LONG-TERM ORBIT STABILITY IN THE PETRA III STORAGE RING

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Abstract

The study of long-term orbit stability in the PETRA III light source plays an important role for the design of its upgrade to PETRA IV. The PETRA III tunnel is made of individual segments that move against each other. Here, the long-term drifts of the tunnel ground that are mostly introduced by temperature variations, are of the highest concern for the PETRA IV alignment tolerances and orbit stability. This paper studies the evolution of the beam orbit and corrector magnet currents over several years and correlates tunnel movement to RMS orbit drifts.

INTRODUCTION

The third-generation light source PETRA III in Hamburg is operated since 2009. An overview of its tunnel layout is shown in Fig. 1. The naming convention to identify locations in the storage ring follows geographic directions. As indicated in Fig. 1, PETRA III provides synchrotron light in the hard X-ray range to its users in the three experimental halls, the so-called *Paul P. Ewald Hall* (Ewald Hall) in the North, the *Max von Laue Hall* (Laue Hall) in the North-East and the *Ada Yonath Hall* (Yonath Hall) in the East.

The storage ring tunnel was build from individual tunnel segments in 1976 to host the electron-positron collider PETRA I. It is constructed of 82 segments [1] with varying length: the major part (57 segments) are 24 m long, the shortest segment measures only 10.4 m, and the three experimental halls build the longest segments with up to 286.0 m (Laue Hall).

Natural ground motion and temperature effects lead to tunnel movements that are not only visible on the particle beam orbit during operation, but that are large enough to create cracks in the wall at every point where tunnel segments connect to each other or to the experimental halls. The movement of these tunnel segments is transferred to the girders and support feet, on which the magnets and other beamline equipment are installed. Therefore, this movement contributes to the misalignment error and, as seen as well in other storage rings [2, 3], this will affect the long-term orbit stability.

For the upgrade to the ultra-low-emittance storage ring PETRA IV [4, 5] it is again foreseen to reuse parts of the existing tunnel. Because of the smaller alignment tolerances, it is important to study the long-term orbit stability of PETRA III in the scope of the risk management strategy for PETRA IV.

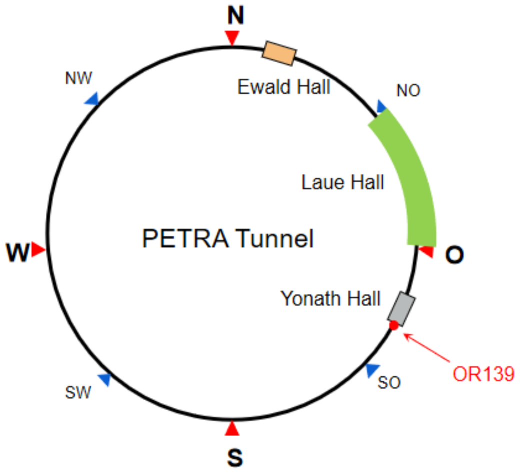

Figure 1: Overview of the PETRA III tunnel layout. Location OR139 (139 m right of East hall) is highlighted (red) as the location of the tunnel motion measurement presented in Fig. 2.

TUNNEL MOVEMENT

The relative movement between two adjacent tunnel segments is monitored in ten locations around the tunnel. These mechanical measurement devices provide data in three dimensions, however only in form of a point like position information. This means that possible tilts or rotations of the tunnel segments to each other remain invisible. The detailed study of the tunnel motion, including the analysis of this mechanical position data and its correlation to environment parameters is presented in Ref. [6].

As an example, Fig. 2 shows the evolution of the longitudinal (in beam direction) and horizontal (radially pointing towards the outside of the ring) position change between the Yonath Hall and the tunnel segment connecting to it on the downstream end (labelled *OR139*, indicating the position 139 m to the right of the East (*Ost* in German) symmetry point, see also Fig. 1). The data over 1.5 years clearly shows a periodic pattern that can be correlated to the temperature changes induced by the normal-conducting magnet cycles, but also to the seasonal change of the outside temperature [6]. The longer the tunnel has time to cool down after switching off the magnets, the larger the floor offset becomes. This effect is especially evident in the longitudinal plane (orange line), where during winter shutdowns tunnel movements in the order of a few millimetres have been observed. Figure 2 highlights the period of the winter (orange shade) and summer (green shade) shutdowns that are the longest cool down periods. But also the shorter service weeks, that usually

