

STATUS OF THE PETRA IV ELECTROMAGNETS

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Abstract

The proposed PETRA IV electron storage ring, that will replace DESY's flagship synchrotron light source PETRA III, will feature a horizontal emittance as low as 20 pm-rad. It is based on a hybrid six-bend achromat lattice. In addition to the storage ring PETRA IV, DESY IV booster synchrotron and the corresponding transfer lines will be renewed. About 4000 magnets will be manufactured. Some of the magnets have demanding specifications due to high magnetic field in the poles. High packing density of lattice elements implies short distances between the magnets and results in magnetic cross-talk.

This contribution presents the details of the design and prototyping of the storage ring electromagnets.

INTRODUCTION

DESY is currently producing the Technical design for the PETRA IV upgrade [1].

Preliminary electromagnetic design of all PETRA IV storage ring magnets has been finished. The resulting models are used for CAD integration, checking the compatibility with the vacuum system and the impact of the cross-talk between the magnets on the beam dynamics. All design simulations were carried out using the Opera-3D program [2]. Three magnet types were chosen for prototyping: the high gradient quadrupole magnet PQA with high permeability poles, the sextupole magnet PSA with integrated correctors and the combined fast and slow corrector FC with eight poles. Dummy magnets of other types will be manufactured and integrated on the first of series girder for evaluation.

TENDERING PROCESS

Tenders of the of prototypes are carried out in several stages, including pre-selection of potential suppliers, based on the experience, production capacity, available personnel, measurement capabilities and other factors.

The electromagnetic design of the prototypes, which includes the geometry of the yokes and coils, is performed at DESY in several iterations according to materials and technological solutions, proposed by the manufacturer. The manufacturer verifies the electromagnetic design and performs the final mechanical and electrical design, based on this electromagnetic model. The manufacturer is entirely responsible for the performance of the magnets.

PQA QUADRUPOLE PROTOTYPE

PQA quadrupole has the highest gradient in the lattice and would be unfeasible with conventional yoke material due to saturation of the poles, caused not only by high gradient, but also by short length of the magnet. Main parameters of the quadrupole are listed in Table 1.

Table 1: Main Parameters of the PQA

Gradient, T/m	115.9
Magnetic length, mm	169
Integrated gradient, T	19.6
Aperture radius, mm	11.0
Pole to pole clearance, mm	8.8
GFR, mm	6.5
Field harmonics $\sqrt{\sum b_n^2}$	$< 5 \times 10^{-4}$
Operational gradient range, %	$\pm 5 \%$
Maximum current, A	73.5
Number of turns per coil	92
Maximum power, kW	0.9
Conductor dimensions, mm	$6 \times 6 - \emptyset 3$
Pressure drop, bar	4
Water flow, liter/minute	1.5
Temperature rise, °C	9

In order to reach the required gradient value, the aperture was reduced from initial 12.5 mm to 11 mm and the magnet was designed with pole tips, made of high permeability material. This approach had been implemented and tested in APS-U magnets [3].

The winner of the PQA prototype tender uses Vacoflux 50 for the pole tip and XC06 steel for the rest of the yoke.

During the optimisation of the electromagnetic design, considerable effort was made to minimise the power consumption of the magnet and at the same not to use excessive amount of yoke materials, especially very expensive Vacoflux 50.

Figure 1 shows the parameters of the yoke geometry optimisation. The gradient is sensitive to the pole angle α and reaches its maximum at $\alpha = 15^\circ$. The gradient increases significantly with the pole piece dimension A until a certain limit, after which the gain is minimal. This limit was chosen as the final dimension of the Vacoflux 50 pieces and checked if is sufficient enough for the secure connection to the rest of the yoke with pins and bolts.

The gradient also increases with the pole root angle β and width B. However, transverse sections of the coils and hence the coil resistance, increase with those parameters as well. So, at a certain point the gain in current is negated with the resistance growth and the magnet power consumption starts to increase. That is why the yoke geometry with race-track coils ($\beta = 0^\circ$) and moderately thick pole roots was chosen.

The configuration of the coils is defined by short distances between the magnets and the parameters C and D were optimised in order to ensure mechanical stability of the yoke.

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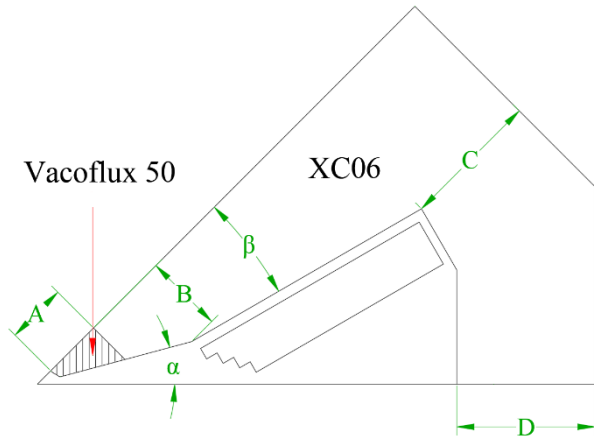


Figure 1: PQA cross-section optimisation parameters.

