DESIGN, CONSTRUCTION AND TESTING OF SMALL, INTENSE PERMANENT MAGNET SEXTUPOLES

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Abstract

The mechanical and magnetic design, the construction and the magnetic testing of a series of permanent magnet sextupoles with 5 mm inscribed radius and field strength of 55,000 T/m^2 are described.

1 INTRODUCTION

Five novel permanent magnet sextupoles have recently been constructed by Sincrotrone Trieste for INFN, Italy and for the Technical University of Chemnitz Zwickau, Germany. The magnets will be used for focusing and spin selection of atomic hydrogen beams. The specification of the magnet called for an internal radius of 5 mm, an outer radius of less than 50 mm, a length of 150 mm, a sextupole coefficient (B/r^2) of at least 50,000 T/m^2, with a "good field region" up to 60% of the inscribed radius. In addition, the magnet had to be compatible with operation under UHV conditions and with a 150 ^{o}C bakeout temperature.

2 MAGNETIC DESIGN

An assessment was first made of the possibility of constructing the magnet entirely out of permanent magnets, as suggested in ref. [1]. Assuming μ=1 material the sextupole strength is given by the following formula :

$$B_3 = \frac{3}{2} B_r \frac{1-(r_1/r_2)^2}{r_1^2} \cos^3(\pi/M) \frac{\sin(3\pi/M)}{3\pi/M}$$

where B_r is the remanent field, and r_1, r_2 are the internal and external radii of the trapezoidal permanent magnet pieces. With reasonable parameters of B_r = 1 T, r_2 = 20 mm, and M = 12 the equation above predicts a maximum sextupole strength of only 45,640 T/m^2, less than the required value. It was clear therefore that a "hybrid" solution with iron poles was required in this case.

A 1/12th segment of the complete magnetic structure, shown in fig. 1, was studied using the POISSON program [2]. It was quickly realised that a region of reverse field is always present in the magnet, up to 1.5-2 T very near the magnet surface and higher than 0.5 T in a region of typically 1 mm^2. Since for NdFeB material the maximum available values of intrinsic coercive force were (at that time) of the order of 0.8-0.9 T, at 150 ^{o}C, it was feared that irreversible losses would be too large in this case. To avoid this problem it was therefore decided to use a material with a higher coercive force, namely Samarium Cobalt.

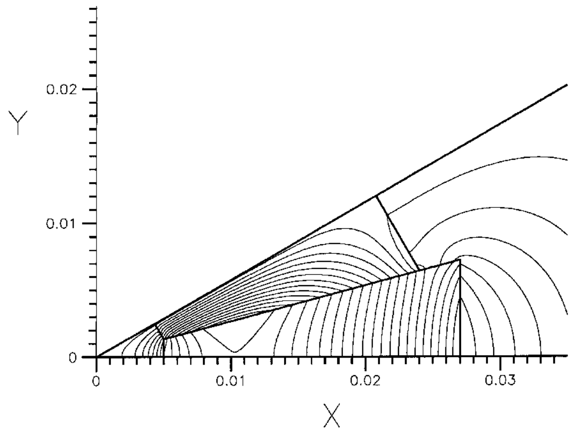

Figure 1: Magnetic flux distribution in a 1/12th segment of the sextupole magnet.

Optimization of the magnet and pole dimensions was carried out assuming $SmCo_5$ material. Armco was chosen as the pole material for reasons of cost, availability and ease of machining. Calculations showed that the highest possible remanent magnet field was not required, since slight adjustments of pole and magnet height could be made to obtain the desired field level. Care was taken to limit the degree of saturation in the pole tip, and reverse field in the magnet. A pole overhang was not found to be beneficial since it caused a reduction in sextupole strength while increasing pole saturation. A magnet overhang at the outer radius was found to increase field strength, but had to be limited so as not to increase pole saturation and reverse field in the magnet. The effect of changing the wedge angles of the pole and magnet was also investigated, however a deviation from the symmetric case was found to deteriorate the field quality (uniformity of sextupole field) significantly. Finally, the effect of shaping the pole surface was studied. A rounded pole was found to give a lower field strength, with no significant change in field quality, and so was not adopted. For the final geometry with pole and magnet heights of 19 mm and 22 mm respectively, a sextupole coefficient of 60,500 T/m^2 was predicted for material with a remanent field of 0.984 T with μ = 1.06.

3 MECHANICAL DESIGN

Given the small dimensions of the magnets and poles, very high mechanical accuracy was essential both to guarantee a successful assembly and to minimize pole positioning errors that could result in poor field quality. The yoke therefore consists of a solid piece which simplifies the construction and eliminates potential positioning errors compared to a split design. Figure 2 shows a cross-section of the magnet.

