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PETRA III Operation with High Availability

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PETRA III Operation with High Availability

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Abstract. The Synchrotron Light Source PETRA III at DESY is one of the most brilliant storage-ring based X-ray sources for high-energy photons worldwide, which offers scientists unique X-ray experiments in a wide range of fields since 2009. The light source is operated mainly in two operation modes with 480 and 40 bunches at a beam energy of 6 GeV with a maximum beam current of up to 120 mA. High reliability is one of the key requirements for a synchrotron radiation facility. The key performance indicators, availability and mean time between failures (MTBF), could be significantly improved during the operation periods of the last years. As the final milestones of the extension project that started in 2014, a new undulator was installed for the beamline P62 in the Paul P. Ewald hall in 2020, and a new dipole beamline (P66) have been installed in the North East section of PETRA III in 2021.

1. Introduction

The Synchrotron Light Source PETRA III is one of the core facilities at DESY offering each year more than 2000 users unique opportunities for experiments with hard X-rays of a very high brilliance in a wide range of fields such as health, energy, materials, earth and environmental science and information technology. In the seventies PETRA was originally built as an $e^- - e^+$ collider, which was later used as a pre-accelerator for the HERA lepton-hadron collider from 1988 to 2007. After the end of the HERA collider physics program, the PETRA ring was converted into a dedicated 3rd generation synchrotron radiation facility, called PETRA III [1], which is operated at a beam energy of 6 GeV.

Beam operation started in 2009 [2] and 14 beamlines in the Max von Laue hall are operational since 2011. Because of the high demand for additional beamlines, the lattice of the ring was redesigned to accommodate additional beamlines in the framework of the PETRA III extension project. In 2014, two tunnel sections of about 80 m each in the North and the East of the PETRA ring were completely reconstructed and new experimental halls were build. The storage ring was recommissioned in 2015 [3]. The present layout of PETRA III is shown in Fig. 1, including the experimental halls of the extension project: Paul P. Ewald in the North and Ada Yonath in the East. Presently, 25 beamlines are operational. The main operational parameters are summarized in Table 1. 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 rad.

2. Magnet Layout and Machine Configurations

The electron beam optics, i.e. the magnet arrangement and settings, in the experimental halls differs from the general arc lattice structure. Panoramic views of the tunnel arrangement and

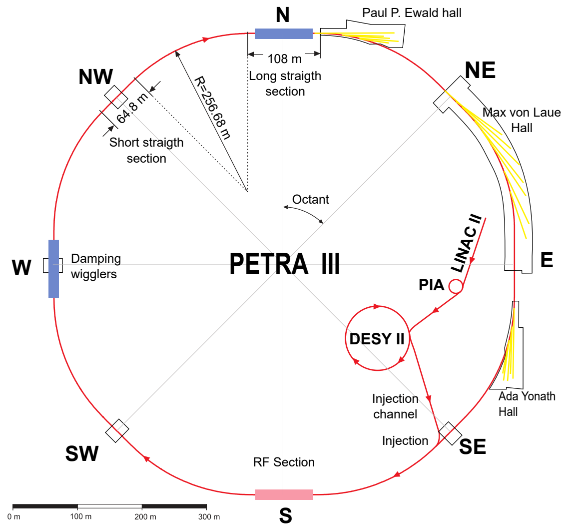

Figure 1: Layout of PETRA III.

Table 1: PETRA III parameters.

Parameter	PETRA III	
Energy /GeV	6	
Circumference /m	2304.0	
Total current /mA	120	100
Number of bunches	480	40
Bunch Population $/10^{10}$	0.5	12.0
Emittance (horz.) /nm rad	1.3	
(vert.) /nm rad	0.01	

Figure 2: Panoramic view of a DBA cell in the Max von Laue hall (top) and a FODO cell in an arc of the PETRA III ring (bottom). The arrows indicate the location of the dipole magnets.

the corresponding optical functions of the two basic cell structures are shown in Fig. 2 and Fig. 3, respectively.

In the octant from North-East to East (Max von Laue hall) nine double-bend achromat (DBA) cells are installed (Fig. 2 (top)). As be seen from Fig. 3 (left), those DBA cells feature zero dispersion straight sections for the installation of 5 m undulators. If a so-called canting is desired, in order to accommodate two beamlines that are each served by a 2 m undulator installed in the same straight section, the zero dispersion is disturbed slightly by the required canting dipole in the center of the straight sections. Within the framework of the extension project, two canted DBA-like cells were as well installed in the North (Paul P. Ewald hall) and the East (Ada Yonath hall) in 2014. The optics in the remaining octants of PETRA III is dominated by a alternating Focussing-Defocussing quadrupole (FODO) lattice structure, see Fig. 2 (bottom) and Fig. 3 (right).

