Investigation of characteristics and sources of beam orbit instabilities in modern light sources

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I.FAST Workshop 2022: Beam diagnostics and dynamics in ultra-low emittance rings
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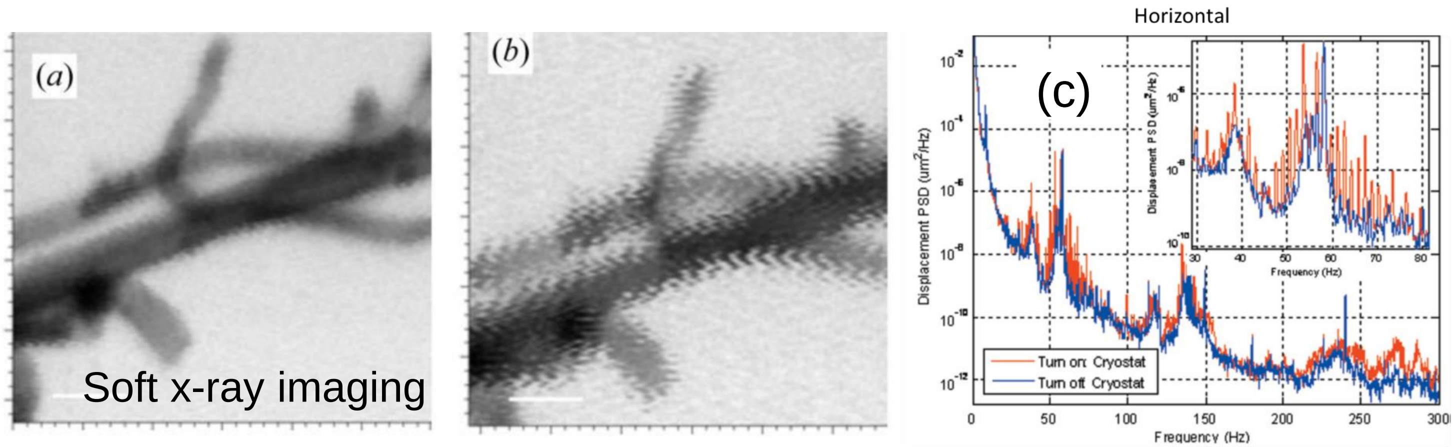
Outline

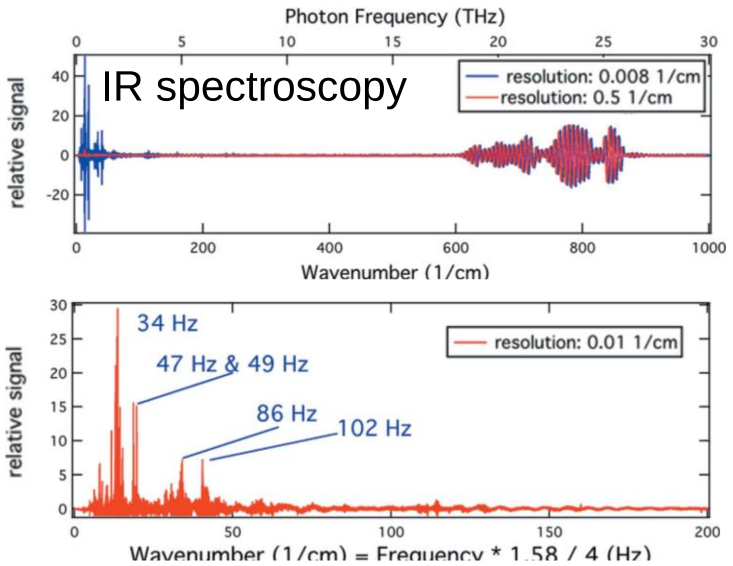
- Beam stability requirements in modern light sources
  - User community experience related to beam stability
- Diagnostics of instabilities – tools and analysis
- A primer: searching for sources and increasing beam stability at NSLS-II
  - Storage Ring
  - Beamlines

Beam stability requirements in modern light sources

- Beam instability becomes a crucial factor for an ultra-low emittance light source
  - Both in term of brightness and resolution of experiment
  - Affects the whole range from IR to Hard X-ray
- In this talk we focus on investigating sources of instability of beam orbit position and angle and on the method to suppress these source
  - Most facilities have a specification of orbit stability within 10% of beam size
- Examples
  - CLS – Vibration from a nearby cryostat affects the quality of the images
  - SLS – noise in the range of <100 Hz impacts the spectral of FTIR



Images from STXM beamline at Canadian Light Source (CLS) with cryostat system's pump (a) off and (b) on **(Li2010)**. (c) Vibration measurement.

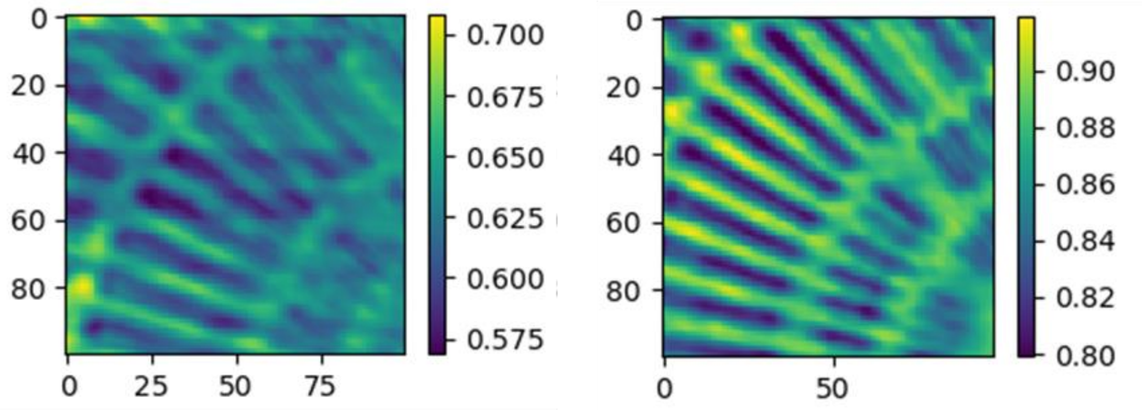


FTIR spectrum for an organic substance measured at the Swiss Light Source(SLS) **(Learch2011).**

Methods on increasing stability

- There are several methods to reduce the impact from beam instabilities
  - E.g., Electron Beam Feedback using correctors, or beamline X-ray feedback using optical elements
- After implementing feedbacks, there is still substantial level of noise in X-ray beams
- This motivates the need to characterize the noise and pinpoint its sources
  - So that we can suppress the noise from the sources directly

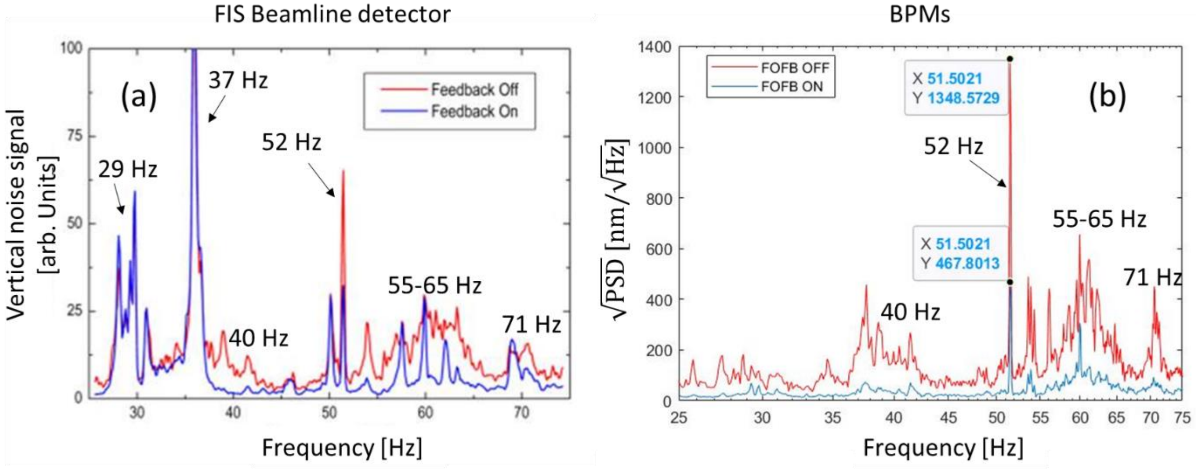
Increasing resolution with PLFB



Comparison of images from the Hard x-ray nanoprobe (HXN) beamline at NSLS-II with local optical feedback off (left) and feedback on (right) with the pixel size was 10x10 nm².

PLFB: Photon Local Feedback

Source of spectral peak is vibration of a DI Water pump



Spectra of (a) beam motion from photon detectors at the FIS beamline at NSLS-II, and (b) electron BPMs data around the neighbor of the beamline, when FOFB was off and on.

Tools and data analysis

Beam position monitor (BPM) is a common tool for investigating the beam stability

First, we introduce the language of beam stability

- Power spectral density (PSD) and its integration (int. PSD)

