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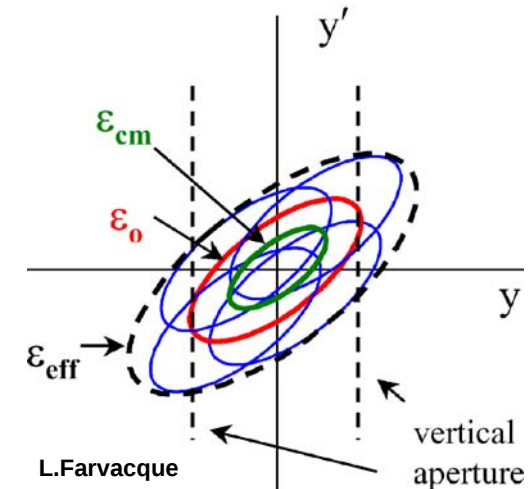


INTRODUCTION

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'
 $\Rightarrow$ *smeared 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):
- $\sigma_{cm} < 1 \mu m$ (SOLEIL: $< 0.8 \mu m$) and $\sigma'_{cm} < 1 \mu rad$ (SOLEIL: $< 0.5 \mu rad$)

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



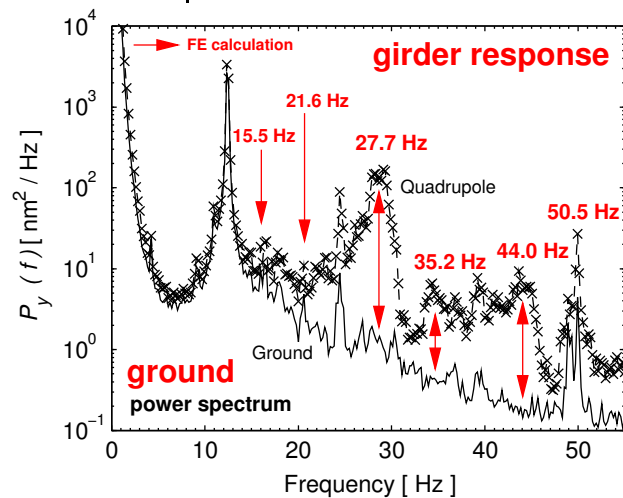
weeks



years

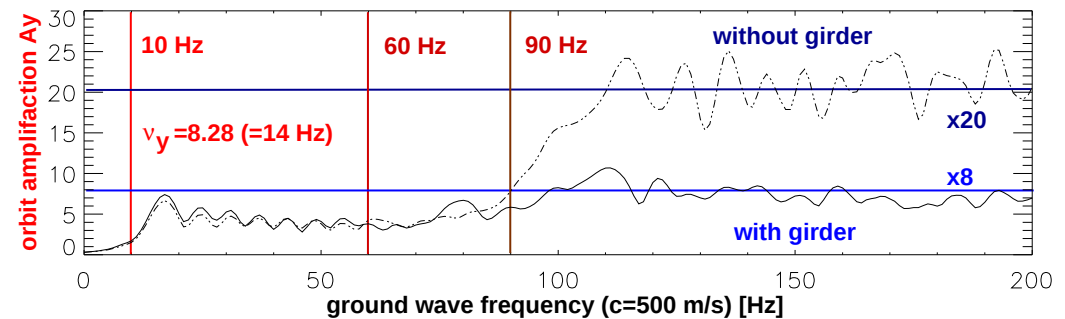
SHORT TERM STABILITY (SLS)

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

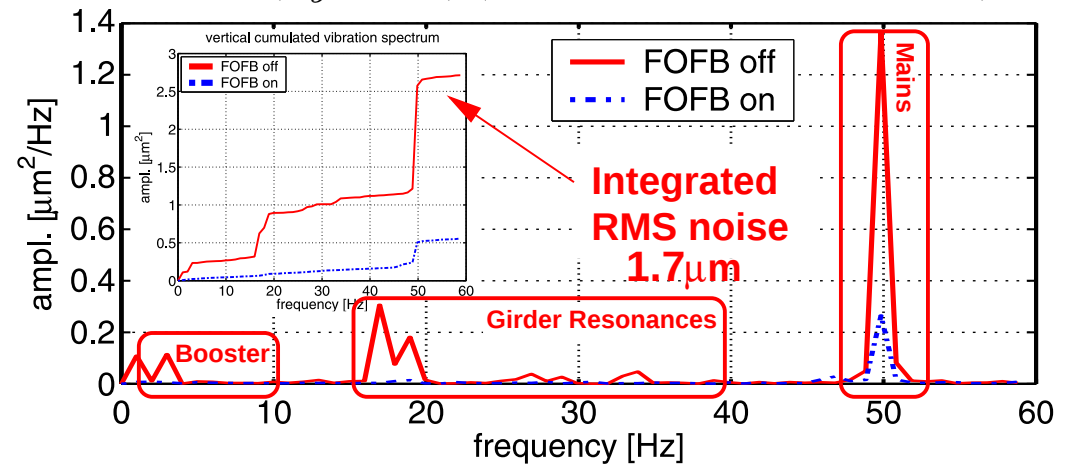


Vertical **vibration** PSD (1-55 Hz) measured on the slab and a girder (S. Redaelli $\Rightarrow$ **THPKF011**).

Vertical orbit amplification factor A_y for planar waves:

