Journal of Physics: Conference Series **3010** (2025) 012030 doi:10.1088/1742-6596/3010/1/012030

PETRA III Operational Performance and Availability in 2023

J. Keil, G. K. Sahoo, M. Schaumann and R. Wanzenberg

Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

E-mail: rainer.wanzenberg@desy.de

Abstract. At DESY the Synchrotron Light Source PETRA III offers scientists outstanding opportunities for experiments with hard X-rays of exceptionally high brilliance since 2009. Parallel to operation with high availability, a comprehensive study program supports hardware and software developments for the forthcoming PETRA IV upgrade. Key aspects in 2023 were the development of commissioning tools and the installation of a prototype PETRA IV 500 MHz Higher Order Mode (HOM) damped cavity. In view of the campus wide infrastructure provisions expected in the next years in parallel to the ongoing beam operation at PETRA III, a series of vibration tests were conducted to assess the impact of anticipated construction activities on beam stability. This paper provides a detailed description of the operation in 2023, reviews the availability and fault statistics and gives an outlook to the next runs.

1 Introduction

The Synchrotron Light Source PETRA III at DESY [1, 2] is worldwide one of the very brilliant storage ring based X-ray sources for high energy photons providing a brilliance exceeding 10^{21} ph/(s mm^2 mrad^2 0.1% BW). It operates at 6 GeV particle energy and provides a horizontal and vertical emittance of 1.3 nmrad $\times$ 0.01 nmrad at photon energies between 150 eV and 200 keV depending on the beamline. During user runs, the storage ring is operated in two distinct modes characterized by their bunch spacing. In the "continuous mode", up to 120 mA are filled in 480 evenly distributed bunches, corresponding to a bunch spacing of 16 ns. The "timing mode" allows users to perform time-resolved experiments and is thus characterized by a considerably larger bunch spacing of 192 ns, corresponding to 40 evenly distributed bunches with a total current of 100 mA.

The beamlines at PETRA III are distributed over three experimental halls. The largest, the 300 m long experimental hall 'Max von Laue', covers one octant of the 2304 m long PETRA storage ring. On the 7000 m^2 large experimental floor 15 beamlines are operated by DESY, Helmholtz-Zentrum Hereon (formerly HZG), and the European Molecular Biology Laboratory (EMBL). The layout of PETRA III facility is shown in Fig. 1, with the Max von Laue hall (b) and the experimental halls of the extension project: Paul P. Ewald (c) in the North and Ada Yonath (a) in the East, which were inaugurated in 2016. Presently, 25 beamlines are operational. In total 80 m of wigglers are installed in the straight sections in the West and the North to achieve the horizontal emittance of 1.3 nm. The synchrotron radiation from the wigglers in the straight section North is used for the beamline P61 in the Paul P. Ewald experimental hall. An detailed overview of the PETRA III beamlines can be found in Ref. [3]

As an upgrade project of PETRA III, DESY is developing the ultimate X-ray microscope for nanoresearch with outstanding potential for industrial users and socially relevant applications in energy research, information technology, mobility, environment and medicine, called PETRA IV [4, 5]. PETRA IV extends the X-ray view to all length scales, from the atom to millimetres. At PETRA III a comprehensive

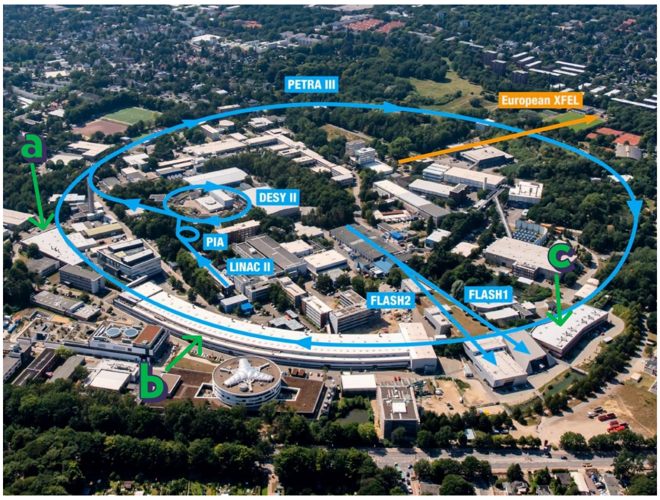

Figure 1: Accelerators at DESY. PETRA III facility encircles the DESY site.

