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A concept for canceling the leakage field inside the stored beam chamber of a septum magnet ☆

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ABSTRACT

The Advanced Photon Source (APS) is planning to upgrade its storage ring from a double-bend achromat to a multi-bend achromat lattice as part of the APS Upgrade Project (APS-U). A swap-out injection scheme is planned for the APS-U in order to keep the beam current constant and to reduce the dynamic aperture requirements. The injection scheme, combined with the constraints in the booster to storage ring transfer region of the APS-U, results in requiring a septum magnet which deflects the injected 6 GeV electron beam by 89 mrad, while not appreciably disturbing the stored beam. The proposed magnet is straight; however, it is rotated in yaw, roll, and pitch from the stored beam chamber to meet the on-axis swap-out injection requirements for the APS-U lattice. The concept utilizes cancellation of the leakage field inside the 8 mm x 6 mm super-ellipsoidal stored beam chamber. As a result, the horizontal deflection angle of the 6 GeV stored beam is reduced to less than 1 μrad with only a 2-mm-thick septum separating the stored beam and the 1.06 T field seen by the injected beam. This design also helps to minimize the integrated skew quadrupole and normal sextupole fields inside the stored beam chamber.

1. Introduction

The Advanced Photon Source (APS) is planning to replace the present storage ring with a new ring, based on a multi-bend achromat lattice, as part of its upgrade project (APS-U) [1,2]. This upgrade will reduce the beam emittance to 42 pm-rad, and increase the brightness and coherent flux delivered to experiments by up to a factor of 500. On-axis swap-out injection [3,4] is planned for the APS-U to minimize the required aperture in the storage ring, while maintaining a stable storage ring beam operating current. In addition, due to the configuration of the booster and storage ring, the trajectory of the injected electron beam must be deflected in both the horizontal and the vertical planes to accomplish injection successfully [5]. The result is a septum magnet which must be rolled (rotated about the longitudinal axis), pitched (rotated about the horizontal axis), and yawed (rotated about the vertical axis) with respect to the stored beam axis. The required roll, pitch, and yaw angles of the septum magnet are 93 mrad, 1.5 mrad, and 47.5 mrad, respectively.

Controlling the leakage field inside the stored beam chamber of the septum magnet is essential in order to keep the effects on the stored beam within tolerable limits. In a traditional design of a Lambertson septum magnet, the leakage field becomes harder to control if the septum is thin and the field for the injected beam is high. In addition to dipole field leakage, the skew quadrupole field inside the stored beam chamber becomes larger if the leakage field is high. In the septum magnet for the present APS machine, the field strength was limited to 0.75 T with a septum thickness of 2.4 mm [6] to avoid these problems. Such limits are not possible in the APS-U configuration.

The specifications for the APS-U septum magnet are listed in Table 1. The available space limitation of 1.78 m results in a peak field for the injected beam of more than 1 T in order to achieve the total deflection angle of 89 mrad. The minimum required septum thickness is 2 mm. A thin septum with a high field makes the design challenging in terms of the deflection angle and skew quadrupole field seen by the stored beam [7]. Furthermore, the required super-ellipsoidal cross-section of the stored beam chamber results in an increased field leakage as compared to the commonly-used round beam chamber.

In order to address these design challenges, a novel concept has been developed. The concept is to place the upstream (US) end of the stored beam chamber under the side leg of the septum magnet in order to create a locally positive vertical component, B_y, of the leakage field. This

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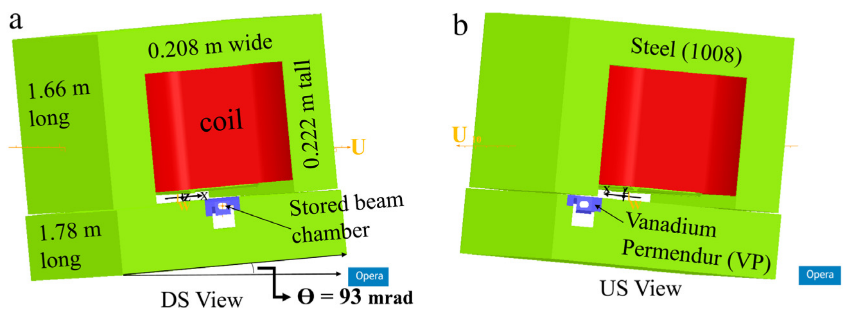

Fig. 1. (a) View of the septum magnet and the stored beam chamber at the downstream (DS) end. (b) View of the septum magnet and the stored beam chamber at the upstream (US) end.

Table 1
Specifications of septum magnet for the APS-U project.

