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VARIABLE PERMANENT HYBRID MAGNETS FOR THE BESSY III STORAGE RING

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Abstract

The Helmholtz Zentrum Berlin (HZB) is working on the conceptual design of a successor source to BESSY II, a new BESSY III facility, designed for a beam energy of 2.5 GeV and based on a multi-bend achromat (MBA) lattice for a low emittances of 100 pm–rad. Bending and focusing magnets in the MBA cells should consist of permanent magnets (PM), to allow for a competitive and compact lattice, to increase the magnetic stability and to decrease the electric power consumption of the machine. However, using pure permanent magnet systems would result in a completely fixed lattice. Therefore, we are developing Variable Permanent Hybrid Magnets (VPHM), combining PM materials like NdFeB with a surrounding soft iron yoke and additional electric coils. This design can achieve the same field strength and field quality as conservative electromagnets, with only a small fraction of the electric power consumption, and a ca. 10% variability in the field amplitudes. With this magnet concept the power consumtion of the BESSY III storage ring can be reduced by more than 0.5 MW. In this paper, design and first optimization results of the magnets will be presented.

MAGNETS FOR BESSY III

The lattice of BESSY III is currently being optimized fulfilling the requirements for a fourth-generation light source with a kinetic beam energy of 2.5 GeV. For the current versions of arc lattices, the overall storage ring needs a circumference of ca. 340 m. Further beam parameter can be seen in Table 1 and in [1–5]. The fixed defined beam energy and the optimized lattice solution resulting in a narrow parameter range for all bending and focusing magnets. Based on the required high magnetic fields and the large number of magnets, the overall power consumption for the storage ring can be estimated to ≈ 750 kW for the magnetic systems in case of conservative electromagnets. Integrated over the 7000 hours beam operation per year, one gets an energy consumption of > 5 GWh per year.

Here, Permanent Magnets (PMs) are a real alternative not only for bending magnets like described in [6] or [7], but also for Quadrupole (QP) magnets, for a sustainable storage ring with a decreased energy consumption of up to 80% for the magnetic system. However, the PM based QP magnets should be adjustable in the range of ±10% of the maximum gradient, to assist the later commissioning and to have the option for small corrections. To build almost all linear magnets with PMs produces a high number of PM based magnets for the BESSY III storage ring (see Table 1) with a strong impact on the tooling and the handling of the PMs and the final magnets. Therefore, a general magnet and PM design is necessary to simplify PM tests as well as construction and tooling of the magnets.

Table 1: Important BESSY III Parameter

Parameter	Value
MBA lattice	6BA
# of arcs	16
circumference	340 m
kin. energy	2.5 GeV
emittance	≈ 100 pm rad
magnet aperture radius	12.5 mm
# of dipol magnets	96
# of quadrupole magnets	≈ 250
# of sextupole magnets	≈ 250

PM DESIGN

The general idea is that the PM design in all magnets has to be as similar as possible. A promising technique is the magnetic bridge where the PM blocks are installed between the return yoke and pole shoes together with an Aluminum framework. Such a geometry is visualized in Fig. 1. The Aluminum framework is used for the mechanical connection, the PM alignment as well as an option for later trimming and shimming of the PM blocks. Less individual PM blocks geometries and less equipment for the tooling and PM block tests will be necessary. This design was used for numerical calculations and optimizations of several concepts for dipole and quadrupole magnets.

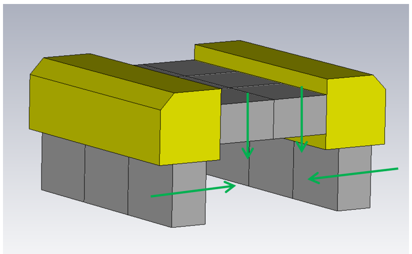

Figure 1: General design of magnetic bridge for all magnets. The PM blocks (grey) with shown magnetization axis (easy-axis = green) and aluminum holders (yellow).

CACULATION TOOLS

For the calculation of the PM based bending and focusing magnets three different 3d field solver tools were tested:

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CST [8], OPERA [9] and ANSYS [10]. As an example, an H-shaped dipole magnet together with the PM bridge design were defined in CST and implemented via step-file in ANSYS and OPERA. The PMs are defined as idealized NdFeB magnets with 1.3 T remanent field and a constant relative permeability of $\mu_r = 1.05$. For the return yoke, Steel-1010 is used which is implemented via hysteresis curves in all three tools. Mesh sizes and accuracy levels were optimized for all three tools individually. In the next step the 3d fields were calculated and the field profiles were compared. Figure 2 shows the calculated mesh and the field for the designed magnet in OPERA. The right plot shows as an example a plot of the vertical magnetic field component as functuion of the horizontal position in the center of the magnet. Here, the resulting field amplitudes and profiles variate in a range of $2 \cdot 10^{-3}$ relative to each other. The main sources for the differences are the individual hysteresis curves of steel-1010 in the three solver ($\approx 10^{-3}$) and the individual mesh optimization. Nevertheless all three results are in good agreement especially for the field profile. It is planned to perform the magnetic design and optimization via OPERA and CST. ANSYS will be used for stress and deformation simulation of the magnets. But it can also be used for detailed material and AC analysis of the magnets, because of the embedded large material database.

