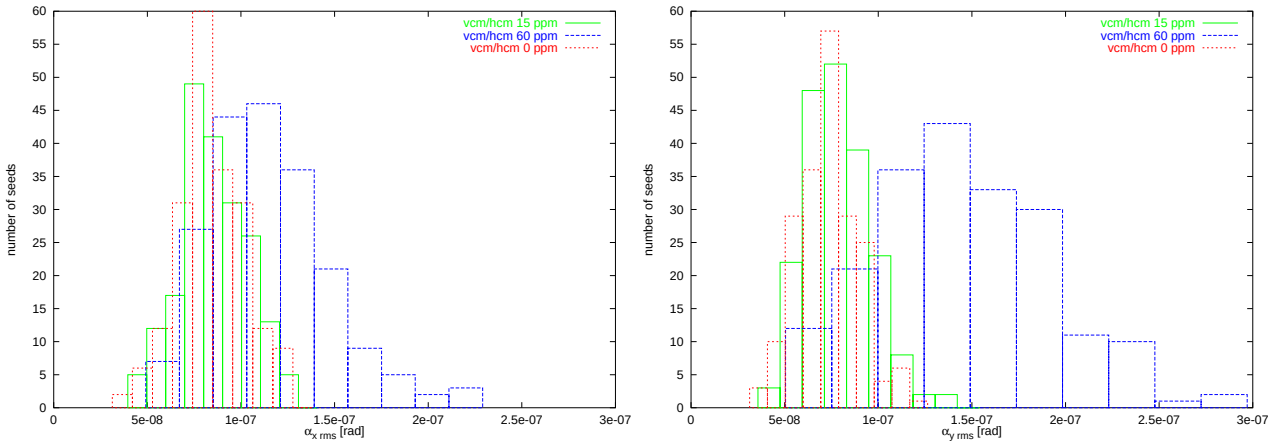
$\rightarrow$ 15 ppm ($\approx$ 10 nrad or 100 μA) sufficient

FOFB - T&S - PS Resolution and RMS Position/Angle @ IDs

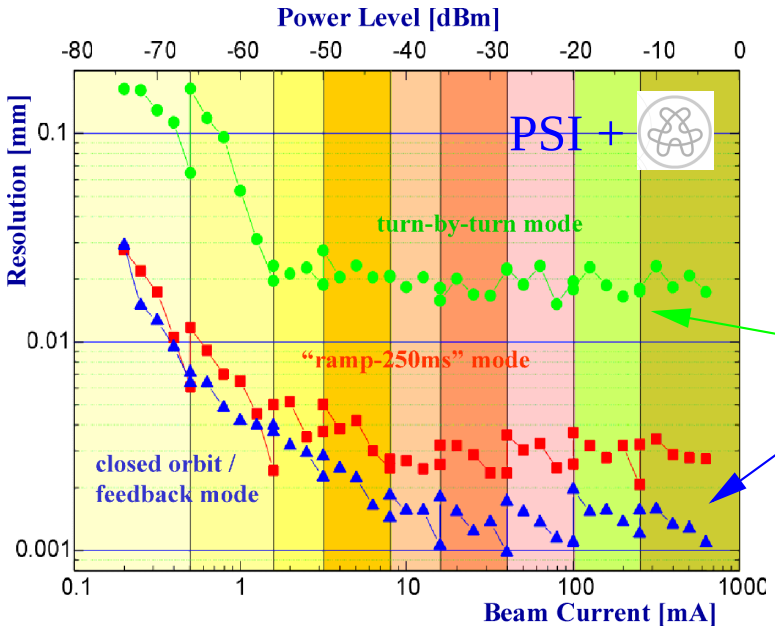
RMS Position @ Insertion Devices with $\beta_x \approx 1.4$m,$\beta_y \approx 0.9$m (x/y_{rms}= 0.5μm for 15 ppm):



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



FOFB - Subsystems - Digital BPM System



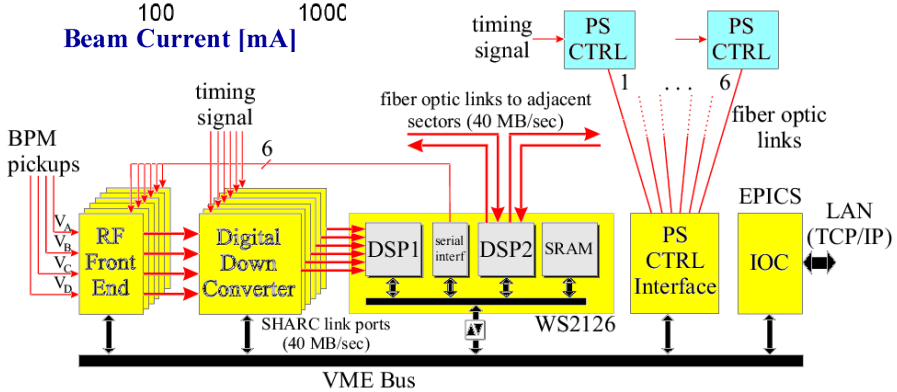
Only One BPM System in Different Operation Mode for All Machines

Turn−by−Turn:
1 MSample/s, <20 μm

Closed Orbit:
4 KSample/s, <0.8 μm

~300 nm <100 Hz

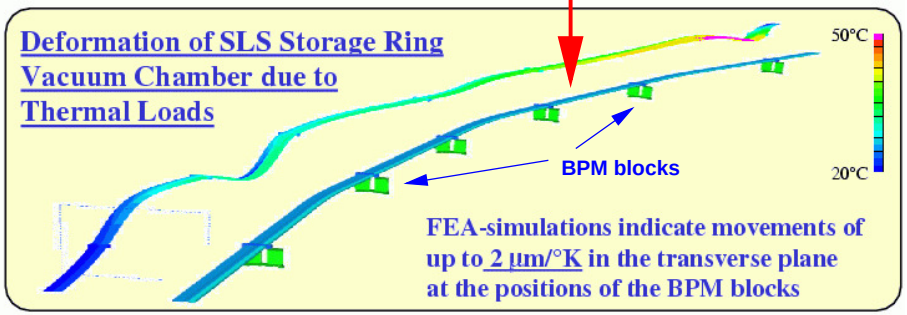
Turn−by−Turn:
Vital for Commissioning



Closed Orbit Mode −> Fast Orbit Feedback

FOFB - Subsystems - POMS

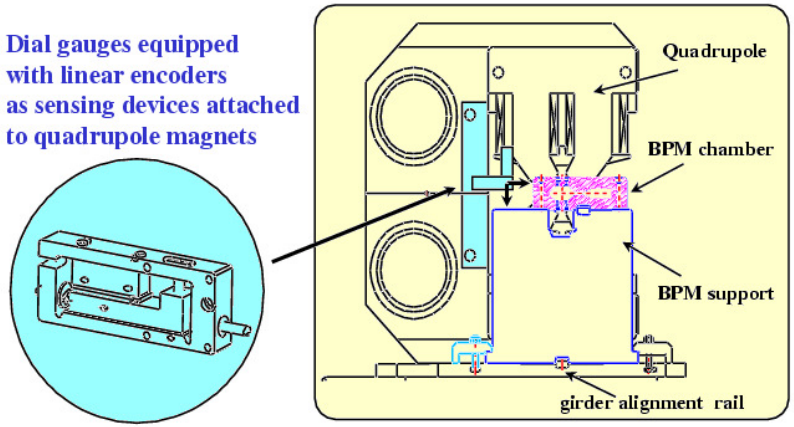
FEA−simulations indicate:
chamber moves ~2µm/K @ BPM blocks



POMS System

- Dial gauges sense transverse movements of BPM block in reference to adjacent quadrupole magnets.
- Linear encoders of type Renishaw RGH24Z50A00A with 0.5 µm resolution are used as sensing devices.
- Complete integration into EPICS control system through serial SSI-interface and 32 channel VME-SSI card.

