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DESIGN OF A PULSED SWITCHING MAGNET FOR THE BEVALAC*

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Summary

The design and construction of a water cooled, pulsed, laminated core dipole magnet which has recently been installed at the Bevalac is described. This new, energy efficient magnet was funded by the DOE In-House Energy Management Program. The magnet has been specifically designed for maximum efficiency in power utilization and has replaced two DC powered magnets in the Bevalac switchyard. It will reduce energy usage by 747 MWh/yr, and it provides the capability of pulse-to-pulse switching in 0.7 seconds between two major beamline channels serving the nuclear science and radiotherapy programs at the Bevalac. A unique feature of this magnet is the core design which utilizes an external structure that remains integral with the core laminations after assembly. The structure provides for both torsional and longitudinal rigidity of the core while also facilitating the precision assembly and compression of the core laminations without the use of special assembly fixtures.

Introduction

The pulsed switching magnet described in this paper has recently been installed in the switchyard of the Bevalac accelerator complex. The magnet is used to bend the Bevalac output beam into two major beamlines as shown in figure 1. These beamlines serve both the nuclear science program and the radiotherapy program for treating cancer patients at the Bevalac. This new switching magnet has replaced two solid core, DC powered dipole magnets. The DC powered dipoles had vertical gaps larger than required for the beam size. Also, their solid cores made pulsed power operation and fast switching between beamlines impossible due to the formation of eddy currents in the magnet cores and the subsequent time required for their decay. This new pulsed switching magnet will provide two significant improvements to the Bevalac operation. First, it will reduce energy usage from 845 MWh/yr, which was required for the previous DC powered dipoles, to 98 MWh/yr, and second, the magnet will improve Bevalac operation efficiency by allowing a direct reduction of the accelerator's operation-overhead time of 88 hours/year[1].

The reduction in energy usage is accomplished by the magnet's use of pulsed power. The magnet's field is turned on and off synchronous with the Bevalac beam and therefore requires DC power only when the Bevalac is "spilling beam". A typical profile of the pulsed magnet's field vs. time at full Bevatron running mode is shown in figure 2. Also, the magnet's vertical aperture of only 10.414 cm (4.100 inches) as compared with the 15.240 cm (6.000 inches) vertical aperture of the previous magnets reduced the field volume with consequently lower power requirements to achieve the necessary magnetic fields.

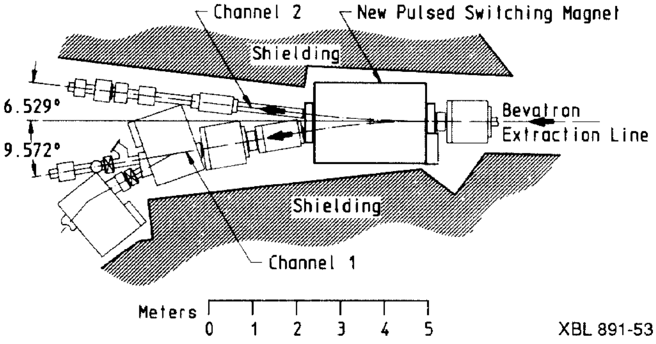

Figure 1: Plan view of magnet in Bevalac switchyard.

The improvement in Bevalac operation efficiency is accomplished by the magnet's fast switching time between the nuclear science and radiotherapy programs thereby reducing the operation's overhead time for this procedure. The previous, solid core magnets required approximately 75 seconds to switch beams between beamlines, due to the eddy currents in the magnet cores and the time required for their decay. This had been the limiting factor in achieving a fast switching capability. The new magnet, however, has been designed with pulse-to-pulse switching capability. Therefore, while many operations are required to switch ions, energies, RF accelerating curves and beam line elements, the switching magnet is no longer a limiting factor in this operation. This time reduction in switching between beamlines relates directly to savings in operating costs by reducing staff operating time, electrical power and consumables such as liquid nitrogen.

Magnet Design

Table 1 shows the design parameters of the magnet, and figures 3 and 4 show the magnet fully assembled and a typical cross section through the magnet. The magnet is an H-gap design with a laminated steel core and water cooled coils of square, hollow copper conductor with saddle shaped ends. The magnet's present maximum field requirement is 1.202 Tesla, however, it has been designed to operate, if required, at fields up to 1.8 Tesla at 89% efficiency[2]. This higher field capability provides for flexibility in meeting the Bevalac's future experimental needs.

