LASER CUTTING FABRICATION OF MAGNETIC COMPONENTS

R. T. Neuenschwander, A. Ricardo D. Rodrigues* , F. W. B. Talarico and C. E. T. Gonçalves da Silva**
Laboratório Nacional de Luz Síncrotron - LNLS/CNPq
Caixa Postal 6192 - Campinas - SP - Brazil.

Abstract

Dipole, quadrupole and sextupole prototypes for the LNLS storage ring have been fabricated using 1.5 mm thick, low carbon steel laminations, with the aid of a CO_2 laser cutter, reaching an overall dimensional accuracy of ± 0.02 mm (standard deviation). The relevant aspects of the technique are presented, together with the results of magnetic and dimensional measurements. The possibility of mass producing these components with the technique is also analyzed.

1. INTRODUCTION

All dipoles, quadrupoles and sextupoles for the transfer line and storage ring will be laminated. These magnets were initially designed to be conventionally fabricated from punched 1.5 mm thick low carbon steel laminations.

After a long time of negotiations with local industry, it was concluded that the price of punching the dipole laminations would be very high and that there would be no warranty of the tolerances. The prices quoted were comparable with that of a laser cutting machine.

Initial tests with this type of tool, installed in a nearby industry, led us to the decision to acquire a laser cutting machine optimized for our needs. All the prototypes described in this work were fabricated with the help of this equipment.

The flexibility to change design, due to the use of numerical control, makes prototype development very fast and allows for nonstandard core designs in which each lamination differs from the others, as used in the second dipole prototype described below.

2. DIPOLE FABRICATION

The dipole is a 1.4 m long C shaped magnet, with 58 mm gap, 2.74 m curvature radius (30 degrees deviation angle) and designed to generate a 1.4 Tesla with a nominal current of 240 amperes. It is composed by approximately 920 low carbon steel laminations with special Rugouski contour at the entrance and exit end-packs.

2.1 First prototype

The first dipole prototype was assembled in a curved girder, with the lamination gap, pointing downwards, touching a vertical reference plate. The laminations were compressed by a 40 ton press and held together by two plates welded on top and bottom of the magnet. After that, four 10 mm thick curved plates were welded in the front and in the back. The main disadvantage of this procedure is that it is not possible to see the pole surface during assembling and before welding.

The final gap of each lamination was measured, after assembling the core, and plotted in Figure 1 as a function of the position of the lamination in the magnet: standard deviation of 0.11 mm (peak-to-peak 0.46 mm). Figure 1 also shows the vertical magnetic field, in the midplane, as measured with a Hall probe. The results indicate the bad quality of the gap profile and its influence on the magnetic field. This gap variation was found to be mostly produced by welding deformation, since the measured variation, before assembling, was much smaller and the "periodicity" of the variation matches that of the welding procedure.

The transverse homogeneity of the field was coincident with that predicted by simulations using the code POISSON [1], indicating no need to modify the shims design.

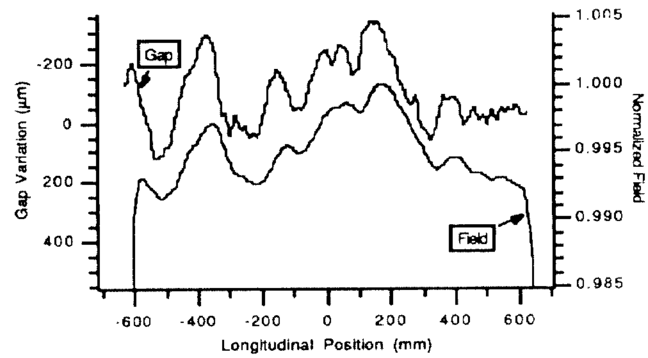

Fig. 1: Longitudinal variation of the welded dipole gap (left axis) and magnetic field (right axis).

2.2 Second prototype

The second design for the dipole avoids welding and its assembly procedure permits to see the gap quality during the process. The laminations are held in place by five tie-rods through the magnet core (Figure 2). In order to have a straight hole inside a curved magnet, we need a hole in a different position for each lamination. The solution can be simply implemented with a laser cutter, by using variable offsets in the program for the lamination profile.

Each tie-rod, with threads and nuts on both ends, can support a tension of 38 tons. A thick steel plate, with four hydraulic jacks, is supported at the ends of the tie-rods. The jacks then compress the laminations, before tightening the screws, facilitating the rotation of the nuts.

The assembly girder (Figures 2 and 3) is now part of the magnet. The girder has a flat surface with a straight guide which is left during machining (Figure 2). This guide fits into a slot made in each lamination, cut by the same subroutine and with the same offset of the holes for the tie-rods. This procedure gives the core its correct circular shape, assuming good regularity of the laminations thickness.

The assembling procedure starts with one end-plate against a reference stopper, that is orthogonal to the girder surface. The laminations are then slid in the proper order and compressed every 20 cm by use of extensions and nuts on the tie-rods. After the last end-plate, the gap height is regularized with a special jack which applies a small pressure on both pole faces. The final step is to apply 40 tons (~9 kgf/cm^2 on the laminations) to the stack and tighten the nuts of each tie-rod.

