DESIGN OF A THIN QUADRUPOLE TO BE USED IN THE AGS SYNCHROTRON*

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Abstract

The Alternating Gradient Synchrotron (AGS) employs two partial helical snakes[1] to preserve the polarization of the proton beam during acceleration. In order to compensate for the focusing effect of the partial helical snakes on the beam optics in the AGS during acceleration of the beam, we introduced eight quadrupoles in straight sections of the AGS at the proximity of the partial snakes. At injection energies, the strength of each quad is set at a high value, and is ramped down to zero as the effect of the snakes diminishes by the square of beam's rigidity. Four of the eight compensation quadrupoles had to be placed in very short straight sections ~30 cm in length, therefore the quadupoles had be thin with an overall length of less than 30 cm. In this paper we will discus: a) the mechanical and magnetic specifications of the "thin" quadrupole. b) the method to minimize the strength of the dodecapole harmonic, c) the method to optimize the thickness of the laminations that the magnet iron is made, d) mechanical tolerances of the magnet, e) comparison of the measured and calculated magnetic multipoles of the quadrupole.

MECHANICAL SPECIFICATIONS

Figure 1 shows an isometric view of the iron core of the "thin" quadrupole.

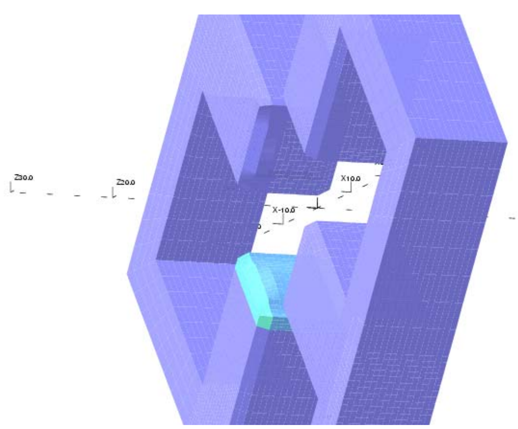

Figure 1: Isometric view of the "thin" quadrupole. The shape of the pole faces is also shown.

The radius of the quadrupole's aperture and the length, width, and height, of the pole piece appears in Table 1. Figure 2 shows one of the quadrupole's coils placed around one of the pole pieces. Each of the four coils, which is made of four layers with 13 turns per layer, has a square cross section with a length of the outer side of 18 cm. The water cooled conductor which allows a maximum current of 350 [A], has square cross section with a side of 8 mm and a hole of 4.3 mm in diameter.

Table 1: Geometrical dimensions of the "thin" quad.

R cm	Length [cm]	Width [cm]	Height [cm]	L_{coil} cm
8.3	10.3	10.2	14.0	18.0

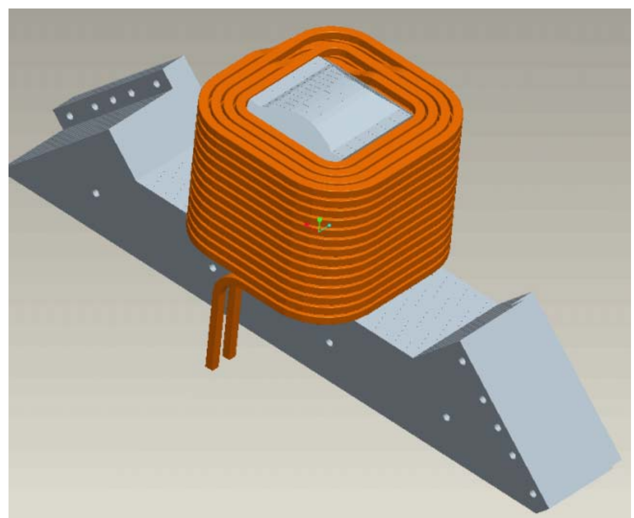

Figure 2: An isometric view of the magnet's coil around one of the quadrupole's pole.

