Ground diffusion and related APS-U stability predictions

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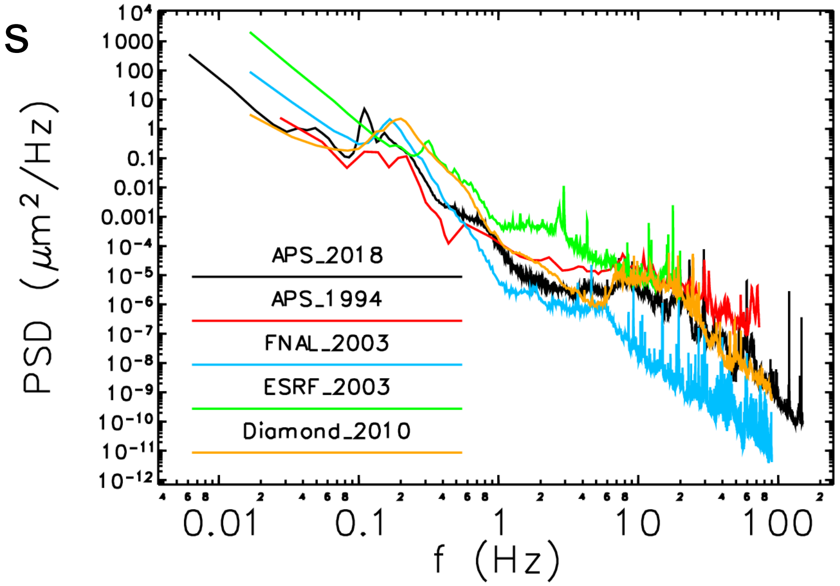
TWG meeting

Outline

- Ground motion introduction
- Diffusion constant estimation from the orbit correction effort
- APS-U predictions

Ground motion spectrum

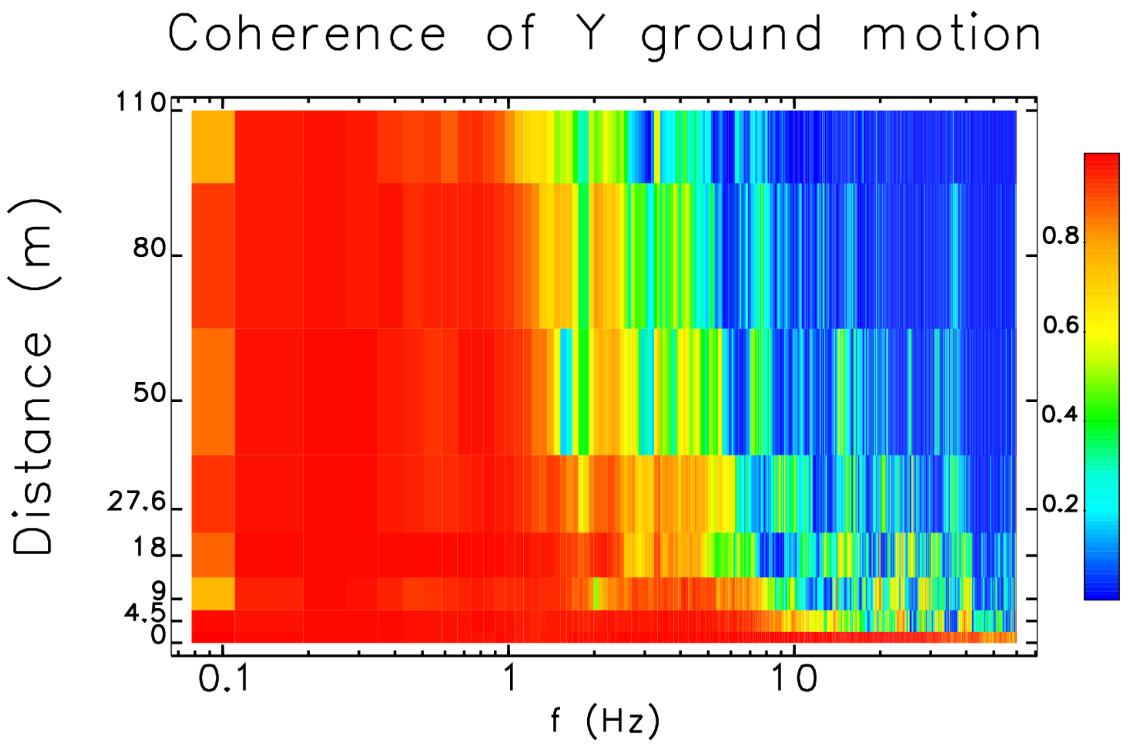
- Ground motion effect on accelerators has been observed long ago
- Ground motion PSD is approximately scales as $1/f^n$, where n is close to 4
- Below 1 Hz, the main sources are earth tides, atmospheric activity, water motion in oceans, temperature variation
- Anthropogenic sources usually dominate above 1 Hz
- APS floor motion is similar to other locations
  - APS measurements were performed using seismometers (0.008 – 50 Hz) and accelerometers (10 – 200 Hz)



