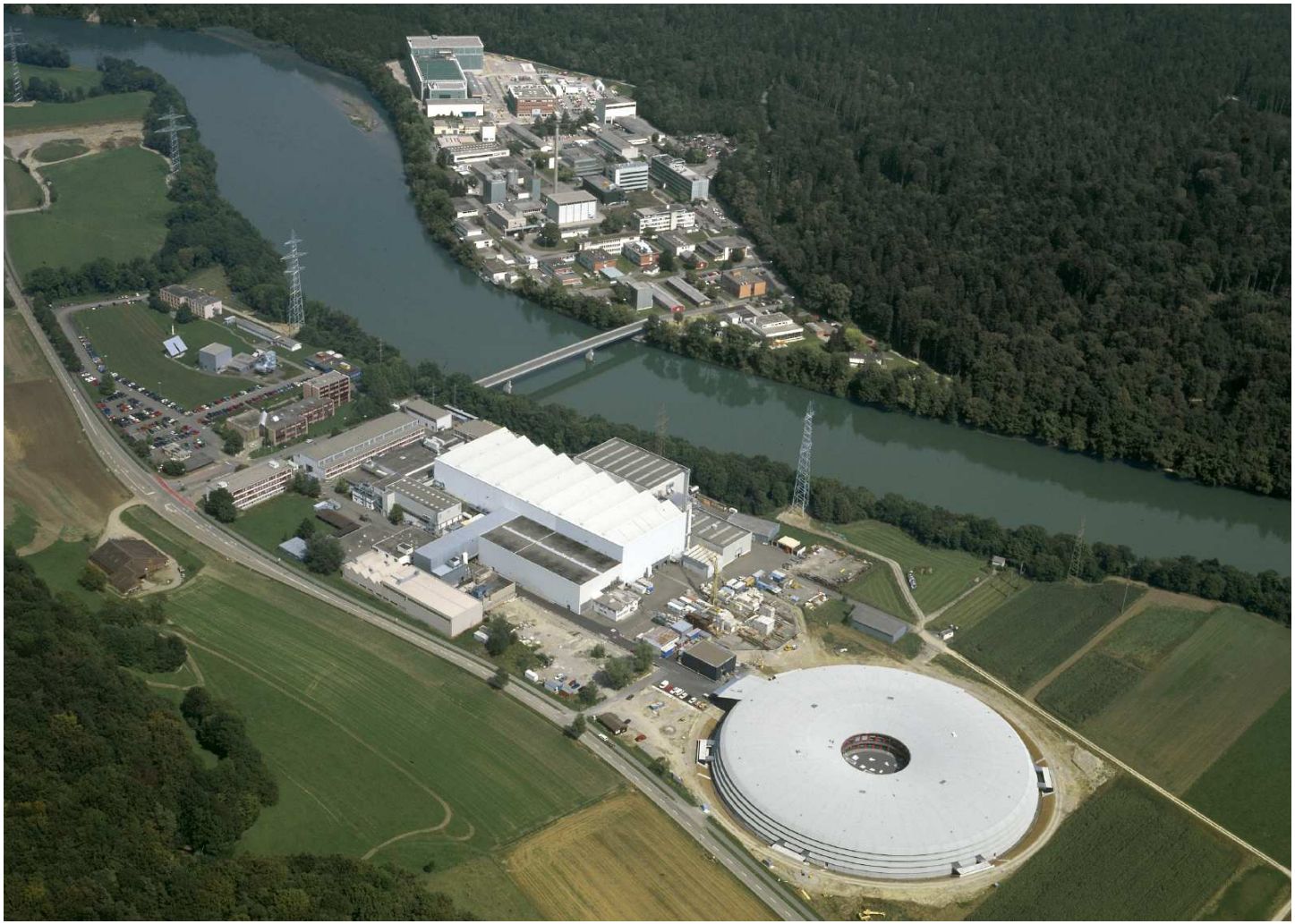
SLS at the Paul Scherrer Institute (PSI), Villigen, Switzerland

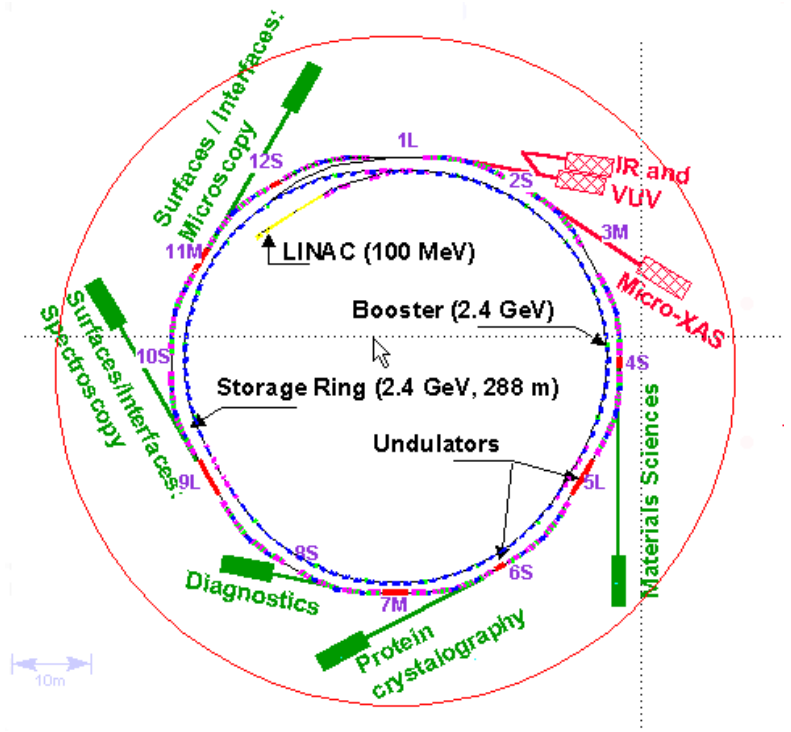


Contents

- SLS Layout
- Booster
- Storage Ring (SR)
  - Beamlines and Insertion Devices
  - Lattice Calibration
  - Innovative Subsystems
  - Stability
  - Slow Orbit Feedback (SOFB)
  - Stability during Top-up Operation
- Conclusions

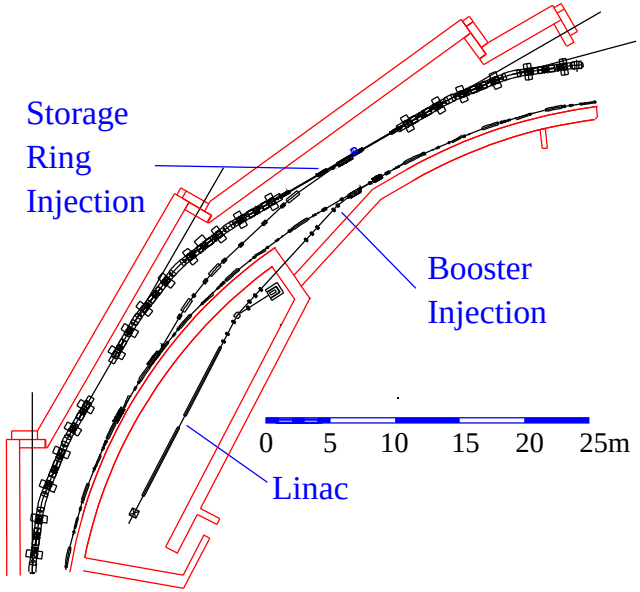
SLS Layout

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



Booster - Design

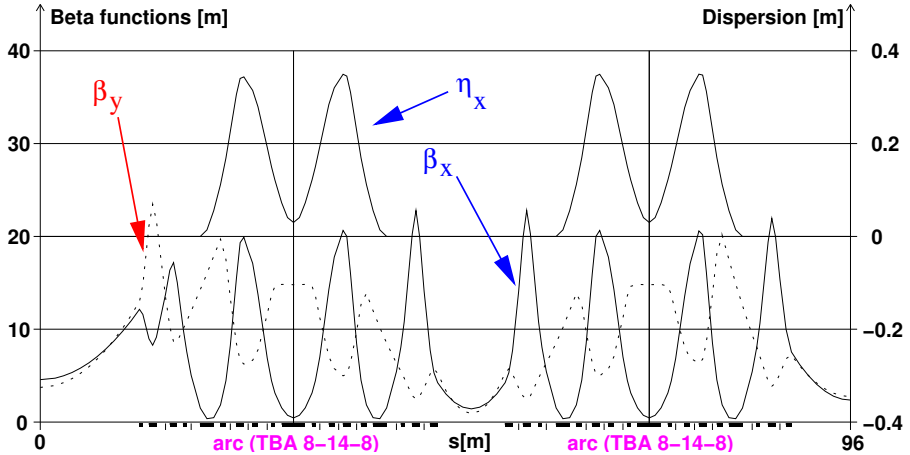
– 3 FODO arcs with 48 BD (+SD) 6.4410 °and 45 BF (+SF) 1.1296 °
– 3 × 6 Quadrupoles for Tuning, 54 BPMs, 2 × 54 Correctors
– ± 15 mm × ± 10 mm Vacuum Chamber
– Energy: 100 MeV → 2.7 GeV, Repetition Rate: 3 Hz, Circumference: 270 m
– Magnet Power: 205 kW, ϵ_x @ 2.4 GeV: 9 nm rad



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)

SR - Design

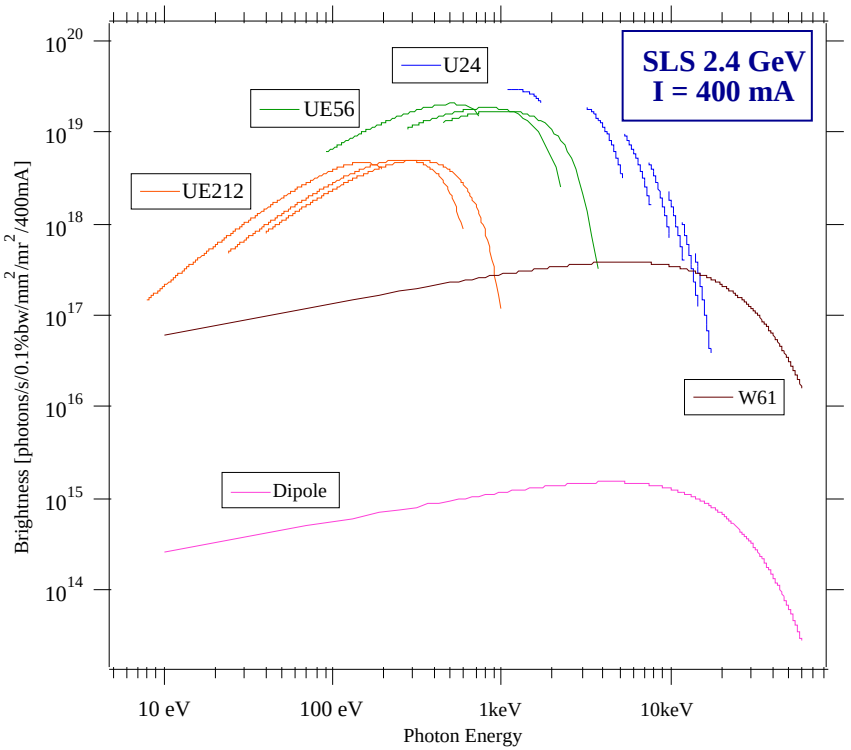
- 12 TBA: 8° / 14° /8 °
- 12 Straight Sections:
  - 3 × 11 m (n**L**)
    - **Injection**, **U212**
  - 3 × 7 m (n**M**)
    - **UE56**
  - 6 × 4 m (n**S**)
    - 2× **RF**, **W61**, **U24**
- Energy: 2.4 GeV (2.7 GeV)
- ϵ_x: 5 nm rad
- Current: 400 mA
- Circumference: 288 m
- Tune: 20.38(.42) / 8.16(.17)
- Chromaticity: -66 / -21



