Beam stability in modern synchrotron light sources

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Brookhaven National Lab
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BROOKHAVEN NATIONAL LABORATORY

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- **SOLARIS**: Adriana Wawrzyniak
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- **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

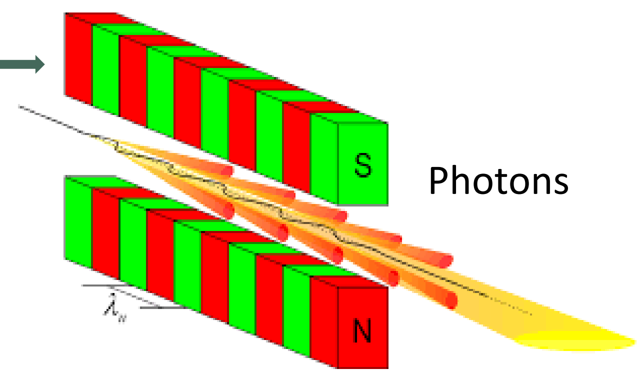
Outline

- The needs for high beam stability
- The means to reach high beam stability
  - Sources perturbing beam stability
  - Feedbacks increasing beam stability
- Summary and outlook

Synchrotron Light sources

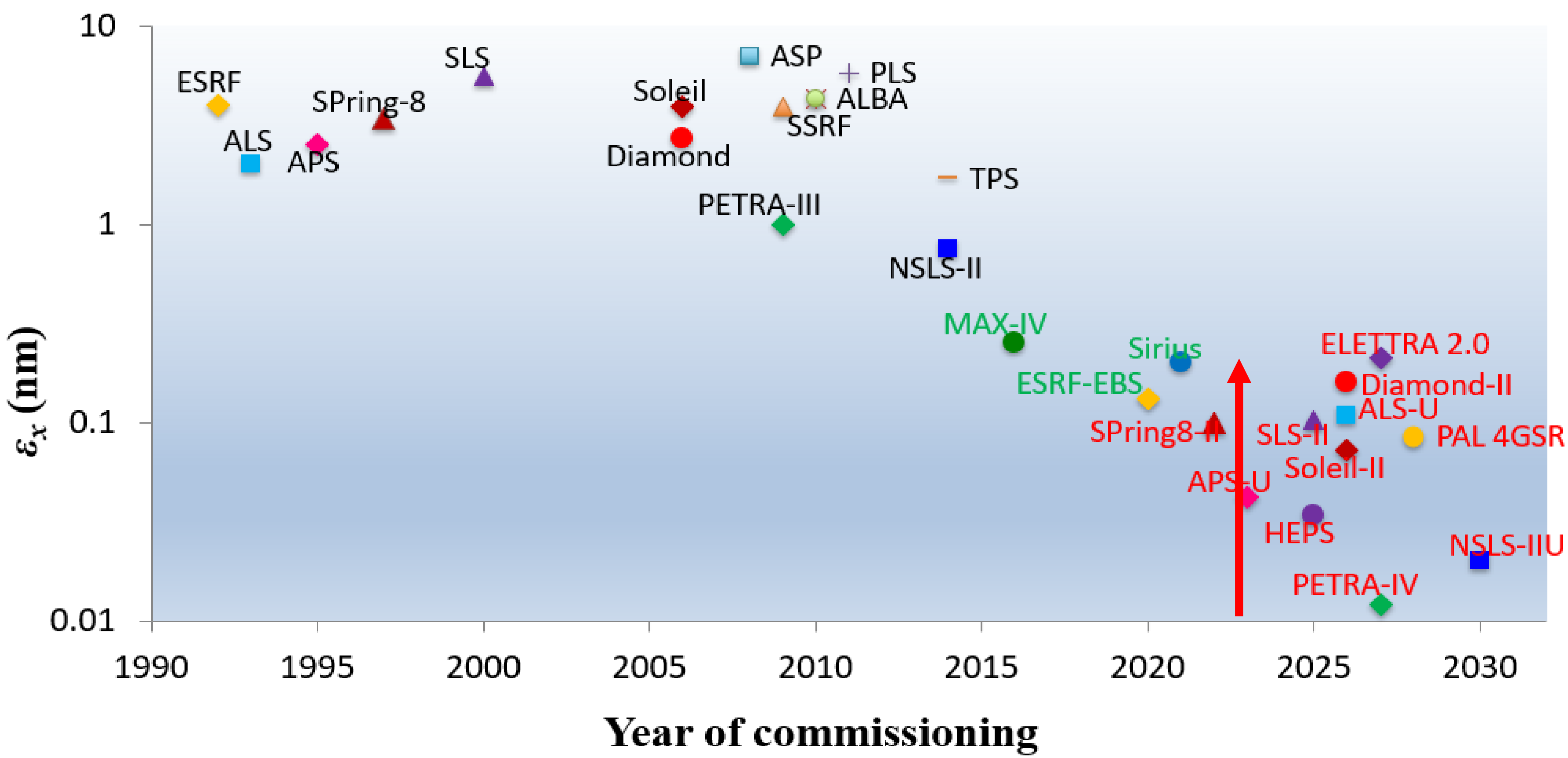
- Produce wide energy range of photons, from Infrared to hard x-ray for science research, such as biology, chemistry, physics, material, medicine, industry
- 50+ facilities, 60000+ users

High energy electron beams, produce photons when they pass through bending magnet or an array of bending magnets



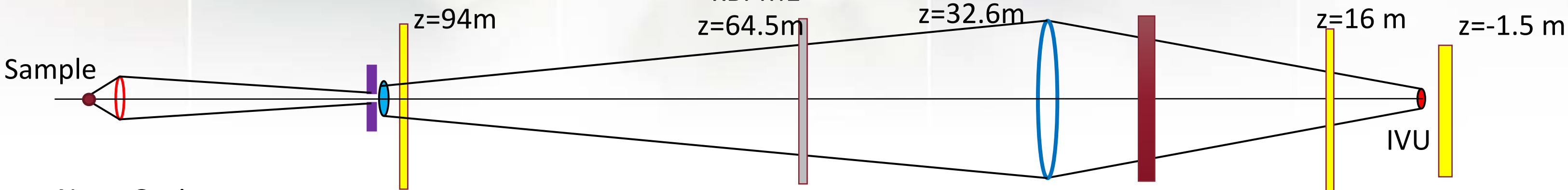
Trend of synchrotron light sources: ultra-low emittance

