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Closed Orbit Stability, Correction and Feedback

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Outline

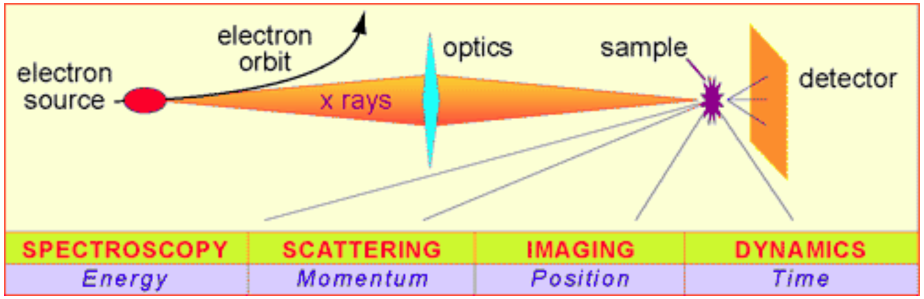
- Introduction/Motivation
- Measurement Methods/BPMs
- Sources of Orbit Noise/Drift
- Orbit Correction/Feedback
  - Correction Algorithms
  - Feedback Systems (Slow, RF, Fast)
- Beam Based Alignment

Motivation

Orbit stability is one of the most important requirement in accelerators

- There are many reasons why good orbit stability is necessary
- Accelerator Physics:
  - Spurious effects (dispersion, coupling, beta beating) due to off ccenter trajectories in magnets
  - Equipment protection
  - Beam-beam overlap at interaction point.
- Users:
  - Stability of photon source point
  - Stability of interaction point in colliders.

Beam Stability: Requirements



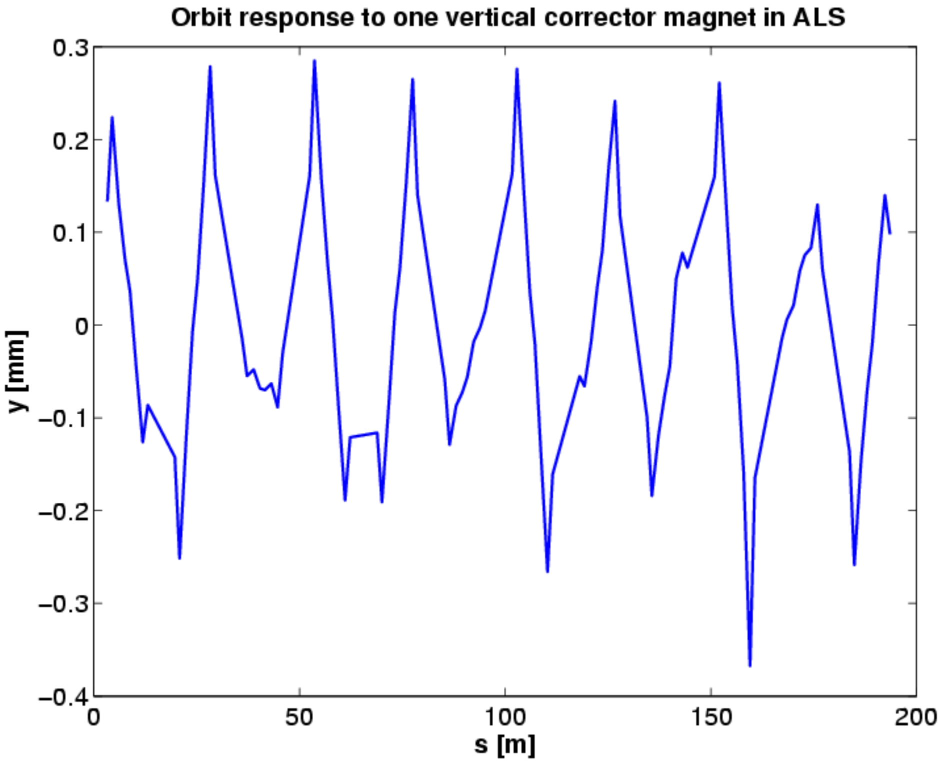
Typical requirements of modern SR user experiments:

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

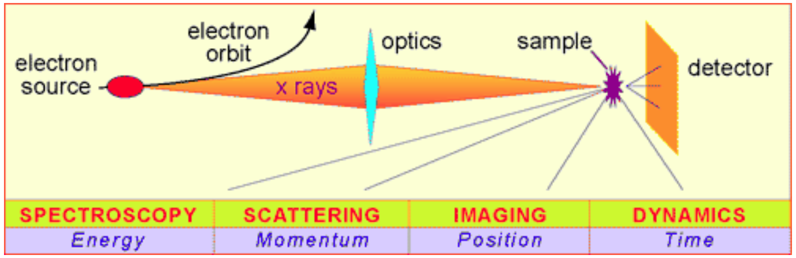
- All of those requirements relate back into stability requirements for beam position + angle, beamsize + emittance, beam energy, beam energy spread, …
- Often stability can be more important to SR users than brightness+flux
- For current SR sources, this means for example submicron orbit stability (for ERLs in both planes)

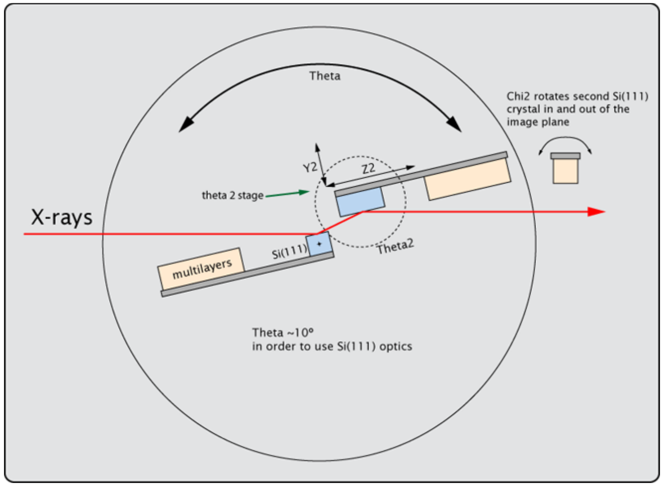
Closed Orbit: 'Definition'

- ☐ The closed orbit is the (periodic) particle trajectory which closes after one turn around the machine (in position and angle) i.e. the fixed point in 4 (6) dimensional space for the one-turn map.
- ☐ The ideal orbit is the orbit through the centers of all (perfectly) aligned magnetic elements.
- ☐ Particles close to the closed orbit will oscillate around it.



Why does the orbit/position need to be constant

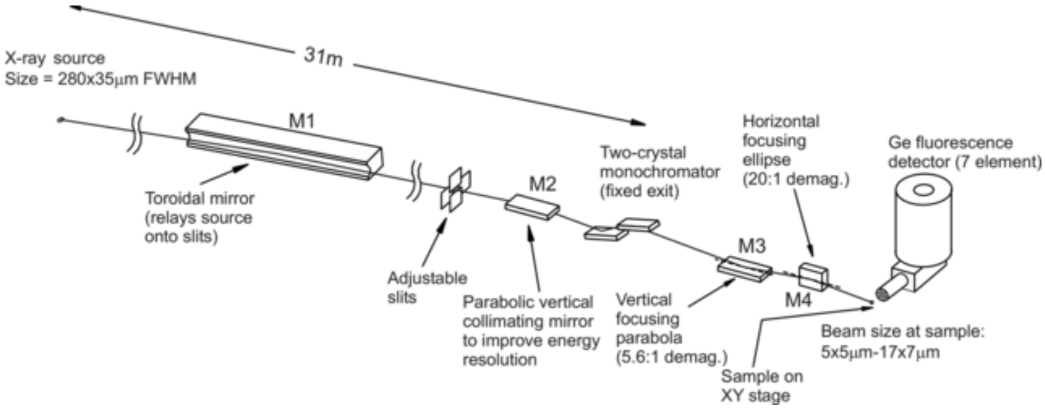




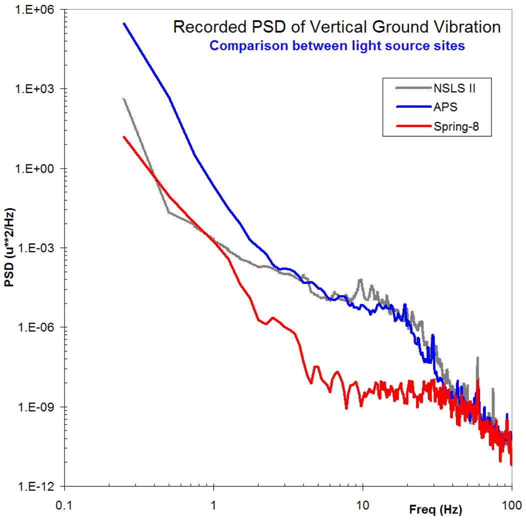
- Without slits it is obvious that beam motion will translate to motion of photon beam on sample, i.e. different sample areas are measured
- Similarly in a monochromator without slits a vertical beam motion translates into a photon energy shift
- With slits, the effects get smaller and smaller with smaller slit size (there still are 2nd order effects because of the beam profile and the nonzero slit size). However, the smaller the slit the smaller the transmission and the larger the intensity fluctuations (and effects of slit alignment and motion).

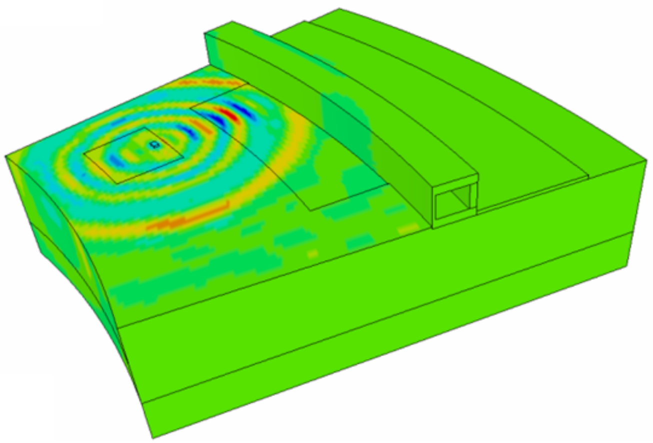
Actual Beamline Example

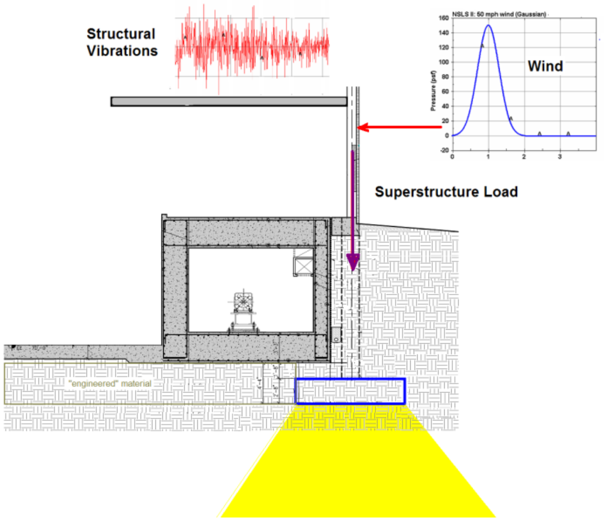
- Beamline 10.3.2 at the ALS
- Hard x-ray, microfocus, micro X-ray absorption or fluorescence, …
- Environmental samples (‘dirt’)
- Very heterogenous