Parameter	Value
Magnet type	DC
Injected beam deflection angle	89 mrad
Field integral for injected beam, Int(By)	1.78 T m
Roll angle	93 mrad
Stored beam deflection angle	<100 μrad
Field uniformity ($\Delta B/B$), over ±2 mm around the injected beam	≤0.001
Insertion length	1.78 m
Aperture of stored beam chamber	8 mm × 6 mm
Septum thickness at downstream end	2 mm
Septum thickness at upstream end	4.56 mm
Septum thickness tolerance	0.050 mm
Beam separation at DS septum	5.5 mm

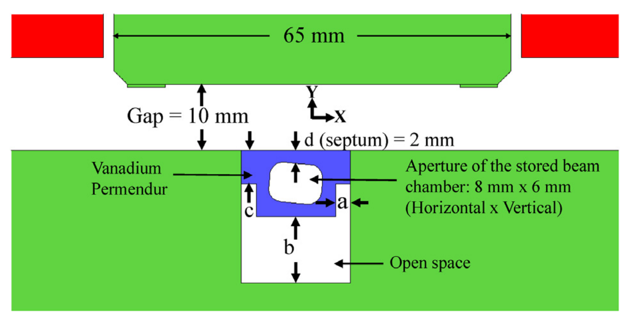

Fig. 2. An enlarged view of the DS end showing details of the stored beam chamber.

helps to cancel the negative B_y leakage field created at the downstream (DS) end of the septum. Furthermore, the concept helps to reduce the integrated skew quadrupole field, as well as the normal sextupole field, inside the stored beam chamber.

Using this approach, described in more detail below, the absolute value of the peak leakage field at the DS end, where the septum thickness is 2 mm, is reduced from 160 to 1 mT by applying three additional concepts to the design of the septum magnet: (1) cut the top pole shorter than the bottom pole at both the US and DS ends; (2) create an open space around the stored beam chamber; and (3) employ Vanadium Permendur, which saturates at a higher field than steel, as the material for the stored beam chamber. We report on the detailed design of the septum magnet, injected and stored beam trajectories, the field along the injected beam trajectory, and the leakage field inside the stored beam chamber that are achieved with this concept.

2. Magnetic design

An H-shaped dipole magnet structure is being developed for the septum magnet as shown in Fig. 1; the design is analyzed and optimized using Opera 3D [8]. To achieve the required integrated field, 11 039 Ampere-turns are needed, which are provided by a coil of 14 layers with 4 turns per layer wound around the top pole. The stored beam chamber is located in the bottom pole, with the US and DS centers of the stored beam chamber offset by 78.87 mm, resulting in a 47.5-mrad yaw angle of the stored beam chamber with respect to the magnet axis. The width of the top pole is 65 mm, the bottom pole is 60 mm thick, and the yoke back leg thickness is 40 mm. As seen in Fig. 2, the gap between the top and bottom poles is 10 mm. Also shown in Fig. 2 is the air gap around the stored beam chamber to reduce the leakage field in the stored beam chamber, and the Vanadium Permendur used as the material for the stored beam chamber due to its higher magnetic permeability. The spaces indicated as “*a*” and “*b*” are optimized to minimize the leakage field inside the stored beam chamber. Dimension “*c*”, is the height of the “wings” of the stored beam chamber, is tapered up on the right and tapered down on the left from DS to US in order to minimize the

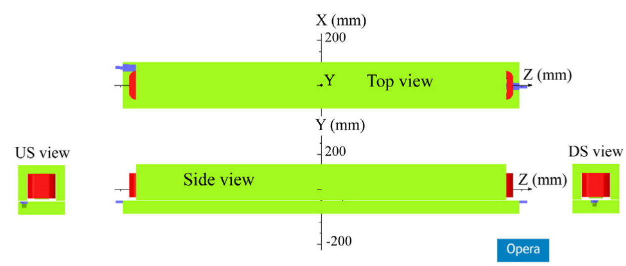

Fig. 3. Different views of the septum magnet and the magnet coordinates with the origin located at the center of the gap in X, Y, and Z.

integrated skew quadrupole in the stored beam chamber. The septum thickness, “*d*”, varies from 4.56 mm at the US end, to 2 mm at the DS end of the top pole, to just 1.4 mm at the end of the bottom pole due to the longer bottom pole and tilt (pitch) of the stored beam chamber. The top pole is 60 mm shorter in length at both ends as compared to the bottom pole, as indicated in Fig. 3, to reduce the flux density on the bottom pole, especially where the septum is only 2-mm thick.

Fig. 4 shows the magnetic field lines in a 2-D model of the magnet cross section at the DS and the US ends. A strong negative B_y field above the stored beam chamber creates a negative B_y leakage field inside the stored beam chamber at the DS end (Fig. 4(a)). By locating the US end of the stored beam chamber under the side leg as shown in Fig. 4(b), a positive B_y leakage field inside the stored beam chamber is created, compensating for the negative B_y field at the DS end. Therefore, in this design the coil width is deliberately small in order to allow placing the US end of the stored beam chamber under the side leg. The placement of the stored beam chamber and the width of magnet top pole were optimized to minimize the integrated B_y field seen by the stored beam. The detailed leakage field profiles in the stored beam chamber that result from implementing this concept are presented in the next section.