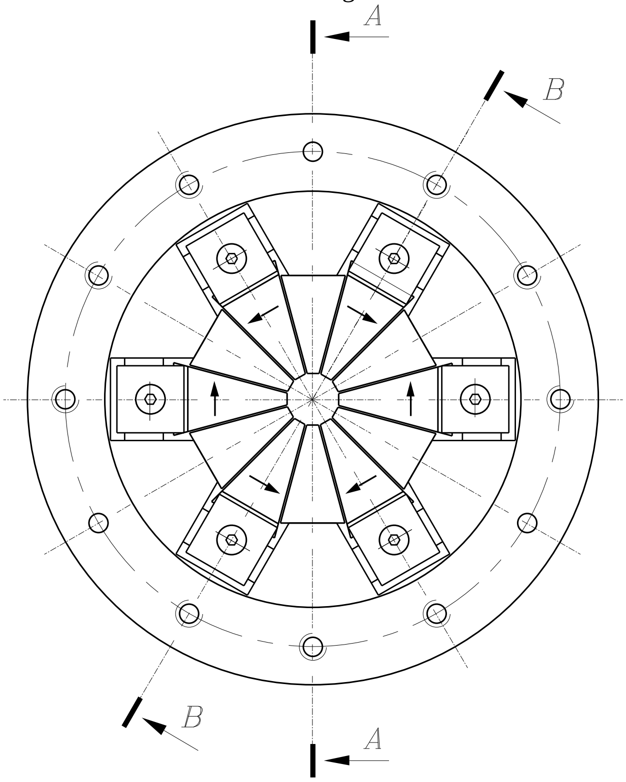

Figure 2: End-view of the sextupole magnet

Figure 3 shows a section through points A-A i.e. bisecting two of the magnet poles. Each pole is accurately positioned by means of 2 pins and fixed using 4 bolts. A further two holes were included for possible use in adjusting the field quality by means of ferromagnetic screws. Figure 4 shows a section that bisects the magnets. Because of the difficulty in producing magnets of the total 150 mm length, two separate magnets each 75 mm long had to be used. The magnets are held in position against the magnetic forces, which act radially outwards, by means of screws which force the magnets inwards. Clamps are used to secure the magnets at either end. For UHV compatibility screws have central holes, and there are additional holes in the structure for pumping the internal spaces.

4 CONSTRUCTION

Construction of the yokes and poles was carried out by Cinel S.r.l., Italy. The yoke is composed of Al alloy and was machined by electro-erosion.

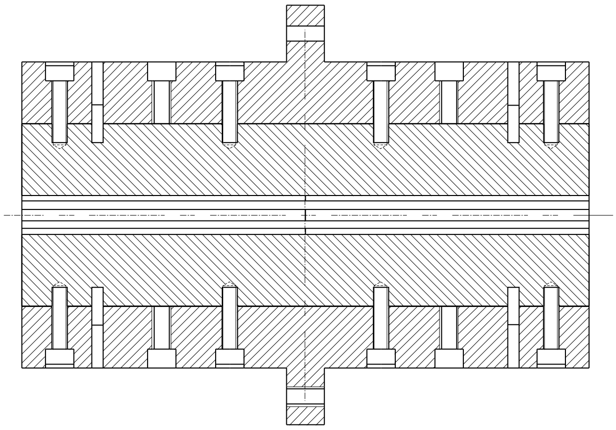

Figure 3: Cross-section through points A-A.

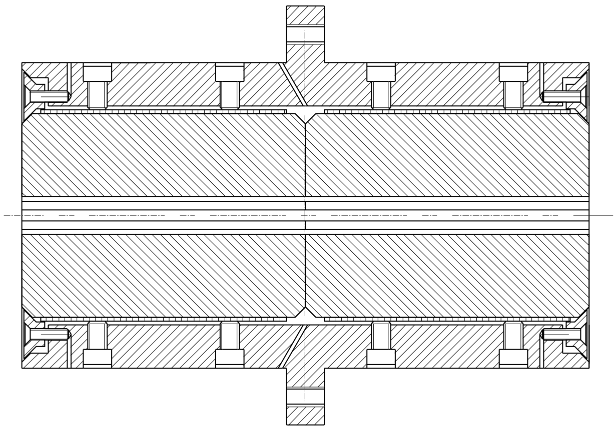

Figure 4: Cross-section through points B-B.

The permanent magnets were supplied by Vacuumschmelze, Germany (VACOMAX 170 HR) with measured B_r = 0.984 T, $\mu_o H_{c,B}$ = 0.929 T and $\mu_o H_{c,J}$ > 1.8 T. The blocks were coated with Nickel for surface cleanliness, ease of handling and assembly, and vacuum compatibility.