Stability / Design



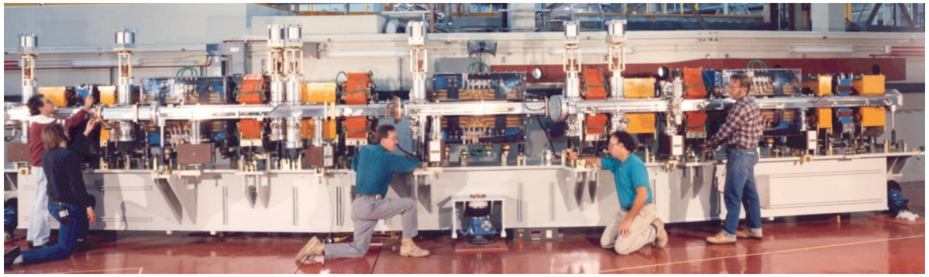


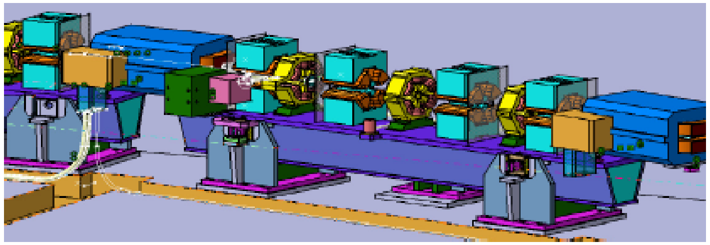


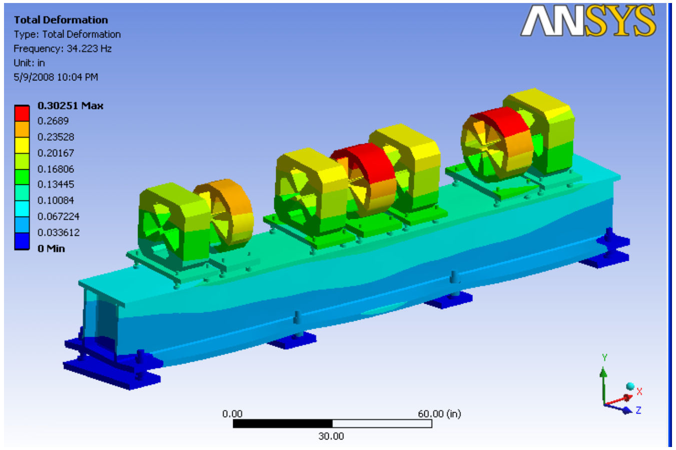
Courtesy: N. Simos, NSLS-II

- 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

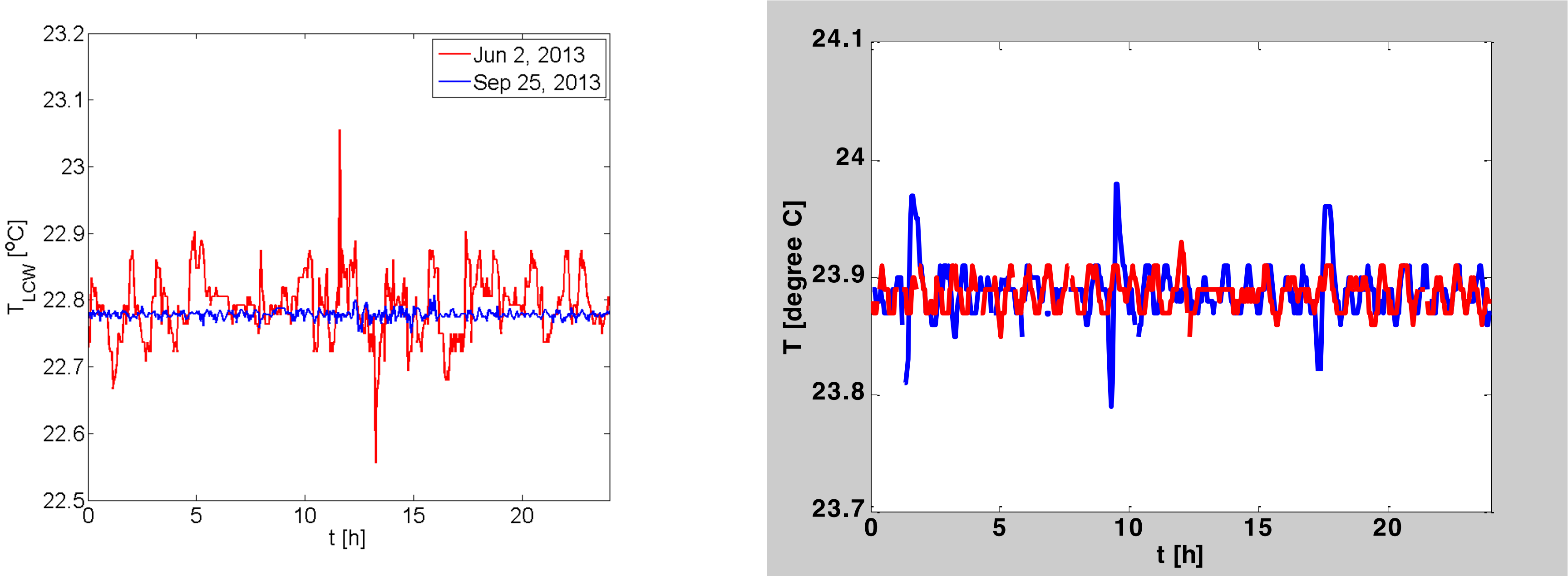

Soleil



NSLS-II: courtesy S. Sharma

- Some early 3^{rd} 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
- Latest designs (Soleil, NSLS-II) avoid this caveat – smaller vibration transmission to beam

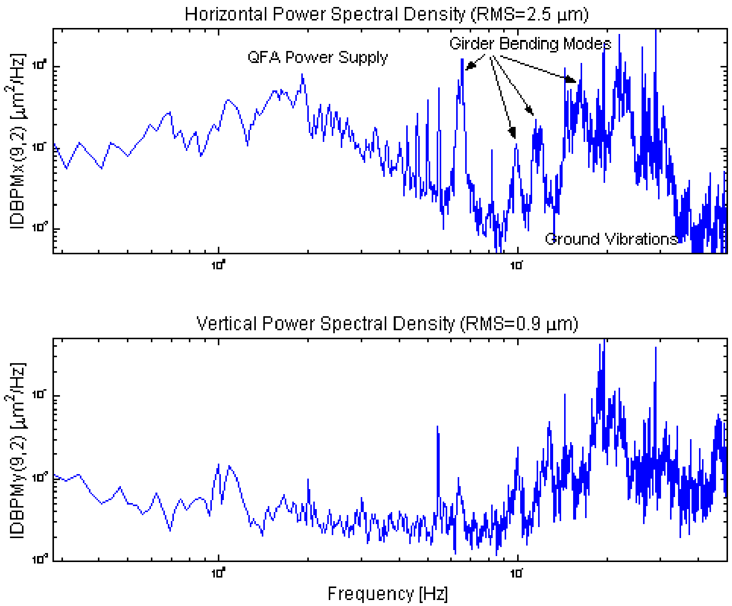
Air/water temperature stability



Left: ALS water temperature, Right: Tunnel air temperature

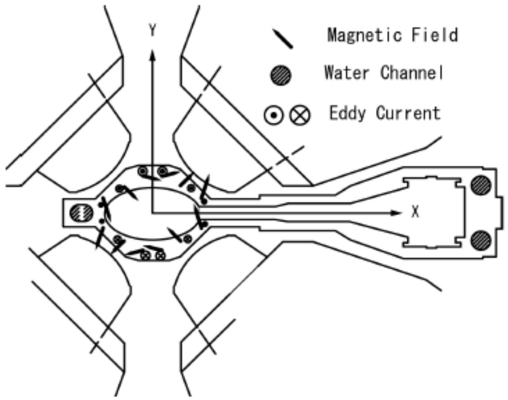
- Stable environmental conditions are extremely important
- State of the art is water and tunnel air temperature stability on the order of 0.1 degree C
- Stable power supply controllers, invar rods for BPM mounts, … also help, but it is always best to also keep the conditions constant

Identify and Fix Problems



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.

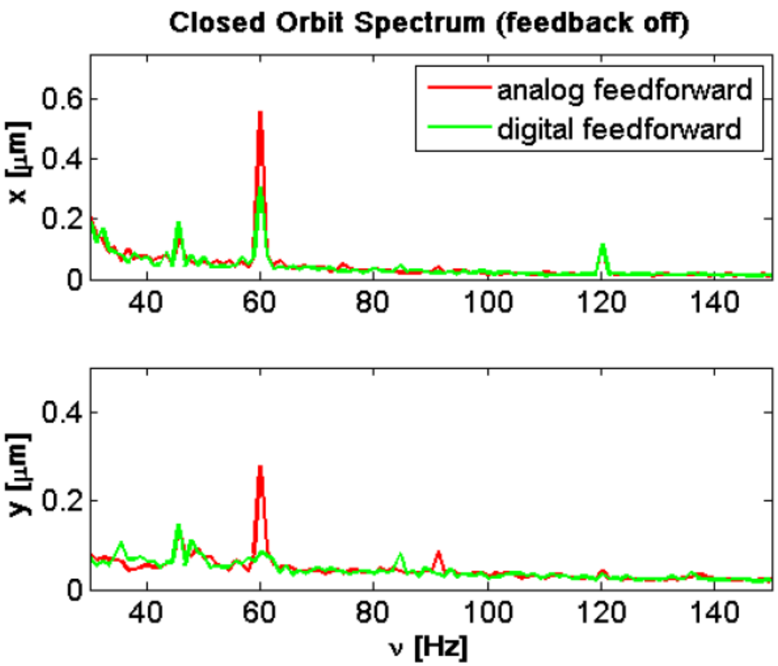
S. Matsui, et al. Jpn. J. Appl. Phys. Vol. 42 (2003) pp.L338

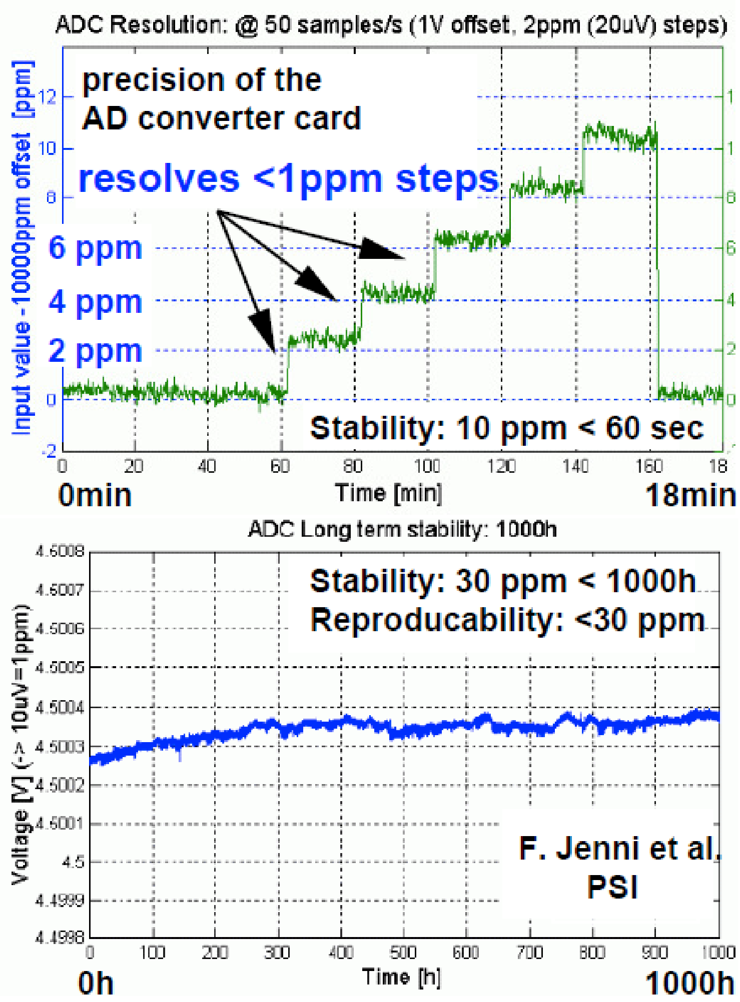
Spring-8: water vibration

- 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 increased over the years


Closed Orbit Spectrum (feedback off)


ADC Resolution: @ 50 samples/s (1V offset, 2ppm (20uV) steps)

precision of the AD converter card

resolves <1ppm steps

Stability: 10 ppm < 60 sec

ADC Long term stability: 1000h

Stability: 30 ppm < 1000h
Reproducability: <30 ppm

F. Jenni et al.
PSI

Closed orbit errors

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

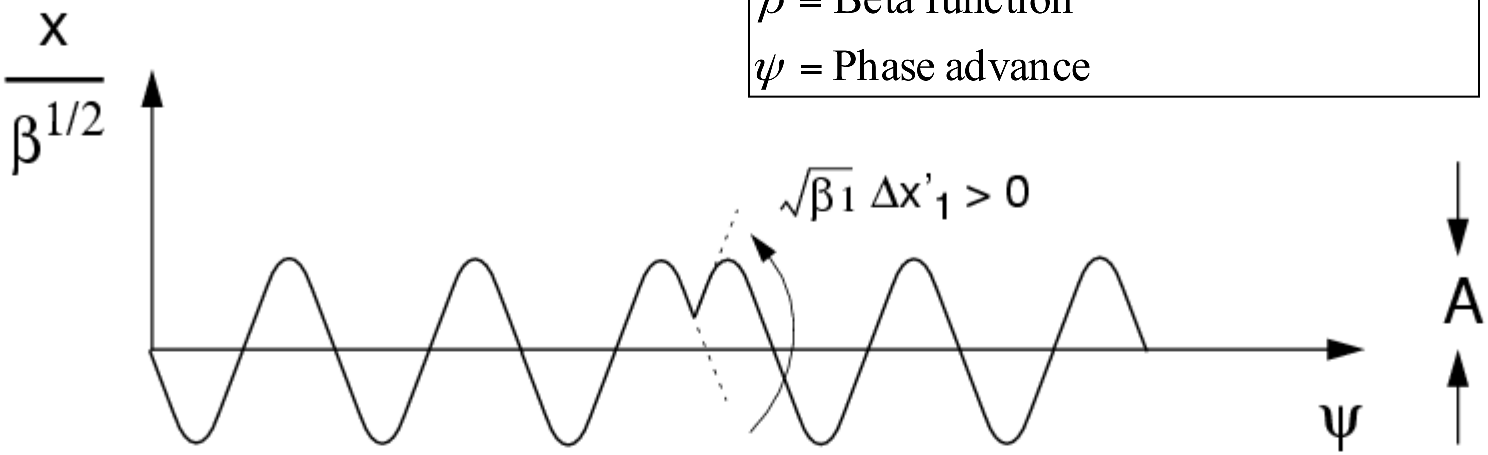
$$x(s) = \Delta x' \frac{\sqrt{\beta(s)\beta_0}}{2\sin\pi\nu}\cos\left(\left|\psi(s)-\psi_0\right|-\pi\nu\right)$$

