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TEMPERATURE EFFECTS ON THE PETRA III TUNNEL STABILITY

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Abstract

The tunnel of the synchrotron light source PETRA III is build from separate segments that are joint together every 24 m. The normal conducting magnets heat up the tunnel when operating, which leads to an expansion of the concrete walls and floor introducing movements between the tunnels segments. Especially during warm-up periods after shutdowns, this results in a drift of the accelerator elements that is transferred on the circulating beam over a duration of days, weeks or months according to the length of the cool-down period. This paper shows that not only inside temperature effects but also seasonal temperature changes are relevant.

INTRODUCTION

The third-generation light source PETRA III in Hamburg is operated since 2009, providing synchrotron light in the hard X-ray range to its users. The user demand for nanometrescale spectroscopy sets the requirements for the planned upgrade to PETRA IV. The upgrade will replace the old PETRA III ring with a ultra-low-emittance storage ring, aiming at vertical emittances lower than 10 pmrad.

A sketch of the PETRA III tunnel layout with its three experimental halls is shown in Fig. 1. The tunnel is made of individual segments of mostly 24 m length. Figure 2 (left) shows a photograph of the cross-section of one of this segments during the tunnel construction in 1976, when the PETRA tunnel was initially built to host an electron-positron collider. First the tunnel floor was poured in long pieces to obtain a continuous surface without gaps along the arcs. Then the tunnel walls and the roof were poured on the floor in segments of 24 m length, divided by rubber sealings. Later the tunnel floor developed cracks at the gaps between the segments, probably due to thermal stress. The main part of the tunnel is roughly 3-10 m underground, except when passing through the experimental halls, that are hosted in buildings on the surface.

In certain places and after heavy rain, water might leak into the tunnel. This indicates that the tunnel segments are moving against each other. As a result, the beamline elements, which are anchored to the tunnel floor, transmit this movements to the circulating beam. Since this movements are in general slow, they show up as continuous drifts of the beam orbit position that are in turn corrected by the orbit feedback in order to provide the required beam stability. A detailed analysis of the effect on the orbit can be found in Ref. [1]. If the disturbances become too large, the orbit correctors might reach their strength limit and thus an optimal orbit correction could no longer be guaranteed.

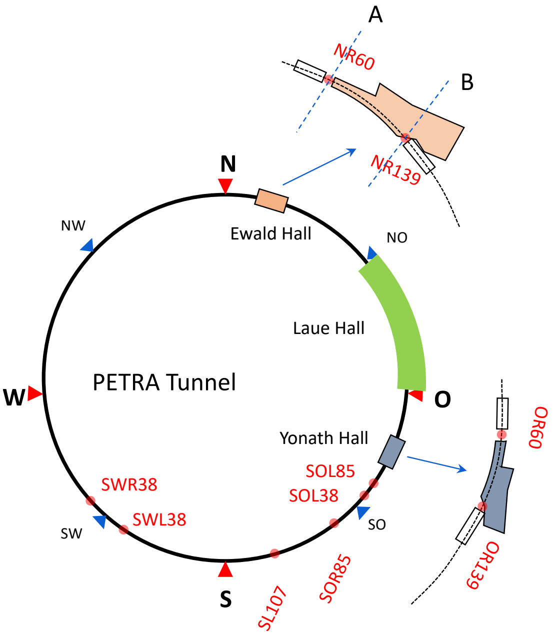

Figure 1: Overview of the PETRA III tunnel layout with its three experimental halls, indicating the locations of the mechanical measurement devices shown in Fig. 2 (right).

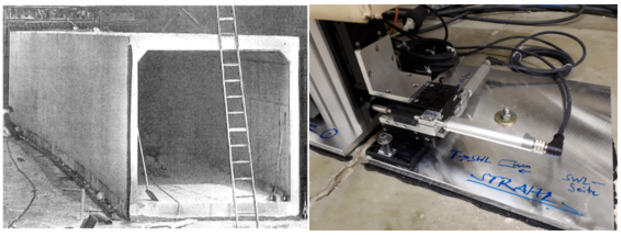

Figure 2: Left: Photograph of the tunnel segment cross-section during the construction of the PETRA III tunnel in 1976. Right: Mechanical measurement device as installed at ten positions around the PETRA circumference, measuring the vertical, horizontal and longitudinal tunnel motion.

The design of the planned upgrade to PETRA IV foresees to keep parts of the tunnel infrastructure and thus the described tunnel segment movements will remain. As part of the risk management strategy for PETRA IV, an understanding of long term tunnel movement and the therewith associated long term orbit stability is required.

