Closed Orbits & Correction Methods

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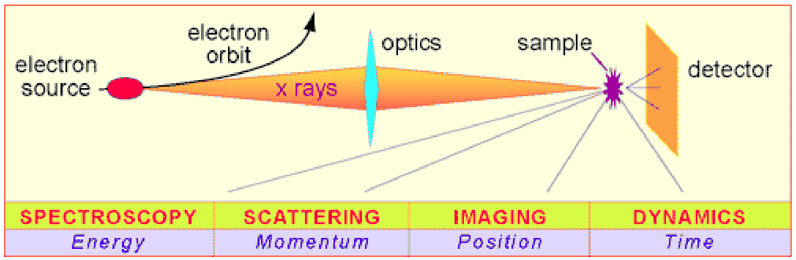
- Introduction/Motivation
- Measurement Methods/BPMs
- The Advanced Light Source (ALS)
- Sources of Orbit Noise/Drift
- Correction Algorithms
- Feedback Systems (Slow, RF, Fast)
- Beam Based Alignment

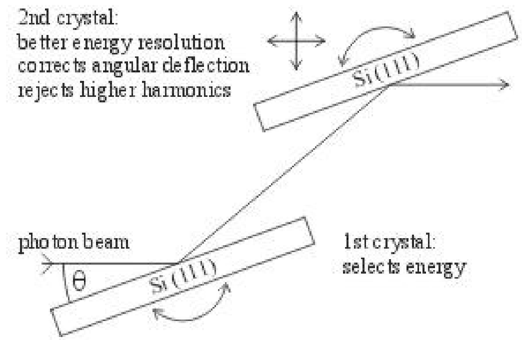
Motivation

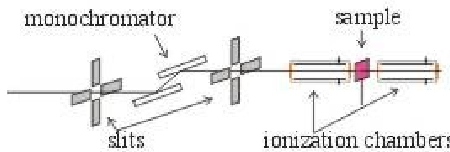
Orbit stability is one of the most important requirement in accelerators

- 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.

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

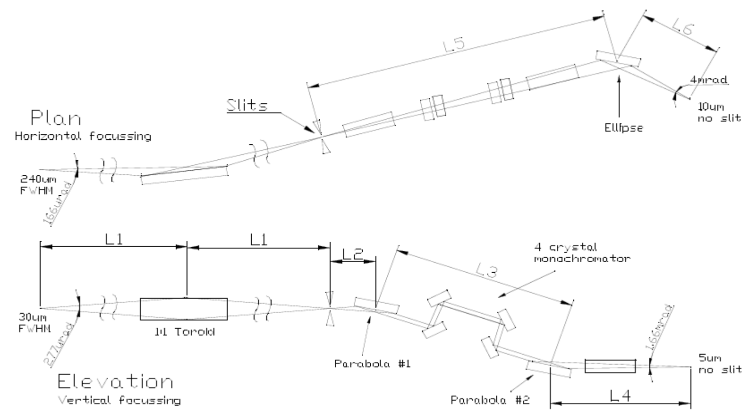


Figure 1. Optical layout. The dimensions L1..L6 and mirror types are as follows:

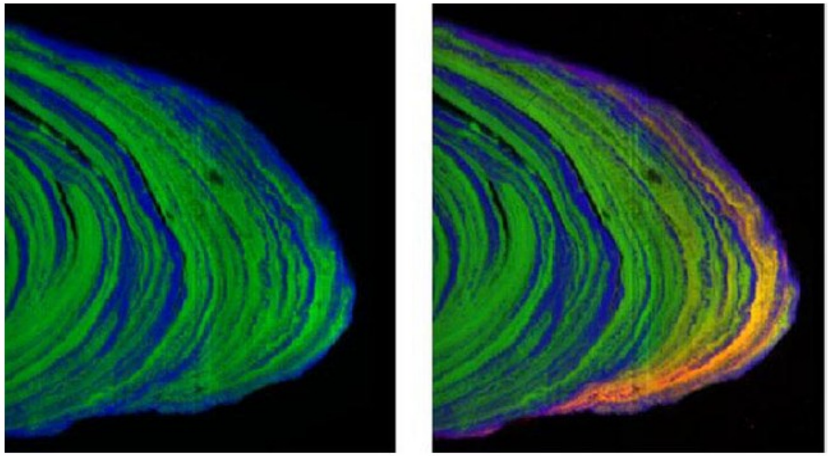


Figure 1. Synchrotron-based micro-X-ray radiation fluorescence (µSXRF) Fe and Mn maps of the outermost Fe and Mn layers of a ferromanganese nodule from the Baltic sea (6600 µm x 3780 µm, step size 15 µm, counting time 250 ms/pixel, red = Zn, green = Mn, blue = Fe, beamline: 10.3.2.). The onion-like structure 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.

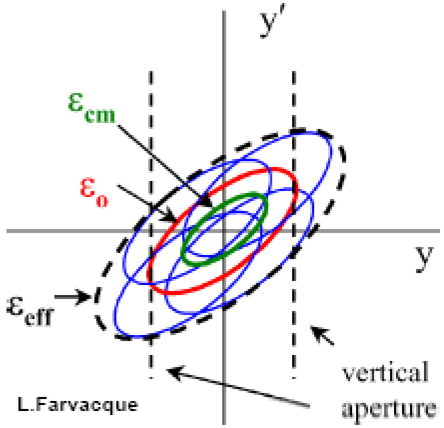
Orbit Stability Requirements

INTRODUCTION

Table 1: Typical stability requirements for selected measurement parameters common to a majority of experiments (Courtesy R. Hettel)

Measurement parameter	Stability requirement
Intensity variation $\Delta I/I$	$<$0.1 % of normalized I
Position and angle accuracy	$<$1 % of beam σ and σ'
Energy resolution $\Delta E/E$	$<$0.01 %
Timing jitter	$<$10 % of critical t scale
Data acquisition rate	$\approx 10^{-3}$-10^{5} Hz
Stability period	$10^{-2(3)}$-10^{5} sec

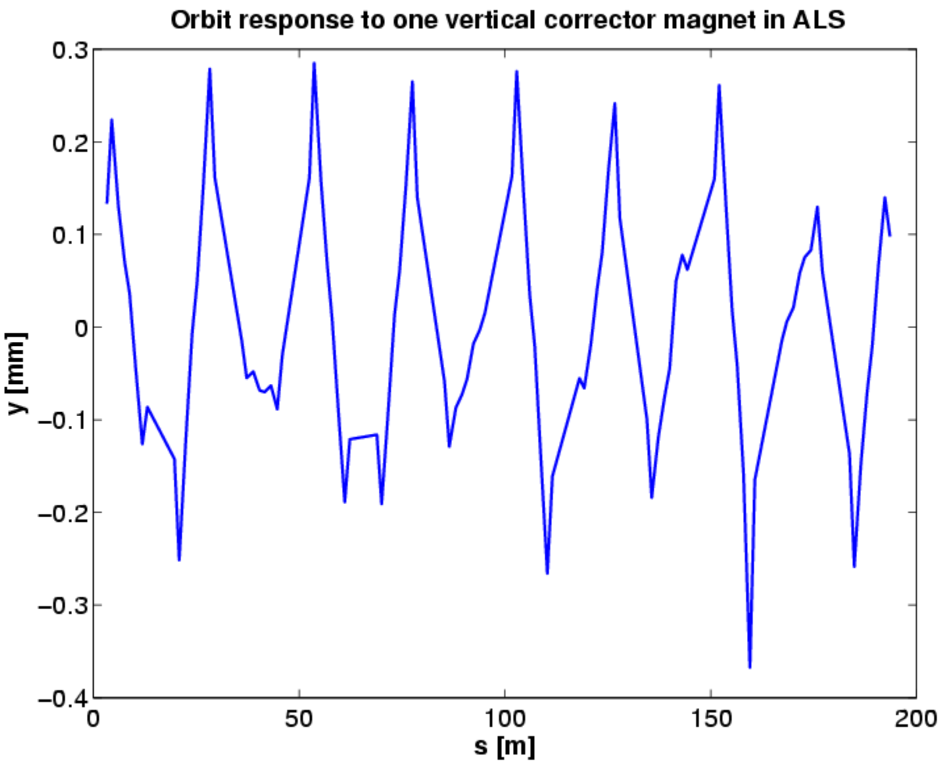
$\Rightarrow$ **Stabilization of the electron beam in its 6D phase space to meet stability requirements for the photon beam parameters. Effect of photon beam instability on flux depends on the time scale of the fluctuation τ_f relative to the detector sampling and data integration times τ_d:**



- $\tau_d \gg \tau_f$:
  $\epsilon_{eff} = \epsilon_0 + \epsilon_{cm}$:
  Motion of $\approx$**30 %** of σ and σ'
  $\Rightarrow$ *smeared out*
  $\Rightarrow$ **10 %** increase in ϵ_{eff}
- $\tau_d \ll \tau_f$:
  $\epsilon_{eff} \approx \epsilon_0 + 2\sqrt{\epsilon_0 \epsilon_{cm}} + \epsilon_{cm}$:
  Motion of $\approx$**5 %** of σ and σ'
  $\Rightarrow$ *new measurement noise*
  $\Rightarrow$ **10 %** increase in ϵ_{eff}

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.
- Particles close to the closed orbit will oscillate around it.
- The ideal orbit is the orbit through the centers of all (perfectly) aligned magnetic elements.



Closed orbit errors

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

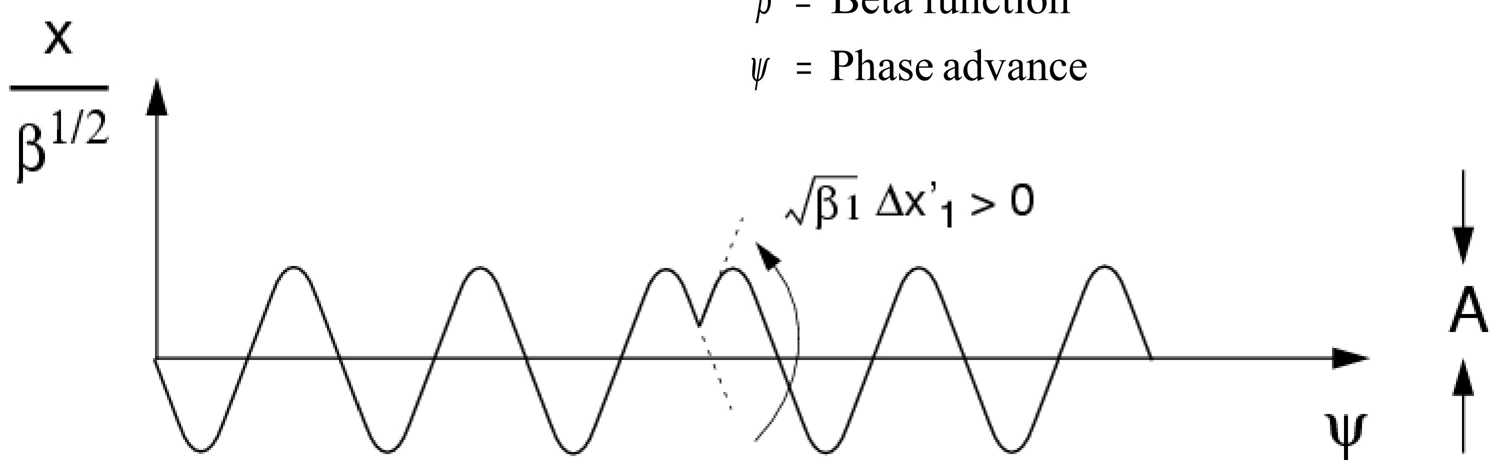
$$x(s) = \Delta x' \frac{\sqrt{\beta(s)\beta_0}}{2\sin \pi \nu} \cos\left(|\psi(s) - \psi_0| - \pi \nu\right)$$

