COMISSIONING OF PETRA III

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Abstract

PETRA III is a new hard X-ray synchrotron radiation source at DESY in Hamburg operating at 6 GeV with an extremely low horizontal emittance of 1 nm rad. The new light source is the result of a conversion of the former storage ring PETRA II. The conversion was carried out from middle of 2007 till March 2009. One eighth of the 2304 m long storage ring was completely rebuild and houses now 14 undulator beam lines as well as the optical and experimental hutches. The remaining seven eighths have been modernized and refurbished and in addition twenty 4 m long damping wigglers have been installed. These are required to achieve the small design emittance. Commissioning of the new light source started at the end of March 2009. In this paper we present the results that have been achieved during commissioning and the experience gained during the first user runs.

INTRODUCTION

In 2002 it was proposed to convert the storage ring PETRA II into a high brilliance hard X-ray light source after the end of the HERA physics program in 2007. This proposal was worked out in detail during the next two years and was published in a technical design report which was the basis for the formal approval of this project. The basic parameters of PETRA III are given in table 1 and more details can be found in the following references [1], [2].

Table 1: PETRA III Parameters

Parameter	PETRA III	
Energy / GeV	6	
Circumference /m	2304	
Total current / mA	100	
Number of bunches	960	40
Emittance (horz. / vert.) /nm	1 / 0.01	
Number of insertion devices	14	

The conversion was carried out from middle of 2007 till March 2009. One eighth of the 2304 m long storage ring has been completely rebuild and the former tunnel has been replaced by a new hall which houses 14 undulator beam lines and the optical and experimental hutches. The number of insertion devices is rather modest for a machine of this size which is due to limited financial resources.

The geometry and the lattice of the remaining seven octants have been kept. The existing hardware has been reused if possible but refurbished and modernized to fulfil the high demands on reliability of a light source.

In addition two damping wiggler sections have been installed in the North and West of PETRA. Each section contains 10 four meter long damping wigglers with a field of 1.5 T. These wigglers are required to enlarge the radiation damping of the machine in order to achieve the very small horizontal emittance of the machine. Details of these two sections and in particular on the complicated vacuum system can be found in the following references [3], [4], [5].

Figure 1 shows a schematic view of PETRA III and an aerial view of the new experimental hall.

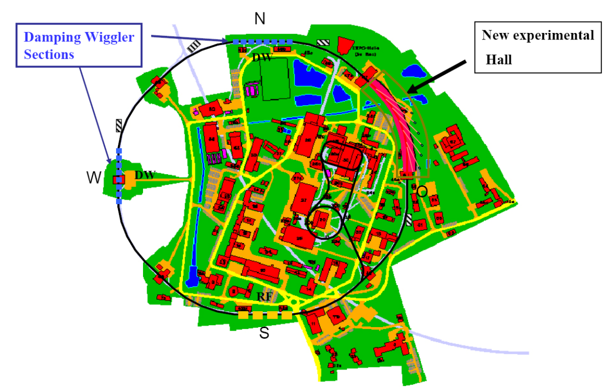

Figure 1: Upper half: Site map of DESY with the PETRA ring. The new experimental hall (purple) is situated between the PETRA halls North-East and East and the damping wiggler sections are in the North and West. Lower half: Aerial view of the PETRA ring and the new hall.

After the conversion had been completed commissioning started in the middle of March 2009.

The first step was to set up and optimize the 190 m long transfer line between the synchrotron DESY II and the

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storage ring. It took a few hours to transfer particles through the line and about 2 days to optimize the optics and the transfer efficiency.

Commissioning of the storage ring was first done without wigglers to simplify matters. The primary objectives were to store and accumulate beam and to set up part of the bunch by bunch feedback system to condition the vacuum system with as much current as possible. In addition first tests of different diagnostic elements were carried out which are for example necessary for the future operation with wigglers and undulators. The diagnostics of the machine are described in detail in [6], [7].

First beam was stored on the 13-th of April. After a preliminary optimization of the machine accumulation could be set up on April 22. With the help of the old PETRA II coupled bunch feedback system about 20 mA could be stored in 70 bunches on April 28 so that the conditioning of the vacuum system could be started.

