EDGE-COOLED, HIGH-CURRENT SEPTUM MAGNET*

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Summary

The resonant extraction system of the Zero Gradient Synchrotron (ZGS) includes a thin septum magnet with a two-turn winding having a total thickness of 0.06 in. The gap height is two in and the length is 20 in. This magnet is excited with currents as high as 7000 A (current density of 130,000 A/in²) to produce a field of 3.5 kG across the gap. Simplicity in design has been used extensively in the building of the core and the winding, resulting in an operation life test of one year to date. This magnet is used in a pulsed mode with a rise time of less than 100 ms and pulses up to 0.8 s in length for slow spills. All portions of the design and fabrication are accomplished by taking advantage of commercially available materials and methods and no sophisticated machining practices were used in making this type of magnet. This paper describes the computer design, the construction practices, and the test data on pertinent parameters.

Conceptual Design

A thin septum (0.1 in or less) bending magnet with a central field of 3000 G over 3.5 in wide by two in high and 20 in long was needed for the proton beam extraction from the ZGS. The central field was to be uniform to 0.1% and the leakage field as small as possible. At first, a single-turn septum was considered consisting of a plain copper sheet 0.1 in wide of various heights. The magnetic field of various spaced cooling holes was calculated using the computer program TRIM. It soon became apparent that a field uniformity of 0.1% could not be obtained close to the septum for discrete cooling holes in the septum.

However, using two septum turns, each 0.04 in wide, yields a field uniformity of 0.1% right up to the septum coil. Cooling holes could be formed between the two turns by using non-metallic spacers 0.04 in thick.

Bonded Lamination

Initial considerations in making this thin septum magnet included a two-turn septum winding with internal cooling in the winding structure. This was attempted by taking a sheet of copper 0.021 in thick and laminating a 0.010-in thick ceramic wafer onto the copper sheet using epoxy as a bonding media. The ceramic was then to be slotted longitudinally to provide water passages over the entire length of the winding. The slots were to be 0.020 in wide and as deep as the thickness of the ceramic wafer. A second sheet of copper would then be bonded onto the other face of the ceramic, producing a sandwich 0.0520 in thick. Upon studying this approach and following a few tests, the following conclusion was evident:

To provide sufficient cooling for the septum winding, the interior of the sandwich would be subjected to pressures in excess of 100 psi. The containment of water pressures of this magnitude requires a substantial bond between the laminations. Considering the fact that the septum intercepts a portion of the accelerated beam, rapid deterioration of the epoxy bond would occur. Lack of a decent bond, with all of this internal pressure present, one can expect water leaks and distortion of the septum surface.

Fused Laminate

Investigations into the use of an inorganic bonding agent led to the use of kiln-fired porcelain. A strong bond was indeed possible with the porcelainizing method, but this approach also had its pitfalls. Difficulties using this technique were two-fold:

a. The high temperature (1600°F). required to fire the porcelain, annealed the copper to make it very soft and a slight force would cause distortion in the surfaces of the septum.

b. When subjecting the porcelainized finish to rapid temperature cycles similar to those occurring during each pulse cycle, the ceramic layer would develop a large number of minute cracks and finally flake away from the metal. This, of course, was due to the difference in the coefficient of expansion of the copper and of the ceramic.

Because of these detrimental physical conditions when using the sandwich laminate approach, the thought of using internal cooling was abandoned. Efforts were then directed to the use of edge cooling.

Commercially available cold rolled sheet copper (electrolytic tough pitch) Rockwell B39 Max, moderately hard, 0.027-in thick, ± 0.0016 in, 99.9% pure copper was used. This possesses good mechanical stability provided it is not annealed and a sandwich of two windings can be made with fair rigidity. The insulation placed between the two copper plates was "H" film. The polyimide possesses a good radiation resistance. Even if exposed to excessive radiation, and with the loss of some of its mechanical strength properties, it still maintains its electrical insulation qualities. Using edge cooling, the mechanical tensile strength properties are not too important since the insulation was used in a compression mode. As long as it does not disintegrate, it is still suitable as an insulator.

One can think of adhering the copper to the film with an epoxy because the strength is important only during the initial fabrication and operation of the magnet. As the magnet is used (pulsed) the windings are

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held together by the magnetic forces even if bonding has disappeared.

