IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

A NEW PULSE MAGNET DESIGN UTILIZING TAPE WOUND CORES*

W. O. Brunk and D. R. Walz

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Summary

Pulse magnets were built utilizing tape wound cores in order to lower magnet power requirements at high pulse repetition rates and high gap flux densities. The primary reason this project was undertaken was to bend higher energy beams with existing power supplies. A decrease in the amount of electrical steel from 2720 kg for the original laminated core pulse magnet design to 260 kg and the elimination of the ceramic vacuum chamber resulted in substantial savings. Two new magnets are now operational with the capability of deflecting 40 to 50 GeV/c beams through $\pm$ 0.35° (6.13 mrad) at a PRR = 360 pps. The old magnets with the same power supplies could only bend 21 GeV/c beams through the same angle. Principal features of this design, including test data, are presented.

Introduction

Pulse magnets were installed[1] in the front end of the SLAC beam switchyard to utilize the multibeam capability of the accelerator and deflect beams on a pulse-to-pulse basis to the various beam lines and research facilities. These magnets have operated with very little trouble since 1966. They are fabricated from 0.36 mm thick stamped laminations of non-oriented transformer iron (Di-Max M-19)†. Their rated mode of operation is PRR = 360 pps, each pulse consisting of a single cycle (360°) of a 600 Hz sine wave with a peak current value of approximately 310 A. The gap is 50 mm and the peak flux density is 0.17 T (1710 G) for the stated peak current. Above 0.2 T the losses were found to be excessive, and reliability was poor. These magnets required rectangular cross section ceramic vacuum chambers, which were expensive (1/3 of the total magnet costs) and provided a great source of procurement headaches stretching over a period of two years.

A second set of pulse magnets was required in 1967 to switch beams to the various targets and beam lines in the SLAC B-target room. To avoid some of the difficulties encountered earlier, the magnets were made as long as possible, the gap was increased to accommodate a ceramic vacuum chamber of circular cross section, and the water-cooled stainless steel end plates were eliminated. The design peak current was 550 A, the gap was 64.3 mm and the resulting peak gap flux was 0.232 T.

These magnets had problems from the onset. Again there were ceramic vacuum chamber procurement difficulties, and, although less expensive, they still came to about 12% of the total magnet cost. The calculated power consumption was some 80% below the actually measured value. This resulted in power supply recharge time problems at the higher pulse rates. Furthermore, at full power the magnets overheated substantially at the ends of the gap where the fringe field is not parallel to the laminations. Subsequently, water-cooled copper plates were clamped to the ends of the poles to straighten the flux and thus reduce hot spots. This decreased hot spot temperatures and increased the beam bending capability from 17 GeV/c to 21 GeV/c at PRR = 360 pps. The power consumption remained very high, suggesting that the flux plates dissipated some of the power previously lost in the core.

The flux plates permitted operation at about the maximum loaded beam energy produced by the accelerator. However, it was obvious that proposed future schemes to increase the beam energy to the 40 to 50 GeV/c level would require new pulse magnets of substantially improved performance. The resulting developmental program had the following objectives: (a) to increase the peak gap flux density, (b) to lower the magnet power losses, and (c) to eliminate the ceramic vacuum chamber.

The partial failure of the flux plates pointed towards a solution utilizing thin laminations of grain-oriented material. The latter exhibits much lower hysteresis and eddy current losses than does the non-oriented material used in the original design. Since these losses are approximately proportional to the square of the peak flux density, the latter could be raised without the losses becoming excessive.

The Model Magnet

A model pulse magnet was designed and built utilizing tape wound cores and various coil configurations. Attempts to measure the power losses electrically, calorimetrically, and by means of thermocouples attached to various points of the core were quantitatively not too successful. However, there were some qualitative results worth mentioning.

1) Copper plates to straighten the flux were placed along the gap and parallel to the core laminations. They did reduce the core losses somewhat, but more importantly, they dissipated more power in themselves than was saved in the core.
2) The magnet coils consumed more power than the core just due to eddy currents in the large conductor wire (2 AWG).

Thus, pulse magnets with large gaps may have large losses near the gap where the fringe fields are not parallel to the core laminations. They also suffer eddy current losses in the magnet windings because of the large leakage flux crossing the coil window. These losses are in addition to the usual I^2R losses in the exciting windings and the hysteresis and eddy current losses in the core material.

