PETRA III: A Third Generation Synchrotron Radiation Source at DESY.

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1. July 2003

Introduction

At present the storage ring DORIS III serves as the main source for synchrotron radiation (SR) at DESY with 9 wiggler beamlines and more than 30 bending magnet stations. Two additional experimental stations are operating at the PETRA II undulator beamline. The energies provided for experiments spread from the VUV to the several 100 keV range.

Being a second generation source, the wigglers and bending magnets of DORIS III provide high flux in quite large beams. Whilst these parameters are ideal for the investigation of large samples, extremely small samples can only be investigated by strongly focused and therefore divergent beams. Due to the large source size of DORIS III it is almost impossible to generate a beam focus in the micrometer range. In this respect modern third generation sources are much more powerful. Due to their low emittance and the use of undulators they are able to provide roughly speaking the same unfocused flux in 1 mm^2 that DORIS III wigglers deliver in several cm^2. These new sources have opened a wide field of new applications, especially those that need to investigate extremely small samples, a microfocus or partially coherent radiation.

DESY's long term perspective is the TESLA linear collider and X-ray free electron laser project. The latter will provide a transverse coherent beam with peak brilliances several orders of magnitude higher than any present synchrotron radiation source. It is DESY's intention to provide also photons of very high brilliance from storage rings to the user community in addition to these new developments. For this reason it has been decided to rebuilt the 2.3 km long PETRA storage ring into a third generation source for hard X-rays from 2007 on.

In the following the plans for rebuilding PETRA will shortly be outlined, followed by the main chapter about the expected beam performance.

A more detailed description about the reconstruction of the storage ring will be presented in a second document (in preparation).

Reconstruction of PETRA

An upgrade of PETRA will include the total rebuilding of one eighth of the storage ring to provide the electron beam optics for 9 straight sections each providing space for one 5 m long insertion device or two 2 m long insertion devices, that can

be inclined by about 5 mrad against each other. The latter scheme would allow concepts similar to the ESRF Troika beamline but with independent undulators and beam paths for each device. In Fig. 1 the position of the new experimental hall is indicated. Depending on the exact beamline outline about 13 beamlines with independent tunable insertion devices will be available. The length of the first undulator (close to hall 47) can be up to 20 meters. If it is required for future upgrades there are two other positions at PETRA (buildings 43 and 45) where such a long undulator could be placed. In addition there are three further positions (in or close to buildings 44, 46 and 48) for normal 5 m long undulators or wigglers. Thus in total about 18 insertion device positions are available.
At present a particle energy of 6 GeV is foreseen with a current of at least 100 mA.

Figure 1: Plan of the DESY site; the new experimental hall is shown in magenta between buildings 47 and 48. Additional beamline buildings are sketched in dark magenta at positions where additional undulator beamlines can be placed in future if there is sufficient user demand.

	ϵ_x [nmrad]	E [GeV]	ϵ_x/E^2		ϵ_x [nmrad]	E [GeV]	ϵ_x/E^2
ERL low_I	0.01	7	0.0002	Soleil	3	2.5	0.48
ERL high_I	0.1	7	0.002	SLS	4.4	2.4	0.763
USR	0.3	7	0.006	Elettra	7	2.4	1.215
PETRA III	1	6	0.027	BESSY II	6	1.9	1.66
APS	3	7	0.061	Spear III	18	3	2
Spring 8	5.9	8	0.092	MAX II	9	1.5	4
ESRF	3.9	6	0.108	ANKA	41	2.5	6.56
PETRA II	25	12	0.173	DORIS III	450	4.5	22.2
Diamond	2.5	3	0.2				

Table 1: Emittance, particle energy and normalized emittance of a number of operating and planed storage rings. 'ERL' denotes the energy recovery linac driven storage ring plans of Cornell university, a high and a low particle current mode are envisaged. 'USR' denotes a study about an ultimate storage ring carried out by the ESRF machine group. 'PETRA III' denotes the upgraded PETRA storage ring study including the damping wiggler option and 'PETRA II' the present design.

The proposed upgrade will provide an emittance of 1 nmrad if a number of damping wigglers with a total length of 100 m will be installed in the long straight sections of the storage ring. The vertical-horizontal emittance coupling is aimed to be 1%. In Tab. 1 the emittance of a number of synchrotron radiation storage rings normalized by the square of their particle energy is shown. It is obvious that an upgraded PETRA storage ring with damping wigglers provides the best basis for a low emittance high brilliance synchrotron radiation source at higher particle energies. Only the USR-study, what is considered to be the ultimate storage ring, and the high energy recovery linac driven sources will provide a smaller emittance. Some other relevant machine parameters are compared with other high energy synchrotron radiation sources in Tab. 2.

