SEPTUM MAGNET DESIGN FOR THE APS-U*

M. Abliz†, M. Jaski, A. Xiao, U. Wienands, H. Cease, M. Borland, G. Decker, J. Kerby
Argonne National Laboratory, Argonne, IL 60439, U.S.A

Abstract

The Advanced Photon Source is in the process of upgrading its storage ring from a double-bend to a multi-bend lattice as part of the APS Upgrade Project (APS-U). A swap-out injection scheme is planned for the APS-U to keep a constant beam current and to enable a small dynamic aperture.

A septum magnet with a minimum thickness of 2 mm and an injection field of 1.06 T has been designed, delivering the required total deflecting angle is 89 mrad with a ring energy of 6 GeV. The stored beam chamber has an 8 mm x 6 mm super-ellipsoidal aperture. The magnet is straight; however, it is tilted in yaw, roll, and pitch from the stored beam chamber to meet the on axis swap out injection requirements for the APS-U lattice.

In order to minimize the leakage field inside the stored beam chamber, four different techniques were utilized in the design. As a result, the horizontal deflecting angle of the stored beam was held to only 5 µrad, and the integrated skew quadrupole inside the stored beam chamber was held to 0.09 T. The detailed techniques that were applied to the design, field multipoles, and resulting trajectories of the injected and stored beams are reported.

INTRODUCTION

On axis swap-out injection [1] is required for APS-U. The electron beam trajectory needs to be deflected in the horizontal and vertical planes before it is injected into the storage ring [2]. The septum needs to be tilted in yaw, pitch, and roll in order to make the required on-axis injection, since the beam comes at an angle from the booster.

To meet the APS-U needs, the septum design must meet the requirements in Table 1. The available space limitation of 178 cm results in a peak field for the injected beam needs of more than 1 T in order to achieve the total deflecting angle of 89 mrad. A thin septum with a high injection field makes the design challenging in terms of the deflecting angle (or field leakage) seen by the stored beam [3]. Furthermore, the required super-ellipsoidal cross-section of the stored beam chamber increases the field leakage in the stored beam chamber compared to the commonly used round beam chamber.

In order to reduce the effect of the field leakage on the stored beam chamber, four different unique ideas were applied to the design of the septum magnet: 1) the top pole was cut shorter than the bottom pole at both US and DS ends; 2) an open space was created around the stored beam chamber; 3) Vanadium Permendur (VP) was selected as the material of the stored beam chamber; 4) the US end of the stored beam was placed under the side leg.

The combination of these four ideas decreased the field leakage inside stored beam chamber dramatically and decreased the integrated skew quadrupole field inside the stored beam chamber. The detailed design, injection and stored beam trajectories, the field along the injection beam trajectory, and leakage field inside the stored beam chamber will be reported.

Table 1: Specification

Parameters	Value	Unit	Parameters	Value	Unit
Magnet Type	DC	---	Insertion Length	178	cm
Injected Beam Deflecting Angle	89	*mrad*	Aperture of the Stored Beam Chamber (H x V)	8 x 6	mm
Injected Field Strength, By	1	T	Septum Thickness at Down Stream End	2	mm
Tilting Angle	93	*mrad*	Septum Thickness at Up Stream End	4.56	mm
Stored Beam Deflecting Angle	< 100	*µrad*	Beam separation at septum	5.5	mm
Injected Field Uniformity	≤ 0.001	---	Septum Thickness Tolerance	50	µm

MAGNETIC DESIGN

An H-shaped dipole magnet structure was designed with Opera 3D for the septum magnet, as shown in Fig. 1 and Fig. 2. A coil, 4 x 12 turns, was wound around the top pole. The gap between the top and bottom poles was set at 10 mm.

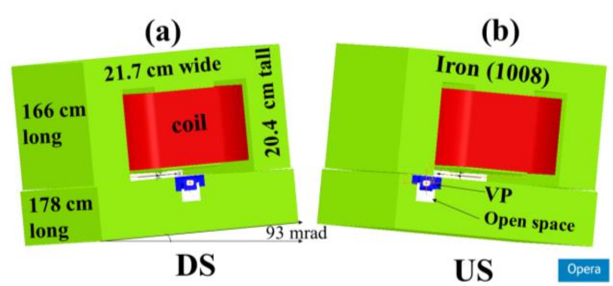

Figure 1: (a) & (b) Views of the septum magnet from the stored beam chamber at the DS and US ends.