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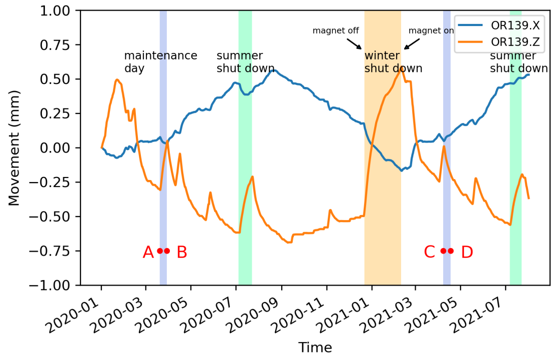

Figure 2: Transverse (blue) and longitudinal (orange) movement measured at the floor connecting the Yonath hall with the tunnel at position OR139. The periods of the winter (orange shade) and summer shutdowns (green shade) are highlighted. In relation to Fig. 3, the blue shades mark the duration of the service week in March 2020 (time A to B) and the warm up period (time C to D) after the proceeding service week in April 2021.

last a few days and are scheduled roughly every six weeks, clearly affect the tunnel movement. As an example, the blue shaded area between point A and B mark the duration of the service week in March 2020. The period between point C and D indicates the warm up period following the service week in April 2021. These two periods are further analysed below and in Fig. 3.

LONG-TERM ORBIT STABILITY

In the following the influence of the tunnel movements on the circulating beam is investigated. As mentioned, the tunnel movement leads to misalignment of beamline elements, that causes changes of the beam position all around the ring. The orbit feedback continuously corrects the orbit to the set reference. This keeps the relative beam positions at the Beam Position Monitors (BPMs) with respect to the reference orbit small, while the information on the misalignment change are encoded in the corrector strengths. In order to look at long-term orbit drifts, the bare orbit

$$X_{bare,i} = M_{ij} * \theta_{corr,j} + X_{BPM,i} \tag{1}$$

at each BPM i needs to be calculated from the *measured orbit* $X_{BPM,i}$ and the *corrected orbit*, using the orbit response matrix M_{ij} and the corrector kick angles $\theta_{corr,j}$ for each corrector j.

For better comparability, it is convenient to look at a difference orbit rather than absolute bare orbits, which is calculated as

$$\Delta X_{bare,i} = M_{ij} * \Delta\theta_{corr,j} + \Delta X_{BPM,i}. \tag{2}$$

Figure 3 compares the bare orbit difference (bottom) for the two intervals marked in Fig. 2. The corresponding orbit at the BPMs (top) and the corrector kick angles (middle) are as well shown.

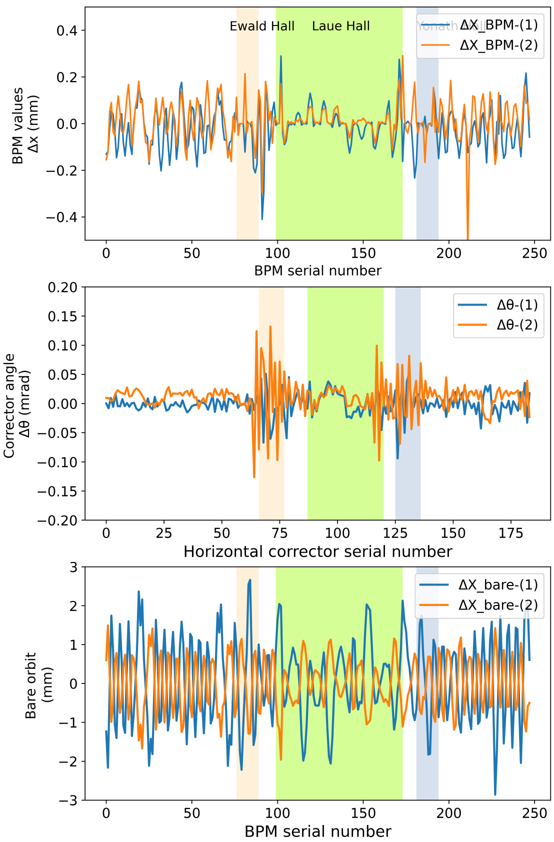

Figure 3: Calculated bare orbit difference (bottom) and underlying difference orbit at the BPMs (top) and corrector kick angles (middle) taken for the two periods marked with the red points in Fig. 2. The blue line represents the difference induced over the length of the service week between time A and B. The orange line represents the time period between C and D taken during the warm up after the proceeding service week. The orange, green and blue shades represent the areas of the three experimental halls.

From the bare orbit differences (bottom) in Fig. 3 it can be seen that the orbit drift during either a cool down or a warm up period, lasting each about 10 days, is with an RMS of 1090 μm (cool down) and 682 μm (warm up), considerably large. Further it can be observed that the orbit offset swaps sign when comparing the cool down and warm up periods. The tunnel walls perform a contraction induced by the falling tunnel temperature and contrarily expand again when heating up after resuming beam operation. As can as well be seen from Fig. 2, the tunnel movement in these two periods goes in opposite directions, thus does the orbit offset. From the corrector strength changes (middle plot) it is evident that the largest corrections are needed in and around the Ewald and Yonath halls and at the exit of the Laue hall.