Measure BPM/Quadrupole offsets with
0.5 µ m resolution in x and y !
0.1 µ m resolution @ short straights

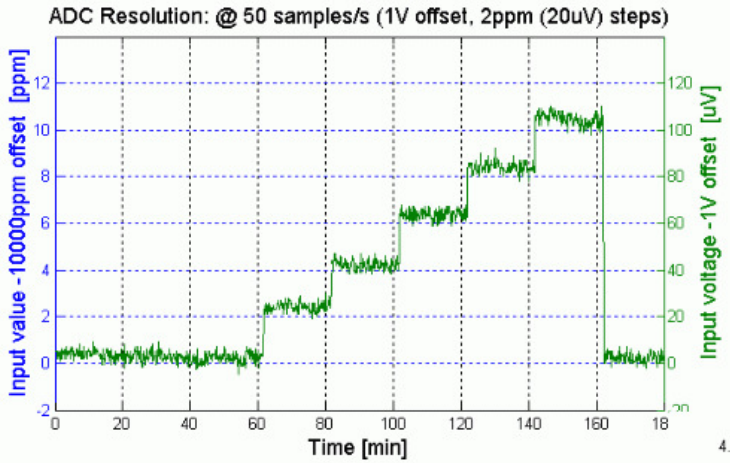


- 6 BPMs per sector (+1 BPM in 5L / FEMTO)
- BPMs rigidly attached to girders (BPM support mounted on girder alignment rail)
- BPM supports serve as supports for the vacuum system (→ BPM chamber)
- Initially planned to be used within the FOFB loop (NOT necessary →Top-Up)

FOFB - Subsystems - Digital Power Supplies

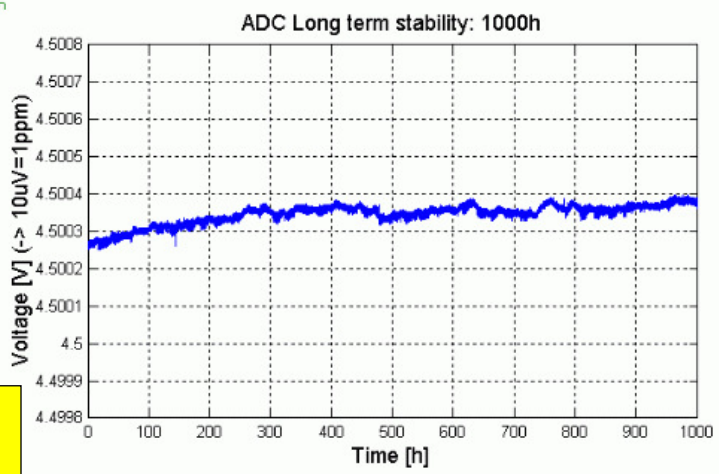
One Digital Control Unit for ~600 power supplies of the SLS

Precision of the AD converter card



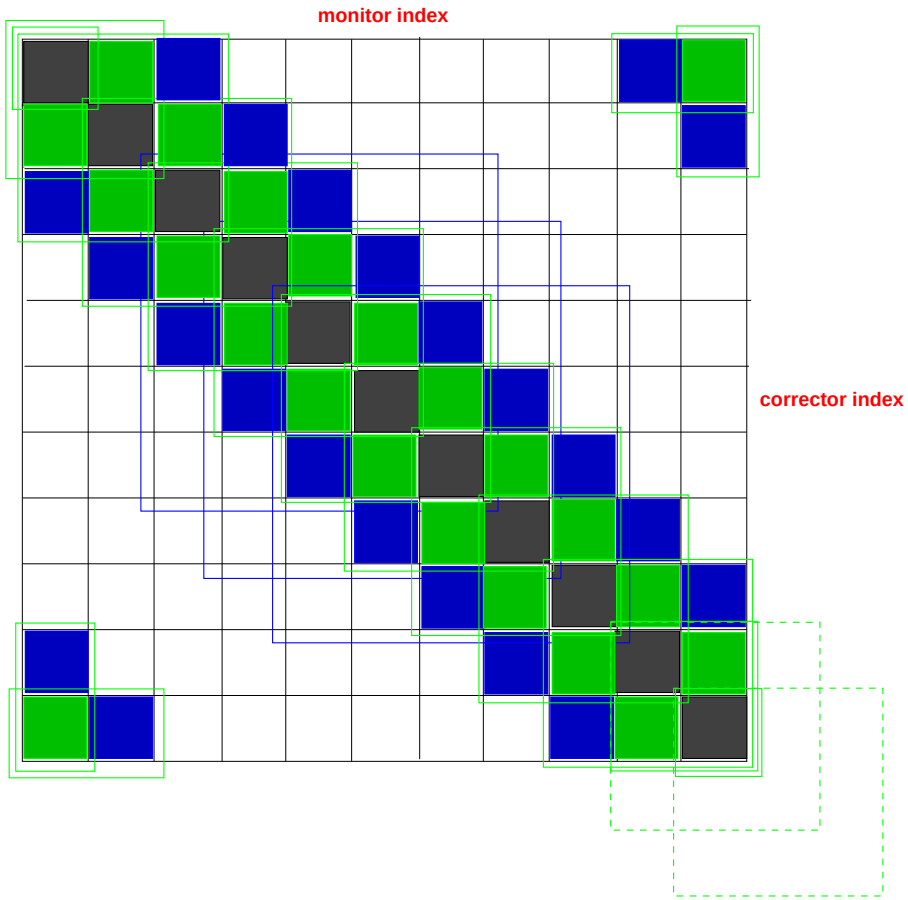
- Long- term stability (1000h) better than 30ppm
- Reproducibility better than 30ppm

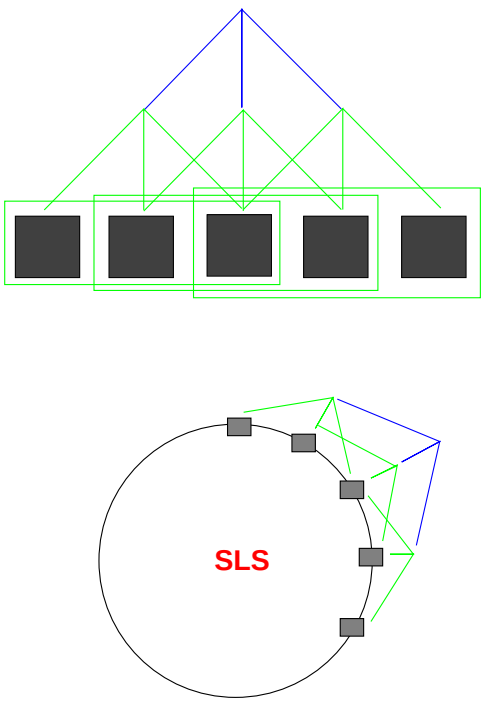
- Resolution up to **1ppm**
- Short- term stability (<60s) better than 10ppm



Short/Long−term: <10/30 ppm

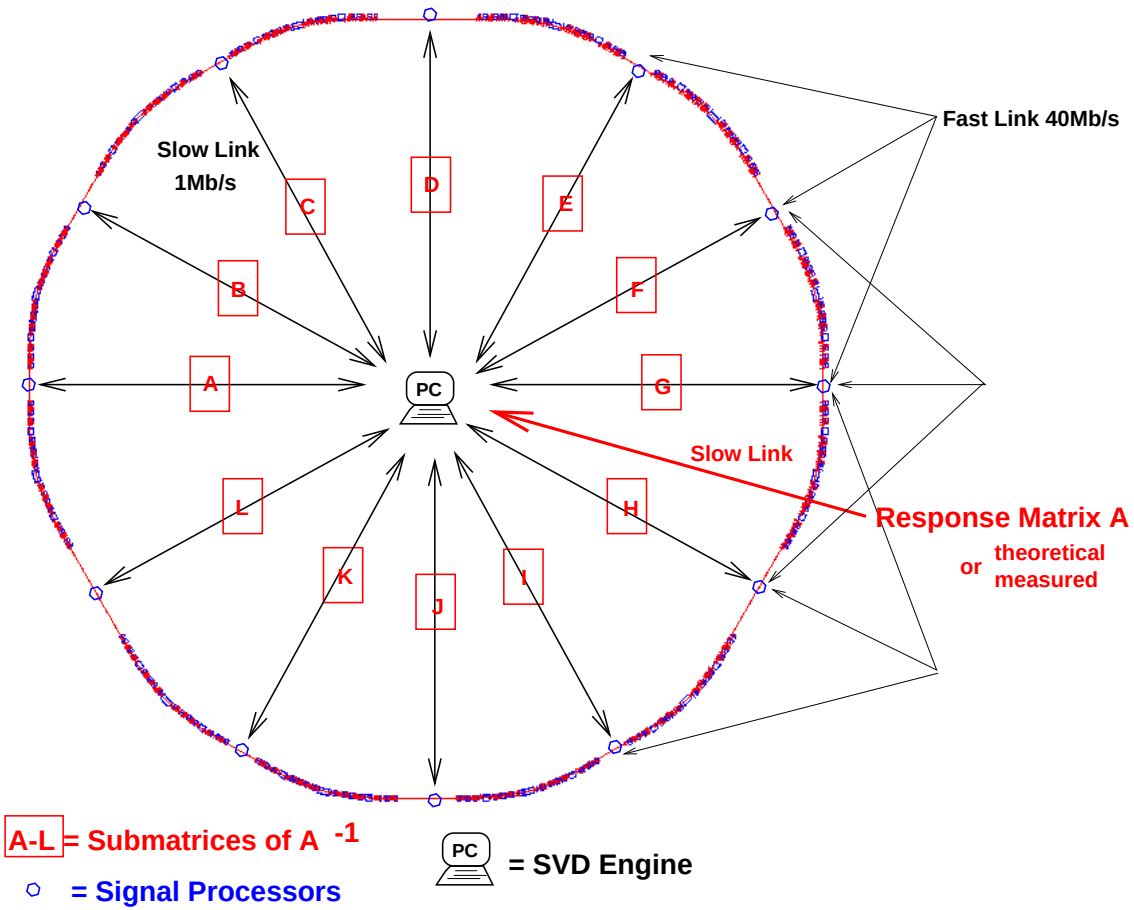
FOFB - Partitioning of Inverse Response Matrix





