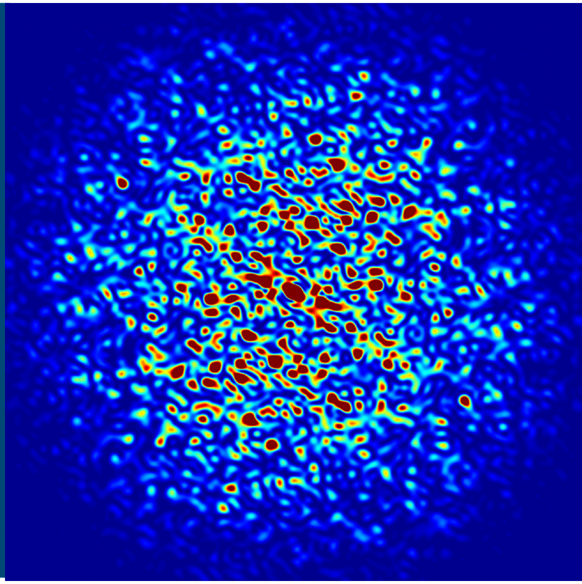
Comprehensive Study of the Expected Orbit Motion in the APS-U Storage Ring



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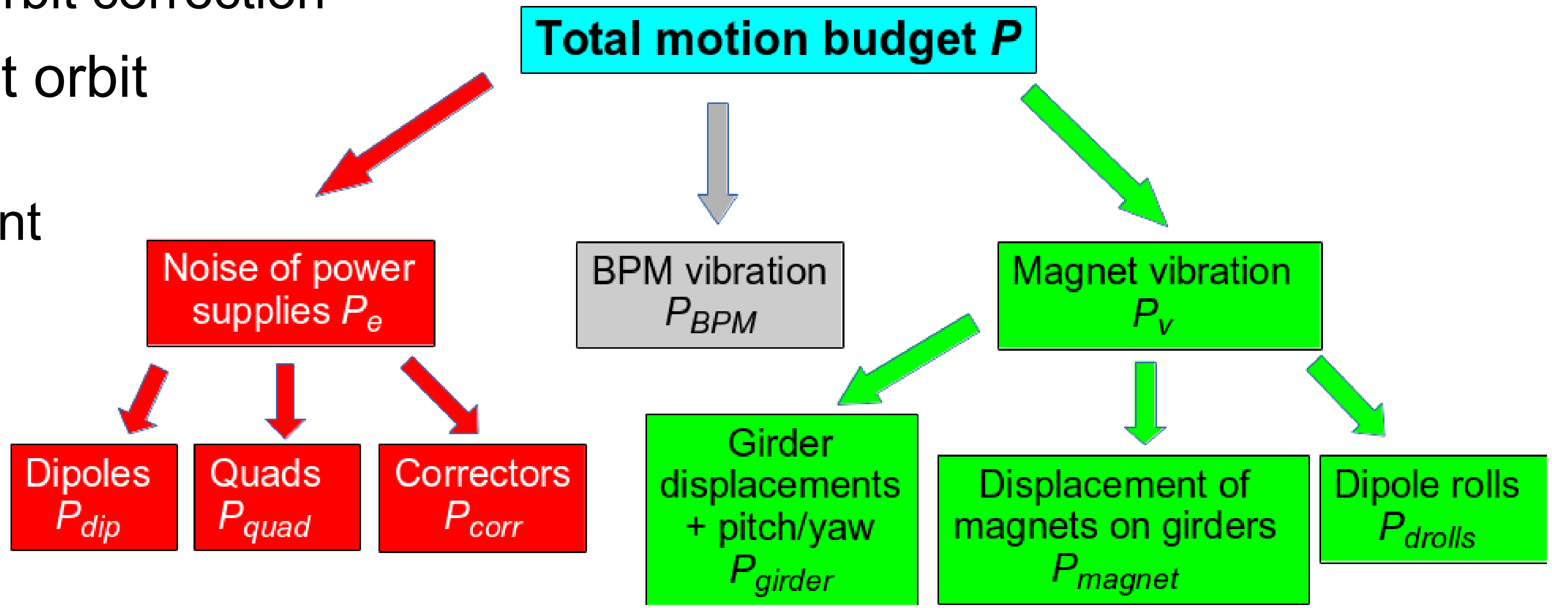
Outline

- Introduction
- Ground motion coherence measurement
- Girder resonant mode simulations
- Orbit motion calculation due to ground vibration and power supply noise
- Summary

There are many contributions into the orbit motion

- Orbit motion is produced by electrical noise in magnet power supplies, by variable magnetic fields generated by vibrating quadrupoles and dipoles, and by mechanical motion of BPMs via orbit feedback
- Relative stability of orbit and user sample is also important
- Orbit stability requirement is very stringent
  - Cannot be achieved without orbit correction
- In some cases, stability without orbit correction is also important
  - Response matrix measurement for lattice correction



Total motion budget P

Noise of power supplies P_e

BPM vibration P_{BPM}

Magnet vibration P_v

Dipoles P_{dip}

Quads P_{quad}

Correctors P_{corr}

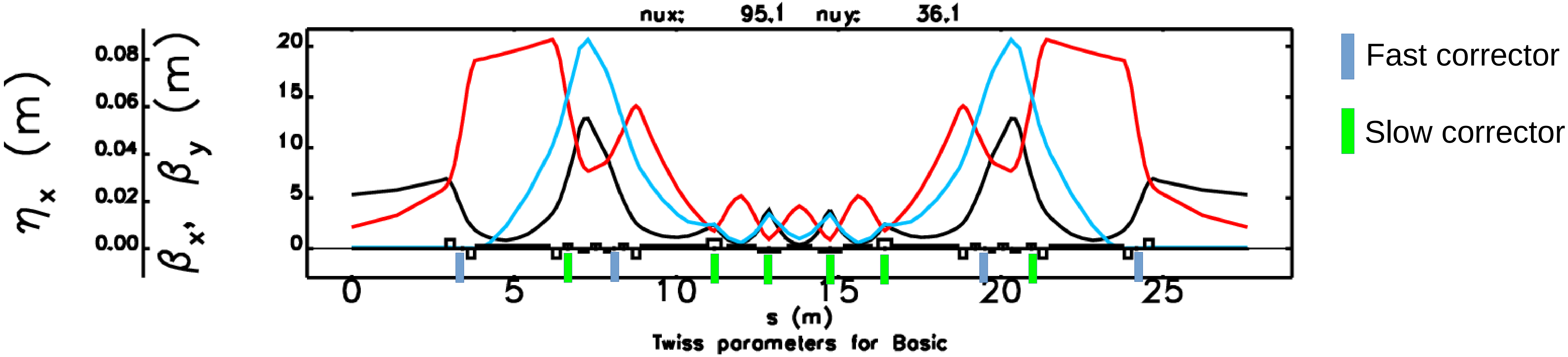
Girder displacements + pitch/yaw P_{girder}

Displacement of magnets on girders P_{magnet}

Dipole rolls P_{drolls}

APS-U correction configuration*

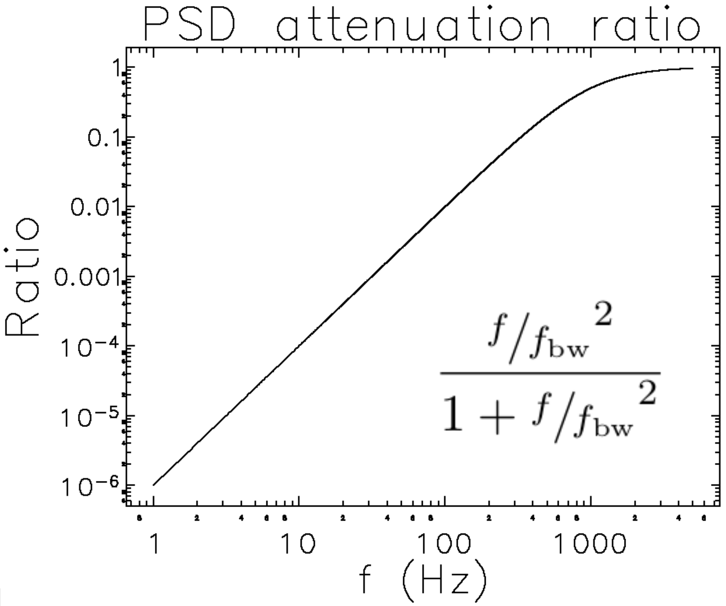
- There are 10 orbit correctors and 14 BPMs (including 2 ID BPMs) per sector
  - All correctors are horizontal and vertical
  - 4 standalone fast correctors (0.3 mrad max angle)
  - 2 correctors inside S1 sextupoles (0.2 mrad max angle)
  - 4 correctors inside Q7 and Q8 quadrupoles (0.16 and 0.2 mrad max angles)
- Standalone fast correctors also serve as skew quadrupole correctors