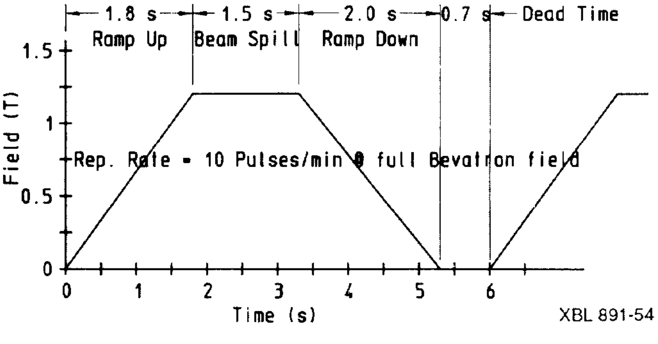

Figure 2: Magnet field vs. time @ full Bevatron field.

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The laminated core is the design feature that contributes the most to energy savings because it minimizes the formation of eddy currents thus allowing for pulsed power operation and fast switching between beamlines. The core has a unique design which utilizes an external structure that remains integral with the laminations after assembly. This design facilitated the precision assembly, compression and support of the core laminations without the cost of special assembly fixtures.

Table 1
Design Parameters for Extraction Line Switching

Bend angle, max.	9.572°
Field @ max. bend angle	1.202 T
Average field deviation	0.07%
Rise time @ full Bevatron field	1.8 s
Magnet gap	10.414 cm (4.100 in)
Pole width	55.88 cm (22.00 in)
Core length	254.00 cm (100.00 in)
Effective length	266.83 cm
Lamination thickness	0.15 cm
Conductor size	1.626 cm sq.
Number of turns, total	160
Peak current	627 A
Current density	346 A/cm^2
Coil resistance, total	0.120 Ω @ 30° C
Inductance, total	0.55 H
Time constant	4.58 s
Total voltage ($V_R + V_L$)	232 V
Pulsed power, average	21.8 kW @ 0.167 Hz
Sum of pulsed, eddy & hysteresis power, average	21.9 kW @ 0.167 Hz
Number of cooling circuits/coil	5
Water flow rate, total	13 gpm @ 35 psi ΔP
Max. coil temp. rise @ DC power	14° C
Total weight	90,000 lbs

Coils

The coils were fabricated from 1.626 cm square x 1.02 cm I.D. OFHC copper conductor. The saddle shaped geometry of the coils was selected since it provided for a more compact core height and subsequently 8,400 lbs. less core weight when compared with the core size required for a "pancake" coil geometry. Each coil was designed with five water circuits to allow for the flexibility of future operation of the magnet, if required, at fields up to 1.8 Tesla. Coil winding and epoxy encapsulation were performed at LBL. The coils were wound using a two axis winding machine whose drive, braking and controls were modified to accept the 5,000 lb. combined weight of the winding form and each coil. The conductors were wrapped with a single, half lapped layer of 0.08 mm (0.003 inch) thick mylar tape followed with a single, half lapped layer of 0.13 mm (0.005 inch) thick dacron tape. The mylar and dacron were simultaneously wound onto the conductor with a winding machine designed and constructed at LBL. After the completion of winding, the coils were removed from the winding form and "ground wrapped" with a single, half lapped layer of 0.25 mm (0.010 inch) thick fiberglass tape. The fiberglass was chosen for the "ground wrapping" since it became transparent after the epoxy encapsulation, thereby allowing for the detection and filling of trapped air bubbles which could precipitate electrical shorts. The winding form was designed to be used as part of the potting mold. After the coils were wound and tested, potting form cover plates and seals were installed over the winding form and the conductors. The coils were then epoxy encapsulated in a vacuum tight mold.

