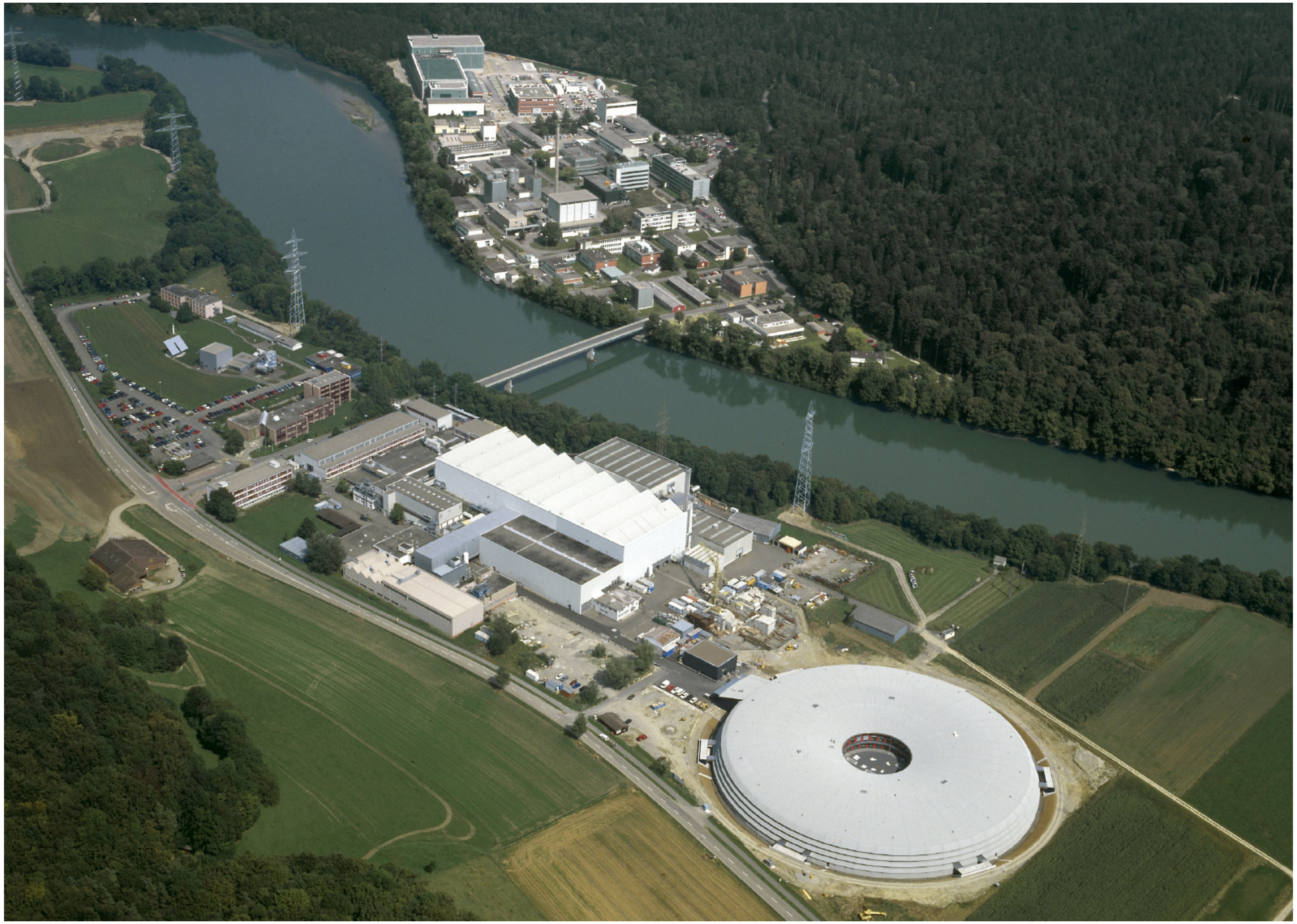
SLS at the Paul Scherrer Institute (PSI), Villigen, Switzerland

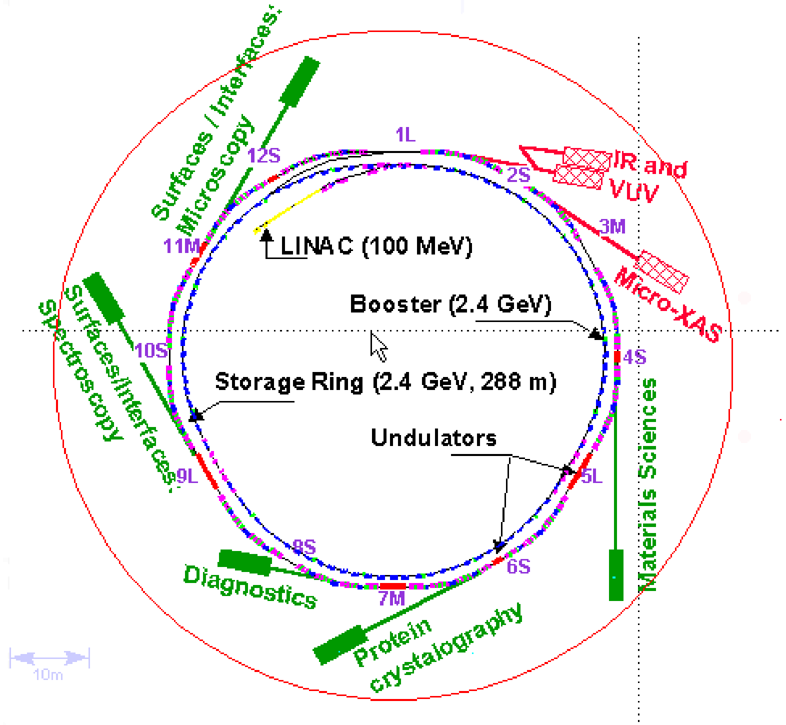


Contents

- SLS Layout
- Booster & Storage Ring (SR)
  - Lattice Calibration
  - Stability
    - Requirements
    - Noise Sources
    - **Short Term**
    - BBA/Golden Orbit
    - Orbit Correction
    - **Medium Term (“Top-up”)**
    - Transition Slow $\longrightarrow$ Fast Orbit Feedback
    - Feed Forward, X-BPM & Bunch Pattern Feedback
    - **Long Term**
- Conclusions

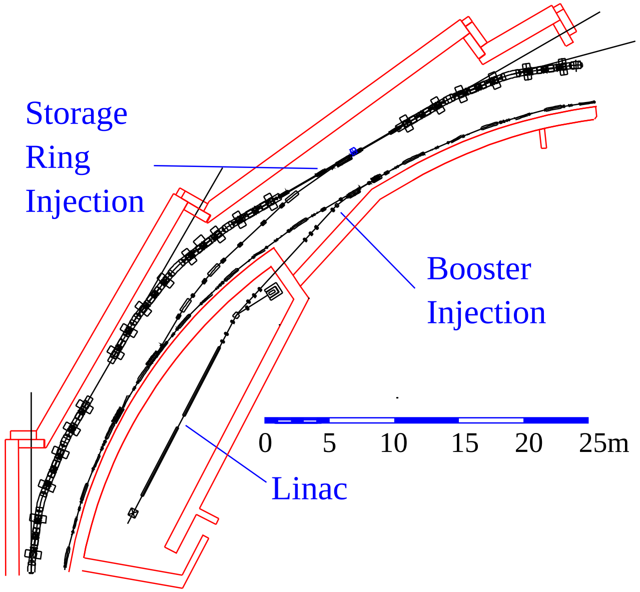
SLS Layout

- 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 nm rad
- Eight Beamlines:
  MS – 4S, μXAS – 5L,
  DIAG – 5D, PX – 6S,
  LUCIA – 7M, SIS – 9L,
  PXII – 10S, SIM – 11M



