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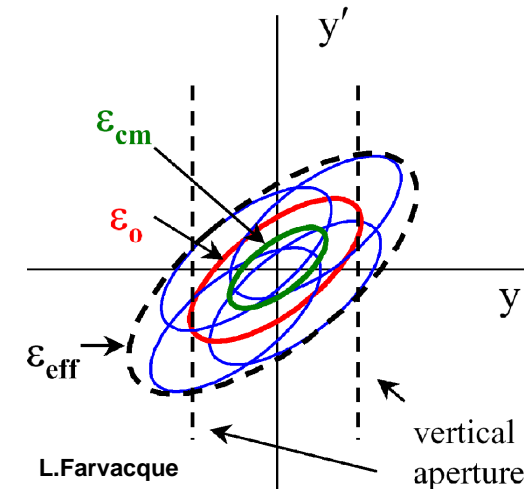
Rabbit Stabilization

INTRODUCTION

Table 1: Typical stability requirements for selected measurement parameters common to a majority of experiments (Courtesy R. Hettel)

Measurement parameter	Stability requirement
Intensity variation $\Delta I/I$	$< 0.1\%$ of normalized I
Position and angle accuracy	$< 1\%$ of beam σ and σ'
Energy resolution $\Delta E/E$	$< 0.01\%$
Timing jitter	$< 10\%$ of critical t scale
Data acquisition rate	$\approx 10^{-3} - 10^5$ Hz
Stability period	$10^{-2(3)} - 10^5$ sec

\Rightarrow **Stabilization of the electron beam in its 6D phase space to meet stability requirements for the photon beam parameters.** Effect of photon beam instability on flux depends on the time scale of the fluctuation τ_f relative to the detector sampling and data integration times τ_d :



- $\tau_d \gg \tau_f$:
 $\epsilon_{\text{eff}} = \epsilon_0 + \epsilon_{\text{cm}}$:
 Motion of $\approx 30\%$ of σ and σ'
 \Rightarrow *smearred out*
 \Rightarrow **10 %** increase in ϵ_{eff}
- $\tau_d \ll \tau_f$:
 $\epsilon_{\text{eff}} \approx \epsilon_0 + 2\sqrt{\epsilon_0 \epsilon_{\text{cm}}} + \epsilon_{\text{cm}}$:
 Motion of $\approx 5\%$ of σ and σ'
 \Rightarrow *new measurement noise*
 \Rightarrow **10 %** increase in ϵ_{eff}

INTRODUCTION

Since most 3rd generation light sources feature:

- **low beta (≈ 1 m) straights** (SOLEIL: ≈ 1.8 m) in order to allow for
- **low gap (< 10 mm) insertion devices (IDs)** (SOLEIL: U20: 5.5-70 mm)

and operate at:

- **very small emittance coupling (< 1 %) values** with
- **horizontal design emittances of just a few (< 10 nm·rad)**
(SOLEIL: 3.73 nm·rad @ 2.75 GeV)

the requirements compiled in Table 1 lead to:

- **sub-micron tolerances for the vertical positional and angular stability of the electron beam @ the ID source points** over a large frequency range Δf : 10^{-5} - $10^{2(3)}$ Hz (timescale: msec - hours/days):
- $\sigma_{cm} < 1\mu\text{m}$ (SOLEIL: $< 0.8\mu\text{m}$) and $\sigma'_{cm} < 1\mu\text{rad}$ (SOLEIL: $< 0.5\mu\text{rad}$)

NOISE SOURCES**Short term (<1 hour):**

Ground vibration induced by human activities, mechanical devices like compressors and cranes or external sources like road traffic potentially attenuated by concrete slabs, amplified by girder resonances and spatial frequency dependent orbit responses, ID changes (fast polarization switching IDs <100 Hz), cooling water circuits, power supply (PS) noise, electrical stray fields, booster operation, slow changes of ID settings, “top-up” injection. Sources of beam motion associated with synchrotron oscillations and single- and coupled bunch instabilities are not considered.

Medium term (<1 week):

Movement of the vacuum chamber (or even magnets) due to changes of the synchrotron radiation induced heat load especially in decaying beam operation, water cooling, tunnel and hall temperature variations, day/night variations, gravitational sun/moon earth tide cycle.

Long term (>1 week):

Ground settlement and seasonal effects (temperature, rain fall) resulting in alignment changes of accelerator components including girders and magnets.

msec



sec



hours



days

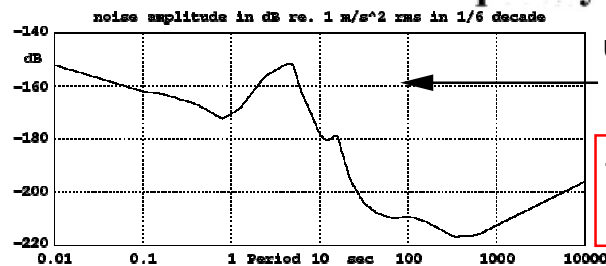
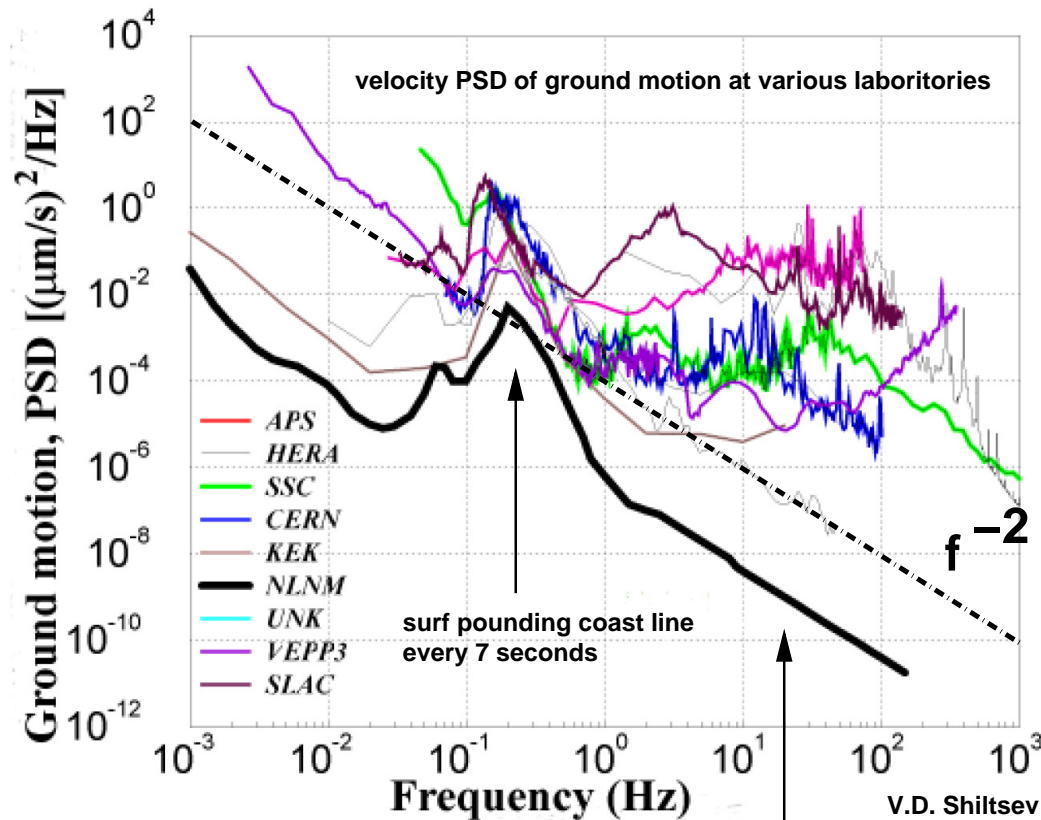


weeks



years

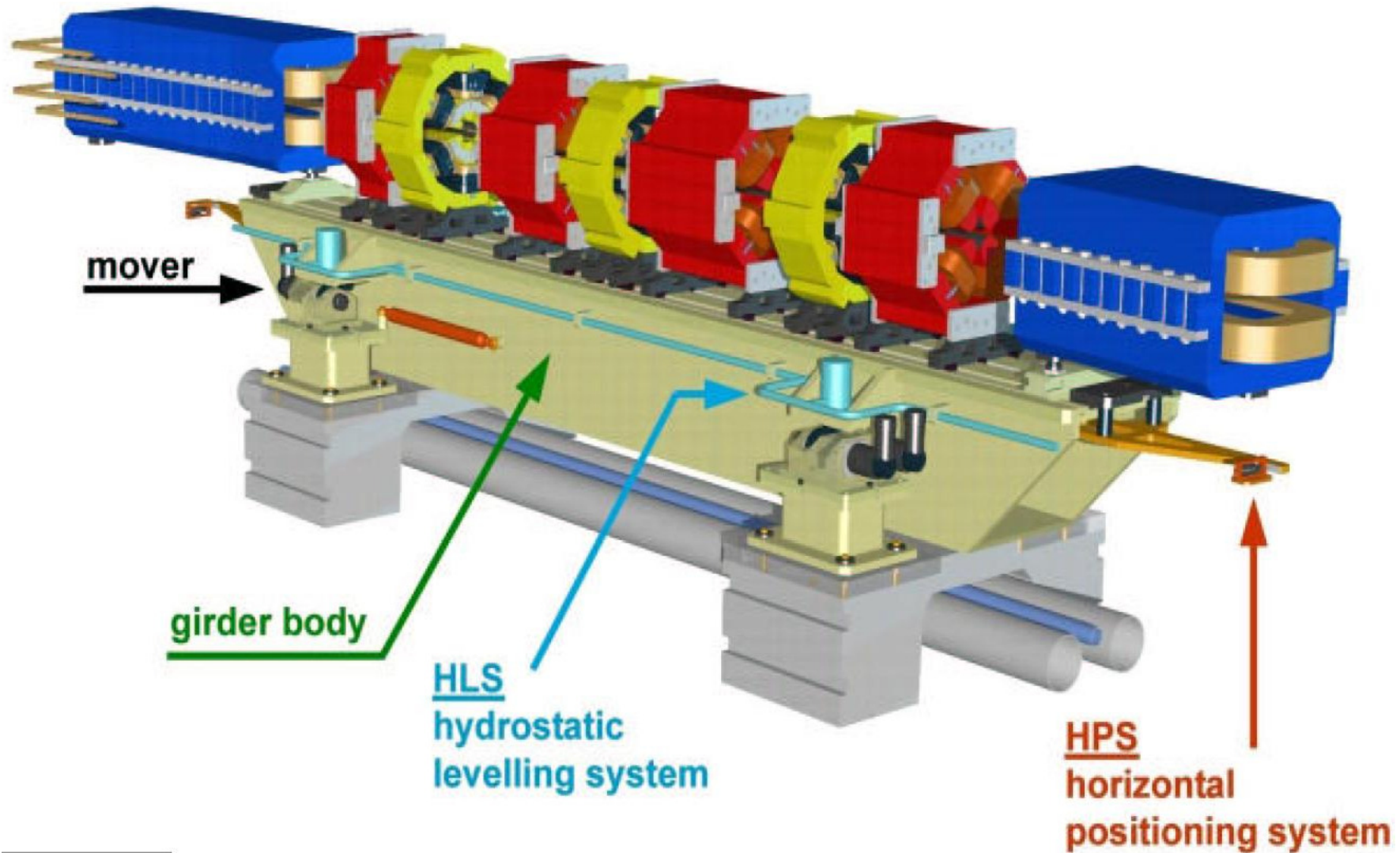
SHORT TERM STABILITY - Ground Motion



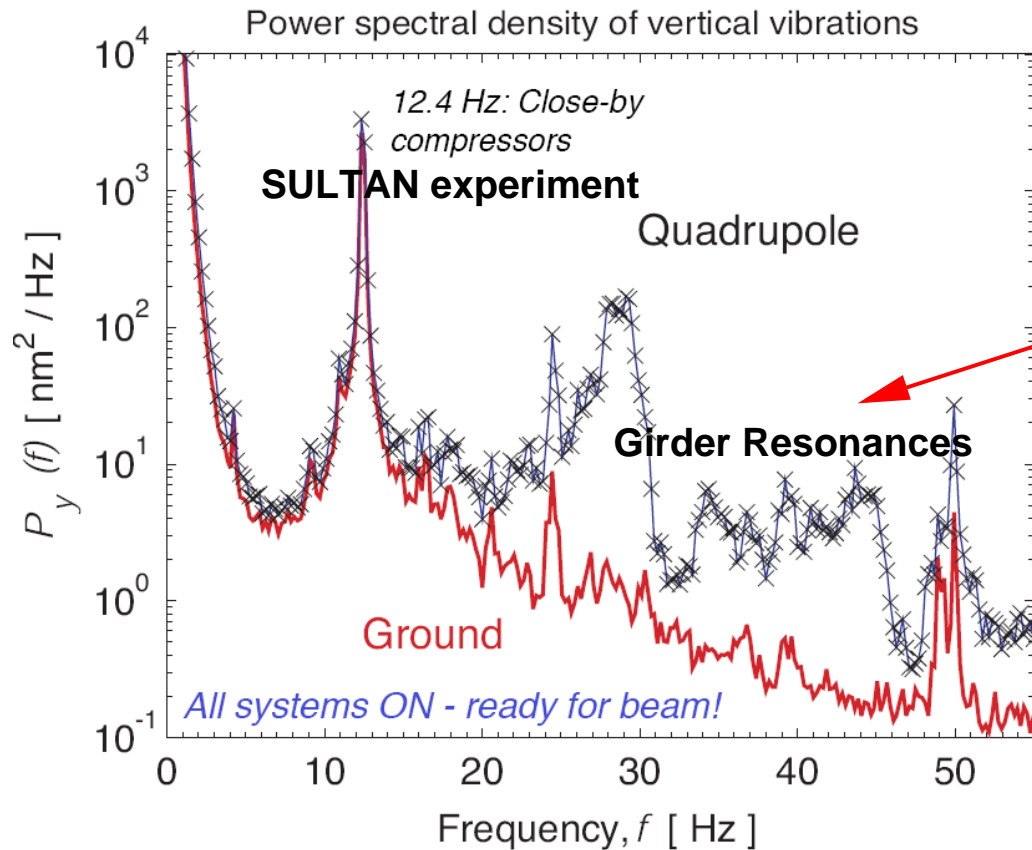
USGS New Low Noise Model (NLNM):
Summarizes the lowest observed seismic
noise levels throughout the freq. band