Core

The magnet core was designed with an H-gap geometry as shown in figure 4. A window frame geometry would have required a substantially wider core in order to maintain the same current density. Significant alterations to the existing Bevatron shielding would have been required to physically accommodate the magnet. Extensive POISSON magnetostatic computer runs were made in designing the core. The 55.88 cm pole width was required due to the bend angles of -9.572° and 6.529° and the requirement for an average field deviation less than 0.1%. The edges of the poles have a 60° taper in order to minimize pole root saturation since the magnet has been designed to operate at fields up to 1.8 Tesla. The pole ends have a 4.45 cm x 45° chamfer to provide a smooth transition, thus minimizing saturation at the ends. The end chamfer also reduces the non-linear focusing effects since the beam exits the magnet along a non-normal trajectory to the magnet end.

The core is a laminated structure using 0.15 cm (0.058 inch) thick carbon steel laminations. This lamination thickness was the practical upper limit for stamping accuracy and handling of laminations this size. The laminations weighed 24 lbs. each. Half of the total number of laminations were stamped from 1004 carbon steel per ASTM specification A424-73, type IIA which was obtained from LBL storage. The other half of the laminations were stamped from 1010 carbon steel having an iron phosphate coating on both sides. The bare steel and the iron phoshate coated steel laminations were alternated during stacking. This provided for a uniform core stack, and the iron phosphate coating between each lamination provided the electrical resistance necessary to minimize eddy currents in the core. The core end plates are 5.72 cm (2.25 inches) thick. They are made of three, 1.91 cm (0.75 inch) thick 1015 carbon steel plates bolted together making an end plate structure with the necessary rigidity for core compression. Eddy current heating calculations showed that the end plate temperature will be at approximately 20° C; therefore, cooling of the end plates is not required.

An external structure was designed for stacking, compressing and supporting the laminations in each of the 42,000 lb core halves. The core has an exterior frame, as shown in figure 4, to which the laminations are keyed in both the vertical and horizontal directions. The

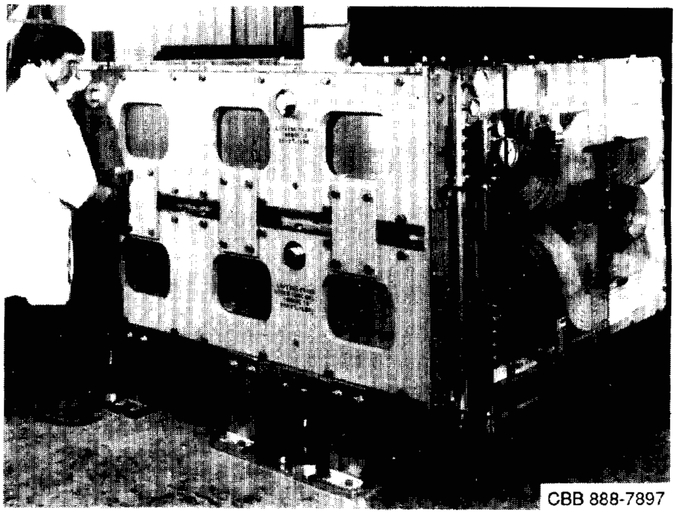

Figure 3: Magnet fully assembled.