Final electromagnetic and mechanical design of the magnet are demonstrated in Fig. 2 and Fig. 3 respectively.

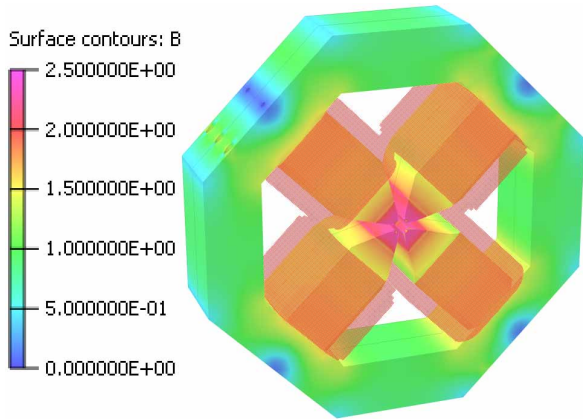


Figure 2: PQA electromagnetic design layout.

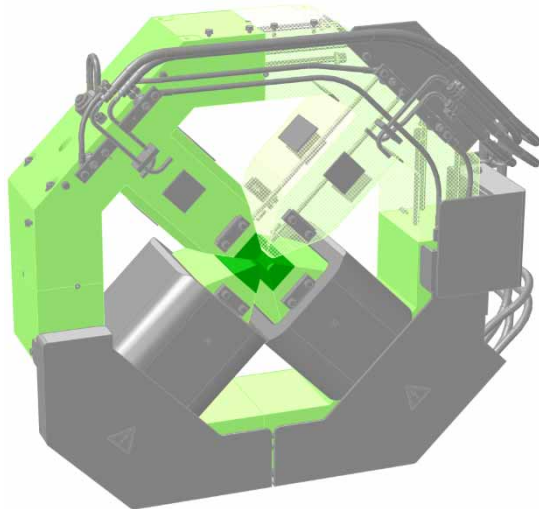


Figure 3: PQA mechanical design.

The magnet safely reaches the required upper limit of the integrated gradient, as shown in Fig. 4

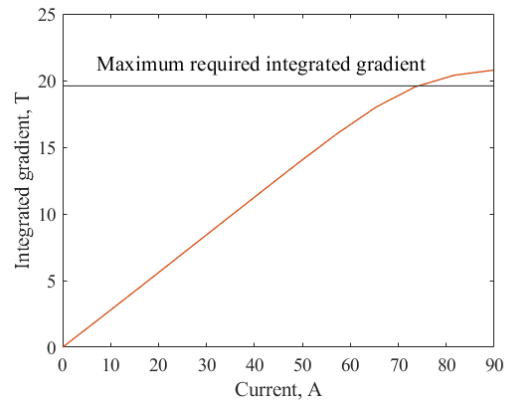


Figure 4: PQA excitation curve.

Two methods of the field quality optimisation were proposed – with and without the pole end chamfer. The manufacturer chose the method with the chamfer as more reliable for production according to their experience.

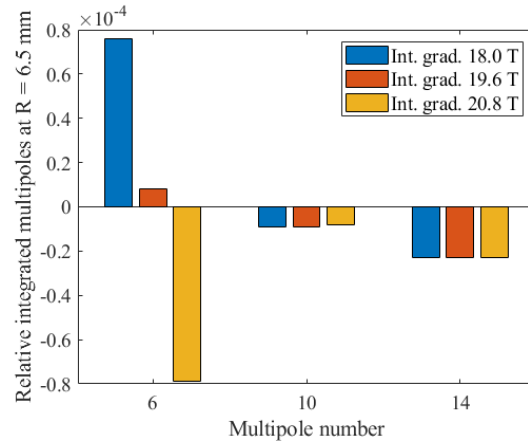


Figure 5: PQA multipoles.

In order to estimate the deformations of the magnet due to gravity and magnetic forces on the girder and during the reassembly process after installation of the vacuum chamber, a series of stress simulations with different fixed surfaces was carried out. Maximum displacement in the yoke in the worst case does not exceed 4.5 μm and as a result, a 0.5×10^{-4} (at 6.5 mm ref. radius) relative octupole multipole may appear.

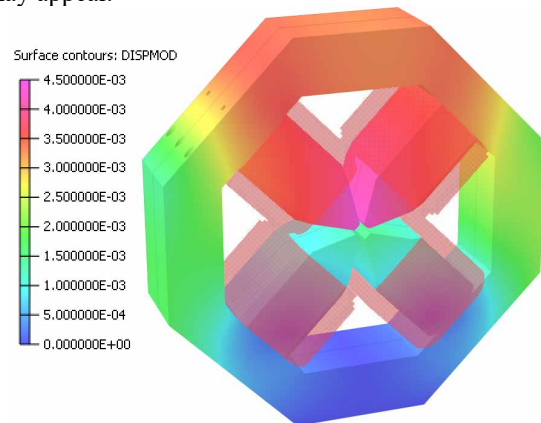


Figure 6: PQA deformation simulation.

