Beam stability requirements for ultra-low emittance circular light sources

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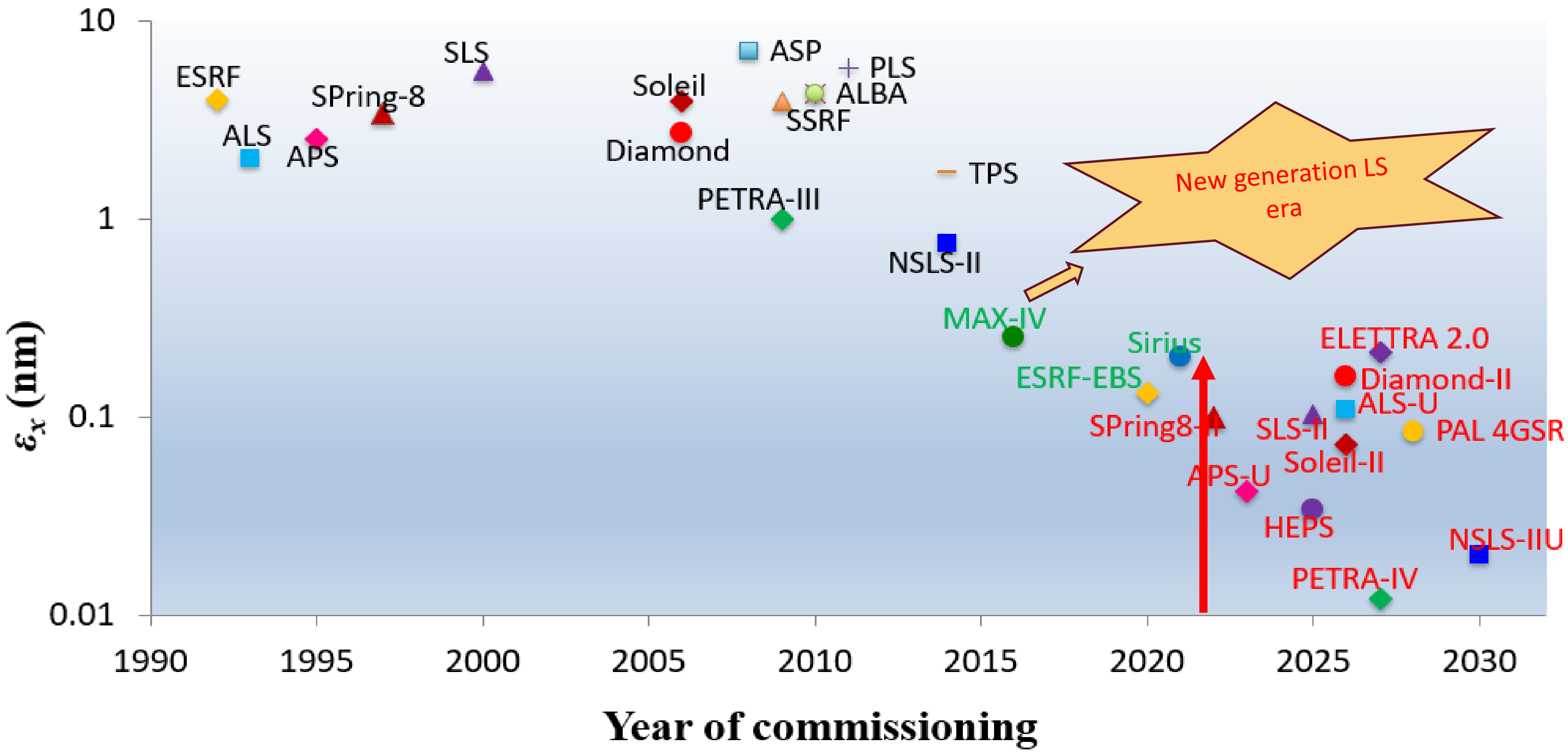
- **SOLEIL**: Laurent Nadolski
- **SPEAR3**: Gierman Stephen; Safranek James; Tian Kai
- **SSRF**: Yin Chongxian; Zhang Wenzhi; Zhao Zhentang
- **TPS:** Chiu Pei-Chen; Hu Kuo-Hwa; Hsu Kuo-Tung; Huang Chih-Hsien

Outline

- Requirements of beam stability
- The means to reach high beam stability
  - Sources perturbing beam stability
  - Diagnostics monitoring beam stability
  - Feedbacks increasing beam stability
- Summary and outlook

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 of experiments



Beam stability requirements at ultra-low emittance lattice

- Electron beam stability are driven by photon beam stability requirements
- Phase space stability:
  - 100s – 10s pm-rad emittance: a few μm beam size and beam divergence
  - Tighter beam position/angular stability: submicron
- Time domain stability
  - From hours to microseconds, depending on experiment sampling rate, data integration period, and scan duration

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

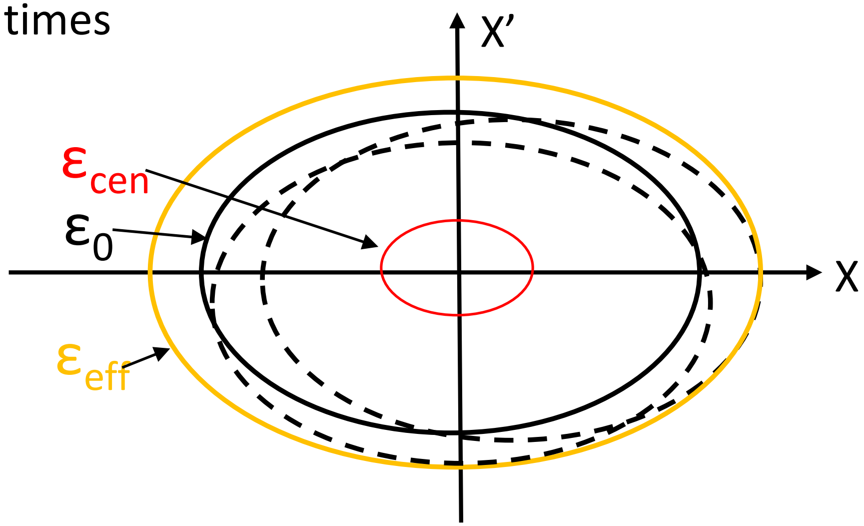
Electron beam

- Position stability: a few % beam size, sub-μm
- Angular stability: a few % beam divergence, sub-μrad
- Large bandwidth feedback: days to kHz
- Beam size stability: a few %
- Emittance stability: a few %
- 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*

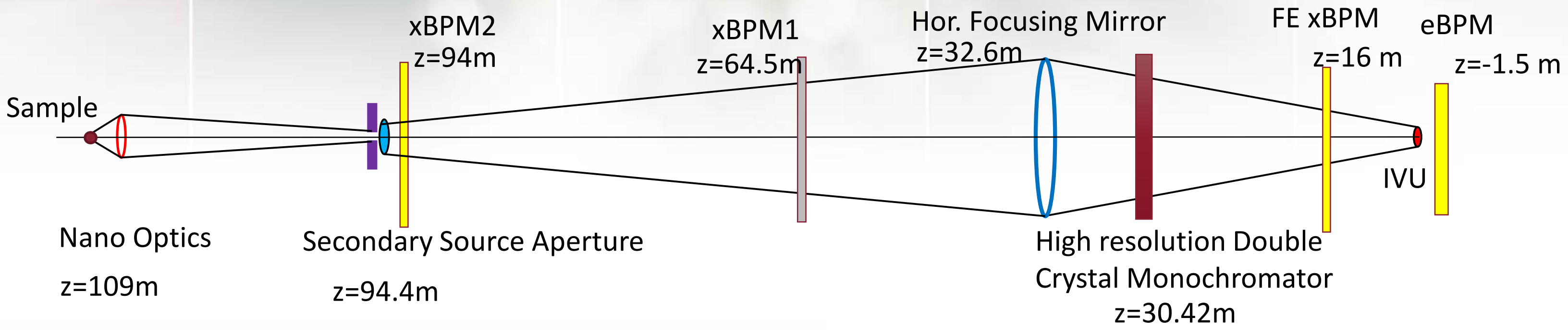
Beam motion caused beam emittance growth

- Fast motion: larger than the sampling and integration rates
  - beam distribution ‘‘smeared out’’ in phase space, increase of effective beam emittance: $\Delta\varepsilon/\varepsilon_{eff} = \varepsilon_{cen}/\varepsilon_0$
  - 30% beam size motion→ 10% ε_{eff} increase
- Slow motion: comparable or less than user data integration rates
  - effective emittance: $\Delta\varepsilon/\varepsilon_{eff} = 2\sqrt{\varepsilon_{cen}/\varepsilon_0}$
  - 5% beam size motion→ 10% ε_{eff} increase
  - More serious for users: beam movement based on scan or sample, introducing measurement noise
  - **Sensitive frequencies motion**: bounded high end by data sampling rates and low end by data integration and sample scan times



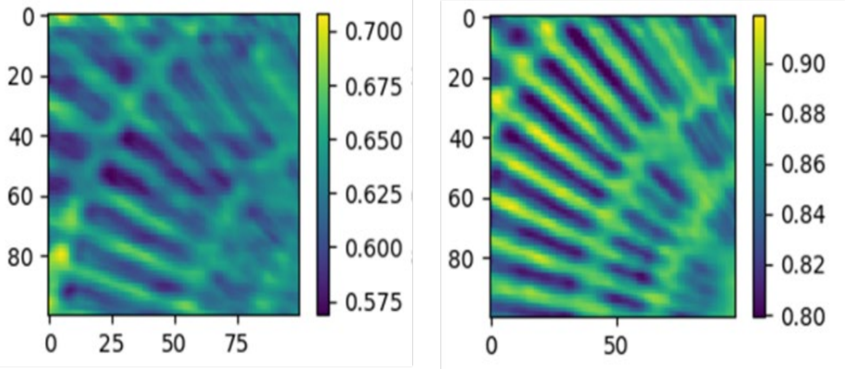
ε_0: unperturbed emittance
ε_{cen}: beam centroid motion emittance
ε_{eff} : effective emittance

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. 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 Hard x-ray imaging