- The rms ground motion increases rapidly when considered for longer time intervals due to $1/f^4$ PSD dependence
  - 1 – 100 Hz: 10 nm
  - 0.01 – 100 Hz: 2 μm

Coherence of ground vibration

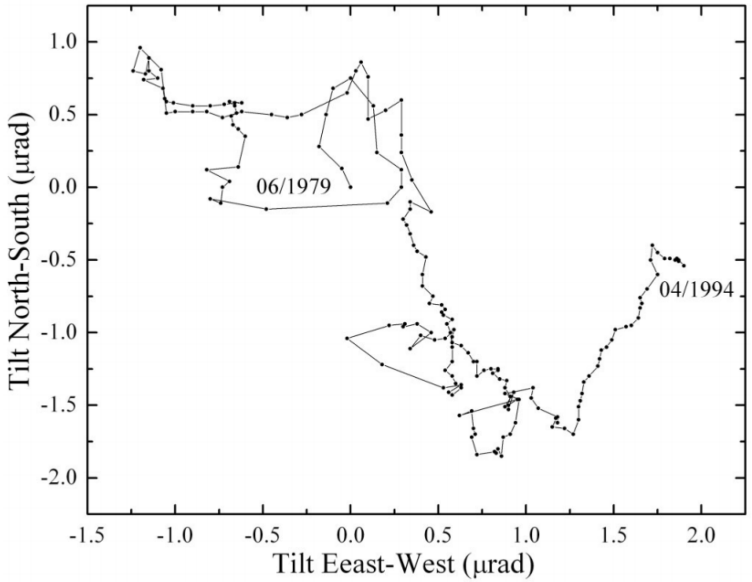
- Fortunately, slower vibration frequencies mean longer wavelengths, and floor points separated by some length L tend to move together
- APS tunnel floor motion coherence was measured using 2 seismometers located at different distances from each other[1]
- We found that the motion below 1 Hz is coherent for distances up to 100 m
  - Measurements below 0.1 Hz are hard due to electronics noise
- It appears that in long-term the entire accelerator and beamlines move together



[1]V. Sajaev, C. Preissner, 2018 IPAC Proc.

Stochastic ground motion

- Unfortunately, vibration is not the only type of ground motion – earthquakes
- Introduction of large scientific facilities like gravitational wave detectors and high-energy particle accelerators drew attention to microscopic long-term ground motion
  - Alignment of mirrors and magnets suffered as a result of ground motion
- Esashi Earth tide station utilized two 50-m-long water levels to measure floor slopes inside a mine over 15 years[1]
  - Looks like diffusive or Brownian motion



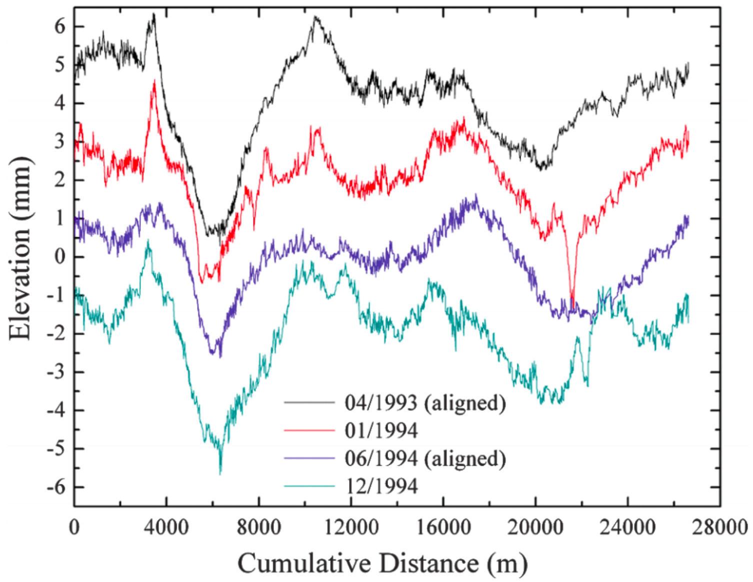
[1]National Astronomical Observatory Mizusawa; V. Shiltsev, PR-STAB, 13, 094801 (2010)

