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State of Beam Stability and Control in Synchrotron Light Sources

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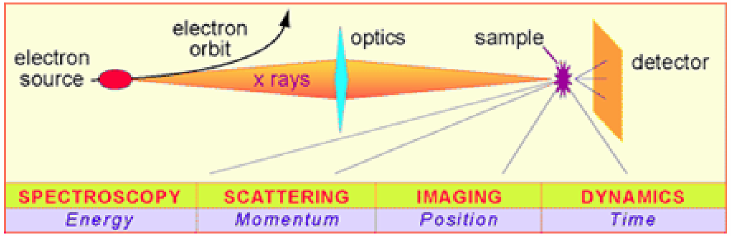
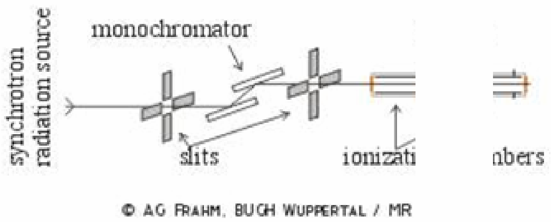
Topics

- Introduction - Importance of Stability
- Stability – from design to operations
  - —Facility design / Disturbance Source Suppression
  - —Damping of vibrations
  - —Active Correction
    - Feed Forward
    - Feedback – Slow/Fast
    - Multibunch feedbacks
- Areas of Concern
  - —Orbit
  - —Beamsize – Lattice function / Coupling / nat. emit
  - —Beam Energy / energy spread
  - —Lifetime, injection efficiency -> Top-off

Motivation





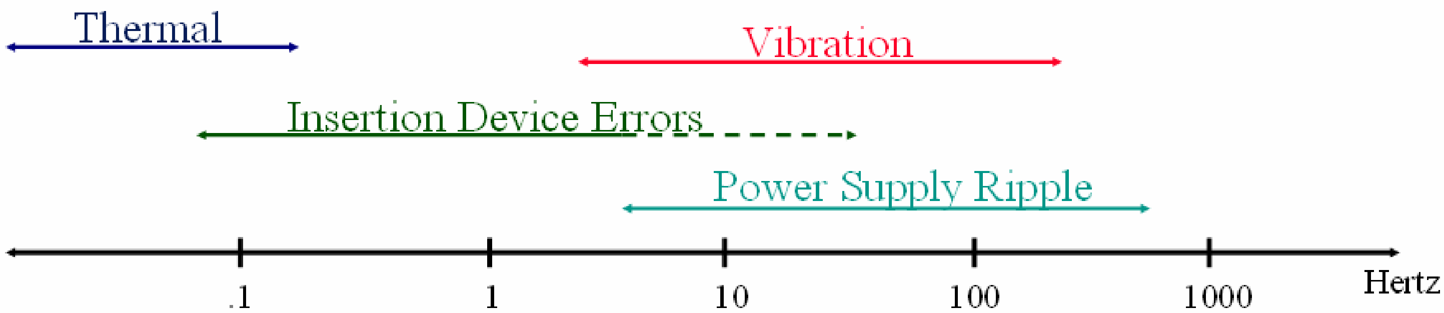
Typical requirements of modern SR user experiments:

(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

- 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

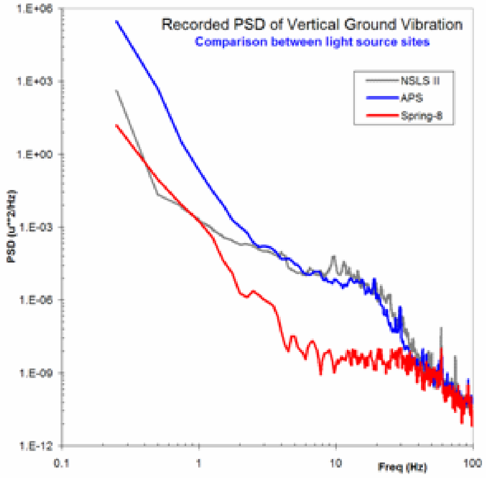
Causes for Orbit Distortions (no F/B)

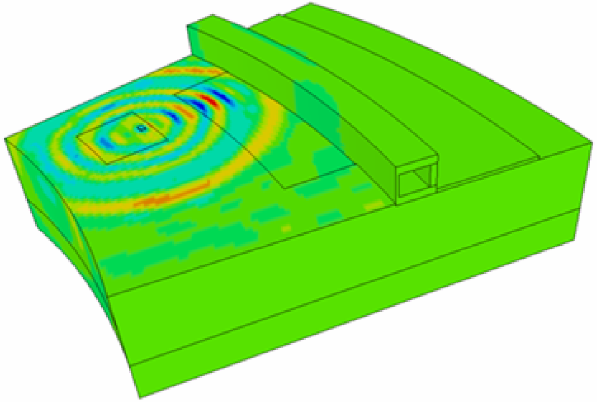


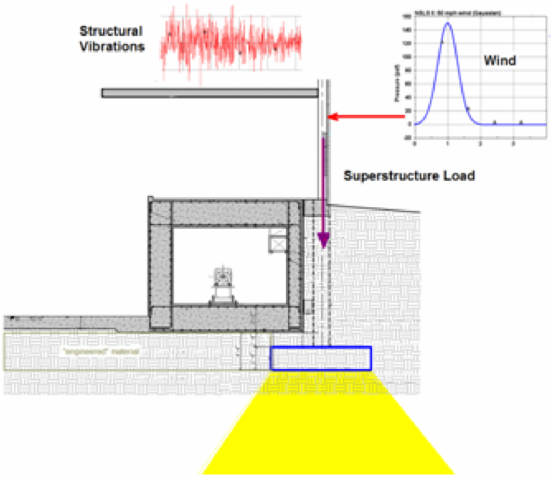
Frequency	Magnitude	Dominant Cause
Two weeks (A typical experimental run)	±200 μm Horizontal ±100 μm Vertical	1. Magnet hysteresis 2. Temperature fluctuations 3. Component heating between 1.5 GeV and 1.9 GeV
1 Day	±125 μm Horizontal ±50 μm Vertical	Temperature fluctuations
8 Hour Fill	±50 μm Horizontal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

Stability / Design



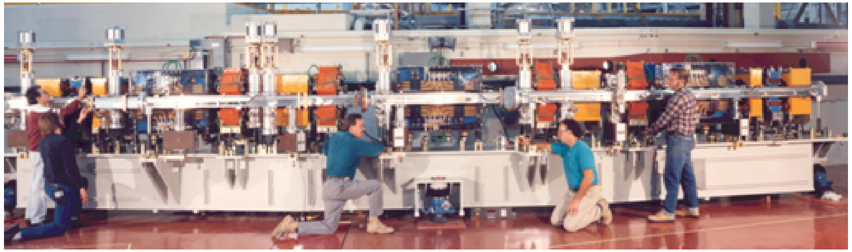




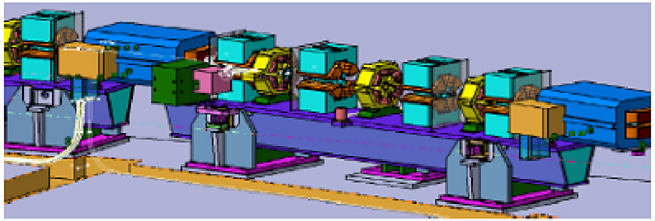
Courtesy: N. Simos, NSLS-II

- **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, …)**

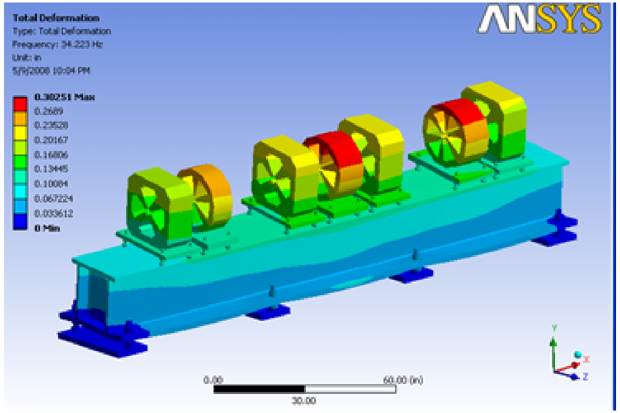
Girder Design



ALS



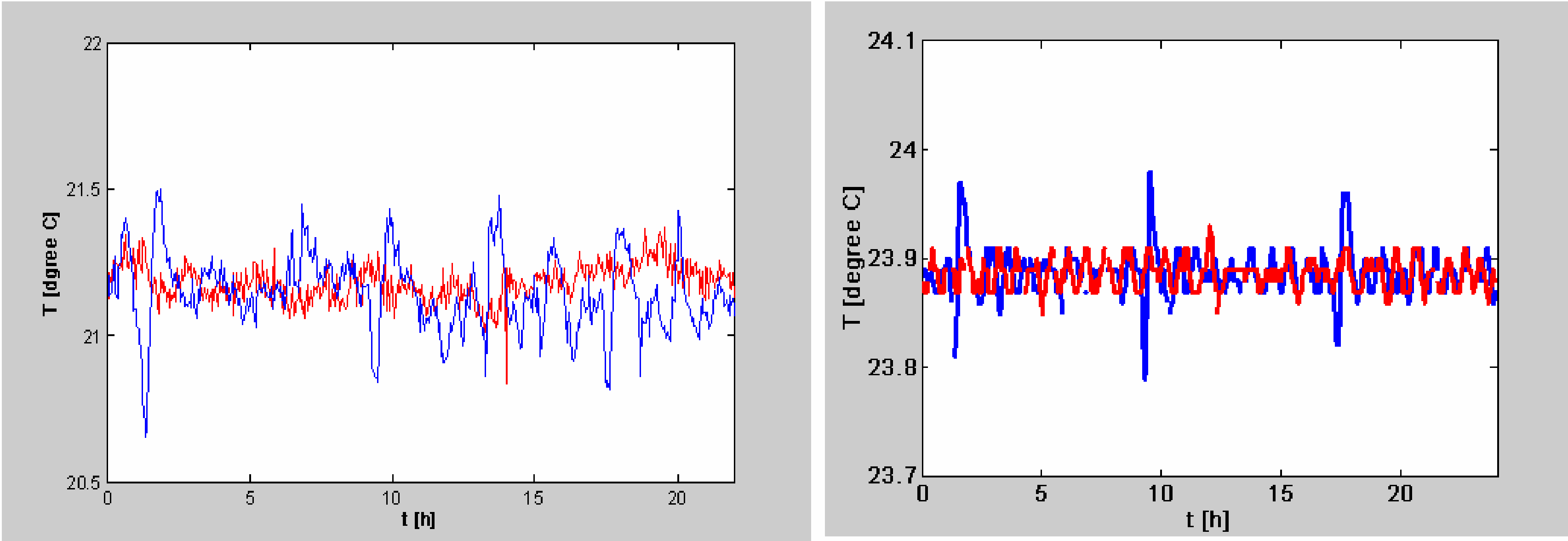
Soleil



NSLS-II: courtesy S. Sharma

- **Some early 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**
- **Latest designs (Soleil, NSLS-II) avoid this caveat – smaller vibration transmission to beam**