Δx = Transverse position

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

β = Beta function

ψ = Phase advance

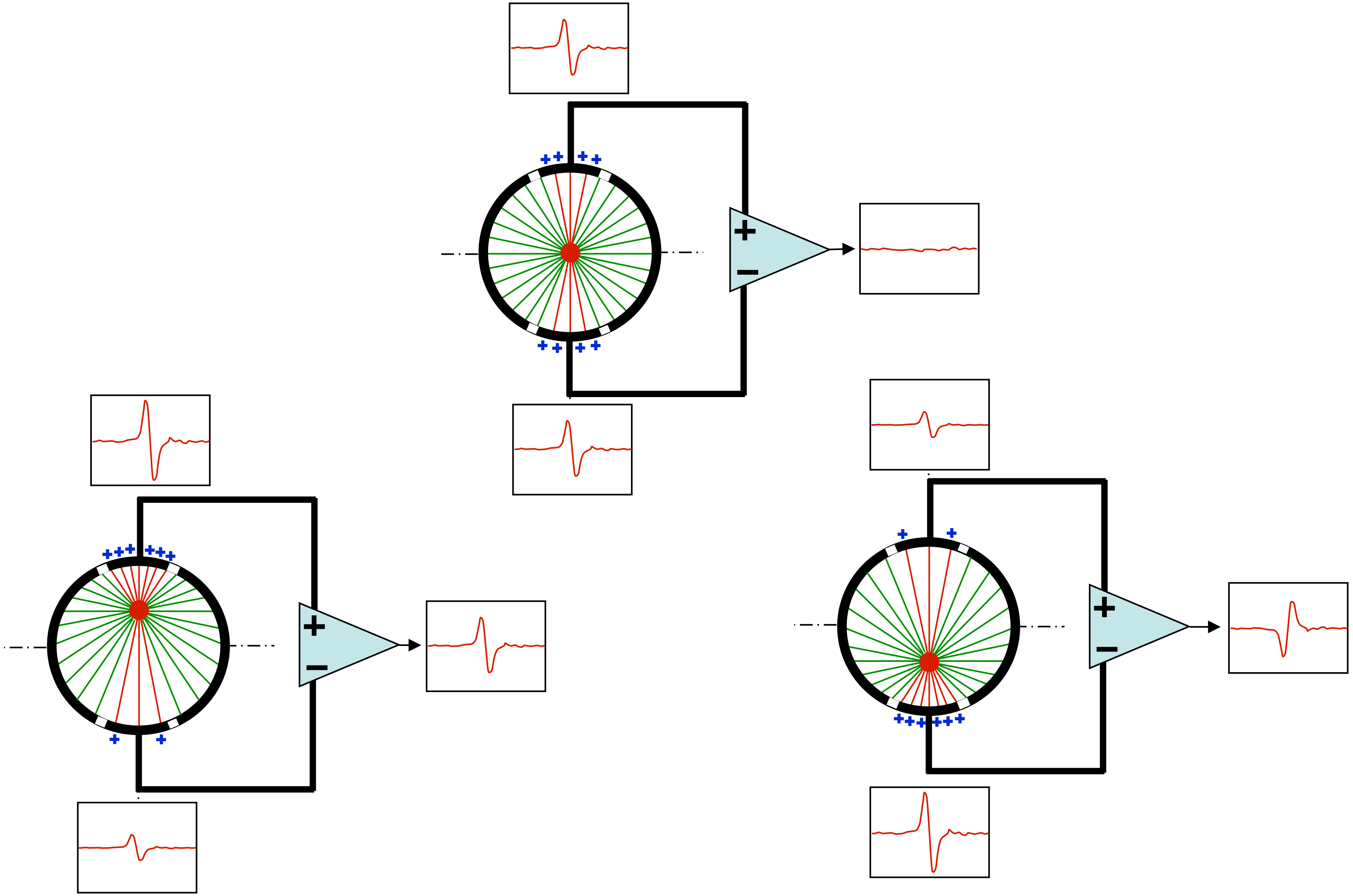


The matrix containing the change in position at every BPM to a kick from every corrector magnet is called orbit response matrix (used in orbit correction). For an uncoupled machine it can be calculated (linear approximation) using above formula.

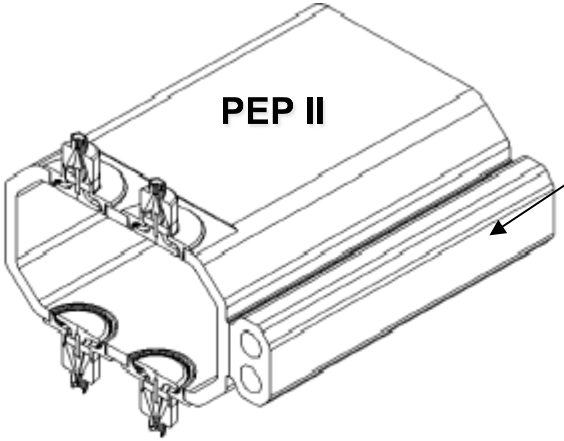
Orbit Measurement Methods

- Main categories are:
  - Destructive/non destructive measurements
  - RF/synchrotron radiation/scattering/absorbing based detection
  - Pure position/profile measurements
  - Fast/Slow (GHz-mHz)
- Linear accelerators and beamlines often use very different methods from storage rings
- Lepton accelerators often use methods different from hadron accelerators

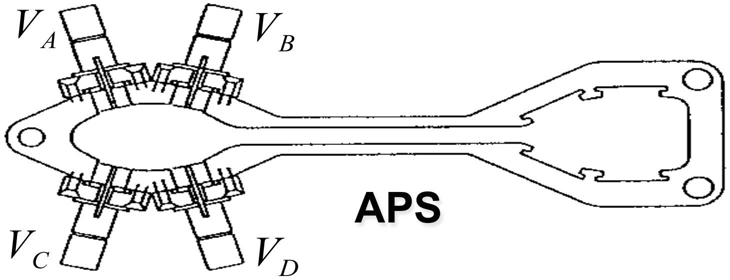
Electromagnetic Beam Position Monitors



Capacitive Pickups

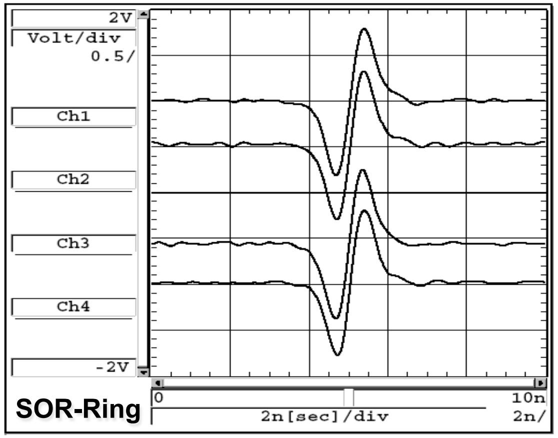


- **Typical geometry used in the presence of synchrotron radiation.**



$$\Delta x = K\frac{(V_A+V_C)-(V_B+V_D)}{V_A+V_B+V_C+V_D}, \qquad \Delta y = K\frac{(V_A+V_B)-(V_C+V_D)}{V_A+V_B+V_C+V_D}$$

- **Capacitive type (derivative response), low coupling impedance, relatively low sensitivity, best for storage rings.**



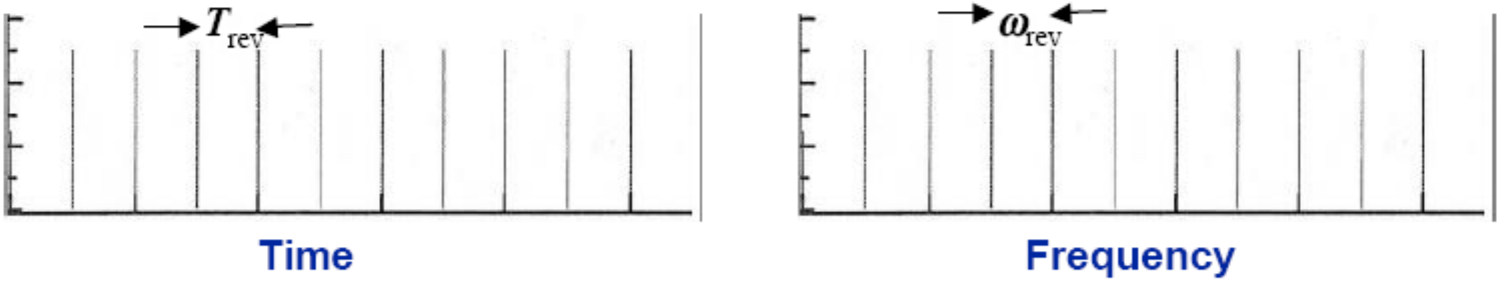
Bunch spectrum

Using a spectrum analyzer with a BPM can yield a wealth of information on beam optics and stability. A single bunch with charge q in a storage ring with a revolution time T_{rev} gives the following signal on an oscilloscope

$$I(t)=\sum_{n=-\infty}^{\infty} q\,\delta(t-nT_{\text{rev}}),$$

where I'm assuming a zero-length bunch. A spectrum analyzer would see the Fourier transform of this,

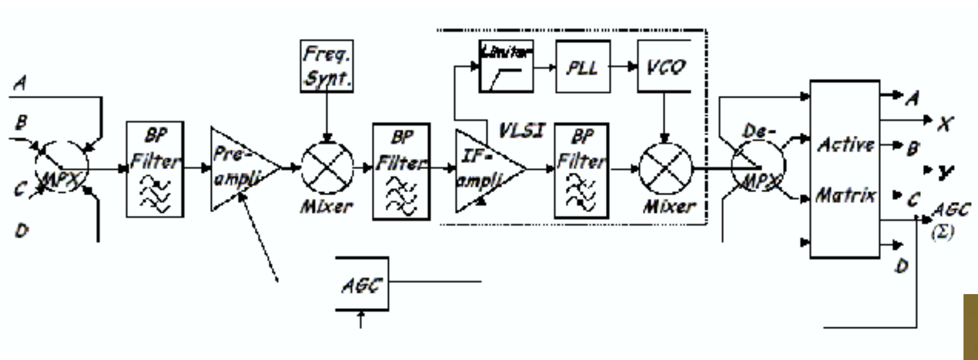
$$I(\omega)=\sum_{n=-\infty}^{\infty} q\,\omega_{\text{rev}}\,\delta(\omega-n\omega_{\text{rev}})$$

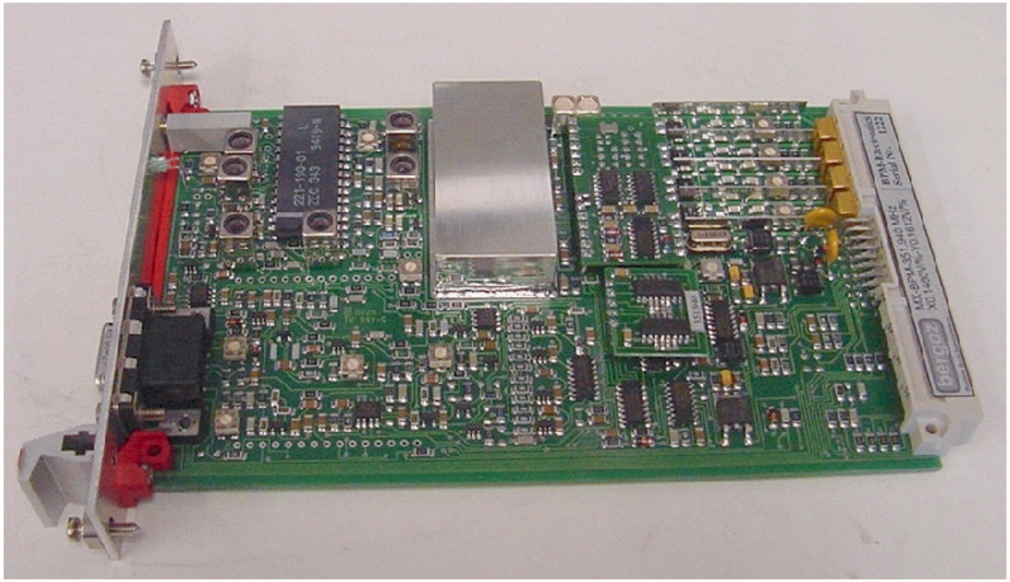


Signal Processing Electronics

Bittner / Biscardi / Galayda / Hinkson/ Unser / Bergoz Narrowband Receiver

Normalization accomplished via multiplexing plus automatic gain control (AGC)*:





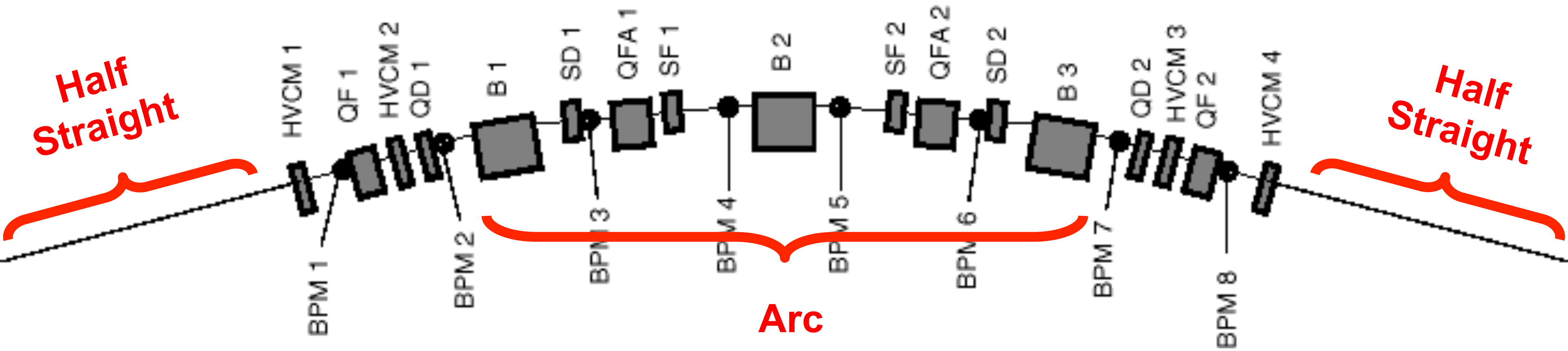
- More recently: Digital BPMs only frontend is analog, followed by ADCs, FPGAs (sometimes DSP) and digital signal processing

