GLOBAL ORBIT FEEDBACK SYSTEMS DOWN TO DC USING FAST AND SLOW CORRECTORS

DIPAC 2009

Basel, Switzerland

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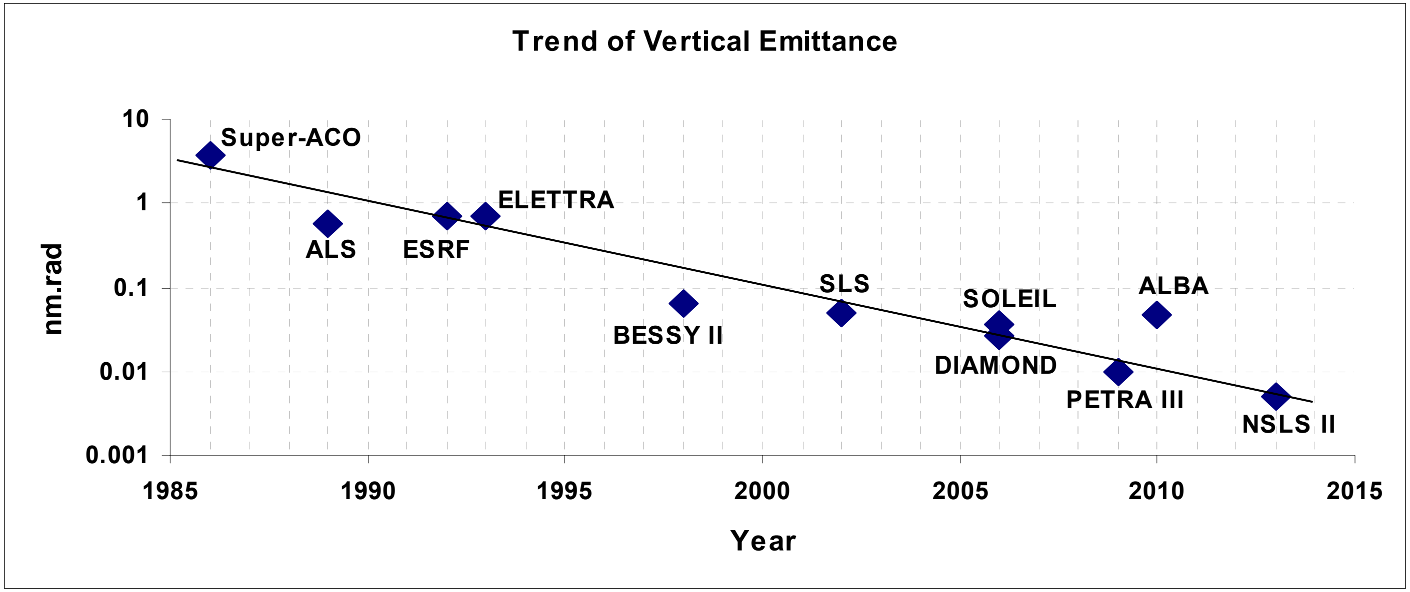
Summary

- **Stability Requirements in Storage Rings**
- Sources of Perturbations
- Orbit Feedback Systems
- Correctors (strong and/or fast)
- Correction Down to DC
  - Frequency Dead Band
  - Fast correctors only
  - Combining Fast and Slow Systems
- Fast Orbit Feedback Systems Status
- Conclusion

Stability Requirements in Storage Rings

- Third generation light sources:
  - High brilliance photon beams are obtained by reducing the emittance in both planes
    - Over 26 years, reduction of the vertical beam size by a factor of 100 in the vertical plane :
      - 1987, Super ACO: vertical beam size in straight sections: 230 μm
      - 2013, NSLS II: vertical beam size in straight sections: ~2 μm



Stability Requirements in Storage Rings

- For users: beam stability ≡ photon flux stability:
  - Photon flux is seen through a slit for most beamlines
    - $\Delta I/I \leq 0.5\%$ requires **$\Delta_Z/\sigma_Z \leq 10\%$** for BL with focusing optics
      $\Delta_Z'/\sigma'_Z \leq 10\%$ for BL with non focusing optics

Stabilization requirements tightened by a factor 100 in 26 years

1987: SUPER-ACO: $\Delta_Z \leq 23$ µm in straight sections
2013: NSLS II: $\Delta_Z \leq 200$ nm in straight sections

Orbit Feedback Systems are mandatory to stabilize beam position

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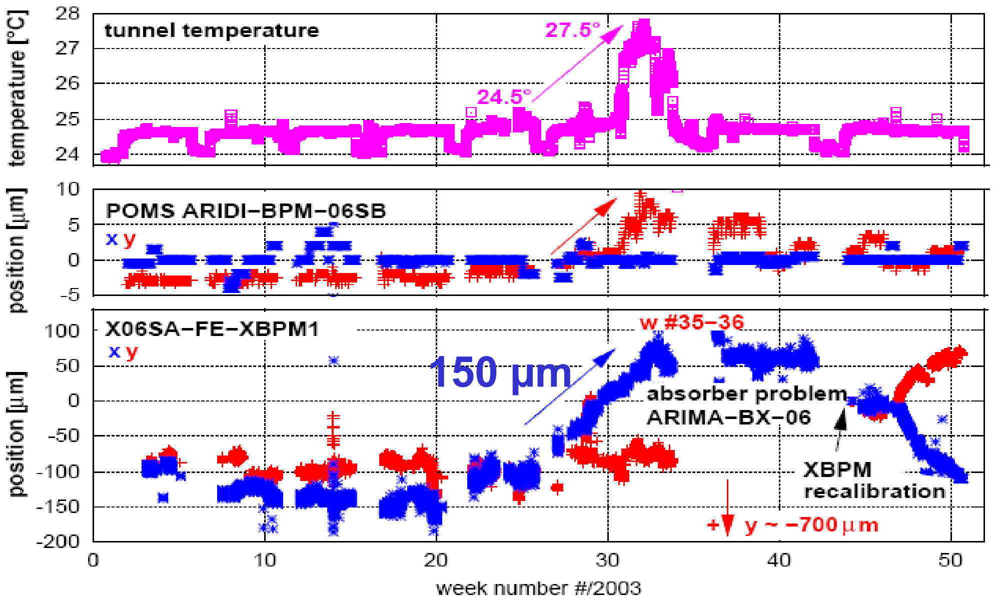
Sources of Perturbations (1)