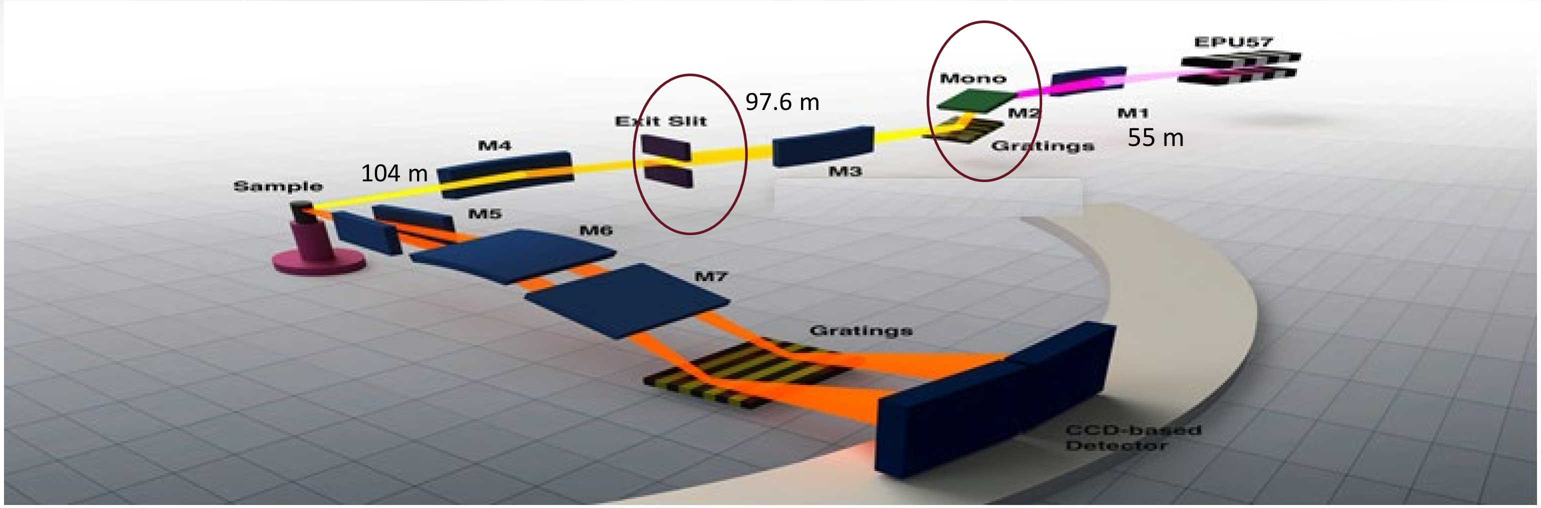


Feedback off

Feedback on

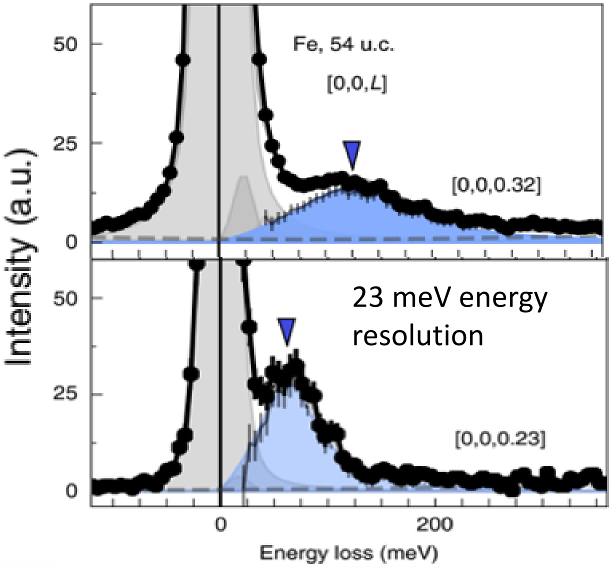
NSLS-II: Yong Chu, Xiaojing Huang

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, ~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

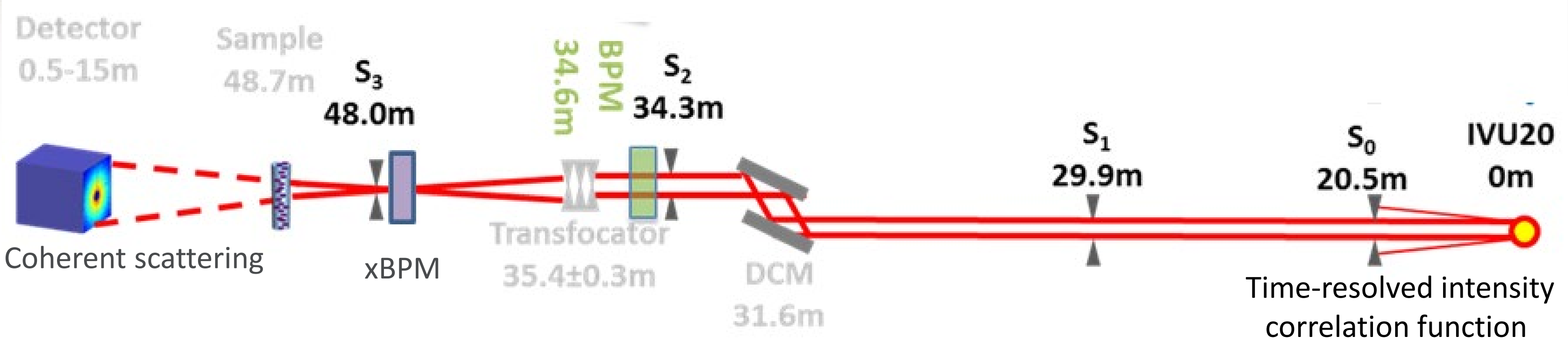


23 meV energy resolution

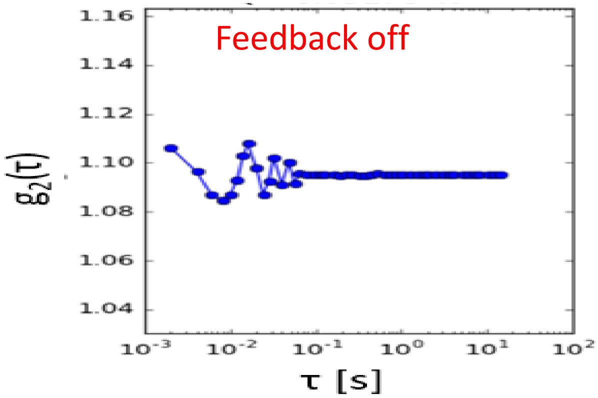
**J. Pelliciari et al., Nat .Mat. 20, 188 (2021)*

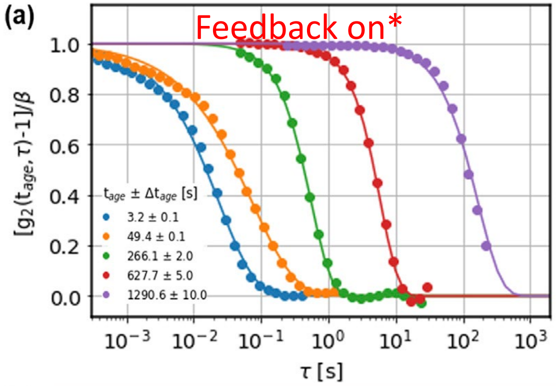
NSLS-II: Valentina Bisogni, Jonathan Pelliciari

Importance of high beam stability: Coherent Scattering



Time-resolved intensity correlation function





- 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

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

Means to reach high beam stability

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

Sources perturbing beam stability

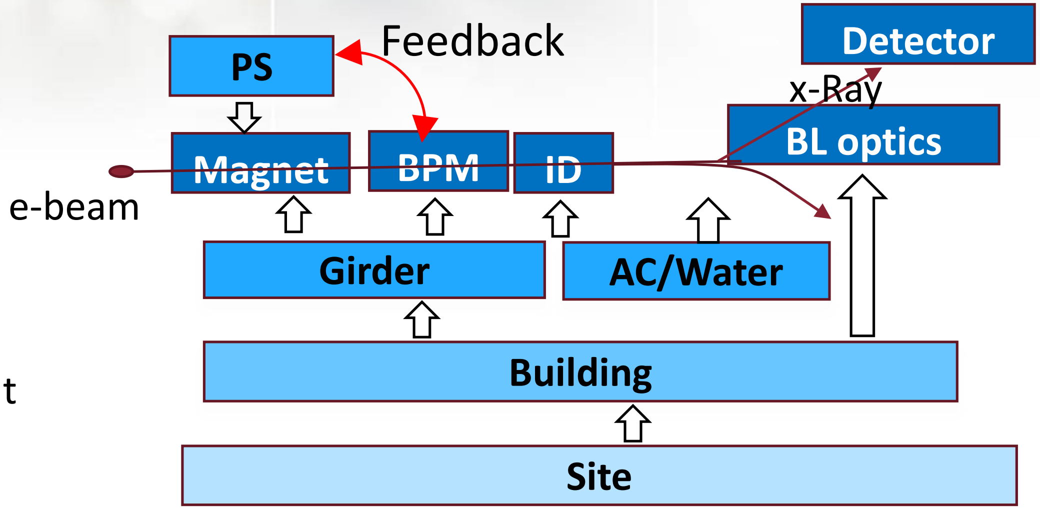
Sources of perturbation: natural + cultural noise

- 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



Feedback

PS

Detector

x-Ray

BL optics

e-beam

Magnet

BPM

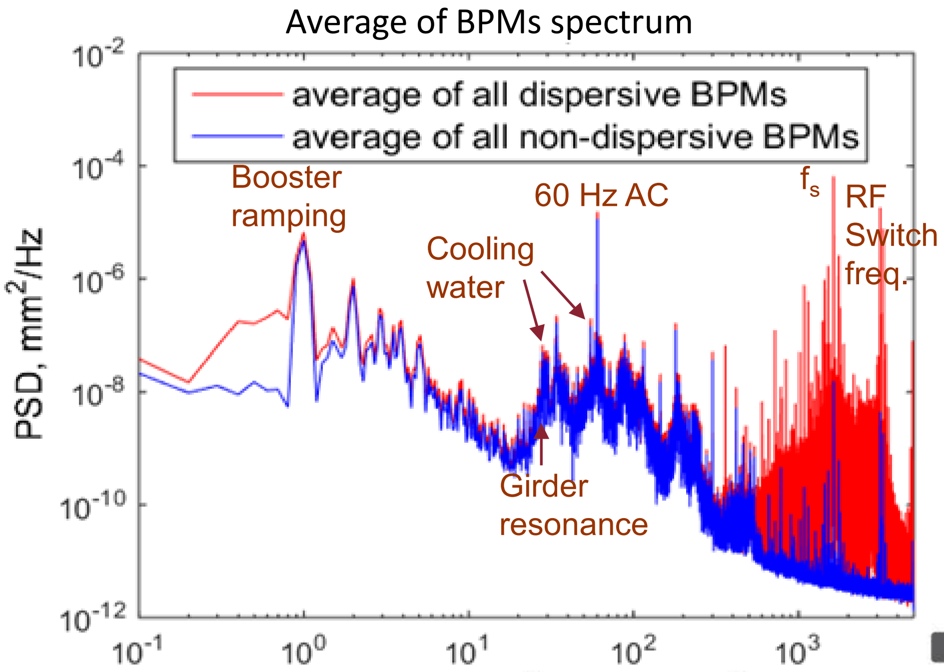
ID

Girder

AC/Water

Building

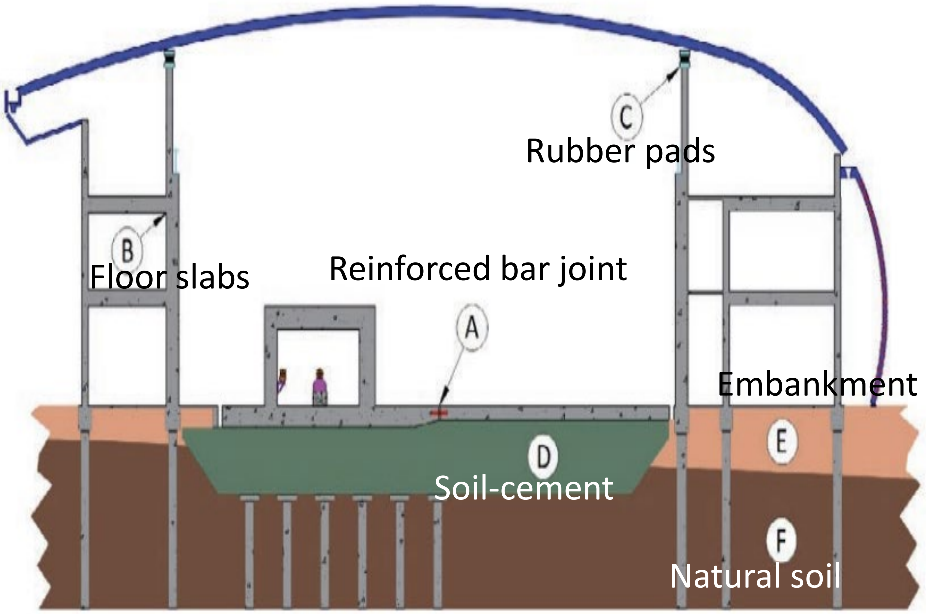
Site



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

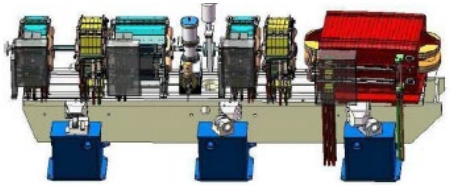
	ALBA	APS	BNL	DESY(XFEL)	ESRF	IHEP	SLAC	Spring-8	SSRF
Night [nm]	9.1	9.8	29.1	35.1	40.2	8.1	4.1	1.8	102
Day [nm]	42	11	80	70	137.2	9	7.4	2.5	444

https://vibration.desy.de/overview

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

Girder support systems

- Environment motion passes to beam motion through Girder
- Easy installation and precision alignment of magnets
- **High mechanical stability (vibration and thermal)**
  - Vibration stability: damp motion
  - Thermal stability: minimize temperature induced distortion
- Different designs, different support points and various alignment mechanisms

