

CURRENT STATUS OF BESSY III MAGNET DESIGN

J. Voelker*, I. Asparuhov, V. Dürr, P. Goslawski, F. Pflocksch,
Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany

Abstract

HZB is developing BESSY III, a future 4th-generation low-emittance diffraction-limited soft-to-tender X-ray synchrotron light source, as a green-field facility in 2035 on the premises of the Adlershof technological campus in Berlin, Germany. We are in the design phase of magnet concepts for all permanent-magnet (PM-)based linear and resistive multipole magnets. Exposition is given to the optimization of the magnetic design and resulting technical considerations for solutions of field tunability and correction, thermal operational stability, and follow-up mechanical realization for the energy-efficient linear optics and ring performance of BESSY III, stepping on lessons so-far learned from the BESSY II+ [1] upgrade and RF2.0 [2] projects. In this paper, we give an overview of the design progress on the PM-based magnets and of considered options for the required higher-order magnet families such as resistive sextupoles and octupoles.

MAGNETIC DESIGN CONCEPT OF PM-BASED MAGNETS FOR BESSY III

As part of the BESSY III [3–6] project - a 4th-generation low-emittance diffraction-limited light source in Berlin - HZB is currently developing the lattice design of the storage ring for a Higher-Order Achromat Multi-Bend Achromat (HOA-MBA). In parallel, the developing of a concept for a sustainable magnet system has been started based mostly on permanent-Magnet (PM-)based magnets for the linear lattice components and electromagnets (EM) for adjustable QPs in the straight, sextupoles (SP) and octupoles (OP). This concept reduces the overall amount of energy per year for the storage ring magnetic system from ≈ 8 GWh to ≈ 2 GWh. Table 1 summarizes the different main types of the latest lattice magnets from a field-generation perspective. Also given are corresponding numbers of sub-types differing by certain physical parameters (length).

All magnets have a minimal aperture radius of 12.5 mm. In a general-purpose approach, PM-based magnets shall use identical PM blocks in terms of dimensions ($35 \times 35 \times 50$ mm³) and material properties (high-remanence N42-grade rare-earth NdFeB) for more robust performance. This approach simplifies the mechanical PM installation tooling for all magnets and the mechanical and magnetic control of the individual PM blocks. The final size of the PM blocks was determined by ensuring that the minimal field requirements of all magnets can be fulfilled. The different magnet designs must be able to handle subsequent field adjustment options, such as mechanical tuners with steel shimming plates. Additionally, Thermoflux plates (based on a NiFe alloy)

[7] will be installed next to the PM blocks to compensate NdFeB temperature dependence and stabilize the magnetic field around the beam trajectory over a wide temperature range [8]. A similar approach is adopted for the magnet design itself: using an identical transverse design for all bending magnets (only their lengths differ) as well as for the quadrupole (QP) and reverse-bend (RB) return yokes. The latter are high-gradient combined-function magnets with a weak additional dipole contribution (see Tab. 1) which can be built as 3- or 4-mm horizontally displaced quadrupole magnets. The horizontal offset requires a slightly larger aperture diameter, but the same outer design as the QP. This approach seeks a reduction in individual-unit fabrication processes with higher reproducibility of individual components.

Magnetic Optimization

All 2D and 3D magnet model field calculations are done with the CST suite [9]. For field optimization, the magnetic multipole contributions are obtained via Fast Fourier Transform (FFT) computation on a 10-mm reference radius. The elimination of unwanted multipole components was performed in two steps: Local 2D optimization followed by a fringe-field optimization for the integrated 3D field. For this, the complex Fourier definition of the 2D magnetic field distribution is used:

$$B = \sum_n (A_n + iB_n) (x + iy)^{n-1},$$

with normal longitudinally integrated multipole components given in “units” derived according to

$$b_n^{\text{int}} = \frac{\int B_n dz}{\int B_2 dz} 10^4. \quad (1)$$

The particular procedure applied in the case of the quadrupole magnets can be found in [10], which exemplifies a strong PM-based quadrupole magnet with motorized tuning plates and electrical-coil correctors for magnetic-gradient variation over a range of >30% with respect to a nominal 100-T/m gradient.

Magnet Field Tunability and Correction

For tuning the magnetic field of a PM-based DP or QP magnet, thick steel tuning plates (shims) can be moved manually or in a motorized manner vis-a-vis the PM-block channel. They work as an additional magnetic load in the magnetic circuit of the magnet and reduce the magnetic flux in its pole shoe as a function of the shim position/insertion depth. While such manually positioned mechanical tuners serve to fine-tune the magnetic field, as per compensating small PM or material parameter variations, the motorized option is reserved for large on-the-spot field adjustments up to some tens

* jens.voelker@helmholtz-berlin.de

Table 1: List of lattice magnets for the BESSY III storage ring with their corresponding field-generation type, numerical, nominal-field/gradient and length distributions.