- Long Term (hours to day)
  - Sun and moon tides (10-30 μm)
  - Diurnal Temperature (1-100 μm)
  - Heat Load (beam decay, electromagnetic IDs)
  - Air and water cooling regulation in tunnel and experimental hall (1-20 μm)

SR Tunnel Temperature, BPM and X-BPM readings



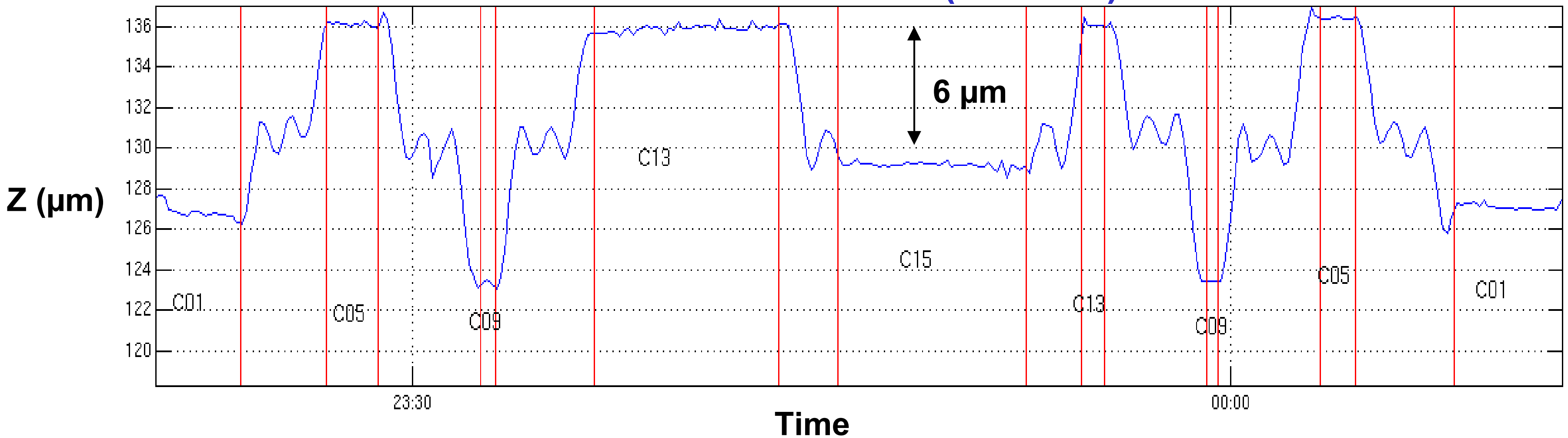
Swiss Light Source 2003

Courtesy Michael Böge

Sources of Perturbations (2)

- Medium Term (seconds to minutes)
  - Experimental hall activities
    - Moving crane
    - Fast switching magnets (dichroïsm experiments)
    - Cryogenic pumps
  - Insertion Devices Transitions (gap and phase changes)

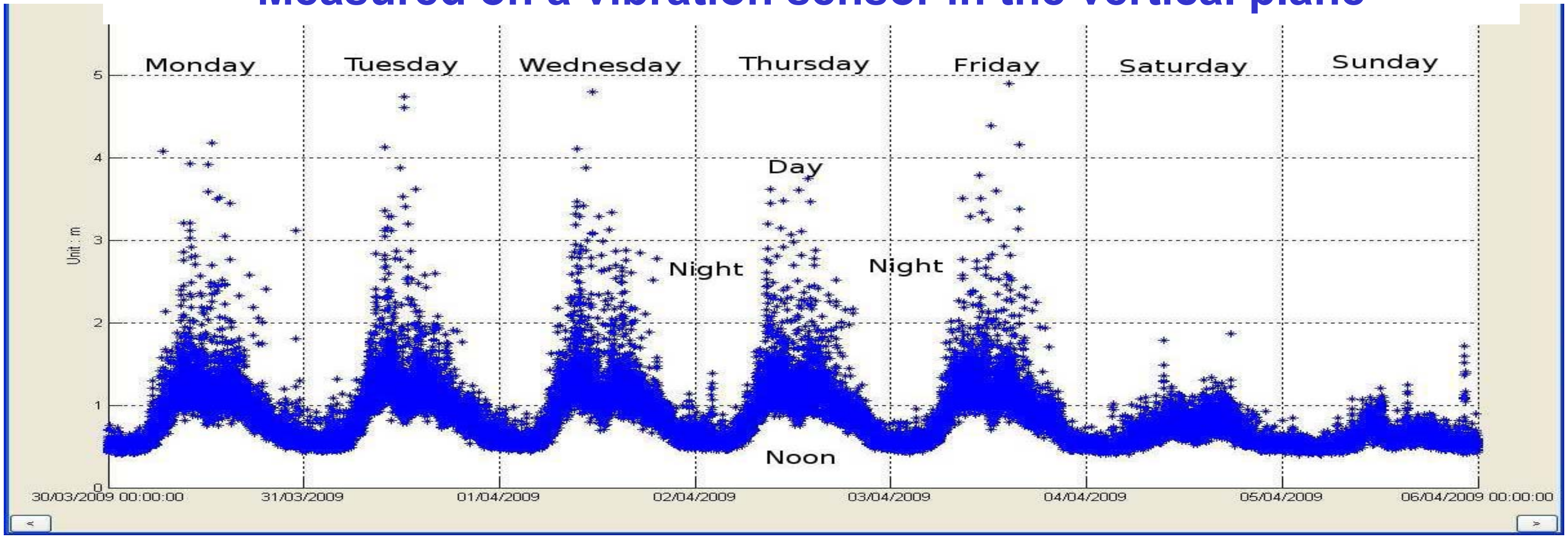
VERTICAL POSITION MEASUREMENT ON BPM C15.3 WHEN OVERHEAD CRANE IS MOVING (SOLEIL)



