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The APS Direct-Drive Pulsed Septum Magnets*

S. Sheynin, F. Lopez and S.V. Milton
Advanced Photon Source, Argonne National Laboratory
9700 South Cass Avenue, Argonne IL 60439, U.S.A.

Abstract

The Advanced Photon Source (APS) consists of four separate machines: linac, booster, positron accumulator ring (PAR) and storage ring (SR), plus three transfer lines interconnecting the machines. At least one thin, pulsed septum magnet is located at each splice joint [1]. The stray field tolerances for two of these septum magnets are very stringent. As an example, for clean operation during the proposed top-up mode in the storage ring, the stray fields from the septum magnet must not exceed 1 G-m. The septum wall thickness must also not exceed 2.4 mm. To meet these requirements, direct-drive septum magnets with magnetic shield pipe around the stored beam region were developed and built. These magnets have now been tested and installed, and are used in daily operation. We describe the magnet(s) design, the measurement results, the actual operation, and performance.

I. INTRODUCTION

There are six pulsed septum magnets interconnecting the four APS machines. Two of these, the PAR injection/extraction septum magnet and the SR injection septum magnet, have a septum thickness of 2.4 mm. The "field-free" region, i.e.,the area where the circulating beam traverses, has strict maximum field requirements of 10 G-m for the PAR and 1 G-m for the SR. Both are of the direct-drive configuration. In this paper, we are concerned with these two magnets only.

Table 1 lists the specification for the PAR and the SR septum magnets.

Table 1: Septum Magnet Parameters

	PAR	SR
Thickness (mm)	2.4	2.4
Peak Field (T)	0.75	0.73
Pulse Width 1/2 Sine-Wave (μsec)	250	500
Peak Current (kA)	13.2	13.6
Peak Power (kW)	58	143
Avg. Power (kW)	0.57	0.11
Leakage Field[a] (G-m)	10	1
Leakage Field[b] (G-m)	20	1
Repetition Rate	60	2

a. Maximum leakage field, defined as the field which makes it into the field-free region, allowed at the bumped beam location.
b. Maximum leakage field allowed on the closed orbit.

Although the two magnet designs, in concept, are similar to one another, in actuality they vary dramatically. The PAR magnet is used for both injection and extraction and must run continually at 60 Hz, its core is in vacuum, and water cooling is mandatory. On the other hand, the SR magnet is used only for injection. It runs at 2 Hz, its core is completely outside the vacuum, and it can be operated air-cooled.

II. DESIGN AND ANALYSIS

Electromagnetic simulations of the main field in the gap and the field-free region for the PAR and SR septum magnets were performed using the OPERA 2-D (PE2D) software [2]. Specifically, transient solutions for various geometries of laminated core, conductors, and the magnetic shields for the field free regions have been analyzed.

In pursuing the engineering design and fabrication of these magnets the following considerations and constraints were taken into account:

1. The steel core and conductors of the SR magnet must be kept out of the vacuum. This is possible because, unlike the PAR magnet, the SR septum magnet is used for injection only; therefore, there is adequate radial distance at the upstream end to allow a vacuum chamber in the gap region of the septum and utilize the magnetic shield in the field free region (i.e. closed orbit) as a separate vacuum channel. These two pipes converge to a common flange at each end of the magnet. A cross-section drawing of the magnet is shown in Figure 1.

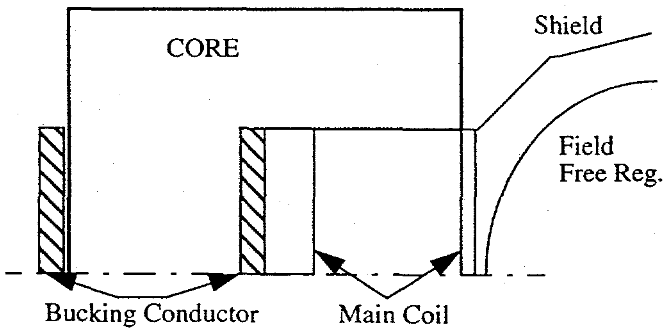

Figure 1: Bucking and main coils in the SR septum magnet

2. The SR septum magnet leakage field must be made < 1 G-m. Although our simulations indicated this to be possible with the basic design, as an added safety margin a backleg "bucking coil" was built into the magnet [3]. This additional winding produces a field in the gap which is in the same direction as the field produced by the main coil; however, outside the gap the field produced is opposite in sign to the leakage field from the main coil.
3. The PAR septum magnet is used for injection and extraction. There is not sufficient radial distance at either end to

