USPAS 2019: Knoxville

Closed Orbit Stability, Correction and Feedback

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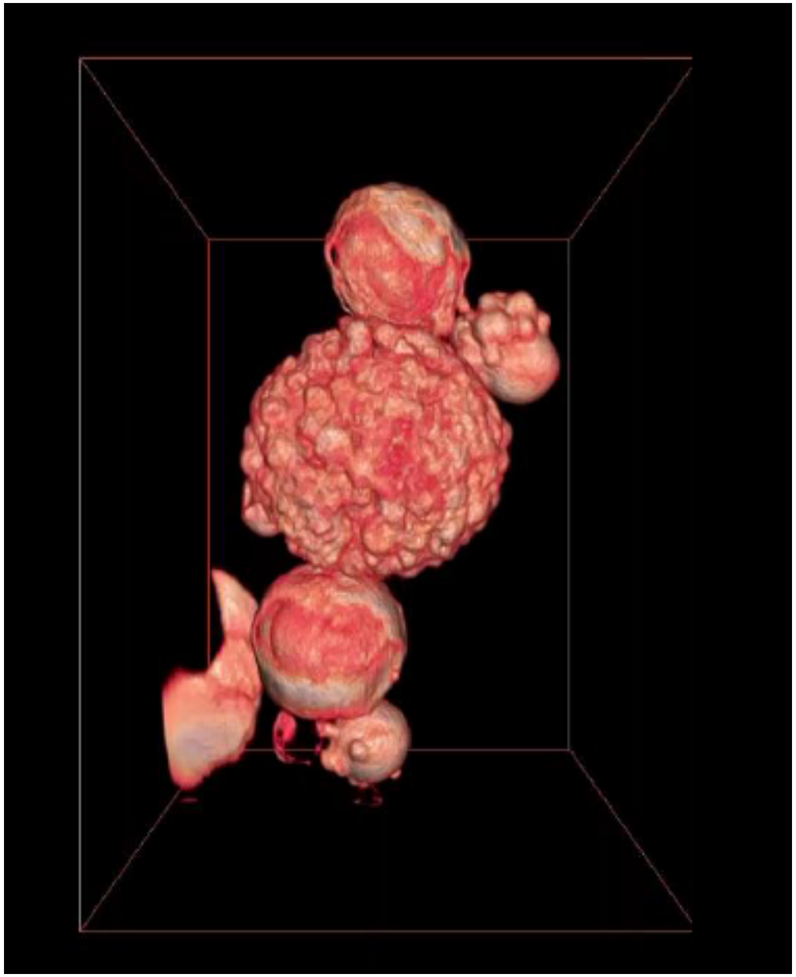
Outline

- Introduction
  - Requirements
- Measurement Methods
- Sources of Orbit Noise/Drift
- Orbit Correction and Feedback
  - Correction Algorithms
  - Feedback Systems (Slow, RF, Fast)
- Beam Based Alignment

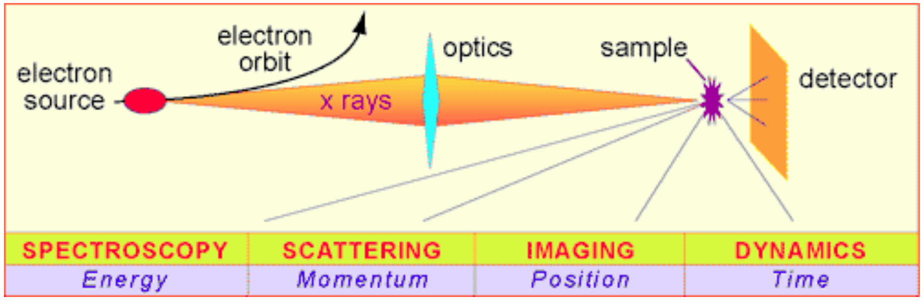
Introduction

- Largest Driver for Beam Stability are usually user experiments:
  - Often stability can be more important to synchrotron radiation users than brightness + flux
  - Stability requirements have evolved as experimental techniques have improved
  - Requirements are beamline/experiment specific and more effort will be needed in future to optimize integrated systems
- But there are accelerator related reasons as well:
  - Lattice distortion (sextupole feed-down, dipole errors, …)
  - Equipment protection (mis-steer)
  - Beam-beam overlap



David Shapiro, ALS

Requirements on 3rd gen SR Rings



Typical requirements of 3rd generation SR user experiments (~2010):

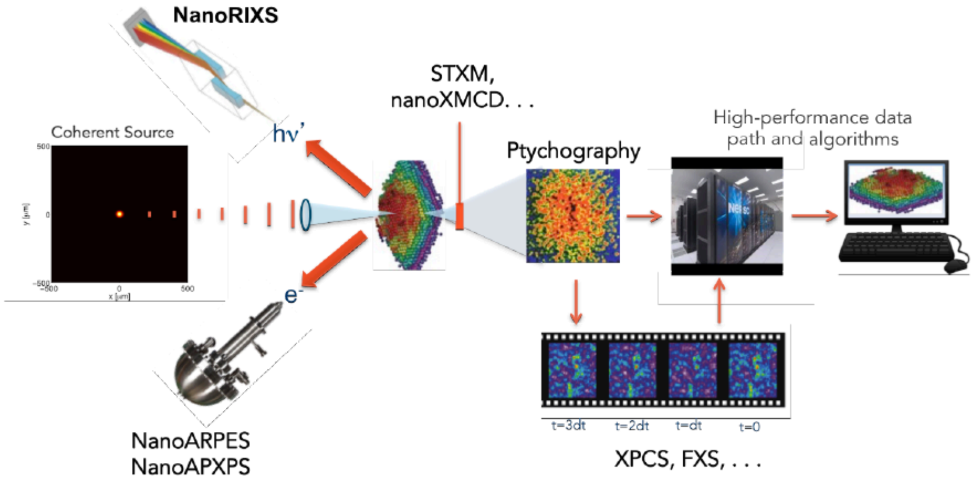
Measurement parameter	Stability Requirement
Intensity variation $\Delta I/I$	<<1% of normalized I
Position and angle	<2-5% of beam σ and σ'
Energy resolution $\Delta E/E$	$<10^{-4}$
Timing jitter	<10% of critical time scale
Data acquisition rate	$10^{-3} – 10^{5}$ Hz

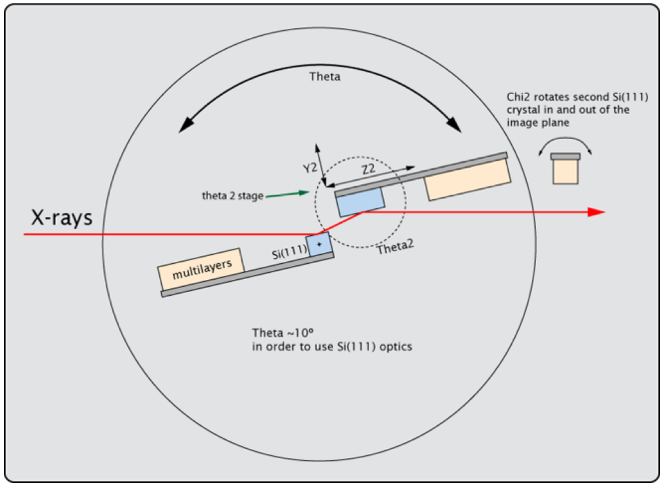
Similar tables, see: Hettel, Boege, …

- All of those requirements either directly specify or relate back into stability requirements
  - beam position + angle, beamsize + emittance, beam energy, beam energy spread, …
  - For current SR sources, this means submicron orbit stability (for MBAs in both planes)

However, requirements are experiment specific and MBAs bring some changes

Why orbit / position need to be constant





- Without slits, beam motion will translate to motion of photon beam on sample, i.e. different sample areas are measured
- Similarly for monochromator without slits vertical beam motion translates into photon energy shift
- With slits, the effects get smaller and smaller with smaller slit size
  - There are smaller 2nd order effects because of beam profile and nonzero slit size
  - However, the smaller the slit the smaller the transmission and the larger the intensity fluctuations
  - Effects of slit alignment and motion also become important

Examples of sensitive Beamlines

- ALS micro-focusing
  - Environmental samples ('dirt')
  - Very heterogenous

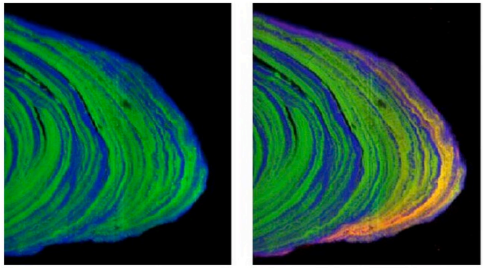
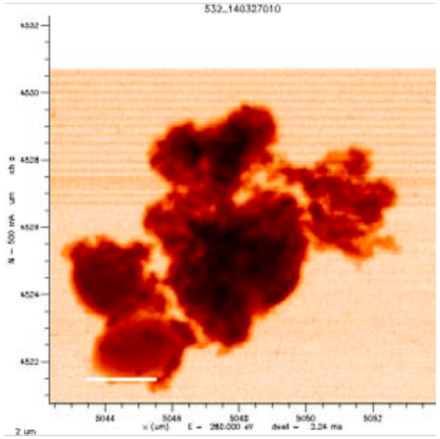


Figure 1. Synchrotron-based micro-X-ray radiation fluorescence (µSXRF) Fe and Mn maps of the outermost Fe and Mn layers of a ferromanganese nodule from the Baltic sea (6600 µm x 3780 µm, step size 15 µm, counting time 250 ms/pixel, red = Zn, green = Mn, blue = Fe, beamline: 10.3.2.). The onion-like structure of growth rims is clearly discernible as few hundreds µm thick Fe/Mn-rich bandings. Zn is exclusively associated with Mn, as indicated by the orange color of the Zn-containing Mn layers, and its concentration increases towards the surface.

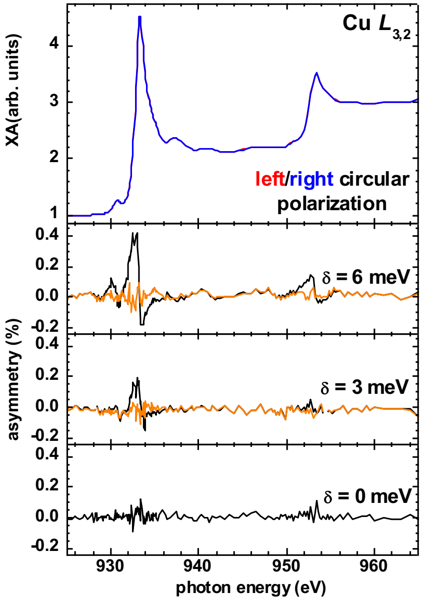
Matthew Marcus, ALS

- ALS STXM
  - Zone-plate imaging using coherent fraction of beam



David Kilcoyne, ALS

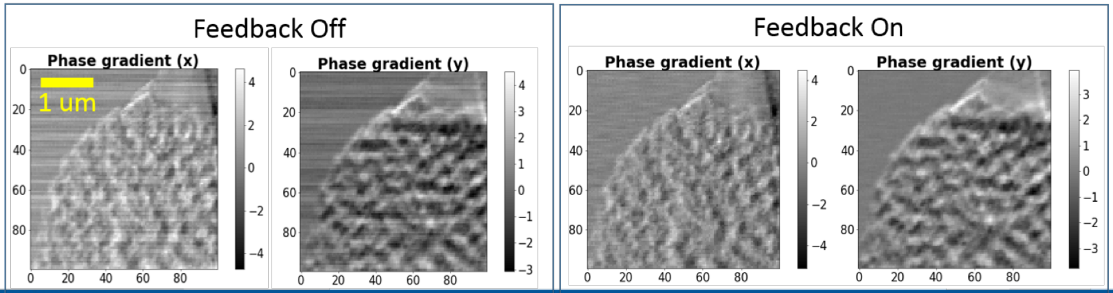
- ALS magnetic spectroscopy
  - Measuring very small dichroism effects
  - Energy stability when switching polarization is critical



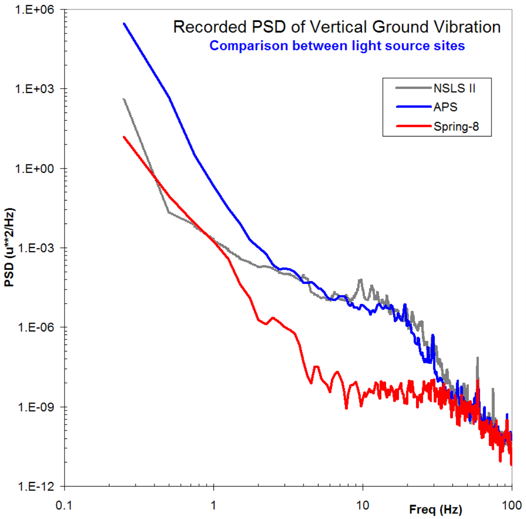
Elke Arenholz, ALS

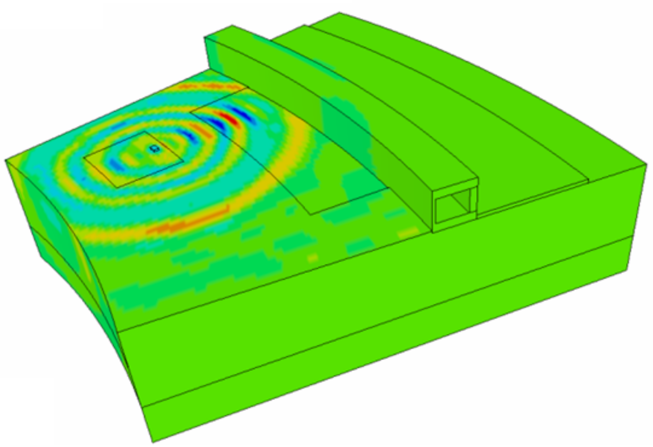
- NSLS-II X-ray nanoprobe
  - *Differential phase contrast imaging sensitive to angular stability*
  - *Horizontal streaks are removed by stabilizing the x-ray beam using active beam positioning feedback.*