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† email address: mabliz@aps.anl.gov

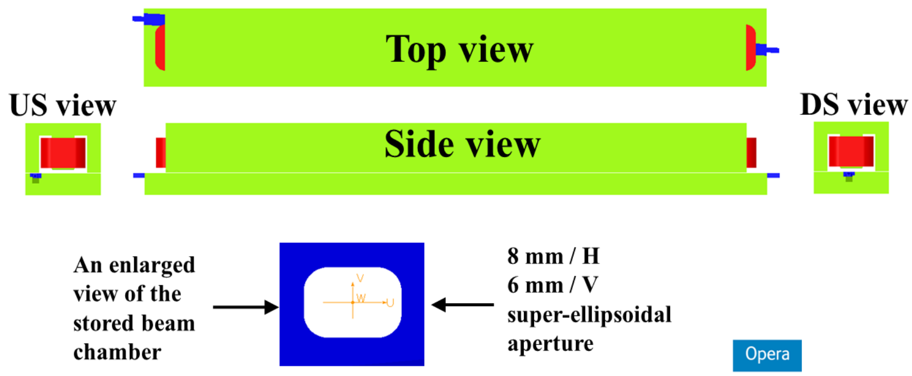

Figure 2: Different views of the septum magnet, and an enlarged stored beam chamber.

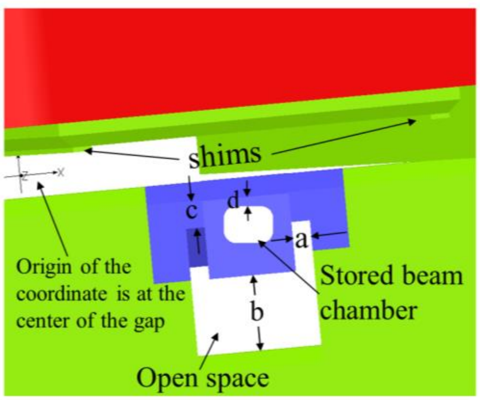

Fig. 3. An enlarged view of the stored beam chamber at the DS end. The origin of the coordinate was set at the center of the gap in X, Y, and Z for the modelling.

The stored beam chamber is located in the bottom pole. The width of the top pole is 6.5 cm, the bottom pole 6 cm, and the thicknesses of the top and side yokes were selected to be 4 cm. The specified septum thicknesses at DS and US are located at the top pole's core length, +/- 83 cm in Z from the magnet center. The upstream and downstream X centers of the stored beam chamber are separated by 7.887 cm, resulting in a 47.5 mrad rotation of the stored beam chamber in the XZ-plane. The iron around the stored beam chamber was cut off and made into an open space, as shown in Fig. 3.

The top pole was designed shorter than the bottom pole as indicated in the Fig. 1 (a). Two shims, 3 mm x 0.78 mm x 165 cm (XYZ), were applied on both sides of the top pole (Fig. 3). The spaces indicated as "a" and "b" were optimized to 3 mm and 15 mm. Dimension "c," which shows the thickness of the VP around the stored beam chamber was tapered up on the right and tapered down on the left from DS to US. The septum thickness, d, was designed to be 1.4 mm, less than required 2 mm due to the longer bottom pole length.

RESULTS

To achieve the required field for the injection beam, a design with 10620 Ampere-turns was chosen. Figure 4 (a) and (b) show the trajectories of the injection and stored beams with a peak field of 1.06 T at the gap center.

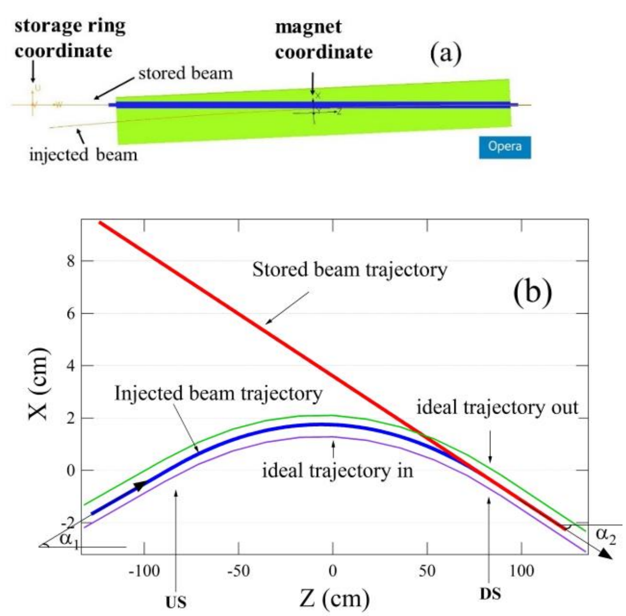

Fig. 4. (a) Top views of injected and stored electron beam trajectories of the septum magnet from the storage ring coordinate (all other parts but the bottom pole of the model is hidden); (b) Plots of injected and stored electron beam trajectories from the magnet coordinate. The ideal trajectory in and out show the allowed range of the injected beam in the XZ-plane using an ideal field.

The trajectories in Fig. 4 (a) refers to the storage ring coordinate system which was set at the US end, and (b) refers to the magnet coordinate which was set at the center of the gap. The outgoing angle, α_2, in Fig. 4 (b), was set for the mechanical tilting angle of the stored beam chamber in XZ-plane, which is 47.5 mrad from the magnet center. The X position of the injected beam at the DS exit of the septum magnet was set to the center of the stored beam chamber, resulting in the trajectory of the injected beam matching the stored beam trajectory at the DS end as in the Fig. 4 (a) and (b).