MAGNETIC SPECIFICATIONS

The magnetic specifications of the "thin" quad are: a) the required integrated gradient $\int Gdl$ of the "thin" quadrupole must have the value of 0.76 [T] or higher, at its maximum current. b) the strength of the first allowed multipole (12-pole) must be below an upper limit, which will keep the strength of the feed-down sextupole (due to a 5 mm transverse misalignment of the quad) below a set limit. c) to establish mechanical tolerances by setting an upper limit on the sextupole caused by the various possible mechanical misalignments and d) low eddy currents in the iron core of the magnet by optimizing the iron lamination thickness. The low eddy currents will minimize their adverse effects on the magnetic field.

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MAGNETIC MODELLING

In order to satisfy the magnetic requirements we performed 2D and 3D magnetic modelling [2].

The 2D magnetic modelling was performed to establish:

- the contour of the pole-face that minimizes the dodecapole multipole. The contour of the pole faces is shown in Fig. 1 and also in Fig. 2.
- an estimate of the ohmic losses which are generated in the magnet's coils because of the eddy currents generated during the ramp-down of the magnet. (These losses were calculated to be 0.8% of the ohmic losses generated by the current which powers the magnet).
- the amount of iron needed to keep the magnetic field in the return iron below 1.5 Tesla.

The purpose of the 3D magnetic field calculations is discussed below.

Minimization of the Dodecapole Multipole

Static calculations were performed on a 3D model in order to determine the amount of chamfer, of the pole pieces at the entrance and exit of the magnet, which minimizes the strength of the integrated dodecapole. This chamfer of the pole pieces which is shown in Figure 1 and 2 was determined to be 22.8^{o} and started 1.27 cm from the edge of each pole piece. The pole face contour as determined in the 2D calculations, in combination with the chamfer of the pole pieces, determined in the 3D calculations, reduced the integrated strength of the dodecapole field at a radius r=7 cm to 0.02% of the strength of the integrated quadrupole field.

Transient Field Calculations

The 3D transient calculations were performed by using the ELEKTRA module of the opera code [2] to help determine an upper limit in the lamination thickness of the magnet iron. The required lamination thickness should be such that it limits ohmic losses, due to eddy currents, below 10 [J] per acceleration-cycle, and also the maximum field achieved by the quadrupole during the 200 msec ramping to be at least 99% of the static field generated by the magnet when it is excited at the same current. In the simulation, for a given lamination thickness, the coil current was ramped from 0 [A] to 350 [A] in 200 msec and, the gradient of the quadrupole and the power dissipated in the laminations were calculated. The simulation was repeated with a different lamination thickness, but always keeping the length of the magnet's iron fixed at 10.3 [cm]. The magnetic permeability of the lamination material was non-linear and similar to that of steel 1010. Fig. 3 shows the quadrupole's Gradient as a function of ramping time for various thicknesses of the laminations. As seen in this figure, for a lamination thickness of 0.595 [cm] the gradient of the quadrapole is almost the same as that of the static field thus the effect of the eddy currents is not significant. Fig. 4 shows the ohmic losses in the laminations. The lowest power loss occurs when the lamination thickness is 0.595 [cm] and it amounts to a total energy of 9 J, dissipated in the iron of the magnet per acceleration cycle. It is noteworthy, as shown by the negative slope of some the curves in Fig. 4, the reduction of the power dissipated in the iron as the field in the iron increases. This can be explained by the increase of the "skin depth" $\delta=(2/\omega\mu_0\mu\sigma)^{-1/2}$ because the permeability (μ) in the iron decreases as the magnetic field increases.