The PSD in position drops of faster
by a factor of $f^{-2} \rightarrow f^{-4}$

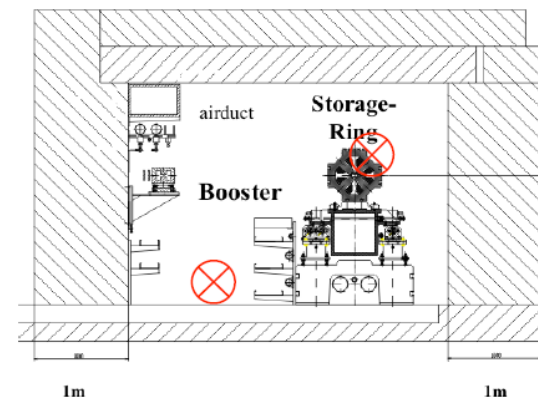
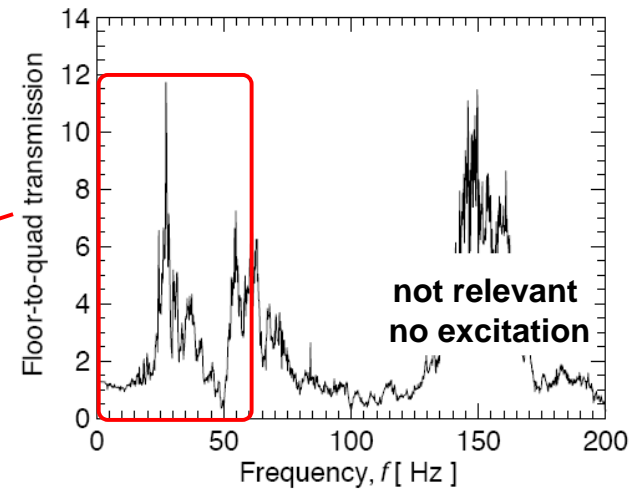
SHORT TERM STABILITY - Girder Design (SLS)



SHORT TERM STABILITY (SLS)



Transmission = amplification of GM due structural resonances of girder and quad.

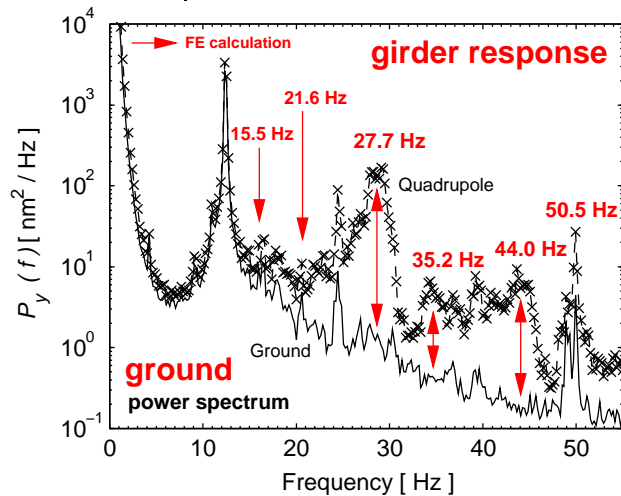


S. Redaelli

Overall motion above 4 Hz: Floor → ~ 30 nm
Quad → ~ 50 nm

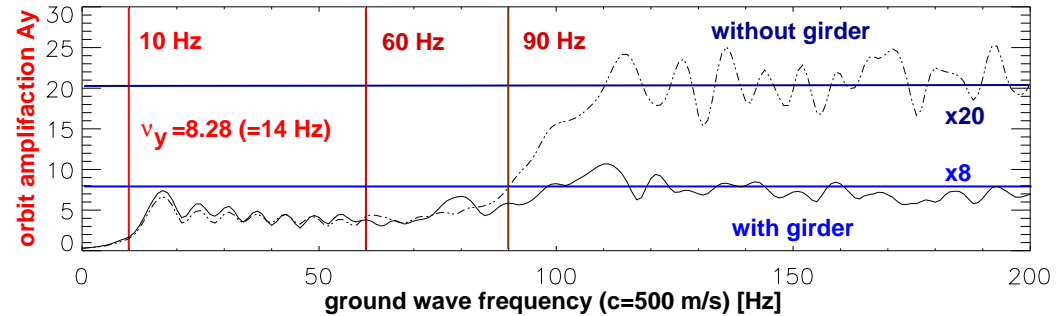
SHORT TERM STABILITY (SLS)

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

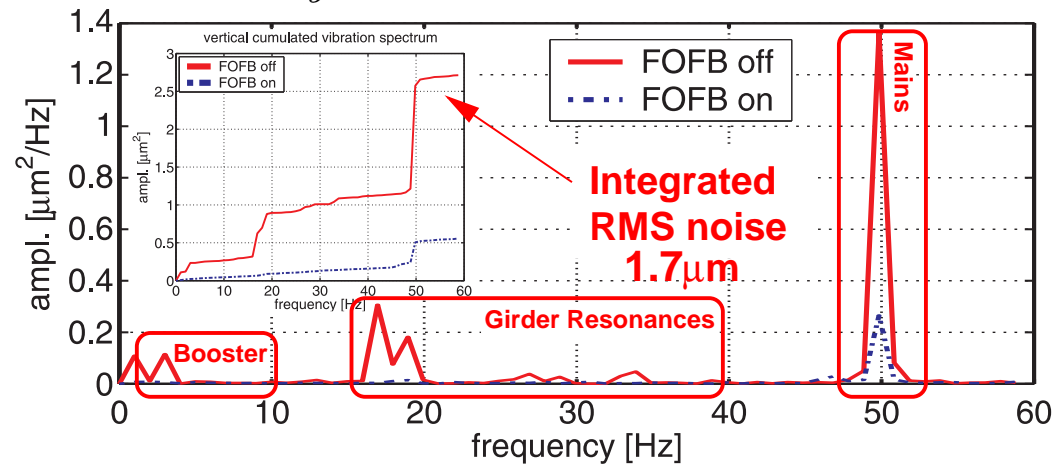


Vertical vibration PSD (1-55 Hz) measured on the slab and a girder (S. Redaelli).

Vertical orbit amplification factor A_y for planar waves:

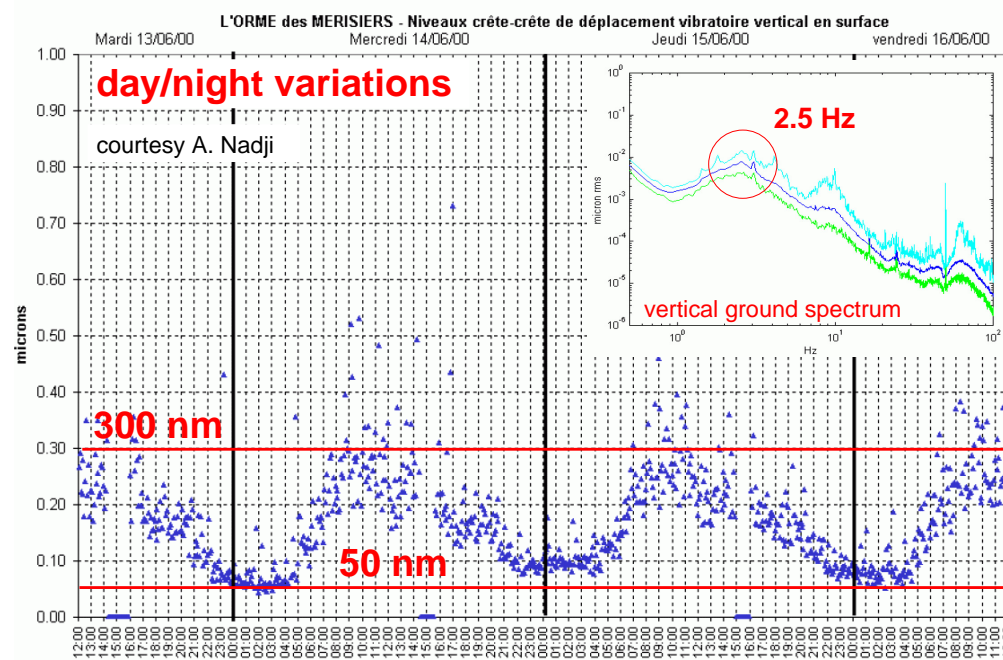


Vertical orbit PSD (1-60 Hz) without and with orbit feedback @ BPM ($\beta_y = 18$ m) (T. Schilcher):



\Rightarrow Integrated RMS motion σ_y only $\approx 0.4 \mu\text{m} \cdot \sqrt{\beta_y}$!

SHORT TERM STABILITY (SOLEIL)



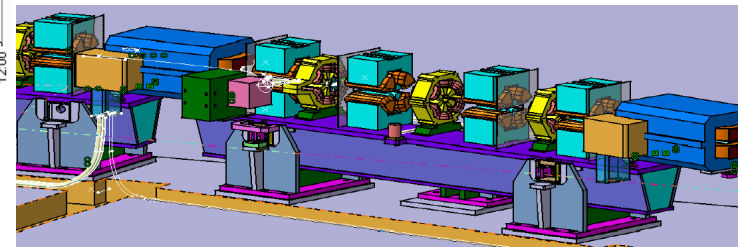
Vertical day/night variations and ground vibration spectrum ($\approx 1-100$ Hz) \Rightarrow **planar wave @ 2.5 Hz with amplitude 800 nm peak-to-peak !**

Reason: trucks with suspension resonance frequencies of ≈ 2.5 Hz (close to typical frequency of the ground) on nearby roads going typically @ 60 km/h (\Rightarrow repair of the paving).

Orbit Ampl.	A_x	A_y
Without girders	30	10
With girders	16	3
Reduction	1.9	3.3

Careful girder design:

- 3 jacks
- 4 supports in upper part of girder
- No rc'ed girder movers (\Rightarrow SLS)



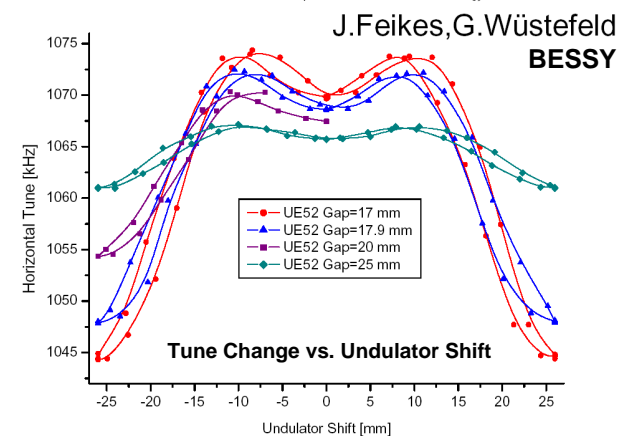
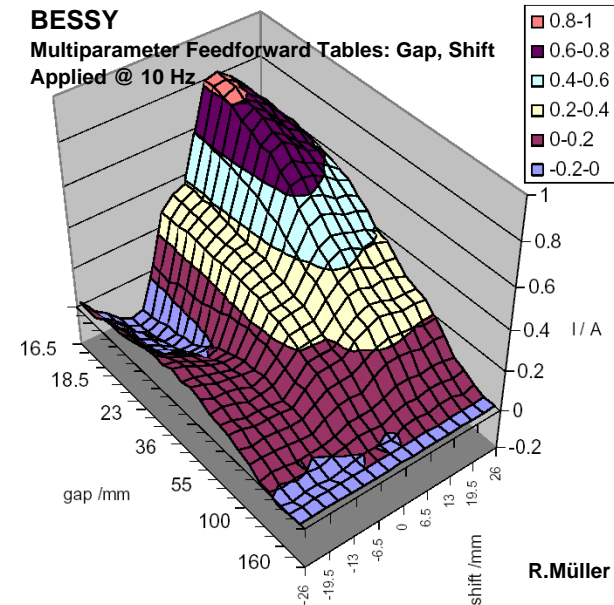
Eigenmodes	1st	2nd	3rd
f [Hz]	46.8	47	54

\Rightarrow **No amplification of planar wave !**

J.M. Filhol

SHORT TERM STABILITY

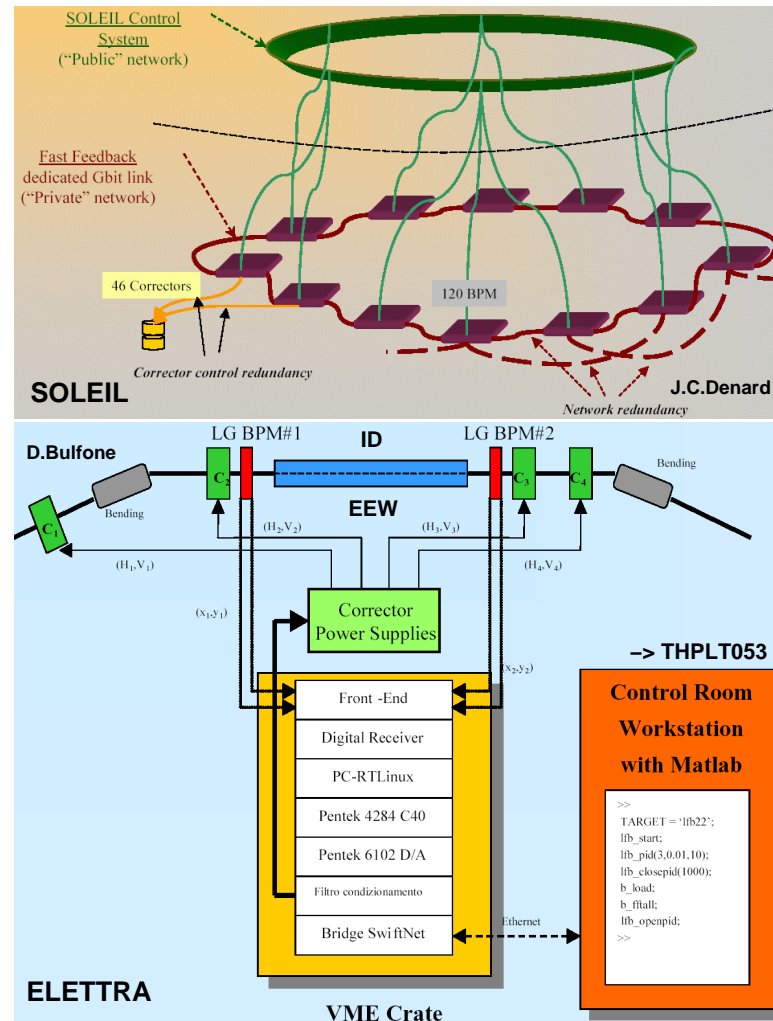
This suggests that a **proper mechanical design can assure short term orbit stability on the micron or even sub-micron level**. Thus the operation of the installed IDs becomes the dominant contribution to the short term noise. Since most of the disturbances are of systematic nature and therefore reproducible, **feed-forward correction tables can help to minimize the perturbation**. Nevertheless the remaining noise is significant and needs to be attenuated by orbit feedback systems featuring large correction bandwidths **>100 Hz !**