$$\mathrm{PSD}(f) = \frac{1}{T}|X(f)|^2,$$

where $X(f)$ is a Fourier transform of beam position $x(t)$

$$\mathrm{Int.\,PSD.} = \sum_{f_i}^{f_f} PSD(f)\,\Delta f$$

* Spectral ranges <1 Hz, 1-100 Hz, 100 Hz to few kHz

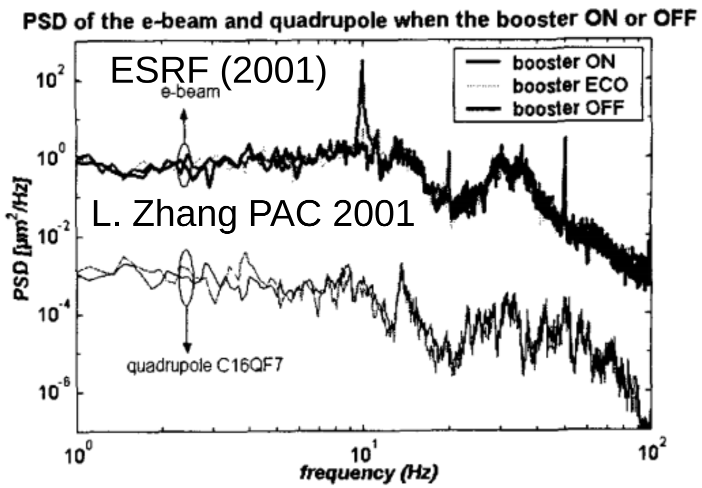
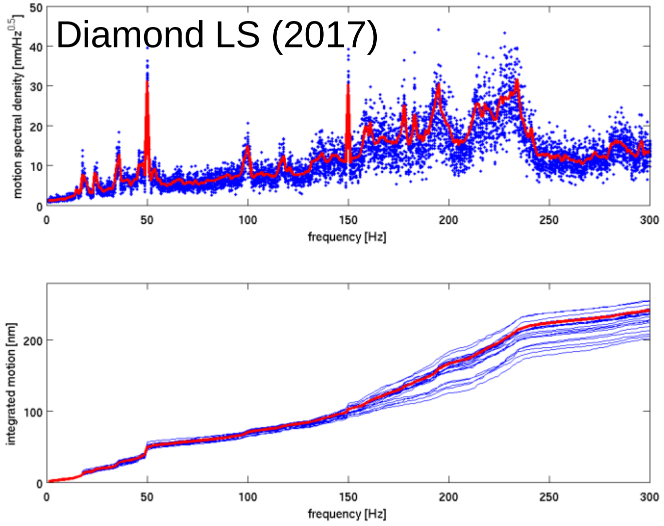
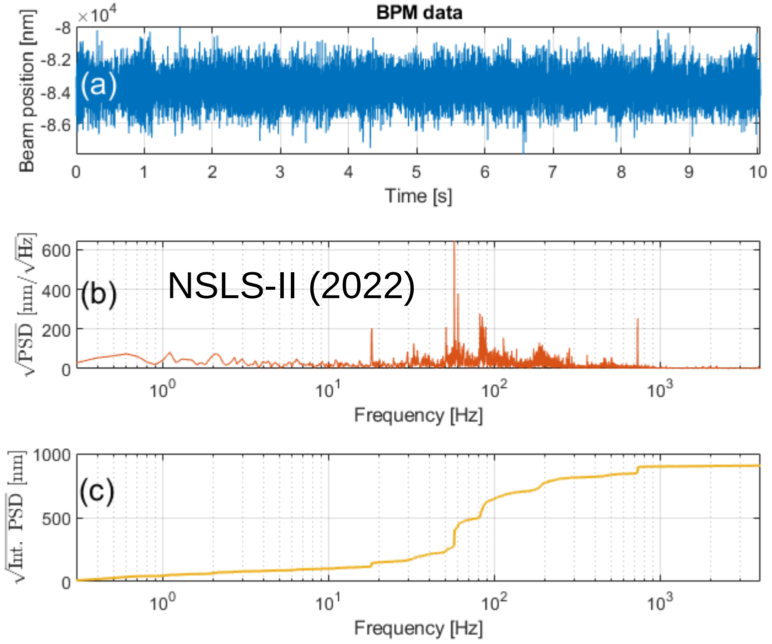


Figure 2: Displacement PSD of the e-beam and quadrupole C16QF7 when booster was ON/ECO/OFF. The three measurements were made at 17:10, 17:40, 16:40 on 29-March-2001, respectively.



Beam Stability at Diamond Light Source, G. Rehm, Aug 2017



Tools and data analysis

- Common method to analyze the location of noise is in using BPM data

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

where R is orbit response matrix, x is a vector of beam positions, and θ is a vector of angle kicks

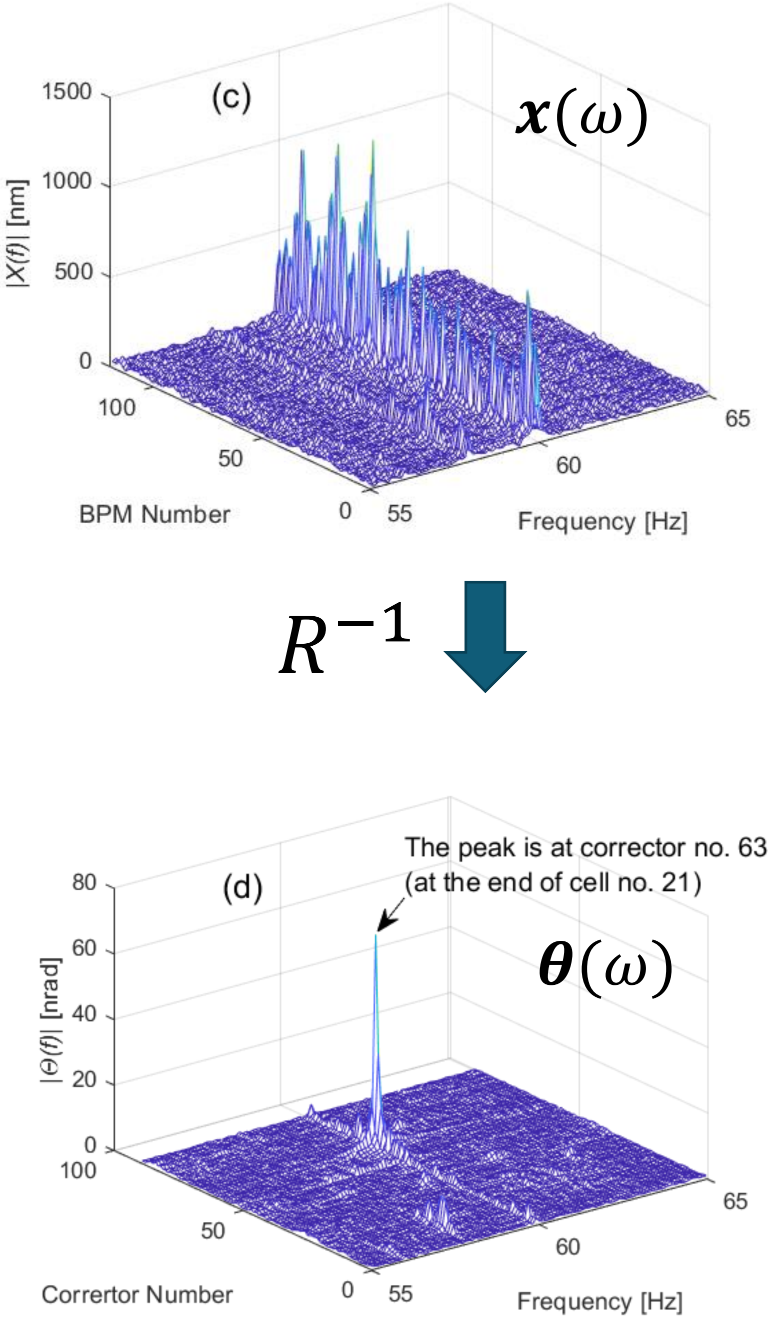
- SVD and regularization are commonly implemented, same as in beam orbit feedback

$$R = U\Sigma V^T, R^{-1} = VDU^T$$

with

$$D = \frac{\sigma_{ii}}{\sigma_{ii}^2 + \mu^2},$$

where σ_{ii} is the ith component of the diagonal matrix Σ



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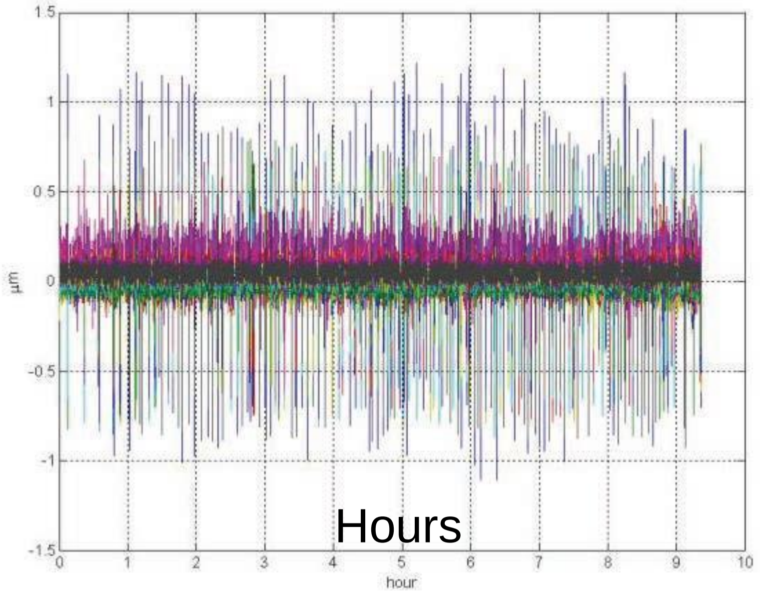
Analysis of Archive Data

- Archives record long-term beam motion
    - Long-term data records – years
    - Many types of processed data – Slow Acquisition (SA) beam position, RMS noise, pumps speed, etc.
    - Archive data is very useful for analysis of the low-frequency range – <10 Hz at NSLS-II
    - Investigation of beam slow drifts and trends



Achieved beam orbit stability at Shanghai Synchrotron Radiation Facility (SSRF) (J. Chen Syn. Rad. News 2019)

Occasionally appeared peaks indicated large RMS displacement

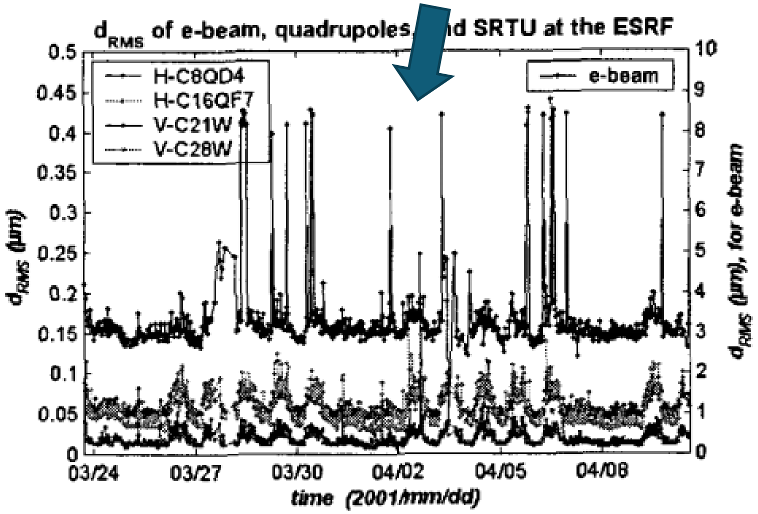
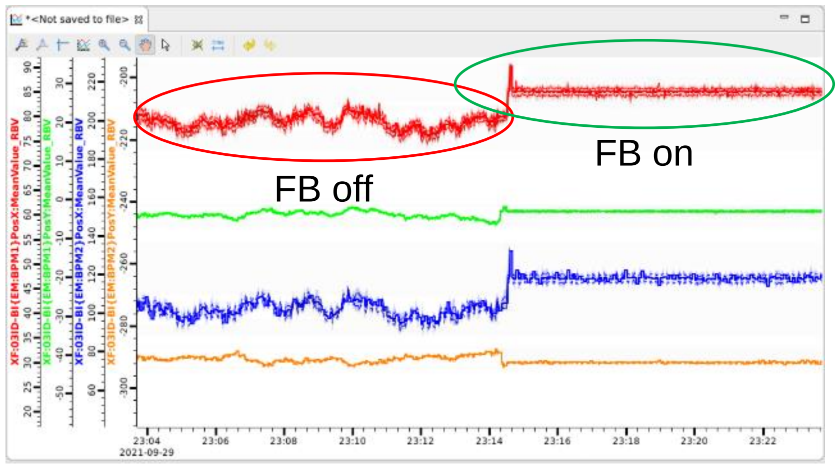


Figure 1: RMS displacement in the frequency range of 4-12 Hz of the e-beam, quadrupoles and SRTU wall versus time.

