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GROUND DIFFUSION MEASUREMENT AND ITS EFFECT ON APS-U ORBIT STABILITY*

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Abstract

Spatial and temporal ground diffusion can be approximately described by the ATL law [1, 2]. Ground diffusion can have an important effect on the long-term stability of accelerator alignment. To estimate the possible consequences of ground diffusion on APS Upgrade [3] performance, the ground diffusion constant of the existing APS tunnel was measured using two methods: the orbit correction effort analysis and the hydrostatic level system. It was then used to estimate the ground diffusion effect on the orbit stability of the APS Upgrade. In this paper, we will describe the diffusion constant measurement and present estimations of the expected APS-U alignment and orbit stability.

INTRODUCTION

Ground diffusion is often described by an empirical "ATL law" [1, 2] as $x^2_{\text{rms}} = AT^{\alpha}L^{\beta}$, where x_{rms} is the rms relative displacement between two points separated by a distance L after a time interval T, and A is a constant that depends on the particular site. The constant exponents α and β are usually assumed to be unity. There are various ways of measuring the constant A as described in [4]. We used two methods – orbit correction effort and hydrostatic leveling system (HLS) measurements. The hydrostatic leveling system directly gives the relative vertical displacement of two points, so the processing is straightforward. The idea behind the method utilizing the orbit correction effort is the following [5]: as the ground experiences diffusive motion over long periods of time, it moves the magnet girders, which results in orbit distortion; orbit correction corrects for this orbit distortion, therefore the orbit correction effort can be used to characterize the ground motion. The calculation goes as follows. The ground motion is described by the ATL law as

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

where constant A has units m/s. More convenient units µm^2/m/s are also often used. This leads to orbit distortion [6]:

$$x^2_{\text{rms orbit}} = \kappa^2_{\text{ground}} A\,T\,C, \tag{1}$$

where κ_{ground} is the orbit amplification factor due to ground motion, and C is the circumference of the storage ring. The orbit errors generated by the ground motion are corrected by orbit correction, and the time evolution of the rms orbit correction effort can be described according to Eq. (1) as:

$$\theta_{\text{rms}} = D\sqrt{T}, \tag{2}$$

where D is the coefficient obtained from the fitting of the archived orbit correction effort. The rms orbit errors that are produced (or corrected) by correctors can be described as:

$$x_{\text{rms orbit}} = \kappa_{\text{corr}} \cdot \theta_{\text{rms}} = \kappa_{\text{corr}} D\sqrt{T}, \tag{3}$$

where κ_{corr} is the orbit amplification factor of the corrector effort. Equating expressions from Eqs. (1) and (3), the ATL coefficient A can be determined as:

$$A = \left(\frac{\kappa_{\text{corr}} D}{\kappa_{\text{ground}}\sqrt{C}}\right)^2. \tag{4}$$

Now to determine the constant A, one needs to find the amplification factors κ and the fitting coefficient D.

ORBIT CORRECTION EFFORT

Typical mean time between faults during APS operation is about 100 hours, or four days. Only uninterrupted run periods were used for analysis because the orbit changes after beam dumps might be caused by other than ground motion changes. 37 uninterrupted periods longer than 5 days were found over the last five years of APS operation. Sudden orbit events not related to diffusive ground motion, such as deliberate user steering, BPM reading jumps due to malfunctions, and others, were removed by the analysis.

APS orbit correction utilizes 80 and 120 correctors in the X and Y planes, respectively. First, the analysis subtracts the initial corrector values from each corrector data set so that the corrector time evolution starts from zero. Then, the corrector rms value is calculated for each subsequent time moment. After that, the median time evolution of the corrector strength is calculated over all data sets. The results are shown in Fig. 1. According to the ATL law, the rms corrector strength evolution should be proportional to $\sqrt{T}$. One can see that the median time evolution of the rms corrector strength follows the square root of time dependence rather well. Coefficients of the $\sqrt{T}$ fit calculated using multiple data sets (before taking median) are given below:

$$D_x = (1.2 \pm 0.3) \cdot 10^{-9}\ \text{rad}/\sqrt{\text{s}}$$
$$D_y = (2.2 \pm 0.5) \cdot 10^{-9}\ \text{rad}/\sqrt{\text{s}}.$$

Orbit distortion due to random correctors is easy to simulate as well as estimate analytically. Simulations using `elegant` [7] give the following values for the orbit amplification factors due to correctors:

$$\kappa_{\text{corr}_x} = 140\ \text{m/rad}, \quad \kappa_{\text{corr}_y} = 46\ \text{m/rad}.$$

As expected, analytic calculations give very close values.