Booster - Design

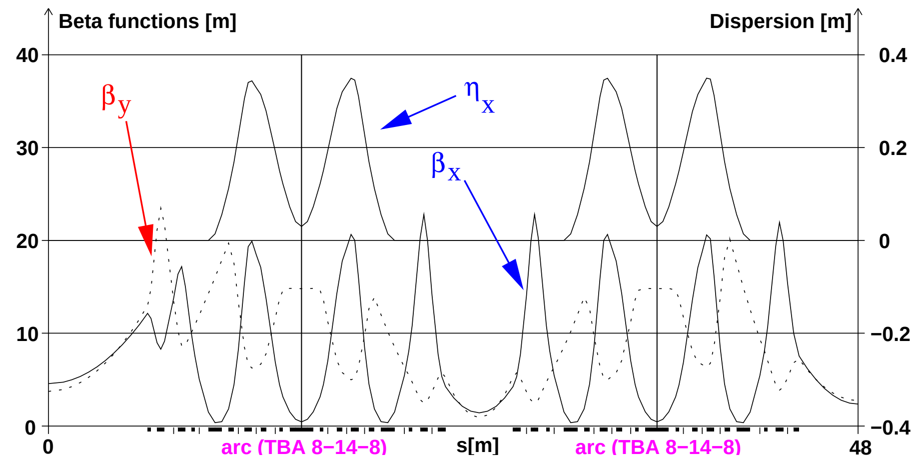
– 3 FODO arcs with 48 BD (+SD) 6.4410 °and 45 BF (+SF) 1.1296 °
– 3 × 6 Quadrupoles for Tuning, 54 BPMs, 2 × 54 Correctors
– ± 15 mm × ± 10 mm Vacuum Chamber
– Energy: 100 MeV → 2.7 GeV, Repetition Rate: 3 Hz, Circumference: 270 m
– Magnet Power: 205 kW, ϵ_x @ 2.4 GeV: 9 nm rad



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 R F 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)

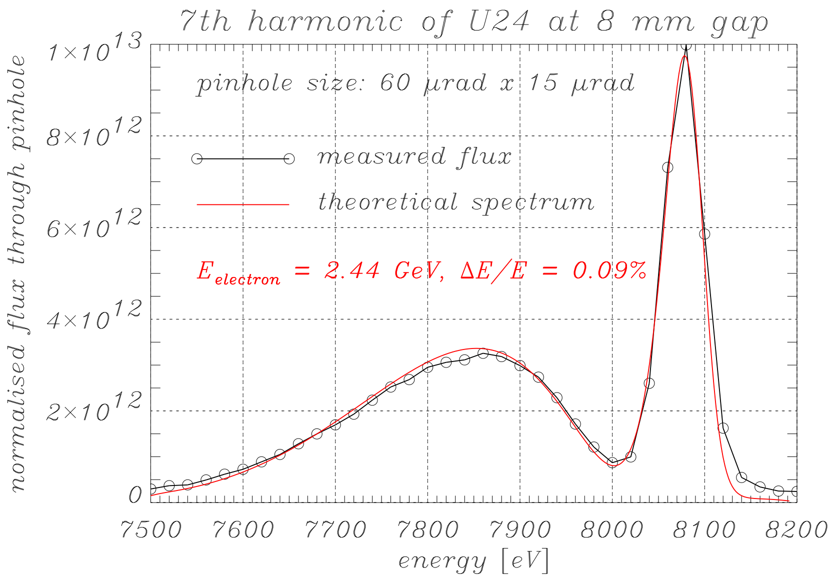
SR - Design

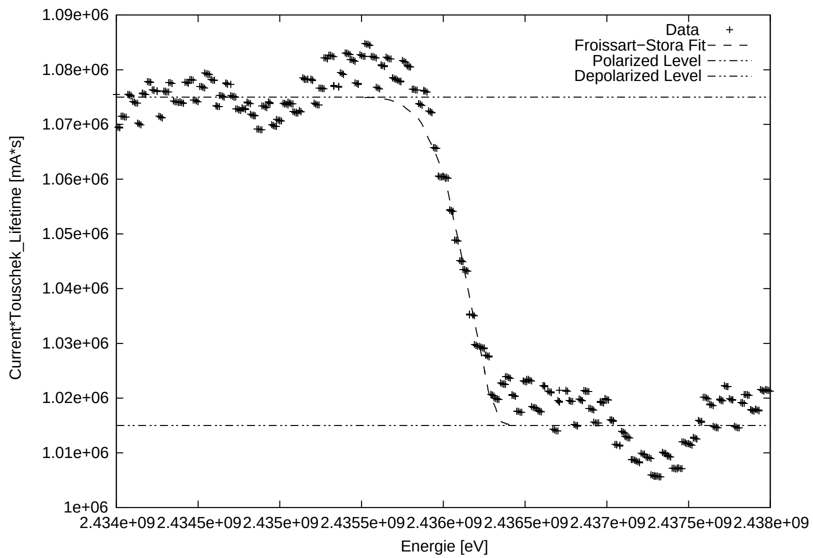
- 12 TBA: 8° / 14° /8 °
- 12 Straight Sections:
  - 3 × 11 m (nL)
    - ∗ **Injection**, 2×**UE212**, **U19**
  - 3 × 7 m (n**M**)
    - ∗ 2×**UE56**, **UE54**
  - 6 × 4 m (n**S**)
    - ∗ 2× **RF**, **W61**, 2×**U19**
- Energy: 2.4 (.7) GeV
- ϵ_x: 5 nm rad
- Current: 350 mA (400 mA)
- Circumference: 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

SR - Lattice Calibration - Energy Spread, Energy





- 7th Harmonic of **U24** at 8 mm gap:
  - $\sigma_e = 0.9 \cdot 10^{-3}$
  - Beam Energy $E = 2.44$ GeV
- Resonant Spin Depolarization: $\nu_{spin} = 5.45$, $P_{eq} \approx 91$ % with $\tau_p = 30$ min
  - Beam Energy $E = 2.4361 \pm 5 \cdot 10^{-5}$ GeV