(L. Zhang, PAC2001)



X-ray beam position from HXN beamline at NSLS-II when local feedback off/on

Pathways to future light sources

- Future light sources require investigating of instability at early stage, i.e. during machine design
  - Small beams and very tight requirements for beam stability
- Examples
  - Calculation of orbit distortion due to girder resonances – affects orbit distortion
  - Calculate amplification factor (AF) from the ground to the beam
  - Beam orbit motion caused by ground motion
- Orbit feedback upgrade
  - Increase bandwidth and gain of FOFB system
    - APS-U – 22 kHz update rate, >700 Hz bandwidth
    - Increase PS bandwidth

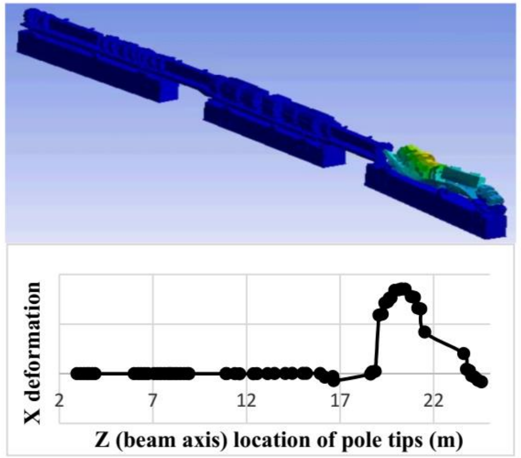
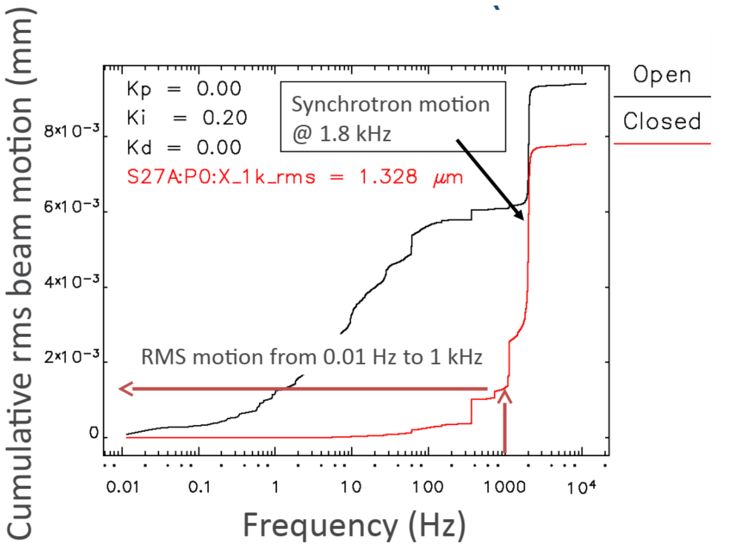
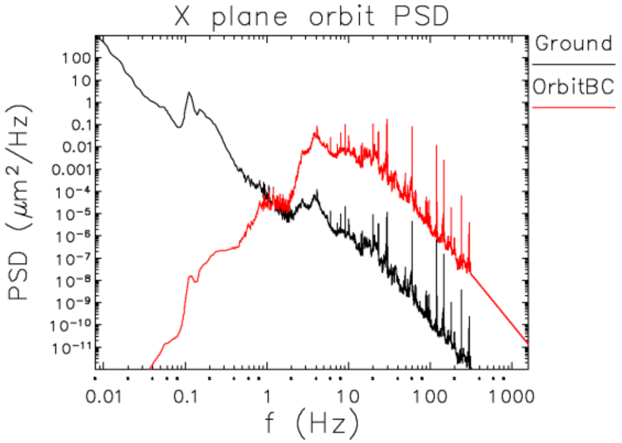


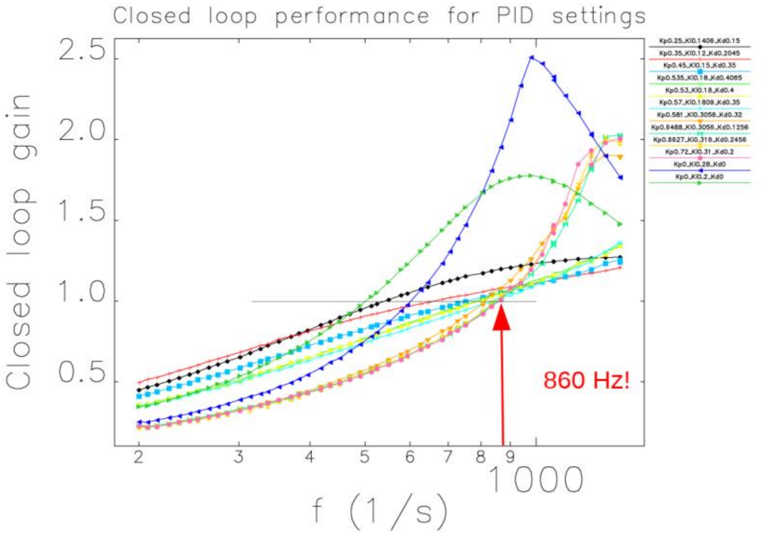
Figure 2: Mode shape illustration and plotted X-direction deformation for mode #10 – a mode which causes a relatively large orbit distortion.

J. Nudell, MEDSI2018





V. Sajaev, BES workshop, 2018



N. Sereno, IPAC2018 (TUZGDB3)

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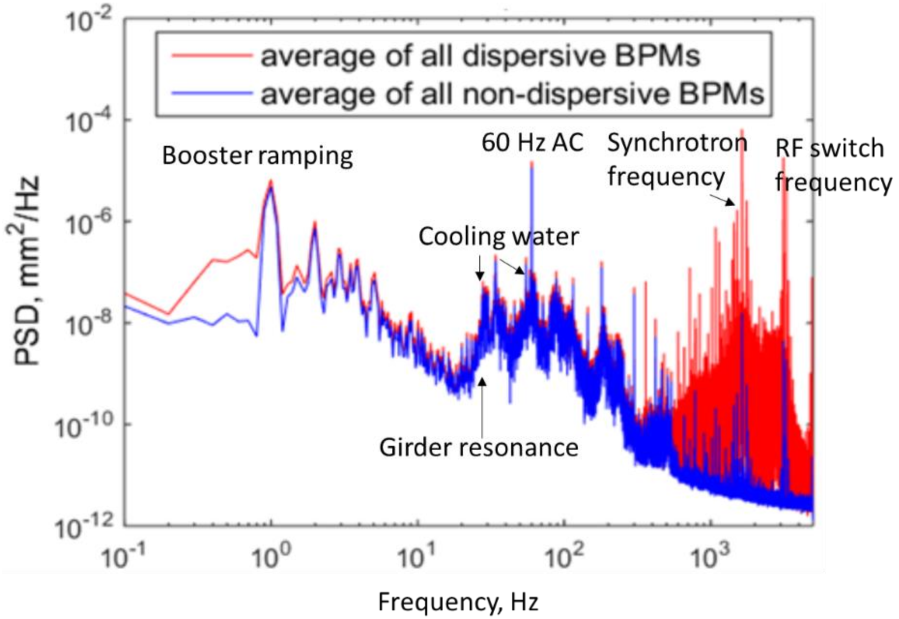
Investigation of beam orbit instability at NSLS-II

- NSLS-II is a third-generation synchrotron light source
  - Located at Brookhaven National Laboratory, Upton, NY, USA
  - Circumference of 792 m (storage ring)
  - 3 GeV, 500 mA beam current with 1 nm-rad horizontal and 8 pm-rad vertical emittance (design)
  - Beam sizes at source points are ~100 um/3 um

- We formed a task force to investigate beam instabilities of the electron/photon beam
  - Characterize the spectra of noise
  - Identify the sources
  - Apply suitable mitigation techniques



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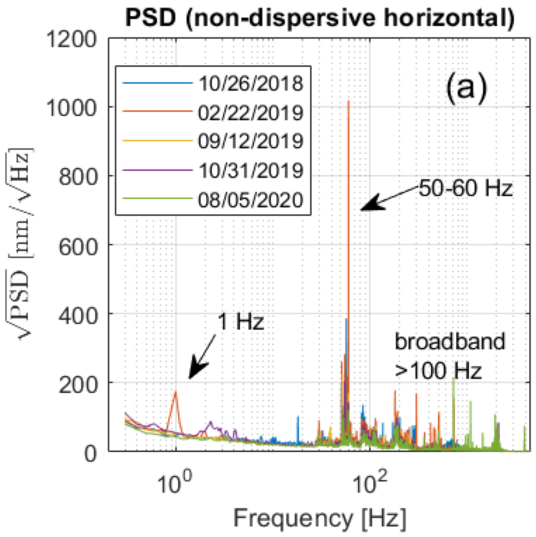
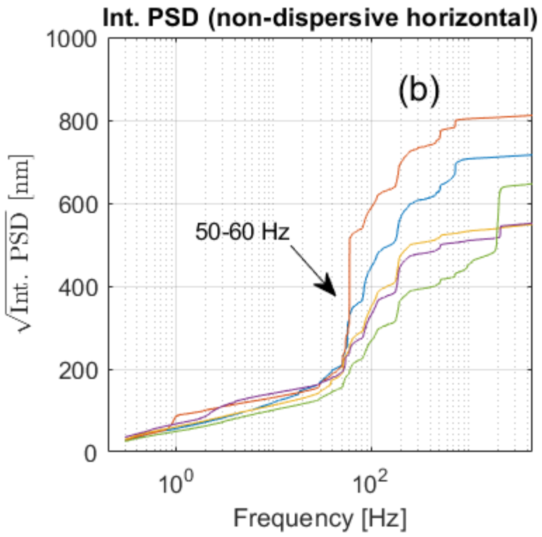
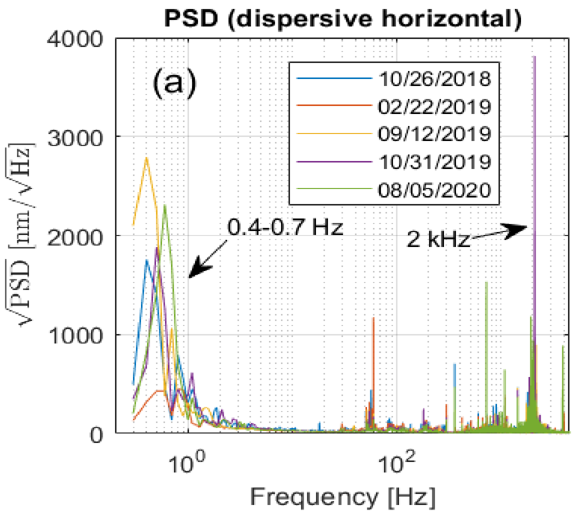
Noise Characteristics