In order to provide reliable machine operation and a beam lifetime limited only by the intrinsic Touschek lifetime the whole vacuum system and a large portion of other infrastructure will be replaced. Planning for a detailed layout of the new experimental hall is under way.

Insertion device characteristics at PETRA III

A minimum aperture of 7 mm and state of the art vacuum pipe design would allow magnetic gaps of the insertion devices down to 9–10 mm without the need of in-vacuum devices. The gaps of in-vacuum devices could probably even be lower than 7 mm as it has been demonstrated successfully e.g. at Spring8, ESRF and SLS. In Tab. 3 typical values for β-functions and photon source sizes at the envisaged insertion device positions are listed and compared with the corresponding values of other 3$^{\text{rd}}$ generation high energy sources. The PETRA III values are preliminary

	DORIS III	PETRA II	PETRA III	ESRF	APS	Spring-8
energy [GeV]	4.5	12	6	6	7	8
max. current [mA]	150	60	>100	>200	100	100
circumference [m]	288.9	2304	2304	844	1104	1436
emittance [nm rad]	450	25	≈1	3.9	5.9	3
coupling [%]	3	3	1	< 0.625	1	0.3
B_{max}@12 keV	10^{15}	10^{18}	$> 10^{21}$	$> 10^{20}$	$> 10^{20}$	$\approx 2 \cdot 10^{20}$
η_{total} @ 1 Å[%]	-	$2.7 \cdot 10^{-4}$	0.24	0.029	0.03	0.025
η_{vert} @ 1 Å[%]	-	0.8	31	16	12.6	19.2

Table 2: Comparison of different source parameters; B_{max} denotes the maximum brilliance at 12 keV in $ph/(s\,mm^2\,mrad^2\,0.1\%\,BW)$. Parameters are selected for normal user mode operation. The vertical and total coherent fraction η_{vert} and η_{total} were calculated according to $flux \cdot \lambda/(4\pi\Sigma_y\Sigma'_y)$ and $flux \cdot \lambda^2/((4\pi)^2\Sigma_x\Sigma'_x\Sigma_y\Sigma'_y)$, respectively. The η-values are the values for the most brilliant insertion devices.

since the optimization procedure is still under way.

The β values for the PETRA III insertion device positions labelled with 'DW-drift' are fixed. For this position, $\alpha_x = -0.7$ and $\alpha_y = 0.7$. The α values of all other PETRA III insertion device positions are zero which holds also for the dispersion in the straight ID sections. In Fig. 2 the brilliance of typical PETRA III undulators is compared to other third generation synchrotron radiation sources. The parameters used for the calculations of this plots are given in the appendix.

In some cases of existing radiation sources (APS, ESRF) the maximum possible length for an insertion device was assumed even if it does not exist with this length at

	β_x [m]	β_y [m]	Σ_x [μm]	Σ_y [μm]	$\Sigma_{x'}$ [μrad]	$\Sigma_{y'}$ [μrad]	ID-length [m]
low-β	1.2	4	34.5	7.3	29	5.2	5
high-β	20	2.38	141	4.2	8.6	5.2	5
20 m-ID	16	10	126	10.7	8.2	2.7	20
DW-drift	16	16	126	12.7	10.5	4.4	5
ESRF low-β	0.5	2.73	60	8.4	89.3	6	5
ESRF high-β	35.2	2.52	403	8.2	11.8	6	5
Spring-8	24.6	3.9	384	7.1	16.5	6.6	4.5
APS	15.9	5.3	217	12.6	15.3	5.7	4

Table 3: Overview of typical β functions, photon source sizes $\Sigma_{x,y}$ and divergences $\Sigma'_{x,y}$ for various ID positions at different storage rings compared to PETRA III. The photon source parameters are given for a photon energy of roughly 12 keV. 'DW-drift' denotes possible undulator positions in the straight sections outside the eighth that will be reconstructed. These values were calculated using the parameters given in Tab. 2.