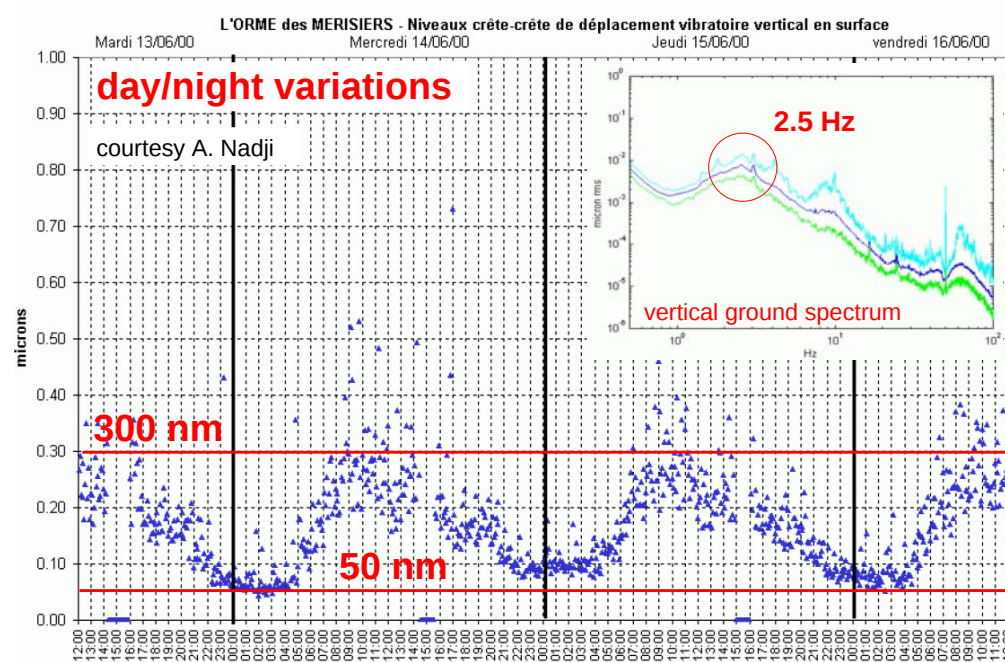


Vertical **orbit** PSD (1-60 Hz) **without** and **with** orbit feedback @ BPM ($\beta_y=18$ m) (T. Schilcher $\Rightarrow$ **THPLT024**):



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

SHORT TERM STABILITY (SOLEIL)



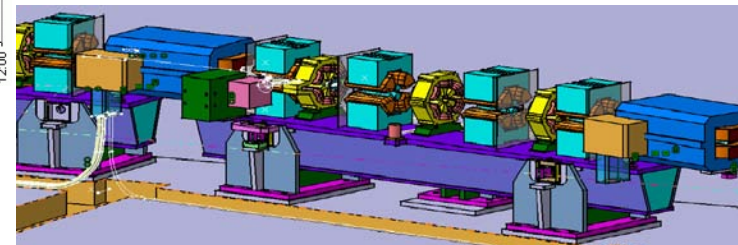
Vertical day/night variations and ground vibration spectrum ($\approx 1-100$ Hz) $\Rightarrow$ **planar wave @ 2.5 Hz with amplitude 800 nm peak-to-peak !**

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

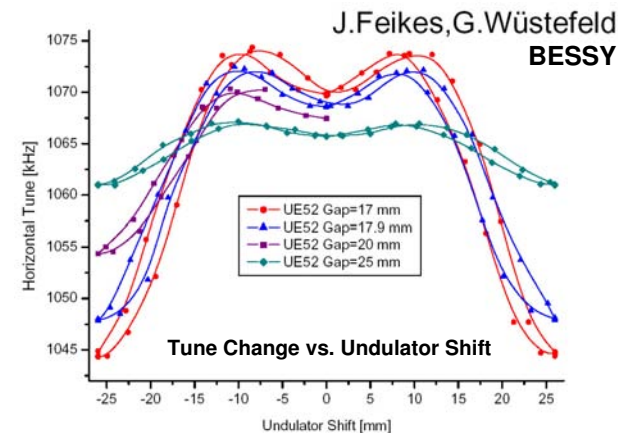
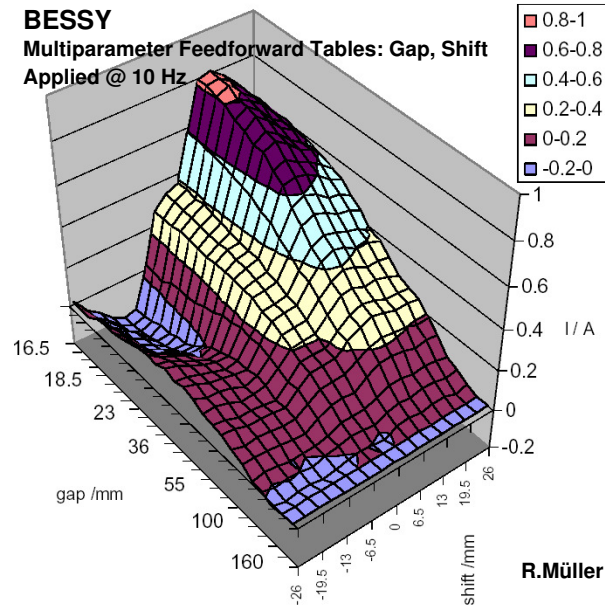
$\Rightarrow$ **No amplification of planar wave !**

J.M. Filhol $\Rightarrow$ **THPKF030**

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.

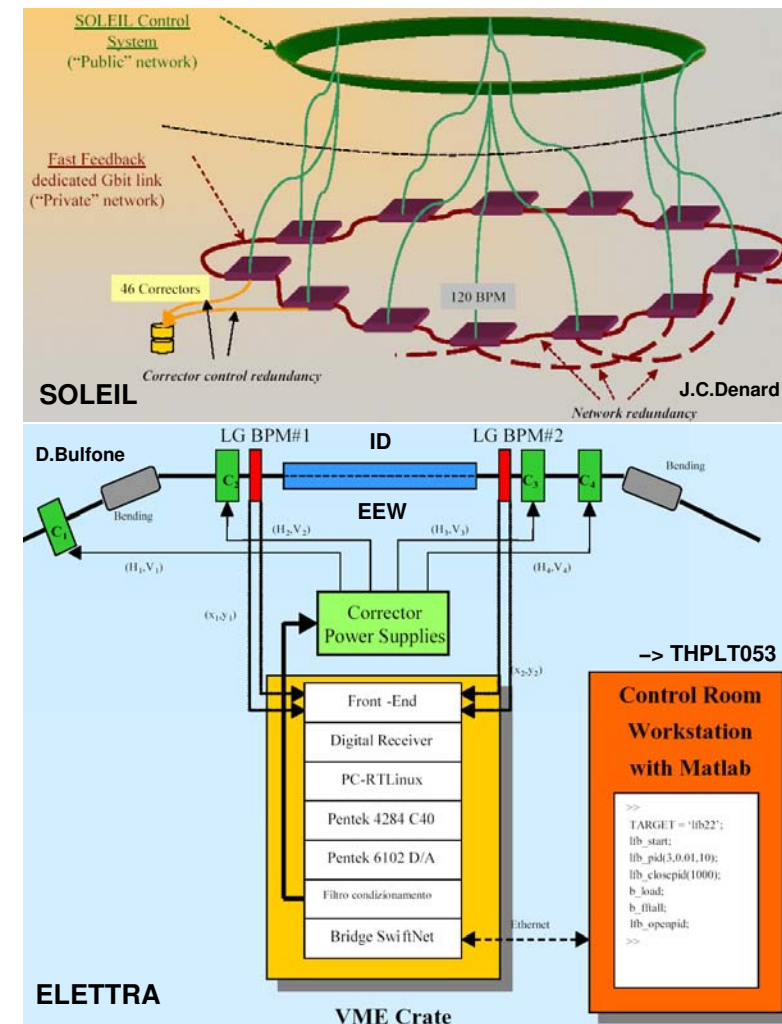
Nevertheless the remaining noise is significant and needs to be attenuated by orbit feedback systems featuring large correction bandwidths >100 Hz !



