

DESIGN AND SIMULATION OF THIN EDDY-CURRENT SEPTUM FOR INJECTION OF DIFFRACTION LIMITED STORAGE RING*

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Abstract

Ultra-low emittance in Diffraction Limited Storage Ring (DLSR) usually has small Dynamic Aperture (DA), which makes the traditional off-axis injection inadequate. Fast kickers together with thin septum magnets or direct current lambertsons could support on-axis injection for closely-spaced bunches with small DA. Thin eddy-current septum prototype had been designed for injection with laminated silicon steel sheets as magnet core. Theoretical analysis and transient simulation had been carried out within OPERA software. Due to the minimum thickness of the septa is only 1 mm, several optimization approaches had been applied, such as shielding with strongly paramagnetic material and exciting with full cycle driving pulse, to satisfy the requirement that the leakage field is less than 0.1% with respect to the main one.

INTRODUCTION

DLSR had been newly constructed or transformed all over the world for its higher brightness and better coherence [1, 2]. Under the funding of ministry of science and technology of China, National Synchrotron Radiation Laboratory (NSRL) cooperates with Shanghai Institute of Applied Physics, Chinese Academy of Sciences (SINAP) and Institute of High Energy Physics, Chinese Academy of Sciences (IHEP) to conduct the key theory and techniques research on DLSR. This article focuses on the research associating with injection technologies.

Small dynamic aperture means that the injection beam and storing beam should be close enough, which determines the thickness of the septum at injection point should be thin enough [3]. In this paper, thin eddy-current septum prototype, deflecting 50 mrad per unit with energy of 2 GeV, had been designed for DLSR injection.

Key parameters of the thin septum were selected or calculated in Table 1 to achieve a balance between physical requirements and engineering practices. Considering the complexity and power consumption, eddy-current type of septum was adopted as the prototype for the project. Besides, Special attention was paid to mechanical support and insulating materials.

MAGNET DESIGN AND OPTIMIZATION

Trajectory of Injection Beam

The foundational structure of eddy-current septum is mature. Difficulty points of this magnet lie on the effective inhibition of the leakage field to 0.1% at 2 mm away

from the septum under such a thin septa (1 mm @injection point). Filed transverse homogeneity on the main filed in the injection path (approximately 5600 Gauss) and peak value of the leakage filed in the storing beam path decayed over 1 ms time should meet the requirements.

Table 1: Parameters of the Thin Eddy-Current Septum

| Parameters | Value |
|--------------------------------------|------------------|
| Beam Energy (GeV) | 2 |
| Deflection Angle (mrad) | 50 |
| Core Length (mm) | 600 |
| Integral Field (T*m) | 0.32 |
| Bend Radius (m) | 12.0083 |
| Peak Field (Gauss) | 5560 |
| Gap Height (mm) | 12 |
| Gap Width (mm) | 40 |
| Good Field Region (mm ²) | 28×10 |
| Field Transverse Homogeneity | 1.5% |
| Mini. Septum Thickness (mm) | 1* |
| Peak Current (A) | 5322 |
| Leakage Field | 0.1 [#] |

* at injection point; optimized to 0.7 mm eventually

[#] 2 mm away from the septa

Figures 1 and 2 show the probable upstream and downstream of the injection beam trajectory respectively. At the upstream, plenty of distance about 5 mm for the injection beam into deflection field area is available and the maximum septa thickness is about 5 mm. More importantly, 8.6 mm exists between the storing beam and the outside surface of the septa.