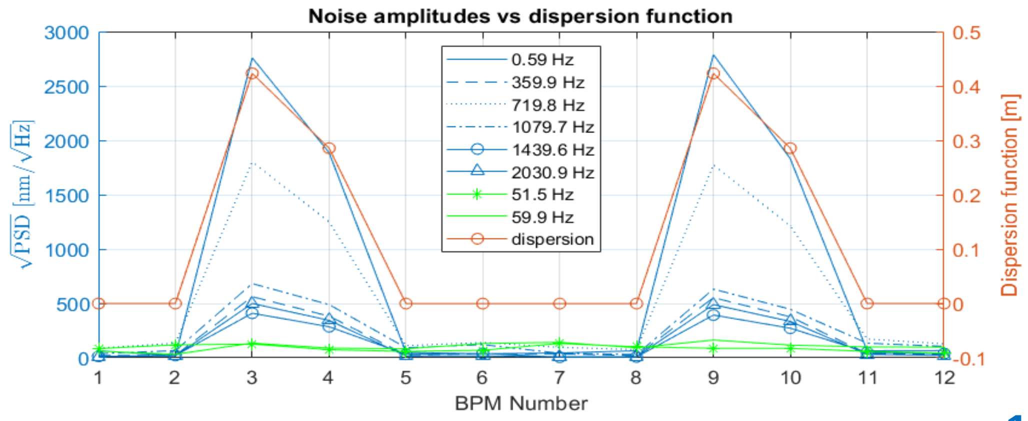
- Our focus was on investigating the source of transverse motion
- We found that the dominant spectral noise is in the range of 50-60 Hz
  - Likely to be mechanical vibrations or electronics
- Also, injection cycle generates noise in 1 Hz range





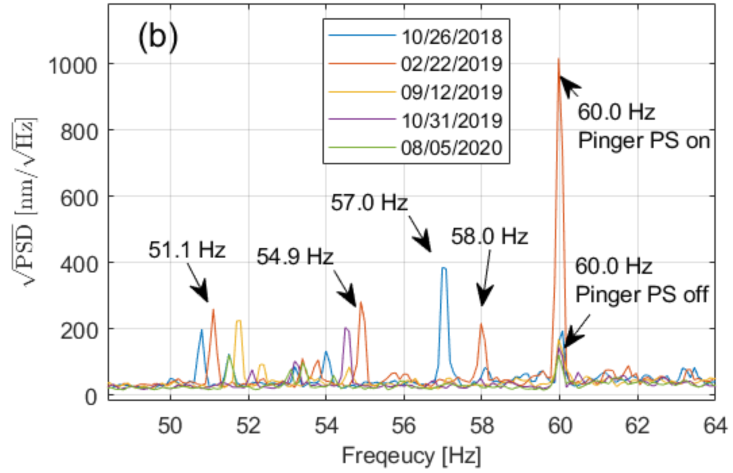
- Dispersive BPMs showed additional peaks
  - 0.4-0.7, 360, 720, 1080, 1440 Hz, and 2 kHz.
  - The patterns were the same as the dispersion function, implies energy instability e.g., RF system



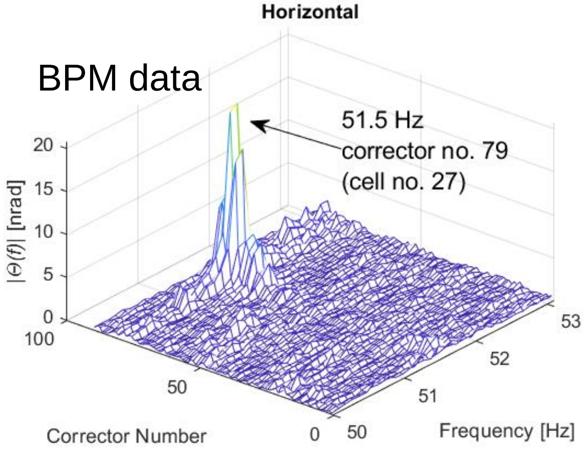


Noise sources

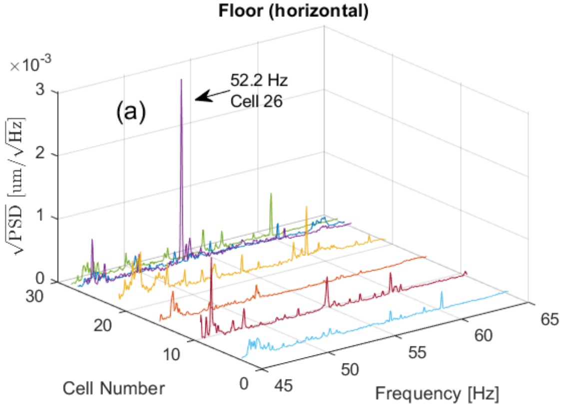
- Investigate the highest peaks
  - Started from 52 Hz
  - Noise locator from BPM data identified the source being in cell 26-27
- Measured vibration around the ring
  - Geophones or accelerometers
  - Found 52 Hz in cell 26 – same as in the BPM data
- Identify which utility system caused 52 Hz noise
  - Turn on/off each system during a shutdown
  - Found that DI water pumps were the sources of the 52 Hz noise

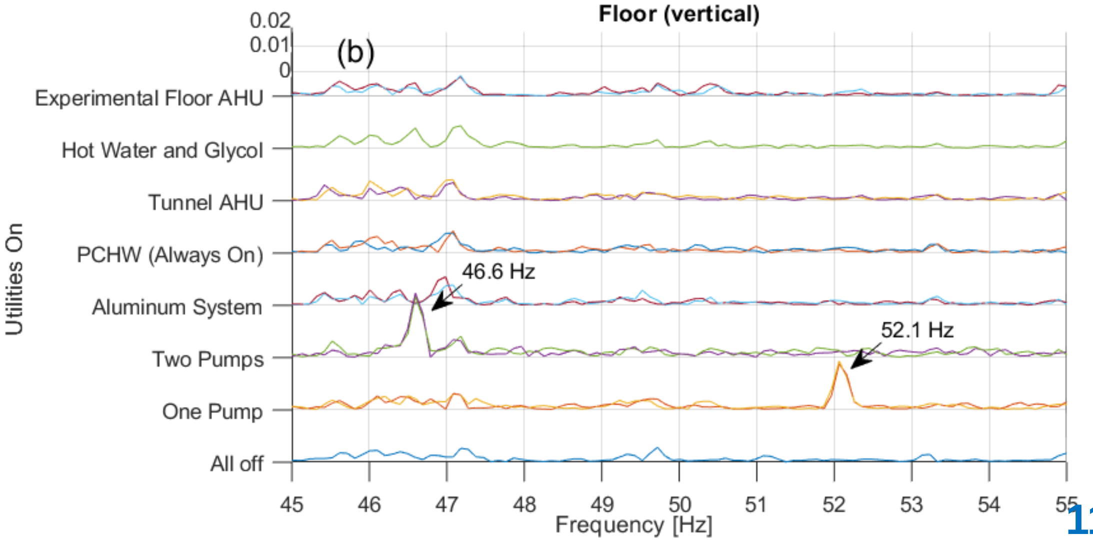


BPM data



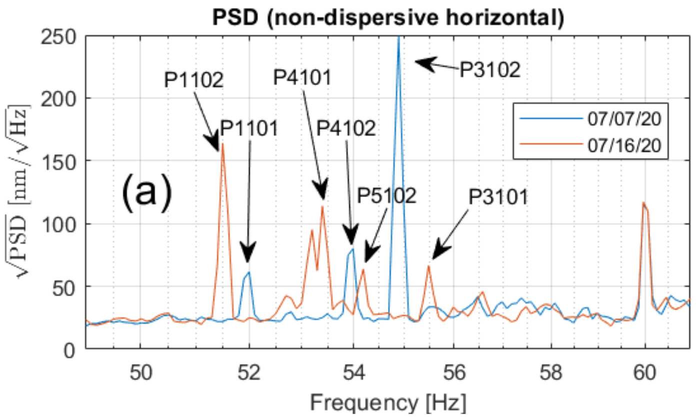
Vibration measurement

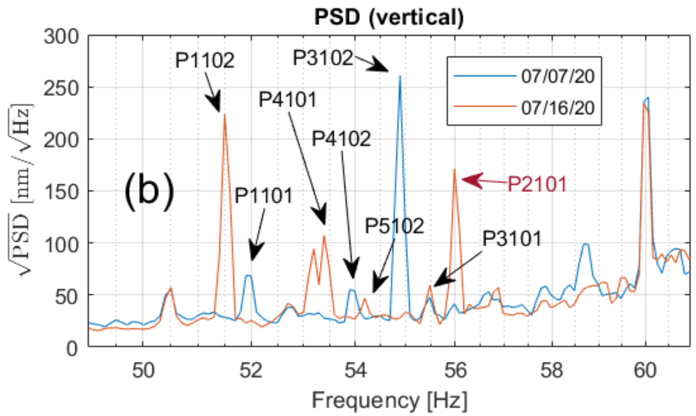


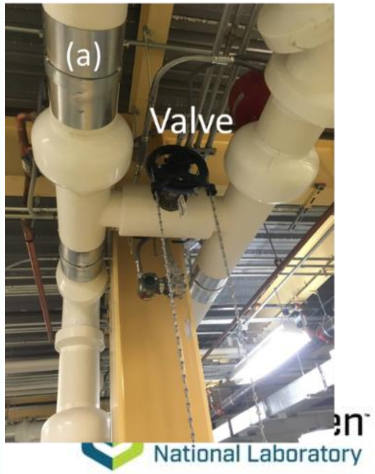


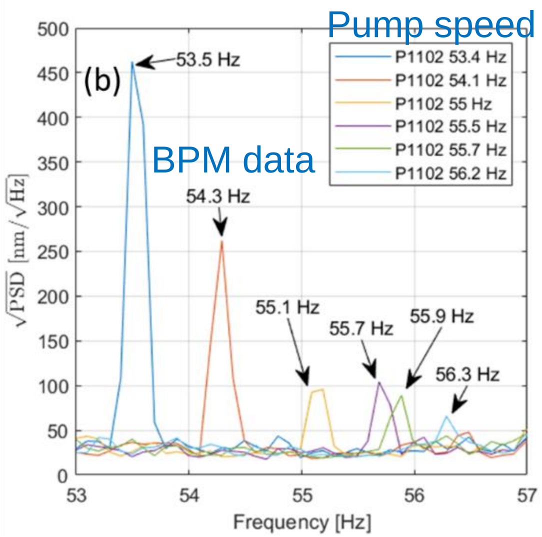
Mechanical noise around 50-60 Hz

- All biggest noise in the range of 50-60 Hz was identified
  - The sources came from DI water pumps
  - Verified by changing the pumps speed – changing the valve change the pump frequency
- Depending on the pump frequency we see attenuation of the spectral peak in the beam spectrum
  - Question: Resonance on the pump's support??