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

Beamlines and Insertion Devices (IDs)

SIS/9L	Surfaces and Interfaces Spectroscopy
ID:	2 × Electromagnetic Twin Undulator
Energy:	**UE212** → 8-800 eV
SIM/11M	Surfaces and Interfaces Microscopy
ID:	2 × APPLE II Type Twin Undulator
Energy:	**UE56** → 90 eV-3 KeV
PX/6S	Protein Crystallography
ID:	In-Vacuum Undulator
Energy:	**U24** → 8-14 KeV (from Spring-8)
MS/4S	Material Science
ID:	High Field Wiggler
Energy:	**W61** → 5-40 KeV



SR - Lattice Calibration - Emittances, Energy Spread I

- **Design and Simulation:**

  Natural Emittance: ϵ_{x0} = 5.0 nm rad

  Emittance Ratio: ϵ_y/ϵ_x = 0.1 %

  Energy Spread: $\sigma_e = 0.9 \cdot 10^{-3}$

- **Measurements:**

  Betatron Coupling κ (Closed Tune Approach):

  – κ = 5.0 % $\longrightarrow$ κ = 0.7 % (sextupole shortcuts)

  – κ = 0.1 % with skew quadrupoles

  Dispersion (Difference Orbit):

  – $\sqrt{< \eta_y^2 >} \approx$ 4 mm

  – $\longrightarrow \epsilon_y \approx$ 15 pm rad, $\epsilon_y/\epsilon_x \approx$ 0.3 %

  Pinhole Array:

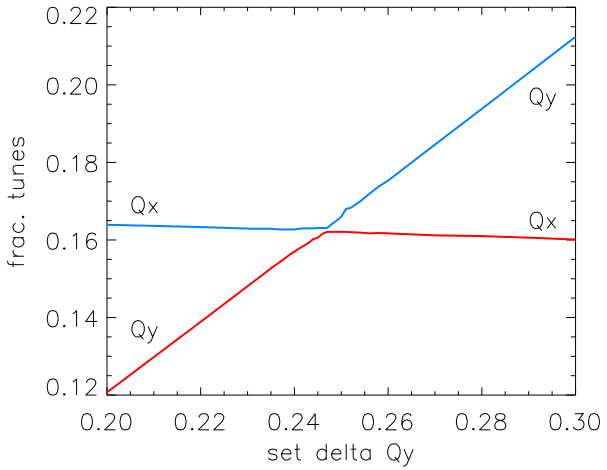
  β_x = 0.8 m,β_y = 14.8 m,η_x = 4.4 cm,$\eta_y \approx$ 1 cm

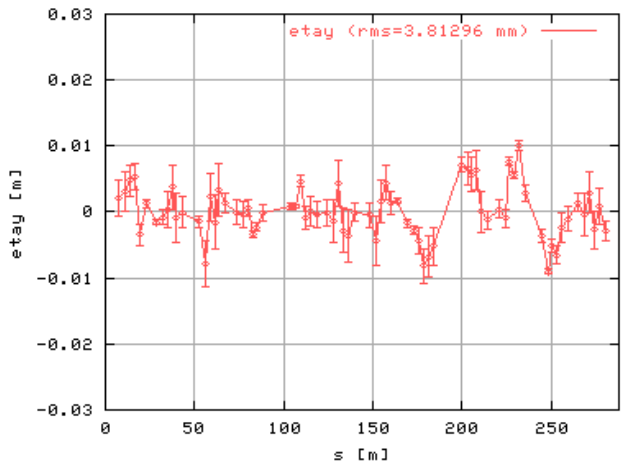
  – On Coupling Resonance:

  – $\sigma_y \longrightarrow \epsilon_{x0}$ = 5.28 nm rad, $\sigma_x \longrightarrow \sigma_e = 1.47 \cdot 10^{-3}$

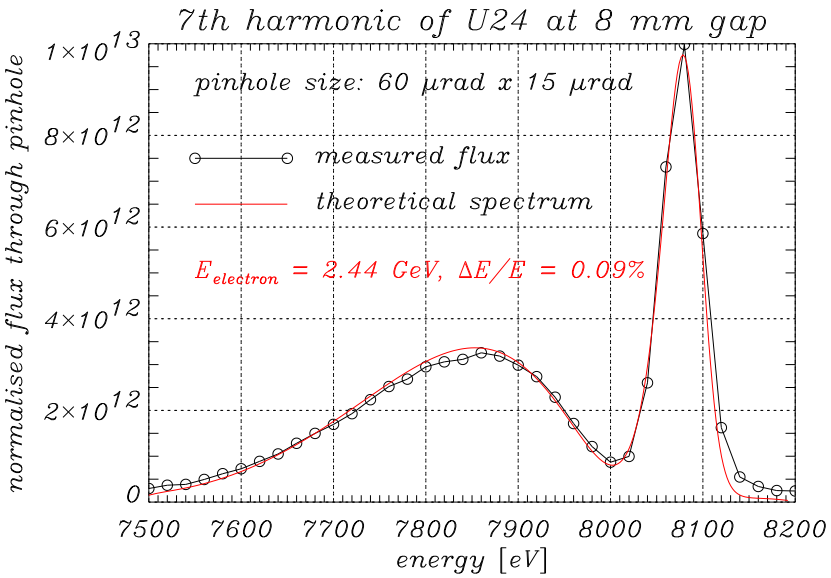
  – At Normal Working Point:

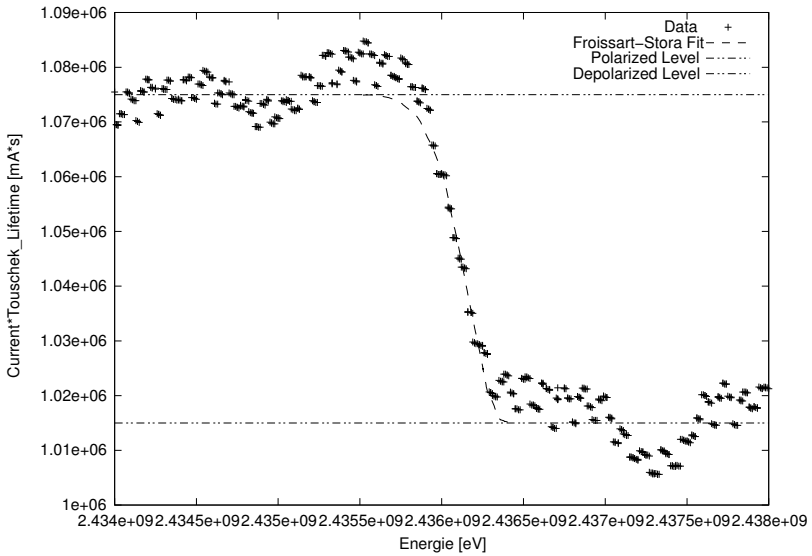
  – $\sigma_x \longrightarrow \sigma_e = 1.5 \cdot 10^{-3}$, $\sigma_y \longrightarrow \epsilon_y/\epsilon_x$ = 1.5 %





SR - Lattice Calibration - Energy Spread II, 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

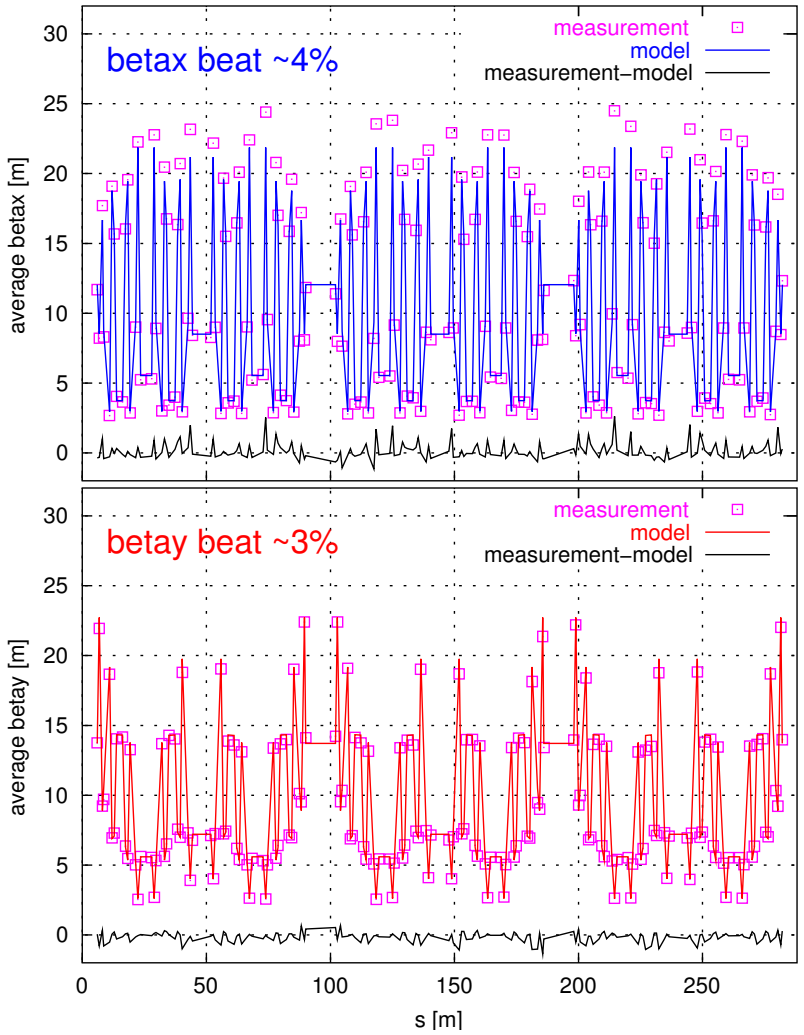
$\longrightarrow\longrightarrow$

Gradient Correction:

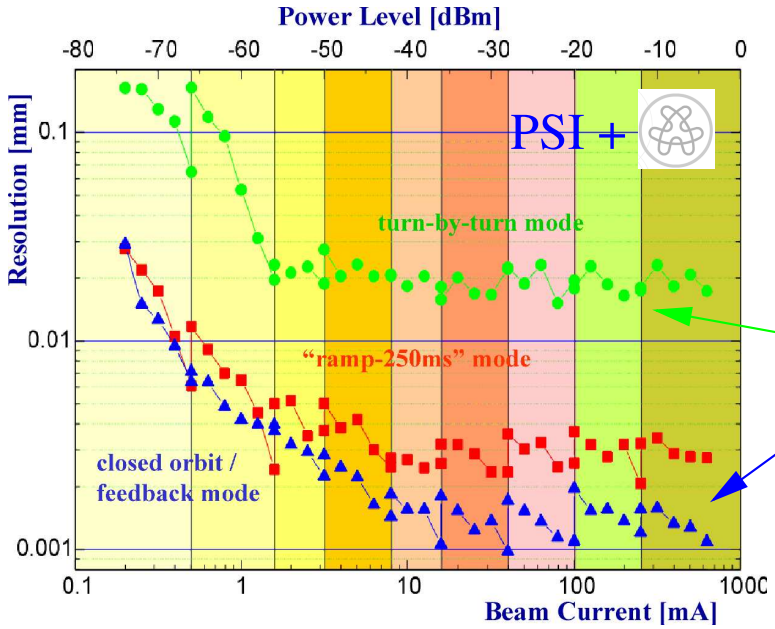
- Procedure:
  1. Measure $< \beta_i >$ for i=1..174