Sources of Perturbations (3)

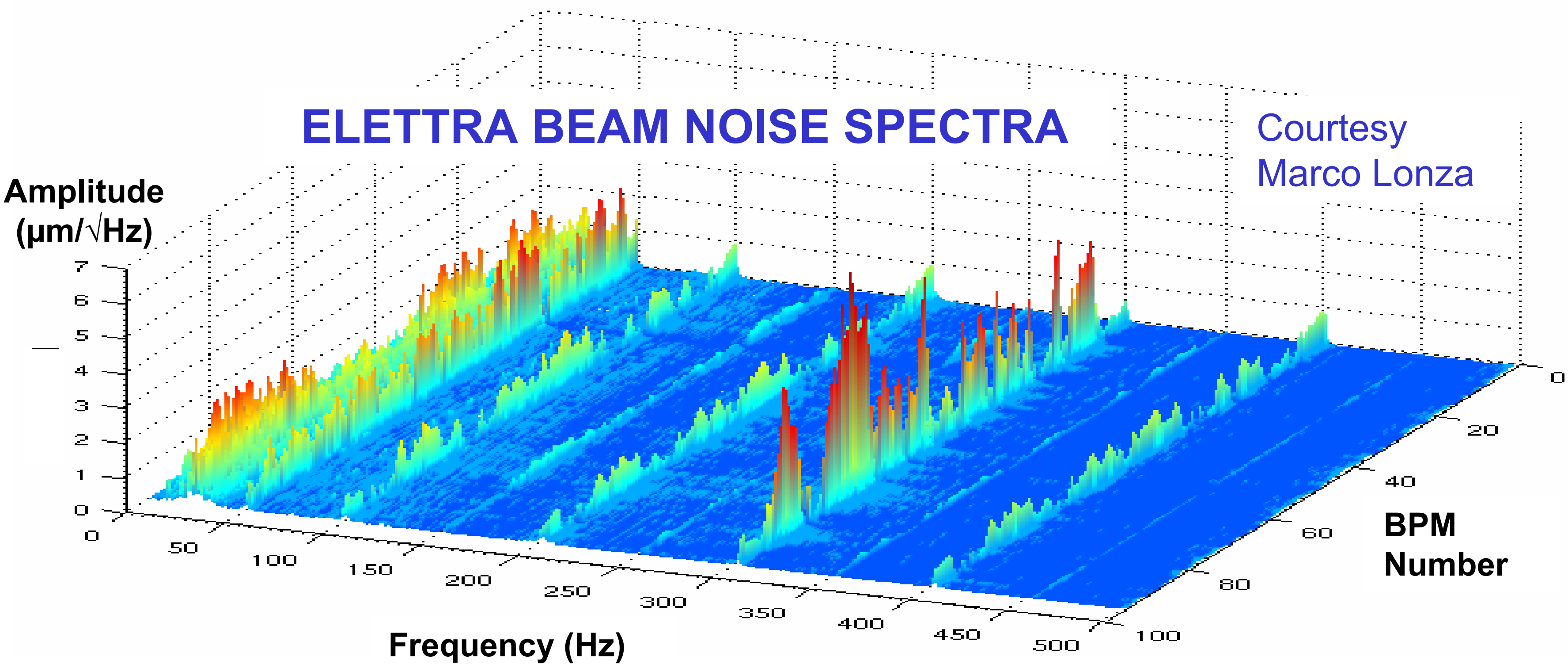
- Short Term (< second)
  - Booster cycling operation (1 to 10 Hz)
  - Ground vibrations (amplified at girder resonance modes)

ENVIRONMENT NOISE OVER ONE WEEK AT SOLEIL
Measured on a vibration sensor in the vertical plane



Sources of Perturbations (3)

- Short Term (< second)
  - Booster cycling Operation (1 to 10 Hz)
  - Ground vibrations (amplified at girder resonance modes)
  - Mains (and harmonics)

