PM MAGNET DEVELOPMENT STATUS FOR BESSYII+

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Abstract

Beam-guiding magnets based on permanent-magnets (PM) combine up to zero power consumption with highly stable magnet operation without field ripple and cooling-water vibration effects for more energy-efficient and stable accelerator operation. As part of the upgrade program BESSYII+, we will install the B2PT dipole triplet as the first PM-based accelerator magnet. It concludes the BESSYII transfer line, transporting the electron beam from the booster to the storage ring and bends the beam into the injection septum of the BESSYII storage ring. The new B2PT is planned with three PM hybrid dipole units of 300 mm length each to substitute the present power-hungry 1-m long electromagnet. The triplet produces a stable magnetic field that can be trimmed during operation by electro-correctors in the outer magnets. The permanent magnetic field reduces injection noise into the storage ring and shrinks the total power consumption by almost 30 kW. This paper reviews simulated beam bending optimization of the B2PT PM triplet and its assembly process opening up to PM magnet development also required for the preparation of the future 4th generation low-emittance source BESSYIII.

BESSYII+ PERMANENT MAGNET PROJECT

The BESSYII+ upgrade is a bridge-technology development project for BESSYIII. Among different topics addressed by the upgrade, the permanent-magnet one involves the replacement of the current B2PT which is a 1-m long 1.6-kA copper-coil 30-kW static C-shaped electro-dipole at the end of the transfer line upstream of the injection septum that provides a field $B_y = 0.78$ T. The replacement B2PT triplet magnet will be a longitudinally symmetric hybrid permanent-magnet assembly of 3 separate dipoles, two identical outer ones and a stronger central one. A first test of assembly procedure and relevant tooling involved for the PMs in the surrounding soft magnetic yoke has been successfully carried out in April 2025. The triplet must provide the newly specified target bending angle $\theta_{trgt} = 7.82^\circ$ for the 1.7-GeV electron beam trajectory towards the septum. The new transfer line magnet will be the first PM-based accelerator magnet at BESSYII. Further magnet projects are planned, like PM bending magnets in the BESSYII storage ring (homogeneous and longitudinal-gradient bend) towards 2.5-GeV 4th generation low-emittance BESSYIII [1, 2]. The main goal of the magnet upgrade is the reduction of the overall power consumption for the subsequent improvement of the energy efficiency of the new facility with enhanced magnet operation stability by elimination of field ripple and vibration sources such as power supplies and cooling channels.

B2PT DIPOLE TRIPLET DESIGN AND TUNING

Figure 1 illustrates the full CST-rendered model of the B2PT symmetric dipole triplet with the three dipoles complemented by corrector coils and trimming plates for integrated magnetic field adjustment [3]. Figure 2 gives the flat H-shaped dipole design employed for the new B2PT chosen for improved compensation of magnetic forces estimated to reach 20 kN. The triplet will have a magnetic field driven by PM blocks nested in a symmetric iron structure for the return yoke and pole pieces (shoes). The positioning of the permanent magnets in place will be done with the help of a dedicated press-in tool [4]. Main B2PT dipole parameters are listed in Table 1 together with possible PM and geometry setups for the triplet elaborated upon below. B2PT PM blocks come in two types, "A" of dimen-

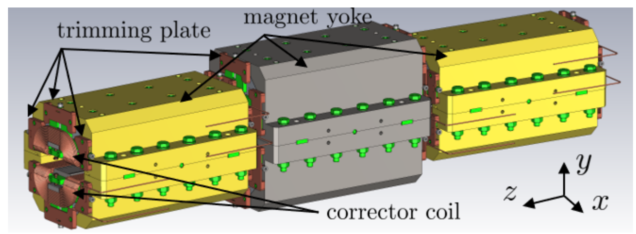

Figure 1: CST magnetomechanical model of the B2PT dipole triplet with some of the visible trimming plates and corrector coils indicated.

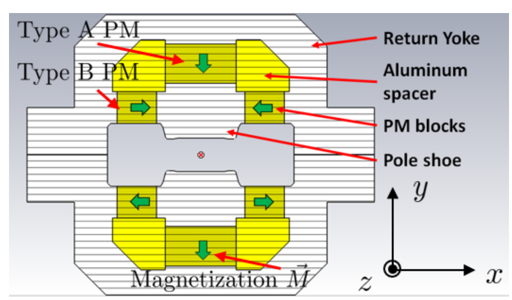

Figure 2: Cross section of one of the B2PT triplet outer dipoles. Magnetization vectors (green) of individual permanent magnets are oriented to produce a vertical dipole field in the gap between pole shoes.