Δx = Transverse position

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

β = Beta function

ψ = Phase advance

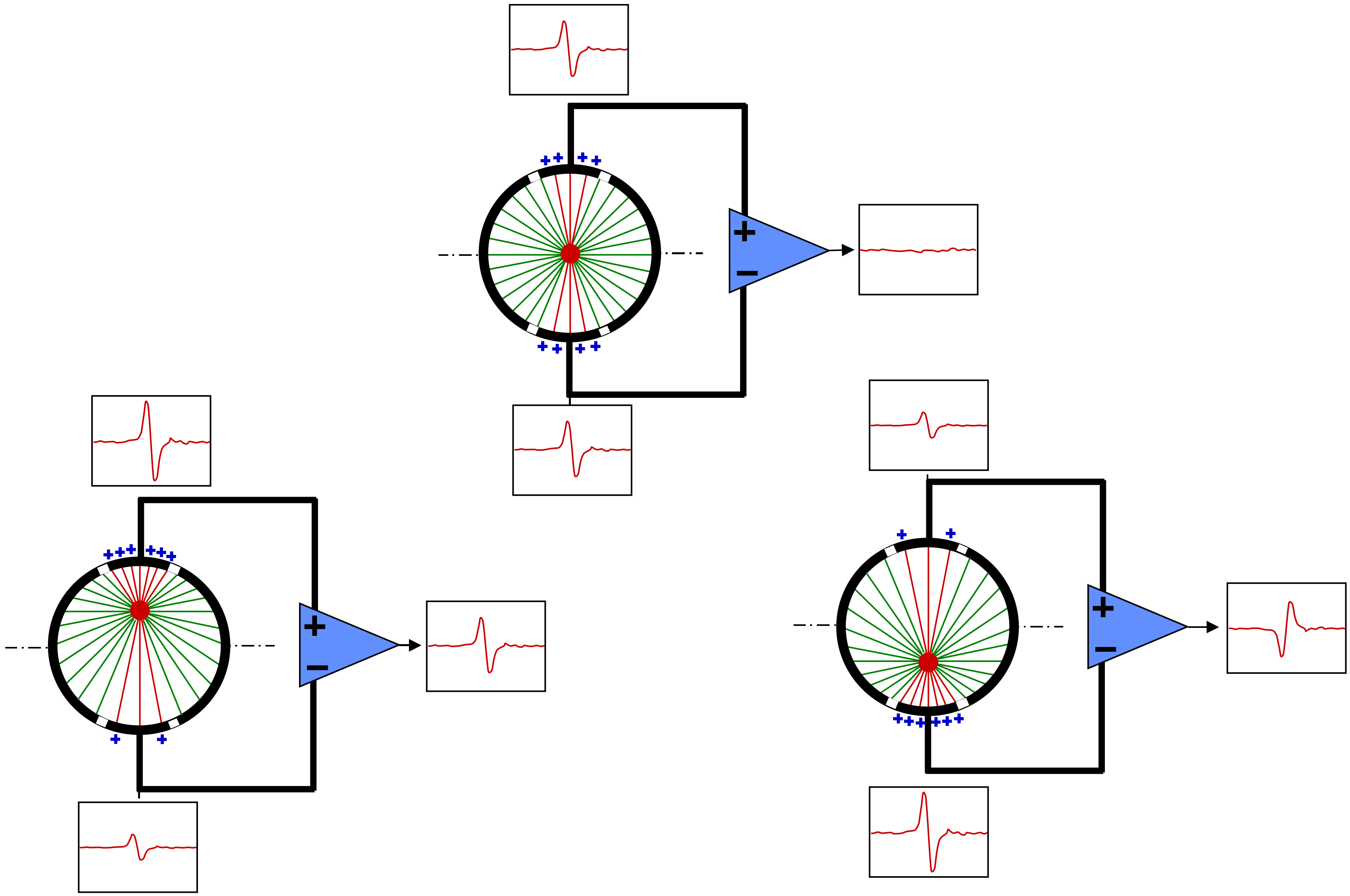


- The matrix containing the change in position at every BPM to a kick from every corrector magnet is called orbit response matrix (used in orbit correction). For an uncoupled machine it can be calculated (linear approximation) using above formula.

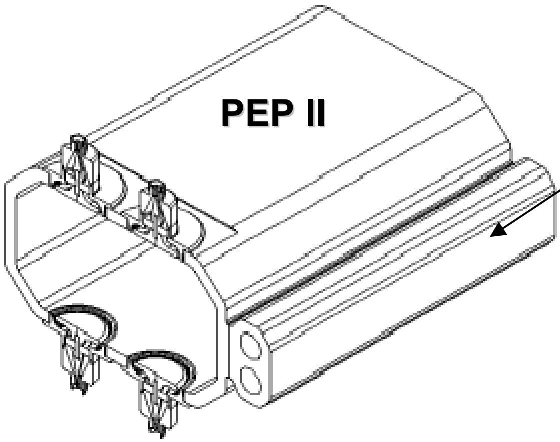
Measurement Methods

- 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

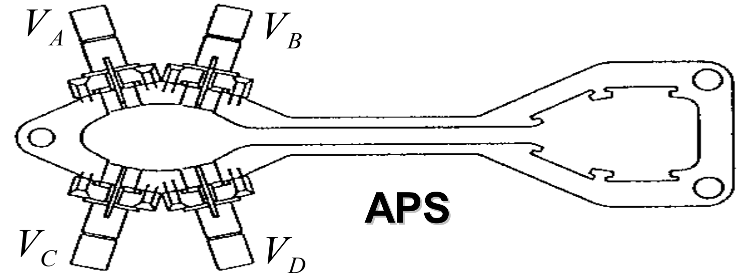
Electromagnetic Beam Position Monitors



Capacitive Pickups

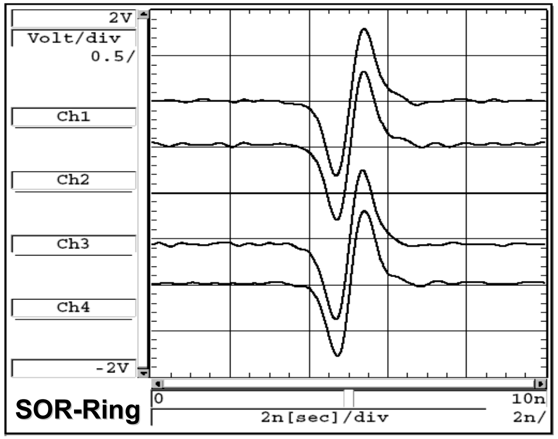


- **Typical geometry used in the presence of synchrotron radiation.**



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

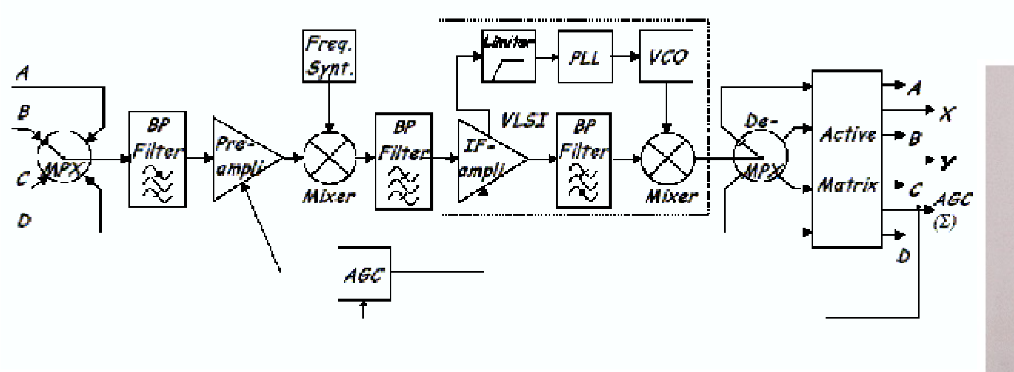
- **Capacitive type (derivative response), low coupling impedance, relatively low sensitivity, best for storage rings.**

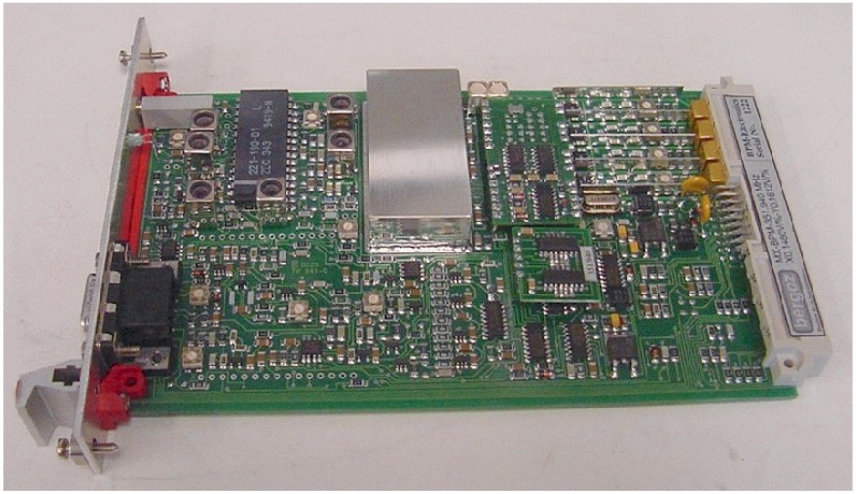


Signal Processing Electronics I (Bergoz)

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

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





Typical F_{rf} = 60 to 800 MHz ,
Receiver IF bandwidth as narrow as a few hundred kHz
Position signal (X or Y) bandwidth a few kHz

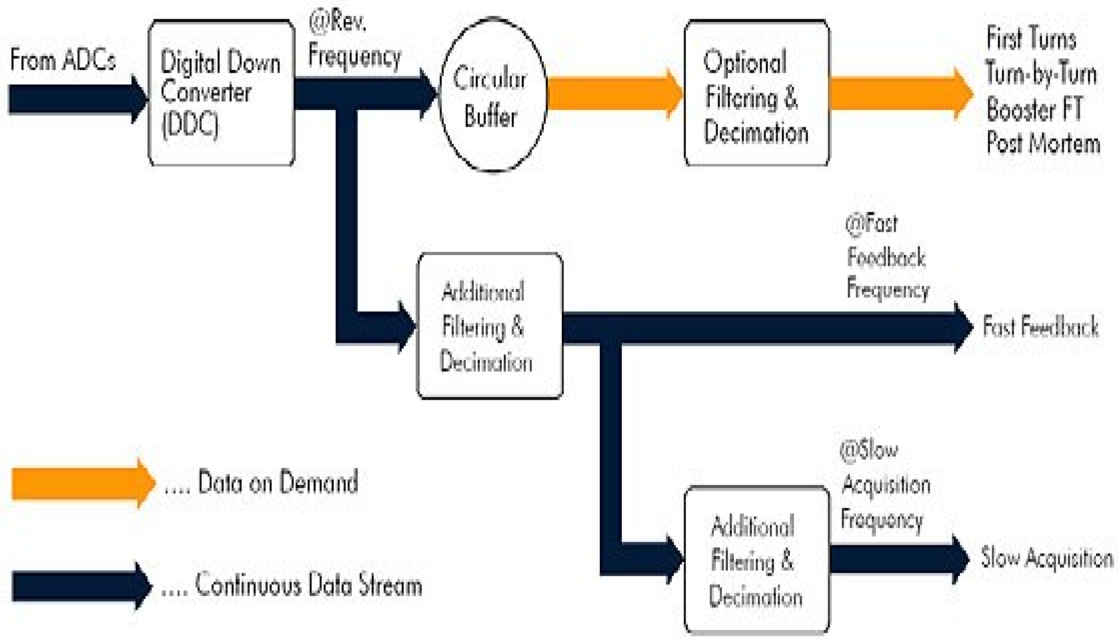
* G. Vismara, DIPAC '99 http://srs.dl.ac.uk/dipac

Signal Processing Electronics II (i-tech, Slovenia)

Libera

When your users demand a stable orbit

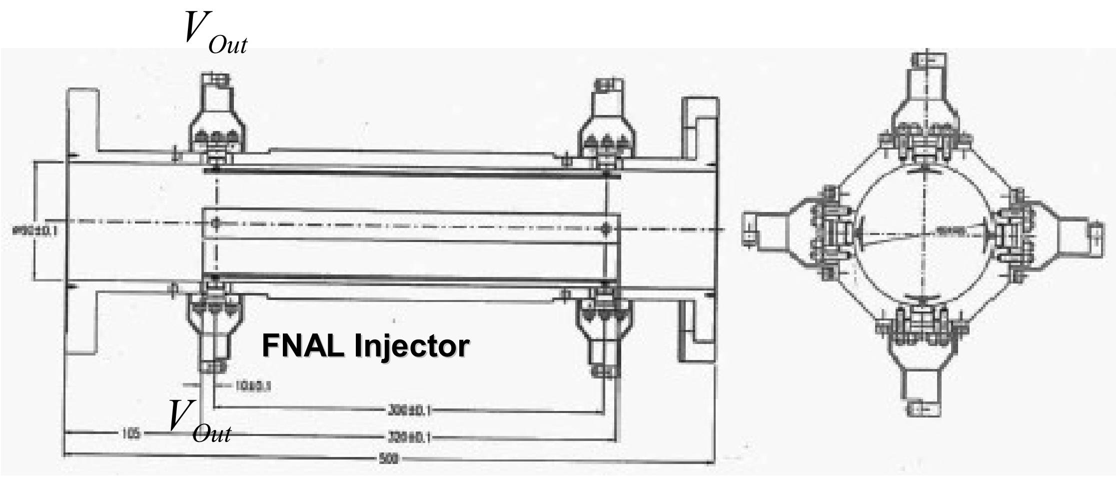
Electron

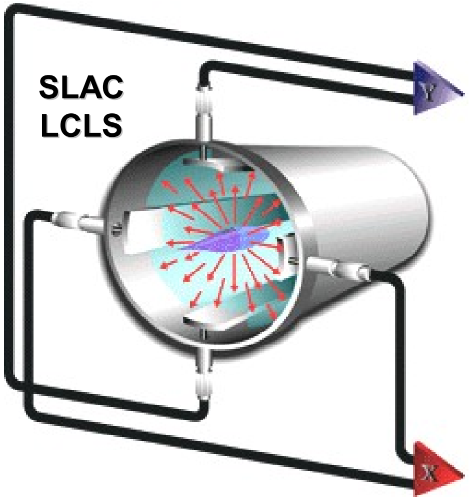


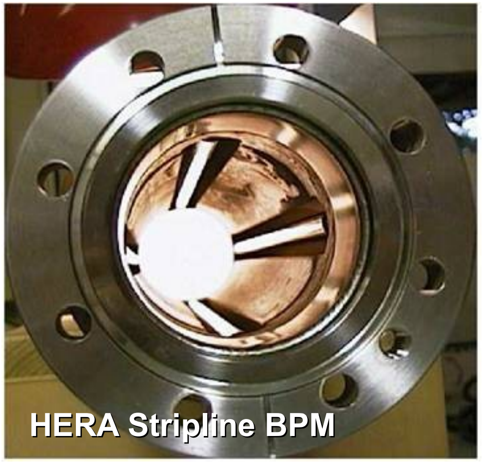
RMS uncertainty 1 kHz bandwidth, Pin = -20 dBm	-90.5dB	0.2 µm
RMS uncertainty 1 MHz bandwidth, Pin = –20 dBm	-63dB	7µm
8-hour stability (ambient temp. = T±1° C)	-80dB	1µm
Temperature drift (ambient temp. range: 10 to 35° C) Bunch pattern dependence	-94dB/°C -80dB	0.2µm/°C 4 µm

