Basic Measurements: Closed Orbit

Orbit stability is one of the most important requirement in accelerators

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

Motivation

- There are many reasons why good orbit stability is necessary:
- Accelerator Physics:
  - Changes in orbit cause changes in gradient distribution (e.g. horizontal offset in sextupoles) or coupling (vertical offset in sextupoles)
  - The dipole errors that cause the orbit changes directly create spurious dispersion (can lead to emittance increase, synchro-betatron coupling, deleterious effects from beam-beam interactions, …) or change the beam energy.
  - Photon beams can be missteered, resulting in damage.
  - Beam-beam overlap at interaction point.
- Users:
  - Stability of photon source point (flux through apertures, photon energy after monochromator, motion of beam spot on inhomogenous sample, …)
  - Stability of interaction point in colliders.

Motivation: User requirements at Light Sources

Most users at the ALS are happy with current level of orbit stability (about 1-2 micron integrated rms motion for frequencies > 0.1 Hz, submicron on the second timescale and a few microns on the h to week timescale)

Two examples of experiments that currently are the most sensitive:

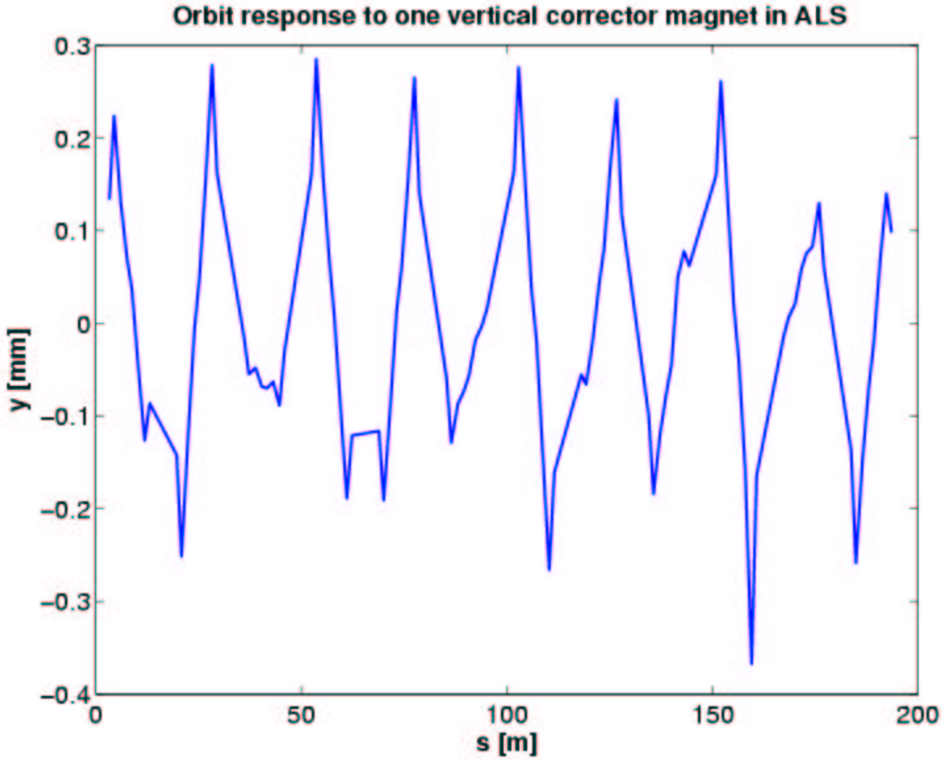
- Micro focusing beamlines on bending magnets (e.g. Micro XAS, especially in combination with molecular environmental science samples, i.e. dirt); problem is that sample is very inhomogenous and small source motion causes the spectrum to change significantly. I_0 normalization does not help!
- Dichroism experiments (i.e. on EPUs) measuring very small polarization asymmetries; orbit motion can cause small shifts of the photon energy out of the monochromator, resulting in fake asymmetries.

After upgrades to the slow orbit feedback (arc sector, chicanes) and the EPU feed-forward, both types of experiments are currently OK with the orbit stability. But orbit jitter shows up as noise in some measurements (relatively short data taking time for each point of spectrum) and experimental techniques are progressing towards measuring smaller effects.

Also: Compensation of beam size variation will introduce orbit errors …

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.



Closed orbit errors

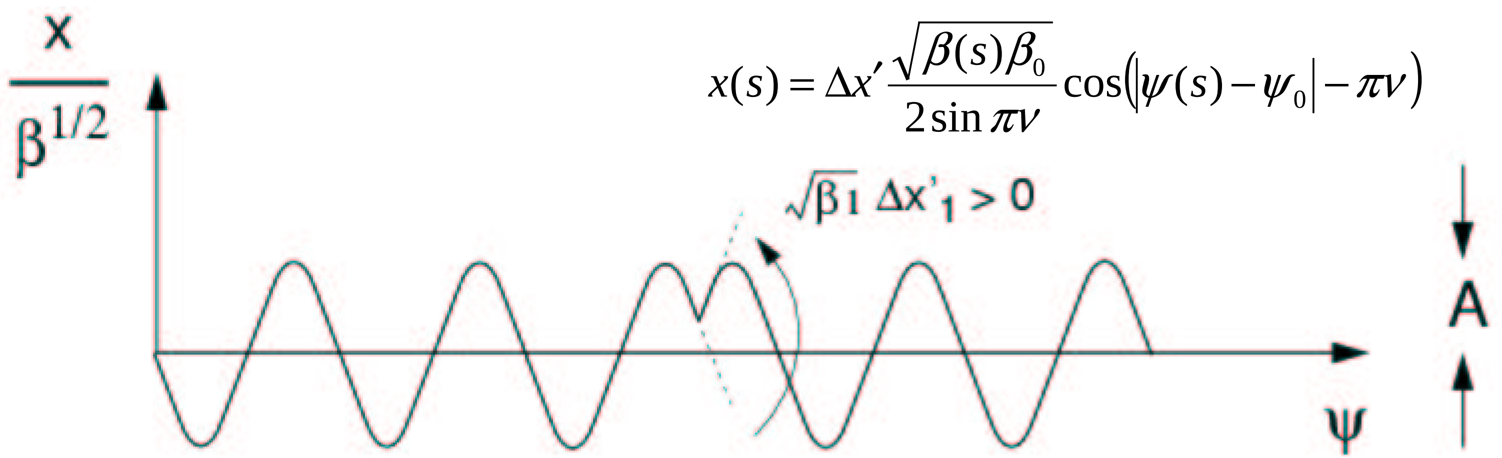
❖ A single dipole error will create an orbit distortion which looks very simple in normalized coordinates:

$$\begin{pmatrix} x_0 \\ x_0' - \Delta x' \end{pmatrix} = M_U \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

$$M_U = \begin{pmatrix} \cos 2\pi\nu + \alpha_0 \sin 2\pi\nu & \beta_0 \sin 2\pi\nu \\ -\gamma_0 \sin 2\pi\nu & \cos 2\pi\nu - \alpha_0 \sin 2\pi\nu \end{pmatrix}$$

$$\Rightarrow x_0 = \Delta x' \frac{\beta_0}{2\tan \pi\nu}; x_0' = \frac{\Delta x'}{2}\left(1 - \frac{\alpha_0}{\tan \pi\nu}\right)$$

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



❖ The matrix containing the change in position at every BPM to a kick from every corrector magnet is called orbit response matrix. 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

Capacitive Pickups

❖ Standard method used at all ‘high’ energy storage rings

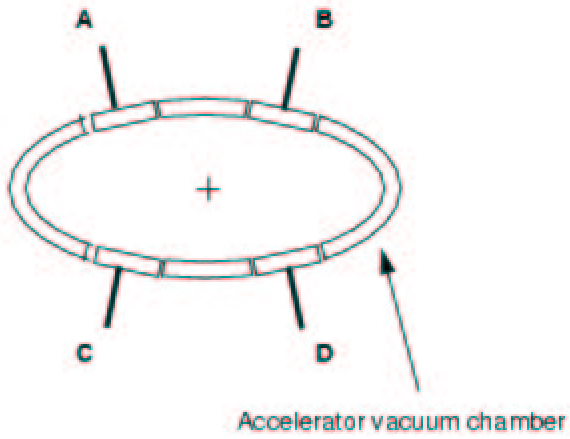
Charged Particle Beam Pickup Electrodes

Capacitive buttons

- Broadband, up to > 10 GHz
- Most effective when button diameter is comparable to the bunch length
- Minimal wakefield interaction with beam

$$X = K_x \frac{A-B+C-D}{A+B+C+D}$$

$$Y = K_y \frac{A+B-C-D}{A+B+C+D}$$



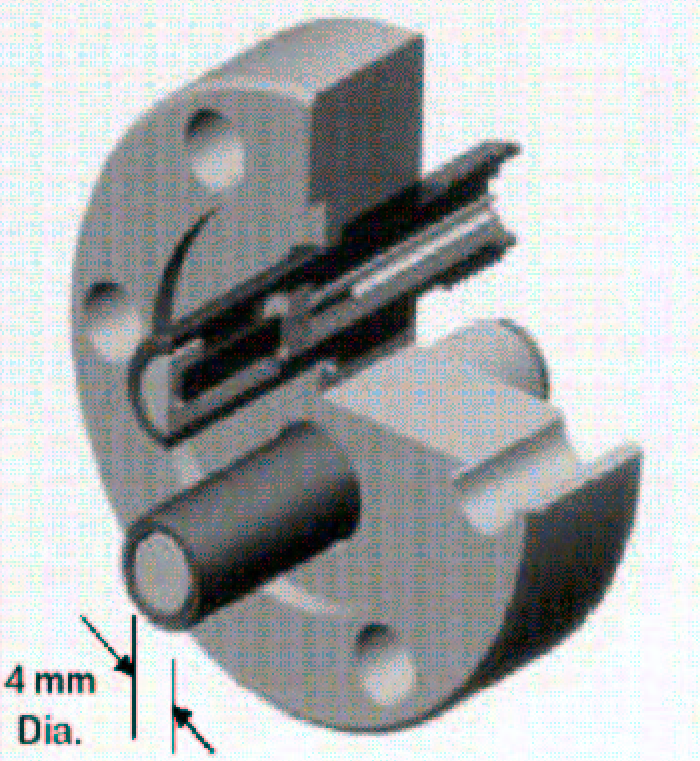
e.g. for round buttons of radius a in round pipe of radius r

$$Z_t(\omega) = V_p / I_b = \frac{a^2 \omega}{2 r \beta c} \frac{R}{(1 + j\omega RC)}$$

where $\beta = v/c$,
R = Transmission line impedance,
C = Button capacitance

Capacitive Pickups

P



Drawing courtesy J. Hinkson ALS

Electrical Specifications:

Frequency: DC to 20 GHz
Impedance: 50 ohm nominal, terminated by a capacitive button
Capacitance: 4.8 pF nominal
VSWR: 1.03:1 max. to 3 GHz, 1.15:1 to 20 GHz
Insertion loss: 0.1 db max. to 3 GHz, 0.5 db max. to 20 GHz
Matching: +/- 0.5 ohm in impedance, and +/- 0.1 pF in capacitance.
Connector: SMA female ,hermetically sealed with glass insulator.
Dielectric Strength: >1500 V at 50/60 Hz
Leakage Resistance: > 10^{13} ohm, from center conductor to outer housing

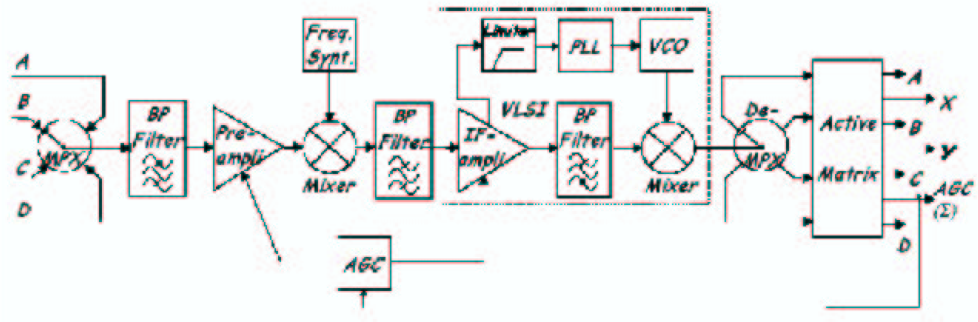
Mechanical Specifications:

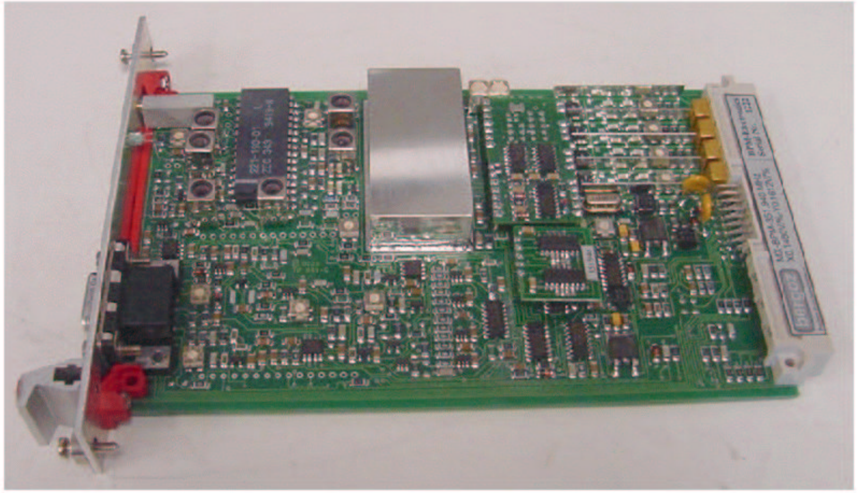
Diameter: 4 mm
Materials: As per Kaman P/N 853881-001
Hermeticity: <10-11 cc He/sec
Radiation: >200 megarads gamma

Signal Processing Electronics

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

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



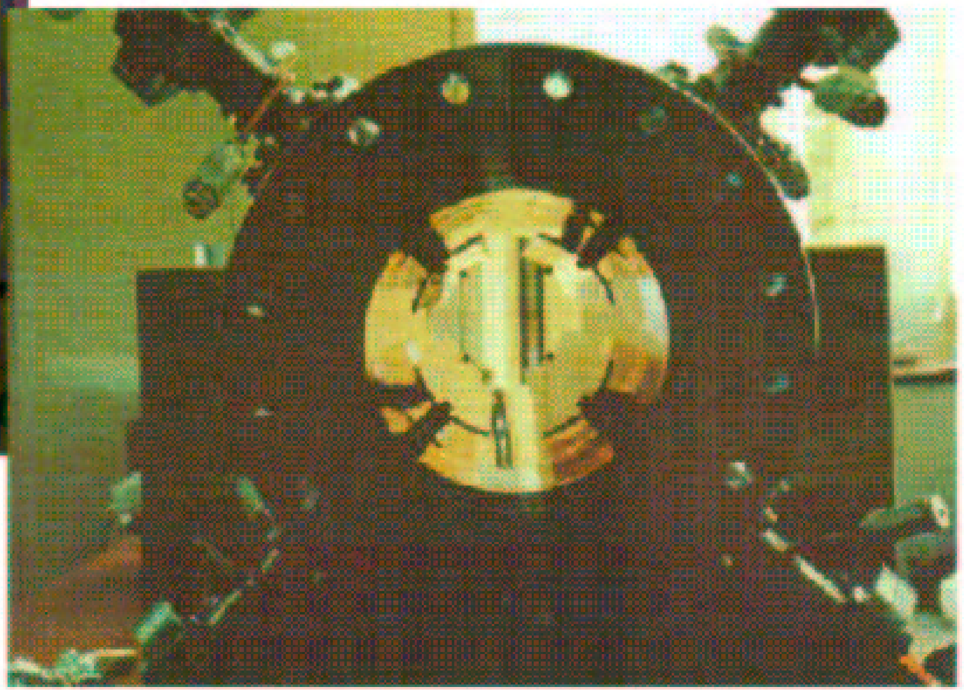


Typical F_{rf} = 60 to 800 MHz ,
Receiver IF bandwidth as narrow as a few hundred kHz
Position signal (X or Y) bandwidth a few kHz

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

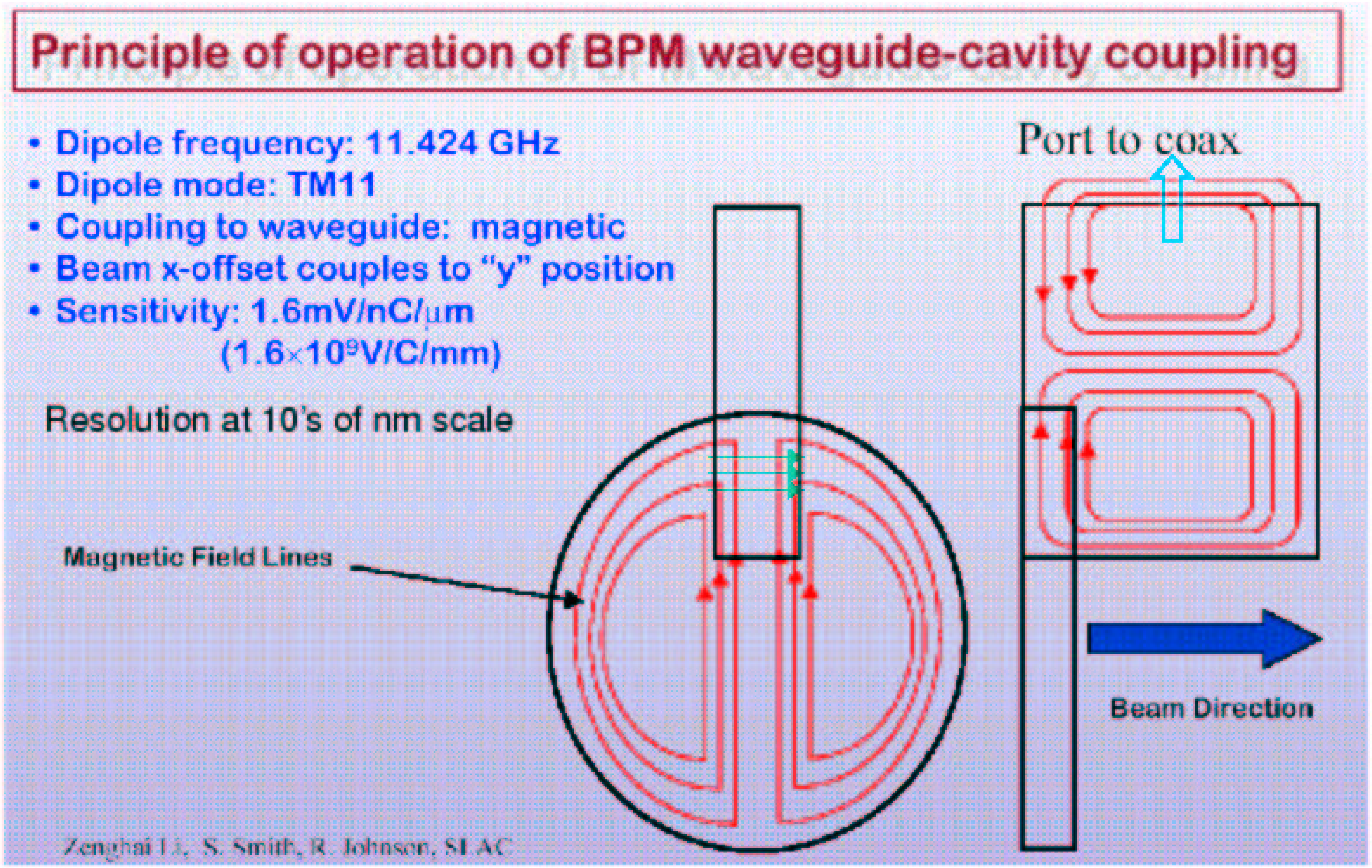
Stripline Pickups

M. Wendt, DESY



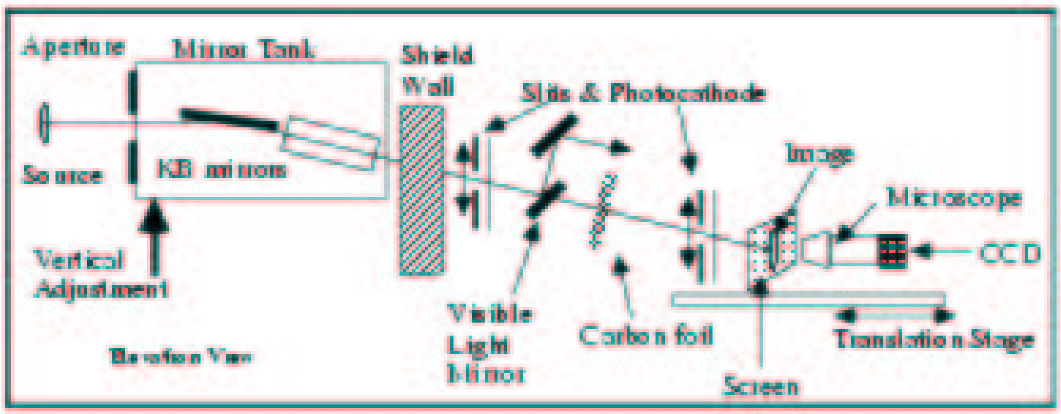
M. Tobiyama, KEK

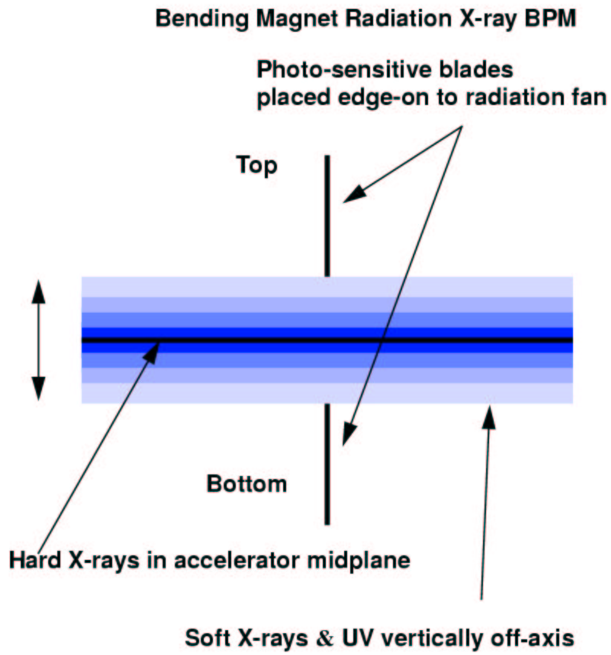
Cavity BPMs



Principle of operation of BPM waveguide-cavity coupling
• Dipole frequency: 11.424 GHz
• Dipole mode: TM11
• Coupling to waveguide: magnetic
• Beam x-offset couples to "y" position
• Sensitivity: 1.6mV/nC/μm
(1.6×10⁹V/C/mm)
Resolution at 10's of nm scale
Magnetic Field Lines
Port to coax
Beam Direction
Zenghai Li, S. Smith, R. Johnson, SLAC

Synchrotron Radiation Diagnostics





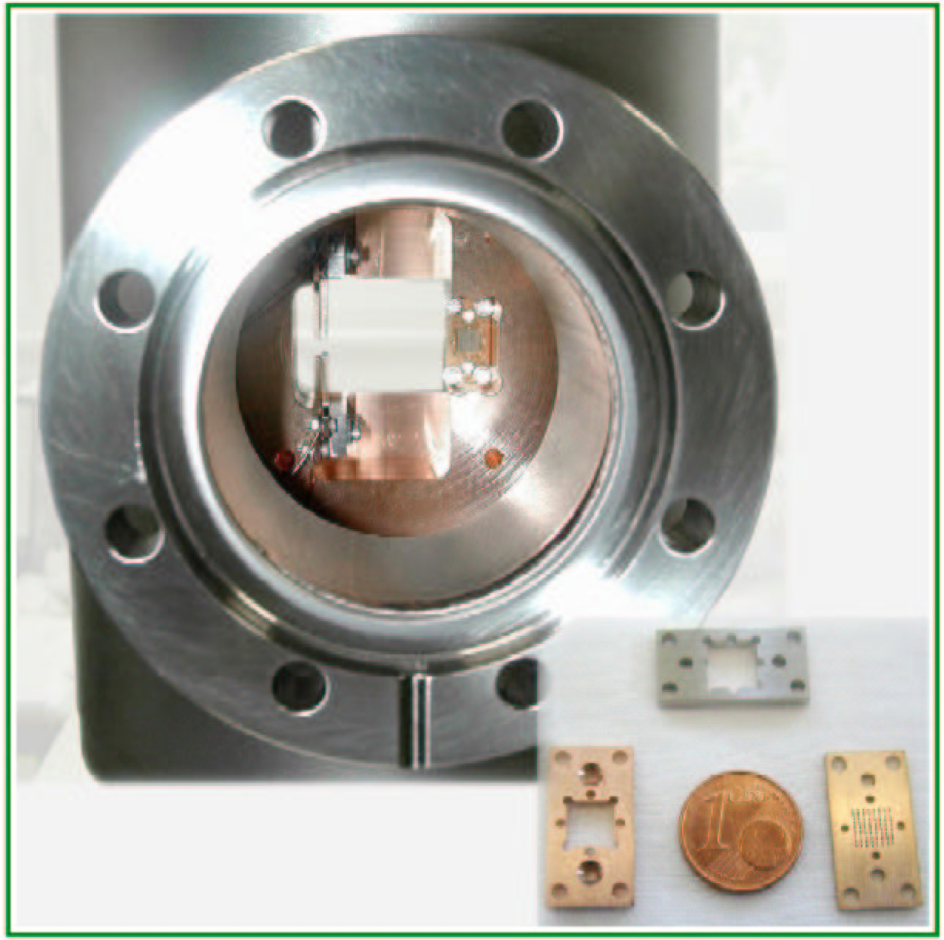
- ❖ Synchrotron Radiation (x-rays) allow precise profile measurements (diffraction limit) and precise position measurements
- ❖ Directly measure signal users are sensitive to
- ❖ Use imaging optics (pinhole, mirrors) for profile+position measurements and blade monitors for position measurements