Magnet Type	# in SR	field / gradient	Length (mm)	tuning and further options
Dipole (PM)	64 / 32	0.63 T / 0.56 T	1100 / 650	1%
Quadrupole (PM)	32 / 128	76 T/m / 80 T/m	180 / 110	$\pm 4\%$
Quadrupole (EM)	64 / 64	82 T/m / 73 T/m	220 / 10	$\pm 10\%$
Reverse-bend (PM)	160	73 T/m + 0.25 T	150	$\pm 4\%$
Sextupole (EM)	176 / 64	4000 T/m ²	100 / 150	$\pm 10\%$
Octupole (EM)	32	30 000 T/m ³	40	$\pm 100\%$

of % during operation. Due to their size, the tuning plates will be subject to large magnetic forces, hence requiring an elaborate gear-based mechanism to be able to move with sufficient accuracy. This will put a limit on the field tuning rate of the magnet. For more rapid but lesser field variations of about $\pm 4\%$, additional small corrector coils will be used in the QP magnets for low-power (low-thermal-loss) corrections (≈ 1 Hz).

MECHANICAL REALIZATION

Bending Magnets

An important boundary condition for the BESSY III lattice comes from the Physikalische Technische Bundesanstalt's (PTB - the German National Metrology Institute) [11] requiring bending-magnet-based radiation sources to be used in metrology-enabling soft-to-tender-X-ray applications. This implies providing homogeneous-field dipole

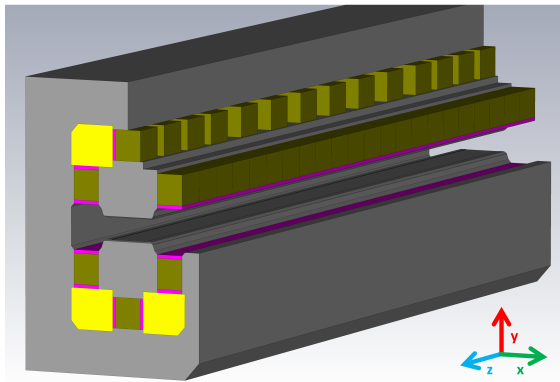


Figure 1: Exploded view of the rectangular-yoke PM-based homogeneous bending magnet showing PM(-row) filling pattern possibilities in the separate yoke channels.

magnets with a homogeneity demand that translates into a relative field flatness of better than 10^{-4} over a span of ± 10 mm along the horizontal and longitudinal dimensions. Therefore, a monolithic rectangular-magnet design for both dipole lengths is preferred. Due to the curved trajectory inside the magnet and the PTB requirements, we define the necessary good-field region of ± 15 mm. For a magnet-gap of 25 mm, a pole shoe width of at least 60 mm is adequate in this context. A 2D optimization of the magnet section and pole shoe profile, based on the the PM block transverse shape, is applied.

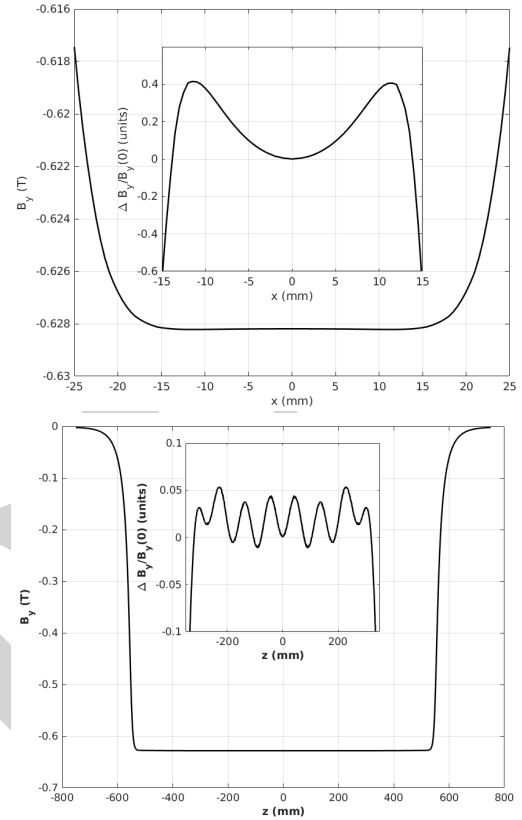


Figure 2: Calculated vertical magnetic field distribution (B_y) in Tesla and relative field variation in units= 10^{-4} , in (top) horizontal x and (bottom) longitudinal direction z of the homogeneous bending magnet.