- Emittance reduction by two order magnitude: increasing brightness and coherence of photon beam
- Photon users: higher spatial resolution, higher energy resolution and faster scan time
    - Beam stability: a crucial parameter to define resolution



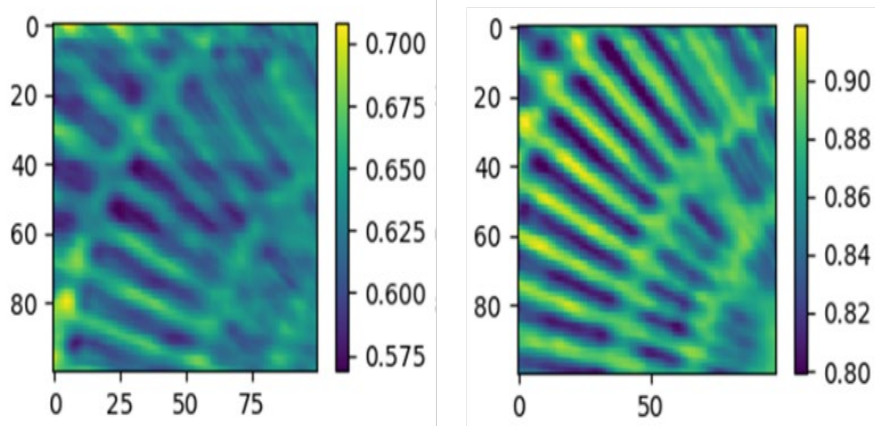
The needs for high beam stability

Importance of high beam stability: nanoprobe 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.

Impact of feedbacks on Hard x-ray imaging

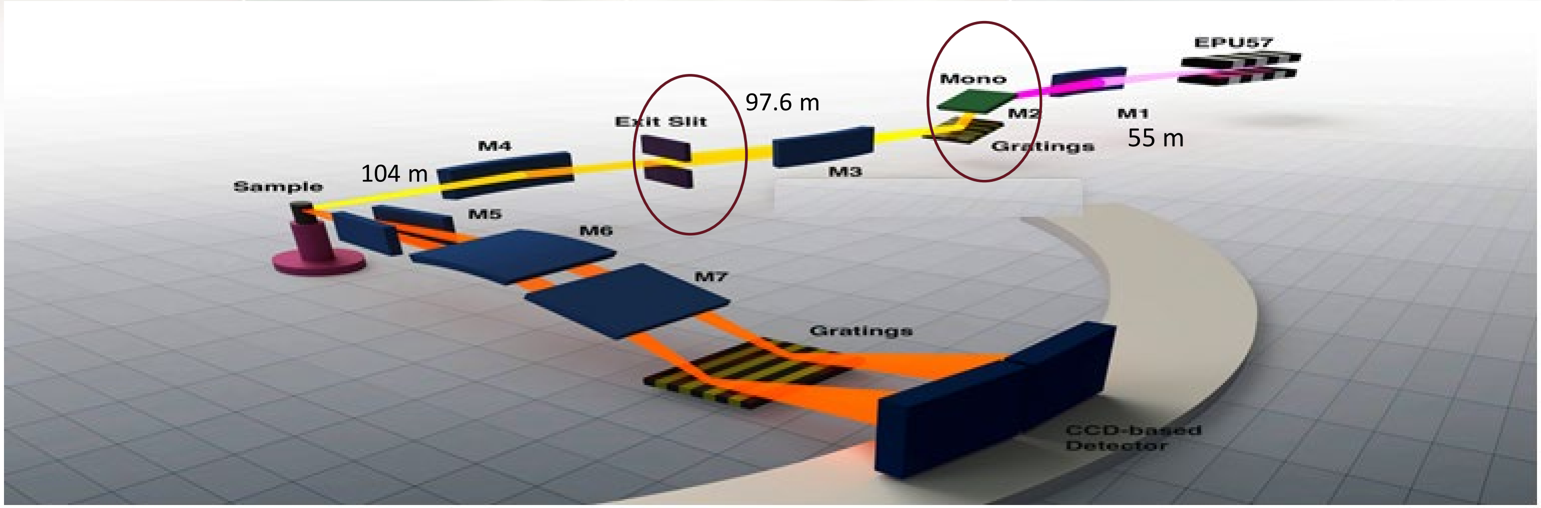


Feedback off

Feedback on

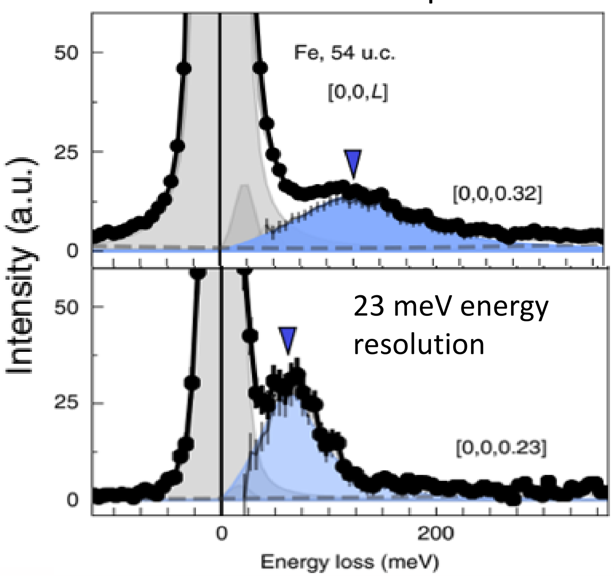
NSLS-II: Yong Chu, Xiaojing Huang

Importance of high beam stability: 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