Courtesy Kurt Vetter

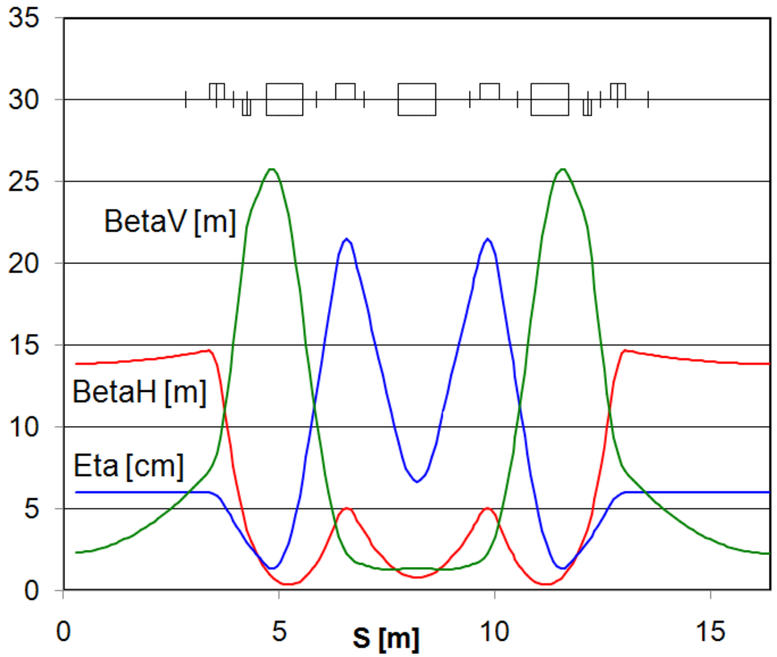
Aerial view of the Advanced Light Source

jc/ALSaerial/11-96

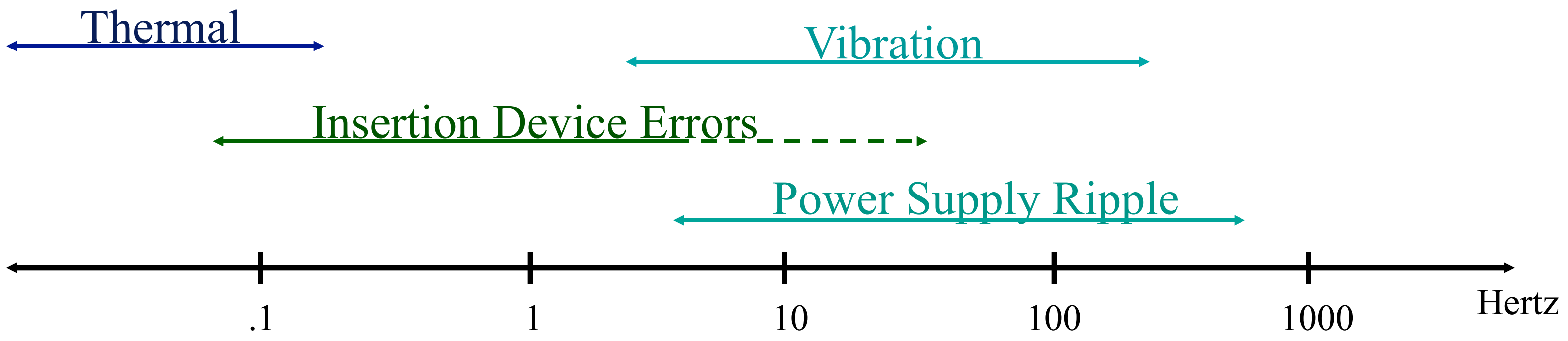
ALS – orbit measurement + correction



- 12 nearly identical arcs – TBA; aluminum vacuum chamber
- 122 beam position monitors in each plane (about 4 of stable type per arc)
- 8 horizontal, 6 vertical corrector magnets per arc (94/70 total)
- 24 individual skew quadrupoles
- beam based alignment capability in all quadrupoles (either individual power
- supplies or shunts)
- 22 corrector magnets in each plane on especially thin vacuum chamber pieces



Causes for Orbit Distortions



Thermal

Vibration

Insertion Device Errors

Power Supply Ripple

.1

1

10

100

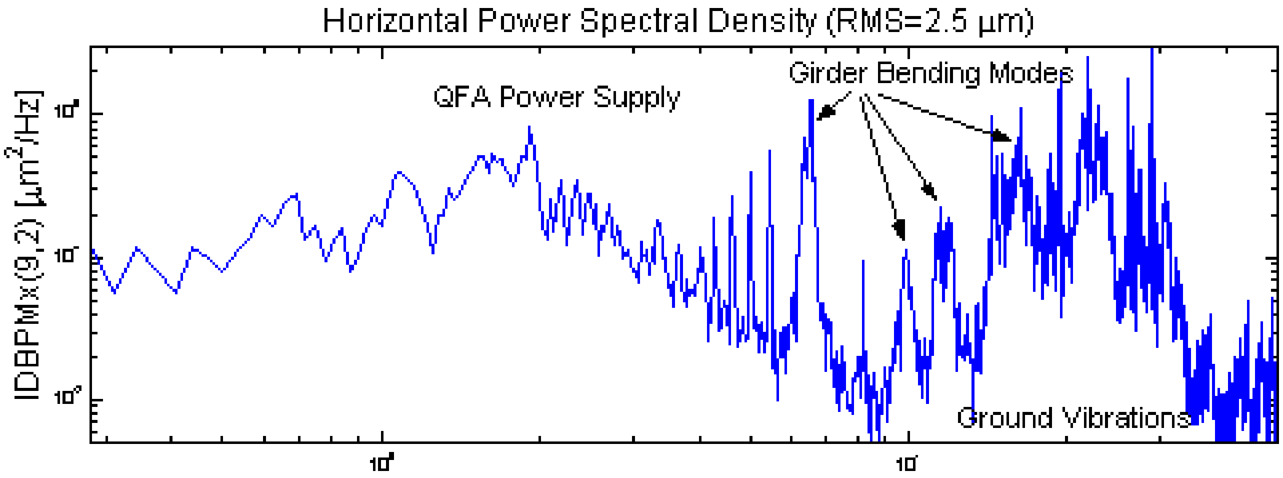
1000

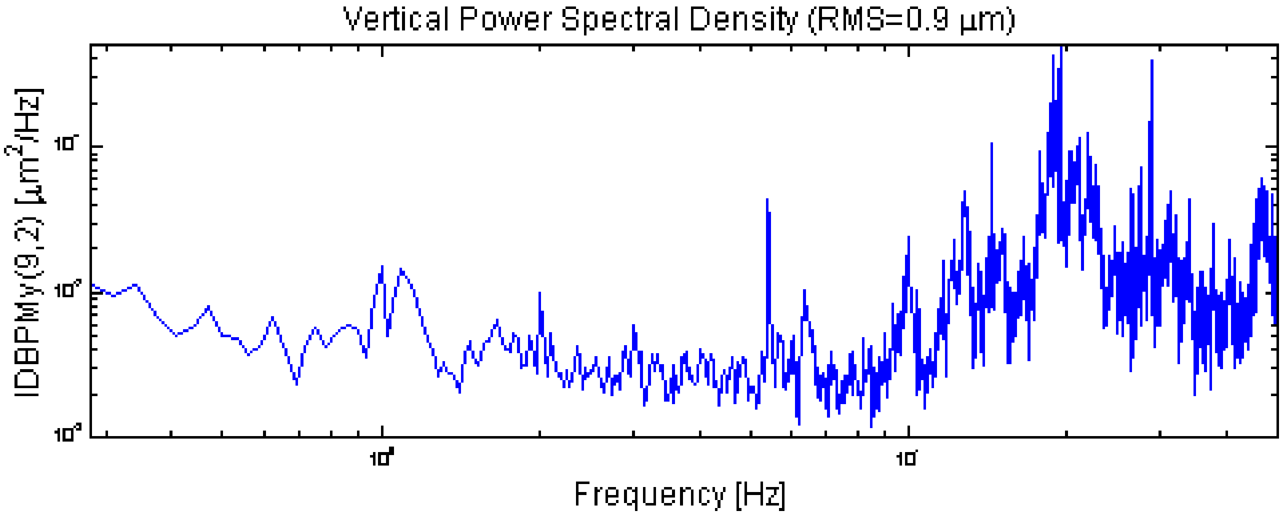
Hertz

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

Beam Stability in straight sections w/o Orbit Correction, w/o Orbit Feedback, but w/ Insertion Device Feed-Forward

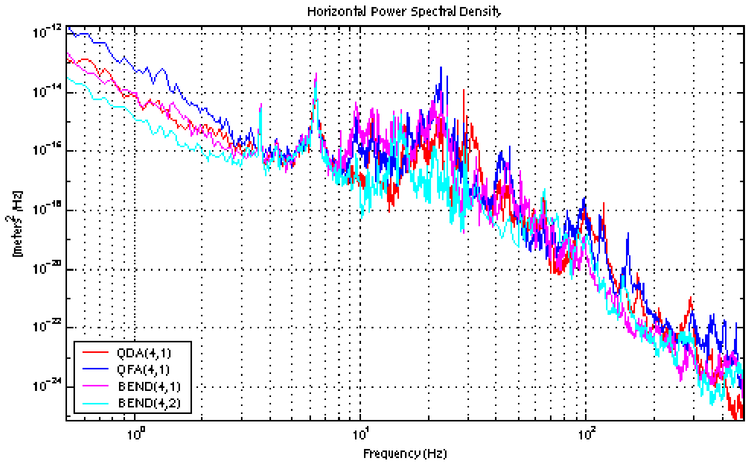
ALS Example: Orbit Power Spectral Density

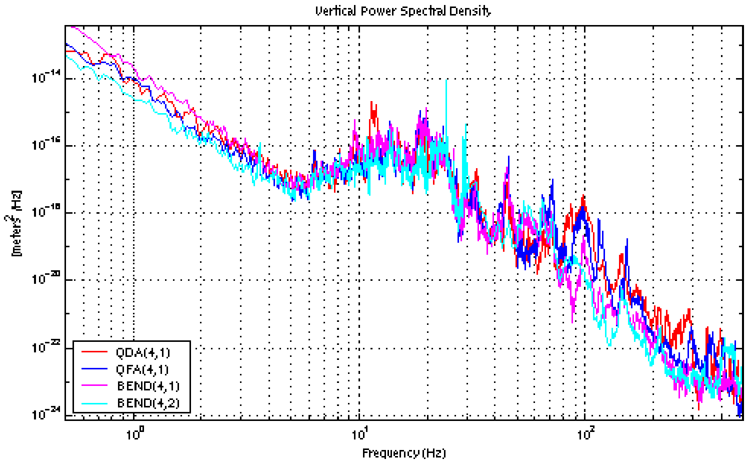


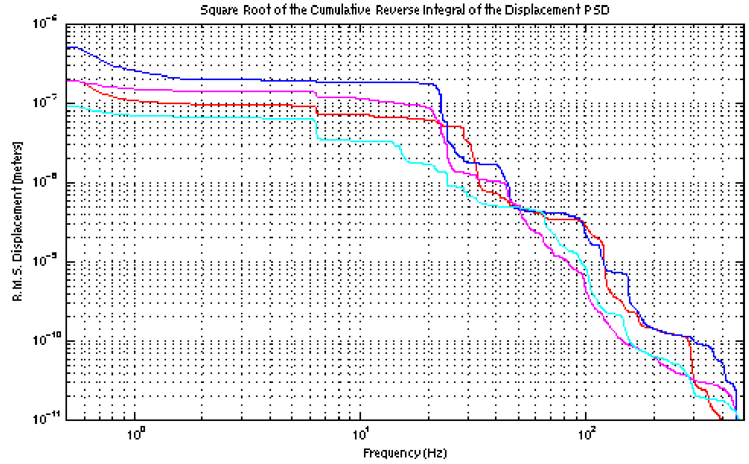


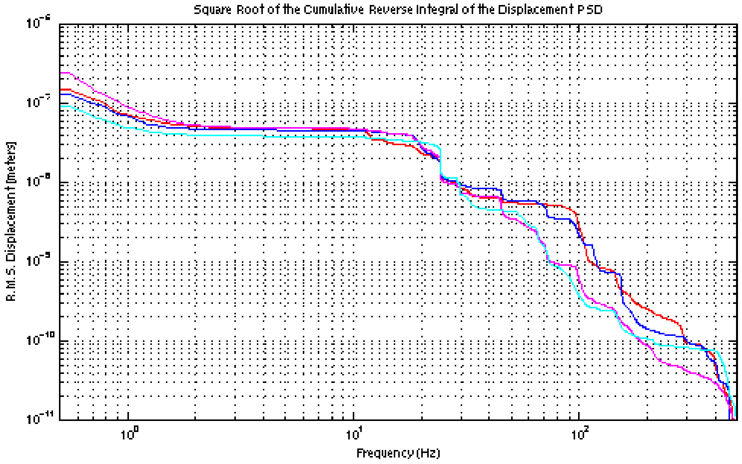
Data taken on 12-12-1999, during a 1.9 GeV user run at 278 mAmps