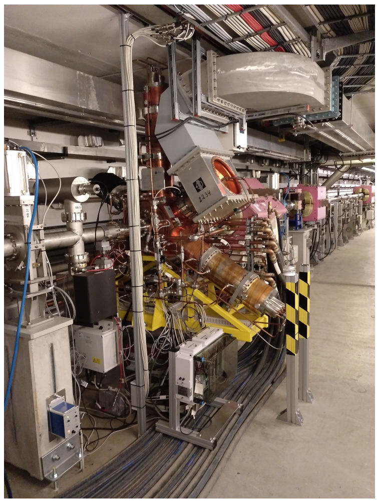

Figure 2: Single cell 500 MHz cavity (PETRA IV prototype).

study program supports hardware and software developments for the forthcoming PETRA IV upgrade. Key aspects in 2023 were the development of commissioning tools and the installation of a prototype PETRA IV 500 MHz Higher Order Mode (HOM) damped cavity, see Fig. 2. During the winter shutdown 2022/23 the single cell 500 MHz cavity was installed in the South of the PETRA III tunnel. In the summer shutdown 2023, the installation of the cavity was complemented with a new RF power source, a 120 kW solid state amplifier. The new cavity was successfully operated upto a voltage of 400 kV, first during beam studies and later also during the standard user operation. Furthermore, a series of vibration tests were conducted to assess the impact of anticipated construction activities, related to the PETRA IV project, on the beam stability.

2 User operation in 2023

Regular user operation resumed on 22 February 2023 after a short commissioning period of less than two weeks. In 2023, 4899 h of beam time were scheduled for the user run, which were delivered with a very good availability of 98.4 %. Necessary maintenance was done in five dedicated service periods distributed over the year and additionally during the three-week-long summer shutdown. On Wednesdays, user operation was interrupted by weekly regular maintenance or machine development activities as well as test runs for 24 h in total. The distribution of the different machine states in 2023 is shown in Fig. 3 in hours and minutes (hh:mm). In addition to the delivered time of 4821 h for the user run, 1133 h of test run time could be provided to the users. 51 % of the user run time was allocated to the 480-bunch mode and 49 % to the 40-bunch mode. The category "Failures" corresponds to faults during the user run, while faults during the test run and study time are summarised in the category "Downtime".

While in 2023 the availability was very good, the average mean time between failures (MTBF) at the end of 2023 was 53 h, which is below the anticipated target value of at least 60 h. The long-term development of the number of faults during user runs of PETRA III normalized to 1000 h of user run time is shown in Fig. 4. The blue bars present the total number of faults, while the red bars exclude faults caused by power interruptions, which are to a large extend short power glitches (less than 120 ms) causing a beam loss. The green line indicates the number of faults that correspond to the target MTBF of 60 h. In 2023, almost one third of the faults were related to power interruptions. Another source of failures was related to the ageing of electronic equipment within the signal distribution of the timing system. The root cause analysis of the faults during the user run was assisted by an internal review process, monitoring all faults of PETRA III, aiming for an improved performance in 2024. Actions and measures initiated by the review panel can only be realised with an essential effort from all technical groups involved.

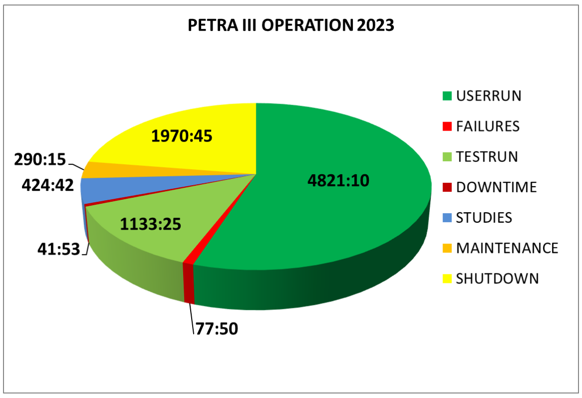

Figure 3: Distribution of the different machine states in 2023 (hh:mm).