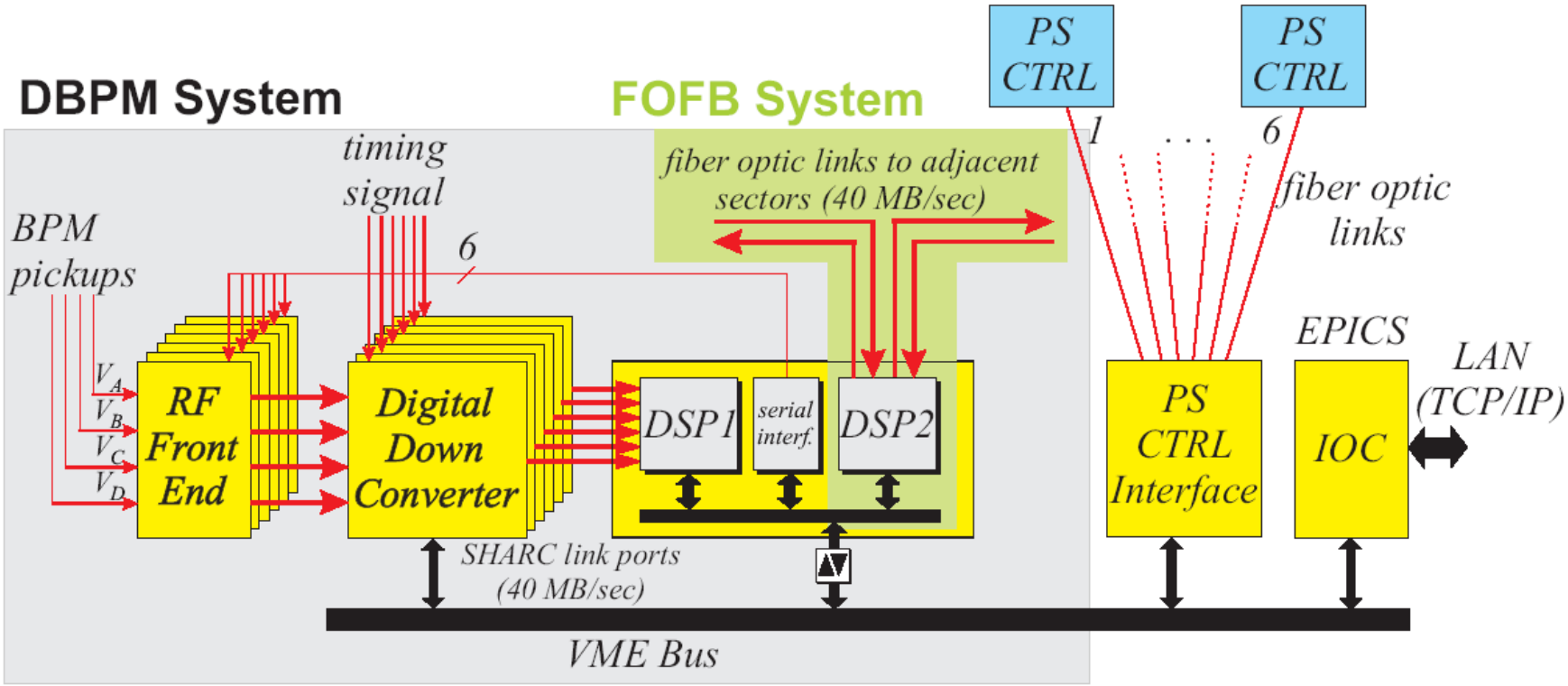
- 12 sectors
- 6(7) BPMs and 6(7) Horizontal/Vertical Correctors per sector (+1 BPM/Correctors set FEMTO)

FOFB - Schematic View

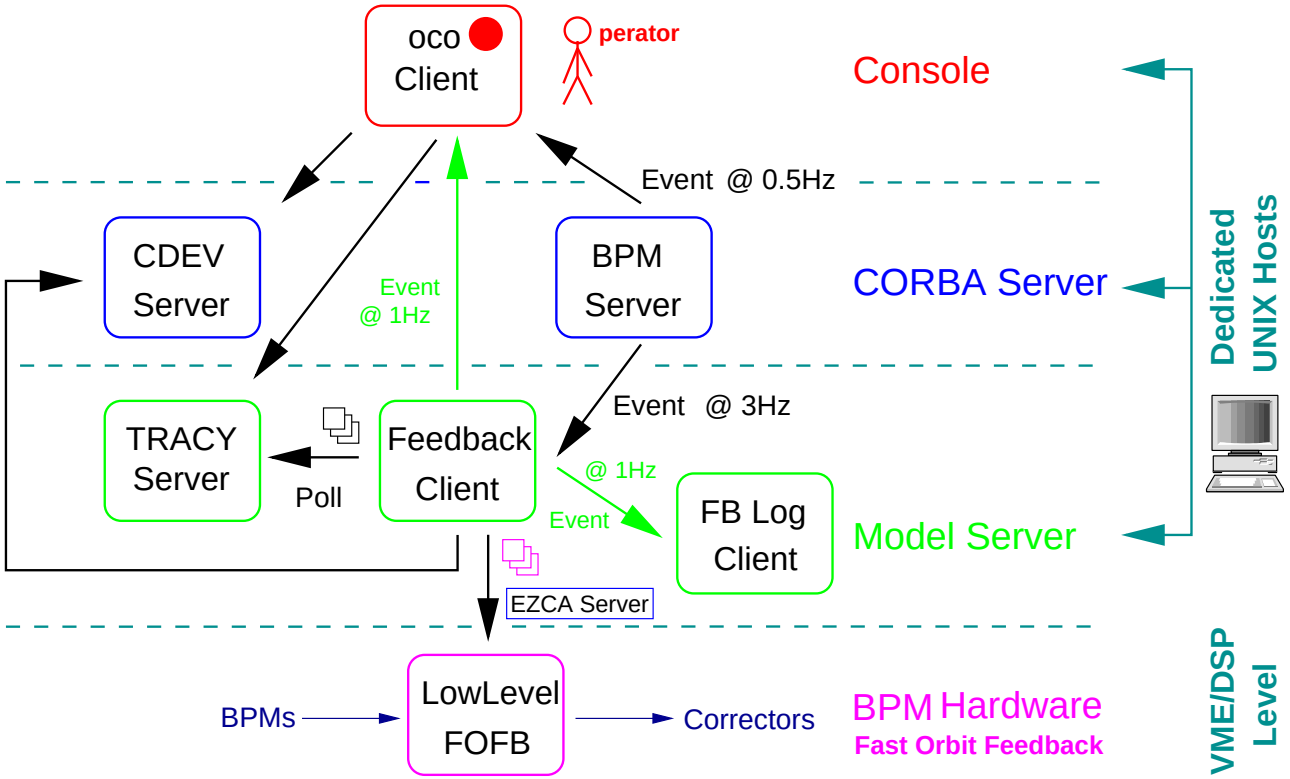


- Dedicated Signal Processors perform Matrix Multiplications in parallel !