The New Pulse Magnet Design

The goal was to design a magnet (referred to as MK-II) which is approximately 1 m long to bend beams of up to 50 GeV/c through an angle of 3 mrad. This requires a gap field of 0.51 T. For a good magnetic design the core steel will then have a peak induction of approximately 0.73 T. This is a modest flux density for transformer designs. It is however a factor of two higher than the maximum possible for the original MK-I SLAC pulse magnets (fabricated with "Di-Max M-19") having gaps of 50 to 65 mm. Epstein sample tests of oriented steel (Armco TG) of 0.15 mm thickness show a loss of approximately 2 W/kg at 0.73 T peak induction and at a frequency of 600 Hz.

†Trade name of the Armco Steel Co.

*Work supported by the U.S. Atomic Energy Commission

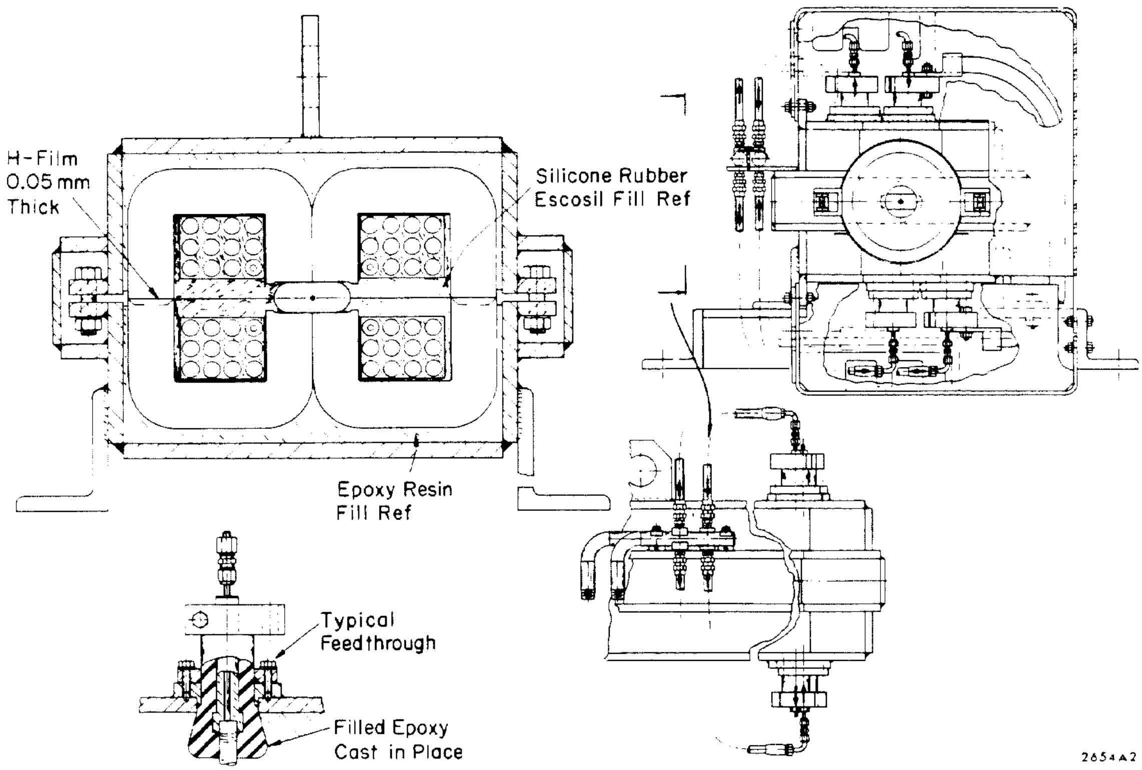

Fig. 1--Magnet assembly drawing; center cross section and lead bushing

The Core

The new MK-II design was built around C cores wound of 0.15 mm thick oriented steel (Armco TG) strips of 117.5 mm width. The material was wound onto a 133.5 mm x 76 mm steel mandril to a winding depth of 38 mm. Each core was annealed and vacuum impregnated with epoxy. Thereafter each core was split asymmetrically into two C core modules such that when one core half is rotated 180° there is a 25.4 mm gap in one leg and no gap in the other. Two such core modules were placed side by side resulting in an H magnet configuration with a 25.4 mm gap, of 76 mm width. Eight of these core modules were placed end to end to form a magnet 940 mm long. Each half was potted into an aluminum vacuum box using heavily filled (Al_2O_3) epoxy resin. The latter provides good thermal conduction from the core to the coil and the vacuum chamber. The potting of the coil and core assembly into the vacuum chamber is illustrated in Fig. 1 above. Also shown are a vacuum feedthrough for the power leads and the external water and power connections. After the core modules were potted into each half of the vacuum chamber all gap and return yoke surfaces were machined as a unit. Finally, the surfaces were etched to remove the shorts between adjacent laminations caused by the machining operation. Various etching processes were tried. Best results were obtained using a slurry of Al_2O_3 in HNO_3. The total weight of steel in the two core halves was approximately 260 kg. A typical core half is shown in Fig. 2 after curing of the epoxy resin and machining and etching of the core.