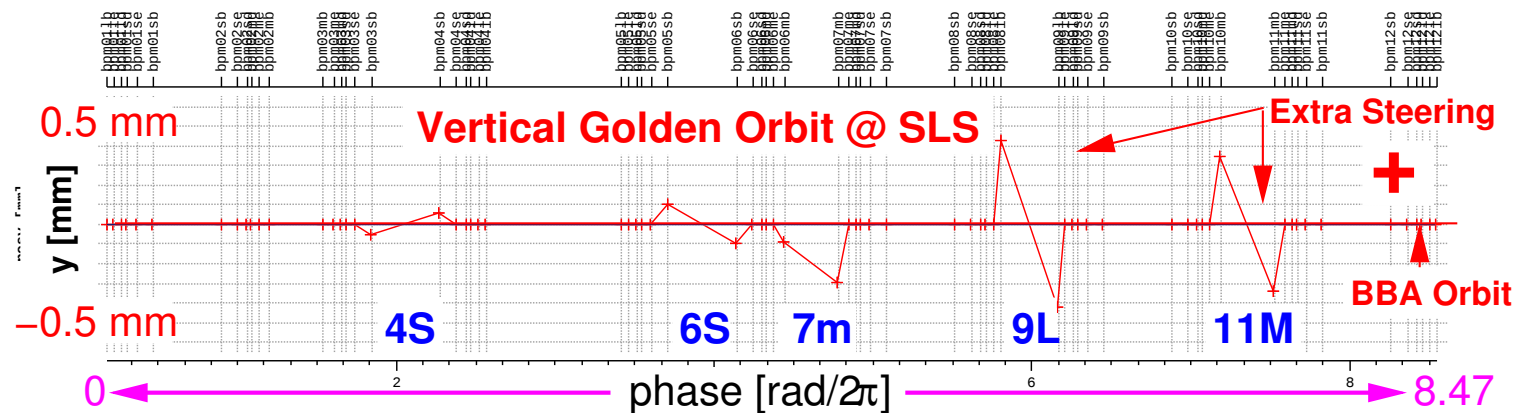
SHORT TERM STABILITY - Orbit Feedbacks

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



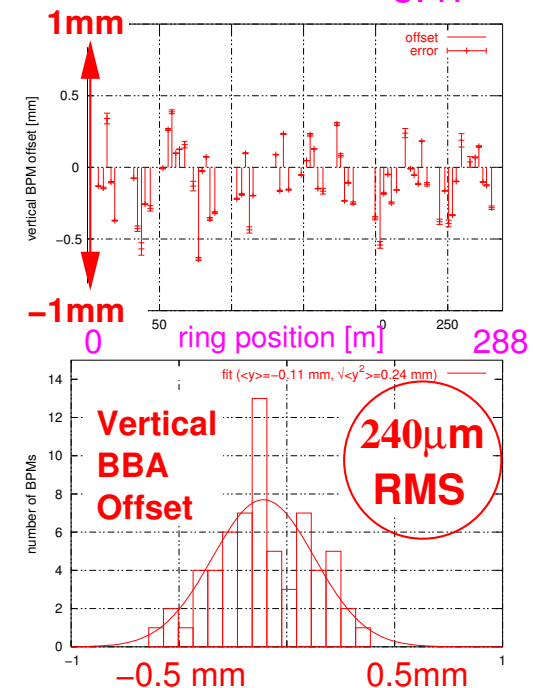
Golden Orbit: goes through centers of quadrupoles and sextupoles in order to minimize optics distortions leading to spurious vertical dispersion and betatron coupling (emittance coupling) + extra steering @ IDs

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 electronical 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

- “Response Matrix” A_{ij} , mapping **Corrector j** ($1 \leq j \leq n$) to the corresponding BPM pattern **BPM i** ($1 \leq i \leq m$) (from model or orbit measurements) needs to be “inverted” in order to get **Corrector j** for given **BPM i**
 - $n = m$: square matrix with n independent eigenvectors not ill-conditioned $\Rightarrow$ unique solution by matrix inversion
 - $n \neq m$: non-square matrix by design or due to BPM failures and/or corrector saturation $\Rightarrow$ solution:
- **Singular Value Decomposition (SVD)** - Decomposes the “Response Matrix”

$$A_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi \nu} \cos [\pi \nu - |\phi_i - \phi_j|]$$
 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

$$A^{-1} = V * 1/W * U^T$$
 - $n > m$: minimizes RMS orbit and RMS corrector strength changes
 - $n < m$: minimizes RMS orbit
 - $n = m$ & all eigenvalues: matrix inversion
 - “Most Effective Corrector” combinations by means of cutoffs in the eigenvalue spectrum
 $\Rightarrow$ SVD makes other long range correction schemes like “MICADO” superfluous

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 - Feedback Implementation I

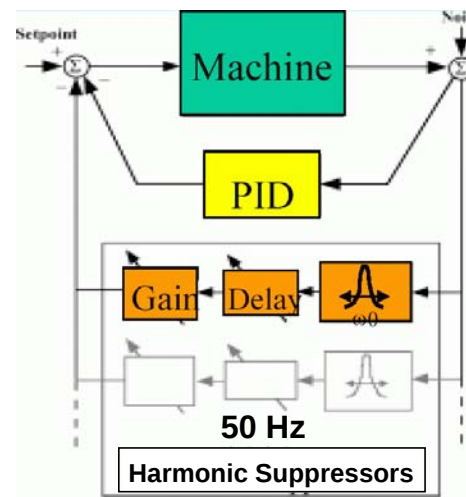
In order to implement a global orbit feedback based on the described algorithm which stabilizes the electron beam with respect to the established “Golden Orbit” up to frequencies ≈ 100 Hz with sub-micron in-loop stability the following is needed:

- 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.