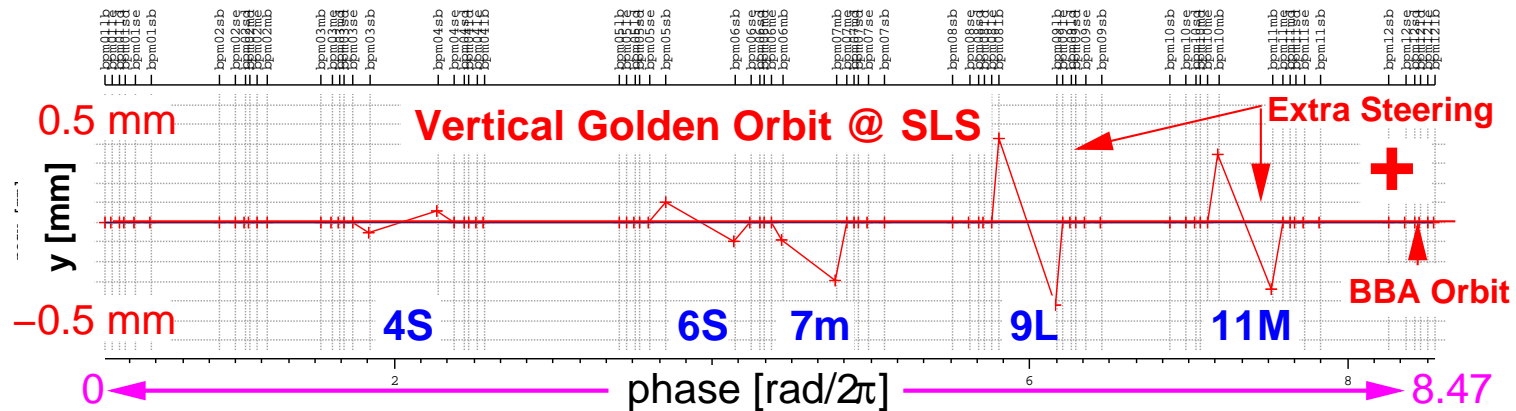
SHORT TERM STABILITY - Orbit Feedbacks

Orbit feedbacks can be divided in two classes:

- **Global feedbacks** compensate for perturbations generated by all IDs based on global orbit and/or photon beam positions by means of global correction.
- **Local feedbacks** compensate for perturbations generated by individual IDs based on local orbit and/or photon beam positions by means of local correction in the vicinity of the IDs.



SHORT TERM STABILITY - BBA/Golden Orbit



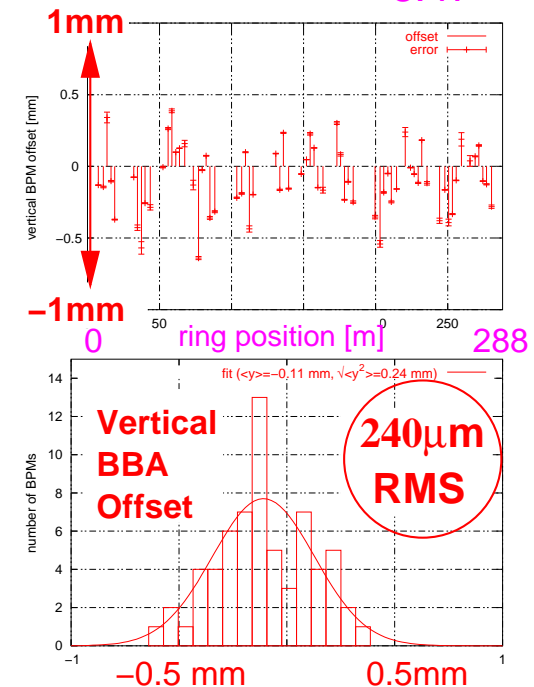
Golden Orbit: goes through centers of quadrupoles and sextupoles in order to minimize optics distortions leading to spurious vertical dispersion and betatron coupling (emittance coupling) + extra steering @ IDs

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 electrical properties of BPM
RMS offset even for well aligned machines $>100\mu\text{m}$!**

DC RMS corrector strength reduced when correcting to BBA orbit !



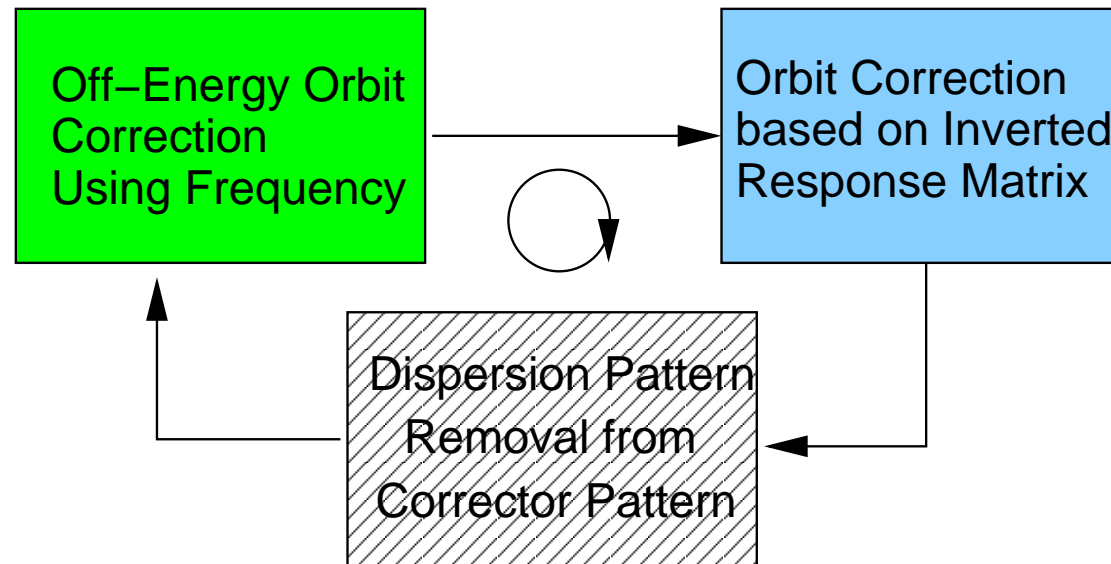
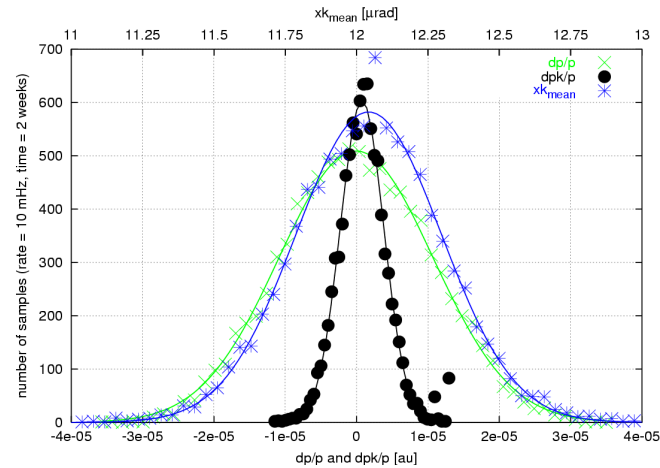
SHORT TERM STABILITY - Orbit Correction

Remarks on matrix inversion:

- Since modern light sources are built with very tight alignment tolerances and BPMs are well calibrated with respect to adjacent quadrupoles, orbit correction by matrix inversion in the $n \times n$ case has become an option since
 - resulting RMS corrector strength is still moderate (typically $\approx 100 \mu\text{rad}$)
 - BPMs are reliable and their noise is small (no BPM averaging is performed which is similar to a local feedback scenario)
- This allows to establish any desired “golden orbit” within the limitations of the available corrector strength and the residual corrector/BPM noise.

Remarks on horizontal orbit correction:

- Dispersion orbits due to “path length” changes (circumference, model-machine differences, rf frequency) need to be corrected by means of the rf frequency f .
- A gradual build-up of a dispersion D related corrector pattern $\sum A_{ji}^{-1} D_i$ with a nonzero mean must be avoided \Rightarrow leads together with rf frequency change to a corrected orbit at a different beam energy.
- Subtract pattern $\sum A_{ji}^{-1} D_i$ from the actual corrector settings before orbit correction in order to remove ambiguity.

SHORT TERM STABILITY - Orbit Correction

SHORT TERM STABILITY - Feedback Implementation I

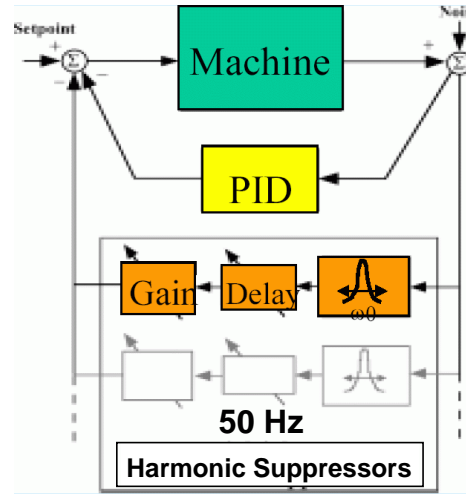
In order to implement a global orbit feedback based on the described algorithm which stabilizes the electron beam with respect to the established “Golden Orbit” up to frequencies ≈ 100 Hz with sub-micron in-loop stability the following is needed:

- BPM data acquisition rates of at least ≈ 1 -2 kHz.
- Integrated BPM noise must not exceed a few hundred nanometers (achieved with modern digital four channel (parallel) and analog multiplexed systems).
- A fast network for BPM data distribution around the ring or a central point since every **Corrector j** in general depends on all **BPM i** readings.
- Since matrix multiplications with the **BPM i** vector can be parallelized a distribution on several CPU units handling groups of **Corrector j** is a natural solution.
- “Inverted” matrix can be sparse depending on the **BPM/Corrector** layout such that most of the off-diagonal coefficients are zero \Rightarrow only subset of all BPM readings in the vicinity of the individual correctors determines their correction values.

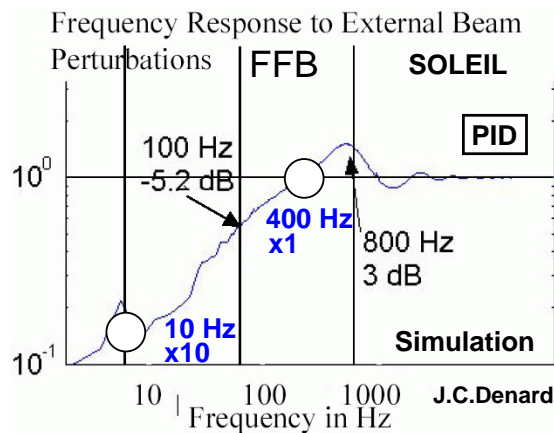
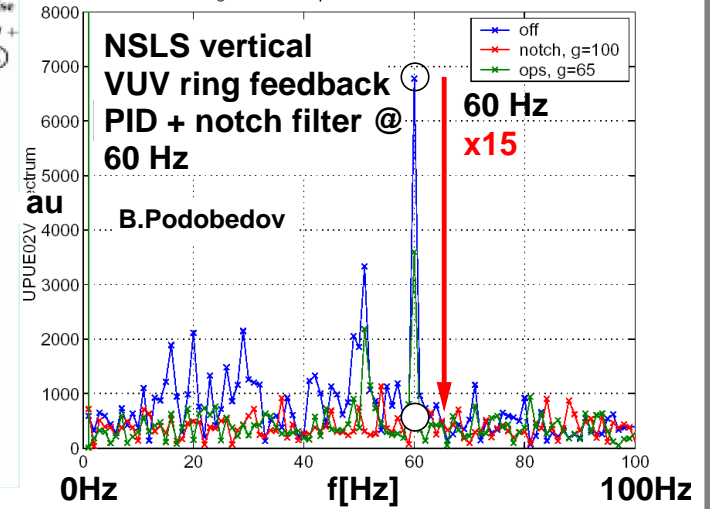
*At the SLS 73 BPMs with adjacent **Correctors** in both planes, phase advance between **Correctors** $< 180^\circ \Rightarrow$ inverted **73x73** matrix “resembles” a correction with interleaved closed orbit bumps made up from 3 successive **Correctors** (“Sliding Bump Scheme”).*

SHORT TERM STABILITY - Feedback Implementation II

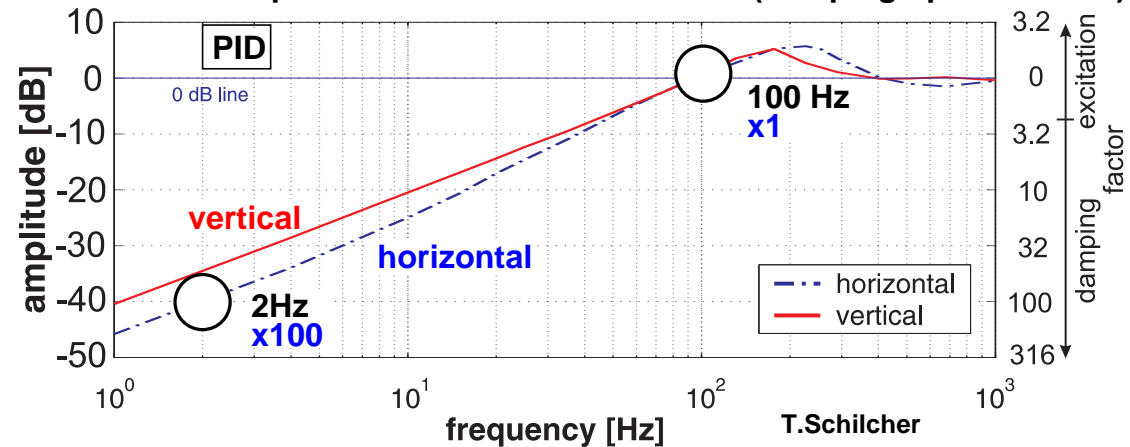
- Feedback loop closed with PID controller function optimizing **gain, bandwidth and stability** of the loop.
- **Notch filters** allow to add additional “**harmonic suppression**” (D. Bulfone) of particularly strong lines at 50/60 Hz.



