Advances in beam stability in low-emittance synchrotron light sources

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U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

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- **ELETTRA**: Giulio Gaio; Emanuel Karantzoulis
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- **HEPS**: He Ping
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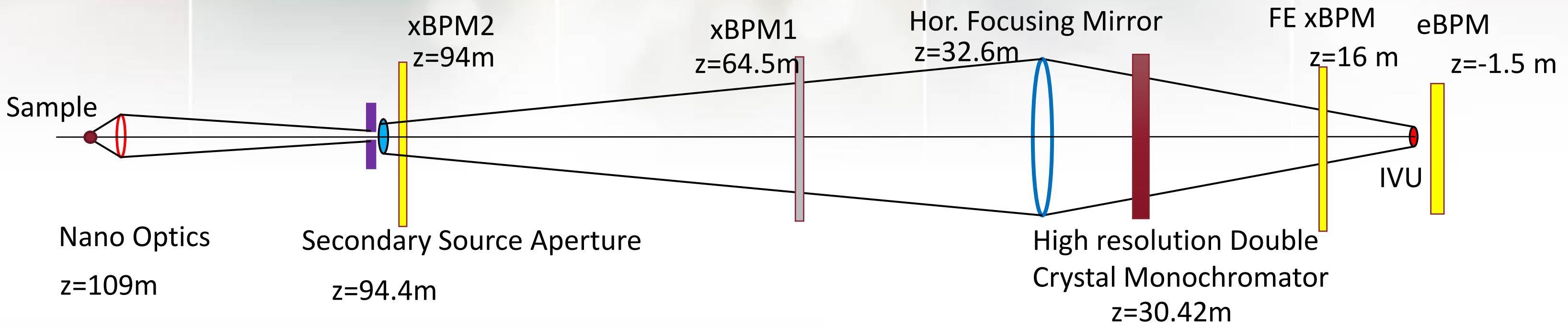
- **PLS**: Seunghwan Shin
- **SIRIUS**: Daniel de Oliveira Tavares; Fernando Henrique De Sá; Liu Lin; Sergio Rodrigo Marques
- **SOLEIL**: Laurent Nadolski
- **SPEAR3**: Gierman Stephen; Safranek James; Tian Kai
- **SSRF**: Yin Chongxian; Zhang Wenzhi; Zhao Zhentang
- **TPS:** Chiu Pei-Chen; Hu Kuo-Hwa; Hsu Kuo-Tung; Huang Chih-Hsien

Outline

- The needs for high beam stability
- The means to reach high beam stability
  - Mechanisms perturbing beam stability
  - Measures to increase stability
- Historical overview
- Achieving high beam stability in light source community
- Future trend and goals
- Summary

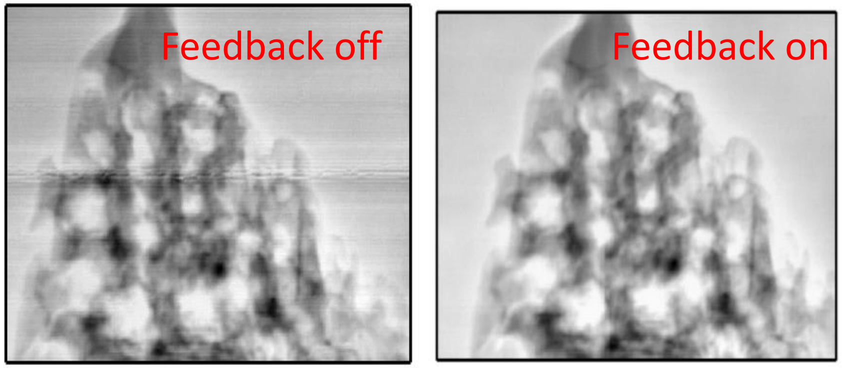
The needs for high beam stability

Needs for high beam stability: HXN imaging



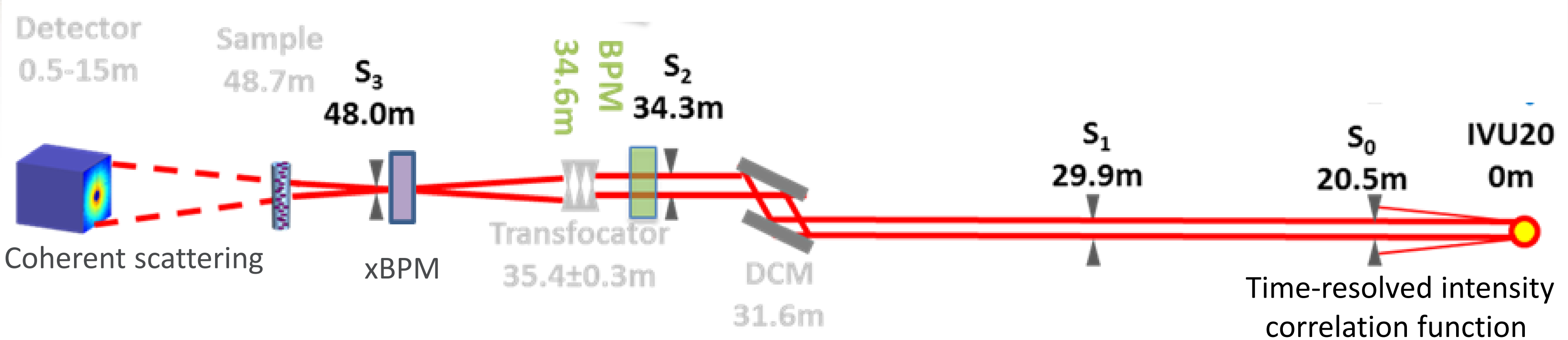
- Hard X-ray Nanoprobe (HXN): provide x-ray imaging capabilities with ~10 nm spatial resolution for nano-scale material characterization
- Stability requirements
    - Position stability is less sensitive with significant source demagnification (3000X for HXN)
    - Angular stability is critical and limits the resolution of differential phase contract imaging
    - Require motion at sample (1 nm, <10% of focus size) from beam angle ~ 100 -10 nrad
- Motion sources: electron beam motion, optics cooling, floor relative drifts, thermal drift. Cause ~200 nrad angular motion
- Measures: PLFB (Photon Local feedback) and active beamline components feedback on xBPMs to maintain long-term drift within 20 nrad

Impact of feedbacks on Ptychography in imaging phase



NSLS-II: Yong Chu, Xiaojing Huang

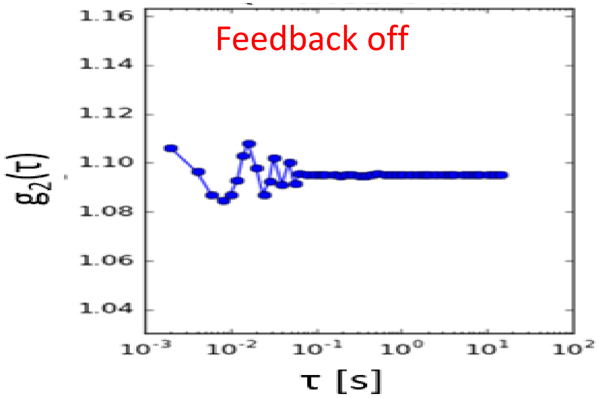
Needs for high beam stability: CHX Coherent Scattering

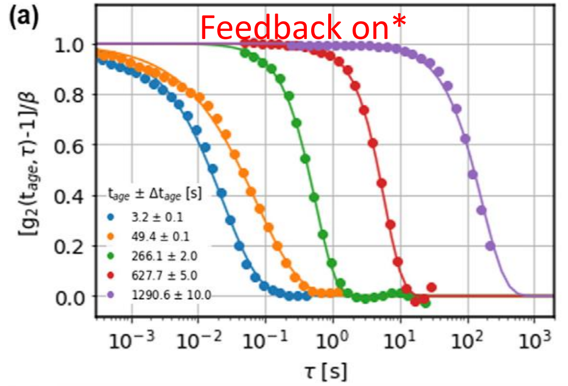


- Coherent Hard X-ray Scattering (CHX): study nano-scale dynamics in materials using x-ray photon correlation spectroscopy with hard x-ray coherent flux (time-resolved coherent scattering of non-stationary, non-equilibrium dynamics via 2-time correlation function)
- Stability requirements
    - Require beam angular stability <50 nrad at sample position
    - Require short to long term stability, 0.1 ms to 6 hr (upto 9 kHz sampling rate) →1 µs in the future
- Motion sources: electron beam motion, cooling water and cryo-cooling on monochromator, thermal drift
- Measures: ID BPM local feedback and active beamline components feedback to reach short- and long-term photon stability <10% aperture size

NSLS-II: Lutz Wiegart, Andrei Fluerasu

Time-resolved intensity correlation function

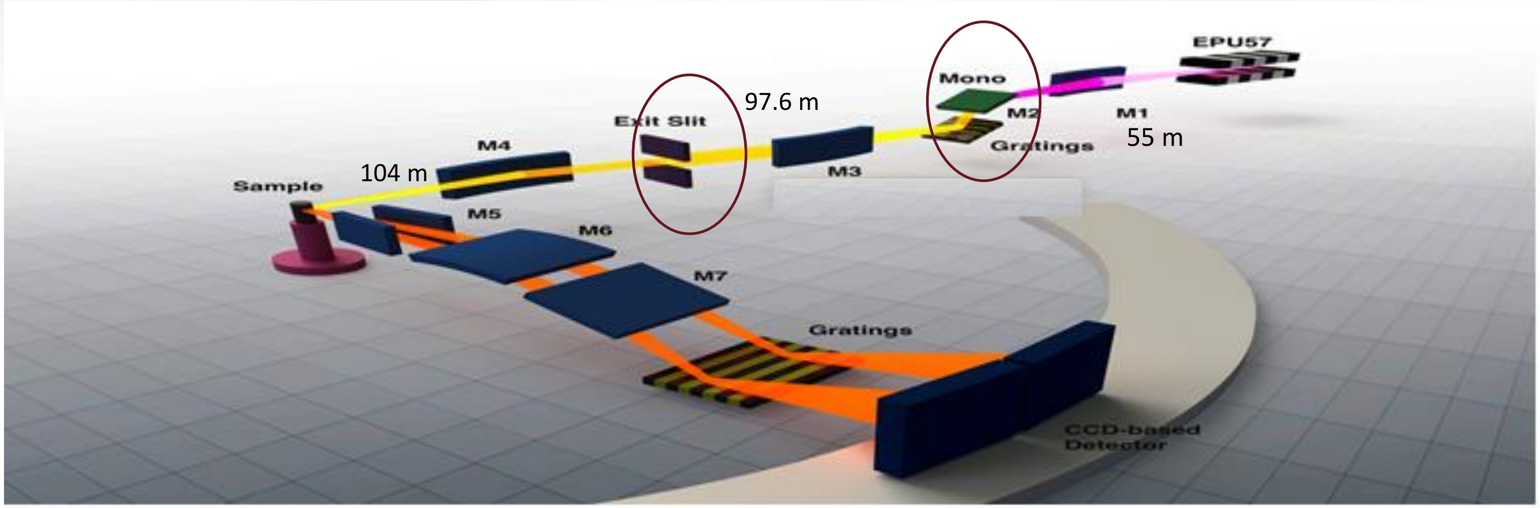




Nati

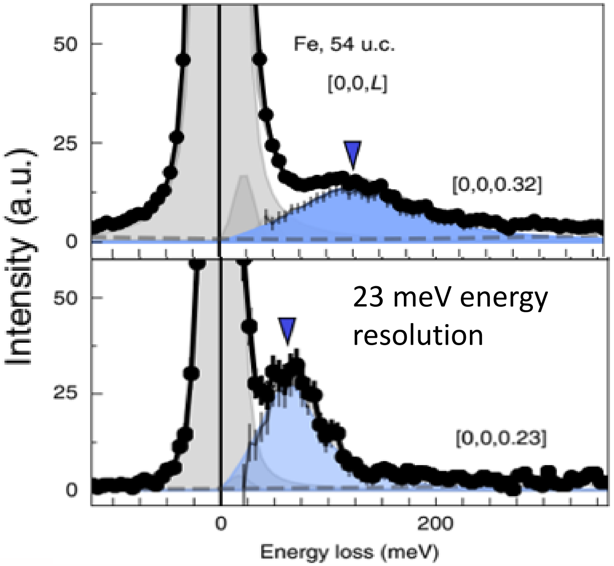
**M. Torres Arango et al. / Materials Today Physics 14 (2020) 100220*