For the study of long-term beam stability, bare orbits are analysed since the beam restart in 2018. Since the extension project started with the construction of the two new experimental halls (Ewald and Yonath halls) in 2014, new undulators and components were installed in the accelera-

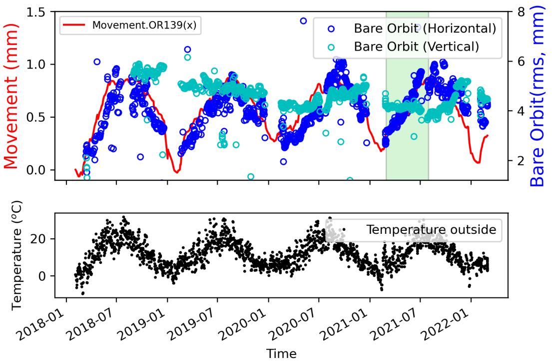

Figure 4: Top: Long-term evolution of the transverse bare orbit (blue and cyan circles, right scale) in comparison to the tunnel movement in the horizontal (red, left scale) directions at location OR139. The green shaded area marks the time period shown in Fig. 5. Bottom: Outside temperature.

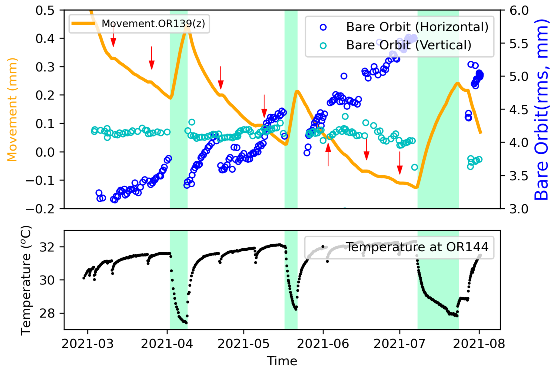

Figure 5: Top: Zoom of Fig. 4 into the summer period March to August 2021. The red arrow mark the dates of the weekly machine study or maintenance days. The green areas represent the service weeks and summer shutdown, during which the machine is off for a few days to several weeks. Bottom: Tunnel temperature at position close to OR139.

tor lattice during each shutdown until summer 2021 [7, 8]. Even though there were still frequent changes, since 2018 the optics is relatively stable, such that a long-term study of the orbit drifts can be performed.

The long-term evolution of the bare orbit is shown in Fig. 4 in comparison to the measured horizontal tunnel movement at position OR139. A clear correlation between the horizontal bare orbit and the horizontal tunnel movement is visible. The sinusoidal pattern over the duration of one year originates mainly from the seasonal change of outside temperature [6], which is shown in the bottom of Fig. 4. Because the orbit is particularly sensitive to transverse magnet misalignment, the outside temperature variation influences the orbit stability on the long-term scale over several years.

Looking more into detail, Fig. 5 shows a zoom to the summer period 2021. The effects of daily machine schedule and operation, i.e. study and maintenance days, service weeks and shutdown, are imprinted on the evolution over short time periods in the order of days and weeks. Those are responsible for the noisy appearance of the data displayed in Fig. 4. Figure 5 however shows that the orbit drifts throughout beam periods are quite smooth, while sudden jumps occur only when the machine is switched off for at least several days. The bare orbit drift in the horizontal plane is bigger compared to the vertical, which can be explained by the existence of dipoles for electron steering and the fact that the orbit is more sensitive to misalignment error in this direction.

CONCLUSION AND OUTLOOK

This paper qualitatively analyses the effect of movement of the tunnel segments on the PETRA III electron orbit. The longitudinal movement of tunnel segments has been measured to reach up to a few millimetres over the duration of winter shutdowns. The transverse movement is usually smaller. However, at the connections of the experimental halls to the adjacent accelerator tunnel also the transverse motion reaches the order of a millimetres. While the longitudinal tunnel motion is dominated by the temperature change inside the tunnel, i.e. operational state of the normal conducting magnets, the transverse motion shows a stronger correlation to the sinusoidal seasonal temperature change. Since the beam orbit is more sensitive to transverse magnet misalignment, the outside temperature dominants the observed pattern on the RMS orbit drift over the year. Nevertheless, shutdowns and service days lead to sudden jumps on the RMS orbit drift when comparing bare orbits before and after the interruption. It needs more study to evaluate whether the shutdown length can be quantitatively related to the expected RMS orbit drift.

ACKNOWLEDGEMENT

The authors would like to thanks J. Klute for his support and advice on the mechanical devices.

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