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The APS Thin Pulsed Septum Magnets*

F. Lopez, F. Mills, S. Milton, S. Reeves, S. Sheynin, K. Thompson and L. Turner
Advanced Photon Source, Argonne National Laboratory
9700 South Cass Avenue, Argonne IL 60439, U.S.A.

Abstract

A thin (2-mm) eddy-current pulsed septum magnet was developed for use in the Advanced Photon Source (APS) machines. A number of different configurations of the magnet were assembled and tested in an effort to minimize the undesired leakage field in the stored-beam region. However, because of measured excessive leakage fields, an alternative direct-drive septum magnet was also constructed and tested. We present here the design specifications and acceptable performance criteria along with results of magnetic field measurements.

1. INTRODUCTION

There are six pulsed septum magnets interconnecting the four APS machines. Two of these have a septum width of 30 mm, while the other four are 2-mm in width. We will focus on the 2-mm thin septum magnets here.

Of primary importance in the specification of a septum magnet is the maximum tolerable field which appears in the "field free" region (the "leakage field"). Two distinct concerns must be considered when writing the performance specifications. The first is the field during passage of the bumped stored beam next to the septum wall during injection stacking. The other is the field seen on the closed orbit at any time during and after the primary magnet pulse. Table 1 lists the maximum allowable leakage fields for the septum magnets in the APS machines along with the major parameters required for the magnets.

Table 1: Septum Magnet Parameters

	PAR	IS Inj.	IS Ext.	SR
Thickness (mm)	2	2	2	2
Peak Field (T)	0.75	0.49	0.73	0.73
Pulse Width 1/2 Sine-Wave (μsec)	330	330	330	330
Peak Power (kW)	29	30	62	62
Avg. Power (kW)	0.574	0.02	0.042	0.042
Leakage Field[a] (G-m)	10	—	—	1
Leakage Field[b] (G-m)	30	30	300	1

a. Maximum leakage field allowed at the bumped beam location.
b. Maximum leakage field allowed on the closed orbit.

The driving factor for the tolerance to leakage fields is different in these machines. For the positron accumulator ring (PAR), the determining factor is injection/stacking efficiency. During the peak of the septum pulse the bumped beam can be so severely perturbed by the leakage field that the stacking rate drops to zero at high stored bunch currents. Furthermore, a delayed leakage field of sufficient strength at the closed orbit can have the same effect. Since the energy of this machine is relatively low (450 MeV), small fields can be disruptive. In the injector synchrotron (IS), the beam is injected on-axis and later extracted in one turn. In this case the stored beam is never close to the septum wall. Only leakage fields near the closed orbit are of concern, and then only at the injection energy (450 MeV). At the extraction energy (7 GeV), the beam is very rigid, and because of the single-turn extraction, only prompt fields could be a problem. The most demanding tolerances are those placed on the leakage fields in the storage ring (SR). In this machine our ultimate goal is to not perturb the stored beam with the leakage fields by any more than the equivalent of a 1% pulsed injection bump closure error. Achieving this level of performance opens up challenging prospects for future top-off operations.

The four thin septum magnets are as similar in design as possible with variations only to accommodate the specific needs of the different machines. The initial magnet design was to be a transformer-driven magnet [1]; it will be referred to here as the eddy-current septum magnet. A generic simplified cross-section of the magnet is shown in Figure 1. The major differences among the magnets are: (1) In the SR magnet, the transfer line and SR vacuum must be separated. (2) The IS injection magnet is curved. (3) The PAR magnet is used for injection as well as extraction and water cooling is needed due to its 60-Hz repetition rate.

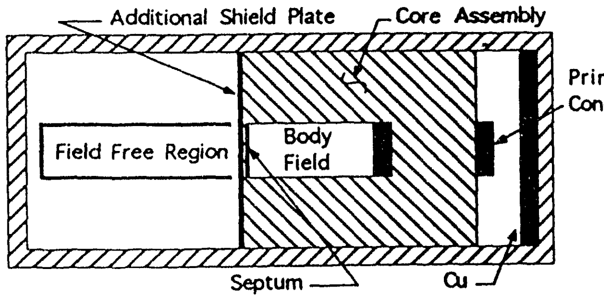

Figure 1: Eddy-current Septum Magnet Cross Section

The initial prototype of this magnet style was built and tested. The IS magnets have been installed. However, as will be explained, the design was found unacceptable for the PAR and storage ring. Another design, a direct-driven septum magnet, is now being considered.

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2. Eddy-Current Magnet Design and Measurements

The basic design of our eddy-current magnet consists of a core of C-shaped laminations with a single-turn backleg winding; the eddy-current shield is the septum itself. In our application the septum consists of 1-mm-thick pieces of Cu and S1010 steel explosively bonded together. The Cu is the primary eddy-current-induced conductor, while the steel is there to attenuate the main field to acceptable levels before it can leak into the field free region. The return path for the eddy currents is completed through interior regions of the vacuum containment enclosure which are clad with Cu.