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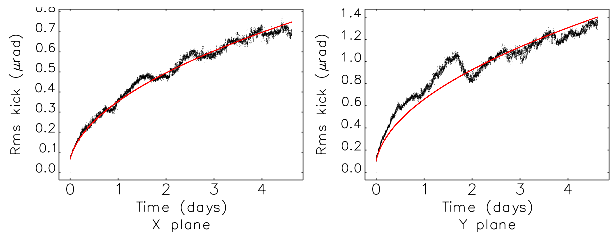

Figure 1: Median time evolution of the rms corrector strength during user operation. Red line shows $\sqrt{T}$ fit.

In order to simulate orbit distortion due to diffusive ground motion, one needs to generate corresponding ground displacement. Generating 1D diffusive displacement is easy – it is a simple random walk sequence where each next value is obtained by adding a gaussian-distributed random step δx to the previous value. For a circular accelerator, the ground displacement needs to be two-dimensional. Generating 2D diffusive displacement is much more involved [8], so it was decided to adopt the following simplified approach to generate ground displacement for APS simulation. First, a 1D transverse random walk displacement sequence $x(n)$ is generated at 1-m intervals, for n from 0 to 1104, where 1104m m is the APS circumference. For a circular machine, the end of the sequence should be equal to the beginning of the sequence. This condition is enforced by subtracting overall slope $(x_{1104} - x_0)/1104$ from every value of the sequence. Here, advantage is taken of the fact that the 175-m APS average radius is very large compared to the displacements, so the problem is almost one-dimensional.

To simulate the orbit distortion due to diffusive ground motion, the horizontal and vertical ground displacements are generated first based on the just-described method. Then, the quadrupole displacements are generated the following way: the first and last quadrupoles on each girder are assigned displacements equal to that of the ground, then the quadrupoles in between are assigned displacements on a straight line connecting the first and last quadrupoles. These displacements are loaded into the `elegant` model and used to compute the closed orbit. This procedure is repeated 500 times with different error seeds, and the orbit rms is calculated at insertion device BPM locations over all orbits and all insertion device BPM locations. The orbit amplification factors of the diffusive motion are then calculated using

$$\kappa_{\text{ground}} = \frac{x_{\text{rms orbit}}}{\delta x \sqrt{N}},$$

where δx is the rms size of the single displacement step and N is the number of sequence steps over storage ring circumference (N=1104 for APS with 1-m-long steps). The values obtained in simulations are

$$\kappa_{\text{ground}_\text{x}} = 2.0, \quad \kappa_{\text{ground}_\text{y}} = 0.70.$$

Now the Eq. (4) can be used to calculate A:

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

Note that since the effect of other events such as user steering, BPM reading jumps, etc cannot be fully excluded, these values should be considered upper limits for the diffusive ground motion constants.

Long-term BPM Noise

Orbit correction reacts to beam position monitor (BPM) reading changes. Those readings are subject to electronic noise. To make sure that the orbit correction action analyzed above is not caused by the BPM electronic noise, the long-term BPM noise was analyzed using a combiner-splitter method [9]. The measurement requires the presence of the beam, so the low-frequency boundary of the analysis was still limited to a few days. It was found that the BPM electronics rms noise was approximately 1.5 μm for horizontal and 0.5 μm for vertical planes in the frequency band between 10^{-5} and 10^{-2} Hz. For the same band, the orbit motion due to ground diffusion is estimated to be 43 μm in horizontal and 23 μm in vertical planes. Clearly, the orbit correction effort shown in Fig. 1 could not be caused by the BPM noise.

HYDROSTATIC LEVELING SYSTEM

A prototype hydrostatic leveling system (HLS) was installed in the APS tunnel in 2014 to test the design intended for APS-U installation [10]. It consisted of three sensors located on a straight line in sequence BP0, AP0, GRID with distances between them of 5 m (BP0 to AP0) and 16 m (AP0 to GRID). After sitting in the tunnel for some time, the sensor signals became very noisy, probably due to radiation damage to the electronics. Four usable three-month-long data sets were found in the data archives.