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separate the vacuum chambers in the gap and in the field-free regions; therefore the entire PAR magnet is placed in a vacuum box. Also, because of the less stringent field-free region leakage field requirements (10 G-m) it does not require the additional bucking coil.

4. The PAR septum magnet is pulsed at a 60-Hz repetition rate; average power is 400 watts in the septum conductor and 170 watts in the backleg conductor. To provide adequate cooling, a special effort in design and fabrication of the septum conductor is required. Since the total septum thickness is only 2.4 mm and the vertical gap is 22 mm (limited by the peak field achievable with the peak current), there is no room to braze the cooling tubes to the septum conductor. Straight extension of the septum conductor outside the vertical gap will result in shunting current out of the gap which in turn will destroy the uniform field in the gap and significantly increase the field in the field free region. For this reason, the septum plate conductor was designed with slots and lugs, effectively open-circuiting this undesirable current path. This open circuit is ruined somewhat by the attachment of the cooling pipes; however, as was found in measurement, the resulting field quality was still within the specifications. The PAR septum plate conductor is shown in Fig. 2.

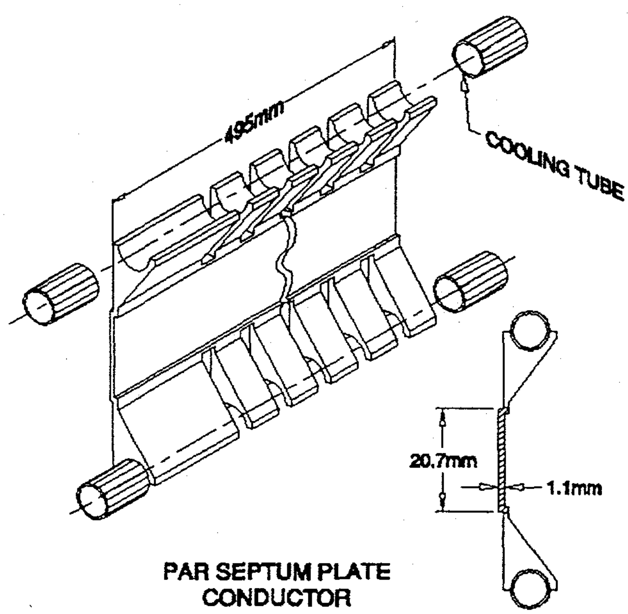

Figure 2

III. MEASUREMENTS AND PERFORMANCE

Measurements were made of the gap and field free regions under various operating conditions. The measurement setup consisted of both PC-board search coils and Hall probes mounted on computer-controlled translation stages. All data logging was automated making measurements very quick.

3.1 Storage Ring

Measurements of the SR septum magnet indicate very little leakage field. At peak current, the field in this region was < 0.5 G-m, well within the specifications without use of the supplemental bucking coil.

The field in the gap was also measured to be within tolerance. Figure 3 shows the body field and the field integral in the gap normalized to the peak pulse current. The average effective length over the current range of interest was measured to be 1.07 m. Some saturation is seen at the higher currents; however, the measured peak integrated field was 0.826 T-m. The is 8% higher than what is required for 7-GeV injection into the storage ring.