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

     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 - Innovative Subsystems - Digital BPM System

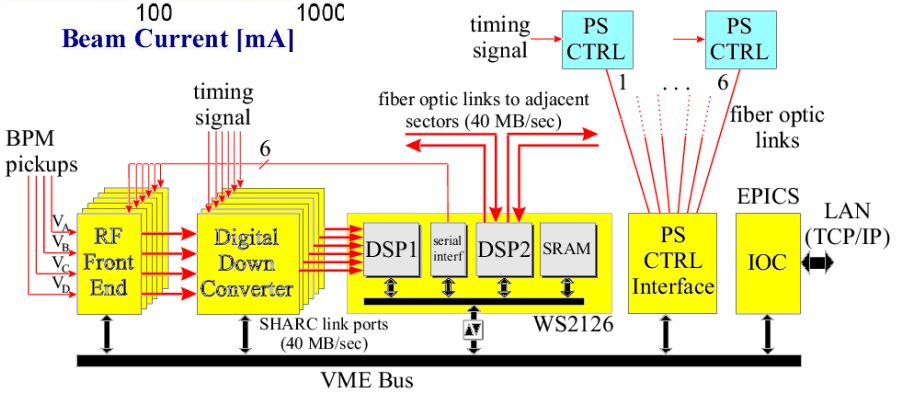


Only One BPM System in Different Operation Mode for All Machines

Turn–by–Turn:
1 MSample/s, <20 mu m

Closed Orbit:
4 KSample/s, <1.2 mu m

Turn–by–Turn:
Vital for Commissioning

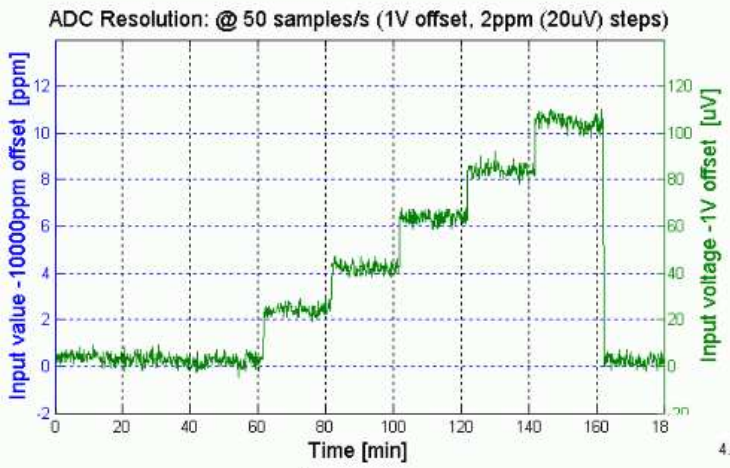


Closed Orbit Mode –> Fast Orbit Feedback

SR - Innovative Subsystems - Digital Power Supplies

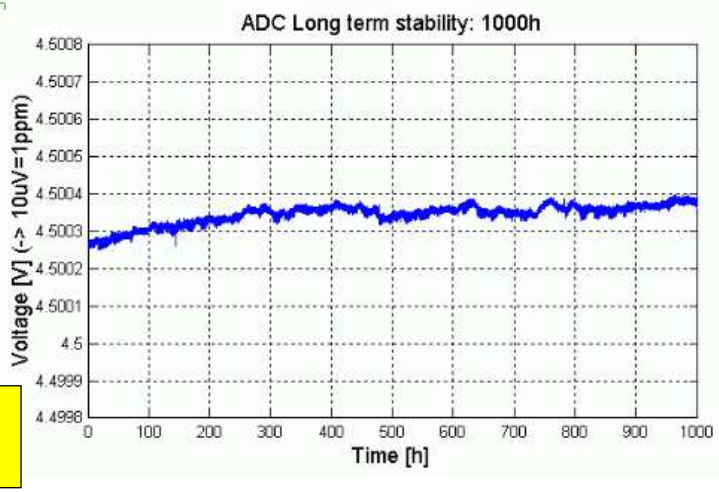
One Digital Control Unit for ~600 power supplies of the SLS

Precision of the AD converter card



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

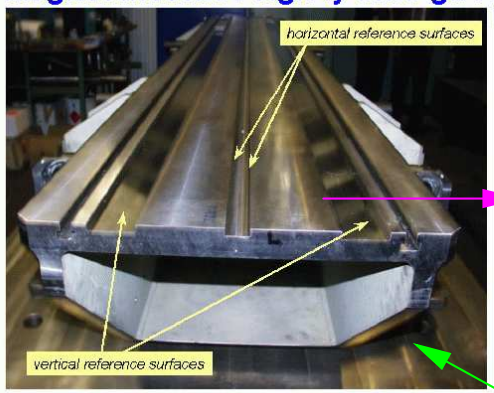
- Long- term stability (1000h) better than 30ppm
- Reproducibility better than 30ppm

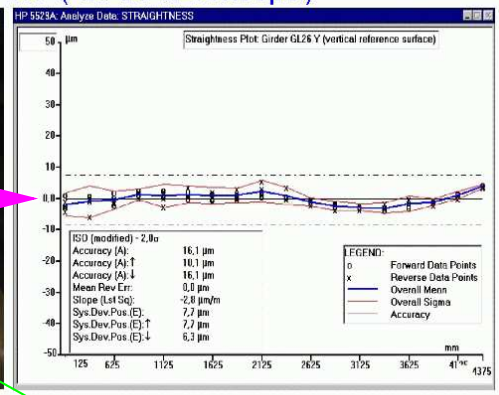


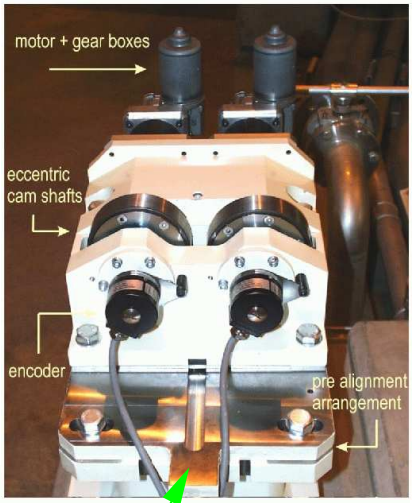
Short/Long–term: <10/30 ppm

SR - Innovative Subsystems - Magnet Girders

Magnet mounted rigidly onto girders ("MAX-2 concept")

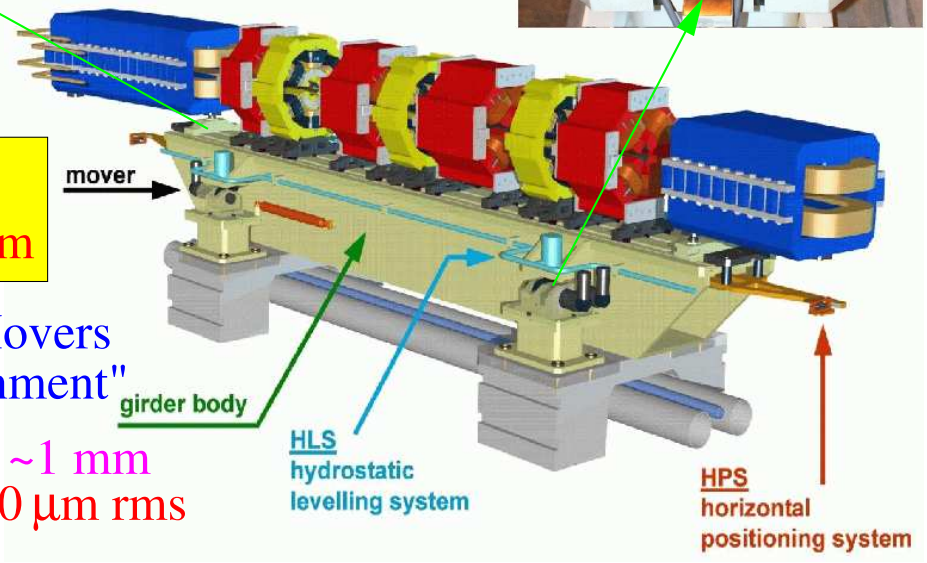






Girders movable in 5 degrees of freedom

Position monitoring systems on girders

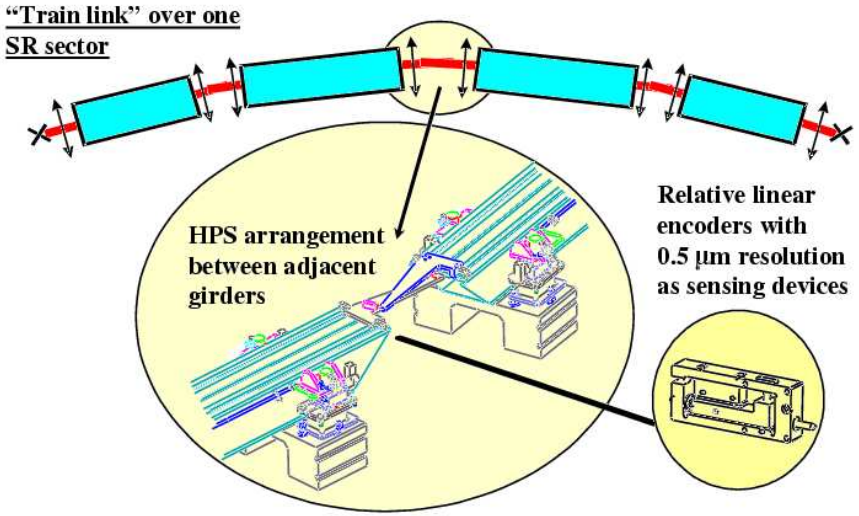


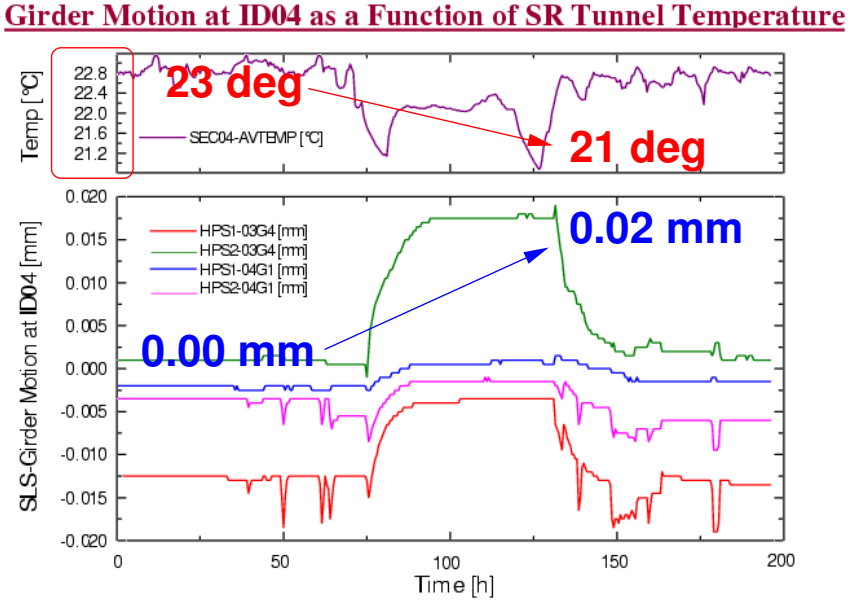
Girder Rail Precision: 15 µm
Magnet Axis Calibration: 30 µm