To allow sufficient averaging, each three-month-long data set was split into 21-day-long subsets with 90% overlap. For each subset, the relative displacement of the sensors was calculated starting from zero. Then, the standard deviation of the displacement was calculated over all subsets for every time moment. Figure 2 shows the resulting time evolution of the standard deviation of the sensor displacement. Like the corrector effort discussed above, the time evolution of sensor displacements should be described by the square root of time. Square root fits are also shown on the plots. The 21-day length of subsets was chosen because for longer subsets the time dependence becomes noisier due to less averaging.

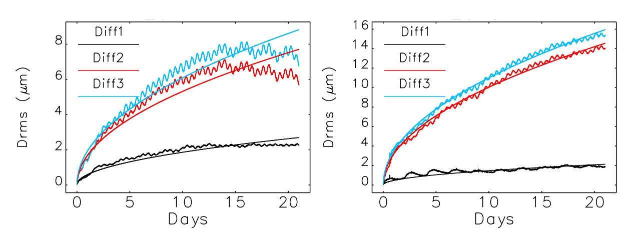

Figure 2: Time evolution of the rms relative displacements of the sensors for two 3-month-long periods. Three values shown are the relative displacements between the three sensors. Square root fits are also shown.

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Table 1 gives the results of the diffusion constant calculation using the fits shown in Fig. 2. One can see that the diffusion constant calculated based on short distance between the sensors is about a factor of 10 less than the ones calculated using the longer distances. It is possible that the thick concrete floor of the tunnel attenuates the ground diffusion for nearby points, but this feature was not studied any further.

Table 1: Ground Diffusion Constant A in Units of 10^{-6} µm^2/m/s Measured Using Hydrostatic Leveling System

Run	BP0 – AP0 L = 5 m	AP0 – GRID L = 16 m	BP0 – GRID L = 21 m
2017–1	0.80	2.0	2.0
2017–3	0.22	6.8	5.6
2018–1	0.50	7.3	6.7
2018–2	0.30	3.8	3.5
Average	0.46 ± 0.26	5.0 ± 2.5	4.5 ± 2.1

APS-U ESTIMATIONS

To estimate the ground diffusion effect on APS-U, a value of $5 \cdot 10^{-6}$ µm^2/m/s will be used for the diffusion constant. The ground and corrector amplification factors for the APS-U lattice were calculated using simulations:

$$\kappa_{\mathrm{ground}_x} = 14, \quad \kappa_{\mathrm{ground}_y} = 16,$$
$$\kappa_{\mathrm{corr}_x} = 90 \text{ m/rad}, \quad \kappa_{\mathrm{corr}_y} = 115 \text{ m/rad}.$$

Below are a few estimations of the expected ground and orbit motion over various time intervals. The maximum available corrector strength is 300 µrad for the fast correctors.

- The expected rms motion of an ID straight section relative to the corresponding x-ray BPM over one week — 8 µm; relative motion of x-ray BPM and a user station over one week — 11 µm ($T = 6 \cdot 10^5$ s, $L_1 = 20$ m, $L_2 = 40$ m)
- Rms orbit change after a month-long maintenance shutdown — 2 mm; corresponding rms corrector effort — 19 µrad ($T = 2.6 \cdot 10^6$ s)
- The expected rms motion of a girder relative to the same girder one sector away over one year — 65 µm ($T = 3.15 \cdot 10^7$ s, $L = 27$ m); rms corrector effort over one year — 65 µrad
- The expected rms motion of a girder relative to the same girder one sector away over twenty years (presumable facility lifetime) — 300 µm ($T = 6.3 \cdot 10^8$ s, $L = 27$ m); rms corrector effort over twenty years — 290 µrad

All numbers obtained above are estimates. Since the ATL constant was determined using one- or three-week-long data, the prediction for longer periods of time could be off. In addition, the numbers are rms values, and the variation from one time period to the next could be rather large. Keeping these limitations in mind, a one-week period should not present any difficulties for the accelerator. A month-long maintenance shutdown could result in 2 mm rms orbit distortion, which means that some sort of first-turn trajectory correction might be needed in order to store the beam (APS-U vertical aperture is only ±3 mm in ID locations). Annual realignment should not be needed, but some realignment will definitely be required after several years.