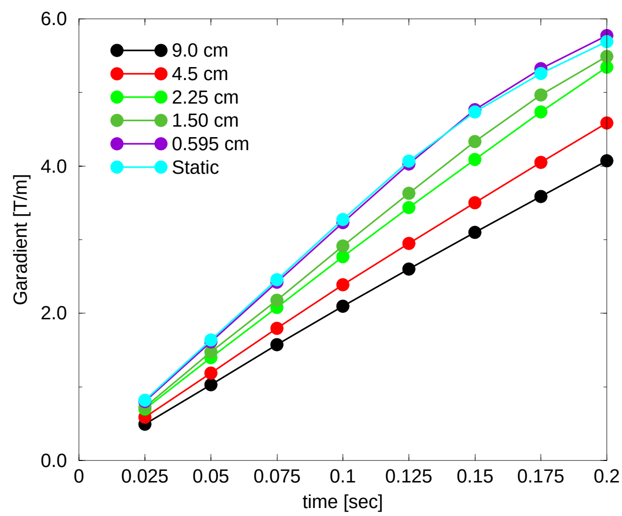

Figure 3: The gradient of the "thin" quadrupole as a function of time during which the current is ramped linearly from 0 to 350 [A]. Each plot corresponds to a different lamination thickness.

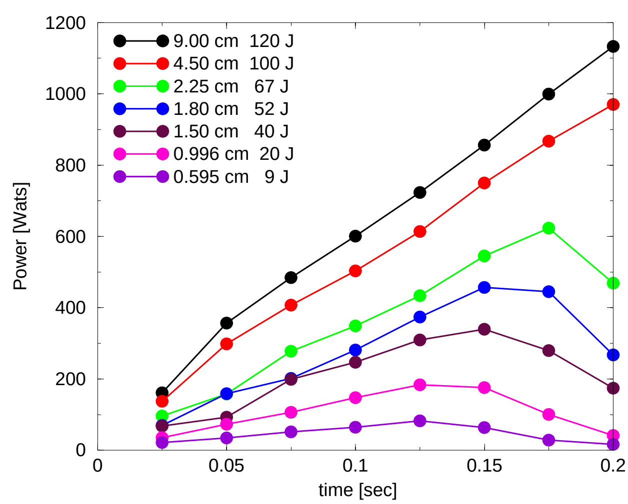

Figure 4: Power dissipated in the laminations as a function of time. Each plot corresponds to a different lamination thickness.

Thus if the value of the skin depth approaches the thickness of the lamination, it affects the eddy currents which flow in opposite directions in the lamination, and partially cancel each other, as a result the ohmic losses are reduced. Figs. 5 and 6, each shows an isometric view of the eddy current density formed in the same lamination at two different times. The cross section of the lamination is

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shown by the grey rectangle in the figure. The eddy currents shown at a latter time (Fig. 6) penetrate more into the lamination and, partially cancel each other.

Mechanical Tolerances

In this study we used the full 3D model of the magnet because the symmetry of the model is broken under a geometric misalignment. The study showed that by displacing laterally (away from the quadrupole axis) one of the poles of the magnet by ±0.25 [mm] the strength of the generated sextupole multipole is well below the maximum permissible limit.

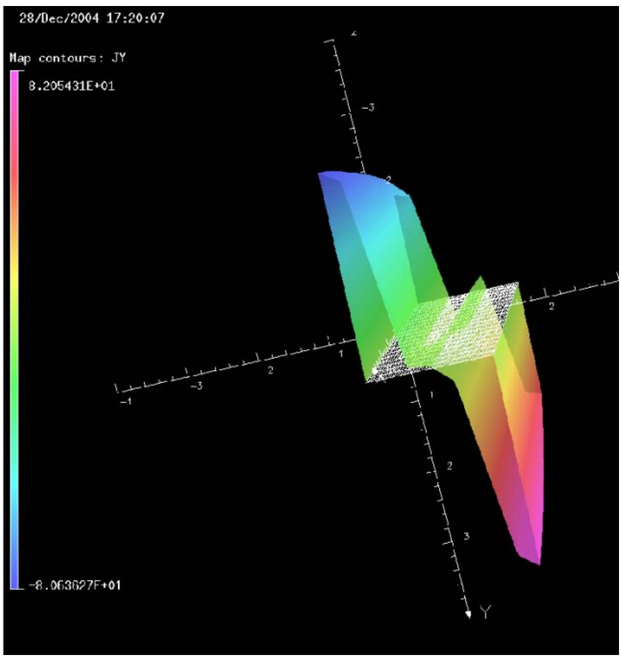

Figure 5: An isometric view of the current density (J_{eddy}) at a particular cross section of a lamination, and time. The cross section of the lamination is shown by the grey rectangle.