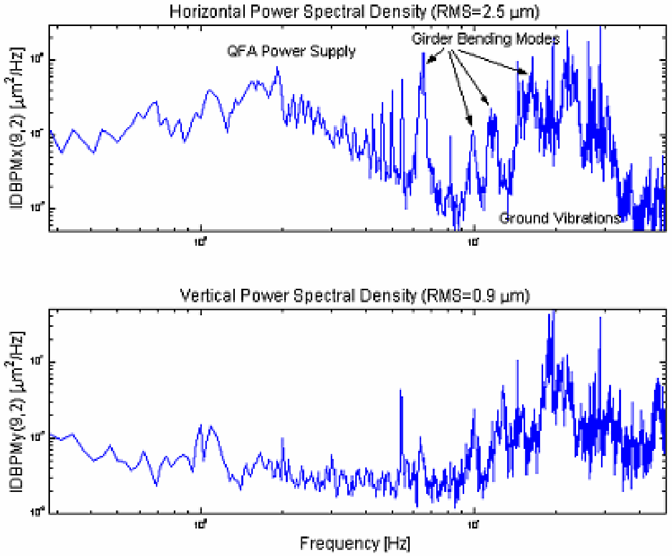
Air/water temperature stability



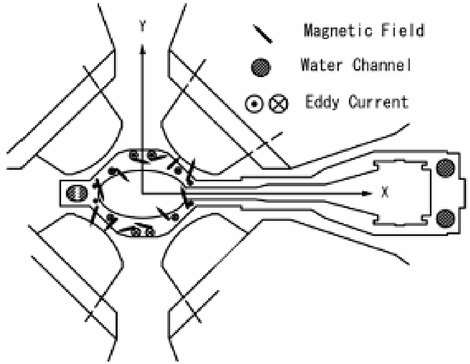
Left: ALS LCW temperature, Right: Tunnel air temperature (red – with top-off)

- **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**

Improvement after construction



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



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

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

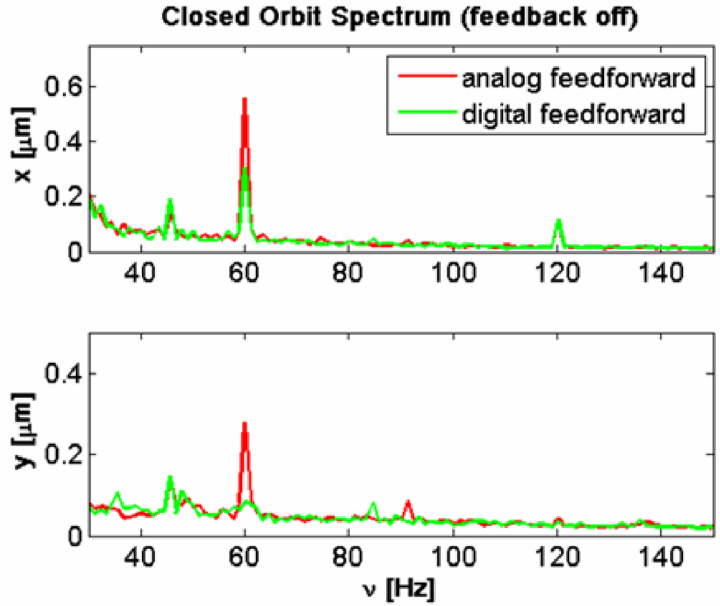
ALS – fixed power supply

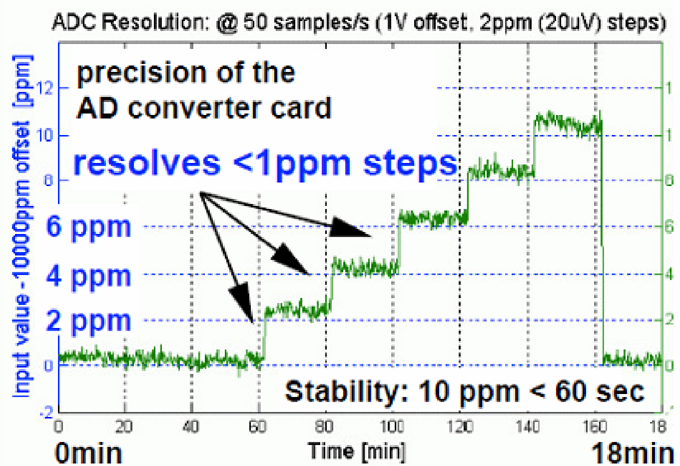
Spring-8: water vibration

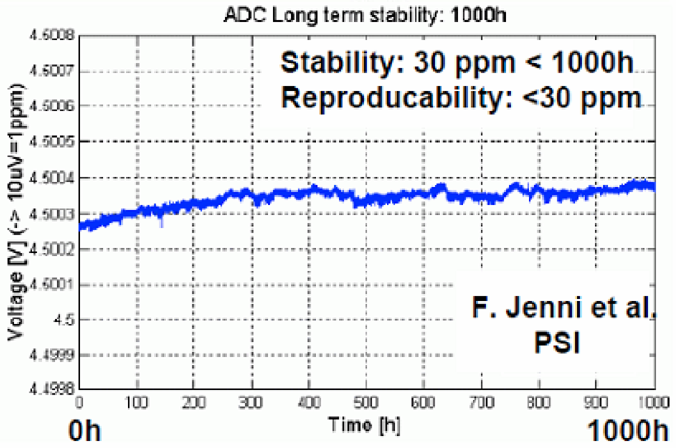
- **Often vibration sources / coupling into sensitive equipment is found during after commissioning**
- **Fixing the worst offenders often gives big benefit**
- **Examples above: Power supply at ALS, water induced vacuum chamber vibration at Spring-8; Another example are viscoelastic damping elements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

Good power supplies are essential

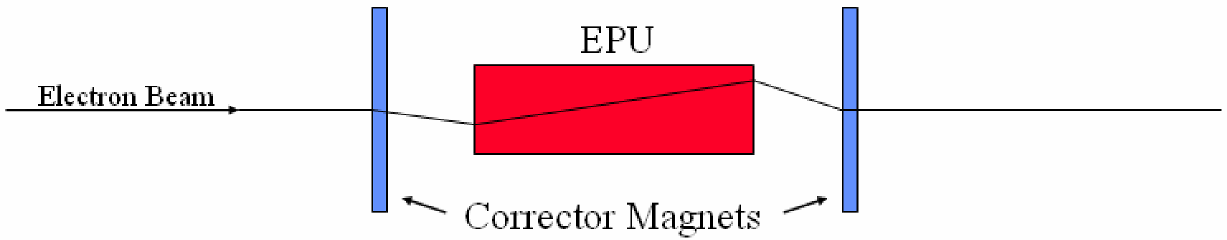
- Strong corrector magnets with high vacuum chamber cut off frequencies can be significant sources of orbit noise
- Observed at several light sources
- Achievable power supply performance increased over the years