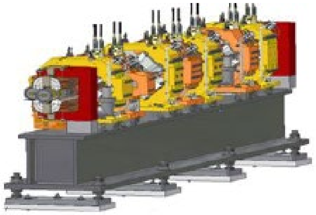


TPS

SIRIUS

APSU

ESRF



NSLS-II

Girder support systems: Vibrational stability requirements

- Low transmissibility ratio →High stiffness and rigidity
- Lowest Natural Frequency of magnet-girder assembly

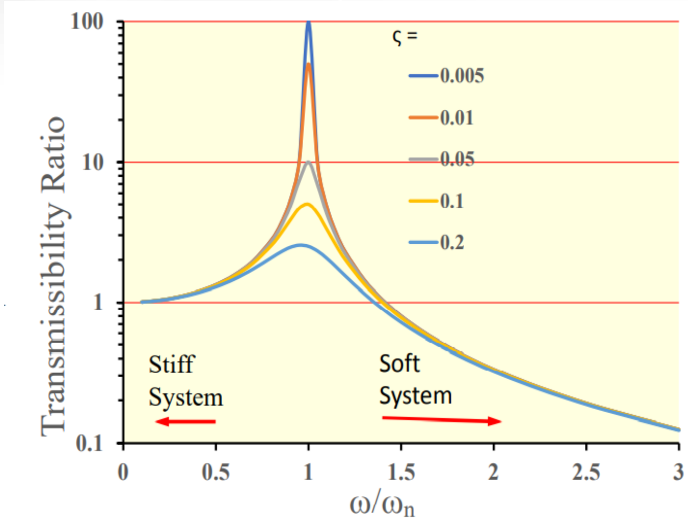
50 Hz (ESRF), 54 Hz (HEPS), 110 Hz (Spring-8-II), 120 Hz (SIRISU)

- Uncorrelated motion: magnet to magnet (on the same girder)

RMS(nm): 25, 150 (V, H) (NSLS-II), 10 (APSU)

- Uncorrelation motion: girder to girder

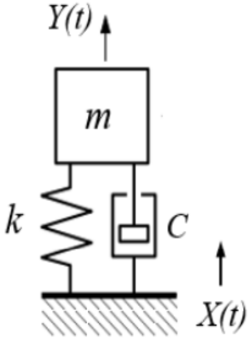
RMS(nm): 70, 600 (V, H) (NSLS-II), 20 (APSU)



Transmissibility Ratios (*Floor-to-Magnet, 1,2 -100 Hz)*

Facility	Lowest Nat. Freq.	Horizontal	Vertical
NSLS-II*	30 Hz	1.03	1.01
TPS (locked)	44 Hz	1.20	1.01
ESRF	42 Hz	1.24	1.21
APSU**	42 Hz	1.30	1.01
SIRIUS	133 Hz	1.30	1.07
SPring-8-II***	27 Hz	3 - 5	2

**With viscoelastic pads, ** Estimates from FE Model, ***Measurements to be verified*



Transmissibility Ratio = Y/X

S. Sharma: Storage Ring Girder Issues for Low Emittance Storage Rings, MEDSI, 2019

Girder support systems: thermal stability requirements

- Thermal stability: minimize temperature induced distortion
  - Viscoelastic pad (NSLS-II): allow relative drift
  - Girder expand without bending
- Tunnel air temperature stability: girder thermal bending
  - 0.1 ^{o}C → 4 nm magnet misalignment
- Floor expansion/contraction: girder deformation
  - 1 µm/m→ 7 nm deformation (viscoelastic pad)

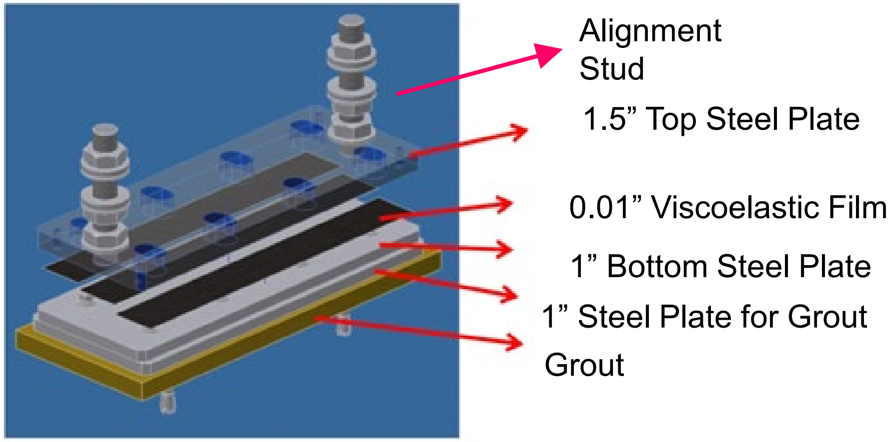
Magnets stability:

25 nm (NSLS-II, 24 hrs)

BPM stability

0.2 µm (NSLS-II, 24 hours)

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



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)
  - Electronics stability

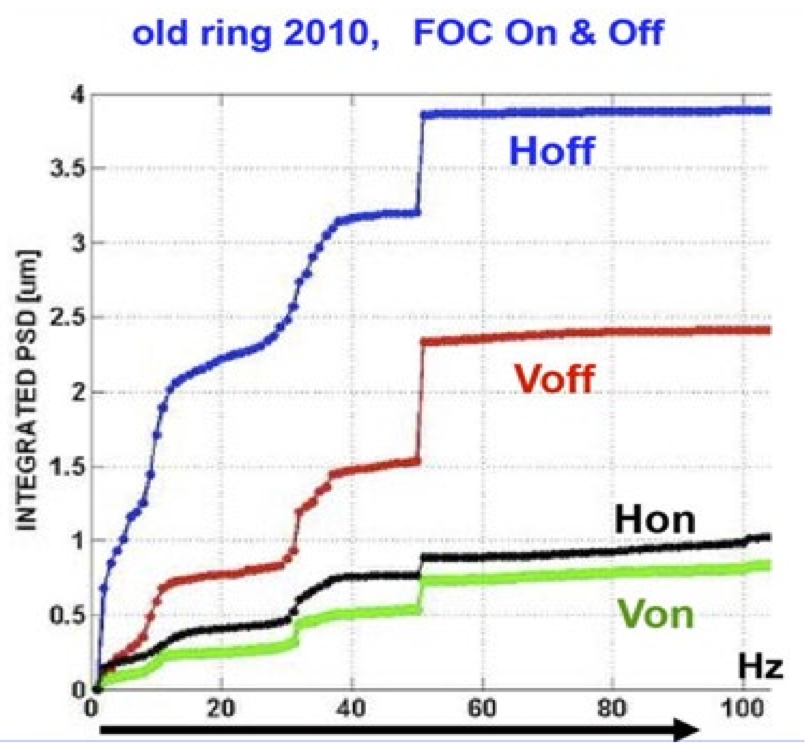
- Beam orbit/circumference
- Feedback

Power Supply stability

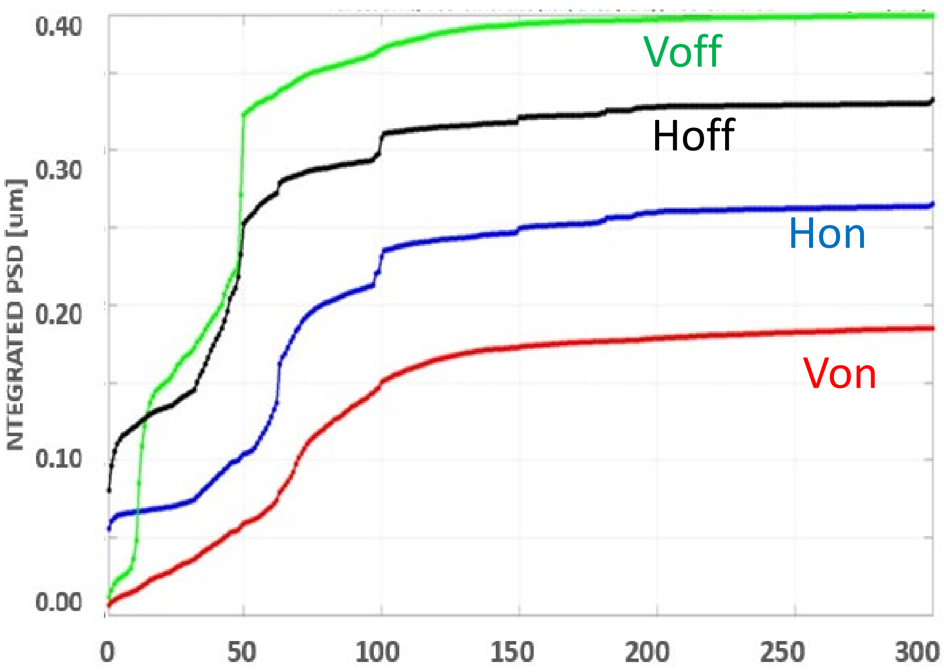
- Magnet power supplies stability directly affects electron beam motion
- Dipole: first order effect. 15 ppm (NSLS-II) 10 ppm (HEPS)
- Quadrupole, sextupole: high order effects. 50/100 ppm (NSLS-II), 10/100 ppm (HEPS), 10-50 ppm (ESRF-EBS)

ESRF-EBS: high beam stability from machine design

- **New girder design**: optimize girder rigidity to minimize the vibration effects
- **High stability power supplies**: accuracy from 10 to 50 ppm (p2p)
- Without Feedback, EBS the integral motion improved by a factor of ~10 (vs ESRF): ~300 nm in both plane, which is better than many 3^{rd} generation light sources with FOFB
- FOFB further suppresses beam motion to ~200 nm


old ring 2010, FOC On & Off

EBS ring 2020, FOC On & Off



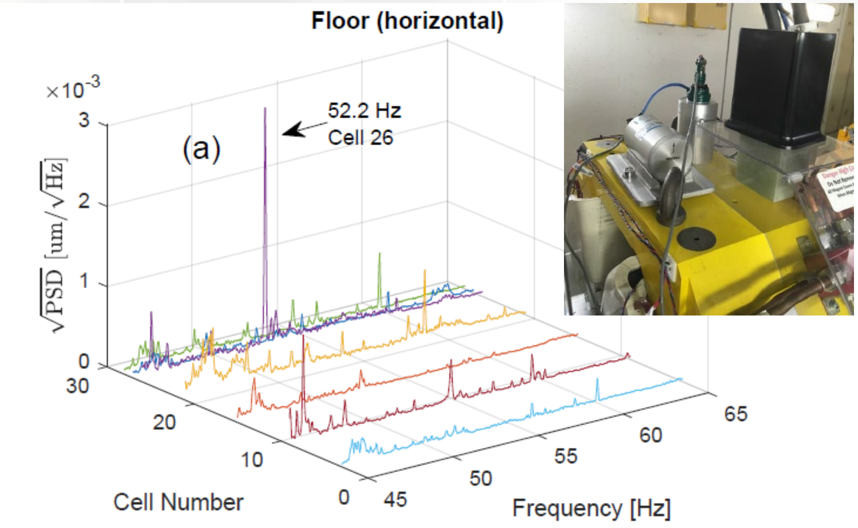
THE ORBIT CORRECTION SCHEME OF THE NEW EBS OF THE ESRF