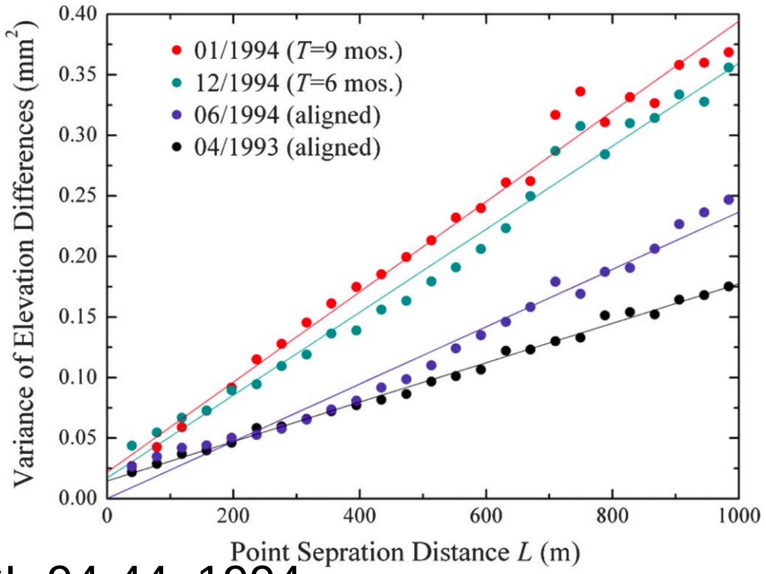
CERN LEP alignment data

- The alignment data of the world largest accelerator LEP (LHC is now in its tunnel) not only showed ground motion, but allowed to quantify the relative rms displacement of two points as a function of the distance between the points[1,2]
- Many measurements show that the stochastic ground motion can be described as diffusion in both time and space, and the relative position of two points can be expressed as

$$x_{\mathrm{rms}}^2 = AT^{\alpha}L^{\beta}$$

where α and β are close to 1





[1]M. Haubin, M. Mayoud, J.-P. Quesnel, and A. Verdier, CERN-SL-94-44, 1994
[2]V. Shiltsev, PR-STAB, 13, 094801 (2010)

Ground motion – ATL law

- Empirical "ATL law" was introduced[1] to describe relative ground motion of 2 points separated by distance *L* after time *T*:

$$x^2_{\text{rms ground}} = A\,T\,L$$

  where A is the "ATL constant" (units are m/s, or more conveniently μm^2/m/s, typical values are $10^{-5\pm1}$ μm^2/m/s)

		A, 10^{-6} μm^2/s/m	Time	Scale	Reference	Comments
		Beam orbit drifts in accelerators				
HERA-*e* vertical	*T*	4 ± 2	25 days	6.3 km	[18]	25 m deep, $\Delta L = 23$ m
HERA-*p* vertical	*T*	8 ± 4	5 days	6.3 km	[17,18]	25 m deep, $\Delta L = 47$ m
TRISTAN vertical	*T*	27 ± 7	2 days	3.0 km	[17,19]	12 m deep, $\Delta L = 47$ m
Circumference KEK-B	*T*	27 ± 3	4 months	3.0 km	[20]	$\beta \approx 2.2$
		Accelerator Alignment Data Analysis				
CERN LEP vertical	*L*, *T*	6.8–9.0	6, 9 mos	26.7 km	[17,26]	45–170 m deep
		3 ± 0.6	6 years	26.7 km	[27]	$\Delta L = 39$ m
CERN SPS vertical	*L*, *T*	14 ± 5	3–12 yr	6.9 km	[28]	50 m deep, $\Delta L = 32$ m
Tevatron vertical	*L*, *T*	4.9 ± 0.1	1–6 yr	6.3 km	[29,30]	~7 m deep, $\Delta L = 30$ m
SLAC PEP vertical	*L*	100 ± 50	20 mos	2 km	[28]	Cut-and-cover tunnel
		Geophysics Instruments Data				
PFO (CA, USA)	*T*	0.7	5 yr	732 m	[32]	Laser interferometer
SLAC linac vertical	*T*	1.4 ± 0.2	0.5 hr	3 km	[34]	$\Delta L = 1500$ m
	T	0.2–2	1 hr	3 km	[35]	From PSD fit
CERN PS pillar	*T*	3 ± 1	2.5 yr	10 m	[36,37]	10 m depth