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Table 1: Magnetic and Geometrical B2PT Parameters

Parameter	Central Dipole	Outer Dipoles
length $L_{z\,mag}$	300 mm	
width	220 mm	
height	238 mm	178 mm
pole aperture (gap)		
spacing d_{inn}	40 mm	
dipole angle η		2.6°
dipole offset Δ	7 mm	
PM type A/B ratio	8/24	10/24
peak field $B_{y\,max}$	0.97 T	0.75 T

sions (length × width × height) 50 × 45 ×25 [mm] and "B" (50 × 20 × 25 mm). The PM material is NdFeB N42 category giving a remanent field B_r = 1.3 T along the easy magnetization axis with linear relative permeability μ_r = 1.05 used in CST for the magnetic simulations. PM block type and magnetization polarization in an individual dipole are given in Fig. 2 in relation to steel yoke and pole shoes with aluminum spacers. Each dipole contains six rows of permanent magnets with a possible total of 6 magnet blocks per row for a resulting 36 magnets per dipole. This capacity is specified with respect to the fulfillment of necessary magnet parameters for a beam bending of 8.2° as planned in the beginning of the project [4]. The number of magnet blocks in the triplet can be changed by symmetric insertion/evacuation of PMs in rows of individual dipoles to modify the dipole magnetic field B_y (PM fill patterns in the triplet). Additional field tuning is provided by steel trimming plates, 12 per dipole in 2 groups of 6 at both ends. These can be manually slided transversely to the dipole gap to reduce the integrated magnetic flux in the gap. The plates can be adjusted symmetrically for overall bending-field tuning estimated at ±3 % or can be used to correct discrepancies among average fluxes of PM rows. These are viewed as main field error sources for the triplet due to PM-block error smoothing by the yoke thickness. An additional approximate 2.6 % of dipole field variation is expected to be technically achievable with low-current air-convection-cooled rectangular coils installed on outer dipoles [4]. This in theory brings the total available triplet field tuning range to $\theta_{tun} = d\theta_{max}/\theta_{trgt} = 5.6\,\%$ at best, considered here. The overall B2PT bending angle must be reduced from the previous 8.19° to 7.82° for reasons of additional injection geometry and septum optimizations leading to a linearized injection line with increased precision measurement capability with respect to that of the 90s, for an already fixed dipole design. This requires a new study of the necessary magnetic configuration of the triplet which is of reduced PM usage relative to the past one and of the proper triplet geometry.

MAGNET TRIPLET ALIGNMENT OPTIMIZATION

Triplet PM fill patterns and geometries, in terms of the geometric angle η and central-magnet horizontal offset Δ that achieve the required final bend angle $\theta_{x\,fnl} \in [\theta_{trgt} \pm \theta_{tun}]$, are investigated first. η and Δ and other relevant parameters are defined in Fig. 3. A longitudinal distance d_{inn} = 40 mm

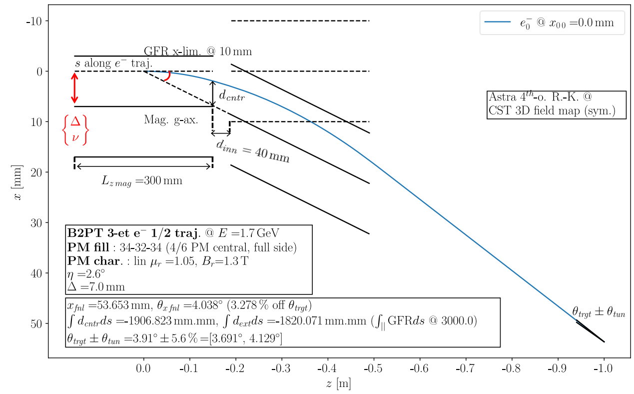

Figure 3: Symmetric half of the B2PT dipole triplet of Fig. 1 relative to resulting 1.7 GeV electron trajectory from ASTRA for initial beam offset $x_{0\,0}$ = 0 mm. Geometry, magnet parameters and dipole-integrated beam paths $\int d_{cntr} ds$, $\int d_{ext} ds$ for $x_{0\,0}$ = 0 mm given in insets.

between neighboring magnets is chosen as space for trimming plates and coils. Due to this, magnetic crosstalk has to be taken into account. Hence, the full 3D triplet configuration fields including crosstalk regions and fringe fields computed with the CST magnetostatic solver have been input into the ASTRA Runge-Kutta single-particle tracker for beam trajectory calculation [5]. Figure 3 gives the right half of the resulting symmetric bent-beam trajectory for an electron with zero initial horizontal beam offset $x_{0\,0}$ = 0 mm relative to nominal central-magnet axis (coordinate system origin). x_0 is used as free parameter for beam-offset minimization in both triplet magnets applied to suitable initial trajectories in terms of $\theta_{x\,fnl}$ and containment in the 10-mm good-field region (GFR), Fig. 4. It shows the central-magnet horizontal field distribution over ±20 mm around the axis (Δ) as well as the GFR field quality.

