STATUS OF THE PETRA IV ACCELERATORS UPGRADE

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Abstract

The PETRA IV project at DESY foresees the upgrade of the 6 GeV storage ring PETRA III to an ultra-low emittance ring accelerator. The new ring will be based on a 20 pm accelerator lattice using a hybrid 6-bend achromat concept. Operation in full coupling mode (12 pm) will provide unprecedented brightness, quasi diffraction limited hard X-ray photons. The upgrade includes the refurbishment of the injector chain with the development of a new booster (DESY IV) and parallel studies for a full energy 6 GeV laser plasma injector. We review here the status of the machine project, the latest development in the different technical subsystems.

PROJECT OVERVIEW

The PETRA IV machine project aims at the construction of an ultra-low emittance storage ring, delivering an electron beam at 6GeV with a 20 pm emittance, to be installed in the existing 2.3 km PETRA III tunnel [1]. The PETRA IV complex will reuse the existing LINAC II (450 MeV) and the PIA accumulator ring, both currently under refurbishment. A new low emittance booster DESY IV, will replace the existing DESY II booster. The storage ring will follow the geometry of the old PETRA collider with 8 octants made of arcs, each hosting nine H6BA cells, connected by long straight section as shown in Fig. 1. The injection from the booster will be located in the long straight section South-East (SE) while a Laser Plasma Injector can be installed in the long straight section in the South (S).

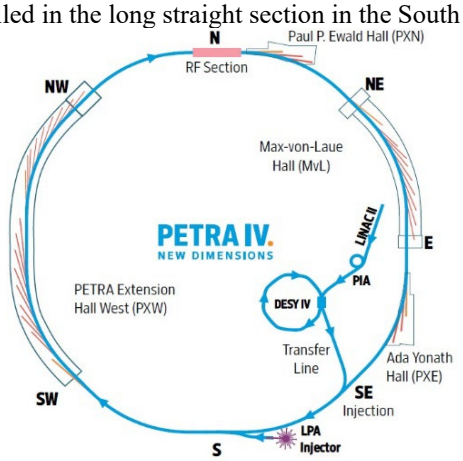


Figure 1: Layout of the PETRA IV accelerators, the injectors and the experimental Halls.

Given the constraints on the DESY campus, only three octants can host beamlines. The facility will reuse the PETRA III experimental halls and will build a new experimental hall covering two octants of the ring in the West. The remaining octants will host damping wigglers for the reduction and control of the emittance. The nominal operational parameters of the storage ring are reported in Table 1. The present timeline assumes that, in funding will be available by mid-2026, the PETRA III shutdown will start in January 2030, and, with two and half year dark period, the machine operation can restart in June 2032. The Engineering Design Report (EDR) is currently under preparation.

Table 1: PETRA IV Main Parameters

Energy	6 GeV
Emittance (with DW)	20 pm
Rel. energy spread (with DW)	9.0·10-4
Loss per turn	4.19 MeV/turn
Momentum compaction	3.3·10-5
βx, βy, (at IDs)	2.2m; 2.2m
RF voltage (main, 3HC)	8 MV, 2.4 MV

LATTICE

The H6BA lattice is a modification of the H7BA developed for the ESRF-EBS. Dispersion bumps are generated to locate the chromatic sextupole families place at π phase advance. This sextupole pairing allow a very effective chromatic correction. Figure 2 shows the optics function in the H6BA cell.

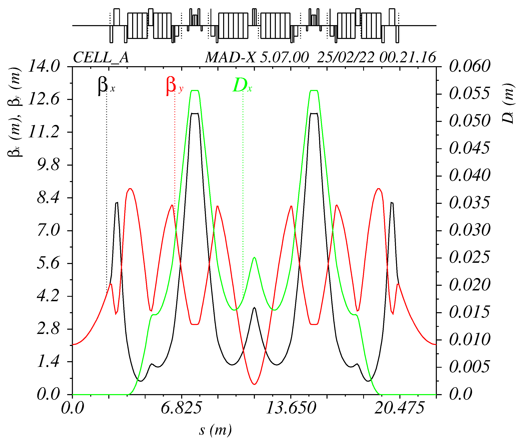


Figure 2: H6BA optics functions and layout from MAD-X.

The cell design is relaxed to provide an emittance of 43 pm. The target emittance of 20 pm is achieved by using damping wigglers. The DA is sufficient to allow off-axis injection [2]. Details of the beam dynamics optimisation are reported in the EDR. Injection will be achieved with a set of fast stripline kickers generating on orbit bump at the injection location where the β_x is increased to 46 m, as shown in Fig. 3.

The fast kickers allow the injection of a single bunch in the 2 ns bunch spacing, with minimal perturbation of the

stored beam and hence much reduce top-up transient. Likewise, the injection from the LPA injector is achieved in the South with a replica of the injection straight, thanks to the modularity of the lattice and the preservation of the transparency conditions [3].