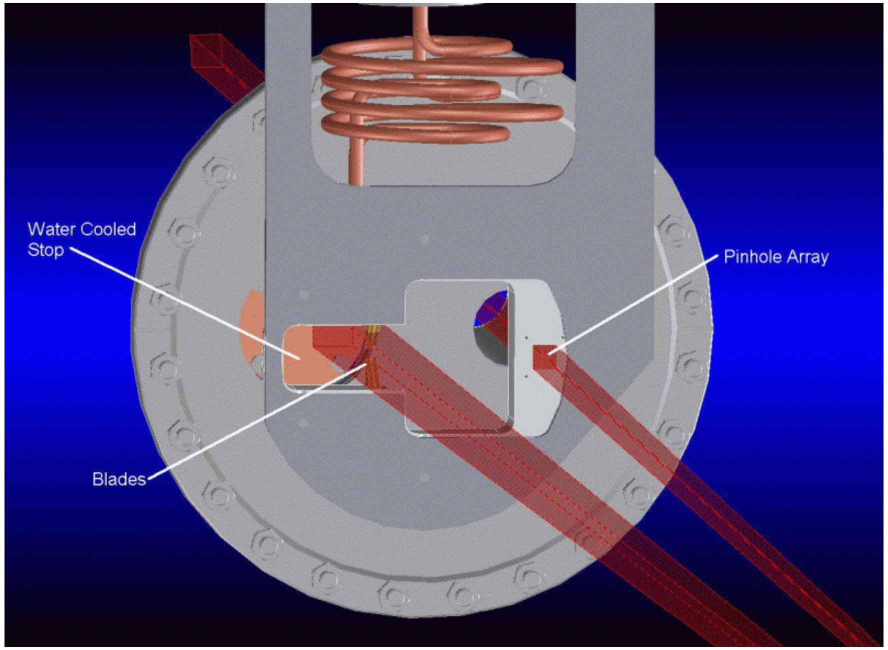
Synchrotron Radiation Diagnostics II

FMB Feinwerk- und Meßtechnik GmbH

Friedrich-Wöhler-Straße 2

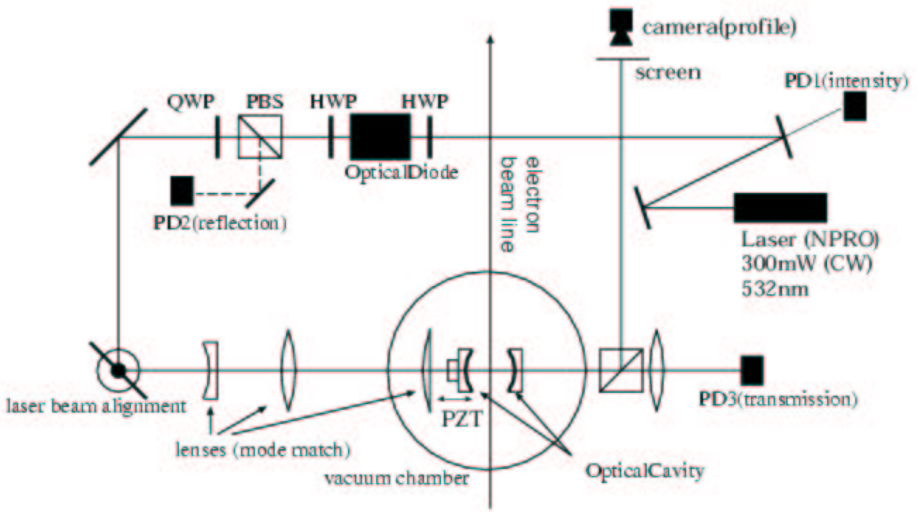
D-12489 Berlin (Germany)

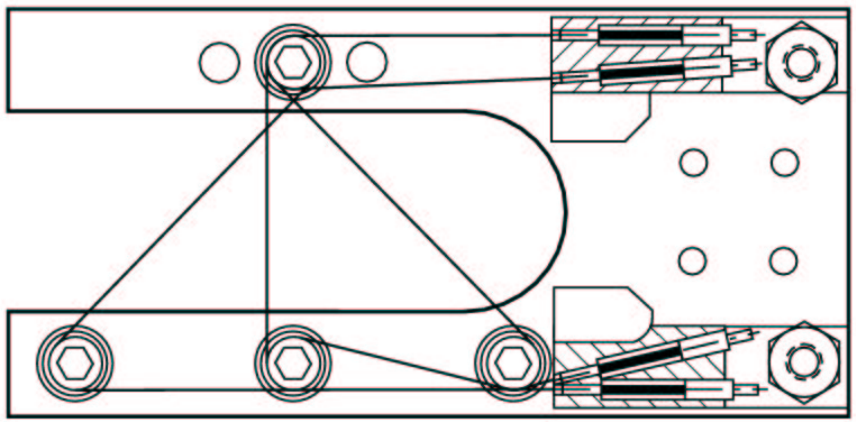




Wire Scanners/Flying Wires/Laser Wires/Screens

- 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.



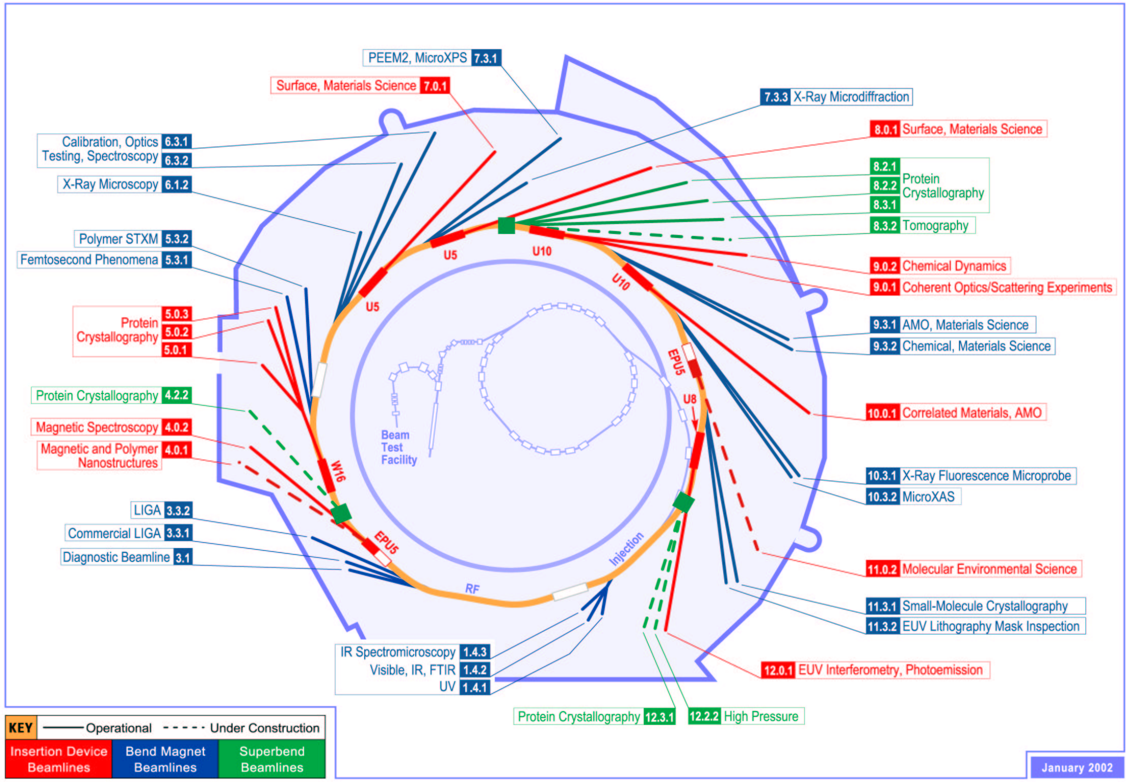


Aerial view of the Advanced Light Source

jc/ALSaerial/11-96

ALS Parameters:

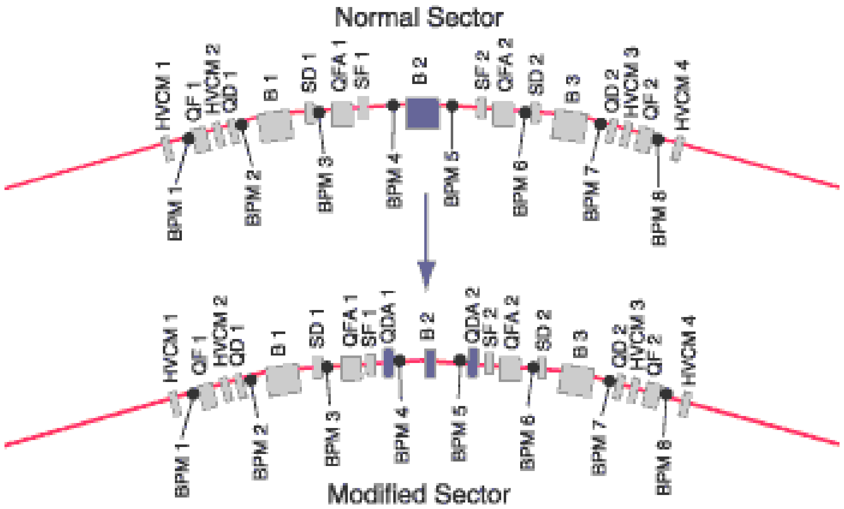
Nominal Energy	1.5-1.9 GeV
Circumference	196.8 m
RF frequency	499.642 MHz
Harmonic number	328
Beam current	400 mA multibunch 65 mA two-bunch
Nat. emittance	6.3 nm at 1.9 GeV
Emittance Coupling	Typical about 2%
Nat. energy spread	0.097%
Refill period	3 times daily multibunch, 12 times daily, two-bunch

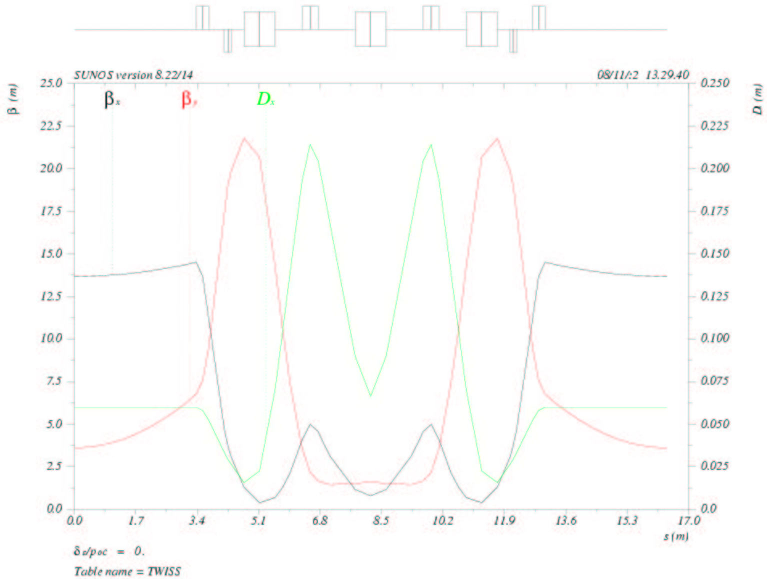


Beam Location	Horizontal	Vertical
Straight Section	30 μm	2.3 μm
Bend Magnet #2	10.3 μm	1.3 μm