E. Plouviez †, F. Uberto, ESRF, Grenoble, France

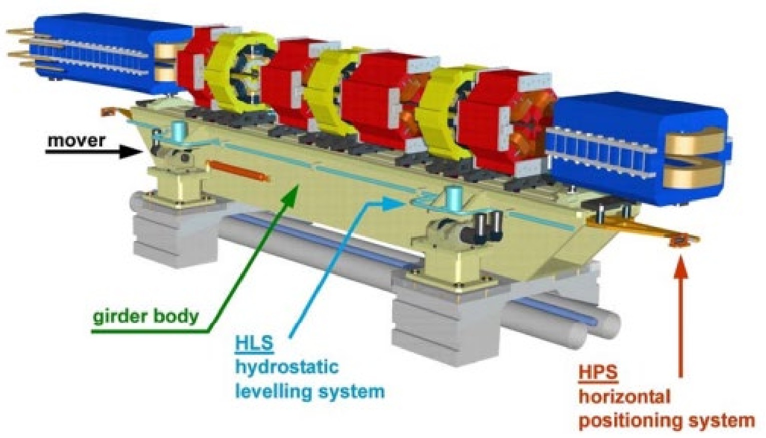
Nat *EBS: Kees-Bertus SCHEIDT*

Mechanical motion measurement tools

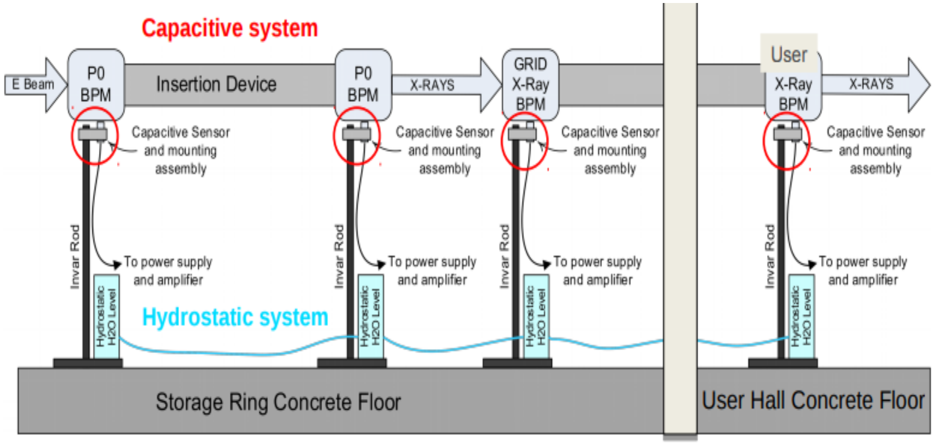
- Short term stability measurement
  - Geophone/accelerometer
- Long term stability
  - Drift between accelerator and experimental floor
  - SLS: support, positioning and position monitoring system
  - APSU: mechanical motion measurement system (MMS) monitoring RF-BPM and X-BPM mechanical movement relative to floor/reference surface with hydrostatic Level System, ~10 nm resolution. Plan to be used for slow drift correction



Geophone for vibration measurement



SLS: Positioning and monitoring system



APSU: Mechanical Motion Measurement system

https://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=B3FEDA0D18093EE07152B59A11AB2645?doi=10.1.1.616.5421&rep=rep1&type=pdf

Beam Diagnostics for the APS MBA Upgrade (cern.ch)

Sources motion propagation to orbit motion

- Orbit motion is produced from mechanical motion of magnets, electrical noise in magnet power supplies to vibrate magnetic field and BPM noise via orbit feedback
- Close orbit distortion

$$x(s) = \sum_j \theta_j \sqrt{\beta(s)\beta_j}\,\frac{\cos(\pi\nu - |\Psi(s) - \Psi_j|)}{2\sin\pi\nu}$$

- Orbit response matrix $\boldsymbol{x} = \boldsymbol{R\theta}$: sources ←→ beam motion

  X: beam position

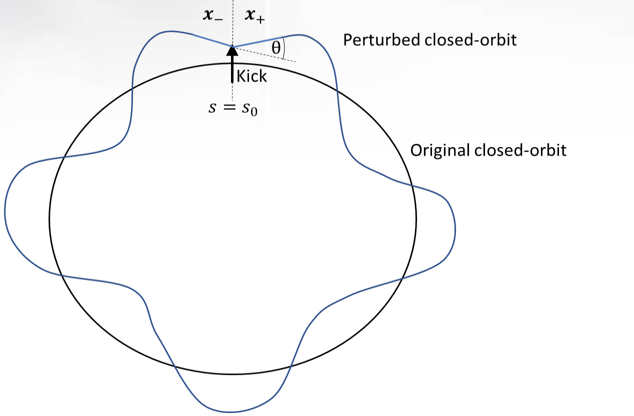
  θ: kick angle

  R: response matrix

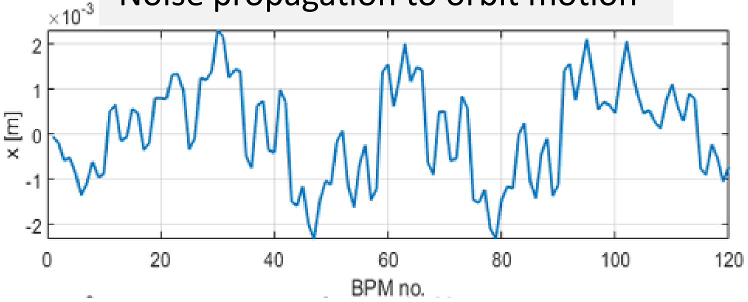
$$R_{ij} = \frac{\sqrt{\beta_i\beta_j}}{2\sin\pi\nu}\cos(\pi\nu - |\Psi_i - \Psi_j|)$$

- Principles of Orbit Feedback and Noise locator

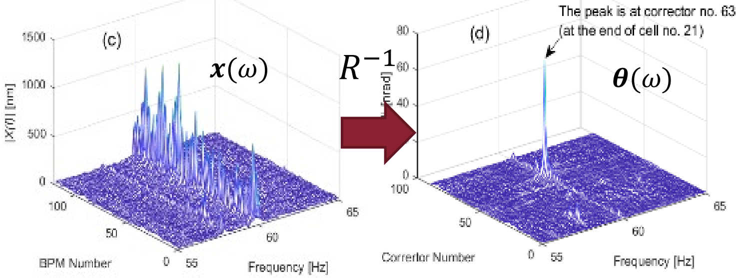
$$\boldsymbol{\theta} = R^{-1}\boldsymbol{x}$$



Noise propagation to orbit motion



Noise propagation to frequency domain



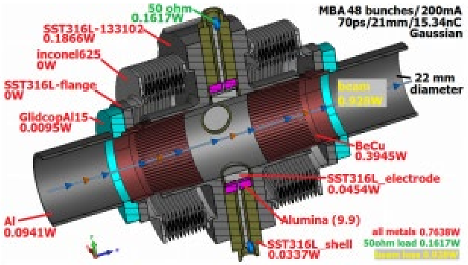
Means to reach high beam stability

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

RF Beam Position Monitors evolution

1980s	Analog signal	100 µm (single channel process -> 4-button multiplexed processor) Seconds to get orbit
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, X/Y/S (NSLS-II) <0.1 (long term)/0.1/1 µm (TPS)/ 5 µm

APSU RF BPM button and Libera Brilliance+ electronics



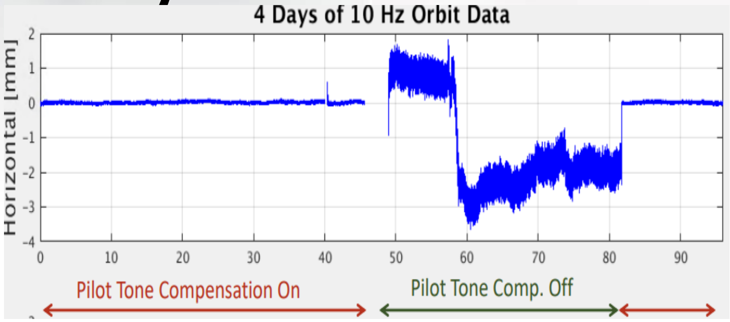
- Tremendous progress on BPM function and resolution improvement
- BPM signals evolve from analog to fast digital
- BPM resolution improves ~one order per decade, 100 µm to 100 nm (follow beam emittance trend), in ~Hz to ~10 kHz fast data to TBT 100s kHz
- Electronics development (AFE and DFE) to improve BPM resolution, stability, data process speed and size

- Design/improvement of BPMs from in-house development (SIRUIS, NSLS-II…) and commercial products (Bergoz, Instrumentation Technologies) in parallel

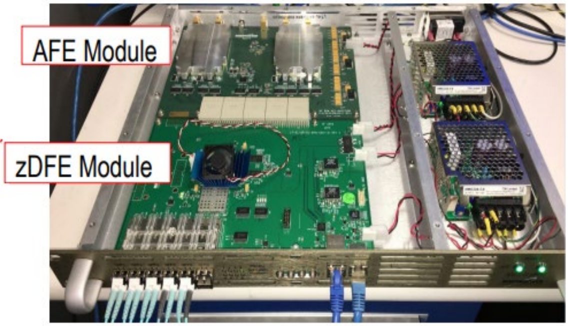
* Refer G. Rehm’s talk: Review of BPM Drift Compensation Schemes, Monday

Efforts to improve BPMs stability

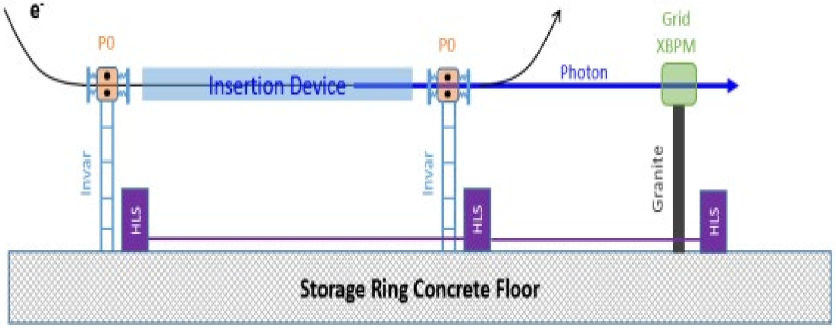
- BPMs stability limit feedback performance: must be better than orbit stability requirements
- BPM electronics improvements
  - High stable temp. control racks: +/- 0.1 ^{o}C (1-3 µm/ ^{o}C)
  - Pilot tone controller (PTC) for BPM electronics self-calibration (ALS)
  - RF switching: <50 nm stability (Libera B+, Sirius)
  - New electronics: zBPM in NSLS-II
- Mechanical motion:
  - High stability BPM support to isolate ground motion: Invar, Granite
  - Mechanical motion monitoring: Hydrostatic level



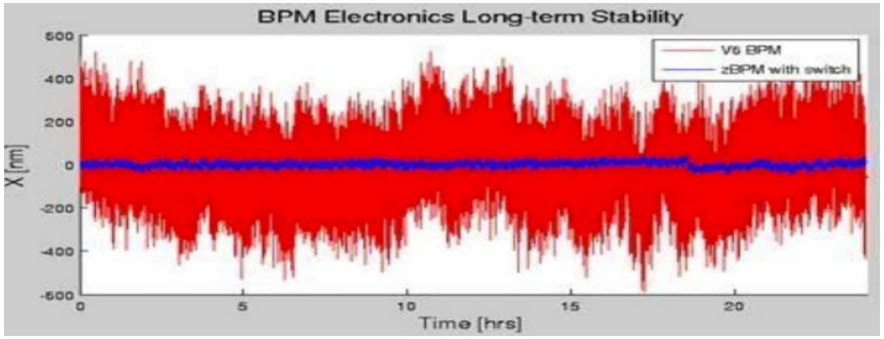
ALS: 0.2 µm long term stability with PTC



NSLS-II: zBPM new electronics



APSU: Invar and granite support on BPMs



BPM electronics long term stability: 130 nm→ 10 nm (BPM VS zBPM)