In general, each DBA cell could be setup with either a so-called 'high-β' optics, featuring an horizontal beta function of about 20 m (as it is shown in Fig. 3 (left)), or a 'low-β' optics, providing a more narrow photon beam thanks to a horizontal beta function of only 1.4 m.

In terms of machine setup, two global optics configurations are provided. The standard configuration that is used for the main part of the user run is the 'high-β' optics, however as well in this configuration two cells are operated with DBA low-β settings, according to the needs of the beamlines P05/P06 and P10, see Table 2. The second so-called 'low-β' optics, that is used for a few weeks per year, is made for the special case of beamline P07. This beamline requires operation in both DBA high-β and low-β configuration, depending on the kind of user experiment. Therefore the need of swapping the machine optic configuration is driven by the request of only one beamline, all other beamlines remain with the same DBA optics in both machine optic configurations.

Apart from the different optic configurations, the storage ring is operated in two distinct modes characterized by their bunch spacing. In the 'continuous mode' 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.

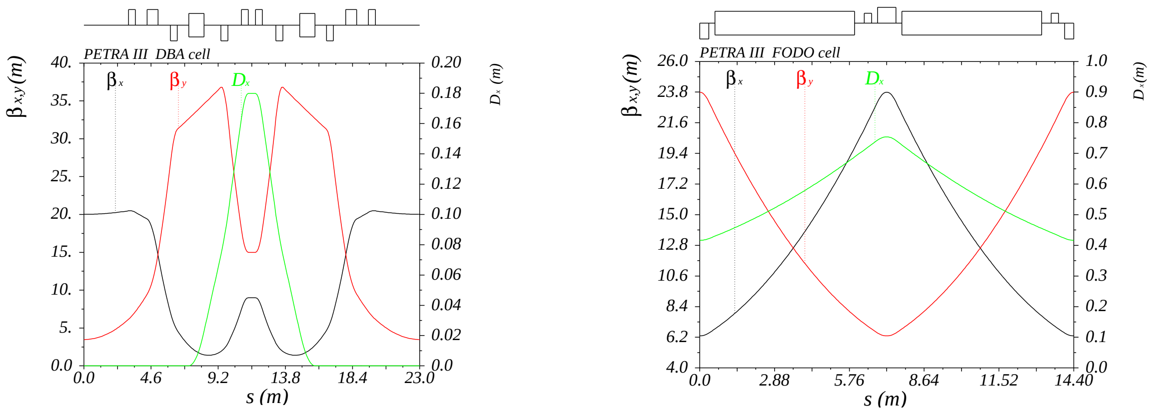

Figure 3: Optical functions of the uncanted, high-β DBA cell (left) and the standard arc FODO cell (right).

3. Beamlines

Even though the extension project began in 2014, new beamlines and front-end equipment have been gradually installed over the years. The last undulator, providing the photon beam to beamline P62 in the Paul P. Ewald experimental hall, has been installed during the winter shut-down 2019/20, see Fig. 4. P62 is a small-angle X-ray scattering beamline for materials research.

The last milestone of the extension project was finalised with the installation of beamline P66 during the winter shut-down 2020/21 and in the summer shut-down 2021. P66 is the first dipole beamline of the PETRA III facility and dedicated to VUV luminescence and reflection spectroscopy experiments. It is located close to the Paul P. Ewald hall in the North East of the PETRA ring, see Fig. 5. Differently to the other beamlines, the photon beam is reflected vertically upwards from the accelerator level into the experimental hutch, which is placed in a building on top of the PETRA III tunnel.