1/10 Electron Beam Size $\Rightarrow$

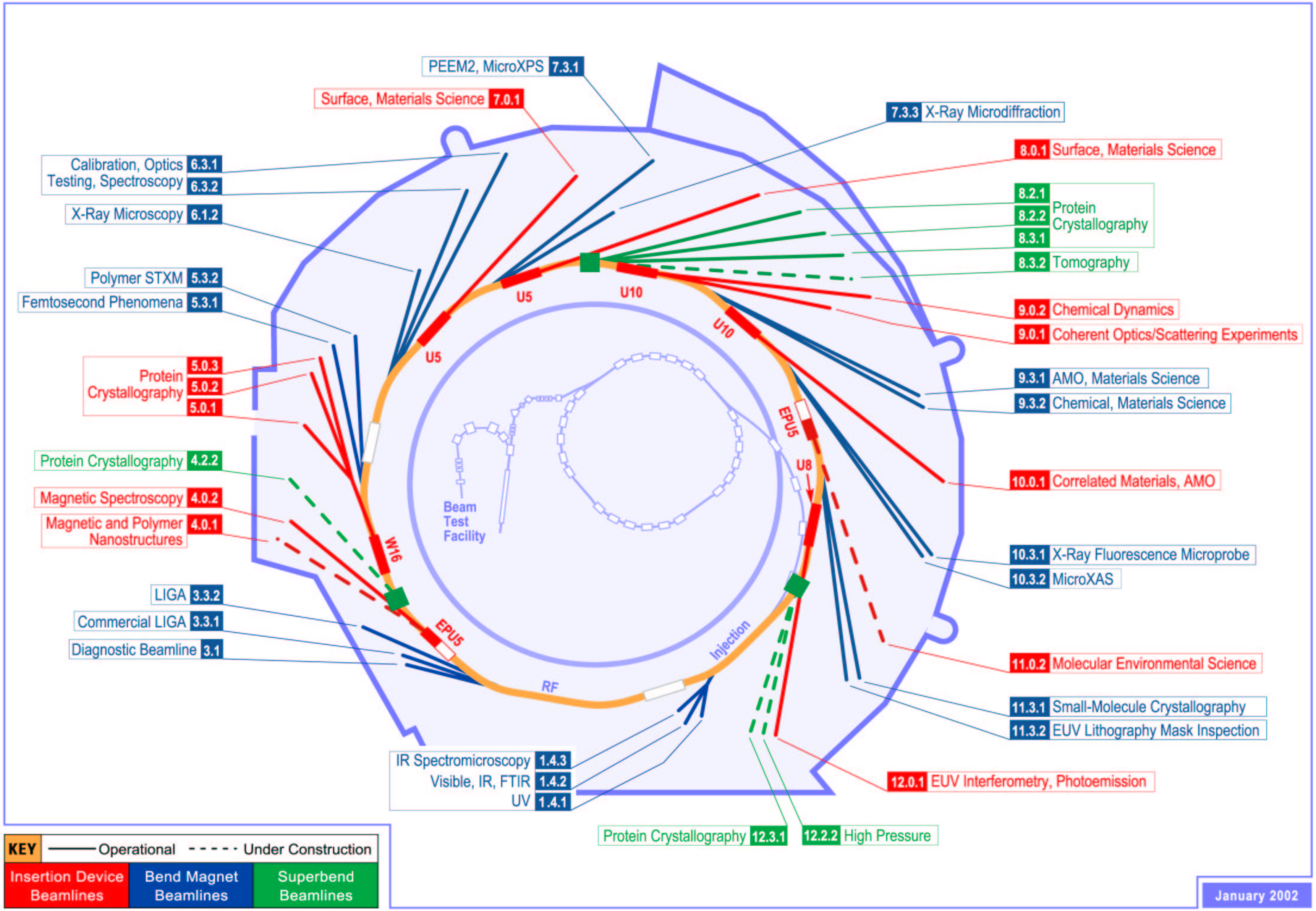
ALS Lattice





- 12 nearly identical arcs – TBA; aluminu
- 96+40 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

Beamlines at the ALS 2002



Instrumentation at the ALS

I. Beam position monitors (BPMs)

Old in-house design (96) plus J. Hinkson/J. Bergoz multiplexed BPMs (currently 40); Bergoz BPMs used in feedback: noise level is about 0.3 – 0.5 microns at 200 Hz bandwidth and 200-400 mA; current dependence less than 5 micron for 200-400 mA

II. Photon beam position monitors (PBPMs)

Several very diverse designs; not integrated with accelerator control system; some beam-lines use them for local feedback (time-scales of feedback range from hours to ms); testing of new hopefully more unified PBPMs to start soon (on bend magnets)

III. Power supplies

All power supplies at ALS are SCR or linear; no switched mode. Noise level is typically less than 10^{-4} integrated over all frequencies (some main supplies 10^{-5}). 16-20 Bit control (all corrector magnets are 20 Bit); corrector bandwidth about 100 Hz.

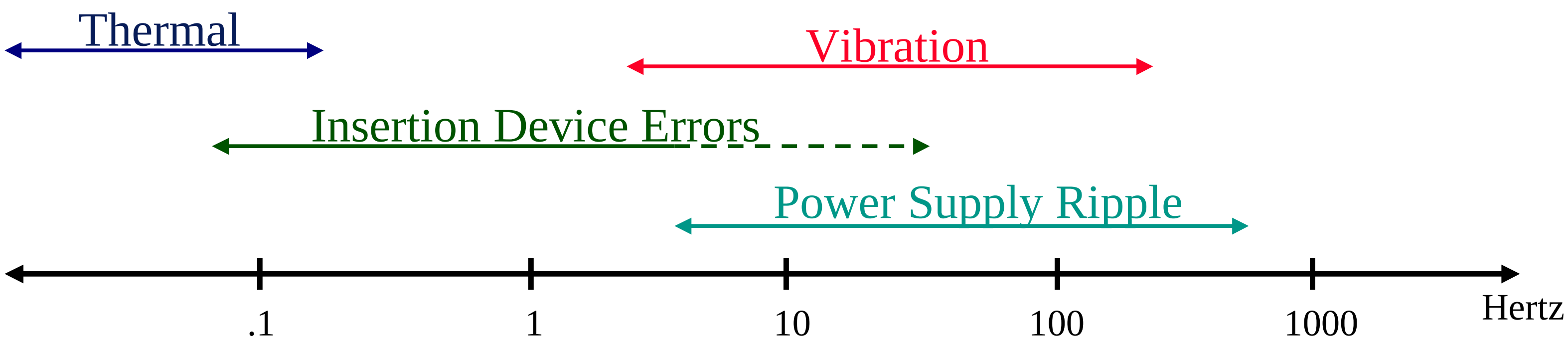
IV. Control system

High level control system has throughput of about 100 Hz and delays of less than 10 ms after upgrade. Low level (fast feedback – distributed cPCI crates) runs at 1 kHz with standard computer and network equipment, network synchronized timing; commissioning is promising so far

V. Other

Tested some simple methods to measure BPM and magnet motion; plan to incorporate measurement of BPM position relative to common accelerator-experiment ground plate into feedback

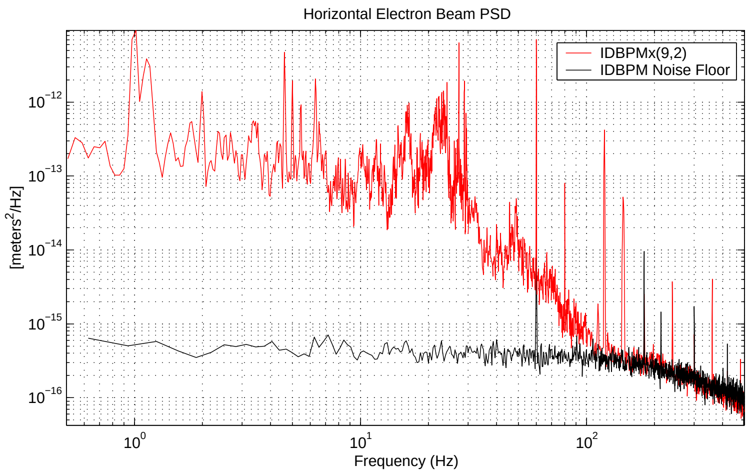
Causes for Orbit Distortions

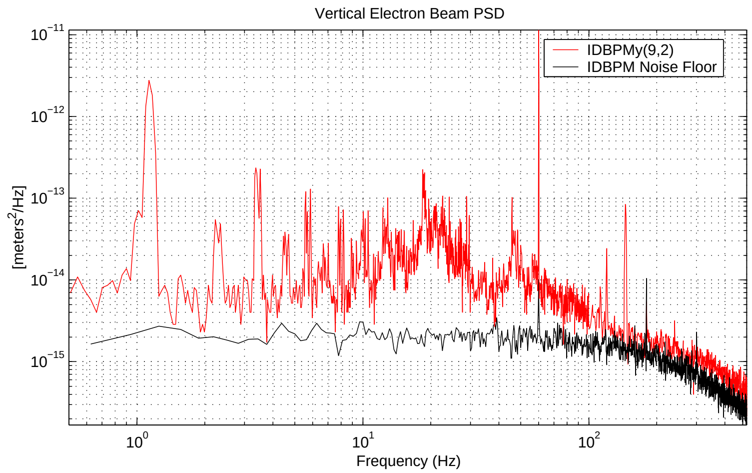


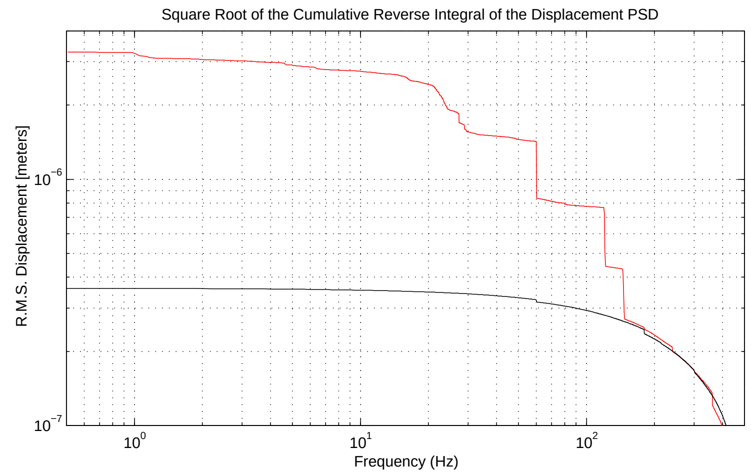
Frequency	Magnitude	Dominant Cause
Two weeks (A typical experimental run)	±200 μm Horizontal ±100 μm Vertical	1. Magnet hysteresis 2. Temperature fluctuations 3. Component heating between 1.5 GeV and 1.9 GeV
1 Day	±125 μm Horizontal ±50 μm Vertical	Temperature fluctuations
8 Hour Fill	±50 μm Horizontal ±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

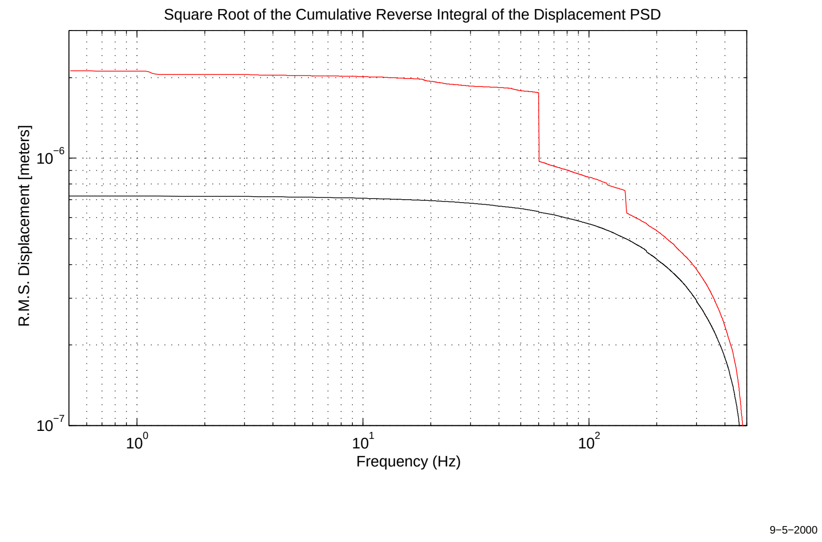
Beam Stability in straight sections w/o Orbit Correction, w/o Orbit Feedback, but w/ Insertion Device Feed-Forward

