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COMPACT HYBRID PLANAR PERMANENT MAGNET UNDULATOR DESIGN FOR THE APS UPGRADE*

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Abstract

We report on the successful design of a compact 28-mm period hybrid planar permanent magnet (HPPM) undulator for the Advanced Photon Source Upgrade (APS-U) project [1]. The design produces a peak field of 9750 G at a gap of 8.5 mm, with a pole width reduced to 35 mm as compared to the planar undulators currently in use at the Advanced Photon Source.

The design includes a detailed investigation into the origin of the HPPM undulator demagnetization. We report on a finding of an optimization method that reduces the demagnetization field and increases the field at the gap center of the design. It includes an optimization of the pole edges to increase the field and decrease roll-off in the transverse direction. Further design optimizations include analyses of the mechanical assembly tolerances and comparison with the original design before building the device. Beam physics analyses included kick-map analysis, dynamic acceptance (DA), local momentum acceptance (LMA), and Touschek lifetime of this design were performed with the 42-pm lattice of the APS-U.

Detailed magnetic design, effective field, field roll-off, magnetic force, and tracking results are reported.

INTRODUCTION

With the APS-U ring design energy of 6 GeV, a 28-mm period undulator is well optimized to create x-rays of optimal energy for a large segment of scientific users. Therefore, a 28-mm period undulator will be produced in the largest quantities in the APS-U era, largely replacing the 33-mm period undulators now at the Advanced Photon Source (APS). The operational magnetic gap of the APS-U undulators will be 8.5 mm, smaller than the current minimum gap of 10.5 mm.

The smaller gap, left unmitigated, would result in an excessive magnetic force, creating an uneven gap over the length that is not desirable to the outgoing particle beam offset. Additionally, the offset will not be consistent when the undulator gap is opened and closed each time by the users due to unstable tuning parameters. Lowering the magnetic force of the design addresses these issues, and is essential to achieve the best performance of the 28-mm period undulator at the operational gap of 8.5 mm.

Narrowing the pole width helps to reduce the magnetic force; however, it increases the field roll-off, which is not desirable from the particle beam dynamic aperture point of view. The electron beam must enter and exit an undulator without being affected by the dynamic multipole fields in the straight section of the storage ring. Therefore, a systematic study on a 28-mm period undulator was performed to search for the possibility of narrowing the pole width while not affecting the passing particle beam dynamics.

A design technique was developed [2] that allowed narrowing the pole to meet these constraints. The optimization resulted in lowering the field roll-off to a level of 2×10^{-4}, increasing the field by 170 G and decreasing the magnetic force by 4.5% more of the design with a 35-mm-wide pole.

We have also found that a large cut on permanent magnet edge reduces the demagnetization field (H field) on the permanent magnet (PM) and increases the induction field (B field) at the gap center. The flux structure around the pole and PM tips analyzed in Opera-2d and -3d supported the finding [3].

A kick-map analysis, the dynamic acceptance (DA), local momentum acceptance (LMA), and Touschek lifetime of the narrowed pole 28-mm period undulator were performed with the 42-pm lattice of the APS-U (tracking) as well. Detailed magnetic design, effective field, magnetic force, and field roll-off and beam dynamics of the undulator are reported.

MAGNETIC DESIGN

A quarter period undulator of the 28-mm period was built with Opera-2d and -3d as in Fig. 1. The pole material is Vanadium Permendur (VP), and the PM material is set to N41Z-GR (Shin-Etsu, Japan). The N41Z-GR has a B_r (remanence) of 12,431 G with an H_{cj} (coercivity) of 29.3 kOe at the surface and a 21.9 kOe in the bulk of the magnet at 25 ºC. All pole and PM dimensions except pole width are optimized to increase the field. Pole-xx chamfer was optimized to decrease the field roll-off and increase the field to achieve the specified field [3]. Figure 2 shows the flux distribution around the corner of the pole and PM with and without optimizing the PM-zz and -zy chamfers (the definition of the chamfers shown in Fig. 1. Most of the flux created by the moment of the PM goes into the pole and defects towards the gap as in Fig. 2 (a). However, in the enlarged image, Fig. 2 (b), some flux, indicated with red arrows, are passing through the PM itself to return to the PM. Please note the directions of those red arrow fluxes [4]. It is opposite to the PM moment. Therefore, it reduces the moment and increases the H field (H = B - M) on that magnet corner. It was the cause of the demagnetizing problem of the hybrid planar permanent magnet (HPPM) undulator.