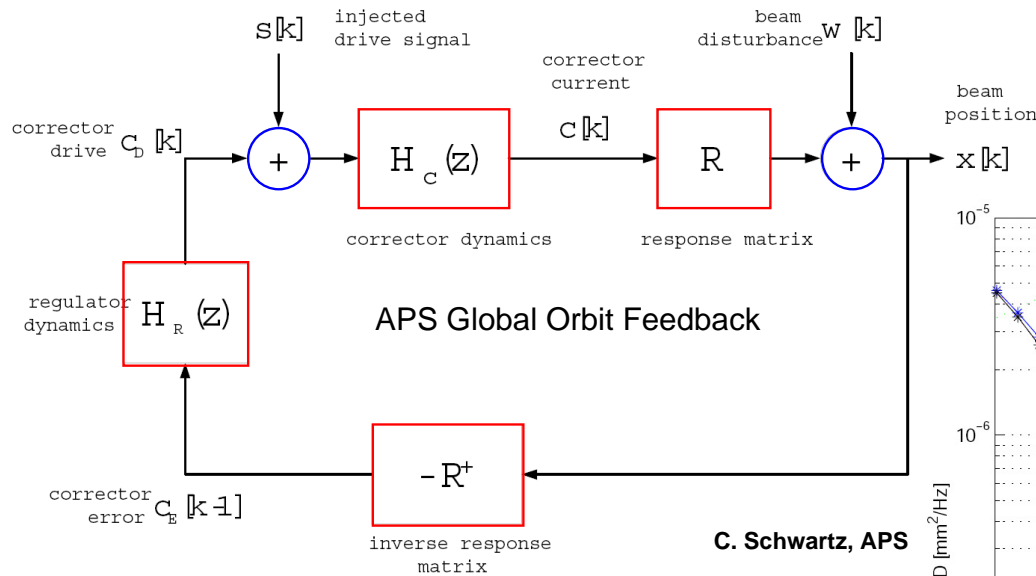
ELETTRA D. Bulfone



Closed loop transfer functions at the SLS (damping up to ~100 Hz)



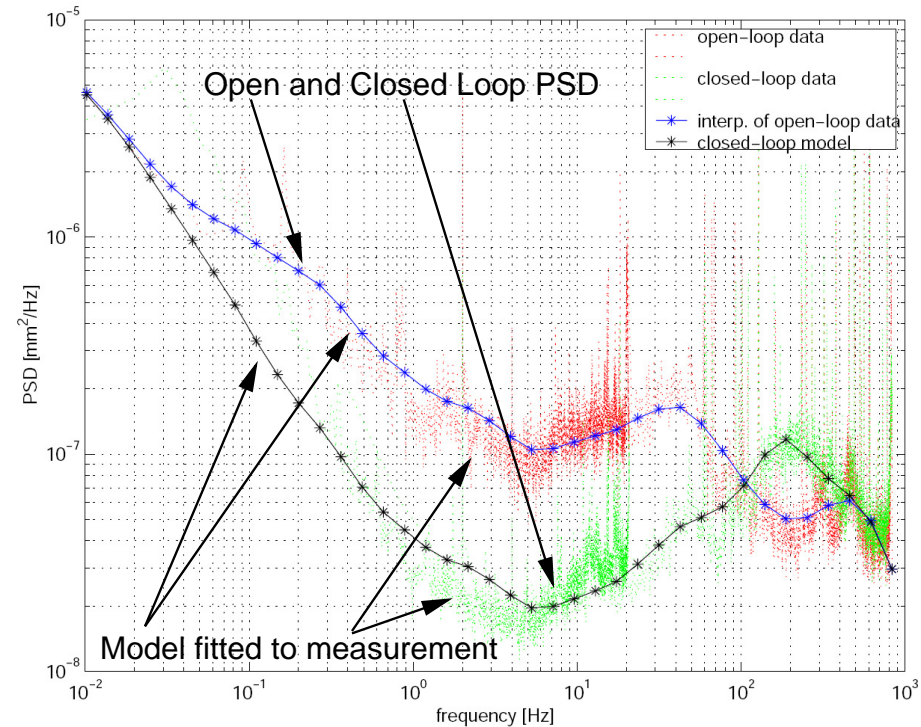
SHORT TERM STABILITY - Feedback Implementation III



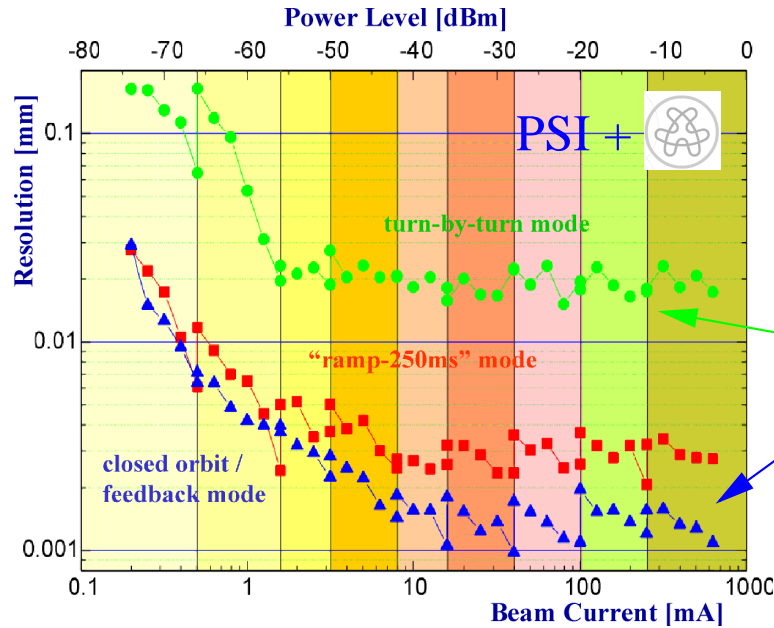
Simulation of the Fast Orbit Feedback loop at APS gives good agreement with measurements of open and closed loop PSDs.

Helps to derive specifications for the various components of a feedback in the design phase.

Allows to change feedback parameters in simulation without touching the running feedback.



SHORT TERM STABILITY - Feedback Implementation IV



Only One BPM System in Different Operation Mode for All Machines

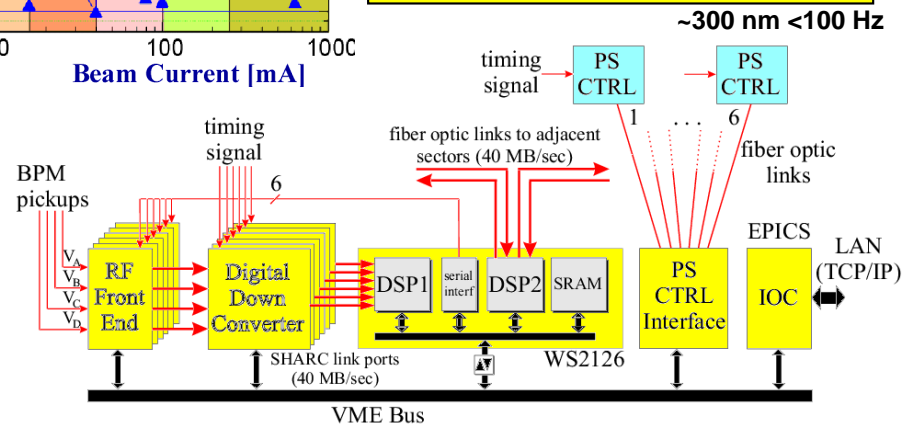
Turn-by-Turn:

1 MSample/s, <math>< 20 \mu m</math>

Closed Orbit:

4 KSample/s, <math>< 0.8 \mu m</math>

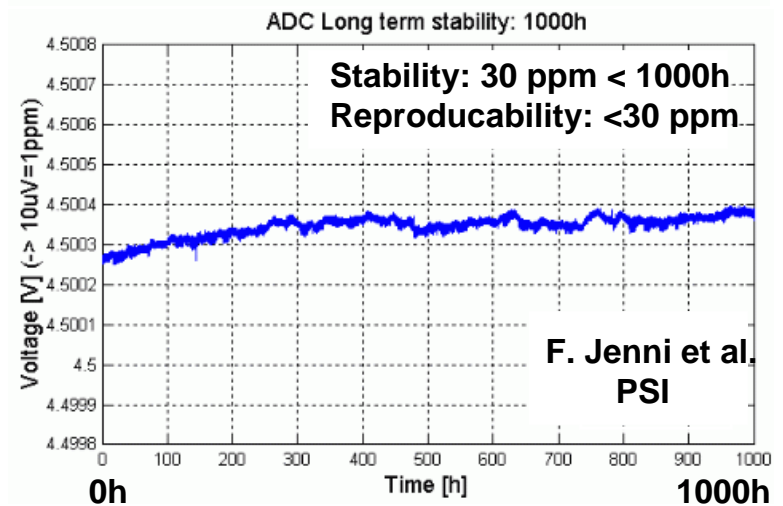
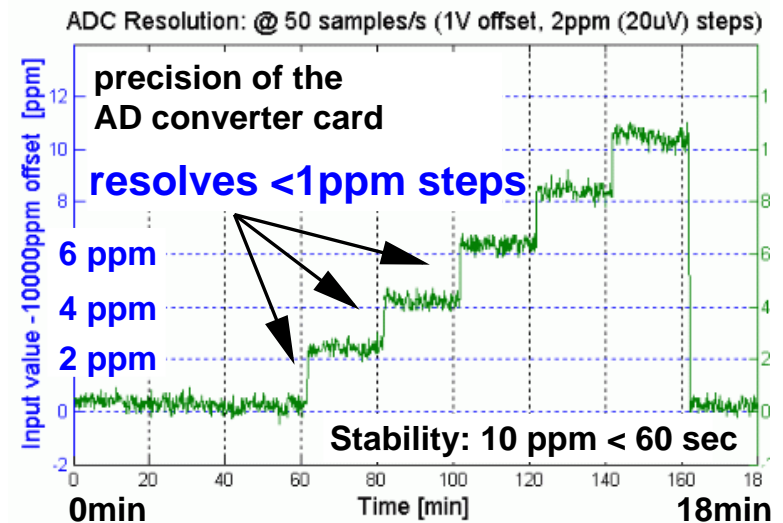
Turn-by-Turn:
Vital for
Commissioning



Closed Orbit Mode \rightarrow Fast Orbit Feedback

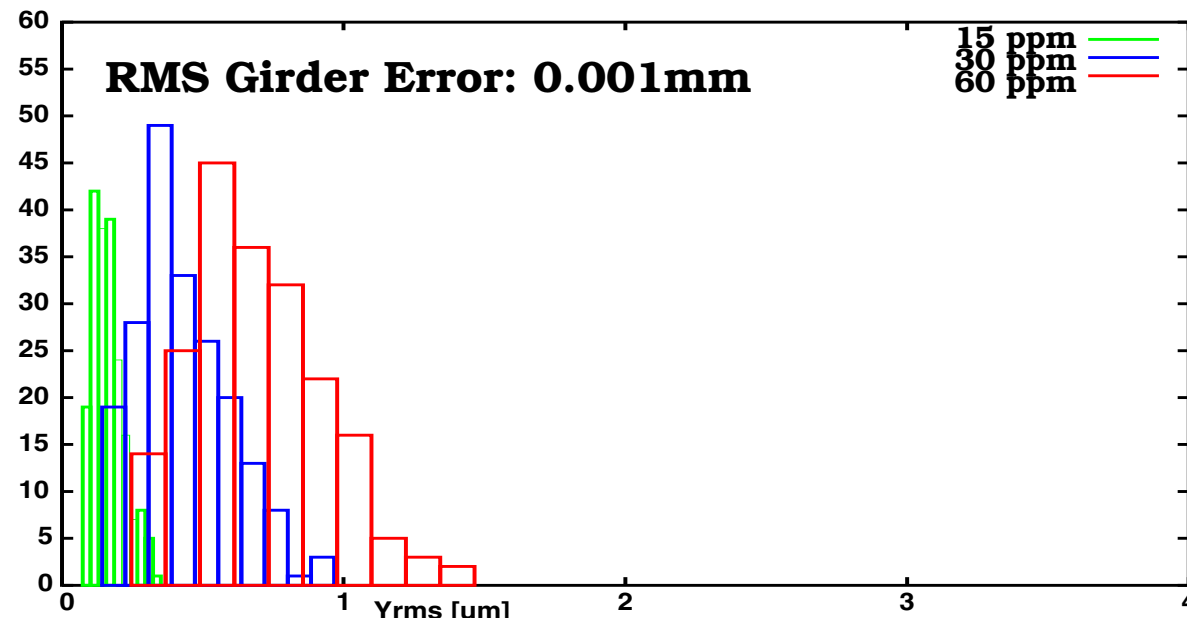
SHORT TERM STABILITY - Feedback Implementation V

- Minimum correction strength defined by power supply (PS) resolution for a strength range Δk must be within the BPM noise: **typically ≈ 10 nrad $\Rightarrow \approx 18$ bit (≈ 4 ppm) resolution for a PS with $\Delta k \pm 1$ mrad.**
- **PS with digital control** have reached noise figures of **< 1 ppm providing kHz small-signal bandwidth \Rightarrow possibility to use the same correctors for DC and fast correction (\Rightarrow SLS).**
- Eddy currents induced in the vacuum chamber should not significantly attenuate or change the phase of the effective corrector field up to the data acquisition rate.
- Eddy currents are proportional to the thickness and electrical conductivity of materials \Rightarrow **thin laminations (≤ 1 mm thickness) or air coils (\Rightarrow SOLEIL) should be used.**
- Low conductive materials preferred for vacuum chambers. Eddy currents in vacuum chambers impose the most critical bandwidth limitation on the feedback loop.