SR - Lattice Calibration - Beta Functions

174 Quadrupoles with Individual PS

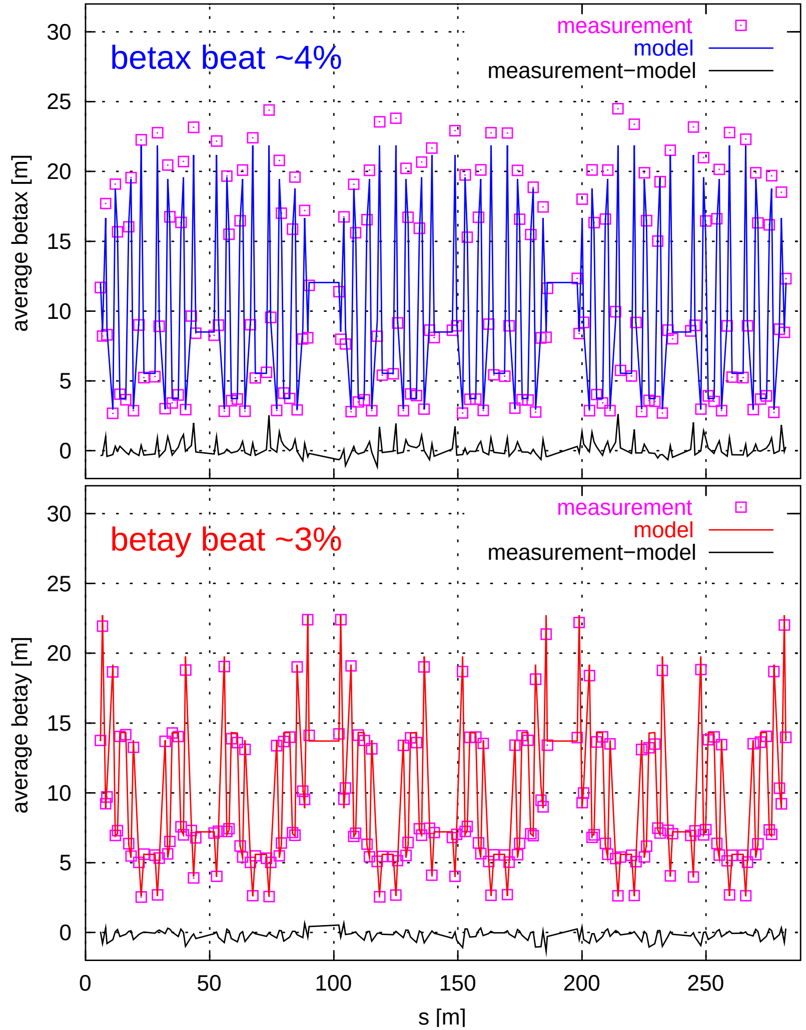
$\longrightarrow\longrightarrow$

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 %



SR - Stability - Requirements

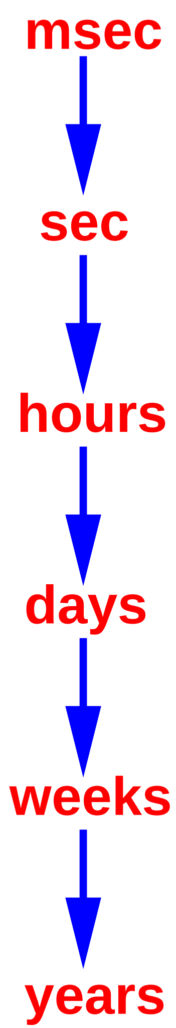
- β_x = 1.4 m, β_y = 0.9 m at **ID** position of section n**S** $\longrightarrow$
  σ_x = 84 μm, σ_y = 7 μm assuming emittance coupling ϵ_y/ϵ_x = 1 %
- With stability requirement $\Delta\sigma = 0.1 \times \sigma \longrightarrow$

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	
→	Maximum Orbit jitter hor./vert	24/15	7.5/1.5	µm
	Attenuation by orbit feedback	−55	−35	dB
→	**Maximum Orbit jitter hor. /vert.**	**40/30**	**130/30**	**nm**

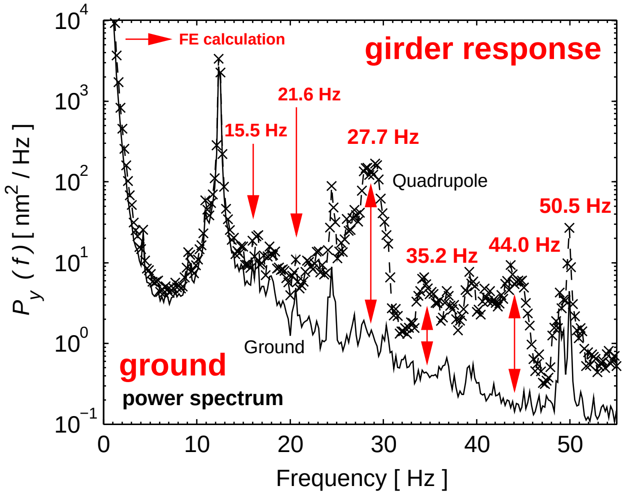
SR - Stability - Noise Sources

- **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.
- **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.



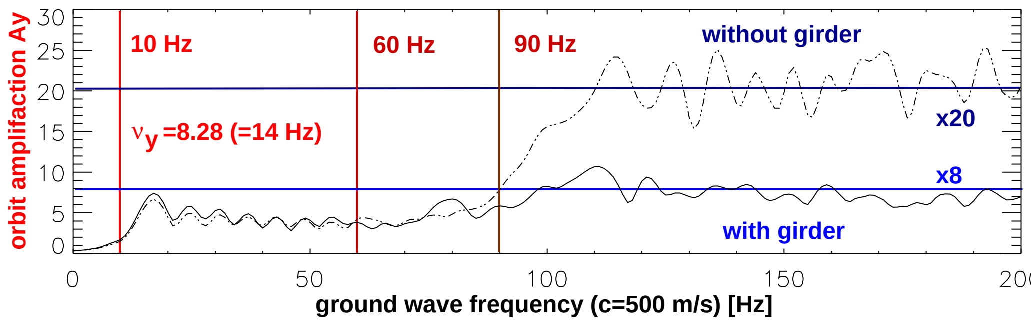
SR - Stability - Short Term

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

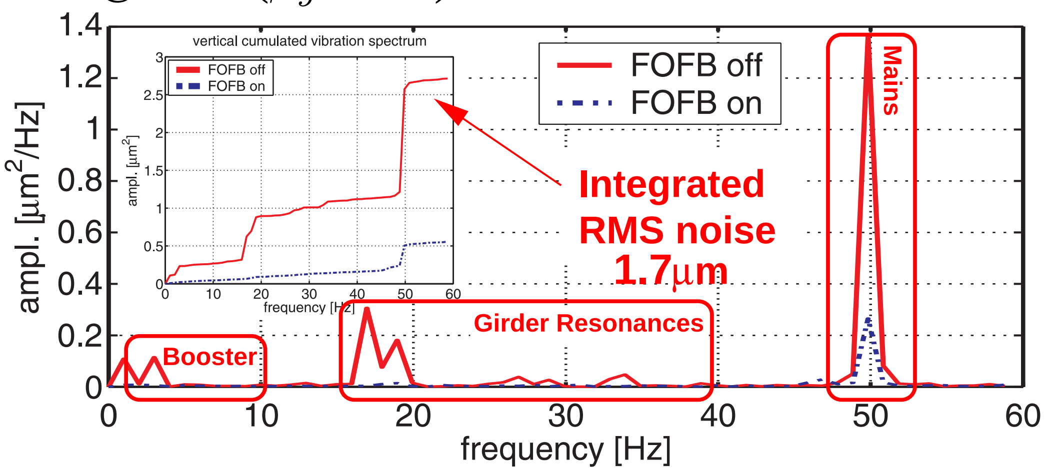


Vertical **vibration** PSD (1-55 Hz) measured on the slab and a girder (Redaelli et al.).