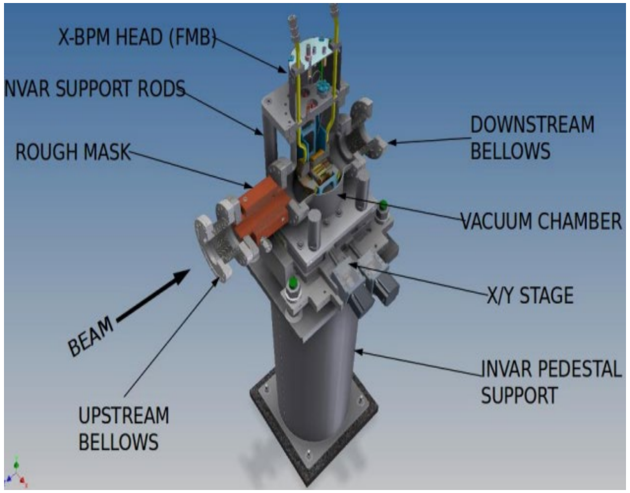
http://accelconf.web.cern.ch/ibic2020/talks/frao03_talk.pdf

https://indico.cern.ch/event/743699/contributions/3072640/attachments/1750517/2836233/ARIES_Workshop_NSLS-II__2018-2_Padrazo.pdf

https://indico.cern.ch/event/743699/contributions/3072640/attachments/1750517/2836233/ARIES_Workshop_NSLS-II__2018-2_Padrazo.pdf

Photon BPM

- Monitor photon beam stability, located at the front end or beamline (10s-100 m from source)
- Sensitive to beam angle stability: a factor of 10 times higher than RF BPMs
  - Most sensitive knobs to control photon beam position at beamlines
- Electronics: similar as RF BPMs, easy to accommodate into e-beam feedback
- ~0.2 µm long term stability
- Used for hard x-rays, position-photon energy dependence. Difficult for soft-x-ray (R&D) or VUV



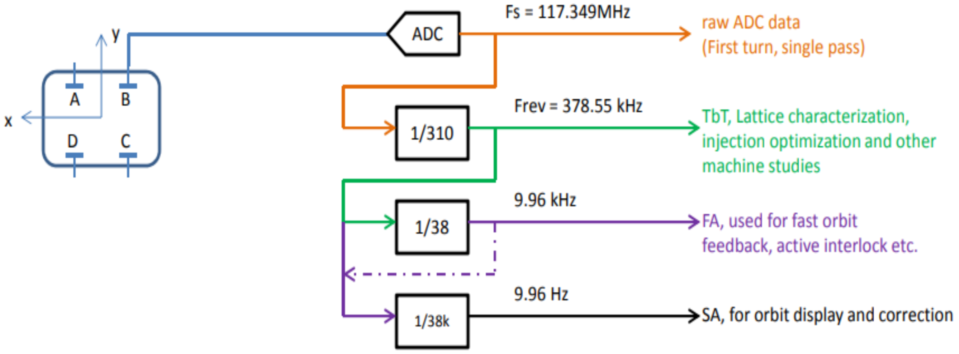
NSLS-II blades photon BPM

APSU Grid photon BPM

BPMs data for stability monitor

- BPM 10 Hz data x, y, intensity: long term beam orbit drift (secs to days), low frequency spectrum (<10 Hz), precise beam lifetime measurement
- BPM 10 kHz data x, y: short term beam stability (ms to secs), noise locator, fast feedback, high frequency spectrum (Hz to kHz), daily track machine performance
- BPM TBT data: beam instability, beam dynamics, injection optimization, collective effect study, beam local lost, feedback etc.

BPM output data



Fs = 117.349MHz

raw ADC data (First turn, single pass)

Frev = 378.55 kHz

TbT, Lattice characterization, injection optimization and other machine studies

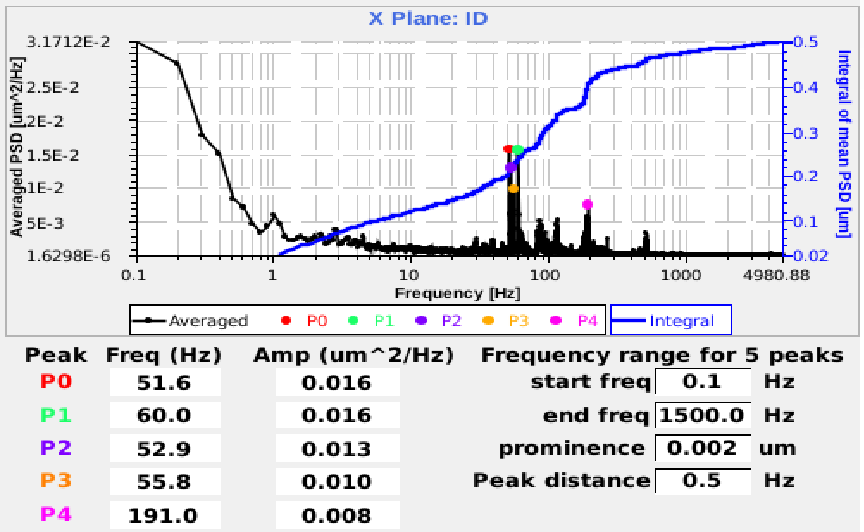
9.96 kHz

FA, used for fast orbit feedback, active interlock etc.

9.96 Hz

SA, for orbit display and correction

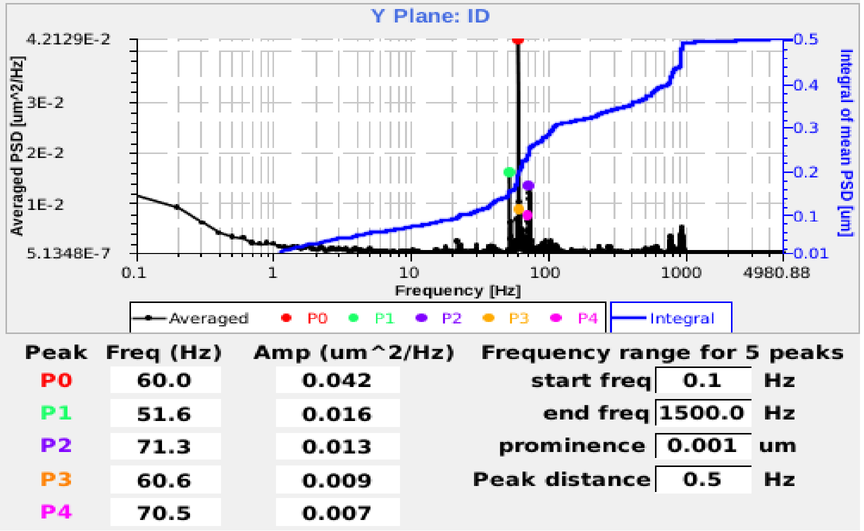
NSLS-II live beam motion spectrum



Peak	Freq (Hz)	Amp (um^2/Hz)
P0	51.6	0.016
P1	60.0	0.016
P2	52.9	0.013
P3	55.8	0.010
P4	191.0	0.008

Frequency range for 5 peaks

start freq	0.1	Hz
end freq	1500.0	Hz
prominence	0.002	um
Peak distance	0.5	Hz



Peak	Freq (Hz)	Amp (um^2/Hz)
P0	60.0	0.042
P1	51.6	0.016
P2	71.3	0.013
P3	60.6	0.009
P4	70.5	0.007

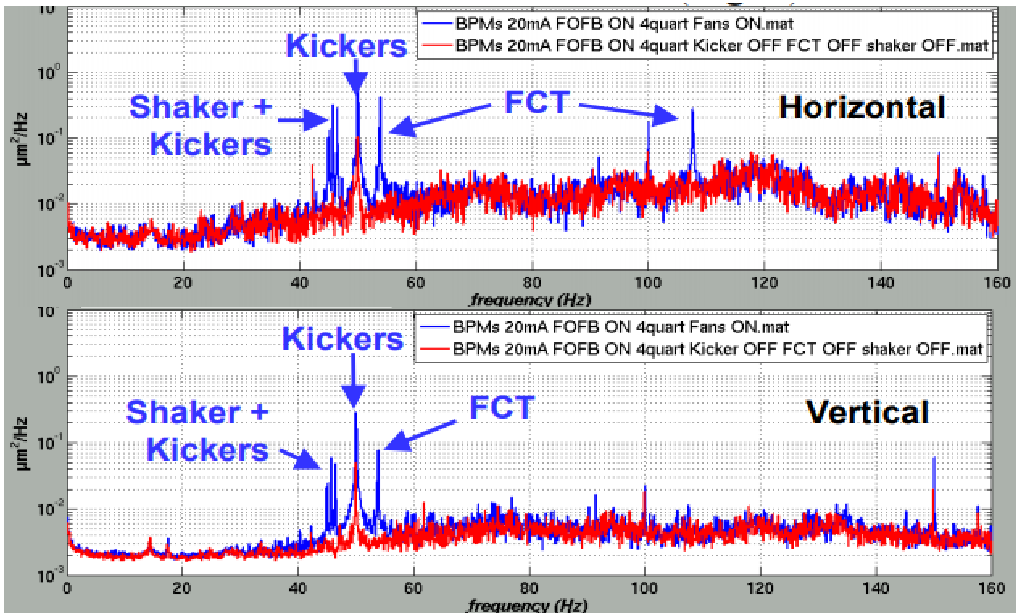
Frequency range for 5 peaks

start freq	0.1	Hz
end freq	1500.0	Hz
prominence	0.001	um
Peak distance	0.5	Hz

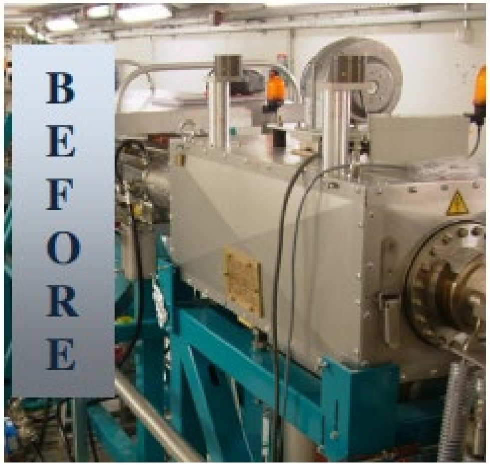
BPM data: improve beam stability from sources

- 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



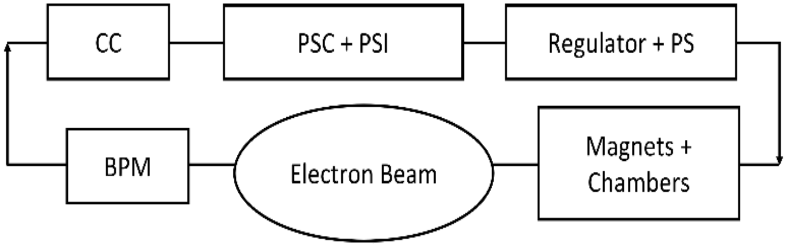
https://accelconf.web.cern.ch/DIPAC2011/papers/tupd78.pdf

Means to reach high beam stability

- Sources perturbing beam stability
- Diagnostics monitoring 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)
  - 30*[6-10] BPMs: 10 kHz sampling
  - 30*3 FC: 10 kHz sampling
  - Fast FOFB correction cycle for large bandwidth
  - FPGA based parallel process Cell Controller and SDI link:
    - High-speed calculation and fast data delivery
    - Receive local BPM data
    - Transfer/receive BPM data in other cells
    - Carry FOFB calculation
    - Transfer PSs setpoints to PSC