RIXS to detect thin film spin excitation



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

NSLS-II: Valentina Bisogni, Jonathan Pelliciari

Means to reach high beam stability

- **Sources perturbing beam stability**
- Feedbacks increasing beam stability

Sources perturbing beam stability

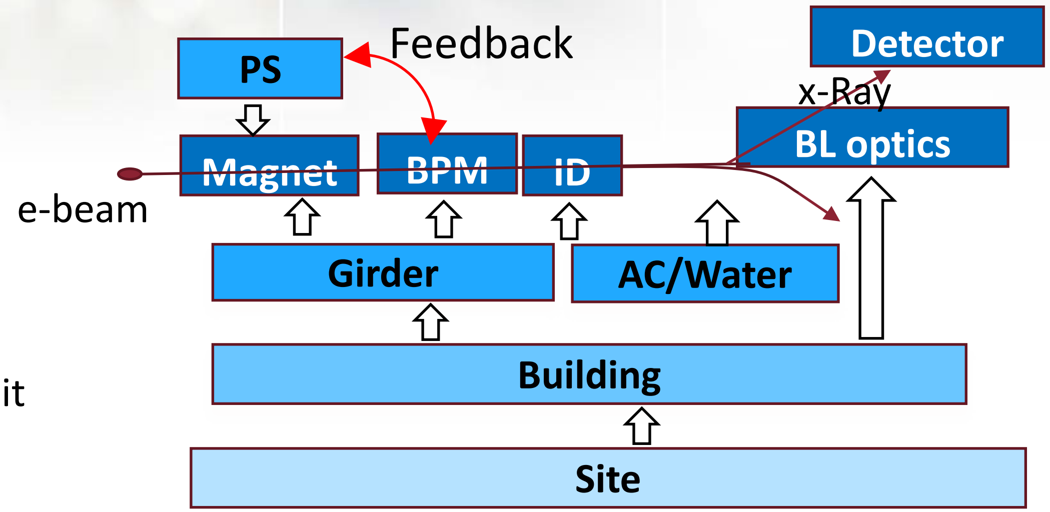
Sources of perturbation: natural + cultural noise

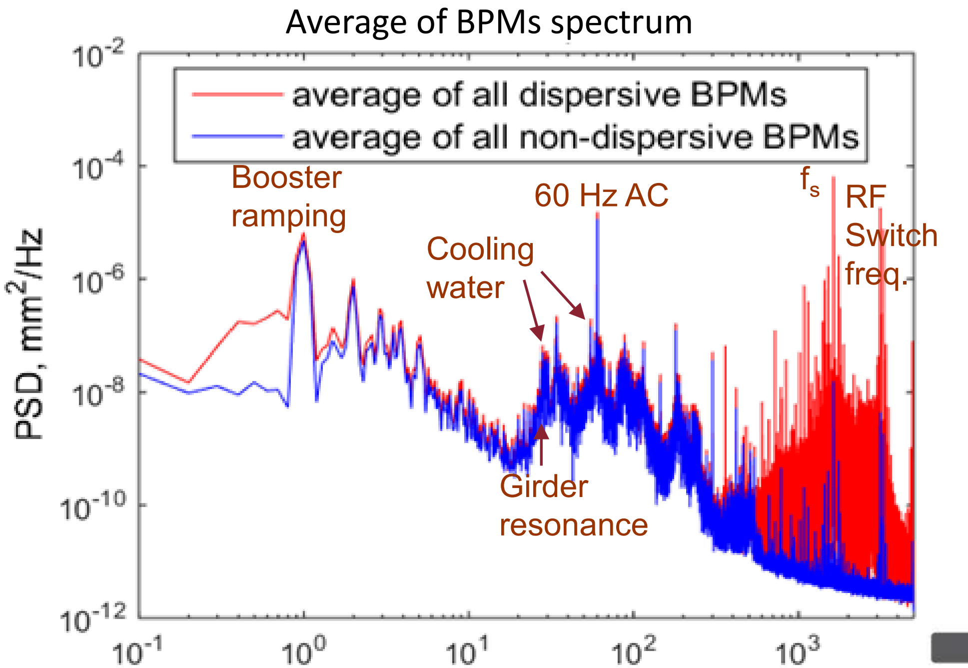
- Long term (weeks - years)
  - Ground settlement
  - Seasonal ground motion
- Medium term (minutes - days)
  - Daily thermal cycle
  - Earth's tides (~12 hrs)
  - Beam intensity/fill pattern
- Short term (milliseconds - seconds)
  - Ocean waves (0.13 Hz), wind
  - Ground vibration due to traffic/trains
  - 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 stability
  - Advances in BPM and feedback systems