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

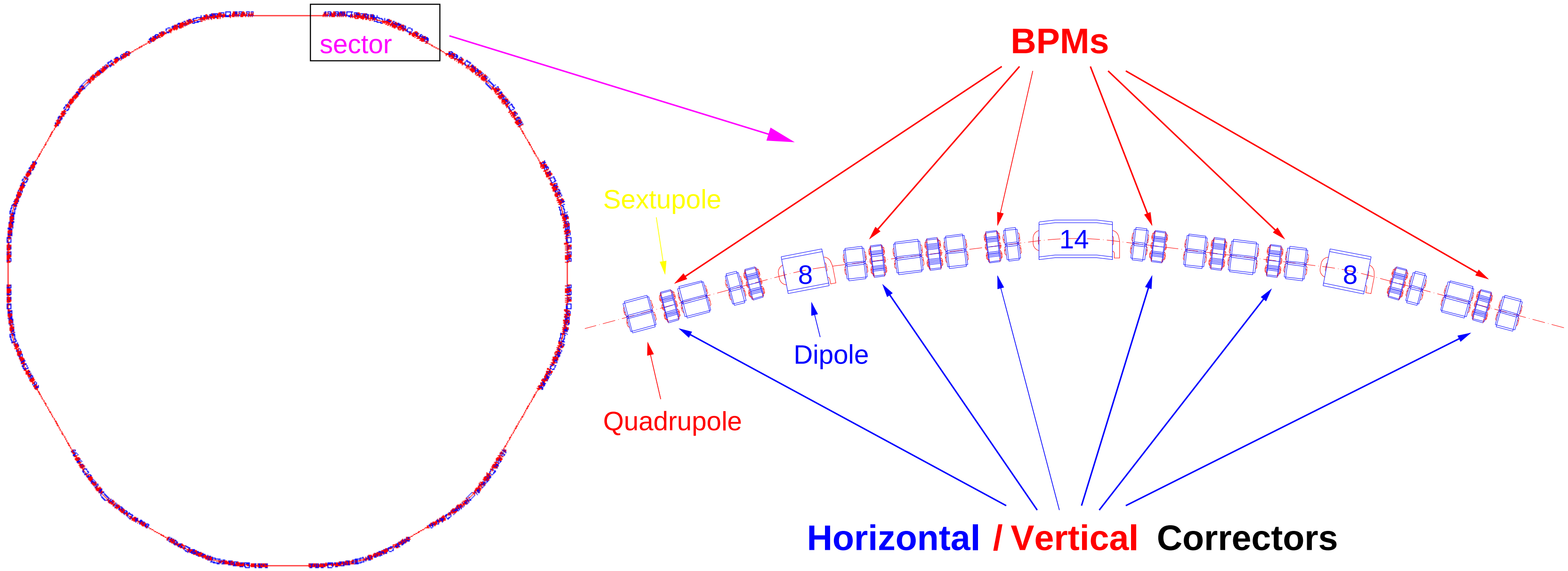


Vertical **orbit** PSD (1-60 Hz) without and with orbit feed-back @ BPM (β_y=18 m):



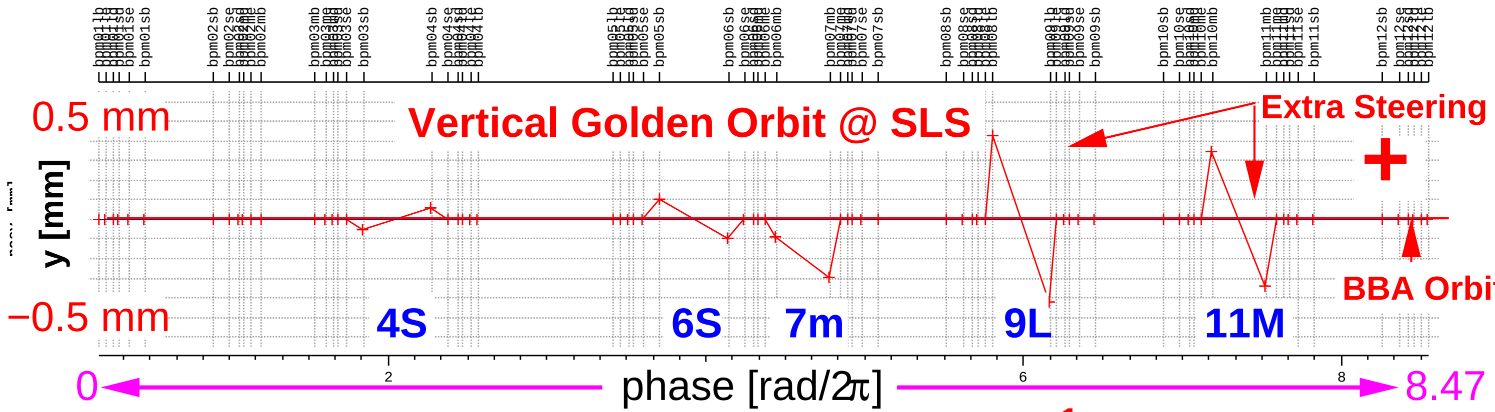
→ **Integrated RMS motion σ_y only ≈0.4 μm $\cdot \sqrt{\beta_y}$!**

SR - BPM/Corrector Layout

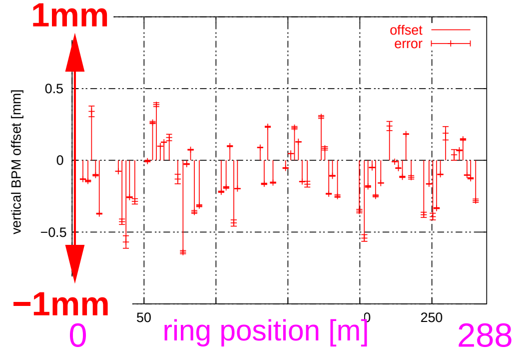


- 12 sectors
- 6 BPMs and 6 Horizontal/Vertical Correctors per sector
- Correctors in Sextupoles, BPMs adjacent to Quadrupoles

SR - 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



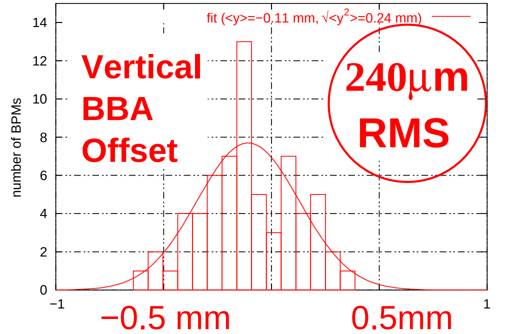
Beam−based alignment (BBA) techniques to find offset BPM − adjacent quadrupole center

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 >100µ m !

DC RMS corrector strength reduced when correcting to BBA orbit !



SR - 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 $\longrightarrow$ unique solution by matrix inversion
  - $n \neq m$: non-square matrix by design or due to BPM failures and/or corrector saturation $\longrightarrow$ solution:
- **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 $A^{-1} = V * 1/W * U^T$
  - $n > m$: 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 $\longrightarrow$ SVD makes other long range correction schemes like "MICADO" superfluous

SR - 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 nxn case has become an option since
  - resulting RMS corrector strength is still moderate (typically $\approx$100 μrad)
  - 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.

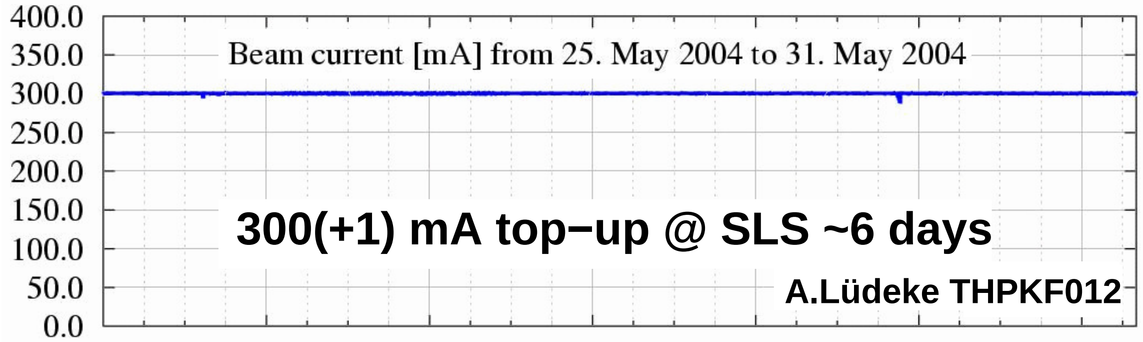
Remarks on horizontal orbit correction:

- 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 $\longrightarrow$ 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.