SHORT TERM STABILITY - Feedback Implementation VI

Optics Code TRACY estimates Residual Vertical RMS Orbit after Orbit Correction as seen by the BPMs (histograms for 200 seeds introducing RMS girder misalignment of $1\mu\text{m}$) for the SLS:

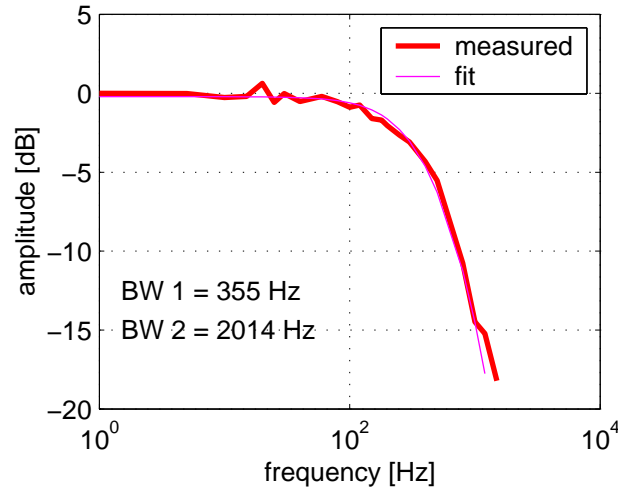


- 1 ppm in amplitude corresponds to a resolution of 10^{-6} at a maximum Current of 7 A ($\approx 860 \mu\text{rad}$ in the vertical plane)
- **60 ppm**: $y_{rms} = 0.75\mu\text{m}$, **30 ppm**: $y_{rms} = 0.5\mu\text{m}$, **15 ppm**: $y_{rms} = 0.25\mu\text{m}$

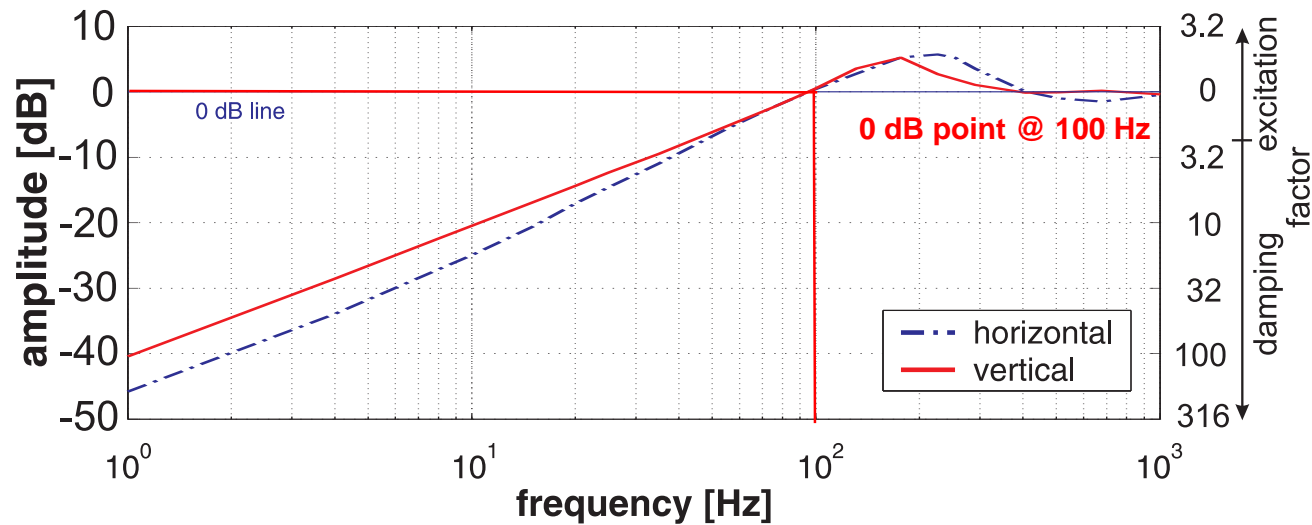
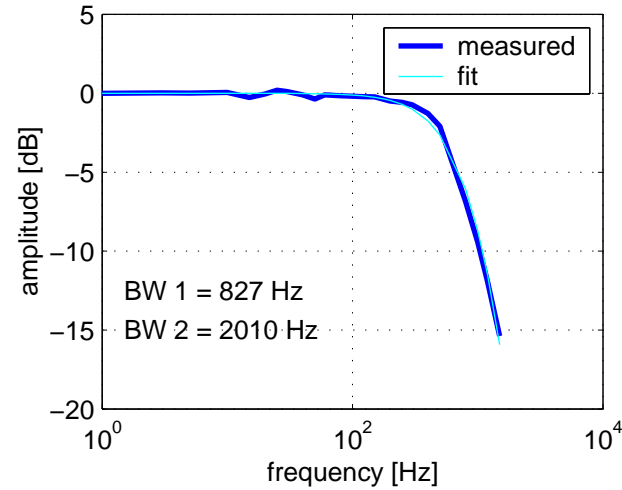
\Rightarrow 15 ppm ($\approx 10 \text{ nrad}$ or $100 \mu\text{A}$) sufficient

SHORT TERM STABILITY - Open & Closed Loop Transfer Functions (SLS)

hor. open loop transfer function



ver. open loop transfer function



SHORT TERM STABILITY - Feedbacks at LS Worldwide

SR Facility	BPM Type	max. BW	Stability
ALS	RF-BPMs	<50 Hz	<1 μm
APS	RF&X-BPMs	50 Hz	<1 μm
ESRF	RF-BPMs	100 Hz	<0.6 μm
NSLS	RF&X-BPMs	<200 Hz	1.5 μm
SLS	RF&X-BPMs	100 Hz	<0.3 μm
Super-ACO	RF-BPMs	<150 Hz	<5 μm
<u>BESSY</u>	RF-BPMs	<100 Hz	<1 μm
<u>DELTA</u>	RF-BPMs	<150 Hz	<2 μm
<u>DIAMOND</u>	RF-BPMs	150 Hz	0.2 μm
<u>SOLEIL</u>	RF-BPMs	150 Hz	0.2 μm
<u>SPEAR3</u>	RF-BPMs	100 Hz	<3 μm
<u>SPring-8</u>	RF-BPMs	100 Hz	<1 μm
APS	X-BPMs	50 Hz	<1 μm
BESSY	X-BPMs	50 Hz	<1 μm
ELETTRA	RF-BPMs	80 Hz	0.2 μm

Compilation of
operational global,
proposed global
operational local
 fast orbit feedbacks at light
 sources worldwide *from*
V.Schlott, EPAC'02

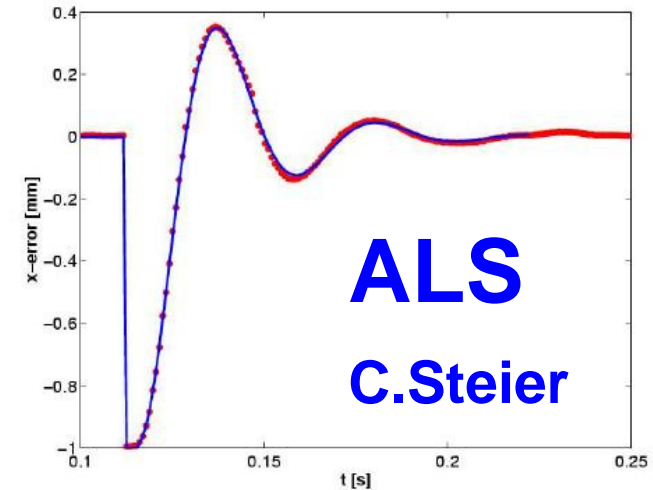
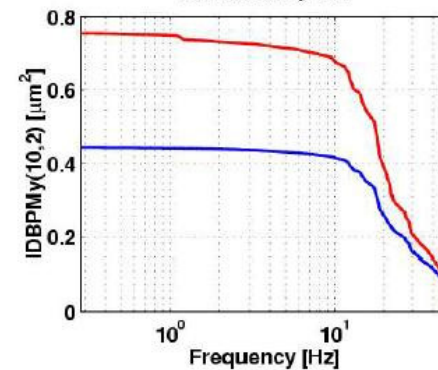
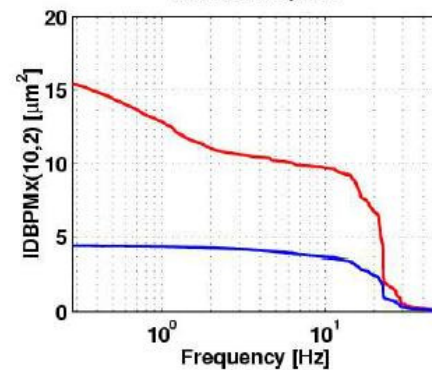
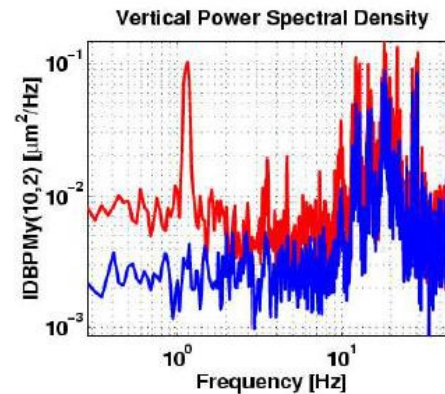
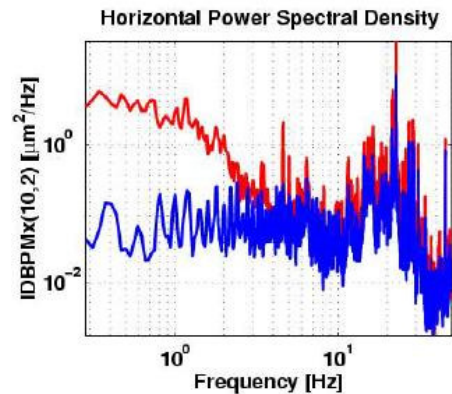
Not in list:

PETRA-3

ELETTRA

NSLS-II

SHORT TERM STABILITY - ALS



- Combination of fast and slow global orbit feedbacks in both planes – no frequency deadband
- Fast Feedback currently 24 BPMs in each plane and 22 correctors in each plane. 1.11 kHz update rate, bandwidth DC-40 Hz.
- Slow Feedback 52 BPMs in each plane, 26 horizontal correctors, 50 vertical correctors, RF frequency correction. 1 Hz update rate, about 60% single step gain, bandwidth DC-0.1 Hz.
- Slow feedback communicates with fast feedback to avoid interference in frequency overlap range. Setpoints/golden orbit used by fast feedback is updated at rate of slow feedback.

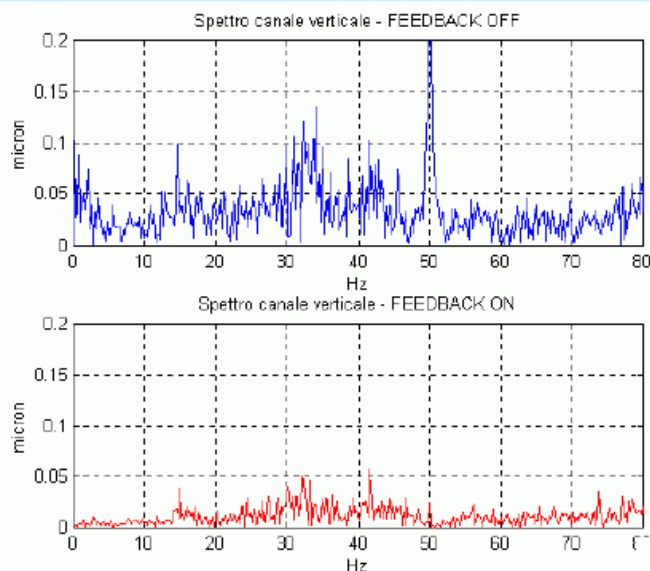
- Beam motion with feedback in open (red) and closed loop (blue).
- Feedback is quite effective up to about 40 Hz
- Correction at low frequencies down to the BPM noise floor (noise floor is not subtracted in above plots).

Global Feedback 1.1 KHz DC-40Hz

SHORT TERM STABILITY - Local Feedbacks

- Local fast orbit feedbacks stabilize orbit position and angle at ID centers locally without effecting the orbit elsewhere by a superposition of symmetric and asymmetric closed orbit bumps consisting of ≥ 4 correctors per plane around the ID.
- Photon BPMs (X-BPMs) which are located in the beam line frontends measuring photon beam positions provide very precise information about orbit fluctuations at the ID source point at a typical bandwidth of ≈ 2 kHz. *With two X-BPMs position and angle fluctuations can be disentangled. Unfortunately the reading depends on the photon beam profile and thus on the individual ID settings.*
 - APS is operating X-BPM based feedbacks on their dipole and ID X-BPMs at fixed gap.
 - BESSY has the prototype for an X-BPM based feedback on an APPLE II ID.
 - ELETTRA implemented a feedback for an electromagnetic elliptical wiggler (EEW) based on a new type of digital “low gap” BPM.
- **If several global and/or local feedbacks are operated they need to be decoupled.** Either they are well separated in frequency which evidently leads to **correction dead bands** (APS) or they run in a **cascaded master-slave configuration** (SLC,APS,ALS,SLS).