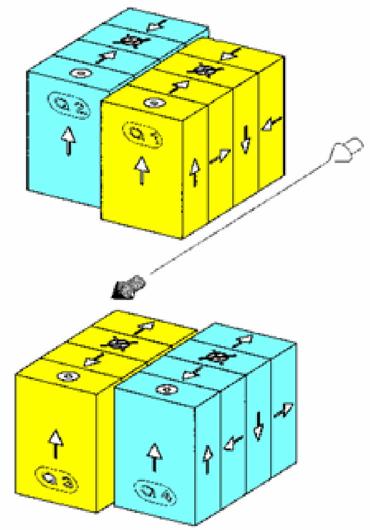




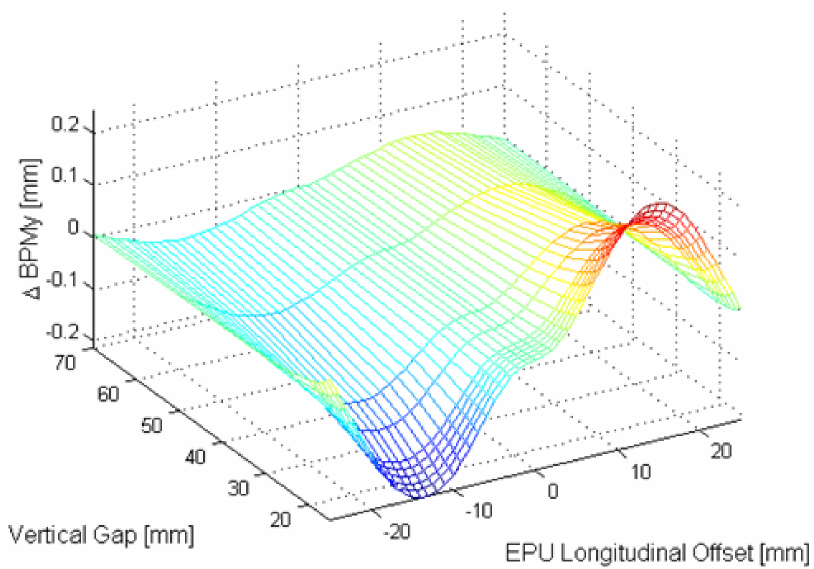


Feed-forward example: EPU COMPENSATION





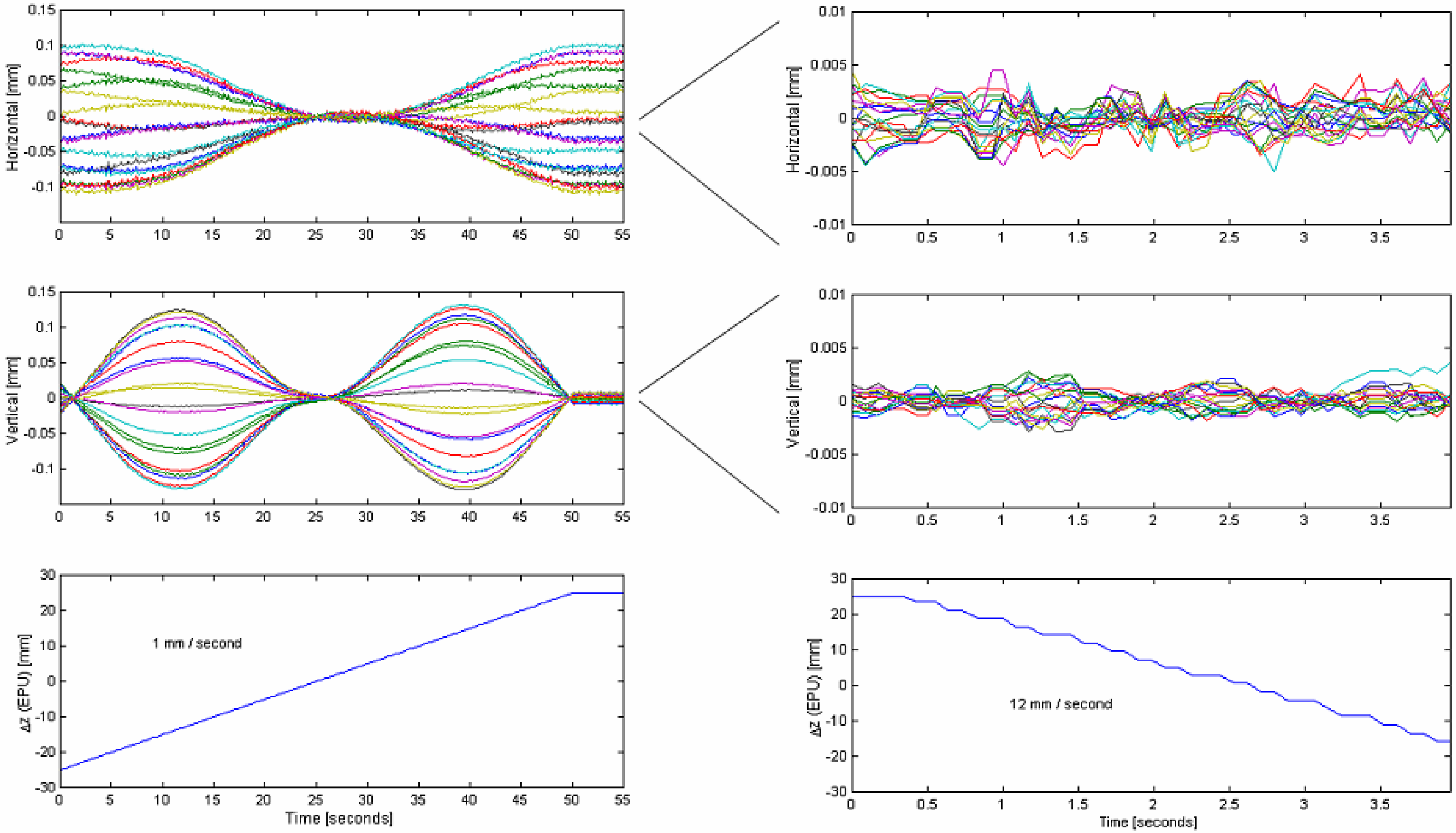
Mechanically, an ALS EPU can move from left to right circular polarization mode in ~1.6 sec.



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

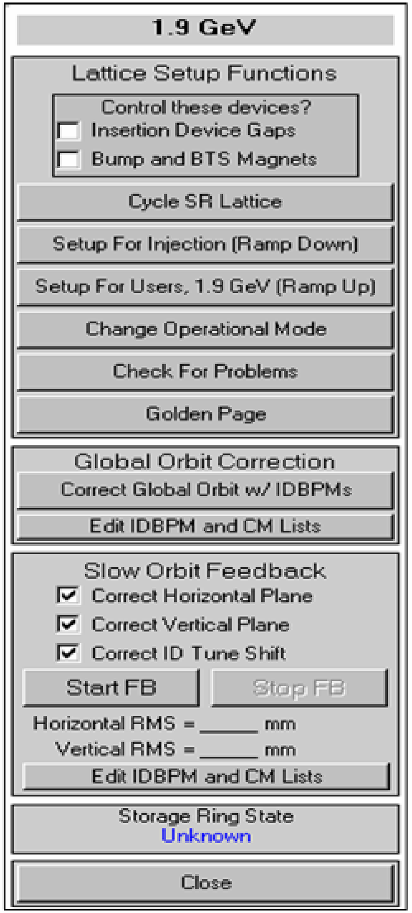


Orbit Feedback

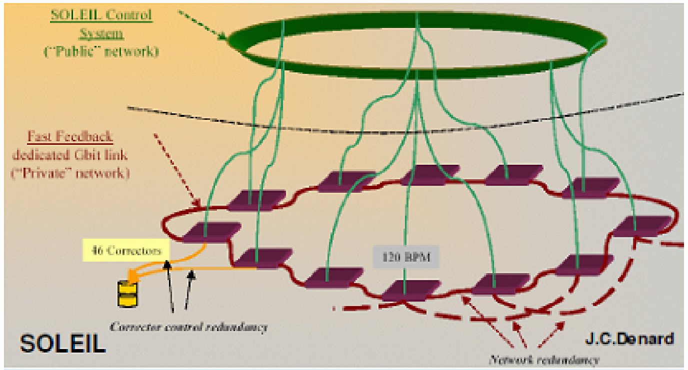
- Even in extremely stable light sources, orbit feedback can always improve stability
- This is particularly true for the effects of insertion device motion (feed-forwards are never perfect)
- Nowadays, all light sources tend to use global orbit feedbacks with some variation of SVD (or direct matrix inversion) – local feedbacks are used less seldom
- Fundamentally, one only needs one (fast) orbit feedback, however, practical aspects often require two (lack of enough fast corrector magnets, lack of strong enough corrector magnets, lack of enough suitable BPMs, …)

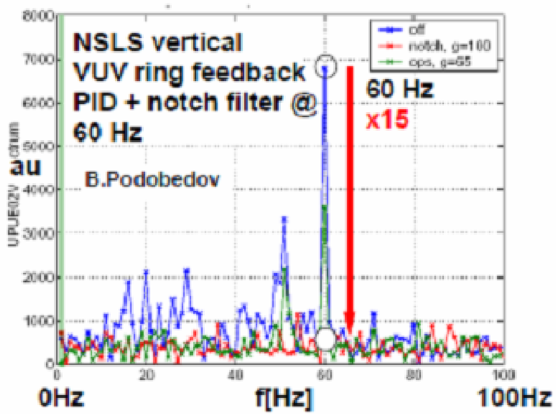
Software used for slow orbit feedback

- All ALS high level controls accelerator physics routines are implememted in Matlab
- Orbit feedback is controlled using a GUI which allows to ramp for injection, do single orbit corrections, standardize the lattice, etc.
- Matlab includes all Matrix manipulation tools necessary and has proven to be very reliable
- Code is very flexible (algorithm development is simple and can if urgent need arises even be done during user operation)
- Based on Matlab Middle Layer – now widely used at many (most) light sources



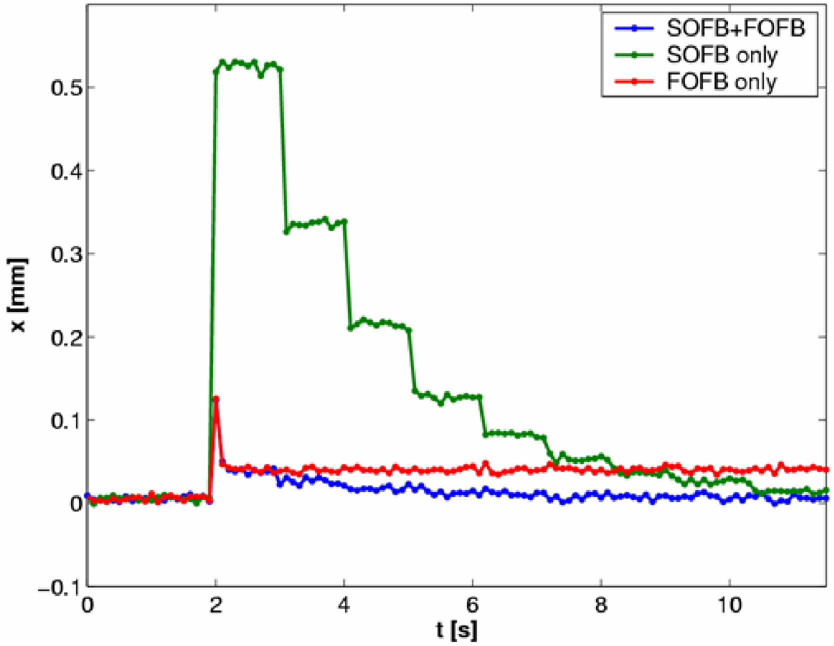
Fast orbit feedback topologies

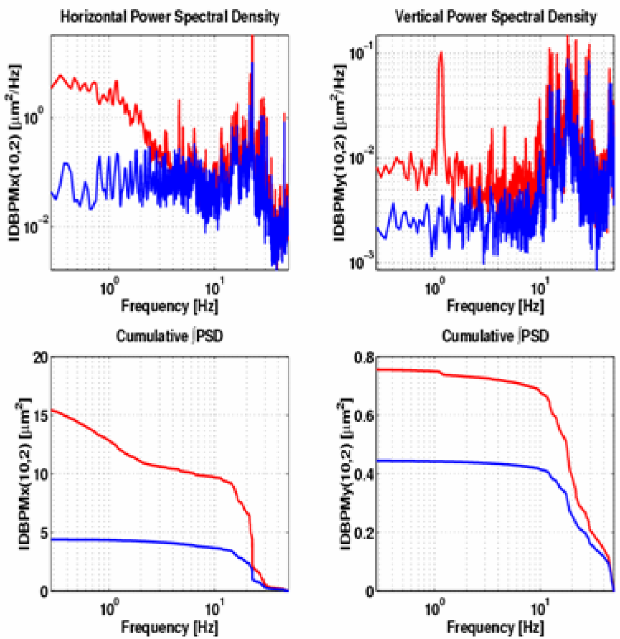




- Many different types of fast orbit feedbacks are in use
- State of the art are systems with update rates of several kHz and closed loop bandwidths between 80 and almost 200 Hz
- In some systems, PID algorithms are supplemented by notch filters, …