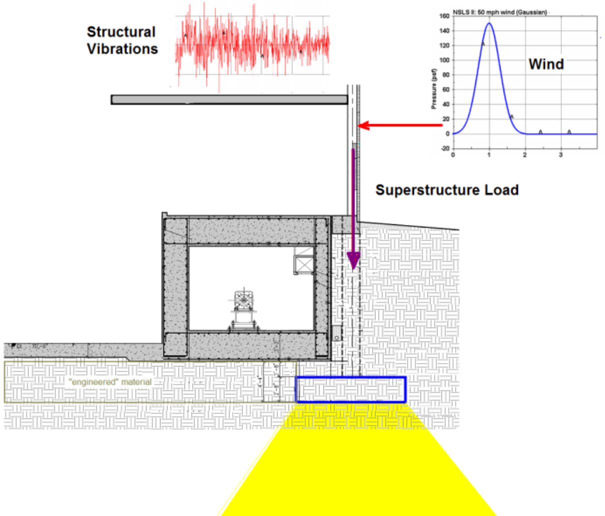
Yong Chu, Petr Ilinski, NSLS-II



Stability at Design stage



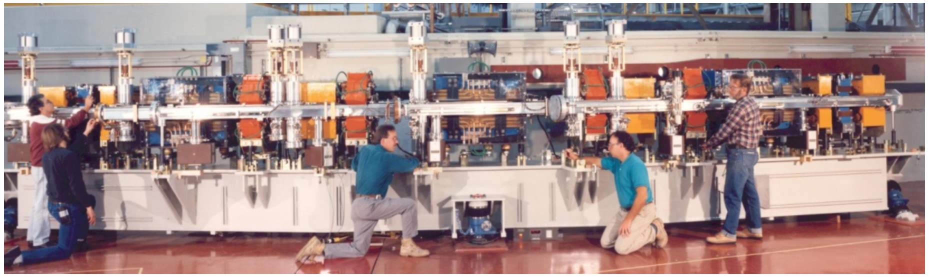




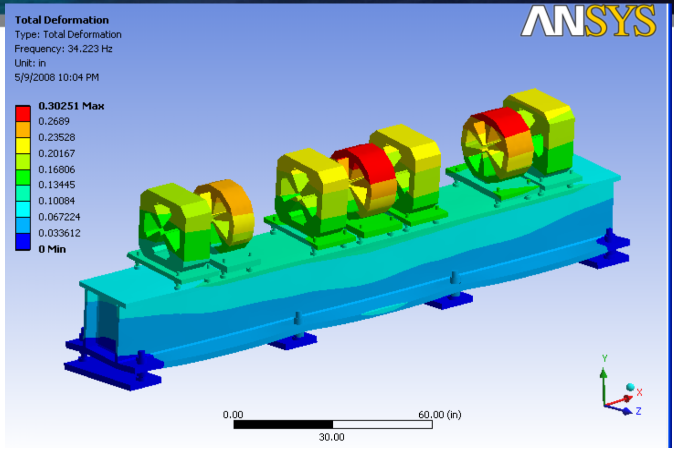
Courtesy: N. Simos, NSLS-II

- One hopefully starts by selecting a good / quiet site (not always possible) - at least need to know all caveats
- Nowadays FEA allows optimization of slab design
- Important: Minimize vibration coupling from pumps, …
- Also keep external disturbances in mind (wind, sun, …)

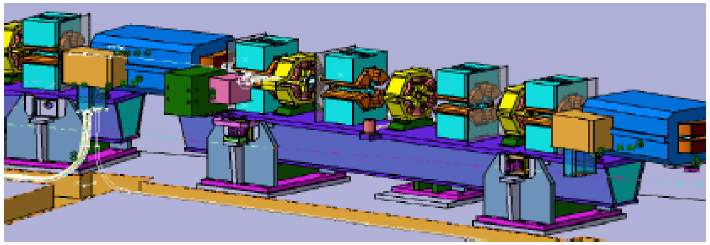
Girder Design



ALS

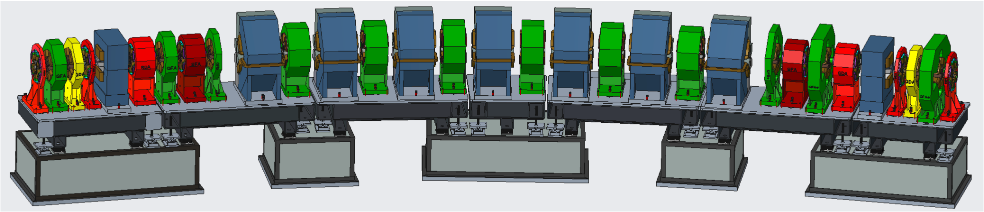


NSLS-II: courtesy S. Sharma



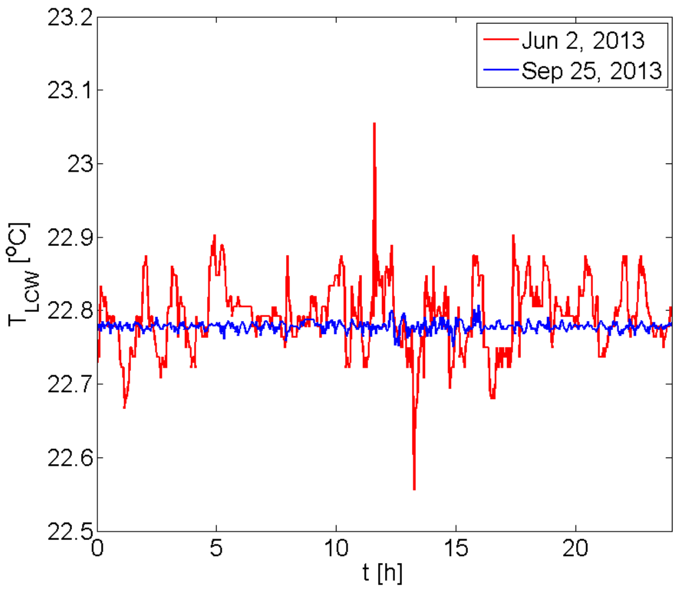
Soleil

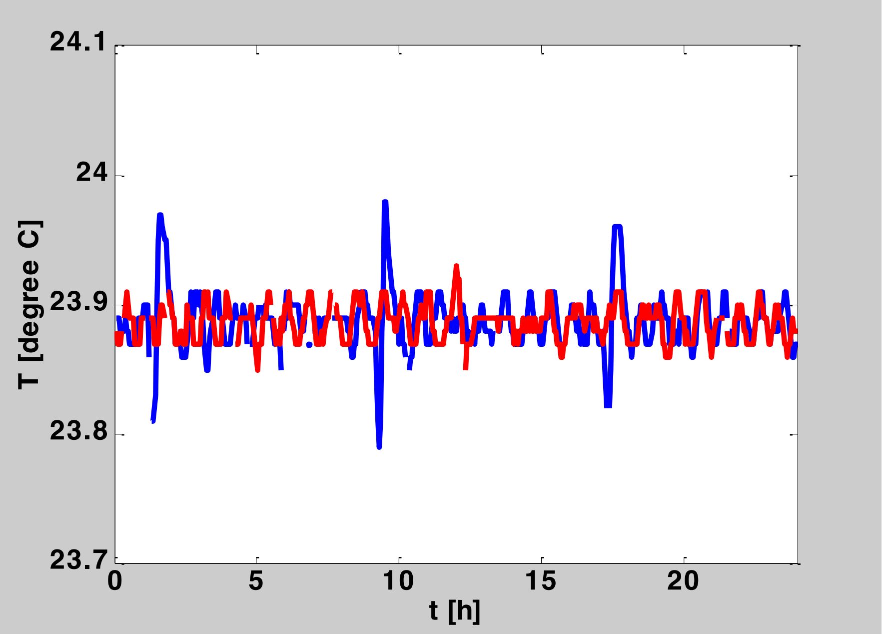
ALS-U



- Some early 3rd generation sources had massive girders (low resonance frequencies – sampling larger ground oscillation amplitudes)
- Later ones had girders with higher resonance frequencies but movers, that significantly lowered them
- Newer designs (Soleil, NSLS-II, …) avoid this caveat – smaller vibration transmission to beam

Air/water temperature stability

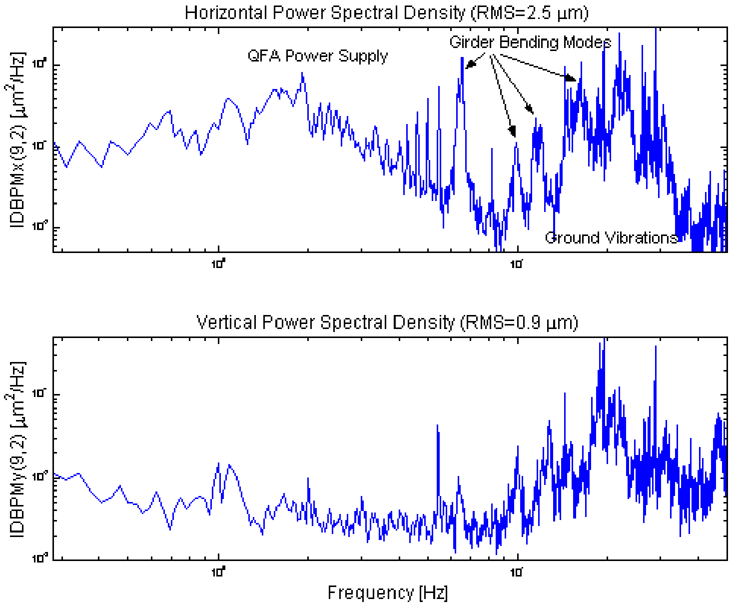




Left: ALS water temperature, Right: Tunnel air temperature

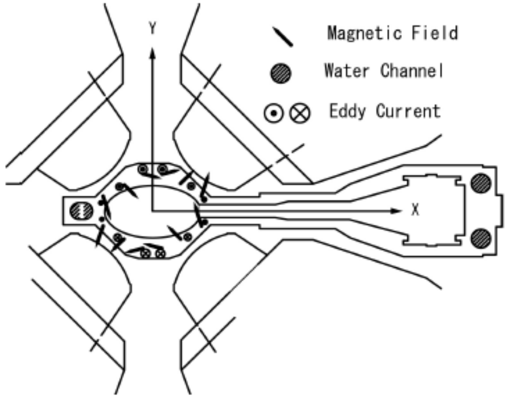
- Stable environmental conditions are extremely important
- State of the art is water and tunnel air temperature stability on the order of 0.1 degree C
- Stable power supply controllers, invar rods for BPM mounts, … also help, but it is always best to also keep the conditions constant

Identify and Fix Problems – Beam-based



Data taken on 12-12-1999, during a 1.9 GeV user run at 278 mAmps

ALS – fixed power supply



Eddy Current made by Q-mag. field kicks the electron beam.

