# Beam Stability Requirements for 4th Generation Synchrotron Light Sources Based on MBA Lattices

**Christoph Steier, ALS-U Accelerator Systems Lead, LBNL**

**1st BES Light Sources Beam Stability Workshop, November 1, 2018**

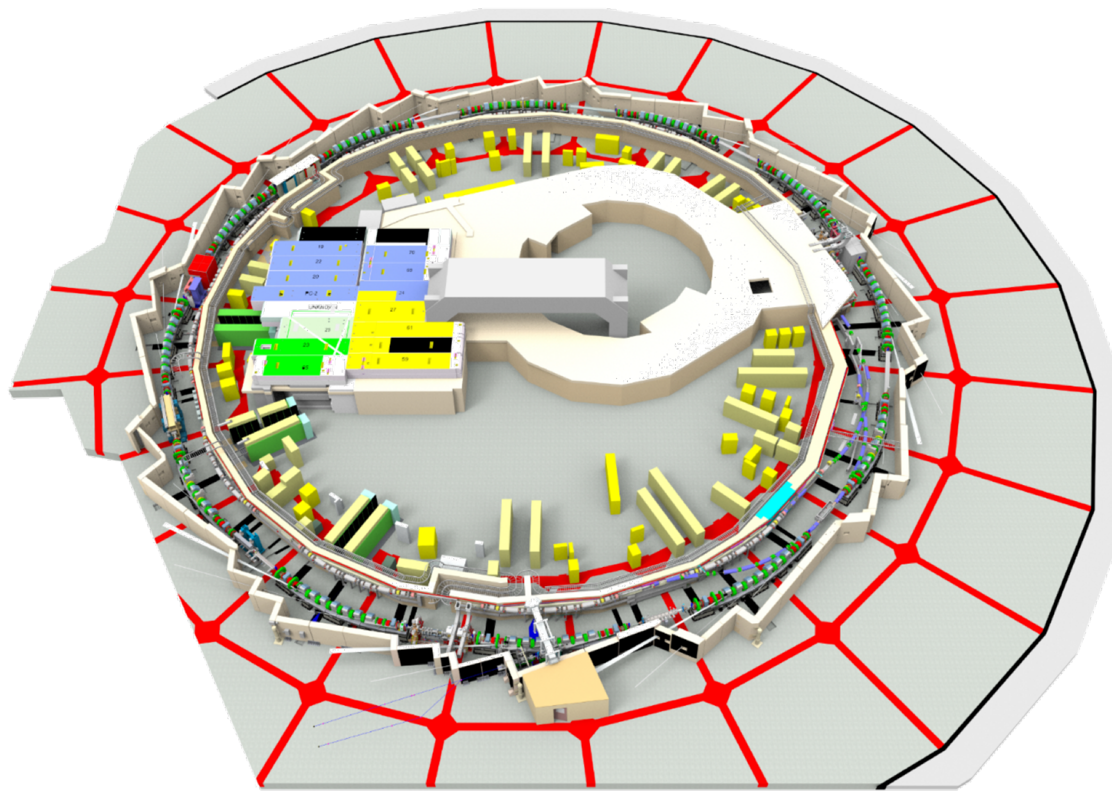
BERKELEY LAB

U.S. DEPARTMENT OF ENERGY | Office of Science

ALS-U ADVANCED LIGHT SOURCE

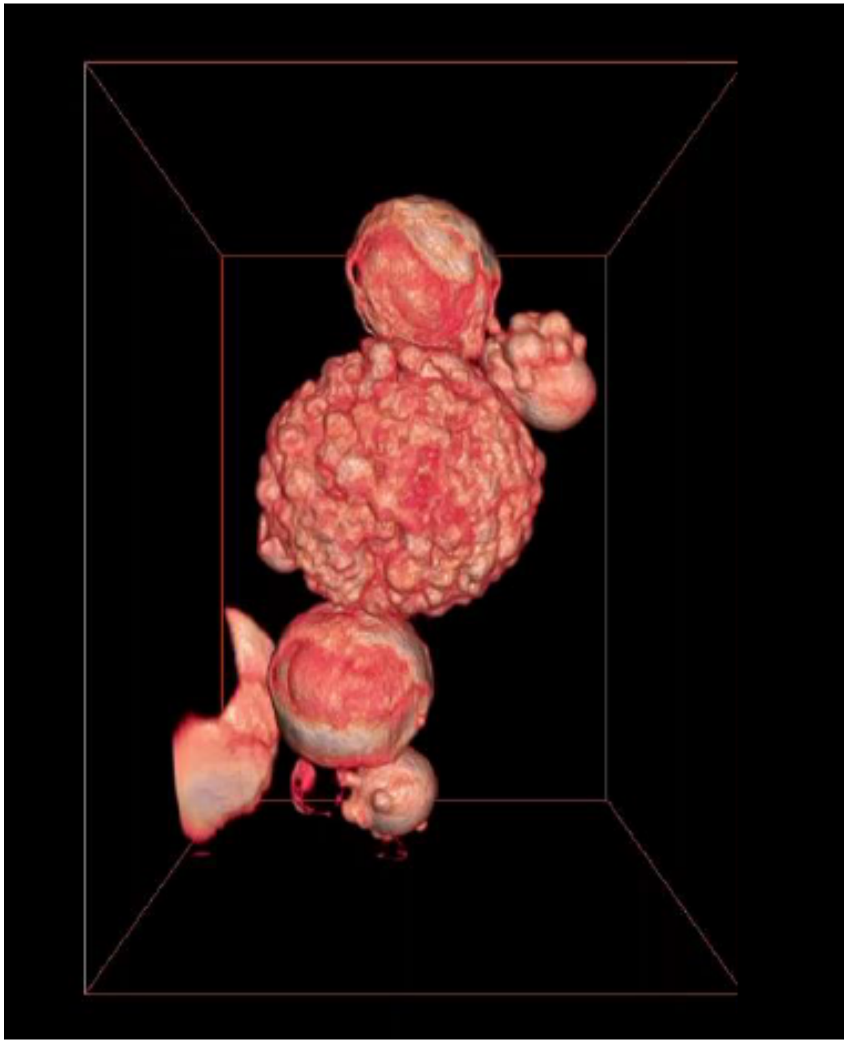
# Outline

- Introduction
- Requirements
  - Changes for MBAs
- Examples
  - Photon Beamlines
  - Stability measures / feedbacks
- Beamsize / Emittance
- Summary



# Introduction

- Often stability can be more important to SR users than brightness + flux
- Important argument in comparison to SASE FELs and potential ERLs
- Stability requirements have evolved and there are some differences for MBA rings
- Requirements are beamline/experiment specific and more effort will be needed in future to optimize integrated systems

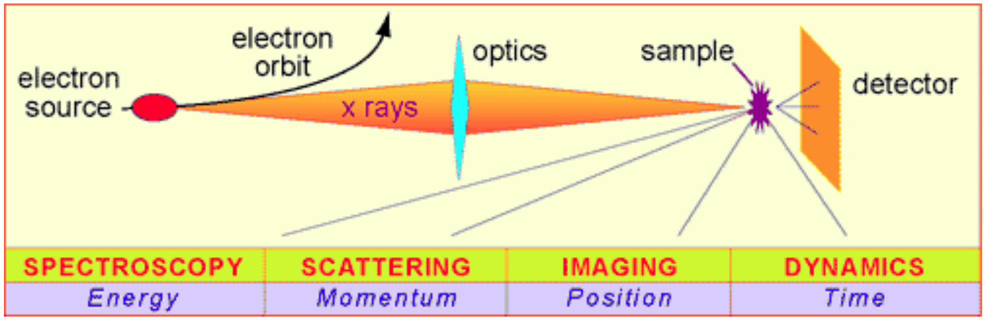


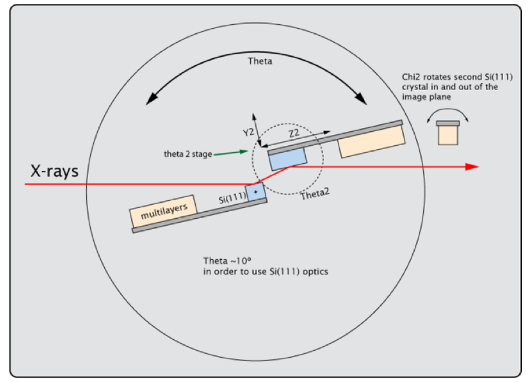
David Shapiro

BERKELEY LAB

ALS-U

# Requirements on 3rd gen Rings




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

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

Similar tables, see: Hettel, Boege, …

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

However, requirements are experiment specific and MBAs bring some changes

BERKELEY LAB

ALS-U

# Examples of sensitive Beamlines

- ALS micro-focusing
  - Environmental samples ( ‘dirt’ )
  - Very heterogenous

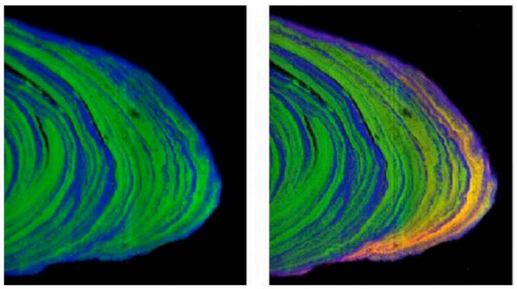
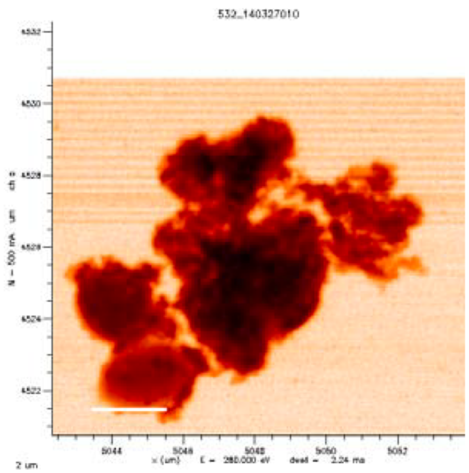


Figure 1. Synchrotron-based micro-X-ray radiation fluorescence (μSXRF) Fe and Mn maps of the outermost Fe and Mn layers of a ferromanganese nodule from the Baltic sea (6600 μm x 3780 μm, step size 15 μm, counting time 250 ms/pixel, red = Zn, green = Mn, blue = Fe, beamline: 10.3.2.). The onion-like structure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

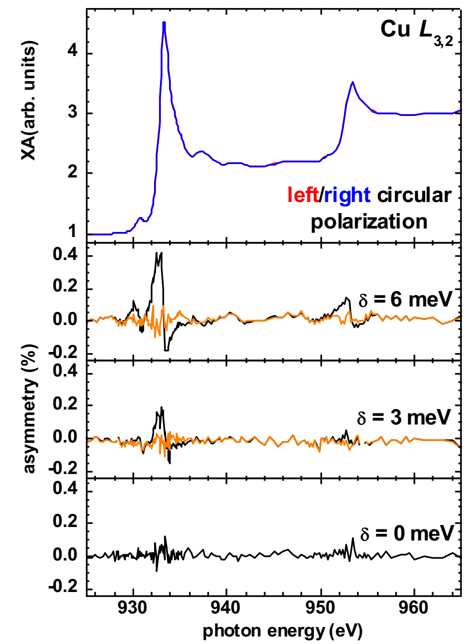
Matthew Marcus

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




David Kilcoyne

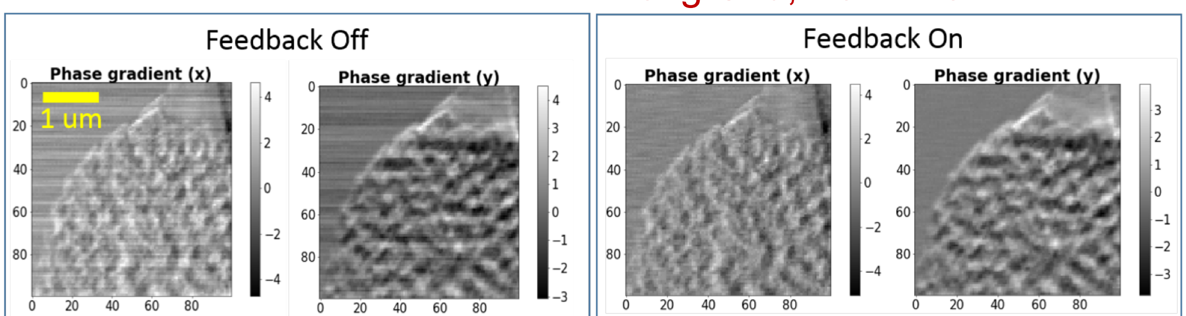
- ALS magnetic spectroscopy
  - Measuring very small dichroism effects
  - Energy stability when switching polarization is critical