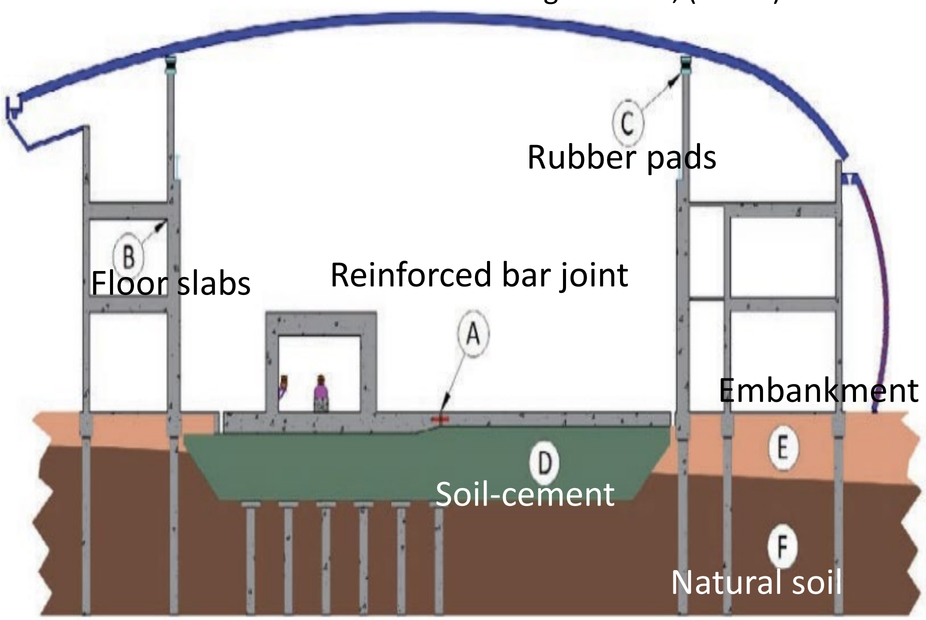




Site selection and building design

- 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



Quietest site
Built on firm rock

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

	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

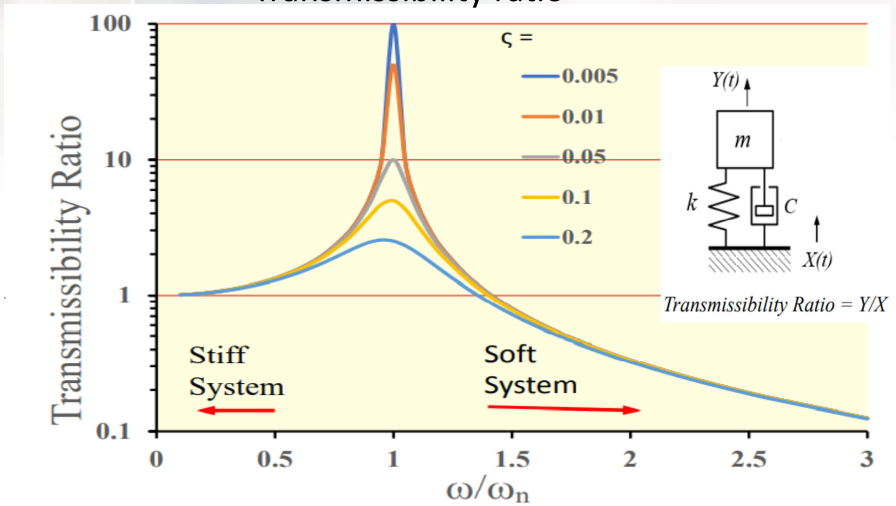
https://vibration.desy.de/overview

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

Girder support design

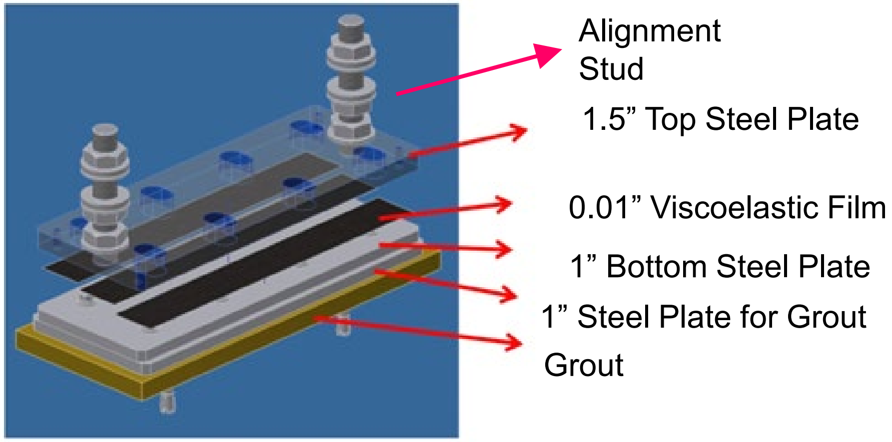
- Easy installation and alignment
- **High mechanical stability**
- Vibration stability:
  - Damp motion
  - Low transmissibility ratio →High stiffness and rigidity
- Thermal stability:
  - Viscoelastic pad: allow relative drift
  - Girder expand without bending

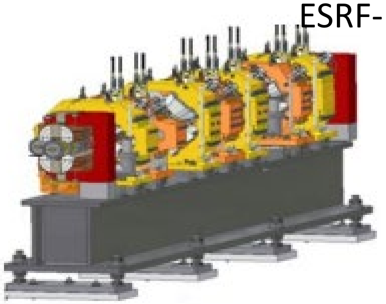
Transmissibility ratio



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

Effects

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

- Beam orbit/circumference
- Feedback

Power Supply stability

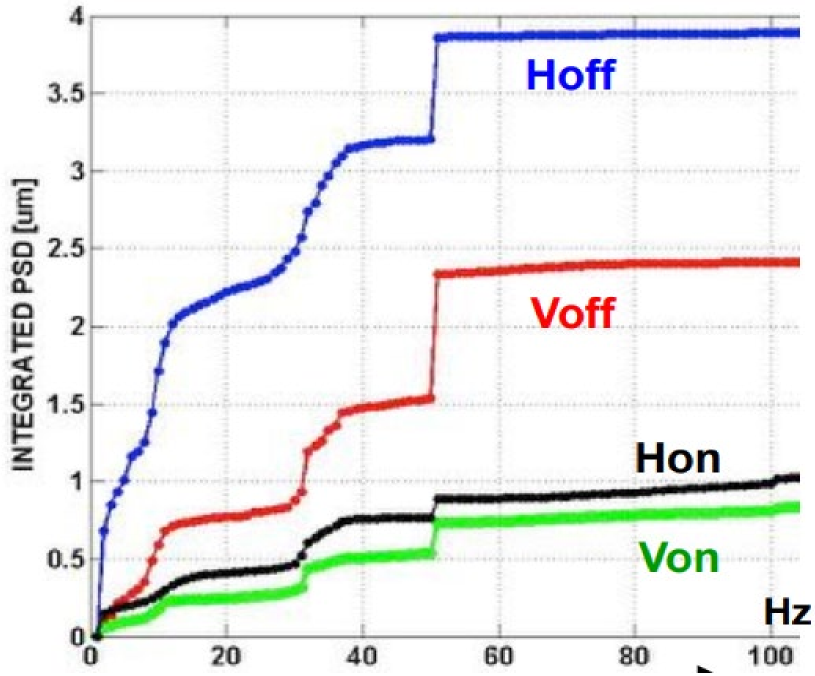
- Magnet power supplies stability directly affects electron beam motion
- Dipole: first order effect. 15 ppm (NSLS-II) 10 ppm (HEPS)
- Quadrupole, sextupole: high order effects. 50/100 ppm (NSLS-II), 10/100 ppm (HEPS), 10-50 ppm (ESRF-EBS)