With this fact in mind, design efforts were directed toward building a two-turn, edge-cooled, thin septum magnet.

Design of Magnet Core

The thin septum magnet required a gap of approximately 2 in high by 4 in wide for a length of 20 in. Because of the low flux density of 3,500 G, a 1.25-in thick pole and yoke were sufficient. Hence, the outer dimensions of the magnet core are 4.5 in high by 5.25 in wide by 20 in long. Commercially available 0.014-in silicon steel transformer laminations were used to enable it to be pulsed in 100 ms. These laminations needed only slight modification. All other dimensions were suitable.

Following the modifications, the laminations were skewed onto four rods coated with a plasma spray ceramic insulation to make a stack 20 in long (Fig. 1).

No extra insulation was added to the surface of the laminations since they had the usual oxide coating used for transformer core application. However, to provide for a better stability to the core assembly, the entire outer surface was painted with a thin flowing epoxy which formed a very solid and firm core after curing at room temperature.

Coil Winding Fabrication

The windings were constructed of copper sheet material (0.027 in thick) cut into an "H" configuration with the horizontal part of the "H" forming the septum winding. The vertical portions of the "H" shape are bent at right angles to the plane of the paper and are used for power connections. The vertical legs were made slightly wider than half the septum portion to reduce the current density. These connections were made symmetrically above and below the magnet mid-plane to prevent a radial field component; thus, vertical displacement of the proton beam entering or leaving the magnet structure was avoided.

Coil Cooling

Water cooling tubes were soldered to the upper and lower edges of the horizontal part of the copper as shown in Fig. 2. The water tubes attached to the septum or front portion of the winding were made of 0.010-in thin walled 0.25-in OD stainless steel. Copper tubing was silver soldered at the ends of the stainless tubes to permit flexing and soldering the tube along the outside edge of the power connections. The stainless tubing was sweated to the copper winding using 50/50 soft solder (melting temperature ~ 125°F). The low temperature of this solder did not affect the hardness of the original copper sheet. Care was taken to make a fillet of about 0.125 in radius to fill the interstice between the round tube and the flat copper for maximum heat conduction.

The use of the thin wall stainless steel tube along the septum edge of the winding produces a small effect on the current distribution in the coil structure. The current in the copper sheet is large in comparison to that in the stainless tube because of the large difference in the resistance between the 0.027-in thick copper sheet and the 0.010-in wall of the stainless tube. These precautions of current distribution in the copper sheet were applied to both sides of the septum portion of the winding. Because the edge cooling tubes carried some current, the fringe field tolerance was relaxed to 1% of the central field at 1 in from the septum.

The winding at the back of the gap was constructed in the same laminated fashion but continuous 1/4-in copper tubing was used along the cooling edges. The copper sheet on both surfaces of this back winding was 0.05 in thick to reduce the current density and to give more mechanical stability to the whole coil assembly.

Insulation Techniques

For each portion of the windings, the two copper sheets (with cooling tubes) were sandwiched together with a 0.005-in "H" film (polyimide) in the center and then bonded together with epoxy. The uniformity of thickness and straightness of this laminate was assured with the use of heavy steel bars to clamp the winding during the curing period.
Following the lamination process, additional strips of "HI' film were cemented to the upper and lower edges of the windings to insulate them from the core iron. The end connections of these windings were bent to fit between the water-cooled ¼-in by 1-in copper bus. All of these copper ends were silver plated to afford maximum conductivity and they interleaved with one another to make a continuous two-turn winding.

The two-turn winding was bolted together with the bus and interleaved insulation as a complete unit that was slipped into the core.

Additional 5-mil polyimide insulation was bonded to the core structure at all areas where the coil came in contact with the iron core to prevent grounding to the iron. Once the coil was placed into the core, the insulation on the coil was free to slip on the insulating film on the core. These two layers of insulation provide the bearing surfaces that allow the movement that occurs while the septum magnet is pulsed. The longitudinal coil expansion during a pulse is about 0.05 in along the beam direction.

This movement is readily visible at the coil connection end of the coil assembly which is attached to the core with bridging stainless steel plates. The power end bridging plates are mounted securely to the coil as well as the iron. The coil connection end bridging plate is secured tightly at the coil but is fastened loosely through slotted holes to the iron. The slots permit longitudinal movement but maintain the alignment in the radial direction. See Figs. 8a and 8b.

