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# A Pulsed Septum Magnet for the APS\*

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## Abstract

A pulsed septum magnet has been designed and constructed for beam injection and extraction in the Advanced Photon Source at Argonne National Laboratory. The magnets will be similar for the Positron Accumulator Ring (PAR), the Injector Synchrotron, and the Storage Ring. The septum itself is 2 mm thick and consists of 1-mm-thick copper and S1010 steel explosion-bonded together. The PAR magnet is driven by a 1500-Hz, 12-kA half sine wave current pulse. The core is made of 0.36-mm-thick laminations of silicon steel. The nearly uniform interior field is 0.75 T and the exterior field is 0.0004 T at the undisturbed beam position and 0.0014 T at the bumped beam position. Testing of the magnet awaits the completion of the power supply.

## I. INTRODUCTION

Pulsed septum magnets are used for injection and extraction of the particle beam in circular accelerators. For the Advanced Photon Source (APS), now under construction at Argonne National Laboratory (ANL), these magnets will be used in the 450-MeV Positron Accumulator Ring (PAR), the 450-MeV to 7-GeV Injector Synchrotron, and the 7-GeV Storage Ring. Requirements for the septum magnets include good field homogeneity in the aperture, low stray field, a thin septum, and rapid excitation and discharge. Both transformer-driven and direct driven septum magnets were analyzed. Analysis showed that for a septum consisting of 1-mm-thick copper and S1010 steel strips explosively bonded together, the transformer-driven magnet has lower external fields and more uniform interior fields than the direct driven, if the septum current is constrained to all flow in the gap region.

The design of the septum magnet described here grows out of earlier septum magnets at ANL [1] and Fermilab [2]. Construction of the first magnet is complete, and testing awaits the completion of the power supply. Table 1 shows the parameters of the septum magnet.

## II. COIL AND CORE ASSEMBLY

The core assembly with septum and coil is shown in Figure 1, and the cross section of the septum magnet is shown in Figure 2. The single turn primary coil consists of a continuous length of OFE copper of rectangular cross section, 15.9 mm by 6.35 mm, with a 4.8-mm diameter hole for water cooling. The coil is formed to the final shape in a winding fixture. The lead ends are left long enough to extend beyond the vacuum enclosure, ensuring there are no braze joints within the vacuum system.

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Table 1  
Septum Magnet Parameters

Maximum Field	0.75 T
Magnet Length	400 mm
Aperture Width	70 mm
Aperture Height	20 mm
Septum Thickness	
copper	1.0 mm
steel	1.0 mm
Pulsed Current	
drive	5960 A
septum	5954 A
Pulse Shape	half sine wave
Pulse Frequency	1500 Hz

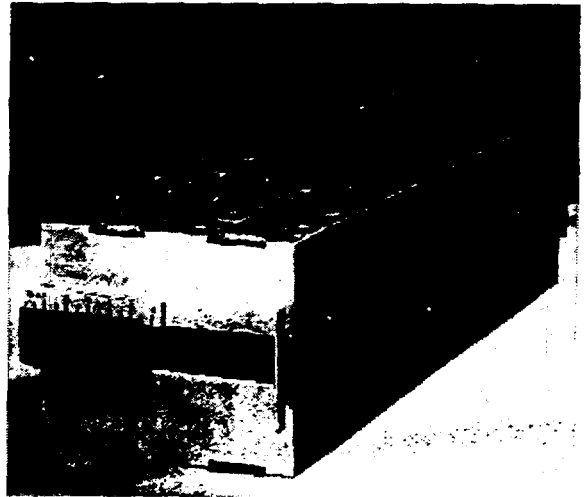


Figure 1. The core assembly with septum and coil, ready for installation in the vacuum enclosure.

Because the coil is inside the vacuum system, polyamide was chosen as insulating material for its good vacuum and dielectric properties. It has good mechanical properties both at operating temperatures and at 260 °C during vacuum bake-out. Insulating sleeve parts are machined from the polyamide and then cleaned by total immersion in an ultrasonic bath. The coil is then enclosed by the sleeve parts, and the laminations are stacked around this assembly in the core stacking fixture to form the core.

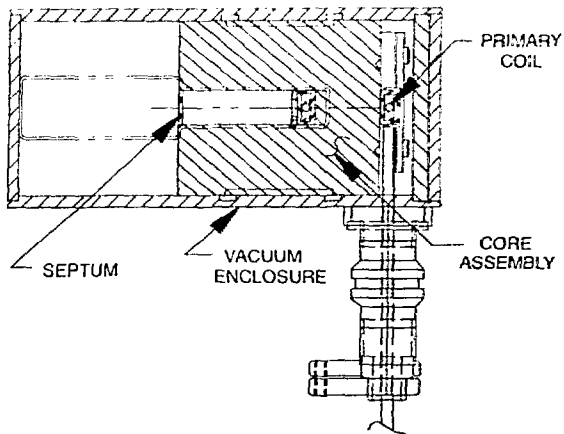


Figure 2. Cross Section of the Septum Magnet.

The core is made of 0.36-mm-thick laminations stamped from AISI type M-22 steel with an AISI C-5 surface insulation coating. The laminations are baked at 750 °C in a vacuum oven at a pressure of  $1 \times 10^{-4}$  Torr, a cleaning process for ultra-high vacuum systems. The laminations are stacked with 13-mm-thick low-carbon-steel end plates in the stacking fixture, which maintains the required surface tolerance. Two 6-mm-thick low-carbon-steel bars are welded to the lamination stack and end plates to constrain the core. The core assembly is structurally robust and can easily withstand the electromagnetic forces it encounters.

