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# STATUS OF THE PETRA IV PROJECT

I. Agapov *, R. Bacher, M. Bieler, R. Böspflug, R. Brinkmann, Y.-C. Chae, H.-C. Chao, H.-T. Duhme, M. Ebert, H.-J. Eckoldt, H. Ehrlichmann, M. Hüning, U. Hurdelbrink, J. Keil, J. Klute, B. Krause, M. Körfer, G. Kube, W. Leemans, L. Lilje, N. Meyners, X. Nuel Gavalda, F. Obier, A. Petrov, N. Plambeck, J. Prenting, C. G. Schroer, G.K. Sahoo, F. Schmidt-Föhre, H. Schlarb, M. Schlösser, M. Schmitz, T. Tempel, M. Thede, M. Tischer, R. Wanzenberg, E. Weckert, T. Wilksen, K. Wittenburg, J. Zhang
Deutsches Elektronen Synchrotron, Notkestrasse 85, 22607, Hamburg, Germany

*Abstract*

Since 2016 DESY has been pursuing R&D towards upgrading its PETRA synchrotron light source to a fourth-generation machine, PETRA IV, which is expected to start operation in 2027. The conceptual design of a 6 GeV seven-bend-achromat-based lattice with an approx. 10 pm emittance along with critically important technical systems has been completed. We will present the status of the project, the expected parameter space of the facility, the lattice design and beam dynamics issues for the main ring, and the key technological challenges faced so far.

## INTRODUCTION

PETRA III [1, 2] is a successful 3rd generation synchrotron light source currently operated by DESY Hamburg. Over the last years various technological advances have allowed to propose and build the so-called 4$^{th}$ generation of storage rings based on stronger focusing lattices ("Multi-Bend Achromats"). The successful commissioning of the 3 GeV MAX IV ring ushered in a wave of facility upgrades, with virtually all major facilities having proposed an upgrade scenario by now. With its large circumference PETRA is uniquely positioned to provide ultra-low emittance electron beams, and in order to continue leadership in x-ray science into the future an initially small design group was formed in 2016 to pursue the conceptual design for the facility upgrade. Around three years of design work have resulted in the Conceptual Design Report which is currently under review and is expected to appear in print towards the end of the year. This paper presents the status of the PETRA IV project with a focus on the summary of the storage ring and injector complex design.

## STORAGE RING AND INJECTOR CHAIN OVERVIEW

### *Introduction to Design Parameters*

Similar to other 6 GeV synchrotron upgrades, the science case of PETRA IV is built around techniques requiring coherent (up to 10 keV) hard x-rays [3]. Due to its circumference, PETRA IV (see Figure 1) is uniquely positioned to reach a natural emittance of about 10 pm, thus reaching unprecedented coherence and brightness. The comparison

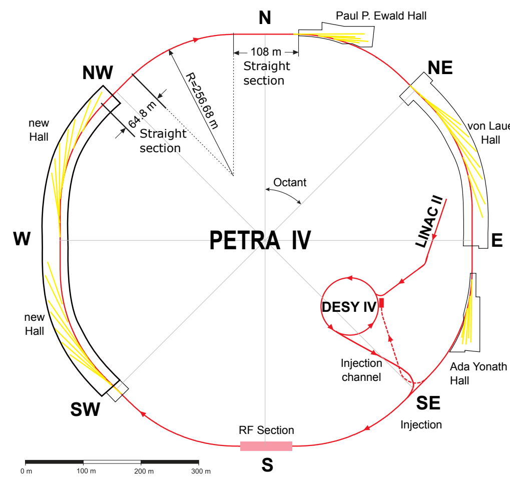


Figure 1: PETRA IV facility layout

of brightness to that of PETRA III is presented in Figure 2, where along with the emittance reduction advances in undulator technology (a short period undulator) and an increase of beam current by a factor of two have been accounted for. While initially a lower energy of 5 GeV was foreseen (which would have resulted in an even smaller emittance), it was later understood that an energy of roughly 6 GeV is optimal for photon flux and brightness, especially in the hard x-ray part of the spectrum. Initially, damping wigglers were foreseen in the lattice, but due to their detrimental effect on the energy spread were later abandoned.

The experimental runs at PETRA IV will be divided in two groups: timing mode (with 80 bunches in the ring) and brightness mode (1600 bunches in the ring). This division is already present at PETRA III albeit with different filling parameters (with 40 and 960 bunches respectively). In a series of science workshops it was identified that both modes of operation are essential for the PETRA IV experimental programme, but requirements on beam parameters in the timing mode can be somewhat relaxed, since experiments requiring high degree of coherence will be performed in the brightness mode of operation. The emittance growth with bunch current and the single-bunch instability threshold influence the choice of RF parameters and fill patterns. We initially considered RF frequencies between 100 and 500 MHz. In the brightness mode no particular gain in emittance could be made from a lower RF frequency: the natural bunch length in a higher-frequency RF system is smaller, but the total