[1]B. Baklakov, et.al., Technical Physics, v.38(10) 1993;
V. Shiltsev, PRL 104(23), p.238501 (2010)

Ground motion – ATL law

- Resulting orbit distortion[1]:

$$x^2_{\mathrm{rms\ orbit}} = \kappa^2_{\mathrm{ground}} A\, T\, C$$

  where κ_{ground} is the diffusion motion amplification factor and C is the machine circumference

- The orbit errors generated by the ground diffusion are corrected by the orbit correction:

$$\theta_{\mathrm{rms}} = D\sqrt{T},$$

- If ATL motion is the main source of the long-term orbit correction effort, measurement of the *D* coefficient would allow us to calculate the ATL constant
- Another possible source of long-term orbit correction effort are Beam Position Monitor (BPM) drifts
  - We were always aware of corrector changes during the week-long runs but never analyzed it and attributed it to BPM drifts
  - We will later show that this effect is negligible

[1]V. Shiltsev, Proc. IWAA 1995, pp. 352-381

Process for *A* calculation:

- The ground motion is described by the ATL law as $$x^2_{\text{rms ground}} = A\ T\ L$$
- This leads to orbit orbit distortion: $$x^2_{\text{rms orbit}} = \kappa^2_{\text{ground}} A\ T\ C$$
- Corresponding orbit correction effort: $$\theta_{\text{rms}} = D\sqrt{T},$$
- The rms orbit errors produced/corrected by correctors: $$x_{\text{rms orbit}} = \kappa_{\text{corr}} \cdot \theta_{\text{rms}} = \kappa_{\text{corr}} D\sqrt{T},$$
- Constant A is obtained using measured value of D and simulated values of κ_{corr} and κ_{ground}: $$A = \left(\frac{\kappa_{\text{corr}} D}{\kappa_{\text{ground}}\sqrt{C}}\right)^2$$