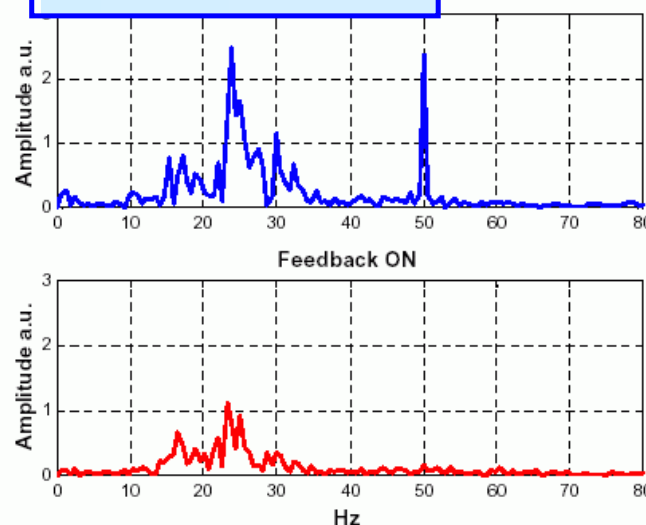
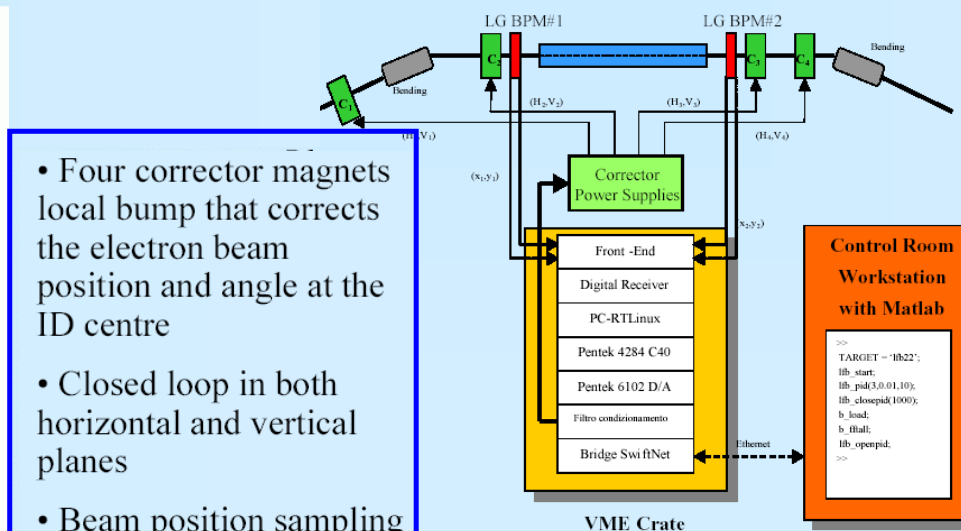
SHORT TERM STABILITY - ELETTRA



- Beam position spectra at low-gap BPM #1 with local feedback off/on. The rms of the position signal in the 0-80 Hz range is reduced from 1.24 μm to 0.2 μm .

Fast Local Feedback
@ EEW (Electromagnetic Elliptical Wiggler)

D. Bulfone



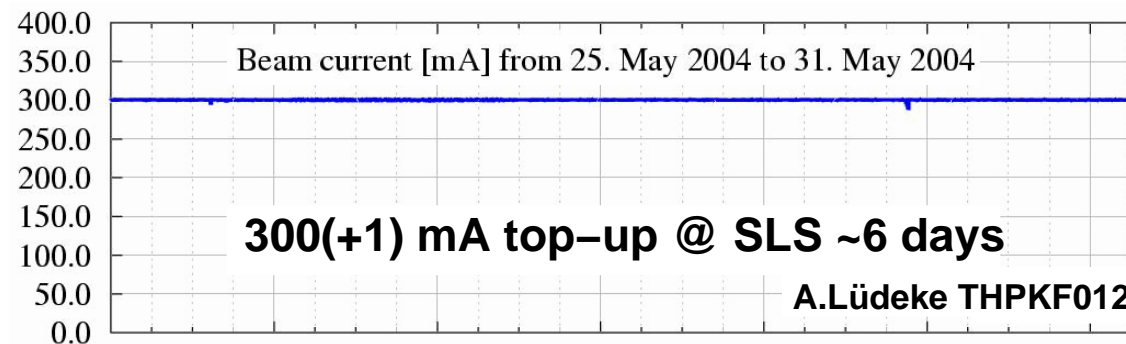
- Beam position spectra at photon-BPM along the corresponding beam-line

Beam position spectra at photon-BPMs at ELETTRA

MEDIUM TERM STABILITY

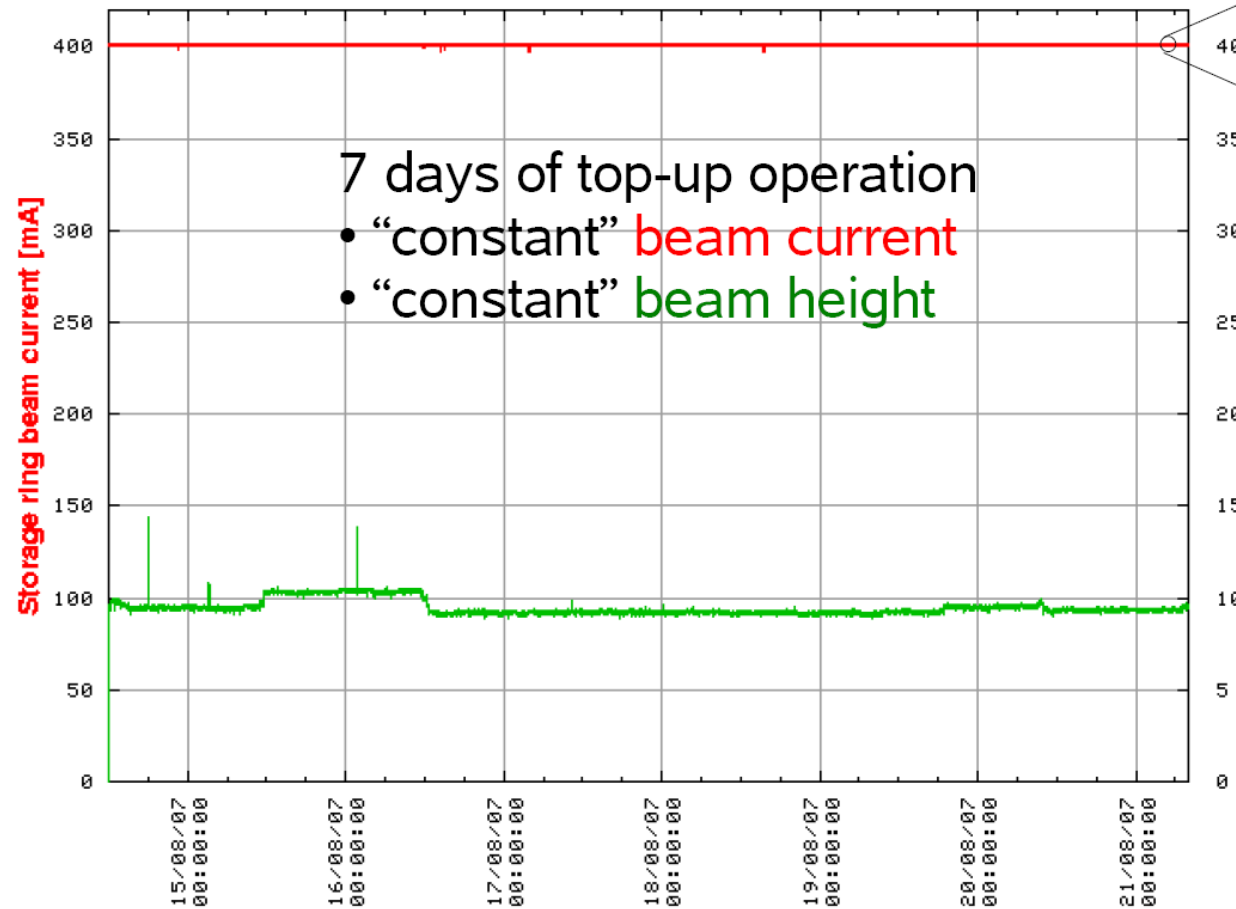
In this regime high mechanical stability is needed to achieve stability on the sub-micron level:

- Stabilization of tunnel, cooling water temperature and digital BPM electronics (T. Schilcher) to $\approx \pm 0.1^\circ$ and the experimental hall to $\approx \pm 1.0^\circ$.
- Minimization of thermal gradients by discrete photon absorbers and water-cooled vacuum chambers.
- Mechanical decoupling of BPMs with bellows, stiff BPM supports with low temperature coefficients (Invar (SPEAR3, SOLEIL), Carbon Fiber (ELETTRA) and/or monitoring of BPM positions (ELETTRA, SOLEIL, DIAMOND, SLS).
- Monitoring of girder positions (Hydrostatic Leveling System, Horizontal Positioning System (SLS)).
- Full energy injection and stabilization of the beam current to $\approx 0.1\%$ (“top-up” operation):



MEDIUM TERM STABILITY - Top-up I (SLS)

Top-up Operation

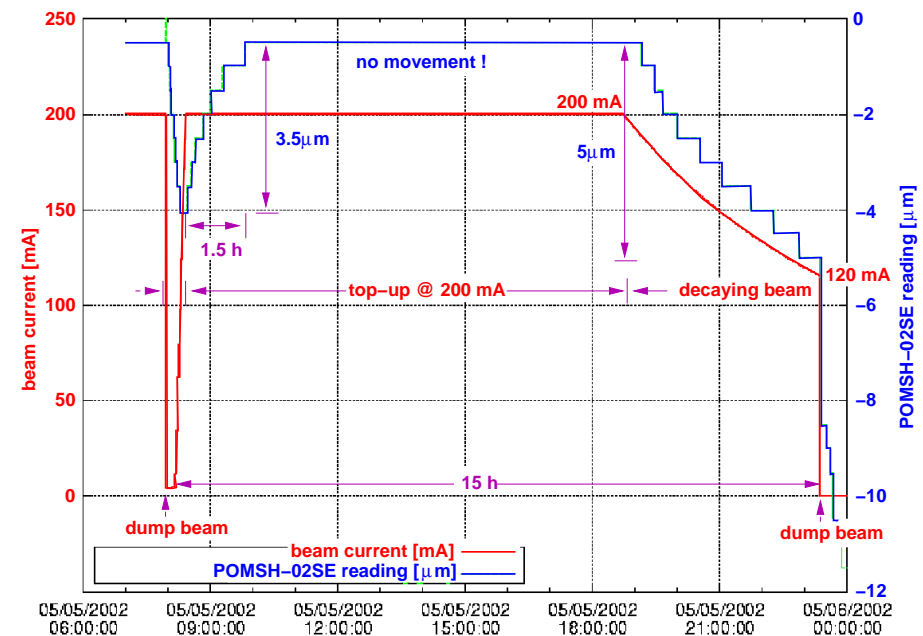


- Lifetime ~ 8 h for:
 - 400 mA
 - Coupling 0.13 %
 - $\epsilon_y = 7$ pmrad

→ inject ~ 1 mA every 100 sec

MEDIUM TERM STABILITY - Top-up II

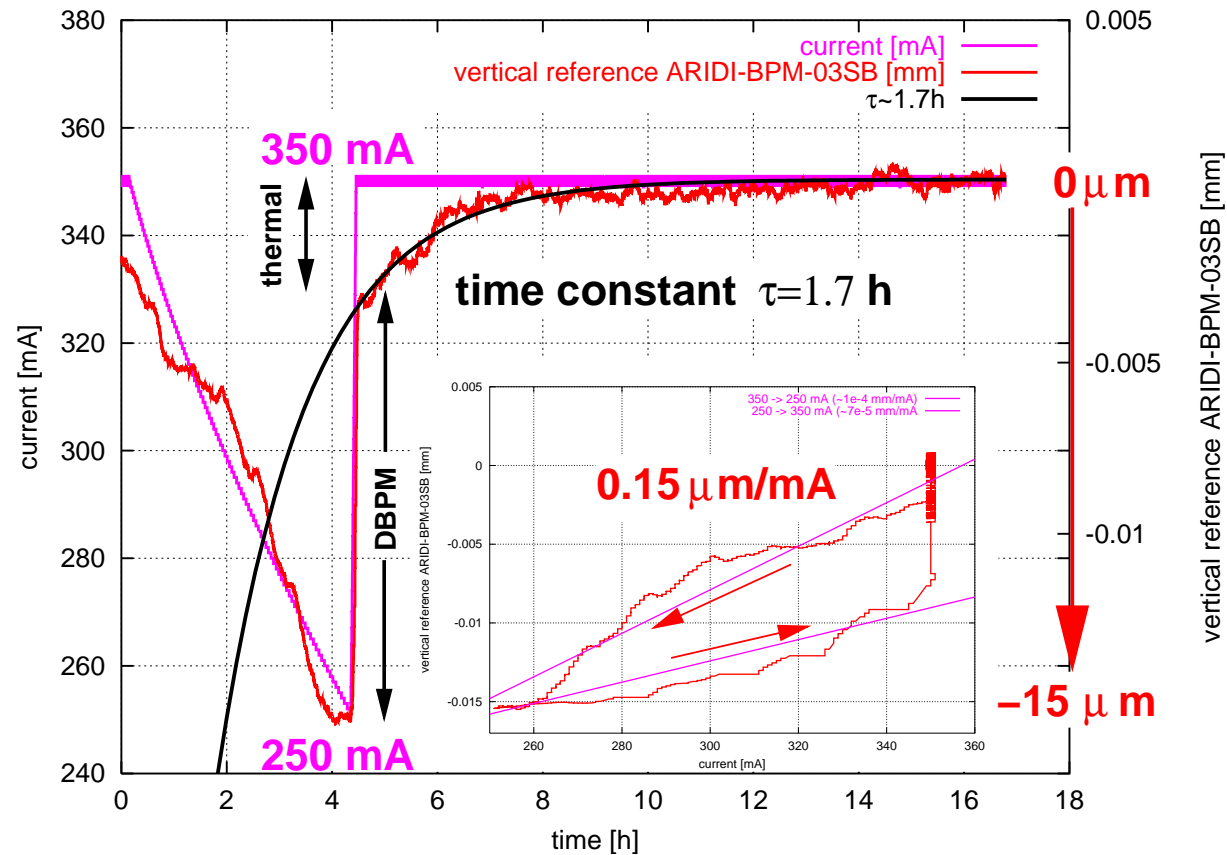
- “Top-up” operation guarantees a constant electron beam current and thus a constant heat load on all accelerator components. It also removes the current dependence of BPM readings under the condition that the bunch pattern is kept constant (B. Kalantari)
- Horizontal mechanical offset ($\approx 0.5 \mu\text{m}$ 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 $5 \mu\text{m}$.
 - “Top-up” operation: **no BPM movement during “top-up” operation at 200 mA** after the thermal equilibrium is reached ($\approx 1.5 \text{ h}$).