*Has nothing to do with calculations presented here

Orbit correction is an integral controller

- Since the correctors accumulate previous correction steps, it makes orbit correction an integral controller
  - Integral controller is essentially a first-order high-pass filter
  - Presently, typical orbit correction bandwidth is a few hundreds of Hz
  - APS-U will have 1 kHz bandwidth
- Adding proportional control changes behavior around bandwidth frequency but not significantly
  - Ignored for presented calculations



for 1 kHz bandwidth

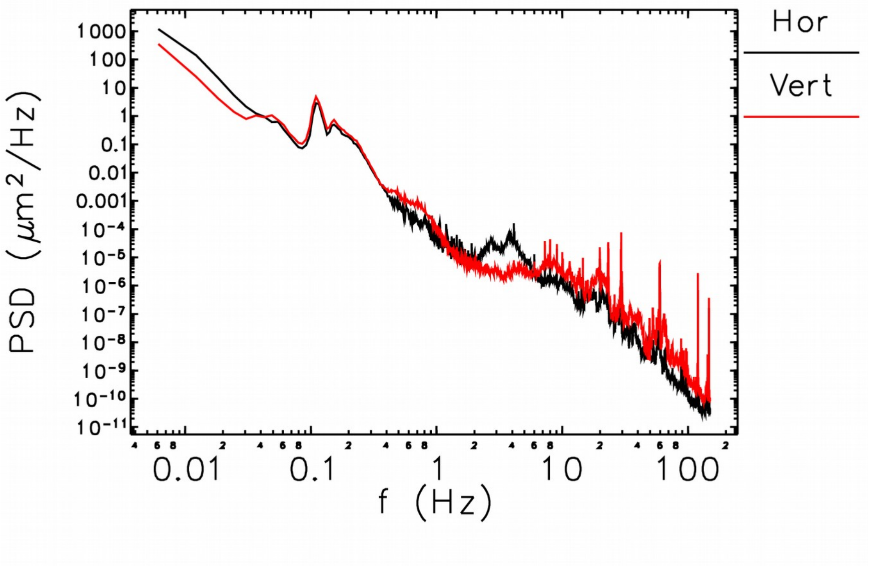
Main question that motivated this study

- APS-U will have small beam size and very tight requirements for beam stability which is defined in band 0.01 – 1000 Hz
- Absolute beam stability when orbit correction is running consists of two contributions – beam motion relative to BPM and BPM motion relative to a reference
- Measured rms tunnel floor motion in that band is about 2 μm

- *How can one expect 0.4 μm beam orbit stability if BPMs move around with 2 μm rms?*

Plane	AC rms Motion 0.01 – 1000 Hz	
Horizontal	1.25 μm	0.25 μrad
Vertical	0.4 μm	0.17 μrad

PSD of APS floor motion

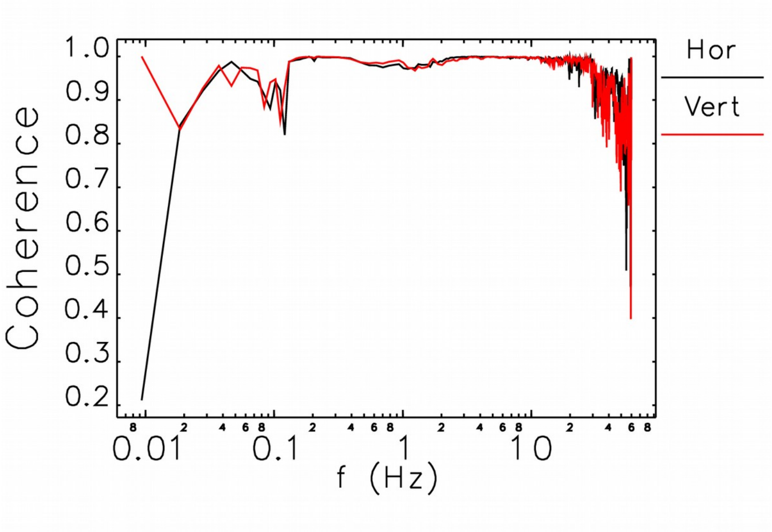


Ground motion is coherent at low frequencies

- Magnitude-squared coherence of two signals *x* and *y* is defined as

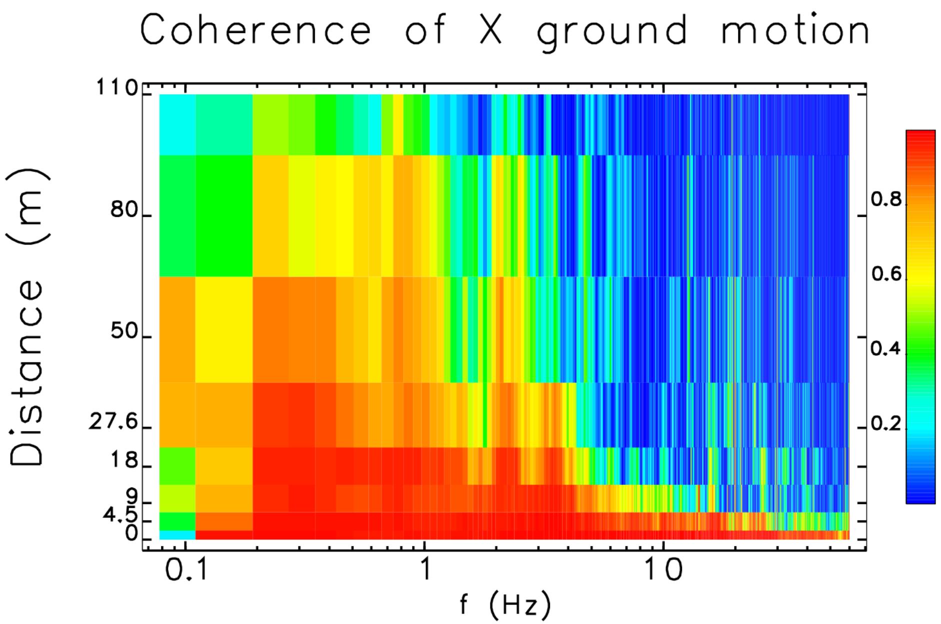
$$C_{xy}(\omega) = \frac{|P_{xy}(\omega)|^2}{P_{xx}(\omega)P_{yy}(\omega)},$$