ELECTRON BEAM PSD

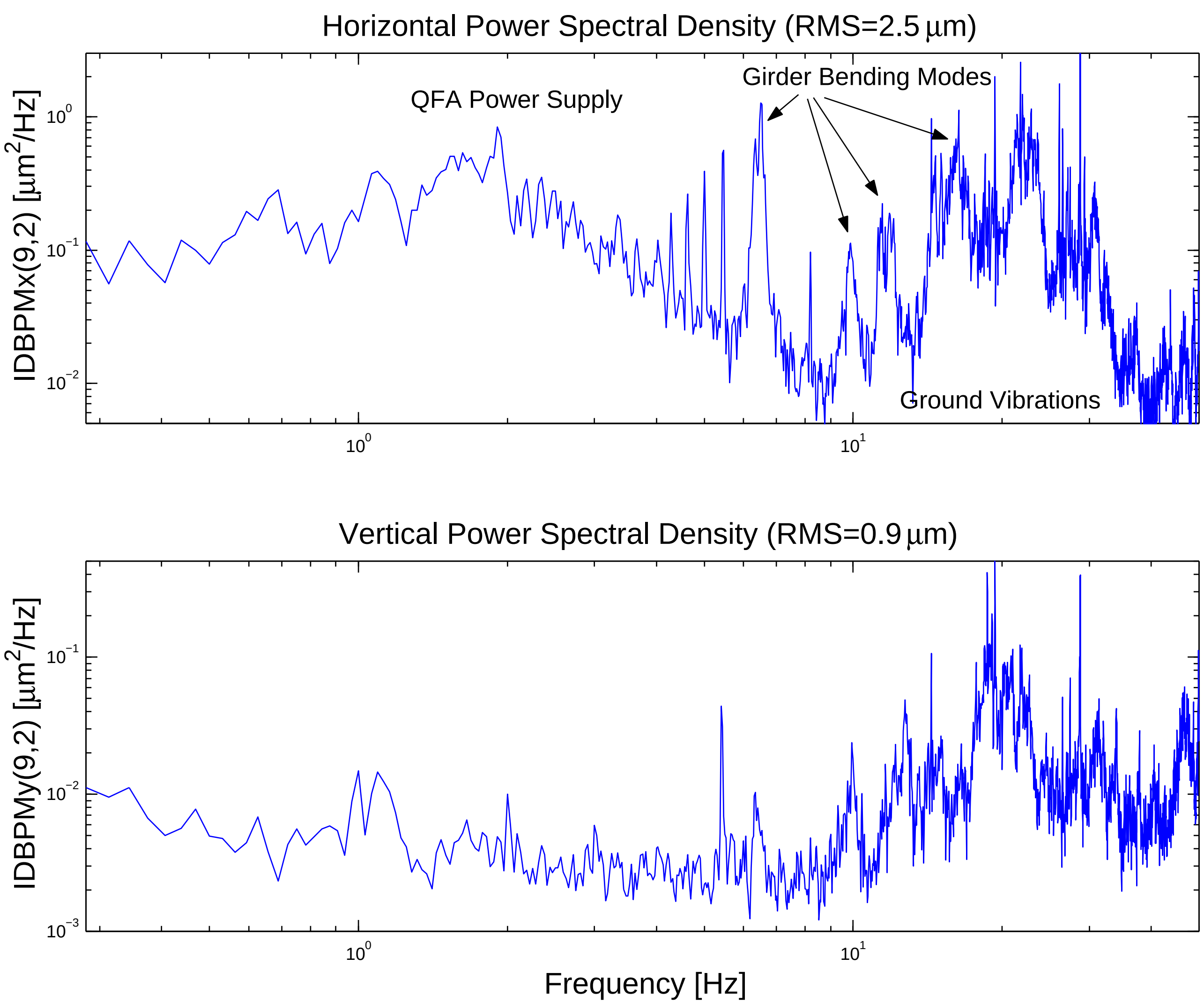






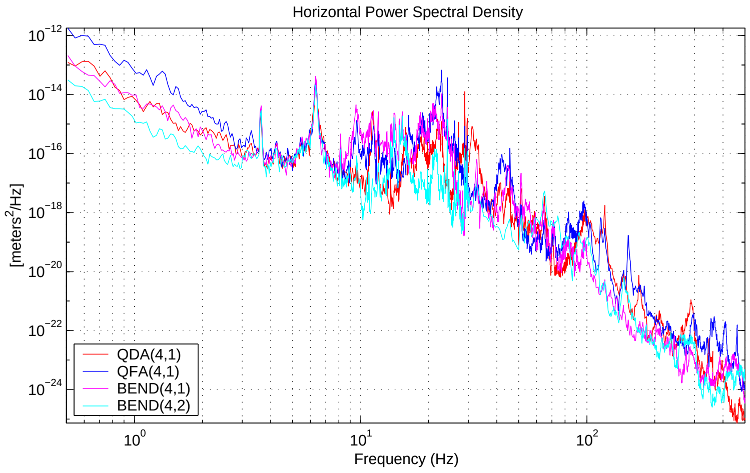


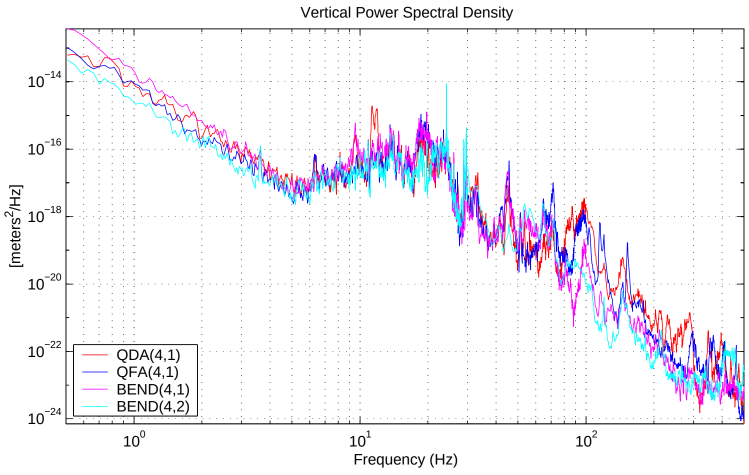
POWER SPECTRAL DENSITY

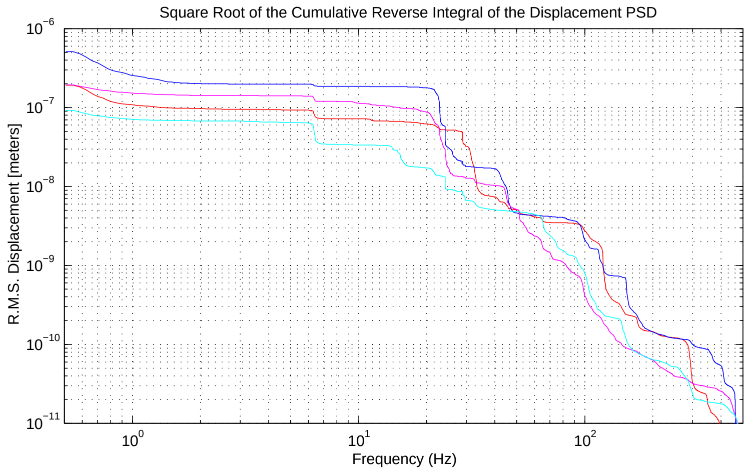


Data taken on 12−12−1999, during a 1.9 GeV user run at 278 mAmps

MAGNET VIBRATION PSD







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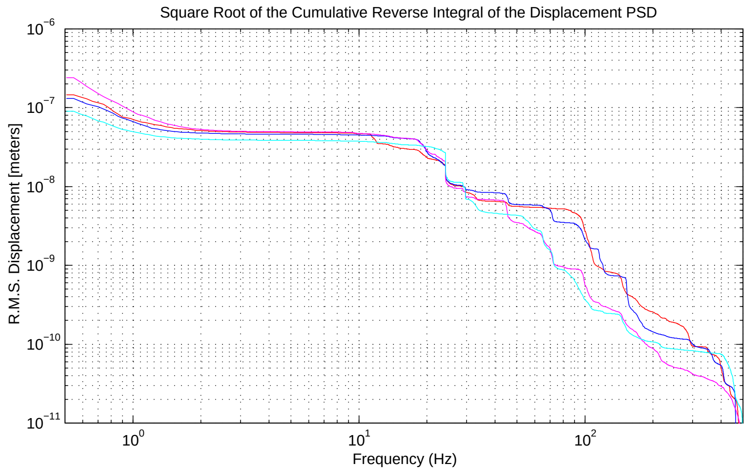

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Orbit Correction Methods

- 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.
- 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, …
- 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)

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

- Where U and V are orthogonal matrices (I.e. $U \cdot U^T = 1, \quad V \cdot V^T = 1$) and S 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
  - M is a set of many (single turn/single pass) orbit measurements
    - U contains an orthonormal set of spatial vectors
    - V contains an orthonormal set of temporal vectors
- Because of othogonality the inverse of M can be simply calculated:

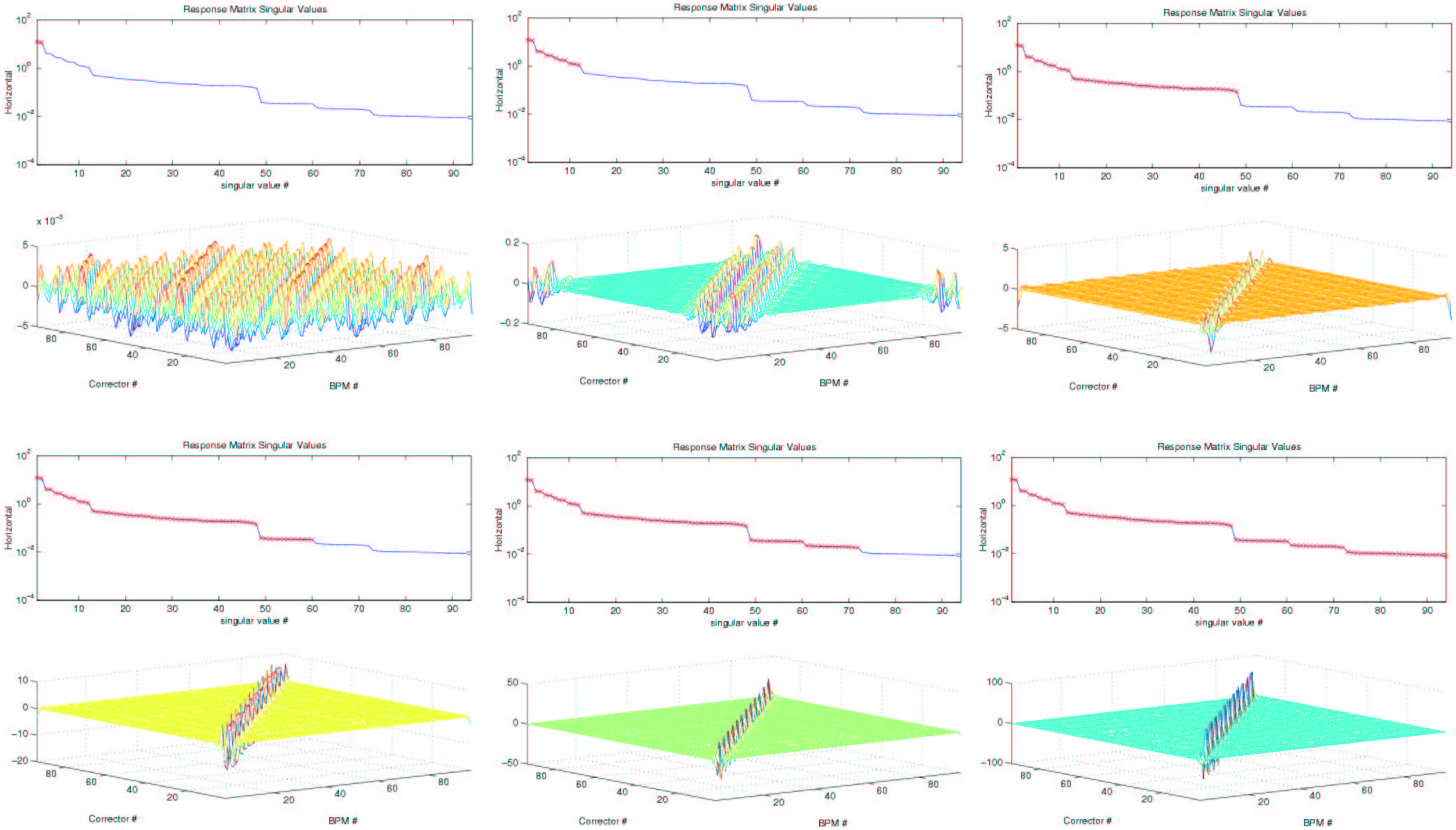
$$M^{-1} = \sum_i \vec{v}_i \frac{1}{\sigma_i} \vec{u}_i^T.$$

In case of very small singular values the inverse can be singular

Advantages of Correction Methods

- To use least square or direct matrix inversion one has to completely trust every BPM reading and in addition a lot of thought has to be put into the BPM and corrector locations (to avoid the creation of unobservable bumps). Methods have the advantage to really minimize the observable orbit error, work well for distributed/numerous error sources and effectively localize the correction.
- MICADO works very well in a case where one has only a few dominant error sources (like moving interaction region quadrupoles). It does not allow good correction for many error sources. If one selects many correctors, it has the same disadvantage as LSQ. One danger is that it alternatingly can select degenerate corrector magnets, resulting in unobservable bumps (IP).
- SVD allows to adjust its behaviour based on the requirements. Cutting very small singular values in the inversion will help to avoid unobservable bumps. Selecting less singular values makes the algorithm less sensitive to BPM errors. As long as a reasonable number of singular values is chosen, SVD still localizes the correction of errors and works well for multiple error sources. Most light sources nowadays use SVD.