The first phase of commissioning ended with the first light on screen monitors in one of the undulators beam lines on the 30-th of April.

The machine was successively improved and the wigglers were installed step by step from July 1 till August 15.

In the following commissioning results will be presented that were gained with all wigglers installed and the first experience of user operation will be described.

OPTICS AND DISPERSION CORRECTION

The optics of PETRA III consists of a FODO lattice in the refurbished seven eighth of the machine and 9 DBA cells in the new eighth. The quadrupoles in the new eighth are all individually powered whereas in the old parts many of the quadrupoles are grouped in families. Prior to optics correction all the BPM have been aligned with beam with respect to the closest quadrupoles. This enables orbit correction to about 150 µm in the horizontal and about 60 µm in the vertical plane. The optics of the machine was determined with the help of an orbit response matrix and changes of the quadrupole settings were calculated to correct the beta beating. For details see reference [8].

Within two iterations the initial beta beating of about 10% in the horizontal and 18% in the vertical plane has been corrected down to about 3% horizontally and 2% vertically. In the new octant the remaining beta beating is of the order of 1% similar to what has been achieved at other light sources. The required changes in quadrupole settings were up to 2.5 % of the nominal value. The tunes are set close to the design values of $Q_x = 36.12$ and $Q_y = 32.30$ and the chromaticity was corrected to about 0.5 in both planes.

In order to meet the design values of the horizontal and vertical emittance the dispersion has to be corrected close to the theoretical values. Especially in the damping wiggler sections the error on the horizontal dispersion should be less than 10 mm and the vertical dispersion should be less the 3 mm. Correction of the horizontal plane is done with the corrector magnets. In the vertical plane the correction can be done with the vertical steering magnets or with the help of 12 dedicated skew quadrupoles. These quadrupoles are installed at locations with high horizontal dispersion and can be used to correct the vertical dispersion locally in the two damping wiggler sections and the new part of the machine or can be used for a global correction. For details and the results of the correction see references [9], [10], [11].

EMITTANCE, ENERGY SPREAD AND COUPLING

Emittance measurements are done with a dedicated diagnostic beam line which is described in detail in [6], [7]. After correction of the dispersion the measured emittances agree very well with the design values. The measured horizontal emittance is 1 ± 0.2 nm rad and the vertical emittance is smaller than 20 pm rad but a precise measurement is still missing. For details see Ref. [12].

The bunch length has been measured with a streak camera and the value of 40 ps is in accordance with theory if an energy spread of 0.012% is assumed.

The width of the coupling resonance has been measured and compensated and the present value is 0.006. The emittance ratio for this coupling value would be 0.05% which indicates that at present the vertical emittance is determined by spurious vertical dispersion.

NONLINEAR DYNAMICS – OFF AND ON MOMENTUM APERTURE

The required on momentum acceptance of PETRA III has to be very large because of the large emittance of 350 nm rad of the synchrotron DESY II at 6 GeV. According to tracking the acceptance should be around 35 mm mrad [13], [14] in the horizontal and about 2 mm mrad in the vertical plane. The measured horizontal acceptance is around 26 mm mrad and the vertical around 1.2 mm mrad. The vertical acceptance is probably smaller than expected since the measured physical aperture limited by the small gap undulator chambers is only 2 mm mrad instead of 2.7 mm mrad. Analysing the detuning with amplitude the acceptance seems to be basically determined by the nonlinearities of the sextupoles which means that the nonlinear fields of the wigglers have been corrected very well with the help of magic fingers. The measured acceptance is big enough for good injection efficiency. Record values are larger than 90 % whereas typical values are around 75 %.

The momentum acceptance has been determined by recording the Touschek lifetime as a function of rf voltage. The measured momentum acceptance of 1.6% is in good agreement with the tracking results of 1.7% [14].

Recent results on investigations of the nonlinear behaviour of PETRA III can be found in Ref. [15] ,[16].