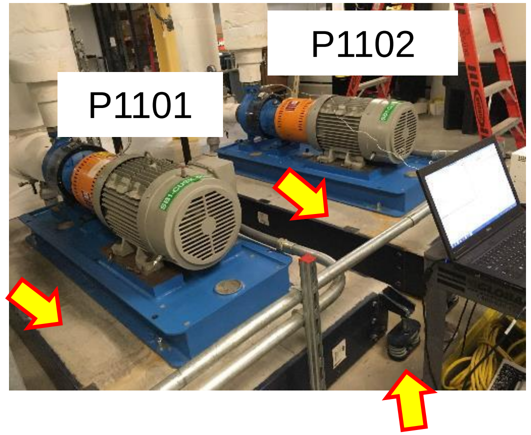




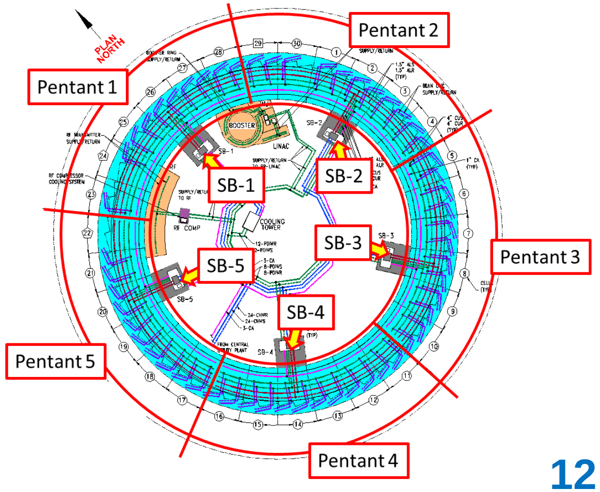




Separated pump stages



Support by springs



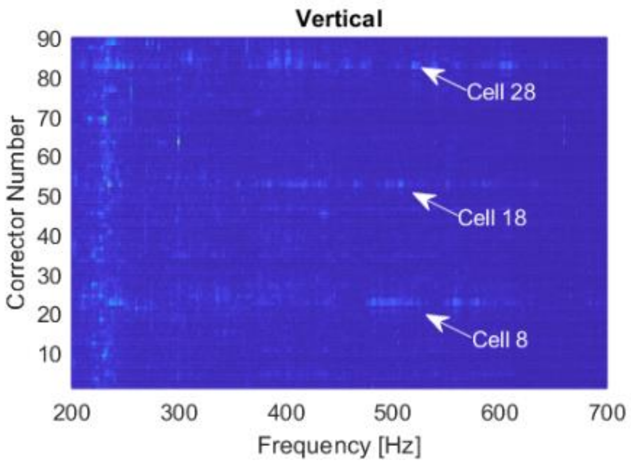
Other noise sources

Other sources were also found

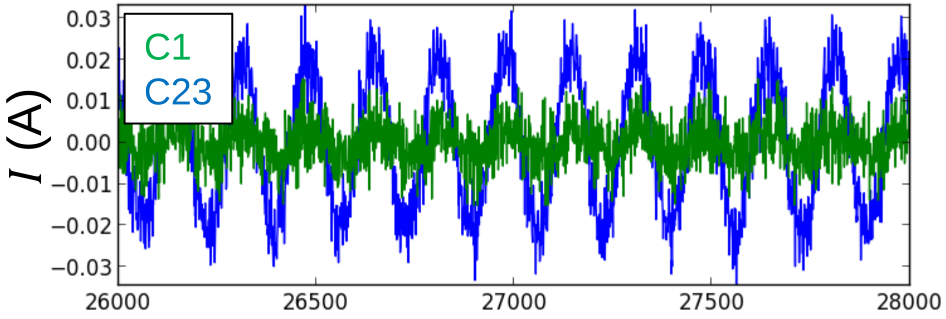
- High frequencies noise from cell 8, 18, 28
  - 6 Damping Wigglers reside in these cells
  - Verified that the noise was not related to the damping wigglers’ gap
  - Potential source – electronic noise (high frequencies)
- A 60 Hz from slow corrector power supplies in cell 22-24

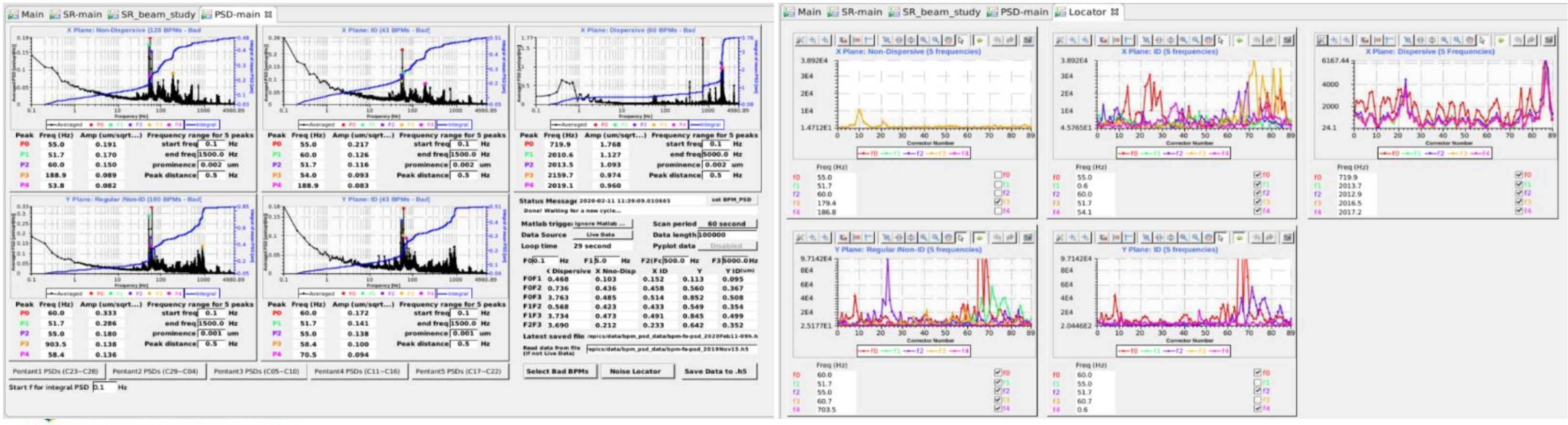
We developed a real-time monitoring for beam orbit instability

- Based on EPICS, CSS, Python
- Find five biggest peaks and their locations
- Recorded in the Archive



Slow correctors power supply



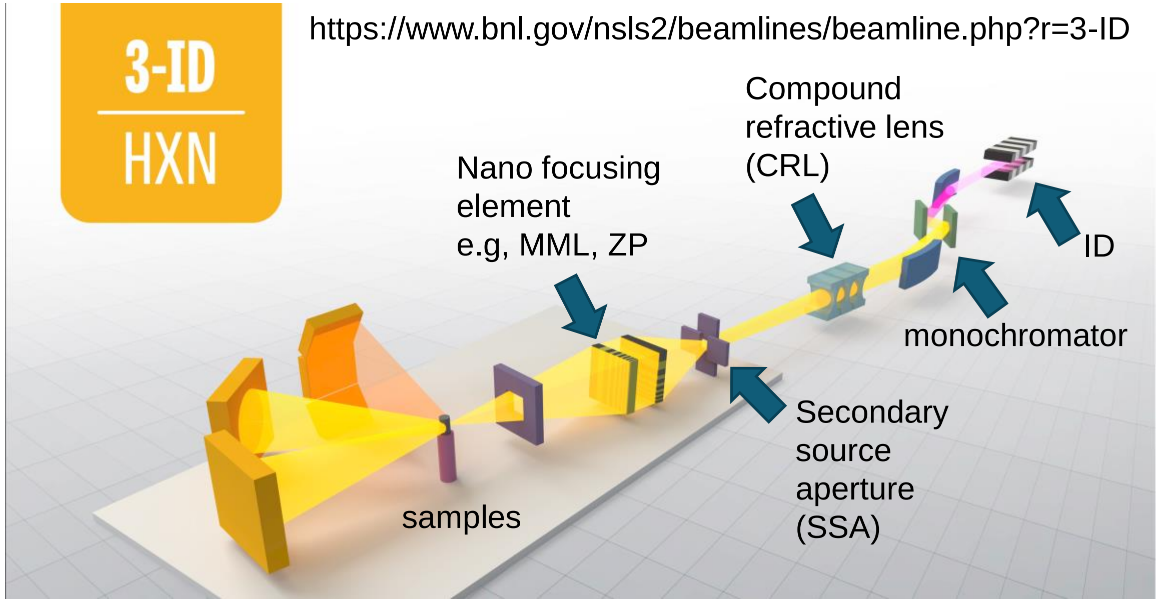


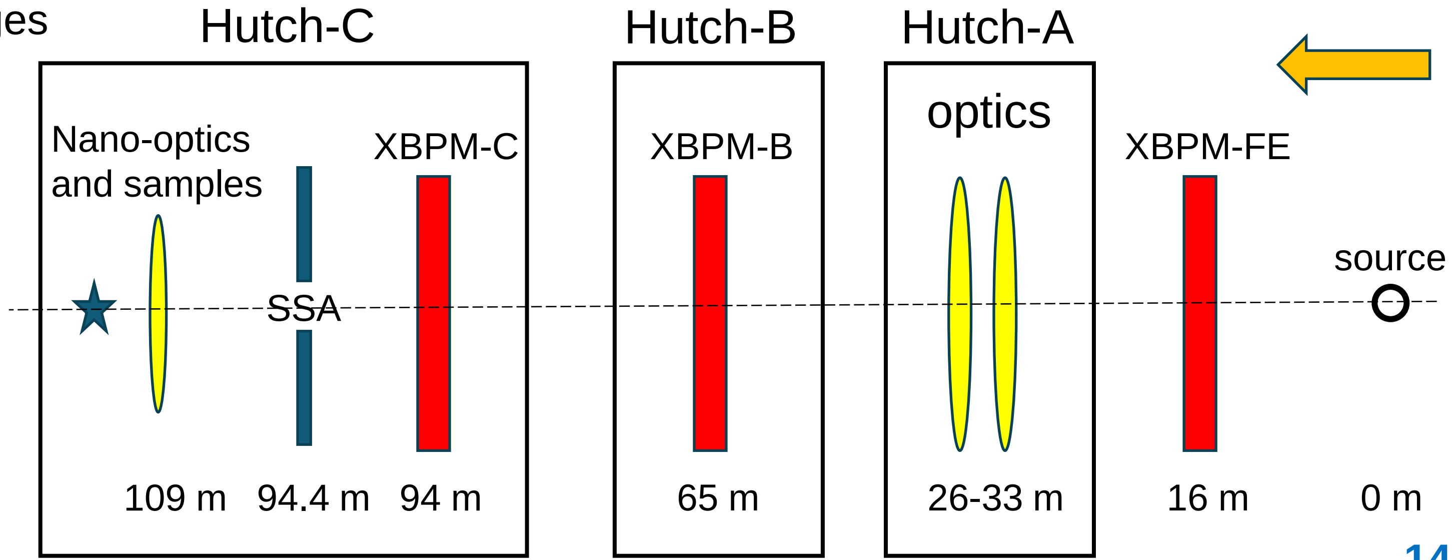
Live monitoring application (CSS pages)

NSLS-II Control Room

Investigation of beamline's instabilities

- We discussed sources of instability and diagnostics in the storage ring
- Next, we investigated the beam stability of a beamline
- We picked one of the most sensitive beamlines at NSLS-II
  - Hard X-ray nanoprobe beamline (HXN)
  - 120 m long instrument
  - Imaging with resolution 10x10 nm^2
- Procedures
  - Collect BPM data, XBPM data, and images
  - Characterize noise and identify the sources





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RF BPM vs XBPM vs camera

Data from XBPM-FE and RF BPM matched well (before optical components)