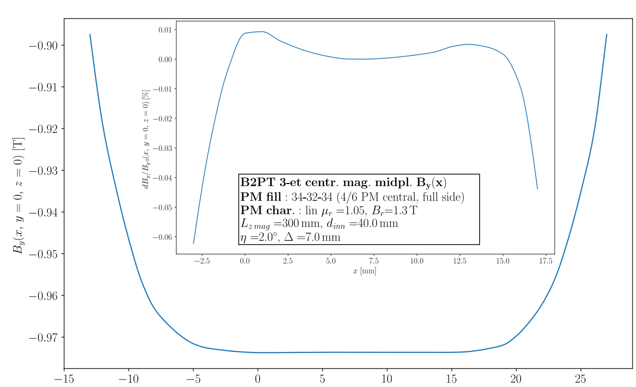

Figure 4: Horizontal field profile $B_y(x, y = 0, z = 0)$ in the central magnet. Field quality over GFR (inner plot).

Figure 3 demonstrates a final bending angle $\theta_{x\,fnl}$ around 3.28 % higher than target θ_{trgt}, hence within technically acceptable tolerance $\theta_{trgt} \pm \theta_{tun} = 7.82^{\circ} \pm 5.6\,\%$, at a distance $z = 1$ m from the central dipole center ($3.91^{\circ} \pm 5.6\,\% \in [3.69^{\circ}, 4.13^{\circ}]$ for the symmetric-half setup of Fig. 3). Integrated horizontal beam offsets $\int d_{cntr}ds$ and $\int d_{ext}ds$ in central and outer dipoles are relevant for beam trajectory average alignment to both dipole magnets' axes via the initial beam offset x_0, with d_{cntr}, d_{ext} the relevant local offsets from axis in the two dipoles, Fig. 3. The displayed triplet over-bending is preferred because the bend angle θ_{xfnl} can be down-tuned to target, in large part with the trimming plates. θ_{xfnl} is achieved for a PM usage pattern 34-32-34 (32 PM blocks in the central and 34 in the outer dipoles), with 2 and 4 "A" PMs spared in top and bottom PM rows respectively, Fig. 2. Relative bend difference $\theta_{off} = (\theta_{xfnl} - \theta_{trgt})/\theta_{trgt}$ for this PM fill is checked for triplet geometries in $[\Delta \in [2, 7]\,[\text{mm}]] \times [\eta \in [2, 5]\,[^{\circ}]]$ to be in the range $[-4.19, 3.36]\,[\%]$. The lower boundary corresponds to a degraded beam trajectory outside of the GFR and is taken as worst-case. For suitable geometries yielding trajectories close to the axes an over-bending $\theta_{off} \approx 3.3\,\%$ is observed, within technical field tunability. A typical on-trajectory interpolated triplet field profile B_y is given in Fig. 5 with corresponding peak fields in Table 1.

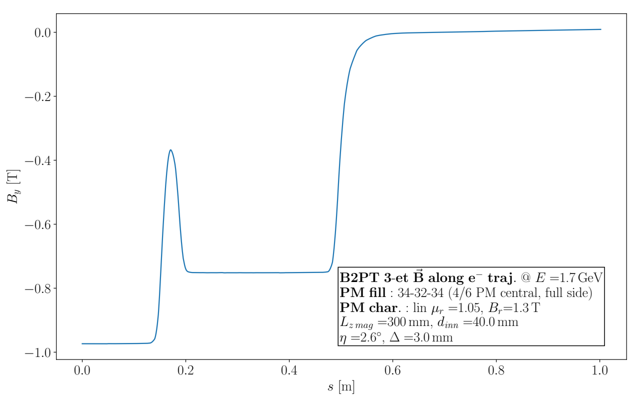

Figure 5: Triplet right-half field profile $B_y(s)$ along the beam trajectory through for a 34-32-34 PM fill and geometry similar to that of Fig. 3.