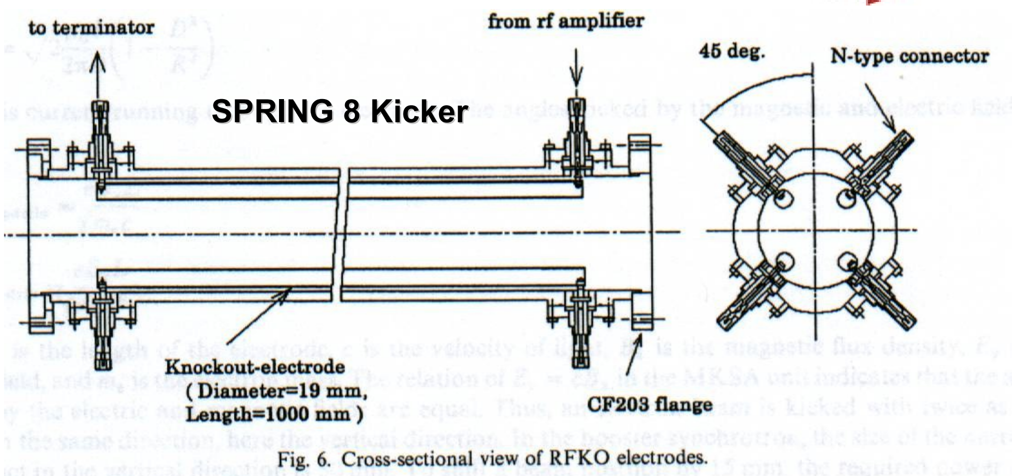
Stripline BPMs

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



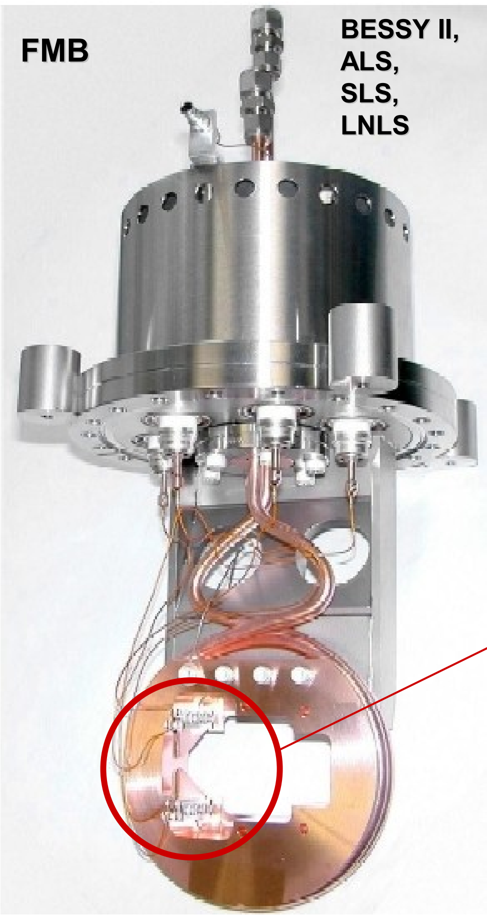


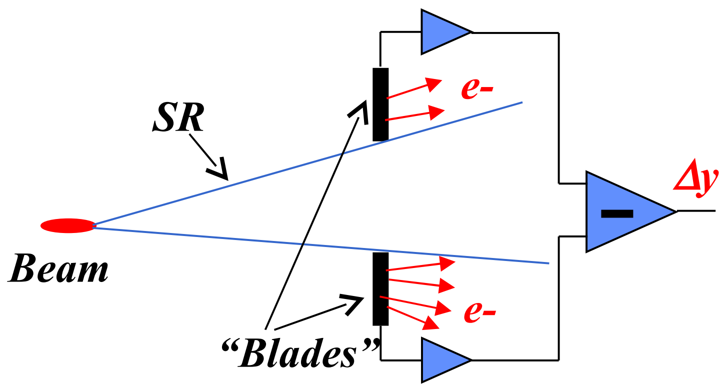




Other BPMs (using Photons)

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



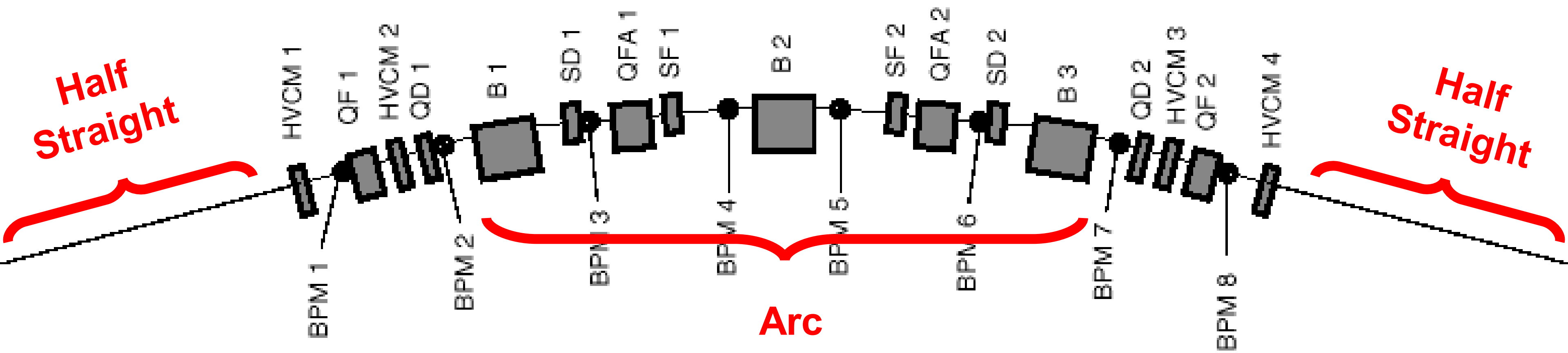


- Work very well for dipoles in the vertical plane – not so simple for insertion devices
- Fundamentally limited in the horizontal plane for dipoles

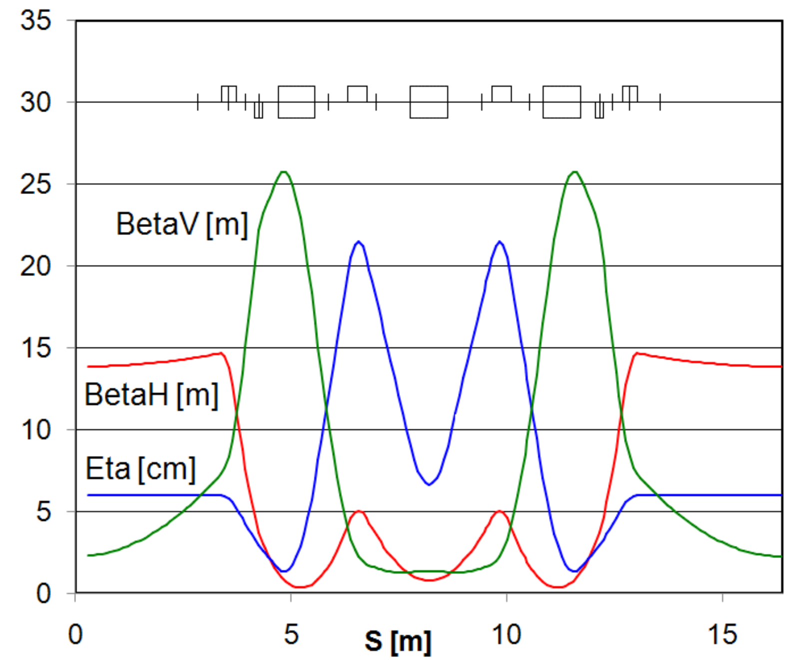
Aerial view of the Advanced Light Source

jc/ALSaerial/11-96

ALS lattice – orbit measurement + correction

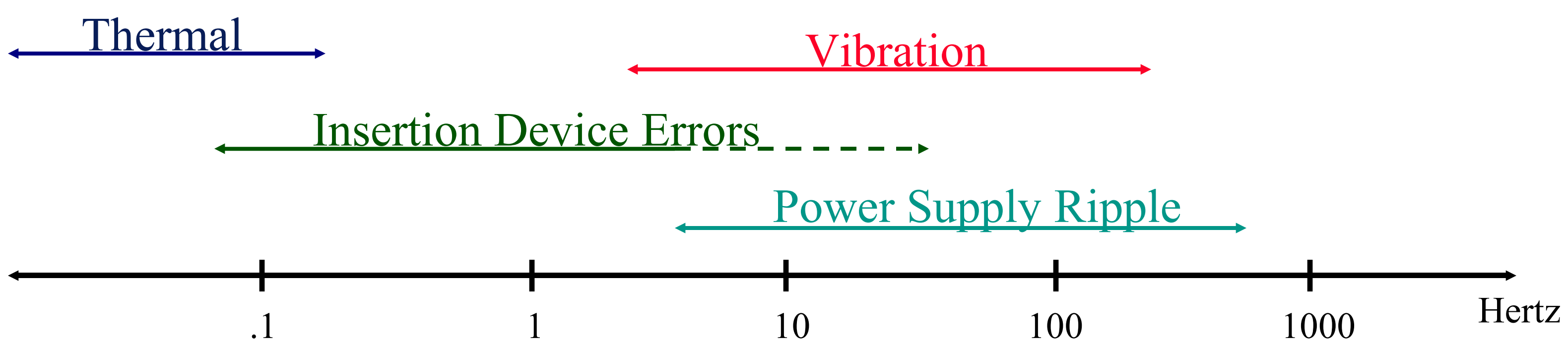


- 12 nearly identical arcs – TBA; aluminum vacuum chamber
- 122 beam position monitors in each plane (about 4 of stable type per arc)
- 8 horizontal, 6 vertical corrector magnets per arc (94/70 total)
- 24 individual skew quadrupoles
- beam based alignment capability in all quadrupoles (either individual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



Typical Error Sources

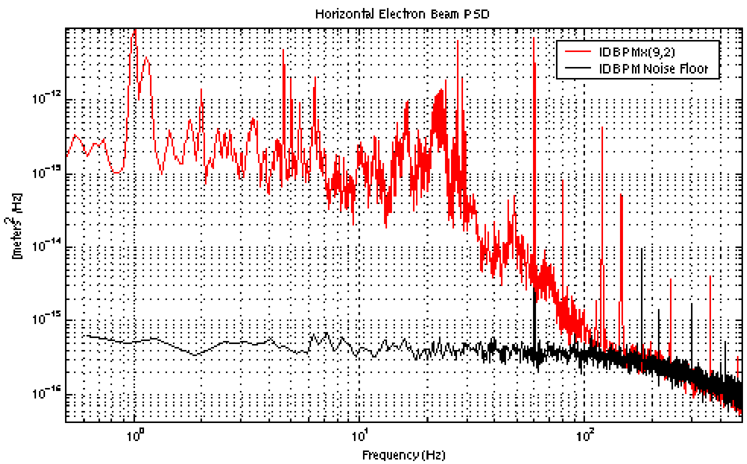
Causes for Orbit Distortions

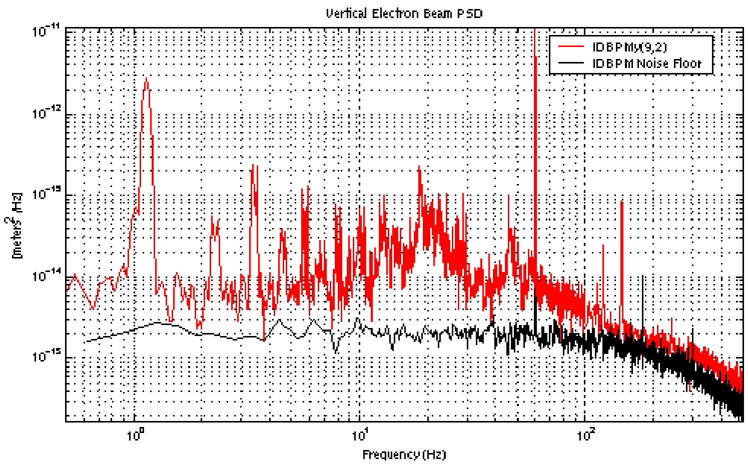


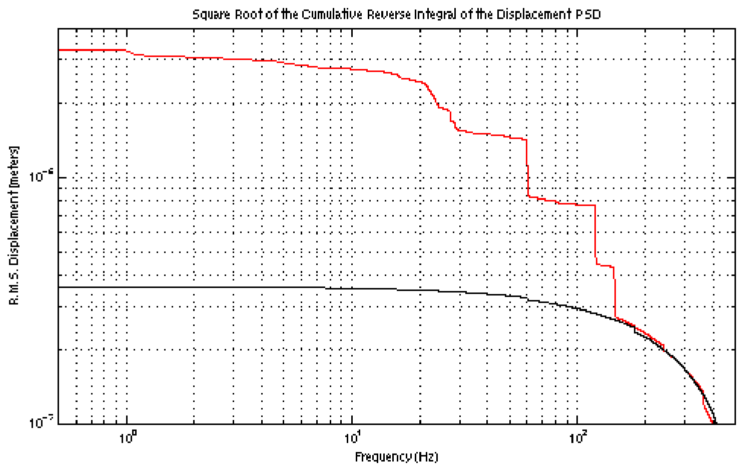
Frequency	Magnitude	Dominant Cause
Two weeks (A typical experimental run)	± 200 μ m Horizontal ± 100 μ m Vertical	1. Magnet hysteresis 2. Temperature fluctuations 3. Component heating between 1.5 GeV and 1.9 GeV
1 Day	± 125 μ m Horizontal ± 50 μ m Vertical	Temperature fluctuations
8 Hour Fill	± 50 μ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