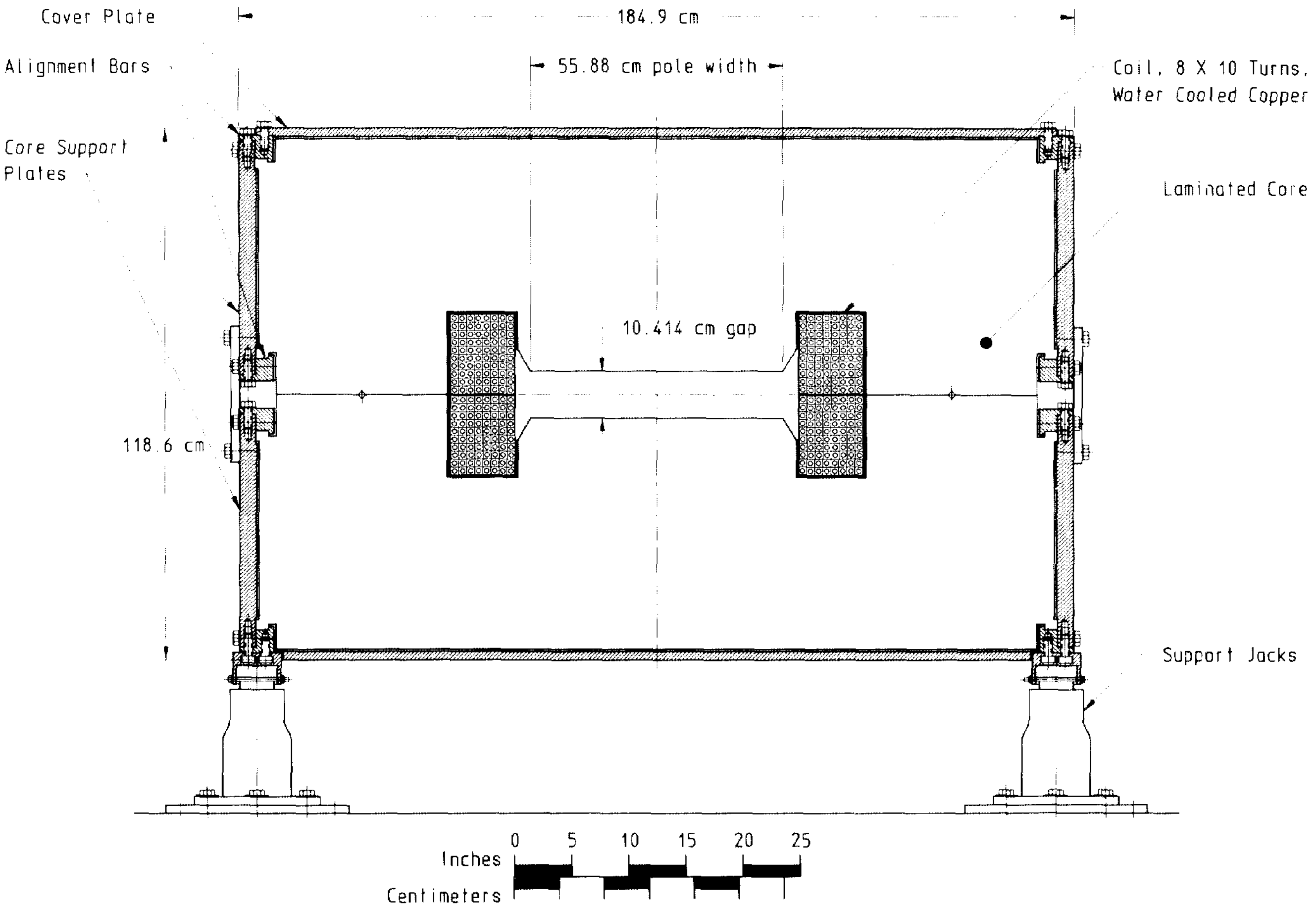

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Figure 4: Typical cross section through magnet.

assembly of each core half was as follows. Core alignment bars which have ground mounting surfaces were bolted to the precision machined edges of the core support plates as shown in figure 4. The support plates, cover plate and end plates were assembled on a precision granite surface table. This exterior frame was assembled onto two thin stacks of laminations temporarily set at each end of the frame and mounted vertical to the surface table. All frame plates were bolted together in this position, and the end plates were also pinned to the side support plates. The two thin stacks of laminations were then removed, and the core frame was set vertically on the floor. Cables from the floor to the frame were used to safely hold the frame in the vertical position. The alignment bars at the open face of the frame were then removed, and the laminations were individually stacked into the vertical frame. Each of the laminations was pushed against the alignment bars at the back of the frame. Also, since the laminations are symmetrical about their vertical centerline they were periodically flipped about the centerline to minimize left-to-right symmetry errors caused by non-uniform lamination material. As the lamination stacking neared the top of the vertically mounted core the alignment bars were replaced on the open face of the frame, and the top end plate was removed. The laminations were then stacked slightly above the core frame, and the end plate was replaced and torqued down. The number of compressed laminations extending past the frame support plates were counted and removed along with the end plate. The end plate was then put back in place and torqued down against the frame support plates and cover plate. A 1.5 mm deflection due to lamination pressure was measured across the end plate. The core was then lowered down to the horizontal position. The core while mounted on its support jacks was measured to be flat within 0.05 mm (0.002 inches) across its full length.

Acknowledgements

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