TOP-UP OPERATION

In 2009 top-up operation with IDs closed was prevented by a large stray field of the septum. The stray field caused orbit distortion of more than 2 mm in the horizontal plane. For operation with closed IDs orbit deviations have to be smaller than 0.5 mm horizontally and 0.25 mm vertically. Otherwise the beam is dumped by the orbit interlock system which protects the vacuum vessel in case of mis-steered photon beams. The septum has been replaced in the winter shut down 2009 / 2010 and the stray field of the new septum is smaller by a factor of 20 compared with the old septum. An automatic top-up procedure has been set-up to keep the beam current constant within 1% for a filling with 70 bunches and 0.25% for a filling with 960 bunches. Presently the machine is routinely operated with 70 bunches at a current of 50 mA and current stability is 1%. The lifetime in this mode is around 4 h and to achieve the current stability demands injection is necessary every 3 minutes.

ORBIT STABILITY – ORBIT FEEDBACK

The insertion devices are installed in two different DBA-cells. One cell type has a high horizontal beta-function of 20 m whereas the other cell type has a low horizontal beta-function of 1m. The orbit should be stable within 10% of the nominal beam size. The orbit stability requirements for both cell types are given in table 2.

Table 2: Orbit Stability Requirements

Stability requirement	Low β_x cell	high β_x cell
horizontal	3.0 µm	14.0 µm
vertical	0.6 µm	0.6 µm

In order to ensure orbit stability passive and active measures have been taken. In the following some of the passive measures are listed:

- The slab of the new hall is a one meter thick monolithic concrete block of 30 m widths and 250 m lengths. This represents a huge optical bench which guarantees stability between source point and sample.
- The super structure of the hall rests on 20 m long sleeved piles. The lower half of the piles rests in the ground but the upper half is isolated from the ground. Thereby vibrations of the super structure of certain frequencies can not couple to the slab.
- The girders have been carefully designed so that the resonant frequencies are all above 40 Hz.
- The air temperature in the accelerator tunnel of the new hall has to be stable within 0.1° C and the temperature of the cooling water has be stable within a few tens of a degree.

From the experience gained in PETRA II it was clear that passive measures would not be sufficient to fulfil the orbit stability requirements but an orbit feedback would be necessary [9].

The orbit feedback uses all beam position monitors and uses a special output port of the BPM electronics. Orbit data is taken at a rate of about 40 kHz. For correction 11 air coils are installed in the seven eighths and 30 air coils in the new part in the horizontal as well as in the vertical plane. The corrector magnets in the seven eighths are necessary to avoid fluctuations of the vertical emittance [9]. The corrector magnets can supply kicks of up to 35 µrad from a few hundred Hz down to the DC level. Orbit data is transferred to a central processing unit where all the calculations are done and the resulting corrector kicks are transmitted to the amplifiers of the air coils. The processing rate is about 15 kHz so that corrections can be done up to a few hundred Hz.

Figure 2 shows the short term stability in the horizontal plane with and without feedback for one high beta cell.