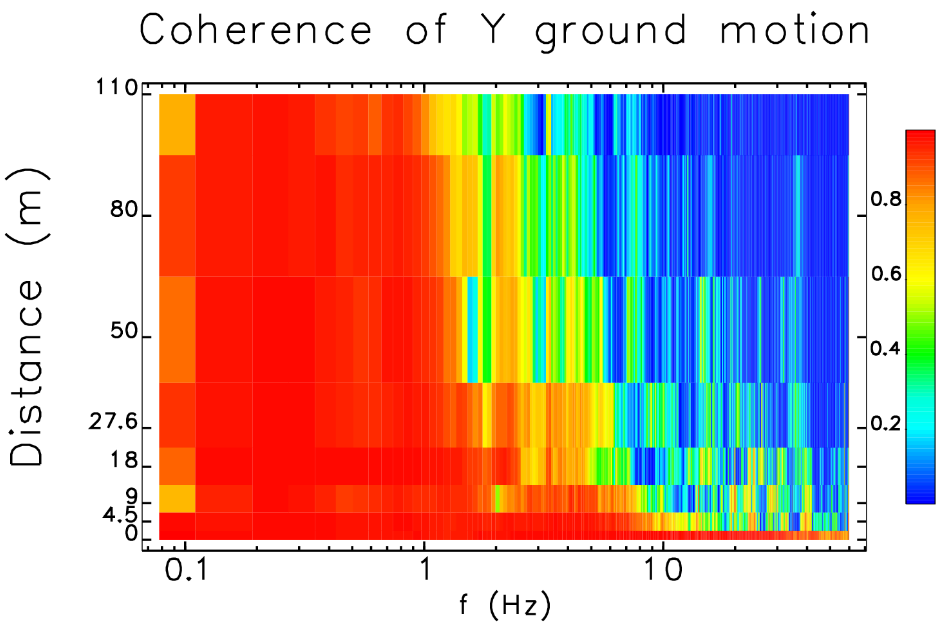
- where P_{xx} and P_{yy} are PSD of individual signals and P_{xy} is cross-spectral density
- Ground motion coherence was measured in APS tunnel using two identical seismometers
- Coherence of 2 sensors sitting next to each other checks measurement validity range
  - Excellent coherence in 0.1 – 20 Hz range and good coherence (> 0.8) in 0.02 – 50 Hz
  - Specified valid measurement range of sensors is 0.008 – 50 Hz
  - Below 0.02 Hz the motion should be coherent as well but the measurement is dominated by electronics noise



APS floor motion is coherent below 1 Hz

- Vertical motion is well coherent below 1 Hz for distances of up to 110 m (4 sectors)
- Reduction of horizontal motion coherence at large distances is explained by the relative rotation of the sensors
  - Sensors were always oriented along the beam trajectory, which results in 36° angle between two sensors at 110 m distance

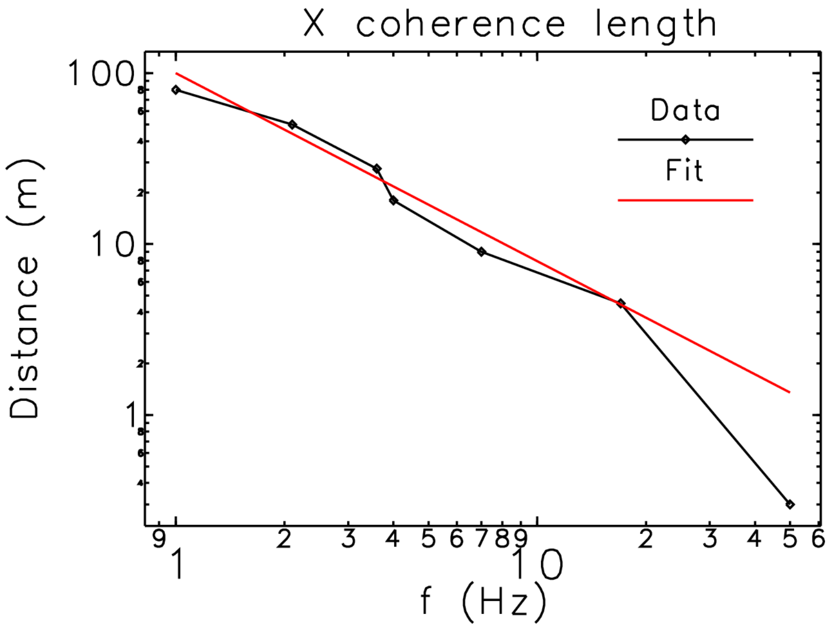


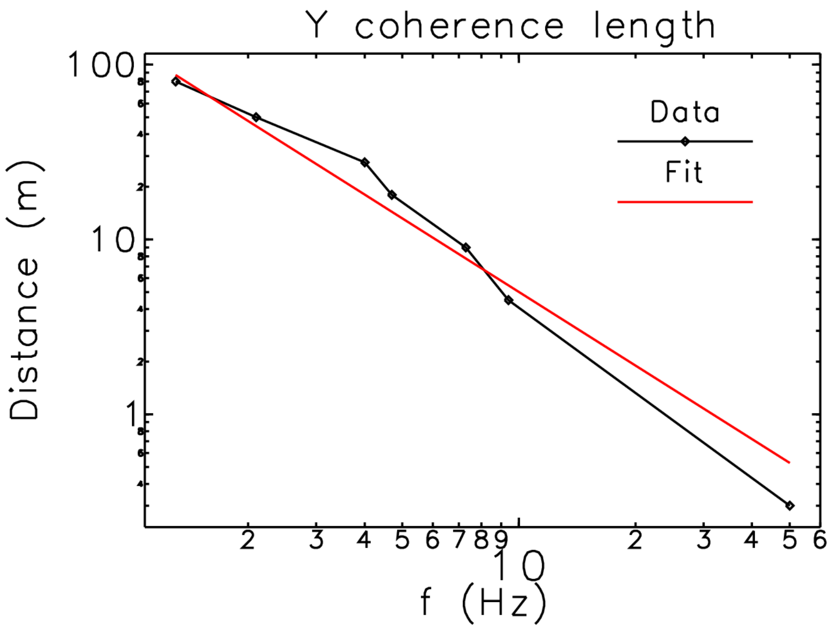


Coherence length dependence on frequency

- The coherence length was determined for each frequency when the coherence exceeds 0.8
- Exponential fit was used to determine empirical dependence:

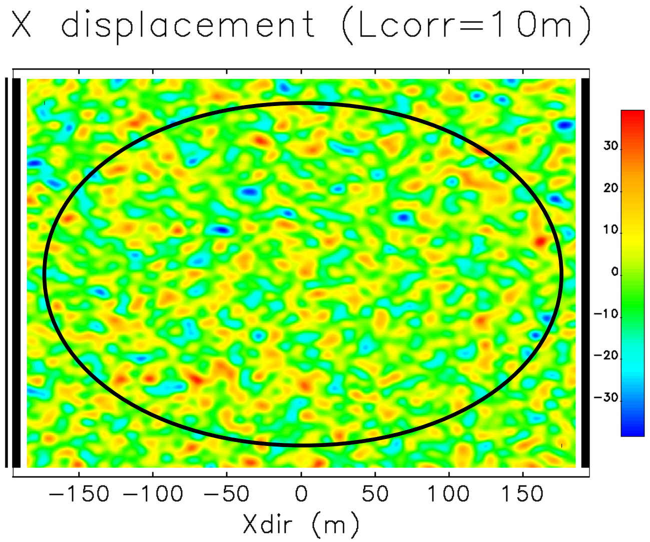
$$L_x \approx \frac{100}{f^{1.1}} \qquad \text{and} \qquad L_y \approx \frac{125}{f^{1.4}}.$$