Example: SVD inverted matrix vs. number of SVs



What has been done at the ALS to maximize stability

“PASSIVE”

(i.e. remove the sources)

- Temperature stability (air below 0.1, water below 0.5 degree peak-to-peak)
- Minimize water induced vibrations
- Power supply stability (no switched mode supplies, thick aluminum vacuum chamber in most magnets)
- Vibration - reduce the effects by mechanical design (ALS has big girders and moderate amplification factors) or remove the source (cryo-coolers).
- Reduce RF-phase noise (mode-0 noise for IR users)

FEED FORWARD

- Insertion device compensation (10 Hz for most IDs, 200 Hz for EPUs)
- Beta-beating, tune and coupling feed-forward presents additional challenges to orbit stability!

FEEDBACK

- Local orbit feedback (not routinely used at ALS)
- Global orbit feedback (1 Hz update rate operational, 1 kHz system in commissioning)
- BPM position detection incorporated into feedback (relative to common accelerator-experiment ground plate)
- Magnet or girder position feedback

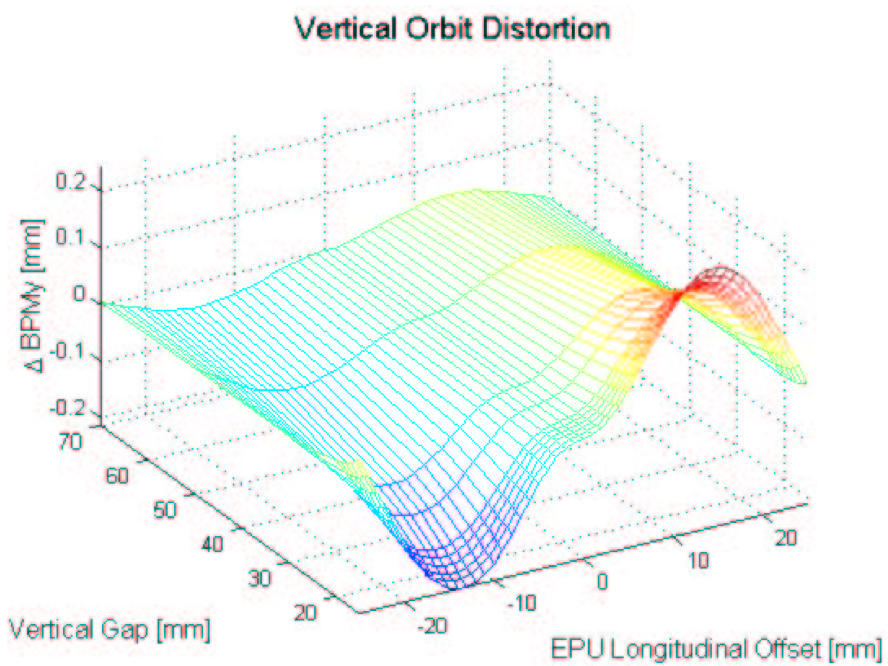
Feed-forward example: EPU COMPENSATION

Apple-II type elliptically polarizing undulators are more complex than other IDs

- The jaws can move in two directions (vertically and longitudinally)
- The motion in the longitudinal direction is fast (up to 17 mm/s at ALS)

This makes orbit compensation more difficult

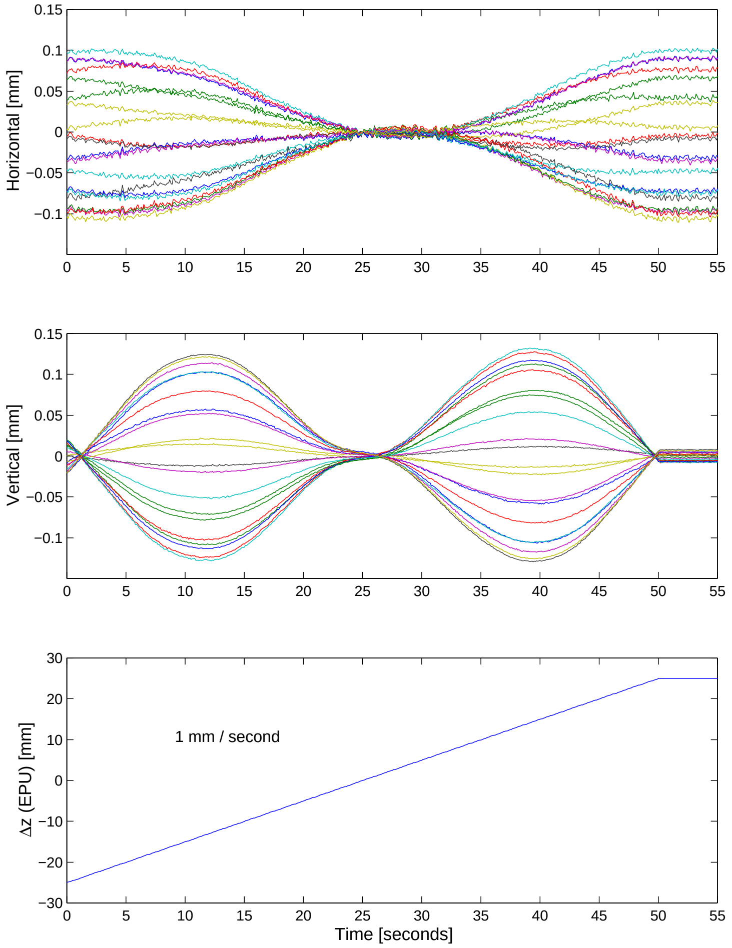
Mechanically the EPU can move from left to right circular polarization mode in ~1.6 seconds



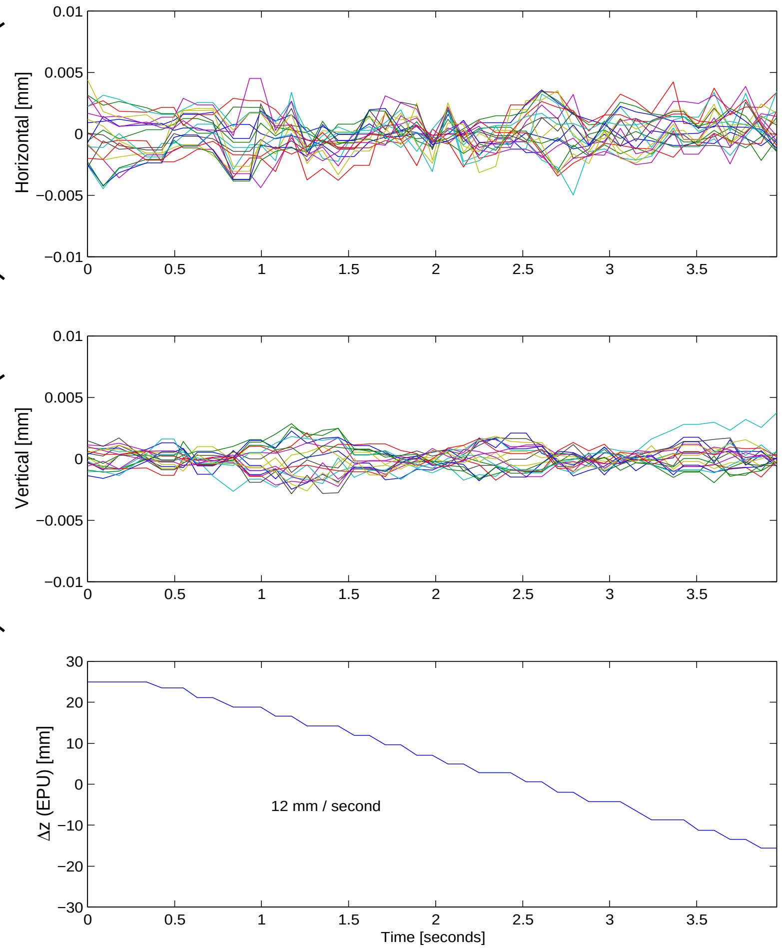
Without compensation the EPU would distort the electron beam orbit by ±200 μm vertically and ±100 μm horizontally. Using corrector magnets on either side of the EPU, 2-dimensional feed forward correction tables are used to reduce the orbit distortion to the 2-3 μm level. Update rate of feed-forward is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

EPU FEED FORWARD ORBIT CORRECTION

Orbit Error without Feed Forward Correction



200 Hertz Feed Forward Correction



Achieved orbit stability at ALS

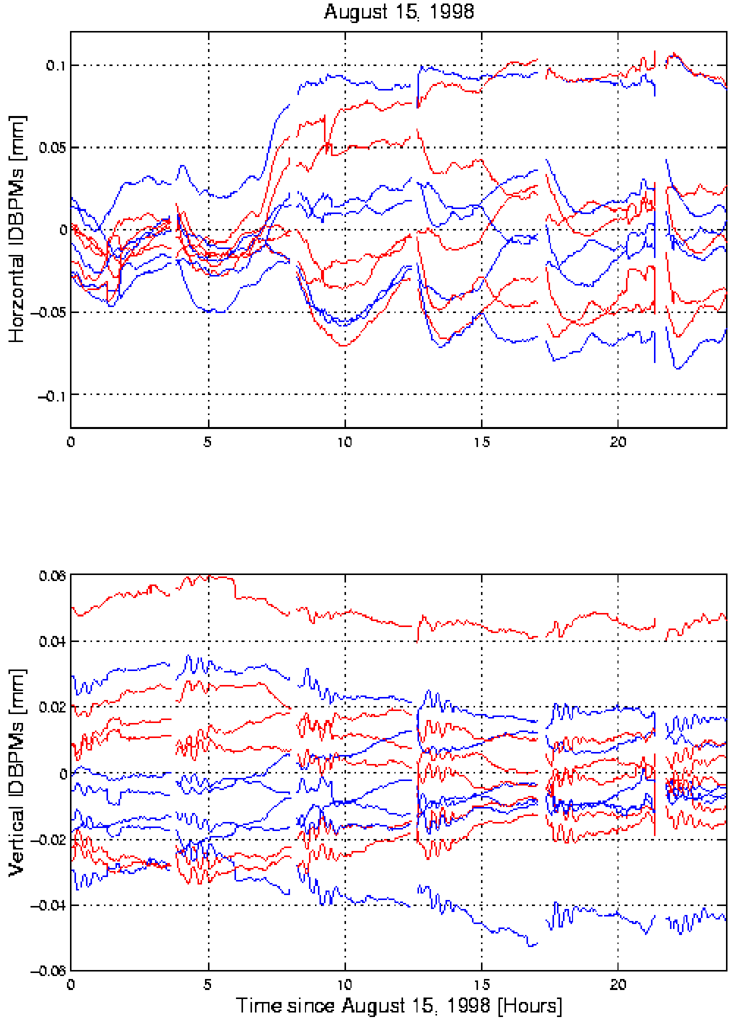
Frequency	Magnitude	Dominant Cause
1 hour – 2 weeks	±3 μm Horizontal ±5 μm Vertical	1. BPM chamber motion 2. BPM electronics drift and systematic errors 3. Limited number of BPMs/correctors
Minutes	< 1 μm	1. BPM noise and beam vibration (aliasing) 2. Corrector resolution (digitization)
.2 to 300 Hz	3 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/ Orbit Feedback and w/ Insertion Device Feed-Forward

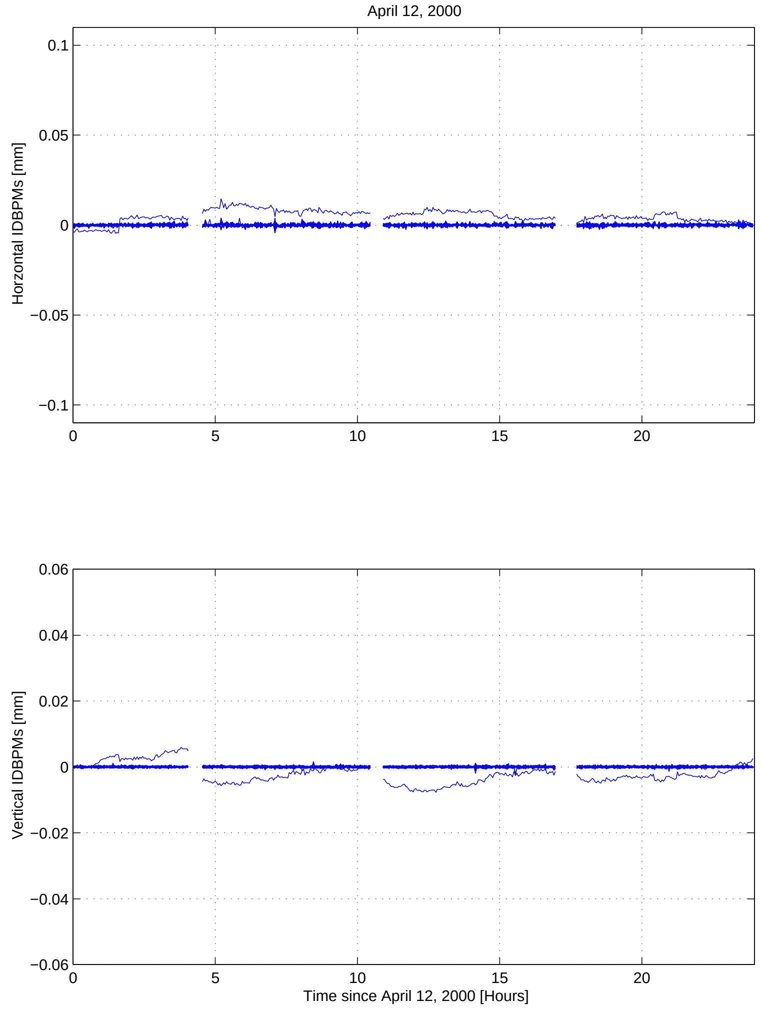
- Improve long term stability with measurement of physical BPM location (relative to ground plate)
- Improve fast jitter with active fast feedback (global)