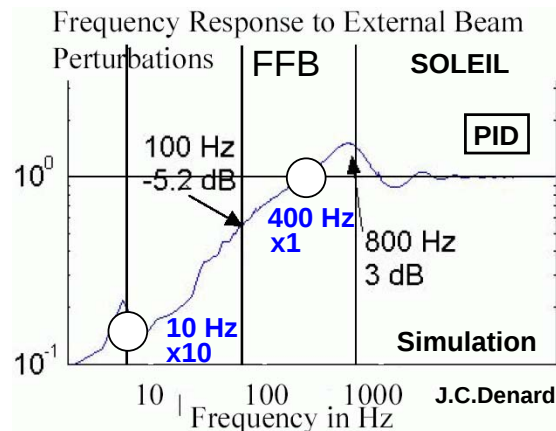
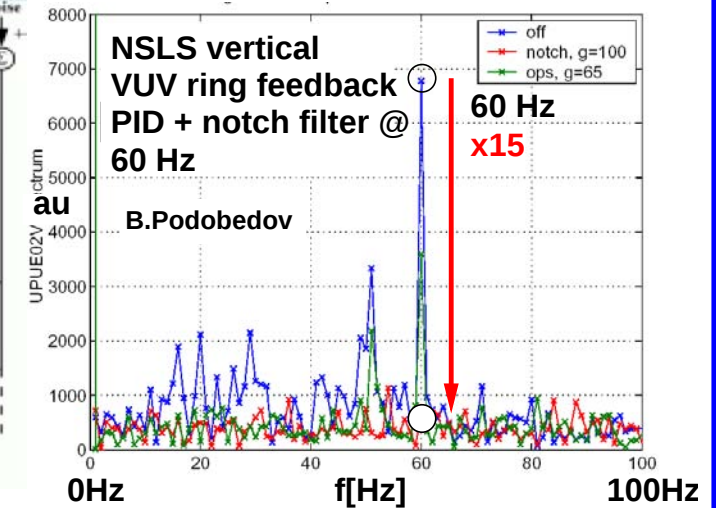
*At the SLS 72 BPMs with adjacent **Correctors** in both planes, phase advance between **Correctors** $< 180^\circ \Rightarrow$ inverted 72×72 matrix “resembles” a correction with interleaved closed orbit bumps made up from 3 successive **Correctors** (“Sliding Bump Scheme”).*

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 $\Rightarrow$ THPLT053) of particularly strong lines at 50/60 Hz.

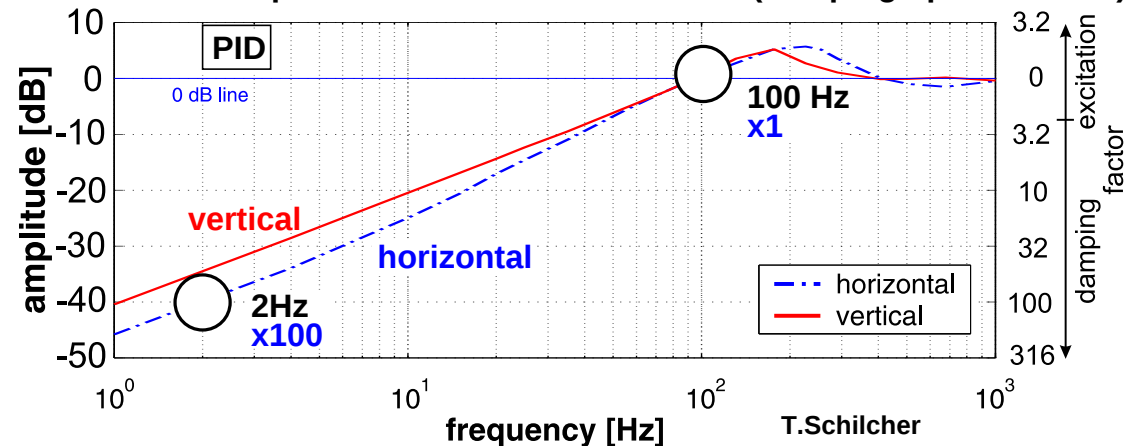


ELETTRA D. Bulfone



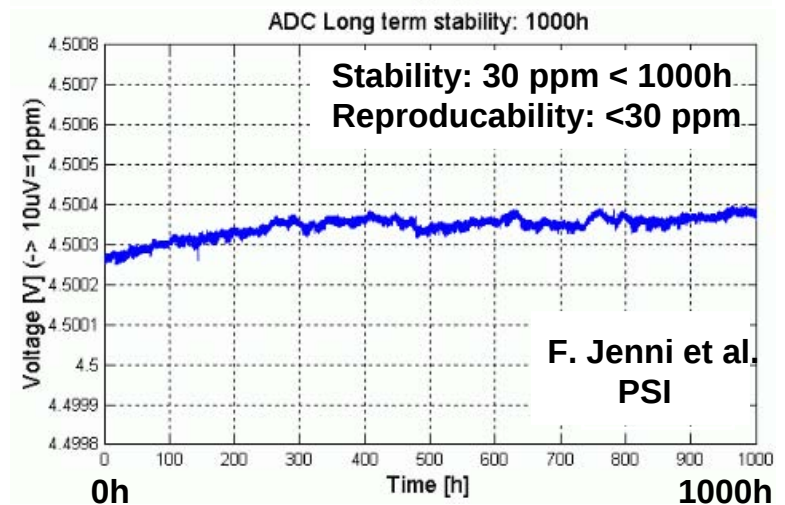
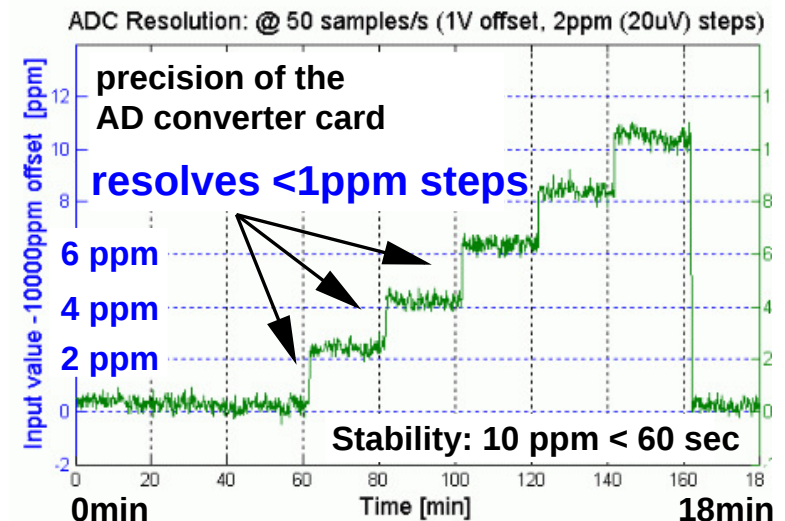
EPAC'04