- APS (1 %), SLS (0.3 %), (A. Lüdeke, SPring-8 (0.1 %) (H. Tanaka) are running “top-up” in user operation.
- ALS (D. Robin) has upgrade plans.
- DIAMOND, SOLEIL prepare for “top-up”.

MEDIUM TERM STABILITY - Top-up III (SLS)

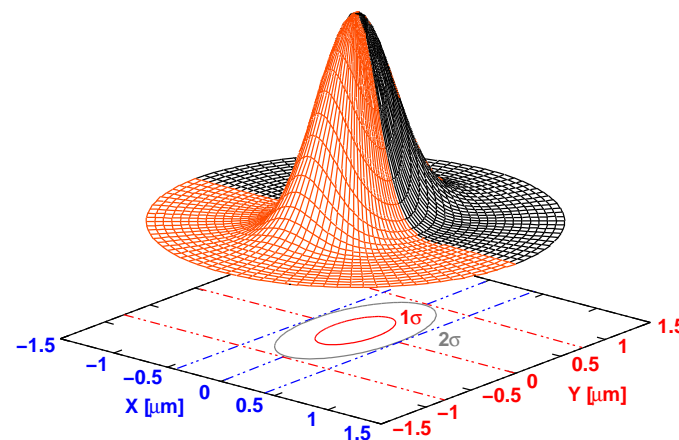
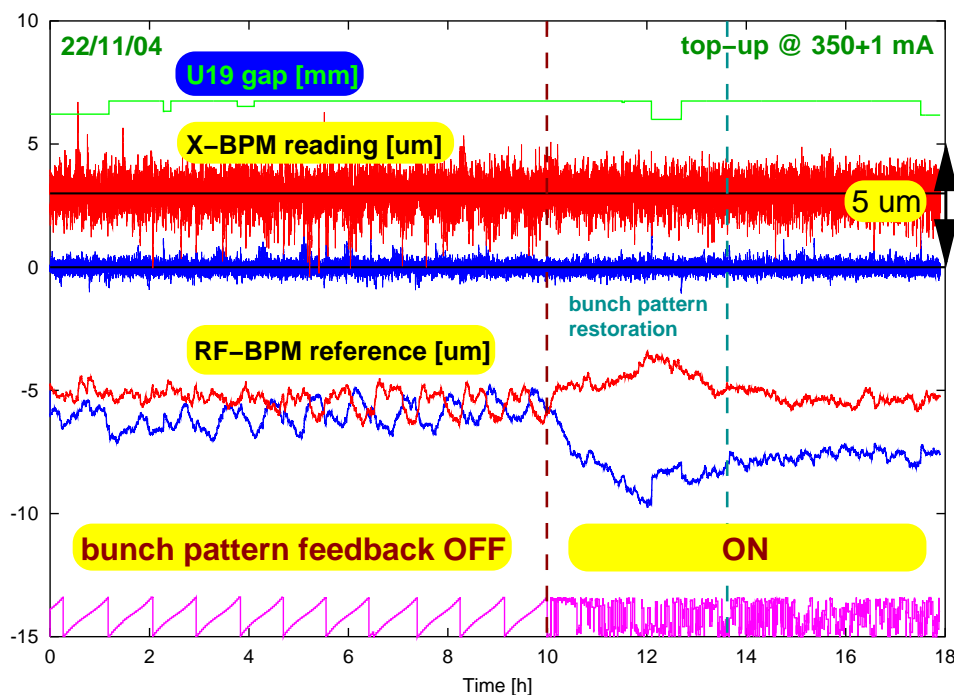
- Change of the vertical BPM reference within the X-BPM feedback loop for decaying beam operation (0-4 h) and “Top-up” (Time constant for getting back to thermal equilibrium $\tau=1.7$ h):



- Large ($\approx 0.1 \mu\text{m}/\text{mA}$) contribution originating from current dependence of digital BPMs

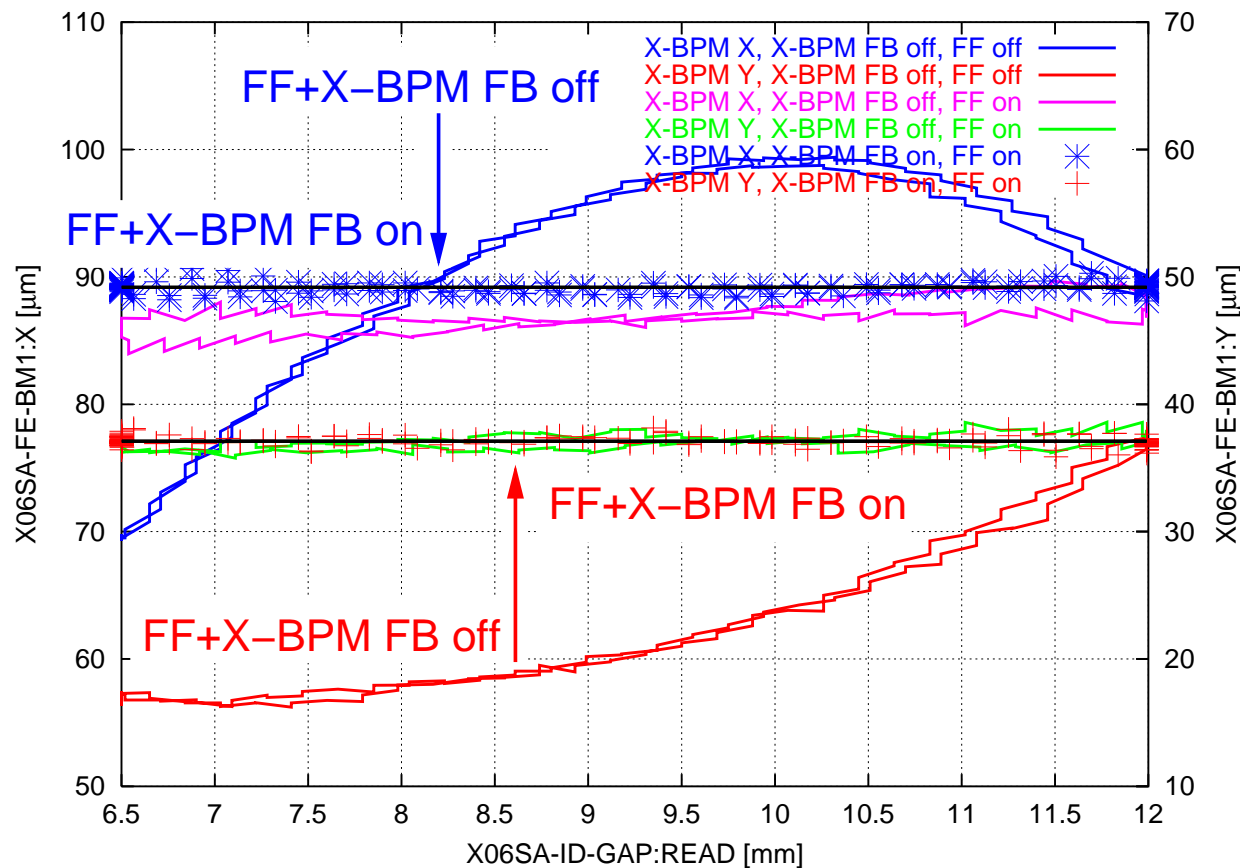
MEDIUM TERM STABILITY - X-BPM & Bunch Pattern Feedback (SLS)

- 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 $\approx 0.5 \mu\text{m}$ for frequencies up to 0.5 Hz.
- X-BPM feedbacks are operational @ the ID beam lines **4S, 6S, 10S** (1 X-BPM \Rightarrow angle only) and the dipole beam lines **2DA, 7DA** (2 X-BPMs \Rightarrow angle & position).



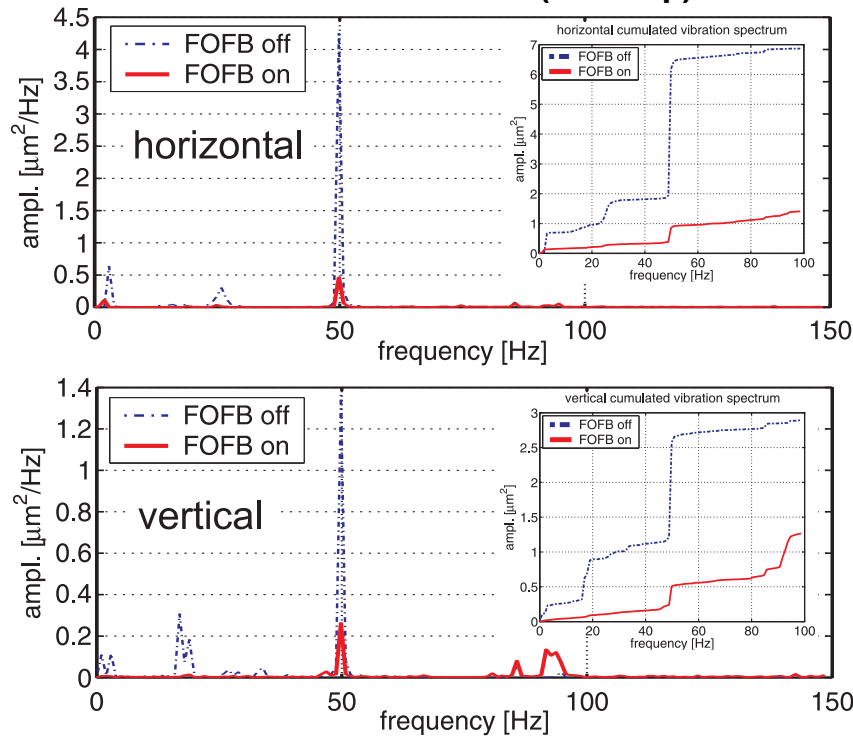
MEDIUM TERM STABILITY - Feed Forward & X-BPM Feedback (SLS)

- The feed forward tables (here for the in-vacuum device 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

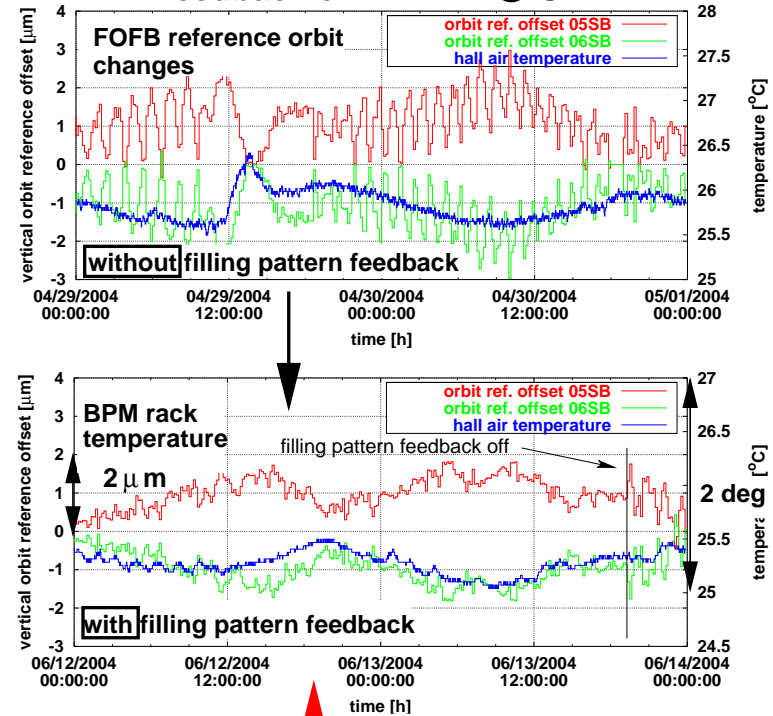


SHORT/MEDIUM TERM STABILITY (SLS)

PSDs on tune BPM (off-loop)



Feedback on X-BPM @ U24



FOFB	horizontal		vertical	
	off	on	off	on
1-100 Hz	$0.83 \mu\text{m} \cdot \sqrt{\beta_x}$	$0.38 \mu\text{m} \cdot \sqrt{\beta_x}$	$0.40 \mu\text{m} \cdot \sqrt{\beta_y}$	$0.27 \mu\text{m} \cdot \sqrt{\beta_y}$
100-150 Hz	$0.08 \mu\text{m} \cdot \sqrt{\beta_x}$	$0.17 \mu\text{m} \cdot \sqrt{\beta_x}$	$0.06 \mu\text{m} \cdot \sqrt{\beta_y}$	$0.11 \mu\text{m} \cdot \sqrt{\beta_y}$
1-150 Hz	$0.83 \mu\text{m} \cdot \sqrt{\beta_x}$	$0.41 \mu\text{m} \cdot \sqrt{\beta_x}$	$0.41 \mu\text{m} \cdot \sqrt{\beta_y}$	$0.29 \mu\text{m} \cdot \sqrt{\beta_y}$