Therefore, a proper cut of the PM corner following the direction of those red arrows fluxes is essential to reduce the demagnetization field and increase the field at the gap center. Note that the returned flux goes quite deep inside the PM; therefore, the PM-zy chamfer needs to be larger

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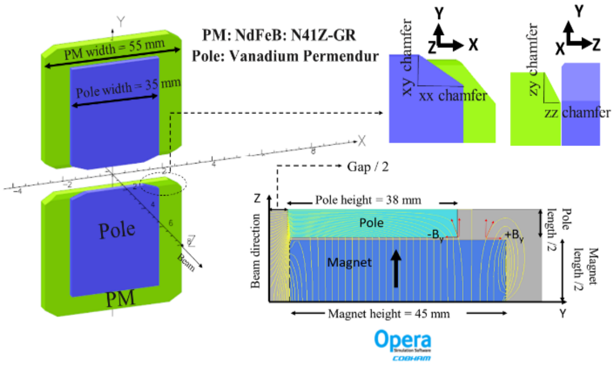

Figure 1: A quarter-period-long narrowed pole 28-mm period undulator designed for the APS-U. The definitions of the chamfers on the pole and magnet edges are shown on top right images. The yellow lines are the magnetic flux lines in 2D (bottom right image). The red arrows show the magnetic flux contributions to the B field components.

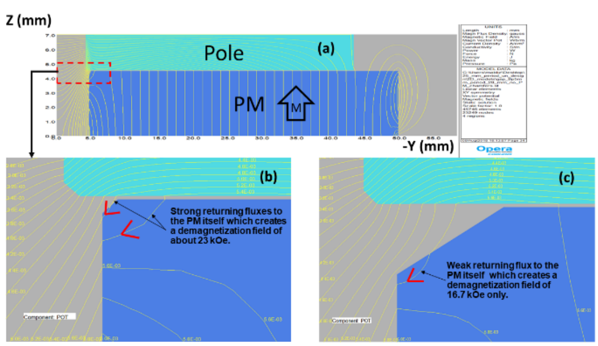

Figure 2: Magnetic flux lines of a quarter-period-long model of a 28-mm-period undulator (the bottom half is shown). The moment is set along the Z (beam axis).

than the zz-chamfer to eliminate them as shown in Fig. 2 (c). The optimized chamfer PM-zz and -zy chamfers were 1.0 mm and 1.8 mm, suggesting the slope of the red arrowed flux in Fig. 2 (b). Figures 3 and 4 show the maximum PM surface demagnetization field and the B_{eff} at the gap center as enlarging the PM-zz and -zy chamfers. The PM-zy chamfer decreases the demagnetization field sharply compared to PM-zz chamfer as in Fig. 3. On the other hand, the B_{eff} increases with enlarging the PM-zz and -zy chamfers and reaches a maximum and then decreases. The results of Figs. 3 and 4 support the origin of the HPPM undulators demagnetization, which is explained in Fig. 2.

To confirm the effect on the stored beam dynamics of a narrowed pole undulator design of APS-U 28 mm, we have performed simulations of acceptance (DA), LMA, and Touschek lifetime with the 42-pm lattice [5]. We have found that even when scaling the kick map [6] for a 30 mm gap to the fields obtained at an 8.5 mm gap, the effect on machine performance is negligible.

To ensure the integrated field errors of the design, we have modelled an 8-period-long APS-U 28-mm period undulator by introducing random assembly errors to each pole and PMs' pieces in the model. The random errors include pole and PMs' widths, heights, lengths, canting angles, and the PMs' remanent field errors. The reason for introducing random errors that are much larger than the specification of 25 µm is to create integrated field errors comparable to the device's actual measurement. The result of the mechanical error analysis in Fig. 5 confirmed that the integrated field errors of the 35 mm wide pole design are comparable to the wide pole design [7].

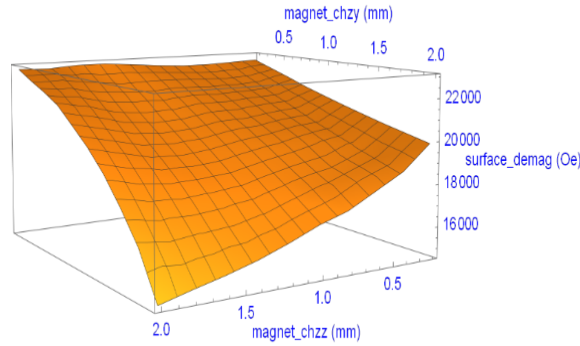

Figure 3: The maximum PM surface demagnetization field of the APS-U 28-mm period undulator design as a function of the PM-zz and -zy chamfers size at a gap of 8.5 mm.

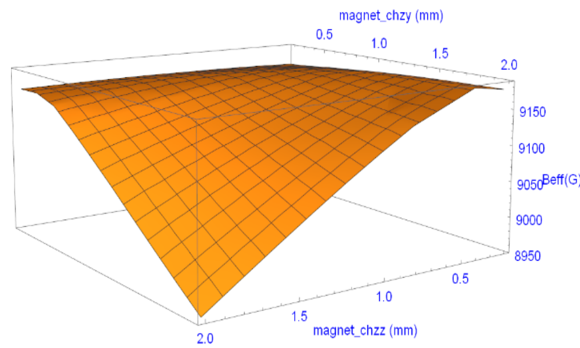

Figure 4: The B_{eff} of the APS-U 28-mm period undulator design as the PM-zz and -zy chamfers change at a gap of 8.5 mm.