Magnet Vibration PSD









5-5-2000

5-5-2000

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:

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

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 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)

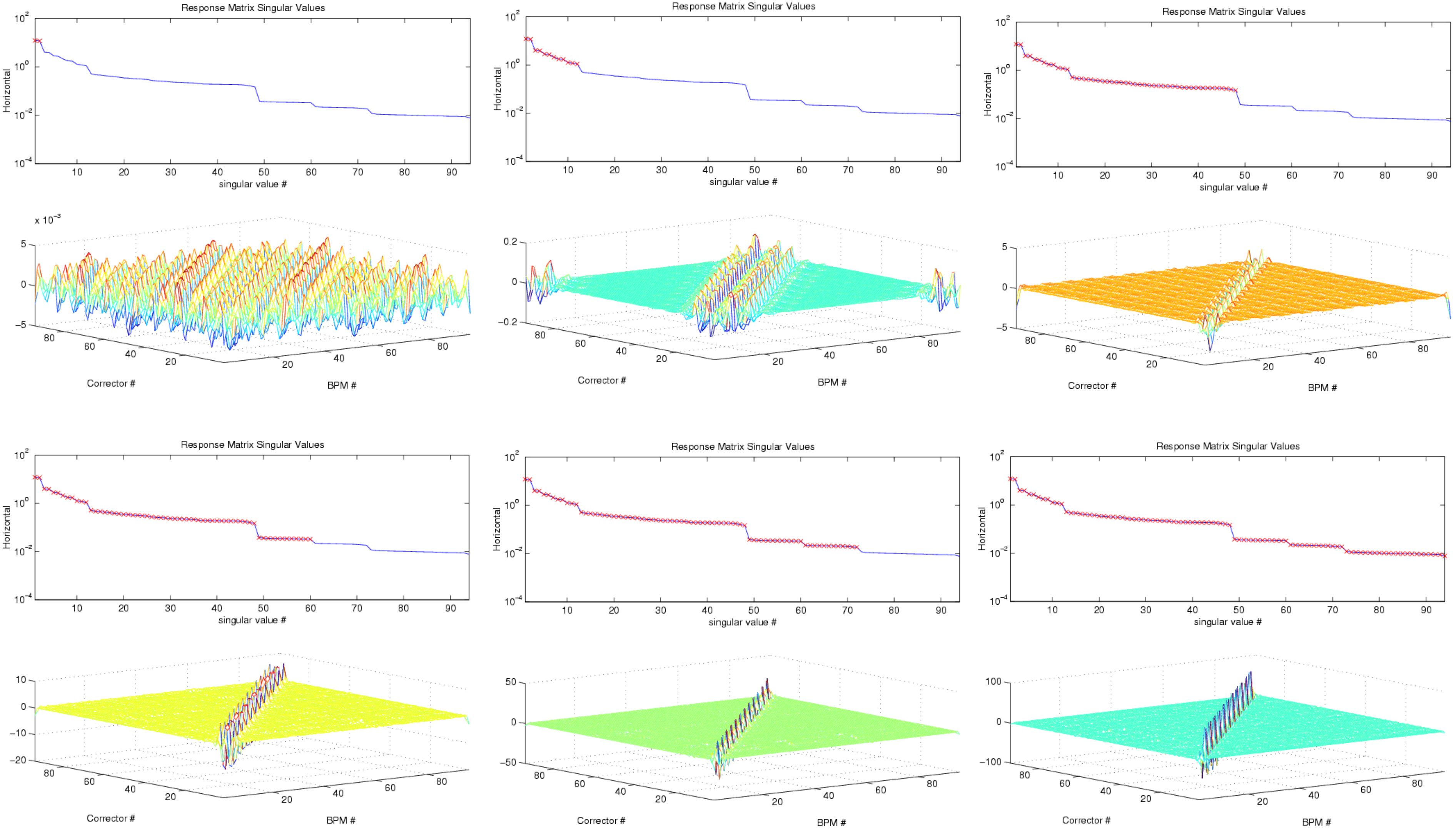
$$M = U \cdot \Sigma \cdot V^T = \sum_i \vec{u}_i \sigma_i \vec{v}_i^T$$

- 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

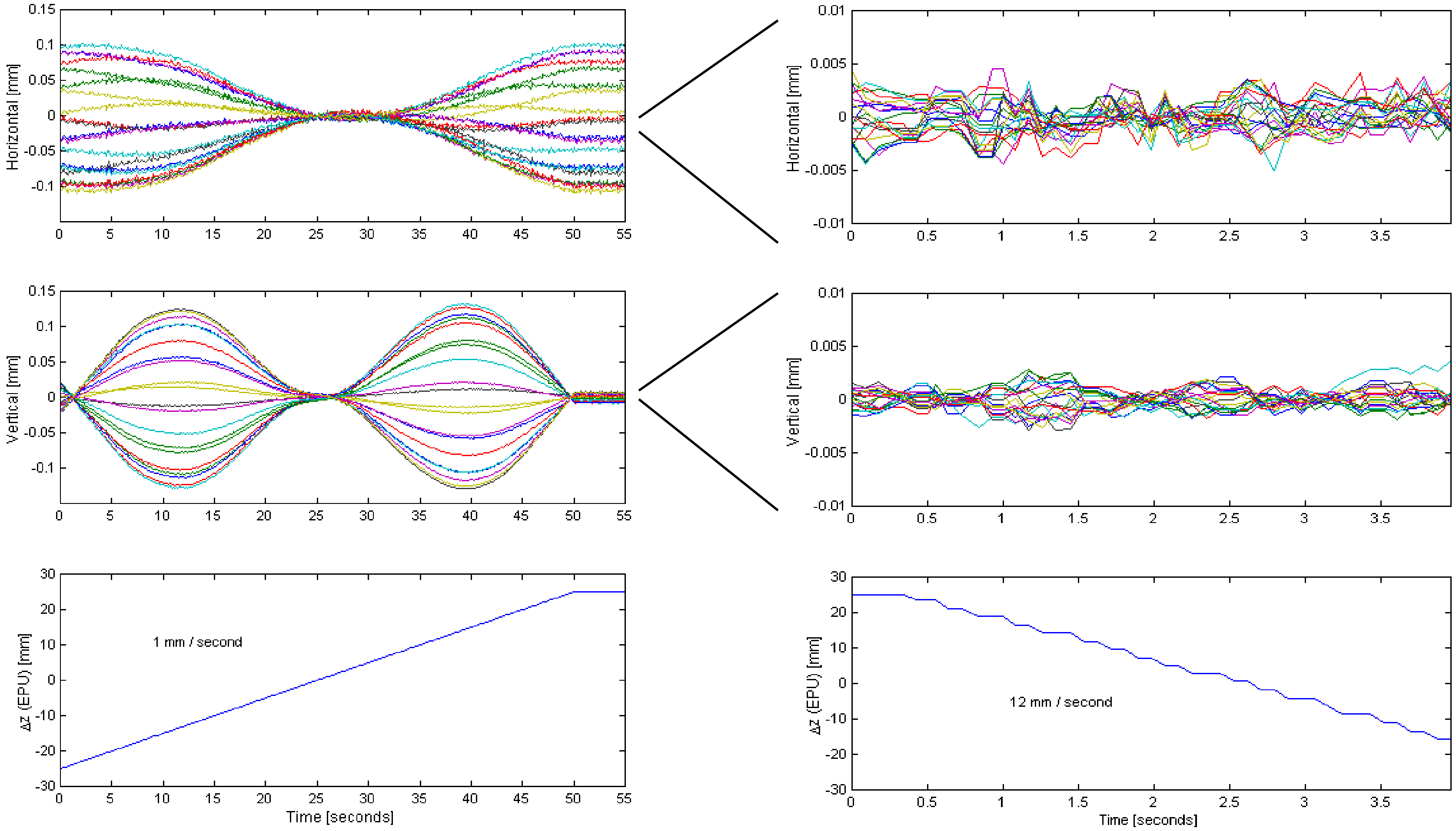
- Least square or direct matrix inversion
  - Disadvantages:
    - Have to trust every BPM reading
    - BPM and corrector locations very critical (to avoid unobservable bumps)
  - Advantages:
    - Minimizes OBSERVABLE orbit error
    - Works well for distributed/numerous errors
    - localizes the 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

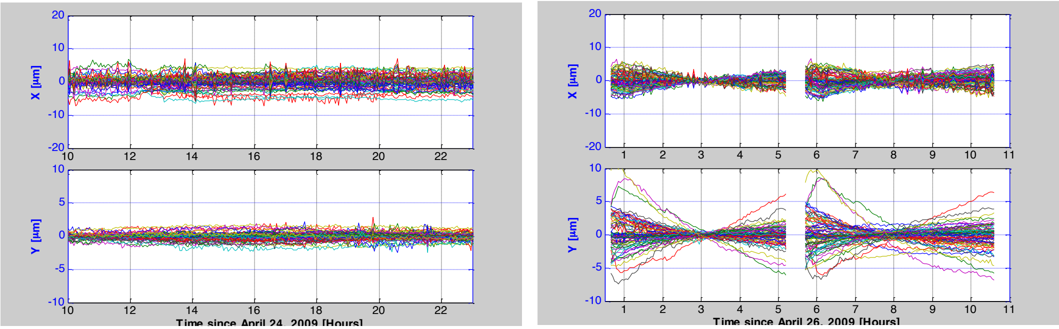
Orbit Error without Feed Forward Correction

200 Hertz Feed Forward Correction

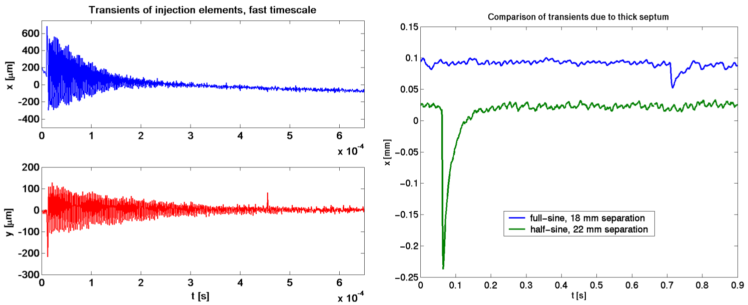


Orbit Feedback

Long Term Stability (with Feedback)



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

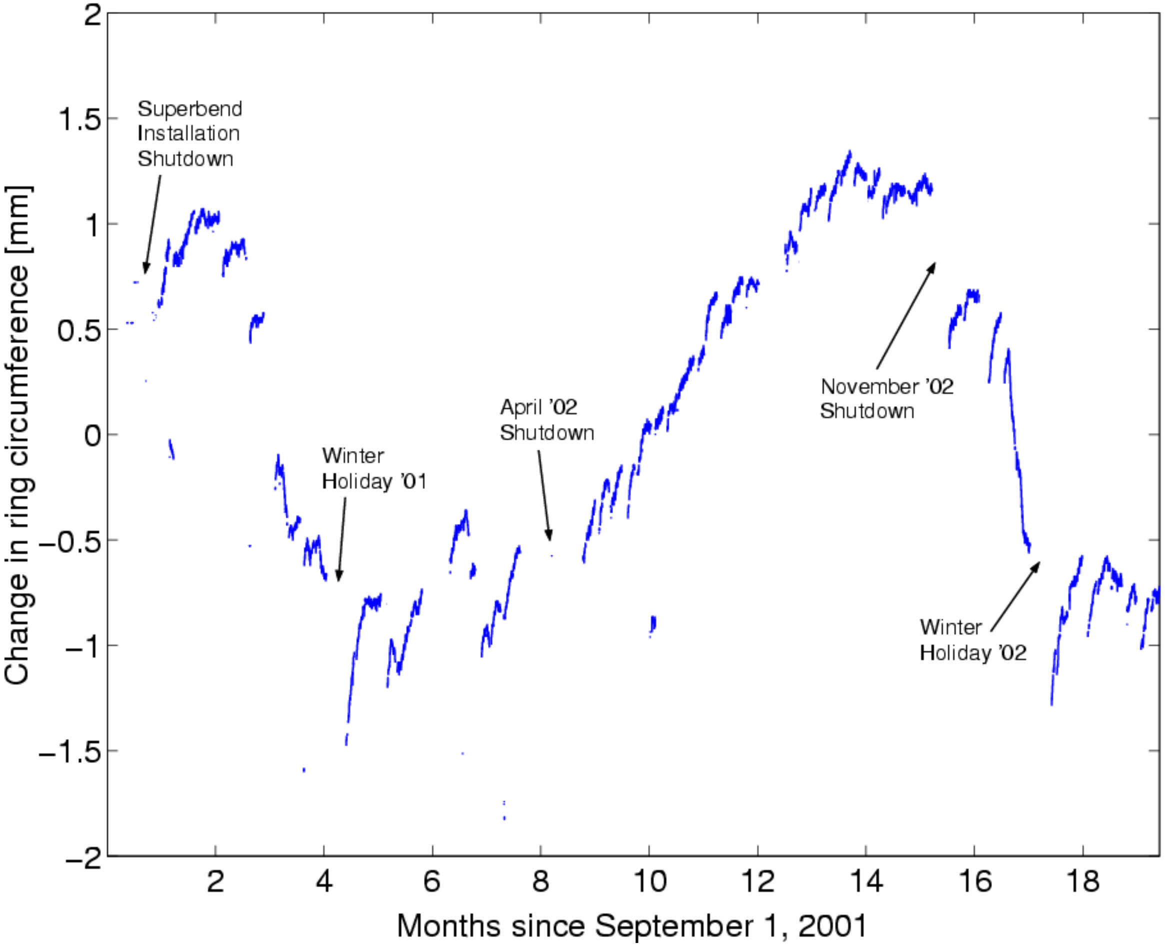


ALS: injection transients (fast+slow)