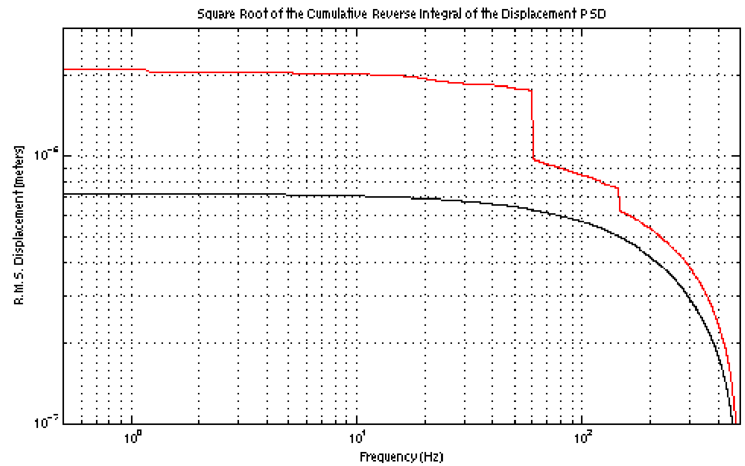
Beam Stability in straight sections w/o Orbit Correction, w/o Orbit Feedback, but w/ Insertion Device Feed-Forward

ELECTRON BEAM PSD

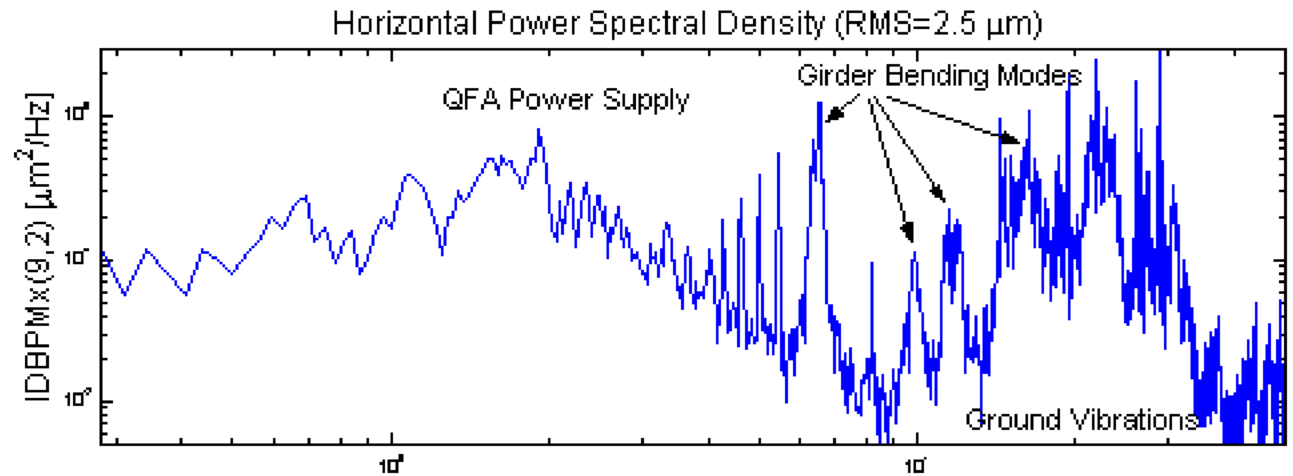


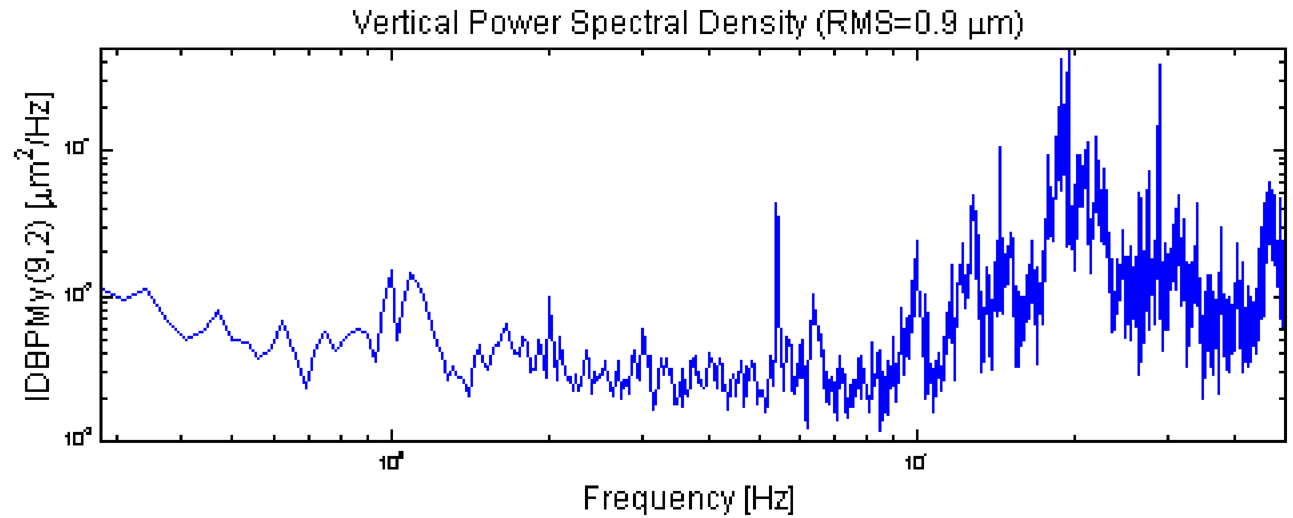






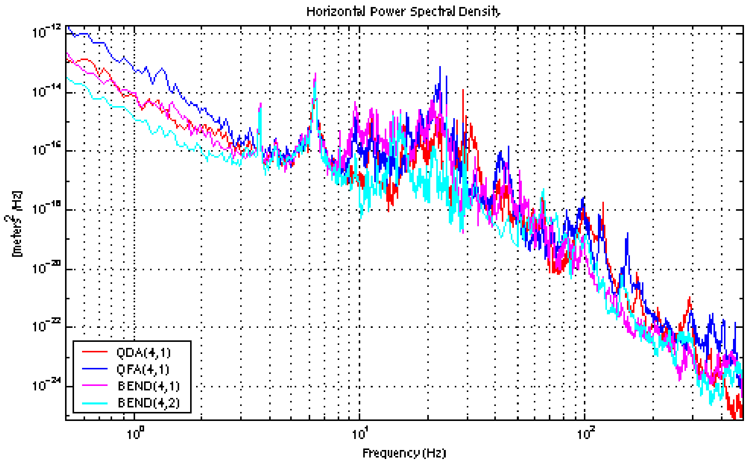
POWER SPECTRAL DENSITY

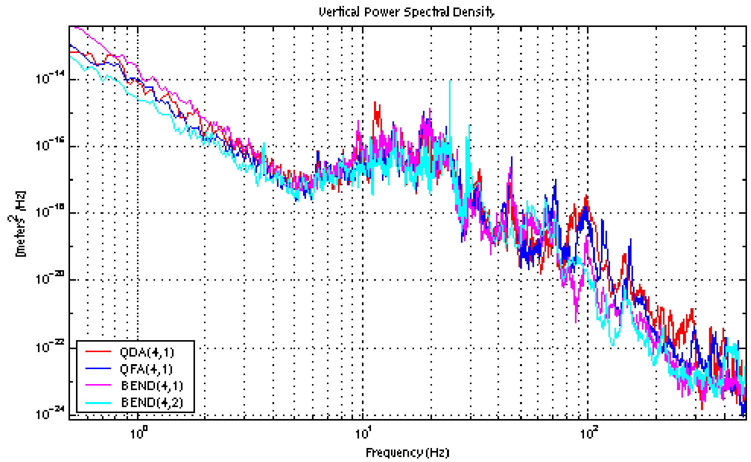


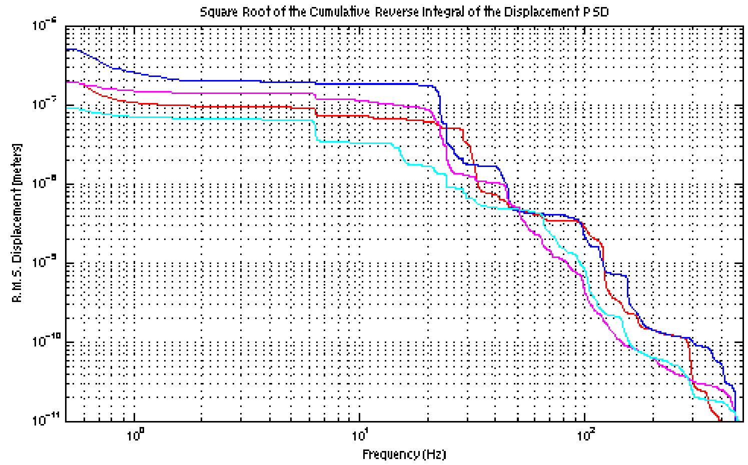


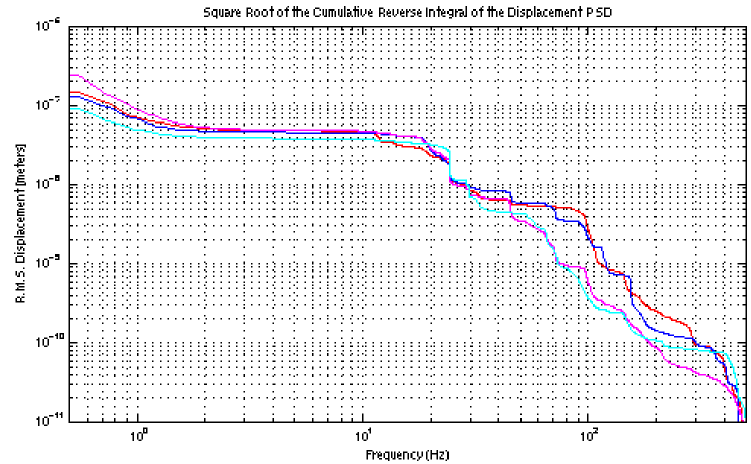
Data taken on 12-12-1999, during a 1.9 GeV user run at 278 mAmps

MAGNET VIBRATION PSD









Orbit Correction Methods

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:

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

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 (in case of equal number of independent BPMs and corrector magnets).
- In case the numbers of correctors and BPMs do not match one can use least square correction (minimizing the sum of the quadratic deviations from the nominal orbit) often with the additional constraint (if solution is degenerate) to minimize average corrector strength.
- SVD uses the so called singular value decomposition. In this method small singular values can be neglected in the matrix inversion.
- MICADO/MEC is a modification of the least square method. It iteratively searches for the single most effective corrector (starting with one up to the selected total number), calculates its correction strength using least square, finds the next most effective corrector, calculates the correction using those two via least square, …
- Local Bumps allow to keep the orbit 'perfect' locally (sensitive SR user, interaction point, …) while relaxing the correction elsewhere.
- Harmonic Correction:

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.

Singular Value Decomposition (cont.)