The total deflecting angle [4] of the injected beam, $\alpha = \alpha_2 - \alpha_1$, was confirmed as -89 mrad from the trajectory in Fig. 4 (b), matching the required angle in the specifications.

The B_x and B_y fields along the trajectory of the injection beam were computed and are shown in Fig. 5. The integrated B_y field deflects the injected beam 89 mrad with the ring energy of 6 GeV as required. The integrated B_x field along the injection beam trajectory was decreased to -302 G-cm by optimizing the shims on both sides of the top pole. The integrated multipole fields, listed in Table 2, were calculated using a 3 mm reference radius centered at injection beam path.

Figure 6 shows the B_x and B_y fields at the center of the stored beam chamber along the length. The peak field is about 10 G at the DS end where the septum is 2 mm. At the US end, the peak field is about 18 G (the purpose of creating the US field will be explained in the paragraph below). The integrated multipole fields in the stored beam chamber, Table 3, were computed in the area of 2.5 mm in radius at the center of the stored beam chamber along the length.

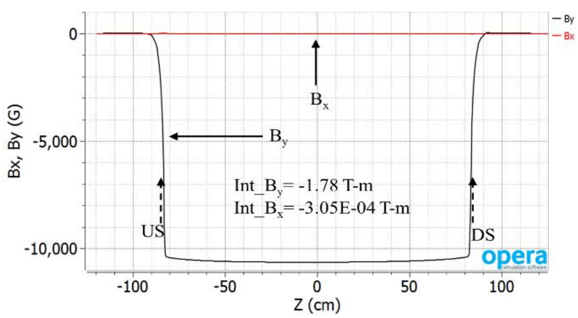

Figure 5: B_x and B_y fields along the injected beam trajectory. The red curve shows the B_x field and the black curve shows the B_y field.

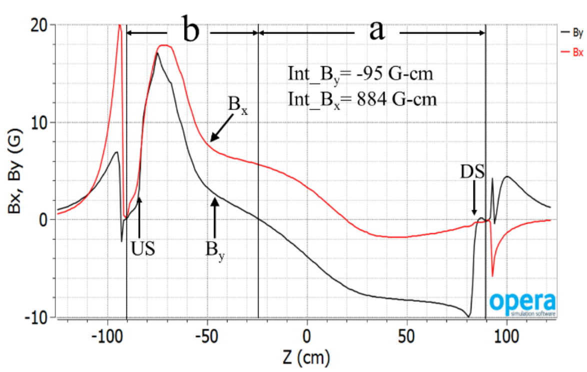

Figure 6: B_x and B_y fields at the center of the stored beam chamber along its length.

Table 2: Injection field multipoles

By field components	Value T (m)$^{-n+1}$	By field components	Value T (m)$^{-n+1}$
b_0	-1.7809	b_5	-1.14e-2
b_1	3.91e-4	b_6	7.2e-3
b_2	-8.93e-4	b_7	4.31e-2
b_3	-4.93e-3	b_8	-1.67e-1
b_4	-4.97e-3	b_9	-4.48e-1

Table 3: Field multipoles inside the stored beam chamber

Normal field multipoles	b_0	b_1	b_2	b_3	b_4	b_5
Value (T mm^{-n+1})	-0.095	0.0771	0.0081	0.0003	0	0
Skew field multipoles	a_0	a_1	a_2	a_3	a_4	a_5
Value (T mm^{-n+1})	0.884	0.0908	0.0029	-0.0026	0	0

DISCUSSION AND CONCLUSION

A septum magnet designed for the APS-U with a 2 mm septum and an injection field of 1.06 T has been presented. The dimensions around the stored beam chamber were optimized to decrease the integrated field leakage in the stored beam chamber. The shims on the pole were optimized to decrease the integrated B_x field along the injected beam trajectory. The effect of the normal field leakage was successfully decreased to 5 µrad by using four techniques. The roles of these techniques in the design are:

1) Making the top pole shorter than the bottom pole to reduce the flux density on the bottom pole for the 2mm septum at the DS end.
2) Making an open space around the stored beam chamber reduces the flux density by reducing the magnetic permeability of the area.
3) Selecting VP for the material of the stored beam chamber, utilizing its higher magnetic permeability to shield the field better than iron.
4) Placing the US end of the stored beam chamber under the side leg creates a leakage field that cancels the leakage field that is created at the DS end. For example, the integrated B_y field leakage in the range “a” is cancelled out by the integrated B_y field leakage in the range “b” in the Fig. 6.

These techniques with the tapered VP parts along the length together reduced the integrated skew quadrupole field inside the stored beam chamber.

The calculated second field integrals (beam offset) showed that there was a 25 µm and 67 µm displacement in horizontal and vertical, respectively, where the stored beam exits from the septum magnet.

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