Frequency Overlap – Master/Slave

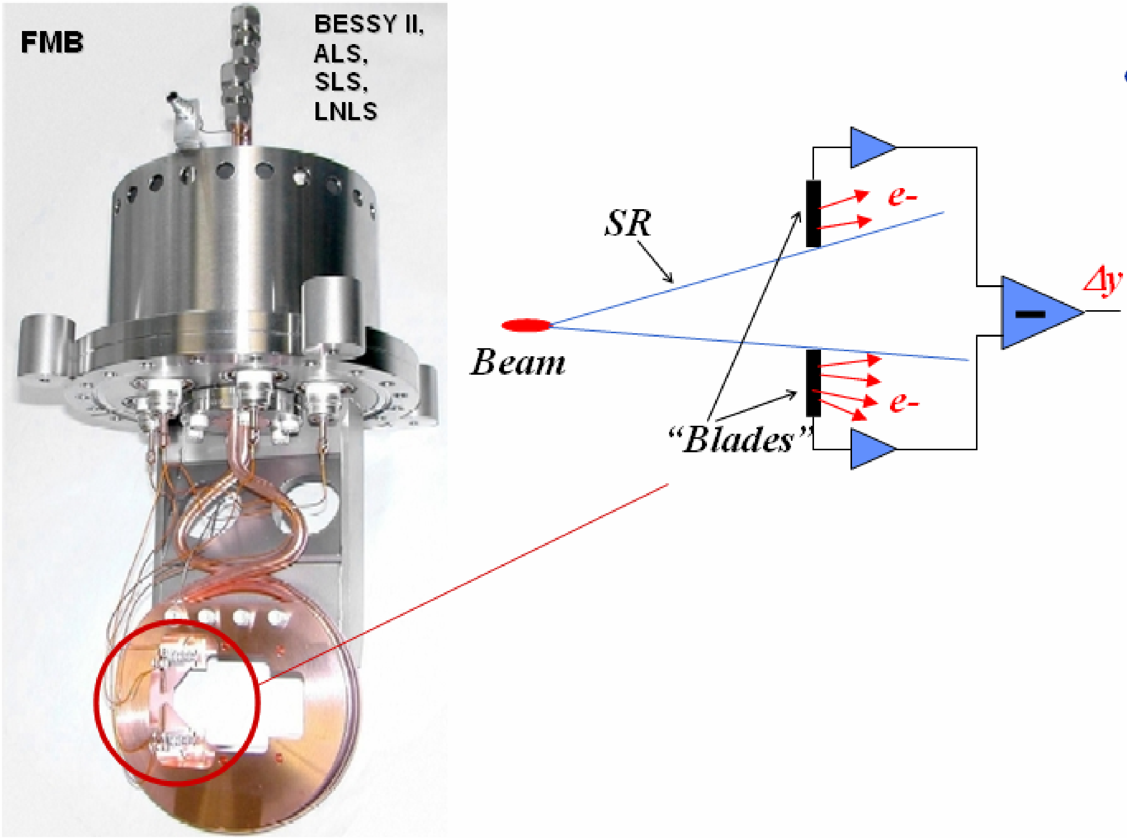




- ALS needs slow and fast feedback (do not have enough fast correctors)
- Avoided frequency dead band – fast system not DC blocked
- Synchronization by SOFB updating FOFB golden orbit
- Combination of both systems provides best of both and no interference!

Photon BPMs

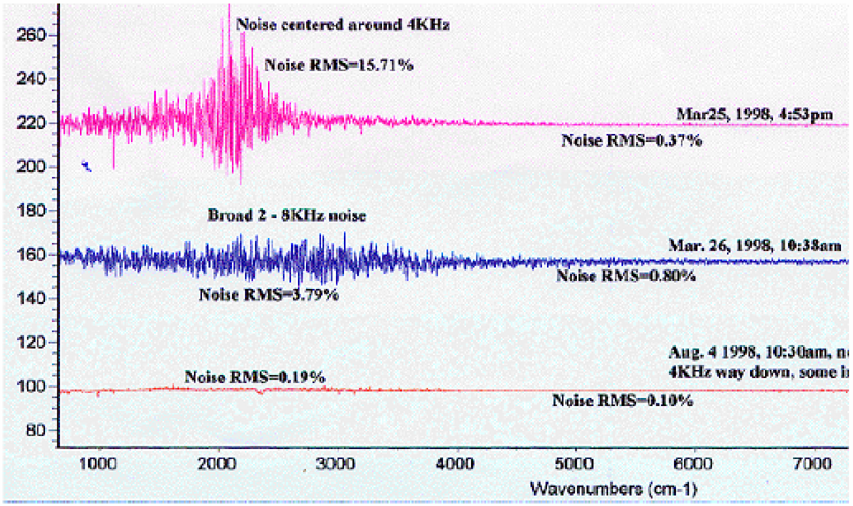
- Synchrotron radiation is abundant in many accelerators – very useful for low noise, non desctructive position measurement

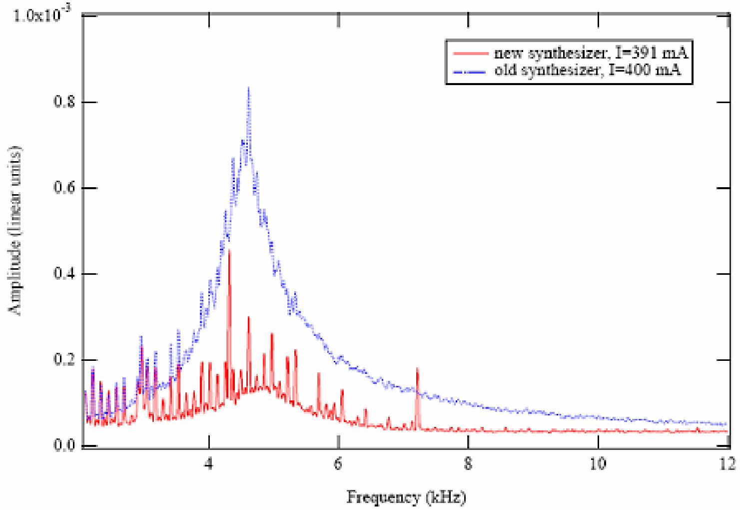


- Work very well for dipoles in the vertical plane – for undulators OK for hard x-rays (with Decker distortions if undulators scan a lot), difficult for VUV, no solution for EPUs

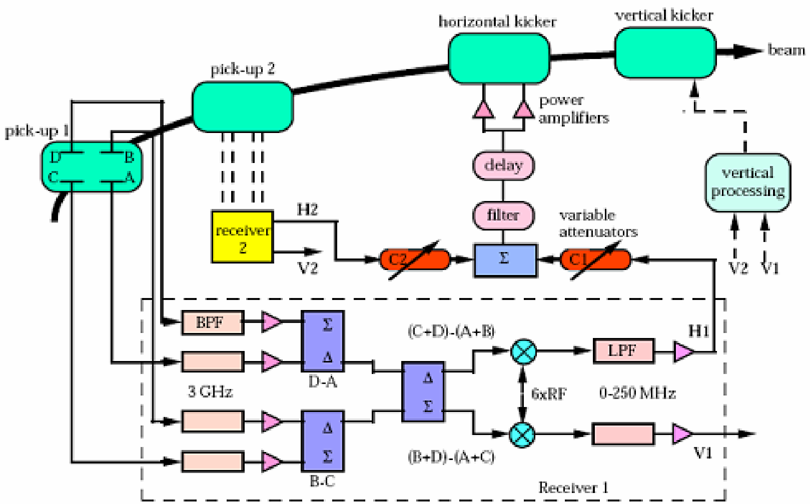
RF phase noise

- Mode 0 motion nowadays is very small – 0.03 degrees rms
- Dominated by noise from master oscillator, rf distribution system, rf frequency correction … not HVPS
  - —Fast RF amplitude feedback reduces effect of HVPS to this level
- Use improved master oscillator + filtering at several points in low level RF frequency distribution system