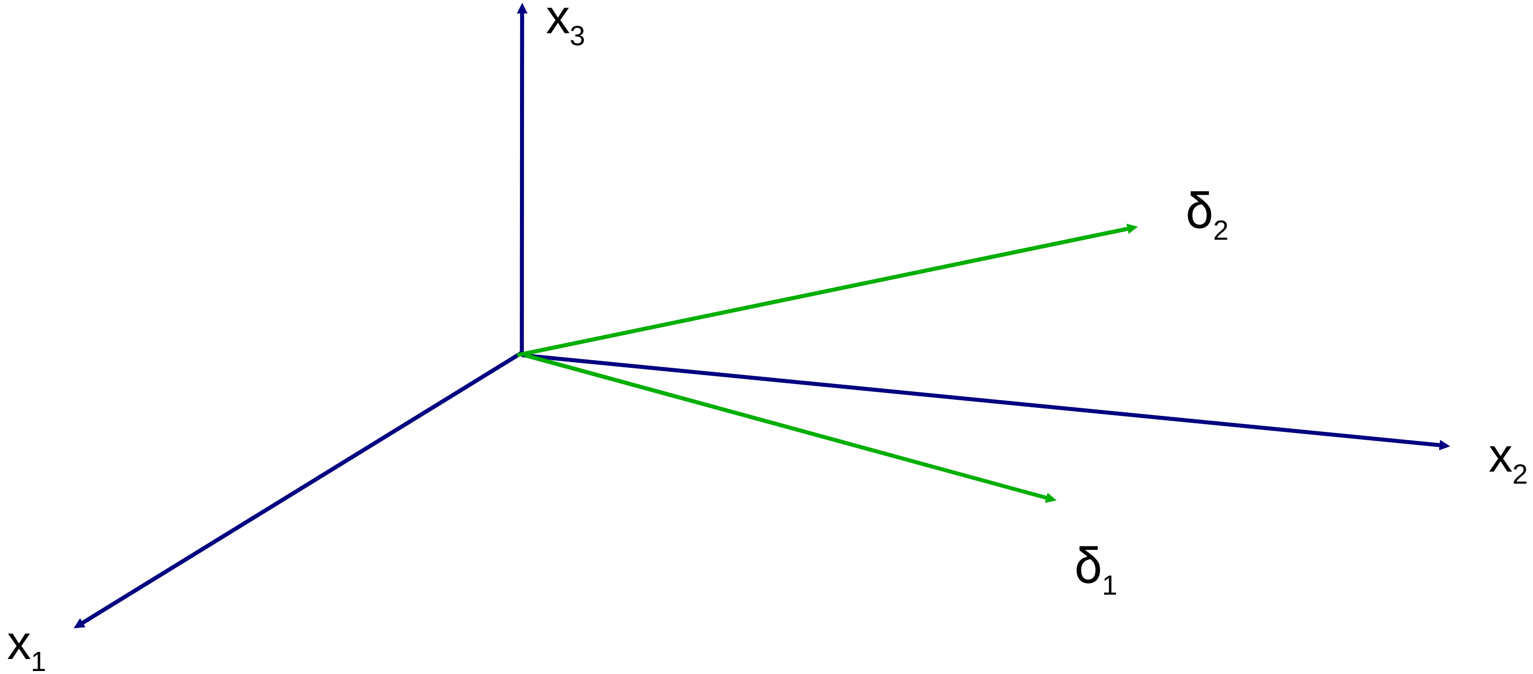
$$\Delta x = M\delta = U \cdot \Sigma \cdot V^T \cdot \delta$$

$$\text{Least Squares}: \delta = \left(M'M\right)^{-1} M'\Delta x$$

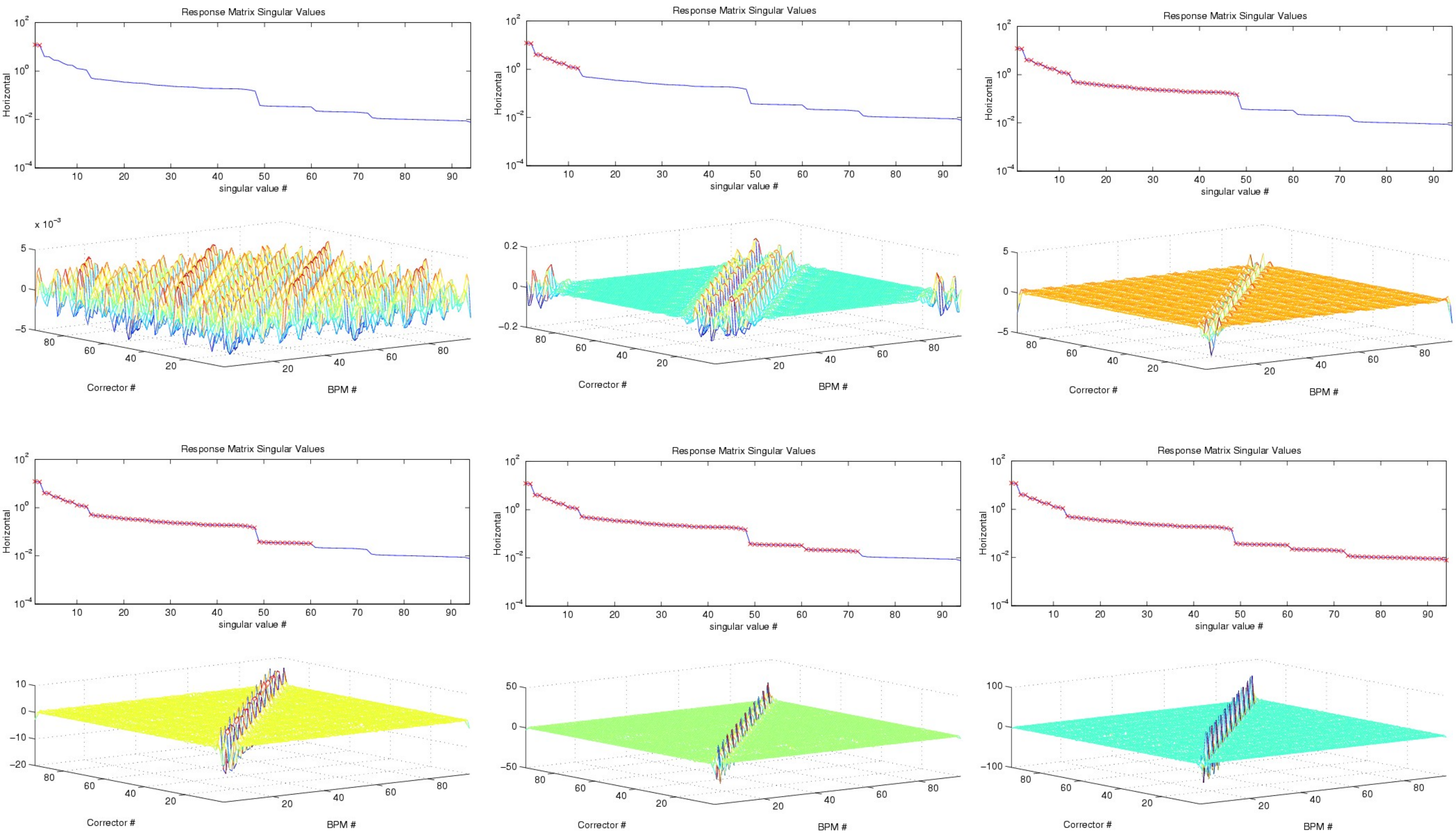
$$\text{SVD}: \qquad \delta = V \cdot \Sigma^{-1} \cdot U^T \Delta x$$

$$\text{Note}: \left\| M v_i \right\|_2 = \sigma_i$$

Least squares can be thought of as a projection on to the columns of M



Example: SVD inverted matrix vs. number of SVs

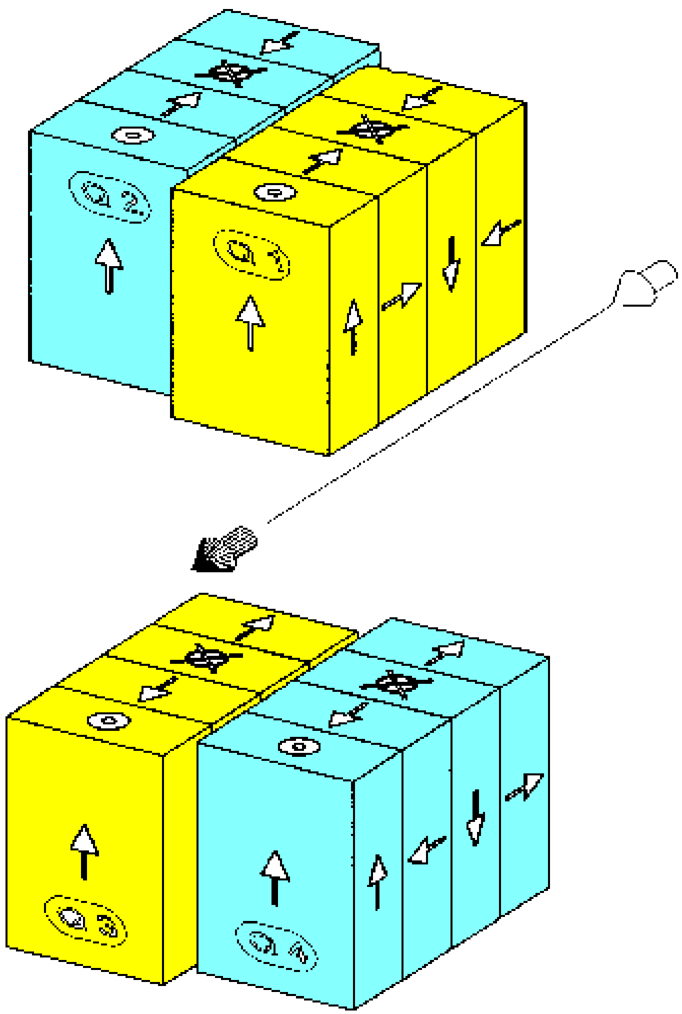


Advantages of Correction Methods

- Least square or direct matrix inversion
  - Disadvatages:
    - 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

Elliptically Polarizing Undulator (EPU)



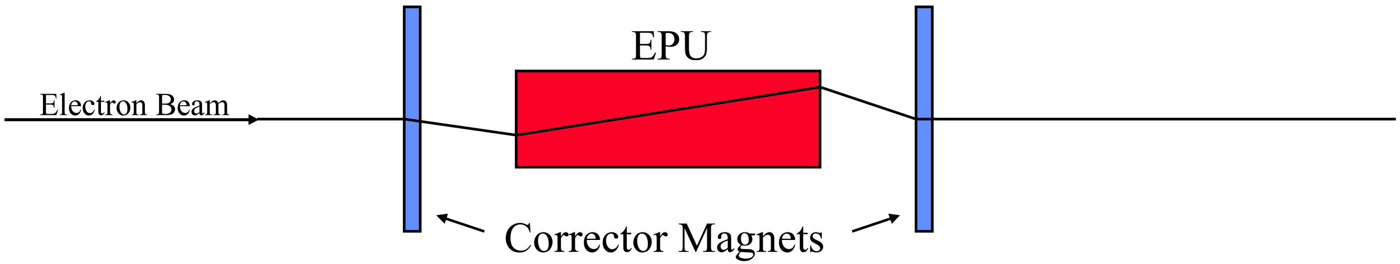
The EPU is different than other insertion devices

❖The jaws can move in two directions
(vertically and longitudinally)

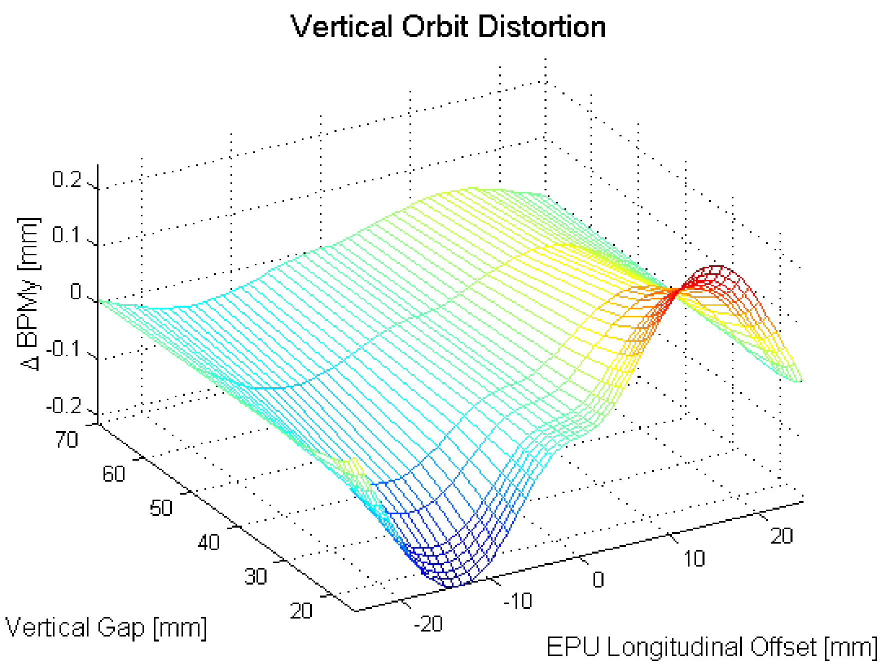
❖The motion in the longitudinal direction is fast
(At the ALS, up to 17 mm/second)

This makes orbit compensation more difficult than other insertion devices

Feed-forward example: EPU COMPENSATION



Mechanically, an ALS EPU can move from left to right circular polarization mode in ~1.6 sec.