Elke Arenholz

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

Yong Chu, Petr Ilinski




BERKELEY LAB

ALS-U

# Brightness / Coherent Fraction

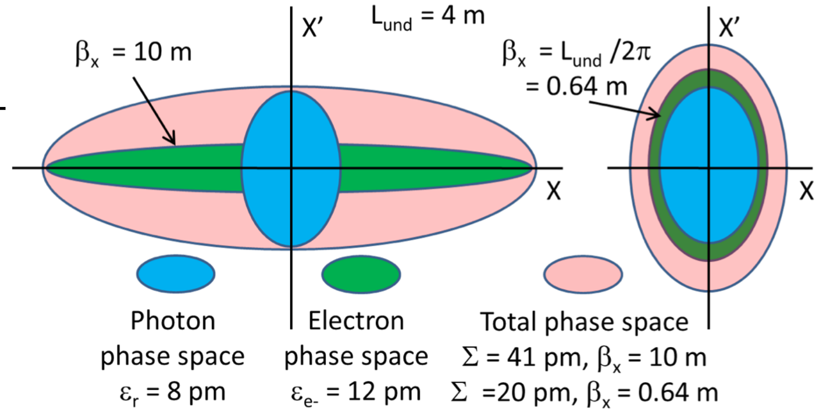
$$\varepsilon_r = \text{diffraction limited emittance} = \sigma_\gamma \sigma'_\gamma = \frac{\lambda}{4\pi} = \begin{cases} \text{80 pm @ 1 keV} \\ \text{8 pm @ 10 keV} \end{cases}$$

**Brightness is inversely proportional to convolution of electron beam sizes and divergences and diffraction emittance**

$$\text{Brightness} = \frac{\text{Spectral Flux}}{(2\pi)^2 \sigma_{Tx}\sigma_{Tx'}\sigma_{Ty}\sigma_{Ty'}}$$

$$\sigma_{Tx} = \sqrt{\sigma_x^2 + \sigma_\gamma^2}$$

Electron Photon




**Coherent fraction = ratio of diffraction-limited emittance to total emittance**

$$f_{coh} = \frac{F_{\mathrm{coh,T}}(\lambda)}{F(\lambda)} = \frac{\sigma_\gamma \sigma'_\gamma}{\sigma_{\mathrm{Tx}}\sigma_{\mathrm{Tx'}}} \frac{\sigma_\gamma \sigma'_\gamma}{\sigma_{\mathrm{Ty}}\sigma_{\mathrm{Ty'}}}$$

DLSRs produce photon beams with dramatically larger coherent fraction due to reduced horizontal emittance

BERKELEY LAB

ALS-U

# Changes for MBAs

- Imaging experiments will become more prevalent
  - At ALS those are the more demanding experiments (STXM, ptychography)
- Time resolution (coherent flux, data rate, detector speed) will increase, making faster time scales more important
  - Example of FTIR being especially sensitive to very small distortion if at unfavorable frequencies (~several kHz) – Does this extend to XPCS (which could go to MHz and beyond)
- Little change in beam parameters in vertical plane, horizontal plane becomes similar to vertical
  - Vibration/noise levels not very different for hor/vert (usually a little larger in x)
  - (lattice) amplification factors could change – for ALS-U seems to be small effect
- Synchrotron tune becomes (very) low
  - Potential problems with orbit/multibunch feedbacks

BERKELEY LAB

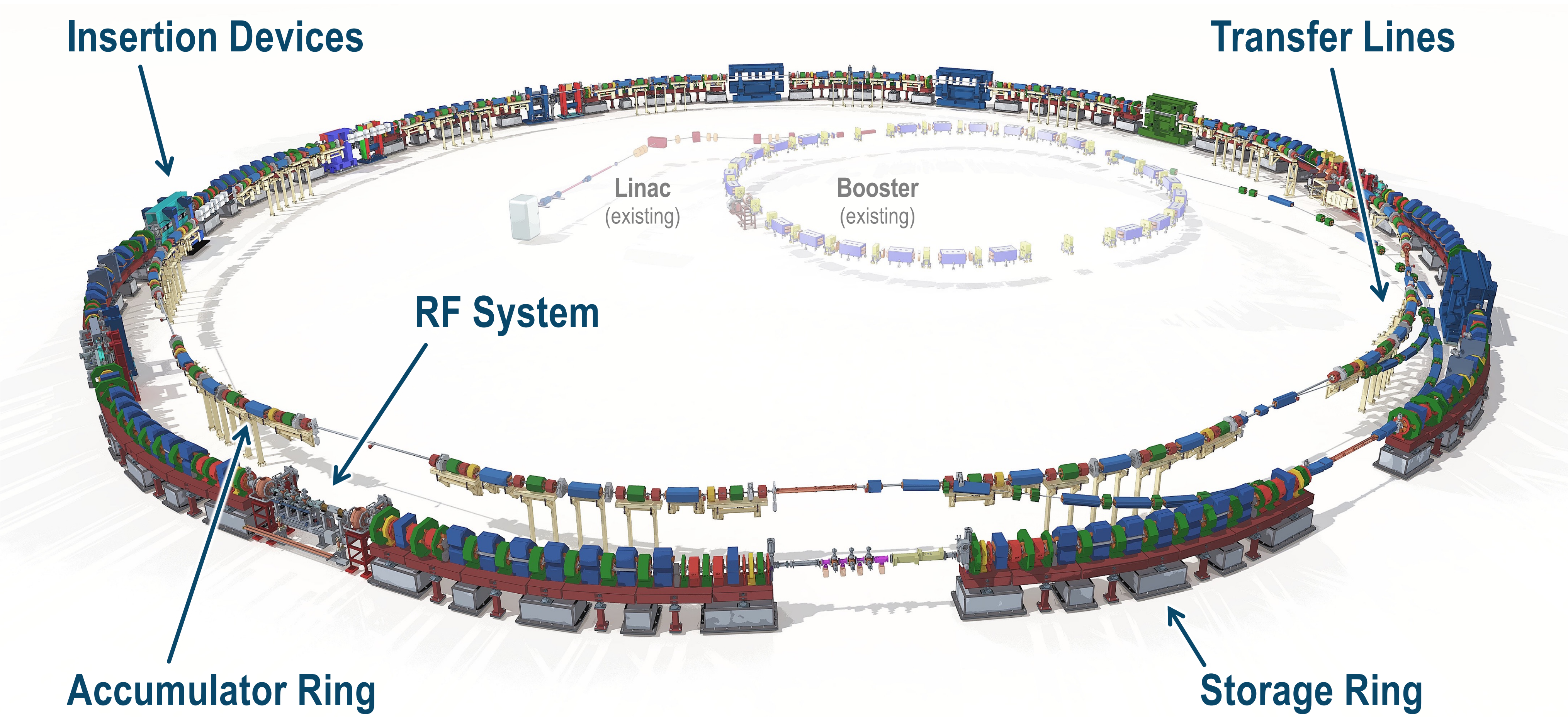


ALS-U

# Changes for MBAs (2)

- Beam emittance will in some cases approach diffraction limit (or optics resolution limit) in which case stability goal will be somewhat relaxed
  - We still often will deal with partially coherent beams and optics are constantly improving – might not help as much
  - Again FTIR is cautionary tale (lock-in amplifier equivalent?)
- 2-5% goal was mostly based on experience in horizontal plane, where we were far away from optics resolution or diffraction limit
  - New facilities typically start with more generic 5-10% goal now (relative to smaller emittances), but need to be aware that this might need to evolve/improve as optics and experimental techniques evolve
- Undulators will have larger effect on emittance/energy spread
- IBS will cause distortion from gaussian beam profiles (significant?)

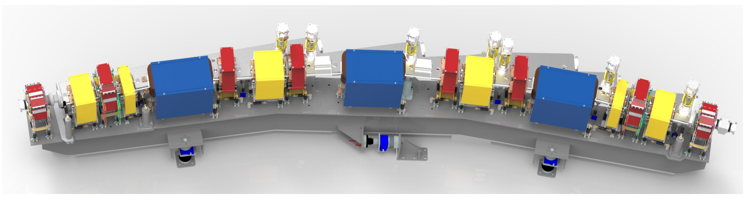
# Practical, realizable, integrated conceptual design has been developed



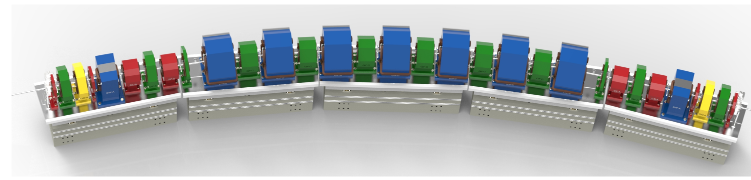

- Insertion device straights + beamlines stay in exactly the same place
- Arcs have different shape (9 vs 3 bends) – circumference 30 cm shorter

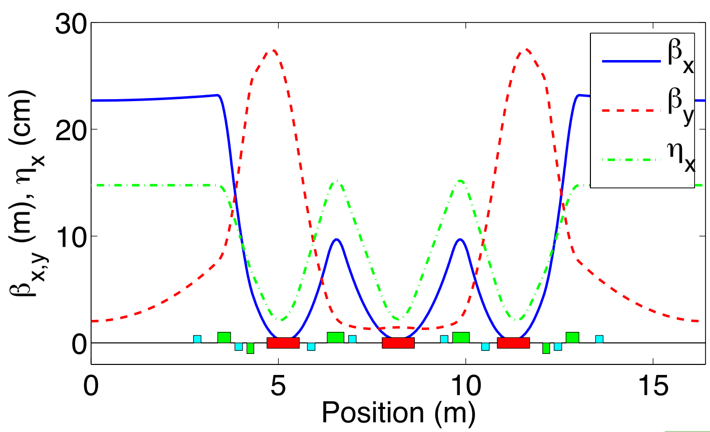
# Nine-bend achromat lattice reaches the soft x-ray diffraction limit up to 1.5 keV

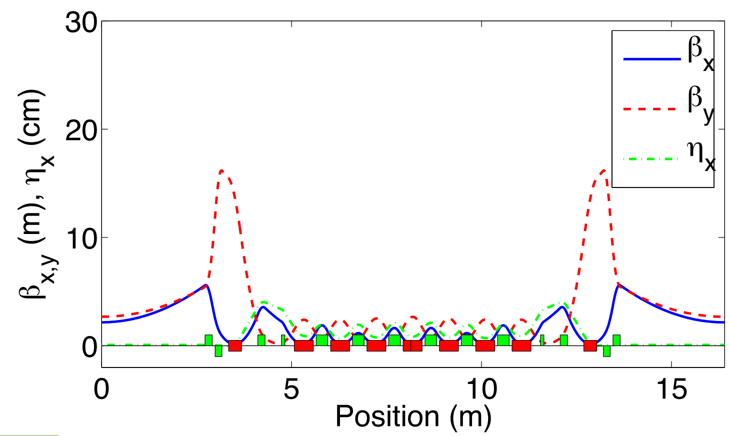
**ALS today : triple-bend achromat**



**ALS-U: nine-bend achromat with reverse bends**






$\varepsilon_x \approx 2000$ pm rad at $1.9 GeV$

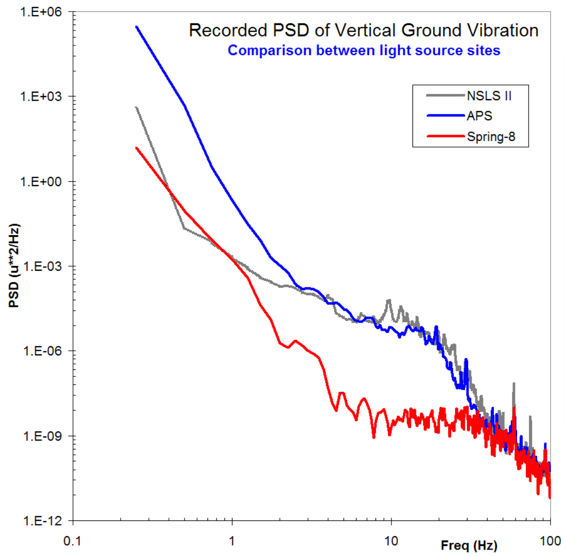
$$\varepsilon_x \approx \sigma_x \sigma_\theta \propto \frac{E^2}{N_D^3}$$