Remotely Controlled Girder Movers
–> "Beam–Based Girder Alignment"

Null Orbit: xrms ~2 mm, yrms ~1 mm
–> Magnet Misalignments < 50 µm rms

SR - Innovative Subsystems - HPS



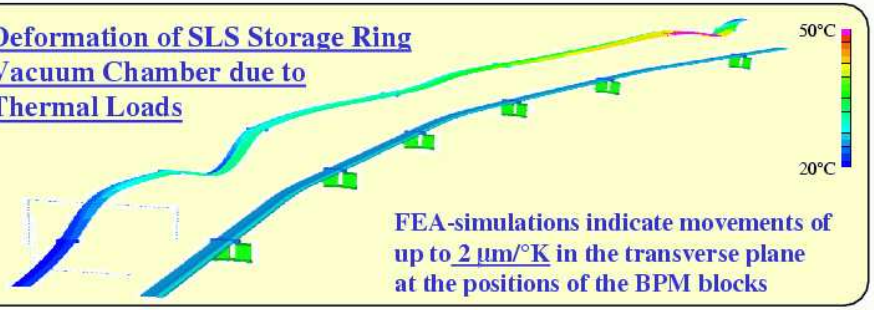


Tunnel Temperature stabilized to <0.5 deg peak-peak

- 4 girders per sector connected through "virtual joints" established by HPS with 0.5 μm precision ($\rightarrow$ "Train link")
- Girders of sector self-contained with 2 reference points at the beginning of straight sections ($\rightarrow \times$)
- Absolute girder positions reconstructed from reference points and "virtual joints"

SR - Innovative Subsystems - POMS

Deformation of SLS Storage Ring Vacuum Chamber due to Thermal Loads



FEA-simulations indicate movements of up to 2 µm/°K in the transverse plane at the positions of the 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.

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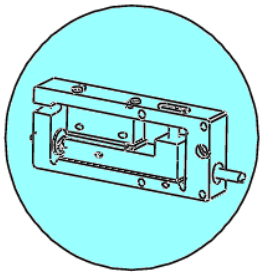
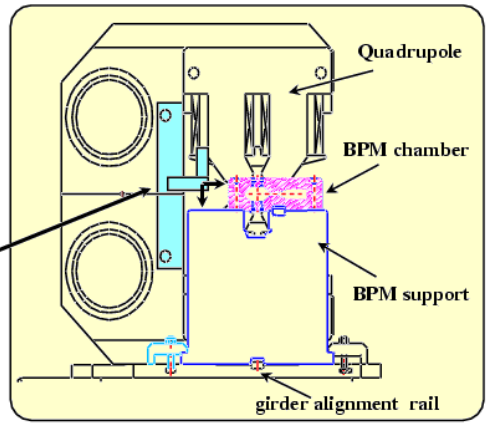
Dial gauges equipped with linear encoders as sensing devices attached to quadrupole magnets

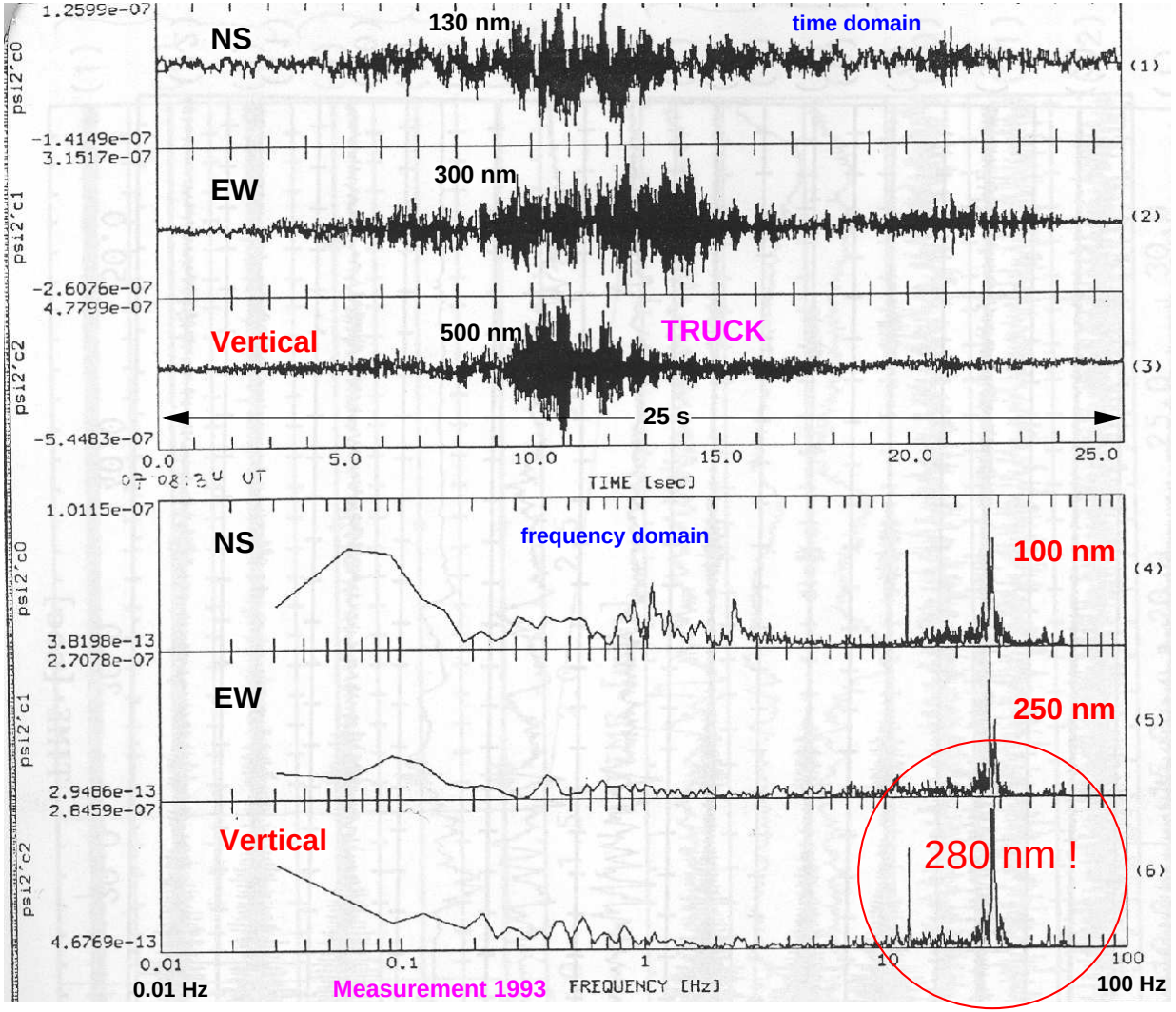




Measure BPM/Quadrupole offsets with 0.5 µm resolution in x and y !

- 6 BPMs per sector
- BPMs rigidly attached to girders (BPM support mounted on girder alignment rail)
- BPM supports serve as supports for the vacuum system (→ BPM chamber)