SR - Stability - Medium Term

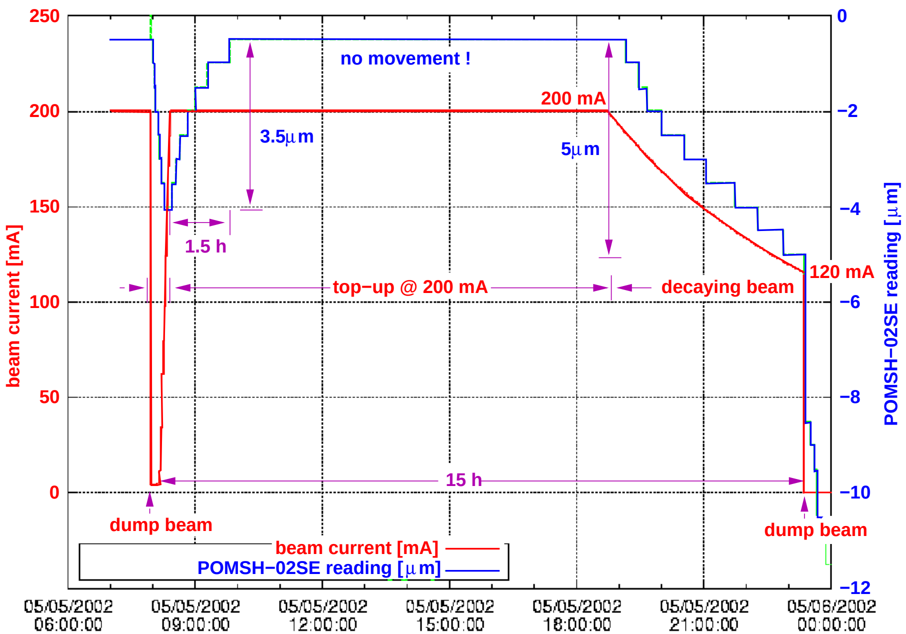
In this regime high mechanical stability is needed to achieve stability on the sub-micron level:

- Stabilization of tunnel, cooling water temperature and digital BPM electronics 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.
- Stiff BPM supports with low temperature coefficients and monitoring of BPM positions with respect to adjacent quads (POMS).
- Monitoring of girder positions (Hydrostatic Leveling System (HLS), Horizontal Positioning System (HPS)).
- Full energy injection and stabilization of the beam current to $\approx$0.1 % ("top-up" operation):



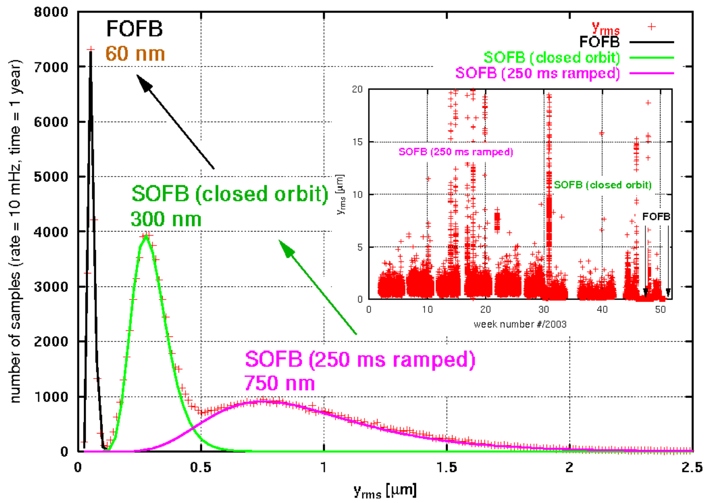
SR - Stability - Medium Term - Top-up

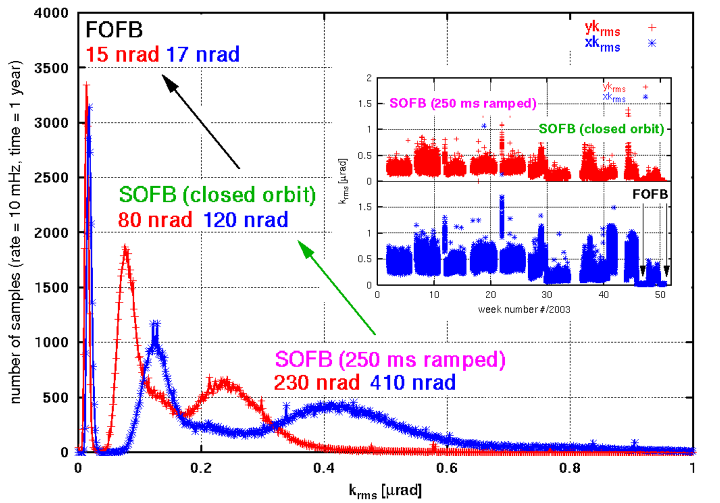
- “Top-up” operation guarantees a constant electron beam current and thus a constant heat load on all accelerator components. It also removes the current dependence of BPM readings under the condition that the bunch pattern is kept constant (B. Kalantari)
- Horizontal mechanical offset (≈0.5 μm resolution) 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

SR - Stability - Transition from Slow to Fast Orbit Feedback

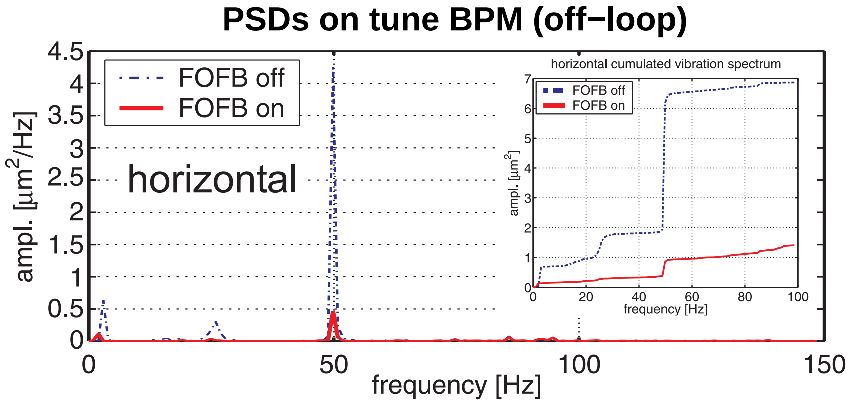


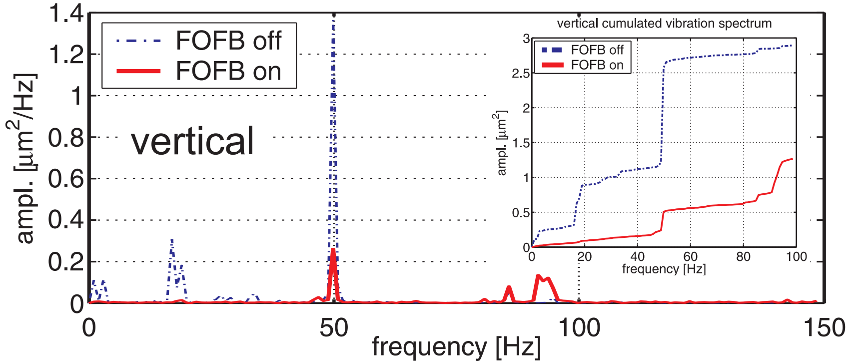


Temporal mean of the RMS orbit deviation from the BPM reference settings x_{rms} / y_{rms} and the corresponding RMS corrector strength xk_{rms} / yk_{rms} in 2003 for three different operation modes:

mode	horizontal x_{rms}	horizontal xk_{rms}	vertical y_{rms}	vertical 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**