FOFB - Hardware Layout

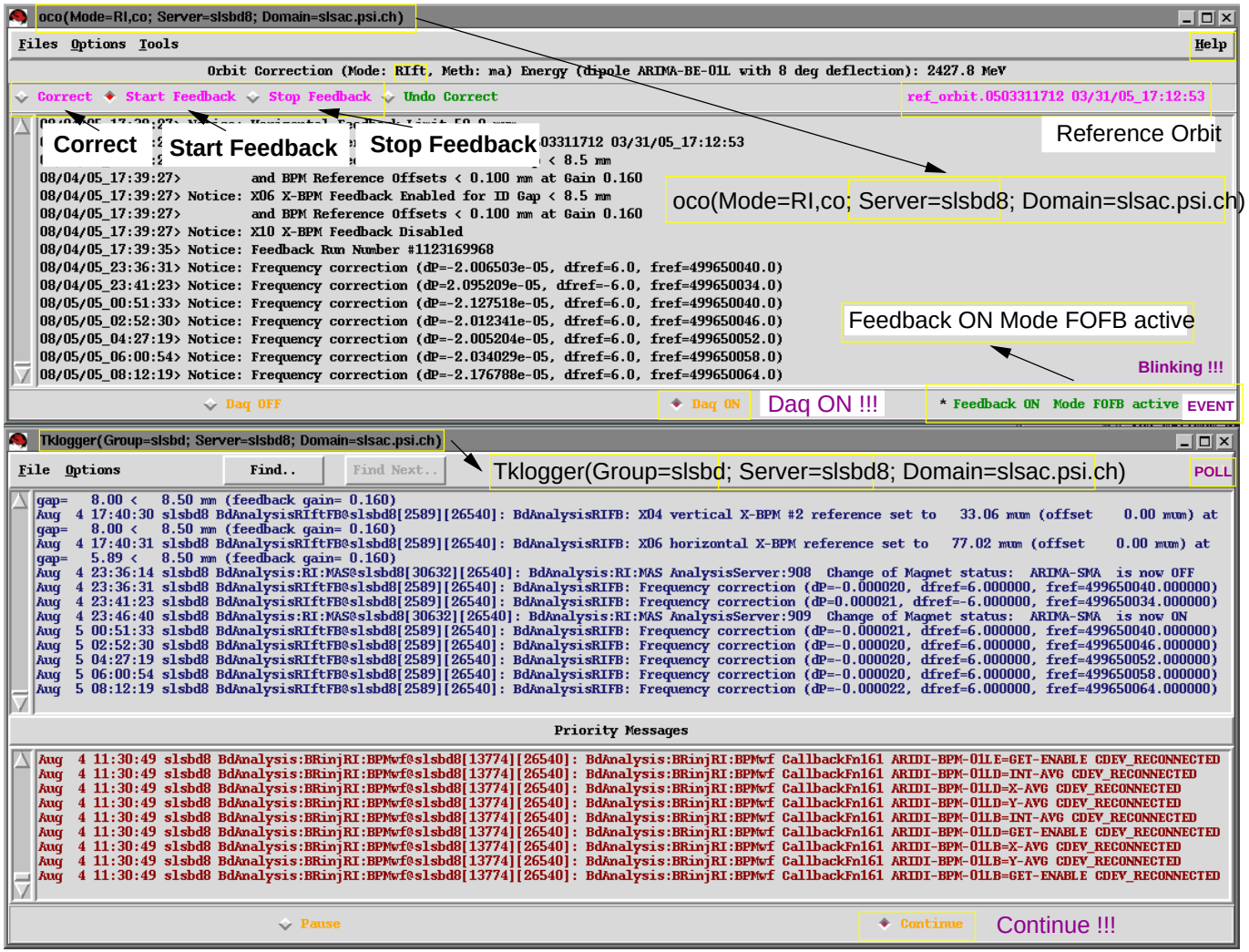


SOFB/FOFB - System Integration

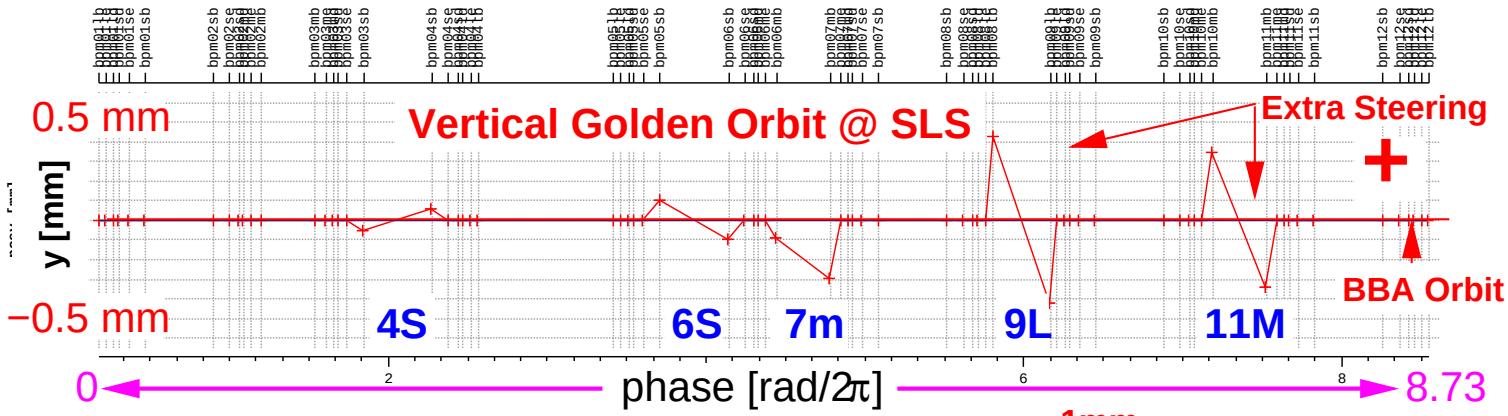


- Development within a Client-Server (Common Object Request Broker CORBA) environment
- Hard Correction ("Matrix Inversion" on the Model based Response Matrix using SVD)
- **SOFB**: BPM Datasets @ 3 Hz, average over 3 successive Datasets => $\approx$ 1 Hz correction rate (toggle between x/y plane => 2 s for full cycle). Corrects orbit to <5 μm before FOFB launch.

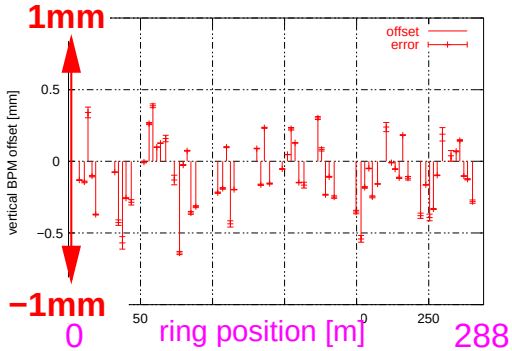
SOFB/FOFB - Operator Interface (Tcl/Tk) “oco Client”



SOFB/FOFB - Beam-Based Alignment & Golden Orbit



Golden Orbit: goes through centers of quadrupoles and sextupoles in order to minimize optics distortions leading to spurious vertical dispersion and betatron coupling (emittance coupling) + extra steering @ IDs



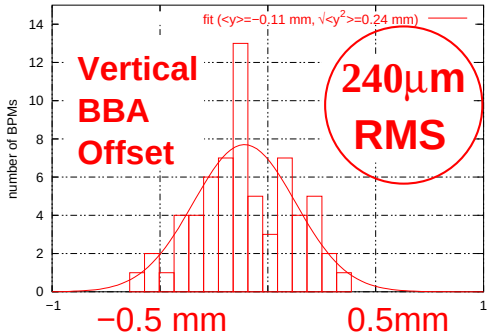
Beam−based alignment (BBA) techniques to find offset BPM − adjacent quadrupole center

alter focusing of individual quadrupoles, resulting RMS orbit change is proportional to initial orbit excursion at location of quadrupole.

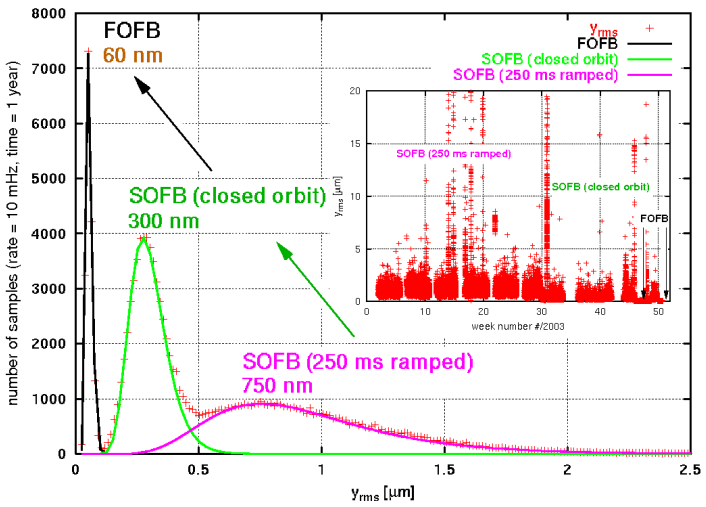
BBA offset = convolution of mechanical and electronical properties of BPM

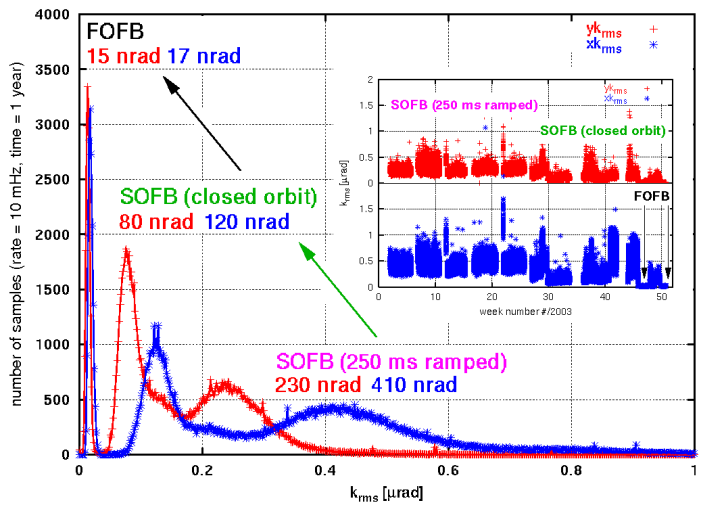
RMS offset even for well aligned machines >100μ m !

DC RMS corrector strength reduced when correcting to BBA orbit !