SR - Stability - Ground Noise



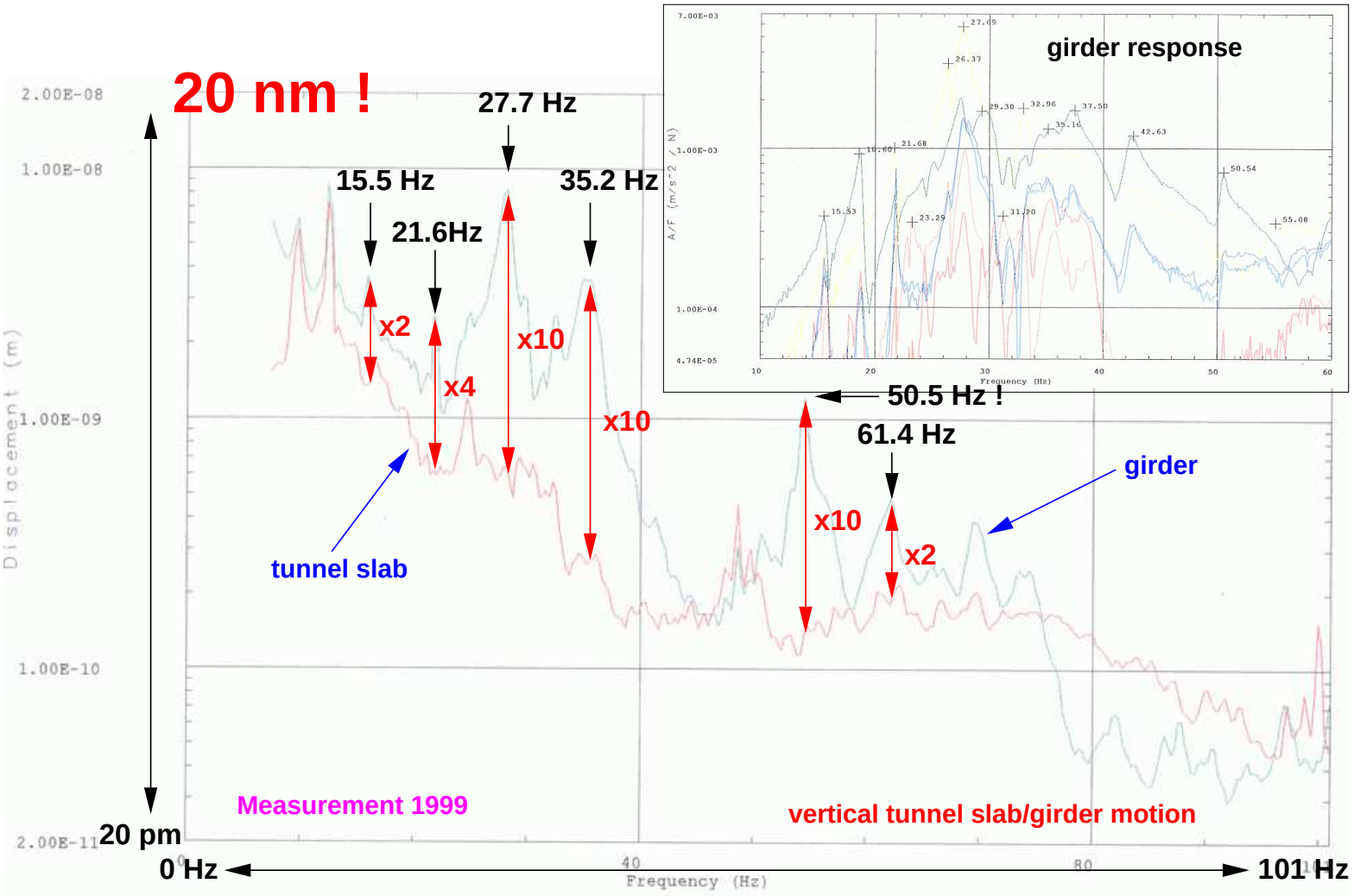
SR - Stability - Worst Case Estimate

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

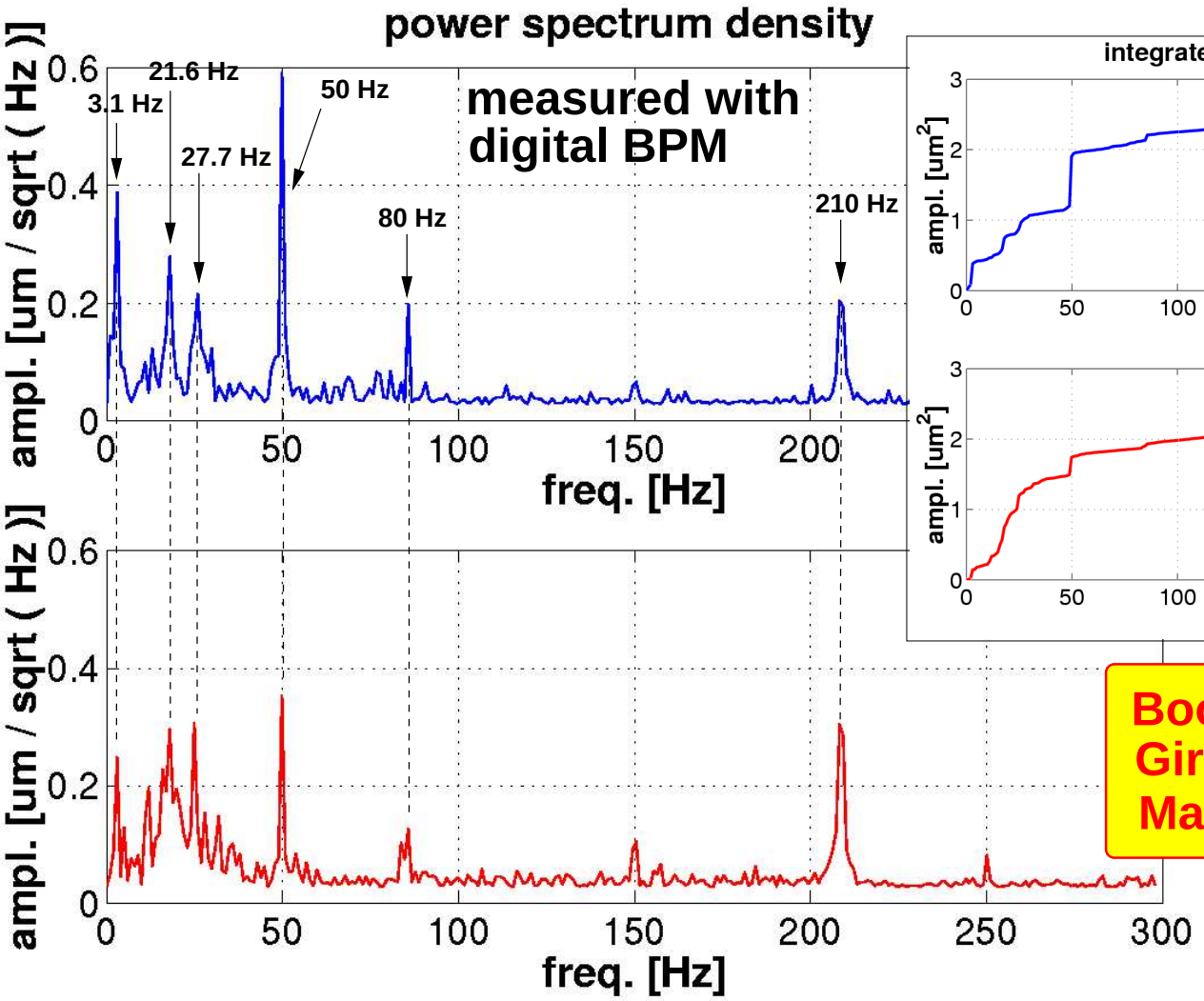
Requirement: Orbit jitter < 1 µm at insertion devices

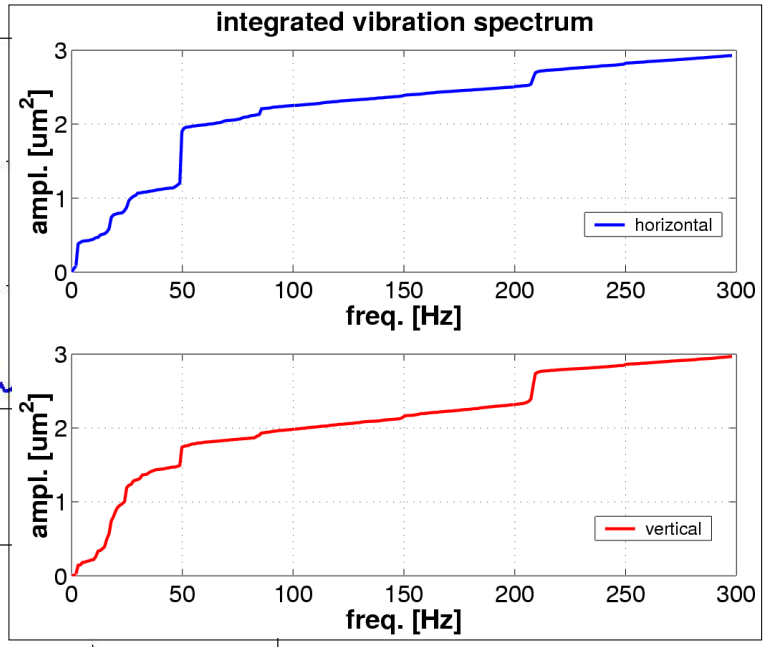
	Worst case Noise estimate	30	60	Hz
	Seismic measurements	300	30	nm
	Damping by hall's concrete slab	neglected		
	Girder resonance max amplification	< 10	< 10	
	Closed orbit amplification hor./vert.	8/5	25/5	
→	Maximum Orbit jitter hor./vert	24/15	7.5/1.5	µm
	Attenuation by orbit feedback	−55	−35	dB
→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

SR - Stability - Girder Response



SR - Stability - Power Spectrum

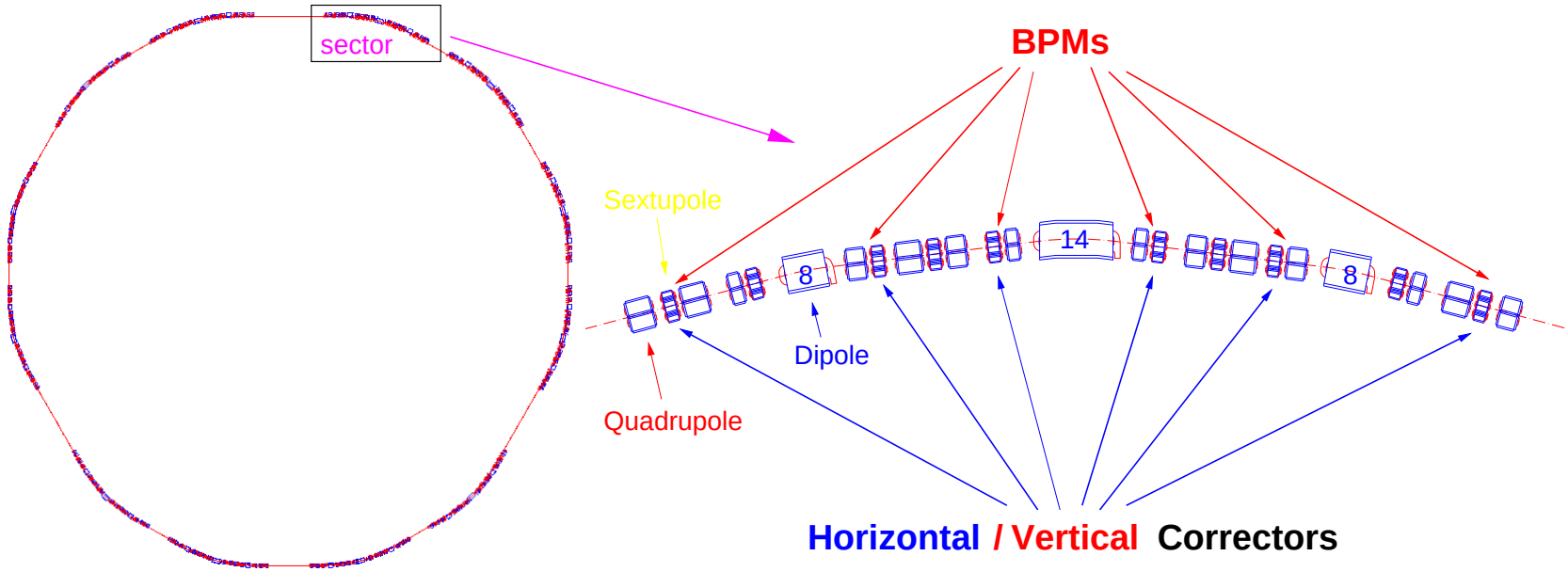




Booster: 3.1 Hz
Girders: 21.6, 27.7Hz
Mains: 50 Hz

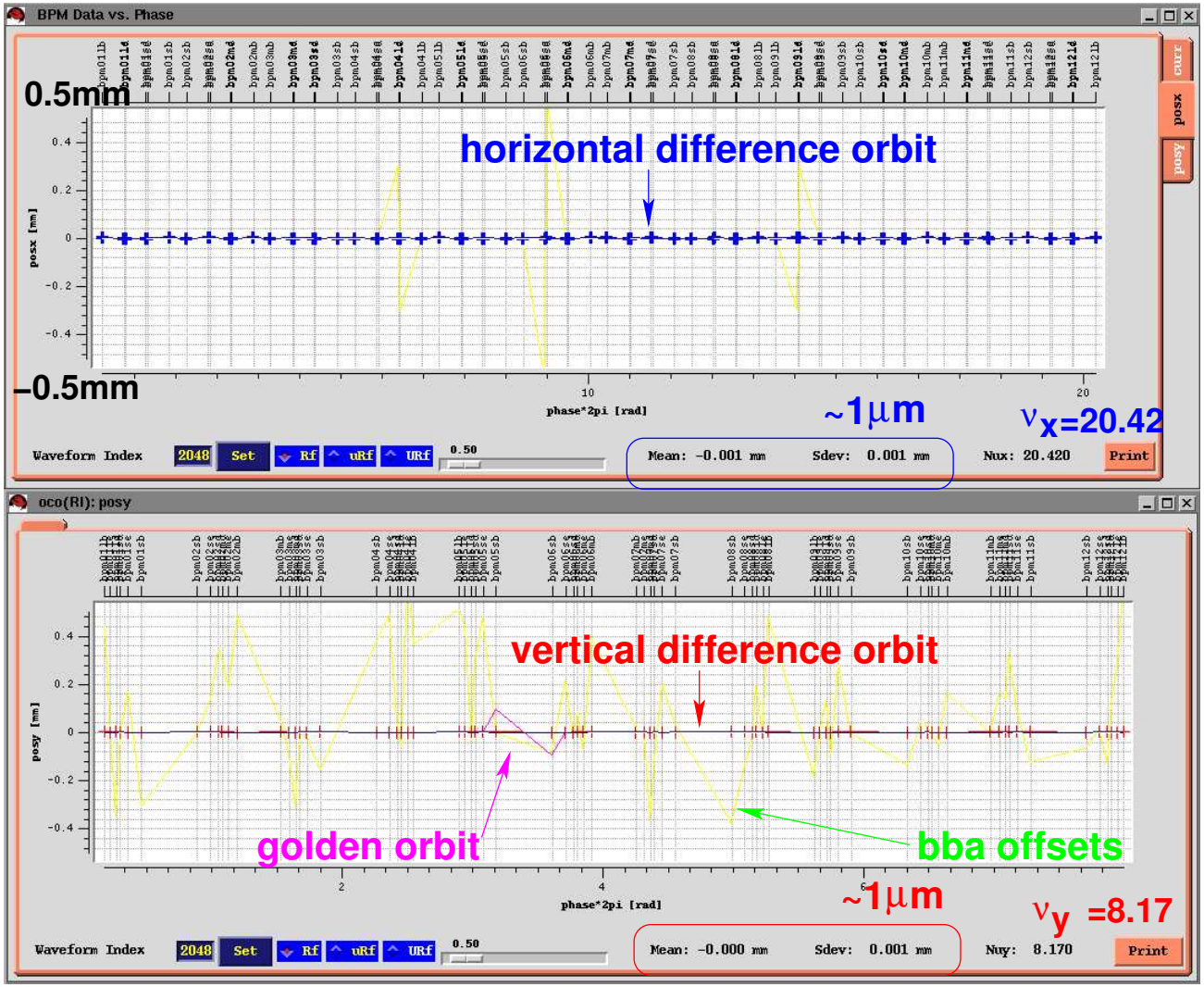
β_x=9m $<\beta_x>$=10m
β_y=21m $<\beta_y>$=11m

