DIRECT-DRIVE AND EDDY-CURRENT SEPTUM MAGNETS*

S. H. Kim†, Advanced Photon Source, Argonne National Laboratory, Argonne, IL

Abstract

Two types of thin septum magnets, direct-drive and eddy-current, were compared mainly in 2-D magnetic aspects. For the direct-drive type, the leakage field depended on the finite permeability of the magnet core, and not on the septum thickness. It was suggested the leakage field be controlled by reducing the current in the septum. There were no significant differences between the two types in thermal problems caused by high current densities in the thin septa. The leakage fields with 2-mm septum thicknesses were calculated using OPERA-2d to compare the two types. For the eddy-current type, the leakage fields calculated using OPERA-2d were compared with the calculations from Halbach's model. The leakage fields for the eddy-current type decayed with long time constants.

1 INTRODUCTION

The essential requirements of a "thin septum" magnet are uniform high magnetic field up to the inner surface of the septum, an acceptable apparent thickness of the septum region, and a low magnetic field (called "leakage" field) in the "field-free region" outside the septum. High current density in a thin septum results in a major thermal problem. The septum magnetic field can be dc or pulsed, but a dc septum is possible only when the required gap field is relatively low or the septum is relatively thick. Otherwise, the magnet must be pulsed, and the duty factor of the septum must be adjusted to reduce the heating to an acceptable level. There are two types of pulsed septum magnets: direct-drive and eddy-current (also called transformer).

Typically, direct-drive pulsed septum magnets achieve required magnetic specifications with special designs for the cooling of the septum region [1,2]. An alternative design of the pulsed septum is the eddy-current type: the driving coil is wound around the flux-return core, and the field-free region must be shielded from the gap field by the eddy currents in the septum conductor. Since there is not much of a space restriction on the thickness of the coil, one can choose a single-turn or multi-turn coil. Magnetic field measurements for the eddy-current type have shown that the peak leakage fields appear after the driving current pulse [3,4]. Halbach has analyzed a model for the eddy-current type and has shown that the leakage field decays with a long time constant [5].

The purpose of this paper is to compare the two types of pulsed thin-septum magnets, mainly in basic 2-D magnetic aspects. Numerical data, if not otherwise specified, are results from the electromagnetic calculations using OPERA-2d [6]. A driving current pulse of a half sine wave with a pulse width of 0.4 ms was used for the calculations

2 DIRECT-DRIVE SEPTUM

A 2-D cross section for the upper half of a direct-drive septum magnet is shown schematically in Fig. 1 with coil C and septum conductor S as the driving current coils. When the field-decay time constant of the steel laminations for the magnet core was comparable to the pulse width of the driving current, it was assumed that the effects of the eddy-current in the core were negligible and that the flux distribution at the peak of the current pulse was not different from that of the static field. The circuital form of Ampere's law could then be applied to take a line integral of static magnetic field along a closed contour abdea (Fig. 1), and the leakage field integral outside the septum written as

$$\int_d^e B_s\, ds = \mu_o (I_c - I_s) - \int_a^d \frac{B_s}{\mu_r} ds, \qquad (1)$$

where B_s is the magnetic field component parallel to ds; I_c and $-I_s$ are the driving currents in C and S, respectively; μ_o and μ_r are the permeability for free space and relative permeability for the magnet core; and the line integral path of B_s/μ_r is inside the magnet core. Since the currents in C and S generally have the same magnitude, the leakage field is determined by the integral B_s/μ_r in the magnet core and has nothing to do with the septum thickness. The leakage field is always in the opposite direction of the main field in the gap.