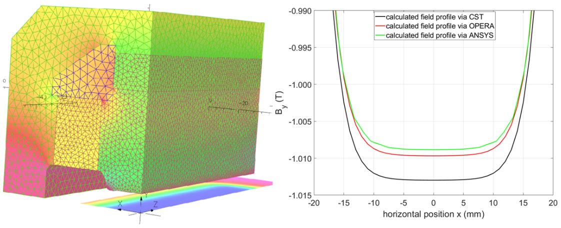

Figure 2: Field calculation of an H-shaped dipole. Left: One-eighth of the symmetric magnet model in OPERA. Left: Horizontal field profile of the magnet setup calculated by the three magnetic solver.

MAGNET DESIGNS

Several PM based magnets for dipole, quadrupole and combined function magnets were designed and numerically tested to estimate the optional magnetic parameter ranges for BESSY III. The limitations are dominated by the defined aperture radius of 12.5 mm and the yoke material. The current working ranges for different magnet concepts can be seen in Fig. 3. It shows the first quadrant of the possible magnetic workspace for dipoles (horizontal axis), quadrupole (vertical axis) and combined function magnets. For BESSY III the magnet designs must achieve magnetic field parameter of at least 1 T for dipole magnets and 80 T/m for quadrupole magnets.

Areas next to the axes can be achieved via dipole and quadrupole magnets with small asymmetries , like curved dipole pole shoes or off-axis quadrupole magnets. However, not all of the workspace combinations are achievable for combined function magnets which are located next to diagonal of the workspace. They need individual optimized pole shoe geometries with often small good field ranges and extravagant designs. For the linear lattice optimization of BESSY III, regions next to the axes of the workspace are preferred without complex combined function magnets. One example of such a lattice is shown in Fig. 4. Two types of dipole magnets (yellow blocks in Fig. 4) are involved in the lattice optimization. On the one side homogenous bends with flat pole shoe design and on the other side transverse gradient bends (TGBs) with curved pole shoes providing an additional quadrupole field gradient. Additionally, to the symmetric QP magnets in the matching cells (red blocks), reverse bends (blue blocks) are required. They must have strong gradients with additional dipole field. This combination can be fulfilled with a strong QP magnet shifted a few millimeter off-axis. As part of the technical design of the magnets, further trimming and shimming plates will be implemented. The trimming plates are thin steel plates located next to the PM blocks, used as magnetic short circuits to reduce the magnetic flux in a pole shoe as function of their installation depth. On the other side, shimming plates are used to compensate the -1×10^{-3} 1/K temperature decrease of the PM remanent field. They consist of NiFe with a quite low saturation field that is correlated to the temperature. In case of the correct thickness, the shimming plates can reduce the temperature variation by 2 orders of magnitude [11]. The thickness value must be adjusted for each magnet geometry and variates between 4 and 8 mm [12].

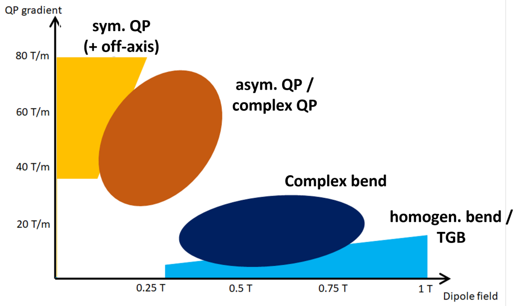

Figure 3: Diagram of the current magnet parameter space for BESSY III with dipole field value at the horizontal axis and the quadrupole field gradients at the vertical axis. Four regions are marked for calculated magnet designs achieving shown parameter combinations.

Bending Magnets

All bending magnets for BESSY III are designed with a C-shaped return yoke for better handling during the installation and for the synchrotron radiation beamlines. Field amplitude and profile can be adjusted via the number of PM blocks in the bridge and the pole shoe design. In case of homogenous bends, with required dipole field values between 0.6 T and 0.7 T, a flat pole shoe will be installed. On the other hand transverse gradient bends (TGBs) need a curved pole shoe design with additional quadrupole components in the range

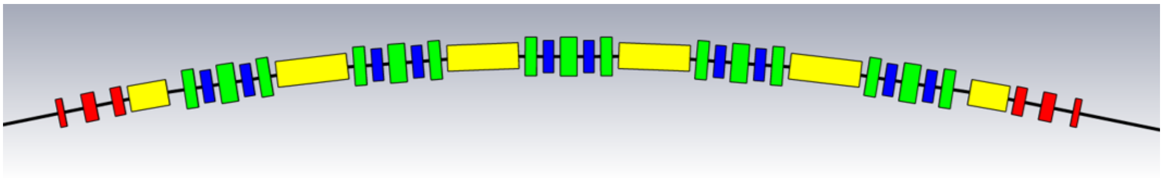

Figure 4: Current option for the BESSY III magnet lattice of one arc with bending magnet (yellow), homogenous quadrupole magnets (red), reverse bends via off-axis quadrupoles (blue) and sextupoles (green).

of 10 T/m and 15 T/m. In both cases the field quality should be in the range of < 1 units unit (unit=1e-4) for a 10 mm reference radius.