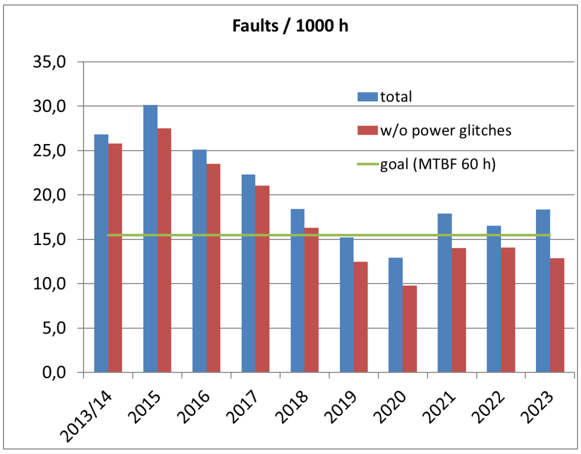

Figure 4: Long-term development of the number of faults during user runs.

3 Impact of construction work on PETRA III's beam stability

In the upcoming years the DESY campus will receive a major upgrade of its support and building infrastructure, also but not only in the context of the PETRA IV project. It is unavoidable that construction work will be performed in parallel to PETRA III operation, coming along with disturbances to the electron and photon beams. It is of fundamental importance to assess the impact of the anticipated construction work in order to be able to coordinate beam time and schedule experiments accordingly, such that the user's needs and expectations can still be satisfied. In 2023, a series of vibration tests were conducted that dedicatedly induced ground motion on several locations across the DESY site.

3.1 Simulation of construction activity along the PETRA ring – a cross-departmental effort

PETRA III is sensitive to a wide range of frequencies that arrive from ground motion through the accelerator tunnel floor. Quadrupoles are the main source of beam disturbances due to ground motion, since they introduce an orbit kick when being displaced. Their individual response induces a forest of lines onto the electron beam frequency spectrum.

The interest within the DESY accelerator and photon science community in the effects of ground vibrations on the electron and photon beam stability in view of the planned construction works during PETRA III operation is large. Four additional study days were dedicated out of the user run in 2023 for investigations on this topic. A working group with around 50 members from the accelerator department, photon science department, construction department and technical groups has been formed. The goal is to identify requirements and capabilities of each party and to exchange ideas and expertise to optimally use the given study time and to develop a common plan on how to mitigate the impact of the upcoming construction activities.

The planning of these cross-departmental study started in early 2023. After setting up the required data taking and communication between the accelerator control room and the beamlines, a two-day vibration test was conducted in September 2023. A rolling compactor (see Fig. 5), usually used for densification of loose ground, was used as vibration source on three future construction sites close to the PETRA ring and along the street on top of the XFEL injector building. Additionally, the drop of a 2-ton shielding stone from about 5 m height (see Fig. 6) simulated the impact of a diaphragm wall grab, which will be used during the construction of the PXW, the new 600-meters-long PETRA IV experimental hall, that will be excavated during PETRA III operation.

3.2 Diaphragm wall construction needs to be further investigated

The results indicate that the construction of two 600-meters-long diaphragm walls to both sides of the PETRA tunnel during beam operation might have a larger effect on the operational conditions than presently assumed by the construction planning. The ground velocities induced by the dropping stone are in the order of the expected ones from the construction of a diaphragm wall in a comparable distance from the tunnel. Orbit derivations of up to 20 % and 110 % of the beam size in the horizontal and vertical plane, respectively, were observed. This is significantly outside the design stability criterion for vibrations

Figure 5: Ground excitation with a vibrating roller in the West area of the PETRA ring. The PETRA tunnel lays only a few meters to the left. The shielding stones in front of the material side entrance are visible on the left side of the picture.

Figure 6: Dropping a 2-ton shielding stone from 5 m height in the North area of the PETRA ring. The PETRA tunnel is only few ten meters away, below the rising ridge on the left side of the picture.

set at 10 % of the beam size. However, it needs to be noted that the impact was simulated on the ground level of the accelerator, excitation from excavation is more likely to arrive from the top, which might lead to a different response due to the different propagation of surface and body waves. A frequency response spectrum of the floor and quadrupole motion is shown in Fig. 7. During the densification test the stability limit was also exceeded by several factors especially in the vertical plane (Fig. 8).

3.3 Certain user experiments will be impossible under the tested conditions

Several PETRA beamlines took part in the study. The purpose, abilities and requirements of PETRA's 25 beamlines are diverse and so is the effect of vibrations to their measurement quality. Both, the vibrations transported by the electron beam onto the photon beam and the direct movement of the photon beamline elements or the sample under investigation are problematic. The sensitivity to either depends on the beamline equipment and measurement method. The analysis is currently still ongoing, however for most beamlines certain experiments will be impossible under the tested conditions, because the beam quality degradation is too large. The cross-analysis between beamlines and the understanding of the variety of impacts coming from the same known vibration source is valuable input for the design of accelerator and beamline diagnostics and the PETRA IV fast orbit feedback. The observations made during this experiment can be used as benchmark for PETRA IV simulations. A continuation of these efforts is foreseen.