SOFB/FOFB - Transition from Slow →Fast Orbit Feedback

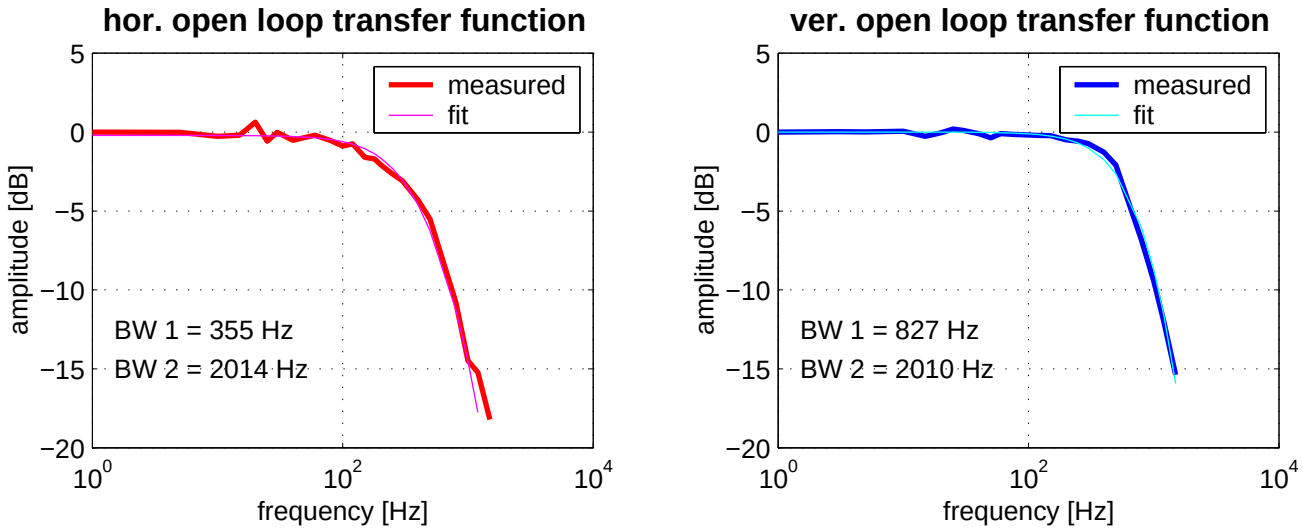


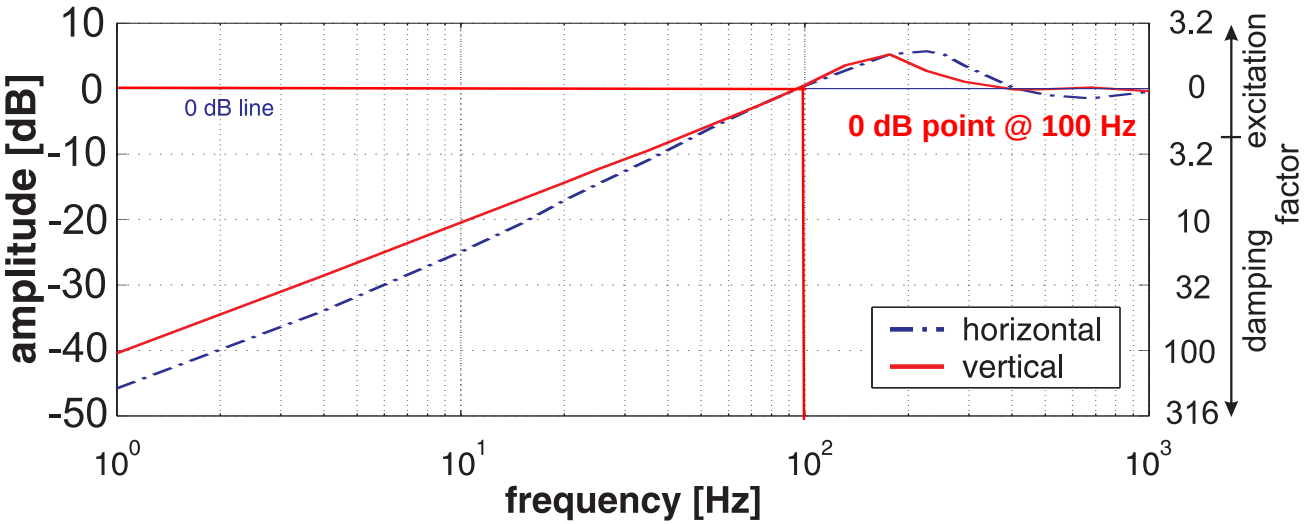


Temporal mean of the RMS orbit deviation from the BPM reference settings x_{rms} / y_{rms} and the corresponding RMS corrector strength xk_{rms} / yk_{rms} in 2003 for three different operation modes:

mode	horizontal		vertical	
	x_{rms}	xk_{rms}	y_{rms}	yk_{rms}
SOFB(250)	1.0 μm	410 nrad	750 nm	230 nrad
SOFB(co)	1.0 μm	120 nrad	300 nm	80 nrad
FOFB	**0.7 μm**	**17 nrad**	**60 nm**	**15 nrad**

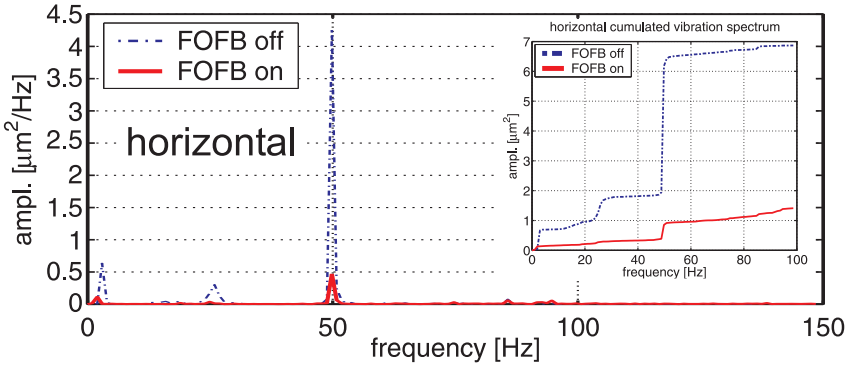
FOFB - Open & Closed Loop Transfer Functions

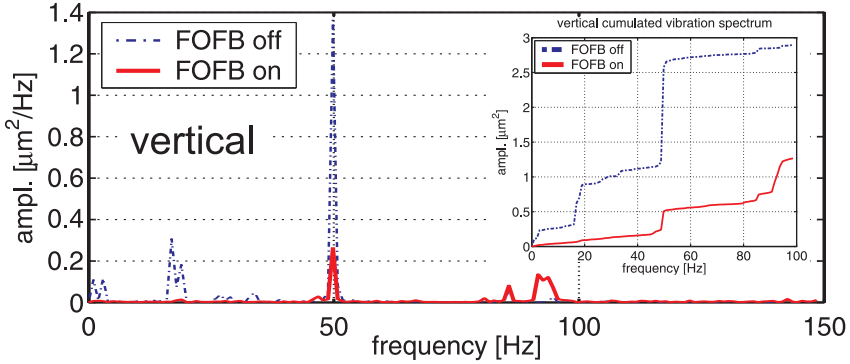




FOFB - Closed Loop Performance & X-BPM Feedback

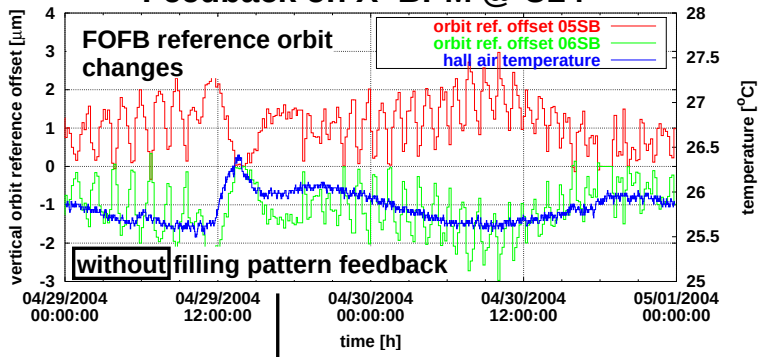
PSDs on tune BPM (off−loop)

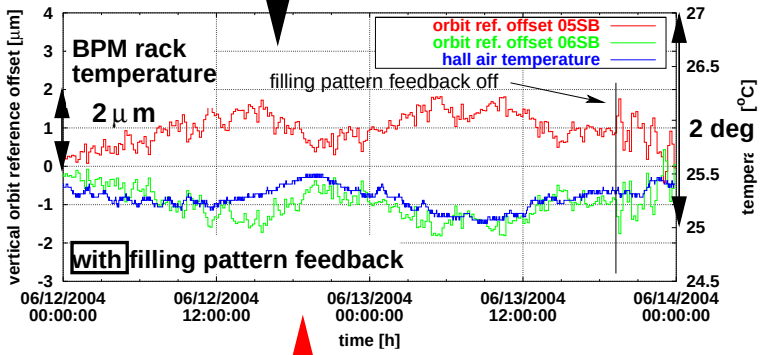




	horizontal		vertical	
FOFB	off	on	off	on
1- 100 Hz	**0.83 µm · $\sqrt{\beta_x}$**	**0.38 µm · $\sqrt{\beta_x}$**	**0.40 µm · $\sqrt{\beta_y}$**	**0.27 µm · $\sqrt{\beta_y}$**
100-150 Hz	0.08 µm · $\sqrt{\beta_x}$	0.17 µm · $\sqrt{\beta_x}$	0.06 µm · $\sqrt{\beta_y}$	0.11 µm · $\sqrt{\beta_y}$
1-150 Hz	0.83 µm · $\sqrt{\beta_x}$	0.41 µm · $\sqrt{\beta_x}$	0.41 µm · $\sqrt{\beta_y}$	0.29 µm · $\sqrt{\beta_y}$