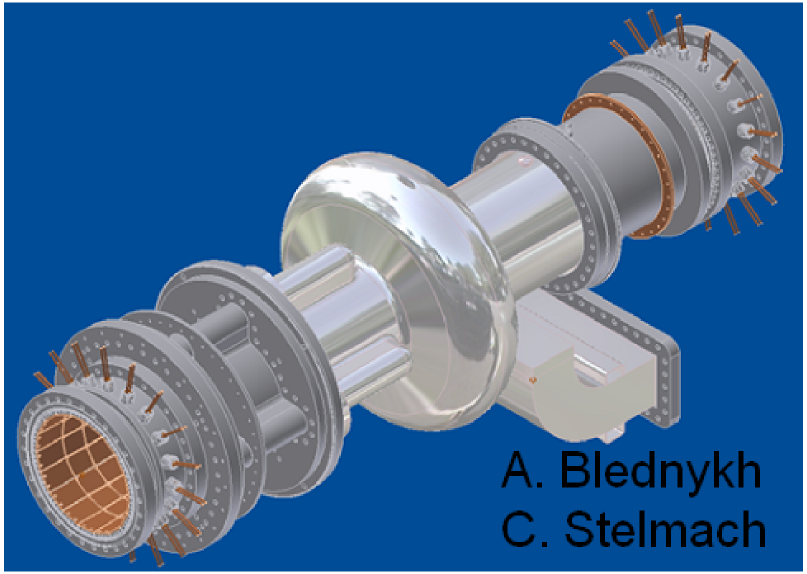




Instabilities / Feedback / HOMs



ALS TFB: W. Barry



- **Very fast stability / single+multibunch instabilities**
- **Routinely addressed by multibunch feedback system (longitudinal/transverse) – most recent ones all digital**
- **HOM free cavities (SC or N/C) help, particularly long.**
- **Transversely feedbacks allow operation with small chrom. -> good lifetime**
  - **Also can be used to increase TMCI threshold (ALS factor >4)**
  - **And finally to reduce duration of injection transients in top-off**

Beamsize Stability

- Because orbit stability is excellent, at ALS we actually receive more complaints about beamsize stability
- Problem is tougher at low energy light sources (beam less stiff)
- Main culprit at ALS are EPUs (elliptically polarizing undulators)
- Some examples of affected experiments:
  - —STXM (scanning transmission X-ray microscopes) – I0 normalization difficult, not included in state-of-the-art beamlines
  - —Microfocus beamlines investigating dirt samples

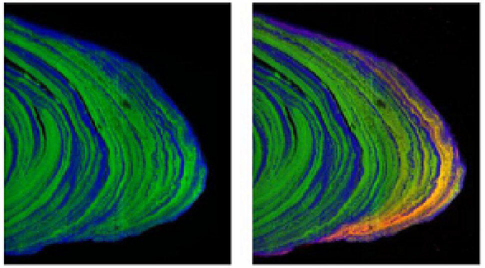
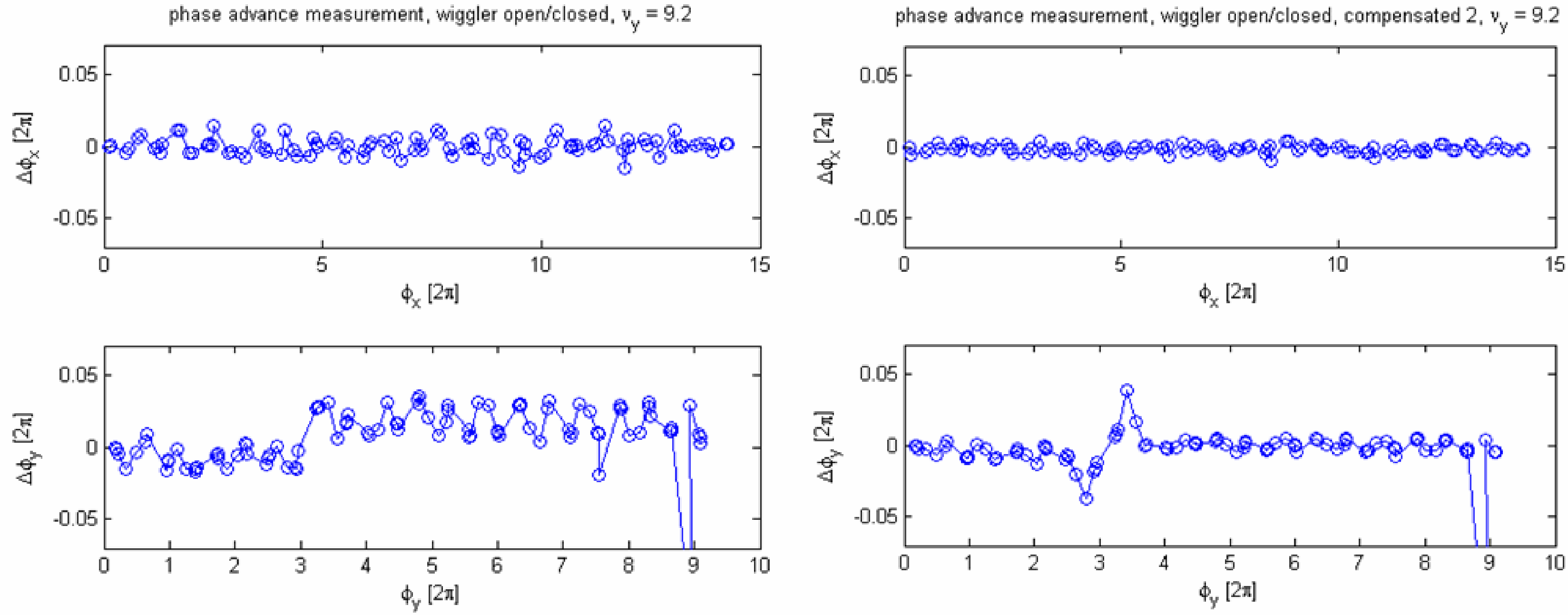


Figure 1. Synchrotron-based micro-X-ray radiation fluorescence (µSXRF) Fe and Mn maps of the outermost Fe and Mn layers of a ferromanganese nodule from the Baltic sea (6600 µm x 3780 µm, step size 15 µm, counting time 250 ms/pixel, red = Zn, green = Mn, blue = Fe, beamline: 10.3.2.). The onion-like structure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

- What needs to be corrected:
  - — Optics distortion (beta functions)
  - — Skew gradients
  - — Potentially horizontal/vertical natural emittance

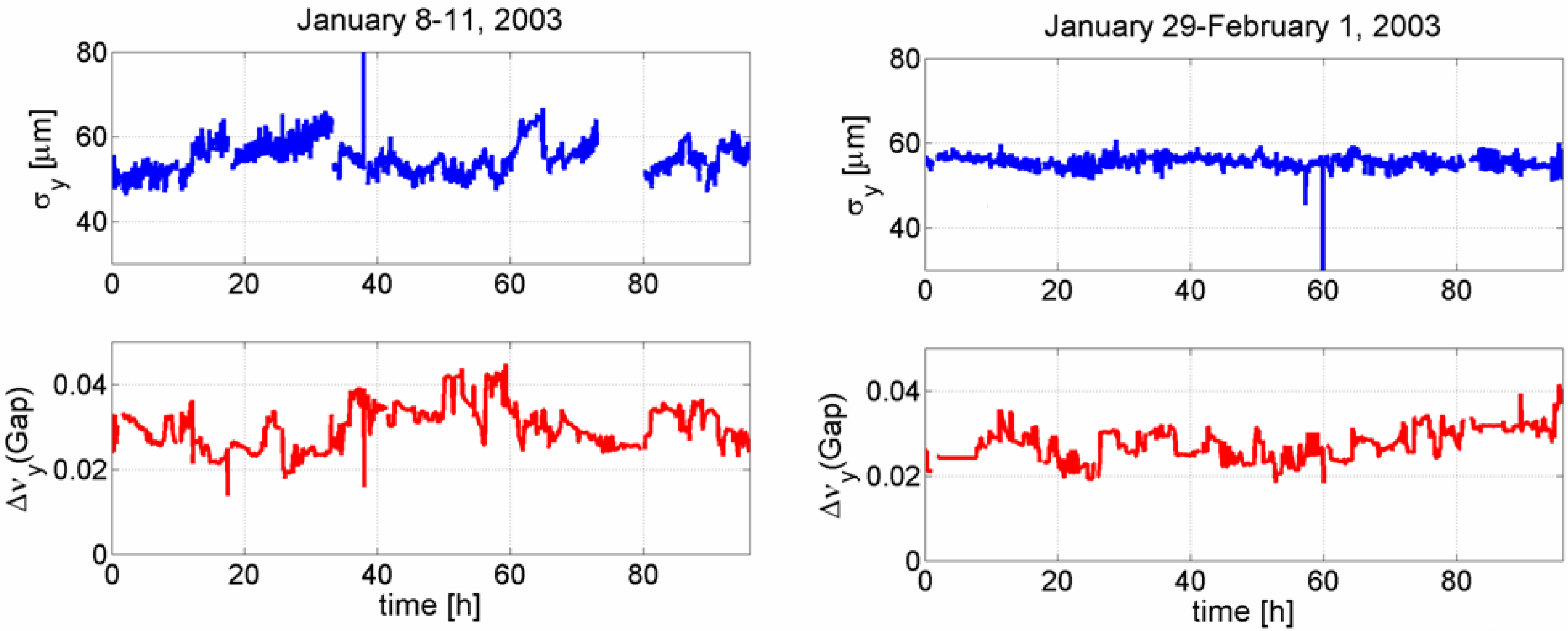
Insertion Device Optics Correction



- Example shown above is the systematic focusing change due to a wiggler and how the local optics feed-forward restores it. One uncompensated wiggler in the ALS produces several 10s of percent beta beating and completely ruins the injection efficiency.
- To find the best lattice correction is not trivial, since keeping beamsizes constant is not the only consideration.
- Maintaining dynamic and momentum aperture is very important as well and optimum solutions are not always obvious (and sometimes require change of the base lattice).
- In newer light sources this can also involve sextupole FF (beyond the scope of this talk).