Figure 1 shows the latest version of the magnetic design for the 1100-mm long bending magnet. Yoke and pole shoes (gray) are of steel 1010. Aluminum spacers (light yellow) mechanically connect the return yoke with the pole shoe and form the channels for the PM blocks (dark yellow) placed in rows. The Thermoflux shimming strips (thin plates) of ≈ 4 mm thickness (purple) are installed next to the PM blocks. The top plot of Fig. 2 shows the horizontal distribution (along x) of the vertical magnetic field B_y in absolute and relative units (Eq. (1)). The final optimization of the 3D field is done in two steps: First, field profile and integrated strength adjustments as function of PM filling pattern are studied [12]. Second, fringe field adjustment to reduce integrated multipoles is achieved by chamfer optimization. One feature of PM-based DP magnets with the 100% PM filling

pattern is an increasing field in the longitudinal direction up to the magnet center. To achieve the field required for BESSY III, only 85% of the maximum PM blocks are necessary. Variations in PM block positions inside the yoke affect the field distribution along the longitudinal direction. The distances between the 14 top- and bottom-row PM blocks were optimized to flatten the longitudinal field profile of the magnet to a variation of < 0.1 unit over the inner 500 mm magnet-length portion. The result of this optimization can be seen in the lower plot of Fig. 2.

Quadrupole Magnets and Reverse-Bends

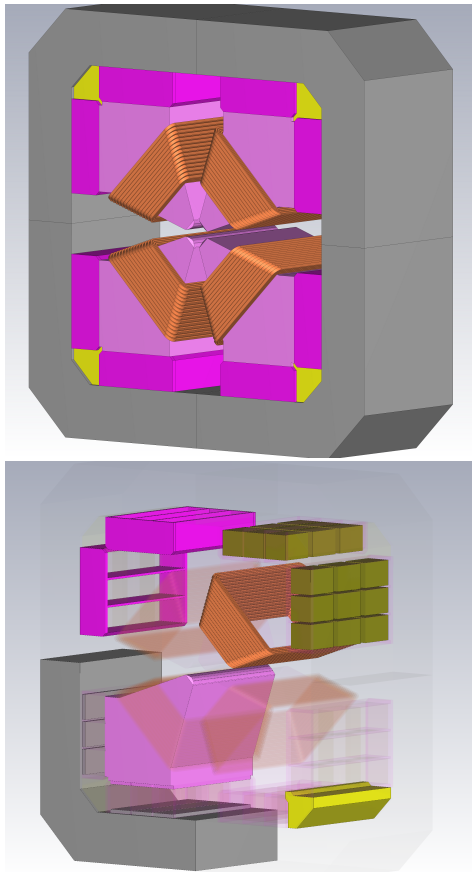


Figure 3: Quadrupole magnet design: (Top) View of the assembled 180-mm long PM-based magnet with NiFe shims and compact corrector coils. (Bottom) Exploded view revealing the PM blocks' disposition with respect to the NiFe shims, magnet yoke, spacer, pole shoe and coil.

The overall 320 PM-based quadrupole and reverse-bend magnets are designed with aperture radii of 12.5 mm and 14.0 mm, respectively. The larger aperture diameter for the reverse-bends is necessary due to the magnet horizontal offset. The respective pole-tip gaps of the two magnet groups are 9 mm and 10 mm. Pole tips and chamfers of both types were individually optimized, suppressing leading-order (integrated) multipoles b_6 and b_{10} to < 1 unit. Here we used a split polynomial profile to have independent geometric parameters for the individual adjustment of the magnetic multipoles. For more details see [10]. Suppression of b_{14}

was so far not possible, with a residual value of < 4 units (at a 10-mm reference radius), negligible for the BESSY III performance. Pole shoes are specified to be of bulk ARMCO steel. The latest design can be seen in the upper illustration in Fig. 3. This 180-mm long magnet is designed for 36 PM blocks (dark yellow) installed in a Thermoflux framework (purple) between the steel-1010 return yoke (gray) and the pole shoe (pink). Individual components are shown in an exploded view in Fig. 3. The latter also shows the four compact corrector coils for small field adjustments required for beam-based alignment techniques during operation or lattice optics adaptations. In numerical lattice studies, a tuning value of $< 2\%$ was determined. To deliver such performance, the air-cooled corrector coils are designed for a tuning range of $\pm 4\%$ at current densities of $\approx 1 \text{ A/mm}^2$, with respect to a stable field gradient of 80 T/m. As an additional option for larger tuning ranges of up to $\pm 10\%$, thick steel tuning plates between adjacent PM blocks are considered to provide such capability without electrical power and consequent heat generation in corrector coils [10]. These plates can be moved in the longitudinal gap between the three PM blocks in one of six rows per QP quadrant.