The prototype magnet was measured. The maximum leakage field as a function of distance from the septum is shown in Figure 2 (No Shield). Peak leakage fields observed 6 mm from the septum were nearly 4% of the main body field or ≈ 300 G. This was well outside the tolerance for all four applications. The generic time structure of the leakage field is shown in Figure 3. It had both a prompt and delayed component. The delayed component exhibited a very long decay time. This same time structure was also seen in a thin prototype eddy-current septum magnet modeled and constructed at ESRF [2].

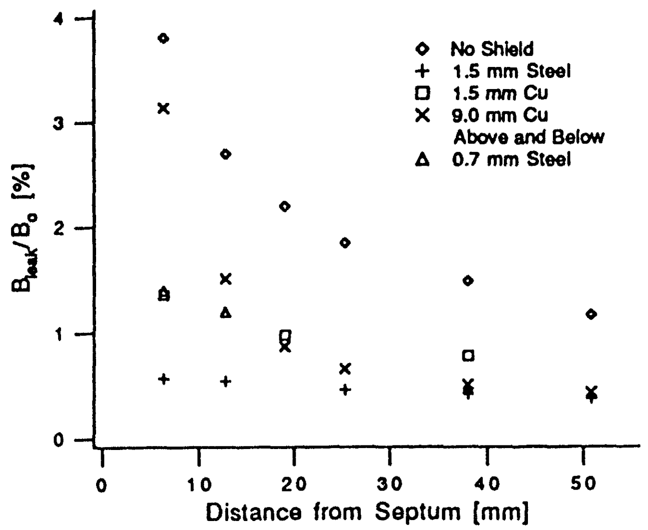

Figure 2: Measurement of the Eddy-current Magnet

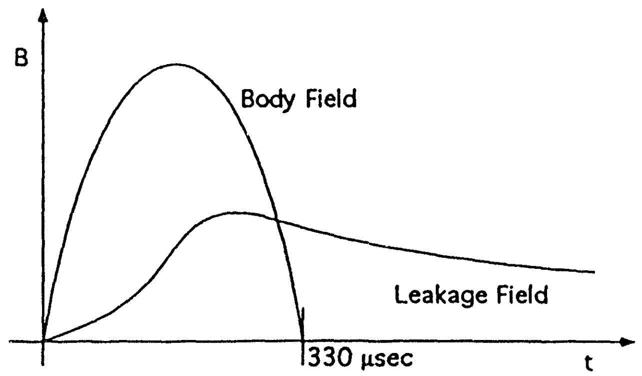

Figure 3: Generic Time Structure of Fields (different vertical scales used for clarity)

Attempts were made to reduce the leakage field to tolerable levels. The first thing tried was to install a 1.5-mm-thick C-shaped low carbon steel magnetic shield forced up against the septum face. This had no positive effect in reducing the leakage field. Cu plates used for the top and bottom of the vacuum enclosure were tried as well as Cu plates placed on the front face of the magnet above and below the septum, but this too did not improve performance dramatically. The third alternative was to increase the thickness of the septum wall by placing a secondary eddy current shield across the entire face of the magnet as shown in Figure 1. The resulting reduced leakage fields with the additional eddy-current shield plates in place are also shown in Figure 2 for comparison. Clearly, the additional steel helped matters greatly. Unfortunately, this was not enough to meet the SR specification; it also increased the septum thickness to an intolerable size for both the PAR and SR.

Because of installation schedule time constraints it was decided to proceed with the construction of the IS septum magnets as designed but with an additional 1.5 mm of steel on the face of the injection magnet and 0.7 mm of steel on the face of the extraction magnet. Due to the simple injection and extraction methods used for the IS this additional material does not significantly decrease the machine aperture.

As a temporary fix for the PAR magnet we placed a 0.7-mm-thick steel shield on the face of the magnet and also installed it. Measurements of the leakage field of this magnet are comparable to those of the IS extraction septum magnet. However, even the 0.7-mm-thick steel shield shows signs of saturating and allows unacceptable leakage fields (Figure 4).

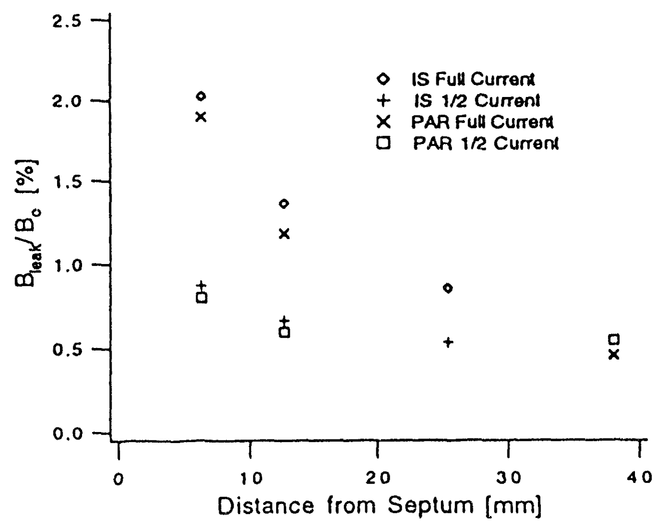

Figure 4: Eddy-current magnet with 0.7 mm steel face shield. Measurements at two different currents.