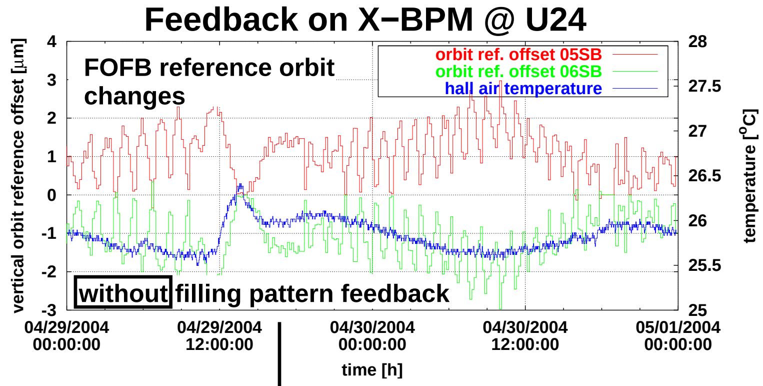
SR - Stability - Fast Orbit & X-BPM Feedback

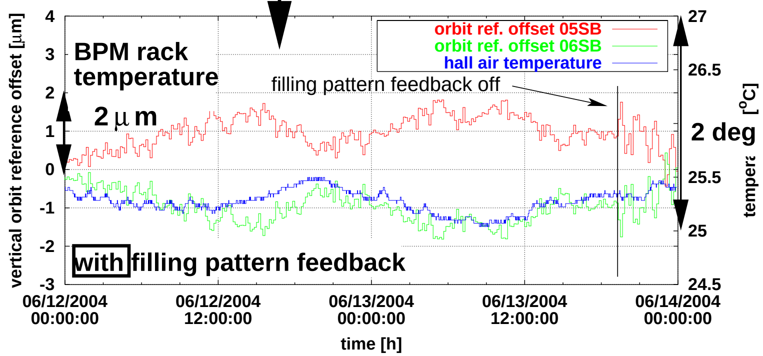


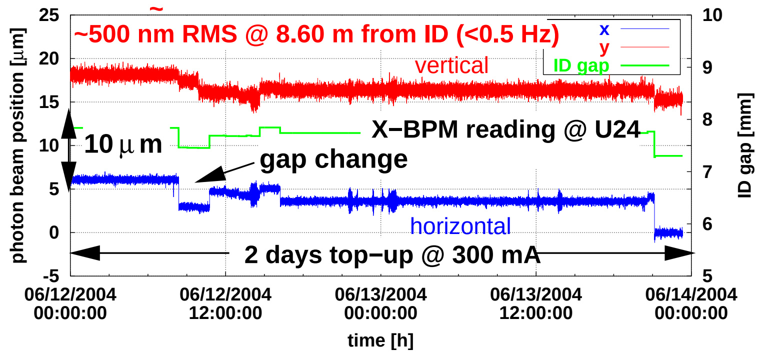


	horizontal		vertical	
FOFB	off	on	off	on
1- 100 Hz	**0.83 µm · $\sqrt{\beta_x}$**	**0.38 µm · $\sqrt{\beta_x}$**	**0.40 µm · $\sqrt{\beta_y}$**	**0.27 µm · $\sqrt{\beta_y}$**
100-150 Hz	0.08 µm · $\sqrt{\beta_x}$	0.17 µm · $\sqrt{\beta_x}$	0.06 µm · $\sqrt{\beta_y}$	0.11 µm · $\sqrt{\beta_y}$
1-150 Hz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