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PSA SEXTUPOLE PROTOTYPE

The PSA design has a conventional sextupole yoke, which will be made of XC06 steel. Each pole of the yoke holds three coils: one water-cooled sextupole coil, large and small air-cooled corrector coils. The main parameters of the magnet are listed in Table 2. The maximum current does not exceed 15 A. That allows saving significant investment costs on power supplies.

Table 2: Main Parameters of the PSA

Operational range of the sextupole strength ($B''/2$), T/m ²	1500 - 3000
Magnetic length, mm	250
Aperture radius, mm	12.5
GFR, mm	7.9
Maximum vertical and horizontal deflection of 6 GeV beam, mrad	1
Maximum skew quadrupole, T/m	2
Field harmonics $\sqrt{\Sigma b_n^2}$ (without correctors)	$< 5 \times 10^{-4}$
Conductor dimensions (sextupole coil), mm	4×4 – Ø 2
Number of turns (per one sextupole coil)	114
Conductor dimensions (corrector coils), mm	5×2
Number of turns (per one small corrector coil)	36
Number of turns (per one large corrector coil)	72
Maximum current, A	15

There are two possible arrangements of the coils, which are shown in Fig. 7. In the first case, the sextupole coil is inside the air-cooled coils. That can be beneficial since the water-cooled coil provides additional indirect cooling to the air-cooled correction coils. In the second case, all three coils are fixed on the pole one after another.

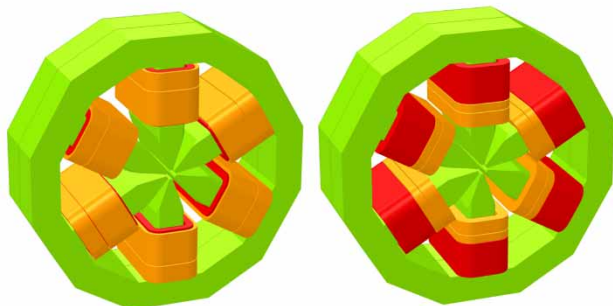


Figure 7: Possible PSA coil configurations.

The coils should be wired as shown in Fig. 8, where coils of the same colour are connected in series and powered by a separate power supply. Four power supplies are used to produce the four field components required for the PSA.

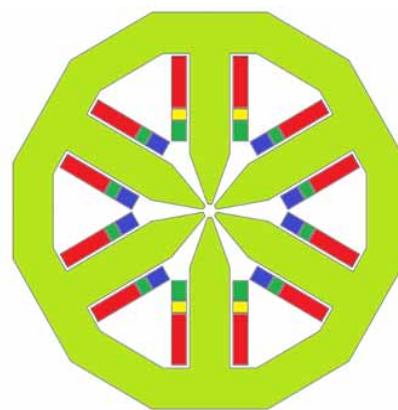


Figure 8: PSA coil wiring scheme.

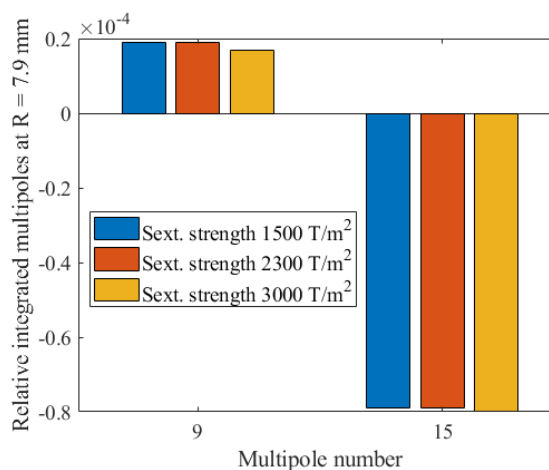


Figure 9: PSA multipoles.

CONCLUSION

The preliminary design of all PETRA IV storage ring magnets is finished, while the preliminary design of DESY IV booster magnets is under revision as a consequence of changes due to the engineering integration in the lattice. We have described in details the PQA high-gradient quadrupole magnet, whose prototype is in the production phase, and the PSA sextupole magnet, whose prototype is in the tendering phase.

REFERENCES

- [1] R. Bartolini *et al.*, “Status of the PETRA IV machine project” in *Proc. 13th Int. Particle Accelerator Conf. (IPAC’22)*, Bangkok, Thailand, Jun. 2022, pp. 1475–1478. doi:10.18429/JACoW-IPAC2022-TUPOMS029
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- [3] Opera-3D, Dassault Systèmes, <https://www.3ds.com/products-services/simulia/products/opera/>.