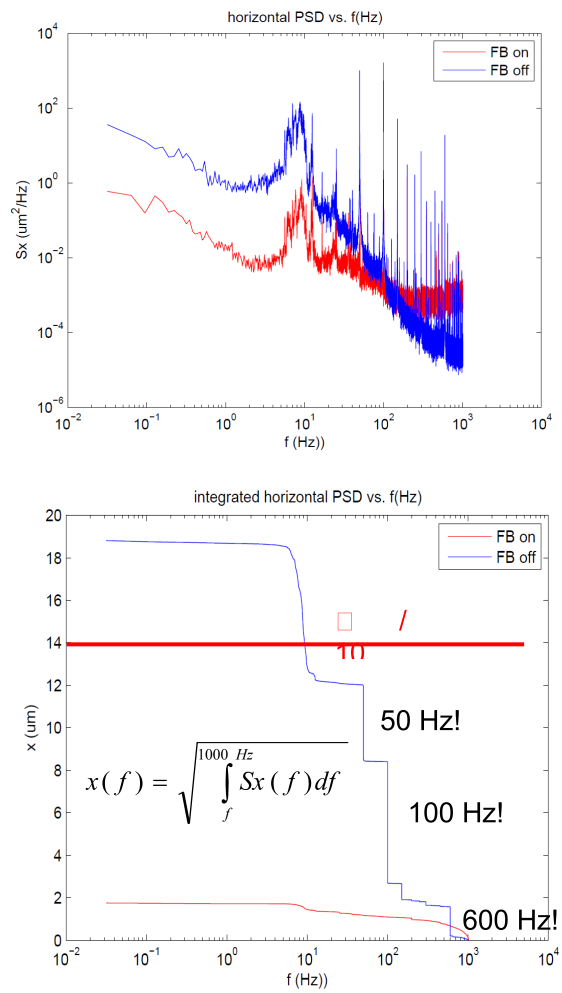


Figure 2: Upper half: Power spectral density of fast horizontal orbit motion. Lower half: Square root of the integrated horizontal power spectrum.

Looking at the data without feedback the main contributions to orbit distortions can be identified. Large contributions are due to the frequency of the mains and multiples of it. These contributions are reduced with special harmonic suppressors. The other large contribution close to 10 Hz is due to the supports of the quadrupoles in the refurbished seven eighths of the machine. Contributions to orbit distortions due to the girders are not visible or at least difficult to identify which indicates the careful design of the girders. The data taken with feedback on clearly shows that the orbit distortions are suppressed below the required values. The same is true for the vertical plane where the rms value without feedback is 2 µm and with feedback 0.4 µm that is below the required limit (see table 2).

Long term stability has been investigated as well. The available data clearly shows that over 20 h the stability requirements can be fulfilled in the horizontal and vertical plane.

CURRENT LIMITATIONS

Single Bunch Instabilities

To find out if single bunch instabilities are a potential problem for PETRA III the broadband impedance of the machine has been investigated in detail [17], [18]. To verify the calculated results on the broadband impedance the transverse coherent tune shift with current has been measured and compared with expectations. The measured values are larger than expected but do not impose a limitation on the single bunch current limit [19]. At present the single bunch current is limited deliberately to 2.8 mA, which is larger than the design single bunch current of 2.5 mA, to protect the beam position monitor electronics.

Coupled Bunch Instabilities

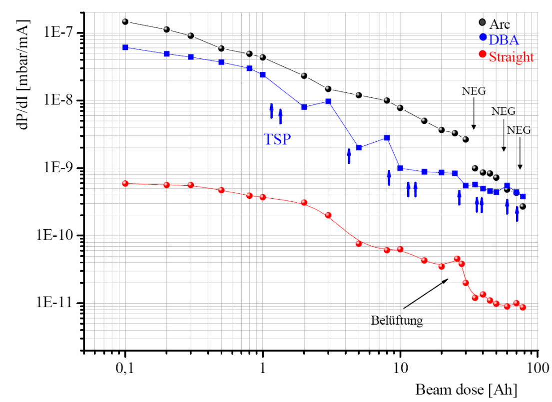
Due to the experience in PETRA II it was expected that coupled instabilities will be a severe problem for PETRA III. The instabilities are mainly caused by the parasitic modes of the seven cell cavities which were already present in PETRA II. Although 4 cavities have been removed from the machine so that only 12 cavities are installed the threshold current for instabilities is well below the design current of 100 mA. To suppress the instabilities powerful broadband feedback systems have been installed in the machine. The basic features of the system are similar to the feedback systems that were installed in PETRA II and are described in Ref. [20].

The transverse systems uses strip-line monitors and two strip-line kickers each fed by two 250 W amplifiers for the horizontal and vertical plane. To combat longitudinal instabilities eight cavities of the Daphne type have been installed each powered by a 500 W amplifier. During tests in October 2009 a current of 89 mA in 960 bunches could be achieved but almost all of the longitudinal amplifiers were destroyed. Meanwhile four of the eight amplifiers have been modified and repaired and during a test in April 2010 a current of 98 mA in 240 bunches could be reached.