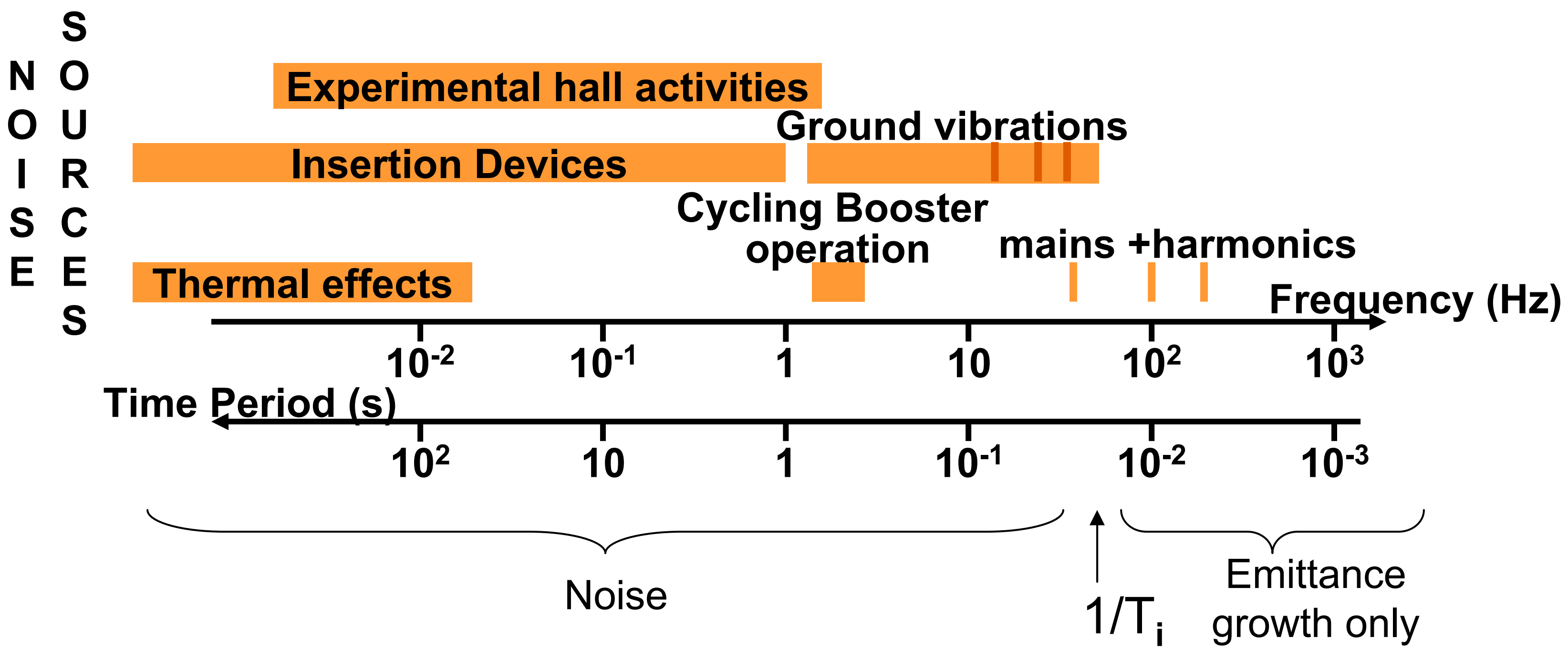


Sources of Perturbations (4)

– Beamlines Integration time:

- If $F_{PERTURBATION} > 1/T_{INTEGRATION}$ → Emittance growth
  → Lower photon flux in a stable way

- If $F_{PERTURBATION} < 1/T_{INTEGRATION}$ → Noise on the measurement



An orbit feedback is needed to stabilize the beam position from DC up to ~100 Hz

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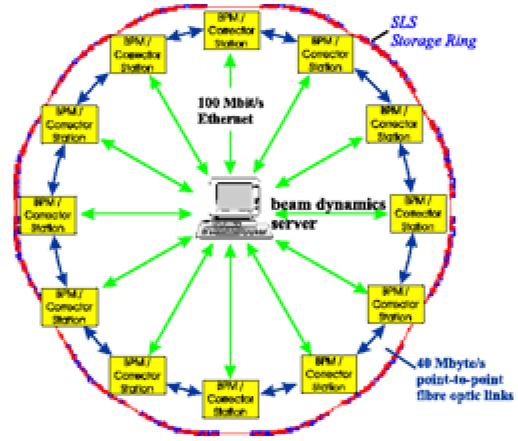
Orbit Feedback Systems

- Global: using all BPMs and correctors

Courtesy
Michael Böge

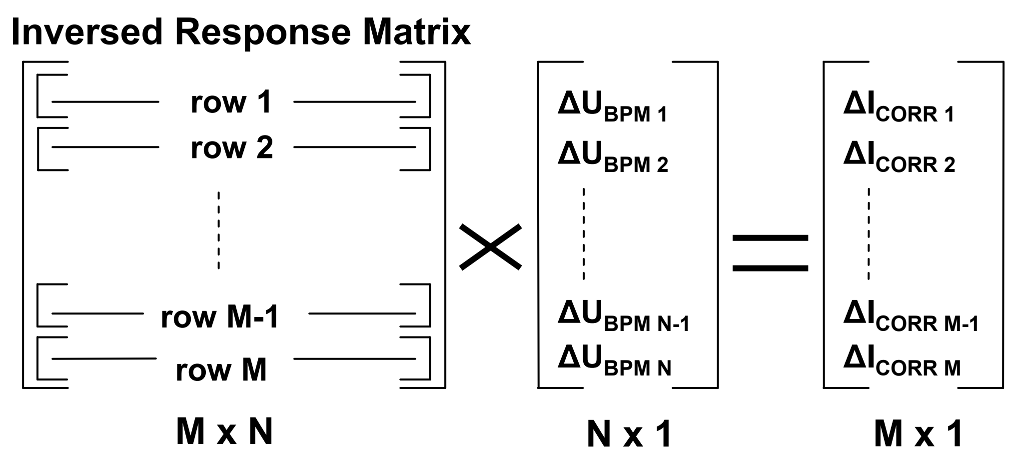


SLS GLOBAL FEEDBACK ARCHITECTURE

- Inverse Response matrix R^{-1} is deduced from the response matrix R using Singular Value Decomposition (SVD) method.