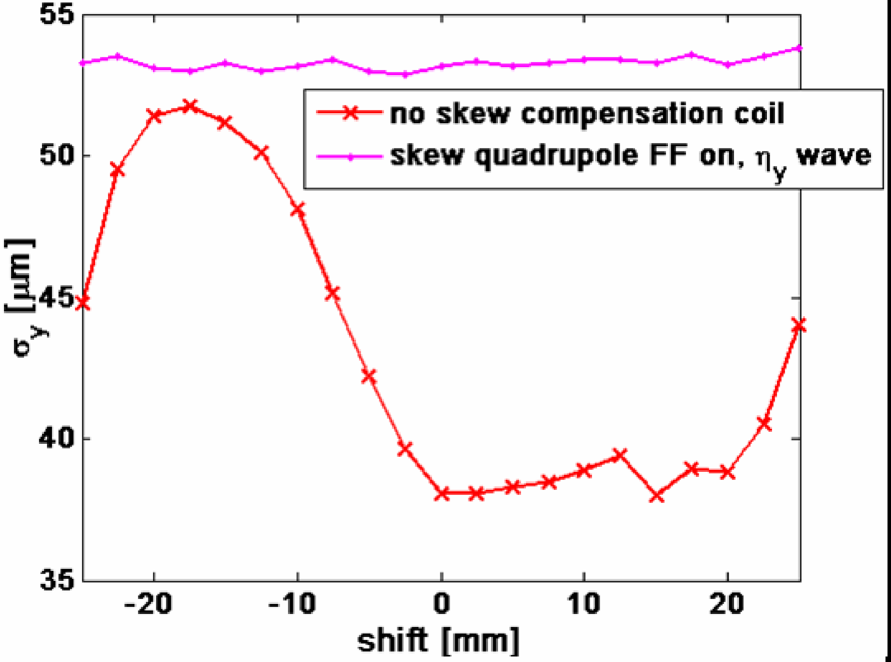
Vertical Beamsize Stability

- One issue affecting the beamsize are residual tuneshifts (after feedforward compensation) when scanning undulators or skew errors inside those undulators (especially EPUs)
- Using dispersion wave instead of coupling resonance to increase vertical emittance improves beamsize stability



Undulator effects on vertical beamsize

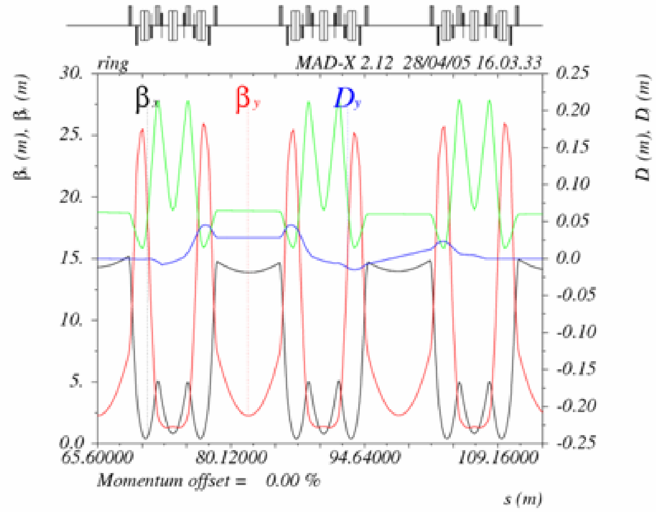
- Vertical beamsize variations due to EPU motion were big problem.
- Is caused by skew quadrupole (both gap and row phase dependent)
- Root cause reduced in newer devices
- Installed skew coils for feedforward correction
- Stability now <1%, relative stability will at first be worse for smaller beamsizes

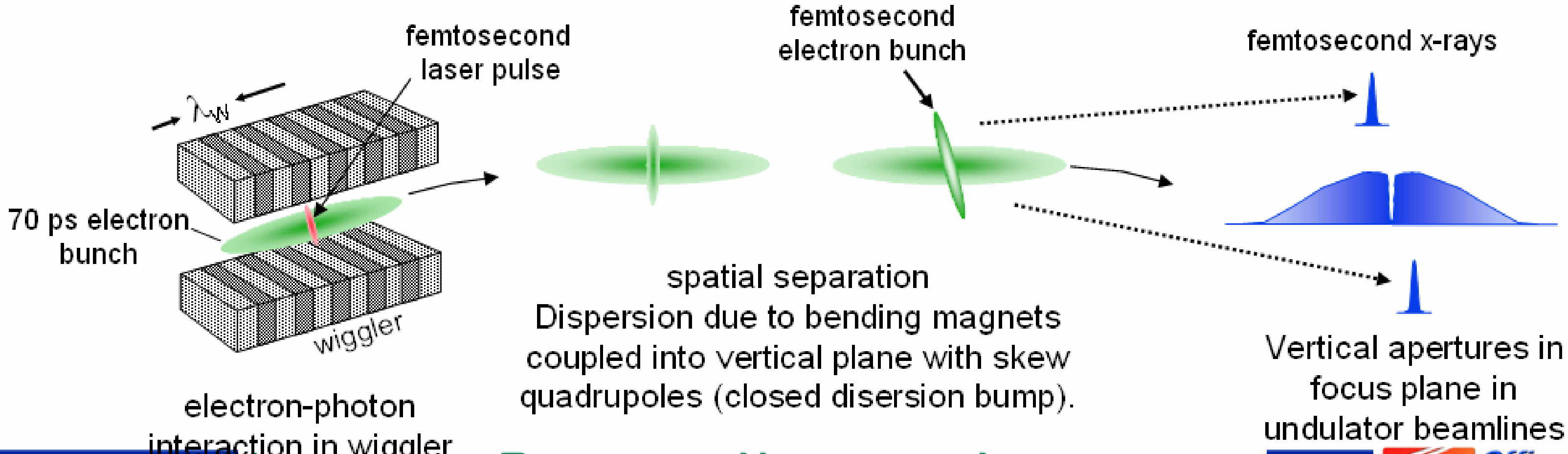


- Just for reference: Whenever an undulator moves, about 120-150 magnets are changed to compensate for the effect (slow+fast feed-forward, slow+fast feedback)

Another Beamsize Stability Challenge Example

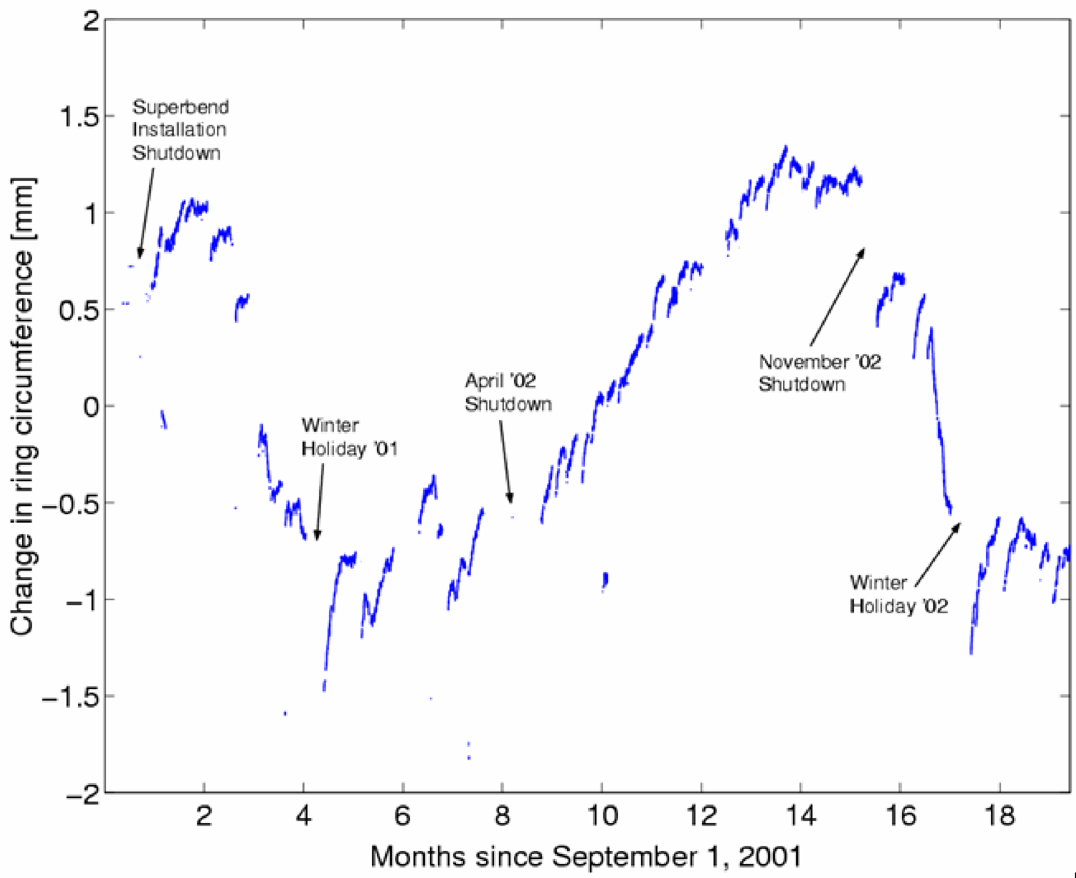
- **Fs-slicing facility at ALS uses vertical separation -> high field undulator in the middle of a sizeable local vertical dispersion bump**
- **To keep vertical (natural) emittance constant, whenever this undulator scans, 20 skew quadrupoles around the ring are used to change a global vertical dispersion wave**



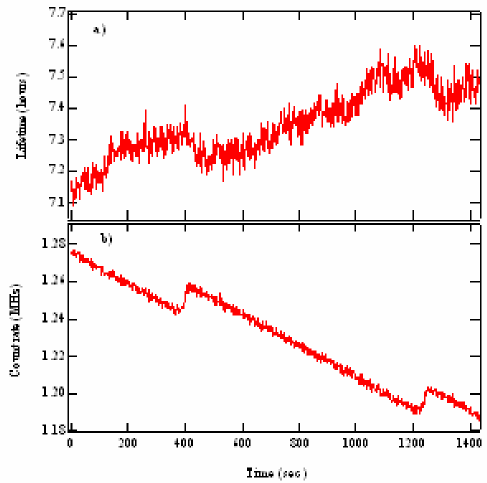


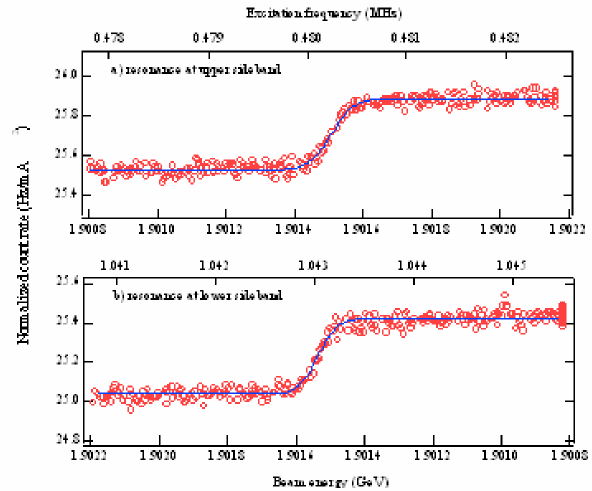
RF Frequency Feedback / Energy Stability