* ilya.agapov@desy.de

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beam charge can be distributed over a larger number of RF buckets. The differences manifest themselves in the timing mode, where however no strict requirements on emittance were given. Based on these considerations a 500 MHz RF system (same frequency as PETRA III) with an additional third harmonic system has been chosen. Without bunch lengthening, single-bunch instability (TMCI) threshold sets a limit of 0.1 mA bunch current according to simulations. The bunch lengthening by approx. factor 10 can be achieved, which allows a timing mode with a somewhat reduced beam current. In the brightness mode, bunch spacing of 4 ns is chosen as baseline based on conservative assumptions about the multi-bunch feedback system bandwidth. Some improvements in this system will allow to reduce the spacing to 2 ns, which will have further positive effect on beam parameters in brightness mode.

The present booster has an emittance which is too large for injection into an ultra-low emittance ring with a tight dynamic aperture. A new booster synchrotron with an emittance of 20 nm will be included in the upgrade programme. Furthermore, a linac which prepares the beam for the booster can be kept, while the present small accumulator ring PIA will be removed and the gun will be upgraded.

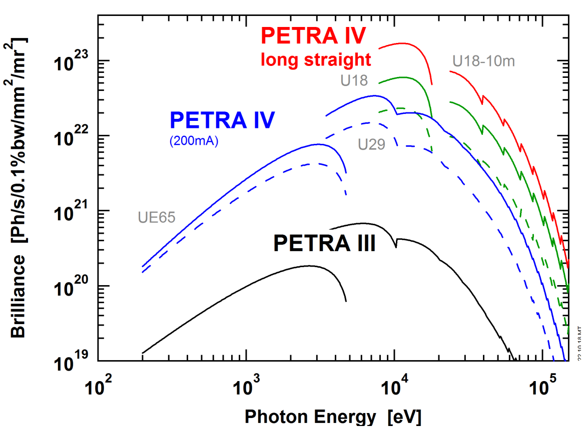


Figure 2: Spectral brightness for a current of 200 mA (blue, green, and red curves) in comparison with PETRA III (black curves) for a ring current of 100 mA. Comparison for a 5mUE65 undulator (P04 beamline at PETRA III) for soft x-rays, and a 5 m U29 undulator (P10 beamline at PETRA III) for hard x-rays. The solid lines correspond to the high-brightness/high-coherence mode, and the dashed lines to the timing mode. Additionally, gains from a 5 m and 10 m long U18 undulators are shown.

### *Baseline Storage Ring Lattice*

Several lattice options were initially studied. While lattice concepts specifically designed for a ring where a small portion of circumference is occupied with insertion devices (initially occupation of two octants was foreseen) were developed, the requirement of extensibility favoured a lattice with uniform cell layout based on the Hybrid Seven Bend Achromat concept. The PETRA IV lattice based on this concept was described in [4]. The difference of the baseline lattice to that presented in [4] is removal of the high-$\beta$ injection section (since on-axis injection has been chosen as baseline) and introduction of additional 10 m long IDs with $\beta^\star$=4 m, which will be used for high-end applications. Apart from usual challenges of DLSR design, the major complication with PETRA IV lattice has been in dealing with the low degree of machine superperiodicity. In contrast to a usual synchrotron light source layout, PETRA was initially laid out for the HEP programme, with eight long straight sections of two different lengths connecting eight octants. This presents some advantages such as abundant space for RF or damping wiggler installation, and possibility of having extra-long ID space adjacent to the arc. On the other hand, the machine periodicity is four at most, which complicates both optics layout and nonlinear dynamics optimization which is mostly based on carefully designing phase advances of the cell, the octant, and the long straights for resonance cancellation. Based on these design principles a lattice with performance parameters listed in Table 1 has been designed. The dynamic aperture (horizontal DA is estimated between ±2 mm and ±5 mm at $\beta$=21.7 m depending on the level of error correction. The local momentum acceptance is sufficient to guarantee more than 4 hours Touschek lifetime in the brightness mode and more than 1 hour lifetime in the timing mode. Both the machine protection system and the injector chain are designed for a minimum 30 minutes lifetime to provide contingency.

### *Further Options and Potential Improvements*

The conceptual lattice design is in place, based on which the layout of technical subsystems is ongoing. Several modifications are however still possible and will be potentially implemented in the first part of the technical design phase. First, introducing reverse bends by offsetting some quadrupoles can be used. to further decrease the emittance, optimize the dynamic aperture and momentum acceptance, and reduce the $\beta$ function at the ID. The current horizontal $\beta$ function both at the normal IDs (6.9 m for 5 m long devices) and at the four super-IDs (4 m for 10 m long devices) is still far from the optimal value, which for the PETRA IV parameter range can be approximated by

$$\beta_R \approx \frac{L}{\pi} \frac{1}{(1+1.41x^2)^{0.19}}$$

which results in approx. 1 m for short and 2 m for long IDs. Here $x = 2\pi n N_w \sigma_E$, $n$ is the harmonic number, $N_w$ the number of undulator periods and $\sigma_E$ the energy spread. Then, the current lattice has a 26.2 m cell length, which is different from the 23 m length in the present experimental halls. Many present beamlines employ canting with angles incompatible with a low emittance lattice, and most beamlines will need to be moved. This removed the preservation of sources locations as a major design constraint and allowed us to increase the cell length. However, further attempts to shorten the cell length to 23 m in one octant to preserve at least some of the source points will be further undertaken.