Three cases were examined for photon beam stability: no x-ray BPM and no hydrostatic leveling system; x-ray BPM without HLS (horizontal plane case); x-ray BPM with HLS (vertical plane case). Using the one-week number from above and assuming that the HLS allows freezing the relative locations of the electron beam BPMs B:P0 and A:P0, and the x-ray BPM, one can calculate the expected x-ray source stability. The results are given in Table 2. Position stability is important to imaging beamlines, while angle stability is important to non-focusing beamlines. One can see that both x-ray BPMs and HLS improve the stability, though not dramatically.

Table 2: Expected Rms Photon Beam Source Stability 60 m Away From ID Over One Week Period Assuming no Beamline Optics. Rms Electron Beam Sizes are 2.4 µrad and 8.7 µm (Fully Coupled Beam, Smallest x or y Numbers)

Case	Angle	Position
No x-ray BPM, no HLS	0.8 µrad	14 µm
x-ray BPM, no HLS	0.43 µrad	14 µm
x-ray BPM, HLS	0.18 µrad	11 µm

CONCLUSIONS

We estimated the horizontal- and vertical-plane ATL constants for the APS floor using multiple sets of one-week-long APS orbit correction data. We also estimated the vertical ATL constant using the prototype hydrostatic leveling system in sector 27. Based on these two calculations, the value of the constant is about $5 \cdot 10^{-6}$ µm^2/m/s in the horizontal and $10 \cdot 10^{-6}$ µm^2/m/s in the vertical.

We then used this constant to make predictions about APS-U girder motion and corrector effort. We estimate that the relative motion of an ID straight section and the corresponding x-ray BPM will be about 8 µm over one week. This motion in vertical plane will be corrected using the hydrostatic leveling system, but it will remain uncorrected in the horizontal plane, generating about 0.4 µrad rms x-ray pointing error. We also estimate that after a month-long maintenance shutdown, the ground motion will result in about 2 mm rms orbit distortion, which means that some sort of first-turn trajectory correction and further commissioning might be needed after every shutdown. As far as girder realignment, we estimate that it will be needed every few years.

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REFERENCES

[1] B. Baklakov *et al.*, "Study of Seismic Vibrationsfor the VLEPP Linear Collider," *Tech. Phys.*, vol. 63, pp. 894-898, 1993.

[2] V. Shiltsev, "Observations of random walk of the ground in space and time," *Phys. Rev. Lett.*, vol. 104, p. 238501, 2010. doi:10.1103/PhysRevLett.104.238501

[3] M. Borland *et al.*, "The Upgrade of the Advanced Photon Source," in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, BC, Canada, May 2018, pp. 2872–2877. doi:10.18429/JACoW-IPAC2018-THXGBD1

[4] V. Shiltsev, "Review of observations of ground diffusion in space and time and fractal model of ground motion," *Phys. Rev. ST Accel. Beams*, vol. 13, p. 094801, 2010. doi:10.1103/PhysRevSTAB.13.094801

[5] R. Steinhagen, S. Redaelli, and J. Wenninger, "Analysis of ground motion at SPS and LEP – implications for the LHC," CERN, Geneva, Switzerland, Rep. CERN-AB-2005-087, 2005.

[6] V. Shiltsev, "Space-time ground diffusion: The ATL law for accelerators," in *Proc. 4th International Workshop on Accelerator Alignment (IWAA'95)*, Tsukuba, Japan, Nov. 1995, p. IV/352.

[7] M. Borland, "elegant: a flexible SDDS-compliant code for accelerator simulation," Advanced Photon Source, ANL, IL, USA, Rep. ANL/APS LS-287, 2000.

[8] A. Wolsky and N. J. Walker, "A model of ATL ground motion for storage rings," in *Proc. 20th Particle Accelerator Conf. (PAC'03)*, Portland, OR, USA, May 2003, paper WPPE036, pp. 2396–2398.

[9] A. Brill, private communication, 2019.

[10] R. Lill *et al.*, "Design and Development of a Beam Stablity Mechanical Motion System Diagnostic for the APS MBA Upgrade," in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, Va, USA, May 2015. doi:10.18429/JACoW-IPAC2015-MOPWI010