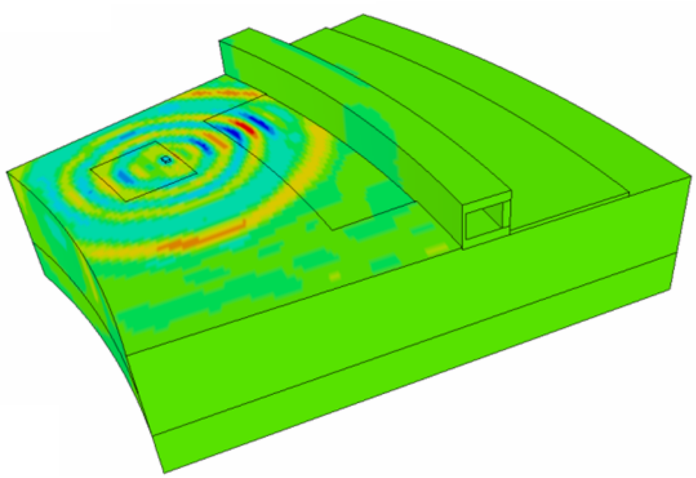
$\varepsilon_x < 75$ pm rad at $2.0 GeV$

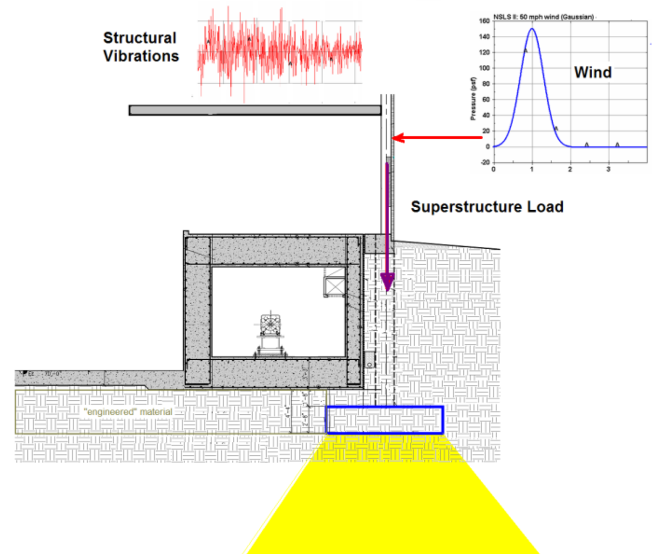
**Large increase in coherent fraction due to lower emittance and smaller β-functions**

# Examples how to achieve Requirements

# Stability / Design






Courtesy: N. Simos, NSLS-II

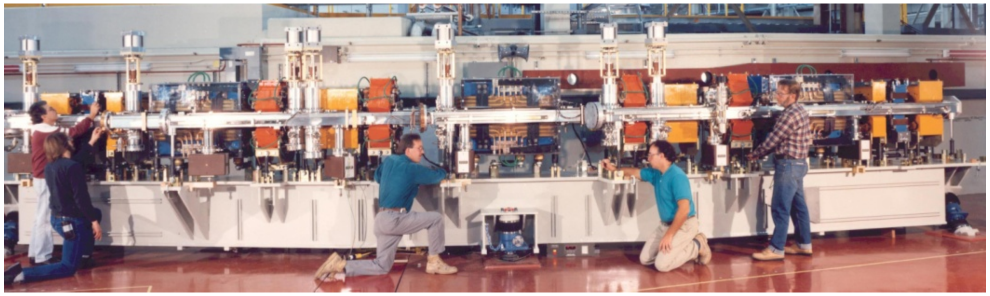
- One hopefully starts by selecting a good / quiet site (not always possible) - at least need to know all caveats
- FEA allows optimization of slab design
- Important: Minimize vibration coupling from pumps, …
- Also keep external disturbances in mind (wind, sun, …)

BERKELEY LAB

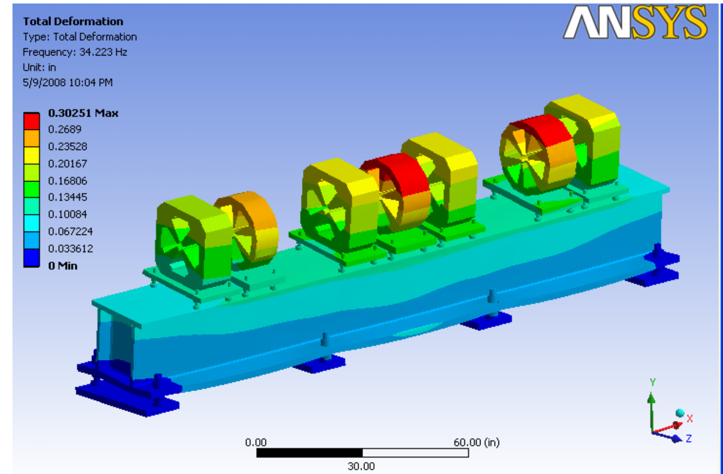


ALS-U

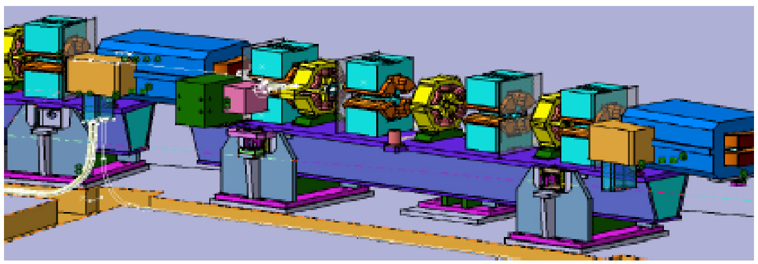
# Girder Design



ALS

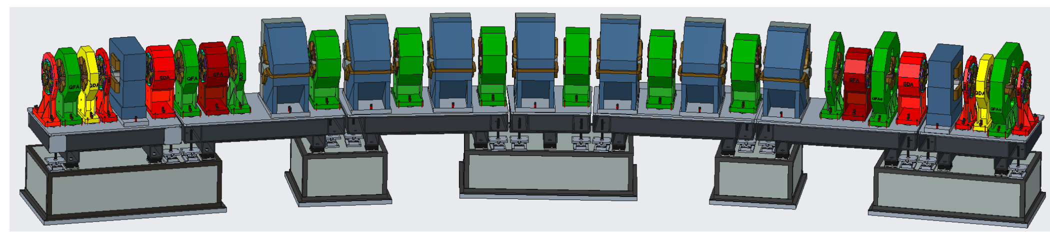



NSLS-II: courtesy S. Sharma



Soleil

ALS-U



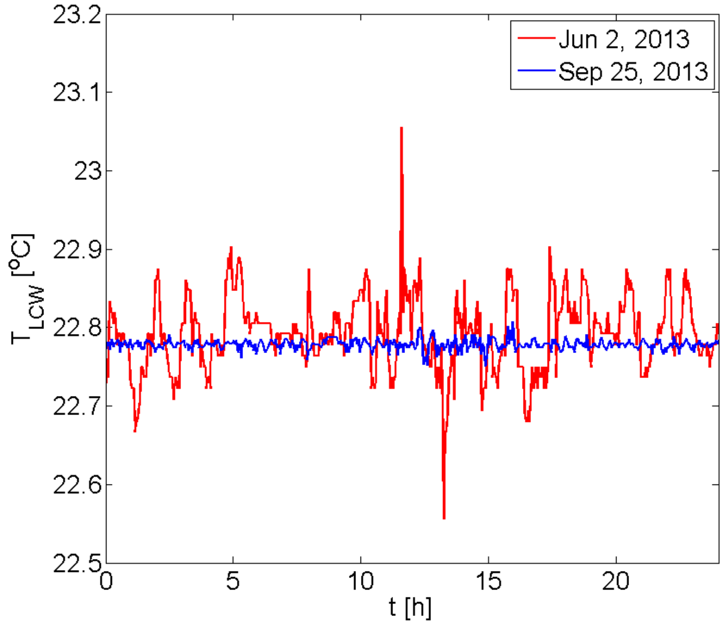
- Some early 3rd generation sources had massive girders (low resonance frequencies – sampling larger ground oscillation amplitudes)
- Later ones had girders with higher resonance frequencies but movers, that significantly lowered them
- Newer designs (Soleil, NSLS-II, …) avoid this caveat – smaller vibration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

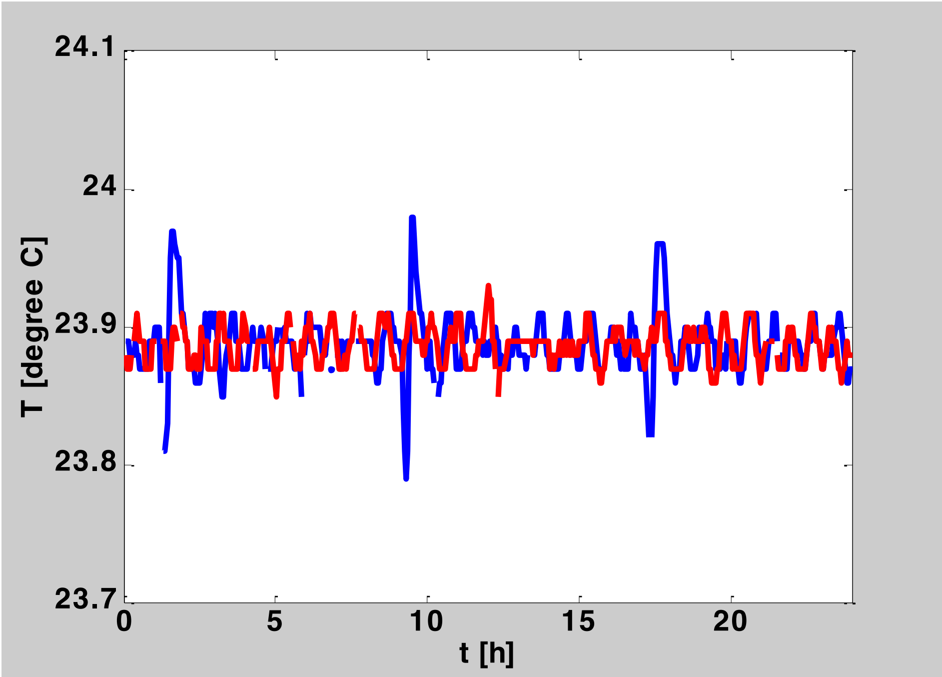
BERKELEY LAB



ALS-U

# Air/water temperature stability



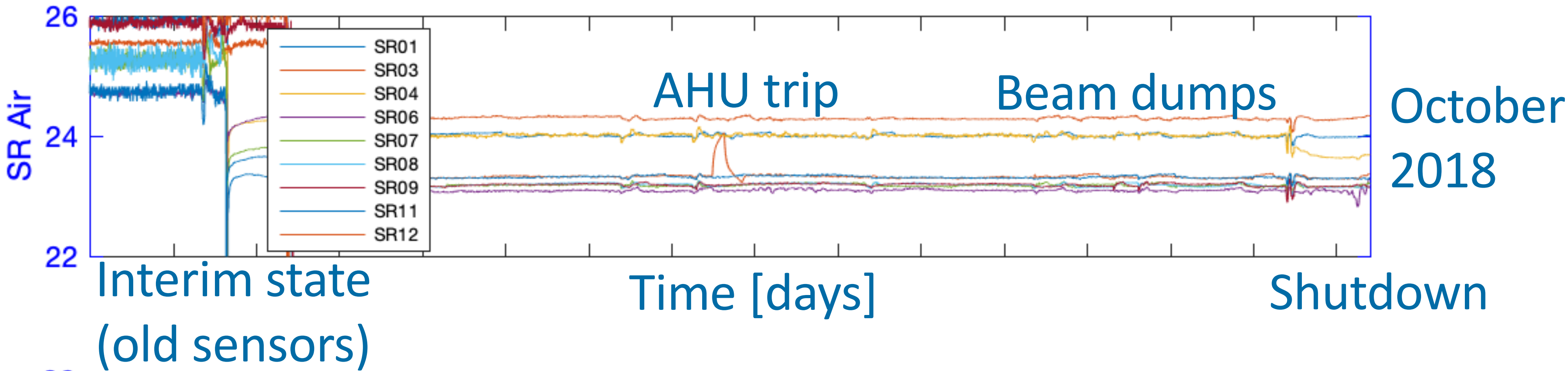

Left: ALS water temperature, Right: Tunnel air temperature

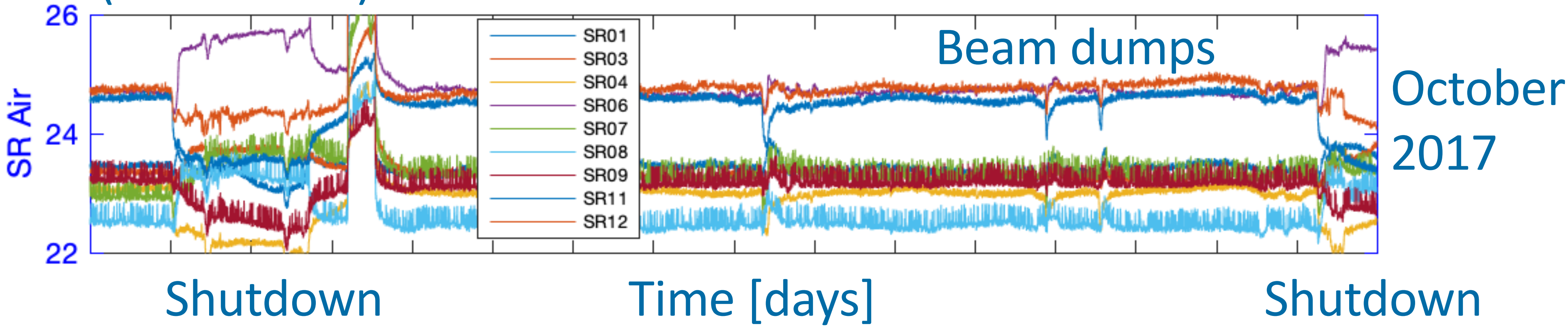
- Stable environmental conditions are extremely important
- State of the art is water and tunnel air temperature stability on the order of 0.1 degree C
- Stable power supply controllers, invar rods for BPM mounts, … also help, but it is always best to also keep the conditions constant