CC

PSC + PSI

Regulator + PS

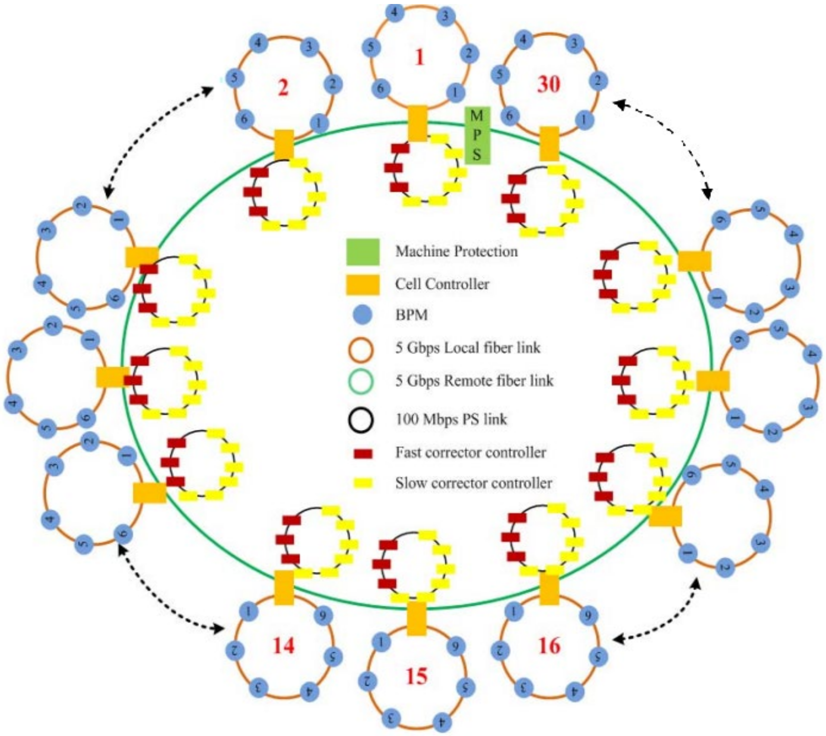
BPM

Electron Beam

Magnets + Chambers

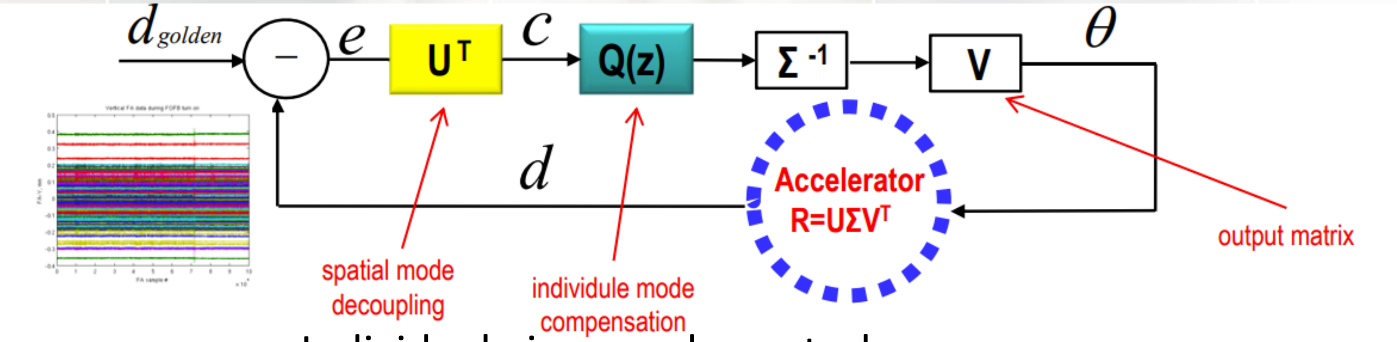
Diagram of FOFB system

NSLS-II FOFB topology



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

Feedbacks: NSLS-II Fast Orbit Feedback



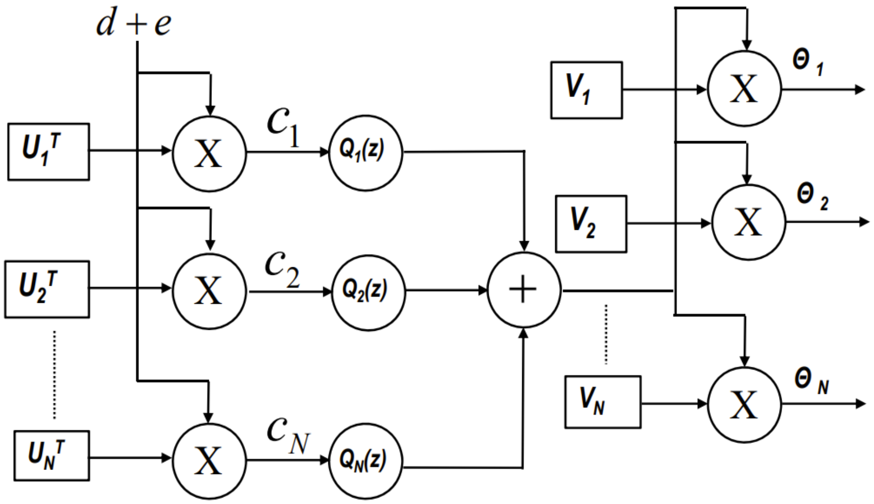
Individual eigenmode control

- Individual eigenmode compensation
  - Control each eigenmode with a different controller with different compensation in the frequency domain

$$\theta = V\Sigma^{-1}U^T x$$

$$\theta_{act} = Q(z)\theta$$

- $Q(z)$: control individual mode compensation and change gain
- Gain and bandwidth: represent FOFB performance to suppress motion→ high gain, large bandwidth



NSLS-II Fast Orbit Feedback with Individual Eigenmode Compensation (cern.ch)

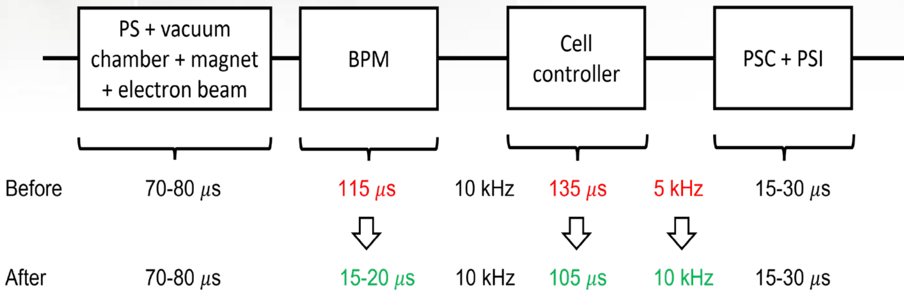
Feedbacks: NSLS-II Fast Orbit Feedback (CONT.)

- Efforts to improve FOFB gain and bandwidth
  - Reduced BPMs delay by 100 µs
  - Increased cell controllers update rate to 10 kHz
  - FOFB loop total latency: 220 µs
- 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

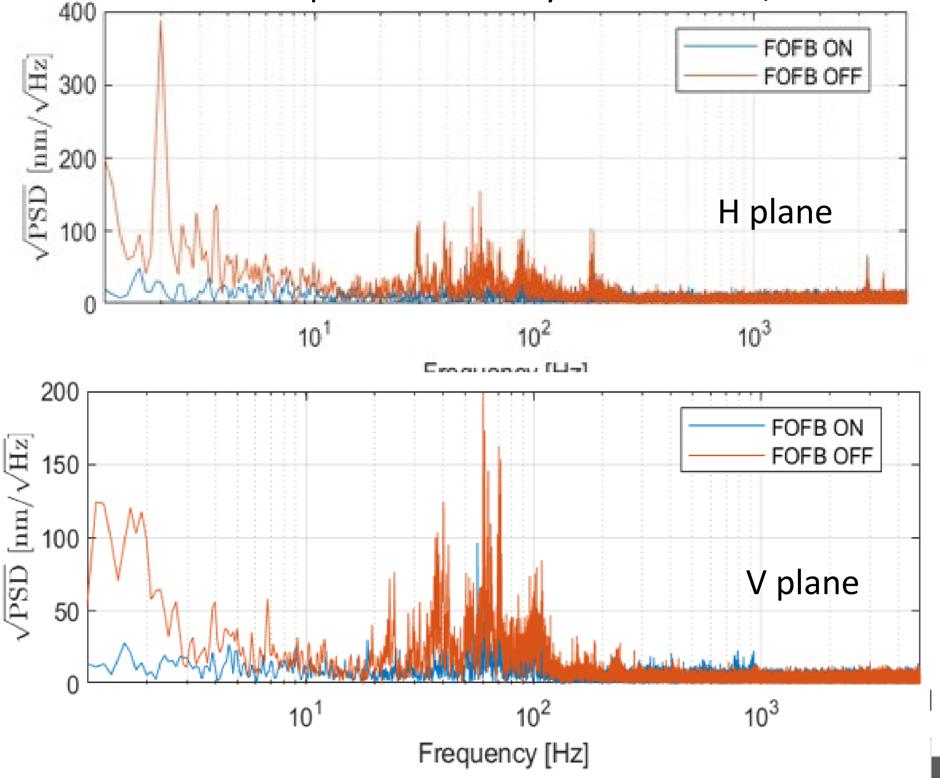
Sukho Kongtawong, Recent improvements in beam orbit feedback at NSLS-II, NIMA 976 (2020) 164250

FOFB stage-to-stage latency and improvements



	PS + vacuum chamber + magnet + electron beam	BPM		Cell controller		PSC + PSI
Before	70-80 µs	115 µs	10 kHz	135 µs	5 kHz	15-30 µs
After	70-80 µs	15-20 µs	10 kHz	105 µs	10 kHz	15-30 µs

ID source position stability feedback ON/OFF



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):

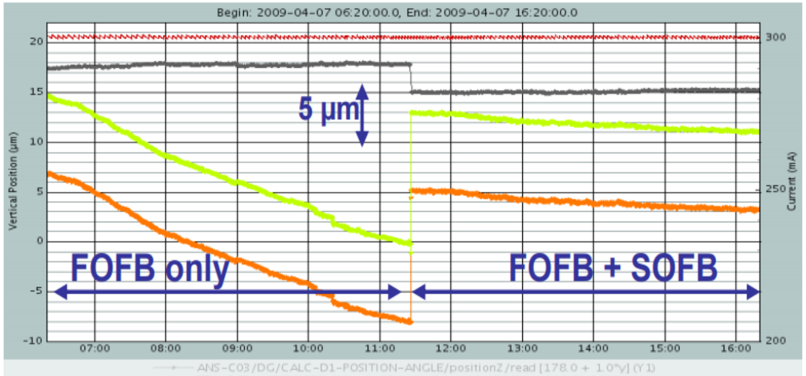
$$\Delta I2_{SOFB} = R^{-1}_{SOFB} * R_{FOFB} * \Delta I_{FOFB}$$

- 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

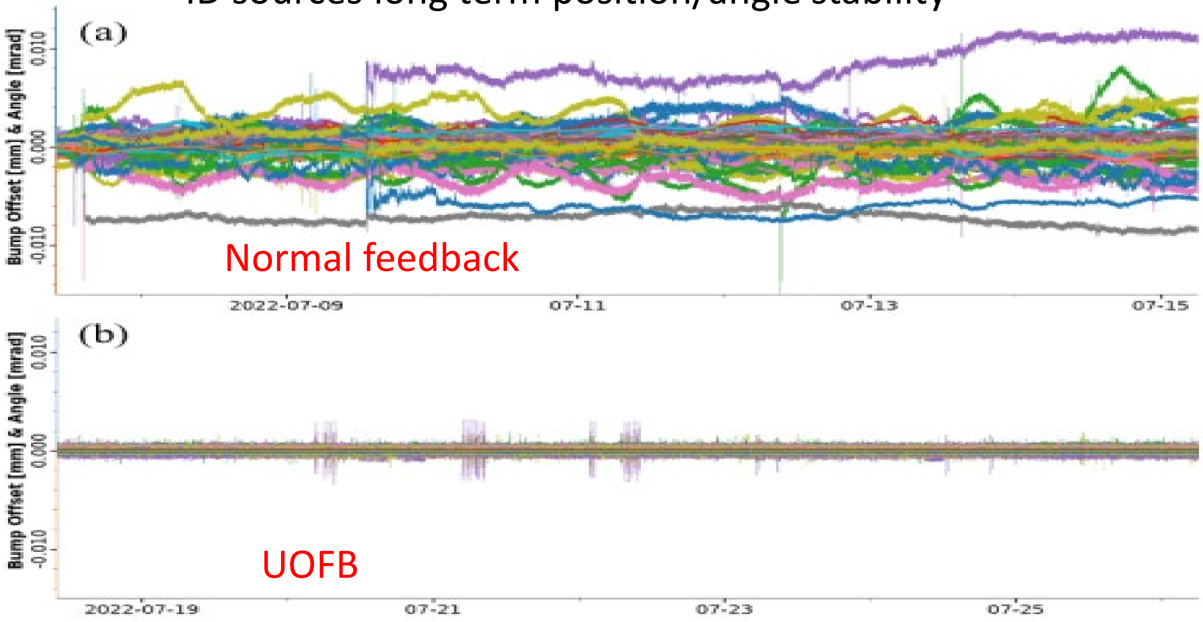


Vertical beam position at one SOLEIL bending magnet source point (BPMs: grey and X-BPMs: orange and green)