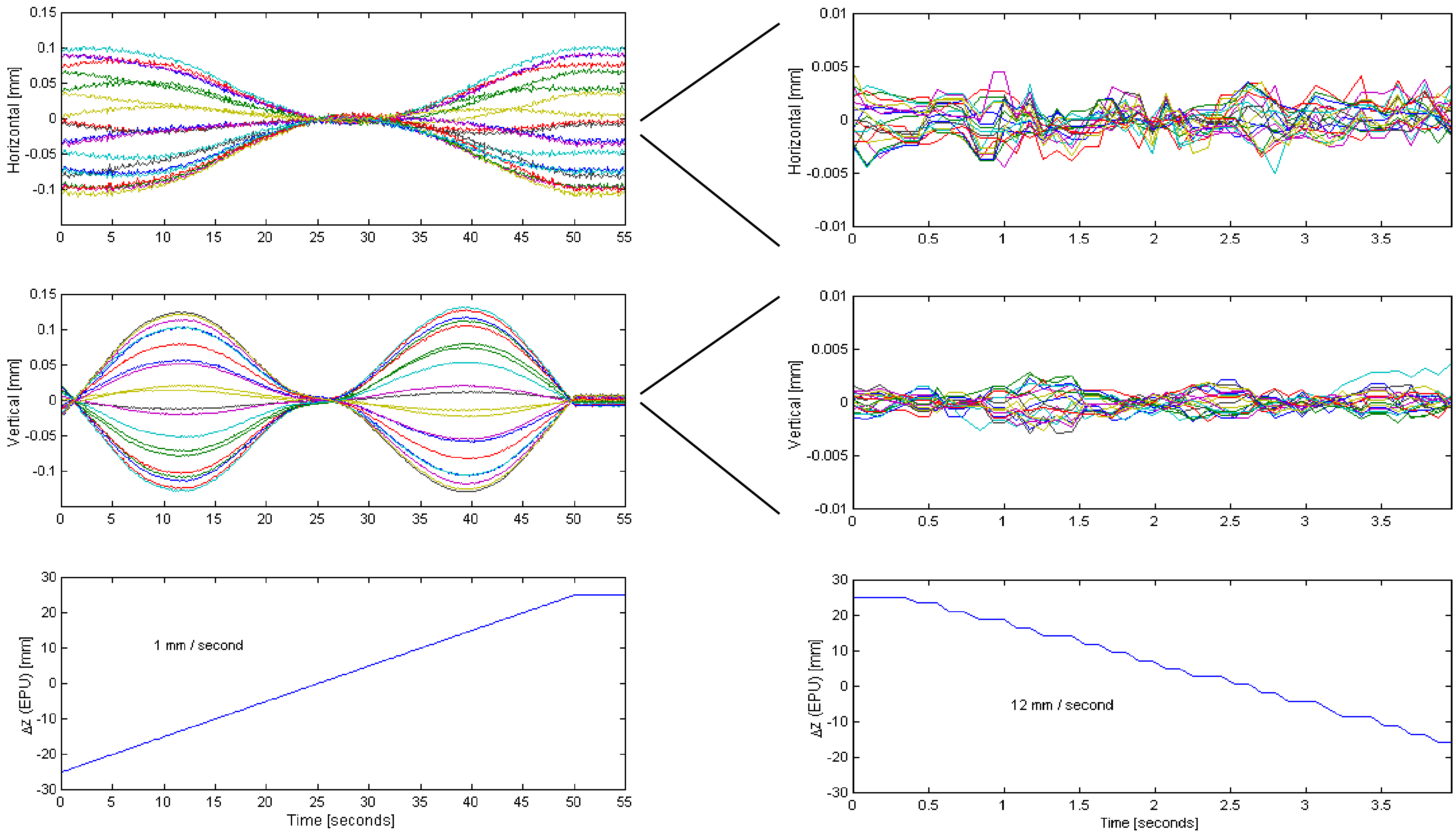


Without compensation the EPU would distort the electron beam orbit by ±200 μm vertically and ±100 μm horizontally. Using corrector magnets on either side of the EPU, 2-dimensional feed forward correction tables are used to reduce the orbit distortion to the 2-3 μm level. Update rate of feed-forward is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

EPU FEED FORWARD ORBIT CORRECTION

Orbit Error without Feed Forward Correction

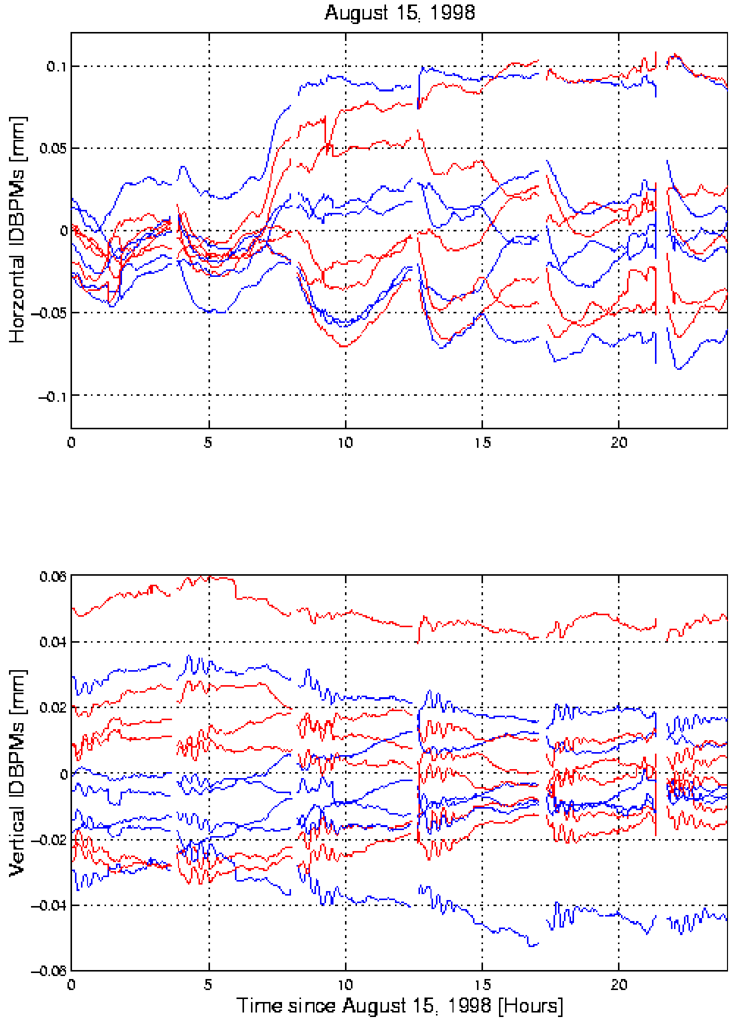
200 Hertz Feed Forward Correction



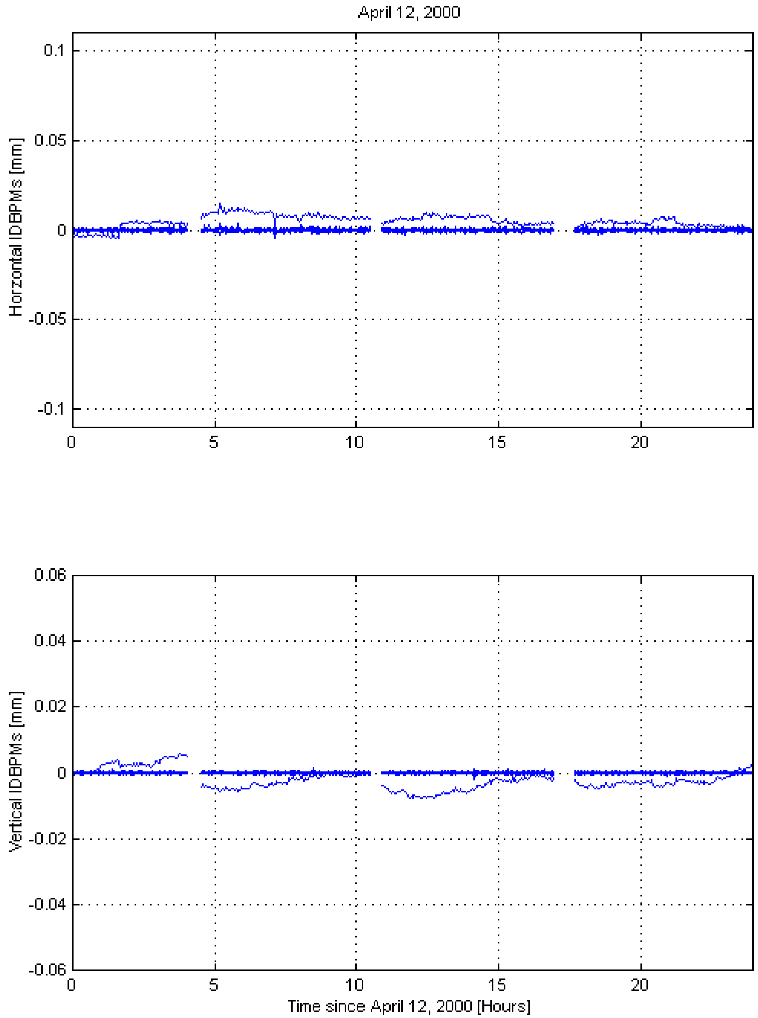
Orbit Feedback

Slow Orbit Feedback

August 15, 1998: w/ ID Compensation
w/o Orbit Correction
w/o Slow Orbit Feedback

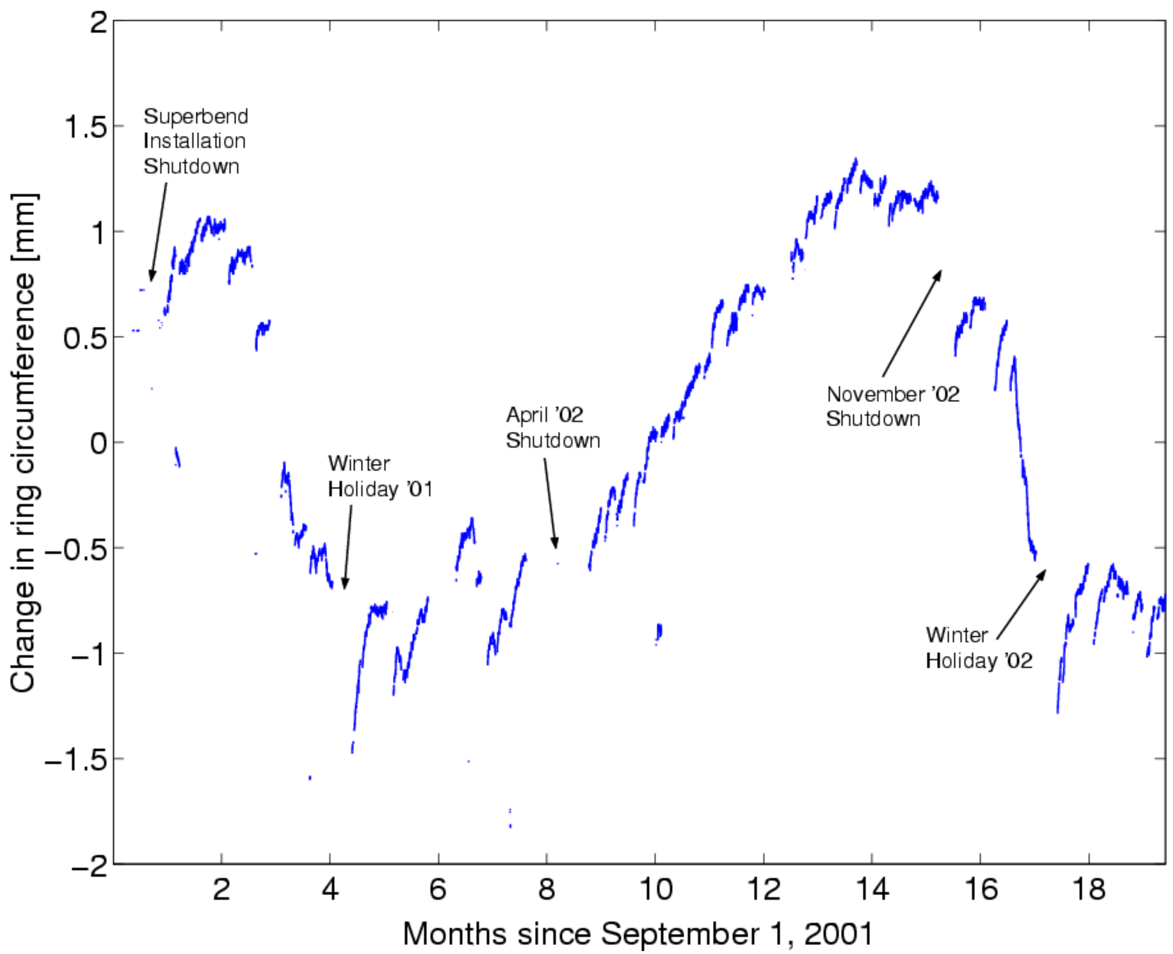


April 12, 2000: w/ ID Compensation
w/ Orbit Correction
w/ Slow Orbit Feedback



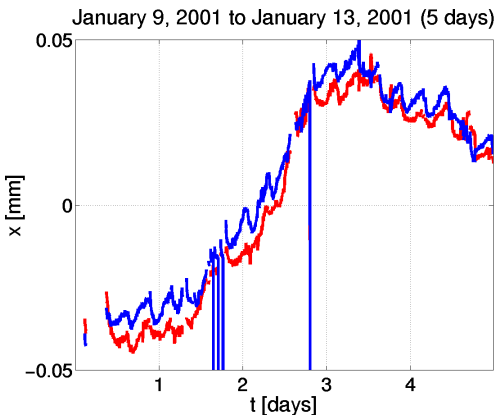
RF Frequency Feedback

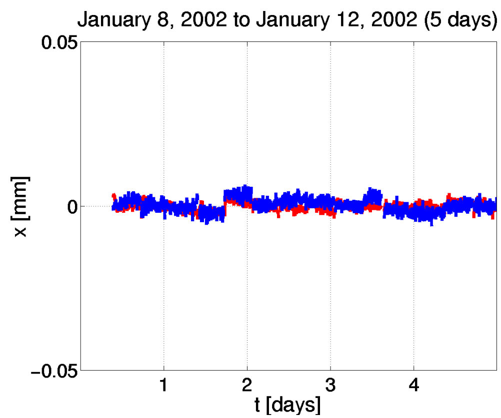
- Circumference of ring changes (temperature inside/outside, tides, water levels, seasons, differential magnet saturation, …)
- RF keeps frequency fixed – beam energy will change
- Instead measure dispersion trajectory and correct frequency (at ALS once a second)
- Can see characteristic frequencies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