BERKELEY LAB

ALS-U

# Commissioning results of new ALS AHU controls



# Orbit Feedback

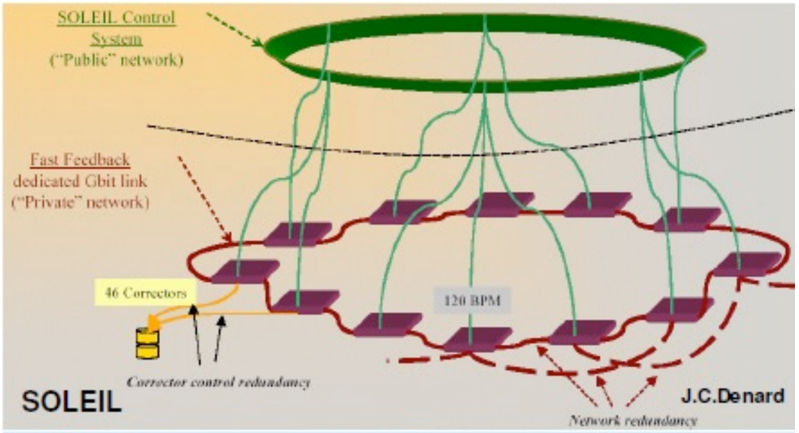
- Even in extremely stable light sources, orbit feedback can always improve stability
- This is particularly true for the effects of insertion device motion (feed-forwards are never perfect)
- Nowadays, all light sources tend to use global orbit feedbacks with some variation of SVD (or direct matrix inversion) – local feedbacks are used less seldom
- Fundamentally, one only needs one (fast) orbit feedback, however, practical aspects often make using two more practical
  - lack of enough fast corrector magnets, lack of strong enough corrector magnets, lack of enough suitable BPMs, differences in e-beam/photon BPMs, …
  - Can be solved in integrated/universal system as well – performance advantage?

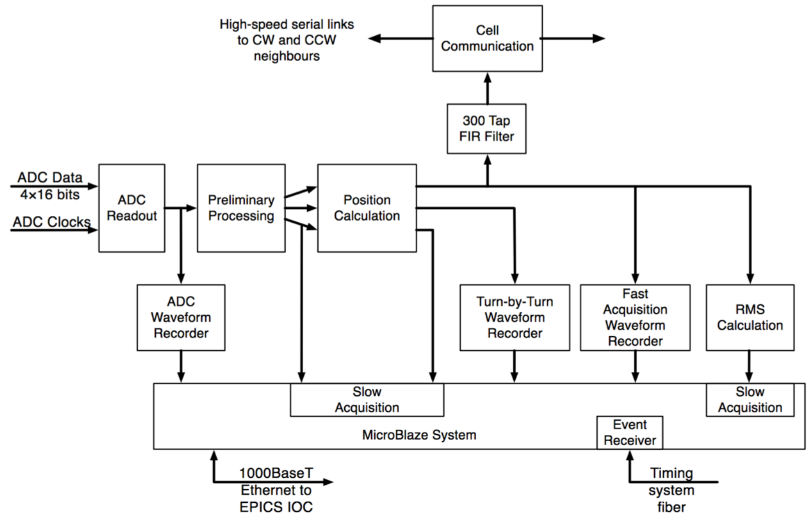
BERKELEY LAB



ALS-U

# Fast orbit feedback topologies



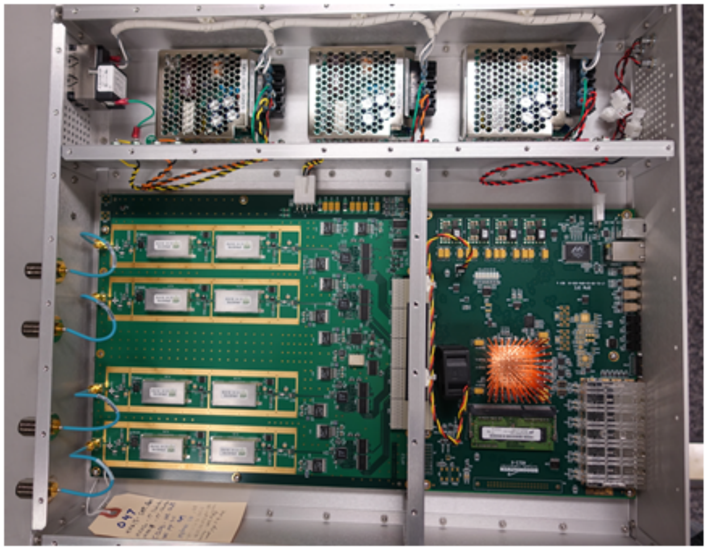

- Many different types of fast orbit feedbacks are in use
- State of the art are systems with update rates up to 20 kHz and closed loop bandwidths approaching 1 kHz
- In some systems, PID algorithms are supplemented by notch filters, …
  - Other filter designs (predictive, …) could improve performance/robustness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

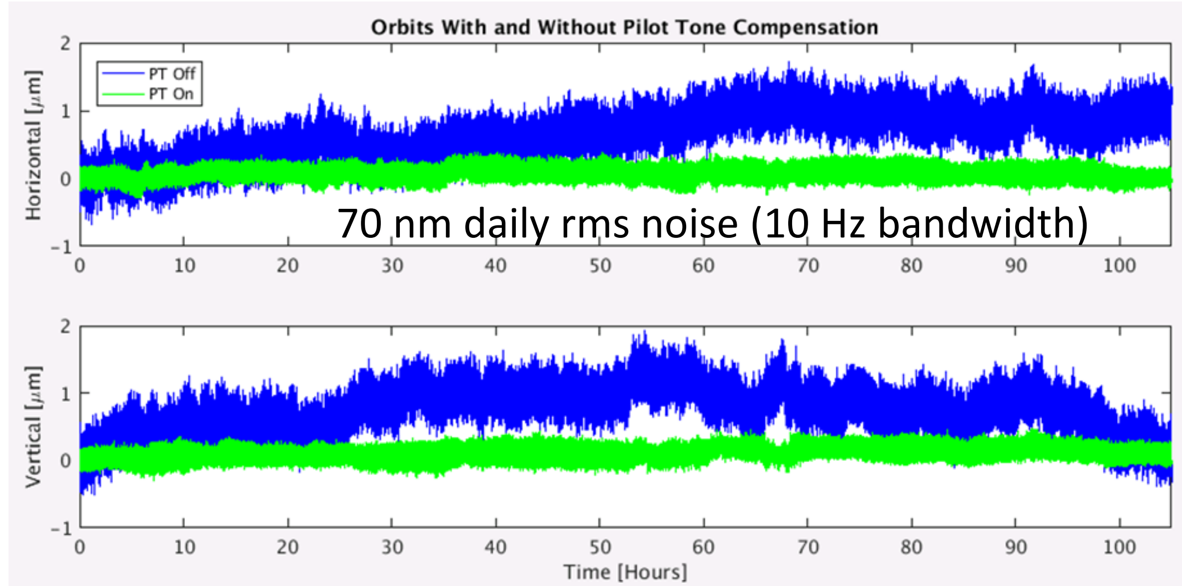
BERKELEY LAB



ALS-U

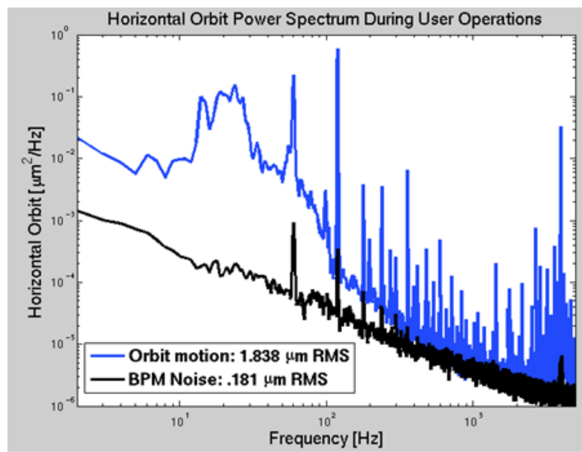
# BPM Trends: Low Noise, High Update Rate, low latency

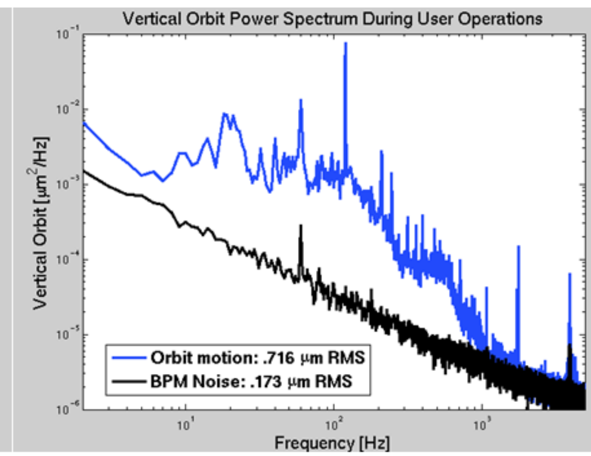





**Strong and effective collaboration with NSLS-II**

**Also need: fast power supplies, magnets, special vacuum chambers, … - development is ongoing**




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

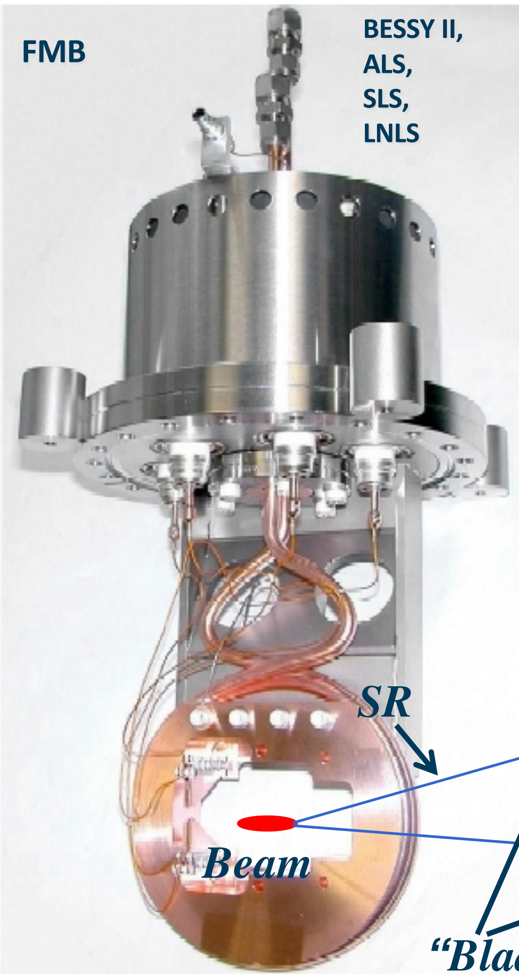
**Greg Portmann, Mike Chin, Eric Norum**