Needs for high beam stability: SIX scattering and spectroscopy



- Soft Inelastic X-ray Scattering (SIX): study electronic excitations with ultrahigh energy resolution (10 meV@1 keV photon energy) and continuous photon energy tunability using resonant inelastic x-ray scattering (RIXS)
- Stability requirements: gratings and exit slit together select the desired energy bandwidth
  - Exit Slit vertical aperture determines the energy resolution and limits beam stability: 5 µm vertical aperture for 10^5 resolution
  - Require sub-µm beam stability at slit (<10%)
- Motion sources: cooling water on mirror, ~20 µm movement at slits
- Measures: improve noise sources
  - Lack of non-invasive photon position monitor for soft x-Ray

RIXS to detect thin film spin excitation



**J. Pelliciari et al., Nat .Mat. 20, 188 (2021)*

NSLS-II: Valentina Bisogni, Jonathan Pelliciari

The means to reach high beam stability

- Mechanisms perturbing beam stability
- Measures to increase stability

Mechanisms perturbing beam stability

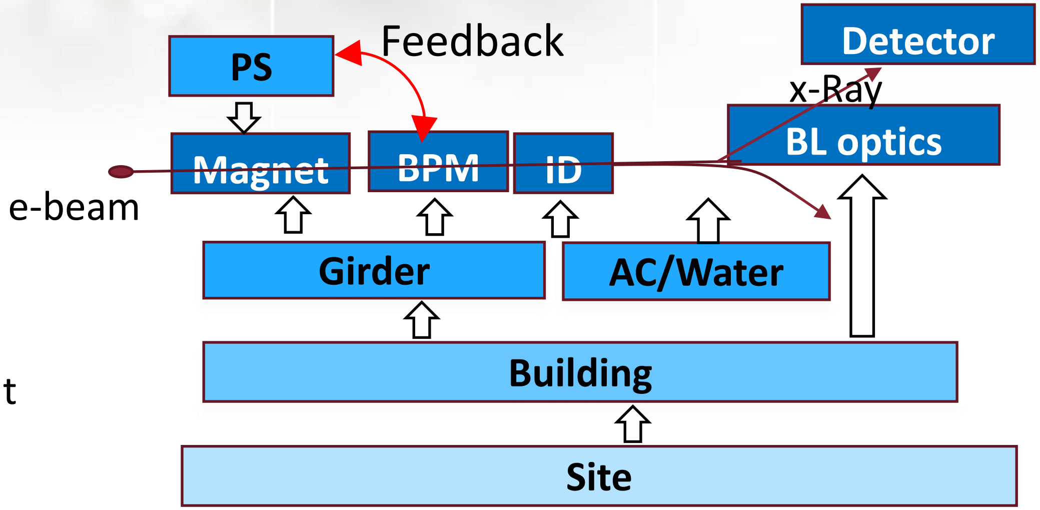
Sources of perturbation: natural + cultural noise

- Long term (weeks - years)
  - Ground settlement
  - Seasonal ground motion
- Medium term (minutes - days)
  - Daily thermal cycle
  - Earth's tides (~12 hrs)
  - Beam intensity/fill pattern
- Short term (milliseconds - seconds)
  - Ocean waves (0.13 Hz), wind
  - Ground vibration due to traffic/trains
  - Rotating machinery (cooling water/AC)
  - Power supply (PS) noise
  - ID gap variation
- High frequency (sub-milliseconds)
  - Synchrotron oscillation
  - Injection transients
  - Beam instabilities

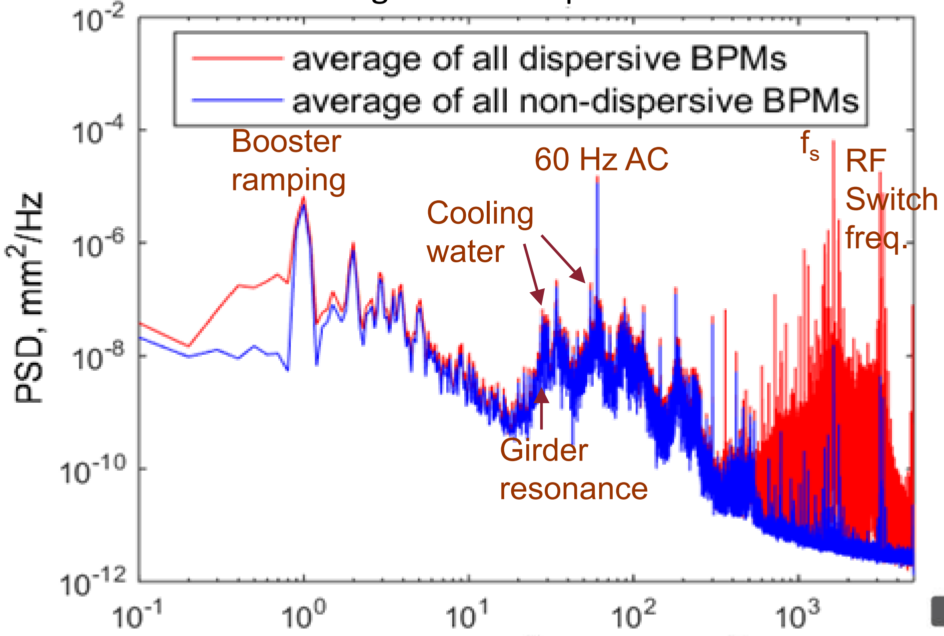
Orbit

Beam Size

- Measures to improve beam stability
  - Building design
  - Girder – mechanical design
  - Advances in PS, BPM and feedback systems



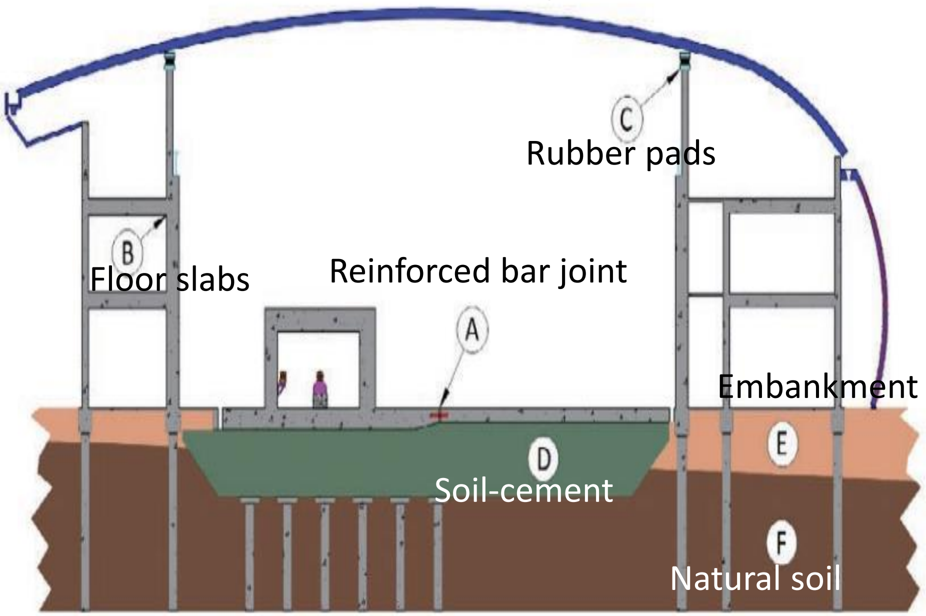
Average of BPMs spectrum



Site selection and building design

- Quiet site selection: the first line defense
  - Natural soil
  - Proximity of highway, railroad, industrial complex
  - Ocean (NSLS-II, 15 km from Atlantic Ocean shoreline)
  - Not always possible to select site
- Building design: minimize noise effect
  - Isolation of base structure
  - Vehicle tunnel/utility tunnel: sensitive to outdoor/tunnel temperature
  - Vibrating equipment: water pump/motor motion reduction, isolation from SR tunnel

Cross-section of the Sirius building*: 11 nm, (2-450) Hz



Overview of measured sites ground vibration (1-100) Hz

Quietest site
Built on firm rock

	ALBA	APS	BNL	DESY(XFEL)	ESRF	IHEP	SLAC	Spring-8	SSRF
Night [nm]	9.1	9.8	29.1	35.1	40.2	8.1	4.1	1.8	102
Day [nm]	42	11	80	70	137.2	9	7.4	2.5	444

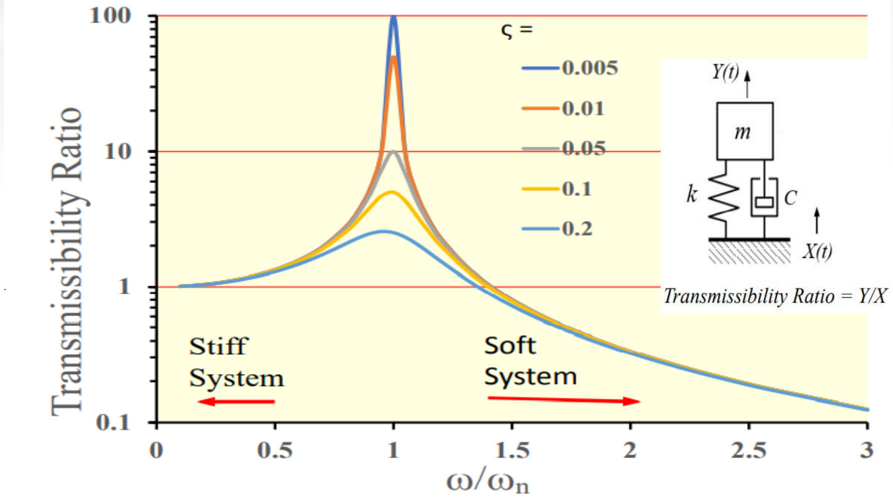
https://vibration.desy.de/overview

*https://www.tandfonline.com/doi/full/10.1080/08940886.2019.1654828

Girder support design

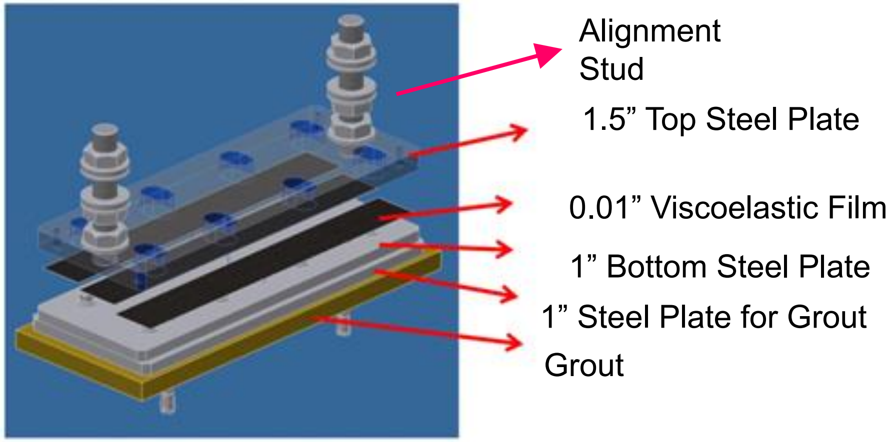
- Easy installation and alignment
- **High mechanical stability**
- Vibration stability:
    - Damp motion
    - Low transmissibility ratio →High stiffness and rigidity
- Thermal stability:
    - Viscoelastic pad: allow relative drift
    - Girder expand without bending