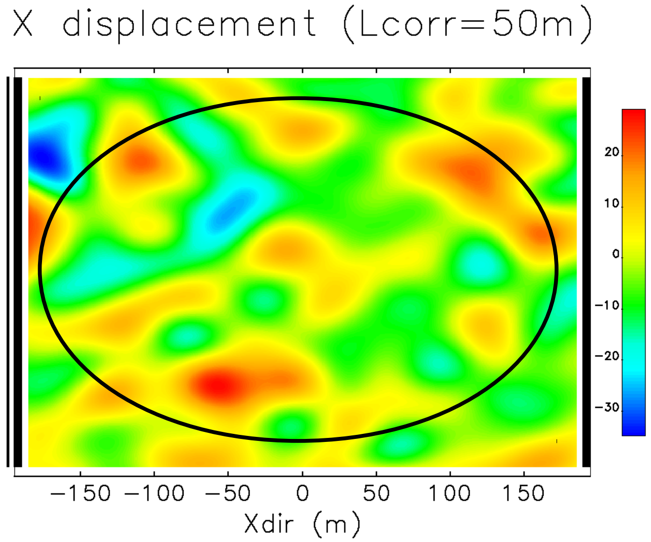




Simulations determine amplification factors as a function of coherence length

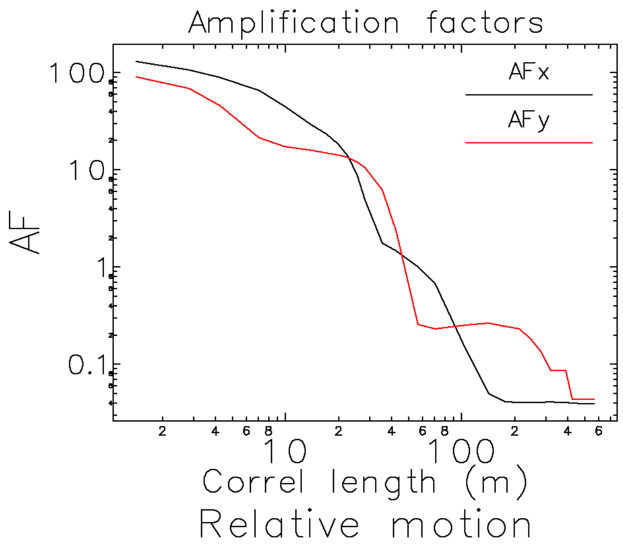
- Orbit amplification factors are calculated using static closed-orbit simulations
- Magnet displacements are generated for different coherence length of the ground deformation
  - Ground displacements *ΔX*, *ΔY*, *ΔZ* with specified coherence length are generated in Cartesian coordinates *X*, *Y*, *Z*
  - Magnet displacement is calculated by sampling the ground displacement at the locations of magnets on one girder and fitting a straight line
  - Magnet displacements are transformed into accelerator coordinates

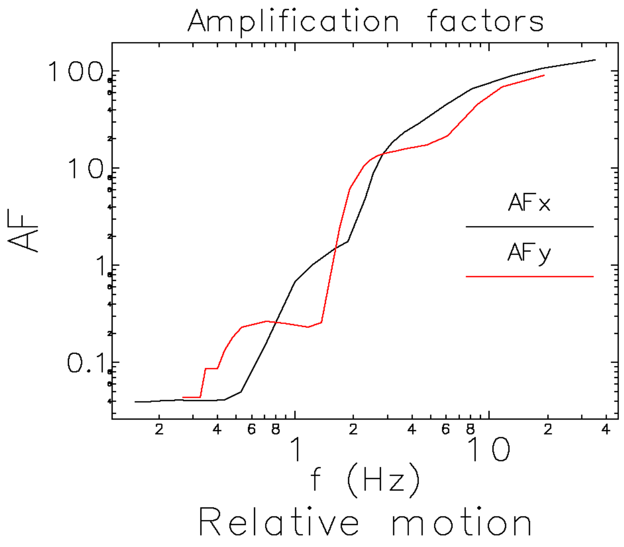




Simulations combined with measurements determine amplification factors as a function of *f*

- Magnet displacements are generated 100 times for each coherence length, and orbit amplification factors are calculated using elegant
  - Ideally, amplification factors should not level out at large lengths but should continue going down
  - Our simulation accuracy does not allow to capture this behavior
- Orbit amplification factors as a function of frequency is obtained by combining simulated amplification factor dependence on coherence length and measured coherence length as a function of frequency

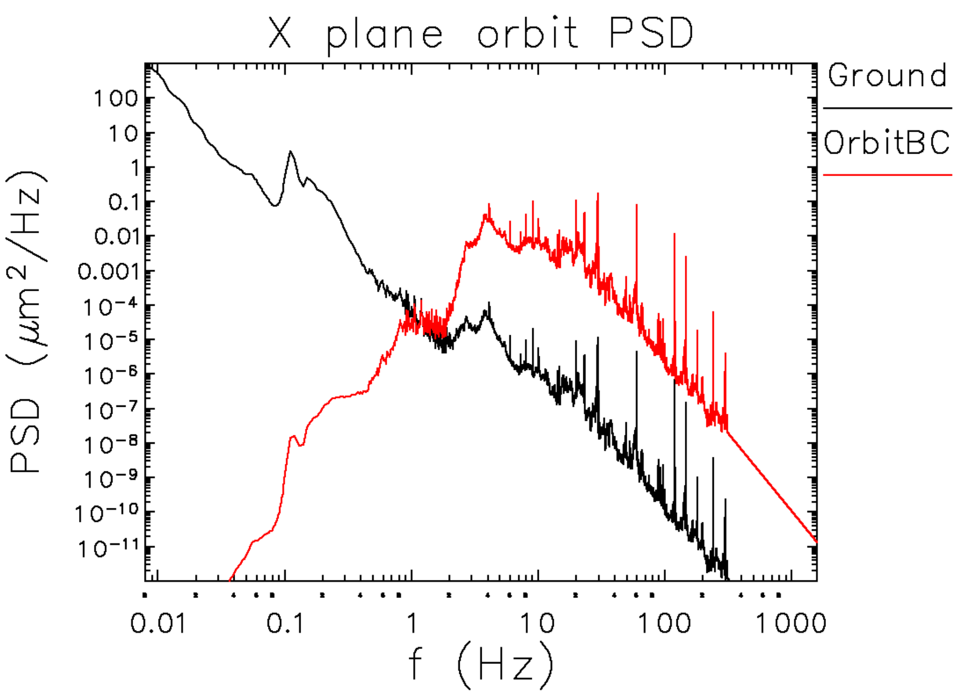


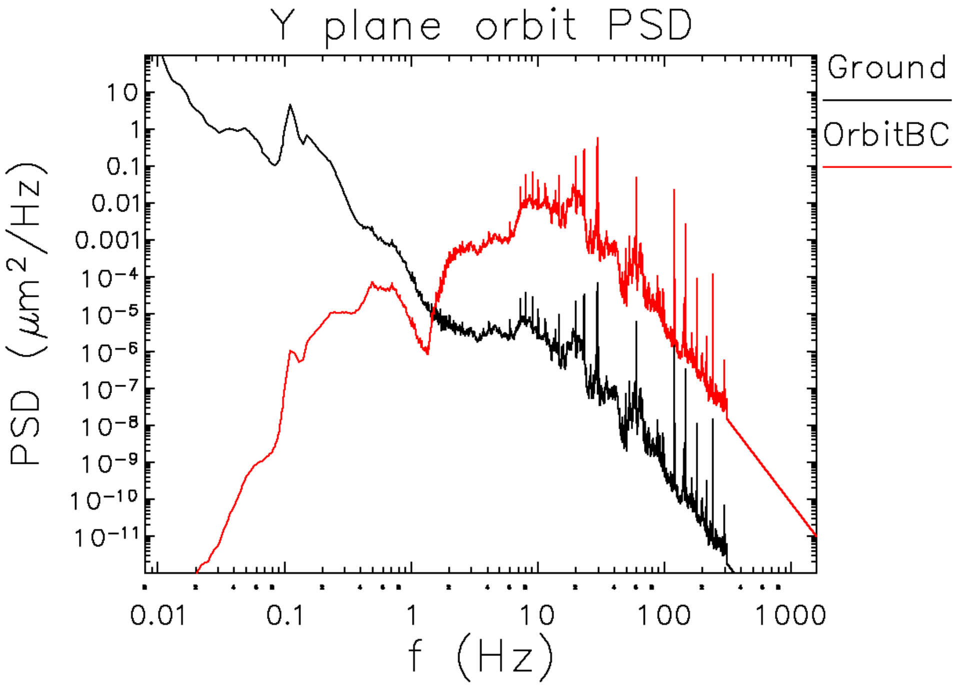


BES Light Sources Stability workshop, November 1, 2018

Orbit motion is calculated by multiplying floor motion PSD by the amplification factor frequency dependence