**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 X BPMs 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

Normal feedback

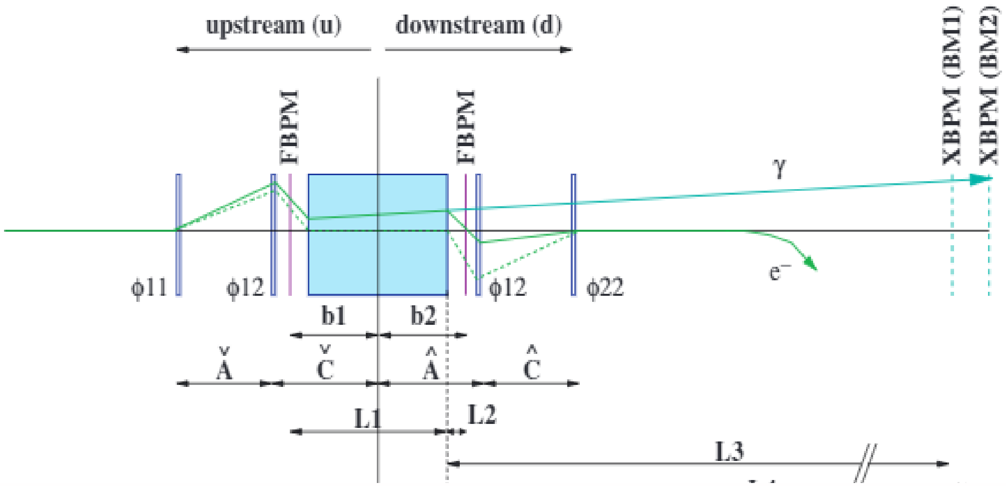
UOFB

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

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

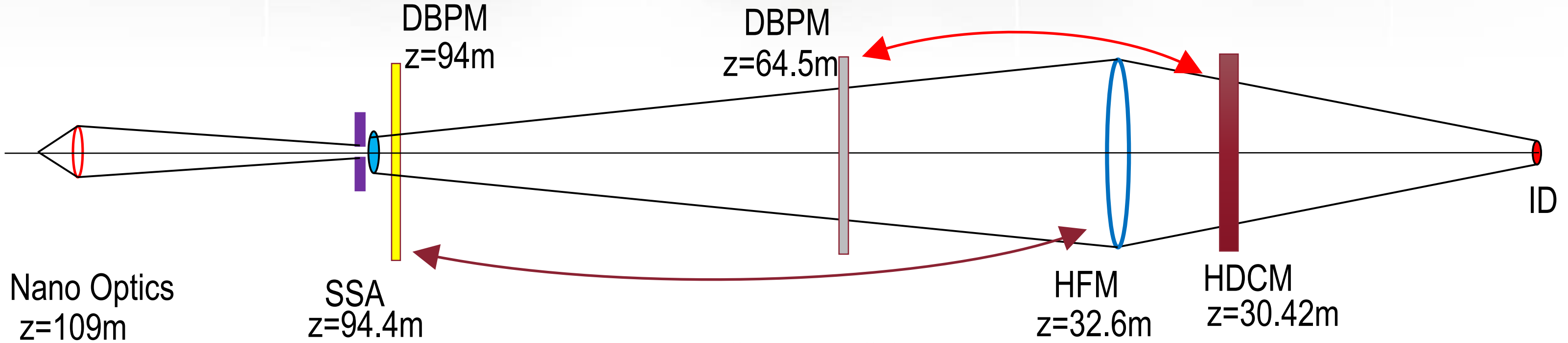
ID local compensation with electron BPM and photon BPM



SLS: J. Chrin

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

Feedbacks: Active beamline components feedback



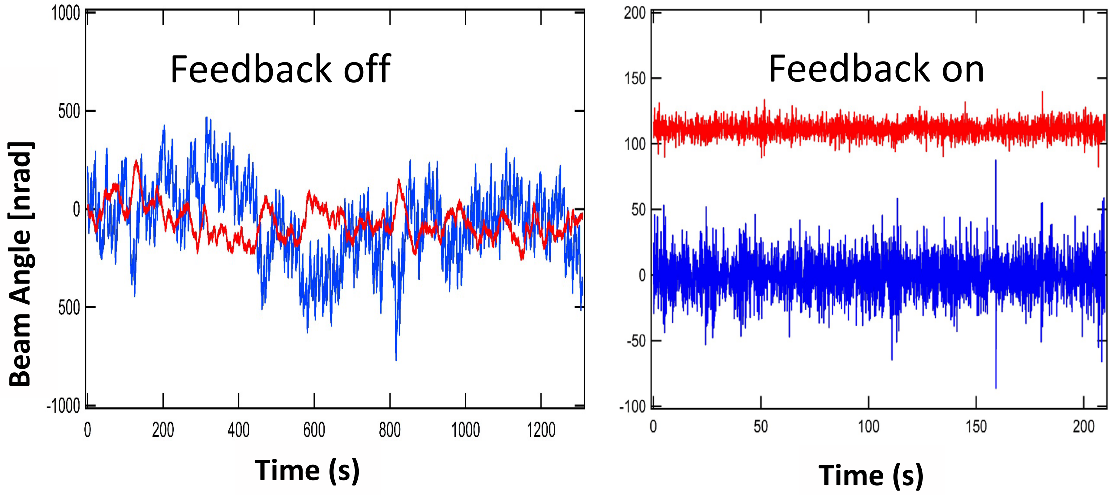
Fast mono beam “angle” feedback using mono pitch and roll

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



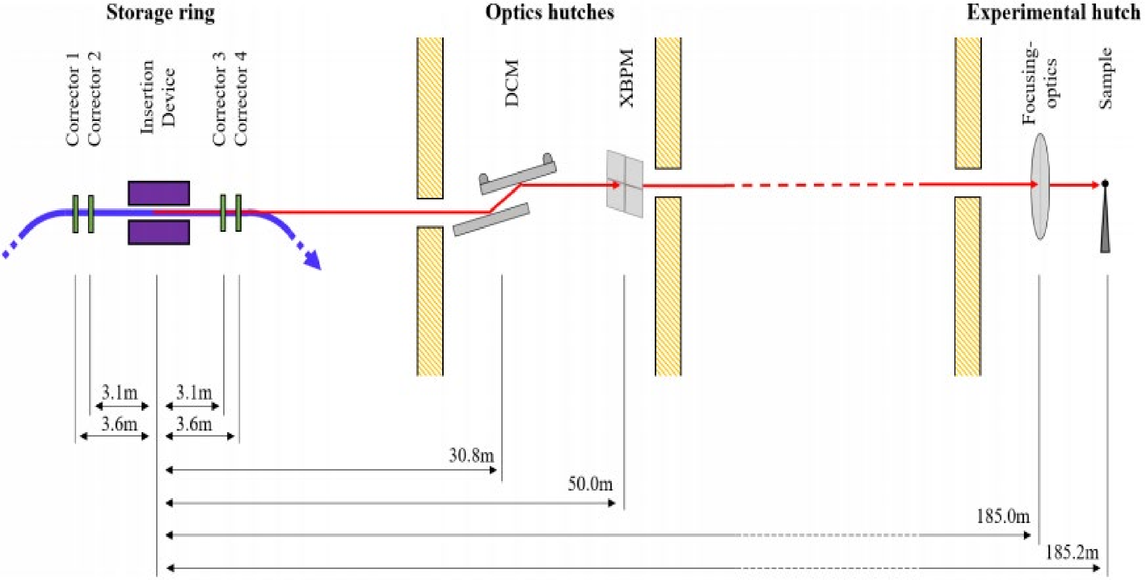
**Petr Ilinski , Active feedback implementation for beamline photon beam stability, 7th DLSR 2021*

Diamond: kHz feedback using beamline xBPM

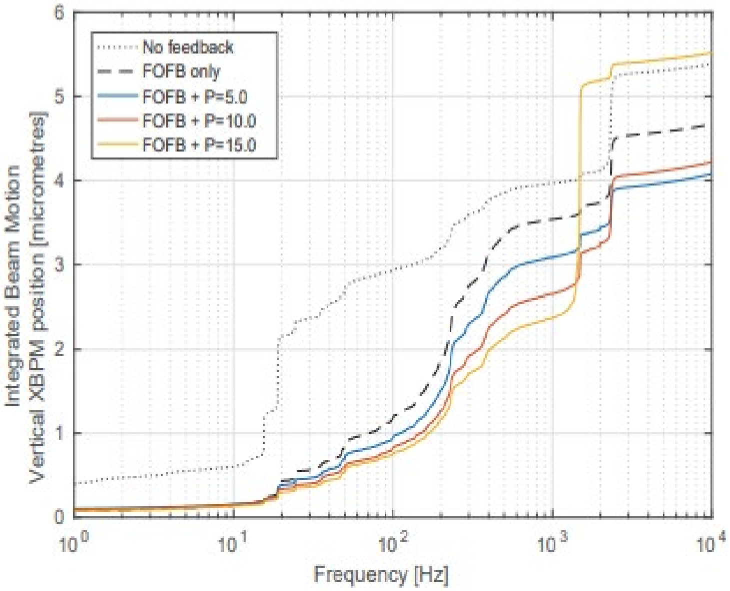
- A new feedback system: control electron beam to keep beam stability at X-ray BPM, close to beamline sample point
- Correct photon beam motion from electron beam and beamline optics
- Using SR four fast correctors for transparent bump correction
- Maintain X-ray beam stability to <3% of a beam size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