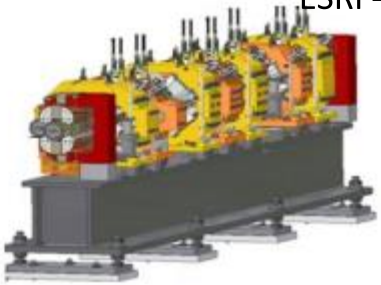
Transmissibility ratio



ESRF-EBS, pedestals Side Supports, 50 Hz

Viscoelastic pad design (*NSLS-II, S. Sharma*)





NSLS-II, Pedestals Bottom supports, 30 Hz

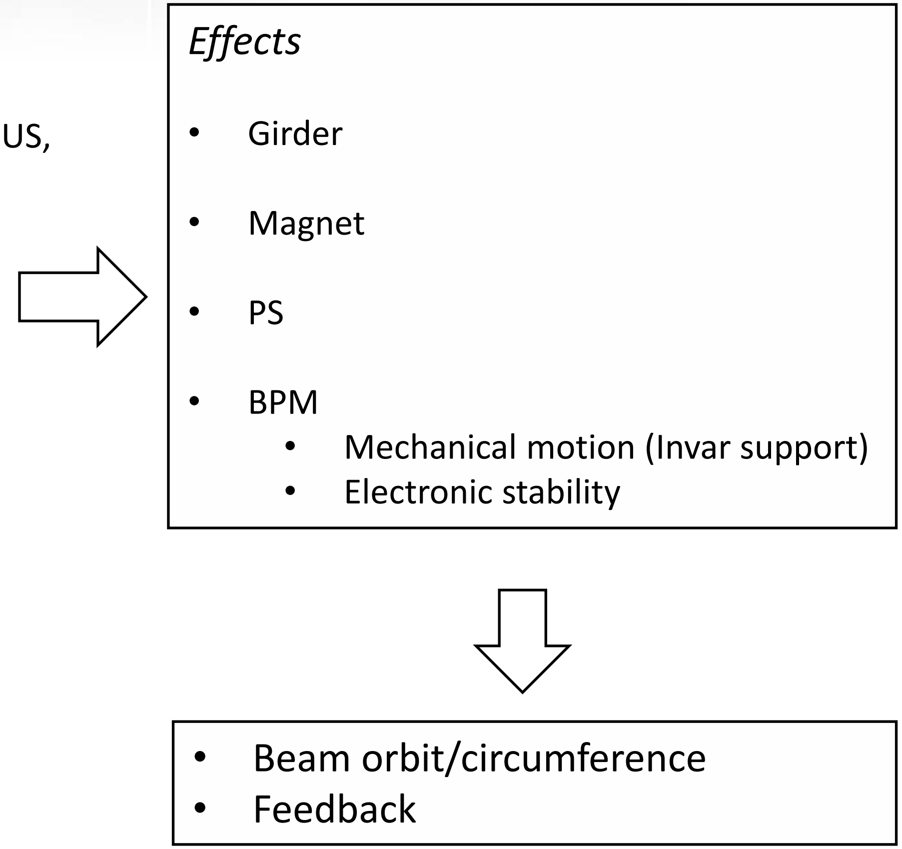
SIRIUS: Plinth Side Supports, 152 Hz

**S. Sharma, Storage Ring Girder Issues for Low Emittance SR, MEDSI SCHOOL 2, 2019*

Thermal stability and Power Supply stability

Thermal Sources

- Outdoor temperature variation
- Tunnel air temperature
  - Temporal: ±0.1 °C < 1 Hour cycle (NSLS-II, ESRF, SIRIUS, APS-U, ALS-U)
  - Spatial: ±0.1 °C/m, ±1 °C entire tunnel (NSLS-II)
- Cooling water temperature
  - DI – Cu (±0.1 °C), DI - Al (±0.05) °C (NSLS-II)
- Heating from synchrotron radiation/impedance
- Beam intensity and filling pattern
- Electronic rack temperature
  - Water cooled, ±0.1 °C (NSLS-II)



Effects

- Girder
- Magnet
- PS
- BPM
  - Mechanical motion (Invar support)
  - Electronic stability

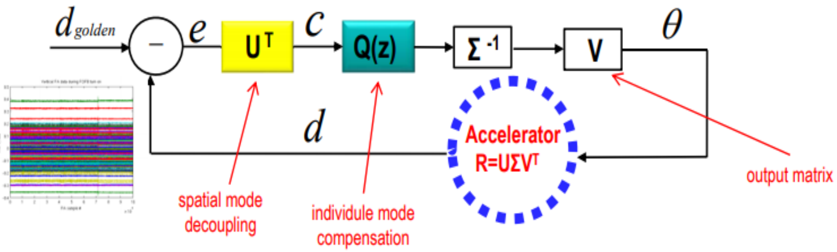
- Beam orbit/circumference
- Feedback

Power Supply stability

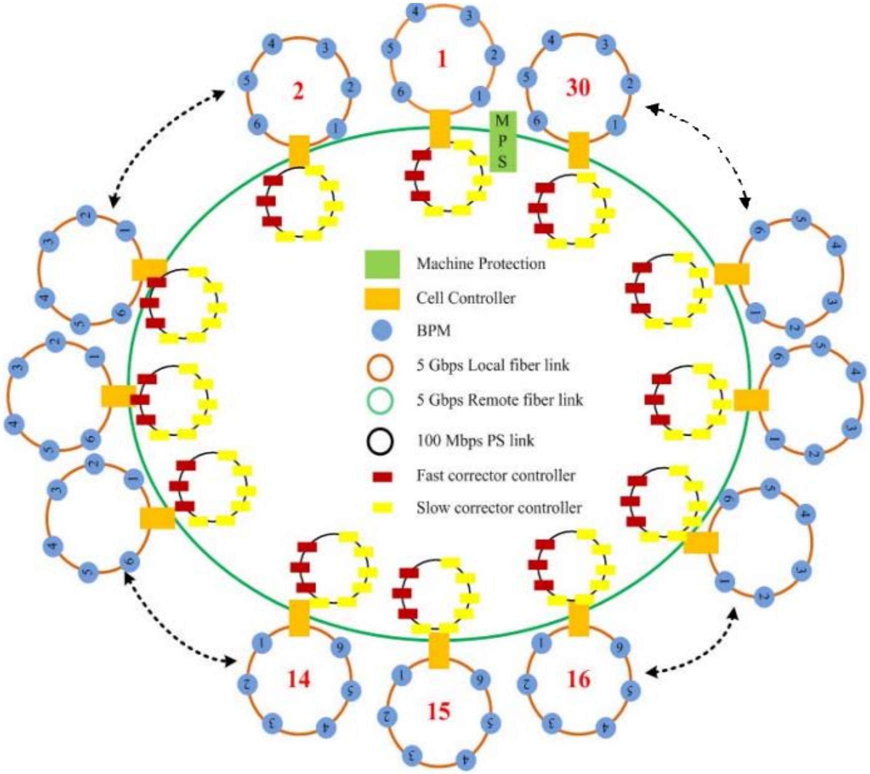
- Magnet power supplies stability directly affects electron beam motion
- Dipole: first order effect. 15 ppm (NSLS-II) 10 ppm (HEPS)
- Quadrupole, sextupole: high order effects. 50/100 ppm (NSLS-II), 10/100 ppm (HEPS), 10-50 ppm (ESRF-EBS)

Feedbacks: Fast Orbit Feedback

- Feedback system: further improve beam stability
- Light sources mostly use global orbit feedbacks based on SVD algorithm
    - Slow corrector: strong kick (mrad). Limited bandwidth, DC to ~Hz
    - Fast correctors: weak kick (10s µrad). ~kHz correction rate and bandwidth, DC to 100s Hz
- NSLS-II fast orbit feedback (FOFB)
    - Individual eigenmode compensation in frequency domain control→ large data calculation
    - Fast FOFB correction cycle for large bandwidth
    - FPGA based parallel process CC and SDI link:
        - High-speed calculation
        - Fast BPM data transfer
        - Fast PS setpoint delivery



FOFB individual eigenmode control



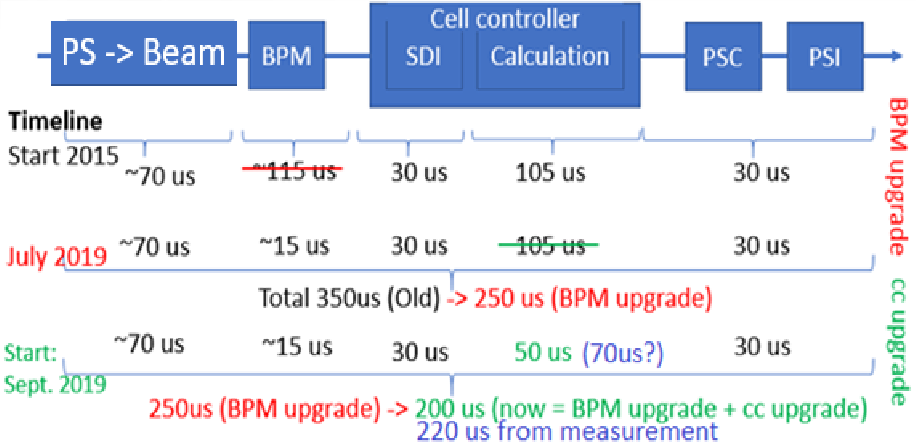
NSLS-II FOFB topology

NSLS-II: Yuke Tian, Kiman Ha, Lihua Yu

Feedbacks: Fast Orbit Feedback (CONT.)