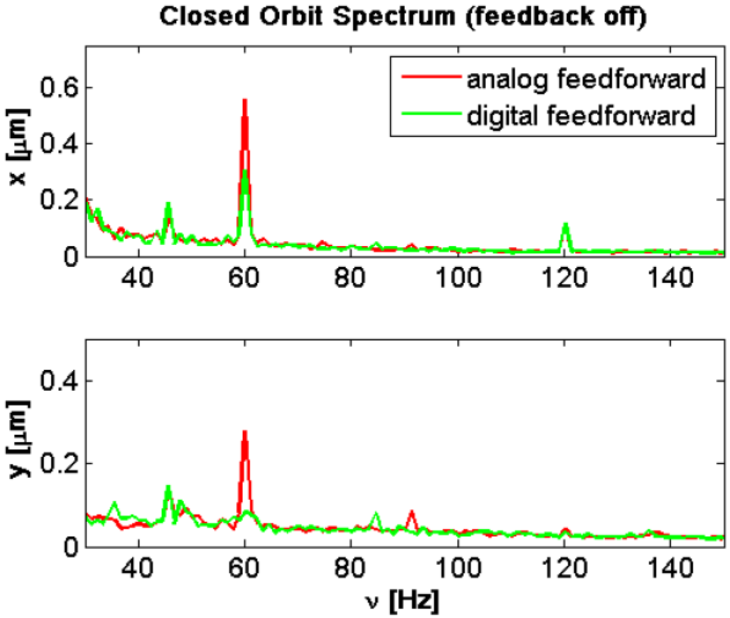
S. Matsui, et al. Jpn. J. Appl. Phys. Vol. 42 (2003) pp.L338

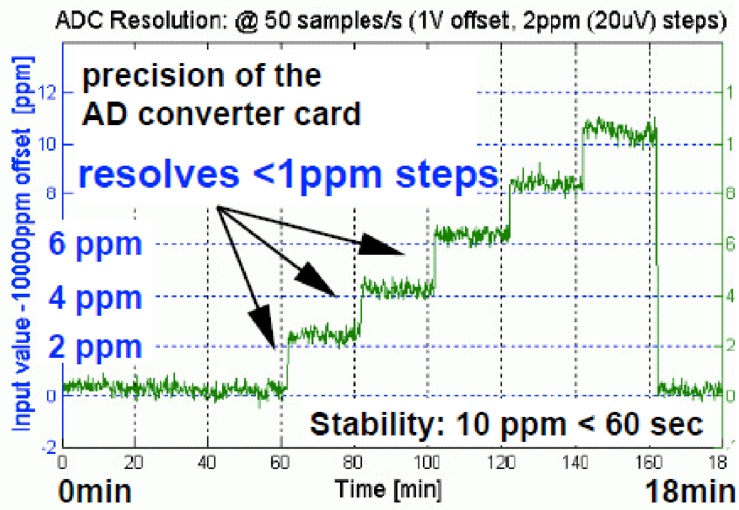
Spring-8: water vibration

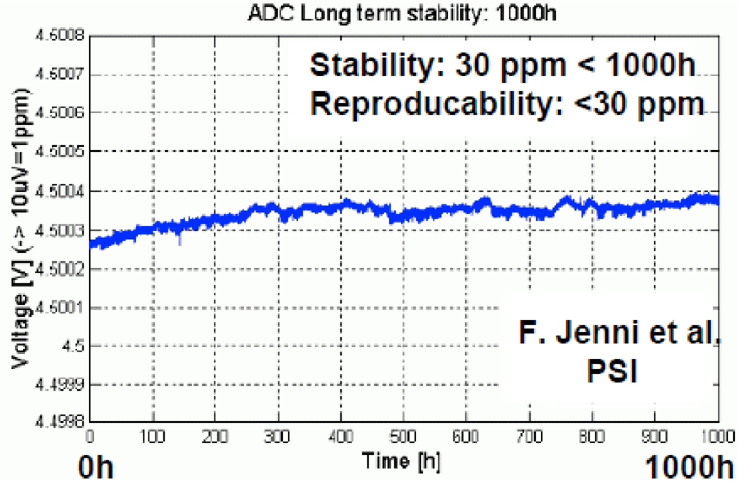
- Often vibration sources / coupling into sensitive equipment is found during after commissioning
- Fixing the worst offenders often gives big benefit
- Examples above: Power supply at ALS, water induced vacuum chamber vibration at Spring-8; Another example are viscoelastic damping elements at ESRF

Good power supplies are essential

- Strong corrector magnets with high vacuum chamber cut off frequencies can be significant sources of orbit noise
  - Observed at several light sources
- Achievable power supply performance is improving
- High resolution, low latency power supplies enable faster orbit feedbacks







F. Jenni et al. PSI

Closed orbit errors

- A single dipole error will create an orbit distortion which looks very simple in normalized coordinates:

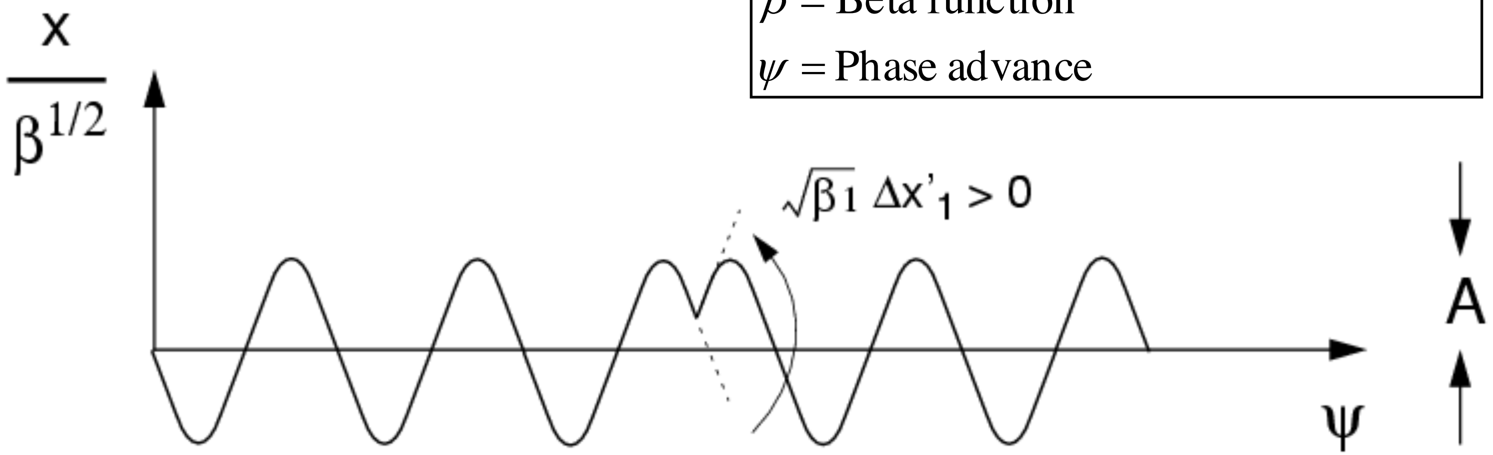
$$x(s) = \Delta x' \frac{\sqrt{\beta(s)\beta_0}}{2\sin\pi\nu}\cos\left(\left|\psi(s)-\psi_0\right|-\pi\nu\right)$$

$\Delta x =$ Transverse position

$\Delta x' =$ Kick strength [radians]

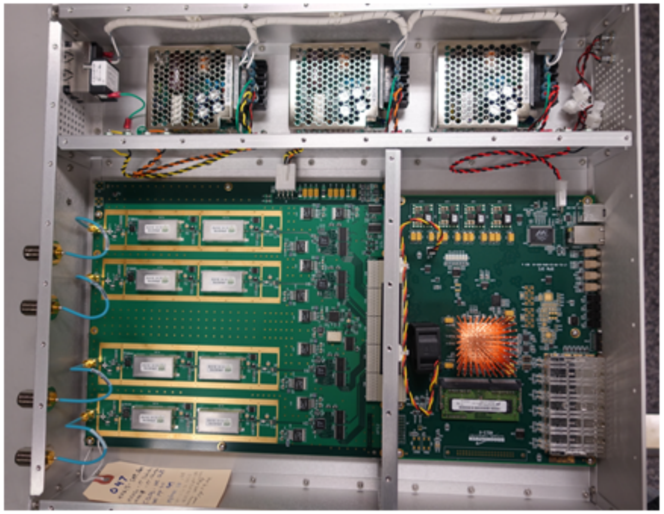
$\beta =$ Beta function

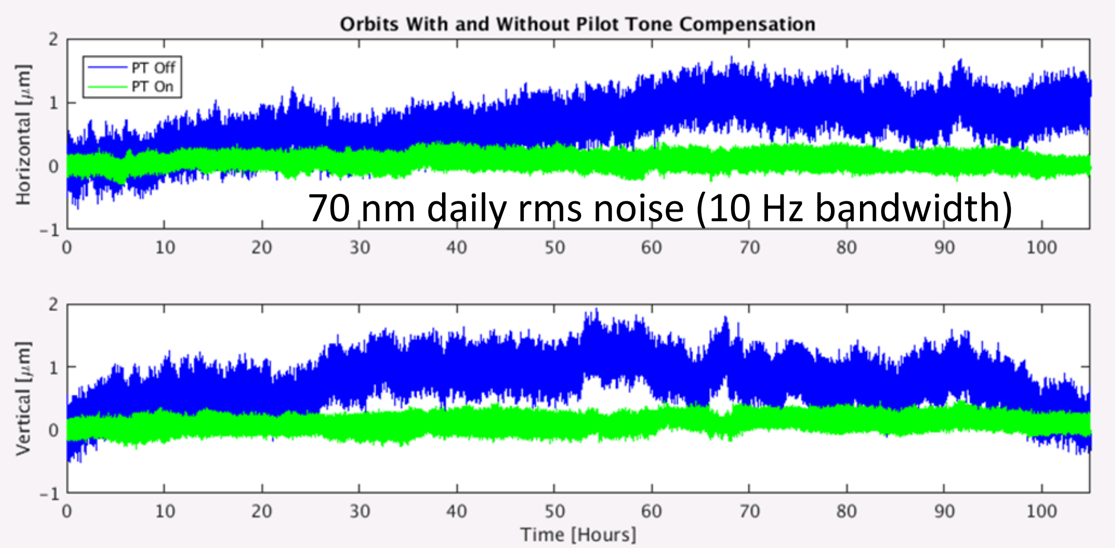
$\psi =$ Phase advance



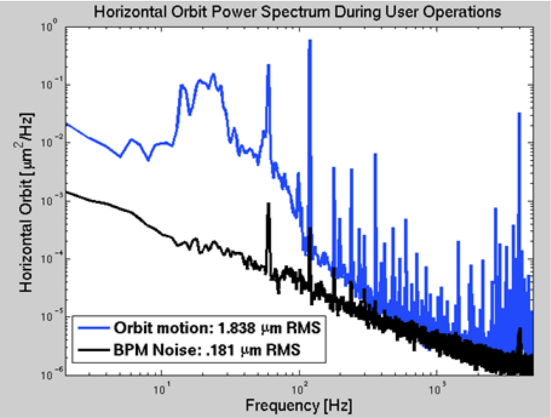
The matrix containing the change in position at every BPM to a kick from every corrector magnet is called orbit response matrix (used in orbit correction). For an uncoupled machine it can be calculated (linear approximation) using above formula.

BPM Trends: low noise, high rate, low latency

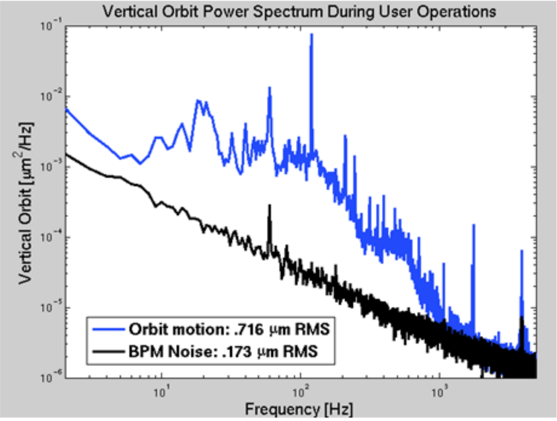




70 nm daily rms noise (10 Hz bandwidth)



Orbit motion: 1.838 μm RMS
BPM Noise: .181 μm RMS



Orbit motion: .716 μm RMS
BPM Noise: .173 μm RMS

Collaboration with NSLS-II

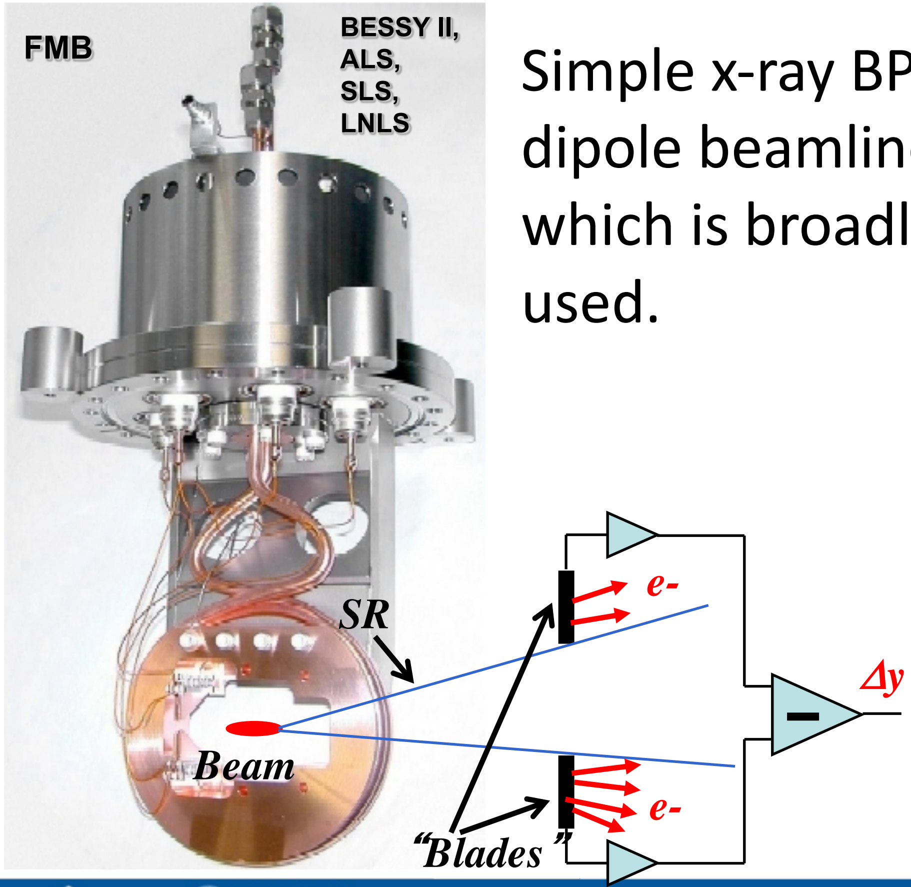
Also need: fast power supplies, magnets, special vacuum chambers, …

- Digital front-end is same as NSLS-II
- Firmware, software, EPICS device support, analog front-end and pilot tone developed at the ALS.