SR - BPM/Corrector Layout



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

SR - SOFB - Golden Orbit

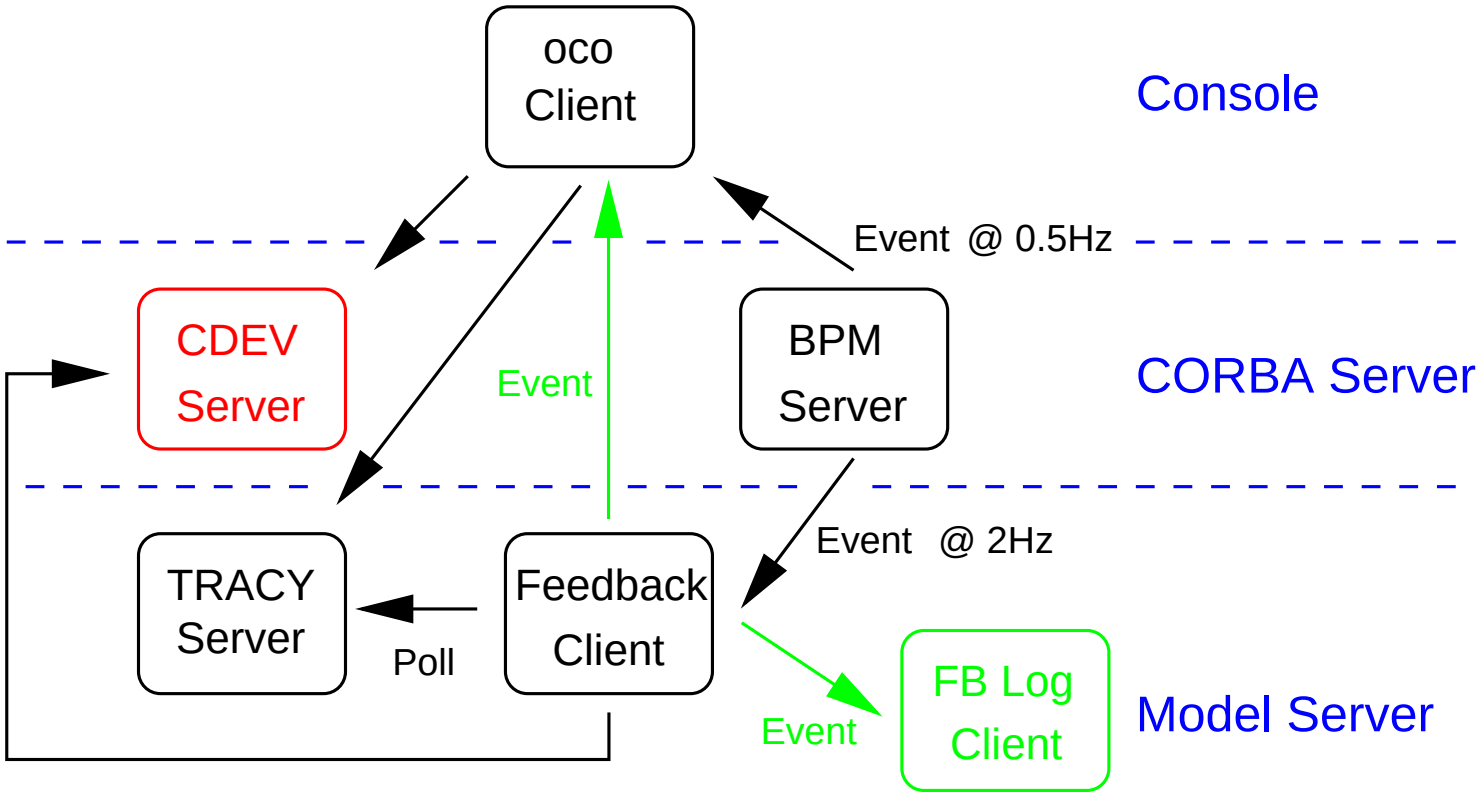


72 BPMs
72 corrs
/plane

0.5 Hz (3 Hz)
refreshrate

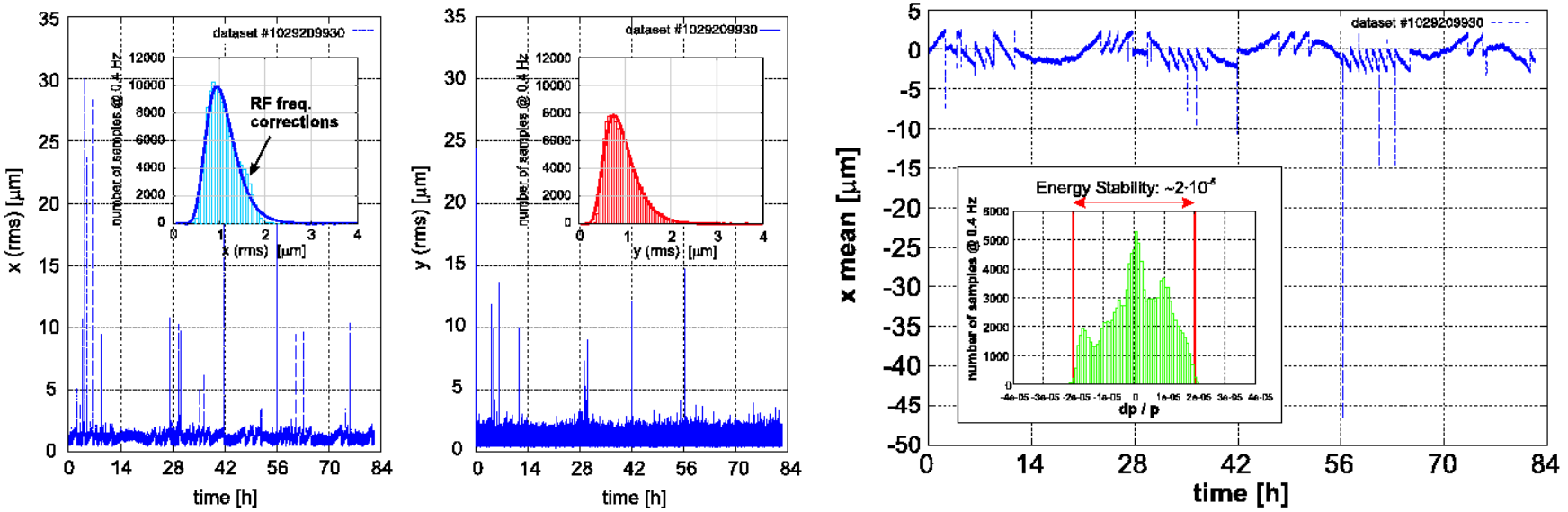
~0.3μm
precision
of BPMs

SR - SOFB - Schematics



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

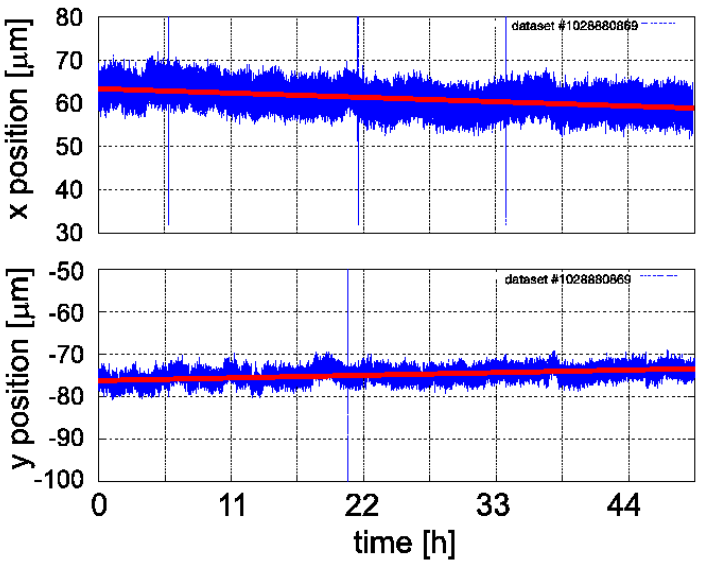
SR - SOFB - RMS/Mean Orbit, Pathlength

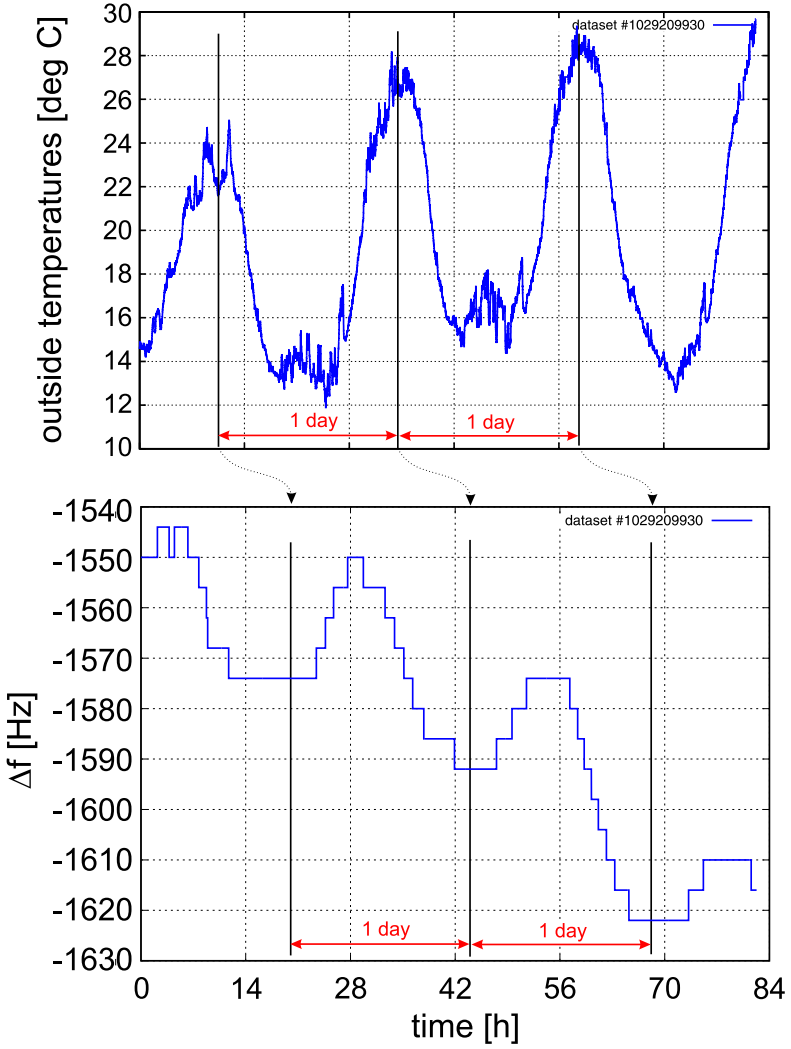


- Sample run Aug, 13-16 2002: x_{rms}, $y_{rms} \approx$ 1 μm (see histograms)
- Off energy dE/E orbits fitted through SVD and subtracted before correction
- RF frequency changed by df whenever |df| exceeds 5 Hz
  (dE/E $\approx 2 \cdot 10^{-5}$) –> correction every $\approx$ 45 min (see “saw tooth”)