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Moreover, advanced options of beam recirculation by capturing the swapped out beam in the booster and using laser plasma acceleration in the injector chain are considered.

Table 1: Summary of Key Parameters

| Parameter | Brightness | Timing |
|---|---|---|
| Circumference | 2304 m | |
| Energy | 6 GeV | |
| Emittance (bare) | 17.4 pm | |
| Energy spread (bare) | 0.7 ‰ | |
| Bunch length (bare) | 4 ps | |
| Bunch length (w. 3rd harm.) | 43 ps | 63 ps |
| Hor. emittance (IDs closed) | 13 pm | 19 pm |
| Vert. emittance (IDs closed) | 3 pm | 4 pm |
| Energy spread (IDs closed) | 1 ‰ | 1.5 ‰ |
| Main RF frequency | 500 MHz | |
| Bunch spacing | 4 ns | 96 ns |
| Stored current | 200 mA | 80 mA |

## KEY TECHNICAL CHALLENGES

### *Magnets*

The magnet design for the main ring could closely follow that of other 6 GeV rings such as ESRF EBS, with two major differences. First, no permanent magnets are foreseen, since at a larger bending radius power consumption in dipoles becomes less prominent, and building up expertise in PM design has not been pursued. Second, considerably stronger sextupoles (up to 4000 T/m$^2$) are required. Design of critical magnets (high gradient quadrupoles, sextupoles) has been performed at the Efremov Institute.

### *Vacuum*

The new vacuum system will be more challenging due to significantly tighter longitudinal spacing and smaller apertures of magnets and other components. A compact storage ring vacuum system design using NEG coated chambers without antechambers is foreseen. NEG films need to be activated at high temperatures > 180 °C in order to initiate pumping. While the baseline is the development of an active heater system a study is currently prepared to understand whether in-situ activation with synchrotron radiation can suffice to achieve reasonable pumping speeds. The target vacuum lifetime is at least 10 h and could be achieved according to simulations.

### *Power Supplies*

The major difference to PETRA III is the large number of magnets, with about 2000 power supplies for main magnets and about 800 for corrector magnets. The so-called hot swap is foreseen to improve availability.

### *Injection and Extraction Kickers*

Kickers with <4 ns rise time, 80 ns flat top and up to 2 Hz repetition rate are foreseen for swap out injection. The kicker will be a modification of the XFEL dump kicker. Bunch trains with 20 ns gaps will be used in brightness mode to accomodate kicker rise and fall times.

### *Alignment*

To guarantee stable beam operation alignment tolerances of 30 µm (rms) magnet-to-magnet and 50 µm (rms) girder-to-girder are specified. These goals can be met, however the preservation of such alignment precision would require some modifications. to the existing tunnel, most notably a better temperature stabilization.

### *RF*

In the new ring single-cell HOM-damped cavities will be used. 24 500 MHz cavities with a total voltage of 8 MV and 24 third harmonic cavities with a total voltage of 2.3 MV will be required.

### *Diagnostics*

PETRA III already has a small vertical emittance of 10 pm. Although PETRA IV will require large coupling ratios to mitigate IBS and Touschek effects, still further reduction (down to 3-4 pm) in vertical emittance is expected. This emittances are within reach for existing techniques such as SR interferometry, but already at the limit, and some improvements are necessary. Good BPM resolution (about 10-20 µm in turn-by-turn and 100 nm (with 300 Hz bandwidth) in stored beam mode) will be required. Heat load on all resistive components is to be kept under control due to small apertures.

### *Controls*

Consolidation of control system landscape as well as modernization of certain components will be required to guarantee reliable operation throughout the PETRA IV facility lifetime.

### *Beam Dumps*

The PETRA IV beam will be swapped out with a target frequency of up to 0.5 Hz in the timing mode. The power density in the extracted beam requires initial beam blowup with a fast kicker in combination with a specially designed beam dump. Moreover, a special emergency absorber is foreseen.

## CONCLUSION AND OUTLOOK

After three years of preparation work a preliminary design of an ultra-low emittance 6GeV storage ring for the PETRA upgrade has been completed. Emittances of 10 to 20 pm (depending on operation mode) can be reached. Conceptual design of all subsystems has been worked out. The technical design phase is planned to start in July 2019. During the technical design phase lattice parameter will be further optimized and detailed design of technical subsystems performed, inclucing prototyping or mock-ups of all critical components. The TDR phase is planned to be accomplished by 2022.

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