ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPM131

DEVELOPMENT OF THE FIRST PERMANENT BENDING MAGNET AT BESSY II

J. Völker*, D. Böhlick, M. Dirsat, V. Dürr, A. Jankowiak, F. Pflocksch, M. Ries,
Helmholtz-Zentrum Berlin, Berlin, Germany

Abstract

Permanent Magnet (PM) based bending magnets are state-of-the-art concepts to gain stable beam operation and to reduce the power consumption of the magnetic system in an accelerator. This is even more true in injector and beam transport beamlines with fixed beam parameters and low repetition rates. An example is the B2PT magnet in the BESSY II transfer beamline between booster and storage ring. It is the last dipole magnet for the final 7.8 deg bending into septum. This one meter long, compact, high current dipole will be replaced by three 300 mm long Variable Permanent Hybrid Magnets. They combine a PM driven strong and stable magnetic field with a small field variability via compact corrector coils. With this new magnet we can reduce fringe fields and vibrations next to stored beam, as well as the total power consumption of the injector by almost 30 kW. In this paper, the design and construction process of the new B2PT magnet will be presented.

MAGNET UPGRADES FOR BESSY II+

In preparation for the upcoming BESSY III [1], HZB also preparing a BESSY II+ program, acting as bridge for BESSY III technologies [2]. Several upgrades are planed for the existing BESSY II accelerator, which is in operation since 1997. Main goals will be the modernisation of accelerator infrastructures and experimental stations (extension of operando options), as well as a more sustainable operation of BESSY II due to reduced energy consumption. For the accelerator part, one focus lies on new hardware components like higher harmonic cavities (HHC) for bunch length control, modernization of power supplies and synchronization systems, as well as development of permanent magnet (PM) based bending magnets in transfer line and metrology suitable dipole magnets for the storage ring. The magnets will be designed as Hybrid Magnets (PMs embedded in a iron yoke) and operated without high current electro coils or water cooling lines. This results in a more stable beam operation due to a minimization of vibrations and ripple effects. Additionally, the power consumption of these strong magnets can be reduced by tens of kW for each magnet. One example is the existing B2PT magnet in the BESSY II transfer line, which is shown in Fig. 1. It is the last static bending magnet upstream of the injection septum of BESSY II storage ring and an extreme compact homogenous dipole magnet with a C-shape Yoke design. To bend the 1.7 GeV electron beam by 7.75° in the 1 m long magnet, a peak field of 0.78 T is required that is produced by two 4-turn coils operated with almost 1.6 kA. The totale power consumption of B2PT (ohmic losses, water cooling, power supply, etc.) is in the range of 30 kW and is therefor one the largest single consumer of BESSY II magnet system. Replacing it with PM based magnets can reduce the BESSY II energy consumption by about 0.2 GWh per year.

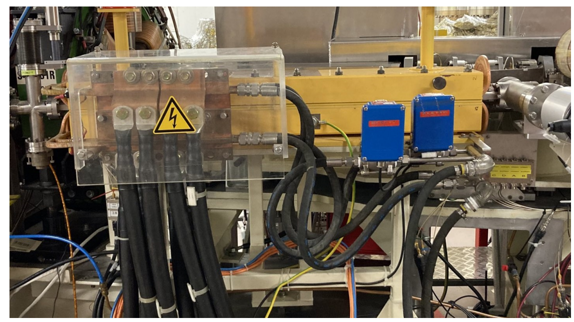


Figure 1: Original high current bending magnet in the injection line of BESSY II.