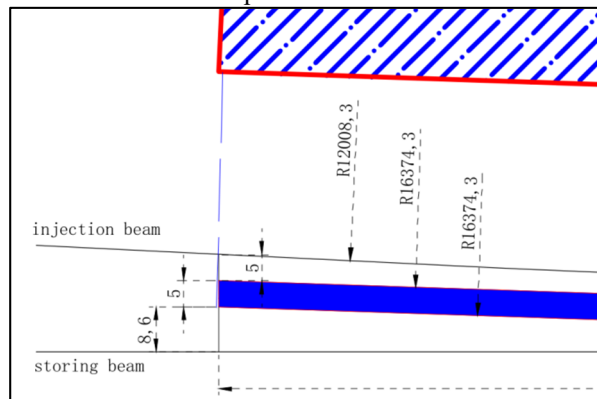


Figure 1: Upstream of the injection beam trajectory.

At the downstream, the injection beam is 1 mm away from the internal surface and the storing beam is 2 mm

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away from the outside surface of the septa within the minimum septa thickness of 0.7 mm (not include the shielding layer).

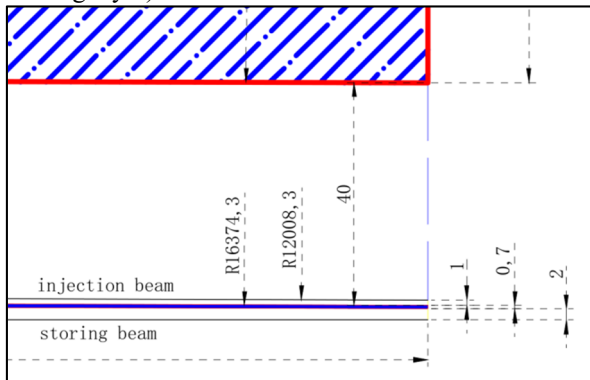


Figure 2: Downstream of the injection beam trajectory.

Magnet Design and Simulation

Generally, the thin eddy-current septum magnet is in C shape structure and the material of septa is oxygen-free high thermal conductivity copper [4]. Laminated steel sheets, which are 0.1 mm thick and double coated with insulating layers, combine as the magnetic core with gap 12 mm in height and 40 mm in width. As for the shielding materials, high permeability and saturation magnetic flux material 10JNHF600 was adopted for simulation analysis.

Figure 3 shows the 2-dimensional magnetic field distribution of the septum with OPERA. Within the scope of 28 mm in x direction and 10 mm in y direction, the main field transverse homogeneity are 0.99% and 0.90% respectively, both of which are better than the design requirement of 1.5%, as shown in Figs. 4 and 5.

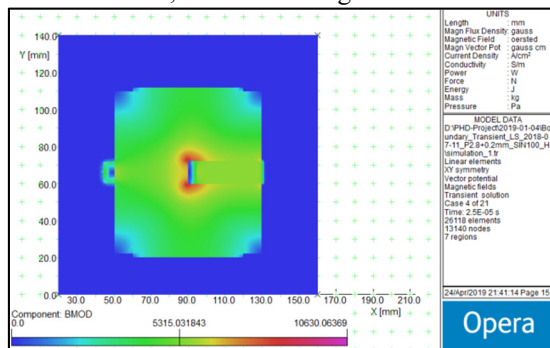


Figure 3: 2-dimensional magnetic field distribution.

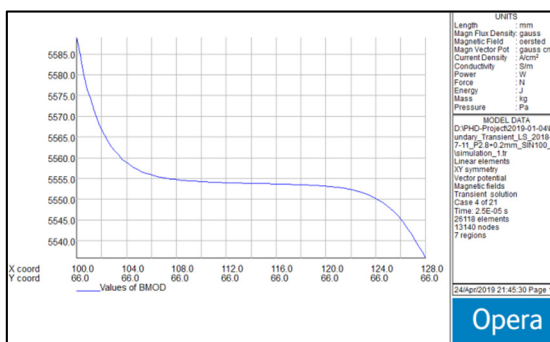


Figure 4: Main field transverse homogeneity in X direction.