- NSLS-II FOFB: 30*6-10 BPMs*3 FC (10 kHz)
- Bandwidth: 400 Hz/300 Hz (H/V) limited by loop latency (220 μs)
- High stable BPM: temp. control, Invar support, Pilot auto calibration (ALS)
- Typical ID source position/angle integrated motion [1-500 Hz]: 0.6% (H) and 7% (V)
- FOFB only: accumulated in a week, ~half of full strength. Not sufficient to maintain long term drift (90 FCs*200 BPMs)
- Measures: local feedback on ID BPM/xBPM interact with FOFB (APS/ALS) to reach μm long term stability

FOFB stage-to-stage latency and improvements



PS -> Beam | BPM | Cell controller: SDI, Calculation | PSC | PSI

Timeline

Start 2015: ~70 us, ~~~115 us~~, 30 us, 105 us, 30 us

July 2019: ~70 us, ~15 us, 30 us, ~~105 us~~, 30 us

Total 350us (Old) -> 250 us (BPM upgrade)

Start: Sept. 2019: ~70 us, ~15 us, 30 us, 50 us (70us?), 30 us

250us (BPM upgrade) -> 200 us (now = BPM upgrade + cc upgrade)

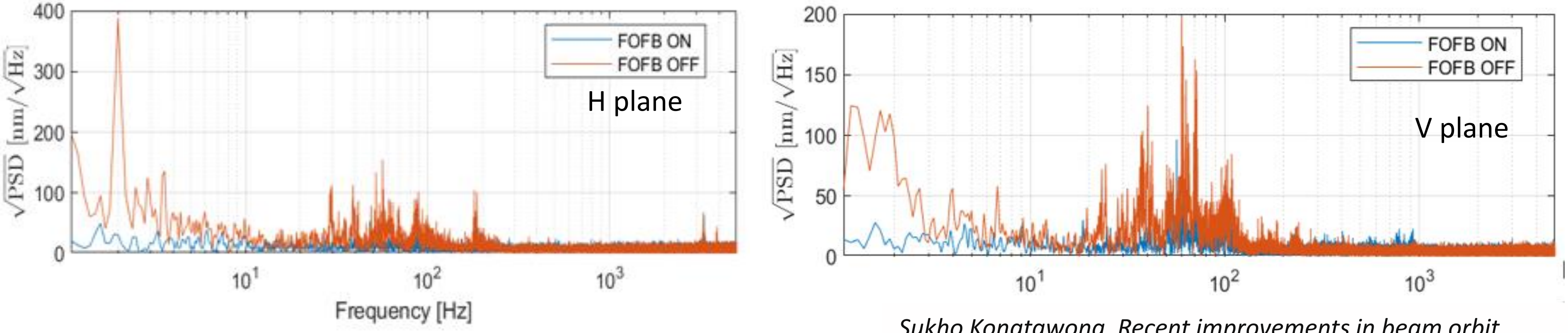
220 us from measurement

BPM upgrade

cc upgrade

NSLS-II: Sukho Kongtawong

ID source position stability feedback ON/OFF



Sukho Kongtawong, Recent improvements in beam orbit feedback at NSLS-II, NIMA 976 (2020) 164250

Feedbacks: Slow and Fast correction combination

- Slow and fast orbit feedback systems are not compatible in a common frequency domain
- I: FOFB with Download (steps in red)
- II. FOFB/SOFB interaction: orbit communication between 2 systems (APS, ALS, ESRF-EBS) (steps in **black**)
- III. FOFB/SOFB interaction and download*: achieve short- and long-term stability at all source points (SOLEIL) (all steps)

SOFB iteration at SOLEIL with 2 independent sets of correctors

- Step 1 (same as before):
  - Read the orbit error ΔU and calculated the new slow correctors setting $\Delta I1_{SOFB}$ to correct it:

$$\Delta I1_{SOFB} = R^{-1}_{SOFB} * \Delta U$$

- Step 2:
  - Calculate the new slow correctors setting in order to cancel the DC current part in the fast correctors (downloading process):

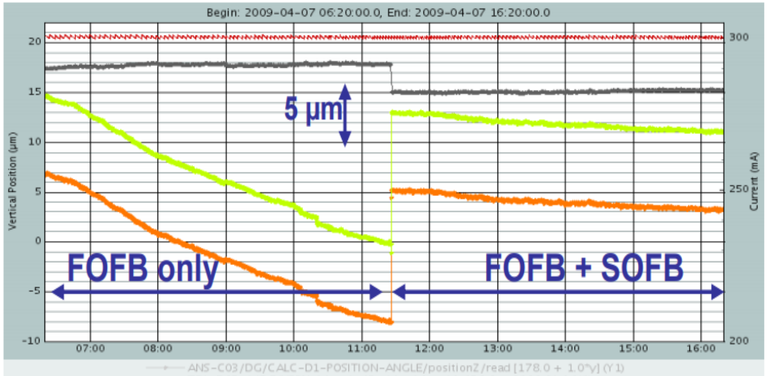
$$\Delta I2_{SOFB} = R^{-1}_{SOFB} * R_{FOFB} * \Delta I_{FOFB}$$

- Step 3 (same as before):
  - Predict the orbit movement ΔW that would be done by applying the previous setting:

$$\Delta W = R_{SOFB} * \Delta I1_{SOFB}$$

- Step 4:
  - Apply the new setting to the slow correctors $\Delta I_{SOFB} = \Delta I1_{SOFB} + \Delta I2_{SOFB}$
  - Subtract the predicted movement ΔW from the FOFB reference orbit

SOLEIL: Nicolas Hubert, Laurent Nadolski



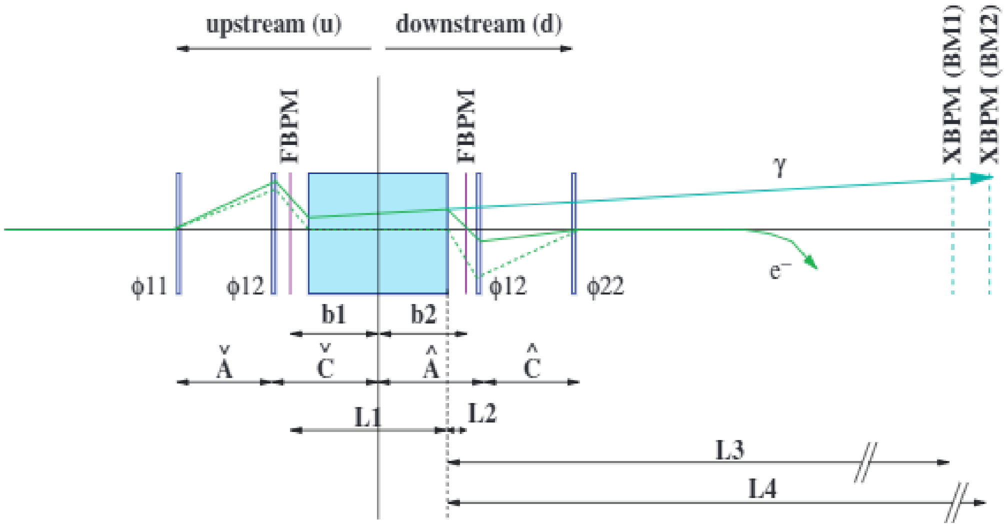
Vertical beam position at one SOLEIL bending magnet source point (BPMs: grey and X-BPMs: orange and green)

**Global Orbit Feedback Systems Down to Dc Using Fast and Slow Correctors, DIPAC 2009, Nicolas HUBERT*

Feedbacks: ID feed-forward correction

- Field integral of ID varies with gap and phase
  - Electron and photon beam position and angular displacement
- Compensation methods: FF correction using local compensation scheme with SR correctors
  - I: Correct motion using electron BPMs, ~ µm accuracy. Good for electron beam stability, but miss the undulator steering on photon beam
  - II: Include beamline photon BPM to correct ID's position & angle. Sub-µrad photon stability (SLS*)
- ID other effects : optics (coupling, tune, beta), DA

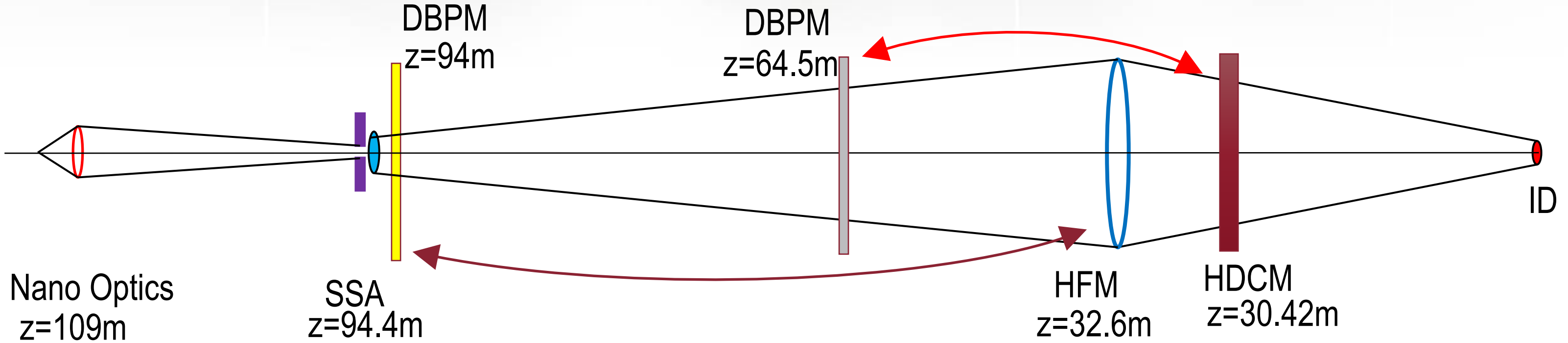
ID local compensation with electron BPM and photon BPM



SLS: J. Chrin

**J. Chrin etc. Local correction schemes to counteract insertion device effects, NIMA 592 (2008) 141–153*

Feedbacks: Active beamline components feedback



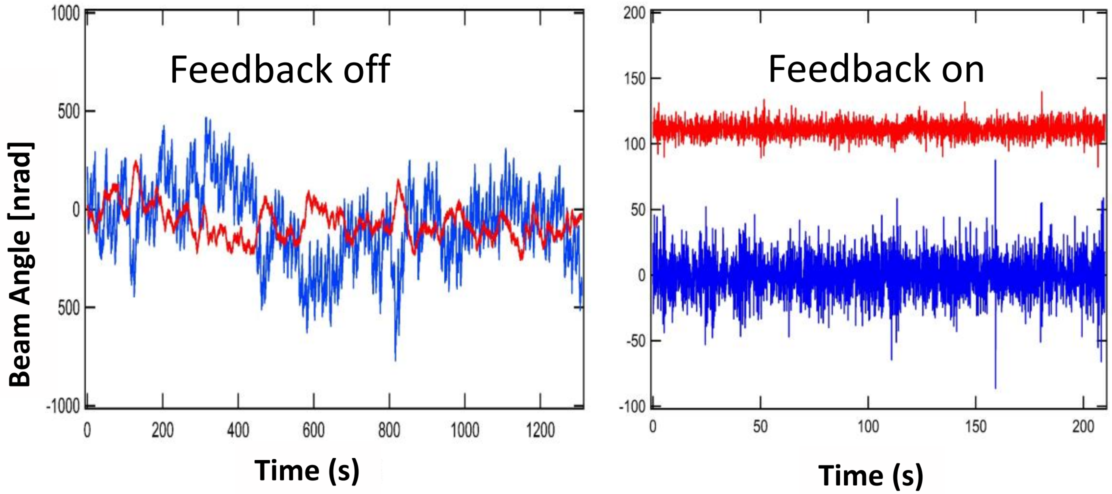
Fast mono beam “angle” feedback using mono pitch and roll