GENERAL DESIGN OF THE PM DIPOLE MAGNET

For the magnetic and technical design of the PM dipole magnet, extensive numerical studies were performed to fulfill all spatial and magnetic requirements of the BESSY II+ injection beamline. These studies were realized mainly with the 3d magnetic field solver of CST [3] and ASTRA [4] for 3D particle tracking. In this context, the magnetic calculations were also tested with OPERA3D [5] and ANSYS [6], with a good agreement between all of them. An example for such a study can be found in [7]. The most important requirements are the existing septum girder setup, which is also part of the BESSY II storage ring, and the small fringe field next to the stored beam. Additionally, the new injector beamline for BESSY II+ needs a larger bending angle of almost 8.19° in front of the septum. Regarding this large angle and the common technique of PM installation in long dipole magnets [8], we decided to separate the 1 m long magnet into three individual dipole blocks with a small angle between them. Each magnet block is a symmetric 300 mm long straight dipole magnet consisting of symmetric pole shoes and return yoke (like steel 1010). Different design concepts were numerically tested and best results were achieved with a flat H-shaped magnet design which also has the advantage of a symmetric compensation of the calculated large magnetic forces of up to 20 kN. Figure 2 shows the cross section of a design fulfilling the spatial requirements next to the septum. It consists of 6 PM rows between the inner pole shoe geometry and the outer return yoke. Aluminum pacer in the corners connect both yoke parts and define the

* jens.voelker@helmholtz-berlin.de

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPM131

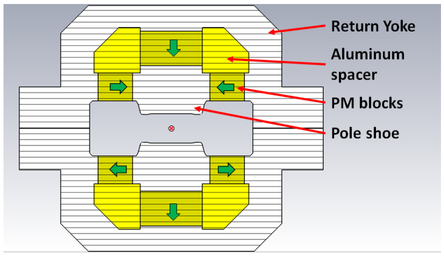


Figure 2: Cut-design of the H-shaped PM-dipole design: Magnetization axis of the PMs as green arrows. Electron beam (red cross) perpendicular to the plane in the center of the poleshoes.

6 gaps for the PMs. Additional yoke extensions can be seen on both sides of the return yoke to increase the cross section in the horizontal plane for more options to guide both half-blocks and installing alignment tools. Additionally, 12 strong metallic springs will be installed there, to reduce the attracting forces by nearly 60% in case of a contact between both half-blocks and almost 100% if both blocks have a gap of more than 1 mm.

However, this flat design is in case of a triplet not sufficient to achieve the necessary integrated bending field. A larger magnet in the center that can produce higher flux densities solves this problem.

The optimization of both magnet geometries were performed regarding the minimization of different PM block and yoke designs. This results in two Types of PM blocks consisting of NdFeB with a N42 magnetization quality :

- **Type A:** 50 mm × 45 mm × 25 mm ($L \times W \times H$); B_r=1.3 T along H
- **Type B:** 50 mm × 20 mm × 25 mm ($L \times W \times H$); B_r=1.3 T along H

Six PM blocks can be installed in a row, resulting in 36 blocks for a complete magnet. As shown in Fig. 2, both flat magnets consist of 2 rows of Type A magnets (up to 12 blocks) and 4 rows of Tyb B magnets (up to 24 blocks). The central magnet consists of 6 rows of Type A magnet (up to 36 blocks).

Additionally to the PM blocks, the poleshoe design should be also identical for all three magnets. The profile of the pole shoe was optimized using 2d field solvers to minimize unwanted higher order multipole (MP) fields in the good field region of $GFR = \pm 10$ mm. This was achieved with a small indentation of 0.55 mm in the center region, suppressing leading MP amplitudes to less than 3 units. The resulting central dipole field distribution is plotted in Fig. 3. These values are acceptable for a single pass bending magnet. In the next step the complete 3d magnetic fields for both types were calculated to study also the 3d effects of a single magnet, but also for the complete magnet triplet.

During this investigation the longitudinal pole shoe chamfers were optimized to minimize the magnetic saturation in these yoke regions and the sextupole effects on the beam. The calculations gave best results for a 45° chamfer with a longitudinal depth of almost 3 mm.

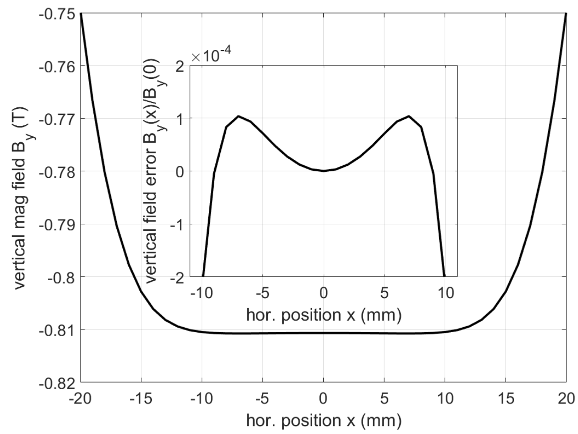


Figure 3: Horizontal profile of the absolute vertical field component B_y at magnet center for both outer magnets. Inner plot shows the relative field variation in the GFR of ± 10 mm along x.