Feedback on X−BPM @ U24

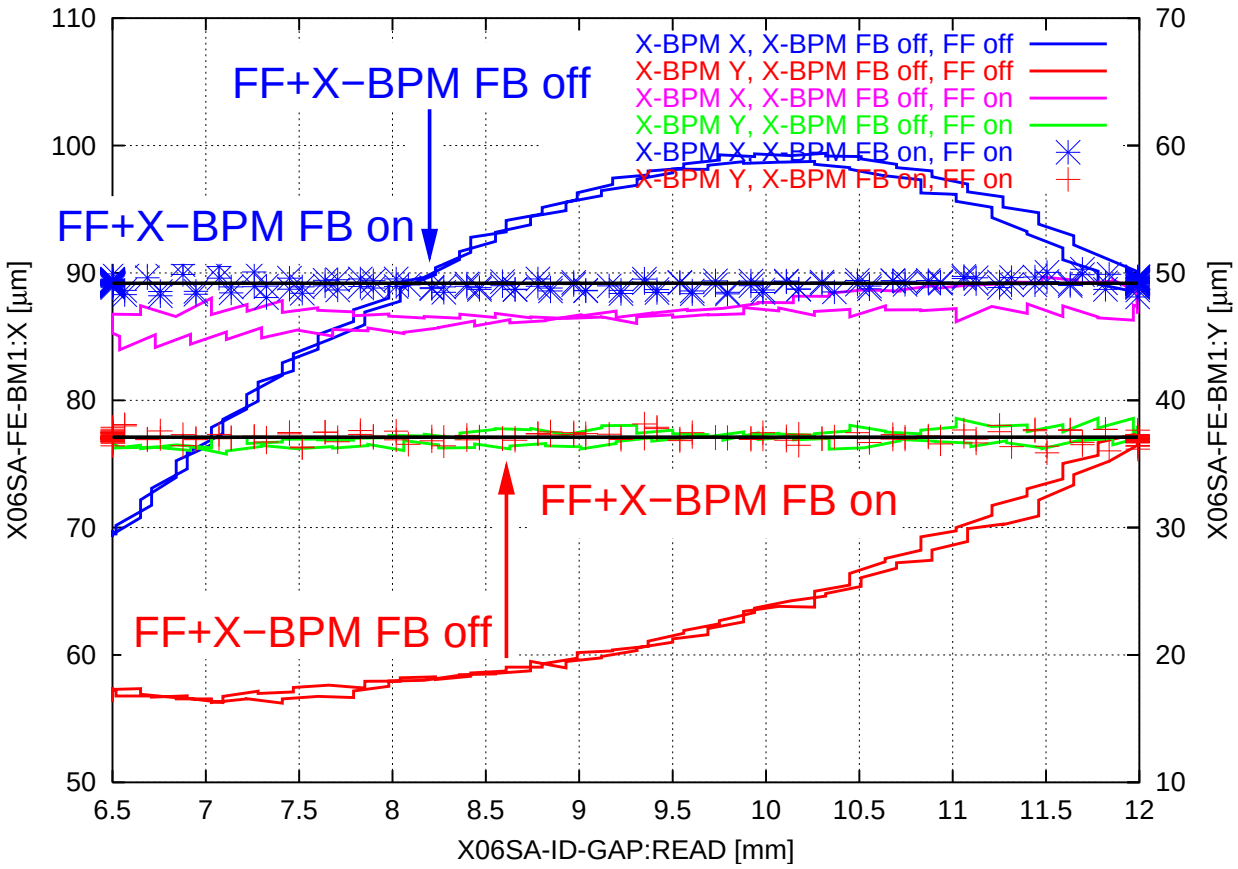




1Hz X−BPM feedback changes the reference of BPMs adjacent to IDs within the FOFB loop in order to stabilize the photon beam position at the X−BPMs −> cascaded feedback

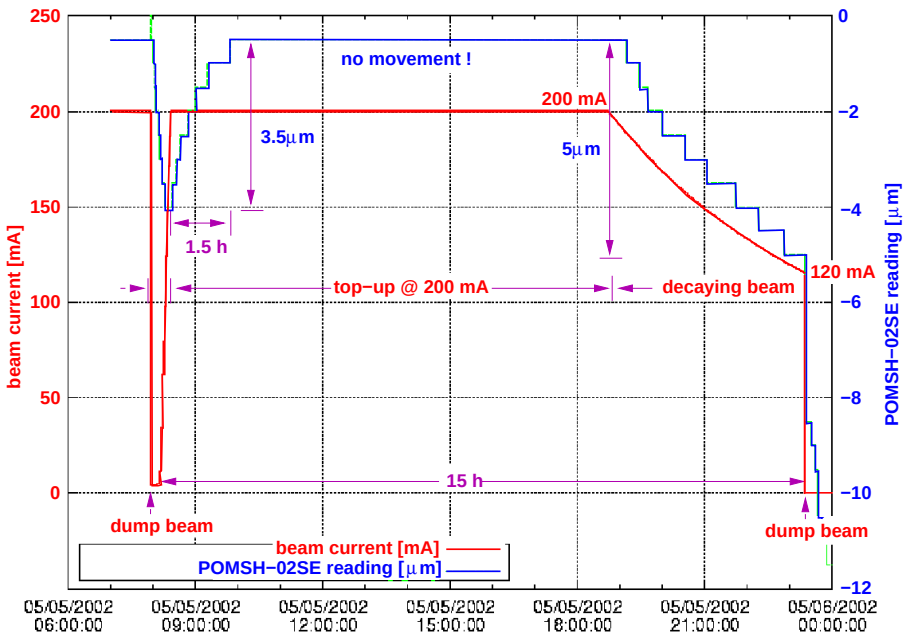
FOFB - Feed Forward & X-BPM Feedback

- The feed forward tables (here for **U24**) ensure a constant X-BPM reading for the desired gap range (here 6.5-12 mm) within a few μm. The remaining distortion is left to the X-BPM feedback



FOFB - Effect of Top-up Operation

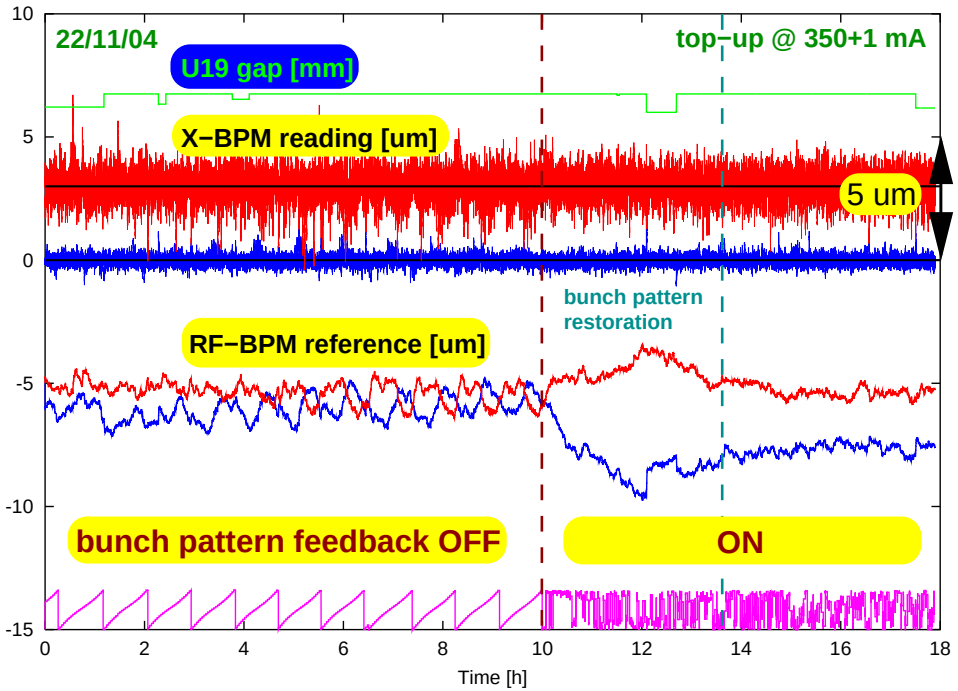
- "Top-up" operation guarantees a constant electron beam current and thus a constant heat load on all accelerator components. It also removes the current dependence of BPM readings under the condition that the bunch pattern is kept constant
- Horizontal mechanical offset (≈0.5 μm resolution) of a BPM located in an arc of the SLS storage ring with respect to the adjacent quadrupole in the case of beam accumulation, "top-up" @ 200 mA and decaying beam operation at 2.4 GeV:
  - Accumulation and decaying beam operation: BPM movements of up to 5 μm.
  - "Top-up" operation: no BPM movement during "top-up" operation at 200 mA after the thermal equilibrium is reached (≈1.7 h).

