DESIGN AND SIMULATION OF THIN EDDY-CURRENT SEPTUM FOR INJECTION OF THE TPS

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Abstract

The eddy current type septum is the development trend for next generation storage ring. To reduce the impact of leakage magnetic fields on the stored beam during injection and develop our technology for the Taiwan Photon Source (TPS), we propose a conceptual design of an eddy current type septum as a replacement.

Theoretical analyses and transient field simulations have been performed using OPERA software to evaluate magnetic behavior under pulsed excitation. Due to the thin septum structure, several optimization strategies have been applied—such as shielding with strongly paramagnetic materials and excitation with a full-cycle driving pulse—to ensure the leakage field remains below 0.1% of the main field.

This paper presents the design approach, analyzes the influence of eddy currents on field distribution, and investigates compensation methods to enhance magnetic field quality and injection performance.

INTRODUCTION

Modern light sources pursuit higher brilliance through diffraction-limited lattices, resulting in a significantly smaller dynamic aperture. This trend requires thinner septum magnets to accommodate the narrower injection acceptance. While direct-drive septa offer precise field control, their complex cooling systems lead to bulkier structures. In contrast, eddy-current septum magnets eliminate internal current loops, allowing for a much thinner and simpler design with easier thermal management. The thin profile and mechanical simplicity of eddy-current septa make them the preferred choice for next-generation storage rings.

For these reasons, although the TPS is currently using direct drive type septum [1], we are going to upgrade an eddy-current septum magnets for its storage ring injection system. This new magnet provides a reliable way to deflect the beam while fitting into tight spaces. More importantly, it meets the strict requirements for low leak-age fields in the storage ring.

As shown in Fig. 1, the bumper height is set at 16.2 mm. This value balances two needs: it must be high enough to avoid hitting the septum wall, yet low enough to reduce kicker power. Because the beams are so close, space for the vacuum chambers is very limited. After leaving 1 mm of clearance on each side for tuning, only 3.0 mm remains for the septum wall. This is why a thin eddy-current septum is essential. It allows both beams to stay in their own spaces without interference, even during early commissioning.

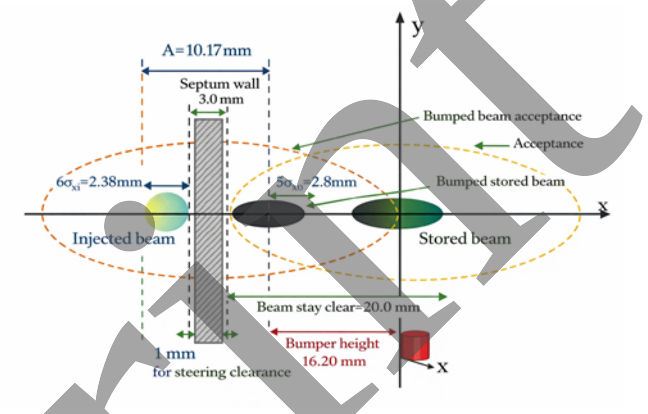

Figure 1: Phase space at the injection point.

Table 1 summarizes the design specifications for the septum magnet. The septum's thickness depends on the limited space at the injection point, where it must fit alongside the vacuum chambers. For the current direct-drive design, the system uses a 300 μs half-sine current pulse to drive the magnet. To achieve the required deflection, we use a 0.8-meter magnet with a core made of 0.3 mm CSC1300 silicon steel. Using thin laminations is important to stop eddy currents, which can cause heat and field distortion. The magnet provides a peak field of 0.694 T. To keep the stored beam stable, the leakage field must be less than 0.1% of the main field. This strict limit prevents unwanted kicks to the electrons, ensuring the storage ring stays stable during the injection process.

Table 1: Target Specifications of the Septum

Parameters	**Value**
Deflection Angle (mrad)	55.5
Core length (mm)	800
Peak field (T)	0.694
Magnet gap (mm)	15
Septum thickness (mm)[a]	<3
Nominal current (A)	8231
Pulse width (μs)	100~300
Pulse shape	Full sine or half sine
Leakage field (%)	<0.1

[a] At the beam injection point into the storage ring

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LEAKAGE FIELD PROBLEM

Leakage Field From a Septum

The main leakage field in stored beam tube can be expressed by Eq. (1) [2].

$$B(d,t) = B_0\left(\frac{\delta}{L_c}\right)\left(d\frac{\sqrt{\mu_0\sigma}}{\sqrt{\pi t^3}}\right)\exp\left(-\frac{d^2\mu_0\sigma}{4t}\right) \quad (1)$$

$$\delta = \sqrt{\frac{T}{\mu\sigma\pi}} \quad (2)$$

In this analytical framework, μ and σ denote the magnetic permeability and electrical conductivity of the material, respectively, while t represents the time variable. The skin depth, denoted by δ, is a critical parameter related to the penetration of the pulsed field into the conductor. Furthermore, d represents the spatial distance from the septum wall, T is the characteristic period of the pulse, $B0$ defines the primary excitation field, and Lc provides an approximation of the magnet gap height.