DAILY ORBIT VARIATIONS WITH AND WITHOUT SLOW ORBIT FEEDBACK

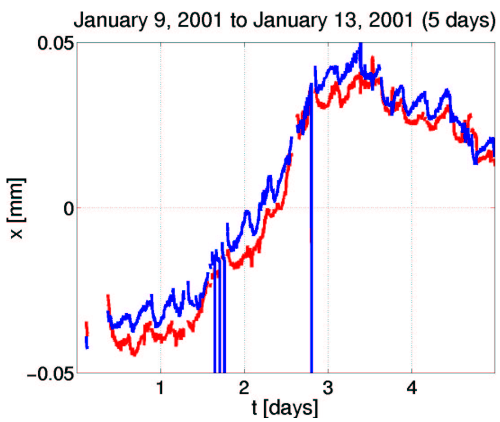
w/ ID Compensation
August 15, 1998: w/o Orbit Correction
w/o Slow Orbit Feedback

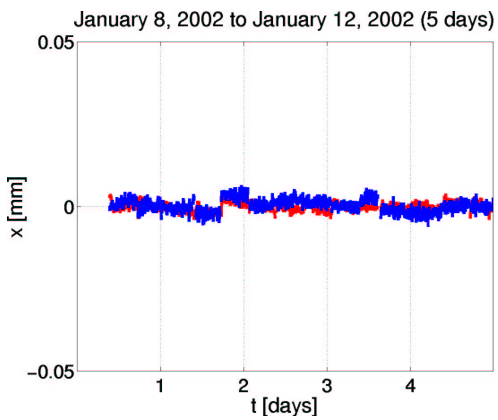


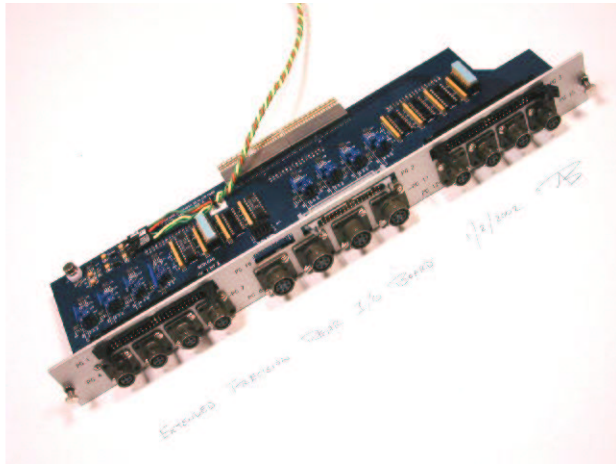
w/ ID Compensation
April 12, 2000: w/ Orbit Correction
w/ Slow Orbit Feedback

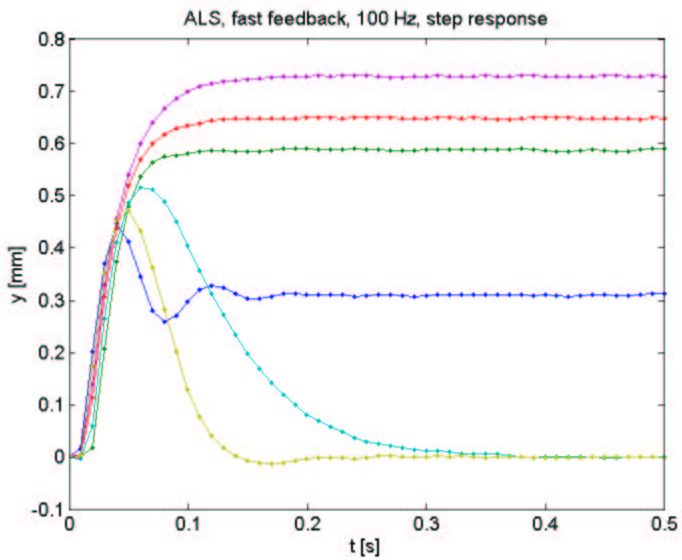


Recent Orbit Feedback Upgrades at ALS





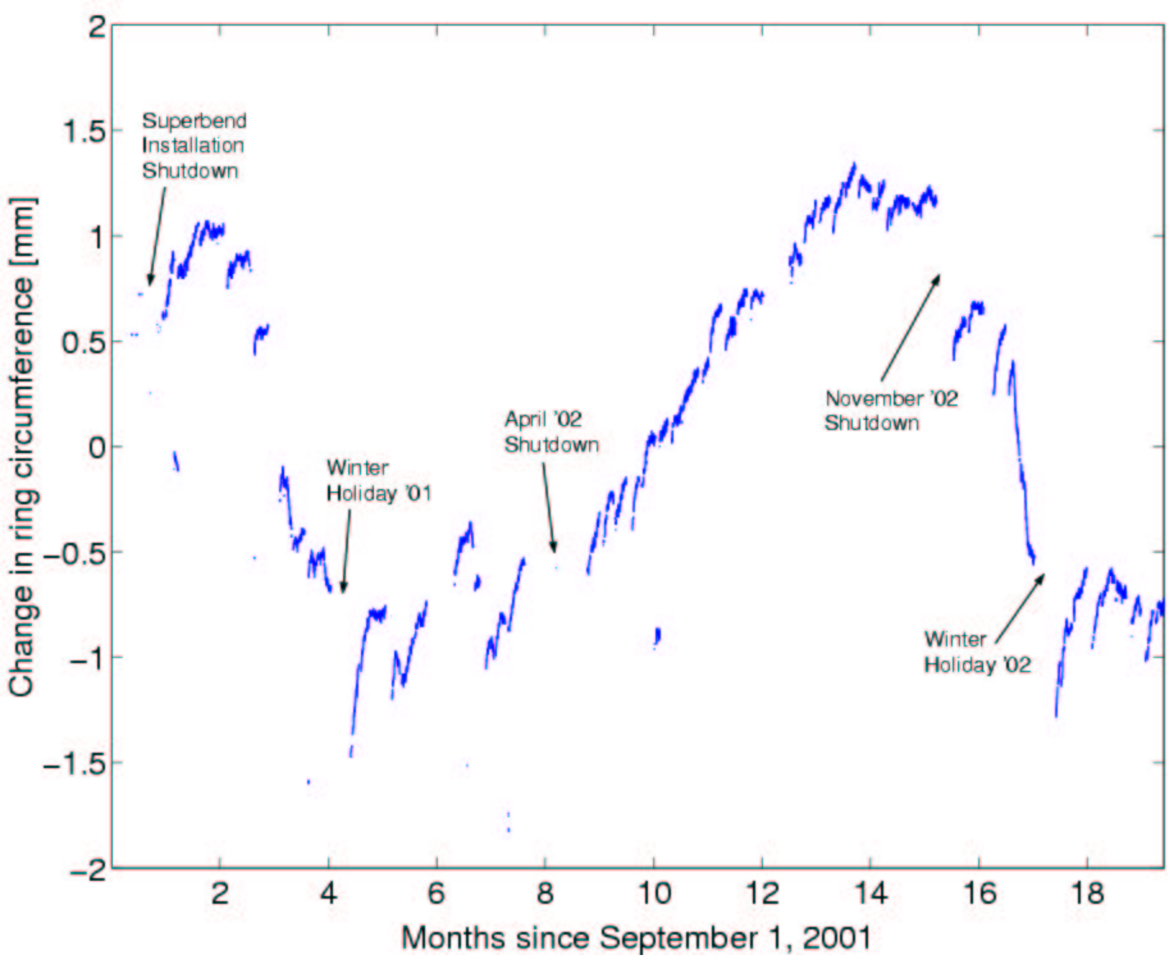




- RF-frequency feedback (significantly improved hor. orbit stability in arcs, energy stability)
- 20 Bit D/A converters (no digitization noise from SVD – mid term orbit stability now typically submicron)
- Start of commissioning of fast orbit feedback (standard hardware, 1 kHz update rate)