- 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

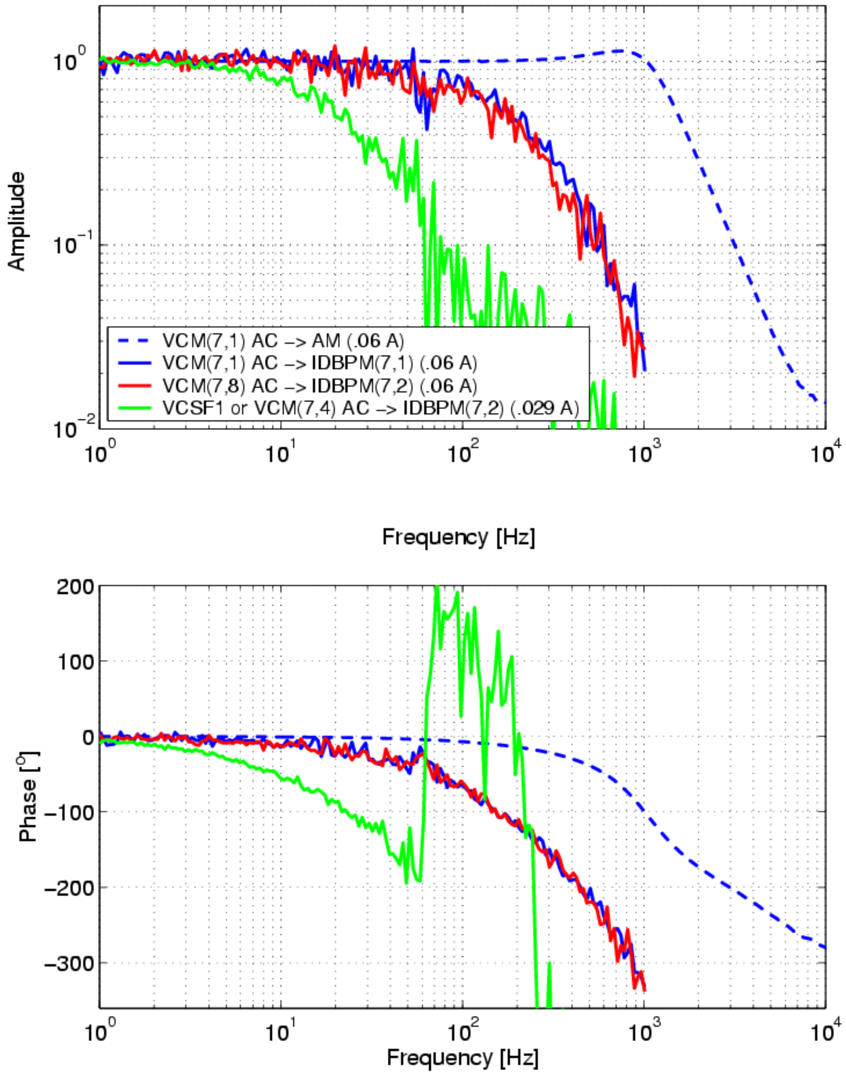
RF Frequency Feedback

- 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

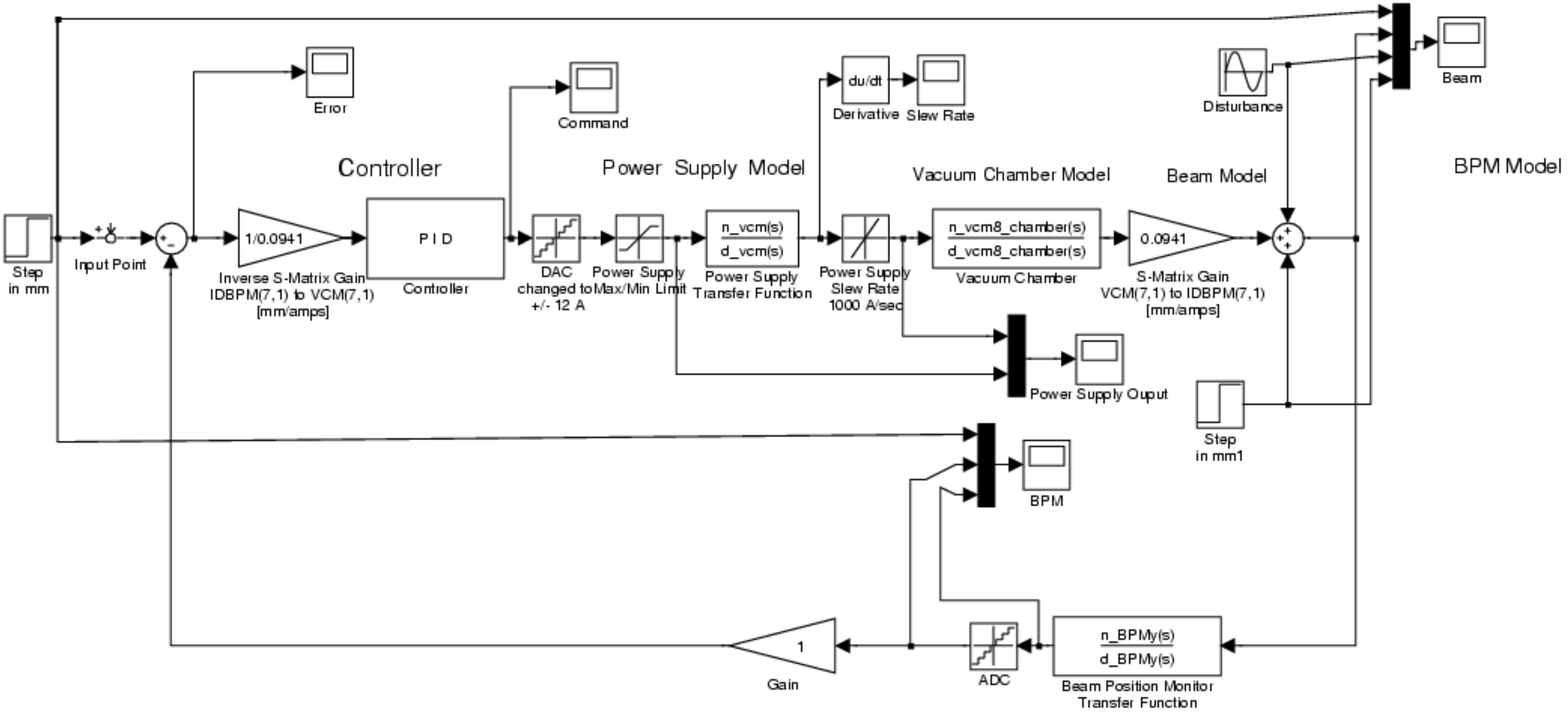


Fast Orbit Feedback

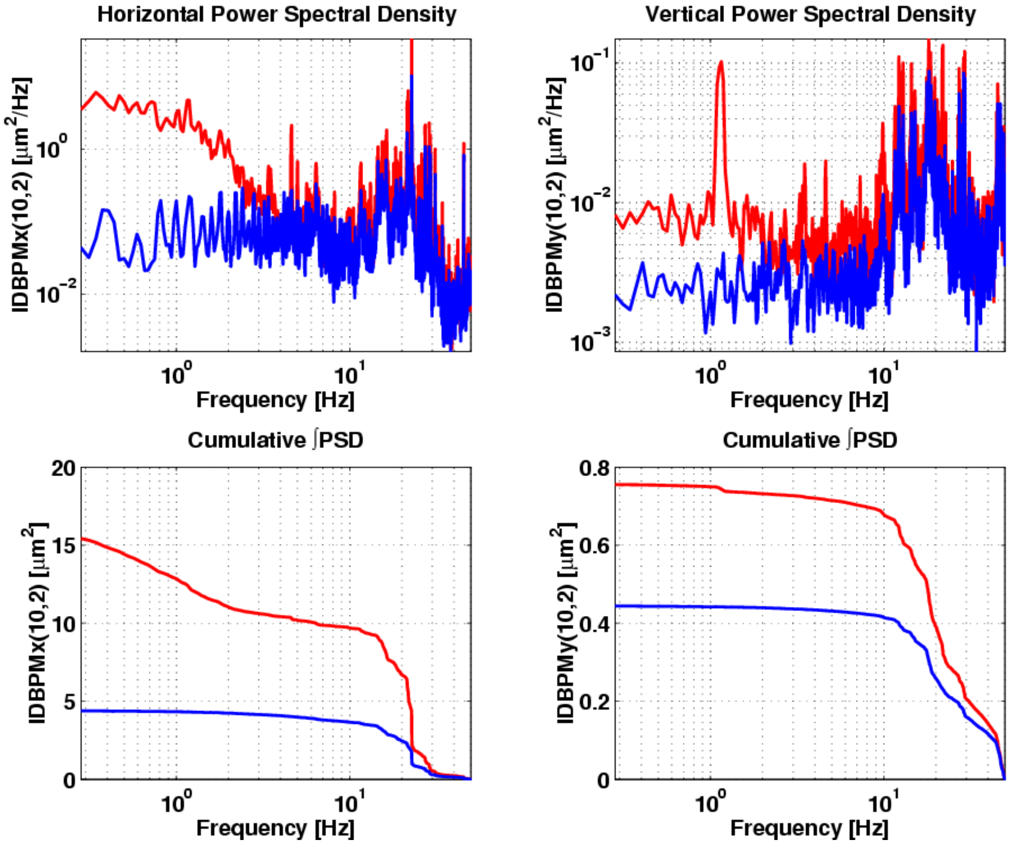
- Time response of all elements becomes important!
- Controller type used is often PID
- System often are distributed (ALS: 12 crates, about 60 BPMs, 22 correctors each plane)



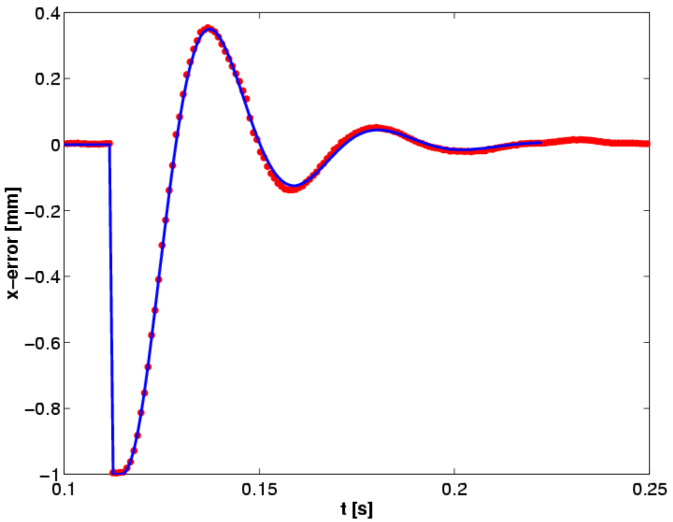
Simulink model of one channel of system



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.

Summary (Orbit Stability)

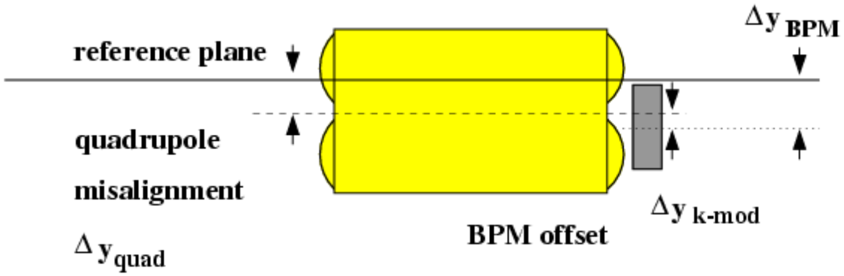
- Stability (orbit, beamsize) is one of the most important performance criteria at accelerators
- Many different methods for position and size measurement exist, tailored to specific needs. Best resolutions are nm scale.
- Multiple noise sources perturb the beam.
  - Passive noise reduction methods helps.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