As characterized by Eq. (1), the leakage of the stored beam exhibits a significant exponential decay as the distance from the septum wall increases. This attenuation behavior underscores the importance of the septum's geometric and material properties in shielding the circulating beam.

Simulation Model

To verify the model and evaluate leakage fields, we conducted numerical simulations using the OPERA Transient EM solver. This allowed precise calculation of eddy current distributions. The magnet structure, as shown in Fig. 2, primarily consists of a silicon steel core, copper coils, a septum, and a mu-metal layer.

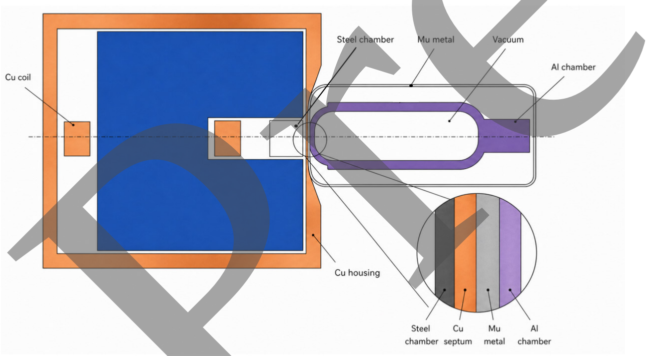

Figure 2: Schematics of the eddy-current septum magnet.

LEAKAGE FIELD SUPPRESSION

Septum Length and Housing

The shielding performance of a septum depends heavily on its geometry. As shown in Fig. 3, simply extending the septum length from 3 mm to 5 mm provides almost no benefit, as the magnetic flux can still bypass the edges of the structure. This indicates that increasing the magnetic path through length alone is insufficient for sup-pressing leakage. In contrast, the 'Full housing' design creates a complete conductive enclosure. This closed structure generates a stronger and more uniform counter-magnetic field.

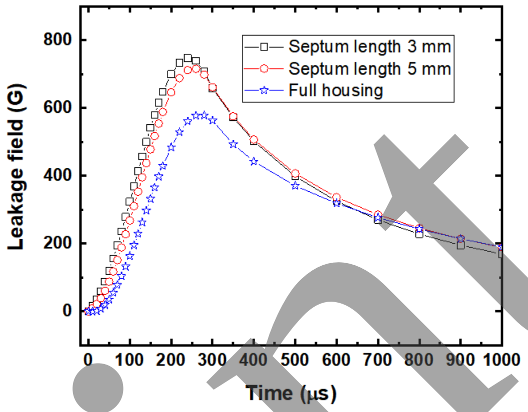

Figure 3: Leakage field with different septum length.

Septum Thickness

Though a thinner septum is desirable to accommodate tight spatial constraints, effective magnetic shielding is governed by the skin depth effect. Based on the formulation in Eq. (2), a 300 μs pulse width dictates a skin depth (δ) of approximately 1.6 mm for oxygen-free copper (σ = 5.8× 107 S / m, $\mu = 4\pi$ × 10−7 H / m). To sufficiently suppress transient leakage fields, the septum thickness is typically designed to be three to four times this value ($3\delta - 4\delta$), as illustrated in Fig. 4.

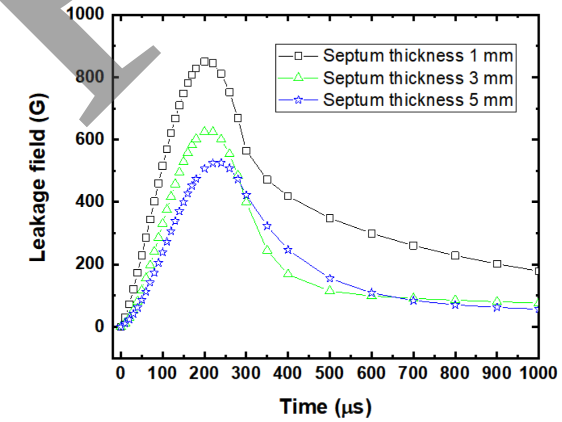

Figure 4: Leakage field with different septum thickness.