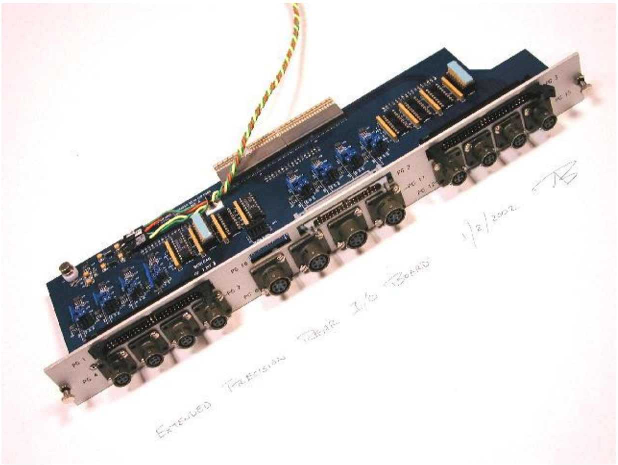


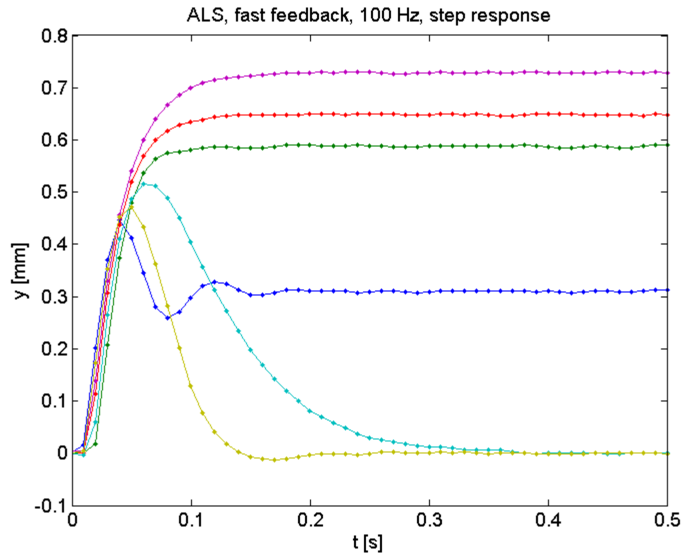
Fast Orbit Feeback

Recent Orbit Feedback Upgrades at ALS





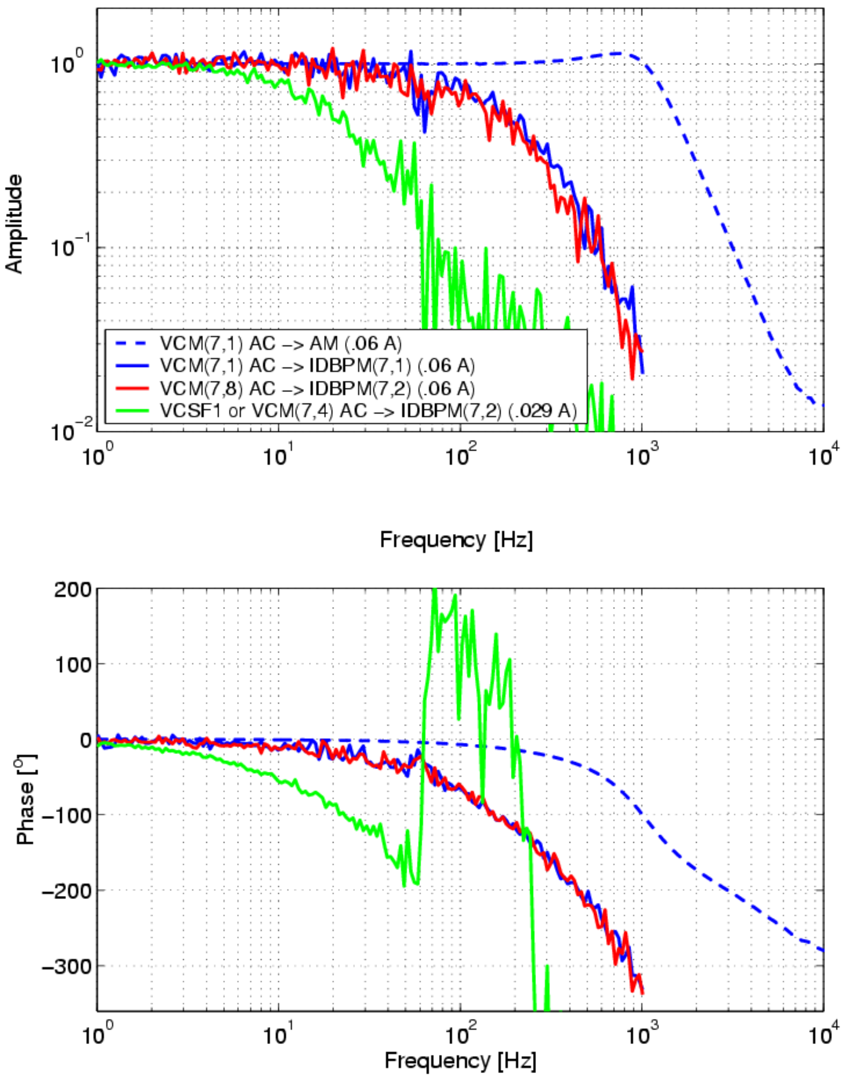




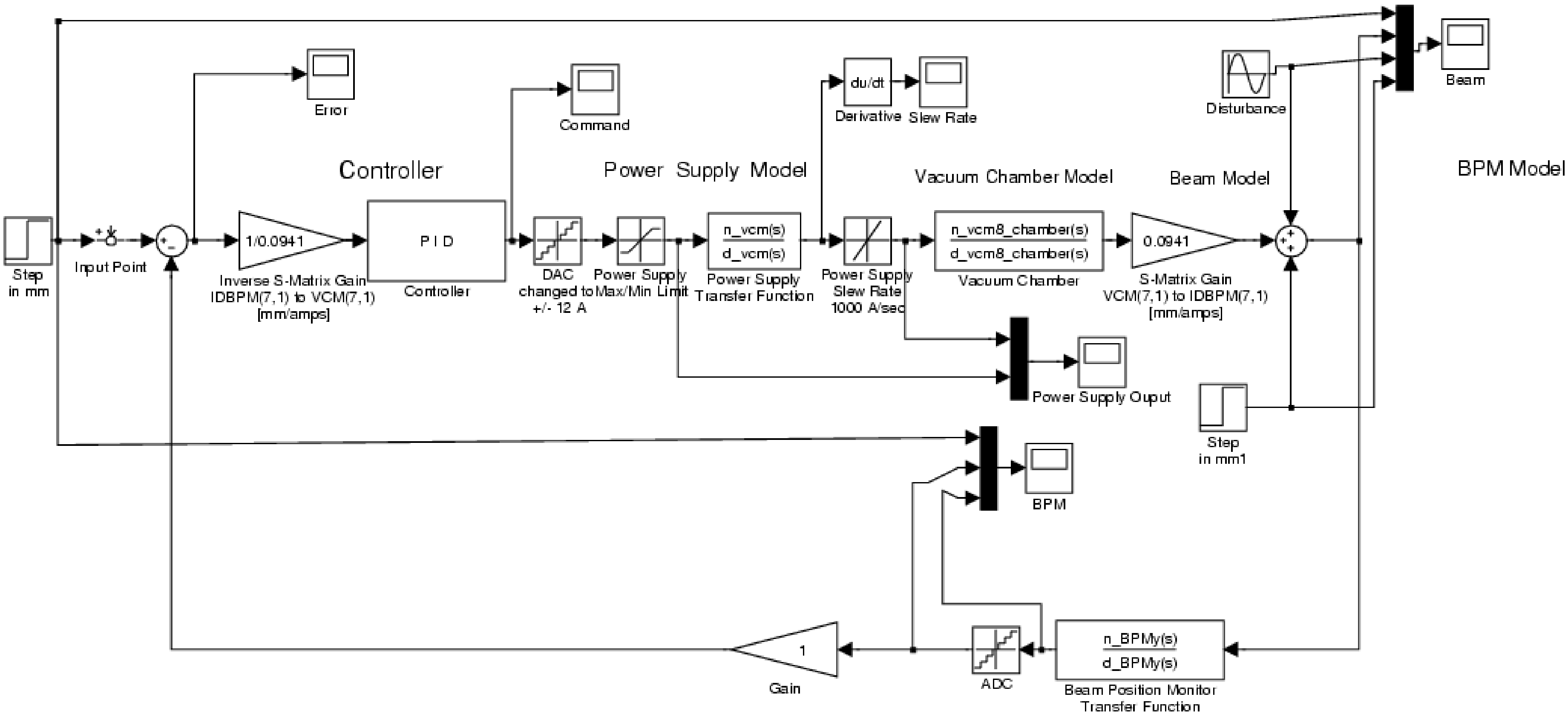
- RF-frequency feedback (significantly improved hor. orbit stability in arcs, energy stability)
- 20 Bit D/A converters (no digitization noise from SVD – mid term orbit stability now typically submicron)
- Start of commissioning of fast orbit feedback (standard hardware, 1 kHz update rate)

Fast Orbit Feedback

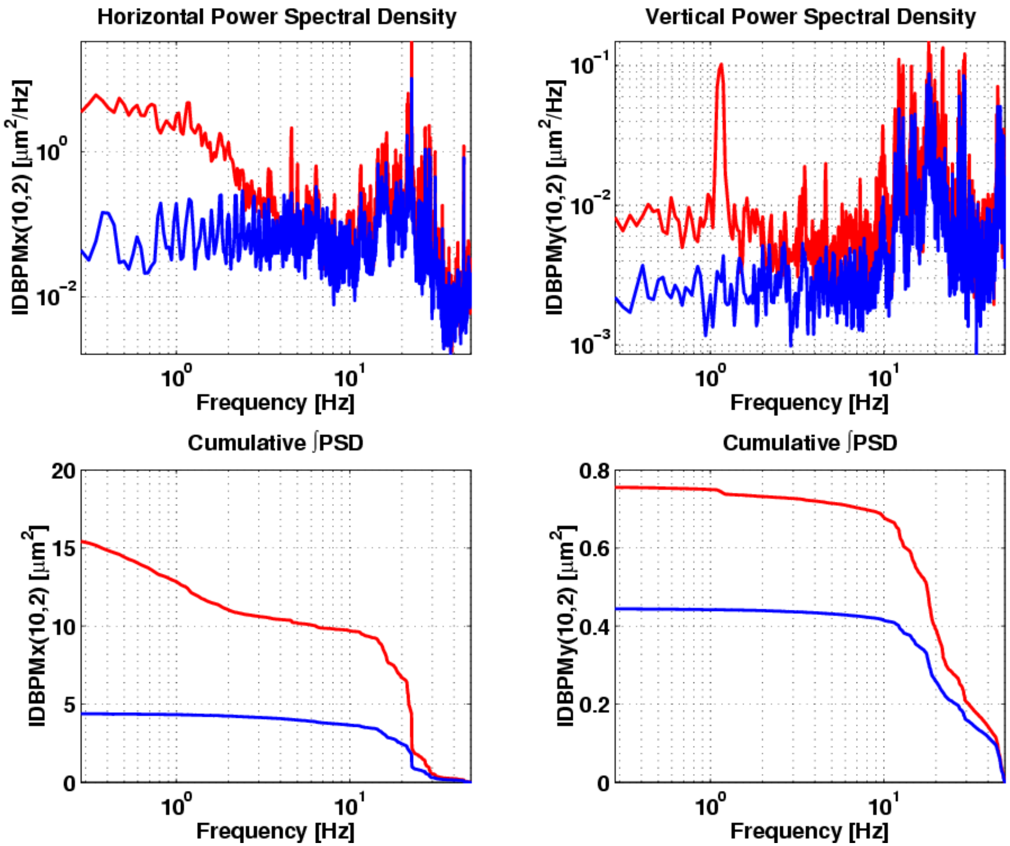
- Time response of all elements becomes important!
- Controller type used is often PID
- System often are distributed (ALS 12 crates, about 40BPMs, 22 correctors each plane)



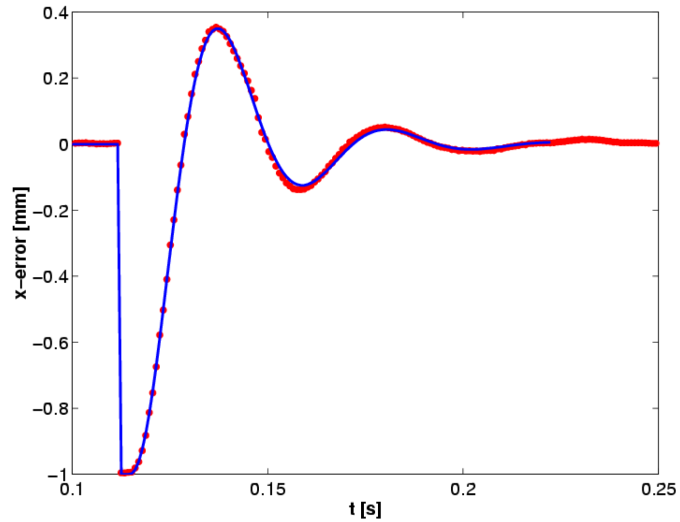
Simulink model of one channel of system



Performance of Fast Orbit Feedback at ALS



Comparison of orbit PSDs with and without fast feedback.
Fast orbit feedbacks are in use at several 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.