Greg Portmann, Mike Chin, Eric Norum, ALS

Photon BPMs

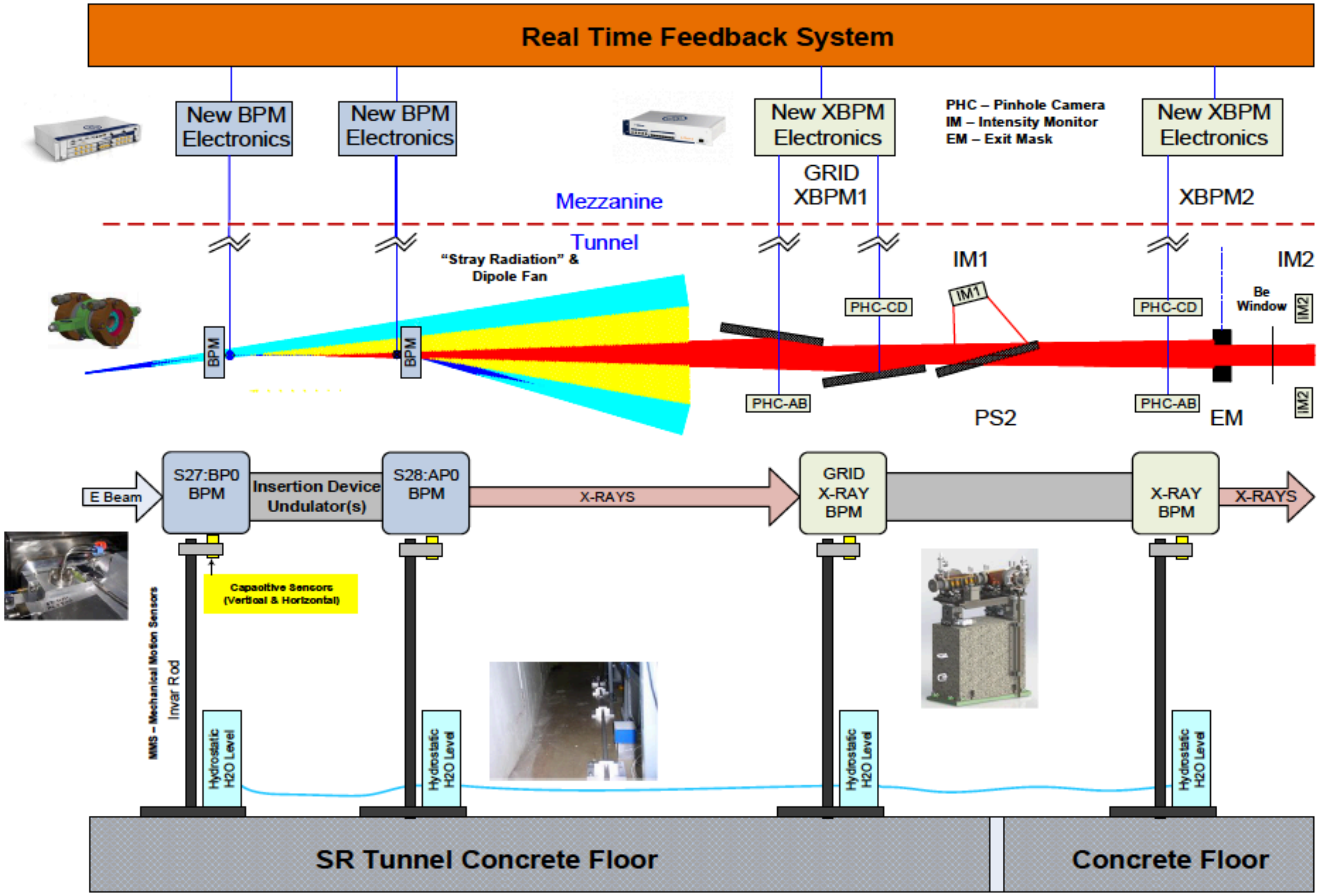
- Synchrotron radiation is often abundant
  - very useful for low noise, non-desctructive position measurement
- Improved lever arm for angular errors of photon beams
- Sensitive to trajectory errors inside undulators



Simple x-ray BPM for dipole beamline, which is broadly used.

- Work very well for dipoles in the vertical plane
- For undulators OK for hard x-rays
  - with Decker distortions if undulators scan a lot
- Many improved solutions for hard x-rays
  - GRID, …
- difficult for VUV, no good solution for EPUs, still

Example of Feedback Integration R+D -

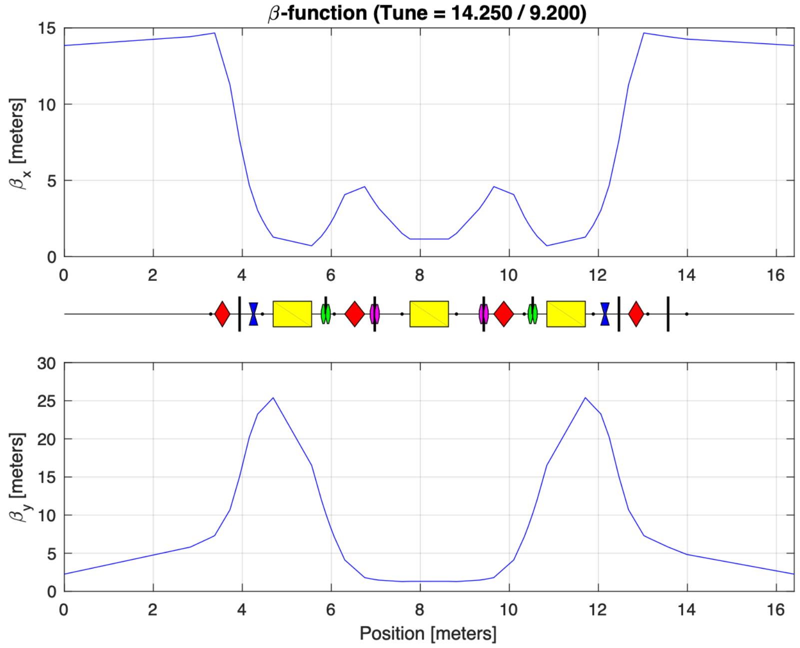


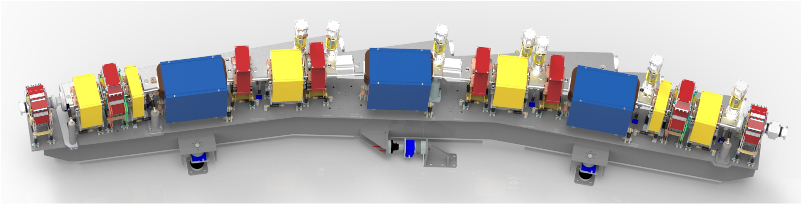
Courtesy: Bob Lill (APS/APS-U)

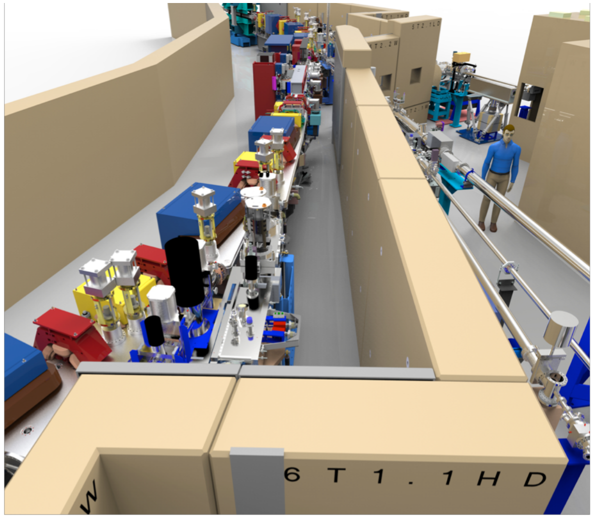
Next some Advanced Light Source Examples

jc/ALSaerial/11-96

ALS – orbit measurement + correction

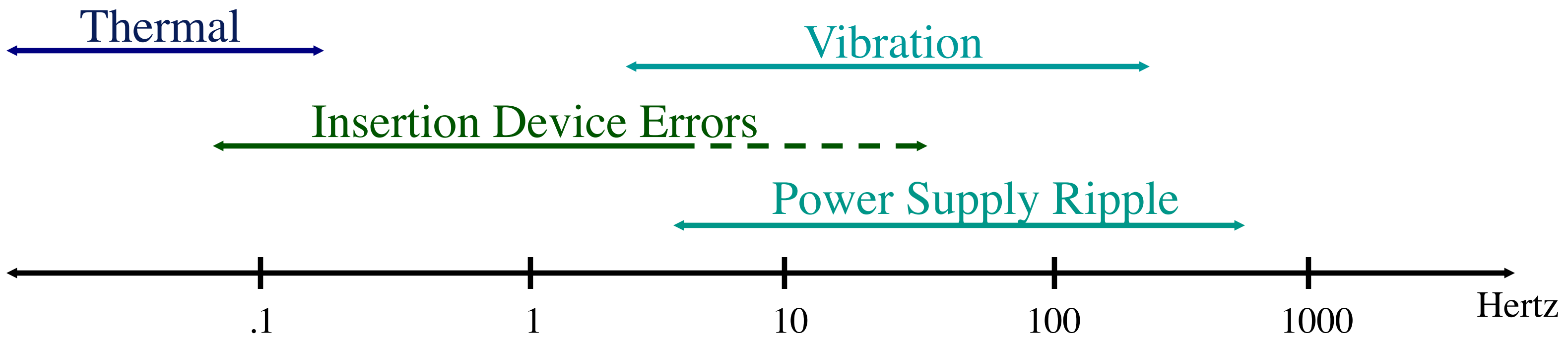






- 12 nearly identical arcs; aluminum vacuum chamber
- 122 beam position monitors in each plane
- 8 horizontal, 6 vertical correctors per arc (94/70 total), 2x22 fast correctors
- 48 individual skew quadrupoles
- Beam based alignment capability in all quadrupoles
  - either individual power supplies or shunts

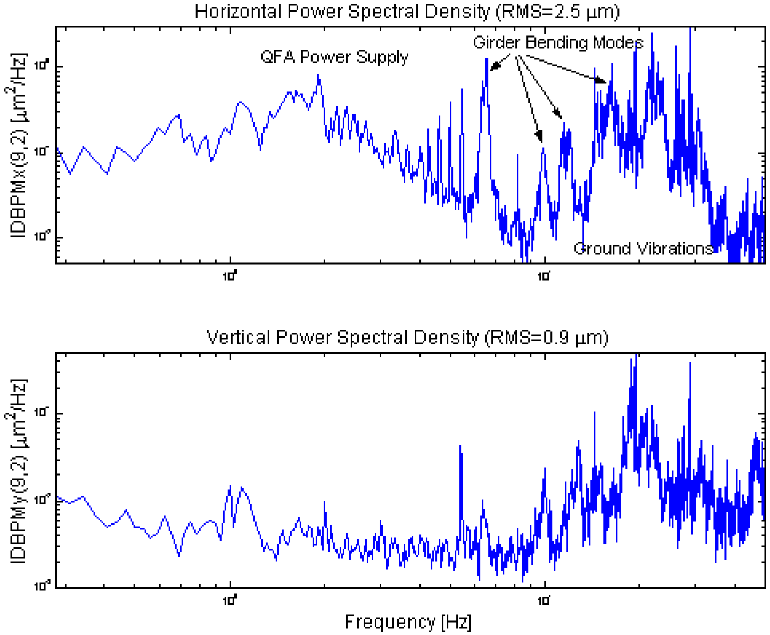
Orbit Drift and Jitter Sources



Frequency	Magnitude	Dominant Cause
Two weeks (A typical experimental run)	±200 μm Horizontal ±100 μm Vertical	1. Magnet hysteresis 2. Temperature fluctuations 3. Component heating between 1.5 GeV and 1.9 GeV
1 Day	±125 μm Horizontal ±50 μm Vertical	Temperature fluctuations
8 Hour Fill	±50 μm Horizontal ±20 μm Vertical	1. Temperature fluctuations 2. Feed forward errors
Minutes	1 to 5 μm	1. Feed forward errors 2. D/A converter digitization noise
.1 to 300 Hz	3 μm Horizontal 1 μm Vertical	1. Ground vibrations 2. Cooling water vibrations 3. Power supply ripple 4. Feed forward errors

ALS Beam Stability in straight sections **without** Orbit Correction, **without** Orbit Feedback, but with Insertion Device Feed-Forward