$\Delta U_{BPM\ i}$: Difference between actual and golden orbits measured on BPM i

$\Delta I_{CORR\ j}$: Corrector current to be added to the corrector j



- 2 kinds of global feedbacks systems
  - Slow: Correction rate and bandwidth limited to a few Hertz (Control system based)
  - Fast: Correction rate of a few kHz and efficient up to a few 100 Hz (Dedicated hardware)

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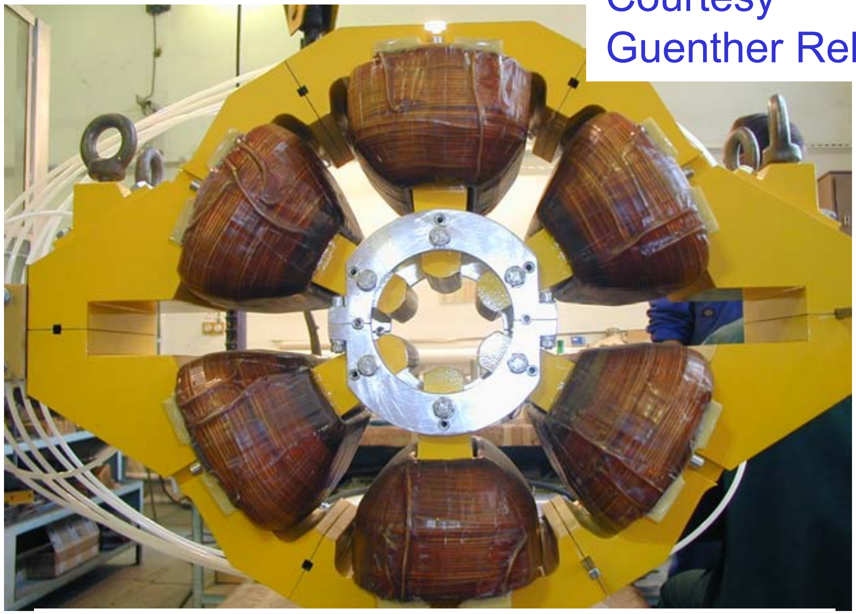
Correctors (strong and/or fast)

- **What kind of correctors should be used for fast corrections?**

- All machines are equipped with 'strong' correctors:
  - Characteristics:
    - Iron-core
    - Strength ~ ±1 mrad
  - First purpose:
    - Correct the closed orbit
    - Slow orbit feedback

Courtesy Guenther Rehm



DIAMOND STRONG CORRECTORS IN SEXTUPOLES

The strong correctors have to meet the following requirements in order to be used for fast corrections ….

Correctors (strong and/or fast)

- Bandwidth much higher than the frequencies to damp (power-supply + correctors + vacuum chamber) :
  - Vacuum Chamber at corrector locations must be in a low conductivity material for avoiding strong eddy current effects
    - Bandwidth limited to few Hz with Al vacuum chamber
  - Power-supplies have to be fast enough
    - setting rates from 1.5 kHz @ APS up to 260 kHz @ PETRA III
  - Laminated corrector yoke (to reduce eddy currents in yoke)
- DAC granularity:
  - Large correction strength
  - Small adjustment steps

  } → high DAC resolution

NSLS II requirements (L.H. Yu et al., EPAC08, Genoa) :
- Kick strength: ±0.8 mrad
- Minimal step size less than 3 nrad

} 19 bit DAC

⇒ Strong requirements for (fast) power supplies

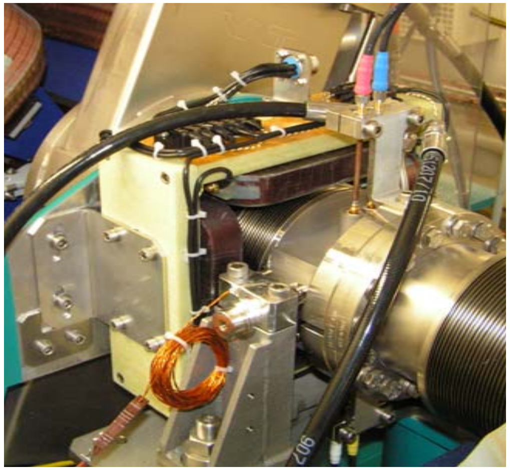
Impacts the design complexity and cost

Correctors (strong and/or fast)

- Reasons to choose additional fast correctors:
  - Vacuum Chamber conductivity
  - Power-supply speed
  - DAC Granularity
  - Update of an older slow orbit feedback system

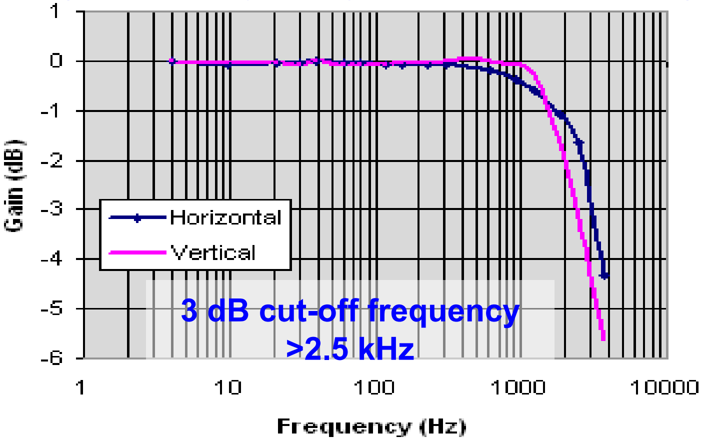
- Designed to have the highest bandwidth:
  - Air coil magnets (low inductance)
    → Weak strength: 10 to 40 µrad (DC strength)
  - Installed over low conductivity sections of the vacuum chamber (stainless steel bellows for example)

- Bandwidth of a few kHz can be achieved (power-supply + corrector + vacuum chamber) :
  → The FOFB bandwidth limitation is not anymore limited by the correctors.