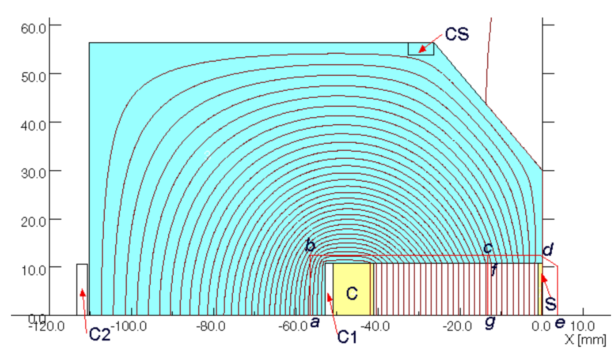

Figure 1: Cross section of the upper half of a direct-drive septum magnet with its magnetic flux distribution. C and S: main coil and septum conductor. C1 and C2: correction coils. CS: correction coil for S. Lines abcd and de denote the line integral paths ad and de in Eq. (1), and gf is the half-gap of the magnet.

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†shkim@aps.anl.gov

Relying on the term B_s/μ_r for reducing the stray field has a certain limit. Increasing the cross section of the magnet core will not reduce the leakage field to an arbitrarily small value. But the leakage field may be reduced by (a) using correction coils C1 and C2, or diverting $-\Delta I$ from the septum conductor to CS in Fig. 1 so that $\mu_o\Delta I$ cancels out the integral B_s/μ_r, and (b) modifying the septum conductor geometry to reduce the current density in the septum near the mid-plane. In the former case, the leakage field may be adjustable during operation or testing of the magnet; the latter case may depend on careful design of the septum conductor.

The leakage fields calculated with a few different configurations of septum geometries and currents are plotted in Fig. 2. Typical permeability values of "1010 steel" for the magnet core were used for the calculations. The leakage field was approximately -1 mT for the gap field of 0.75 T. By diverting 0.16% of the septum current to CS, the leakage field was nearly cancelled with the line integral term B_s/μ_r. Redistribution of a small fraction of the septum current or the "air" gap between the septum and the magnet core also changes the leakage. For a gap of 0.3 mm, which increases the effective current density by 2.7%, the leakage field was -8 mT. When the total current in the septum was unchanged, different values of the leakage fields near the septum converged to a single value, roughly -1 mT, at a larger distance from the septum, as expected from Eq. (1).

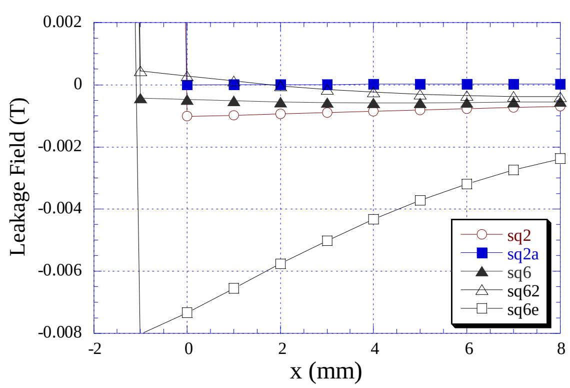

Figure 2: Leakage fields of direct-drive septum magnets. The outer surfaces of the septa were located at x = 0 for sq2 and sq2a, and x = -1.0 for sq6, sq62, and sq6e. The current I_s was varied: sq2 (I_s not changed); sq2a (0.16% of I_s diverted to CS); sq6 (0.27% of I_s to S_2, thicker part of S near the magnet pole); sq62 (0.76% of I_s to S_2); and sq6e (0.3-mm air gap between the septum and magnet core).

3 EDDY-CURRENT SEPTUM

The magnet core cross section of Fig. 1 was used for an eddy-current type using coils C1 and C2 for the driving current pulse. Since the current I_s in the septum conductor is zero in Eq. (1), a large amount of the flux must be shielded in the x = 0 plane. Figure 3 shows the flux distribution at the end of the pulse width (0.4 ms) when the gap field is nearly zero. The front of the magnet, except the septum area, was shielded with a high-conductive copper plate, and the septum was a Cu-Fe composite with a thickness of 2 mm.