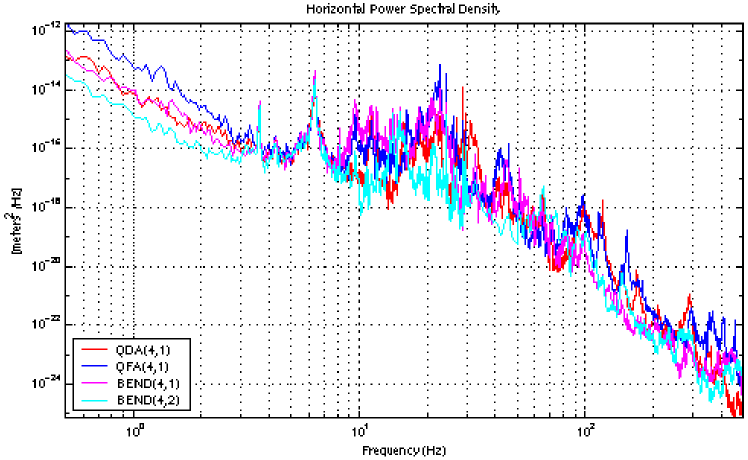
Old ALS Example: Orbit Power Spectral Density

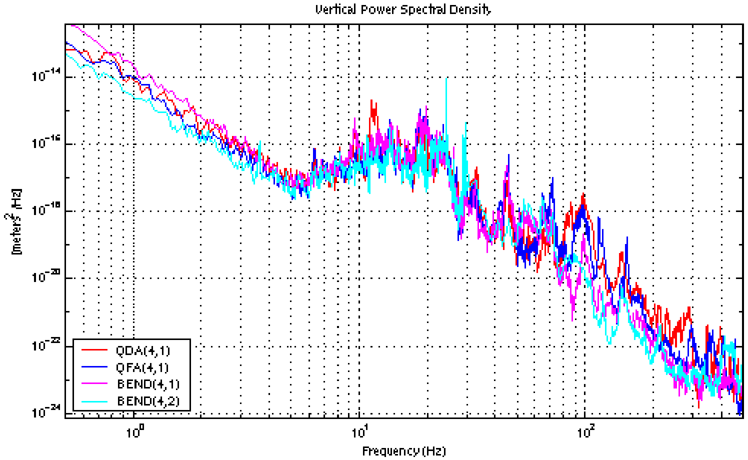


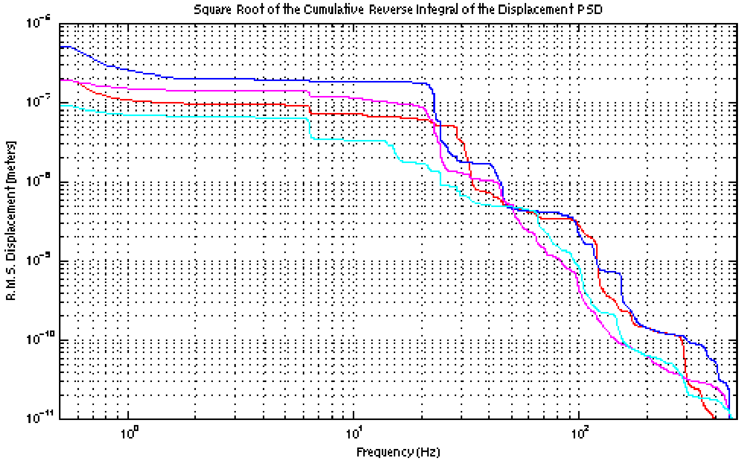
Data taken on 12-12-1999, during a 1.9 GeV user run at 278 mAmps

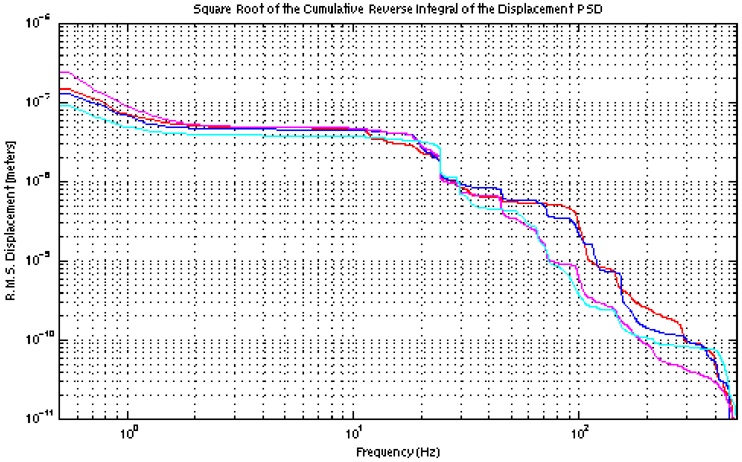
- Ideally one tries to identify all jitter/noise spikes on orbit spectra
  - Can localize by using multiple BPMs (and virtual SVD correction)
  - Measurements of vibrations of elements or FEA mode analysis can help
- Power supply spikes can be identified by high resolution DCCTs, …
  - Again multiple BPMs can help with localizing

Magnet Vibration PSD









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Orbit Correction

By measuring the orbit distortion in N BPMs along the ring, we find the set of displacements:

$$\mathbf{u}_N = \{u_1, u_2, \ldots, u_N\}$$

By using M correctors magnets, we can find a set of kicks that cancels the displacement of the beam at the BPM positions. This is obtained when:

$$-u_j = \frac{\sqrt{\beta(s_j)}}{2\sin(\pi\nu)} \sum_{i=1}^{M} \sqrt{\beta(s_i)}\, \theta_i \cos\nu\left[\left|\varphi(s_j) - \varphi(s_i)\right| + \pi\right] \qquad j = 1, 2, \ldots, N$$

Or in matrix representation, when:

$$-\mathbf{u}_N = \mathbf{M}\boldsymbol{\theta}_M \qquad with \quad M_{ji} = \frac{\sqrt{\beta(s_j)\beta(s_i)}}{2\sin(\pi\nu)} \cos\nu\left[\left|\varphi(s_j) - \varphi(s_i)\right| + \pi\right]$$

The kicks that need to be applied to the steering magnets for correcting the closed orbit distortion, can be obtained by inverting the previous equation:

$$\boxed{\boldsymbol{\theta}_M = -\mathbf{M}^{-1}\mathbf{u}_N}$$

The elements of the response matrix $\mathbf{M}$, can be calculated from the machine model, or measured by individually exciting each of the correctors and measuring the induced displacement in each of the BPMs.

Orbit Correction Methods

- Simplest method is the direct inversion of the orbit response matrix (equal number of BPMs and correctors).
- In case of unequal numbers use least square correction (minimizing the sum of the quadratic deviations from the nominal orbit) often with additional constraint to minimize average corrector strength.
- MICADO/MEC is a modification of LSQ. It iteratively searches for the single most effective corrector, calculates its correction strength, finds the next most effective corrector, calculates the correction using those two, …
- SVD uses the so called singular value decomposition. In this method small singular values can be neglected in the matrix inversion.
- Local Bumps allow to keep the orbit ‘perfect’ locally (sensitive SR user, interaction point, …) while relaxing the correction elsewhere.

Singular Value Decomposition

- Any Matrix M can be decomposed (SVD)

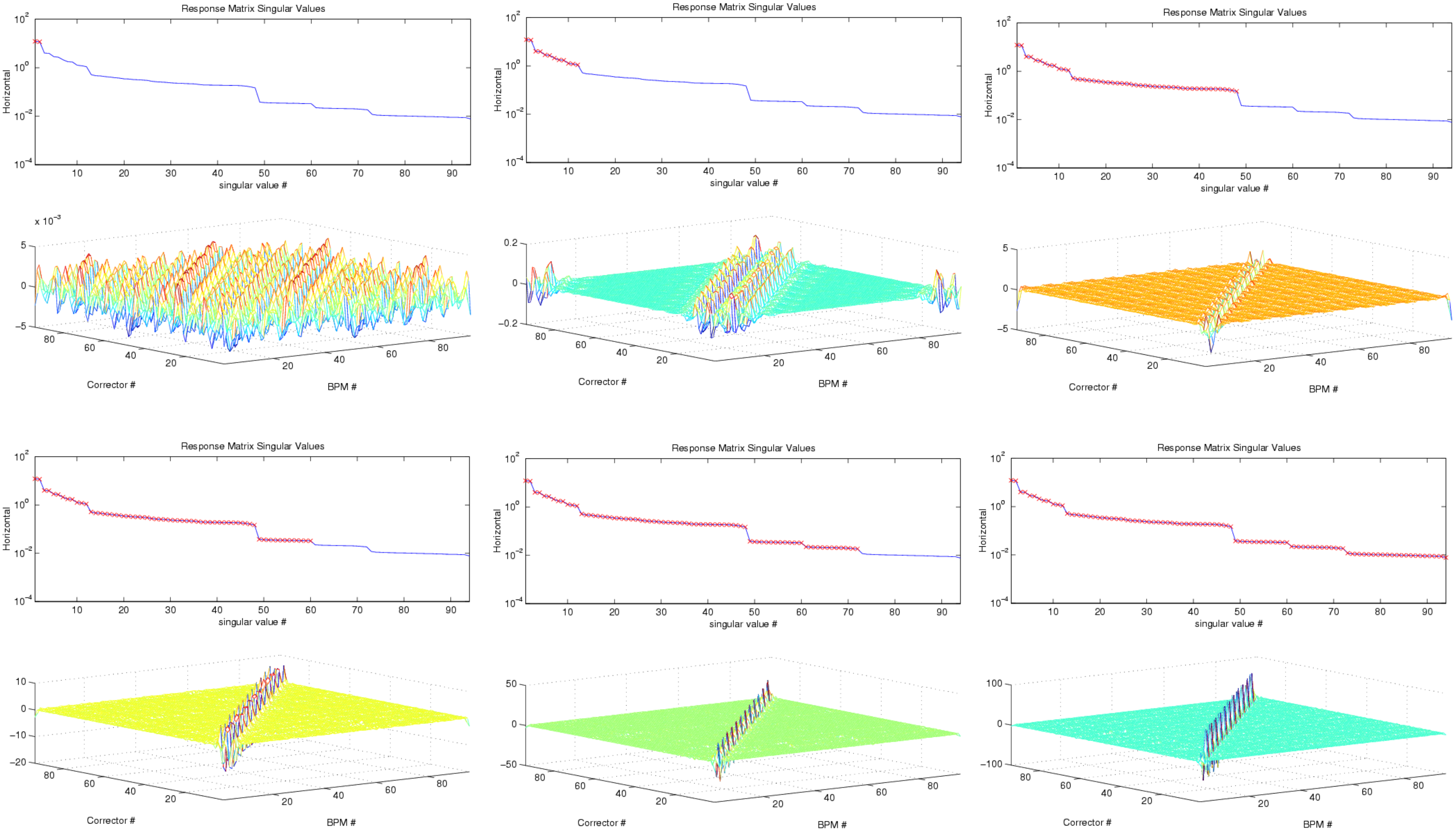
$$M = U \cdot \Sigma \cdot V^T = \sum_i \vec{u}_i \sigma_i \vec{v}_i^T$$

- Where U and V are orthogonal matrices (I.e. $U \cdot U^T = 1$, $V \cdot V^T = 1$) and Σ is diagonal and contains the (σ_i) singular values of M.
- Examples:
  - M is the orbit response matrix
    - U contains an orthonormal set of BPM vectors
    - V contains an orthonormal set of corrector magnet vectors
- Because of orthogonality the inverse of M can be simply calculated:

$$M^{-1} = V \cdot \Sigma^{-1} \cdot U^T = \sum_i \vec{v}_i \frac{1}{\sigma_i} \vec{u}_i^T .$$

Singularities and small singular values can be removed by removing columns of U & V.