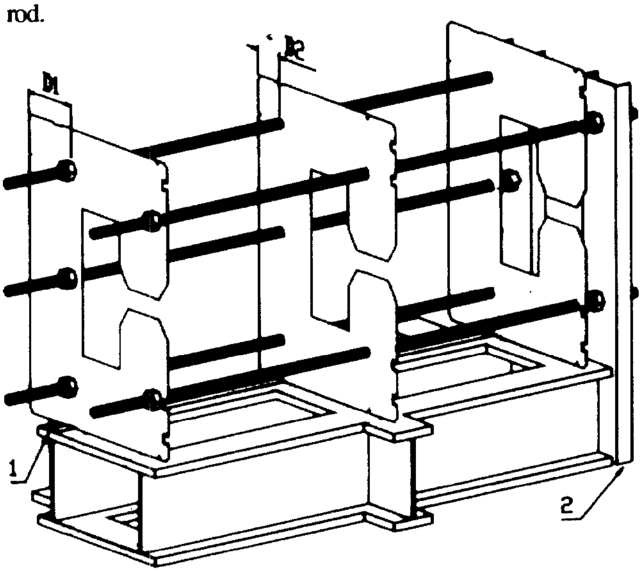

Fig. 2: Schematic view of the assembling device showing the girder, with the reference guide, the laminations with the holes in different positions and the tie-rods.

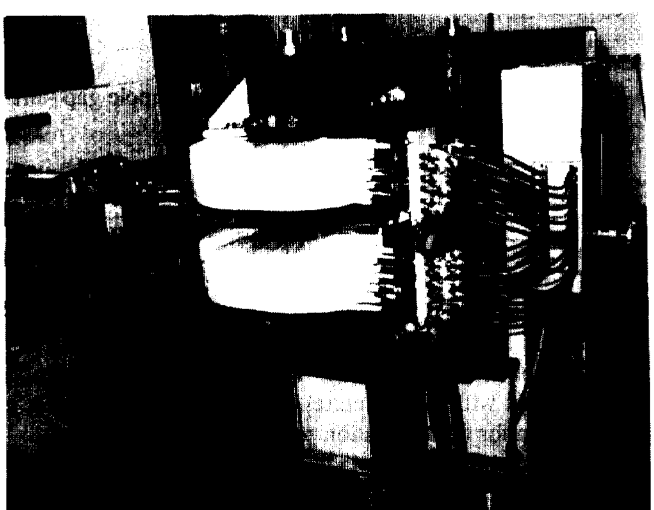

Fig. 3: Second prototype dipole in the measurement setup.

Several details are involved in the laser milling process, in order to achieve the tight tolerances of the laminations. The first cut is for strain relieve. It runs through the middle of the gap and opens the coil window of the C-shape magnet. A subprogram then opens all the holes and guiding slots with the proper offset. The remaining of the contour is then cut at high speed externally and low speed for the gap. To cut the 72 special laminations for the Rugouski contour, another variable offset is introduced in the program. Each pair of laminations takes 20 minutes to be cut. The standard deviation of the dipole gap variation, measured before assembling, was 0.022 mm and all of the laminations had gap variations within the interval ±0.06 mm.

The mechanical measurements demonstrate the better quality of this second assembling procedure as shown in Figure 4. The standard deviation of the gap errors in the assembly is 0.026 mm (peak-to-peak 0.15 mm), preserving reasonably well the original accuracy (0.022 mm std).

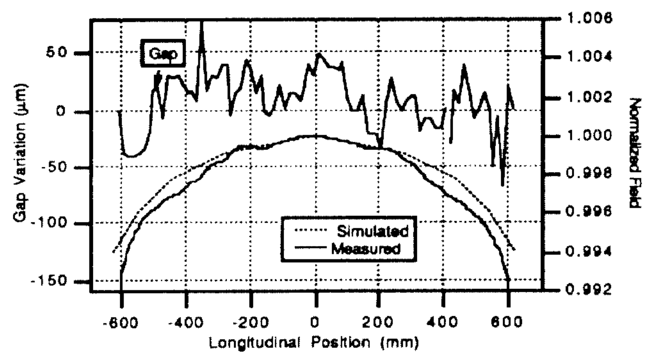

Fig. 4: Longitudinal distribution of the gap variation and field for the second dipole (no weldings) prototype.

The magnetic measurements showed no influence of the hole for the tie-rods in the transverse field homogeneity, as predicted by simulations (Figure 5). However, we failed to predict its influence in the longitudinal direction: the vertical field on the central orbit decreases from the center of the dipole towards the entrance and exit. Later simulations, using POISSON and taking into account the variable position of the tie-rods holes, predicted a similar effect (Figure 4).