Mu-Metal Shielding

Adding a mu-metal layer is essential to support the copper septum's shielding [3, 4], although this method introduces structural complexity. While copper uses eddy currents to block rapid magnetic changes, it cannot stop all field diffusion. Mu-metal has high permeability and acts as a "magnetic shunt" to absorb this remaining leak-age. As shown in Fig. 5, we optimized the thickness ratio within a limited 3.0 mm space. The best result comes from 1.2 mm of copper combined with 0.2 mm of mu-metal. This proves that copper provides the main shielding for high-frequency pulses, while mu-metal handles the residual flux. If the mu-metal is too thin, it fails to redirect the field effectively, leading to higher leakage.

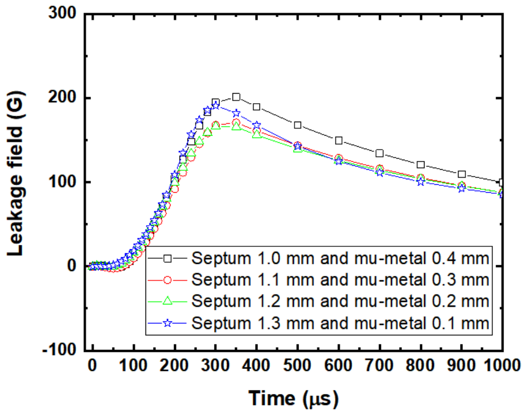

Figure 5: Leakage field with different thickness.

Pulse Width Effects

According to Eq. (2), a shorter current pulse is theoretically preferable for reducing the leakage field. This relationship is clearly demonstrated in Fig. 6, where a 150 μs pulse results in negligible leakage compared to the significantly higher peaks seen with a 300 μs pulse. However, in practice, shortening the pulse width greatly increases the maximum voltage across the magnet. This high voltage creates significant challenges for power supply design and can impair long-term operational reliability.

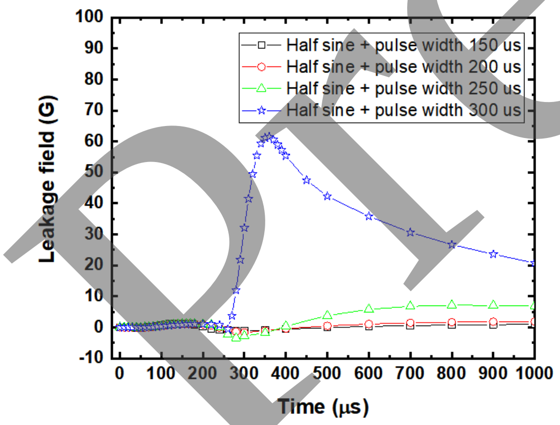

Figure 6: Leakage field with different pulse widths.

Pulse Waveform Effects

Another widely adopted approach in synchrotron light sources is modifying the drive current from a half-sine to a full-sine waveform [1, 5]. As previously observed, a half-sine pulse leads to a fast rise in leakage followed by a long, problematic exponential decay. In contrast, Figure 7 demonstrates that a full-sine pulse not only significantly reduces the peak leakage magnitude to below 2 G, but also facilitates a much faster decay. This waveform effectively 'cancels out' the residual magnetic flux, ensuring the leakage returns to near-zero levels shortly after the pulse. This characteristic is vital for maintaining the orbital stability of the stored beam during high-repetition injection.

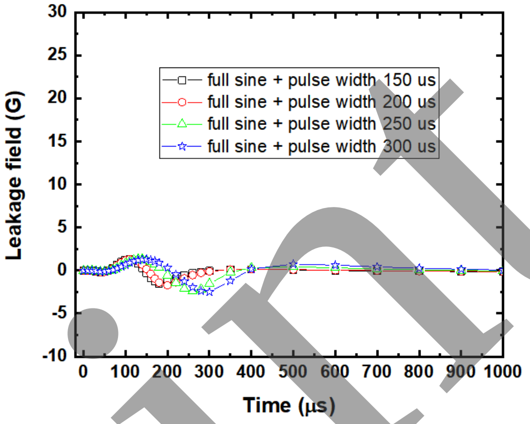

Figure 7: Leakage field with full sine pulse.

CONCLUSION

This study optimized the TPS injection septum by balancing shielding and space constraints. A hybrid design, using 1.2 mm copper and 0.2 mm mu-metal with a full housing, significantly reduced leakage. Additionally, shifting to a 150 μs full-sine pulse effectively eliminated the diffusion tail. These improvements ensure a stable magnetic environment and reliable beam injection for next-generation light sources.

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