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SIMULATION STUDY WITH SEPTUM FIELD MAP FOR THE APS UPGRADE*

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Abstract

One of the biggest challenges faced by the Advanced Photon Source Upgrade injection system design is the septum magnet. Not only does the required leakage field inside the stored beam chamber need to be smaller than for the present ring, the magnet has to be slightly rotated about the z-axis to provide a gentle vertical bend that brings the injected beam trajectory close to $y = 0$ when it passes through the storage ring quadrupole magnets upstream of the straight section. For the convenience of magnet design, the magnet has also yaw and pitch angle about the stored beam coordinate system. This paper describes the coordinate system transformation necessary to properly model the magnet from field maps. The main field is checked by tracking the injected beam backwards, while leakage fields are included in dynamic aperture simulation and beam lifetime calculation. Simulation results show that the magnet design satisfies the physics requirements.

INTRODUCTION

On-axis swap-out vertical injection was chosen for the Advanced Photon Source Upgrade [1] (APS-U) to allow pushing the beam emittance to an extremely low value [2]. Detailed descriptions of the beam transport line design and the extraction/injection section optimization can be found elsewhere [3, 4].A schematic of injection section is shown in Fig. 1. The septum magnet needs to be slightly rotated about the stored beam z-axis (roll angle) to provide a gentle vertical bend that brings the injected beam trajectory close to $y = 0$ when it passes through the upstream storage ring quadrupole magnets Q1 and Q2 as shown in Fig. 1. To best utilize the uniform field region of the magnet, the magnet is also installed with a yaw angle respect to the stored beam z-axis. Finally, to reduce the leakage field inside the stored beam chamber, the septum sheet that separates the injected beam and the stored beam chamber has a gradually reduced thickness from ~4.4 mm at the upstream end to 2 mm at the downstream end, i.e. a pitch angle. Details on the magnet design can be found in [5, 6].

To verify the magnet design, both the injected beam trajectory and the impact of leakage field to the stored beam dynamics are simulated using the field map calculated from the magnet design model. Due to the complexity of magnet geometry (three rotation angles), a careful coordinate system transformation is required. This paper describes the way to obtain the transformation matrix, then gives simulation results for both the injected and stored beam. Simulation results show that the magnet design satisfies the physics requirements.

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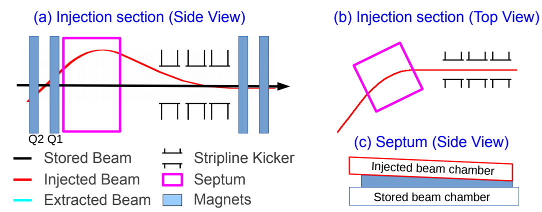

Figure 1: Schematic drawing of injection region and septum placement. (a) The septum has a roll angle to provide a gentle vertical bend; (b) The septum has a yaw angle; (c) The septum has a pitch angle to reduce the leakage field.

COORDINATE SYSTEM TRANSFORMATION

The septum magnet is designed using Opera-3D [7]. The coordinate system used in the design is fixed to the magnet and is referred as local coordinate system (X,Y,Z) in this paper. To simulate the leakage field, the field map needs to be transformed to the stored beam coordinate system, which is referred to as the global coordinate system (x,y,z) in this paper. To calculate the transformation matrix (also to check the magnet design), we use points on the upstream and downstream edge of stored beam chamber as fiducial points. Their global coordinates (x,y,z) are known from the design requirement, while their local coordinates (X,Y,Z) are given from Opera-3D. The fiducial marks are selected so that the x, y, and z-axis can be easily determined, as shown in Fig. 2. One can see that to determine the transformation matrix, a minimum of four fiducial markers is required. We used eight points to obtain some redundancy. As one can see from the same figure, one erroneous data point was found. The

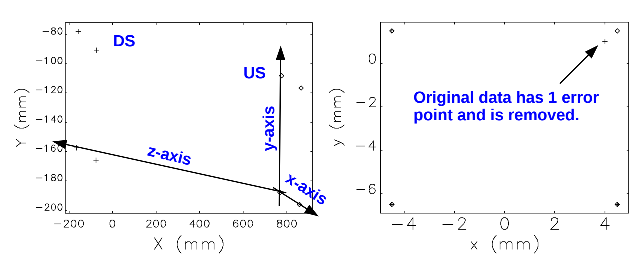

Figure 2: Coordinates of fiducial markers on the stored beam chamber edge: left - local coordinate system; right: global coordinate system (an error in one data point was found).

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transformation between (X,Y,Z) and (x,y,z) can be written as:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} \qquad (1)$$

where $R = \Theta\Phi\Psi$, with:

$$\Theta = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix},$$

$$\Phi = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix},$$

$$\Psi = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

where θ, ϕ, and ψ are yaw, pitch and roll angle respectively as defined in `elegant` [8], and x_0, y_0 and z_0 is the shift of septum magnet with respect to the global coordinate system origin. (Note: the rotation angles are non-commutative, so if one uses different conventions for the definition of the three rotation angles, results will be different.)