MEASUREMENTS

The multipoles at a given radius (r) and distance z from the centre of the quadrupole can be expressed as:

$B_r = \Sigma\{a_n(r,z)\cdot\cos[(n+1)\theta] + b_n(r,z)\cdot\sin[(n+1)\theta]\}$

{n=1 Quad n=2 Sext. ..}. The integrated strengths of the normal multipoles, $B_n=\int b_n(r,z)\cdot dz$, and of the skew multipoles, $A_n=\int a_n(r,z)\cdot dz$, of the quadrupole were measured with the rotating coil method and also calculated using the results from the 3D simulations. The first and second columns of Table 2 shows the calculated and measured integrated strength of B_1 and the ratios $R_n=10^4\cdot B_n/B_1$ for the first three allowed multipoles, at r=7 [cm] and magnet current I=310 [A]. The third row shows the specified upper limit of the quantity R_5 for which the strength of the feed down sextupole can be tolarated. There was no need to set an upper limit for the quantities R_9 and R_{13} because the feed down multipoles due to the calculated or measured strength of B_9 and B_{13}, are too small to be measured . The relatively large discrepancy between the theoretical and measured R_n values, as appears in Table 2, is due to a small modification of the built quadrupole. In this modification, we had to “shave” ~2 mm of iron from each end of the quad for the coils to fit into the pole piece. Even with this modification, the measured strengths of the dodecapole multipole is by a factor of ~7 less than the specified upper limit.

Table 2: The integrated B_1 strength and the ratios R_n of the first three allowed multipoles at r=7 [cm].

T [GeV]	B_1[T]	R_5	R_9	R_{13}
Calc.	0.88	-20	-210	-35
Meas.	0.89	+55	-45	-13
Spec.	0.76	<400	Not Spec.	Not Spec.

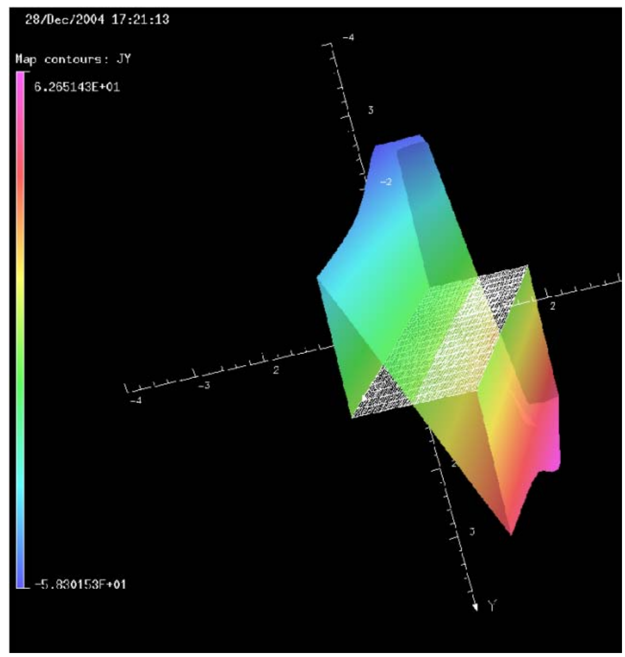

Figure 6: Same as in Fig. 5 but at a later time. Note the opposite travelling eddy currents (J_{eddy}), are overlapping at the centre of the lamination. This overlapping causes the partial cancellation of the eddy currents, thus the ohmic losses due to eddy currents are reduced.

CONCLUSIONS

We designed and built a “thin” quadrupole, 10 cm long. The measured strength of the first allowed multipole (dodecapole) was well below the specified value. The lamination thickness which was determined with transient field calculations generated the expected magnetic multipoles and ohmic losses in the laminations.

REFERENCES

[1] H. Huang, et al., Proc. EPAC06, (2006), p. 273.
[2] OPERA computer code. Vector Fields Inc.