SOLEIL Fast Corrector

Combined transfer function
(power-supply + magnet + vacuum chamber):



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Correction Down to DC:

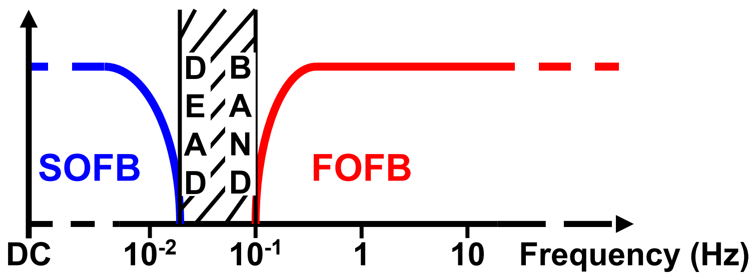
- How to make slow and fast orbit feedback systems work together?

- Slow and fast orbit feedback systems are not compatible if they have a common frequency domain:
  - Both systems fight each other
  - The weakest correctors saturate (the fast ones) after few iterations of the slow system

Different approaches have been implemented over the years in order to solve this issue…

Correction Down to DC:

- **‘Dead Band’ approach** :
  - Separate Slow and Fast Orbit Feedback by a frequency dead band



- FOFB efficiency is suppressed at low frequencies (< 0.1 Hz)

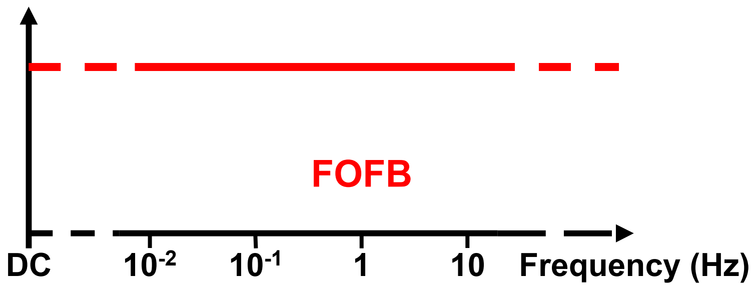
- Advantages:
  - 2 independent systems

- Disadvantages:
  - Dead band needs to be wide enough to keep the two systems stable
  - No correction within the dead band frequencies

→ This approach is not used anymore …

Correction Down to DC:
FOFB only

- **'FOFB only' approach**:
  - Fast orbit feedback is the only system used to correct the orbit from DC:



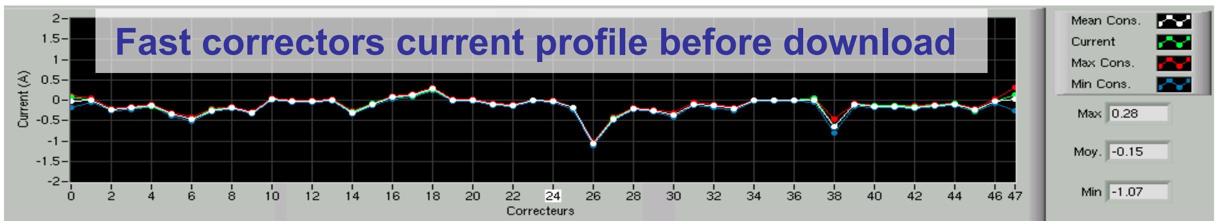
- Orbit is aligned on the golden orbit with the strong correctors and then FOFB is correcting around this orbit

- Advantages:
  - Only one system
  - Continuous frequency domain where perturbations are damped

- Disadvantages:
  - Limited excursion range of the fast correctors
    - May saturate if position is drifting
  - Orbit will be efficiently corrected only around fast corrector locations

Correction Down to DC:
FOFB only, with download

- Solution to prevent fast correctors saturation:
  - Download the DC part of the fast (& weak) correctors into the slow (& strong) ones



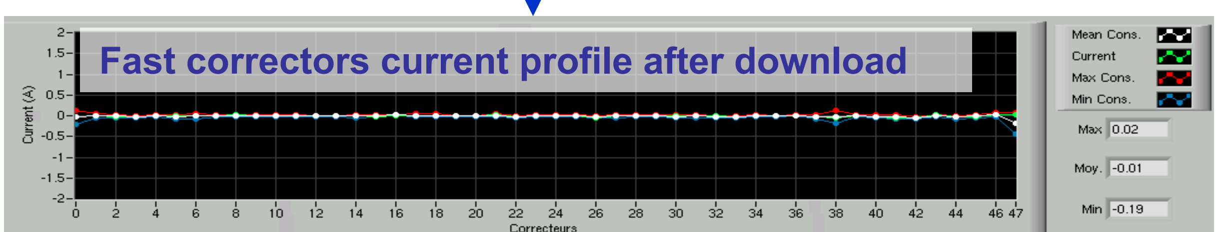
$\Delta V = R_{FOFB} * \Delta I_{FOFB}$

Orbit created by the DC current in the fast correctors

$\Delta I_{SOFB} = R^{-1}_{SOFB} * \Delta V$

New set points for slow correctors

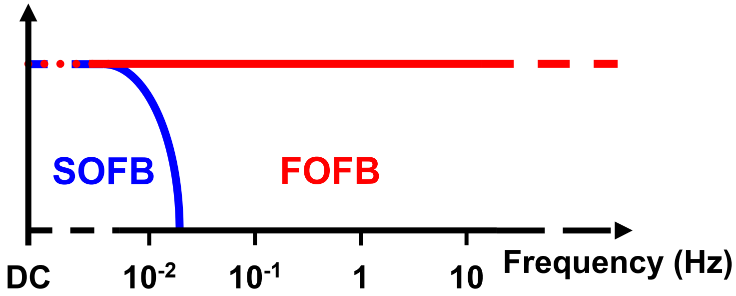
Calculation only



FOFB always running

Correction Down to DC:

FOFB and SOFB on a common frequency domain



- Feedback systems efficiency depends on:
  - Number of correctors
  - Location of correctors
- Fast correctors are generally less numerous than slow ones and are on the straight sections

- How to also benefit from the efficiency of slow correctors?