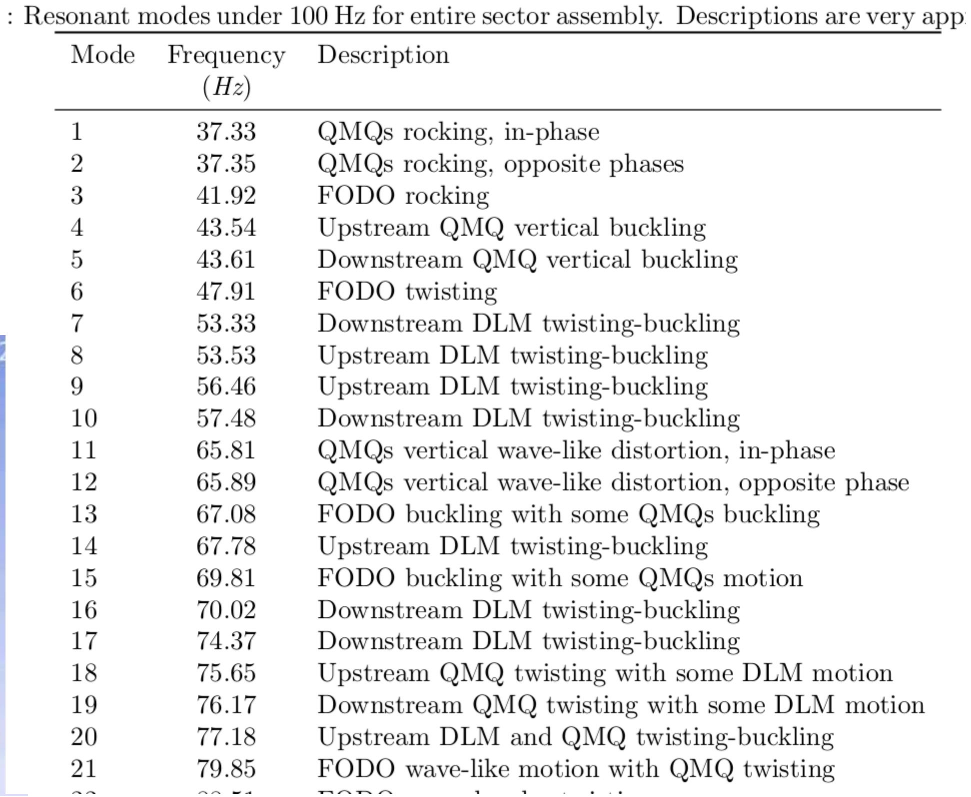
- Floor motion PSD is measured using seismometer (0.008 – 50 Hz range) and accelerometer (2 – 200 Hz range)
- PSD of the orbit motion due to solid-body girder motion is obtained by multiplication of the floor motion PSD and orbit amplification factor frequency dependence squared





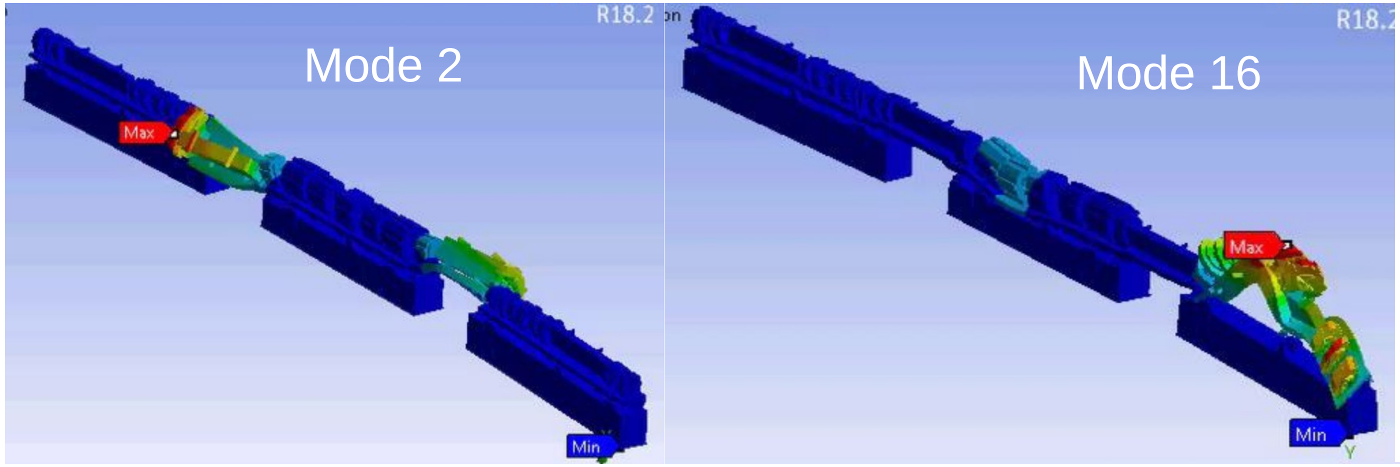
APS-U girder deformations are simulated using ANSYS

- 3 main girders are connected together by smaller modules making it one structure that needs to be simulated together
- Stiffness matrix for each support component was determined through measurements and then used in ANSYS to predict girder resonant modes
- Simulations were benchmarked on single modules



: Resonant modes under 100 Hz for entire sector assembly. Descriptions are very app

Mode	Frequency (Hz)	Description
1	37.33	QMQs rocking, in-phase
2	37.35	QMQs rocking, opposite phases
3	41.92	FODO rocking
4	43.54	Upstream QMQ vertical buckling
5	43.61	Downstream QMQ vertical buckling
6	47.91	FODO twisting
7	53.33	Downstream DLM twisting-buckling
8	53.53	Upstream DLM twisting-buckling
9	56.46	Upstream DLM twisting-buckling
10	57.48	Downstream DLM twisting-buckling
11	65.81	QMQs vertical wave-like distortion, in-phase
12	65.89	QMQs vertical wave-like distortion, opposite phase
13	67.08	FODO buckling with some QMQs buckling
14	67.78	Upstream DLM twisting-buckling
15	69.81	FODO buckling with some QMQs motion
16	70.02	Downstream DLM twisting-buckling
17	74.37	Downstream DLM twisting-buckling
18	75.65	Upstream QMQ twisting with some DLM motion
19	76.17	Downstream QMQ twisting with some DLM motion
20	77.18	Upstream DLM and QMQ twisting-buckling
21	79.85	FODO wave-like motion with QMQ twisting



`elegant` is used to calculate mode amplification factors

- Magnet displacements and tilts for each mode are entered in `elegant`, and orbit amplification factors are calculated for every mode
- Orbit amplification factors for entire ring are calculated assuming that vibration in different sectors is independent; different modes within a sector are considered independent too

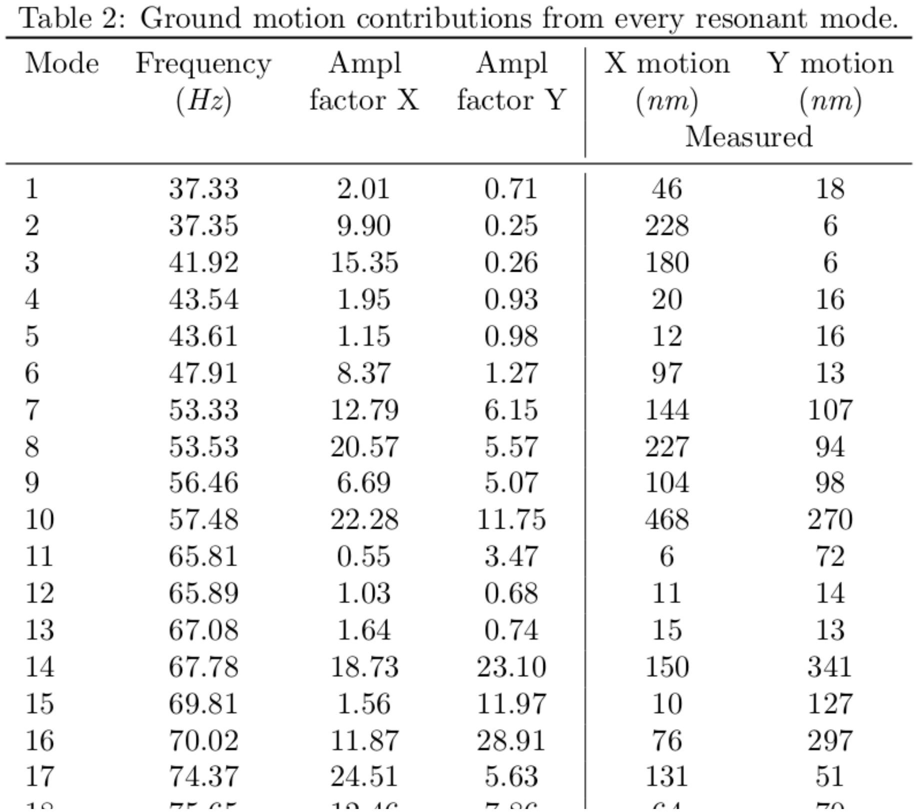
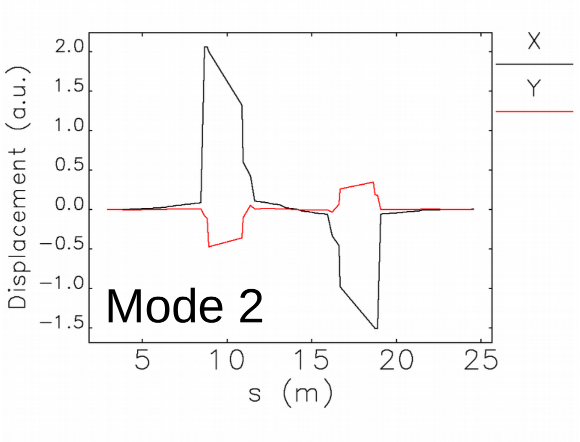
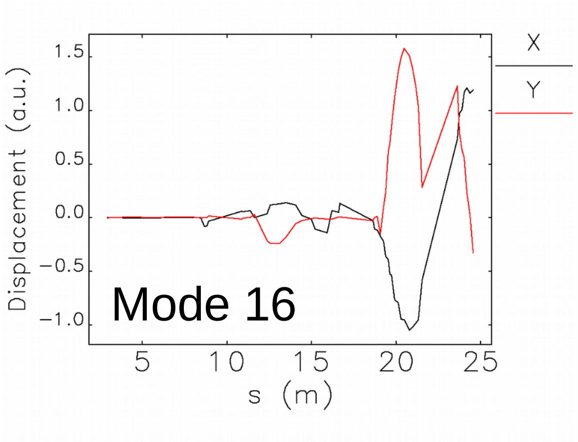