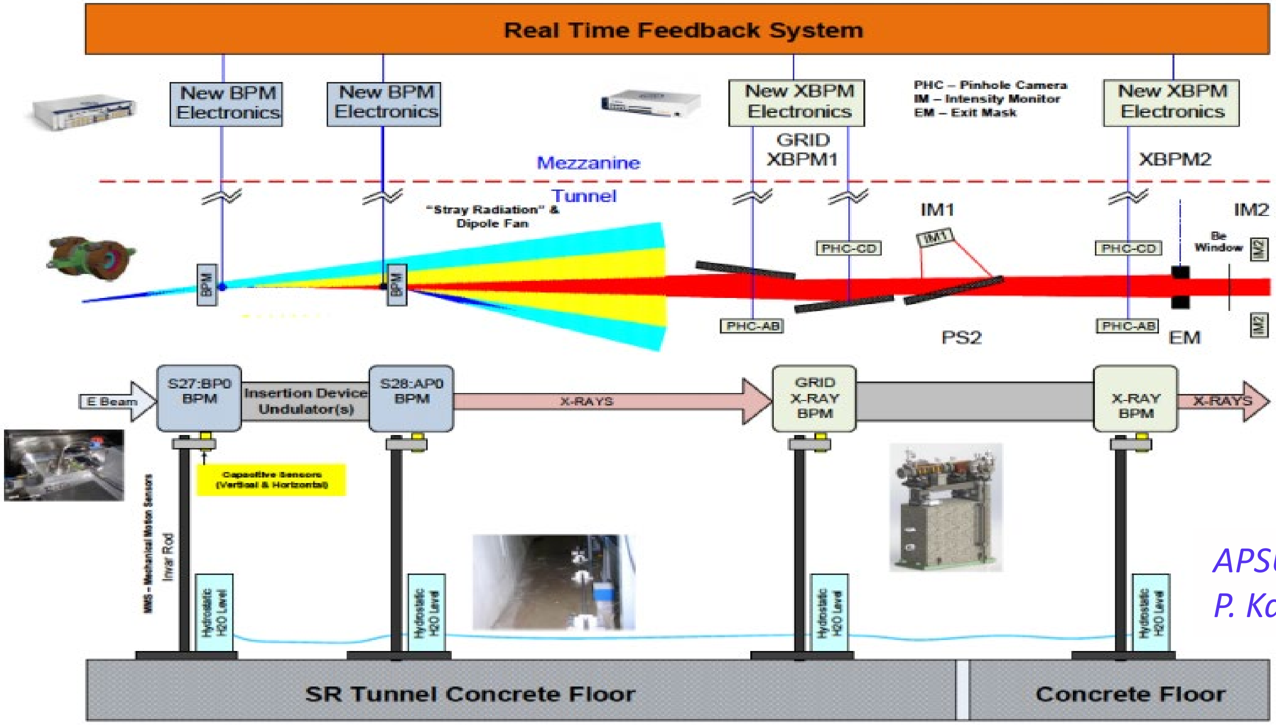
List of feedback systems in light sources

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+ Fast	10		2/5% w/o FOFB
NSLS-II	Slow+ Fast	10	400	
PETRA III	Slow+ Fast	10	200	
PLS	Fast	4	100	
SIRIUS	Fast	25	1000	
SLS	Fast	4	100	
SOLARIS	SOFB+ FOFB	2		
SOLEIL	Slow+ Fast	10	200	
SPEAR3	Fast	4	100	
SSRF	Slow+ Fast	10	100	
TPS	Fast	10	300	

*Fast feedback systems not in operation

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: $x_{rms\ ground}^2 = ATL$ → 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)



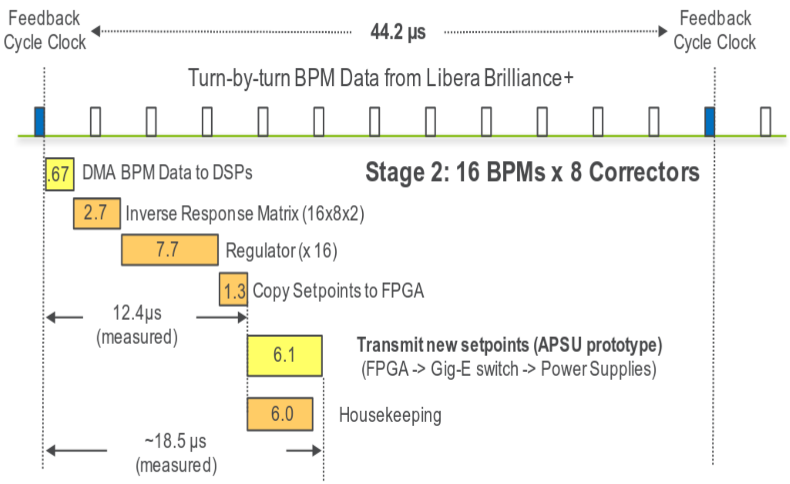
APSU: N. Sereno, J. Carwardine, P. Kallakuri , M. Borland

**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 sampling rate, 10 kHz bandwidth
  - Lower processing latency to 44.2 µs
- Unified feedback algorithm: combines fast and slow correctors without compromising spatial or dynamical performance
- Demonstrated APS-U fast feedback on APS with 1 kHz bandwidth

Feedback communication latencies



Feedback Cycle Clock

44.2 µs

Feedback Cycle Clock

Turn-by-turn BPM Data from Libera Brilliance+

Stage 2: 16 BPMs x 8 Correctors

.67 DMA BPM Data to DSPs

2.7 Inverse Response Matrix (16x8x2)

7.7 Regulator (x 16)

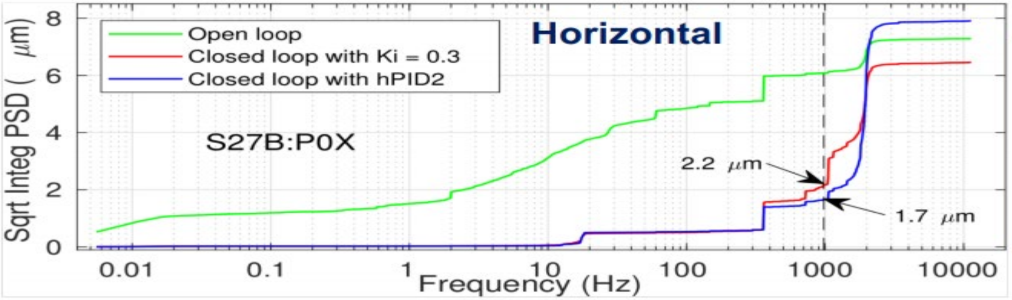
1.3 Copy Setpoints to FPGA

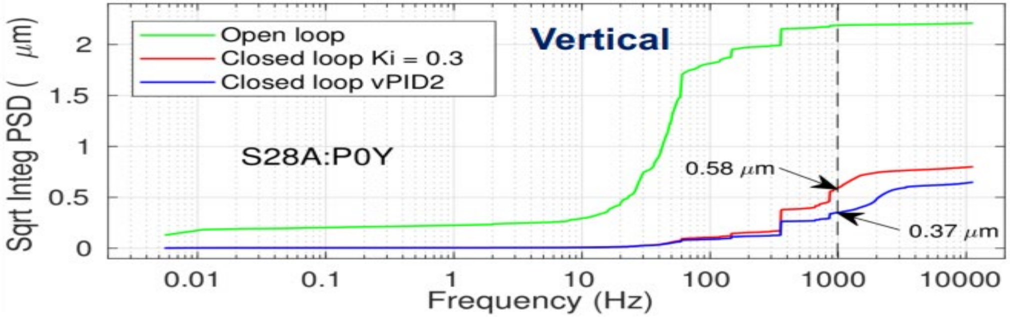
12.4µs (measured)

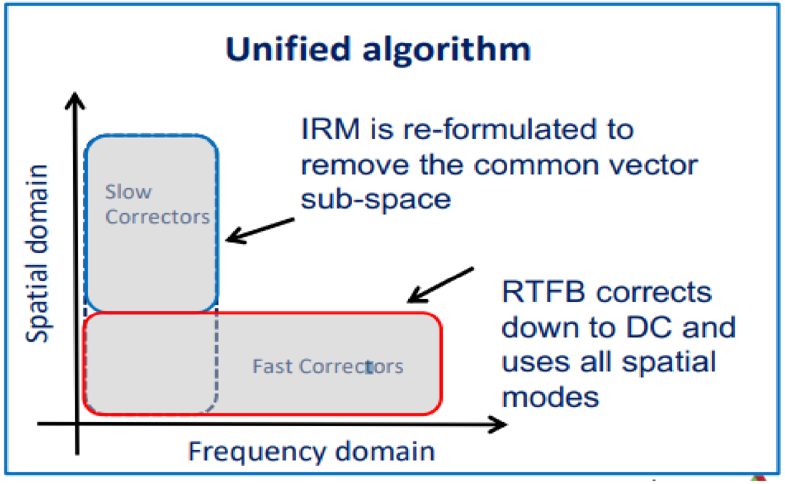
6.1 **Transmit new setpoints (APSU prototype)** (FPGA -> Gig-E switch -> Power Supplies)

6.0 Housekeeping

~18.5 µs (measured)







Unified algorithm

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

Summary and outlook

- New synchrotron light sources approach diffraction limit emittance, lower by two order magnitude with smaller beam size
- Tighter tolerance on beam spatial and time domain stability from 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: BPMs (speed and resolution), Power Supply (stability and controls)
  - Advances in Feedbacks (FOFB, photon feedback)
- Towards the future, unified feedback system is the trend to stabilize both electron and photon beam motion in a larger bandwidth

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- J. Carwardine, APS upgrade integrated Beam stability experiments using a double sector in the APS Storage Ring, IBIC 2018

Thanks for your attention!

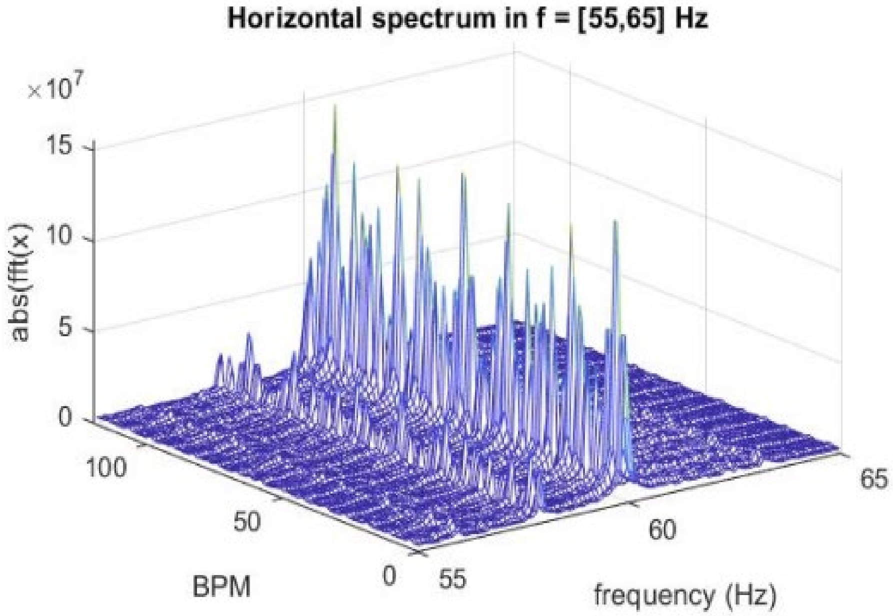
Contact: gwang@bnl.gov

Feedbacks: Noise locator

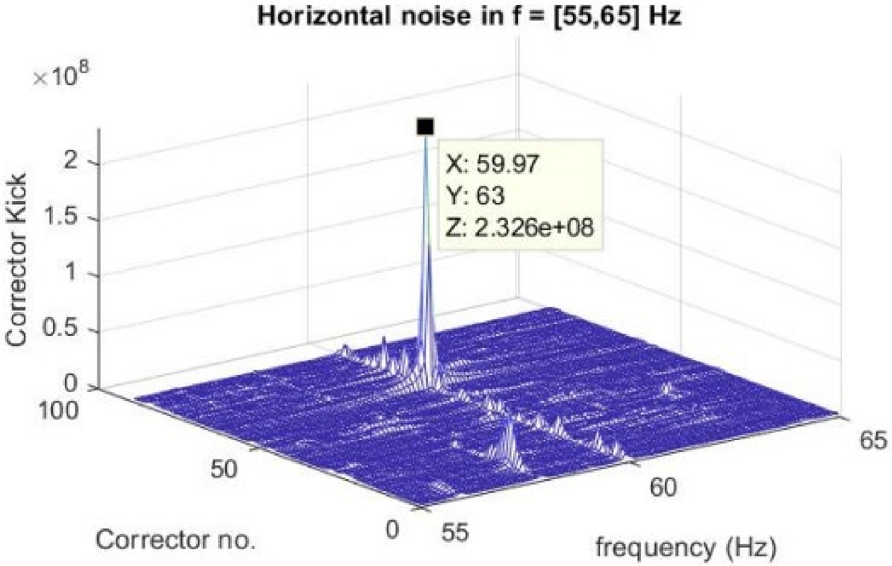
Pin-point the motion source's potential location

- 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