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



SHORT TERM STABILITY - Feedback Implementation III

- 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 - Feedbacks at LS Worldwide

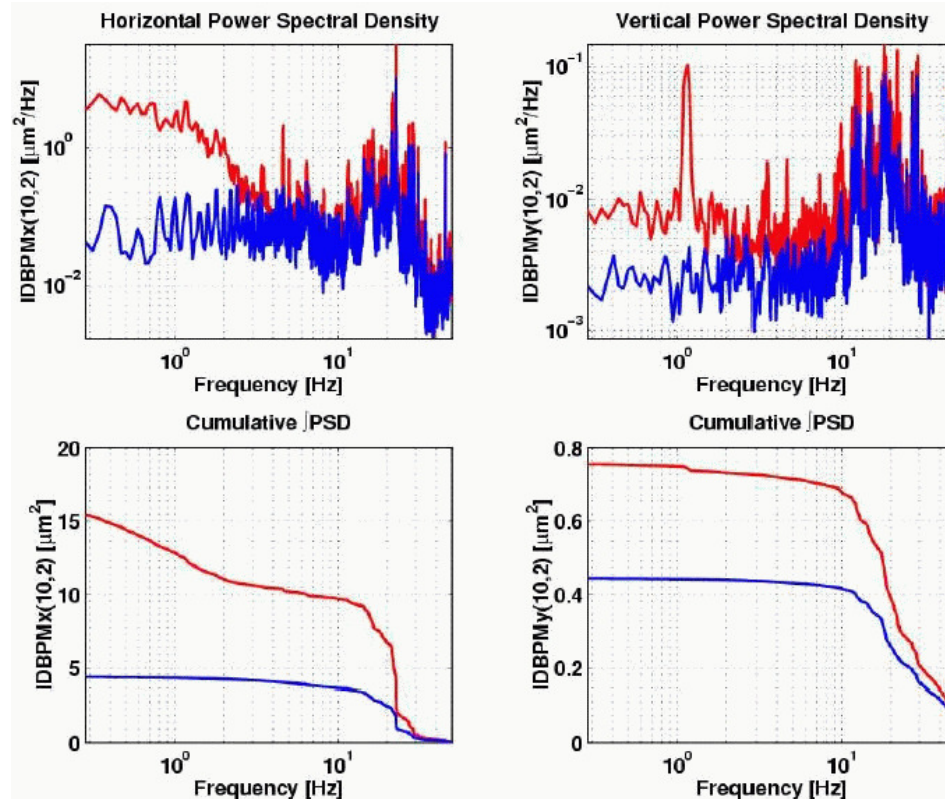
SR Facility	BPM Type	max. BW	Stability	Paper ID
ALS	RF-BPMs	<50 Hz	<1 μm	THPLT141
APS	RF&X-BPMs	50 Hz	<1 μm	
ESRF	RF-BPMs	100 Hz	<0.6 μm	
NLS	RF&X-BPMs	<200 Hz	1.5 μm	
SLS	RF&X-BPMs	100 Hz	<0.3 μm	THPLT024
Super-ACO	RF-BPMs	<150 Hz	<5 μm	op <12/03
<u>BESSY</u>	RF-BPMs	<100 Hz	<1 μm	THPLT021 THPLT127 THPKF030 THPKF082 THOACH03
<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	THPLT053

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

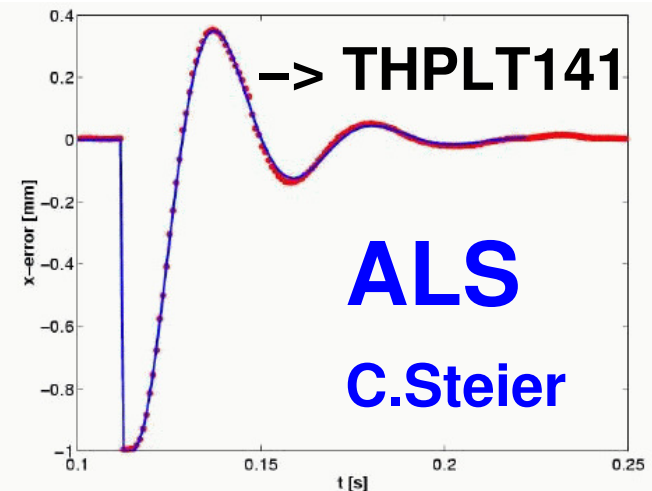
Not in list:

PETRAIII(THPKF019)

ELETTRA(THPLT053)

SHORT TERM STABILITY - ALS

- 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).



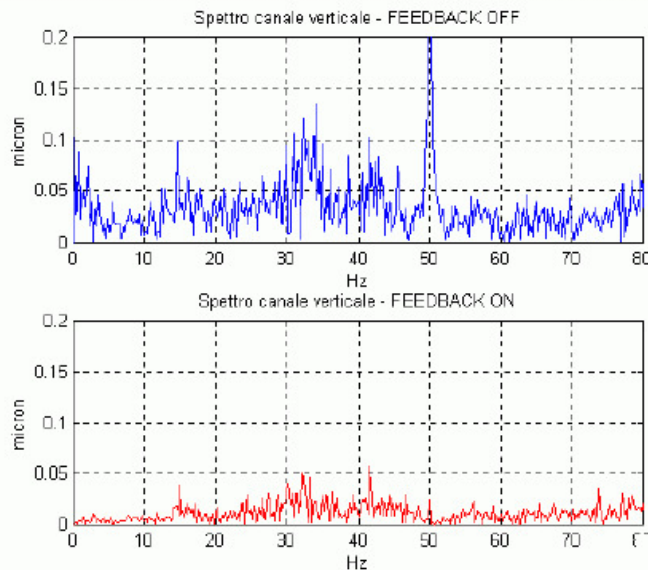
- Combination of fast and slow global orbit feedbacks in both planes – no frequency deadband
- Fast Feedback currently 24 BPMs in each plane and 22 correctors in each plane. 1.11 kHz update rate, bandwidth DC-40 Hz.
- Slow Feedback 52 BPMs in each plane, 26 horizontal correctors, 50 vertical correctors, 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.