In total 25 beamlines are now in operation at the synchrotron light source PETRA III. A complete list is summarized in Table 2. The list is grouped according to the cell number in the different experimental halls. The cell number 0 corresponds to the long straight sections in the North, North-East and East, while the other cells are typically related to the straight sections in the DBA cells, which, as explained above, can be either high-β or low-β cells. Furthermore,

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Table 2: PETRA III beamlines

Cell		Beam-line	Insertion device (length, type)	Energie range / keV	Experimental method
Max von Laue Hall					
0	high-β	P01	2 x 5 mU32	2.5 - 80	High Resolution Dynamics Beamline
1	high-β	P02.1 P02.2 P03	2 m U23 2 m U29	60 25.7, 42.9, 60 9 - 23	Powder Diffraction and Total Scattering Extreme Conditions Micro- and Nanofocus X-ray Scattering
2	high-β	P04	4.9 m U65 (APPLE)	0.25 – 3.0	Variable Polarization XUV
3	low-β	P05 P06	2 m U29 2 m U32	5 – 50 5 – 45	Imaging and Tomography Micro/Nano-Probe
4	high- or low-β	P07	4 m U21 (IV)	30 – 200	High Energy Materials Science
5	high	P08 P09	2 m U29 2 m U32	5.4 – 29.4 2.7 – 31	High Resolution Diffraction Resonant Scattering and Diffraction
6	low-β	P10	5 m U32	5 – 20	Coherence Applications
7	high-β	P11 P12	2 m U32 2 m U29	5.5 – 30 4 – 20	Macromolecular Crystallography Bio SAXS (EMBL)
8	high-β	P13 P14	2 m U29 2 m U29	4.5 – 17.5 7 – 26.7	Macromolecular Crystallography I (EMBL) Macromolecular Crystallography II (EMBL)
Ada Yonath Hall					
0	high-β	 P21b P21a	 4 m U21 (IV) 2 m U29	 40 - 150 52, 85, 100	High energy material science Diffraction & Imaging Broad band diffraction
1	high-β	P22 P23	2 m U33 2 m U32	2.4 - 30 5 - 35	Hard X-ray Photoelectron Spectroscopy In situ X-ray diffraction and imaging
2	high-β	P24 P25	2 m U29	8, 17 - 44	Chemical Crystallography in preparation
Paul P. Ewald Hall					
0		P61 P61A P61B	10 x 4 m Wiggler	40 - 200	High Energy wiggler beamline White Beam Eng. Materials Science Large Volume Press
1	high-β	P62 P63	2 m U32	3.5 - 35	Small-Angle X-ray Scattering for Materials Research in preparation
2	high-β	P64 P65	2 m U33 0.4 m U33	4 - 44 4 - 44	Advanced X-ray Absorption Spectroscopy Applied X-ray Absorption Spectroscopy
North-East					
		P66	Dipole magnet	0.004 - 0.04	VUV luminescence and reflection spectroscopy

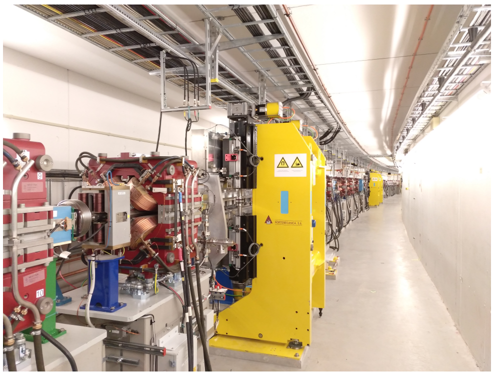

Figure 4: Undulator and front-end components of beamline P62 in the PETRA III tunnel of the Paul P. Ewald hall (installed in 2020).

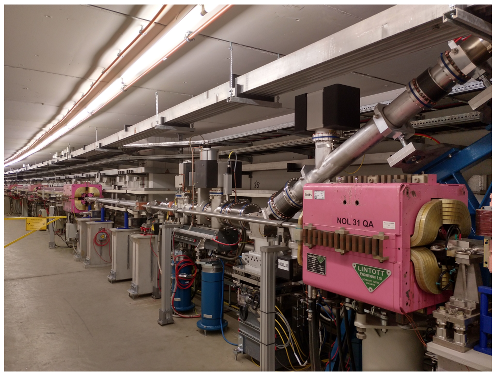

Figure 5: Dipole magnet and front-end components of the dipole beamline P66 in the PETRA III tunnel (installed in 2021).

the cells may be canted to accommodate two 2 m-long insertion devices, instead of one 5 m-long insertion device for an uncanted cell. The canting angle in the Max von Laue hall is 5 mrad, while in the Paul P. Ewald hall and Ada Yonath hall the canting angle is 20 mrad. An exception is cell 0 in the Ada Yonath hall, where the insertion devices are canted by 1 mrad.