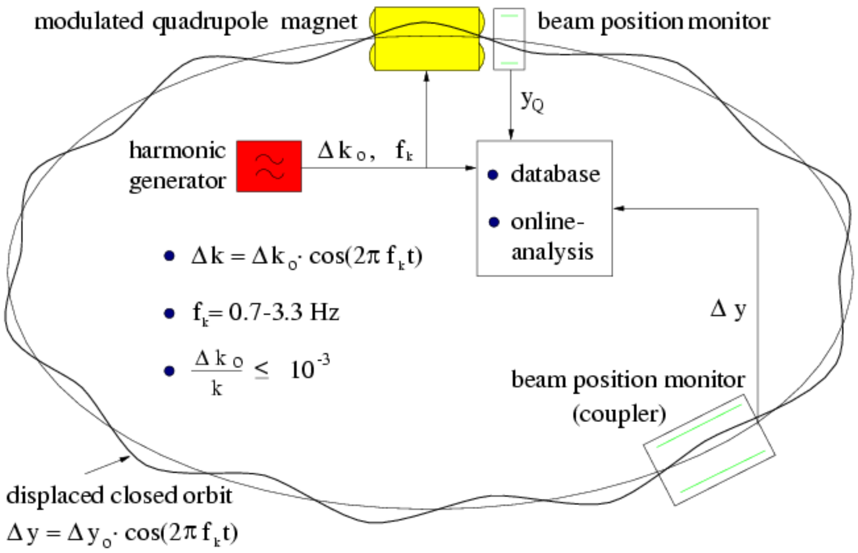
Beam Based Alignment

- 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

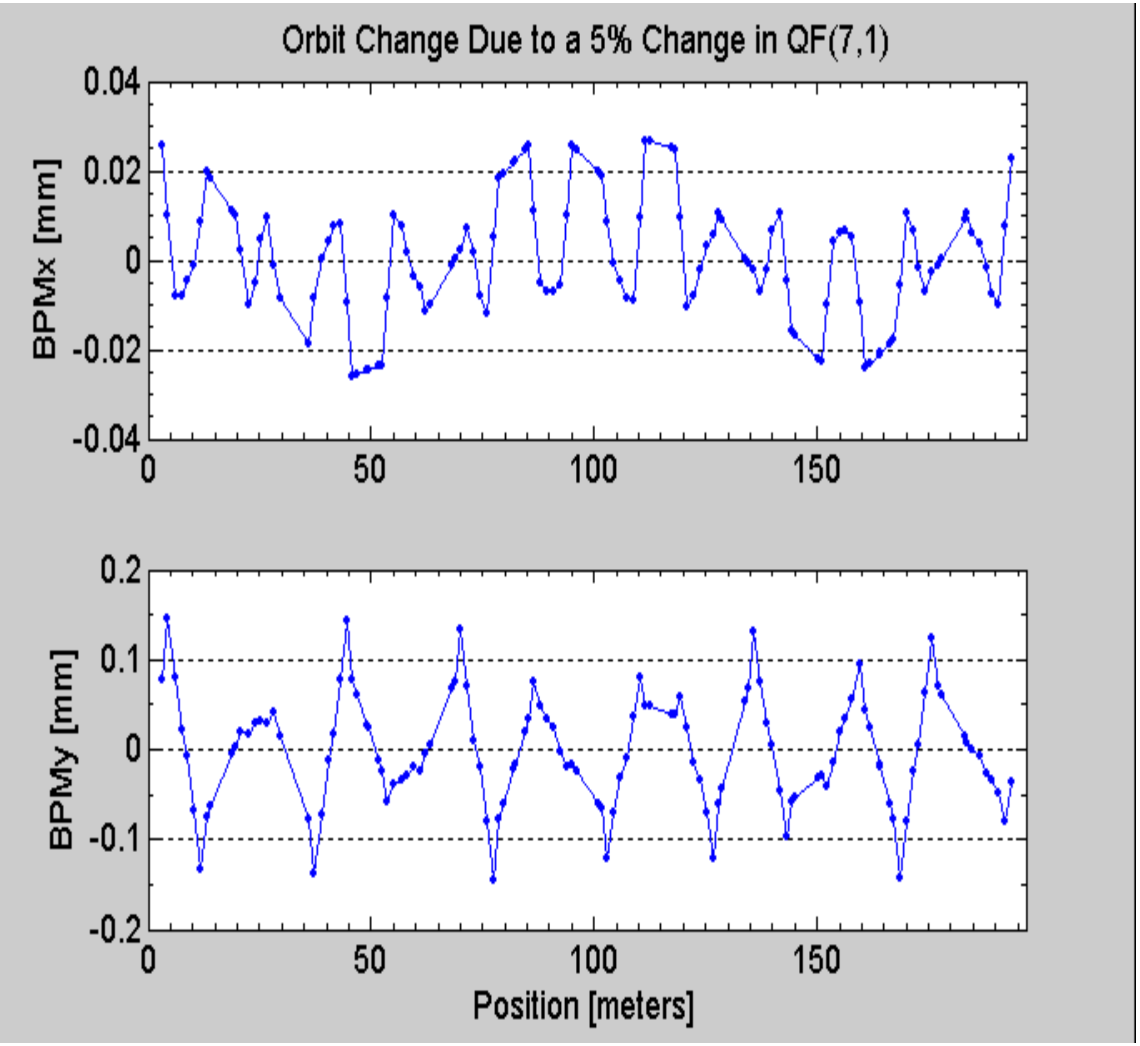
Beam Based Alignment: Method 1

- 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

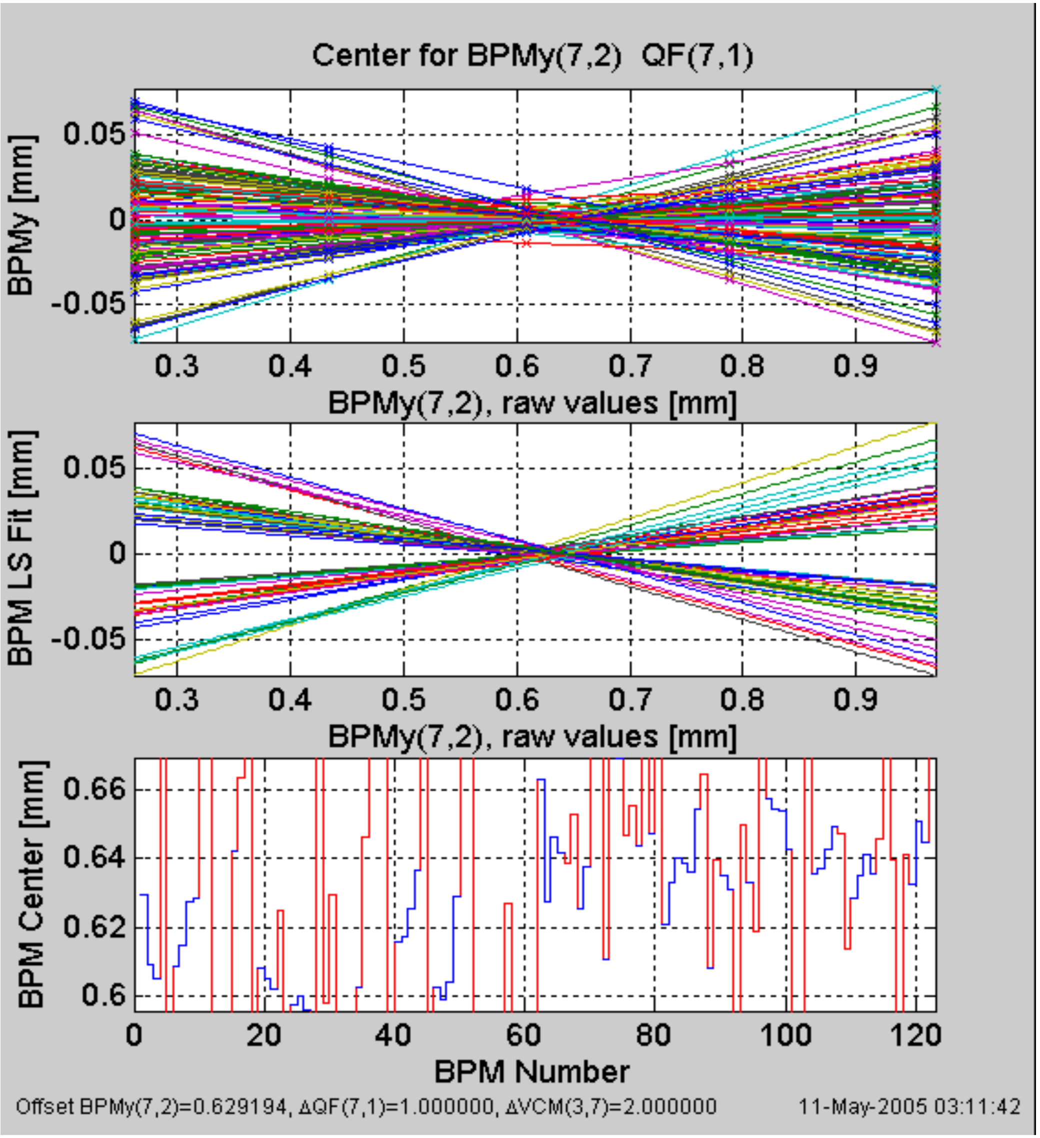
Δx = Transverse position

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

β = Beta function

ψ = Phase advance

Method 3: MML Beam Based Alignment



- The offset of all quadrupoles at ALS (and many other accelerators using the MML) can be found with beam based alignment.
- The algorithm is fully automated.
- BPM offset at ALS are fairly significant (rms of 300-500 microns) but very stable.
- Offsets are typically measured annually or after hardware changes or realignment.
- Main problem were systematic errors due to C-shaped magnets.

Summary

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

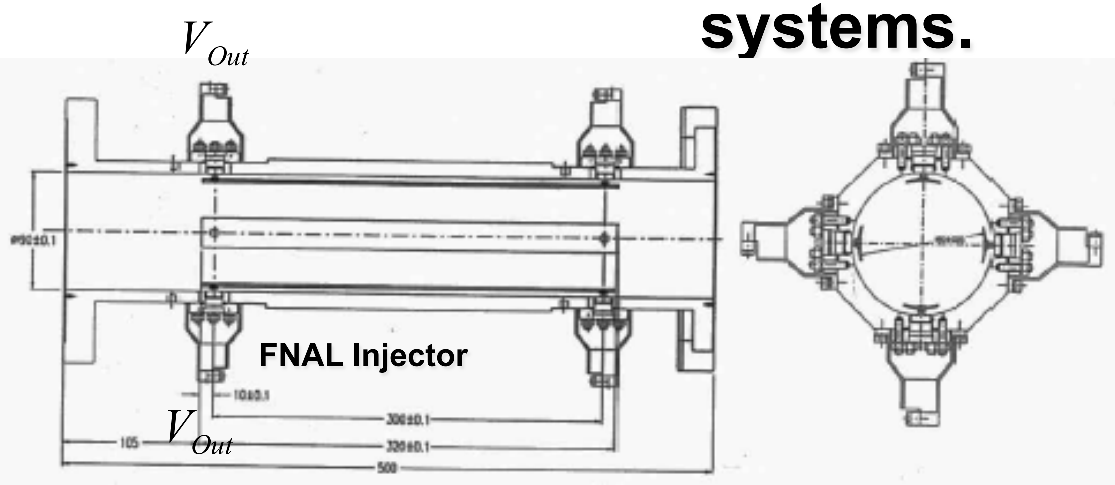
Further Reading (incomplete list):

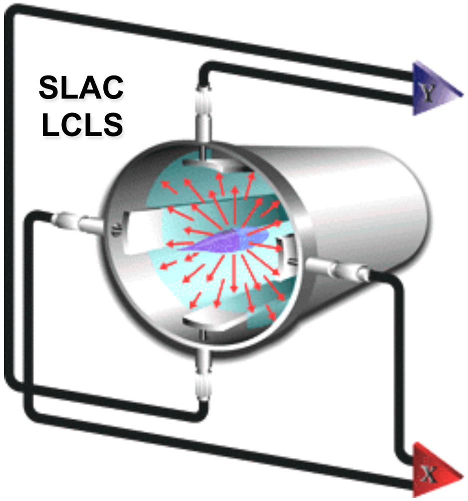
- B. Hettel, Rev. Sci. Instr. 73, 3, 1396
- W.H. Press et al., Numerical Recipes, Cambridge U. Press (1988) p. 52
- Presentations at 2nd International Workshop on Beam Orbit Stabilization (2002): http://www.spring8.or.jp/ENGLISH/conference/iwbs2002/abstract.htm
- Presentations at the 3rd International 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

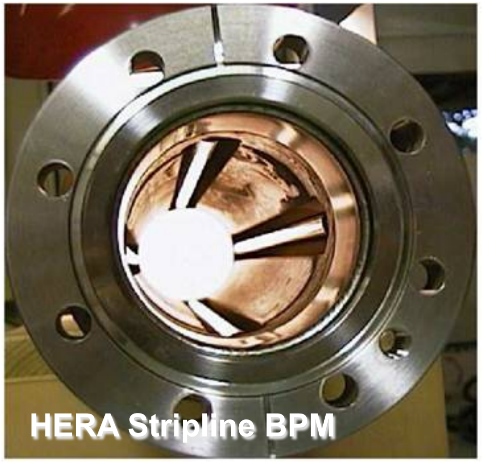
Backup Slides

Stripline BPMs

- **Stripline structures are also widely used as the “kicker” in transverse and longitudinal feedback systems.**