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

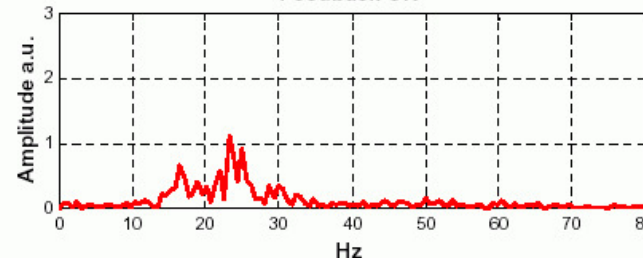
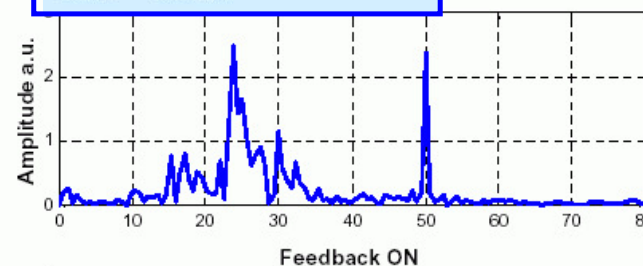
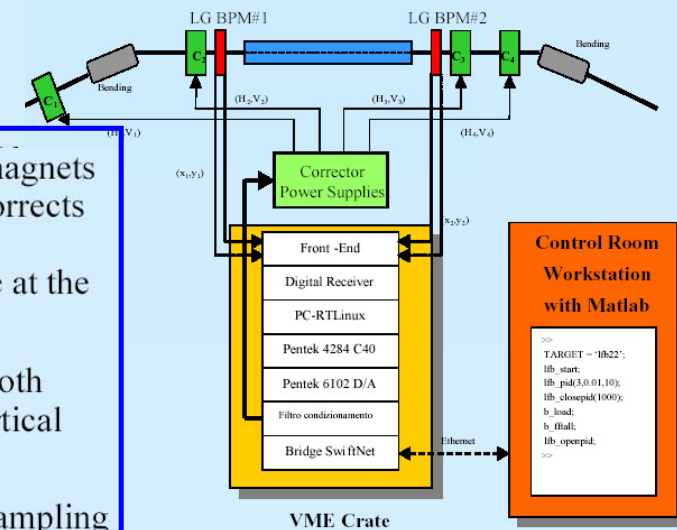


- Beam position spectra at low-gap BPM #1 with local feedback off/on. The rms of the position signal in the 0-80 Hz range is reduced from 1.24 μm to 0.2 μm .

Fast Local Feedback
@ EEW (Electromagnetic Elliptical Wiggler)

D. Bulfone

- Four corrector magnets local bump that corrects the electron beam position and angle at the ID centre
- Closed loop in both horizontal and vertical planes
- Beam position sampling rate = 8kHz



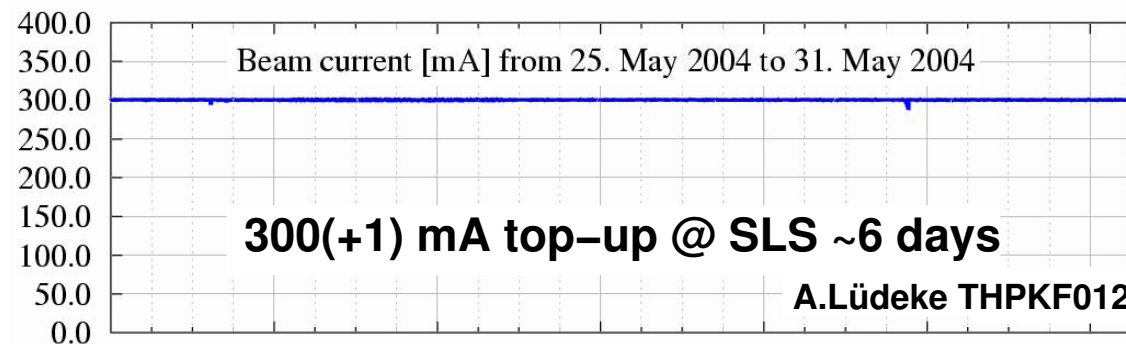
- Beam position spectra at photon-BPM along the corresponding beam-line

at BPMs at ELETTRA

MEDIUM TERM STABILITY

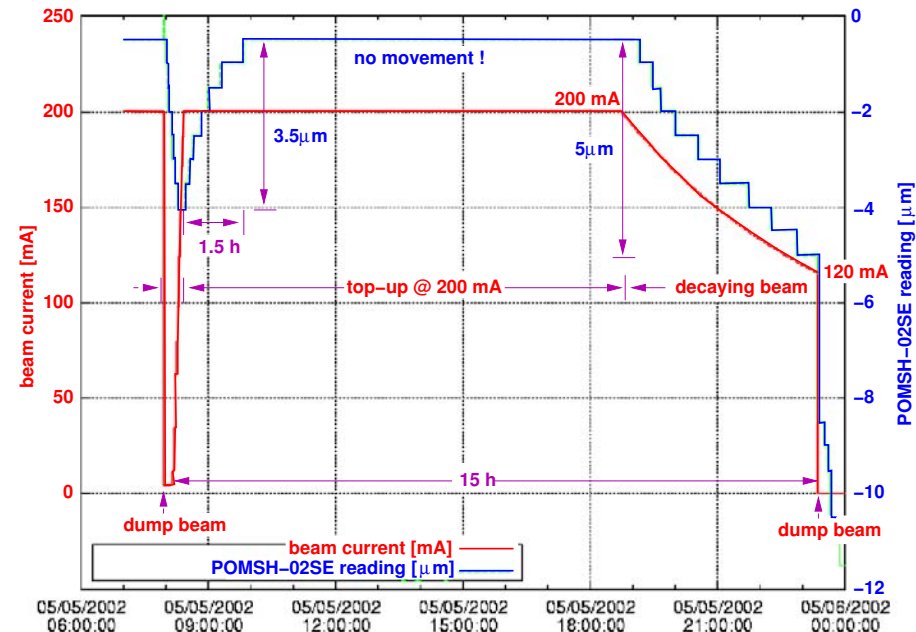
In this regime high mechanical stability is needed to achieve stability on the sub-micron level:

- Stabilization of tunnel, cooling water temperature and digital BPM electronics ($\Rightarrow$ T. Schilcher **THPLT024**) 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