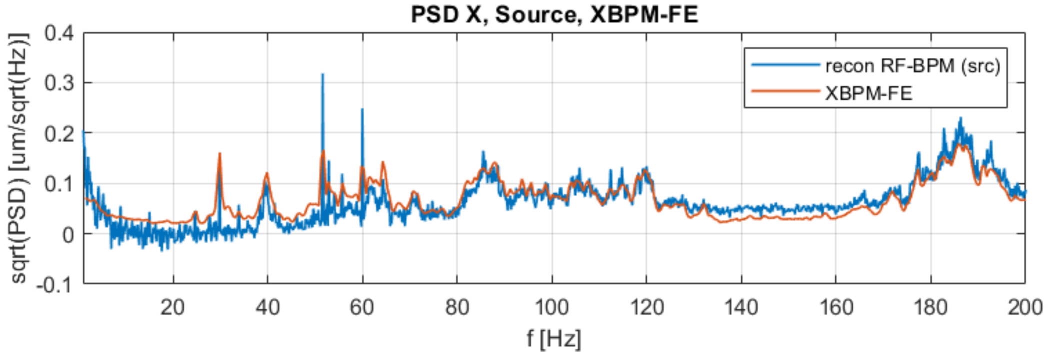
- Noise from DI water cooling (~50 Hz), and corrector magnets’ ripple (60 Hz) can be seen before beamline optics

Compare XBPM hutch-B and hutch-C

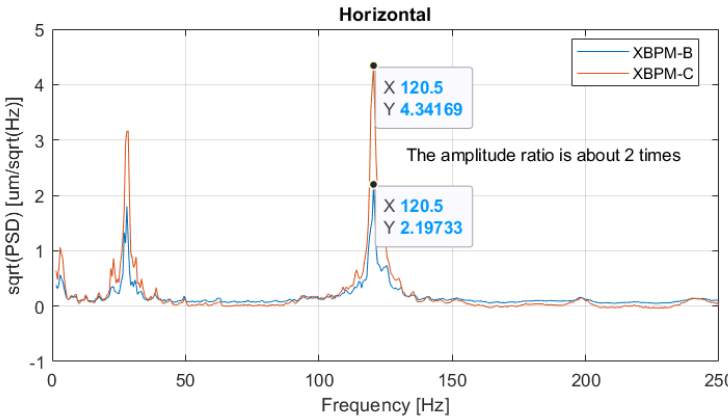
- Different spectral from the XBPM-FE
  - Dominant peaks were 28 Hz and 120 Hz
- Horizontal: the amplitudes at 28 Hz and 120 Hz were twice in XBPM-C
  - Indicate the horizontal angle vibration from hutch-A
- Vertical: only 120 Hz
  - Same amplitudes in hutch-B and hutch-C
  - Not angle kick in the vertical plane

Consistent with optics in hutch-A, which kick the beam in the horizontal plane

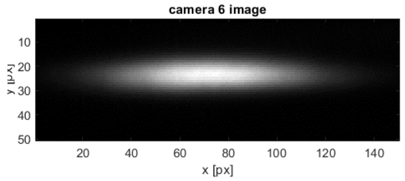
spectral of beam position from XBPM-FE and rf-BPM (before optical component Hutch-A)



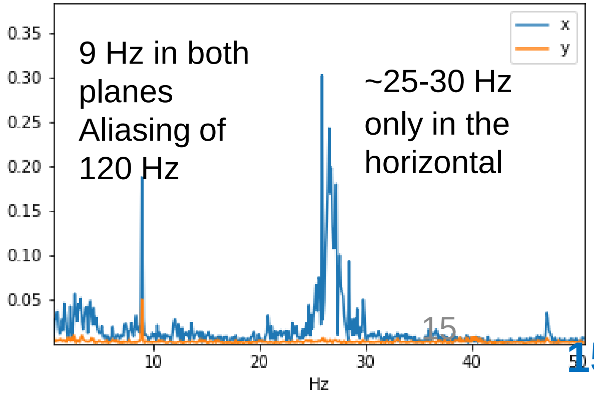
XBPM from hutch-B and hutch-C shows 28 Hz and 120 Hz



Analysis of images from a camera showed the same frequencies.



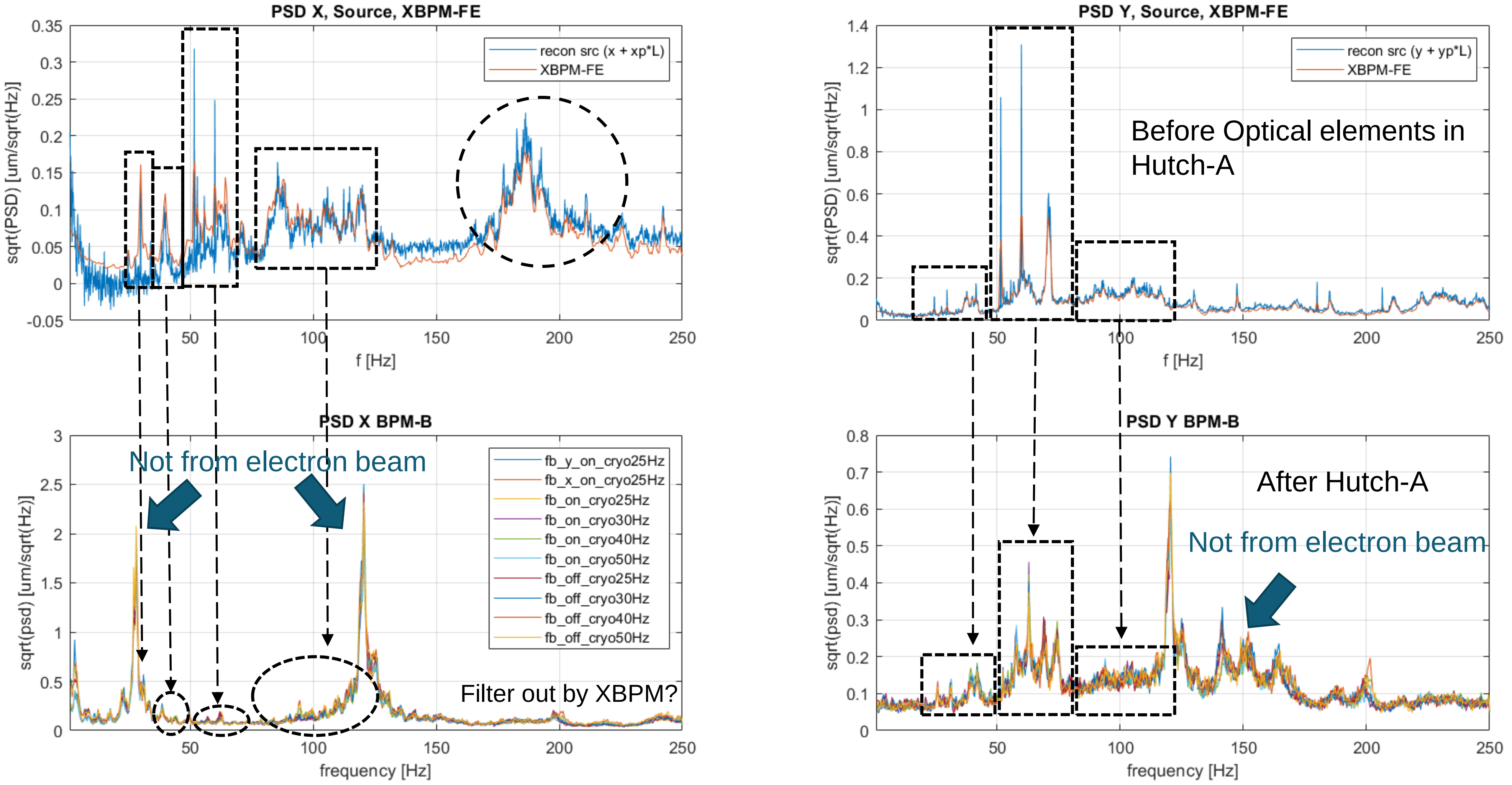
Camera after SSA



Impacts of electron beam on X-ray beam stability

- 28 Hz and 120 Hz were **not** from the electron beam
- The impact of the electron beam on X-ray beam stability is smaller in the horizontal
- The vertical electron noises' amplitude were comparable to the peaks above 120 Hz

Electron vs X-ray hutch B



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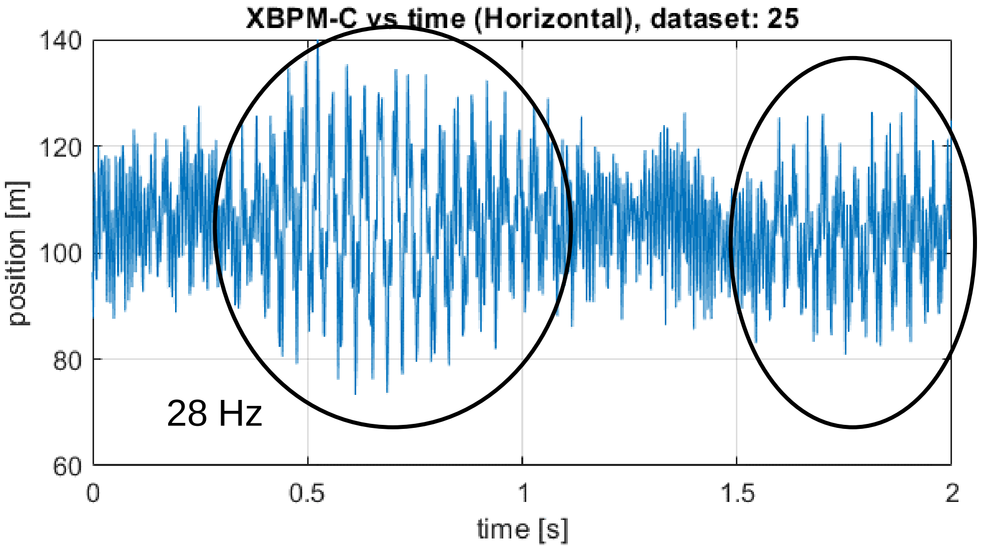
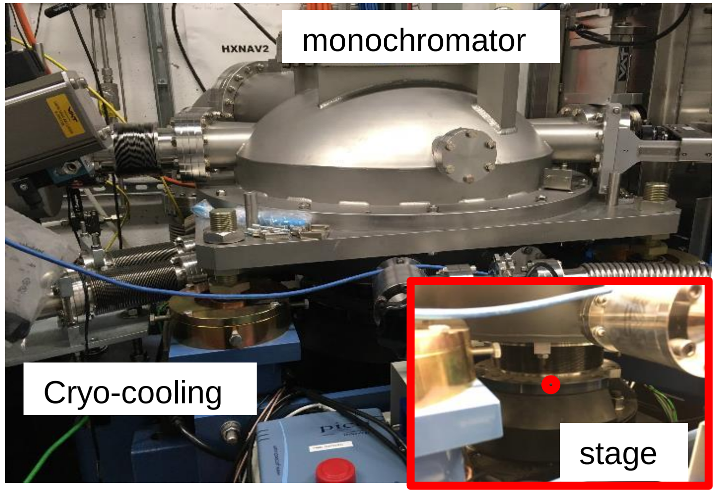
Investigation of the sources and effects