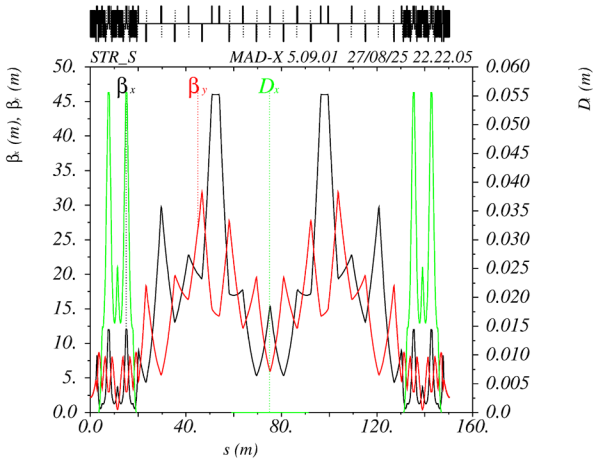


Figure 3: Optics functions and layout of the injection sections in SE and S (for the LPA injector).

MAGNETS

The H6BA cell consists of 6 dipoles, two of which are combined longitudinal and transverse gradient dipoles (DLQs) and four combined dipole quadrupoles (DQs). The cell has 17 quadrupoles arranged in eight families, six sextupoles arranged in two chromatic families and four octupoles. The dipoles are all designed from permanent magnets. The DLQs consist of four modules with a dipole field of 0.6 T to 0.3 T while the DQ have. The quadrupoles triplet in the straight section requires a relative high gradient of 115 T/m, achieved with an aperture of 11 mm and high permeability pole. A campaign of prototypes has been carried out to test the feasibility of the most challenging magnets. Figure 4 shows the prototype of the high gradient PQA magnet.

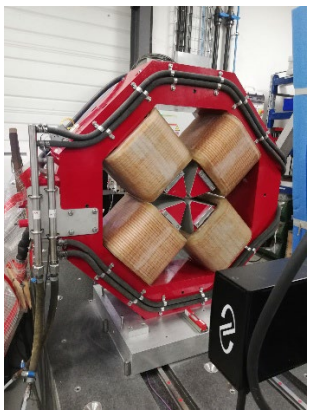


Figure 4: Prototype of the high gradient quadrupole PQA.

The mechanical tolerances required can be achieved by wire erosion of the quadrupole poles. Particular care should however be provided in the control of assembly of the poles, as the beam dynamics is particularly sensitive to random errors. The root mean square of the sum of the harmonics up to n = 10, should be kept under 5 units (at a reference radius Ro = 6.5 mm).

The orbit and coupling correction will be guaranteed by 5 combined correctors per cell, including skew quadrupole components, following the APS-U design, supplemented by corrector magnets embedded in the sextupoles. Prototypes with different lamination thickness (1mm and 0.3 mm) have been produced with the aim to achieve orbit control up to 1 kHz bandwidth.

The total power consumption of the magnet systems has been reduced to about 1 MW with a careful optimisation of the cross section of coils and cables.

GIRDERS

The magnets in the H6BA cell will be distributed on a a set of four girders of 4.8 m and 4.2 m length, of three different types, the last one being the symmetric of the first one. The girder design is based on the topological optimisation of the structure, using as constraints the stiffness, the eigenfrequencies, and the minimisation of the weight. The girders should not have eigenfrequencies below 30 Hz although higher eigenfrequencies designs will be favoured (above 50 Hz). The overall weight of the fully loaded girder must not exceed 12 tons due to the quality of the concrete slab in the old tunnel part of the PETRA IV tunnel. The naked girder weights less than 5 tons. The topological optimised girder can be built with a cast iron manufacturing process. A prototype of the first girder in the cell was built to verify the feasibility of the concept, measuring the eigenfrequencies content and the mover system that allow a precise positioning of the girder to within ±0.5 mm. The prototype girder was also populated with the available prototype magnets, a dummy replica of the remaining ones and a full vacuum string, including BPMs blocks and relative supports. This has allowed to test the assembly process and carry out vibration test with realistic weights. Figure 5 shows the assembled prototype girder. Vibration tests including water flow, alignment and transport test are planned for the coming months.



Figure 5: Prototype of the first girder of the H6BA cell.

The girders will be supported on both ends with movers for all degree of freedom. The baseline design foresees the remote control of the adjustment of the position of the girders, limited to ±0.5 mm**.** This is considered sufficient to

control the alignment girder-to-girder to within 100 mm using beam-based alignment strategies.

TECHNICAL SUBSYSTEMS

The PETRA IV project hinges on the development of technical subsystems based on state-of-the art technology choices in several domains.