4 Study for PETRA IV: Orbit feedback using photon beam signals

The beamlines at PETRA III require high positional stability of the photon beam on their samples. Passive measures such as good temperature control in the accelerator tunnel and in the experimental halls as well as the use of top-up operation with 1% (peak-to-peak) current variation help to achieve this goal. In addition, a fast orbit feedback system (FOFB) stabilizes the position of the electron beam. Higher weighting factors of Beam Position Monitors (BPMs) near undulators are used to stabilize the electron beam position in the undulators at a μm-level.

Nevertheless, small changes in the photon beam position on the sample can still be observed. The reasons for this are the mechanical movement of the BPMs with changes of the cooling water temperature, the air-temperature and fill-pattern dependent BPM electronics, but also the change of the thermal load on the monchromator crystals with beam current and undulator gap.

In contrast to other storage rings, PETRA III has no X-ray BPMs between undulators and monochromators to improve the stability of the photon beam. Although photon BPMs are present in some beamlines of PETRA III, they are not integrated into the orbit feedback.

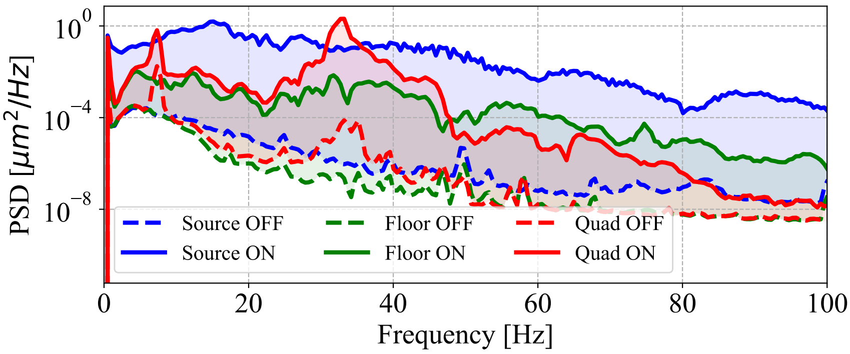

Figure 7: Frequency spectra of the measured ground vibrations during the stone drop experiment close to the source (solid blue), on the tunnel floor (solid green) and on top of a quadrupole (solid red). The dashed lines show the corresponding quite spectra without excitation. Note the broad ground excitation over all frequencies (blue and green) and the clear resonant response of the quadrupole at its eigenfrequencies of around 8 Hz and 32 Hz (red).

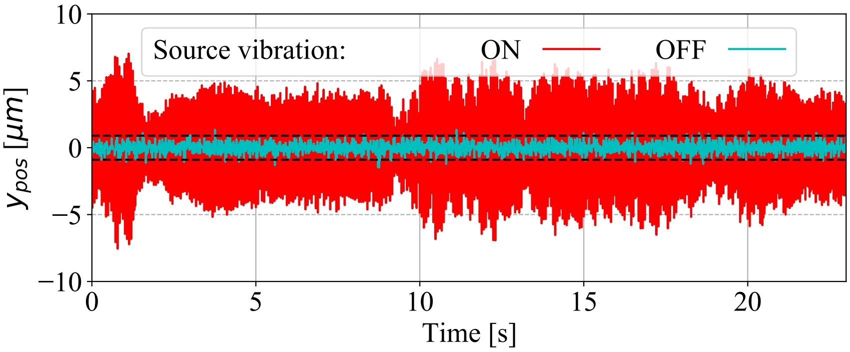

Figure 8: Vertical electron beam position changes at the undulator of beamline P07 during the excitation with a vibrating roller (red) and a quiet reference without excitation (light blue). The PETRA III stability goal of 10% of the beam size is marked by the two black dashed lines.

4.1 Experimental test of the integration of photon BPM data into the FOFB

In PETRA IV, the requirements for beam stability will increase due to the smaller beam sizes and the higher thermal load on the monochromator crystals. In order to test new concepts for stabilization at PETRA IV, it was shown with an proof-of-principle study at PETRA III that data from a photon beam position monitor can be used together with the FOFB to stabilize the photon beam position even better.