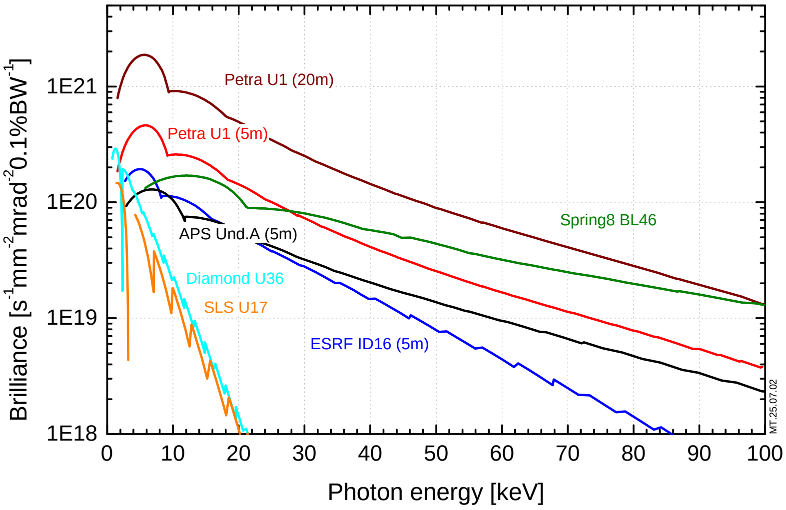

Figure 2: Comparison of the brilliance of two typical PETRA III undulators with those of other third generation sources. The calculations assume ideal undulators, e.g. the brilliances in the higher energy region will generally be marginally smaller.

present. It was shown e.g. by the ESRF insertion device group, that the deviation of a carefully shimmed undulator from an ideal one is about 30 % at the 15th harmonics. This error will increase at higher energies/harmonics. These findings should give an indication for the reliabilities of the calculated values at higher energies (>50 keV) in Fig. 2. The brilliance of several PETRA III undulators for different length and electron optics is compared in Fig. 3a. The parameters used for these calculations are given in the appendix. Some of the β-functions used for these calculations are not exactly those given in Tab. 3 which may lead to slightly different results.

Especially the materials science community is interested in photon energies close to 100 keV and more. This is the regime where mainly wigglers have to be used. In Fig. 3b the flux of a number of insertion devices through a $1 \times 1\text{mm}^2$ pinhole in

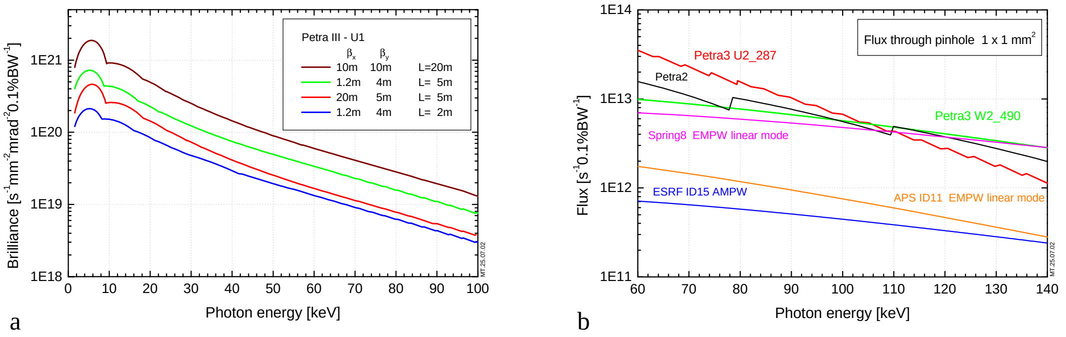

Figure 3: a. Comparison of the brilliance of typical PETRA III undulators for different length and beta functions. b. Flux through a $1 \times 1\,\text{mm}^2$ pinhole 35 m from the source of a number of high energy radiation insertion devices. See main text and appendix for further explanations.

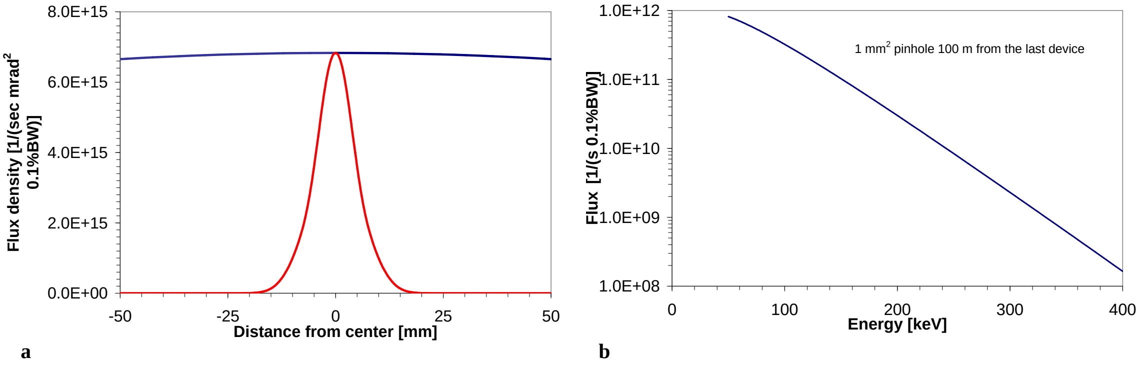

Figure 4: a. Beam profile at 100 m after two damping wigglers (the two devices themselves are 100 m separated); The narrow, red profile shows the vertical profile, the blue line represents the horizontal one. b. Flux through a 1 mm^2 pinhole 100 m behind an array of two 12 m long damping wigglers.