The total magnetization strength and its angle of deviation were measured by the supplier using a Helmholtz coil system and these data were used to perform a crude sorting of the blocks. Blocks with the largest angular deviations and smallest strength were firstly eliminated. The remainder were then ordered in terms of the total magnetization and divided into groups of six, in order to minimize the variation of magnetization within the group. The two groups of six that compose each magnet were then selected so as to result in similar total strength.

Before assembly in clean room conditions all pieces were firstly cleaned using a commercial solvent. The poles were attached and then the magnets inserted from the ends and clamped into position. The completed magnets were subjected to heat treatment at 150 ^{o}C in a vacuum oven. During this process pressure and residual gas analysis measurements were made. The results showed that after treatment the total pressure reduced from 1-2 10^{-6} mbar to 2-5 10^{-10} mbar. Initially various mass groups were present, notably H_2O, HO, H and H_2. After cooling the residual gas was composed essentially only of H_2.

5 MAGNETIC MEASUREMENTS

Because of the very small magnet aperture, measurements had to be restricted to the field integrals using a stretched wire bench that is normally used for measurement of insertion devices [3]. In this system a single 20-strand wire is translated within the magnet gap while the return side of the coil remains fixed in position. Two types of measurement were made by means of linear and circular scans.

In the first type of measurement, the wire was translated in the horizontal direction providing a measurement of the vertical field integral. Measurements were taken at a grid of points with 0.25 mm spacing; at each point the field is integrated over 0.5 mm. In order to overcome statistical fluctuations of about 1 % in the integral values, due most probably to the positioning accuracy, the data were averaged over ten scans. An attempt was made to fit a polynomial to the data in order to extract the harmonic content, however this proved unreliable. Instead the local sextupole coefficient was obtained by least-squares fitting a quadratic function to each group of 5 points.

The first magnet to be built was measured both before and after heat treatment at 150 ^{o}C. Before treatment a sextupole field of 57,625 T/m^2 was obtained, assuming a magnetic length of 150 mm. The discrepancy of 5 % with respect to the POISSON prediction is not at present understood. One possibility is that it is caused by the working point in some regions of the permanent magnet material being driven too far in the 3rd quadrant, either in the final geometry or during assembly.

After heating the strength was determined to be 3.1 % lower due to irreversible magnetization losses. No change was observed in the sextupole field homogeneity. The measurement of all five magnets yielded an average strength of 55,876 T/m^2 with total spread of 1.7 %. No significant variation was observed in field quality. Figure 5 presents the average of the values of sextupole coefficient as a function of horizontal position; the error bars represent the rms variation over the series of 5 magnets. It can be seen that the field quality is very good up to a radius of 3 mm, beyond which it begins to deteriorate, in good agreement with the POISSON prediction.

The second type of measurements were made by performing a circular scan with a radius of 3.5 mm. Data were taken at intervals of 2π/32 radians, although at each point the integration was made over 2π/16 radians. After Fourier Analysis the data yielded the multipole terms directly [3]. As before, each magnet was measured 8-10 times and the results averaged. The result for the main sextupole term was an average of 55,718 T/m^2 with a total spread of 1.4 % for the 5 magnets, in excellent agreement with the results from the linear scan. No higher harmonics up to 18-pole could be measured within the reproducibility of the system, which was about 0.3 % (rms) of the main component at the measurement radius. Lower order terms were consistent with a positioning accuracy of the magnet with respect to the measurement bench of the order 0.1 mm.

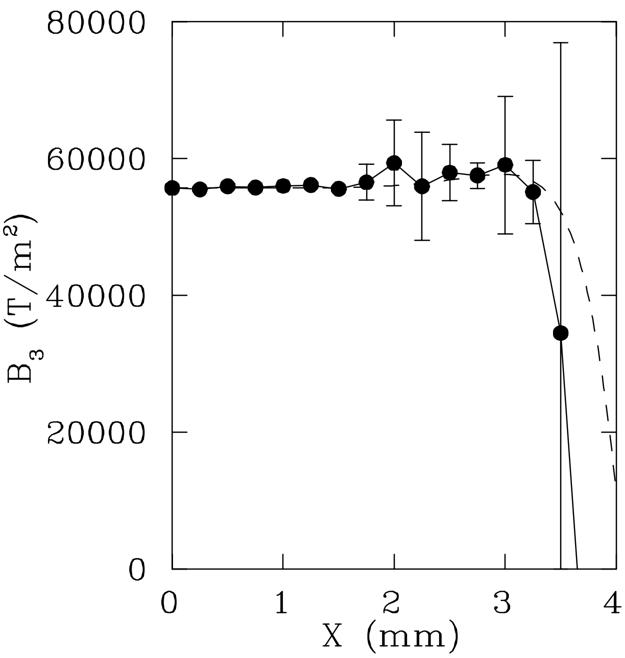

Figure 5: Measured (points) and predicted (dotted line) variation of sextupole coefficient with horizontal position

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