Example: SVD inverted matrix vs. number of SVs



Trade-offs of Correction Methods

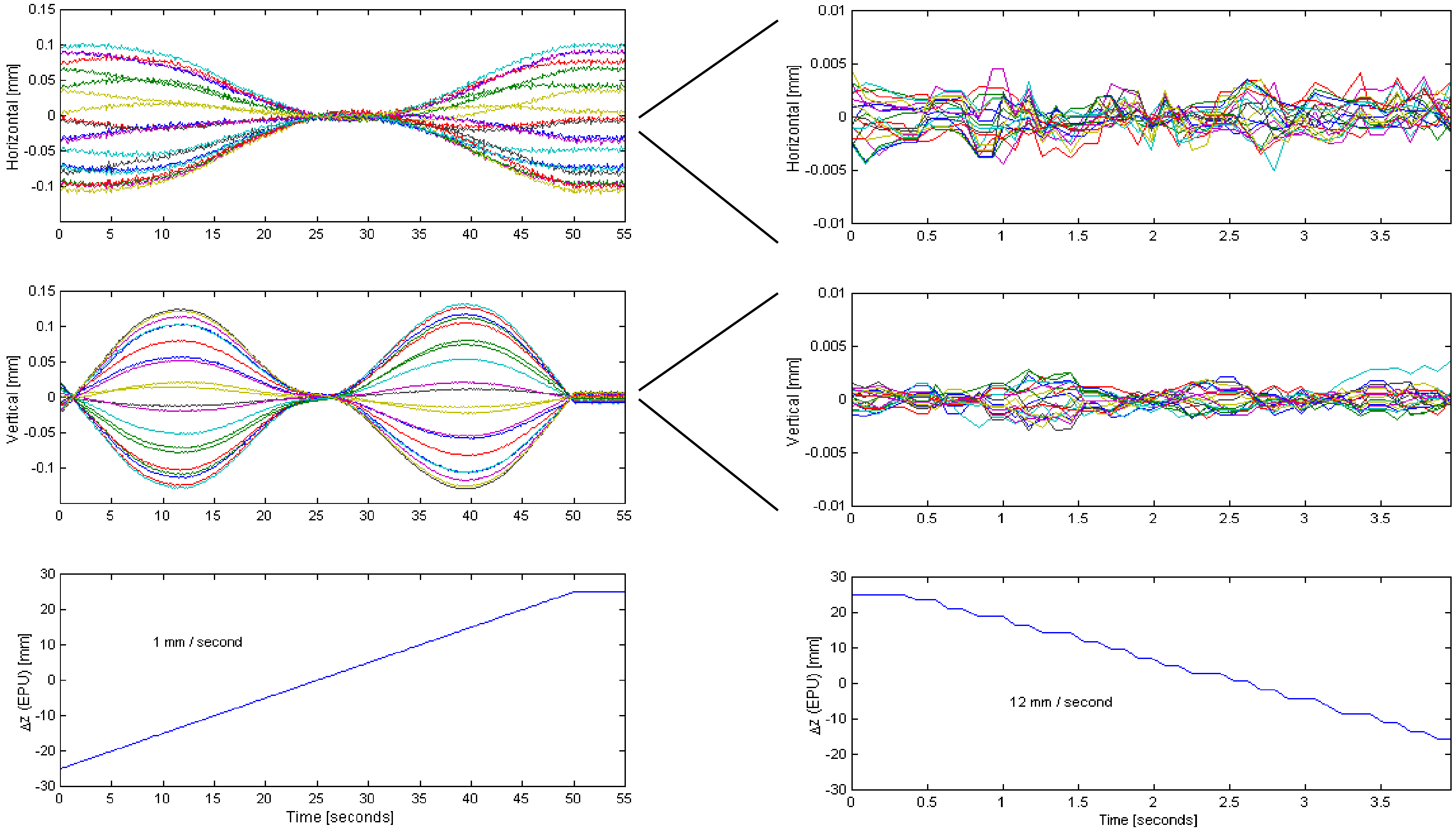
- Least square or direct matrix inversion
  - Disadvantages:
    - Have to trust every BPM reading
    - BPM and corrector locations very critical (to avoid unobservable bumps)
  - Advantages:
    - Minimizes OBSERVABLE orbit error
    - Works well for distributed/numerous errors
    - localizes the correction.
- MICADO
  - works well for few dominant errors (IR quads in colliders)
  - Does not allow good correction for many errors.
- SVD
  - allows to adjust behavior based on requirements.
  - Most light sources nowadays use SVD.

Insertion Device Compensation

EPU Feed Forward Orbit Correction

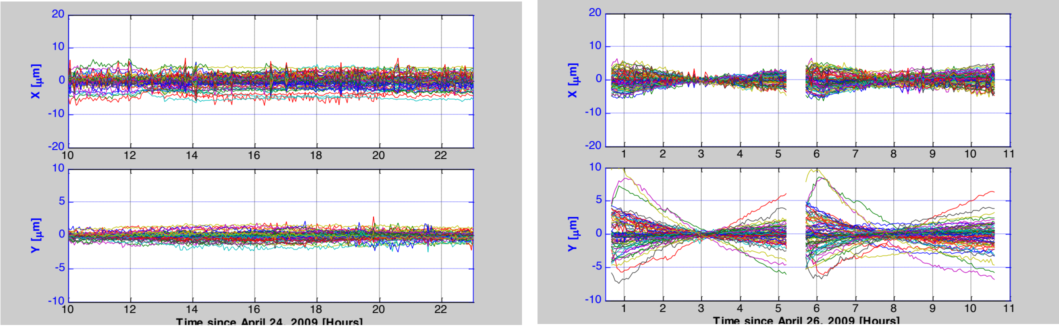
Orbit Error without Feed Forward Correction

200 Hertz Feed Forward Correction

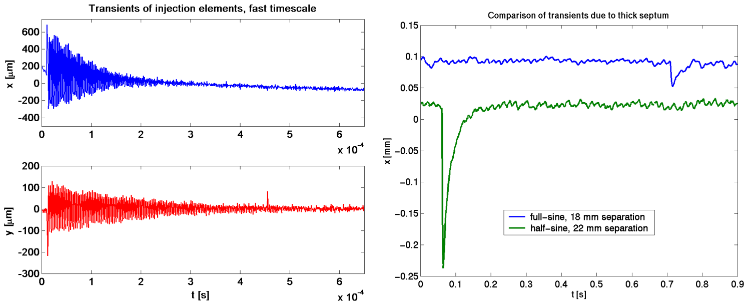


Orbit Feedback

Long Term Stability (with Feedback)



ALS: mid term orbit stability (with+w/o Top-off)

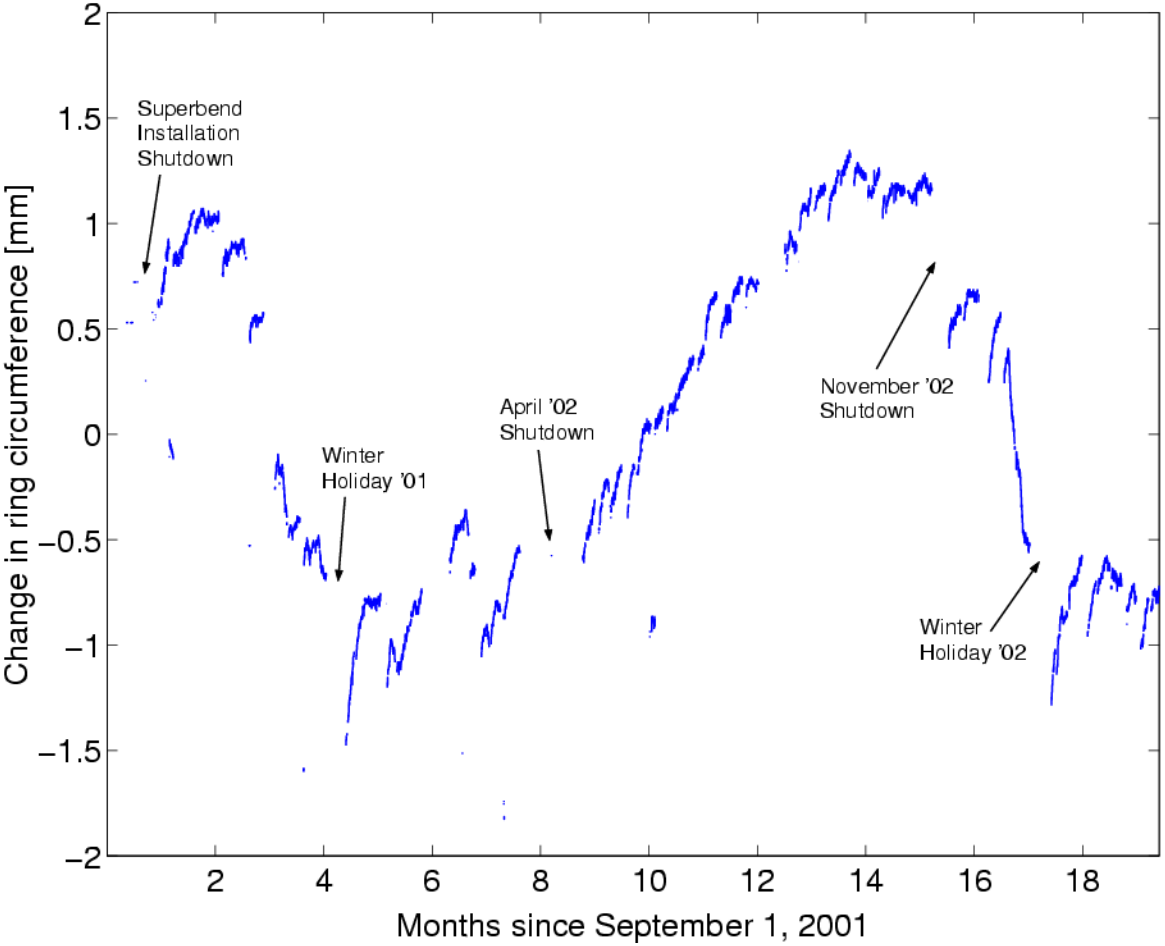


ALS: injection transients (fast+slow)

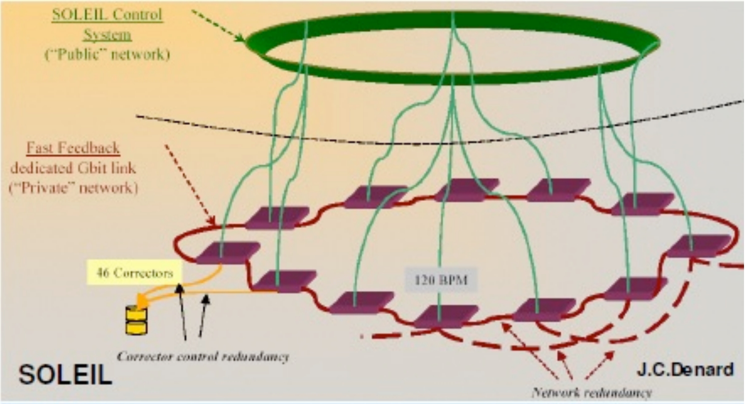
- Top-off greatly improves the mid- and long-term stability (also for user beamline optics)
  - It does present some additional challenges in form of injection transients, however, currently the benefits greatly outweigh those.
  - Injection transients can be improved with better injection element design (magnets and pulsers), use of transverse multibunch feedbacks, or use of multipoles as injection kickers

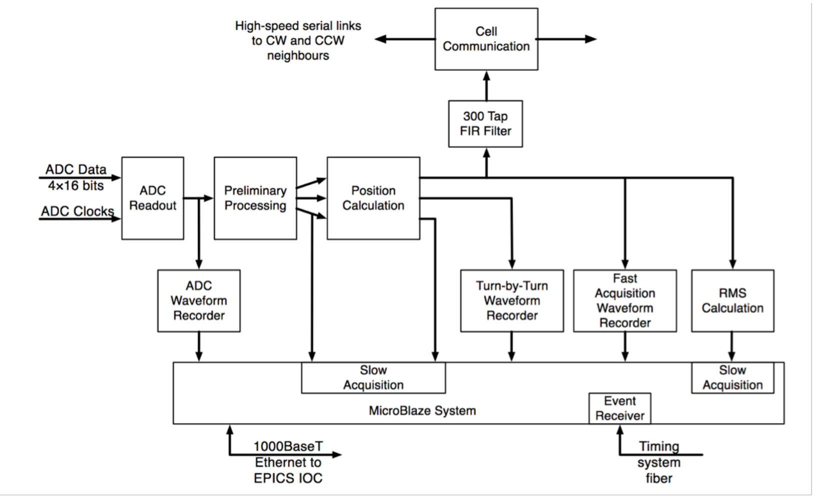
RF Frequency Feedback

- Circumference of ring changes (temperature inside/outside, tides, water levels, seasons, differential magnet saturation, …)
- RF keeps frequency fixed – beam energy will change
- Instead measure dispersion trajectory and correct frequency (at ALS once a second)
- Can see characteristic frequencies of all the effects in FFT (8h, 12h, 24h, 1 year)
- Verified energy stability (a few 10^{-5}) with resonant depolarization