Slow mono beam “position” feedback for stable beam intensity through SSA

NSLS-II: Yong Chu, Xiaojing Huang, Petr Ilinski

- Knobs: mono crystal Pitch & Roll (100 Hz), mirror Pitch (5 Hz)
- Objects: Dimond BPMs
- Reach high photon beam position/intensity (SSA) and angle stability
- Limited bandwidth using optical components (mirror, mono-crystals etc) to correct photon beam motion

Angular Stability with feedback OFF/ON



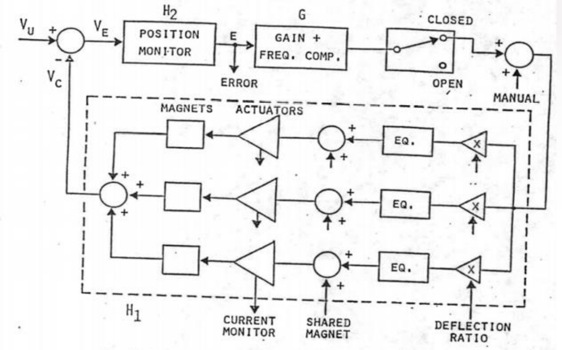
**Petr Ilinski , Active feedback implementation for beamline photon beam stability, 7th DLSR 2021*

Historical overview

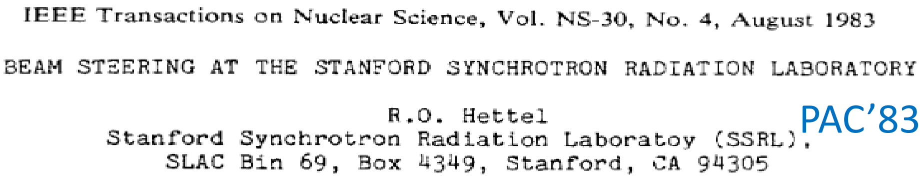
History: feedback

- 1980s: beam steering, analog signal
  - Many seconds to acquire and correct beam orbit
  - Local bump feedback based on photon monitors to suppress ~ a few Hz motion. First applied in SSRL by R. Hettel
- 1989: real time global orbit feedback
  - Based on ring harmonic mode with SR BPM
  - Applied in NSLS VUV ring by L. Yu
- 1990’s: SVD global orbit feedback, digital signal
  - Use orbit respond matrix and select singular values
  - Applied in NSLS/SPEAR by Y. Chung etc
- Global feedback with fast (and slow) correctors using SVD-method: expand to larger bandwidth with faster sampling rate
- **R. Hettel**: tremendous progress on beam stability over 30+ years by the measures taken to stabilize accelerator components, reduce electrical noise etc., and the development of modern fast global orbit feedback systems using high resolution electron and photon beam position monitor

SPEAR: 3-magnet bump feedback loop



3-MAGNET STEERING SERVO SYSTEM

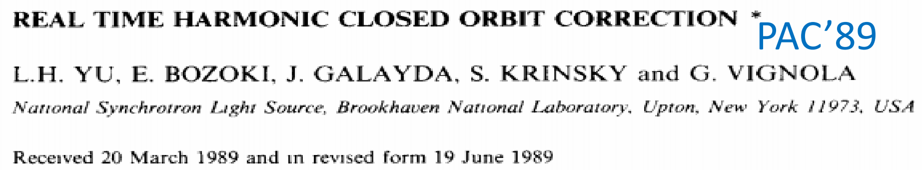


IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

BEAM STEERING AT THE STANFORD SYNCHROTRON RADIATION LABORATORY

R.O. Hettel
Stanford Synchrotron Radiation Laboratoy (SSRL),
SLAC Bin 69, Box 4349, Stanford, CA 94305

PAC’83



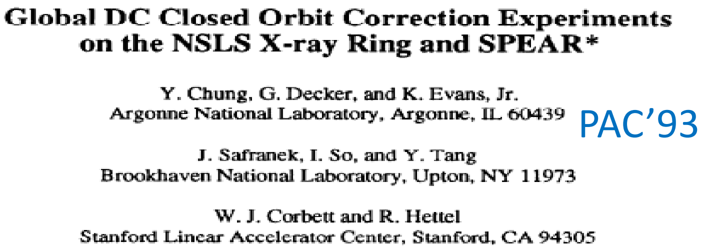
REAL TIME HARMONIC CLOSED ORBIT CORRECTION *

L.H. YU, E. BOZOKI, J. GALAYDA, S. KRINSKY and G. VIGNOLA

National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973, USA

Received 20 March 1989 and in revised form 19 June 1989

PAC’89



Global DC Closed Orbit Correction Experiments
on the NSLS X-ray Ring and SPEAR*

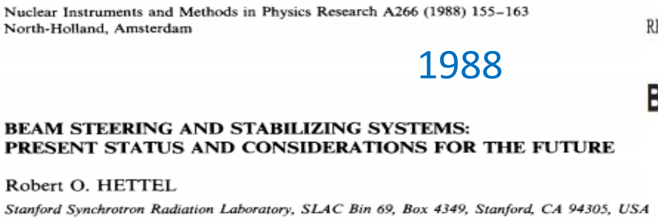
Y. Chung, G. Decker, and K. Evans, Jr.
Argonne National Laboratory, Argonne, IL 60439

J. Safranek, I. So, and Y. Tang
Brookhaven National Laboratory, Upton, NY 11973

W. J. Corbett and R. Hettel
Stanford Linear Accelerator Center, Stanford, CA 94305

PAC’93

R. Hettel >30 years experiences…



Nuclear Instruments and Methods in Physics Research A266 (1988) 155–163
North-Holland, Amsterdam

1988

BEAM STEERING AND STABILIZING SYSTEMS:
PRESENT STATUS AND CONSIDERATIONS FOR THE FUTURE

Robert O. HETTEL
Stanford Synchrotron Radiation Laboratory, SLAC Bin 69, Box 4349, Stanford, CA 94305, USA

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 3

2001

Beam stability at light sources (invited)

R. O. Hettel[a]
SSRL, Stanford Linear Accelerator Center, Stanford, California 94309

Light Source Beam Stabilization: Earlier Times

2018

R. Hettel
2018 BES Light Sources Stability Workshop
LBNL
November 1, 2018

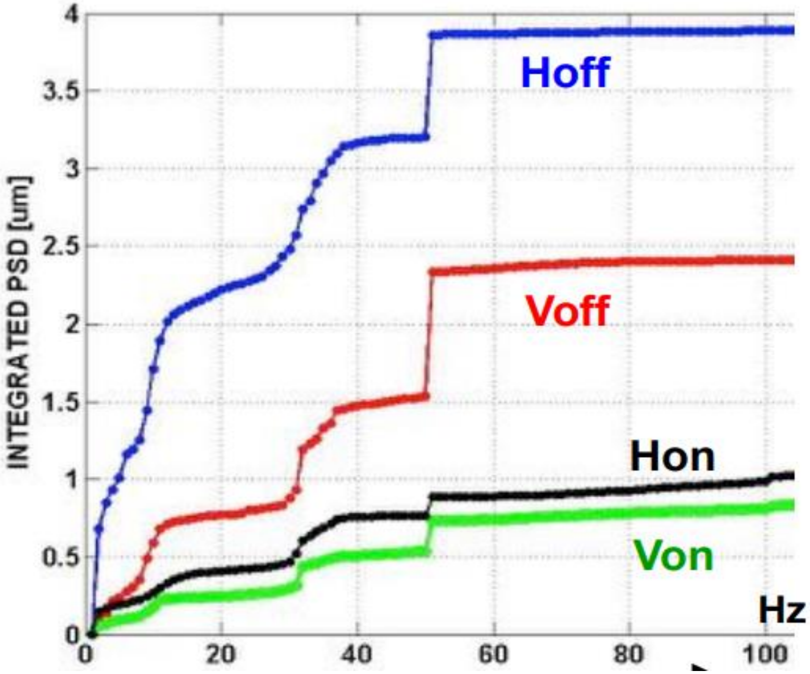
Achieving high beam stability in light source community

ESRF-EBS: design improvement

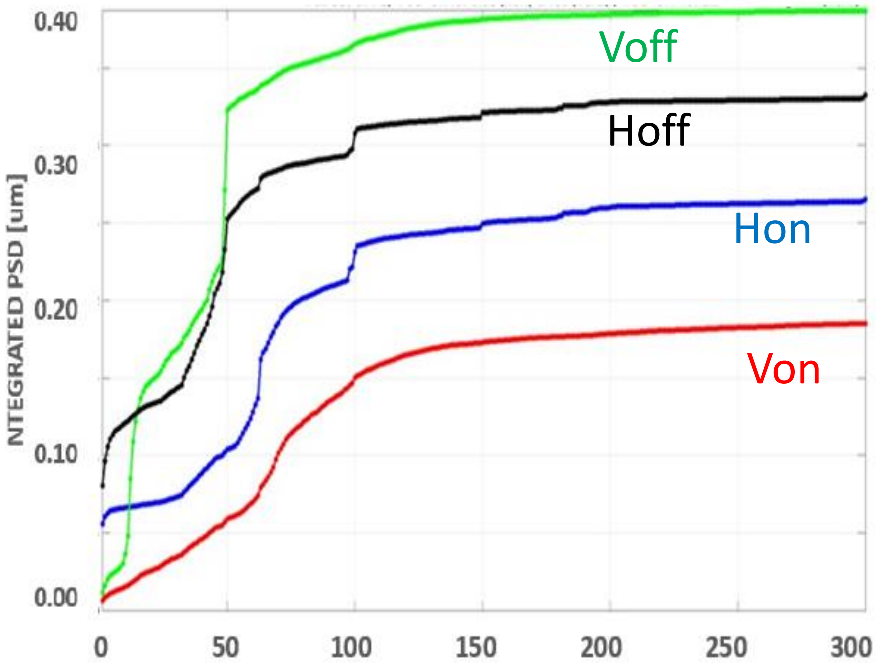
- New girder design: girder rigidity optimization to minimize the vibration effects
- High stable power supplies: accuracy in 10 ~ 50 ppm
- Without Feedback, the integrated motion improves by a factor of ~10 (vs old ring): ~300 nm (H/V)
- FOFB improves beam motion further to ~200 nm