- Suspected that the noise sources of 28 Hz and 120 Hz were in Hutch-A (horizontal mirrors or monochromator)
- Amplitude of 28 Hz vibration was not steady – probably related to turbulence of cooling system
- Plan to measure the vibration of each element in Hutch-A
  - Local water-cooling pumps
  - Cryo-cooling
  - Optical stages
- Plan to simulate the effects of these instabilities to the images of HXN
  - SRW – effects of steady misalignments has been studied (O. Chubar)
  - Including beam vibration calculation (S. Kongtawong, 2022)





Summary

- We presented effects and requirement of beam stability of modern light sources around the world
- Tools and analysis for diagnostic
  - BPM, XBPM
  - Vibration – geophones, accelerometers
  - Archivers – long-term monitoring, low-frequency
  - Analyze noise location in corrector domain – inverse response matrix
- Future light sources
  - Estimate effects of beam stability – amplification factor from ground motion
  - Upgrade beam correction systems
- We investigated the dominated contributions in the noise affecting electron beam orbit stability at NSLS-II
  - Use BPM data and vibration data to identify the sources
  - 50-60 Hz had the biggest amplitudes – verified to be from DI water pumps
- We investigated x-ray beam instability at the HXN beamline
  - The dominated noises at HXN were 28 Hz and 120 Hz – not from the electron beam, likely to be cooled mirrors in hutch-A
  - Effects of electron instability were comparable to the beamline noise in the vertical plane – small in the horizontal plane
  - Need to investigate the sources of vibration further, including water cooling, cryocooling

References

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Additional slides

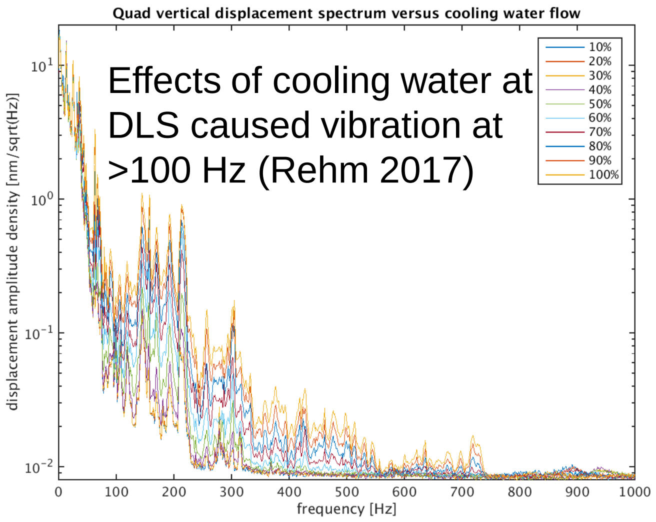
Sources of beam orbit instability

Various types of noise sources cause beam instability at all ranges of frequency

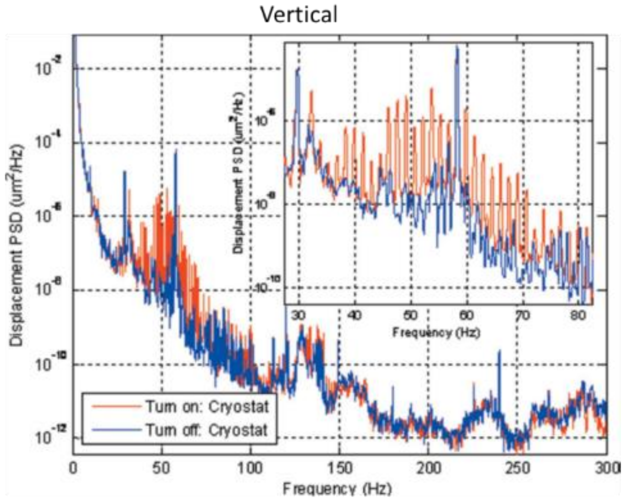
- RF noise
- Cooling systems
- Injection
- Ocean's tide
- Etc.

Examples

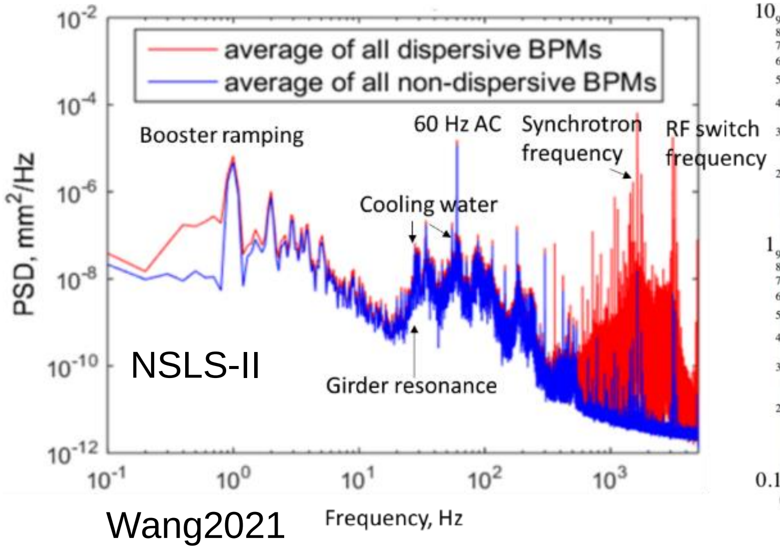
- DLS found that noise >100 Hz came from excessive cooling water flows
- Cryostat caused noise at STXM (CLS) beamline that affected quality of images
- Pulse width modulation of a klystron at SLS affected IR spectra
- NSLS-II identified several noise sources ranging from low (injection) to high (RF system)



Effects of cooling water at DLS caused vibration at >100 Hz (Rehm 2017)

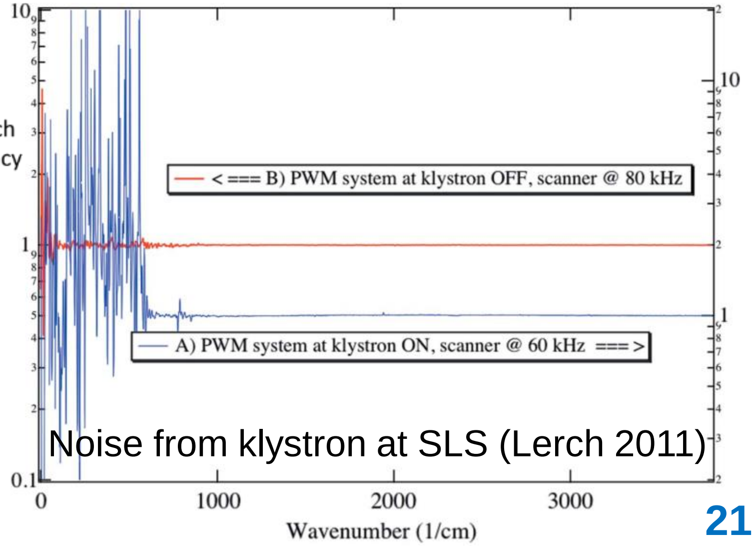


Cryostat caused noise around 50 Hz at CLS (Li 2010)



NSLS-II

Wang2021



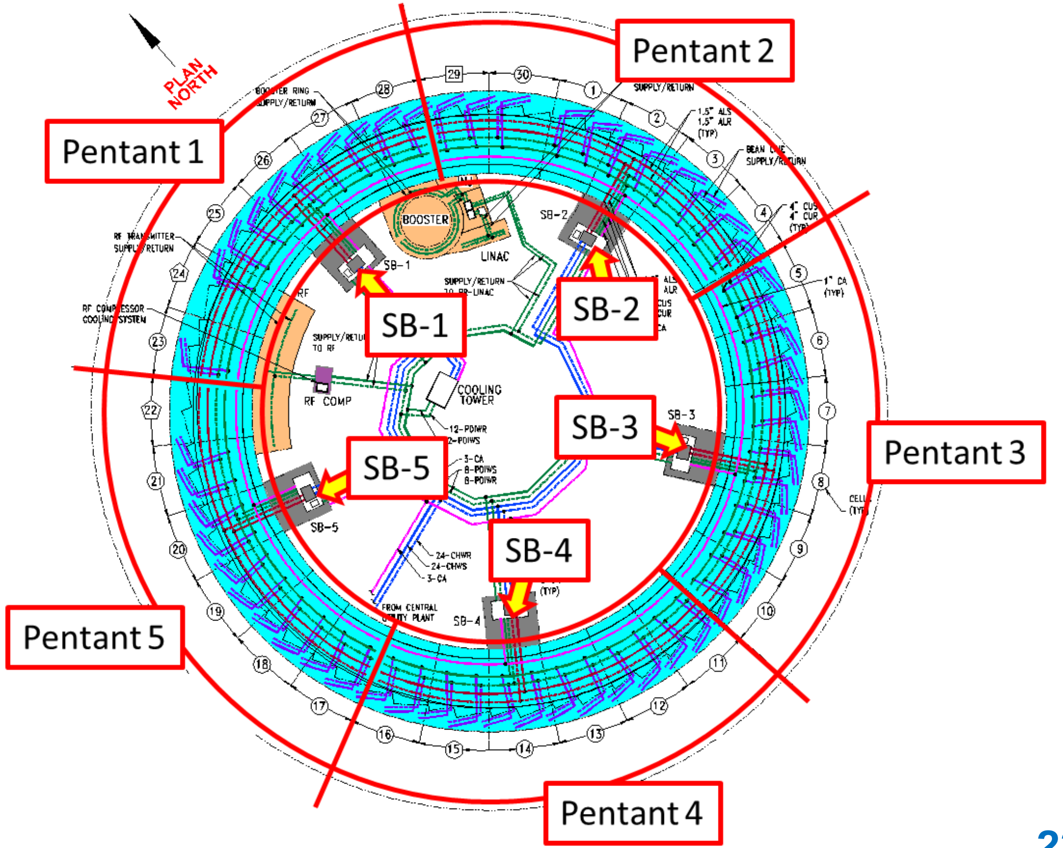
Noise from klystron at SLS (Lerch 2011)

Brookhaven National Laboratory

Potential noise sources at NSLS-II (<100 Hz)

N. Simos 2019

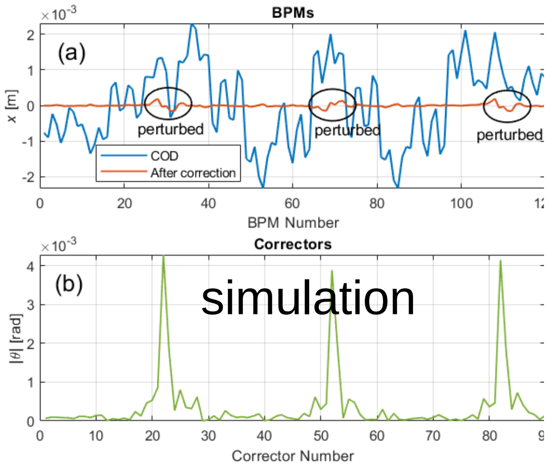
- NSLS-II has 30 cells
  - 5 Pentants
  - Service building per Pentant (6 cells)
    - Utility systems e.g. water-cooling, cyo-cooling, air
  - Steam tunnel under ground
  - RF cooling system
- Long Island sound – ocean’s tide
- Highway – noise from traffic