**Septum Bracing**

The septum winding is further contained in the iron core with back insulated 1/16-in thick stainless steel retainers that are screw fastened to the upper and lower open ends of the yoke. It is important that these retainers be truly straight, particularly at the edge touching the cooling tubes since the magnetic field tends to push the septum out of the iron. The extreme ends of the septum are not held back by these retainers. Thus, care must be taken in aligning these ends properly when securing the bridge plates holding coil to core. The force at peak current is about 200 lbs on the two edges along the upper and lower water tube.

**Power Connections**

The septum and back coil end connections were bent backwards and contoured to fit between the 0.25-in by 1-in water-cooled copper buswork. These coil end connections were also stacked with G-10 epoxy-filled fiberglass insulation to make a two-turn winding as shown in Fig. 3. This assembly of interleaving was finally secured together and to the core iron with insulated nuts and bolts.

For the sake of clarity, only the top view power schematic is shown in Fig. 3. An opposite-hand power connection exists on the bottom of the coil. The two sets of power connections (top and bottom) are interconnected with vertical busses, once the coil is set into the core. This results in a single power connection for each polarity of the power source.

This coil assembly, when completely installed in the magnet iron, ready for powering, has a resistance of 0.00088 Ω at the power connection busses. The entire magnet has a leakage resistance to ground greater than 100 MΩ. The deviation in the linearity of the septum over the entire length is less than ± 0.002 in.

**Water Connections**

The water tubes used for the edge cooling of the septum and back winding were bent to fit the contours of the power and interconnecting busses. Following the shaping of this tubing, each was soldered to the outer edge of each of the busses to get maximum heat transfer. Finally, all of the ends of these tubes were terminated in parallel at insulated connections at the manifolds for a complete eight-path cooling system as shown in Fig. 4.

**Magnetic Field Parameters**

Upon application of 6000 A to this magnet, the central field was measured at 2952 G. Figure 5 is a plot of Bd vs Current. With the above value and the readings of this plot, the effective length of this magnet is 21.5 in.
Fig. 5 /Bdl vs Current

Fig. 6 /Bdl vs Radial Distance from Face of Septum

Septum Deflection

While pulsing, the deflection of the septum was monitored with a differential transformer sensor. The largest deflection observed during the 6000-A pulsing duty for a four-hour period was 0.002 in.

Cooling Water and Septum Temperature Test

Water leak tests were made with a hydrostatic pressure tester and the entire system was subjected to a 500-psi static pressure test. The individual silver soldered copper to stainless tubing joints prior to assembly were tested at 1500 psi. This test we felt was necessary because of the severe duty the stainless tubing would experience hammering away at the coil retainer during each pulse of the magnet.

During magnet testing, the supply water pressure was 180 psi and the temperature was 25°C. The return water pressure was 90 psi and the temperature was only a few degrees higher than the supply, depending on current and pulse length. The water flow was 22 gal/min.

While testing with a 6000-A current, 800 ms pulse length, 4-s repetition rate, a temperature plot at the vertical center of the septum was made and is shown in Fig. 7.

Two methods were employed to determine the septum temperature:

a. A Barnes Engineering Model R-4G1 infrared radiation thermometer, with a response time of 10 ms, was focused to a 0.06-in spot on the central plane. To provide a more uniform target radiance, a 0.004-in coating of aluminum paint was applied at the spots being observed.

b. To check the measurements, several stick-on chemical temperature indicators were also applied to the septum. These heat sensors responded after a few pulses and agreed very closely with the temperatures read on the infrared thermometers.

Water flow was changed from 22 gal/min to 18 gal/min during a portion of these tests and caused only a 7% increase in peak septum temperature.

The septum magnet installed in the ZGS has a water flow of 14 gal/min. No temperature check could be made in its normal working position because of inaccessibility. However, no serious temperatures have been reached as the magnet has been in operation for about one year.

Fig. 7 Temperature vs Location on the Septum

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EXPLODED VIEW OF THIN SEPTUM MAGNET
(WITH WATER COOLING TUBES REMOVED)

FIGURE 8a

FIGURE 8b COMPLETE ASSEMBLY