Vacuum

The vacuum system of PETRA IV will make extensive use of small aperture NEG coated chambers. The arc sections are based on a cylindrical pipe with inner radius 10 mm and outer radius 11.5 mm except for triplet where the shape will be elliptical with inner dimension inner radius will be 20 mm x 13 mm. The sectioning of the vacuum pipes will follow the four girders structure of the cell with one valve to separate the cell vacuum. The absorbers in the arcs are located at the end of DL2. Extraction of the photon pipe is achieved with 6 mm internal vertical aperture through the magnetic poles of the PQD quadrupole whose vertical pole-to-pole distance is limited to 11 mm.

Vacuum pressure simulations show that NEG coated chamber can provide an adequate pressure level better than 10^{-8} bar after 100 Ah. In situ NEG activation is foreseen by means of thin heat tapers of 400 μm thickness.

RF

PETRA IV will operate the main RF system at 500 MHz, based on 24 normal conducting single cell HOM damped RF cavities. The main RF system will provide 800 kW synchrotron losses and the nominal voltage is 8 MV.

The 24 normal conducting 500 MHz HOM damped cavities are a development of the original BESSY design (shown in Fig. 6). They guarantee a well controlled HOM spectrum that allows operation in brightness mode and timing modes. A prototype was successfully installed in the PETRA III ring in 2023. The cavities will be grouped in 6 RF stations, each driving a block of 4 cavities with their own SSA transmitter. Each cavity must deliver a voltage of 333 kV (transit time corrected from the 475 kV in the cavity gap) that is well within the maximum voltage that can be safely operated. With a shunt impedance of 3.4 MΩ per cavity, the power input to each cavity is 37.4 kW for replacing the beam energy and 16.3 kW foreseen for the copper loss in the cavity. Including 5% transmission losses we foresee a total input power 56.4 kW per cavity. Each cavity is fed by a SSA that can deliver 80 kW with an efficiency of 50%. A simplification of the RF-trip compensation scheme has allowed the reduction of the SSA power from the 120 kW foreseen in the original concept [1]. The total power budget for the main RF system is therefore about 2.6 MW in normal operation.

PETRA IV will operate an active third harmonic cavities system consisting of 24 cavities operating at 1.5 GHz to guarantee the bunch lengthening required for stable operation. The expect voltage at ideal bunch lengthening will be 2.4 MV.

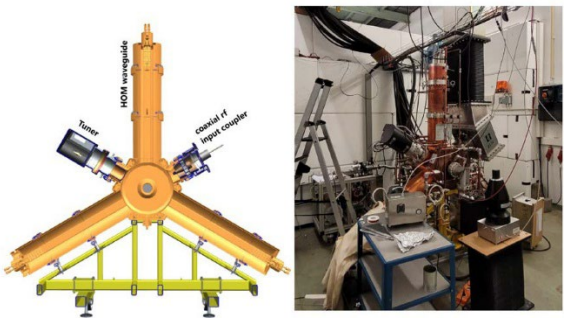


Figure 6: 500 MHZ HOM BESSY-type damped cavity.

The harmonic cavity design is based on a single cell HOM damped cavity developed in a collaboration between ALBA-HZB-DESY already tested successfully in the BESSY-II ring [4]. An alternative design based on the Shintake cavity concept [5] is under prototyping and will be tested at the end of 2026. The HC active system allows large flexibility to set amplitude and phase at different operating currents for optimal bunch lengthening at different currents. A total voltage of 94 kV per cavity and with a shunt impedance of 1.5 MΩ per cavity, it requires 3.33 kW per cavity. This power will be provided by 10 KW SSA transmitters. The total power budget for the HC is 240 kW.

STRATEGY FOR THE INJECTOR

The baseline injector for PETRA IV consists of the existing LINAC II (450 MeV), the PIA accumulator which have served as injector for PETRA III and before for the PETRA collider since the 1970s. The existing booster DESY II emittance does not sustain a clean injection in the PETRA IV ring, due to its large emittance (335 nm). For this reason, the baseline injector is based on a new Booster (DESY IV) delivering a 6 GeV beam with 20 nm and up to 2 nC charge in single bunch. A new transfer line from the booster to the storage ring will be built since the injection point of PETRA IV will be different form PETRA III.

DESY has also developed the concept of a full energy 6 GeV injector based on Laser Plasma Accelerator [6]. The experimental activities have progressed with the first demonstration of energy compression of laser plasma electron beam up to 280 MeV in the LUX experiment at DESY [7]. The same system has been later used to perform the first experimental test of the injection of LPA beam into a booster ring using the DESY II booster at 350 MeV. At the same time the beam was injected in the PETRA III ring providing the first proof of principle of Top-Up injection using an LPA. The LPA R&D activity will continue in 2026 with a final decision on the injector choice to be taken in the second half of 2027.

CONCLUSION

We presented the status of the PETRA IV machine project. The prototype programme of the main subsystems is well advanced. Its completion in 2026 will allow to the project start the Calls for Tender, foreseen by the first half of 2027.

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