An example of fiducial markers setup is shown in Fig. 3, there are eight points with local coordinates (X,Y,Z), namely, 1: $(-0.15, 0.2, -0.8)$; 2: $(-0.15, 0.2, 0.8)$; 3: $(0.15, 0.2, 0.8)$; 4: $(0.15, 0.2, -0.8)$; 5: $(-0.2, 0.15, -0.8)$; 6: $(-0.2, -0.15, -0.8)$; 7: $(0.2, 0.15, 0.8)$; 8: $(0.2, -0.15, 0.8)$ on the machined surface of septum magnet. Using the transform matrix R from magnet design model (checked with simulation), their global coordinates (x,y,z) are (only 4 of them are listed): 1: (-0.242448, 0.190862,-1.790838); 2: (-0.166612,0.195429,-0.192643); 3: (0.131765,0.223149,-0.206880); 4: (0.055929,0.218582,-1.805075). The yaw angle for projection line of 1→2 and projection line of 4→3 to z-axis is: 47.415-mrad; The pitch angle for line 1→2 and line 4→3 to their projection line is: 2.854-mrad; The roll angle between line 1→4 and line 2→3 to x-axis is: 92.532 mrad.

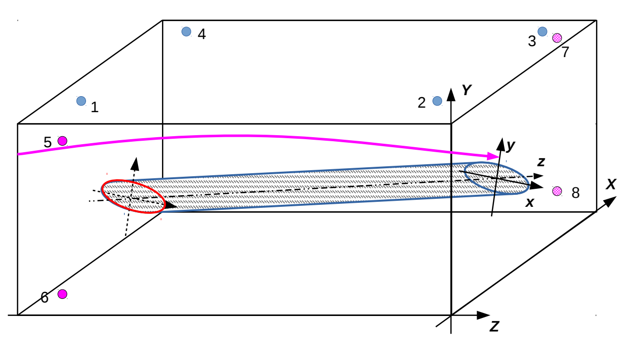

Figure 3: Schematic diagram of septum magnet geometry and eight fiducial markers. Only the stored beam chamber is illustrated. The injected beam chamber will be a similar box as the magnet itself.

Reasons for not using the same fiducial markers as used for calculating the transformation matrix are: first the stored beam chamber edge is not visible after the septum is built. Second the stored beam chamber may have manufacturing errors, for example if the stored beam chamber has an error on roll angle; the leakage field is small, so the impact of such a roll on the stored beam is negligible; however, if we correct the roll, the vertical bend to injected beam will be changed significantly; thus in practice the septum should be aligned with respect to the designed injected beam trajectory not the stored beam chamber.

INJECTED BEAM TRAJECTORY

To check if the magnet design satisfies the physics requirements, we tracked the injected beam back through the designed magnet field map [9] using `elegant`'s `FTABLE` [10] element. The steps for this back-tracking need careful attention:

- Transform particle coordinates to the septum local coordinates system, i.e. $[X, Y, Z]^T = R^{-1}[x - x0, y - y0, z - z0]^T$, see Equ.1, and $[p_X, p_Y, p_Z]^T = R^{-1}[p_x, p_y, p_z]^T$.
- Flips the coordinate frame, i.e. $Z' = -\vec{Z}$ and $Y' = -\vec{Y}$, then $X' = X$ $p_{X'} = p_X$, $B_{X'} = B_X$; $Y' = -Y$, $p_{Y'} = p_Y$, $B_{Y'} = B_Y$; and $Z' = -Z$, $p_{Z'} = p_Z$, $B_{Z'} = B_Z$;
- Change particle's sign! This is important since the convention for a dipole magnet is clockwise bending. When you change tracking direction, it means you are using a negative bend or tracking a positron instead of an electron.

Figure 4 shows the injected beam trajectory from a hard edge model and using the field map. Not surprisingly, the injected beam trajectory is changed. The total deflecting angle and separation distance were checked and satisfy the physics requirements, but the upstream injected beam transport line need to be updated as described in [4].

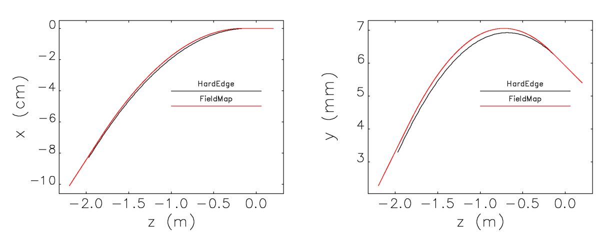

Figure 4: Calculated injected beam orbit from hard edge model (black), and designed septum magnetic field map (red).