Fast orbit feedback topologies

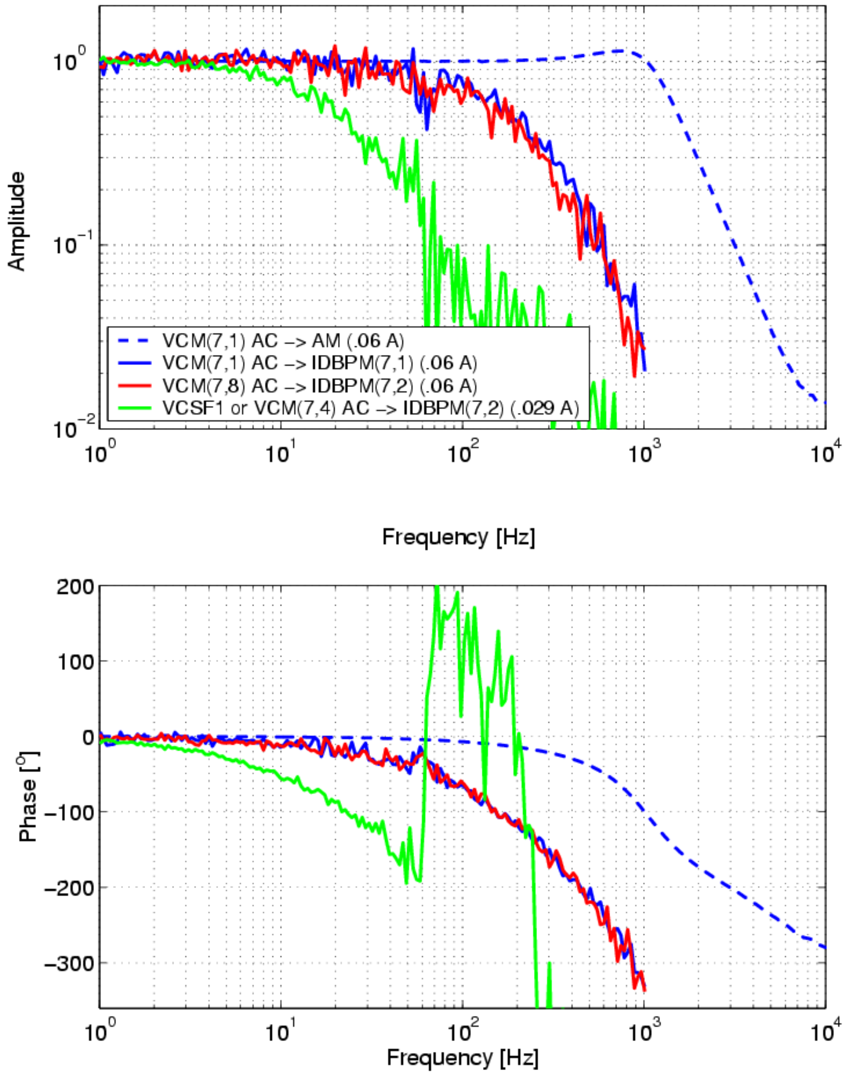




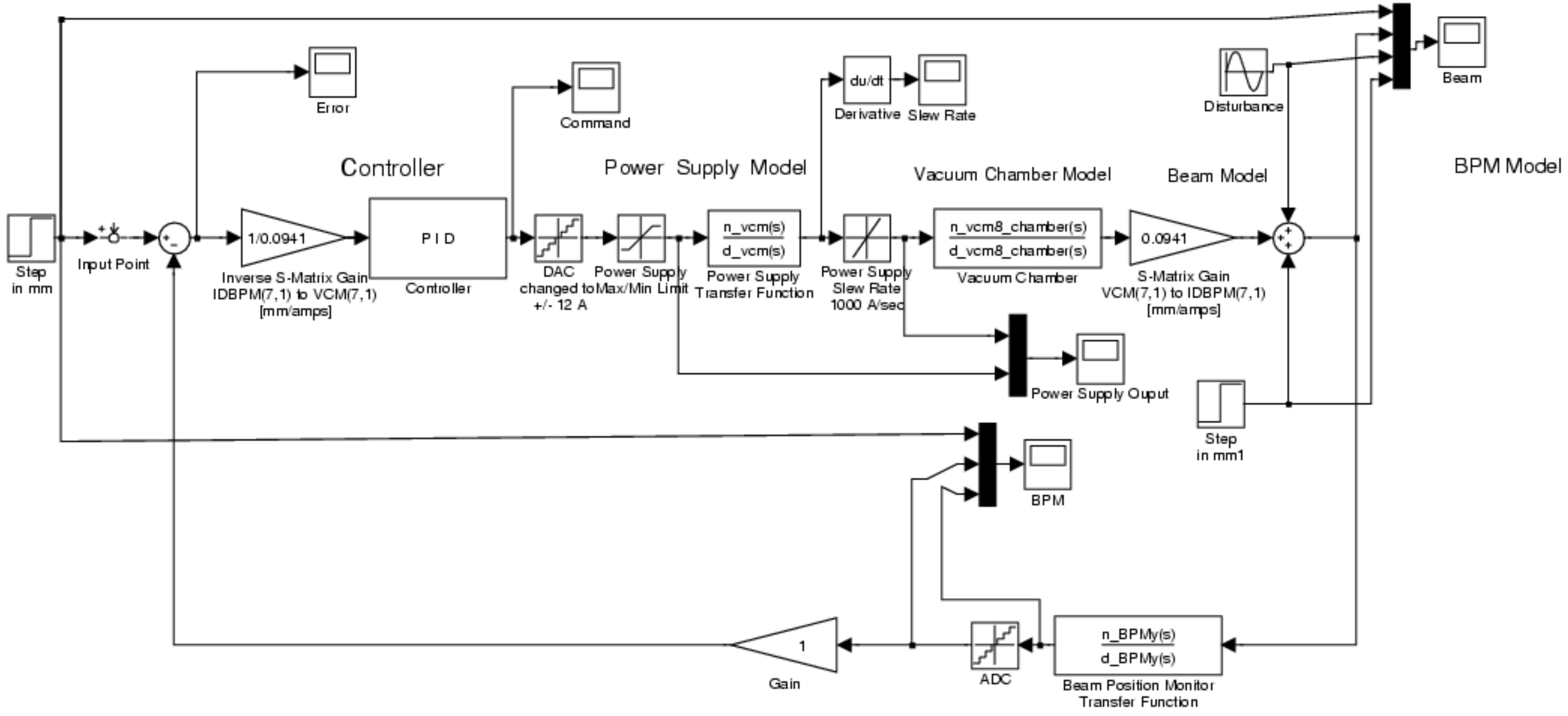
- Many different types of fast orbit feedbacks are in use
- State of the art are systems with update rates up to 20 kHz and closed loop bandwidths approaching 1 kHz
- In some systems, PID algorithms are supplemented by notch filters, …
  – Other filter designs (predictive, …) could improve performance/robustness further

Fast Orbit Feedback

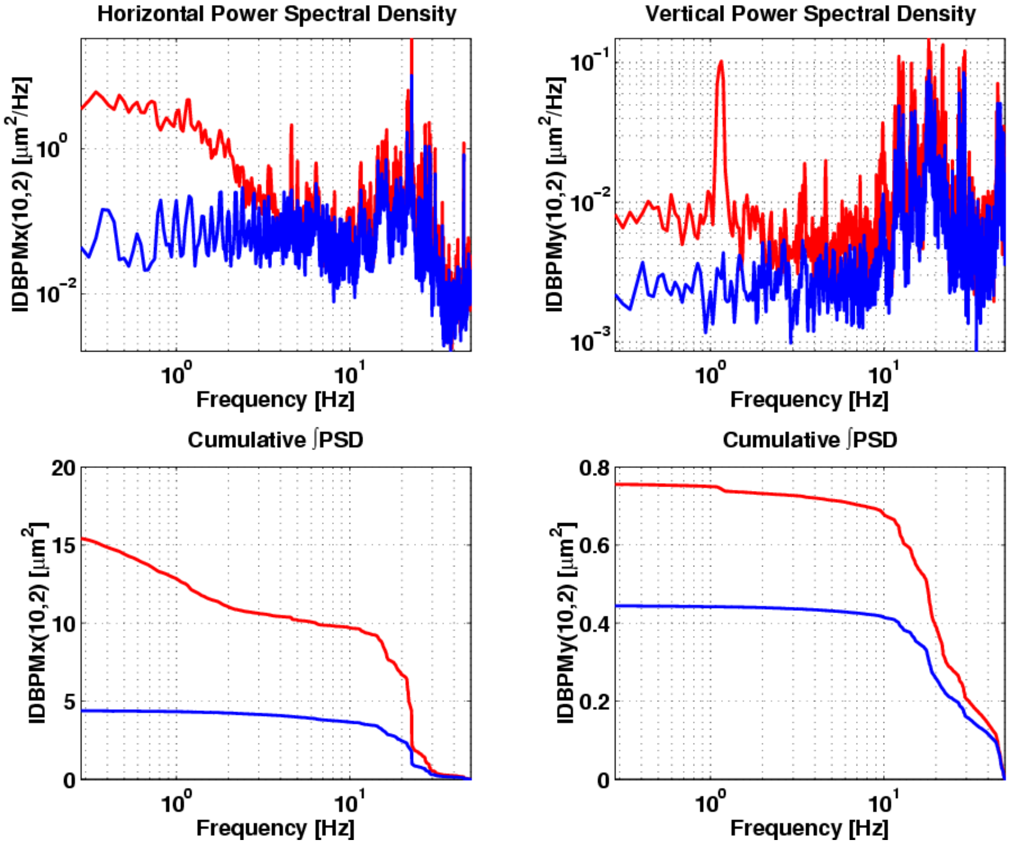
- Time response of all elements becomes important!
- Controller type used is often PID
- System often are distributed (ALS: 15 crates, about 100 BPMs, 22 correctors each plane)



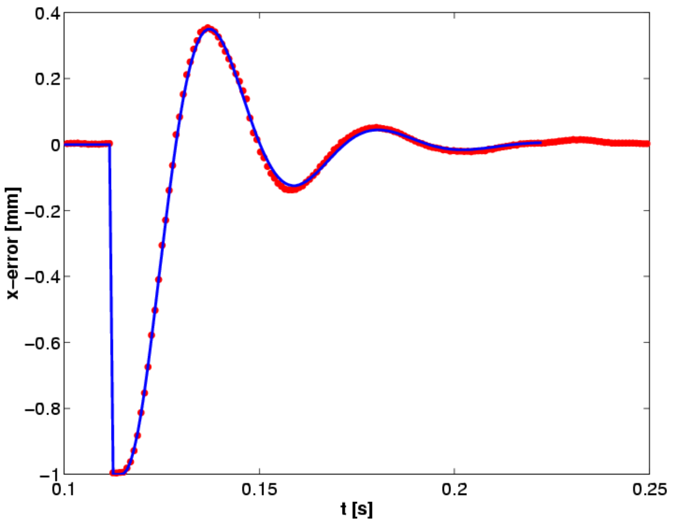
Simulink model of one channel of system



Performance of Fast Orbit Feedback at ALS



Comparison of orbit PSDs with and without fast feedback.
Fast orbit feedbacks are in use at most light sources: APS, NSLS, ESRF, SLS, …



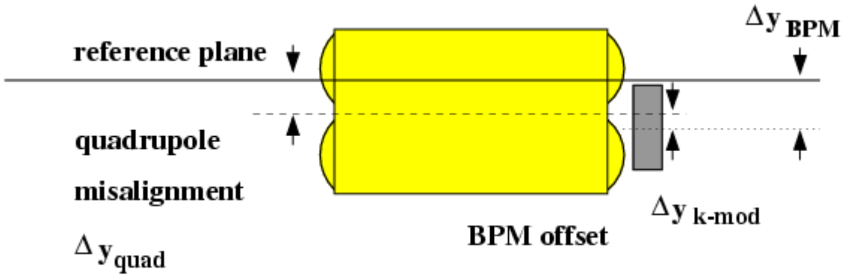
Comparison of simulated (Simulink) and measured step response of feedback system in closed loop in a case where PID parameters were intentionally set to create some overshoot.

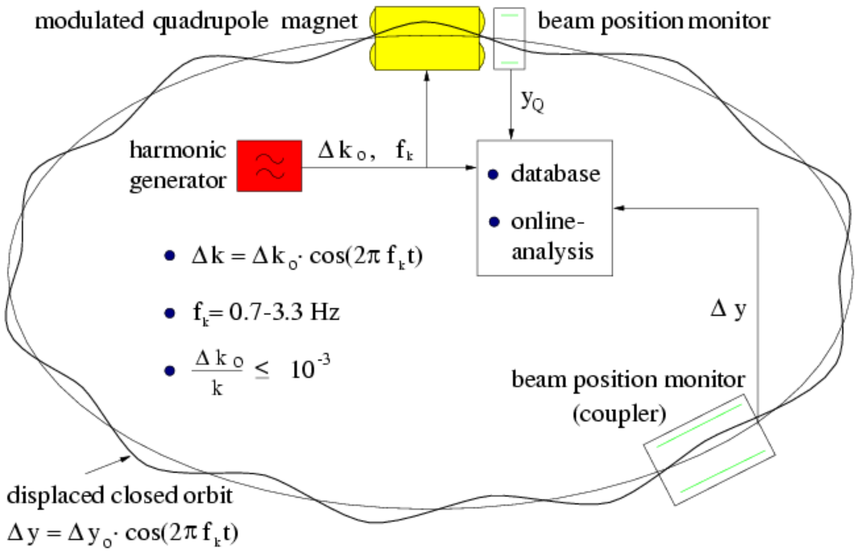
Beam Based Alignment

- BPMs centers are not known well enough relative to center of magnetic elements (vacuum chamber positioning, button positions, button attenuations, cable attenuations, signal electronics asymmetries, …)
- Want to correct orbit to the center of magnetic elements to achieve optimum performance
- Non centered beam can reduce physical/dynamic aperture
  - in quadrupoles: spurious dispersion, larger sensitivity of closed orbit to power supply ripple
  - in sextupoles: gradient errors (horizontal offsets), coupling errors (vertical offsets)
- Allows to link beam position (photon beams) to magnet alignment grid – helps to allow predictive optimum alignment of beamlines