MAGNETIC ADJUSTMENT AND TUNING

Due to the use of PMs, the strength of the magnet is almost defined by the magnetic volume and magnetization quality of the PM blocks. Small uncertainties of the individual PM values have to be considered for the resulting field strength but even more for the magnetic multipoles. Here, the Hybrid design with quite thick yoke pieces helps to shift the source of magnetic field uncertainties from the individual PM block parameter to an averaged parameter of the complete PM row. To change these averaged values, it is possible to variate the number of PM blocks or to install magnetic trimming plates at the ends of the magnet. These variable steel plates (orange plates in Fig. 4) working as an adjustable magnetic load between pole shoe and return yoke. The individual position of a trimming plate change the integrated magnetic flux of a row and can be used to reduce the differences between the six rows, or to change the overall dipole field strength. With

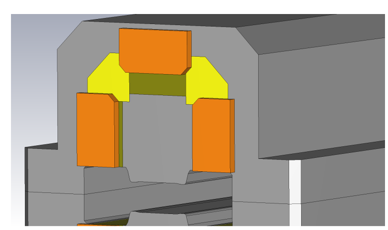


Figure 4: Design of the magnet trimming plates (orange) placed on both ends of each PM row for a precision and symmetric adjustment of the relative and total field distributions.

these 12 trimming plates per magnet, an overall variation in the range of $> \pm 3\%$ with respect to a pre-trimmed setup can be achieved. This adjustment can be done only manually during the initial magnetic tuning or during a beam shut down phase. Another option, is the installation of additional corrector coils in the outer magnets to change the overall dipole field strength during beam operation.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPM131

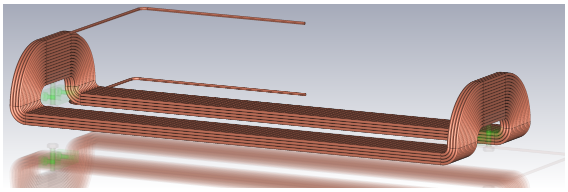
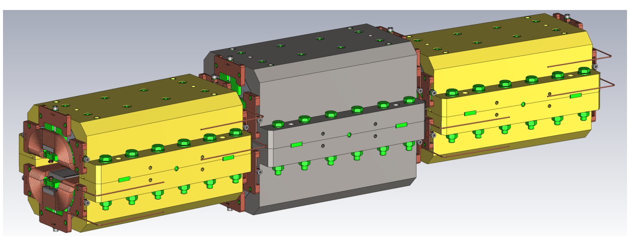


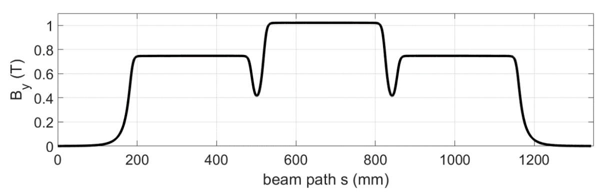
Figure 5: Flat corrector coil design with bended end caps to adjust the integrated magnet field of the magnet triplet.

The four 330 mm long copper coils are designed as rectangular coils with bended end caps as it can be seen in Fig.5. The coils will be installed next to the vertical PM blocks (see Fig. 2) and operated with current densities of $\pm 2.5\,\mathrm{A/mm^2}$ (air convection cooling regime). The integrated bending field of the triplet can be changed by $\pm 2.6\%$ using both corrector magnets simultaneously.

The complete technical setup of the PM triplet incl. trimming plates and corrector coils, is shown in Fig. 6a. As a last step, a precision overall field adjustment to the 1.7 GeV beam, via a change of the PM block number per row and the correct trimming position, as well as an alignment between the three magnets is necessary.