4. User operation

After the 2020/21 winter shut-down regular user operation was resumed on 15 March 2021, after a short commissioning period of about two weeks. Originally, 4824 h of beam time were planned for the user run. Nevertheless, due to the COVID19 pandemic the schedule had to be revised resulting in a delayed start of the activities in the winter shut-down. Fortunately, any further impact of the pandemic on the installation work and the user operation could be mitigated with additional safety measures. Considering the challenging condition of the pandemic in 2021, a good resilience of the user operation of PETRA III was achieved and finally 4632 h of beam time could be scheduled for the user run. In addition to the regular user run, 1003 h of test run time were planned. Test run refers to beam time that does not count towards the official user run, because it might still be interrupted by machine setup or study activities. This time is not guaranteed as user time, but is an appreciated extra beam time for the beamlines.

4.1. Maintenance

The necessary maintenance was done in five dedicated service periods distributed over the year and additionally during the three-week long summer shut-down period. On Wednesdays, user operation was interrupted by weekly regular maintenance or machine development activities, which is usually followed by a test run until the next morning.

4.2. Availability and Mean Time Between Failures

The key performance indicators are availability and mean time between failures (MTBF). In 2020, the average availability was 98.8%, which was a new record for PETRA III. Unfortunately, this high level of availability could not be maintained in 2021, where the user beam time was delivered with a good but not excellent availability of 97.3%. In 2021, only a few but major faults significantly affected the average availability: a water leak in the injectors, a complicated problem with the multibunch-feedback electronics, a series of power glitches, a fault of the remote emergency system, and a reoccurring problem with the switches of the injection kicker.

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In Fig. 6 the evolution of the yearly availability, and in Fig. 7 the MTBF during user run time is shown since the last year before the extension project was implemented in 2015. A clear trend of continuous performance improvement from one year to the next could be achieved. This availability statistics are based on a metric that is in agreement with internationally recognized performance characteristics, and does not include 'warm-up' time after each fault. In general, the number of faults has decreased during the last six years, indicating that the improvement of the technical reliability of PETRA III has made significant progress. This was assisted by an internal review process that monitors the availability of PETRA III and guarantees a good root cause analysis of all faults during the user run. The harmonization of the quality standards in the technical groups with respect to quality control and documentation is as well been addressed. Since power glitches affect the availability of all accelerators at DESY, a dedicated task force investigates the cause and consequences of each event.

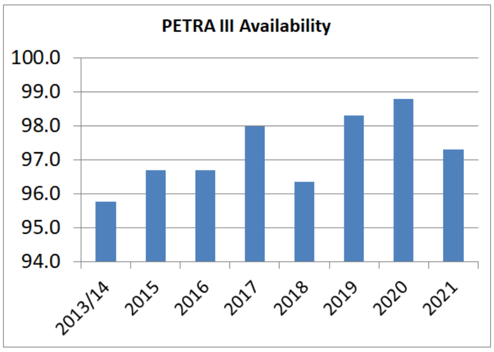

Figure 6: PETRA III availability.

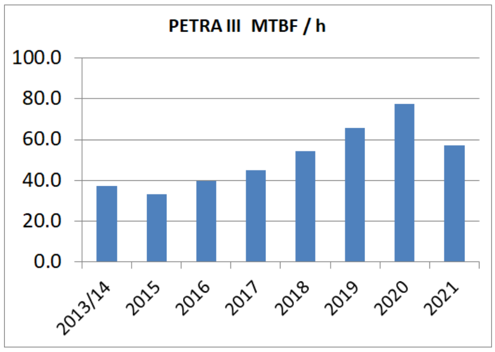

Figure 7: PETRA III MTBF.

5. Conclusion and Outlook

The Synchrotron Light Source PETRA III, one of the core facilities at DESY, is operated with a high availability in two operation modes with 480 and 40 bunches at a beam energy of 6 GeV. In the next years, 2 further beamlines will be constructed and become operational. In the framework of the PETRA IV project [4], it is foreseen to upgrade the existing facility to a synchrotron radiation source with an ultra-low emittance, based on a multi-bend achromat, which was pioneered at MAX IV [5] and ESRF-EBS [6, 7]. Unique new experiments and scientific opportunities will be made possible. Presently, the technical design of the PETRA IV project is in preparation and strongly supported with a study program at PETRA III.

Acknowledgments

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