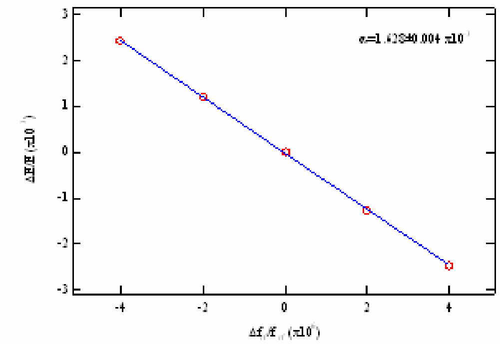
- Circumference of ring changes (temperature inside/outside, tides, water levels, seasons, differential magnet saturation, …)
- RF keeps frequency fixed – beam energy will change
- Instead measure dispersion trajectory and correct frequency (at ALS once a second)
- Can see characteristic frequencies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

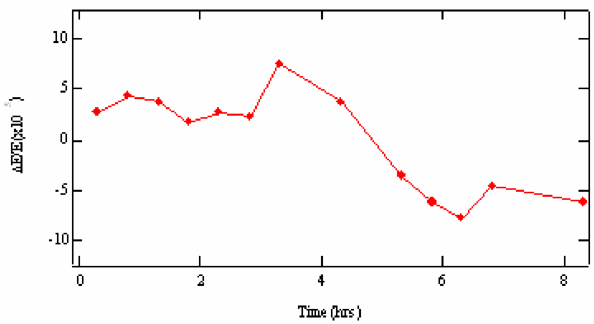


Energy calibration (resonant depolarization)



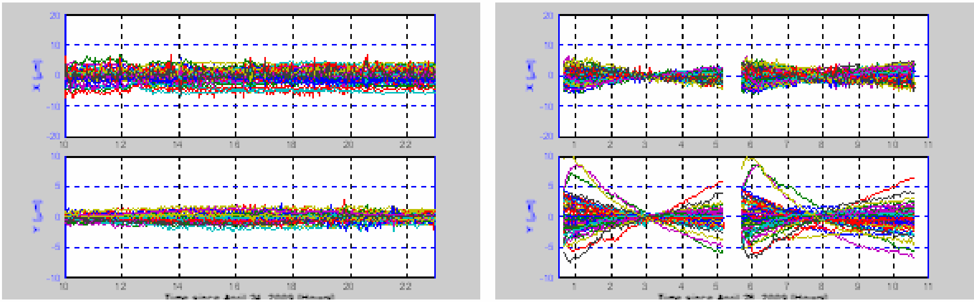




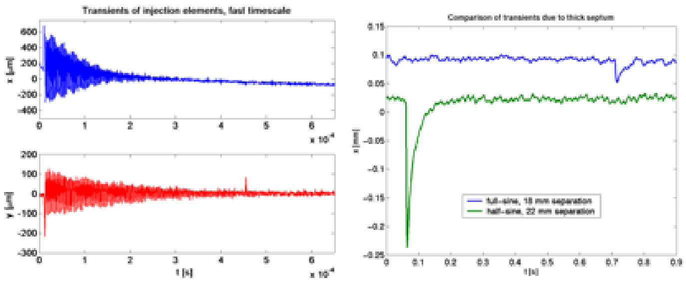


- High precision measurement of beam energy is relatively simple at low energy light sources like ALS
- Allows some conclusions about long term orbit/magnet/ground plate stability
- Implemented rf-frequency feedback at ALS and verified it with energy measurements
- Some radiation standards applications require extreme stability (example: BESSY)

Top-off / Stability interplay with dynamic (momentum) aperture



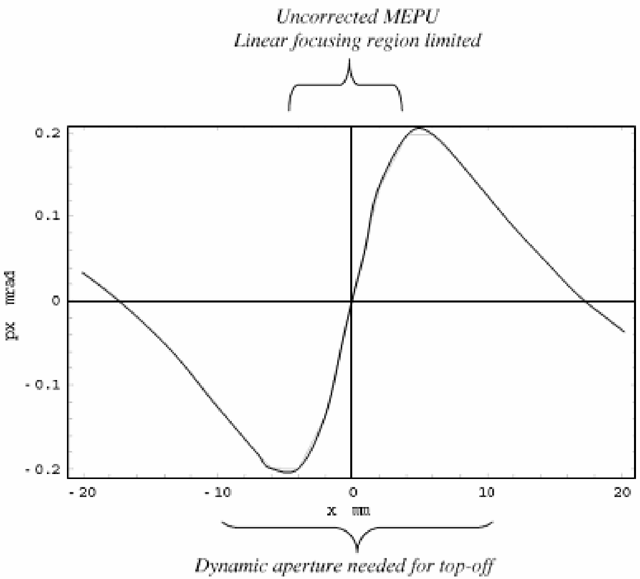
ALS: mid term orbit stability (with+w/o Top-off)



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**
- **However, in top-off the dynamic (and momentum) aperture still has an effect on stability**
- **Insertion devices (for example EPUs) have the potential to substantially reduce the injection efficiency enough to reduce the stored current (this also can produce increased radiation dose rates).**
  - **Therefore keeping the nonlinear properties of the machine 'stable' remains important**

EPU Dynamic Multipole Fields



Nonlinear Kick:

- **Spoils Dynamic Aperture**
  - **Worse for large period EPUs**
- **Impacts Lifetime and Injection Efficiency**
- **Successfully compensated last year on 5 cm period EPUs (where effect was smaller)**

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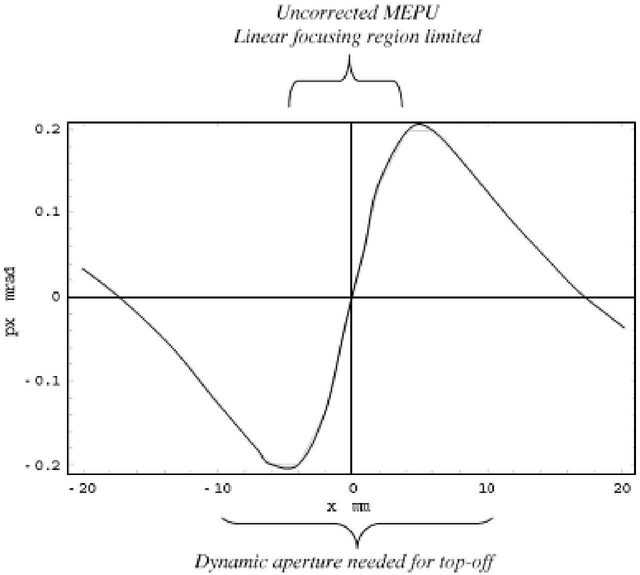