Table 2: Ground motion contributions from every resonant mode.

Mode	Frequency (Hz)	Ampl factor X	Ampl factor Y	X motion (nm) Measured	Y motion (nm) Measured
1	37.33	2.01	0.71	46	18
2	37.35	9.90	0.25	228	6
3	41.92	15.35	0.26	180	6
4	43.54	1.95	0.93	20	16
5	43.61	1.15	0.98	12	16
6	47.91	8.37	1.27	97	13
7	53.33	12.79	6.15	144	107
8	53.53	20.57	5.57	227	94
9	56.46	6.69	5.07	104	98
10	57.48	22.28	11.75	468	270
11	65.81	0.55	3.47	6	72
12	65.89	1.03	0.68	11	14
13	67.08	1.64	0.74	15	13
14	67.78	18.73	23.10	150	341
15	69.81	1.56	11.97	10	127
16	70.02	11.87	28.91	76	297
17	74.37	24.51	5.63	131	51



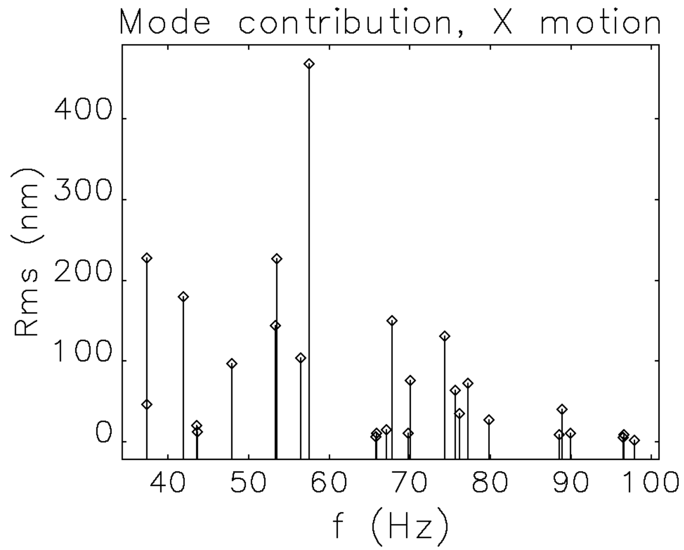


Resonance curve is used to calculate rms motion due to a mode

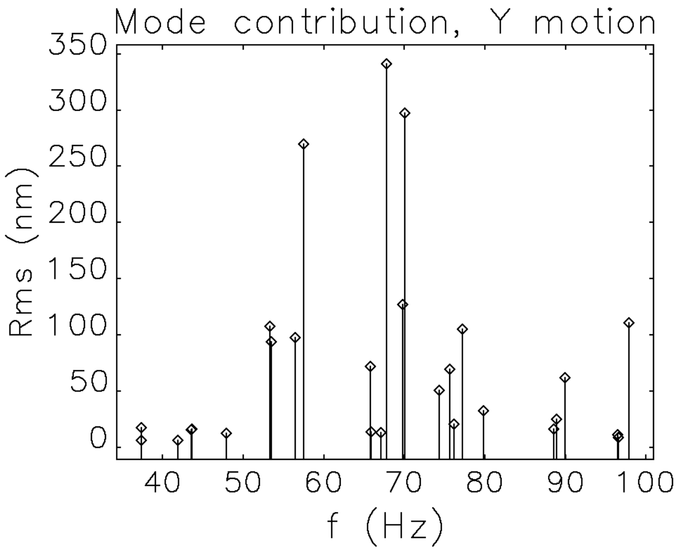
- For frequencies close to resonance, the motion amplitude can be described by resonance curve:
  - Hard to calculate far from resonance
  - Deviation from the resonance curve can be neglected between 0.5f_0 and 2f_0

$$\frac{x(\omega)}{X} = \frac{Q}{\sqrt{(\omega - \omega_0)^2 \left(\frac{2Q}{\omega_0}\right)^2 + 1}},$$

- *Q* factor is measured to be about 50
- Resulting orbit motion due to a mode is calculated using measured ground motion, resonance curve, and orbit amplification factor
  - Integration is limited to 0.5f_0 and 2f_0 band