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

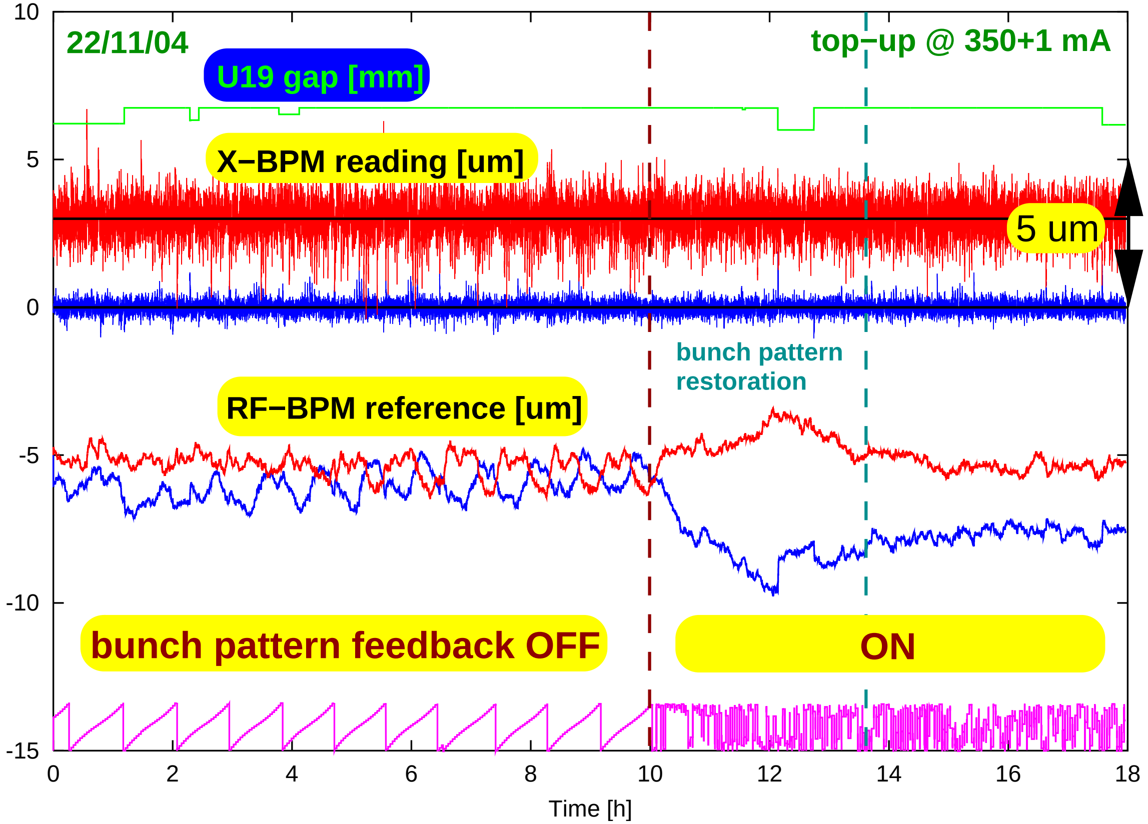


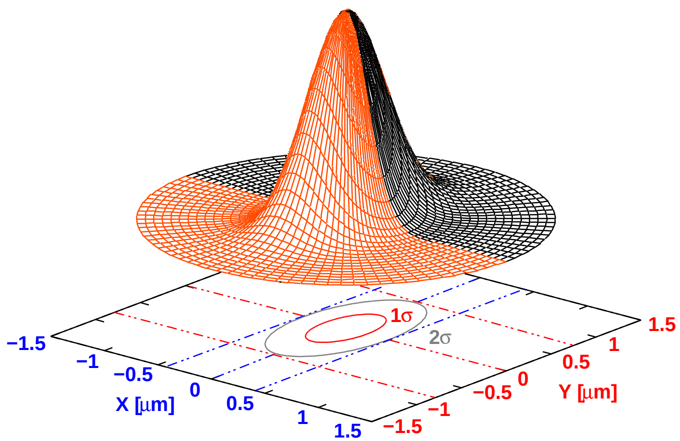




SR - Stability - X-BPM & Bunch Pattern Feedback

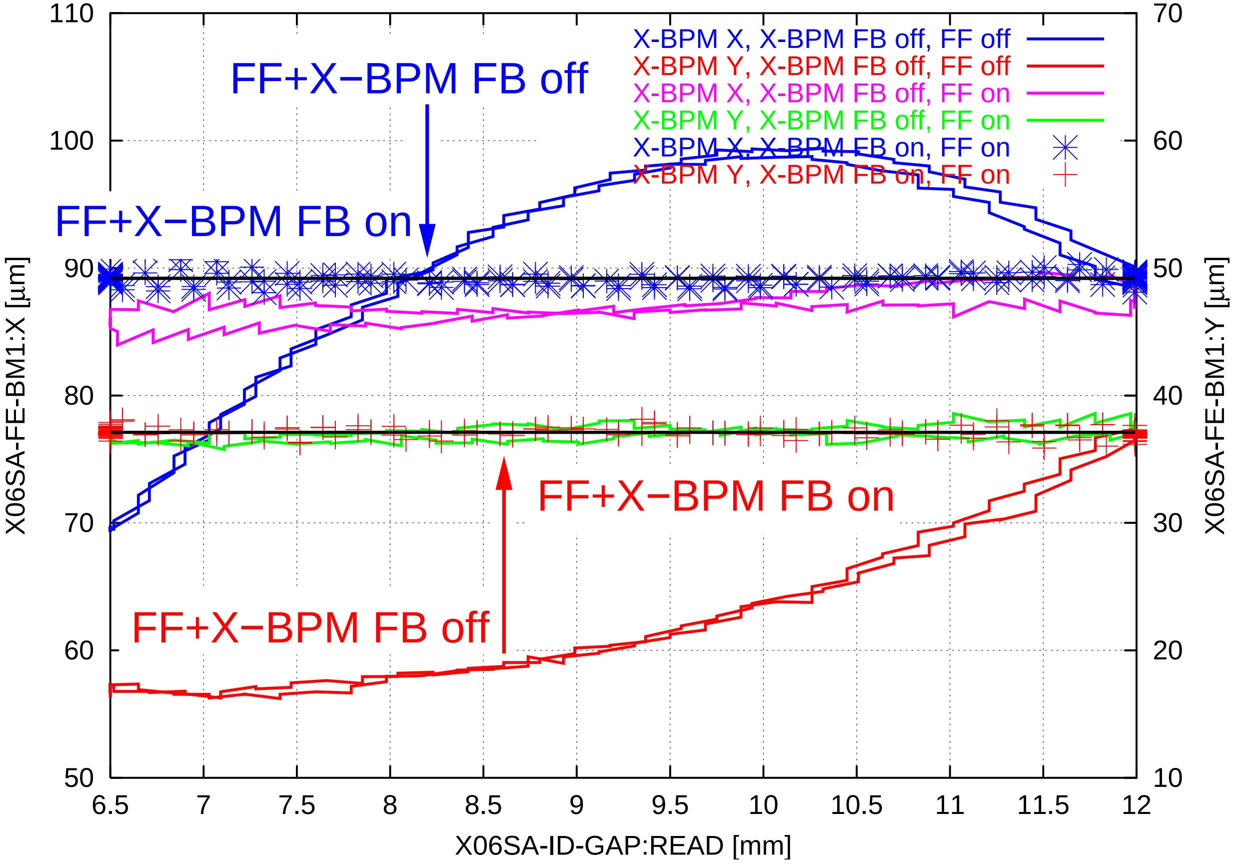
- The bunch pattern feedback maintains the bunch pattern (390 bunches (≈1 mA)) within <1 %
- The X-BPM feedback (slave) stabilizes the photon beam (≈9 m from source point) by means of changes in the reference orbit of the fast orbit feedback (master) to ≈0.5 μm for frequencies up to 0.5 Hz





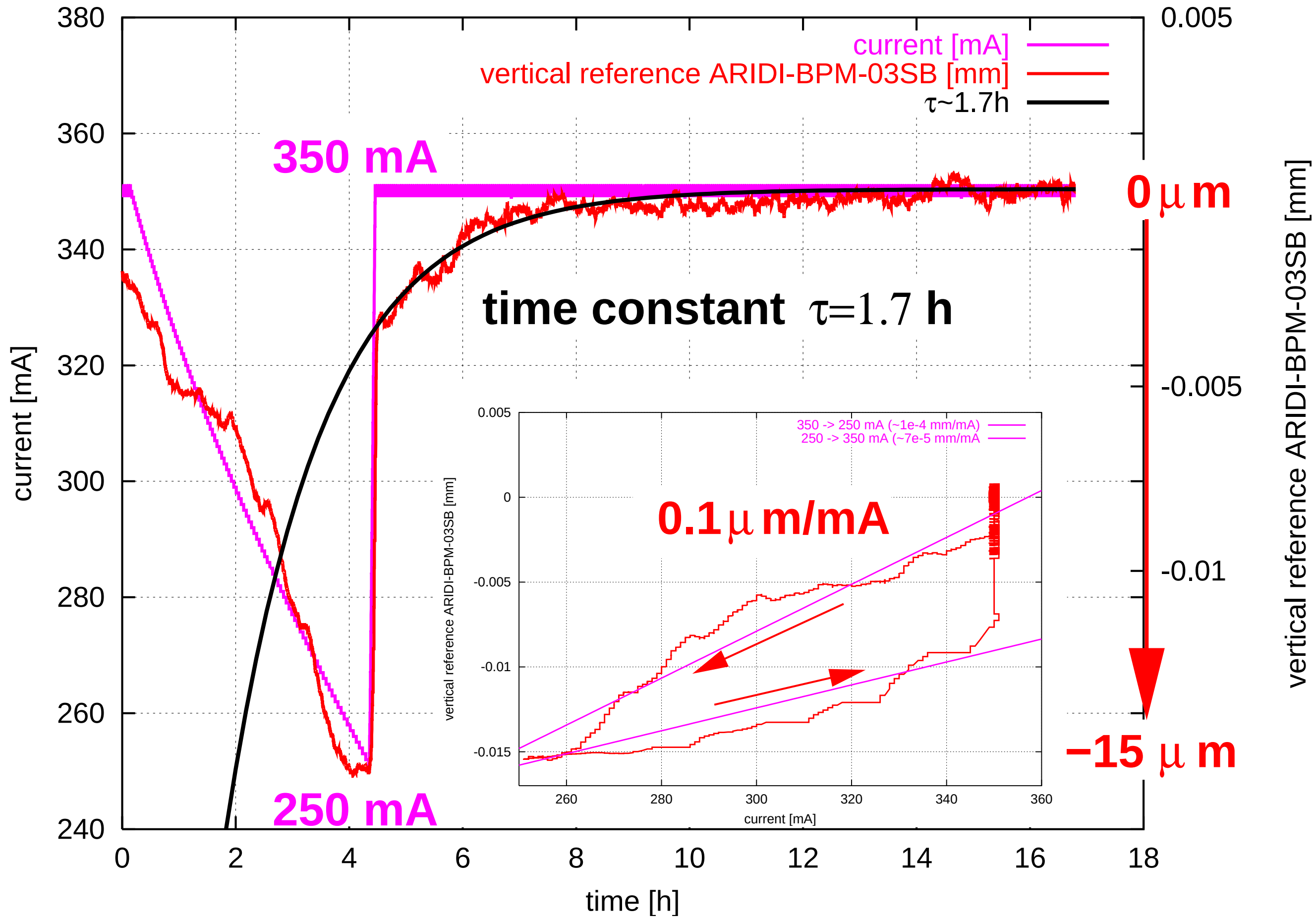
SR - Stability - Feed Forward & X-BPM Feedback