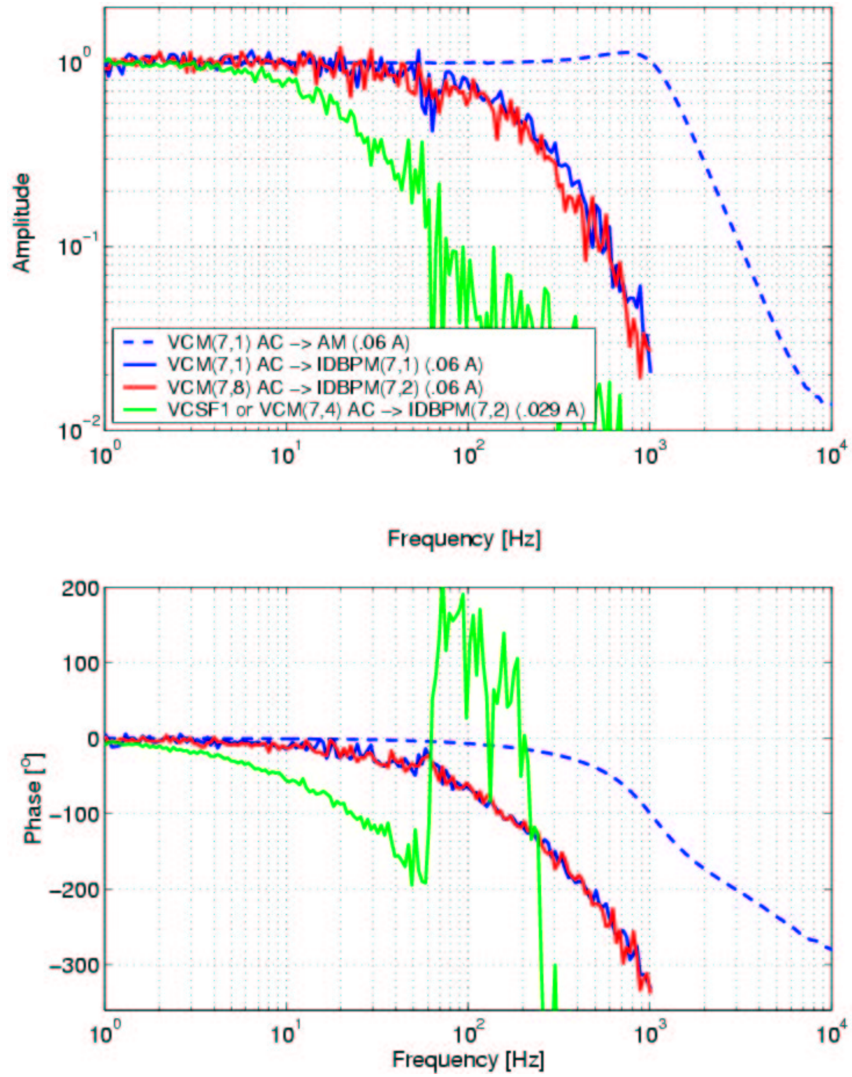
RF frequency feedback

- 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

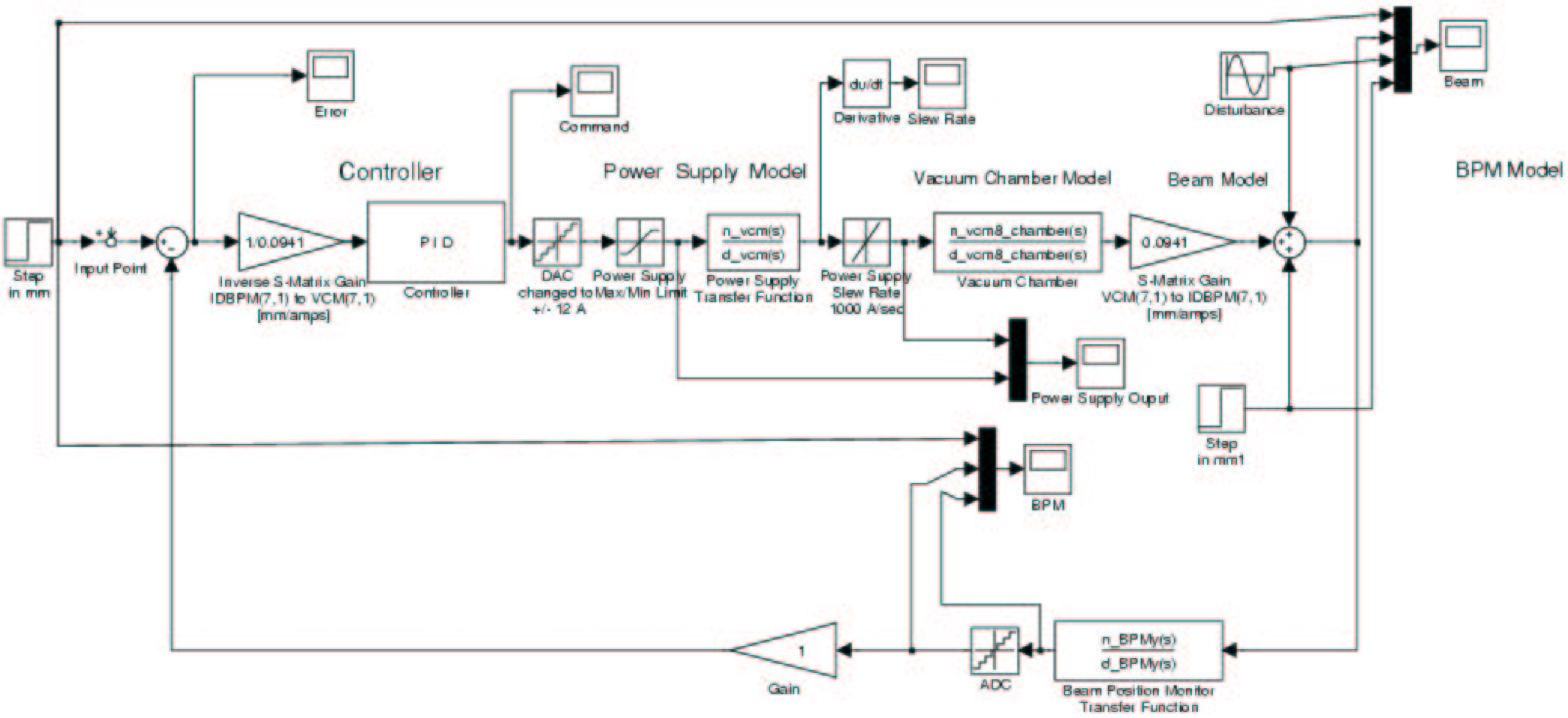


Fast Orbit Feedback

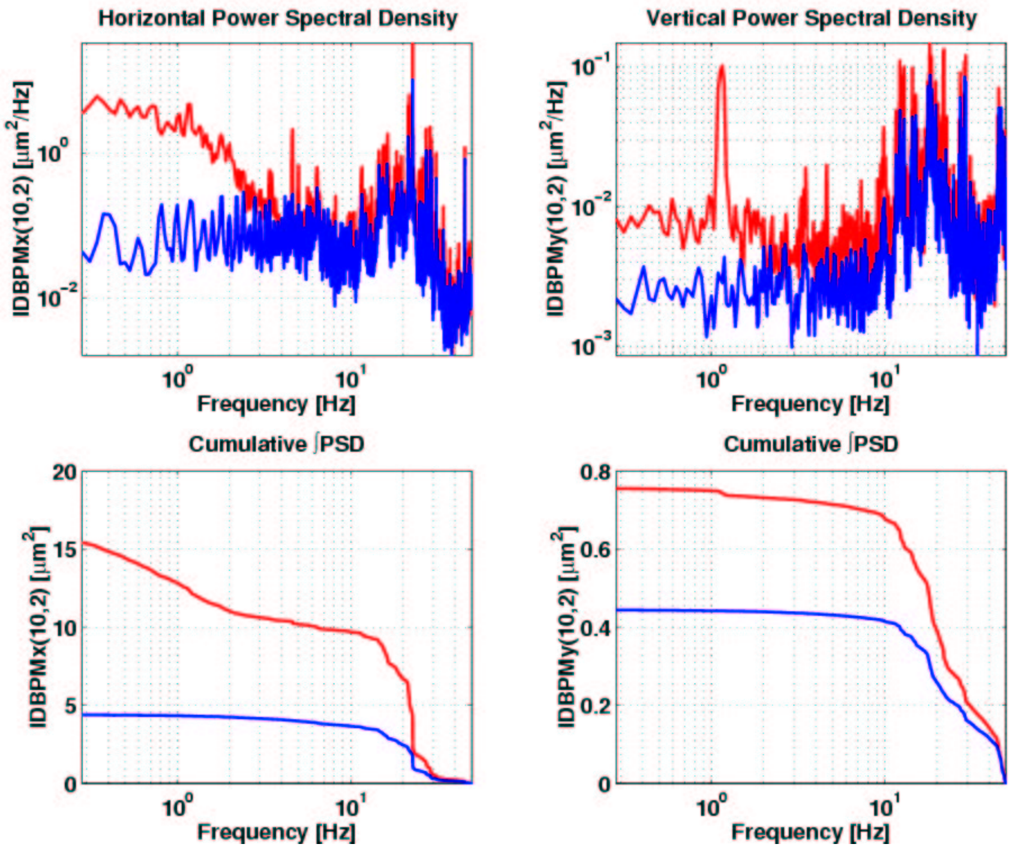
- Time response of all elements becomes important!
- Controller type used is often PID
- System often are distributed (ALS 12 crates, about 40BPMs, 22 correctors each plane)



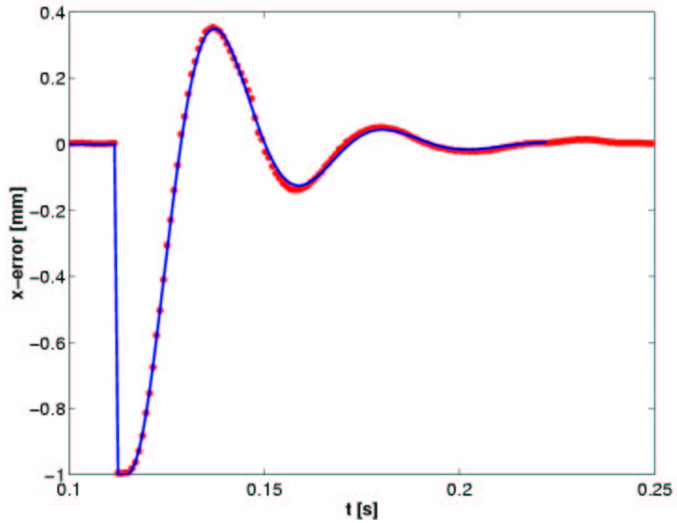
Simulink model of one channel of system



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.

Further Improvements

The ALS stability requirement of 1/10 the beam size is almost achieved

Obstacles:
• Vacuum chamber motion

For fast orbit jitter we try to get significantly below 1/10 of the beam size; Why? A) It seems achievable. B) It will reduce the signal noise for some very sensitive experiments (dichroism, micro focus), which have short data taking times at each spectral point.

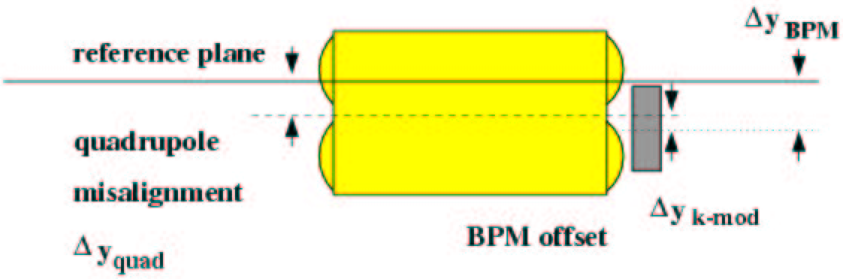
How to get there:
•Vacuum chamber motion monitoring
• Faster control system (1 kHz global orbit feedback)
• More BPMs
• Even better storage ring temperature control
• Synchrotron light BPM
• Top-off

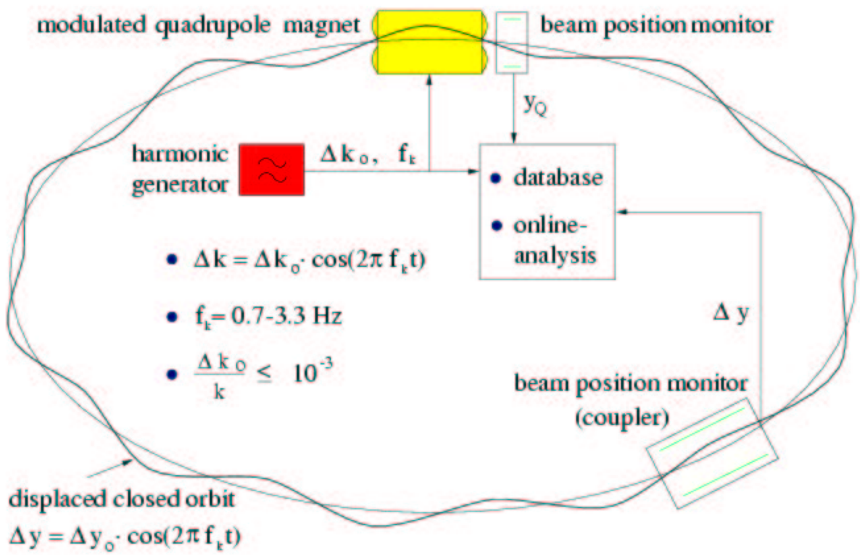
Beam Based Alignment

- 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, and:
  - 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, …)

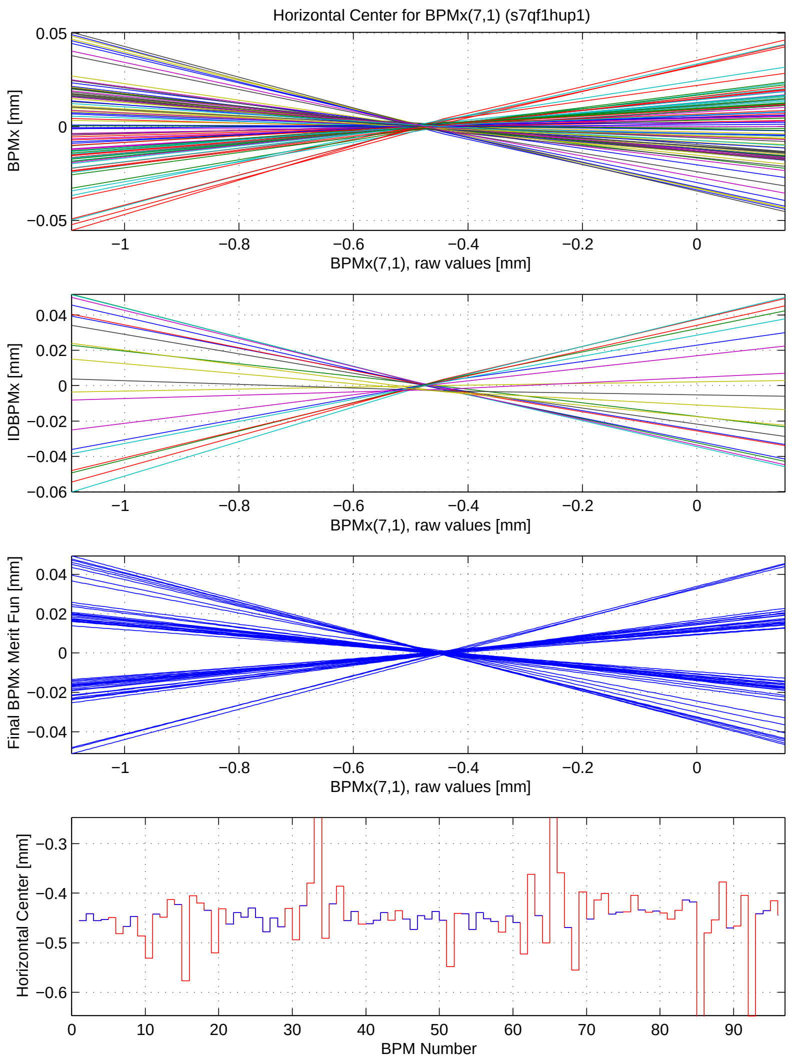
Beam Based Alignment

- 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.





Beam based alignment example: ALS



- All quadrupoles at ALS allow beam based alignment
- Automated computer routine – is performed regularly
- Main problem were systematic errors due to C-shaped magnets
- Offsets are fairly significant (rms of 300-500 microns) but very stable
- Beam based alignment only necessary after hardware changes or realignment
- Information from orbit response matrix analysis (with and w/o sextupoles) is in good agreement

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