BERKELEY LAB

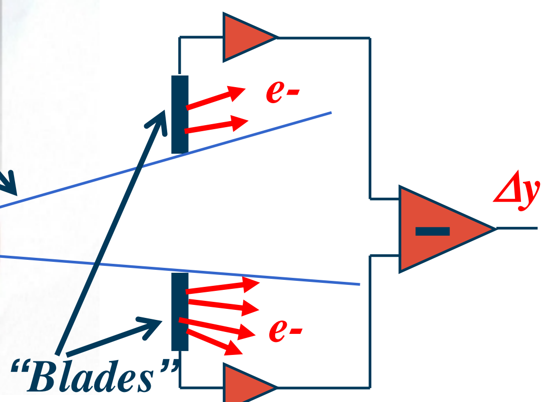
ALS-U

# Photon BPMs

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

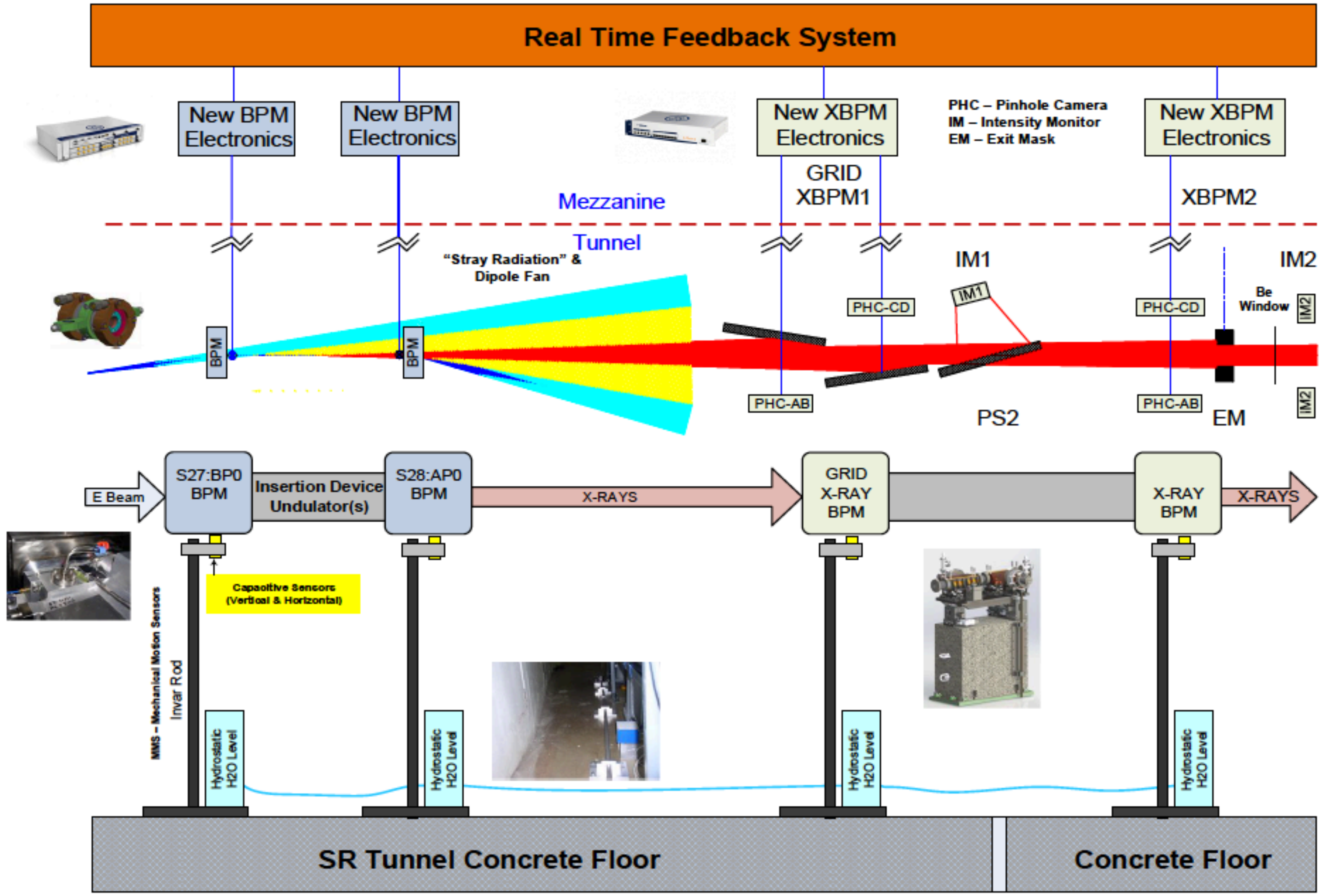



Simple x-ray BPM for dipole beamline, which is broadly used.




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

# Example of Feedback Integration R+D - APS




Courtesy: Bob Lill (APS/APS-U)

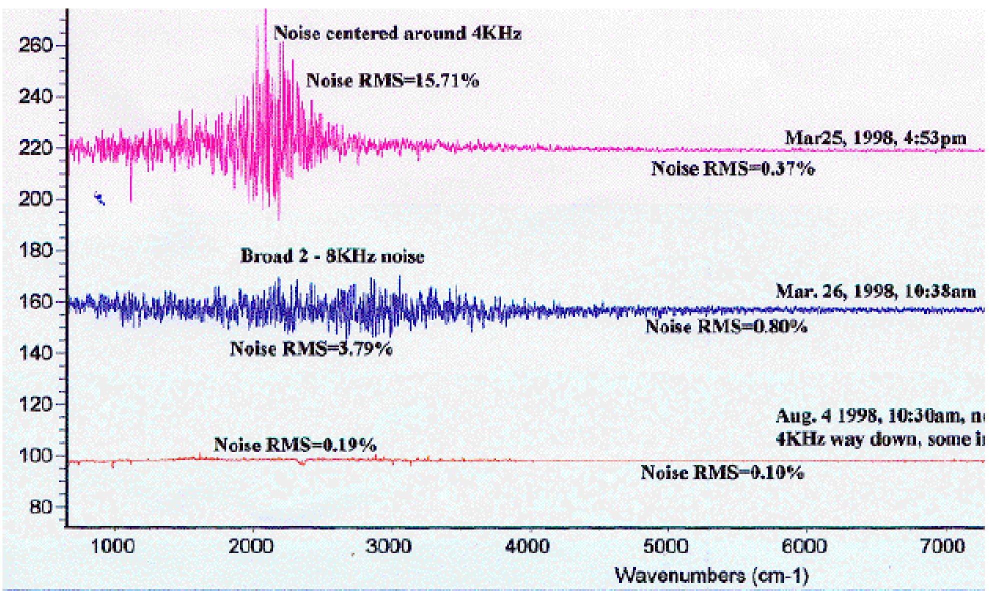
BERKELEY LAB

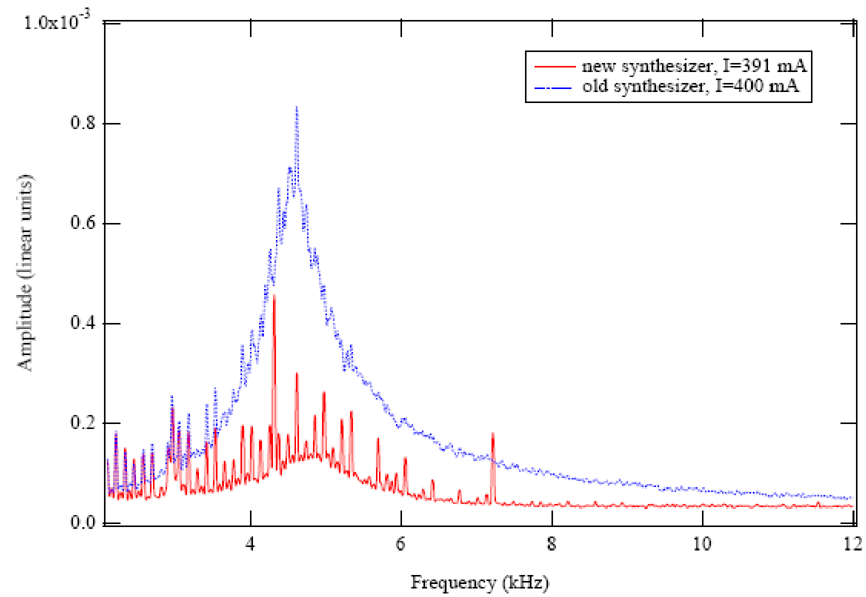
ALS-U

# High Frequency / Multibunch Stability

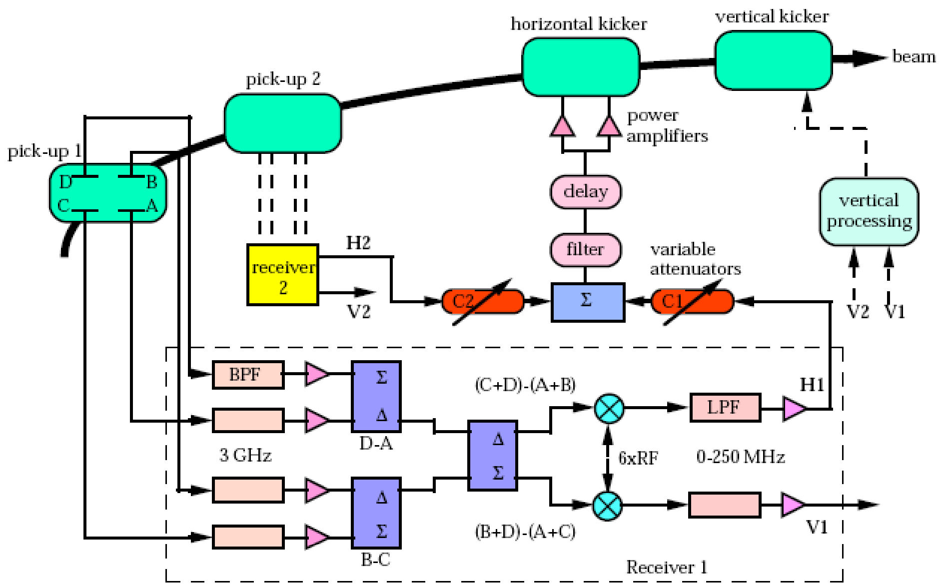
# RF phase noise

- 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
- Additional challenge for feedback systems when synchrotron tune drops into FOFB bandwidth – need to couple FOFB and RF feedbacks (PEP-II woofer)

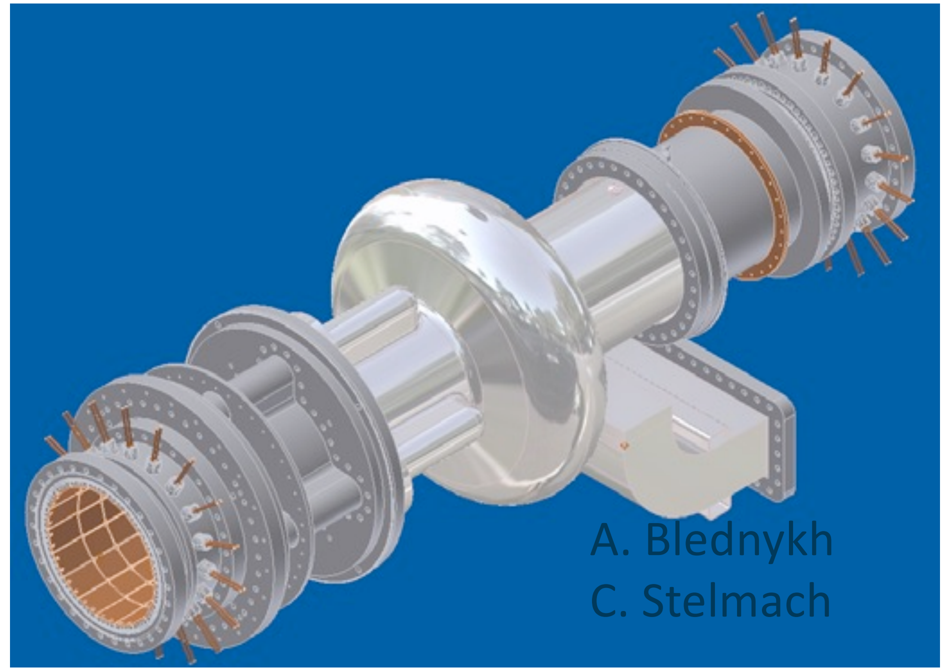


# Instabilities / Feedback / HOMs




ALS TFB: W. Barry




- Very fast stability / single+multibunch instabilities
- Routinely addressed by multibunch feedback system (longitudinal/transverse) – most recent ones all digital – with low synchrotron tune some overlap with FOFB
- HOM free cavities (SC or N/C) help, particularly longitudnally
- Transversely feedbacks can allow operation with small chromaticity
  - Also can be used to increase TMCI threshold (ALS factor >4)
  - Reduce duration of injection transients in top-off/swap-out