TUNNEL TEMPERATURE

Since PETRA III is operated in topup mode with DESY II as a full energy injector, the PETRA III electromagnets are kept at a constant field. The high constant current in the magnets coils heats up the tunnel during operation, as can be

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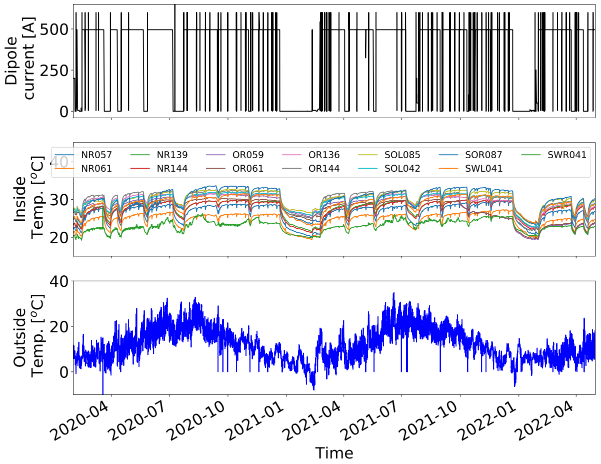

Figure 3: Dipole magnet current (top), floor temperature inside the tunnel at indicated locations (middle) and outside temperature (bottom) between 2020 and 2022. Floor temperature measurements were installed in February 2020.

seen in Fig. 3. During shutdowns, when the magnet current is switched off, the tunnel inside temperature quickly drops. The PETRA III beam time schedule features shutdowns of several weeks in winter (Dec-Feb) and summer (Jul-Aug), service weeks of several days every about six to eight weeks and maintenance periods of a few hours every one or two weeks. This is clearly imprinted on the tunnel temperature. The longer the shutdown, the larger the temperature drop. A closer look revels a sinusoidal modulation of the inside temperature on top of the magnet current correlation, which is induced by the seasonal variation of the outside temperature. The tunnel air (floor) temperature variation over the year is up to $\Delta T = 18\,\mathrm{K}$ (12 K).

Figure 3 (middle) plots the tunnel inside temperatures at different locations. All show the correlation to the operational magnet cycle, however the baseline temperature is not constant around the ring. The tunnel ventilation system pushes outside air clockwise through the tunnel in six independent sectors. Because of the heat produced by the magnets, the air heats up from the inlet to the extraction points, leading to a variation of the tunnel air (floor) temperature around the circumference of up to 16 K (10 K). Note that only the Max von Laue Hall has a climate control unit that regulates the temperature to ±1 K.

TUNNEL MOVEMENT

In order to understand and monitor the movement between adjacent tunnel segments ten mechanical devices have been installed over selected connection points. The locations are indicated in Fig. 1. The naming of the points follows the PETRA III naming convention: cardinal direction (North, East (in German 'Osten'), South, West) and number of meters to the left (L) or right (R) from a symmetry point looking from the centre of the ring.

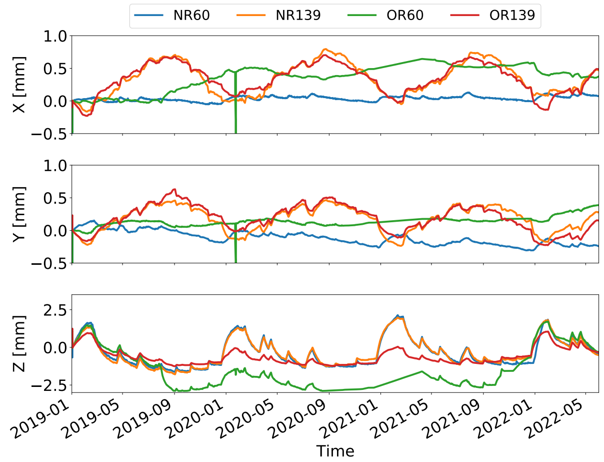

Figure 4: Measured movement at the four stations on the extremities of the two extension experimental halls (Paul Ewald Hall and Ada Yonath Hall), exact locations are indicated in Fig. 1.

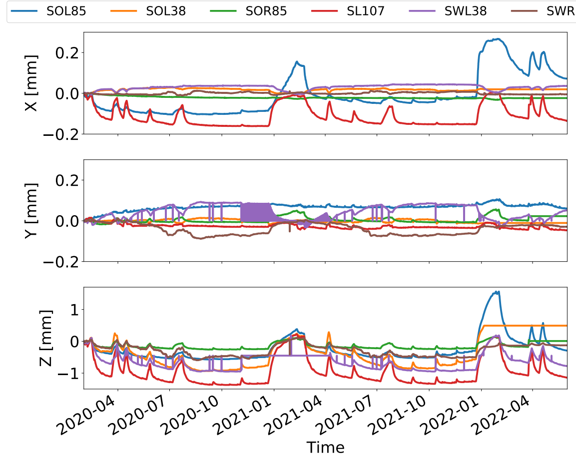

Figure 5: Measured movement between tunnel segments at the six measurement stations between SOL85 and SWR38, locations are indicated in Fig. 1. These measurement devices were installed later compared to the ones in Fig. 4, and are only operated since February 2020.