Figure 6 scans triplet setups $\{\Delta, \eta\}$ in terms of simultaneous minimization of integrated offsets $\int d_{cntr}ds$, $\int d_{ext}ds$ for initial offsets $x_0 \in [0, 11]\,[\text{mm}]$. It shows the difference in integrated offset zero-crossing, $\chi_{cntr} - \chi_{ext}$, with $\chi_{cntr} = x_{0\,\min(|\int d_{cntr}ds|)}$ and $\chi_{ext} = x_{0\,\min(|\int d_{ext}ds|)}$ the x_0-values that minimize in absolute terms the respective integrated beam offsets in the two dipoles, for a beam energy reset $dE/E \in [-4.19, 3.36]\,[\%]$ taken as the final bend-angle error θ_{off}. Suggested from Fig. 6, a triplet $\{\Delta = 7\,\text{mm}, \eta = 2.6^{\circ}\}$ is illustrated in terms of outer-dipole beam offset $\int d_{ext}ds(x_0)$ in Fig. 7. Expected linear offset variation with x_0 is observed within the integrated GFR $\int_{||}\text{GFR}ds = 3000\,\text{mm.mm}$ along the dipole length $L_{z\,mag}$. $\chi_{ext} \approx 6.37\,\text{mm}$ is yielded with corresponding $\chi_{cntr} - \chi_{ext} \approx 9\,\mu\text{m}$. It is seen on the right of Fig. 7 that the bend-angle error θ_{off} during beam x_0-scan is maintained

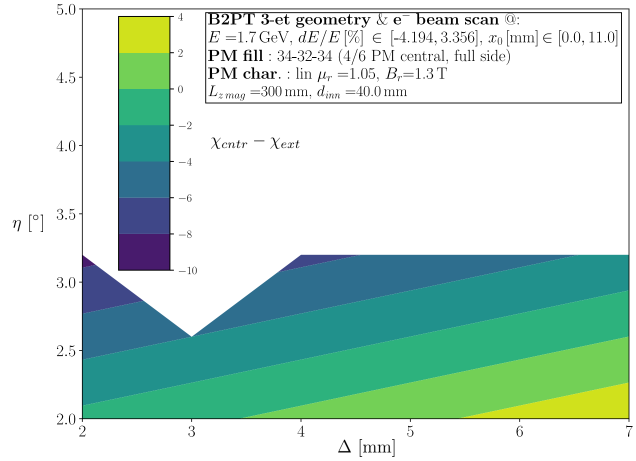

Figure 6: Zero-crossing difference of beam offset integrals $\int d_{cntr}ds$, $\int d_{ext}ds$ with triplet setup $\{\Delta, \eta\}$ for an initial beam offset scan range $x_0 \in [0, 11]$ mm.

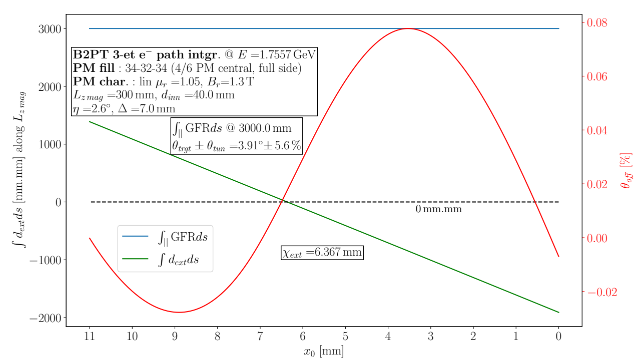

Figure 7: Left: Evolution of outer dipole beam offset integral $\int d_{ext}ds$ with initial beam offset x_0 relative to integrated GFR $\int_{||}\text{GFR}ds = 3000\,\text{mm.mm}$ for B2PT triplet geometry $\{\Delta = 7\,\text{mm}, \eta = 2.6^{\circ}\}$, Fig. 3. Right: Corresponding relative bend angle variation.

well within tunable range of 5.6 %. An optimal initial beam offset is deduced $x_0 \in [6.37, 6.38]\,[\text{mm}]$ for integral offset cancellation in central and outer dipoles while respecting the new BESSYII+ injection beam bending requirement.

CONCLUSION

New B2PT PM dipole triplet studies build on previous investigations following the BESSY injection geometry modification. They produce parameter values allowing to select convenient triplet geometries for fulfillment of the new beam bending angle requirement between booster and storage ring for BESSYII+. Efficient use of the permanent-magnet design is found for this. The PM magnet pioneer at BESSYII is ready for assembly with major components delivered, paving the way for subsequent PM projects for BESSYIII.

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