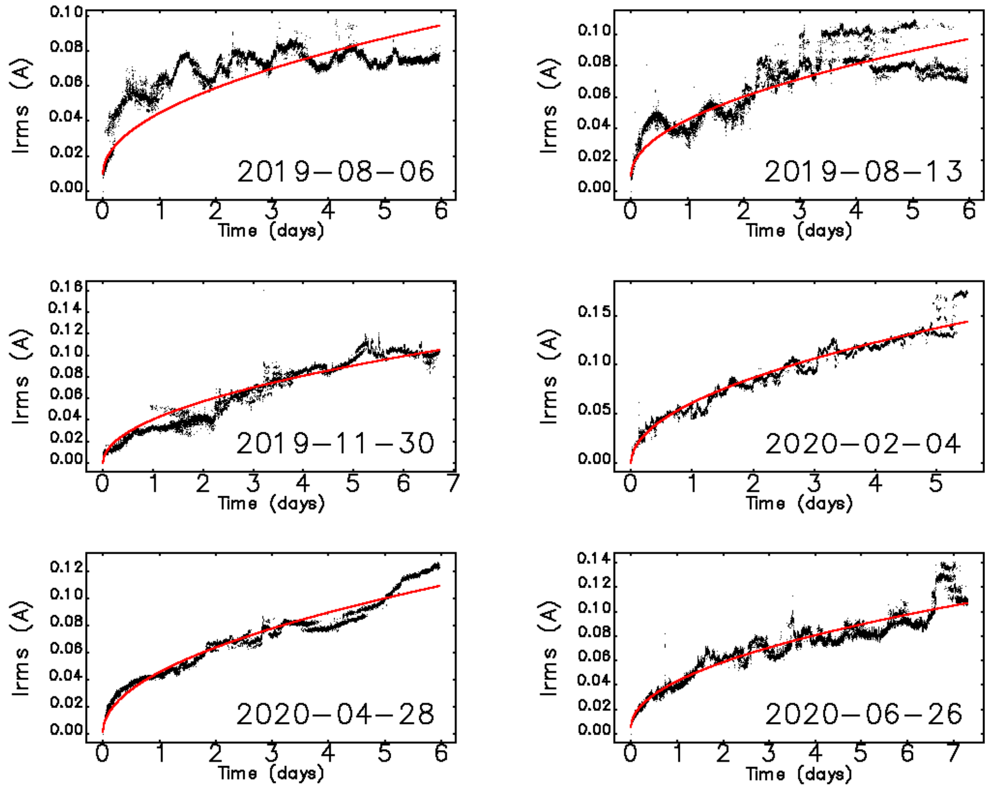
Corrector effort analysis

- Found 37 uninterrupted beam operation periods longer than 5 days over last 5 years
- Sudden orbit events like user steering and BPM reading jumps are not related to ground diffusion and need to be excluded
  - Automated artifact removal took care of some of the events but not all of them
- Used rather simple processing after that:
  - Initial corrector value is subtracted from each corrector data to start from zero
  - For every time moment, rms corrector strength over all correctors (80 for X and 120 for Y planes) is calculated
  - Fit sqrt(T) function

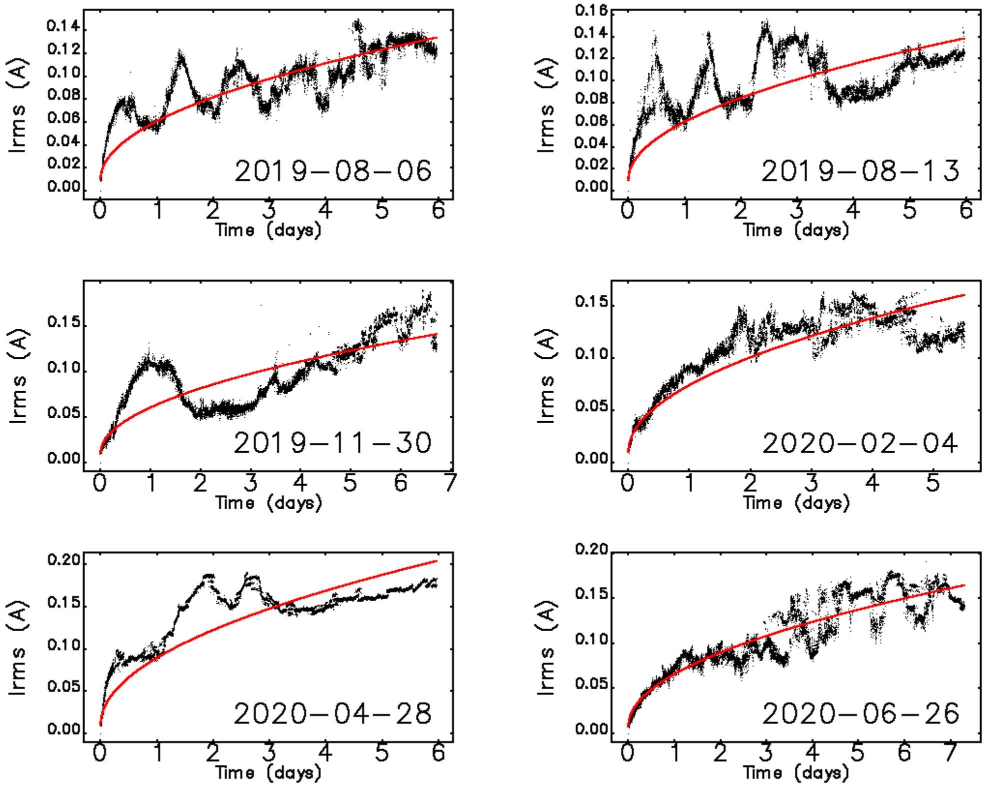
Corrector data do resemble sqrt(T) dependence

- Rms corrector effort for 6 typical operation periods
  - The data mostly fits √T behavior