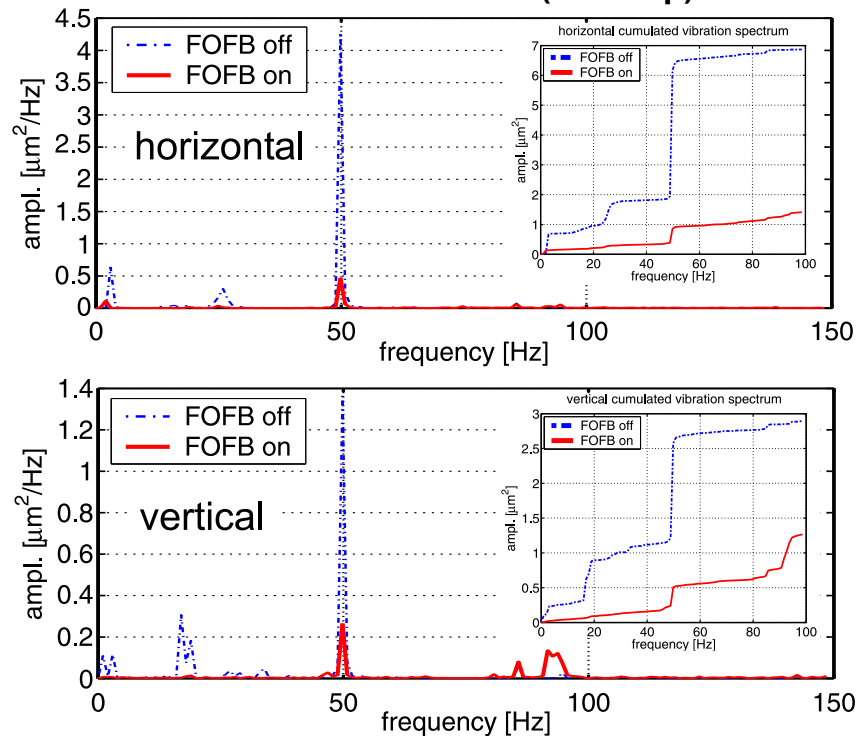
- “Top-up” operation guarantees a constant electron beam current and thus a constant heat load on all accelerator components. It also removes the current dependence of BPM readings under the condition that the bunch pattern is kept constant ($\Rightarrow$ B. Kalantari **THPLT186**)
- Horizontal mechanical 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 %), ($\Rightarrow$ A. Lüdeke **THPKF012**), SPring-8 (0.1 %) ($\Rightarrow$ H. Tanaka **THOACH03**) are running “top-up” in user operation.
- ALS ($\Rightarrow$ D. Robin **THPKF076**) has upgrade plans.
- DIAMOND, SOLEIL prepare for “top-up”.

SHORT/MEDIUM TERM STABILITY - SLS

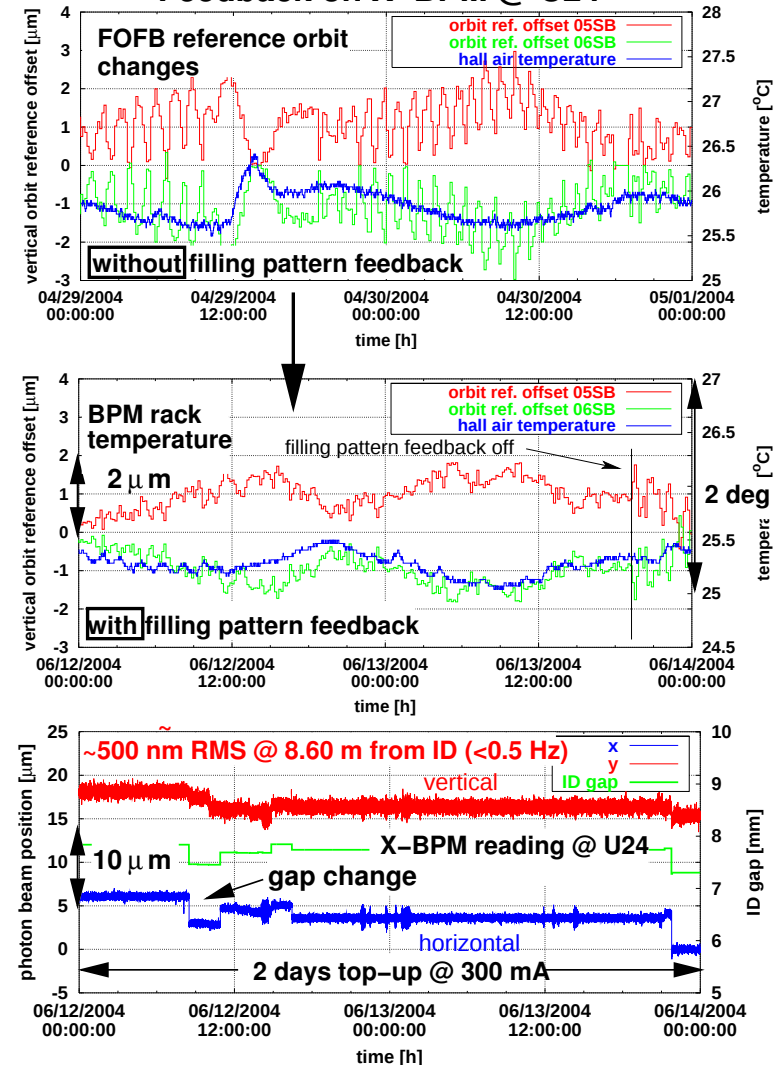
PSDs on tune BPM (off-loop)



	horizontal		vertical	
FOFB	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	$0.83 \mu\text{m} \cdot \sqrt{\beta_x}$	$0.41 \mu\text{m} \cdot \sqrt{\beta_x}$	$0.41 \mu\text{m} \cdot \sqrt{\beta_y}$	$0.29 \mu\text{m} \cdot \sqrt{\beta_y}$