Recently it has been observed that for currents beyond 50 mA a vertical blow up of the beam occurs. There are indications that not all bunches of a multi bunch filling are effected and in the tune spectrum of the effected bunches additional lines appear. Part of the problem is associated with the feedback system because some of the additional tune lines can be affected by changes of the phase and gain of the vertical feedback. Presently there is no complete explanation of this effect and further studies are required.

VACUUM AND BEAM LIFETIME

The vacuum system of PETRA III has been described in detail in Ref. [21], [22].



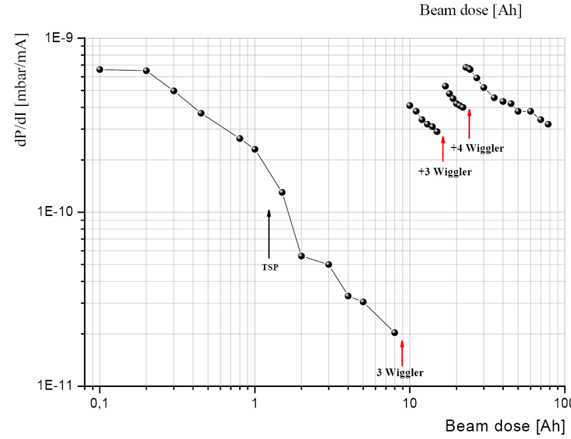


Figure 3: Upper half: Dynamic pressure rise vs. beam dose for the arcs, straights of the refurbished seven eighths and the DBA cell of the new eighths Lower half: Dynamic pressure rise vs. beam dose for the two damping wiggler sections

At the start of commissioning the static pressure was around a few times 10^{-7} mbar and the dynamic pressure rise was of the same order. As expected the arcs in the seven refurbished eighths contributed the most to the mean pressure of the machine. In 2009 and 2010 an integrated dose of about 80 Ah was accumulated and the static pressure went down to $4 \cdot 10^{-10}$ mbar. The lifetime for a current of 10 mA distributed of a large number of bunches increased from about a few ten minutes at the beginning of the commissioning to 35 h at present.

The dynamic pressure rise as a function of integrated dose (D) for different parts of PETRA III is shown in figure 3. The wiggler sections started conditioning only after the installation of the wigglers. The conditioning of the vacuum system of the rest of machine behaves as expected and the dynamic pressure rise in the arcs of the refurbished seven eighths follows a $D^{-0.8}$ law which is typical for a system containing stainless steel and aluminium chambers. According to measurements the residual gas consists of 90% hydrogen and about 10% CO.

INSERTION DEVICES – BEAM LINE COMMISSIONING

Three 2m long undulators had been installed before commissioning started.

Meanwhile 10 of the 14 foreseen undulators were installed including a 5 m long device and the Apple II undulator. The basic parameters of the IDs are given in table 3. For details see also Ref. [23].

Table 3: ID Parameter

Parameter	U29	U32	U23	UE65	U19	U32_10
Minimum gap (mm)	9.5	9.5	9.5	11.0	7.0	12.5
Period length (mm)	29	31.4	23	65.6	19	31.4
Length (m)	2 / 5	2	2	5	4	10
Peak field (T)	0.81	0.91	0.61	1.03	0.7	0.68
1st harmonic (keV)	3.5	2.4	8.0	0.3	10.2	3.6
Total power (kW)	7.5	3.8	1.7	11.8	4.5	10.7

Three beamlines finished commissioning and they are doing first experiments with friendly users. In the second half of 2010 they will start operation with regular users. Five beamlines are in the process of commissioning and they will start operation with friendly users in the second half of 2010. The remaining six beamlines will start commissioning in the second half of 2010.

The impact of the IDs on the machine is either compensated or negligible. Closing the ID gaps generates closed orbit distortions of about 100 μm horizontally and about 50 μm vertically. Trim coil feed-forward tables have been set up to reduce the effect in both planes by an order of magnitude and the remainder is compensated by the orbit feedback.

Changes of the vertical tune of 0.0015 have been observed whereas no change of the horizontal tune has been seen. The associated change of the optics is of the order of a percent so no optics corrections have been foreseen yet.

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