(a) Technical design of of Magnet triplet.



(b) Field profile along trajectory.

Figure 6: Magnet triplet in final configuration for the installation in the injection line of BESSY II.

TRIPLET ALIGNEMENT

The different magnetic flux densities in the three magnets, resulting in different bending radii for the magnets and therefore to a not homogenous beam trajectory through the triplet. The positions and the orientation of the three magnets were optimized to minimize the average beam offsets in each magnet, regarding the geometric axis. Here, the important parameters are the angle between the inner and outer magnets, as well as the horizontal displacement of the inner magnet. Both must be optimized for each triplet setting, resulting from the different symmetric PM filling pattern in the PM rows. In all cases, a distance of 33 mm between the three magnets should be fixed as space for trimming plates and coils. Due to this, the magnetic cross talk effects are not neglectable, so that the complete 3d field was calculated for each setting and was directly used for the single particle tracker. For each tracking study, symmetric beam trajectories with different central horizontal offsets and particle momentum were determined, fulfilling the overall bending angle of 8.19°. The resulting 3d trajectories for all triplett settings were compared with the magnet geometry. For the ideal setting, the resulting beam trajectory must have in all three magnets a minimal horizontal variation along the magnet block orientation and a center of gravity identically with the geometric axis of the magnets. So for each triplet setting, there is only one optimal solution for the four parameter: initial horizontal beam offset upstream the triplet, the "natural momentum", the magnet angle and the inner horizontal magnet offset. As a last step, a triplet setting has been choosen having a natural momentum of less than 4% above the necessary 1.7 GeV, which is adjustable by the trimming plates of the magnets. The best szenario was found were the inner magnet is completely PM filled and the outer magnets were reduced by one Type A block per raw (four PM blocks in total). The optimized values for this setup are shown in Table 1 and the field on reference trajectory is plotted in Fig. 6b.

Table 1: Magnet Parameters of the Triplet

	inner magnet	**outer magnet**
magnet length	300 mm	300 mm
magnet width	220 mm	220 mm
magnet height	238 mm	178 mm
magnet gap	20 mm	20 mm
magnet angle	2.88°	
magnet distance	33 mm	
horizontal offset	0.7 mm	0 mm
# type A PMs	36	12 (10)
# type B PMs	0	24
peak field	1.08 T	0.79 T
corrector coils	-	2 × 60 winding

CONCLUSION AND OUTLOOK

In this paper, we presented the general design and numerical optimzation steps for the first PM based bending magent triplet for BESSY II. In June this year, the final charge of the PM blocks will be delivered to HZB and individually measured. In parallel, the construction of the yoke Aluminum pieces will start. A first prototype of the corrector coil design is currently under manufacturing by an external winding company. All parts will be assembled at the end of the year via a press tool guiding the PM blocks inside the magnet yoke. For each type, at least one spare magnet will be built as reference and demonstrator for radiation and thermal stress tests.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPM131

REFERENCES

[1] P. Goslawski *et al.*, “BESSY III - Status and Overview,” presented at IPAC’23, Venice, Italy, May 2023, paper MOPA174, this conference.

[2] O. Schwarzkopf *et al.*, “Materials discovery at BESSY”, *Eur. Phys. J. Plus*, vol. 138, 2023. doi:10.1140/epjp/s13360-023-03957-8

[3] CST Studio Suite, https://www.3ds.com/.

[4] K. Floettmann, ASTRA - A Space Charge Tracking Algorithm, https://www.desy.de/~mpyflo/.

[5] OPERA - Electromagnetic and Electromechanical Simulation, https://www.3ds.com/.

[6] ANSYS - Maxwell, https://www.ansys.com/.

[7] J. Völker, V. Dürr, P. Goslawski, A. Jankowiak, and M. Titze, “Variable Permanent Hybrid Magnets for the Bessy III Storage Ring”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, pp. 2763–2766. doi:10.18429/JACoW-IPAC2022-THPOTK001

[8] R. P. Walker *et al.*, “Diamond-II Technical Design Report”, 2022. https://www.diamond.ac.uk/Diamond-II.html