ELECTROMAGNETS AND STEERERS

For more flexibility, especially in terms of capability to vary non-linear optics parameters, SP and OP magnets, as well as QPs in the straight, will be operated as electromagnets. As an example, the 240 SP magnets will consist of water-cooled copper main coils providing 4000 T/m^2 at an aperture radius of 14.5 mm. Pole tip and chamfer were optimized to suppress the leading-order integrated multipole b_9 . Each magnet has six passively cooled corrector coils, that can be used as horizontal, vertical or skew-quadrupole (SQP) correctors, enabling a steering angular kick of up to 1 mrad or a SQP gradient of 5 T/m. For vertical steering, only the four side coils are needed and for skew-quad correction only top and bottom ones. Therefore, these two corrector options can be realized in one sextupole. However, for horizontal correction, all six coils are required. Additional effects due to saturation and integrated multipole components are still under investigation.

CONCLUSION

In this paper, we presented the status of the magnetic design for the upcoming BESSY III Storage Ring dominated by PM-based linear magnets such as dipoles and quadrupoles. These magnets combine high-precision magnetic field distributions of highly stable operation (thermal and mechanical) with electrical or mechanical-tuner options for field variation over the necessary range. The developed design concept minimizes the number of different yoke shapes and is based on a uniform PM block shape for all magnets. The energy consumption of the BESSYIII SR magnet system can be reduced with this concept by almost 80% compared to that of a fully resistive magnetic setup. First prototypes are planned for 2027.

REFERENCES

- [1] O. Schwarzkopf *et al.*, "Materials discovery at BESSY", *Eur. Phys. J. Plus*, vol. 138, 2023.
[doi:10.1140/epjp/s13360-023-03957-8](https://doi.org/10.1140/epjp/s13360-023-03957-8)
- [2] RF 2.0 research facility website, <https://rf20.eu/>
- [3] P. Goslawski *et al.*, "BESSY III overview and its bending sources", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024.
[doi:10.18429/JACoW-IPAC2024-TUPG28](https://doi.org/10.18429/JACoW-IPAC2024-TUPG28)
- [4] B. Alberdi-Esuain, M. Abo-Bakr, P. Goslawski, "Simulated Commissioning and Lattice Robustness for BESSY III", presented at the IPAC'26, Deauville, France, May 2026, paper THP2035, this conference.
- [5] M. Abo-Bakr, P. Goslawski, J. Voelker, "The BESSY III Injection Scheme", presented at the IPAC'26, Deauville, France, May 2026, paper THP2147, this conference.
- [6] B. Kuske, B. Alberdi-Esuain, "On the Optimization of the Non-Linear Performance of 4th-Generation Light Sources", presented at the IPAC'26, Deauville, France, May 2026, paper WEO5M03, this conference.
- [7] Vacuumschmelze, "Soft Magnetic Materials and Semi-finished Products", 2002, <https://vacuumschmelze.de>
- [8] C. Calzolaio, "Magnets for the Swiss Light Source Upgrade at PSI", presented at 2nd PerMaLIC (Permanent Magnet LEAPS Internal Collaboration) Workshop, Nov. 2022, Barcelona, Spain.
- [9] Simulia Website, <https://www.3ds.com/de/products/simulia/cst-studio-suite/electromagnetic-simulation-solvers>
- [10] J. Voelker *et al.*, "Prototyping of a Tunable Permanent Magnet Quadrupole", presented at the IPAC'26, Deauville, France, May 2026, paper MOP7066, this conference.
- [11] A. Gottwald *et al.*, "Metrology with synchrotron radiation at PTB", *European Physical Journal Plus*, vol. 137, no. 11, Nov. 2022, [doi:10.1140/epjp/s13360-022-03417-9](https://doi.org/10.1140/epjp/s13360-022-03417-9)
- [12] I. Asparuhov *et al.*, "PM magnet development status for BESSYII+", in *Proc. 16th Int. Particle Accelerator Conf. (IPAC'25)*, Taipei, Taiwan, June 2025.
[doi:10.18429/JACoW-IPAC2025-THPB043](https://doi.org/10.18429/JACoW-IPAC2025-THPB043)