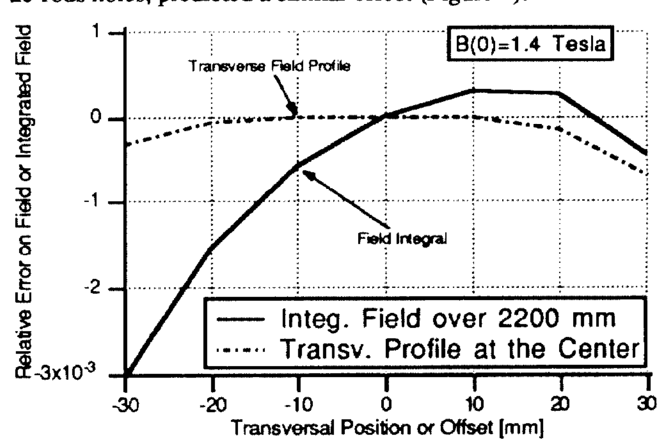

Fig. 5: Transverse field profile and integrated field over the electron orbit as a function of the offset, for 1.4 Tesla nominal field.

One additional effect is related to the integrated field. Figure 5 also shows the integral of the measured field along the orbit of the electrons as a function of its offset from the center of the pole. The data include two straights of 40 cm outside each side of the core. The variation of the integrated field (Figure 5), much higher than the transverse field profile, is due to the field produced by the coils at the entrance and exit of the magnet. This effect has been studied by Tatum *et al.* [2] and minimized by properly shaping the coils ends.

2.3. *Dipole Mass Production*

Mass production of the whole set of 12 dipoles for the LNLS storage ring would take about six months to cut the laminations, which compares well with the time to get them punched from the local industry (5 months, including tools).

Since there are ~460 different types of profiles, the shuffling procedure, necessary to evenly distribute small variations in material properties, has to be done before milling the laminations to the final shape in lots of 24 equal profiles.

3. QUADRUPOLE AND SEXTUPOLE

The quadrupole core is assembled in four blocks. Each block is stacked on a simple bench, using two perpendicular chamfers in each end of the pole tip as references. In the first quadrupole prototype, the four pieces were held together by eight screws pulling just the end-plates towards each other. For the second quadrupole prototype, a different clamping scheme was developed, with eight screws distributed along the side of each pair of poles, providing a much more uniform pressure on the interface between them. In order to achieve this, two types of laminations are used and stacked in a way that leaves niches for the eight screws. The sextupole core follows the same scheme.

The harmonic contents of the second quadrupole prototype, with a square pole end, are shown in Figure 6. They were measured using a pair of radial rotating coil with normalized radii of 1, 5/8, -1/8 and -1/2 connected either in the non-bucked (quadrupole) or bucked (higher harmonics) configurations. The induced signals are collected synchronously with the pulses of a shaft encoder (1024/turn) and directly Fourier analysed, without integration. The revolution frequency, 3 Hz, is stable within ±0.01%.

CONCLUSIONS

We have demonstrated that the mechanical tolerances required for storage ring magnets can be achieved by the laser cutting process. It is also an ideal process for prototyping work, the production of special purpose devices, such as septa magnets, and production runs of small and medium size accelerators.

It was also demonstrated the possibility of assemblying large laminated magnets without welding or gluing the laminations.

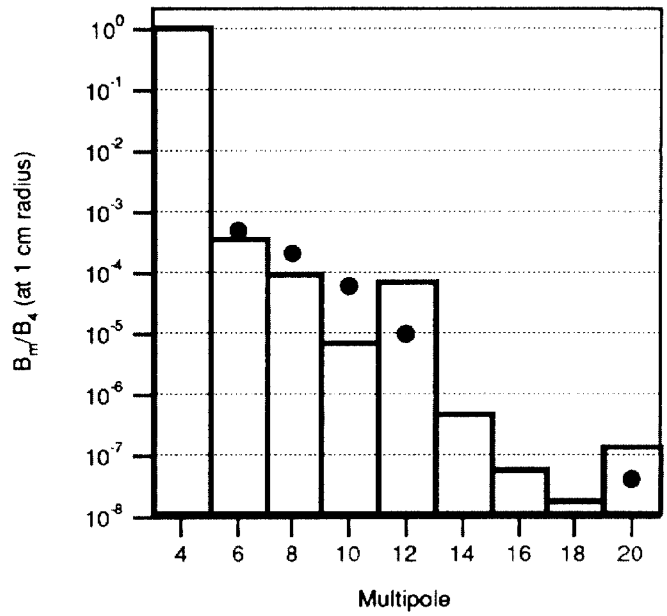

Fig. 6: Normalized harmonic contents of the second quadrupole, measured with a rotating coil. The full circles are the rms values for the randon multipole errors assumed in the dynamic aperture calculations.

---

* Also at IFQSC/DFCM/University of São Paulo
** Also at IFGW/University of Campinas

[1] User's Guide for the POISSON/SUPERFISH Group of Codes, Los Alamos Accelerator Code Group, LA-UR-87-126.
[2] B. A. Tatum *et al.*, "Design, Construction, and Field Mapping of the HISTRAP Prototype Dipole", Proc. IEEE-PAC, p. 393, 1989