ESRF-EBS: Kees-Bertus Scheidt, Qing QIn

Old ring 2010, FOC On & Off



New ring 2020, FOC On & Off

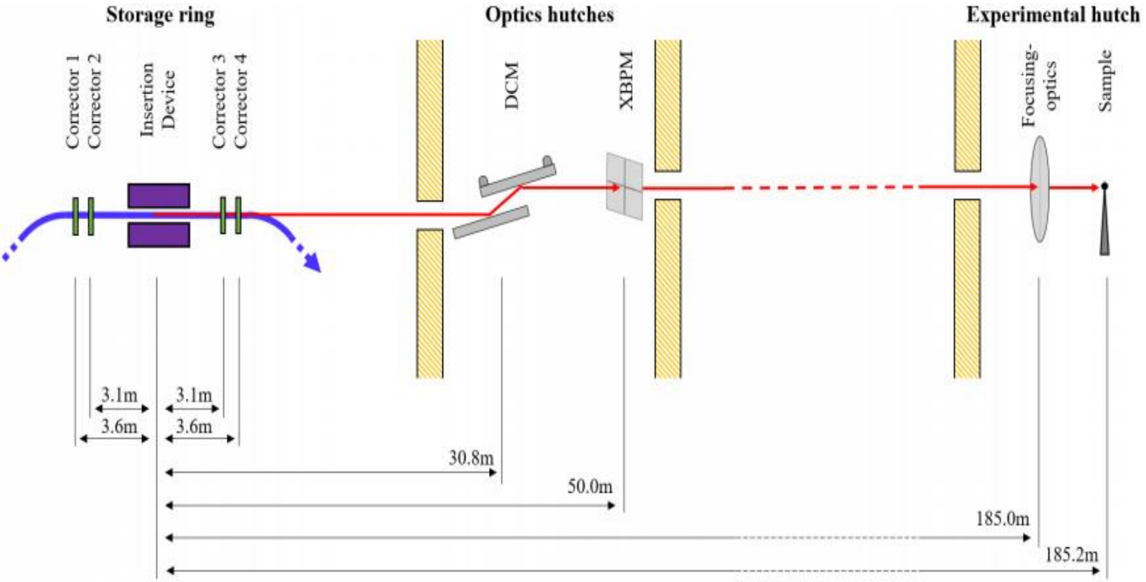


Diamond: kHz feedback using beamline xBPM

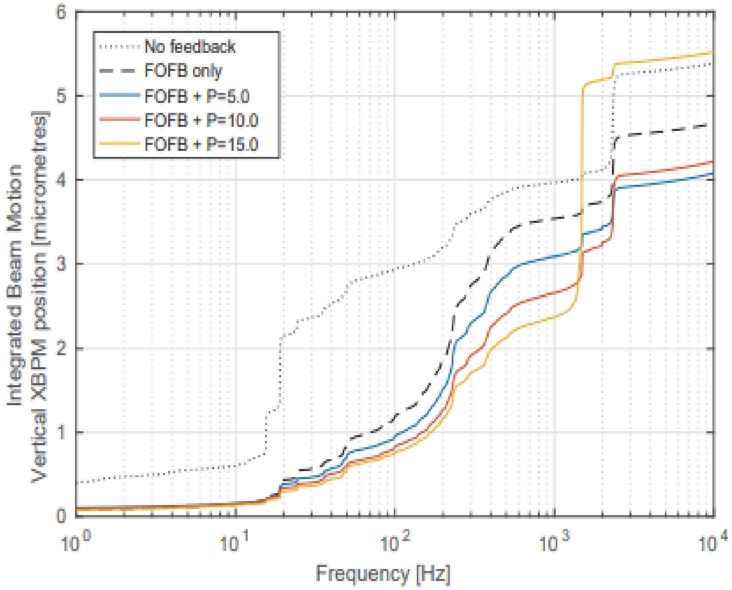
- A new feedback system: control electron beam to keep beam stability at X-ray BPM, close to beamline sample point
- Correct photon beam motion from electron beam and beamline optics
- Using SR four fast correctors for transparent bump correction
- Maintain X-ray beam stability to <3% of a beam size with bandwidth >1kHz

Diamond: C. Bloomer

Layout of the beamline and source point



Feedbacks impacts on X-ray BPM



C. Bloomer, fast feedback using electron beam steering on beamline x-Ray BPM, IBIC2019, p172-176

List of feedback systems in light sources

Light source	Feedback type	BPM sampling rate [kHz]	Bandwidth [Hz]	Note
ALS	Slow + Fast	1.1	60	
ALBA	Fast	5	100	
APS	Slow + Fast	1.16	80	
APSU*	Slow+ Fast	22.6	1000	Demonstrated
BESSY II	Fast	2.4	40	
CLS	Slow		45	
DIAMOND	Fast	10	130	
ELETTRA	Fast	10	150	
ESRF-EBS	Slow+ Fast	10	500	
HEPS*	Slow+ Fast	22	500-1000	
MAX IV*	Slow	10	~ Hz	2/5% w/o FOFB
NSLS-II	Fast	10	400	
PETRA III	Slow+ Fast	10	200	
PLS	Fast	4	100	
SIRIUS*	Fast	25	1000	
SLS	Fast	4	100	
SOLEIL	Slow+ Fast	10	200	
SPEAR3	Fast	4 kHz	100	
SSRF	Slow+ Fast	10	100	
TPS	Fast	10	300	

*Fast feedback systems not in operation

Future trend and goals

- Requirements
- Orbit stability
- Emittance stability

Future: beam stability requirements in low emittance lattice

- Electron beam stability requirements are driven by photon beam parameters' stability*
- Low horizontal emittance: 100s – 10s pm-rad (close to vertical plane emittance and diffraction limit)
- Besides tighter beam position/angular stability, other beam parameters (emittance, tune, size) stability is becoming more and more critical

Photon beam

- Higher intensity, brightness
- Smaller beam size & divergence
- Higher coherent fraction
- Large data acquisition range (µs-hrs)
- Faster detector (kHz-MHz)
- Higher energy resolution

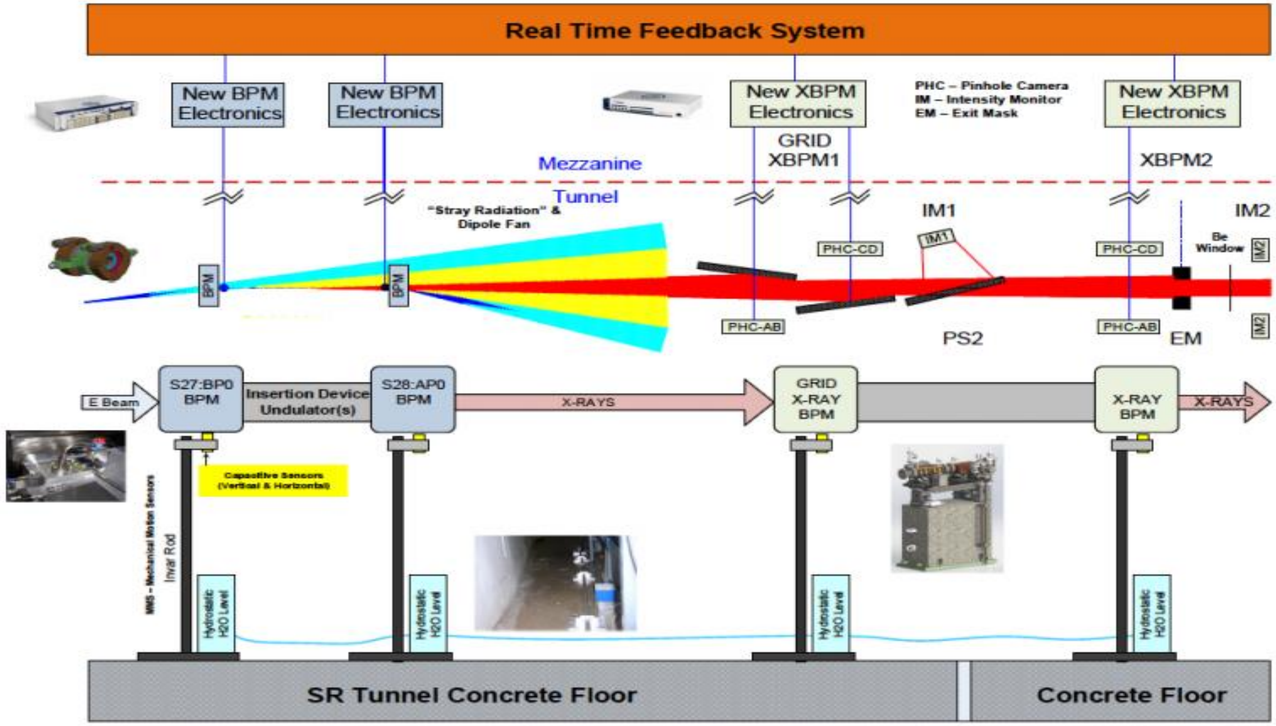
Electron beam

- Position stability: a few % beam size, sub-µm
- Angular stability: a few % beam divergence, sub-µrad
- Large feedback bandwidth: >kHz
- Beam size stability: a few %
- Emittance stability: a few %
- Tune stability: ~10^{-4}
- Energy stability

**Bob Hettel, Beam stability at light sources (invited), Review of Scientific Instruments 73, 1396 (2002);*
**Christoph Steier, Beam Stability Requirements for 4th Generation Synchrotron Light Sources Based on MBA Lattices, BES LSs stability workshop2018*

Unified feedback system

- Increasing position/angular stability requirements: important to feedback on beamline components
  - Limitation on electron BPM resolution
  - Mechanical/thermal instability causes relative ground motion of experiments with respect to accelerator floor
  - Ground motion, 'ATL law' : relative ground motion of 2 points separated by distance L after time T: $x^2_{rms\ ground} = ATL$ → long term photon source stability* (Vadim Sajaev)
- A unified electron orbit/photon trajectory feedback system needed to stabilize beam at the sample—B. Hettel (advocated many years ago)



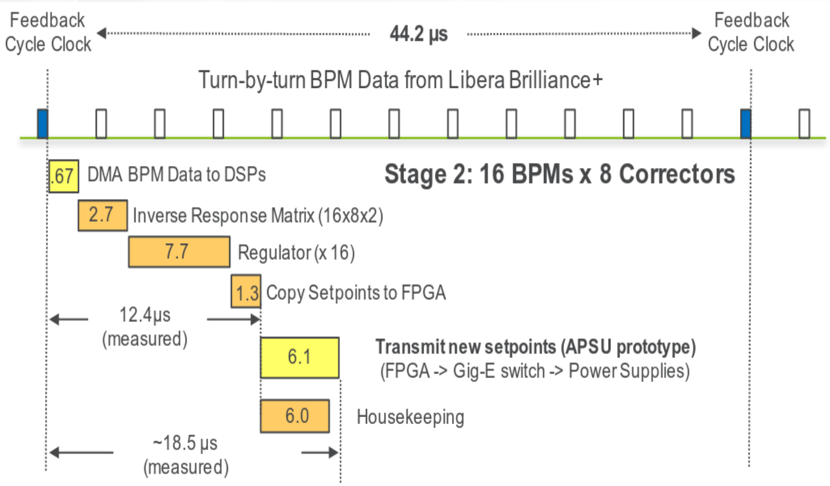
APS: Bob Lill

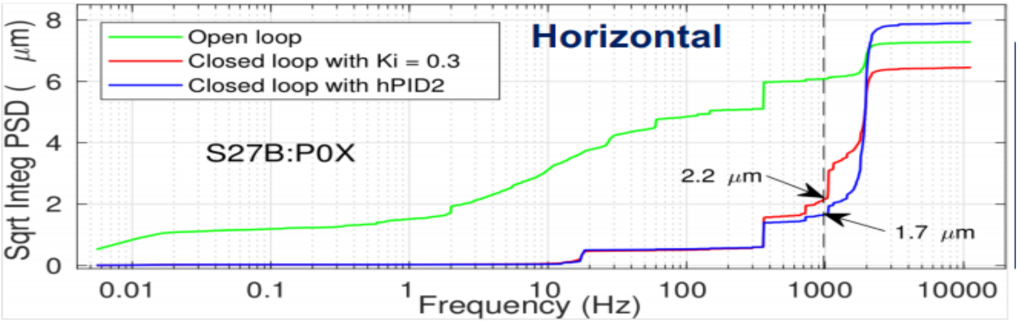
**Predicting orbit motion for the APS Upgrade storage ring, Vadim Sajaev, 7th-dlsr-2021*