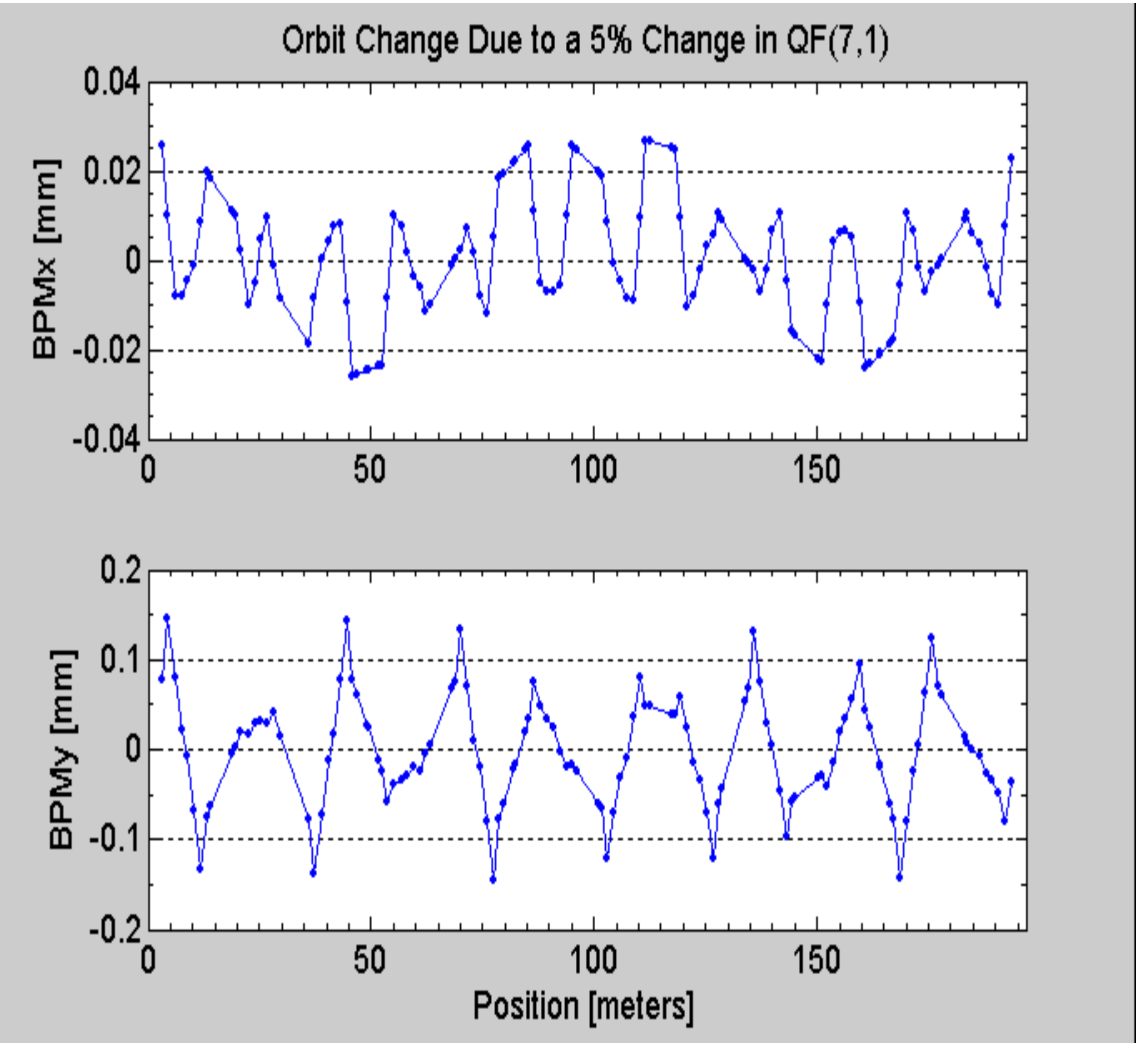
Beam Based Alignment: Method 1

- BPM centers can be determined relative to adjacent quadrupole (or sextupole, skew quadrupole, using other techniques).
- Basic principle is that a change in quadrupole current will change the closed orbit if the beam does not pass through the quadrupole center.
- Sweeping the beam across a quadrupole and changing the quadrupole strength allows to find the centers.





BBA, Method 2



Orbit change for a quadrupole change

(A. Wolski & F. Zimmermann)

$$\Delta x(s) = -x_{off} \frac{C(s,s_0)K_f - C(s,s_0)K_i}{1 - C(s,s_0)K_i}$$

$$C(s,s_0) = \frac{\sqrt{\beta(s)\beta_0}}{2\sin \pi\nu} \cos\left(\left|\psi(s) - \psi_0\right| - \pi\nu\right)$$

x_{off} = Initial offset at the quadrupole

K_i = Initial focusing value

K_f = Final focusing value

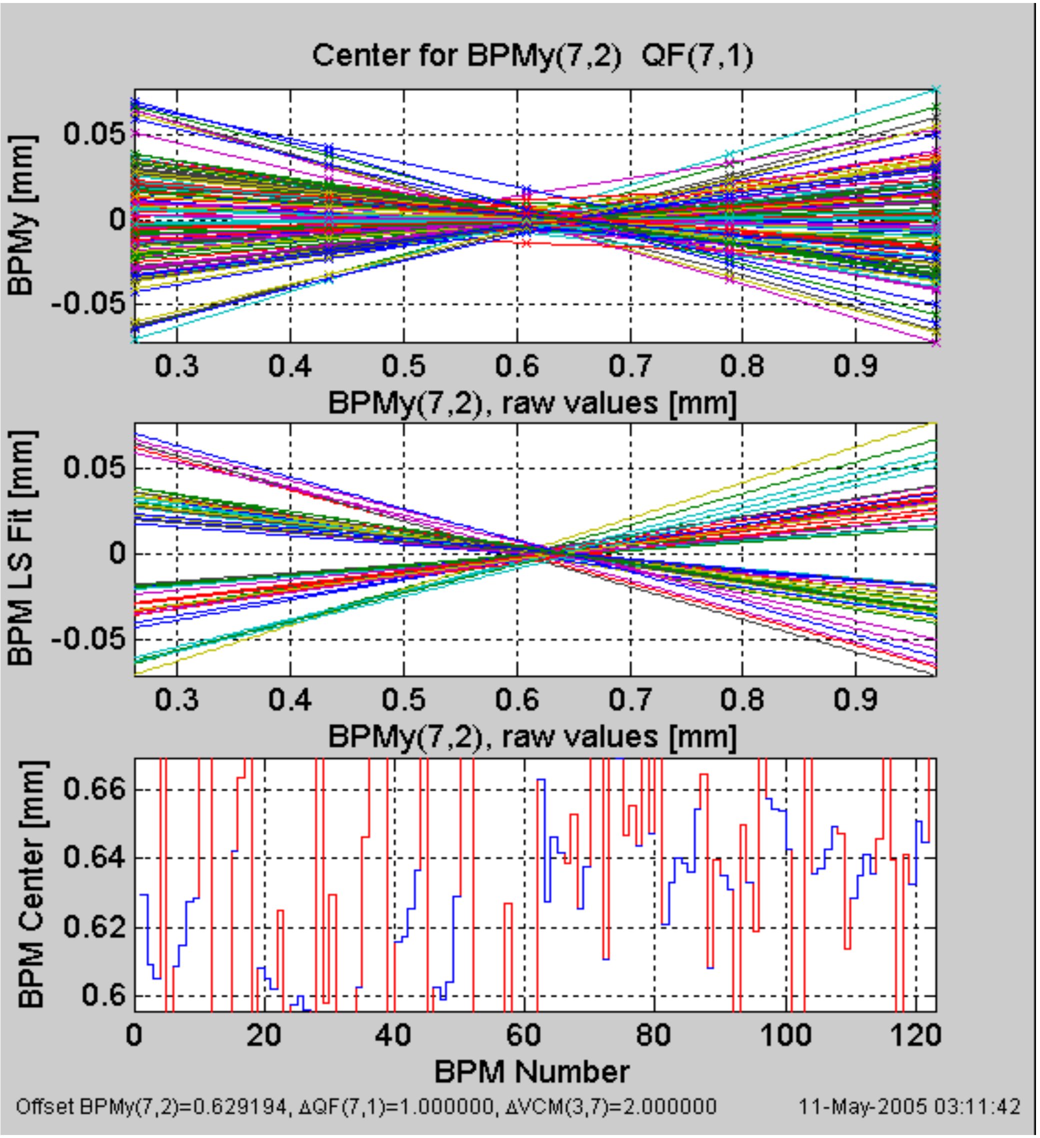
Δx = Transverse position

$\Delta x'$ = Kick strength [radians]

β = Beta function

ψ = Phase advance

Method 3: MML Beam Based Alignment



- The Matlab Middle Layer uses a third beam-based alignment technique
  - Shown in computer class and Xiaobiao’s intro lecture
- The algorithm is fully automated.

- BPM offsets at ALS (like many rings) are fairly significant (rms of 300 microns) but very stable.
- Offsets are typically measured annually or after hardware changes or realignment.

- Main challenge at ALS are systematic errors due to C-shaped magnets.

Summary

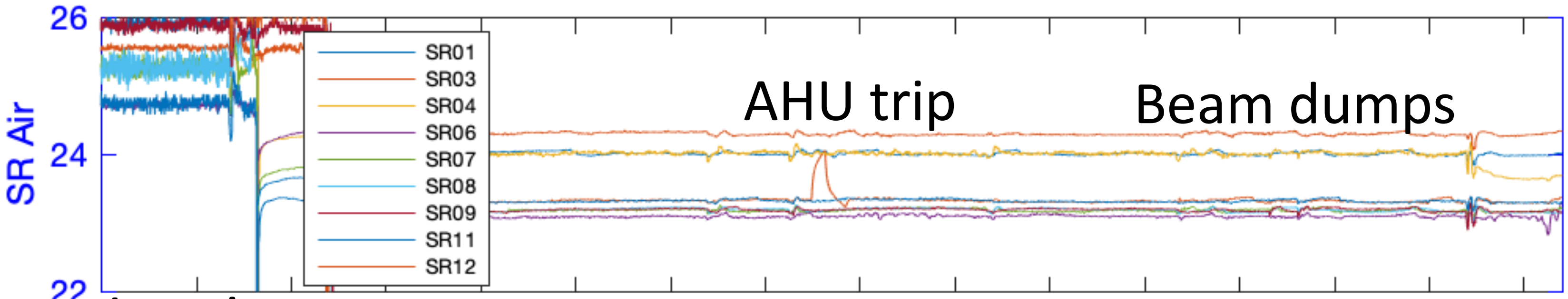
- Stability (orbit, beamsize) is one of the most important performance criteria at accelerators
- Many different methods for position and size measurement exist, tailored to specific needs. Best resolutions are nm scale.
- Multiple noise sources perturb the beam.
  - Passive noise reduction methods helps.
- Different correction algorithms are available. Advantages depend on the situation.
- Orbit feedbacks are used routinely, nowadays with several (up to 20) kHz update rate.
- Beam based alignment is essential to improve accelerator performance

Some Material for Further Reading:

- Presentations at 2018 BES Light Sources Beam Stability Workshop: https://www.aps.anl.gov/BES-Light-Sources-Beam-Stability-Workshop/Presentations
- B. Hettel, Rev. Sci. Instr. 73, 3, 1396
- W.H. Press et al., Numerical Recipes, Cambridge U. Press (1988) p. 52
- Presentations at 2nd International Workshop on Beam Orbit Stabilization (2002)
- Presentations at the 3rd International Workshop on beam Orbit Stabilization (2004): http://iwbs2004.web.psi.ch/program/orals.html
- A. Friedman, E. Bozoki, NIM A344 (1994) 269
- J. Carwardine, F. Lenkszus, Proceedings of the 1998 Beam Instrumentation Workshop, http://www.slac.stanford.edu/pubs/confproc/biw98/carwardine.pdf

Backup Slides

Commissioning results of new ALS AHU controls



AHU trip

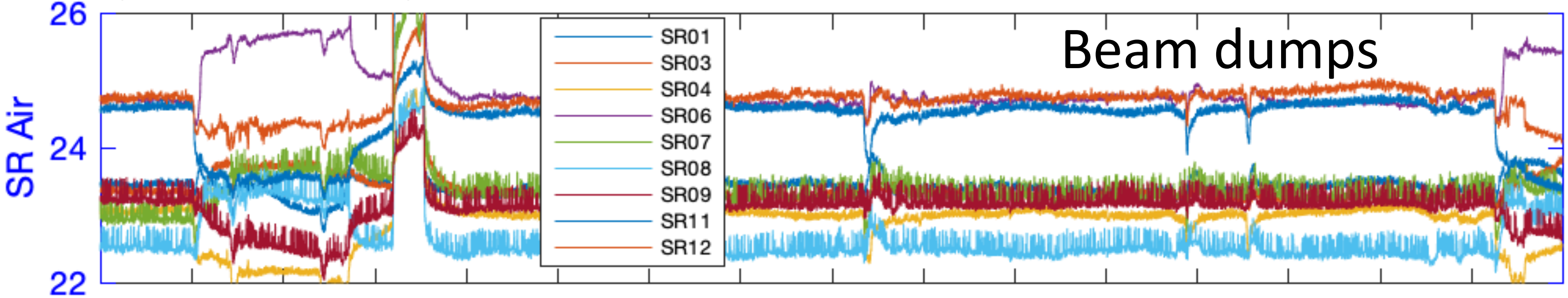
Beam dumps

October 2018

Interim state
(old sensors)

Time [days]

Shutdown



Beam dumps

October 2017

Shutdown

Time [days]

Shutdown