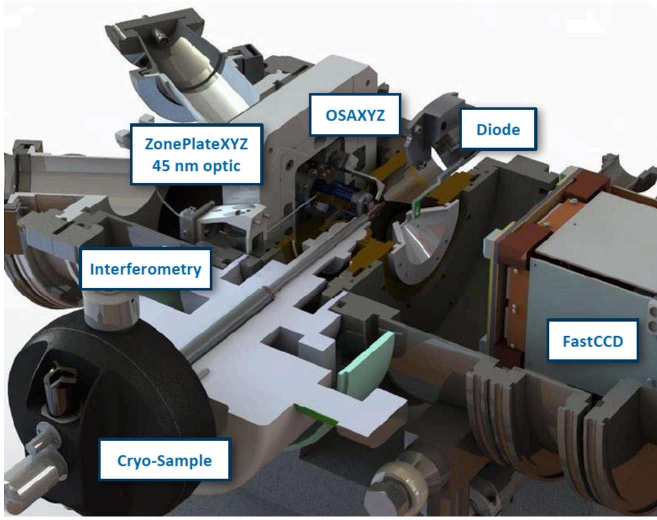
BERKELEY LAB



ALS-U

# 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 even in state-of-the-art beamlines
  - Microfocus beamlines investigating heterogeneous samples





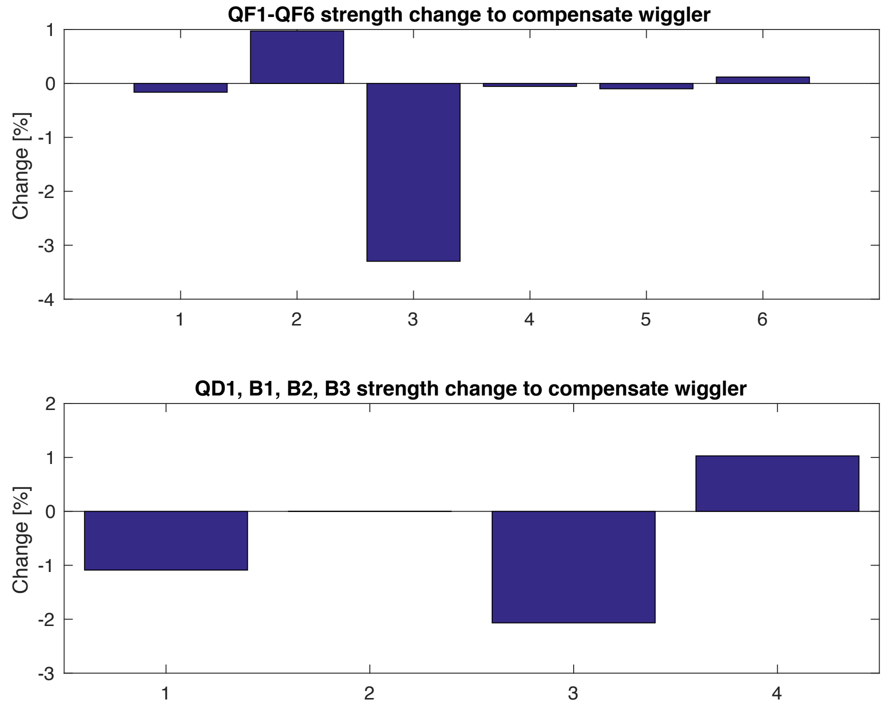
- **What needs to be corrected:**
  - **Optics distortion (beta functions)**
  - **Skew gradients**
  - **Potentially horizontal/vertical natural emittance**

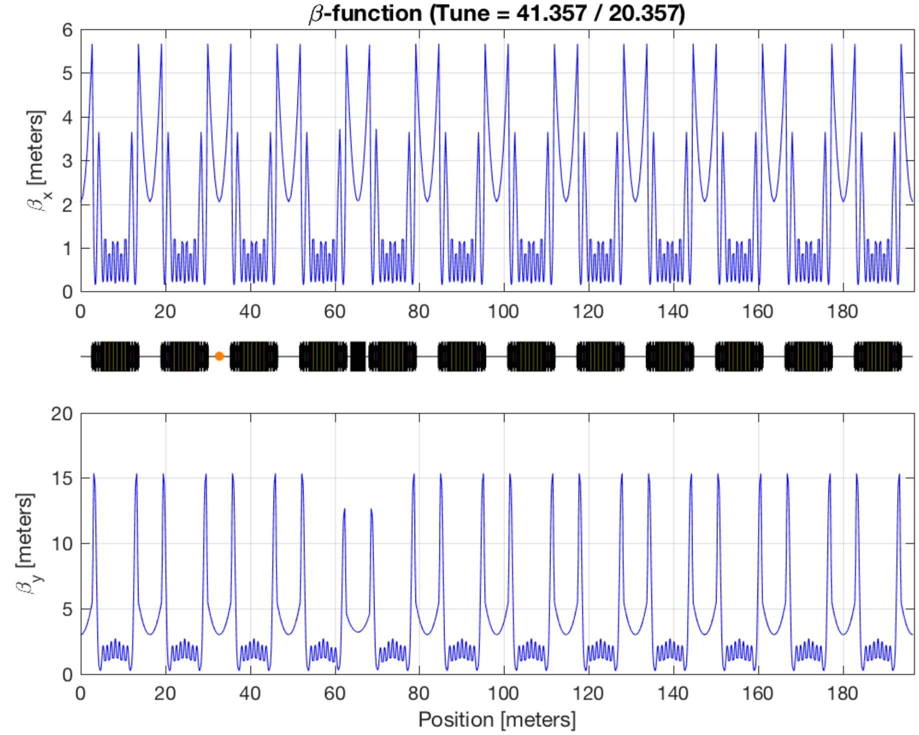
BERKELEY LAB



ALS-U

# Beta Beating Compensation can be complex (ALS-U)

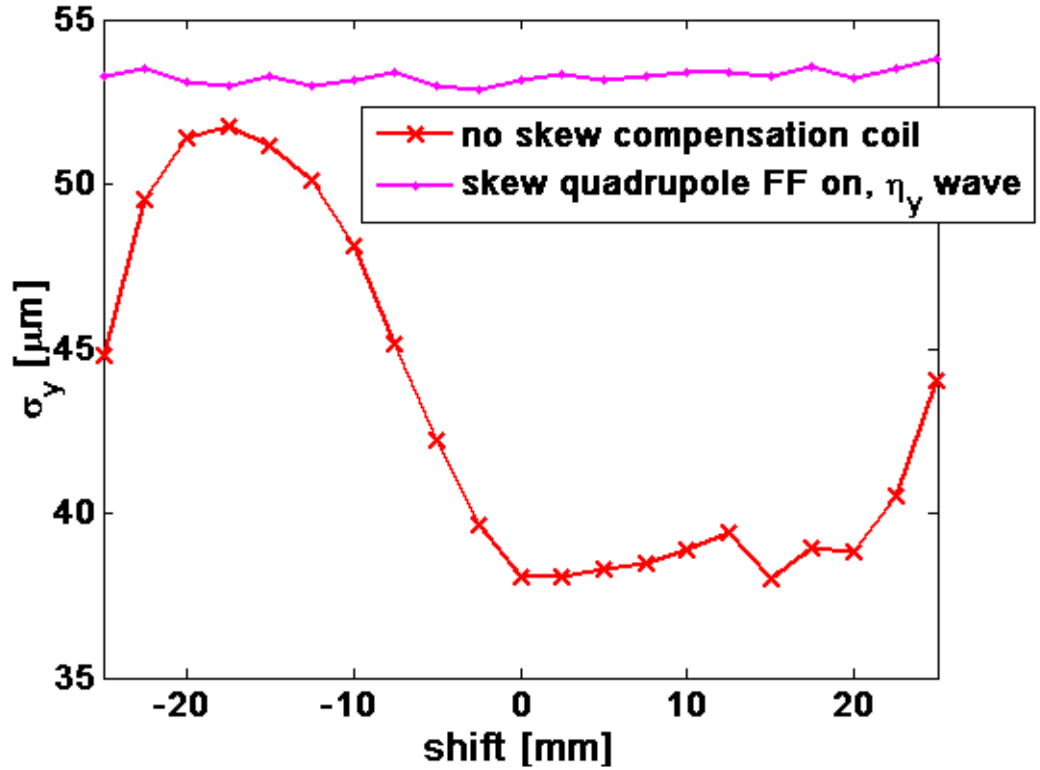



- Shown is local tune, phase advance, beta beating compensation for tune shift of W114, $\Delta\nu_y = 0.035$
- Within tuning range of magnet designs
- Acceptable dynamic and momentum aperture impact

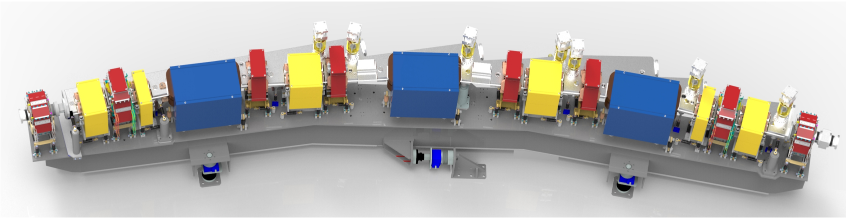
# EPU effects on vertical beamsize

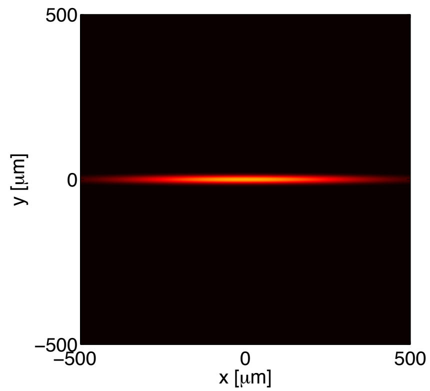
- Vertical beamsize variations due to EPU motion were big problem.
- Is caused by skew quadrupole (both gap and row phase dependent)
- Root cause reduced in newer devices
- Installed skew coils for feedforward correction
- Stability ~1% - deteriorates over time
- Recent tests of machine learning algorithms to reduce residual (Leemann, Hexemer) encouraging

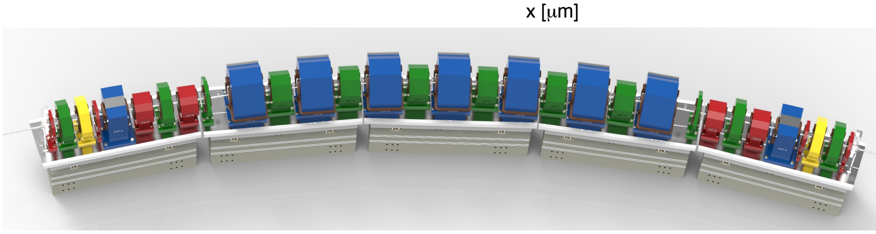


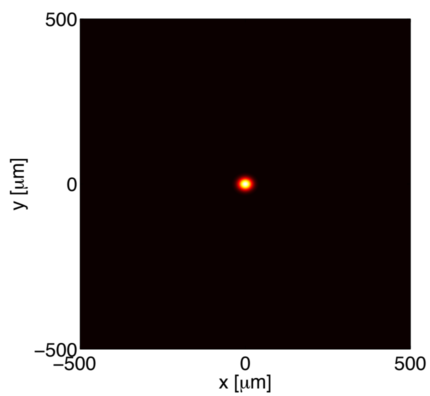

**For reference: Whenever an undulator moves, about 120-150 magnets are changed to compensate for the effect (slow+fast feed-forward, slow+fast feedback)**

# MBAs and round (large coupling) beams








- If beam is truly diffraction limited, there is no benefit from vertical emittance being smaller than horizontal
  - However, definition of 'diffraction limited' usually is electron and diffraction emittance being equal, i.e. 25% coherent fraction (2 planes)
- Touschek lifetime, IBS, … would continue to get worse with smaller bunch volume
- Some user experiments (like diffractive imaging, STXM, …) work with round pinholes, would throw away flux if emittances are not equal