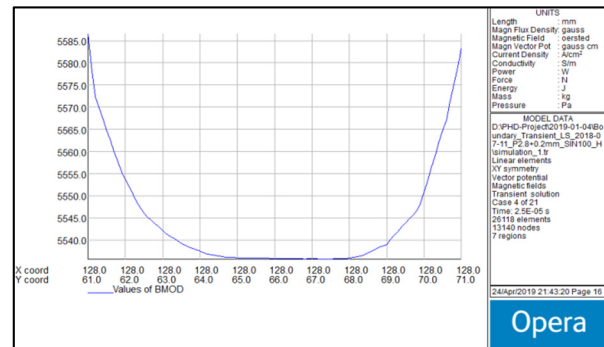


Figure 5: Main field transverse homogeneity in Y direction.

When exciting the coil with microsecond of rise and falling time, the septa could induct eddy-current immediately. Assuming that the thickness of the septa is linear change from 5 mm at upstream to 1 mm at downstream in order to simplify the issue. Five models had been proposed with the septa thickness of 1 mm, 2 mm, 3 mm, 4 mm and 5 mm respectively to analysis the leakage field issues. To reduce the influence caused by the eddy-current field on the next bunch of electron beam, the output time of the simulation results are from 0 to 1.0E-03 s in step of 1.0E-06 s in transient solution with nonlinear analysis tolerance of 1.0E-03. Peaks of leakage field over 1 ms and leakage field at the peak of main field are shown in Table 2.

Table 2: Leakage Field in Different Thickness of Septa

| Thickness | Peak of Leakage Field | Leakage Field@ Peak of Main Field |
|-----------|-----------------------|-----------------------------------|
| 1mm | 147.6Gauss | 27.8Gauss |
| 2mm | 92.8Gauss | 1.2Gauss |
| 3mm | 57.1Gauss | 0.1Gauss |
| 4mm | 37.0Gauss | 0.1Gauss |
| 5mm | 26.3Gauss | 0.1Gauss |

Although the leakage field within peak of main field is negligible, the peak of leakage field which decays over 1 ms is so large to tolerate and needs to be optimized.

Minimizing the Leakage Field

Under certain assumption, theoretical analysis for the leakage field in 3-dimansinal could be simplified as one dimensional problem with formula [5]:

$$B_m(d) = \frac{2\sqrt{2}T_0}{\sqrt{\pi}\epsilon\lambda_c d\sigma\mu_0} * B_0 \quad (1)$$

$B_m(d)$ is the leakage field which varies with thickness d and λ_c is the characteristic length of the exponential decay for $B_m(d)$.

Approaches to inhibit leakage field are very clear from formula (1): widening the exciting pulse, thickening the septa or using materials with higher electric conductivity. Unfortunately, these variables were all fixed or limited in the project. A half sine wave with a certain ratio of recoil

could do some help. Simulation results showed that combination of 100-percent positive and 70-percent negative sine wave could get the ideal solution as shown in Fig. 6. More importantly, deploying the thickness ratio between the high magnetic permeability material and oxygen-free copper could greatly reduce the leakage field. 1 mm of pure copper left 147.6 Gauss of leakage field while combination of 0.7 mm copper and 0.3 mm 10JNHF600 could just leave 9.5 Gauss only, as shown in Fig. 7.

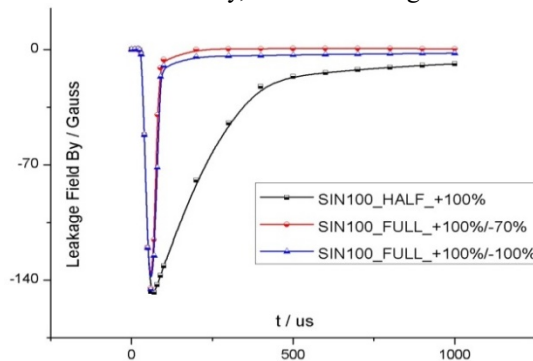


Figure 6: Exciting with a half sine wave and a certain ratio of recoil.