  → Find a way to have both SOFB and FOFB correcting down to DC

- **Approach:**
  - Avoid fast and slow system fighting each other
  - Solution based on APS and ALS experience: communication between 2 systems. The goal is to blind the FOFB from the SOFB action.
    - SOFB predicts how its next iteration will change the orbit
    - SOFB subtracts this predicted change from the present FOFB reference orbit

Correction Down to DC:
FOFB/SOFB interaction

SOFB iteration details (APS and ALS operation):

- Step 1:
  - Read the orbit error ΔU and calculate the new slow corrector settings that will correct it:

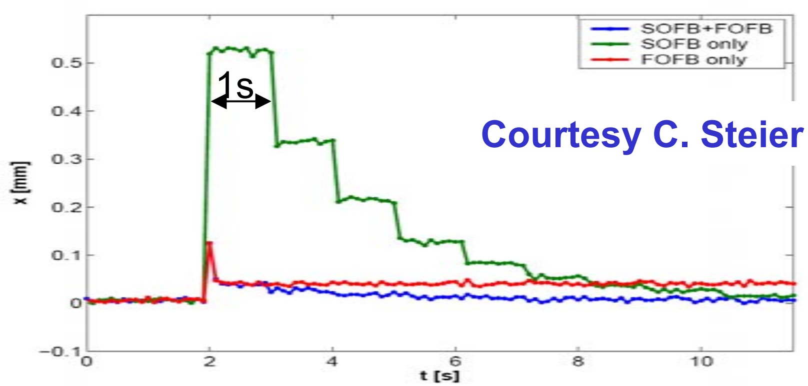
$$\Delta I_{SOFB} = R^{-1}_{SOFB} * \Delta U$$

- Step 2:
  - Predict the orbit movement ΔW that would be induced:

$$\Delta W = R_{SOFB} * \Delta I_{SOFB}$$

- Step 3:
  - Apply the new setting ΔI_{SOFB} to the slow correctors
  - Subtract the predicted movement ΔW from the FOFB reference orbit

FOFB always running



Response of the fast and slow orbit feedback systems to a step in a corrector magnet at ALS

Stable if fast correctors are a subset of the SOFB ones (APS and ALS cases),

Not stable with 2 fully independent sets of correctors
(SOLEIL experience: saturation of fast correctors in few minutes)

Correction Down to DC:
FOFB/SOFB interaction and download

SOFB iteration at SOLEIL with 2 independent sets of correctors

- Step 1 (same as before):
  - Read the orbit error ΔU and calculated the new slow correctors setting $\Delta I1_{SOFB}$ to correct it:

$$\Delta I1_{SOFB} = R^{-1}_{SOFB} * \Delta U$$

- Step 2:
  - Calculate the new slow correctors setting in order to cancel the DC current part in the fast correctors (downloading process):

$$\Delta I2_{SOFB} = R^{-1}_{SOFB} * R_{FOFB} * \Delta I_{FOFB}$$

- Step 3 (same as before):
  - Predict the orbit movement ΔW that would be done by applying the previous setting:

$$\Delta W = R_{SOFB} * \Delta I1_{SOFB}$$

- Step 4:
  - Apply the new setting to the slow correctors $\Delta I_{SOFB} = \Delta I1_{SOFB} + \Delta I2_{SOFB}$
  - Subtract the predicted movement ΔW from the FOFB reference orbit

FOFB

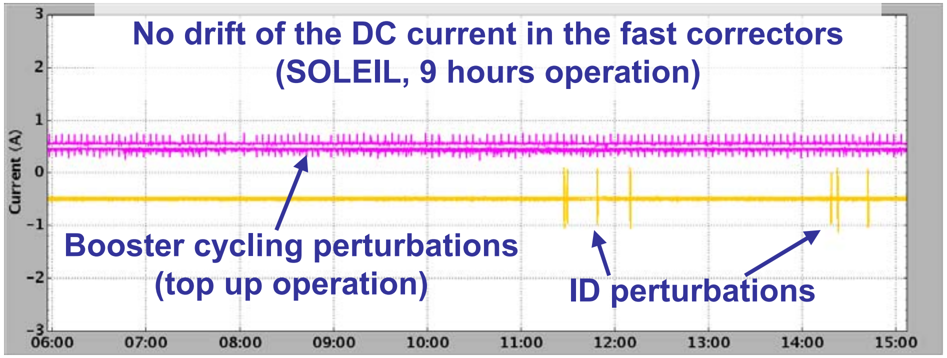
always

running

Correction Down to DC:
FOFB/SOFB interaction results

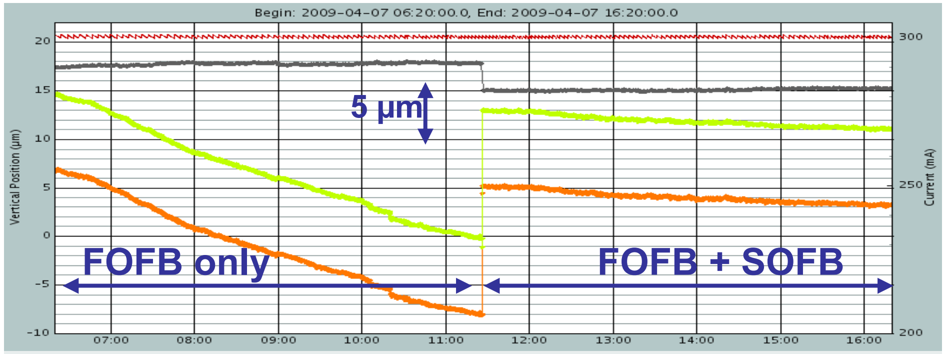
- FOFB and SOFB work together in a stable way:

No visible drift on the current in the correctors after one week of operation



- Cumulates the efficiency of the 2 systems:

Orbit is well stabilized even far from fast correctors (in the arcs)



Vertical beam position at one SOLEIL bending magnet source point (BPMs: grey and X-BPMs: orange and green)

- The interaction (slow correction, download process and change of FOFB reference) does not generate parasitic orbit steps

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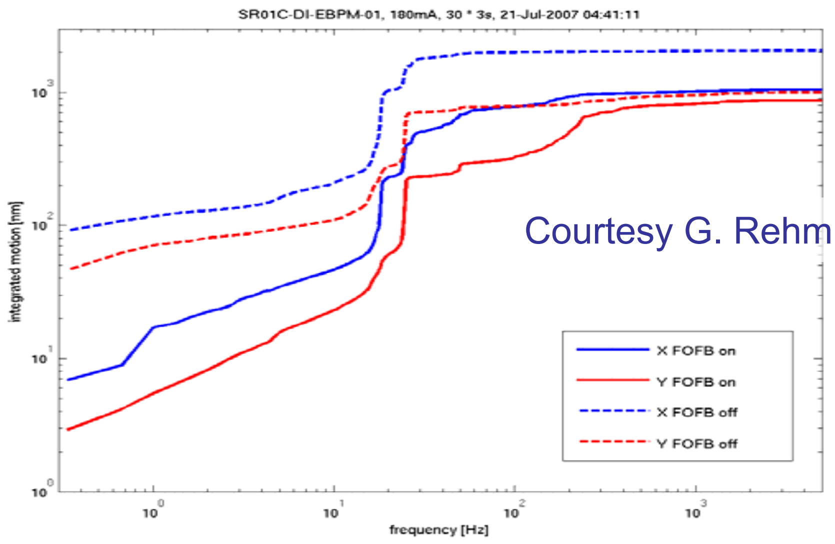
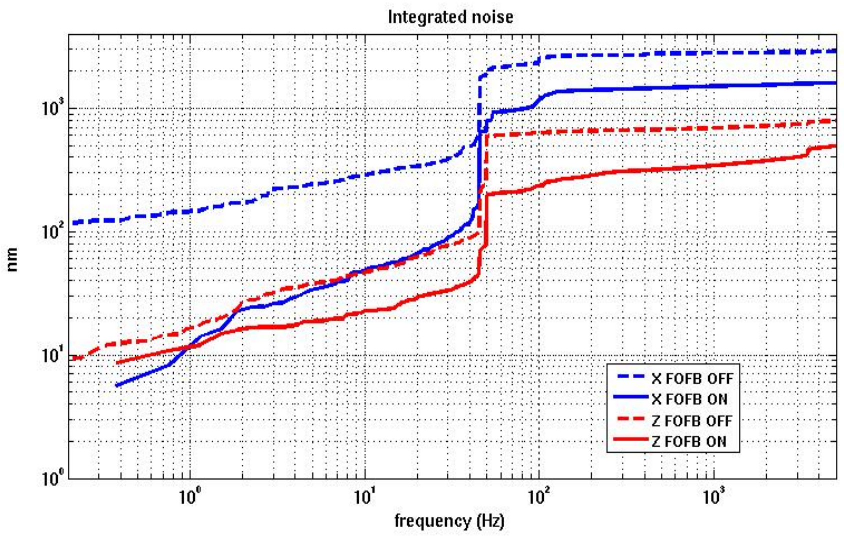
Fast Orbit Feedback Systems Status

- Needs and requirements are machine specific:
  - No unique solution for orbit feedback system designs
  - Achieved performances are generally good enough to meet user requirements



DIAMOND cumulated PSD in a straight



SOLEIL cumulated PSD in a straight

Fast Orbit Feedback Systems Status

SR Facility	FB type (users operation)	Sets of correctors	Bandwidth	Motivation
ALBA*	Fast	Strong	DC - 130 Hz	
BESSY II *	Fast	Strong	DC - 40 Hz	
DIAMOND	Fast	Strong	DC - 130 Hz	
ELETTRA	Fast	Strong	DC - 150 Hz	
ESRF-U*	Fast	Strong	DC - 150 Hz	
SLS	Fast	Strong	DC - 100 Hz	
SPEAR3	Fast	Strong	DC - 100 Hz	
ALS	Slow + Fast	Strong (+ Fast as a subset of slow ones)	DC - 60 Hz	
APS	Slow + Fast	Strong (+ Fast as a subset of slow ones)	DC - 100 Hz	
ESRF	**Slow + Fast**	**Strong + Fast**	**DC - 150 Hz**	**Historical**
NSLS II*	**Slow + Fast**	**Strong + Fast**	**DC - 500 Hz**	**DAC Granularity Bandwidth**
PETRA III*	**Slow + Fast or Fast**	**Strong + Fast**	**Dead-band or DC - 500 Hz**	**Bandwidth**
SOLEIL	**Slow + Fast**	**Strong + Fast**	**DC - 250 Hz**	**Al vacuum chamber Bandwidth**
SSRF*	**Slow + Fast**	**Strong + Fast**	**DC - 100 Hz**	**2 systems that can be commissioned independently**

* Feedback systems that are not yet commissioned

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- With two orbit feedback systems working together, machine stability benefits from:
  - The slow system that provides good long term stabilization at all source points (also at bending magnets)
  - The fast system that suppresses shorter term beam perturbations

- The use of a different set of fast correctors for fast corrections seems to be a good choice for
  - New machines:
    - Requiring high frequency corrections (above 100 Hz)
    - Requiring large kick strength with high resolution
    - With Aluminum vacuum sections at strong corrector locations
  - Older machines:
    - That want to upgrade their orbit feedback system at a reasonable cost

Acknowledgements and References

I would like to thank the following colleagues for fruitful discussions and all information they provided:

ALS: C. Steier, T. Scarvie

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APS: G. Decker

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