Mode contribution, X motion

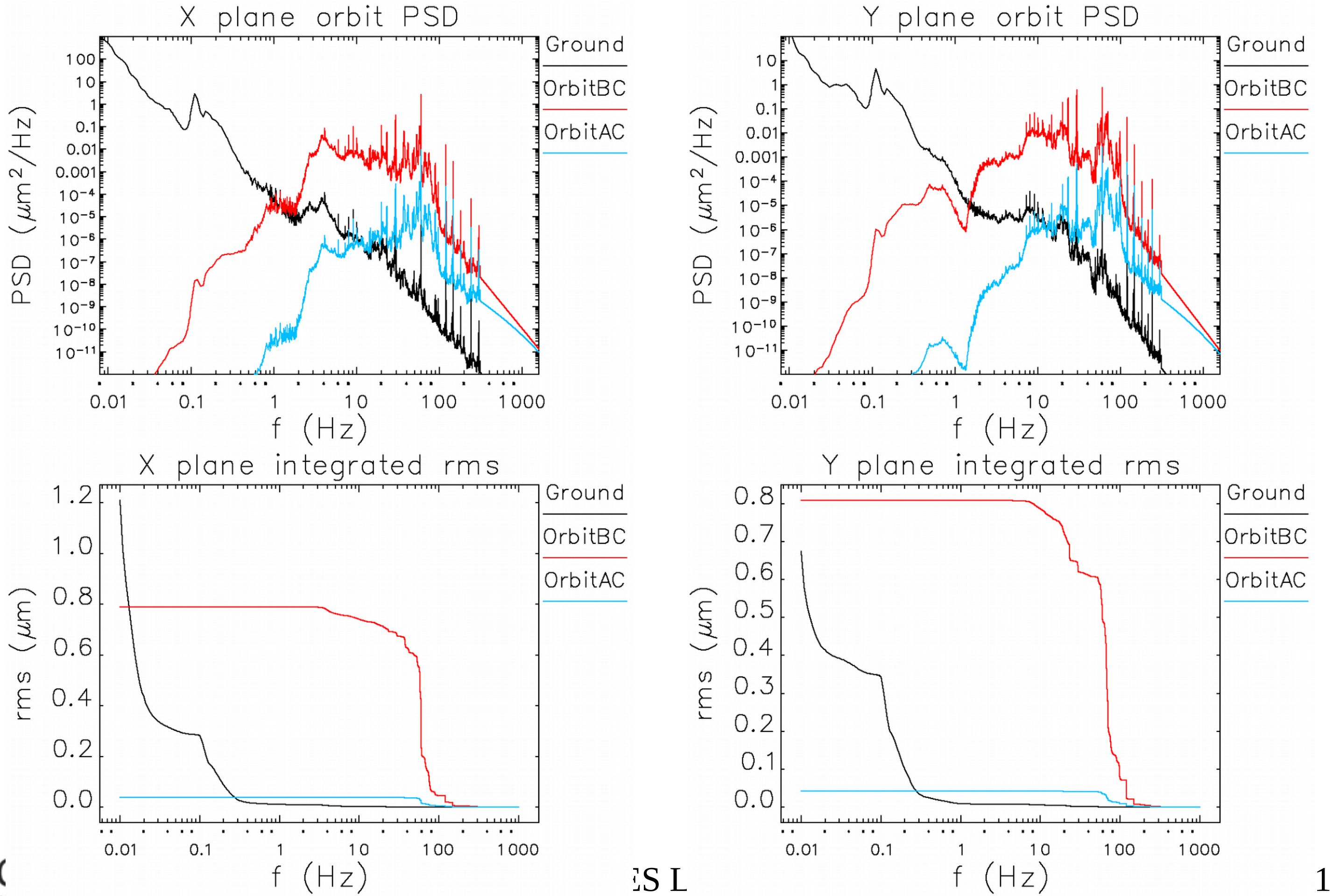
No orbit correction


Mode contribution, Y motion

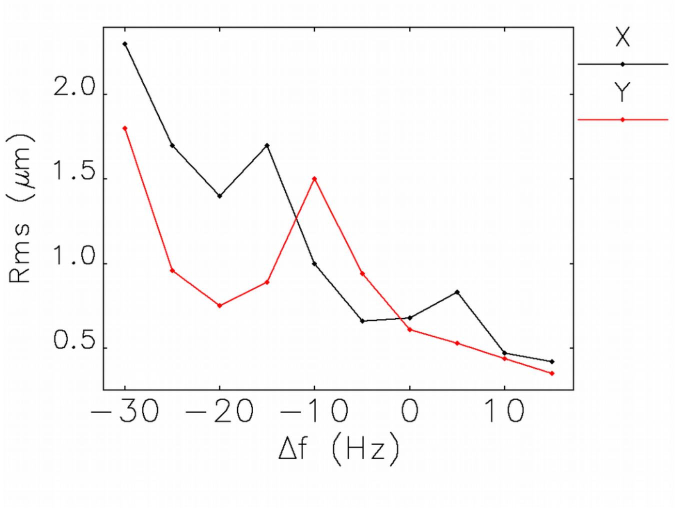
No orbit correction

Ground motion contribution is small with orbit correction running

- No magnet vibration other then mode related is expected; vacuum chamber vibration due to water flow was measured to be negligible
- Ground motion alone will result in 800 nm rms orbit noise without orbit correction and 40 nm with orbit correction (BPM electronics noise ignored)

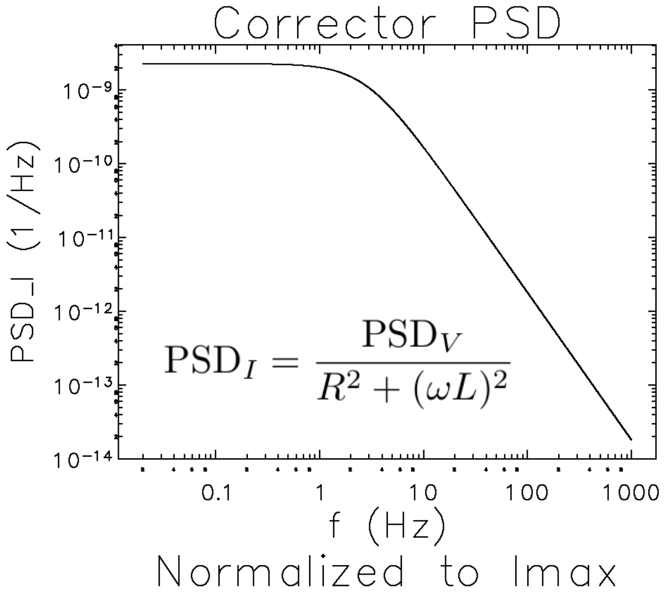


Orbit rms motion as a function of artificial shift of all resonant modes

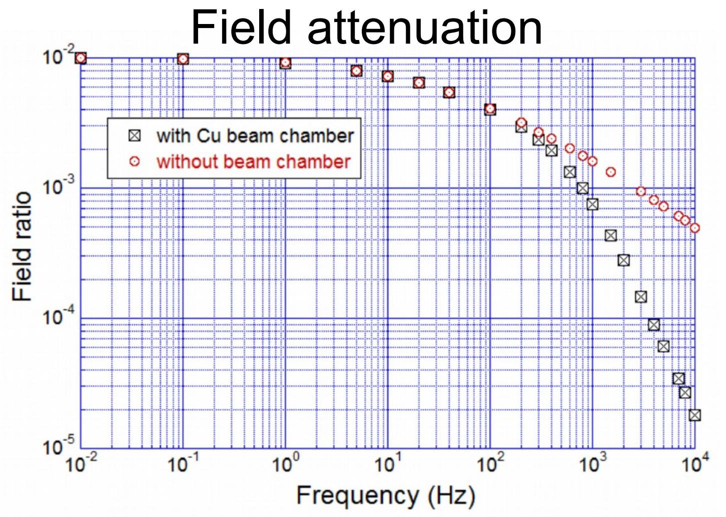


Measured voltage PSD and magnet parameters are used to obtain current PSD

- Output voltage PSD for test power supplies was measured to be nearly constant as a function of frequency
- Current PSD can be obtained from the voltage PSD using magnet resistance and inductance
  - R=0.3, L=0.017
- Solid-core magnets and vacuum chamber attenuate electrical noise at high frequencies
  - Simulations of field attenuation were performed using OPERA[1]



$$\mathrm{PSD}_I = \frac{\mathrm{PSD}_V}{R^2 + (\omega L)^2}$$



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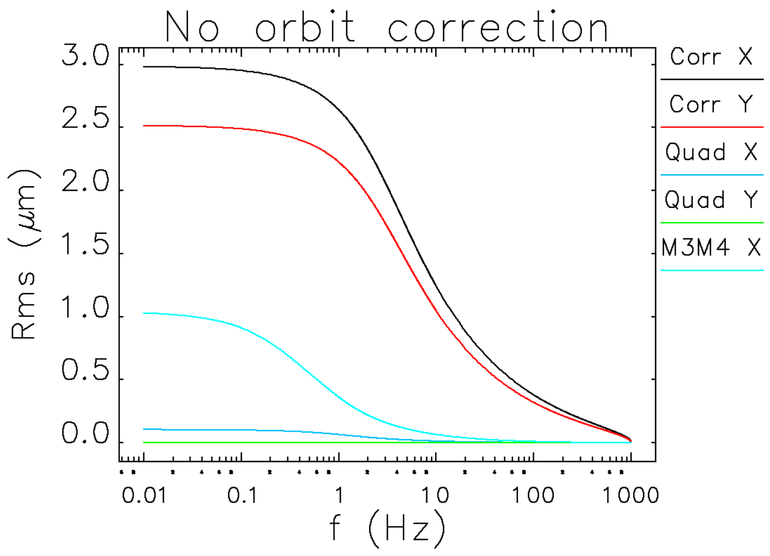
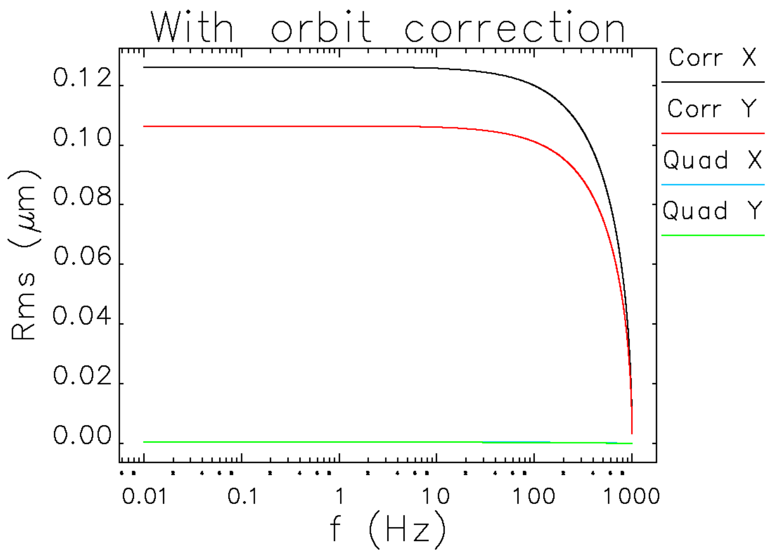
[1] S. Kim, Private communication