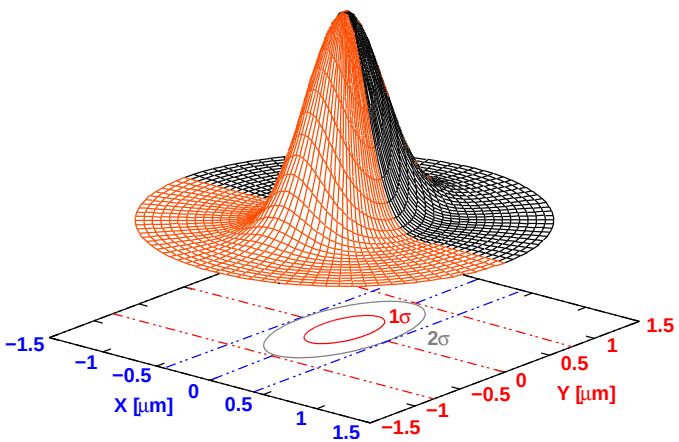


- 0.3 % current variation (350 (+1) mA) @ $\tau \approx 11$ h
- Injection every ≈ 2 min for ≈ 4 sec

FOFB - Top-up - X-BPM & Bunch Pattern Feedback

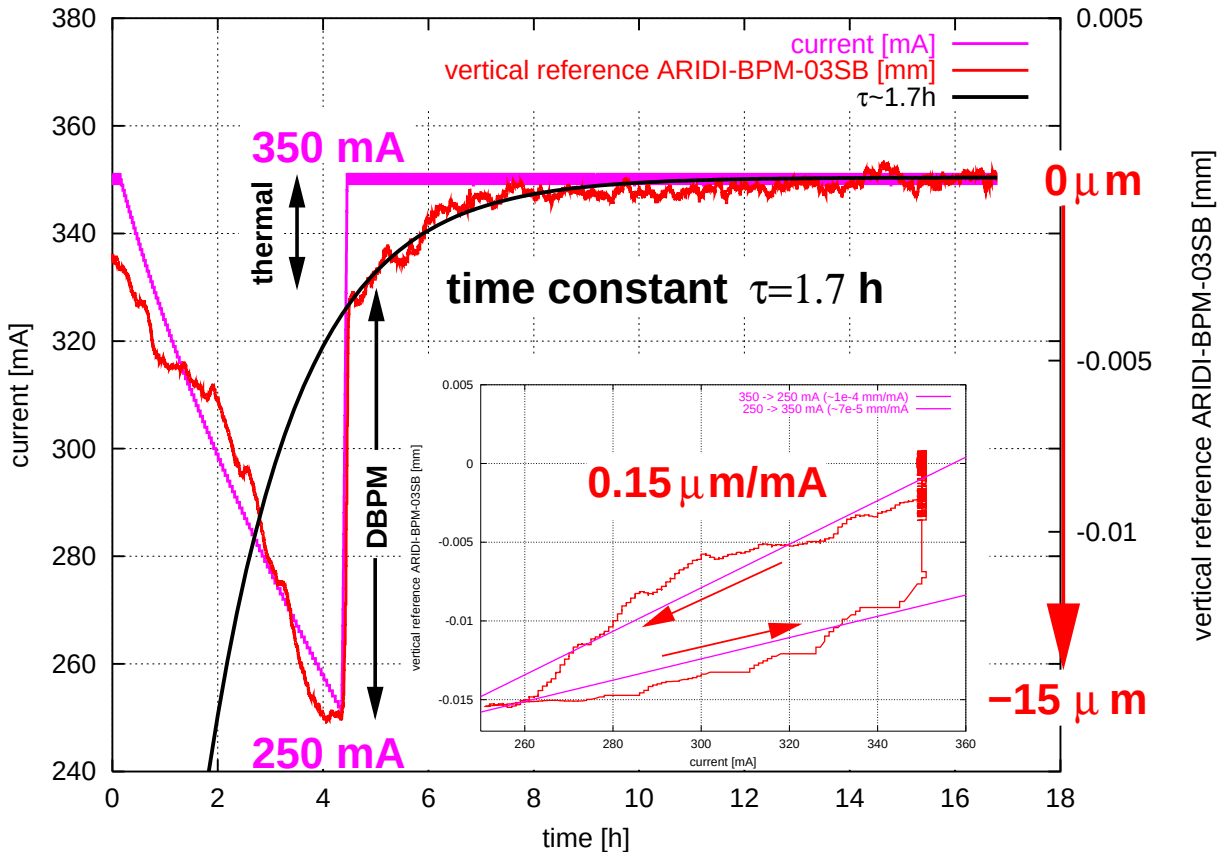
- The bunch pattern feedback maintains the bunch pattern (390 bunches (≈1 mA)) within <1 %
- The X-BPM feedback (**slave**) stabilizes the photon beam (Example beam line **6S**: 1 X-BPM ≈9 m from source point (**U19**)) by means of changes in the reference orbit of the fast orbit feedback (**master**) to ≈0.5 μm for frequencies up to 0.5 Hz.
- X-BPM feedbacks are operational @ the ID beam lines **4S**,**6S**,**10S** (1 X-BPM→angle only) and the dipole beam lines **2DA**,**7DA** (2 X-BPMs→angle & position).





FOFB - Top-up - Thermal Equilibrium

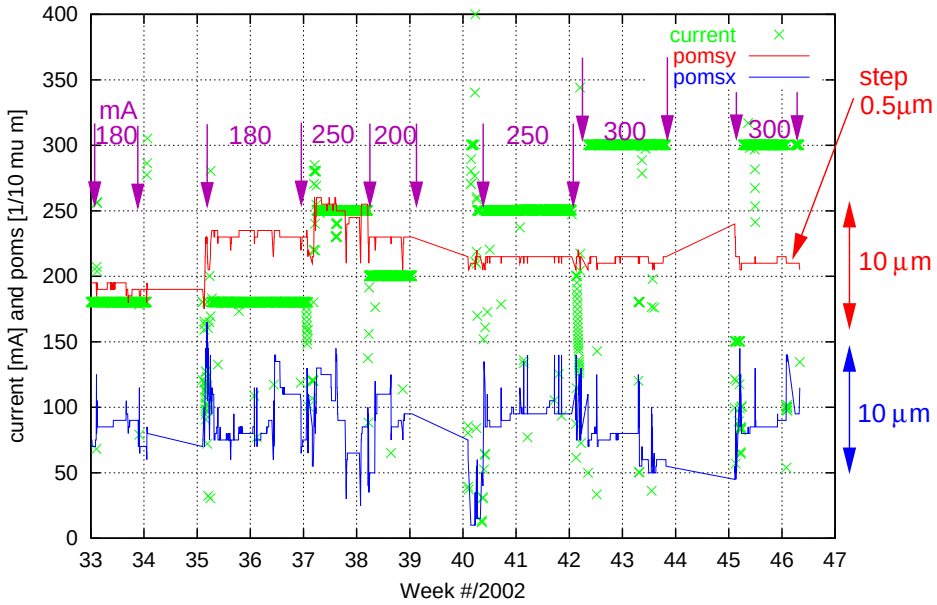
- Change of the vertical BPM reference within the X-BPM feedback loop for decaying beam operation (0-4 h) and "Top-up" (Time constant for getting back to thermal equilibrium τ=1.7 h):

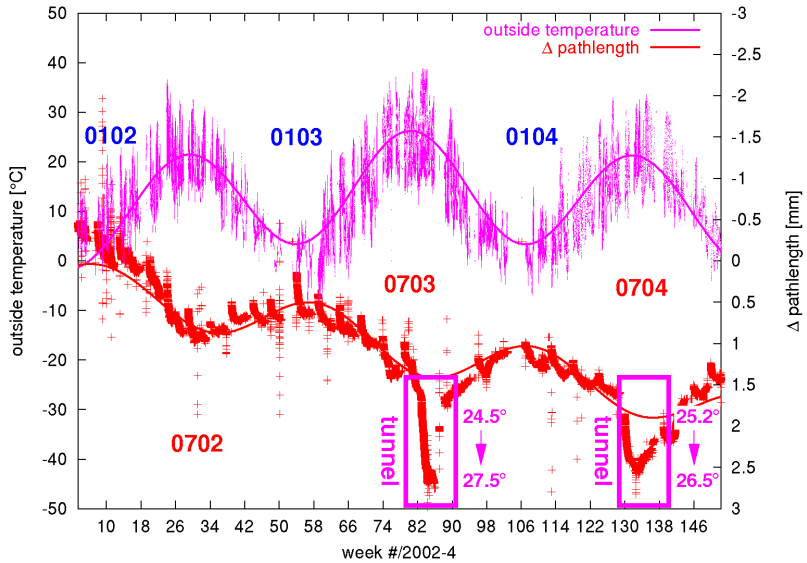


- Large ($\approx$0.1 μm/mA) contribution originating from current dependence of digital BPMs