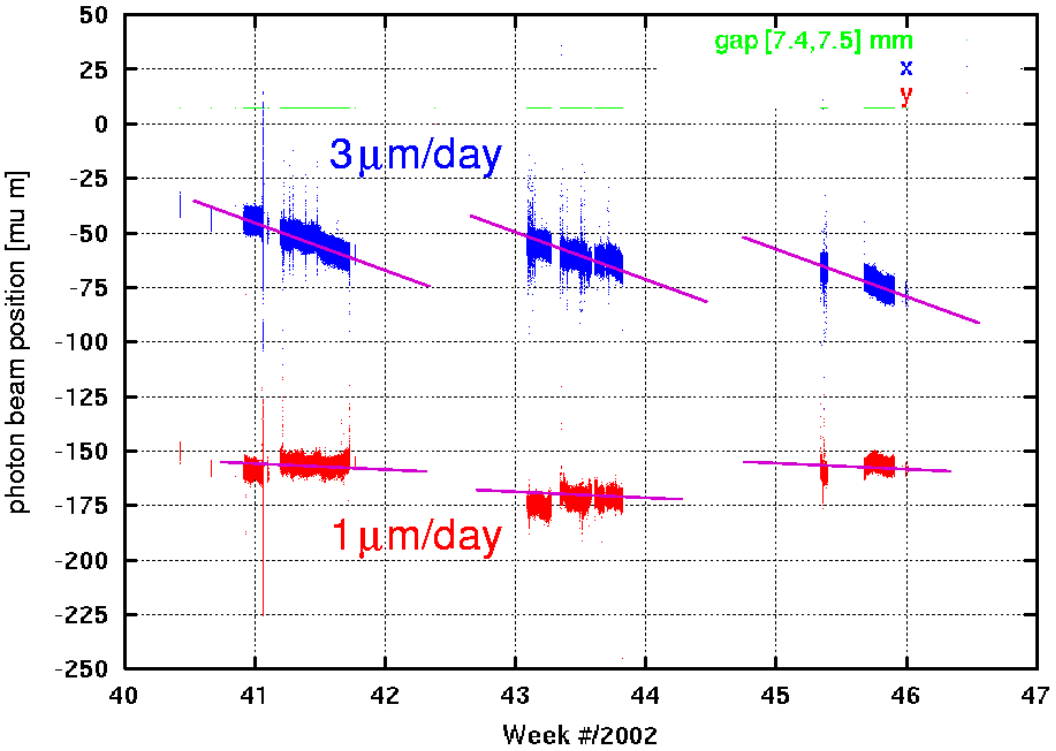
SR - SOFB - RF changes vs. T, X-BPM Readings

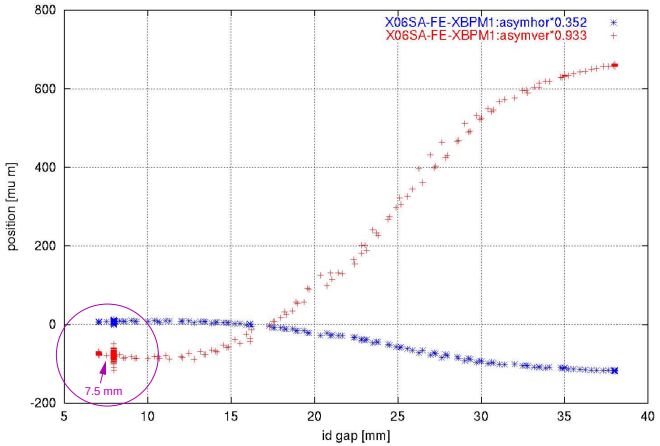
- Outside air temperature and RF frequency changes –>
- X-BPM @ **PX**
  ≈ 8.6 m from ID **U24**:
  σ_x = 2.7 μm (drift: 2.3 μm)
  σ_y = 1.5 μm (drift: 1.7 μm)
  $\sigma_{x'} < 0.31$ μrad @ source point !
  $\sigma_{y'} < 0.18$ μrad @ source point !





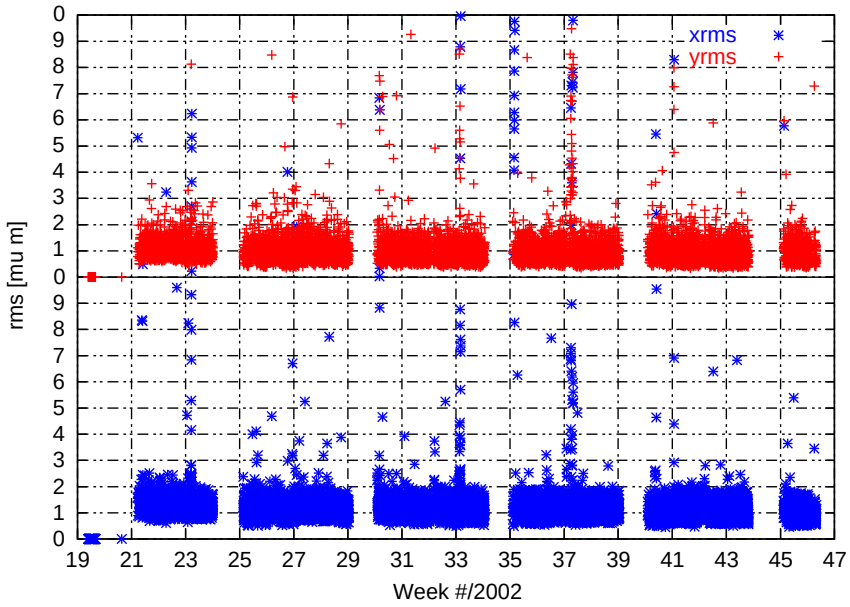
SR - SOFB: X-BPM Readings for u24@gap=7.4 mm

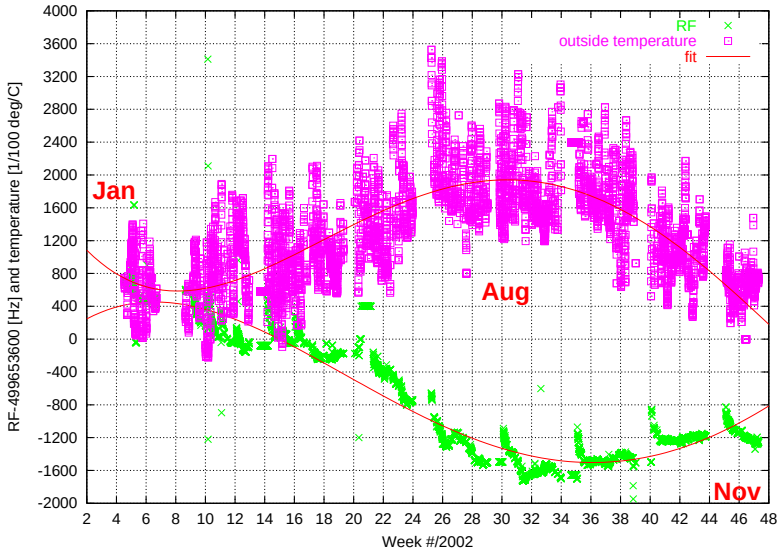


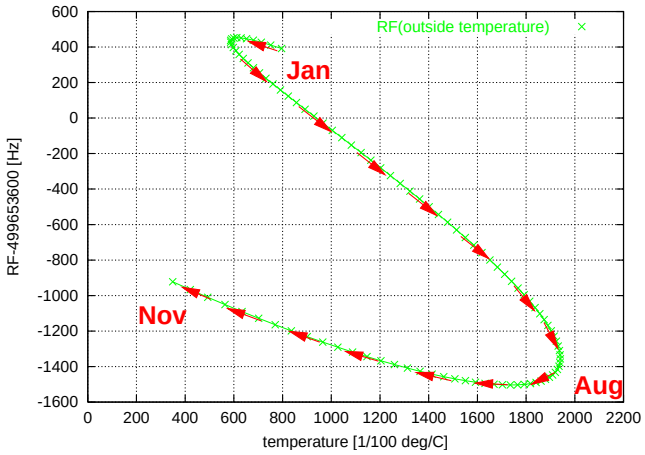


- **U24** X-BPM readings over 7 weeks
- **U24** gap range [7.4,7.5] mm
- Strong dependence of X-BPM reading on photon beam profile for large gaps