- 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



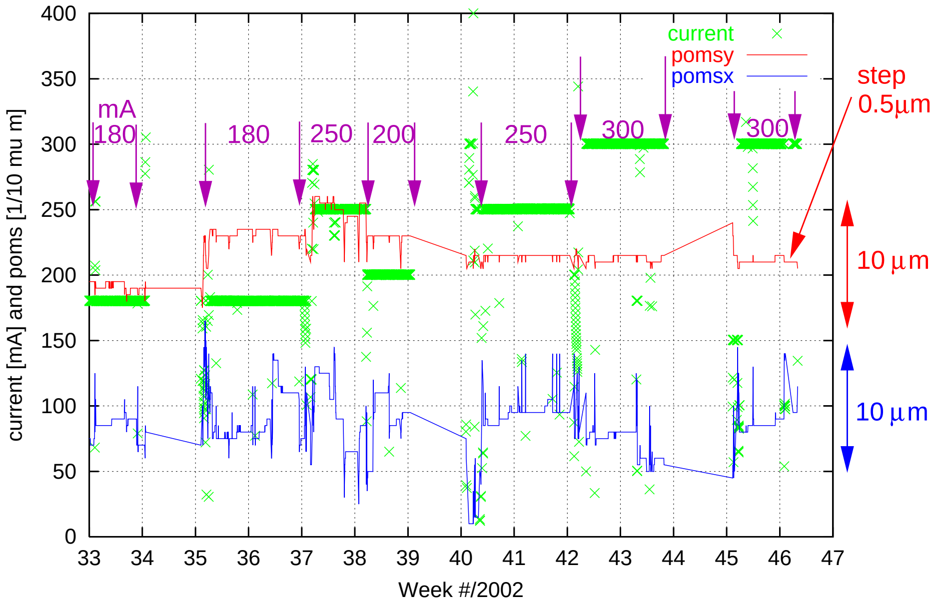
SR - Stability - Medium Term - Top-up

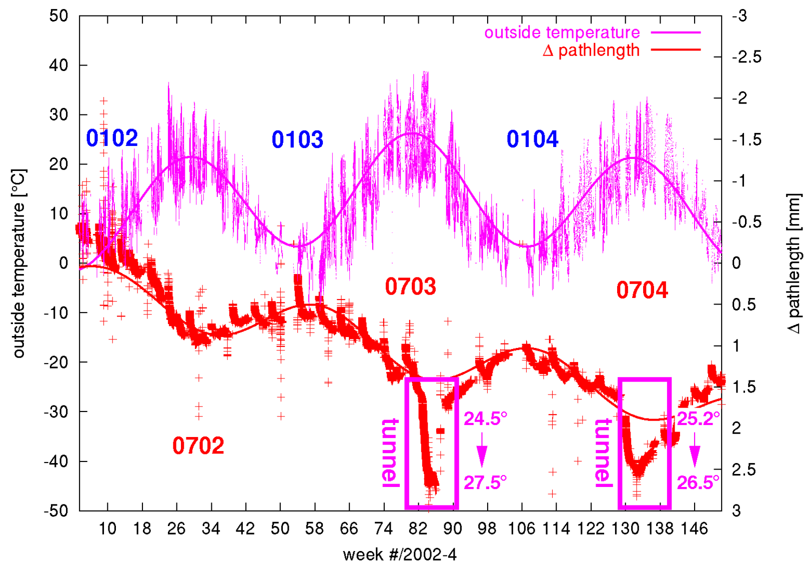
- Change of the vertical BPM reference within the X-BPM feedback loop for decaying beam operation (0-4 h) and "Top-up" (Time constant for getting back to thermal equilibrium τ=1.7 h):



SR - Stability - 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 3 years of SLS operation (→ Δ circumference ≈ 3 mm) (right plot)

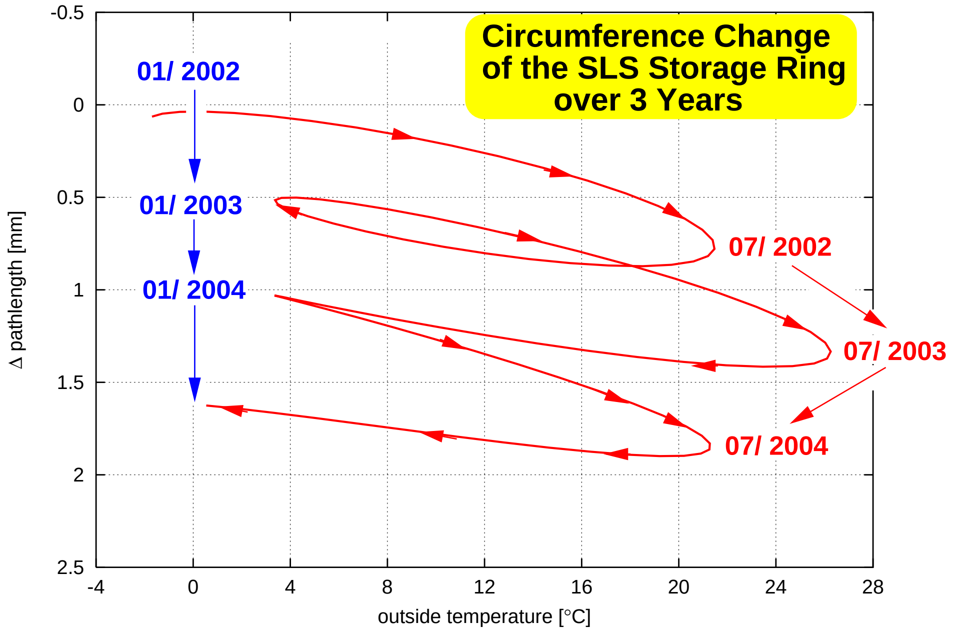


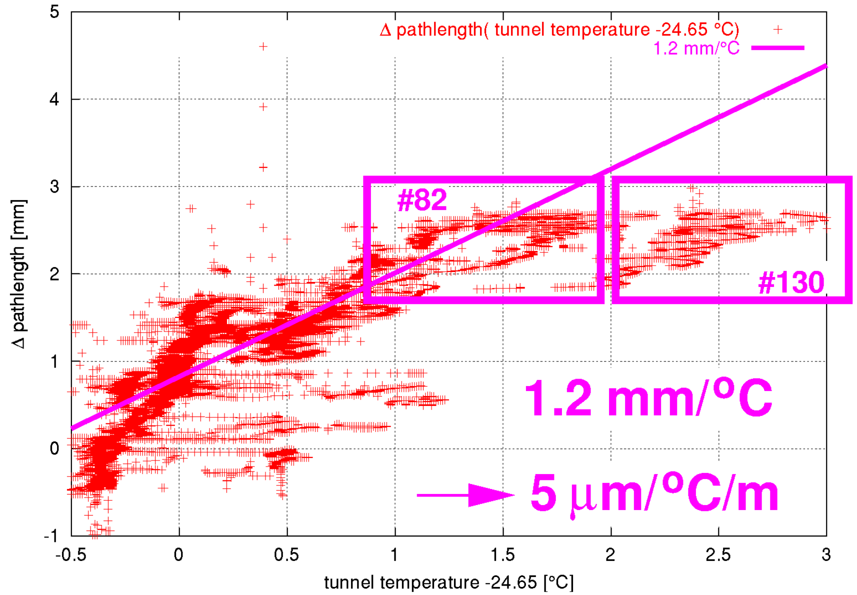


- Severe problems with the cooling capacity of the SLS during the hot summer 2003 (#82)! Again "scheduled" problems in 2004 (#130) due to the cooling system upgrade!

SR - Stability - Long Term Stability

- Fitted circumference change over 3 years of SLS operation (→ Δ circumference ≈ 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 ≈ ±0.1° is needed to guarantee sub-micron movement !

Conclusions

- The fast orbit feedback and X-BPM feedbacks guarantee excellent **short term stability** up to 100 Hz.
- “Top-up” Operation allows to maintain this degree of stability on the **medium term scale** over weeks.
- **Long term stability** suffered from problems with the cooling system during the summer months over the last 2 years.