The Coil

Also shown in Fig. 2 is a coil assembly ready for potting. The coil conductor is made up of 161 No. 20 AWG wires wound in 5 layers over a 4.8 mm diameter stainless steel tube core. The latter acts as the major heat sink of the magnet when connected to the LCW water system. Each of the exciting coils is made up of 12 turns of this conductor. The turn to turn insulation is provided by 8 layers of 0.127 mm thick glass tape plus approximately 1.6 mm of heavily filled epoxy resin. High thermal conductivity epoxy and silicone resins were used throughout to allow the coil cooling tube to remove all the power dissipated in the core and coil assemblies.

Fig. 2--Etched core half and unpotted coil

Calculations and Measured Results

The hysteresis and eddy current loss in the magnet core can be calculated from Epstein sample curves

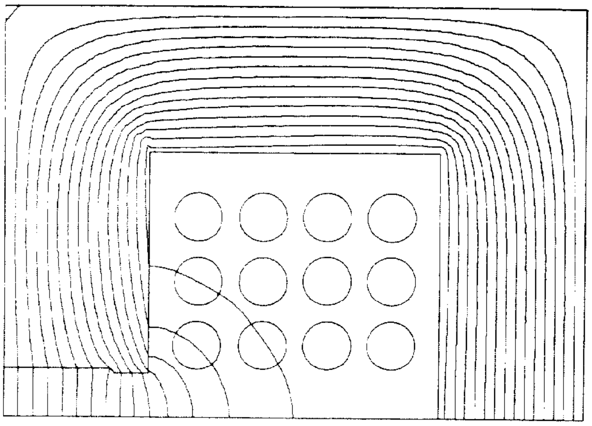

Fig. 3--Computer generated flux plot at I_{peak} = 500A

for the core material if the peak flux density is known. In the region close to the gap the peak flux density is not known, since the flux is not parallel to the laminations. A crude picture of the peak fields and the field shape was obtained by calculating the two-dimensional dc case with the computer program "POISSON". The computer generated flux plot to which field values were added is shown in Fig. 3. The plot is not quite representative of the actual ac case for several reasons: (a) it is for 1010 steel and not the grain-oriented steel which was used in the MK-II design. This results in calculated fields that are lower than actual fields. The difference as measured on the model was approximately 2.5% for a peak current of 500 A - (b) POISSON cannot calculate the flux-straightening effect of the interlamination insulation, nor can it compute the increase in flux density in the steel due to the stacking factor. The former would tend to decrease the fringe fields in the coil window. The latter is a linear effect and enters as a constant factor of the peak flux density in the steel.

For a peak current of 370 A and PRR = 360 pps of 590 Hz sine waves Fig. 3 gives a peak flux density in the core material of 0.73 T. For the latter the gap flux is approximately 0.5 T which results in a field integral of 0.48 T-m (0.48 webers/m). The field integral versus current relationship for the new MK-II design is shown in Fig. 4. The CW core loss is 5.1 W/kg and at PRR = 360 pps the losses are 3.1 W/kg.

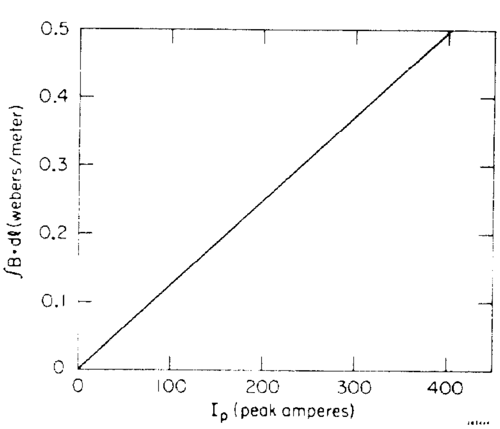

Fig. 4-- ∫ Bdl vs I_{peak} as measured

Thus, for a 260 kg core the losses are 800 W.

Next the coil losses can be calculated. The rms value of 370 A peak current is 262 A, and the series exciting coil resistance is 13.16 mΩ at 40°C (neglecting the stainless steel water tube). The CW I^2R loss in the coil is then 900 W, or 550 W at PRR = 360 pps.

The gap loss can be calculated from the following equation[2]:

$$W_g = G l_g d f B_m^{\ 2}$$

where W_g = gap loss in watts, G is a numerical constant = 3.88×10^{-4}, l_g = length of gap in mm, d = width of the core in mm, f = frequency in Hz, and B_m = peak flux density in teslas. For the numerical values given above W_g = 2910 W. Since this figure represents two gaps in one tape wound core, the real CW loss in the gap is then ≈ 1450 W, and for PRR = 360 pps the loss is 1450 x 0.61 = 885 W. This figure is of the same order of magnitude as the hysteresis and eddy current losses in the core as calculated above.