ESRF-EBS: design improvement

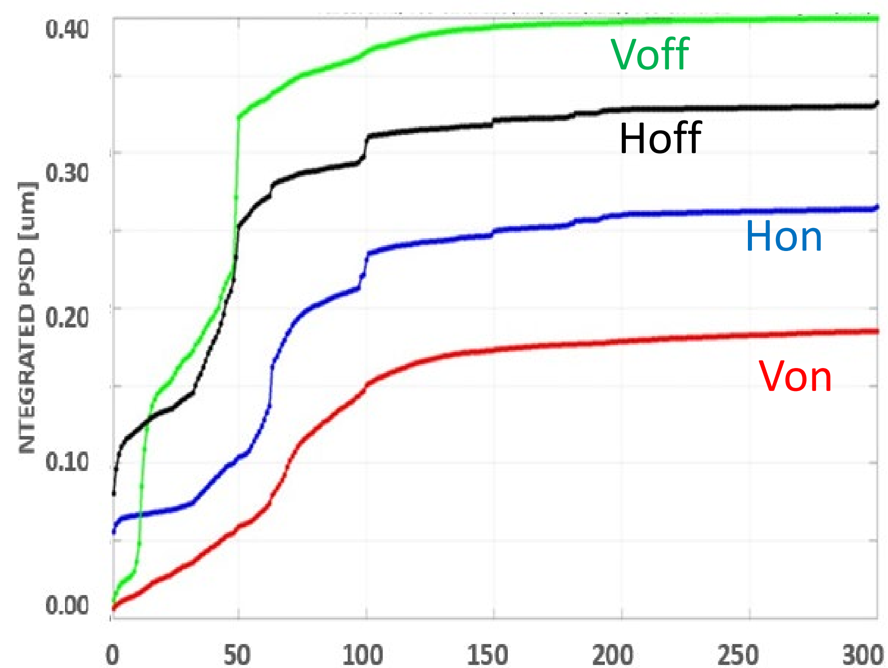
- **New girder design**: optimize girder rigidity to minimize the vibration effects
- **High stability power supplies**: accuracy from 10 to 50 ppm (p2p)
- Without Feedback, the integrated motion improves by a factor of ~10 (vs old ring): ~300 nm (H/V)
- FOFB improves beam motion further to ~200 nm

ESRF-EBS: Kees-Bertus Scheidt, Qing QIn

Old ring 2010, FOC On & Off



New ring 2020, FOC On & Off



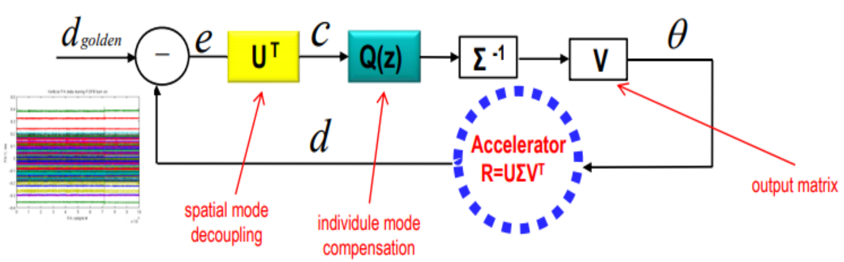
Means to reach high beam stability

- Sources perturbing beam stability
- **Feedbacks increasing beam stability**

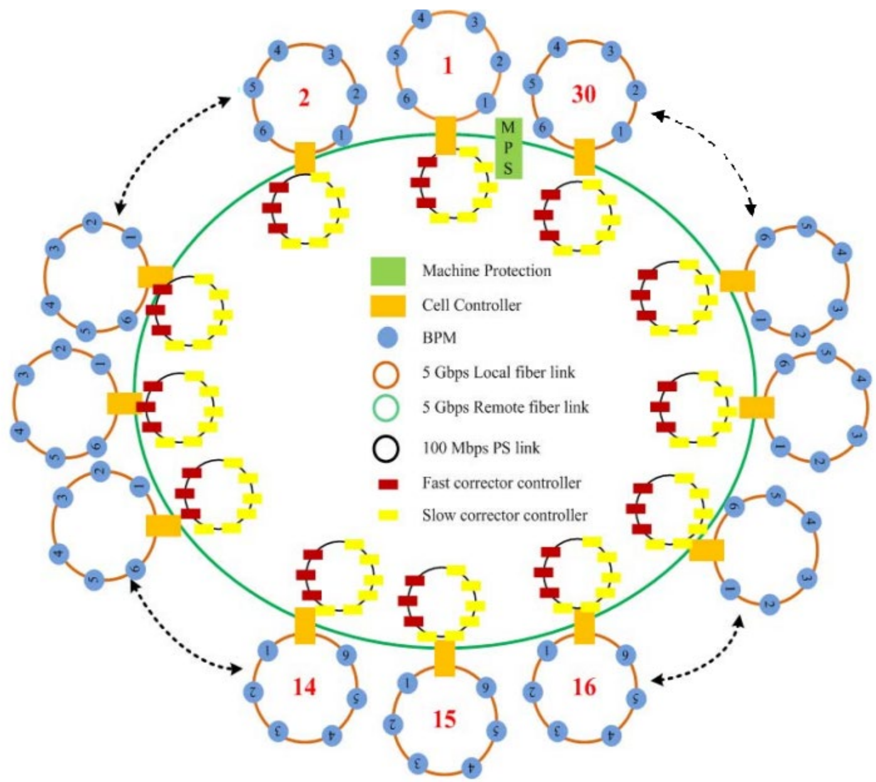
Feedbacks: Fast Orbit Feedback

- 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



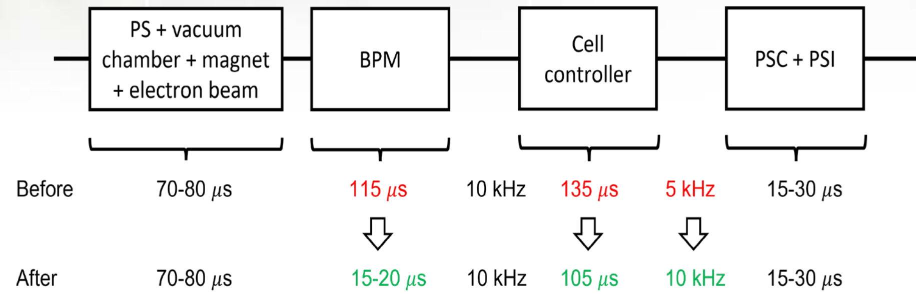
NSLS-II: Yuke Tian, Kiman Ha, Lihua Yu

Feedbacks: NSLS-II Fast Orbit Feedback (CONT.)