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

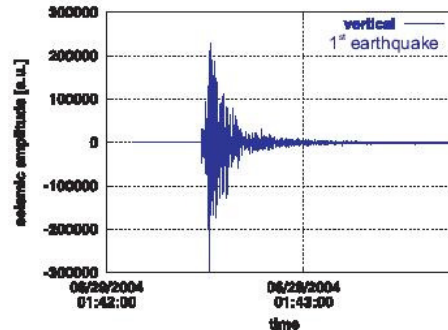
SHORT TERM STABILITY - Earthquake 06/29 (SLS)

earthquake: 4.0 on Richter scale

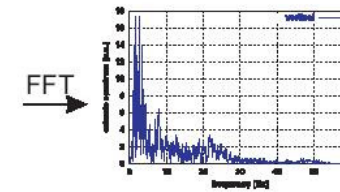


epicenter:
~ 5 km from PSI

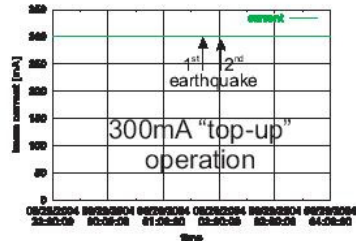
sources:
Swiss Seismological Service
ETH-Hänggerberg
CH-8093 Zurich
Switzerland



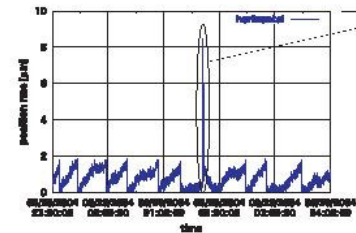
T.Schilcher THPLT024



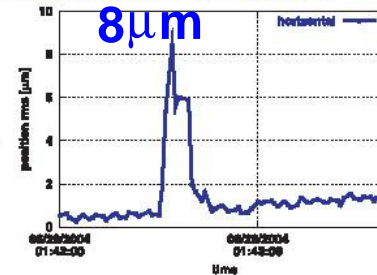
storage ring
beam
current:



horizontal
orbit RMS:
over 6 hours



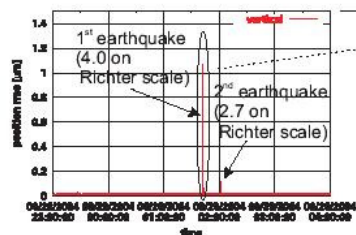
horizontal orbit RMS:



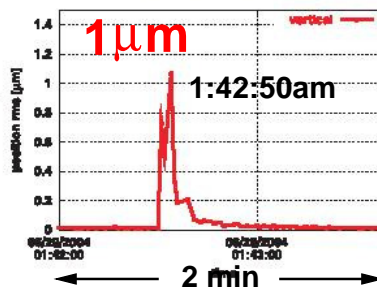
$f < 1.5$ Hz

- archived position data:
- recorded with a rate of ≤ 1 Hz (~0.6 Hz)
 - each sample is a time average of the orbit RMS (72 BPMs) over 320 ms

vertical
orbit RMS:

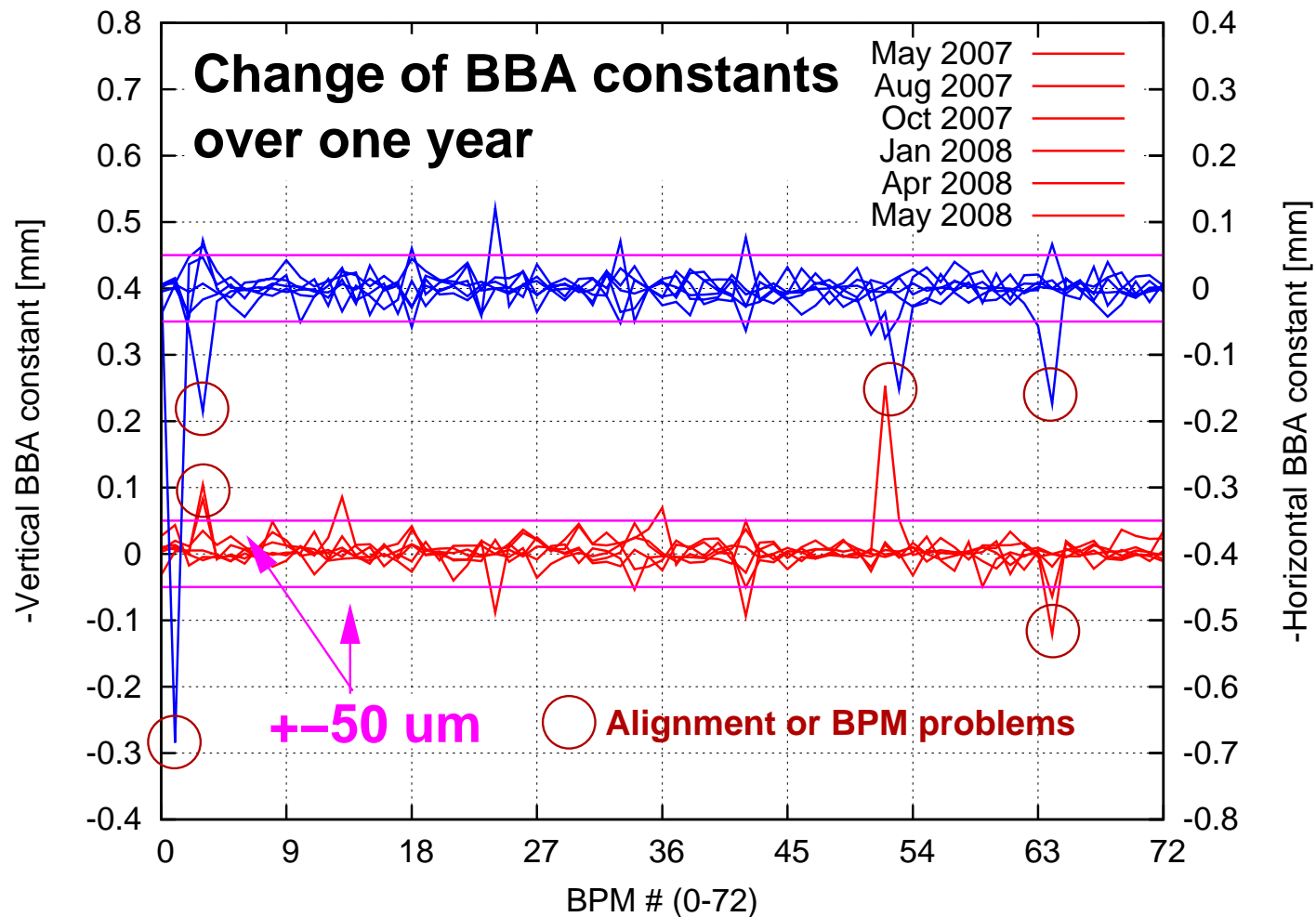


vertical orbit RMS:



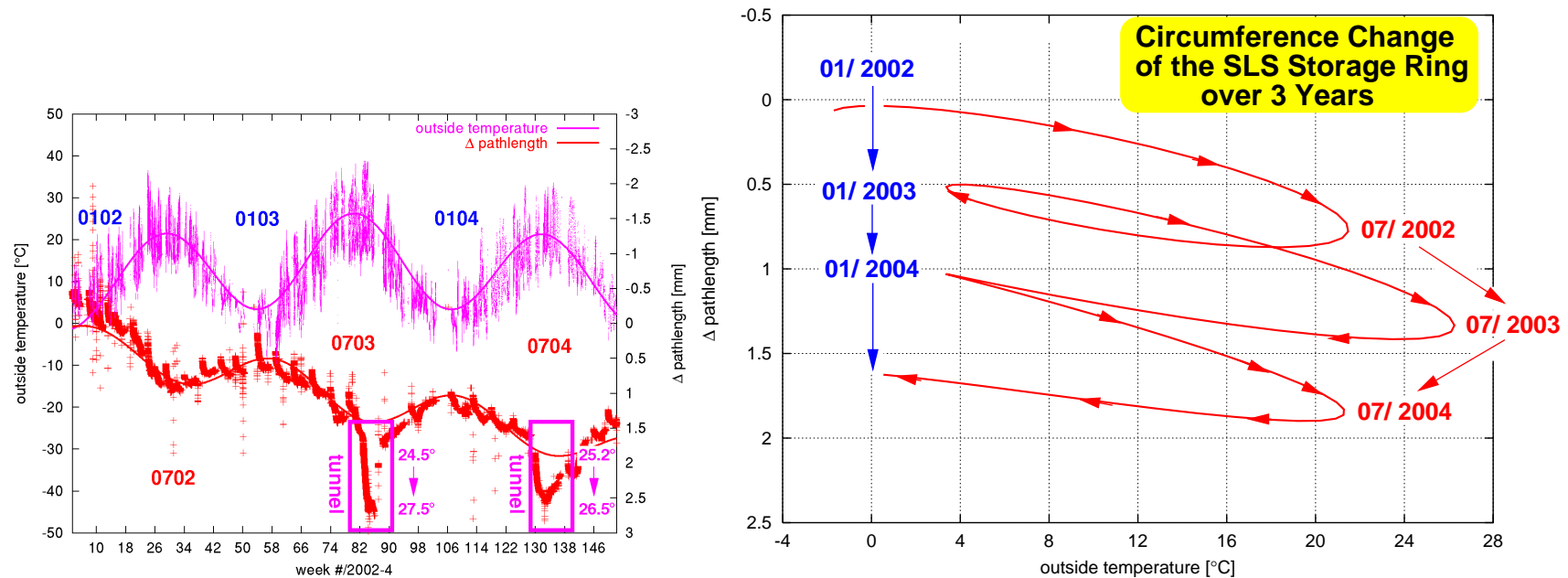
Conclusion

- Earthquake induced orbit distortions lay in the freq. range where FOFB provides high gain for suppression
- FOFB avoided beam loss
- orbit distortions during earthquake stayed in the μm range due to the fast feedback

LONG TERM STABILITY - BBA Measurements over 1 Year (SLS)

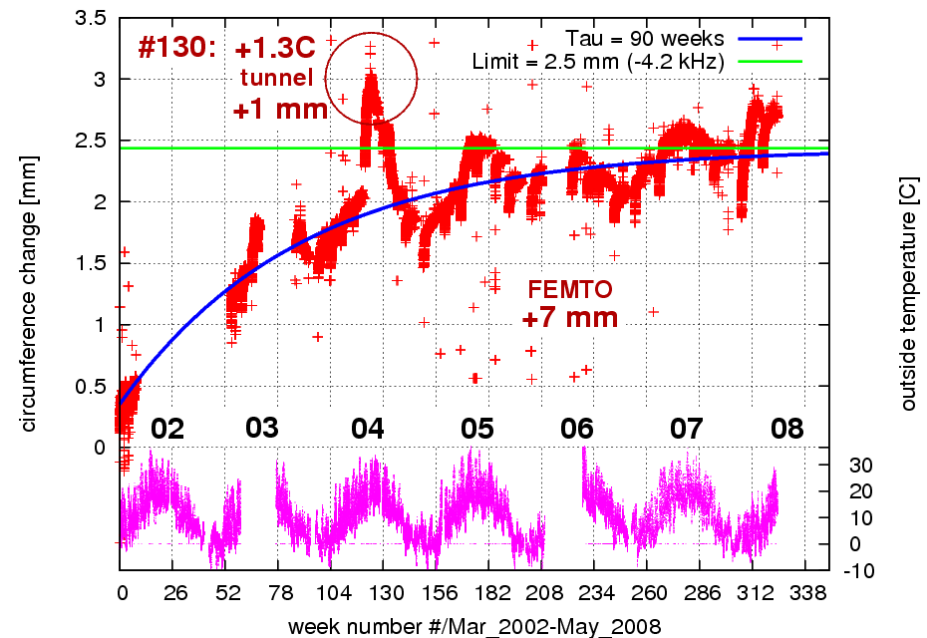
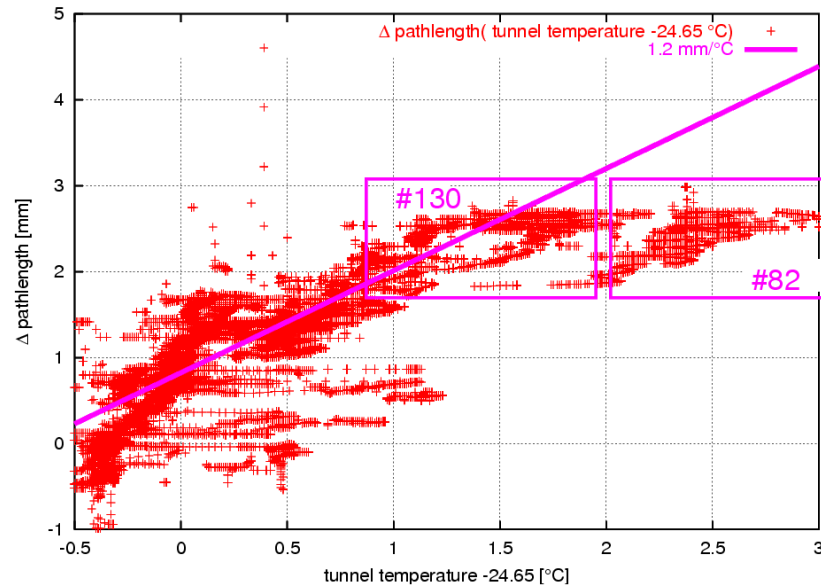
LONG TERM STABILITY - Circumference I (SLS)

- Circumference change and outside temperature over 3 years of SLS operation (left plot)
- Fitted circumference change over 3 years of SLS operation ($\Rightarrow \Delta$ circumference ≈ 2 mm) as a function of the fitted outside temperature (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!

LONG TERM STABILITY - Circumference II (SLS)



- Stabilization of the **tunnel temperature** to $\approx \pm 0.1^\circ$ is needed to guarantee sub-micron movement (see linear fit in left plot) !
- Change of the circumference over 6 years of SLS operation is saturating with an exponential time constant of $\tau = 90$ weeks and an asymptotic circumference change of 2.5 mm (the change due to installation of FEMTO chicane has been removed, see fit in right plot).