### III. SECONDARY TURN AND VACUUM ENCLOSURE

The septum is a crucial part in the design of the magnet. Because it is thin and subject to magnetic, thermal, and machining forces, the proper bonding between copper and steel is essential. Explosion bonding was selected over brazing or roll bonding because it can consistently achieve void-free, very strong mechanical bonds. After 3.2-mm-thick low carbon steel and C102 OFE copper are explosively bonded together, the septum is machined to its final thickness: 1 mm of copper and 1 mm of 1010 steel.

The weld between the septum and the core must carry the combined thermal and magnetic forces. Electron-beam welding was selected for this critical joint because of the dimensional precision that can be attained and because of the depth of penetration of the weld. The resulting welds at the transition between the laminations and the septum steel are very smooth and continuous. Examination of test samples showed that these joints were not contaminated by copper.

The completed core assembly is placed inside the vacuum enclosure, made of plates of the same bonded steel and copper as the septum. The secondary turn is made up of the copper panels that face the inside of the enclosure. The enclosure is welded, then cleaned by total immersion in an ultrasonic bath. The secondary turn is completed by welding the septum to the

copper inner face of the enclosure. After electrical checks are completed, the top of the enclosure is welded in place. Vacuum feedthroughs and flanges complete the assembly.

### IV. ELECTROMAGNETIC DESIGN

The electromagnetic design involved choosing between a directly driven or transformer-driven magnet, choosing the form of the septum, and considering the consequences of current above and below the level of the aperture. The electromagnetic design was carried out with the magnetostatic, steady-state AC, and transient solvers of the 2-D analysis code OPERA-2D (formerly PE2D) [3].

Both directly driven and transformer-driven septum magnets were considered. For the direct drive, the current in the septum of necessity is exactly that which is needed to produce the required field in the gap. For the transformer drive, the driven current determines the field in the gap, and the septum current is somewhat less, just enough to establish a zero current in the exterior region. The transformer-driven case was found to yield an exterior field about a factor of ten lower than the directly driven case, at both the bumped beam position and the undisturbed beam position as seen in Fig. 3.

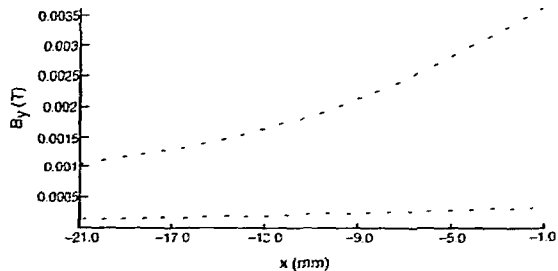


Figure 3. Flux density (T) as function of position (mm) outside the septum. Upper curve: with directly driven septum. Lower curve: with transformer-driven septum.

For the composite septum, the steel part of the septum contains the flux that penetrates the copper part. That effect was found to more than compensate for the fewer skin depths of copper with the composite septum.

It is necessary to locate the septum in slots in the yoke, in order to restrain it against magnetic forces. Consequently, there is some current flow above and below the 20-mm-thick region of the aperture and septum. Some earlier experiences [2] suggested that those currents could lower the homogeneity of the field in the aperture and increase the field leakage outside. But analysis of geometries with and without such currents showed effectively no differences. Uniformity of the field in the aperture is shown in Figure 4.

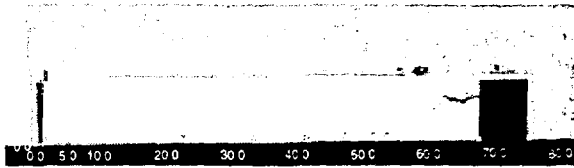


Figure 4. Flux density within the aperture. Contour spacing: 0.0002 T. Contours above 0.742 T and below 0.7406 T are not shown.

## V. SEPTUM POWER SUPPLY

The four single-turn transformer septum magnets for the PAR, the Injector Synchrotron, and the Storage Ring are powered by capacitor discharge circuits. These are designed to produce half-sine-wave pulses with a base width of 1/3 ms and peak currents repeatable within 0.05% and adjustable from 470 A to 4.7 kA. The capacitor discharge circuits are transformer coupled for impedance matching to the magnet. The peak currents of the transformer secondaries range from 11.4 kA to 16.888 kA. Figure 5 shows a diagram of the power supply. The switch S4 may either be gated or not, depending on the need to reset the magnet steel.

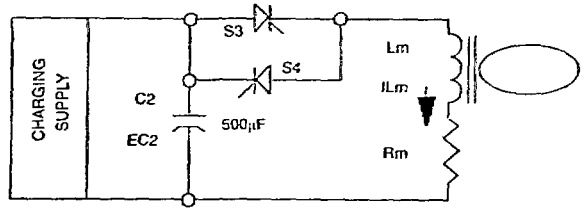


Figure 5. Diagram of the Septum Magnet Power Supply.

## VI. CONCLUSIONS

This design is found to satisfy the conditions required of a septum magnet, both mechanically and electromagnetically. Voltage and inductance testing has begun, and field properties will be measured when the power supply is available.

## VII. REFERENCES

- [1] M. Foss, K. Thompson, and W. Praeg, "A Transformer Septum Magnet," *IEEE Trans. Nucl. Sci.* NS-26, pp. 4024-4026 (1979).
- [2] J. A. Satti and S. D. Holmes, "A Pulsed Septum Magnet for the Fermilab Antiproton Source," *IEEE Trans. Nucl. Sci.* NS-32, pp. 3628-3630 (1985).
- [3] OPERA-2D (PE2D) is available from Vector Fields, Inc. Aurora, IL, USA.