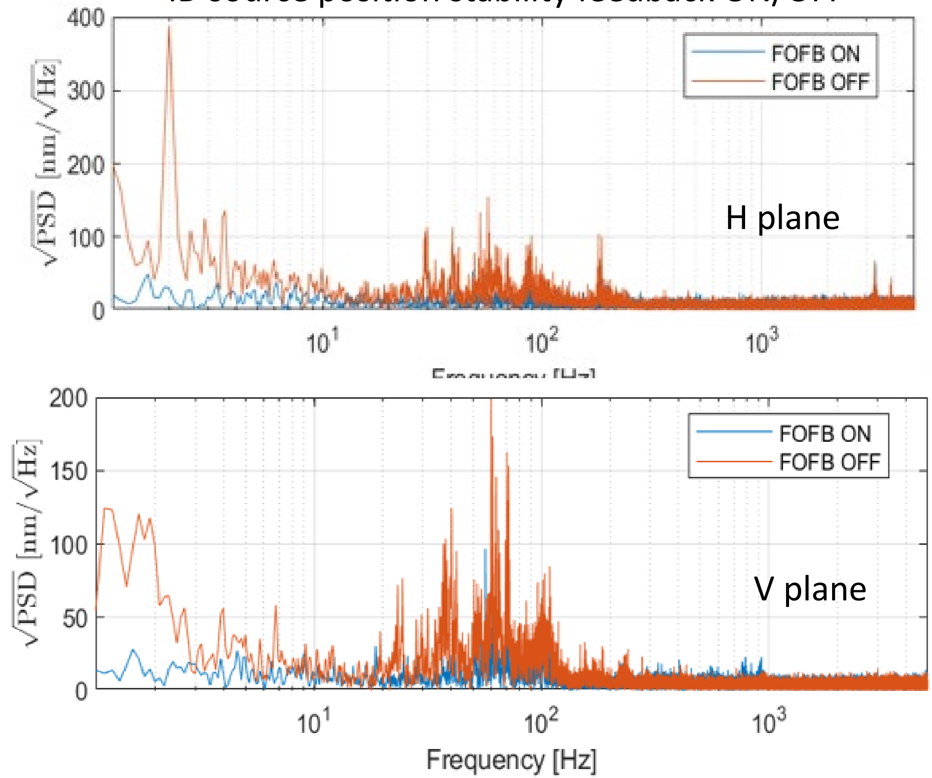
- Efforts to short FOFB loop total latency
  - Improve FOFB gain and bandwidth
  - Reduced BPMs delay
  - Increased cell controllers
- Bandwidth increase from 250 Hz to 400 Hz (horizontal) and 300 Hz (vertical)
- Gain increased by 10 dB (3 times) and integrated PSD motion reduced by 30% (at 500 Hz)
- 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: unified orbit feedback on ID BPM/xBPM and interact with FOFB (APS/ALS/SOLEIL) to reach µm long term stability

NSLS-II: Sukho Kongtawong

FOFB stage-to-stage latency and improvements



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 (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):

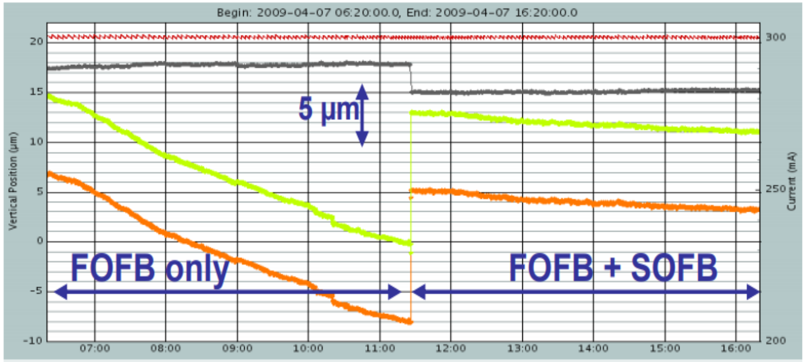
$$\Delta I2_{SOFB} = R^{-1}_{SOFB} * R_{FOFB} * \Delta I_{FOFB}$$

- 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



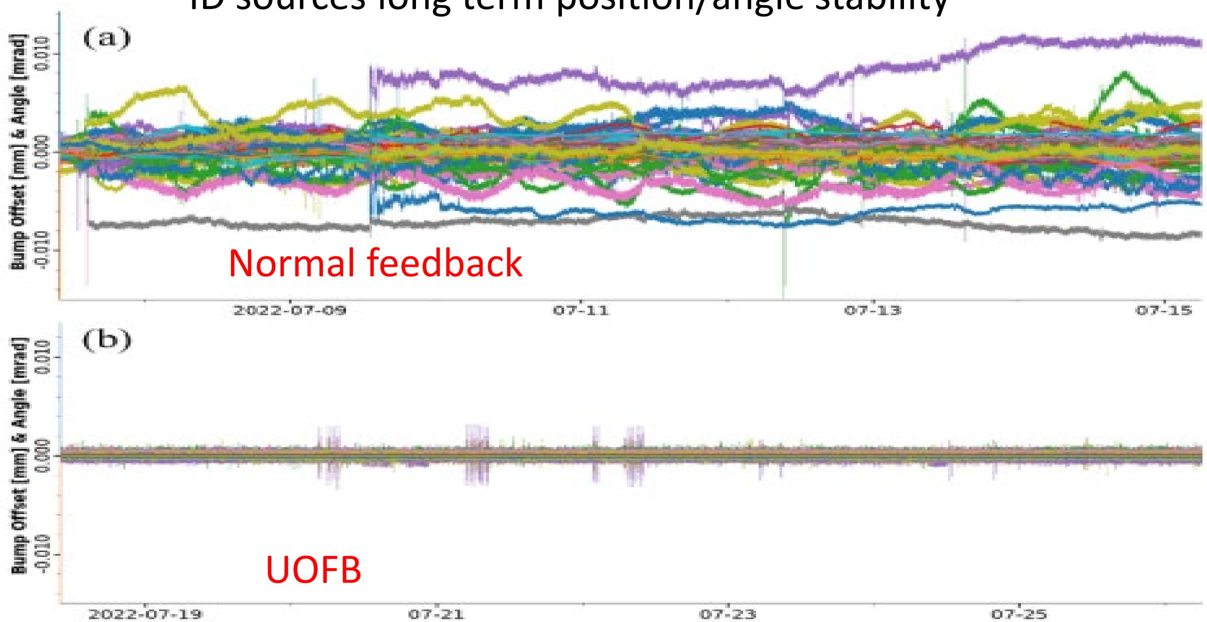
Vertical beam position at one SOLEIL bending magnet source point (BPMs: grey and X-BPMs: orange and green)