J. Krempasky et al. THPLT023, B. Kalantari et al. THPLT024, T. Schilcher et al. THPLT186

Feedback on X-BPM @ U24



SHORT TERM STABILITY - Earthquake 06/29 @ SLS

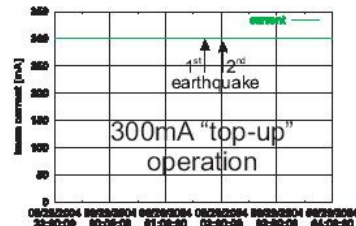
earthquake: 4.0 on Richter scale



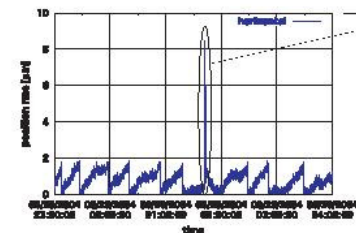
epicenter:
~ 5 km from PSI

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

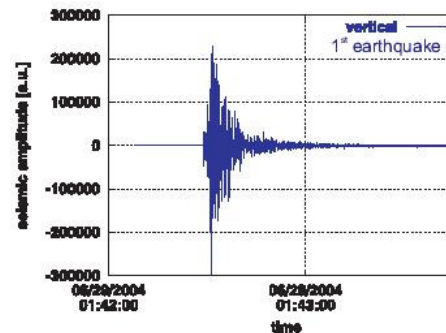
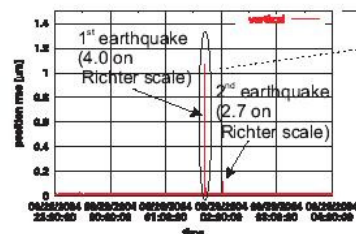
storage ring
beam
current:



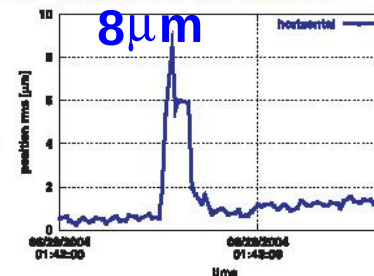
horizontal
orbit RMS:
over 6 hours



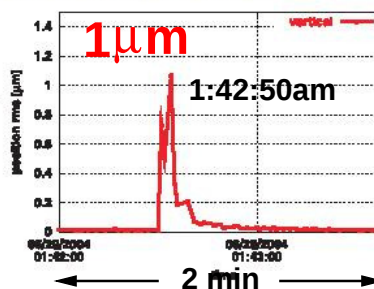
vertical
orbit RMS:



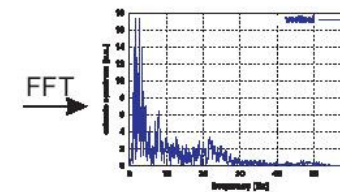
horizontal orbit RMS:



vertical orbit RMS:



T.Schilcher THPLT024



$f < 1.5$ Hz

archived position data:

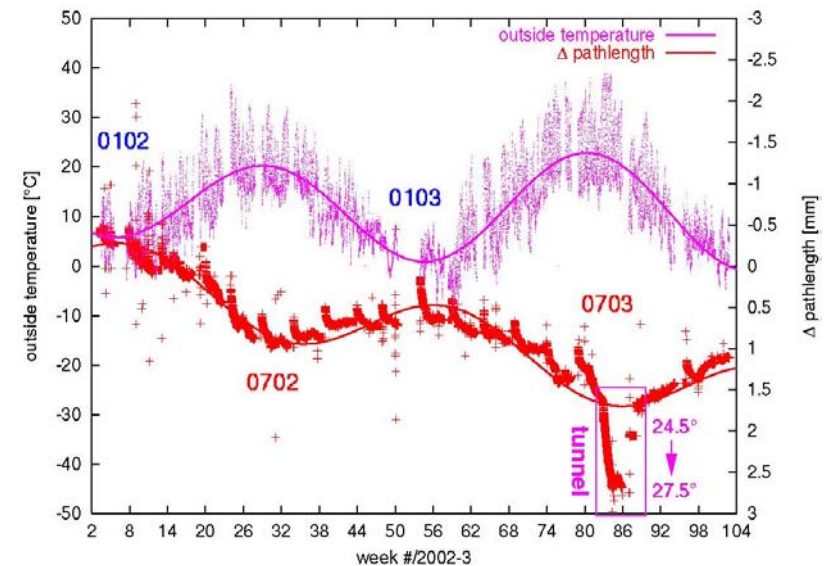
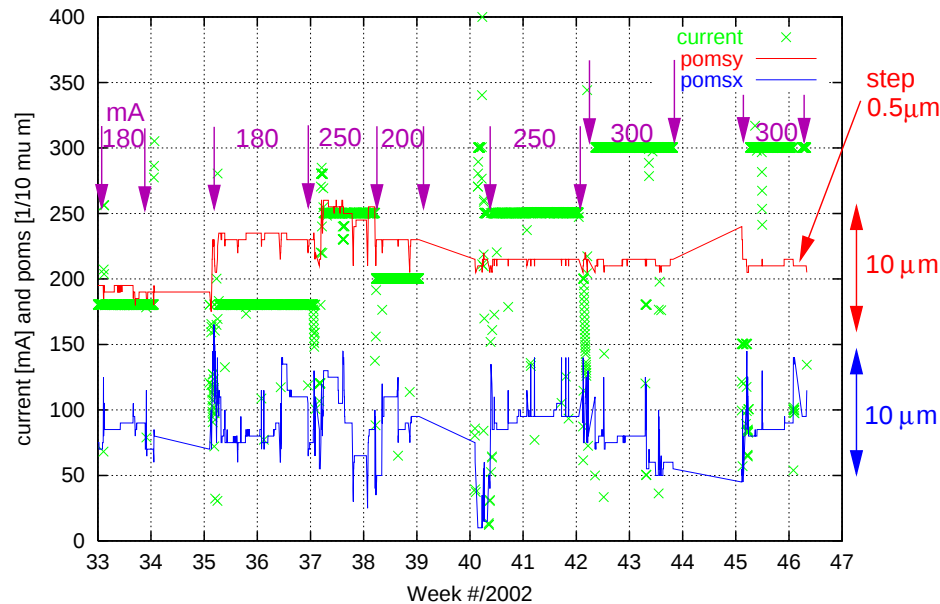
- recorded with a rate of ≤ 1 Hz (~ 0.6 Hz)
- each sample is a time average of the orbit RMS (72 BPMs) over 320 ms

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

- 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 2 years of SLS operation ($\Rightarrow \Delta \text{circumference} \approx 2 \text{ mm}$) (right plot)



- Difficult task to guarantee sub-micron long-term stability. But since beam lines can be realigned or recalibrated between measurements campaigns which require short and medium term sub-micron stability this seems acceptable.

CONCLUSIONS

- Short and medium term sub-micron orbit stability can be achieved in 3rd generation light sources.
- Fast orbit feedback systems and “top-up” operation are key ingredients to reach this level of stability.
- The stability of beam line components apart from X-BPMs has not been discussed.

But it is evident that the achieved stability needs to be maintained throughout the beam line. To this end fast feedbacks on monochromators and other optical components have the potential to improve the stability of the beam line optics considerably.

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