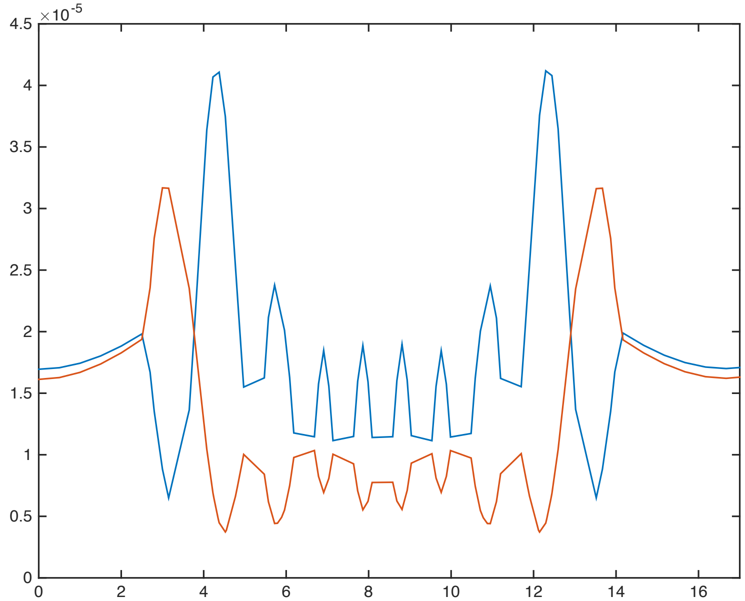
BERKELEY LAB

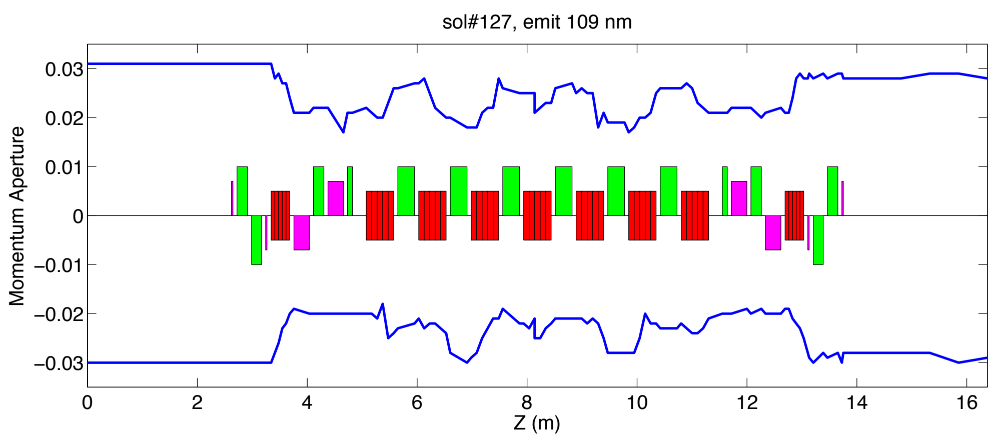
ALS-U

# Methods to achieve large emittance ratios in MBAs

- Damping Wigglers
  - Vertical DW
  - Local vertical dispersion bump in DW
- Möbius Accelerator
- Betatron Coupling
  - Equal fractional tunes
  - Resonance Excitation (time dependent fields)
- Issues to consider: Complexity, Space, Total Emittance, Possibility of different injection schemes, Impact on nonlinear Beam Dynamics, Stability of Emittance

# ALS-U example: Coupling Resonance




- Simulated operation on coupling resonance, with moderate coupling errors
- Result are almost equal emittances (60 pm in this case)
- Dynamic and momentum aperture are similar
  - Detuning with amplitude means that coupling at larger amplitude, where it matters for beam losses, does not really change

If Jx > 1, emittance on coupling resonance is > ½ natural emittance

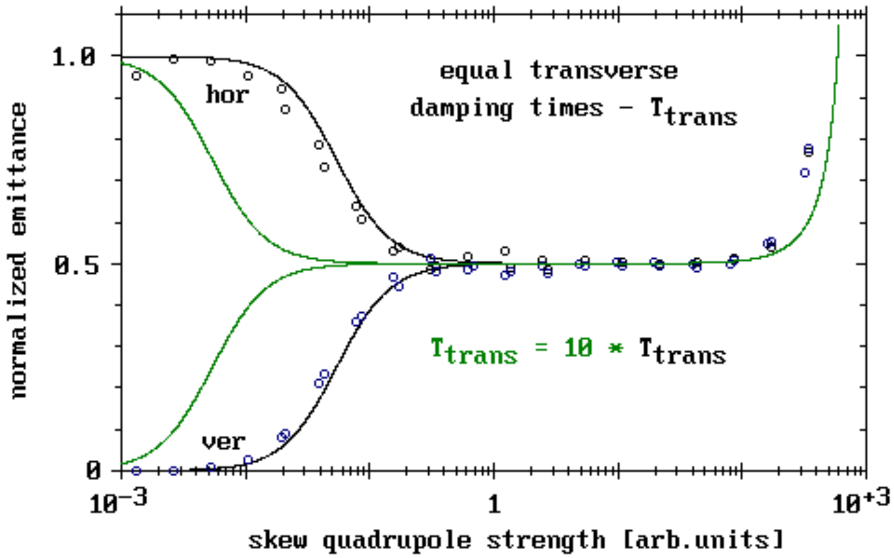
BERKELEY LAB



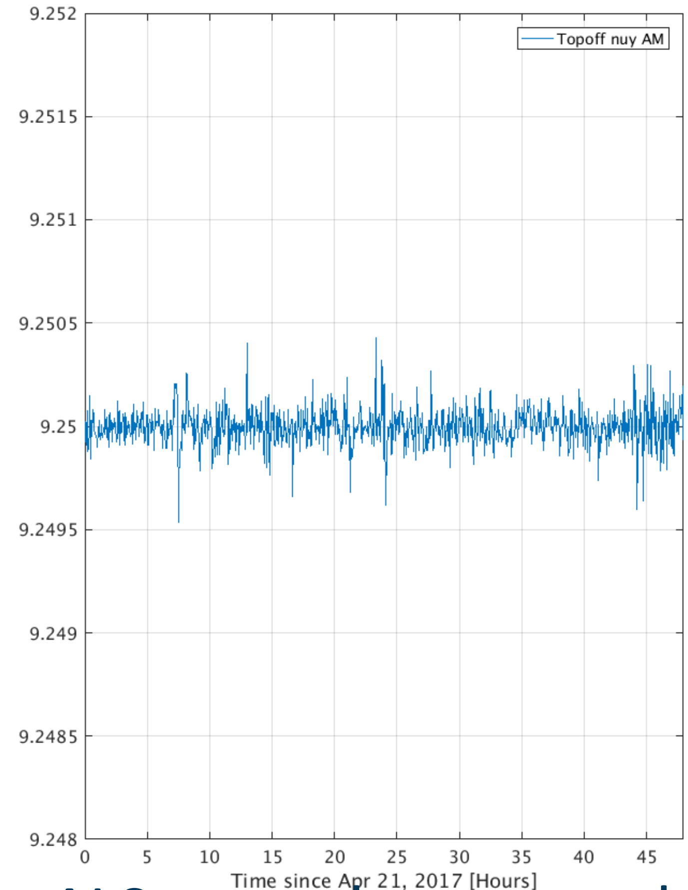
ALS-U

# Beamsize Stability on Coupling Resonance

Peter Kuske




- For equal emittance, fairly insensitive to coupling terms over wide range
- Dependence on tune not too steep for moderate coupling




- ALS example: tune stability with FF and tune FB
- Expect reasonable stability – plan to test on ALS

BERKELEY LAB

ALS-U

# Emittance Stability and Undulators

| | $\varepsilon_x$ [nm rad] Without IBS | $\varepsilon_x$ [nm rad] With IBS |
|---|---|---|
| Bare lattice | 0.326 | 0.453 |
| Bare lattice with LC | 0.326 | 0.372 |
| Lattice with four PMDWs and LC | 0.263 | 0.297 |
| Lattice with four PMDWs, ten IVUs, and LC | 0.201 | 0.231 |

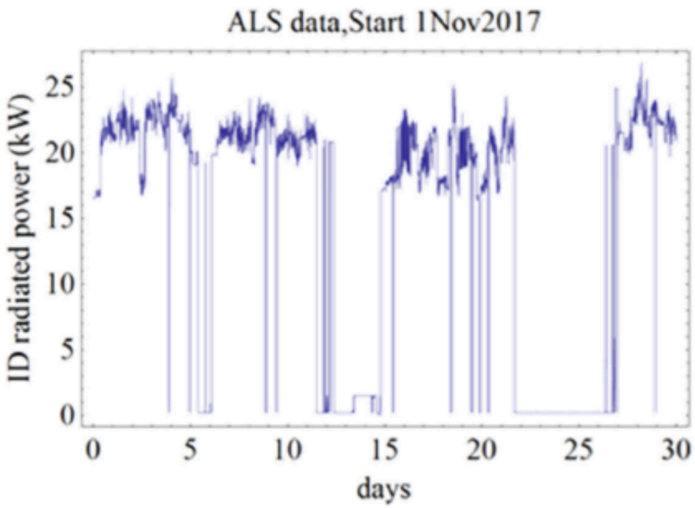
Max-4 example: S. Leemann, et al., PRSTAB 12, 120701 (2009)

- DLSRs / MBAs / Rings with low average bend magnet field have Beamsize stability issue beyond coupling
- Significant variation of energy loss per turn results in variation of damping times, natural emittance, energy spread
- Extend of effect varies, but can be >20% (including machines already in operation)
- This does not just mean emittance goes down as more undulators are installed, also depends on undulator scans (larger field variation for longer period undulators – ALS: undulator energy loss varies 50% typical week)
- (Additional) Damping wigglers can help in correction, but expensive (cost, space, RF) – full range might not be feasible
  - Other means are less efficient (e.g. limited tunability of MBA lattices)
  - Need to better understand user requirements / impact of uncorrected or partially mitigated

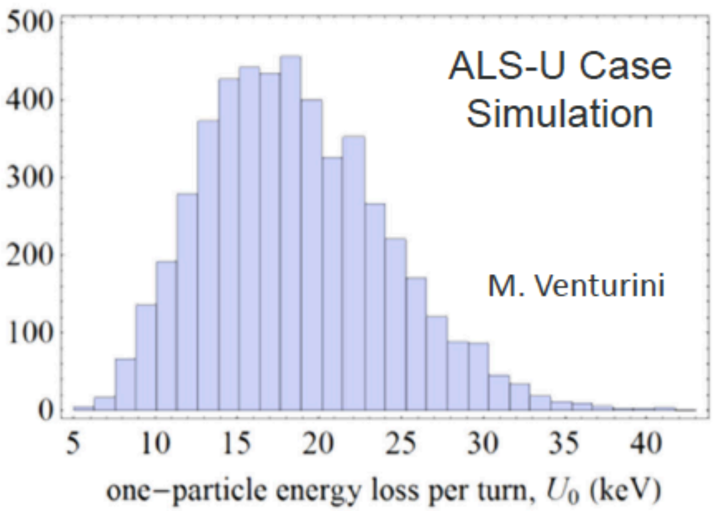
# ALS-U example

ALS Insertion Devices

| Name | Alias | BL | New? | $\lambda_u$ (mm) | $BX_{max}$ (T) | $BX_{min}$ (T) | $BY_{max}$ (T) | $BY_{min}$ (T) | No. periods |
|---|---|---|---|---|---|---|---|---|---|
| EPU50 | | 4.0.2 | No | 50 | 0.58 | 0.1 | 0.8 | 0.1 | 37 |
| QEPU90 | MERLIN | 4.0.3 | No | 90 | 0.78 | 0.06 | 1.18 | 0.06 | 20.5 |
| U114 | | 5.0.1 | No | 114 | 1.94 | 0.03 | 0 | 0 | 29 |
| EPU38 | COSMIC | 7.0.1 | No | 38 | 0.89 | 0.11 | 0.67 | 0.11 | 44.5 |
| EPU70 | MAESTRO | 7.0.2 | No | 70 | 1.18 | 0.07 | 0 | 0 | 26.5 |
| U50 | | 8.0.1 | No | 50 | 0.85 | 0.1 | 0 | 0 | 80 |
| U100 | | 9.0.1 | No | 100 | 0.98 | 0.05 | 0 | 0 | 43 |
| U100 | | 9.0.1 | No | 100 | 0.8 | 0.05 | 0 | 0 | 43 |
| EPU50 | | 11.0.1 | No | 50 | 0.85 | 0.1 | 0.57 | 0.1 | 36.5 |
| EPU50 | | 11.0.2 | No | 50 | 0.85 | 0.1 | 0.58 | 0.1 | 37 |
| U80 | | 12.0.1 | No | 80 | 0.8 | 0.07 | 0 | 0 | 55 |




Random ID gaps variation generates random beam radiated power variations.




$<U_0> = 18.5$ keV, $\sigma_{U0} = 5.6$ keV

$\Delta\varepsilon/\varepsilon \sim 7$ % (4 sigma)

Sannibale, Venturini, Steier

# Potential Solutions for ID induced emittance changes

- Potential mitigations for undulator induced natural emittance changes include:
  - One (or multiple) variable gap wiggler can maintain a constant emittance but requires a dedicated wiggler.
  - Dispersion bump in an existing fixed gap wiggler does not require a dedicated wiggler but requires knobs for the bump control, significant size bumps, and could affect beam dynamics.
  - Small electron beam momentum variations could be used but they move dipole source points, shift photon energy and potentially challenges the ring dynamic aperture.
  - Control by IBS requires significant bunch length shortening using harmonic cavities, affecting lifetime and stressing cavity tuning control.