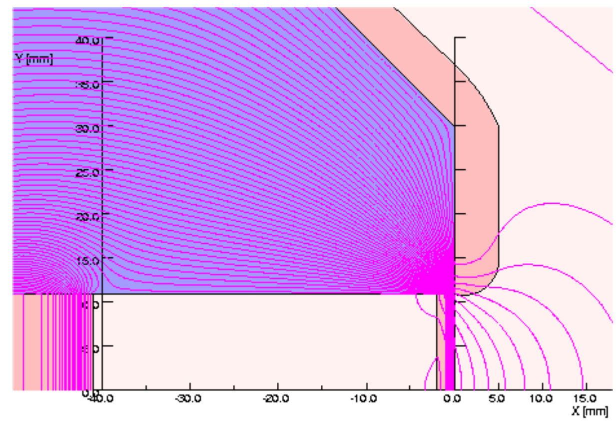

Figure 3: Magnetic flux distribution for an eddy-current Cu-Fe septum magnet at the end of the current pulse (0.4 ms) when the gap field is zero.

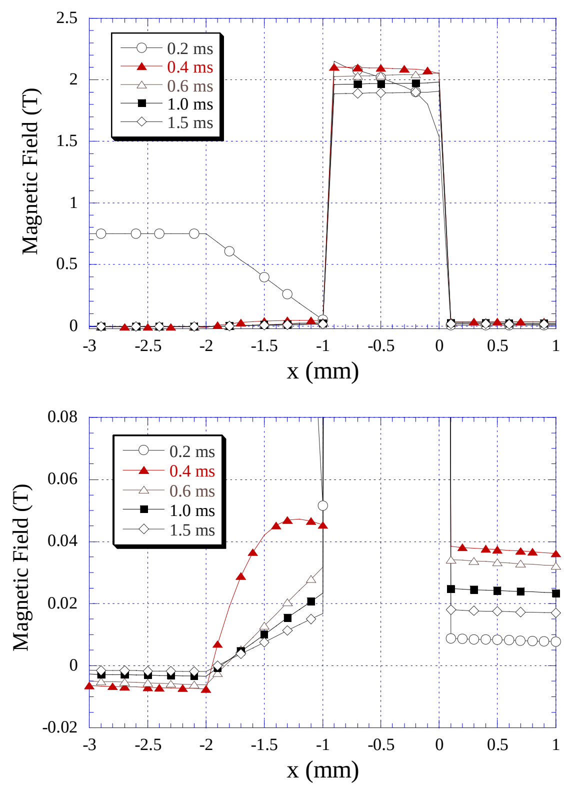

Figure 4: Magnetic fields near the 2-mm Cu-Fe septum ($-2.0 \le x \le 0$) of an eddy-current septum magnet were calculated during and after the current pulse. The fields in the steel septum are over 2 T (*top*), and the leakage fields are shown in expanded scale for the vertical axis (*bottom*).

Nonlinear calculations of the vertical fields near the mid-plane of the septum region during and after the current pulse are plotted in Fig. 4. In the steel part of the septum the relative permeability varied between 45~167 depending on the location and time. The time constants calculated for the copper and steel with μ_r = 100 were 0.064 ms and 0.64 ms, respectively. At the peak of the current pulse, (0.2 ms), when the field did not penetrate the steel part of the septum completely, the leakage field was relatively low. The eddy current in the septum at 0.2 ms was approximately 98% of the peak driving current when a return path for the eddy current was allowed for efficient shielding of the field. At the end of the current pulse, the leakage field reached a peak and began to decay. The field penetration across the steel was nearly complete at 0.4 ms, and from 0.6 ms it began to decay from the peak field over 2 T. The field decay slowed down as the permeability increased at lower field. After 1.5 ms, the leakage field remained at 0.017 T, and the magnetic field in the steel part of the septum only decayed less than 10% of its peak value.