3. Cu/Steel Interface

Halbach [3] has analyzed a model for the eddy-current septum magnet driven with a 1/2 sine-wave uniform magnetic field. Calculations with the APS magnet parameters show a tangential field in the Cu at the Cu/Fe interface of ≈ 90 G. Since iron saturates at fields of roughly 2T, this implies a relative permeability in the Fe of ≈ 200. The steel is thus highly saturated and loses its capacity to prevent field from leaking into the field free region. In order to prevent saturation, a septum thickness of at least 3 mm would have to be used with 90% of the thickness being Cu. Even with such a septum the leakage field would still be on the order of ≈ 6 G. These results were confirmed by computer simulation.

In our particular prototype, the problem of the steel saturating was compounded by the use of the explosion-bonded Cu/steel composite material. The explosion bonded interface is wavy with peak-to-peak variations on the order of 0.5 mm. This does not allow for very accurate control of the material thickness ratio.

Another surprising result of Halbach's calculation was a decay time of the eddy currents on the order of 100 msec. Because of this, cumulative effects of the pulses must be considered for repetition rates of greater than a few Hz. If sufficient time is not allowed for the field within the iron to decay these fields will continue to increase until the iron reaches saturation. For such a magnet, a reset pulse is crucial to prevent saturation due to this long time constant.

4. Direct-Driven Magnet Design and Measurements

It became clear that the eddy-current magnet might not meet our design specifications; thus we decided to pursue in parallel the building of a more conventional direct-drive septum magnet. In this style of magnet, amp-turn loss in the core is the primary contributor to the leakage field. Without magnetic shielding these are on the order of 0.1% -> 0.4% of the body field. Furthermore, the spacial characteristics of the leakage field are also different. Whereas the leakage fields from the eddy-current magnet emanate tangentially from the septum itself, those of the direct-drive magnet originate primarily from the core and are thus much easier to exclude from entering the field-free region.

Figure 5 shows a cross-section of the APS direct-drive septum magnet. The septum width is 2.3 mm at its minimum. The leakage fields are prevented from entering the field-free region by a low carbon steel shield. This shield also serves as the vacuum vessel for the stored beam. It will be Ni-plated on the inside to reduce vacuum degassing of the steel. Our design also completely removes the magnet core laminations from the vacuum by inserting a thin Inconel vacuum chamber into the main field region. This greatly improves vacuum performance and also eases future maintenance on the magnet. At our chosen pulse frequency, calculations and simulations show that the eddy currents induced in this chamber do not significantly distort the magnet field quality of the body field during the time of the bunch passage when dB/dt is small.

As a further enhancement to the performance of the magnet, we are also pursuing the addition of a backleg winding which would compensate for amp-turn losses in the core and thus further reduce the leakage field.

A simple 1-m-long prototype direct-drive septum magnet was built with a minimum septum thickness of 2.3 mm. The measured integrated leakage field was 0.5 G-m (0.007% of the peak body field) at 6 mm from the septum wall. This easily meets the design specifications set forth.

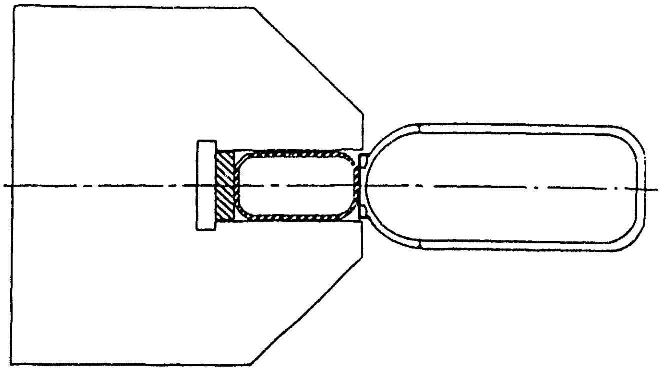

Figure 5: Direct-driven Septum Magnet Cross Section

5. Conclusions

The eddy-current septum magnet built for the APS has not as yet been able to deliver the level of performance which was demanded of it. The Fe in the septum was found to saturate. The time constant of the eddy currents are also much too long to run at moderate repetition rates such as 60 Hz for the PAR.

We have now built and tested both eddy-current and direct-driven septum magnets at the APS. The measured superior leakage-field properties of the direct-driven septum magnet seem to make it more suitable for our critical applications.

6. Acknowledgements

We express great thanks to K. Halbach for developing the theory which governs the behavior of eddy-current septum magnets. We also would like to thank E. Rodgers for many useful discussions regarding the engineering aspects of the direct-driven septum magnet.

7. References

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