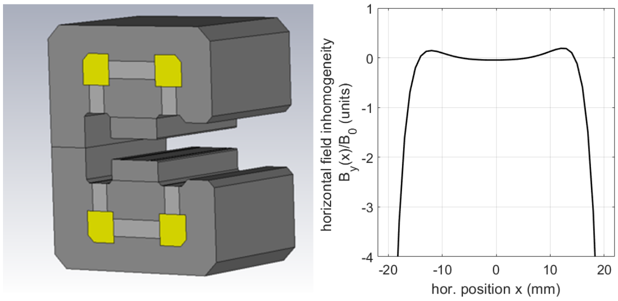

Figure 5: Homogenous bending magnet with a symmetric pole shoe (left) for flat dipole field between ±15 mm and an inhomogeneity of <0.2 units on a 10 mm reference radius. Calculated inhomogeneity of the field profile for the B_0 = 0.833 T dipole.

Figure 5 shows the magnetic design of a 300 mm long single homogenous bend cell and the calculated horizontal field profile. A complete bending magnet structure consists of up to four of these cells. The 50 mm wide pole shoe has a retreated plane in the center of 0.25 mm to suppress higher order multipole components. This single dipole cell design can achieve 0.833 T in the gap. This field can be reduced by a reduction of the overall PM block volume (number of blocks or length of a single PM block) and via trimming plates. If the magnetic holes in the PM bridge are shorter than the minimum dimension of the pole shoe, no variations in the field profile will be detectable.

The second type of bending magnets is the TGB with an asymmetric pole shoe to produce an additional magnetic gradient in the transverse direction. Thereby, magnetic field value, gradient and linearity depend on the curvature of the pole shoe and the magnetic volume of the PMs. The main TGB design for BESSY III can produce dipole fields between 0.5 T and 0.8 T with additional gradients of up to 20 T/m. The exact pole shoe design must be optimized for the required lattice values.

Focussing Magnets

For QP magnets, the PM bridge is located between the return yoke and the pole finger itself. This design combines PMs with conventional QP designs, that allows to install also a compact corrector coil arond the pole finger. The design of such a Variable Permanent Hybrid Magnets (VPHM) can be seen in the left image of Fig. 6. Depending on the length of the magnet, gradients of > 80 T/m are possible. In combination with an air-convection cooled corrector coil (current densities of < 2.5 A/mm^2) an additional field variation can be achieved (right plot of Fig. 6). The initial coil width in this design has a thickness of 20 mm and is quite to strong. In later designs the coil dimension are reduced. Multipole terms in the QP field depend in first order on the pole shoe design and in second order on the saturation effects of the pole tip. Here, the dominating multipole is $b_{12} \approx$ 2units.

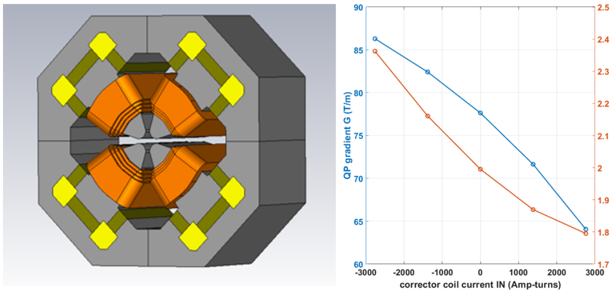

Figure 6: Design of a symmetric quadrupole magnet in a VPHM design for gradient up to >80 T/m (left). Calculated field gradient and dominating multipole on axis as function of the corrector current (right). The field inhomogenity is in the range of 2 units.

A similar QP design will be used as a reverse bend in BESSY III that need ≈ 80 T/m gradient added to a 0.25 T dipole field. This additional dipole field can be achieved by a 3 mm horizontal offset between magnet axis and beam which is inside the tolerances for a 12.5 mm aperture radius.

CONCLUSION

For the future BESSY III storage ring a magnet design based on Permament Magnets was developed. For this hybrid concept, PM blocks with equal dimensions are implemented in the yoke of the magnets to work as main magnetic source. Several magnet designs were calculated, like homogenous and transverse gradient bends, as well as fucusing magnets. Three magnetic solver were tested for the calculations with consistent resulting curves. The calculated designs for the magnets fulfill the requirements for the current BESSY III latice layout and will be optimized to the exact necessary parameters. Also, the development for mag-

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net tooling and measurements was started and a first test magnet will be build in next year.

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