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

Slow and Fast orbit feedback: NSLS-II

- UOFB: unify normal operation feedbacks, slow orbit feedback (SOFB), fast orbit feedback (FOFB), and RF frequency feedback (RFFB) into one feedback
- Include 180*2 DC, 90*2 fast correctors, RF frequency and 224*2 RF BPMs and 3*2 xBPMs in feedback
- Be flexible to adjust ID bump, BM bump and X BPM photon local bumps at any time
- Maintain beam long-term orbit stability for all beamlines within in ~µm

ID sources long term position/angle stability



Y. Hidaka, UNIFIED ORBIT FEEDBACK AT NSLS-II , NAPAC22

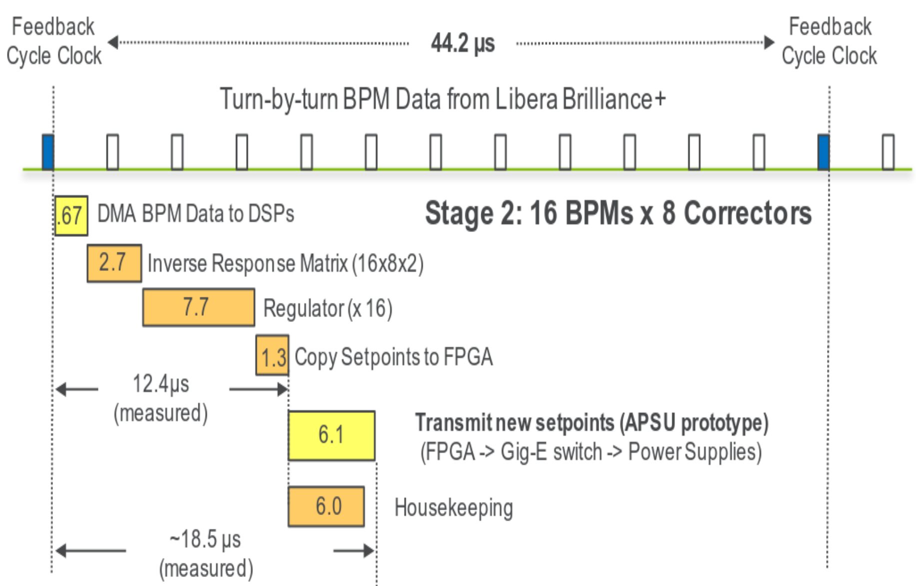
Future trend on beam stability

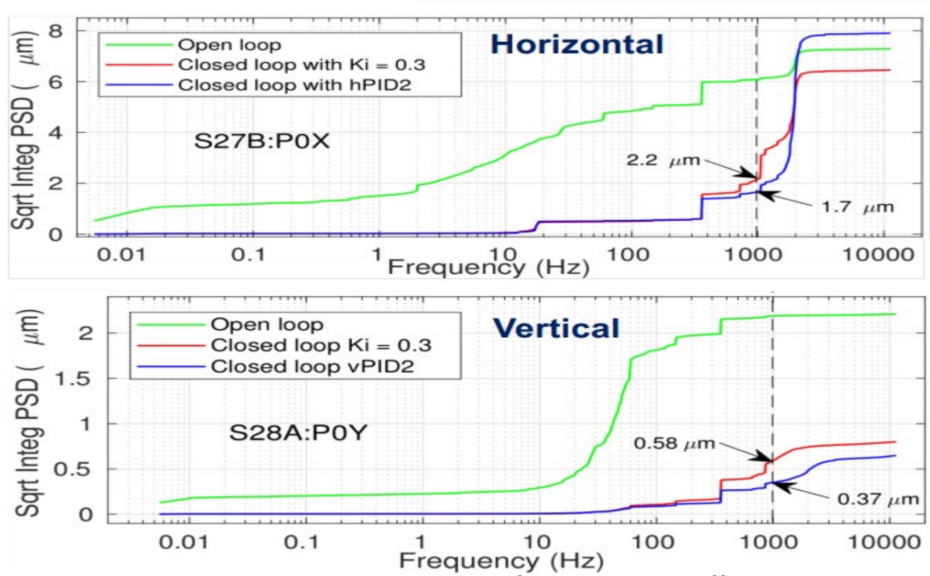
- Tighter beam position/angular stability: a few % beam size, sub-µm/µrad
- Larger feedback bandwidth: >kHz

APSU

- Unified electron orbit/photon trajectory feedback system needed to stabilize beam at the sample
- Expand feedback bandwidth/minimize latency: 44.2 µs
  - BPM higher sampling rate: 271 kHz TBT data
  - Faster correctors: 22.6 kHz sampling rate, 10 kHz bandwidth
- Demonstrated APS-U fast feedback on APS with 1 kHz bandwidth

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





Summary and outlook

- Beam stability is a key parameter for high-performance beamlines
- Our community invented and continue to develop 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
- Towards the future, unified feedback system is the trend to stabilize both electron and photon beam motion in a larger bandwidth with tighter tolerance on beam spatial and time domain stability

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Thanks for your attention!