A photograph of such a device is shown in Fig. 2 (right). On each side of a tunnel-segment gap, mounting plates are both, bolted and bonded to the concrete. The relative movement of the tunnel segments is measured by three sensors integrated in XYZ cross roller measuring stages and are each capable of recording absolute values with a resolution of 368 nm. Coordinates are aligned to the storage ring coordinate system, where Z is longitudinal, Y is vertical and X is radial (from the ring's origin) directions. Note, that with this measurement potential angular or rolling movements of the segments are invisible. Since only a relative measure is provided, the results leave room for interpretation. For example, it is not possible to distinguish by how much each

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single element moved in the given direction, such that in an extreme case one segment could be at rest while the other does the entire shift. On the other hand, a zero measurement could as well mean that both segments moved by the same amount in the same direction.

Figures 4 and 5 show the measured tunnel movements in the ten equipped locations (note the different y-scales). The movement in longitudinal direction is everywhere the largest and reaches up to about 3 mm, while the transverse movement only reaches up to 1 mm at the exits of the extension experimental halls (NR139 and OR139), everywhere else it stays within a few hundred micrometers.

CORRELATION ANALYSIS

Observations

The movement in each measured point shows correlations to the tunnel inside and outside temperature, as can be seen when comparing Fig. 4 and 5 to Fig. 3. The peaks dominating the longitudinal movement originate from the shutdown periods. The seasonal sinusoidal modulation of this pattern is especially visible during summer times.

However, the specific shape and amount of movement through a shutdown and warm-up period is influenced by several factors with varying impact around the circumference such that each point follows an individual evolution.

From OR20 to SOL30 heaters have been installed on the tunnel inside wall to keep the tunnel temperature more stable. They have been switched on from April 2019 to Sept. 2021. A strong effect is visible on the movement at OR60, entrance of Ada Yonath Hall (see Fig. 4). Here the gap in the longitudinal plane closes further than usually during the summer time and stays at this level with a smaller variation through the winter shutdown 2019/20 compared to the previous year. In the radial direction a relative position shift between the tunnel segment and the hall entrance takes place, which stabilises over the winter shutdown 2019/20. In the vertical plane the effect is too small to be clearly identified. Unfortunately, this device was not operational for several month [1]. Recent data with heaters off shows that the trend from before Sept. 2019 is being recovered.

A fraction of the movement that is not explained by the above mentioned sources remains, where the contribution seems to vary between locations. The west part of the tunnel runs up to 10 m underground below a public park, while in the north and east the tunnel runs either through an experimental hall on the surface or about 3 m underground below the campus infrastructure. Additional weight and earth temperature changes, by e.g. rain water, could be further environmental sources to introduce tunnel shifts that do not follow a regular pattern and could lead to differences around the ring.

Concrete Expansion Hypothesis

The length expansion, Δl, of concrete for a temperature change, ΔT, follows a linear law:

$$\Delta l = \alpha_{concrete} \times \Delta T \times l \tag{1}$$

where l is the original length of the concrete slab and $\alpha_{concrete}$ the expansion coefficient of concrete, which depends on its exact composition. A standard value from literature is around $\alpha_{concrete} = 1 \times 10^{-5}/\mathrm{K}$. Taking the peak tunnel floor temperature variations of $\Delta T = 12\,\mathrm{K}$ quoted above and the length of a standard tunnel segment of $l = 24\,\mathrm{m}$, an expansion of $\Delta l = 2.9\,\mathrm{mm}$ of such a tunnel segment is to be expected. This is in agreement with the movement measurements, considering that due to the measurement setup the results in Fig. 4 and 5 only indicate the relative shift between the two connected segments, rather than an absolute knowledge of the movement of each single element.

Reconstruction Attempt

A reconstruction model, based on exponential fits to the cool-down and warm-up periods of a selected winter shutdown and a sinusoidal fit to the outside temperature, was build to better understand the behaviour of the tunnel drifts for the given observation points. The fitted contraction and expansion behaviours were applied triggered by the magnet current evolution. In some points the observed evolution can satisfactorily be reproduce, however in other points the drifts do not seem to follow a repetitive pattern. Although some correlation to the operational schedule can be identified everywhere, the motion here is dominated by other sources that are not covered by this simple empirical model.

CONCLUSION AND OUTLOOK

Mechanical devices have been installed in the PETRA III tunnel, measuring the movements between tunnel segments in selected locations mainly at the connections between tunnel and experimental halls and in the east-south quadrant. Correlations to the tunnel inside temperature and outside temperature could be made. However, there are other, more minor contributions that have not yet been clearly identified. The influence of individual environment parameters seems to vary at the measurement locations.

The coverage of mechanical movement devices in the tunnel is not sufficient to obtain a global model for the tunnel movements around the circumference. The installation of more device at several subsequent tunnel segments would provide further understanding of the movement behaviour over sectors. Especially further measurements in the eastern half of the ring that will remain for PETRA IV could provide relevant information for the design of compensation systems.

REFERENCES

[1] L. Liao, M. Bieler, J. Keil, C. Li, M. Schaumann, and R. Wanzenberg, “Long-Term Orbit Stability in the PETRA III Storage Ring”, presented at the IPAC’22, Bangkok, Thailand, Jun. 2022, paper TUPOMS020, unpublished.

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[1] between Sept. 2020 to April 2021, data is linearly interpolated in Fig. 4