The leakage fields as a function of times from the start of the current pulse are plotted in Fig. 5 for several cases of 2-mm septa. The data for tr0 were calculated from Halbach's model for Cu septum with a_1 = 10, where $a_1 = D/d_1$ is the ratio of chamber width to the septum thickness [7]. Calculations from the model also showed that when the time constant τ_1 for a copper septum was larger than the current pulse-width t_o, the peak of the leakage field appeared just after τ_1, and for τ_1 smaller than t_o, the peak appeared at (0.5~1)t_o. The data for tr2 and tr3 in Fig. 5 were calculated using OPERA-2d [6] for Cu and Cu-Fe septa with beam chamber, and those for tr4 and tr5 were without beam chamber.

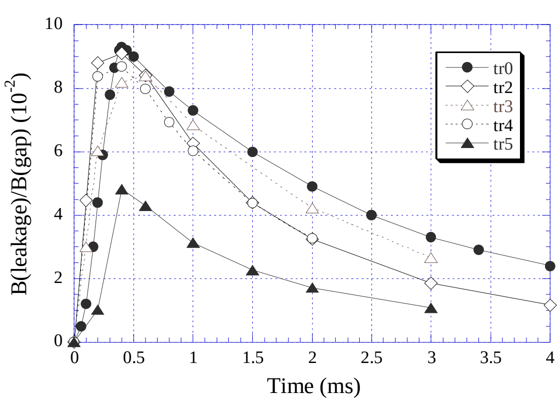

Figure 5: Leakage fields as a function of the time from the start of the current pulse were calculated for eddy-current septum magnets with $\omega_o\tau_1$ = 2 and 2-mm septa. tr0: Cu septum, from Halbach's model for a_1 =10. tr2: Cu septum for a_1 =10. tr3: Cu-Fe septum for μ_r = 20 and a_1 =20. tr4: Cu septum without beam chamber. tr5: nonlinear calculation for Cu-Fe septum without beam chamber.

The dominant term of the leakage field $B(t)$ calculated from Halbach's model [5] for $t_o \le t$ is given by

$$B(t) \approx \frac{2a_1^{1/2}}{s_o + 1/s_o} \frac{(1+e^{s_o\omega_o t_o})e^{-s_o\omega_o t}}{(1+2a_1)\sin(a_1^{-1/2})}, \qquad (2)$$

where $s_o = 1/(\omega_o \tau_1 a_1)$. Equation (2) roughly follows $1/(\omega_o\tau_1 a_1)\exp[-t/(\tau_1 a_1)]$ when s_o has a value of much less than 1. From an approximate calculation for a Cu-Fe septum, Halbach has concluded that the results for the pure Cu septum apply to the Cu-Fe septum when the iron has zero conductivity and a_1 is replaced by $(D + \mu_r d_2)/d_1$, where d_2 is the thickness for the iron. For D = 20 mm, μ_r = 20, and d_1 and d_2 = 1.0 mm (data tr2 and tr3 in Fig. 5), a_1 = 40. The time constant τ_1 = 0.26 ms for the 2-mm Cu is reduced to 0.065 ms for the 1-mm Cu. This makes $\tau_1 a_1$ unchanged from that of tr0 in Fig. 5, which may be interpreted as the magnetic flux in the steel sheet d_2 being evenly distributed in $\mu_r d_2$.

4 CONCLUSIONS

For the direct-drive septum magnet, the leakage field depends on the finite permeability of the magnet core, and may be reduced by adjusting the current (I_c–I_s) in Eq. (1). Reducing the thermal loading and avoiding cyclic fatigue in thin septa remain major problems for long-term stable operations. For the eddy-current type, the induced eddy current in the septum is 98% of the peak driving current, and a return-path of the eddy current should be allowed for efficient shielding of the leakage field. Therefore, mechanical and thermal problems due to the high current density in the thin septum should not be different between the two types. For the eddy-current type, the peak of the leakage field appears after the driving current pulse. Calculations of the leakage fields from Halbach's model and OPERA-2d agree fairly well for a ratio of the chamber dimension to the septum thickness of 10. Generally, the results from OPERA-2d are not very sensitive to the chamber dimensions.

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