SR - SOFB: Long Term Stability - BPMS

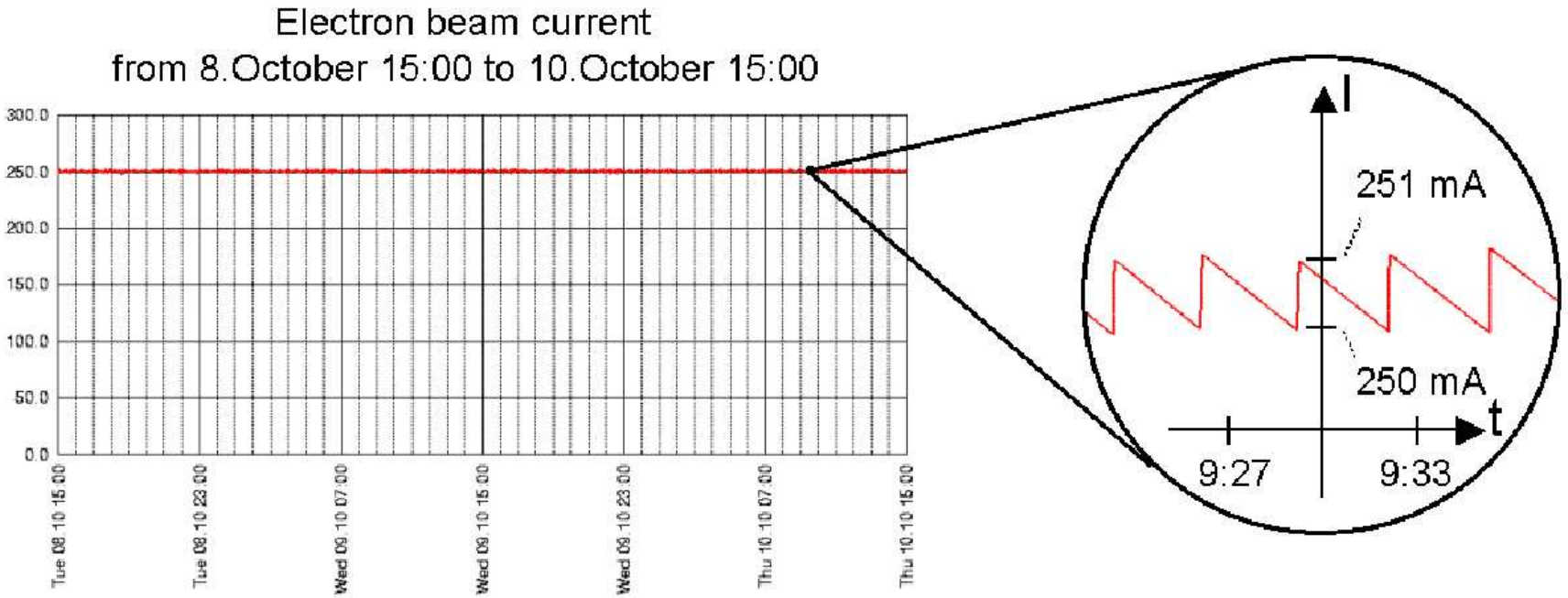






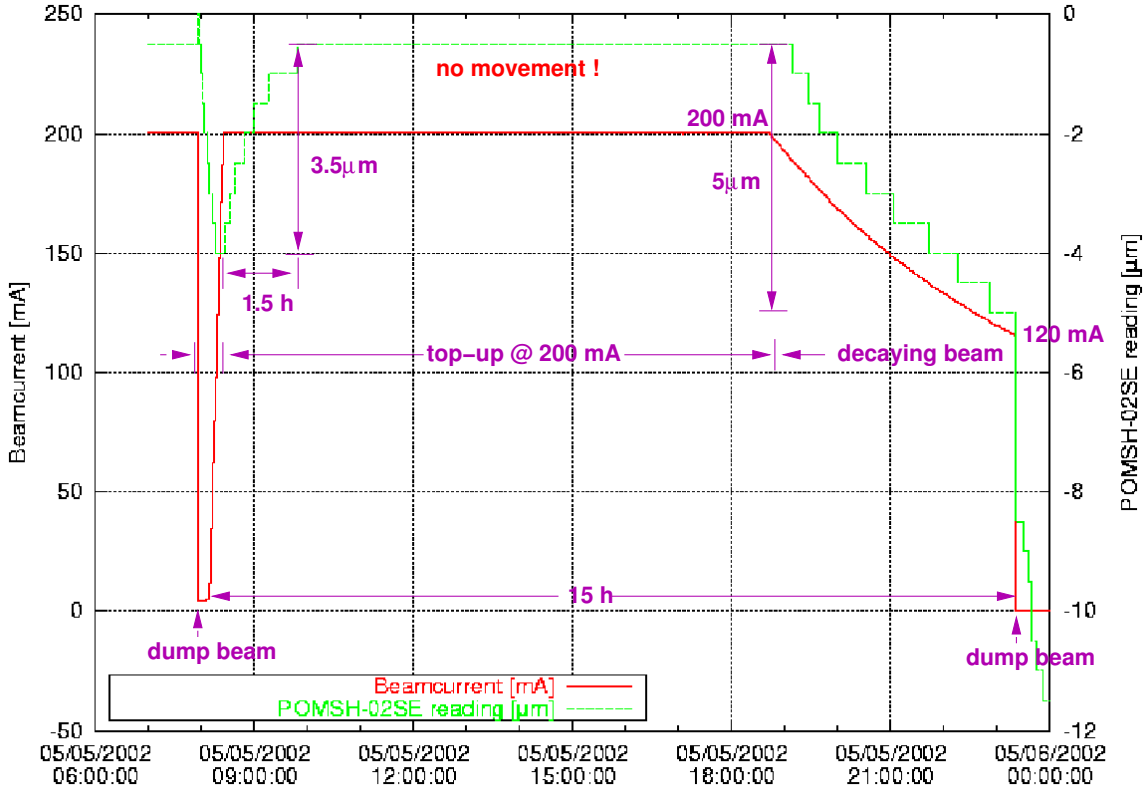
- x_{rms} and y_{rms} over 28 weeks
- Outside air temperature and RF frequency in 2002
- RF frequency vs. outside air temperature in 2002 (df ≈2000 Hz ≈1.2 mm !)

SR - Stability - Top-up



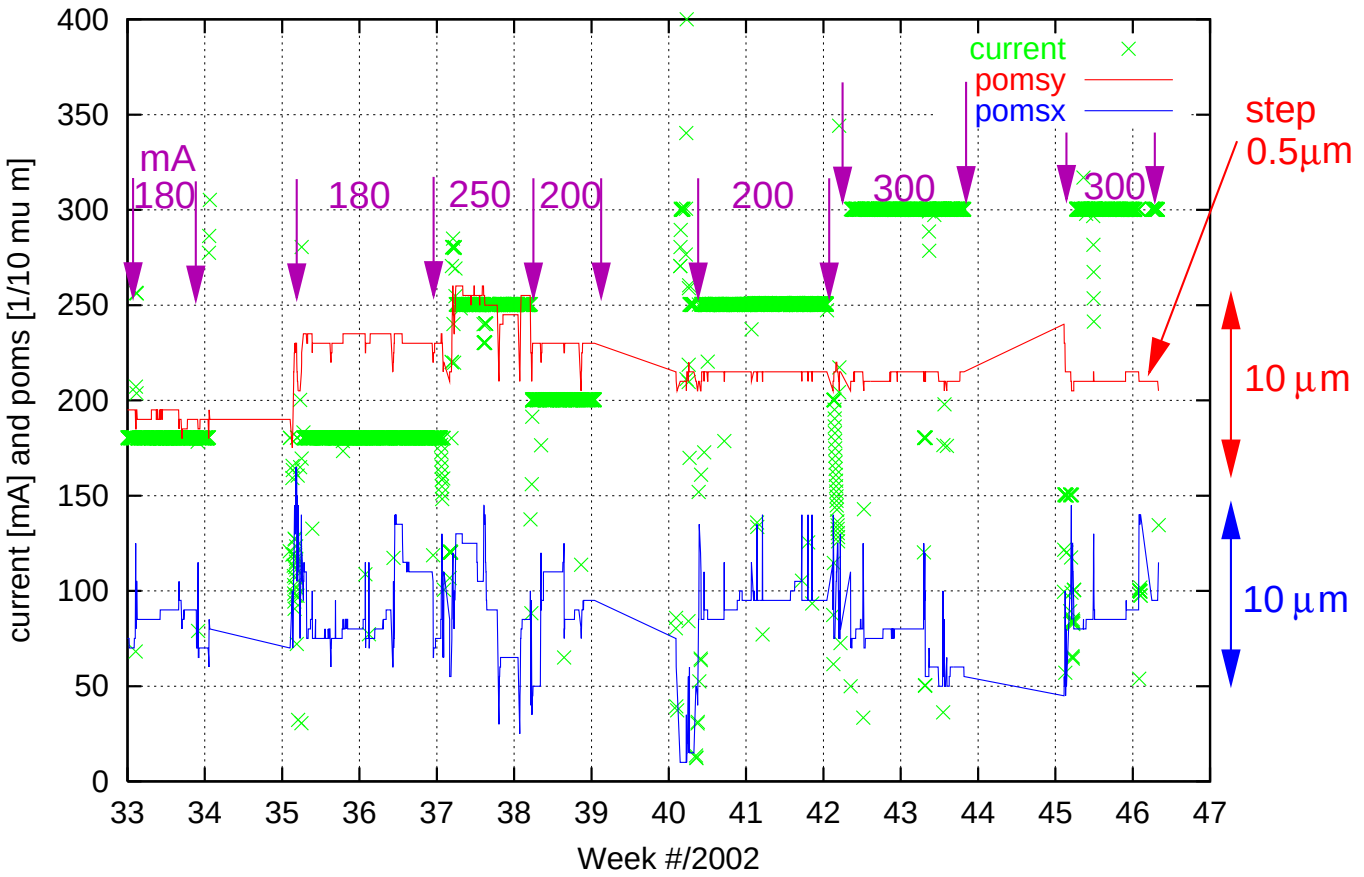
- 2 days run @ 250 mA with a deadband of 1 mA in October
- τ=12 h @ I=250 mA (I$\times\tau$=3 Ah)
- time between injections dt=3 min ($\approx$960 injections in 48 h)
- **SR in thermal equilibrium !**

SR - Stability - POMS



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

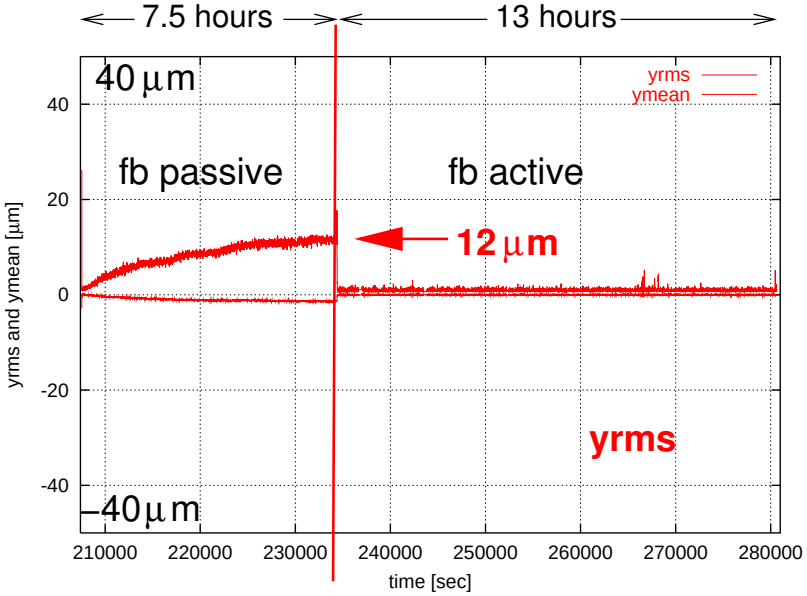
SR - Long Term Stability - POMS

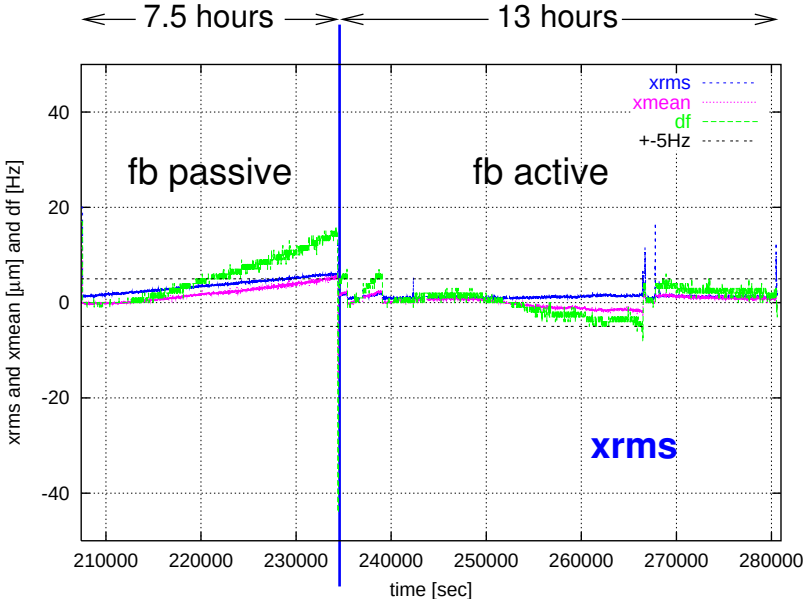


- POMS Readings for ARIDI-BPM-05SB upstream of **U24**

Conclusions

- For frequencies >0.2 Hz: residual orbit noise ≈ 1 μm level
- For frequencies <0.2 Hz: SOFB for "long term" drifts:





- **ID** operation induced distortions (≈10 μm) corrected by SOFB
- Pathlength changes corrected by means of the frequency
- "Golden Orbit" established by SOFB
- Top-up operation is vital for μm level stability !