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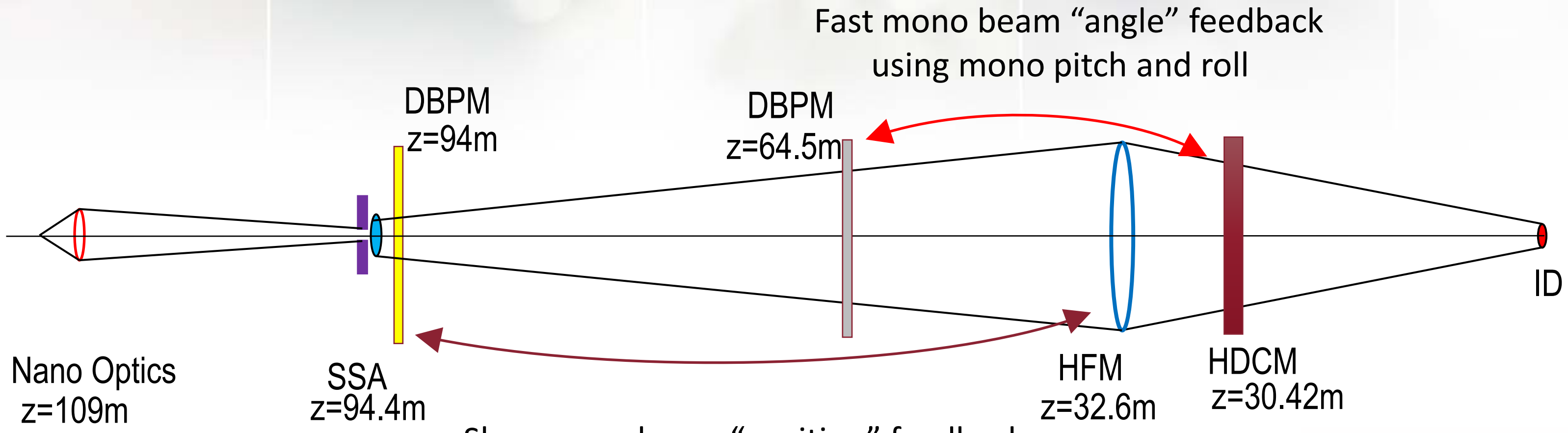
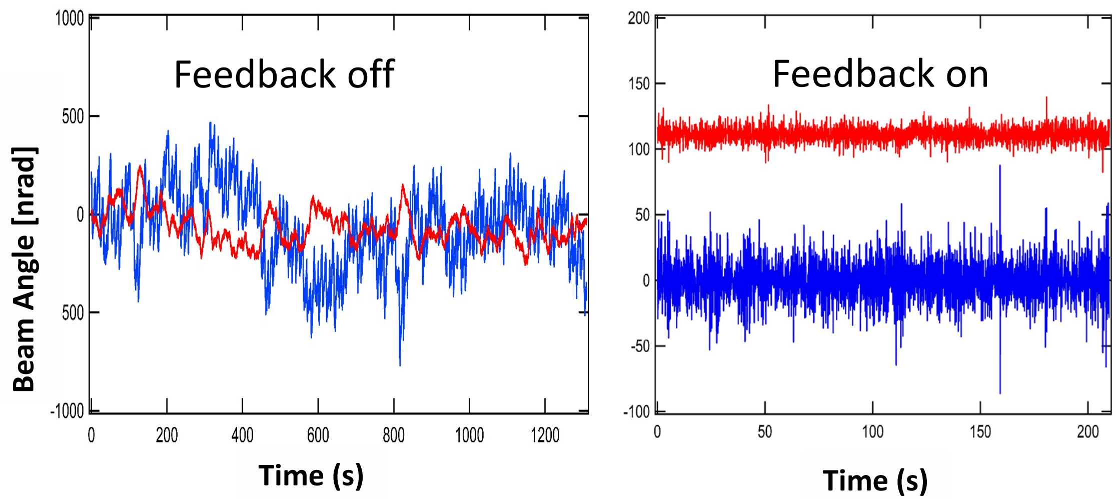
Feedbacks: Active beamline components feedback



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

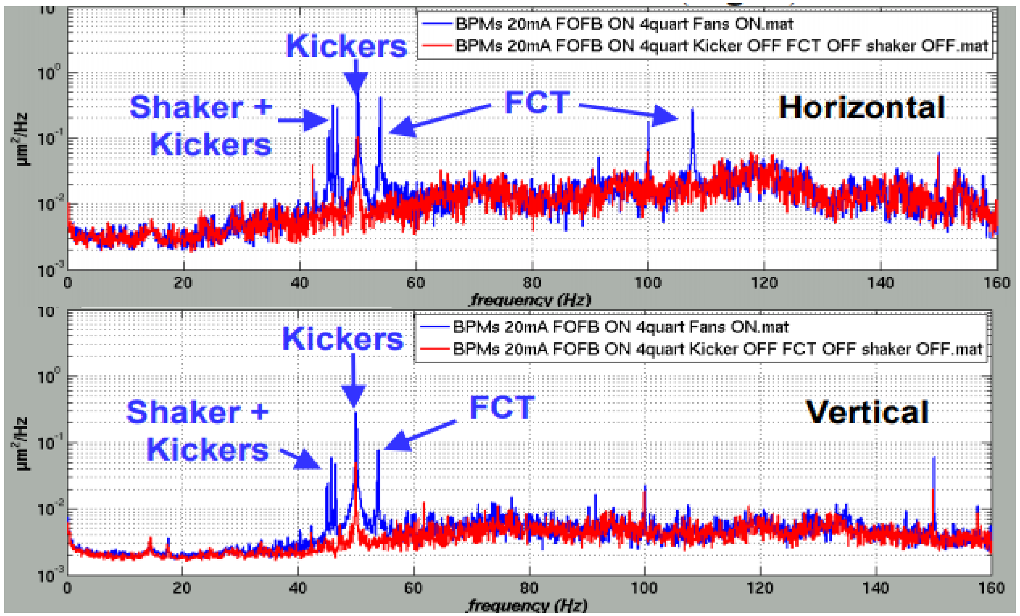


Petr Ilinski , Active feedback implementation for beamline photon beam stability, 7th DLSR 2021

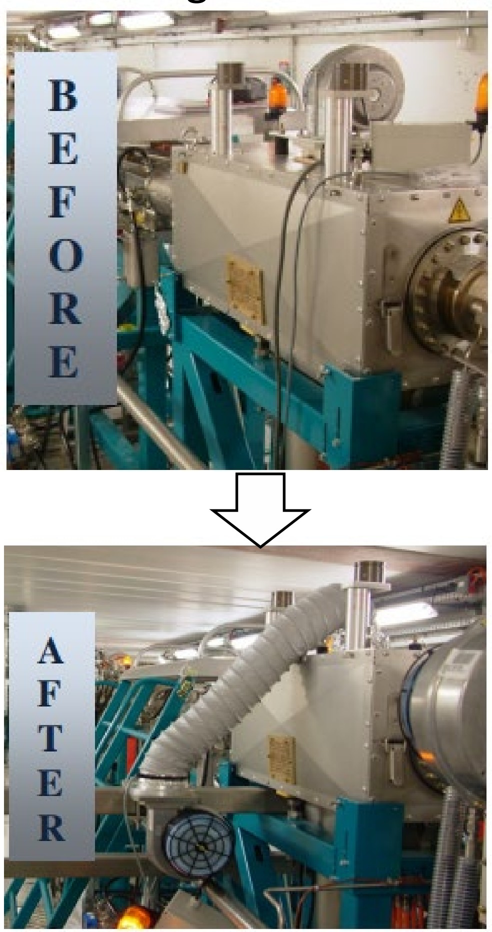
BPM data: localize noise sources

- Noise locator: pinpoint motion sources and improve them at SOLEIL
- 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