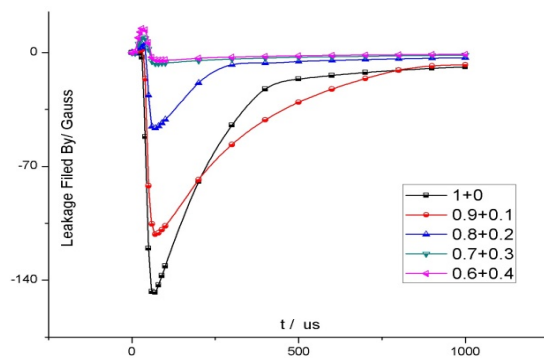


Figure 7: Deploying the thickness ratio between high permeability material and copper.

By deploying the thickness ratio, 0.3 mm high permeability layer of 10JNHF600 had been adopted by fixing it onto the surface of the thin septa. The final simulation results met the 0.1% requirement eventually as shown in Fig. 8. Besides, reasonable applying of double sine could also effectively reduce the integral leakage field.

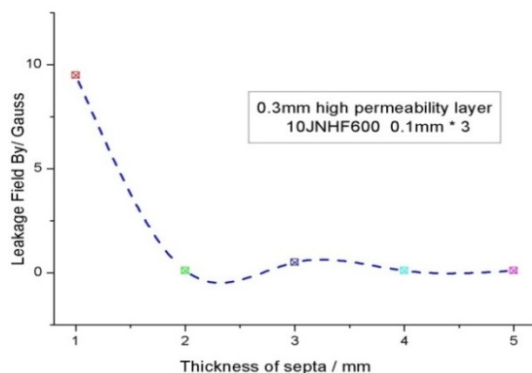


Figure 8: Final simulation on leakage field varying with thickness.

MECHANICAL AND PROCESS DESIGN

Power consumption, insulation in high vacuum, and precision-machined of the thin septa are the touch points. Laminated silicon steel and hollow coil could reduce core and coil loss respectively [6]. DuPont vespel had been chosen as insulation materials to deal with high vacuum and temperature environment. The general framework and coil support structure are as shown in Figs. 9 and 10.

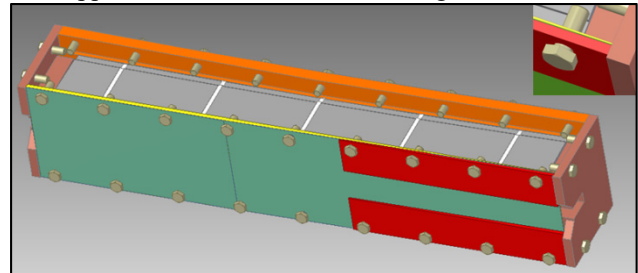


Figure 9: General framework of the thin septum.

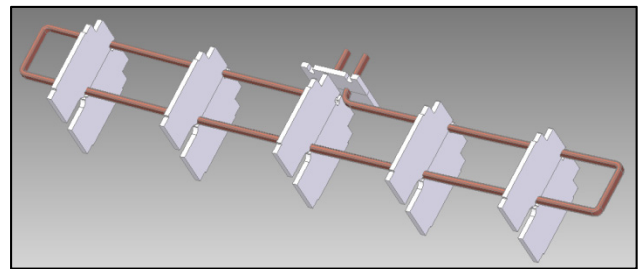


Figure 10: Coil support structure of the thin septum.

SUMMARY AND OUTLOOK

Thin eddy-current septum aiming at the on-axis injection for DLSR had been calculated, simulated and optimized at SSRF. Through multiple optimization approaches, integral leakage field could satisfy 0.1% theoretically. Challenges on mechanical and structure design need to be taken seriously. Magnetic measurement, including effective magnetic length, field transverse homogeneity needs to be conducted timely. The stability and reliability of the septum for beam experiments exists a lot of uncertainties, which needs further research and more engineering experience.

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