Orbit motion is calculated using orbit amplification factors

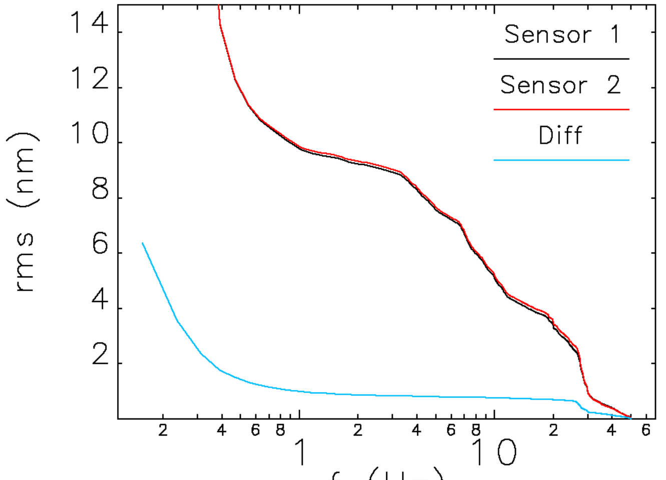
- Orbit amplification factors are calculated for every type of magnet assuming independent noise on every magnet
  - Noise amplification is frequency independent
- Corrector noise is the dominating effect
  - Rms orbit motion without orbit correction is about 3 µm
  - Rms orbit motion with orbit correction is about 120 nm
- Not all magnet parameters are known yet, some assumptions are made



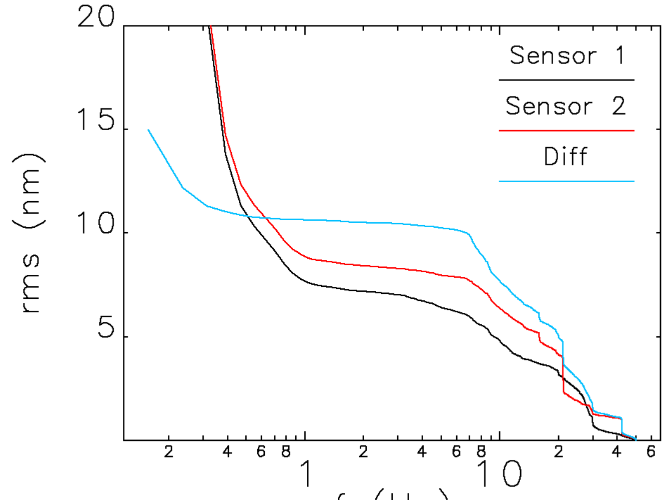


Relative motion of user sample and radiation point is small

- The user will see one more noise contribution: relative motion of the sample and the radiation point
  - It is the relative ground motion at distance of about 50 m
- We have measured the rms relative motion of the APS tunnel floor at different distances
- The measurement becomes unreliable at frequencies lower than 0.4 Hz (probably due to electronics noise)
  - The lower the frequency, the less relative motion should be seen; increase below 0.4 Hz when two sensors are sitting next to each other is non-physical
  - We use the rms motion in the band 0.4 Hz to 1 kHz as approximation for the full band
  - This approach should work in the absence of ground diffusion, which should be small above 0.01 Hz
- Relative motion of two points on the tunnel floor separated by 50 m is ~10 nm in 0.01 Hz to 1 kHz band



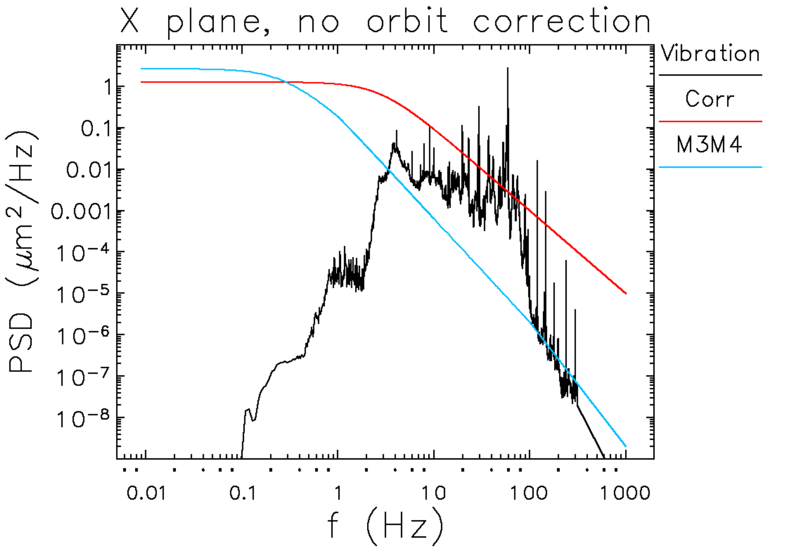
Distance 0.3 m

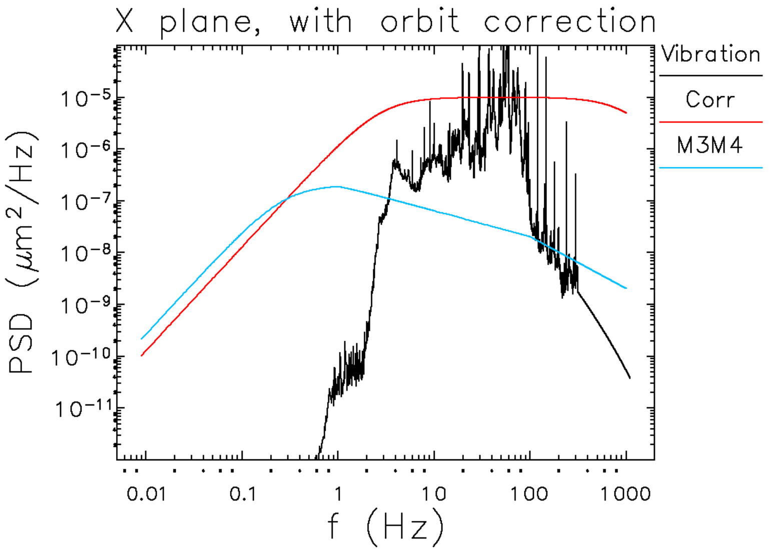


Distance 50 m

Overall motion is dominated by the corrector noise

- Correctors dominate the orbit noise in both planes
- Orbit motion with orbit correction is small
- Response matrix measurement accuracy using DC differential measurement[1] is not great
  - Using AC response matrix measurement will likely be required





Expected overall orbit motion:

	X (μm)	Y (μm)
No orbit correction	3.18	2.53
With orbit correction	0.13	0.11
RM measurement (DC, 1 second)	0.83	0.58
RM measurement (AC, 100 Hz)	0.03	0.03

[1] L. Emery, AOP-TN-2017-020

Conclusion: expected orbit motion will satisfy requirements

- APS floor motion coherence was measured
  - Coherent at large distances below 1 Hz
- Girder deformation modes were simulated using ANSYS
  - Entire sector was simulated as one unit
  - Many resonant modes starting at 37 Hz
- Due to relatively quiet environment at APS and due to ground motion being coherent below 1 Hz, expected orbit motion due to ground vibration is small:
  - 800 nm without orbit correction and 40 nm with orbit correction
- Overall expected orbit motion will be dominated by power supply noise of orbit correctors:
  - 3 μm without orbit correction and 0.13 μm with orbit correction