Achieved orbit stability at ALS

Frequency	Magnitude	Dominant Cause
1 hour – 2 weeks	± 5 μ m Horizontal ± 3 μ m Vertical	1. BPM chamber motion 2. BPM electronics drift and systematic errors 3. Limited number of BPMs/correctors
Minutes	<< 1 μ m	1. BPM noise and beam vibration (aliasing) 2. Corrector resolution (digitization)
.2 to 300 Hz	<2 μ m Horizontal <1 μ m Vertical	1. Ground vibrations 2. Cooling water vibrations 3. Power supply ripple 4. Feed forward errors

Beam Stability in straight sections w/ Orbit Feedback and w/ Insertion Device Feed-Forward

Beam Based Alignment

of

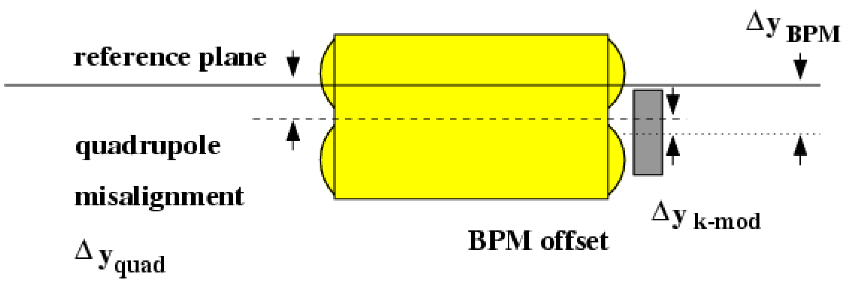
Quadrupoles Magnets

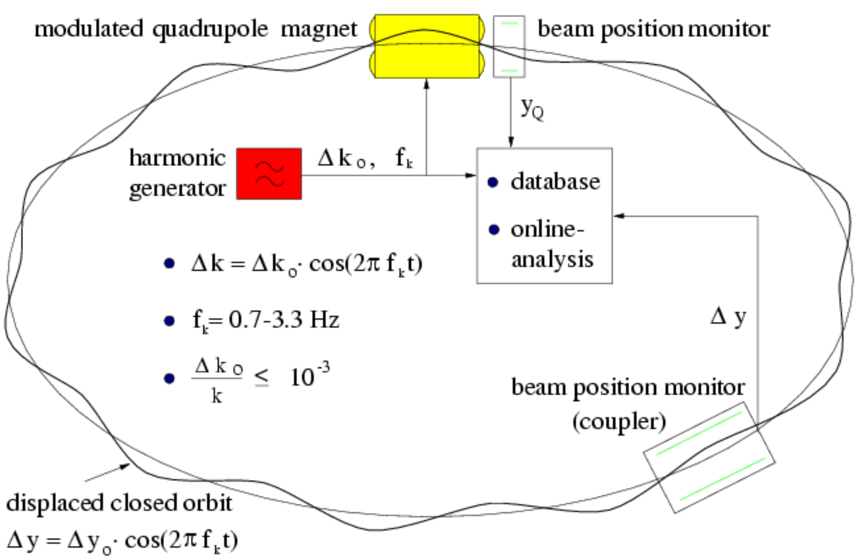
Beam Based Alignment

- To achieve optimum performance (dynamic aperture, beamsize, …) of accelerators, it is necessary to correct the beam to the center of magnetic elements
- Non centered beam can reduce physical 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
- 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, …)

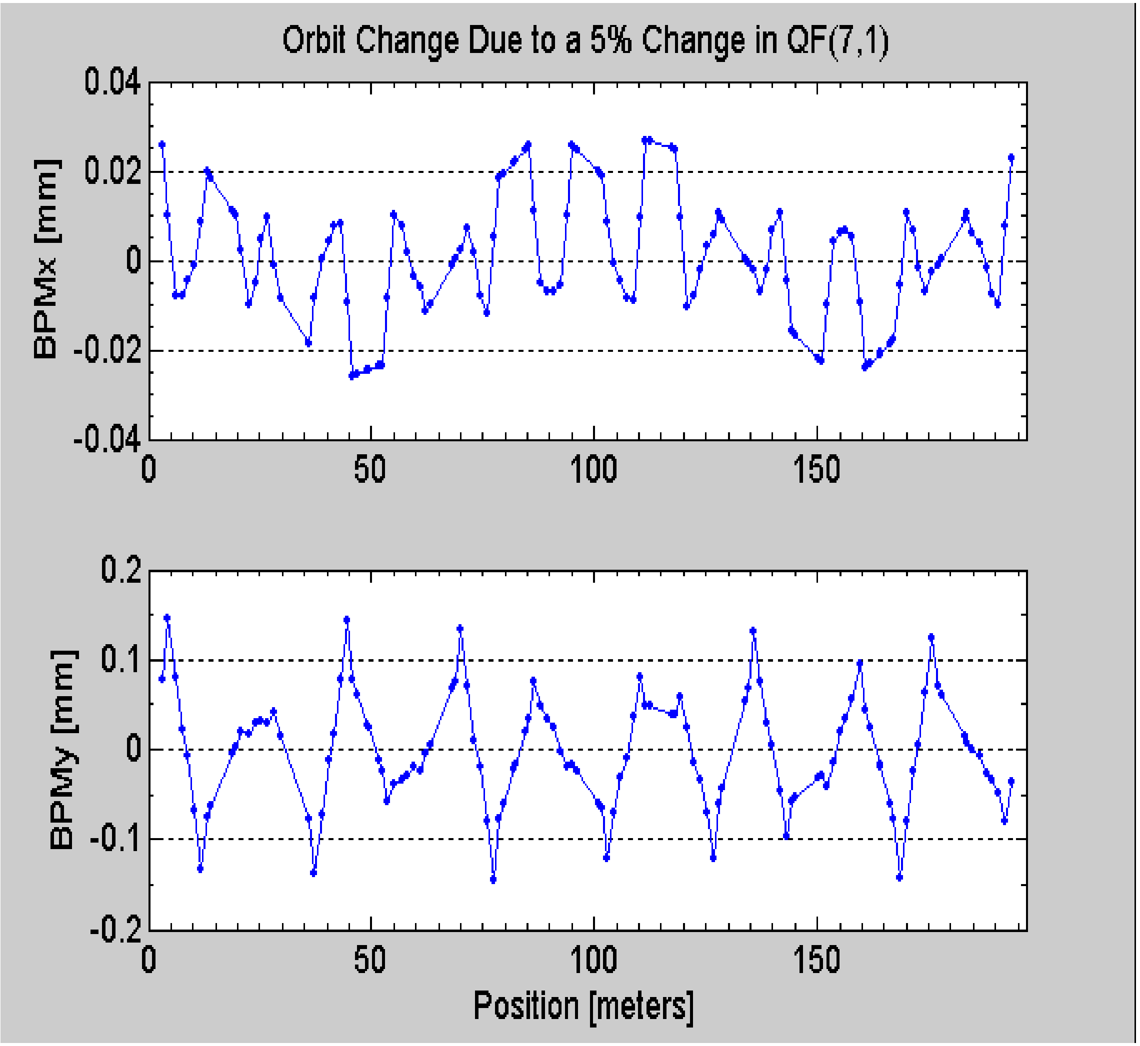
Beam Based Alignment

- 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.





Orbit Change Due to a Quadruple Change



Orbit change for a quadrupole change

(A. Wolski & F. Zimmermann)

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

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

x_{off} = Initial offset at the quadrupole

K_i = Initial focusing value

K_f = Final focusing value

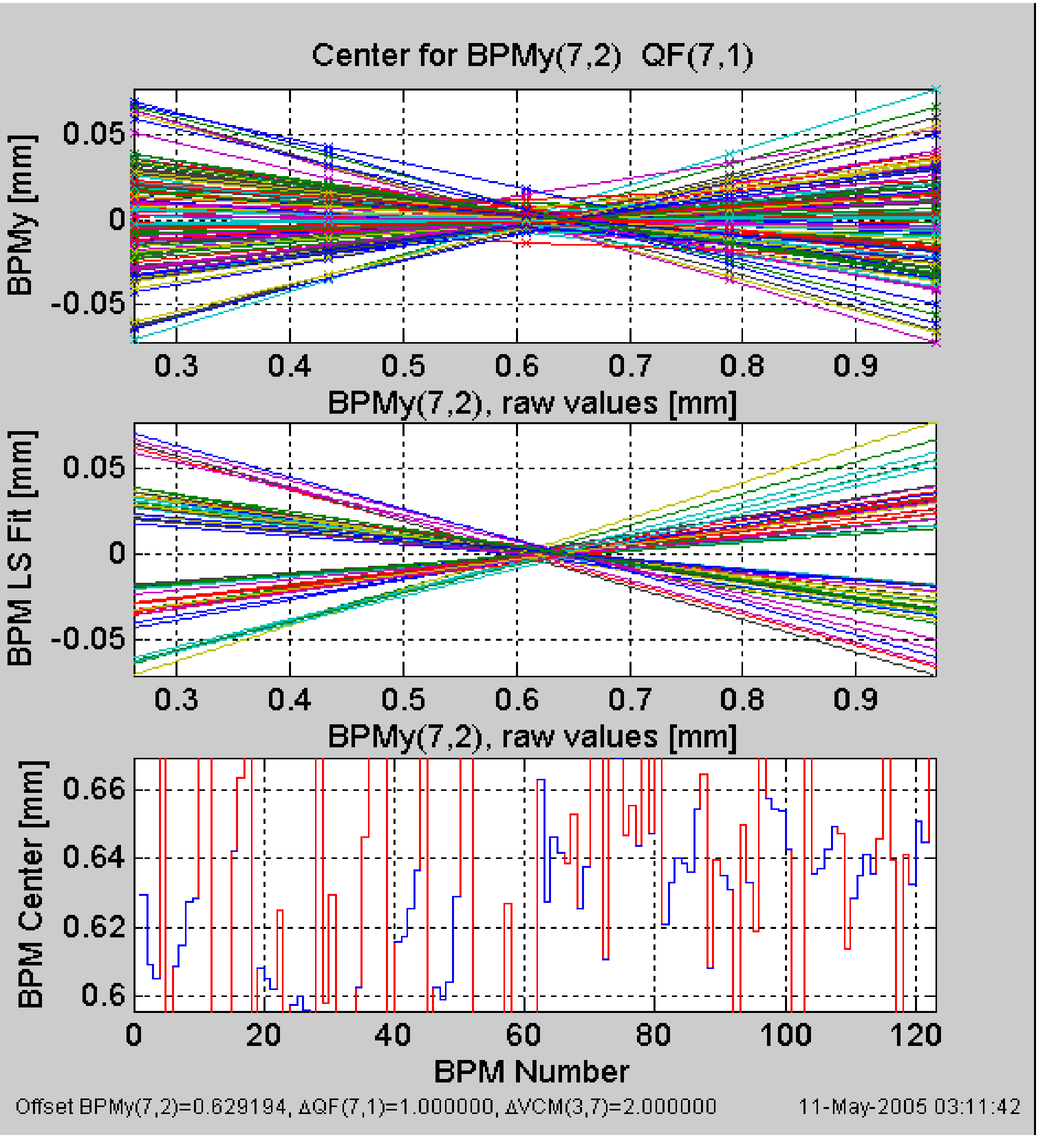
Δx = Transverse position

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

β = Beta function

ψ = Phase advance

Beam Based Alignment at the ALS



- 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.
- Offsets 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
- 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