SEPTUM LEAKAGE FIELD

The septum leakage field map was calculated from magnet design [9]. It was given in the septum (local) coordinate system originally, and then transformed to a field map in the stored (global) coordinate system. Using it as `FTABLE` [10]

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input, the kickmap [11] of the leakage field can be calculated and used for subsequent tracking simulations. The leakage field has to be corrected using nearby magnets, using the required correction strengths are listed in Table1; these are well within the magnet adjustment range [12]. For example, the required Q1 adjustment is about 0.6% of its nominal value. Figure 5 shows closed orbit variation from septum leakage field before and after local correction. The beta beatings are reduced from peak-to-peak values of 4.93% (H) and 4.25% (V) to 1.83% (H) and 2.24% (V); rms values of 1.68% (H) and 1.3% (V) to 0.61% (H) and 0.76% (V).

Table 1: Required corrector strength for calculated septum leakage field

Corrector Name	Strength	Units	Note
S39B:FH1	-25.3	μrad	h-corr
S39B:FV1	26.4	μrad	v-corr
S40A:FH1	14.2	μrad	h-corr
S40B:FV1	2.6	μrad	v-corr
S39B:FS1	0.0041	Tm	skew-Quad
S39B:Q1	0.0225	Tm	normal-Quad

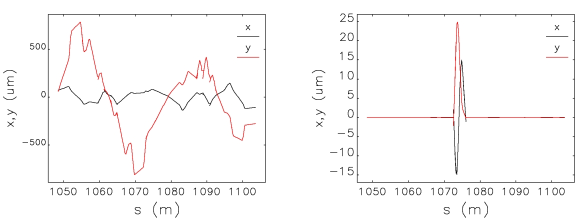

Figure 5: Closed orbit without (left) and with (right) septum leakage field correction.

Using Pelegant [13], the machine performance was checked with the septum leakage field plus local corrections together with other machine errors (100 random seeds [14, 15]) used for the machine robustness checkout. Figure 6 shows the simulated dynamic apertures (DA) and Fig. 7 shows the cumulative Touschek lifetime distributions for machine with and without septum leakage field. To understand how much leakage field can be tolerated, an intentionally doubled leakage field strength was also simulated and results are shown in the same plots for comparison. While the beam lifetime is generally not impacted by the leakage field, the DA is reduced when particles has both large x and y amplitude errors; the reduction becomes more obvious when the leakage field strength is doubled. After some investigation, we found the source is the irregular skew term from the rotated septum magnet.

SUMMARY

The septum magnet has a complicated geometry configuration due to physics requirements (pitch and roll angle)

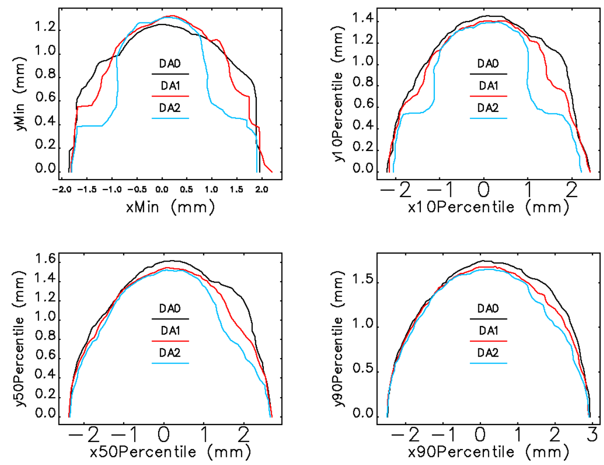

Figure 6: Simulated DA: DA0 - without septum leakage field; DA1 - with calculated septum leakage field; DA2 - Septum leakage field error doubled.

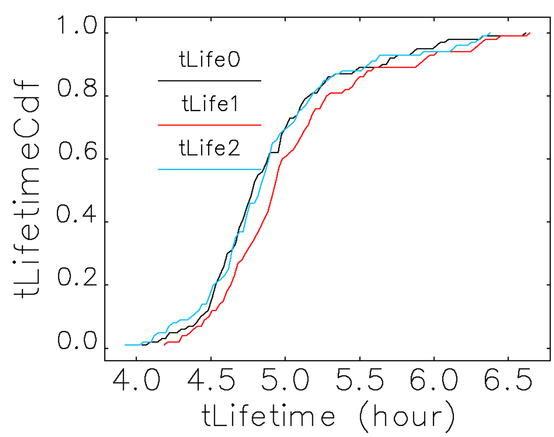

Figure 7: Simulated cumulative Touschek lifetime distribution: tLife0 - without septum leakage field; tLife1 - with calculated septum leakage field; tLife2 - Septum leakage field error doubled.

and mechanical design (yaw angle). The coordinate system transformation between septum local system and stored beam global system has been studied carefully and a fiducial configuration used for later magnet installation was illustrated. The quality of magnet design has been checked on both the injected beam trajectory and leakage field perturbations to the stored beam, and results show that it satisfies physics requirements.

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