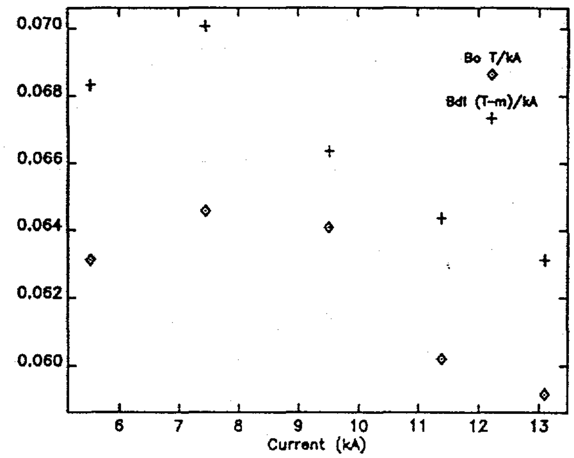

Figure 3: SR septum magnet main field measurements

The effectiveness of the air cooling was checked by operating the magnet at full field strength and repetition rate (2 Hz) for many hours. The maximum temperature change measured was 23°C.

This magnet is presently installed in the SR and its performance with beam has been measured. Preliminary measurements indicate that the leakage field at the position of the stored beam is indeed below 0.5 G-m. Our measurements indicate no influence of the septum field on the closed orbit of the beam.

3.2 PAR

The primary challenge of the PAR magnet is to build it durable enough to withstand the 60-Hz repetition rate at full field strength. An initial magnet was constructed and installed in the machine only to fail catastrophically after three weeks of operation. The failure was attributed to poor mechanical contact between the cooling tubes and the septum copper. Inadequate cooling was the result, and the septum copper literally blew itself apart.

The design was modified to provide much better mechanical/thermal contact between the stainless steel cooling tubes and the septum copper. First, however, we set about insuring that the mechanical fix did not spoil significantly the field properties.

A series of measurements were made on an early prototype of the PAR septum magnet. Cooling tubes, septum conductor, and shield pipe were assembled in various ways to encompass all cases of electrically insulated or shorted components in the circuit. The impact of each case on the field quality at full strength (13.2 kA, 0.75T) was measured. Table 2 contains the results of these measurements. The best compromise of effective cooling and ideal electrical insulation of the septum conductor is Case 3 where the shield pipe is electrically insulated from the septum conductor and the stainless steel cooling tubes are brazed directly to the septum conductor lugs. The measured leakage field was 4.4 G-m, below the 10 G-m design goal, and the field distortion was still tolerable.

Table 2: Prototype PAR Measurements

Case	Main Field Bdl [T-m/kA]	Main Field Bdl rel. diff%	dB/B [%]	Leakage [G-m]
1	0.0255503	0.00	1.7	3.8
2	0.0254943	-0.22	1.2	38
3	0.0257437	0.76	2.5	4.4
4	0.0256601	0.43	2.5	31
5	0.0253744	-0.89	1.4	48

Case descriptions:

1. The reference case. The shield pipe is electrically insulated from the septum. There are no cooling tubes.
2. The shield pipe is shorted to the septum. There are no cooling tubes.
3. The shield pipe is electrically insulated from the septum. The cooling tubes are brazed to the septum.
4. The shield pipe is shorted to the septum. The cooling pipes are brazed to the septum
5. The septum conductor is spot welded to the shield pipe in 8 places. Thin wall cooling tubes are brazed to the septum.

Construction of the final version of this magnet is nearly complete. However, as a result of the testing performed on the prototype, we fully expect this magnet to perform within the design performance specifications.

IV. CONCLUSIONS

We have built both the SR and PAR thin septum magnets. The SR magnet meets the design performance specifications, and, in fact, the leakage fields of the SR magnet are better by at least a factor of 2 than the design goals. The PAR magnet has yet to see extended running time. It should easily meet the field free region design goals; however, the real test will be when we run it at 60 Hz for long periods of time at full field strength.

V. ACKNOWLEDGMENTS

We express great thanks to K. Halbach for motivating our switch to the direct-drive septum magnet. We also would like to thank C. Doose and S. Kim of the Magnet Measurement Group for their commitment to making the magnetic measurements for us.

VI. REFERENCES

[1] F. Lopez, F. Mills, S. Milton, S. Reeves, S. Sheynin, K. Thompson and L. Turner, "The APS Thin Pulsed Septum Magnets," *Proc. of the 1994 EPAC*, 2406-2408 (1994)

[2] VECTOR FIELDS Ltd, Oxford, England, "Software for Electromagnetics," 1992.

[3] K. Halbach pointed out this possibility to us.