35 m distance from the source is compared as function of photon energy. The choice of a $1 \times 1\text{mm}^2$ pinhole is rather arbitrary and especially the insertion devices with a larger K-value (*e.g.* all MPW devices) will provide a significant higher total flux through larger apertures.

A number of users on different workshops were interested to learn more about the radiation properties of the damping wigglers at PETRA III. This information is shown in Fig. 4. Obviously these devices provide a rather large beam with significant flux at higher photon energies. If similar properties are of general user interest, it is certainly possible to find more specific solutions to fulfill user demands in the

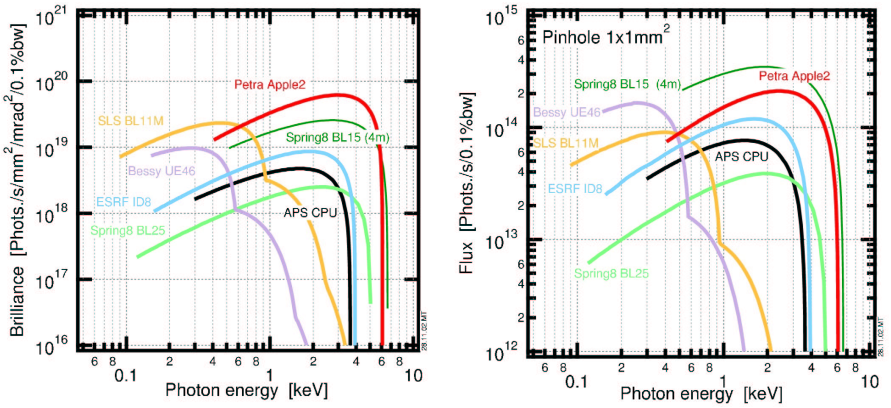

Figure 5: Comparison of the brilliance (left) and the flux through a 1 mm^2 pinhole (right) of a proposed 2 m long PETRA III soft X-ray undulator and several existing soft X-ray and VUV insertion devices. All calculations have been carried out for undulator segments of 1.65–2 m length except for those with the length specified explicitly.

high energy photon regime.

High energy storage rings are very well suited to provide circular polarized soft X-ray undulator radiation which is only obtained at an high degree of polarization in the fundamental line of a helical undulator. A comparison of a proposed PETRA III device with other existing devices is shown in Fig. 5.

Summary and Conclusion

The reconstruction of one eighth of the present PETRA storage ring at DESY into a third generation synchrotron radiation source running at 6 GeV with 1 nmrad emittance will provide 13–15 high brilliance undulator beamlines. There are various options in order to provide more beamlines if this will be required in future. Due to the small emittance and the possibility to install long undulators PETRA III will be the most brilliant source in the X-ray regime until the first linac driven sources will be available.

The particle energy E was defined to 6 GeV which is a compromise in order to obtain a critical energy ($E_c \propto E^2$) high enough for hard X-ray applications and a small source size which depends on the emittance ($\epsilon \propto E^2$) for microfocus experiments or those that exploit the coherence properties of the beam.

The vertical photon beam source sizes of PETRA III will be comparable to present high energy 3$^{\mathrm{rd}}$ generation sources at a slightly smaller divergence. The main advantages of PETRA III will be in horizontal photon beam source size and divergence due to the smaller emittance. This results in a slightly larger coherent fraction in the vertical direction and a total coherent fraction of about one order of magnitude higher compared to ESRF, APS and Spring-8.

At the assumed 1% horizontal-vertical coupling the maximum brilliance of the longest PETRA III undulators will be above 10^{21} and even the standard 5 m devices should provide about $6 \cdot 10^{20}$. The brilliance of the short 2 m insertion devices, which are foreseen for split straight sections, will be higher than 10^{20} which is comparable to the maximal values that are available from present day sources. At higher photon energies (60–100 keV) storage rings running at significantly higher particle energies like Spring-8 perform slightly better than PETRA III for the same undulator length. Low emittance storage rings operating at lower energies are comparable in brilliance at low energies (1-3 keV) to the high energy sources, however, their undulator brilliance drops rather fast at energies above 5 keV. Theoretically, undulators at PETRA III seem to perform better than wigglers up to 100 keV photon energy if a small and parallel beam is needed. For energies significantly higher than 100 keV wigglers are superior in any case.