FOFB - Long Term Stability - Annual Variations

- Horizontal BPM/Quadrupole offsets for BPM upstream of **U24** over 14 weeks @ different top-up currents (180, 200, 250, 300 mA) with 3 shutdowns (left plot)
- Circumference change over 3 years of SLS operation (→ Δ circumference ≈ 3 mm) (right plot)

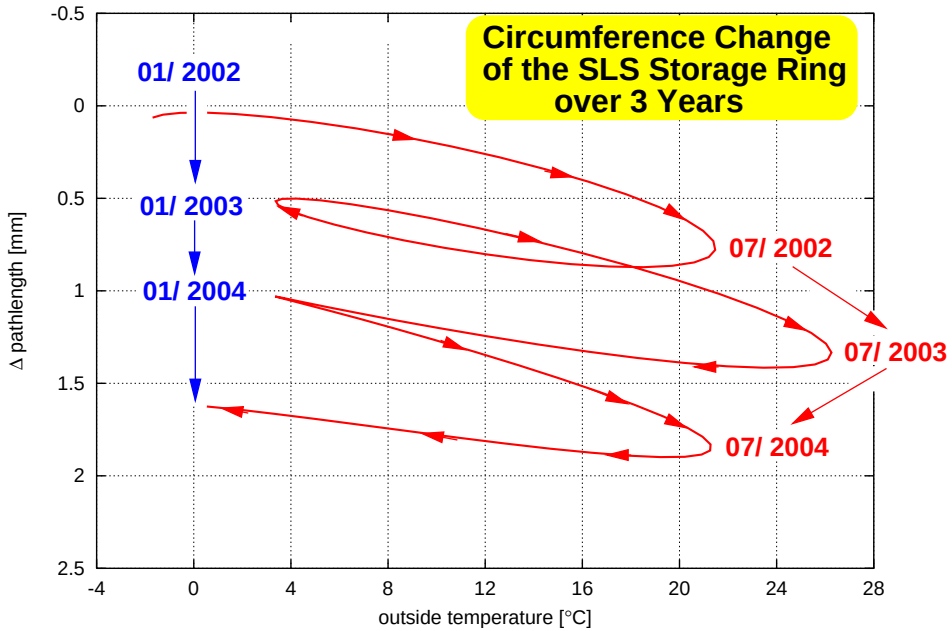


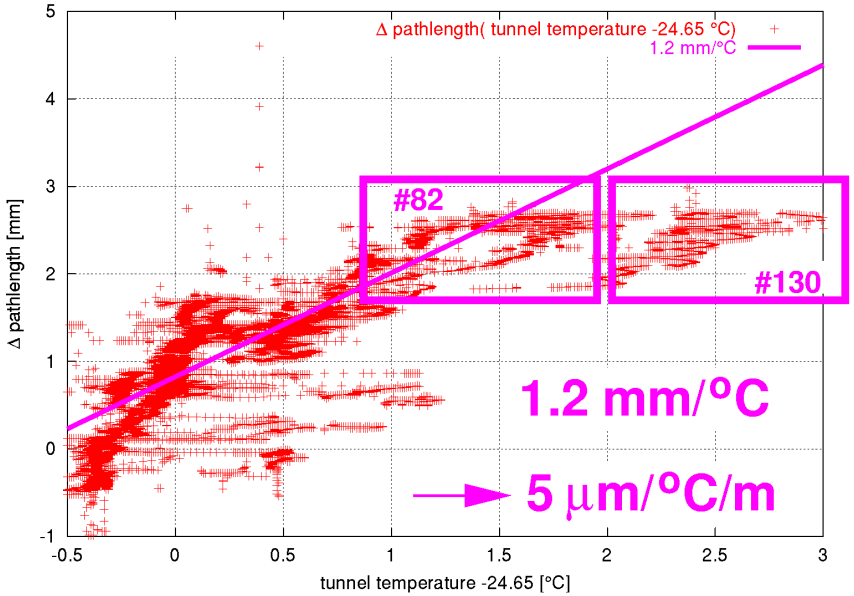


- Severe problems with the cooling capacity of the SLS during the hot summer 2003 (#82)! Again "scheduled" problems in 2004 (#130) due to the cooling system upgrade!

FOFB - Long Term Stability - Temperature Stability

- Fitted circumference change over 3 years of SLS operation ($\rightarrow$ Δ circumference $\approx$ 2 mm) as a function of the fitted **outside temperature** (left plot)
- Circumference change as a function of the average **tunnel temperature** (right plot)





- Stabilization of the **tunnel temperature** to $\approx \pm 0.1°$ is needed to guarantee sub-micron movement !

FOFB - Outlook - Limitations

BPM system operates at its limit (computing power, hardware, network)
Design age ~ 10 yrs: no spare parts, risk of failures due to aging

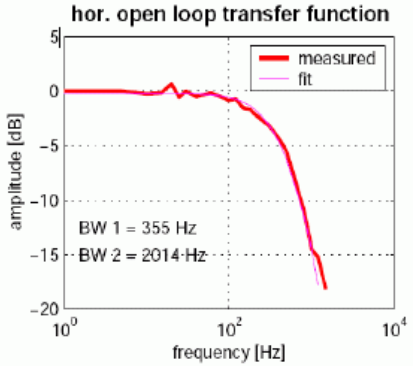
New system: possibilities ↔ requirements ?

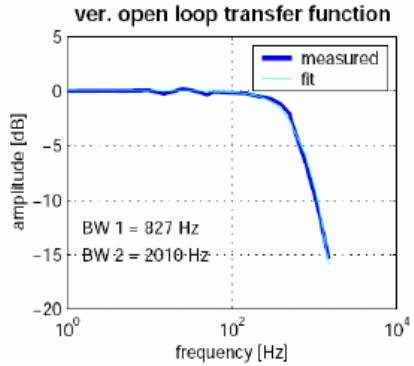
Higher resolution: 300 nm → 100 nm ?

Higher frequency: 100 Hz → 200 Hz ?

limited by vacuum chamber & magnet iron →

⇨ Local kHz FB for IR-beamline ?



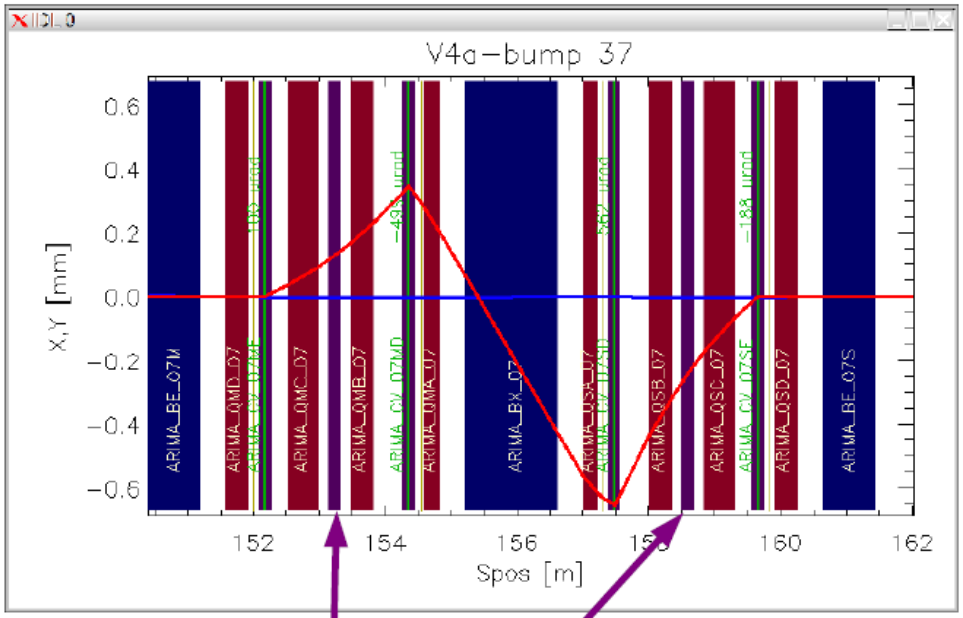


XBPM upgrade: 1 Hz → 4 kHz (new electronics) → **X–BPM FOFB @ 4 kHz**

FOFB - Outlook - Upgrades

Vertical bump ±300 μrad at few Hz

Frequency spectrum < 100 Hz for FOFB !



Orbit excursion in **sextupoles**

➔ **coupling increase by 0.8‰**

⇩

Coupling Feed Forward:

☺ all sextupoles have additional coils to be used as correctors or **skew quads**

⇨ Get power supplies for available sextupoles SF-07M, SF-07S

⇨ Drive local skew quadrupole ramps

➔ **coupling increase by 0.08‰** ✔

Plans for integration of 48 skew quads within the FOFB loop in order to make user bumps "coupling transparent" & to correct local coupling.