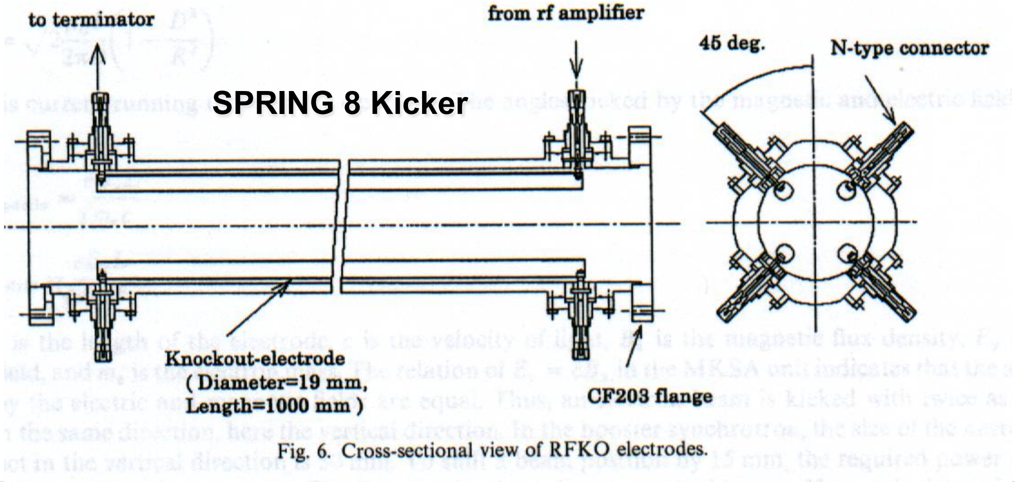
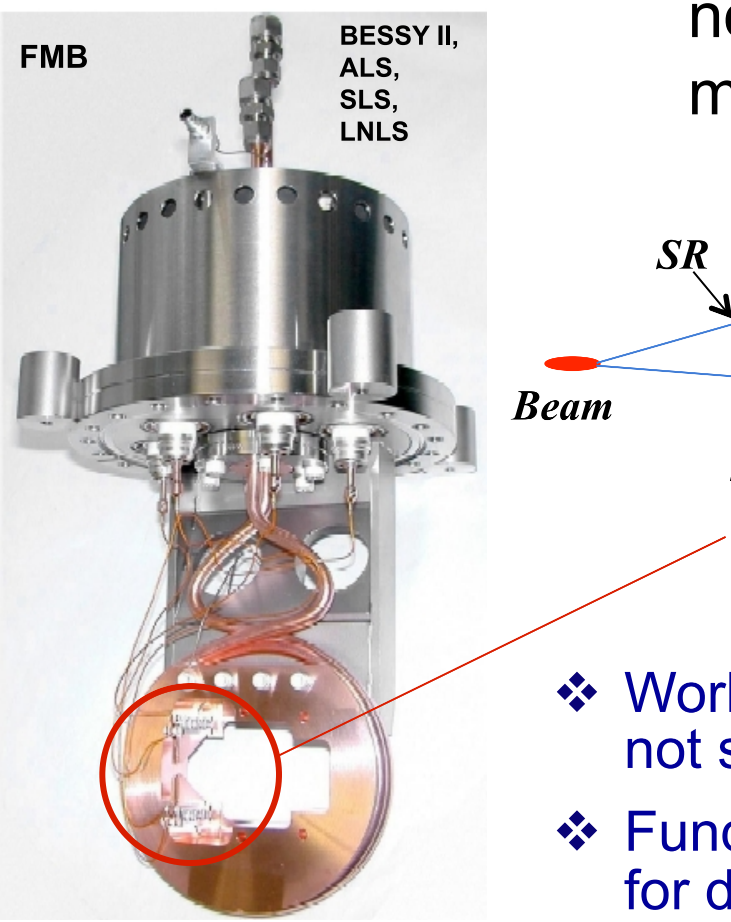


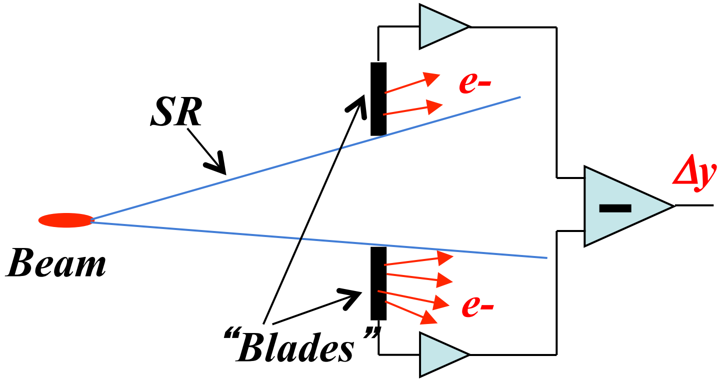
Fig. 6. Cross-sectional view of RFKO electrodes.

Other BPMs (using Photons)

- Synchrotron radiation is abundant in many accelerators – very useful for low noise, non desctructive position measurement

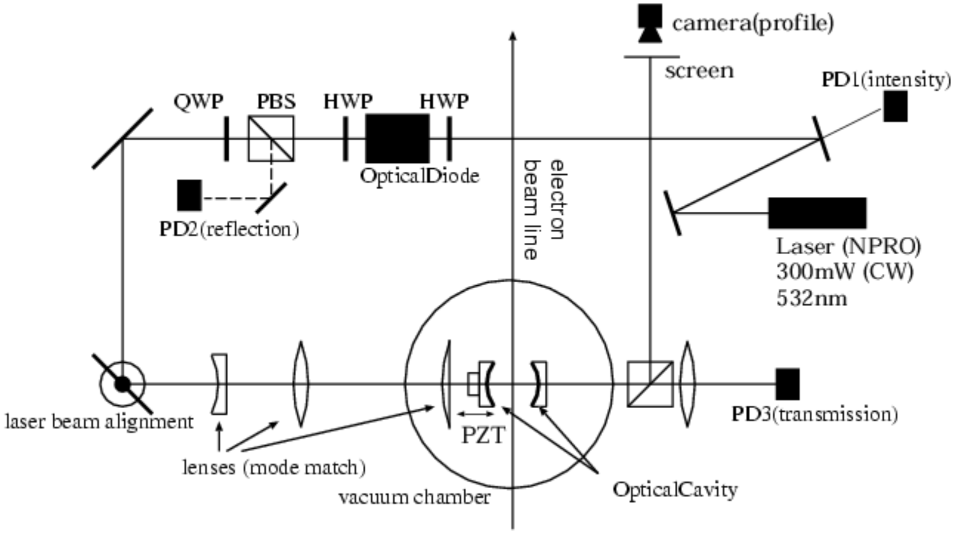


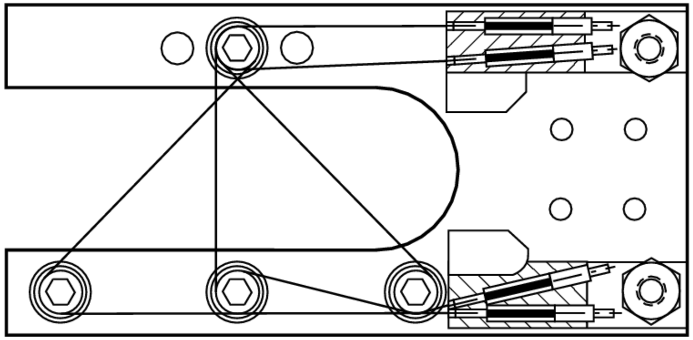
- ❖ Work very well for dipoles in the vertical plane – not so simple for insertion devices
- ❖ Fundamentally limited in the horizontal plane for dipoles

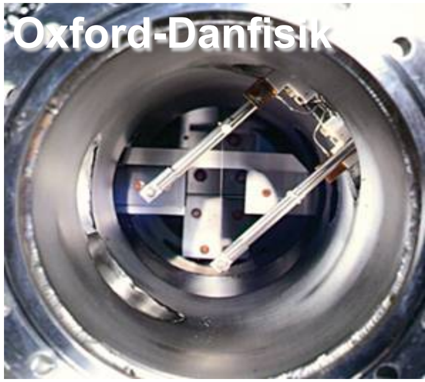


(Flying) Wire Scanners/Laser Wires/Screens

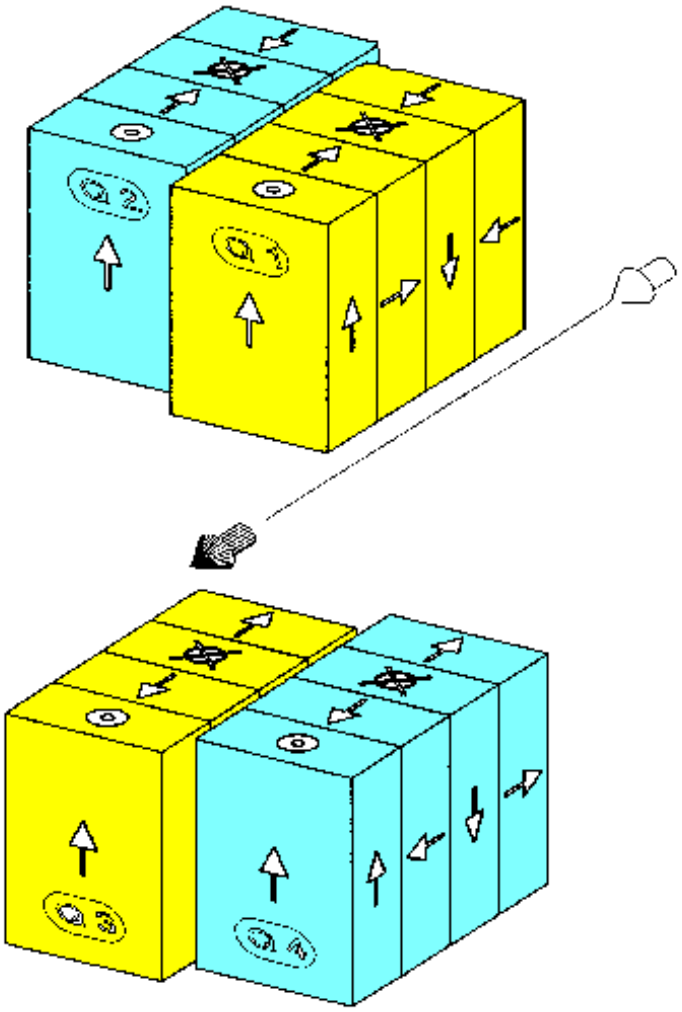
- Wire Scanners (SLAC/SLC) and screens are mostly used in beamlines and Linacs. Can achieve resonable high resolution but are usually destructive. Both can measure position and profile.
- Flying wires are less destructive and laser wires (KEK/ATF) are minimally destructive and provide excellent resolution (however they are slow)
- Some laser or interferometer based schemes achieve nm type resolutions.







Elliptically Polarizing Undulator (EPU)



The EPU is different than other insertion devices

❖The jaws can move in two directions

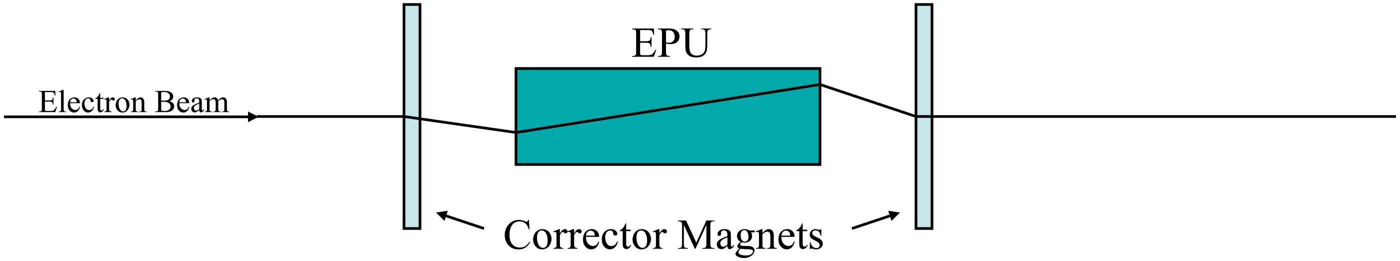
(vertically and longitudinally)

❖The motion in the longitudinal direction is fast

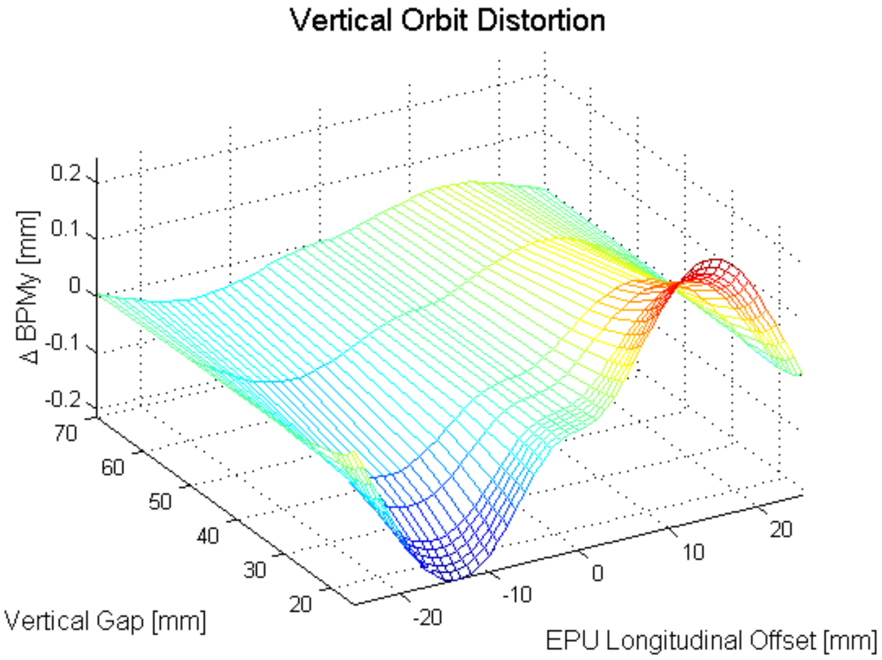
(At the ALS, up to 17 mm/second)

This makes orbit compensation more difficult than other insertion devices

Feed-forward example: EPU



Mechanically, an ALS EPU can move from left to right circular polarization mode in ~1 sec.


Vertical Orbit Distortion

Without compensation the EPU would distort the electron beam orbit by ±200 μm vertically and ±100 μm horizontally. Using corrector magnets on either side of the EPU, 2-dimensional feed forward correction tables are used to reduce the orbit distortion to the 2-3 μm level. Update rate of feed-forward is 200 Hz.

Feed-forward tables based on beam based measurements are much more accurate than ones based on magnetic bench measurements.

For even faster switching devices (CPW, …) eddy current effects make beam based optimization even more important.