The main applications at PETRA III will exploit the small source size. However, wigglers and also the damping wigglers of PETRA III will provide large beams at very high photon energies, which could be interesting for materials science applications.

In addition, PETRA III is a very interesting source also for the soft X-ray community if circular polarized light is required.

Appendix

Parameters used for the calculation of the brilliance and flux plots in Figures 2 and 3. The symbols 'ϵ' and 'κ' denote the emittance and the coupling constant, respectively. For all other quantities the usual notation was used. All brilliance and flux data were calculated using the program *Spectra* (Takashi Tanaka and Hideo Kitamura, RIKEN, Institute of Physical and Chemical Research).

The parameters given below for PETRA III insertion devices correspond to the values used to calculate the graphs shown in figures 2-5. For any further PETRA III calculations the following parameters should be used: (i) β-functions from Tab. 3, (ii) the standard PETRA III undulator will have a period of about 28 mm and a maximum K of 2.2, (iii) possible undulator lengths will be 2 or 5 m.

Undulators:

- PETRA III U1(20m): 6 GeV, ϵ=1 nmrad, κ=1 %, $\beta_x = 10$ m, $\beta_y = 10$ m, K$_{\text{max}}$=3.4, 100 mA, 31.9 mm period, 626 periods (please read the comments above).

- PETRA III U1(5m): 6 GeV, ϵ=1 nmrad, κ=1 %, $\beta_x = 20$ m, $\beta_y = 5$ m, K$_{\text{max}}$=3.4, 100 mA, 31.9 mm period, 156 periods (please read the comments above).

- Spring-8 BL46: 8 GeV, ϵ=5.9 nmrad, κ=0.2 %, β_x=24.4 m, $\beta_y = 3.9$ m, K$_{\text{max}}$=2.6, 100 mA, 24 mm period, 187 periods.

- ESRF ID16: 6 GeV, ϵ=3.9 nmrad, κ=0.75 %, β_x=35.2 m, $\beta_y = 2.52$ m, K$_{\text{max}}$=2.3, 200 mA, 35 mm period, 141 periods.

- APS - Und.A: 7 GeV, ϵ=3 nmrad, κ=1 %, β_x=15.9 m, $\beta_y = 5.3$ m, K$_{\text{max}}$=2.78, 100 mA, 33 mm period, 148 periods.

- Diamond: 3 GeV, ϵ=2 nmrad, κ=1 %, β_x=2.5 m, $\beta_y = 2.5$ m, K$_{\text{max}}$=2.02, 300 mA, 36 mm period, 125 periods.

- SLS: 2.4 GeV, ϵ=4.3 nmrad, κ=1 %, β_x=1.65 m, $\beta_y = 1.35$ m, K$_{\text{max}}$=1.59, 400 mA, 17 mm period, 117 periods.

High energy photon insertion devices:

- APS-ID11 EMPW: 7 GeV, ϵ=3 nmrad, κ=1 %, $\beta_x = 15.9$ m, $\beta_y = 5.3$ m, K$_{\text{max}}$=14.4, 100 mA, 160 mm period, 17 periods.

- ESRF ID15 AMPW: 6 GeV, ϵ=3.9 nmrad, κ=0.75 %, β_x=0.5 m, $\beta_y = 2.73$ m, B_0=1.84 T, E_c=44.1 keV, 200 mA, asym. period length: 230 mm, 7 periods.

- PETRA II: 12 GeV, ϵ=25 nmrad, κ=3 %, $\beta_x = 55$ m, $\beta_y = 24$ m, K$_{\text{max}}$=1.81, 50 mA, 33 mm period, 121 periods (please read the comments above).

- Spring-8 BL08 EMPW: 8 GeV, ϵ=5.9 nmrad, κ=0.2 %, β_x=24.4 m, $\beta_y = 3.9$ m, K_{max}=13.1, 100 mA, 120 mm period, 37 periods.
- PETRA III U2: 6 GeV, ϵ=1 nmrad, κ=1 %, $\beta_x = 20$ m, $\beta_y = 5$ m, K_{max}=2.7, 100 mA, 28.7 mm period, 174 periods (please read the comments above).
- PETRA III W2: 6 GeV, ϵ=1 nmrad, κ=1 %, $\beta_x = 20$ m, $\beta_y = 5$ m, K_{max}=7.7, 100 mA, 49 mm period, 102 periods.