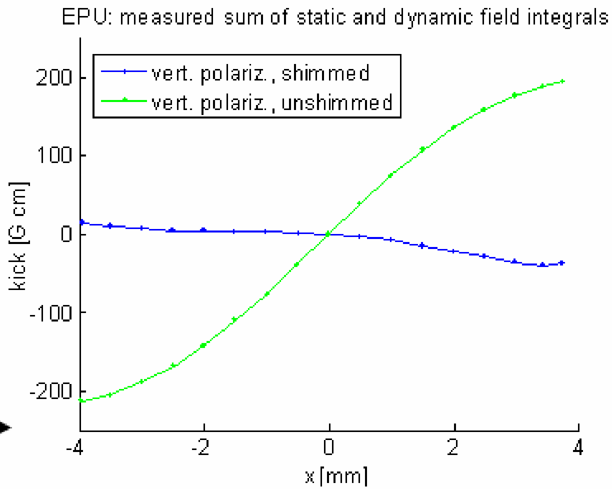

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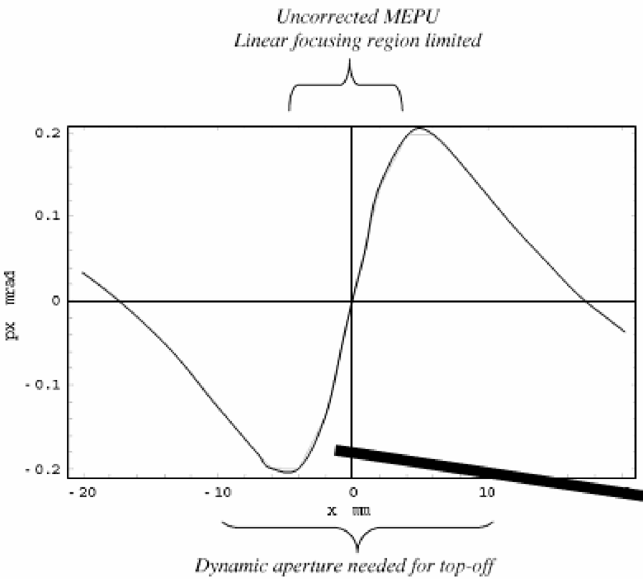
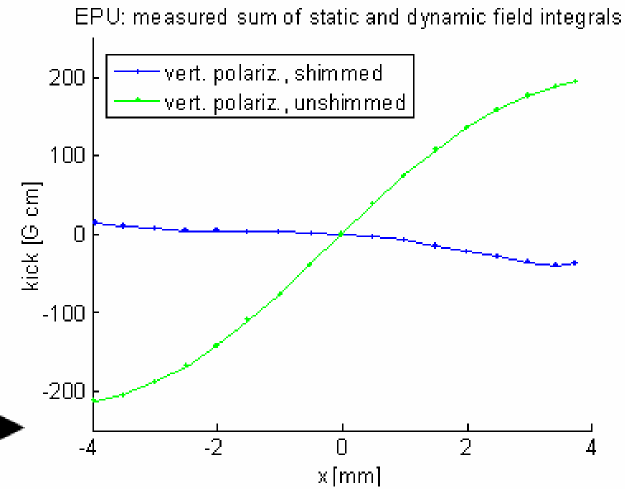
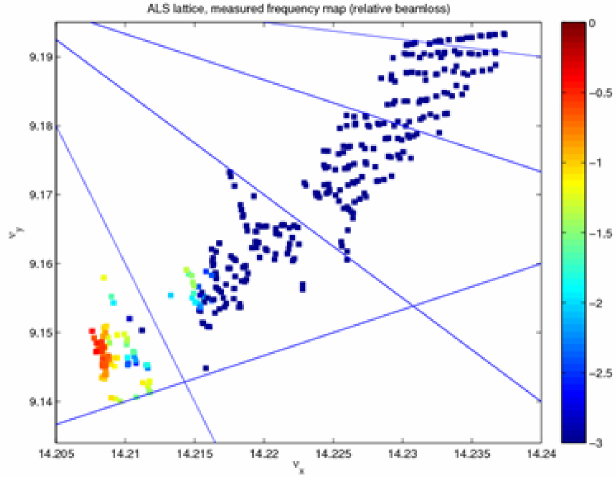


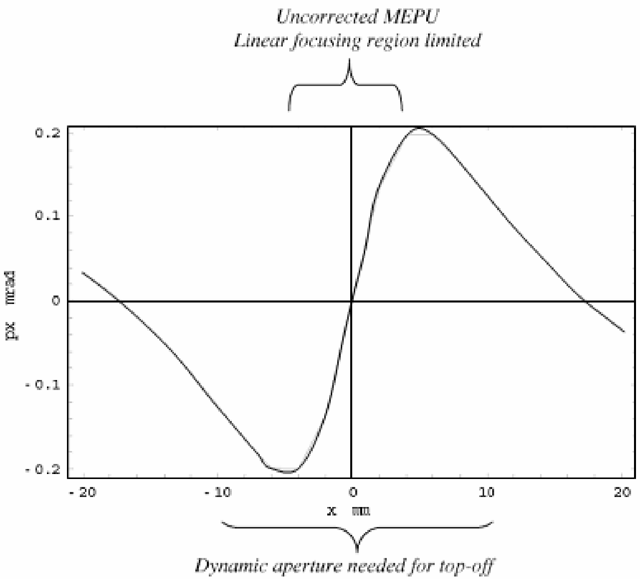


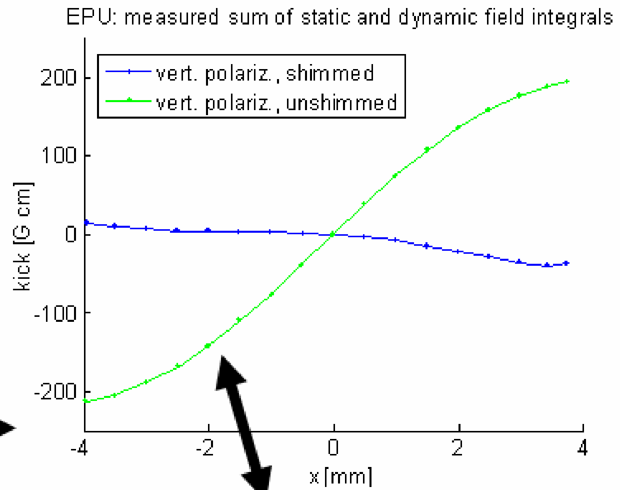


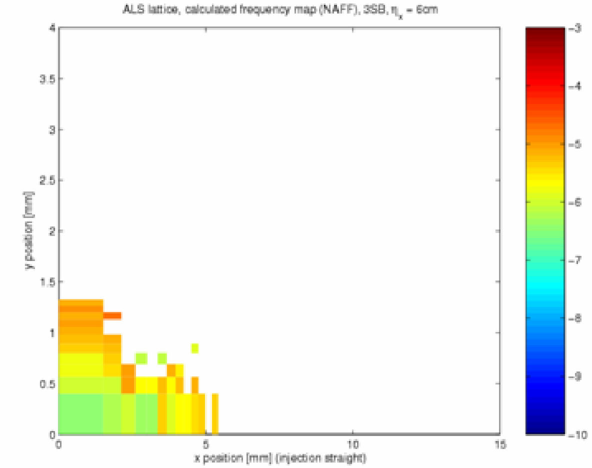
Nonlinear Kick:

- Spoils Dynamic Aperture
  - Worse for large period EPUs
- Impacts Lifetime and Injection Efficiency
- Successfully compensated last year on 5 cm period EPUs (where effect was smaller)

EPU Dynamic Multipole Fields







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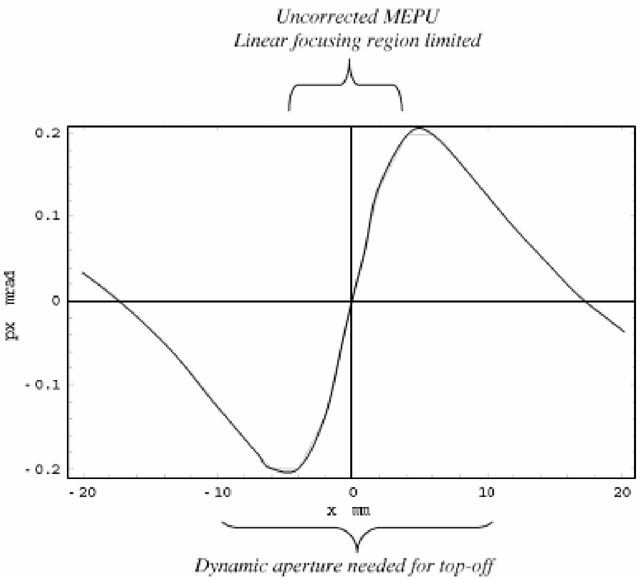

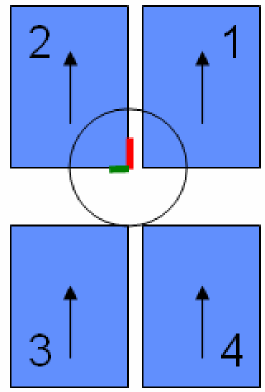

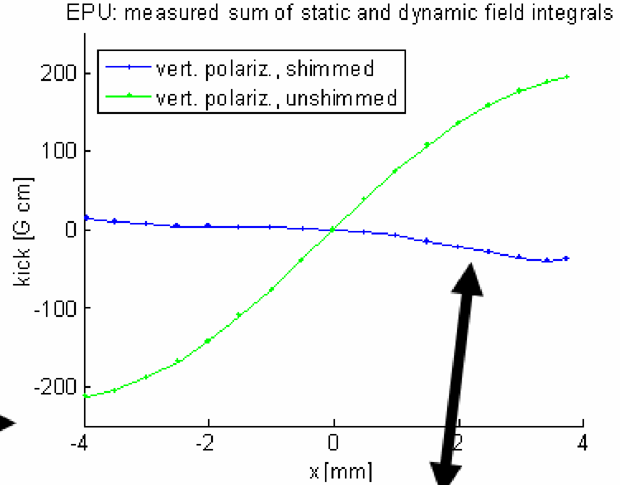

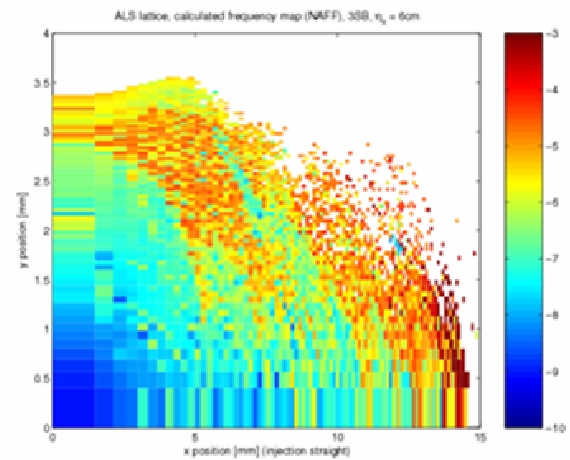

Nonlinear Kick:

- **Spoils Dynamic Aperture**
  - **Worse for large period EPUs**
- **Impacts Lifetime and Injection Efficiency**
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Outlook / Challenges

- Light source development continues to ever smaller emittances -> tighter stability requirements
- Photon BPMs work well for hard x-ray undulators (potentially with Decker distortions), not so well for VUV, no good solution for EPUs
- Increasing number of fast switching insertion devices (EPUs, …) at low/intermedium energy light sources -> more perturbations
- Truly transparent top-off has not been achieved, yet.
- And of course: How do we get close to what we have today in storage rings when moving to ERLs, FELs, or even ultimate storage rings (with new injection methods)

Summary

- Stability is one of the most important deliverables of light sources
- Very integrated problem:
  - includes all phases of facility design, commissioning, operations
  - Includes orbit, beamsize, energy, at various time scales
- Orbit:
  - Short and medium term (hours – 200 Hz) sub-micron orbit stability is achieved in 3rd generation light sources.
    - Important: Fast orbit feedback (fast end) systems and "top-off" operation (slow end)
    - Biggest obstacle: Insertion devices
- Beamsize:
  - Relative beamsize stability of better than 1% can be achieved
    - Main gain is execellent compensation of Insertion devices (FF system)
- In reality, the accelerator and the user beamlines are one integrated system and should be optimized as such. This has been started, but is not very advanced, yet. Usually both are optimized independently
- The author gratefully acknowledges contributions from many colleagues !