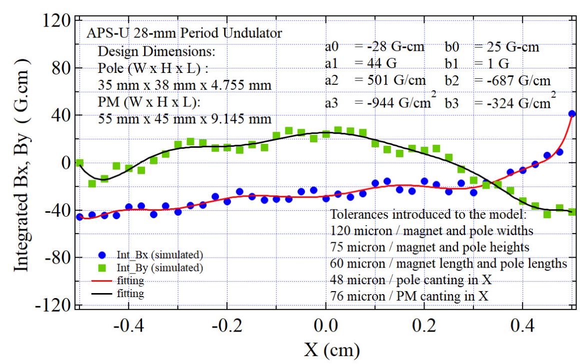

Figure 5: Simulation results of the integrated Bx and By field errors over the length of the APS-U 28-mm model at each different position in X. The "a" and "b" components inserted in the plot represent the integrated field errors of B_x and B_y, respectively.

The optimized design parameters of the APS-U 28-mm period are shown in Table 1. The force (per half period) designed for the APS-U 28 mm period was 77 N, about 30% reduction of conventional design [8]. The magnetic

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force of the APS-U 28-mm at the closed gap of 8.5 mm was verified in a different method as well [9].

Table 1: Design Parameters of the APS-U 28-mm Period HPPM Undulators

Design Parameter	Value	Unit
Gap	8.5	mm
B_{eff}	9,150	G
Magnetic Force (per half period)	77	N
Roll-Off	2.2	G
Demagnetization Field	10.2 / 16.7	kOe
Temperature Resistance (Bulk / Surface)	139 / 129	°C

CONCLUSIONS

We have successfully designed and built a compact HPPM undulator for APS-U of 28 mm, which creates about 9750 G peak field at a gap of 8.5 mm. The measured B_{eff} was 9505 G, about 4% higher than the design, which is the highest field among the APS undulators. We have reduced the magnetic force by 30% of the design successfully by narrowing the pole width from 44 to 35 mm and applying a large cut on the pole edge. The measured integrated dipole and harmonic fields along the devices' length in a range of ± 6 mm X are minor, or some of the devices did not even need to tune due to the reduced force of the design.

The field of the APS-28 mm period at a gap of 8.5 mm is close to the APS 36-mm period undulator, a gap of 10.5 mm (operational gap). The number of periods of the 28- and 36-mm period undulators in a length of 2.4 m is 86 and 67. It means the force of the APS-U 28 mm period needs to be decreased by 28% (86 / 67) at least to manage the magnetic force by comparing rationally.

The magnetic force of an HPPM undulator increases as a function of squared field, reducing the force of the design was critical to build the device successfully. In fact, the force of the HPPM undulator increases not only as a function of the field but also as a pole's width. Therefore, we have narrowed the pole width to 35 mm to reduce the force of the design. The optimized large pole-xx chamfer of 6 mm reduced the magnetic force about 4.5% more of the design. Therefore, the designed force of the APS-U 28 mm was even lower than the current APS 27-mm period by 14%. Normally, the magnetic force of the HPPM increases as the period length enlarges due to increased field. Furthermore, the optimization technique of the pole-xx chamfer has also helped to increase the field about 1% to achieve the specified field of the design.

We have also investigated the origin of the HPPM undulators' high demagnetization field. The reason was the direction of the fluxes that pass through the PM corner close to the pole tip. The fluxes are opposite the PM moment at that corner; therefore, it increases the H field (demagnetization field) H = B - M. Removing the PM corner (PM-zz and -zy chamfers) is equal to eliminating the magnetic resistance for the fluxes to pass through the PM corner. We have confirmed this point by reading the demagnetization field and B_{eff} by enlarging the design's PM-zz and -zy chamfers, e.g., the B_{eff} increases as the PM-zz and -zy chamfers enlarge in the beginning and reach maximum and then decrease. We have also found that the fluxes that pass the magnet corner start deep in the PM height. Therefore, a large cut of 1.8 mm of PM-zy reduces the demagnetization field more without reducing the field itself.

Furthermore, it is a compact design. Both pole and PMs of the design are cut in size, only $35 \times 38 \times 4.755$ mm^3 and $55 \times 45 \times 9.145$ mm^3 in width × height × length, respectively. Also, the optimized PM-zz and -zy chamfers of the APS-U 28 mm undulators will make the devices last long without demagnetization from radiation heat in the tunnel. Also, the narrowing of the pole width reduced the material cost of the APS-U 28-mm period undulator by 34%.

We have also successfully designed and built some other period compact HPPM undulators, the APS-U 21 mm and APS-U 25 mm undulators, which have a narrowed pole equal to or smaller than the APS-U 28 mm period undulator.

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