X correctors



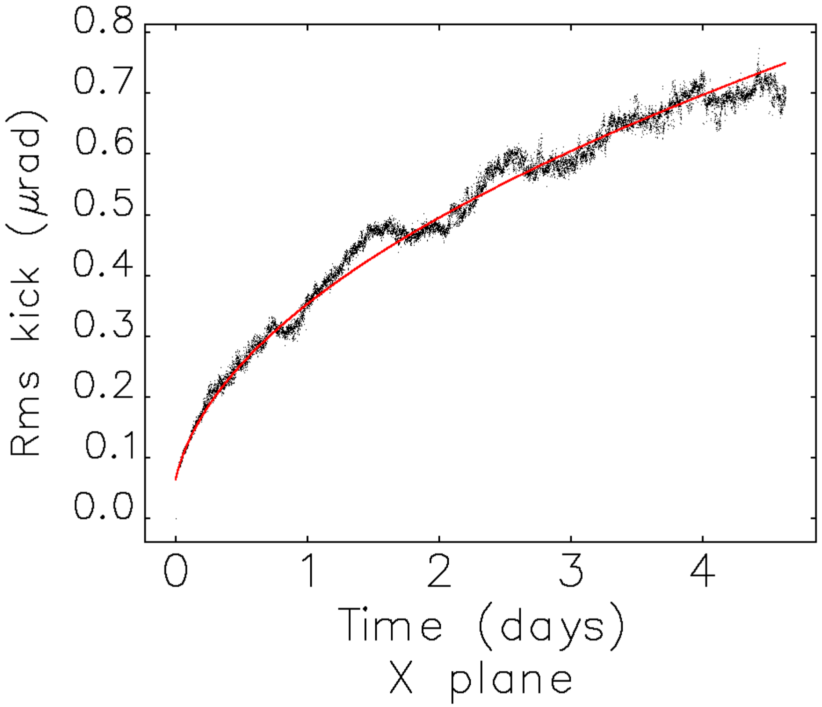
Y correctors



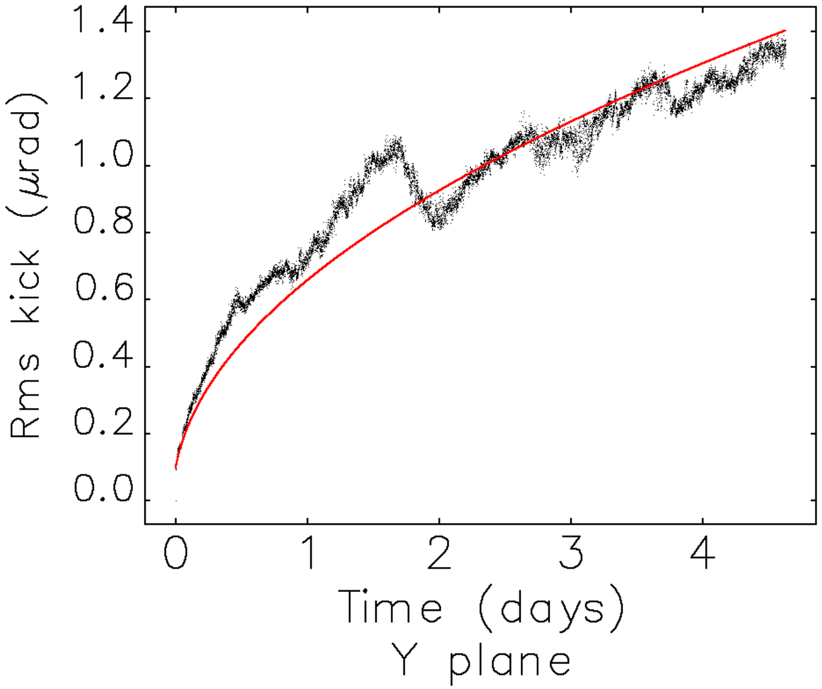
Median corrector data fits √T well

- All 37 data sets were used to calculate median rms corrector effort, which showed rather good √T behavior

Horizontal correctors



Vertical correctors



Results for *A* are in the middle of the other facilities' values

- Calculations give

$$A_\mathrm{x} = 5.4 \cdot 10^{-18}\ \mathrm{m/s}, \quad A_\mathrm{y} = 1.0 \cdot 10^{-17}\ \mathrm{m/s}$$

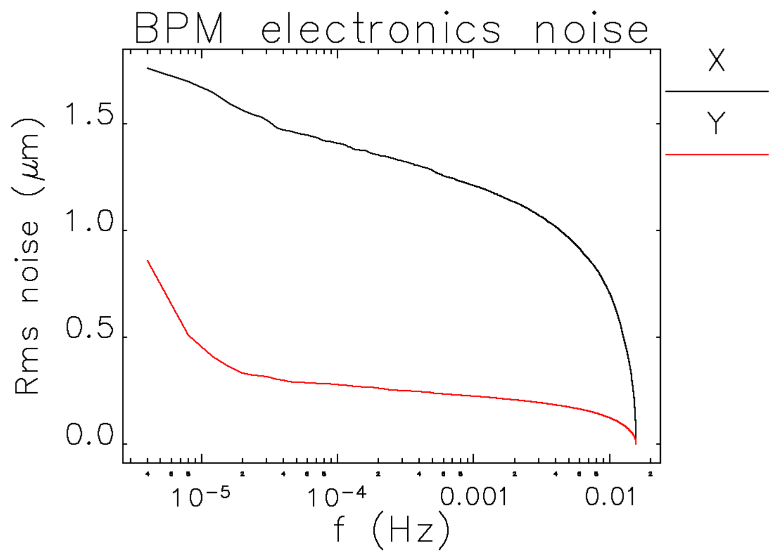
- In practical units:

$$A_\mathrm{x} = 5.4 \cdot 10^{-6}\ \mu\mathrm{m}^2/\mathrm{m/s}, \quad A_\mathrm{y} = 1.0 \cdot 10^{-5}\ \mu\mathrm{m}^2/\mathrm{m/s}.$$

- This numbers are considered upper limits since not all non-ATL orbit events were excluded (user steering, malfunctioning BPMs, etc)

BPM noise is small

- Beam Position Monitor electronics noise can be measured using combiner-splitter
- Measurements were performed during Run 1, 2018
  - Noise PSD was averaged over many one-day-long intervals
- Over one day (10^5 seconds), the BPM electronics rms noise is 1.5 μm in X and 0.5 μm in Y planes
- The rms corrector efforts during that time correspond to 43 μm in X and 23 μm in Y planes
- Clearly, long-term orbit correction effort is not cased by BPMs



ATL ground motion will affect APS-U orbit much stronger than APS

- Simulations give much larger ATL ground motion amplification factors for APS-U than those of APS – by a factor of 7 in X and by a factor of 22 in Y
  - It means that the same ground displacement will cause 7 to 22 times larger orbit distortion
  - It is a consequence of much stronger focusing of APS-U lattice
  - It is not really a concern – the changes are slow and the orbit correction will take care of it

Long-term photon source stability – one week

- Will use $A=5\cdot10^{-6}$ $\mu m^2/m/s$ for APS-U ground motion estimates

Rms motion of A:P0 relative to B:P0	5 m	1 week	4 μm
Rms motion of ID straight section relative to x-ray BPM	20 m	1 week	8 μm
Rms motion of x-ray BPM relative to a user station	40 m	1 week	11 μm
Rms corrector effort		1 week	9 μrad

- This results in the following photon source stability as seen by a user 60 m away* (rms electron beam sizes for full coupling are 2.4 μrad and 8.7 μm):
  - Source is important for imaging beamlines
  - Angle is important for non-imaging beamlines

	Case	Source angle	Source position
	No x-ray BPM, no HLS	0.8 μrad	14 μm
X -plane →	x-ray BPM, no HLS	0.43 μrad	14 μm
Y -plane →	x-ray BPM, HLS	0.18 μrad	11 μm

*User hatches are located on a different slab, so motion could be larger

Long-term stability – month to lifetime

- Will use $A=5\cdot10^{-6}$ for APS-U ground motion estimates

Rms orbit change after 1-month shutdown	1 month	2 mm
Rms corrector effort after 1-month shutdown	1 month	19 μrad
Rms displacement, girder to girder one sector away	1 year	65 μm
Rms corrector effort	1 year	65 μrad
Rms displacement, girder to girder one sector away	20 years	300 μm
Rms corrector effort	20 years	290 μrad

- Will likely need some sort of commissioning after 1-month shutdown (1st-turn correction + orbit + optics)
- Will likely need girder re-alignment every few years

Conclusions

- Estimated diffusion constant for APS tunnel floor: $A \approx 5–10 \cdot 10^{-6}$ μm^2/m/s
  - Used orbit correction effort over 5-day-long data sets
  - It is somewhat small for an on-surface tunnel
- Due to strong APS-U focusing and betatron tune close to integer, the ground diffusion effect on the orbit will be 20 times larger than that of APS
  - Will not be an issue for orbit correction
- Estimated that the source position relative to the end station will be changing over a week by ~20% of the beam size in angle and ~100% of the beam size in position
  - If that is not acceptable, a beam position monitor at the end station should be considered
- Closed orbit will likely be exceeding aperture after month-long maintenance shutdowns
  - Some sort of first-turn correction/commissioning will be required
- Girder re-alignment will likely be needed every few years (not needed annually)