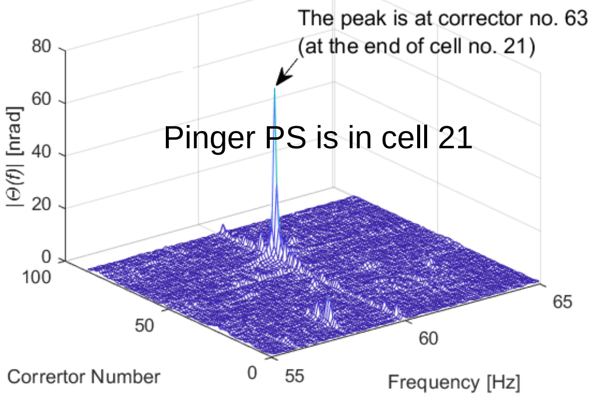


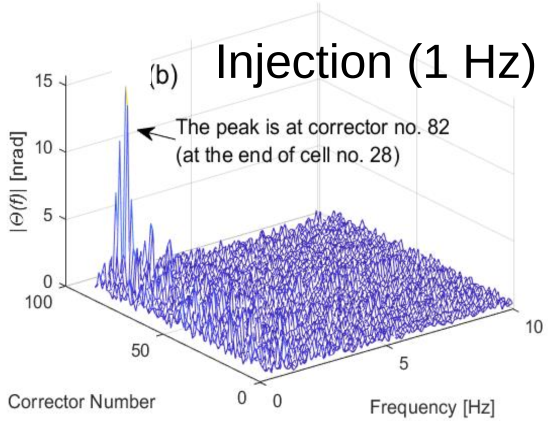
Noise locator analysis

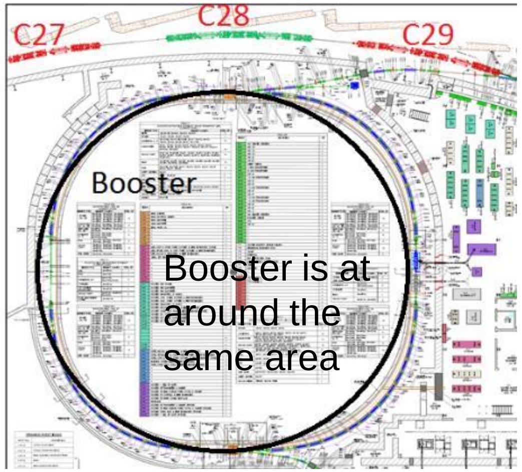
Test the method

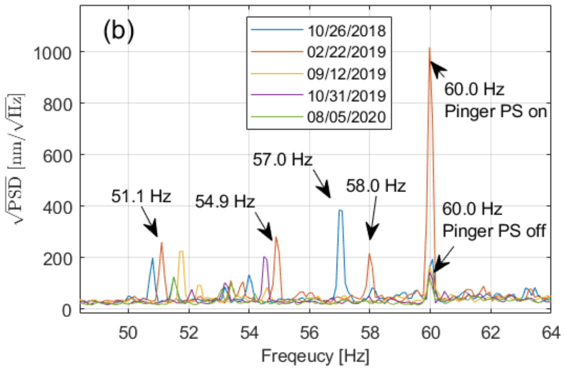
- Tested with simulation (Elegant)
- Benchmarked against well-known noise sources
  - Pinger power supply 60 Hz
  - Injection 1 Hz
- Gave correct source locations

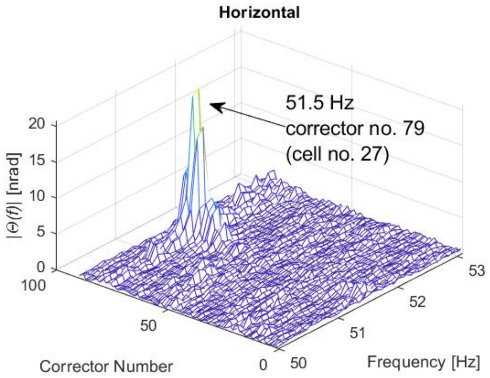




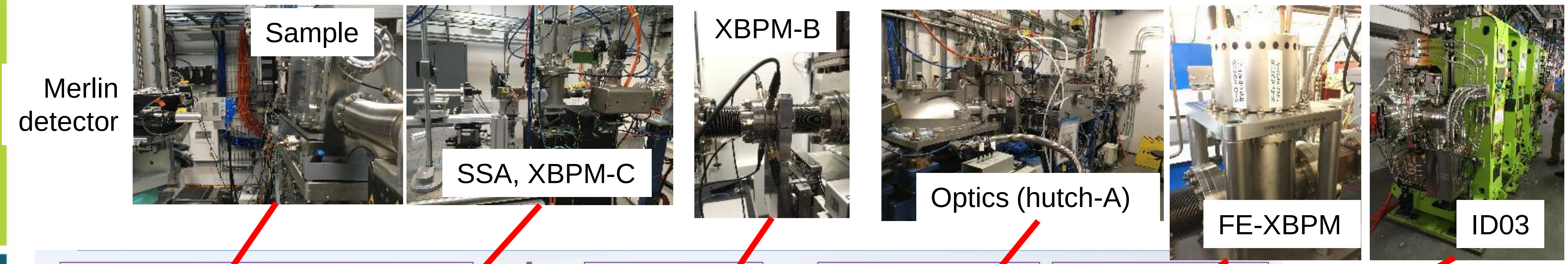


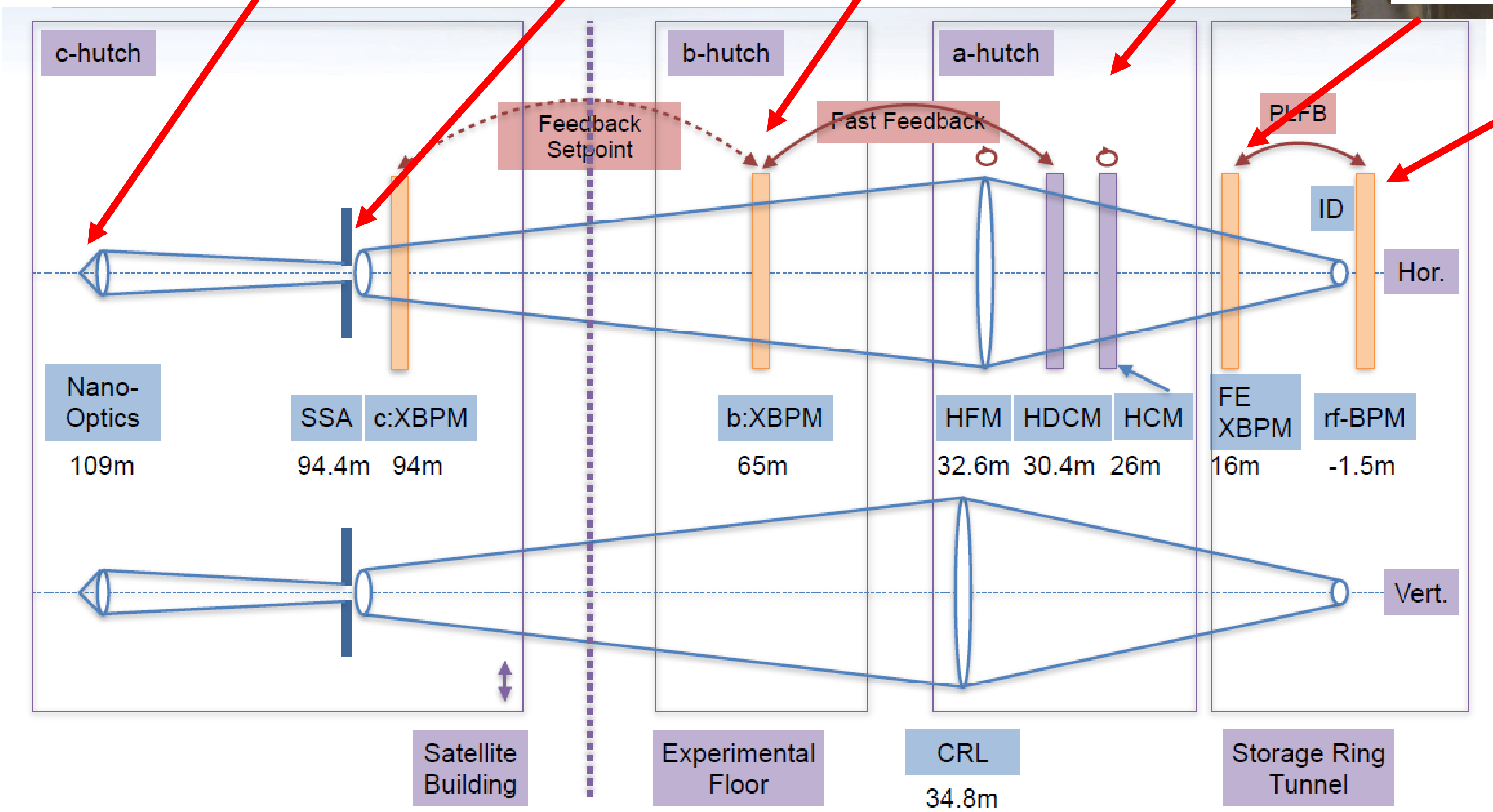


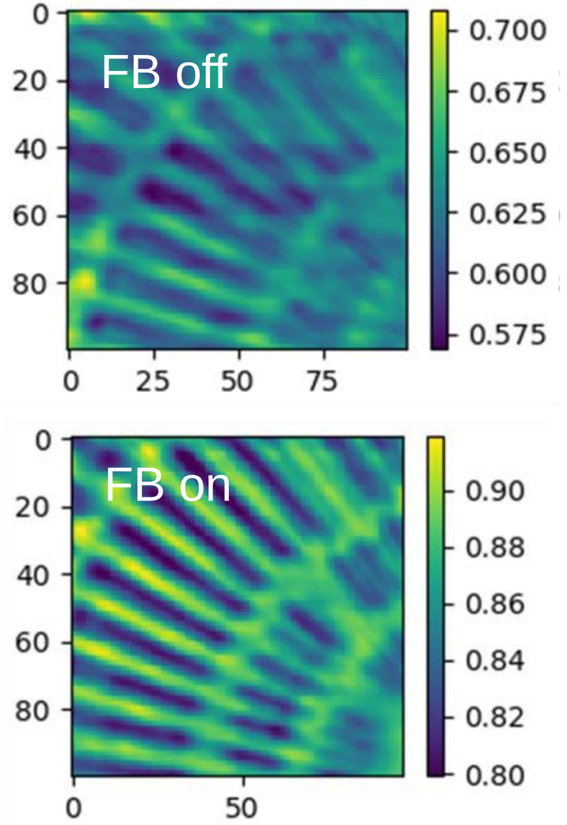




HXN’s layout







Local feedback can only suppress low-frequency noise and drifts (<1 Hz)

P. Ilinski, Active beamline feedback implementation for photon beam stability, DLSR7 2021, MAX IV Laboratory, Lund, Sweden