# Outlook / Challenges

- Light source development continues to ever smaller emittances, i.e. tighter stability requirements (mostly horiz.)
- Improvements seem possible by treating accelerator + photon beamline as integrated system
- Photon BPMs work well for hard x-ray undulators (potentially with Decker distortions), not so well for VUV, still no good solution for EPUs
- Large number of fast switching insertion devices (EPUs, …) at low/intermedium energy light sources mean more perturbations
- Truly transparent top-off or swap-out injection is very difficult.
  - Achieving similar relative stability when moving to high rep-rate FELs, or MBAs (with new injection methods) is feasible but difficult
    - Swap out presents some new challenges compared to top-off

# A complementary view (NSLS-II)

## Some Bullets from NSLS-II Beam Stability Task Force

- Absolute majority of NSLS-II beamlines are happy with presently provided e-beam stability [at ID source points: single digit microns/micro-radians pk-to-pk for long-term drift, <10% of beam size in V. (much smaller in H.) rms for short-term (0.1-5000 Hz) ].
- Studies with dynamic local bumps showed that our most sensitive beamlines could detect singe-digit micron or micro-radian orbit motions (but not sub-um/sub-urad!).
- These agree with SRW simulations (10% of beam size variation in pointing stability should not be noticeable at the sample compared to the effects due to typical beamline optics misalignments and surface imperfections). More true for DLSR?
- Beamline local feedbacks (which steer photon beam using mono XBPMs for position sensing and use piezo-driven mirrors and monochromator crystals as actuators) have performed superbly at HXN and CHX and their use is promoted throughout the facility. HXN reported ~10 nm positional stability on the sample.
- These feedbacks are crucial to remove photon beam disturbances coming from beamline elements, due to vibrations, heat loads, etc., (as well as small e-beam orbit residuals), even though beamline designs were heavily optimized for stability.
- Similar beamline feedbacks are greatly desired by our soft-XRAY beamlines, but this still requires R&D. Most importantly, non-intercepting, coherence-preserving, soft-XRAY BPMs do not exist. This must be solved for soft-XRAY DLSRs!

Boris 10-31-18

# Summary

- Stability Requirements for MBAs are generally an evolution of 3rd generation requirements
  - More study might be needed to understand integrated accelerator/high performance beamline systems to refine requirements
  - Requirements involve not just position/angle, also size, emittance, energy spread
- The number of imaging beamlines (especially using coherence) is expected to grow
  - They tend to be more sensitive ones on current rings
- Relevant time domains will change for MBAs
  - High coherent flux and faster undulators might extend in ns (or even ps) range
- MBAs can require larger emittance ratios than currently in use
  - Multiple ways to achieve (including operating on coupling resonance)
  - Beam dynamics impact manageable
  - Beamsize stability requires good tune control, reasonable resonance strength
- Insertion devices provide new challenge to emittance stability if they contribute significantly to total energy loss
- Good Photon BPMs for EPUs still not in hand

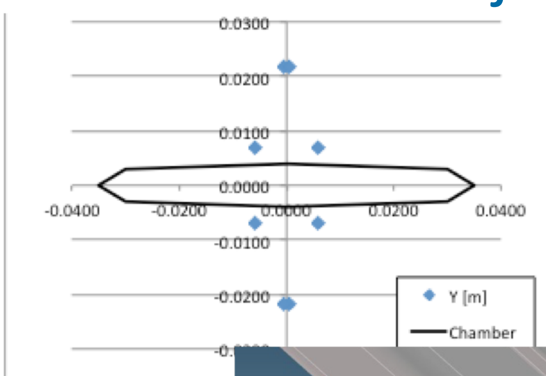
# Acknowledgments

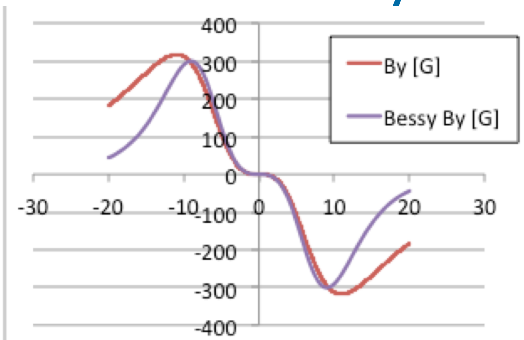
- I have tried to incorporate input from many people (thanks for answering my request)
- I believe most input is mentioned, but in some cases very brief (and distributed among the slides)
- Thanks to: Peter Kuske, Laurent Nadolski, Nick Sereno, James Safranek, Jeff Corbett, Boris Podobedov, Timur Shaftan, Guimei Wang, Yuke Tian

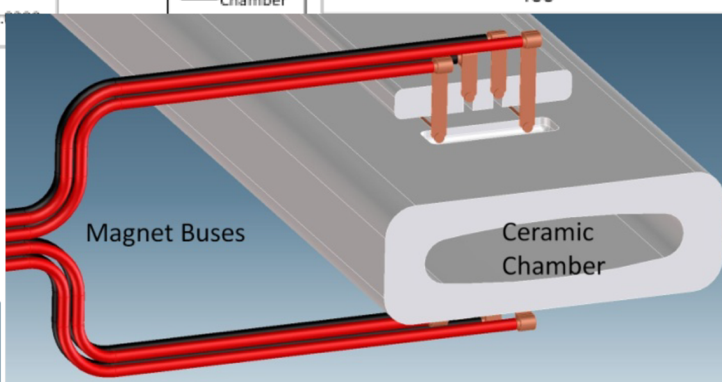
# Backup slides

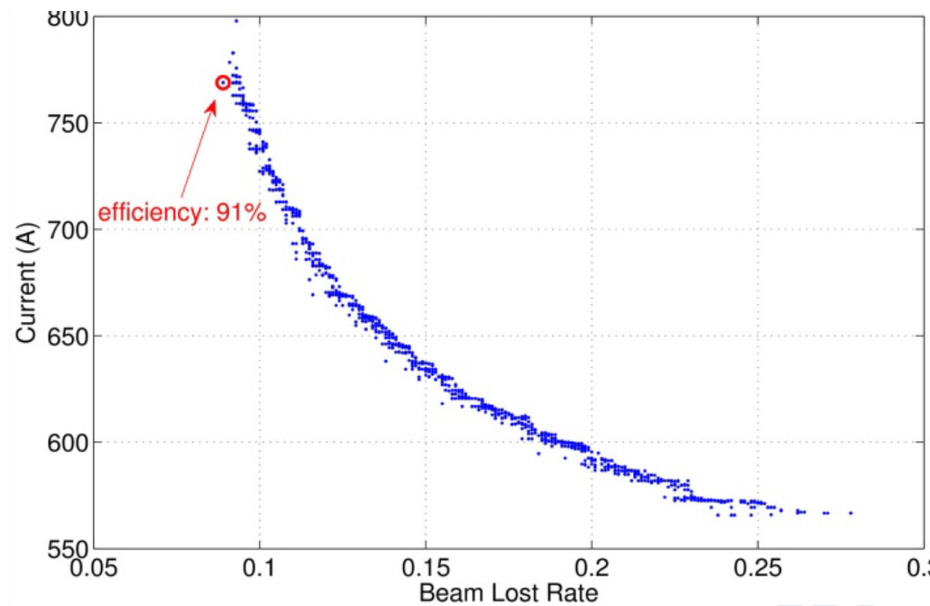
# Nonlinear Injection Kicker

- ALS is developing a nonlinear injection kicker
  - Planned to be installed in January next to 6 mm stripline kicker
  - Started design from earlier BESSY effort
  - Application is both ALS and ALS-U accumulator
- Kicker / conductor geometry optimized by MOGA integrated with full injection efficiency calculation



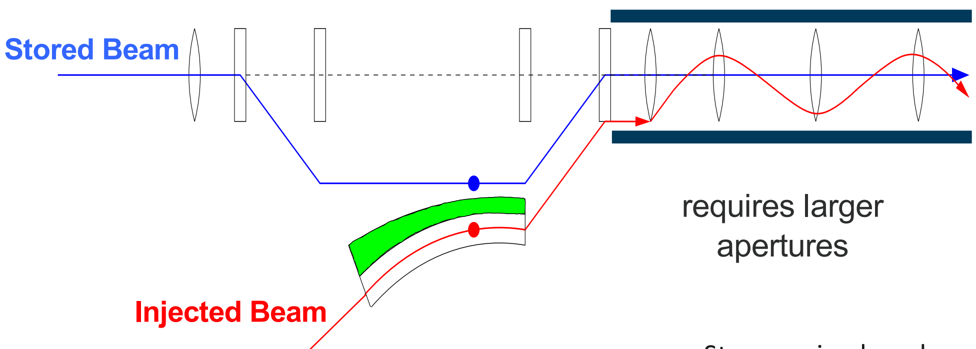



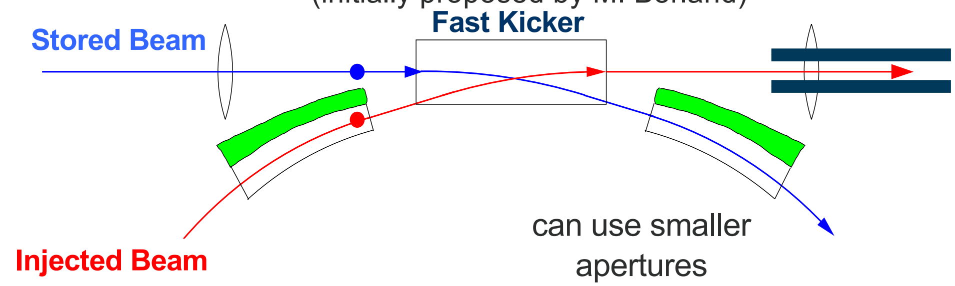
# Specific ALS-U feature – Bunch train swap-out

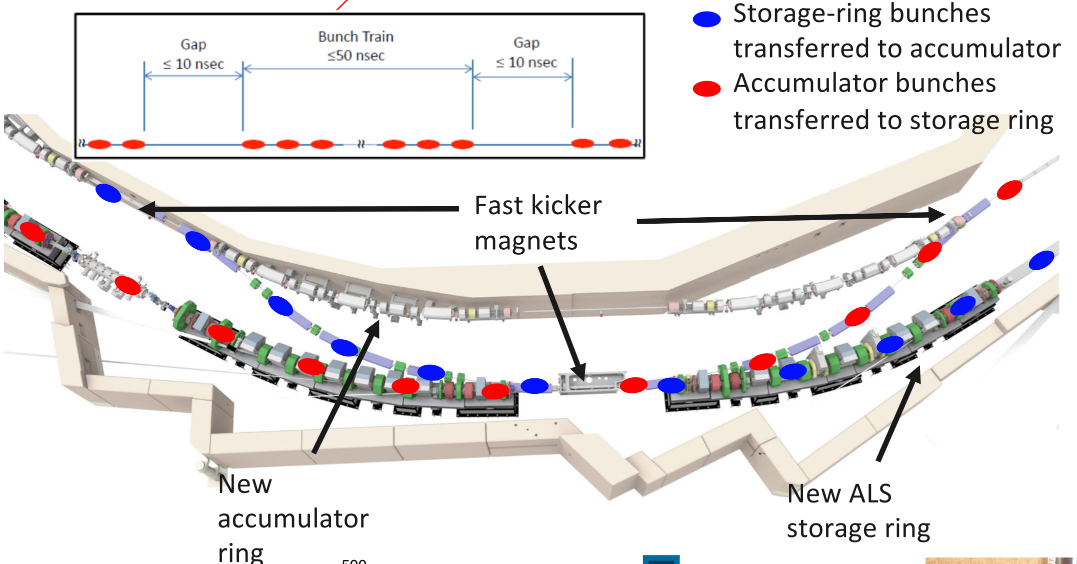
## Off-axis injection + accumulation




## On-axis swap-out injection

(initially proposed by M. Borland)



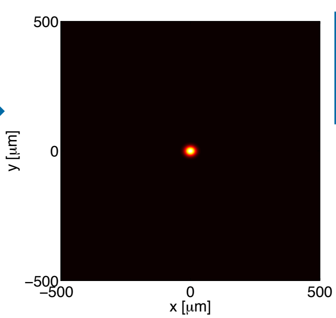

## Swap-out enables:

- MBA lattices with smaller dynamic apertures → higher brightness
- Small round apertures → improved undulator performance

## Bunch train swap-out with beam recovery in accumulator:

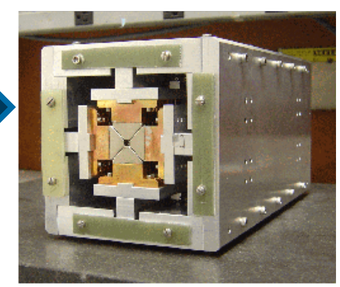
- Lower demand on the injector
- Very small (~nm) injected emittance

Allows lattices with stronger focusing + h[illegible]ness




Allows for **small (~6mm) round** apertures

Permits higher performance polarizing undulators



**Delta undulator** (Cornell)

BERKELEY LAB

ALS-U