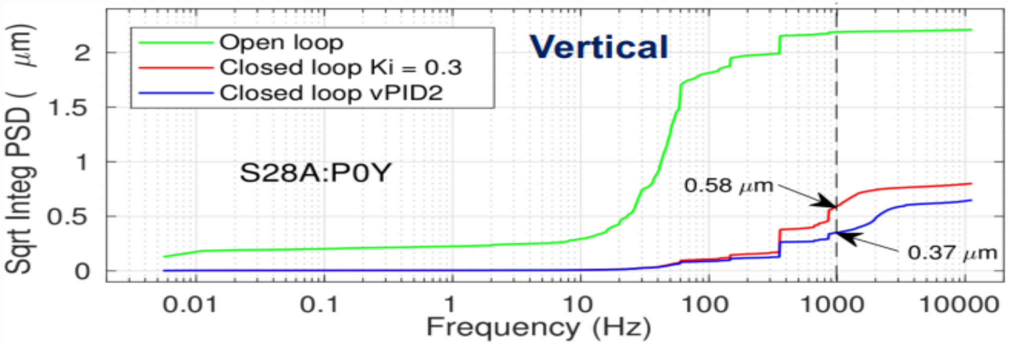
APS-U: 1 kHz large bandwidth orbit feedback

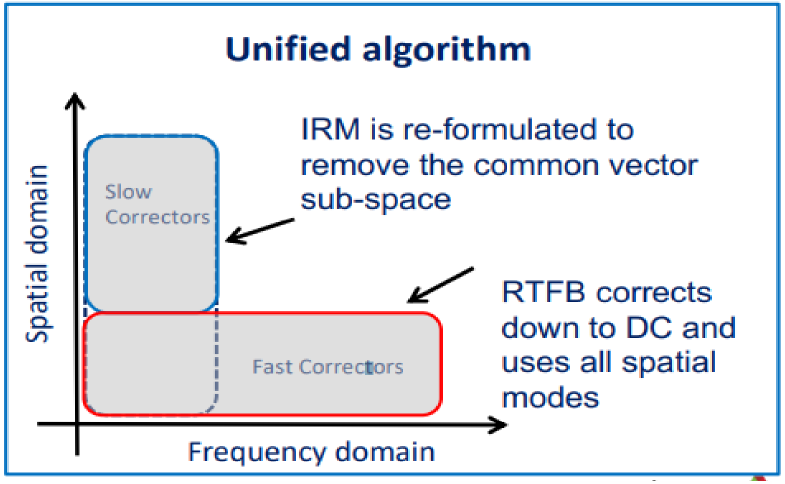
- Require <10% beam size/divergence stability (0.01-1000 Hz)
- Expand feedback bandwidth/minimize latency:
  - BPM higher sampling rate: 271 kHz TBT data
  - Faster correctors: 22.6 kHz
  - Lower processing latency to 44.2 µs
- Unified feedback algorithm
- Demonstrated APS-U fast feedback on APS with 1 kHz bandwidth

Feedback communication latencies









IRM is re-formulated to remove the common vector sub-space

RTFB corrects down to DC and uses all spatial modes

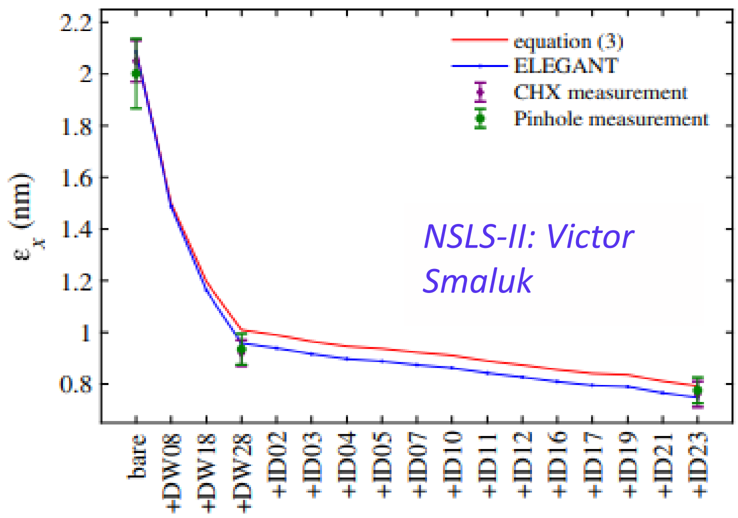
APSU: N. Sereno, J. Carwardine, P. Kallakuri , M. Borland

Horizontal emittance stability

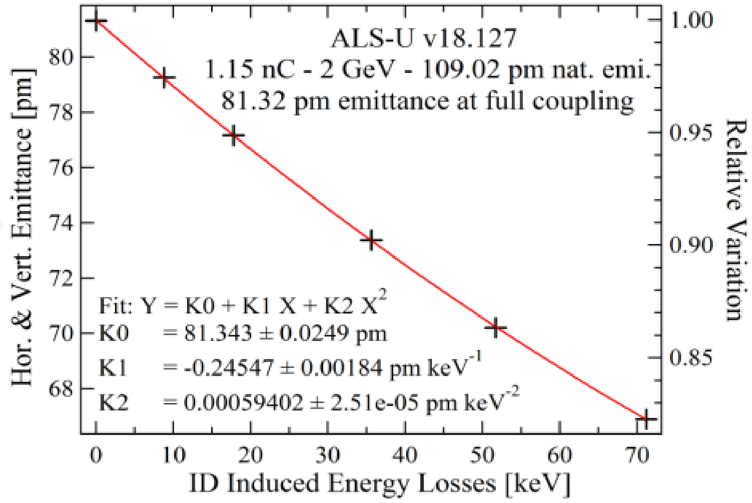
- In low emittance lattice, IDs caused energy radiation is comparable with bending magnets
- IDs' gap variation: impact on beam natural emittance/energy spread → affect beam size, coherent fraction
  - NSLS-II emittance (0.9 nm) change: damping wigglers (DW) 100%, other 17 IVUs and EPUs: 15%
  - MAX IV emittance (0.3 nm) change: DWs 25%, other IVUs 30%
  - ALS-U (80 pm): 20 keV energy loss from IDs results ~6% of emittance change
- Critical to maintain beam emittance
- Emittance stability (ALS-U)*
  - Variable gap wiggler
  - Dispersion bump in a wiggler
  - Small beam momentum variation
  - Intra-beam scattering (IBS)
  - Transverse plane "white noise" excitation

**Compensation of emittance and beam size variations induced by insertion devices, F. Sannibale, BES LSs stability workshop2018*

IDs impact on H emittance



NSLS-II: Victor Smaluk



ALSU: F. Sannibale, C. Steier

Vertical emittance stability

- ***Small emittance ratio (V/H):*** linear coupling to control vertical emittance
- ID motion-coupling dependence
- Coupling feedforward correction with skew quads
- Machine learning based feed-forward correction to maintain beam size (0.5%)/emittance using vertical dispersion wave (ALS: Leemann)

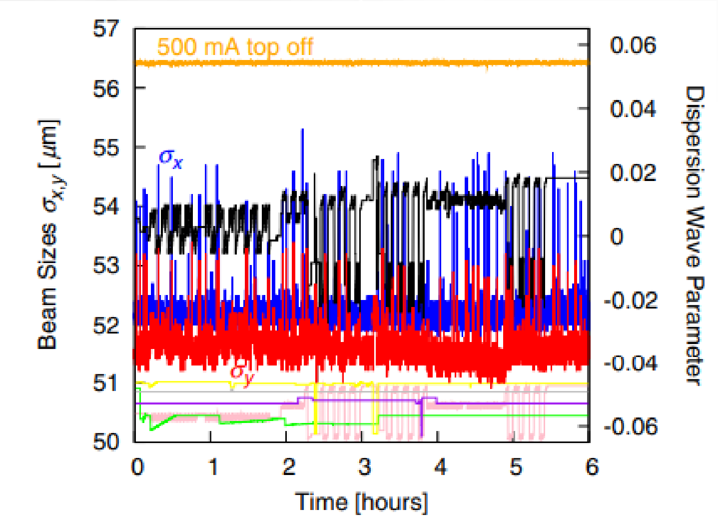
- ***Equal emittance/round beam***: coupling resonance*
- Sensitivity of emittance to tune depends on coupling stopband width
  - Emittance more sensitive to tune with smaller coupling stopband width
  - Large coupling stopband width affects injection efficiency
- ID motion-coupling affects stopband width
- Tune stability: ~ 10^{-4} ~10^{-5}
  - Control with feedforward and feedback

S. C. Leemann etc., Phys. Rev. Lett. 123, 194801

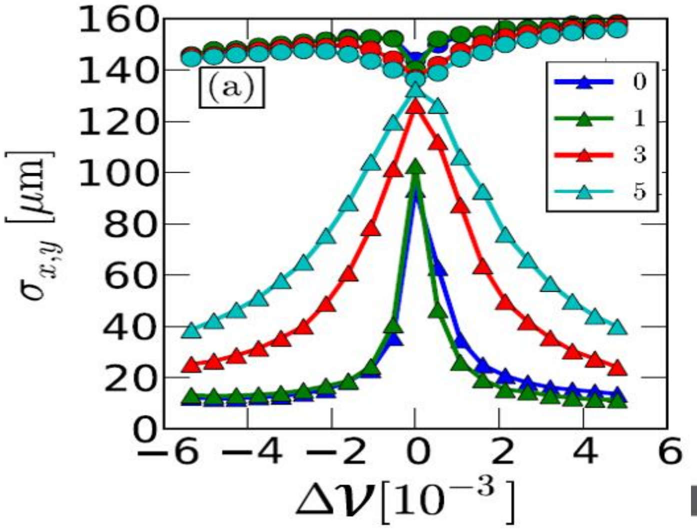
P. Kuske, Injection of Round Beams, low emittance workshop, 2020

Y. Hidaka, Round beam studies at NSLS-II, IPAC2018

ALS ML-Based beam size stabilization*



NSLS-II beam size-Δtune dependence with different stopband width*



Summary

- Beam stability is a key source characteristic for high-performance beamlines
- In the past decades our community invented different means and methods to advance beam stability
  - Investing in facility construction early in attempt to reduce the environmental noise sources
  - Improvements in stabilization of accelerator components
  - Advances in Feedbacks (FOFB, photon feedback, feedforward)
- Over the past 30+ years we accomplished tremendous progress in algorithms (correction methods and DSP), BPMs (speed and resolution), Power Supply (stability and controls)
- Towards the future we see large increase in beam brightness and coherent fraction with low emittance lattice
  - Unified feedback system is the trend to stabilize both electron and photon beam motion in a larger bandwidth
  - Besides beam position/angular stability, stability of other beam parameters (emittance, tune, size) is becoming more and more critical

Thanks for your attention!