The eddy current losses in the multistranded conductor and cooling tubes are difficult to assess for this geometry and an estimate will therefore have to suffice. Assuming that these losses are 2/3 of the I^2R losses, or 550 x 2/3 = 365 W, the total loss in the magnet can be summed up as $W_{tot} = W_{core} + W_{coil} + W_{gap}$ = 800 + 550 + 365 + 885 = 2600 W.

After installation in the beam switchyard the magnet was operated for several hours at a peak current of 370 A, a frequency of 590 Hz and PRR = 360 pps. The steady state power losses dissipated into the water were calorimetrically measured to be 2650 W. This is in close agreement with the value calculated above for a peak current of 370 A. However, it should be stressed that the confidence factor for the calculation of the gap loss is low and the evaluation of the eddy current losses in the coils was based on a guess. At steady state the outer surface of the aluminum magnet housing and vacuum chamber was approximately 55°C. Thus, several hundred watts were lost due to natural convection and thermal radiation.

After 6 months of operation the two magnets have only developed one fault. Both magnets shorted to the vacuum housing (ground) in the area where the coil leads penetrate the vacuum barrier. Changes in the detailed design of the feedthrough were made and the magnets are back in service.

Conclusions and Recommendations

The MK-I and MK-II designs are hardly comparable on performance since the gap dimensions are so different. However, the new MK-II design magnets require less than half the peak current and voltage and only about 12% of the total power of the old MK-I design magnets when operated at the maximum field integral of the old design. At twice this field integral the power consumption is still only approximately 50% of the consumption of the old MK-I design at its maximum. Magnets built to the new MK-II design cost approximately 50% of the original MK-I design after adjustment for inflation.

Some of the limitations and drawbacks of the MK-II design are as follows: Since the magnets are canned there are large surface areas of epoxy and silicone resins exposed to the vacuum. This is of no consequence in SLAC's beam switchyard where the pressure requirements are only of the order of 10^{-4} to 10^{-5} torr. However, for ultrahigh vacuum applications utilizing ion pumps, ceramic vacuum chambers would probably be required and some of the advantages of the MK-II design would be lost.

The rather large gap losses incurred in the new design, because the laminations are parallel to the long gap dimension, are a disadvantage. The sum of the calculated core and gap losses is almost 1700 W or 6.5 W/kg, the latter being equivalent to 10.6 w/kg for CW operation. Several semi- or non-oriented materials are available which could be designed to exhibit half this loss when used as stamped laminations in the center of the magnet.

Summarizing, the evidence points to gap losses and conductor eddy current losses as constituting about half of the total losses in pulse magnets. A reduction of these losses is accomplished by the following steps:

1. Utilization of lowest loss material available.
2. Application of thinnest lamination commensurate with acceptable stacking factor.
3. Arrangement of lamination direction such that the plane of the stray field at the edge of the gap is parallel to the plane of the laminations.
4. Utilization of a coil conductor made up of as many small wires as practical, and of water cooling tubes of a material having as high a resistivity as is available.

The ultimate design for a 600 Hz pulse magnet might then be a composite of stamped laminations and tape wound cores. The stampings would compose the center portion of the magnet yoke and would be stacked in the same manner as in the original MK-I design. The tape wound cores would form the end pieces. The shape of the stampings should be adjusted to limit peak induction to 0.5 to 0.6 T. (Deltamax† in 0.127 mm thick laminations shows an Epstein sample CW core loss of 2.75 W/kg at these operating parameters). The end pieces should be about one magnetic gap long and could be of regular grain-oriented steel in a tape wound type of construction. This arrangement of the lamination direction might reduce the gap losses to a practical minimum. Such a design would be more expensive than the MK-II design as disclosed above, but it could be justified in areas requiring the ultimate in performance.

References

1. H. Brechna, "A pulsed bending magnet for the beam switchyard of the Stanford Two Mile Linear Electron Accelerator", SLAC Report No. 28 (1964).
2. R. Lee and D.S. Stephens, "Gap loss in current limiting transformers", Electromech. Design Vol. 17, No. 4, pp. 24-26 (1973).

Acknowledgement

The authors would like to express their appreciation for the valuable contributions made by the SLAC Fabrication Shop. Specifically, the efforts of S. Butler on the core machining techniques, those of L. Didier and C. Kennedy who developed the core etching process, and W. Shetler's ideas on precision assembly deserve to be mentioned.

†Trade name of the Allegheny Ludlum Steel Company.