Since a complete integration of the photon BPM signal in the orbit feedback was not easily possible, the control of the photon beam position was realized by changing the reference orbit of BPMs near the undulator with an additional software feedback loop. The center of the beam spot on a scintillator screen of beamline P07 downstream of the monochromator was used for this experiment.

Figure 9 (left) shows the angle of the photon beam as a function of time while the additional feedback loop was in operation. To test the controller, some artificial changes were made to the position of the photon beam in both planes. The controller, operating in the figure with a feedback gain of 0.2, was able to eliminate these disturbances by returning the angle of the photon beam in the undulators to the target value of $0\,\mu rad$ (Fig. 9, right). It can also be seen in the horizontal plane that a non-zero angle of the electron beam is needed to correct long-term drifts of the photon-beam. With a higher feedback gain of 1 the disturbances are typically corrected within one or two loop cycles.

Although the additional software control loop works slowly due to technical limitations within the

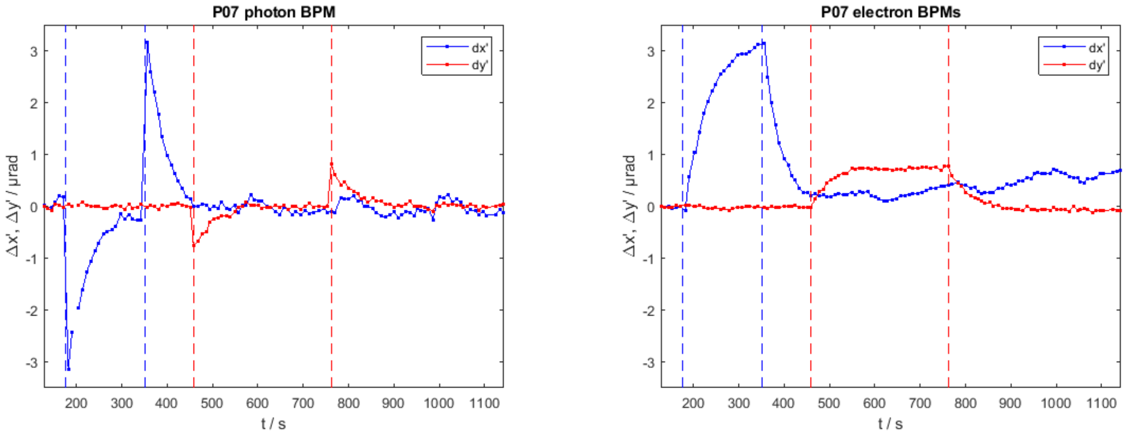

Figure 9: The position at the photon monitor at beamline P07 is maintained by reference orbit changes of the electron beam. Left: Angle of photon beam calculated from photon monitor. Right: Angle of electron beam calculated from BPM data near the undulator.

FOFB, it shows that it is possible to successfully correct these drifts of the photon beam position. Further studies are planned to investigate the mutual influence in canted undulator cells.

5 Plans for the next operation period

The winter shutdown 2023/24 is dedicated to maintenance work, including the exchange of the power coupler of the single cell 500 MHz cavity, a survey of the wiggler section in the West of PETRA III and the placement of a fibre optical cable around the full tunnel circumference, extending the iDAS [6] network on the DESY campus, a developing technique to measure ground vibrations by the length variations of such cables. In 2024, further studies are planned to support the technical design for the planned upgrade of PETRA III to PETRA IV.

Acknowledgments

The authors would like to express their gratitude to the technical groups and the numerous individuals supporting the PETRA III operation. Without their efforts, achieving and maintaining the desired performance would not be possible. We would like to thank O. Gutowski for his collaboration especially during the vibration and XBPM studies.

References

[1] K. Balewski *et al.*, "PETRA III: A low Emittance Synchrotron Radiation Source", DESY-2004-035 (2004).

[2] M. Bieler *et al.*, "Status of the Recommissioning of the Synchrotron Light Source PETRA III", IPAC2015, Richmond, VA, USA (2015).

[3] M. Bieler *et al.*, "PETRA III Operation with High Availability", J. Phys.: Conf. Ser. 2380 012002 (2022).

[4] C.G. Schroer *et al.*, "PETRA IV: upgrade of PETRA III to the Ultimate 3D X-ray microscope", Conceptual Design Report, DESY, PUBDB-2019-03613.

[5] R. Bartolini *et al.*, "Status of the PETRA IV machine project", IPAC2022, Bangkok, Thailand (2022).

[6] `https://wave-hamburg.eu/`