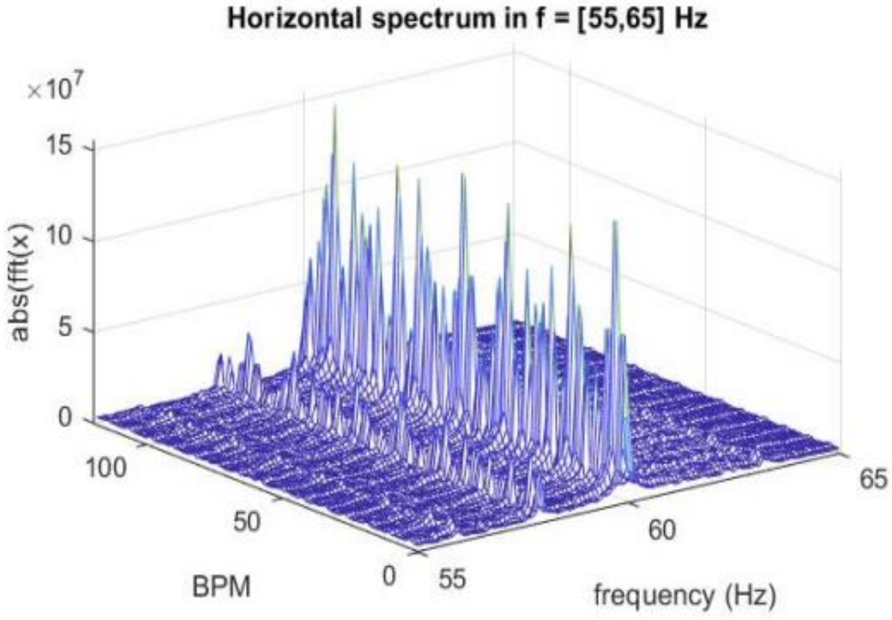
Contact: gwang@bnl.gov

Feedbacks: Noise locator

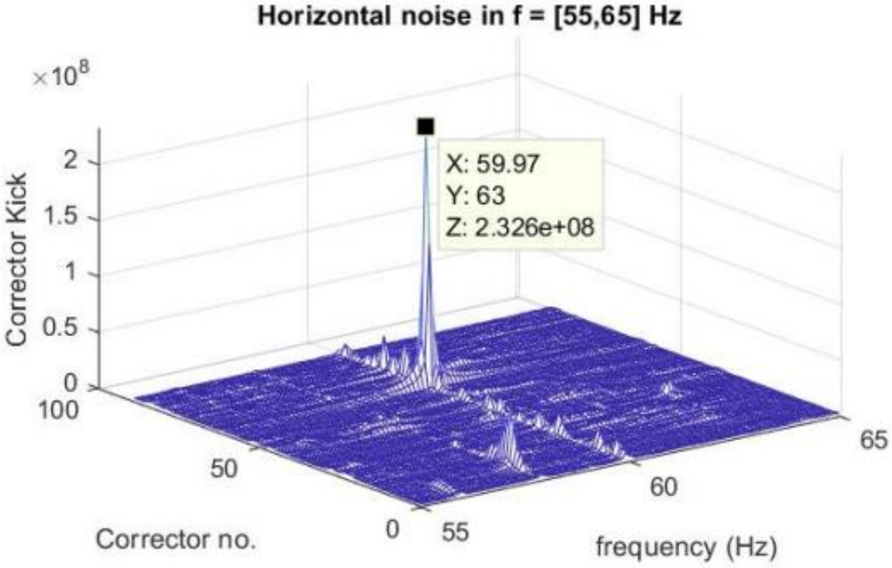
Pin-point the motion source's potential location

- Analyze individual BPM (10 kHz) spectrum with FFT to get amplitude and phase components
- Extract single frequency motion at all BPMs
- Pseudo AC orbit correction to get efficient corrector strength
- Check the aera of the most efficient correctors + noise frequency
- NSLS-II implements operation tool for live motion spectrum and noise locator

BPM spectrum amplitude



Pseudo AC orbit correction



NSLS-II: Sukho Kongtawong
BESSY/Diamond: Guenther Rehm

History: BPM

1980s	Analog signal	100 um (single channel process -> 4-button multiplexed processor)
1990s	Digital signal	~Hz, ~1 kHz, TBT (100s kHz) ~30 (long term)/25/500 µm (APS early)
2000s	Digital & FPGA	~Hz, ~10 kHz, TBT (100s kHz) ~3 (long term)/0.2 /3 µm (SOLEIL)
Now	Fast speed and big memory Resolution, stability	~Hz, 10 kHz, TBT, Gated/BbB <0.1 (long term)/0.1/1 (Sirius/Libera B+)/ 5 µm (NSLS-II)

BPMs for SPEAR II-1980

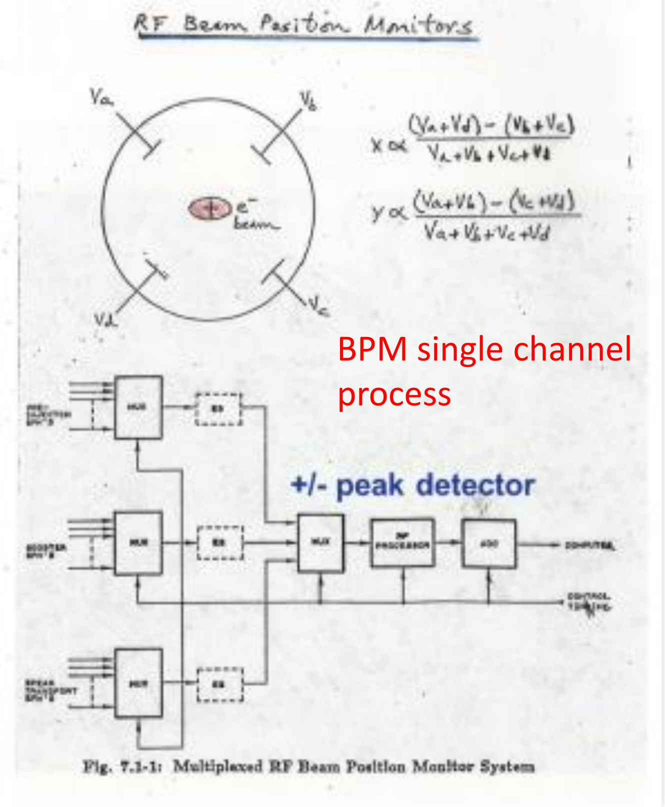


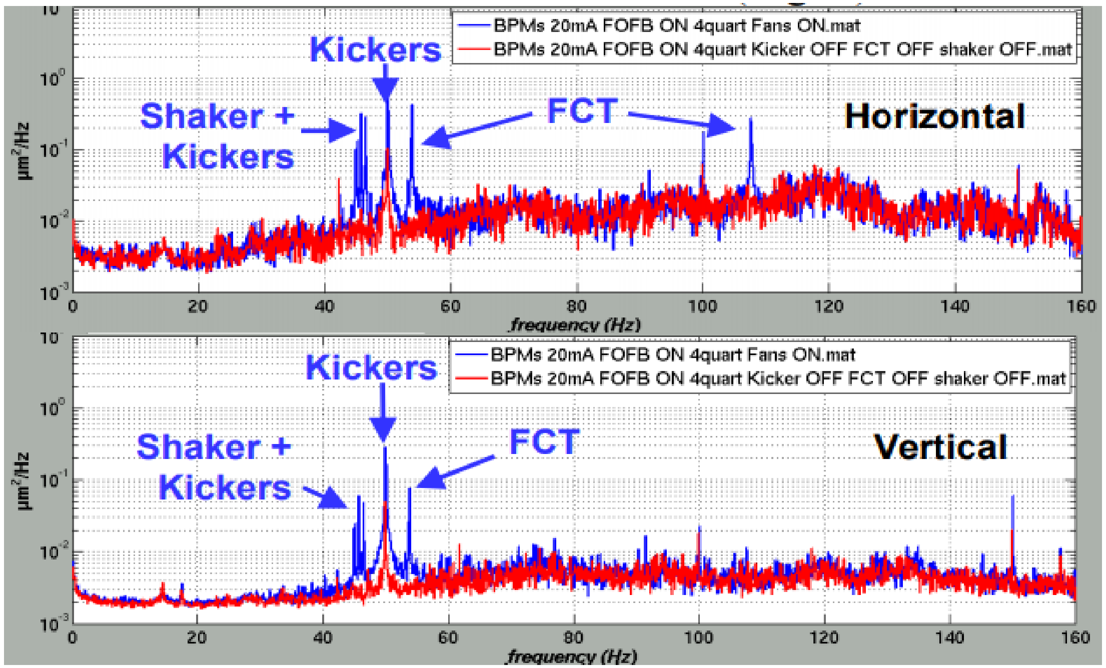
Fig. 7.1-1: Multiplexed RF Beam Position Monitor System

- Great progress on BPM development
- Digital signal processing is a big step of evolution
- Electronics development to improve BPM resolution, stability, data process speed and size
- BPM resolution improves ~one order per decade (follow emittance trend 10 nm-rad to 10 pm-rad)
- Design/development of BPMs from labs (SIRUIS, NSLS-II…) and commercial products (Bergoz, Instrumentation Technologies) in parallel

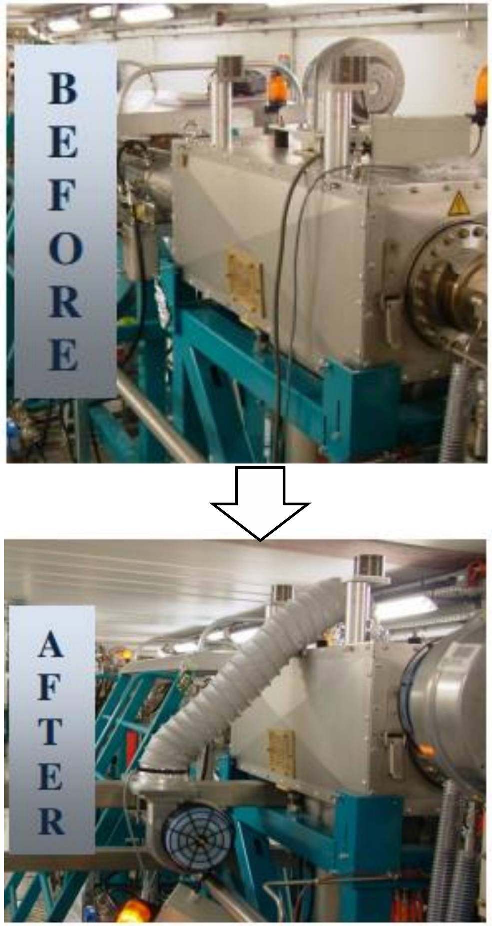
SOLEIL: identify and suppress noise sources

- Identify orbit spectrum peaks frequency: 46/50/54/128 Hz
- Localization method to identify the noise sources: cooling fan in kickers, FCT and shaker
- Technical solutions: reposition fans
- The integrated noise spectrum improved by a factor of 2 in both planes.

Beam spectrum before and after noise suppression



Cooling fan



https://accelconf.web.cern.ch/DIPAC2011/papers/tupd78.pdf