MAGNETIC MODELING, MEASUREMENTS AND SORTING OF THE CNAO SYNCHROTRON DIPOLES AND QUADRUPOLES

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Abstract

CNAO is a synchrotron accelerator presently under commissioning in Pavia. The aim of this accelerator is to treat tumors with hadrons and to perform advanced clinical and radiobiological research. The CNAO will start treating patients with protons (60 – 250 MeV range) and carbon ions (120 – 400 MeV/u range) in three treatment rooms with four beam lines. Future upgrade with gantries are foreseen.

This paper describes the design, magnetic measurements and sorting criterion used for the sixteen synchrotron main dipoles and twenty-four quadrupoles. The magnetic measurements results are compared with magnetic simulation.

INTRODUCTION

The CNAO synchrotron physical performances derive from a set of medical specification; mainly from the dose delivery precision, beam size accuracy at the patient and beam position accuracy. To obtain the needed accuracy at the patient location also the synchrotron magnets have very strong requirements in term of integral homogeneity. These tolerances have been achieved not only with an accurate design but also with a strong follow up of the construction steps and an accurate campaign of magnetic measurements. As final step the position of each magnet in the ring was decided by taking into account the real performances of each magnet and simulating their effects on the beam.

DIPOLES

The main parameters of the dipoles are: gap = 72 mm, deflection angle = 22.5°, bending radius = 4.231 mm, maximum field = 1.5 T, good field region = 120x56 mm^2, integral homogeneity < $\pm 2.0 \cdot 10^{-4}$.

The synchrotron ring comprises sixteen dipoles. A seventeenth dipole is connected in series with the others and is used to measure the B field (B-train). Since the power supply is unique, the integral field and the dynamic performances of the magnets should be as homogeneous as possible. It has been chosen to use the same dipoles also in the extraction lines in order to have a larger pool in which to choose, which has improved the performances by at least a factor two.

These dipoles do not work at constant field level, but must be ramped in order to follow the growth in energy of the beam. For this reason the yoke is not solid but laminated. Particular care has been taken in the composition of the yokes. The steel supply has been divided in eight classes based on the value of the coercive field (measured for each batch by the supplier). After defining the shuffling procedure, the B-H curve of a stacked sample has been measured in order to confirm the validity of the method.

The dipole's design has been carried out by using 2D and 3D FEM code [1]. On the basis of 2D model the lamination profile has been optimized. With the 3D model, the homogeneity of the dipole field has been evaluated by tracking particles with zero divergence and with a starting point inside the limits of the good field region. Far enough from the dipole, it is required that the relative bending error would be less than $2 \cdot 10^{-4}$. To optimize the homogeneity out of the middle plane a chamfer of 20 mmx20 mm has been foreseen. To permit the possibility to correct local deviations of the magnetic length of the real magnets, the dipole ends are equipped with seven removable blocks, already chamfered, with the possibility to insert extra laminations in each block.

Magnetic Measurements

The dipoles were magnetically tested at CERN (see Figure 1) using a dedicated fluxmeter, i.e. a set of 12 parallel 2755 mm-long search coils, shaped to follow the theoretical beam orbit and covering a width of ~190 mm. An additional coil, placed on its own support, has been used as a moveable reference. In pulsed powering mode between currents I_1 and I_2, digital integration of the induced voltage provides the change of integrated field ($\int BdL_2 - \int BdL_1$) irrespective of the function I(t) followed.

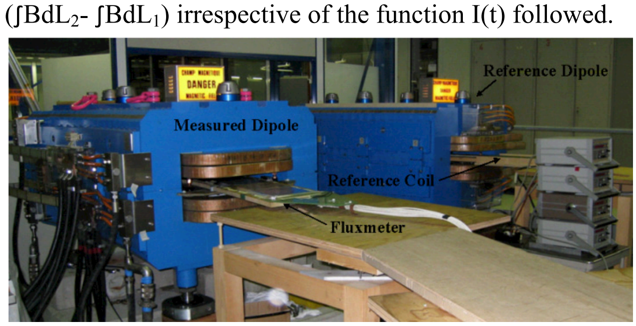

Figure 1: Measurements set-up at CERN site showing the measured dipole with the fluxmeter and the reference dipole containing the reference coil.

The homogeneity in the horizontal plane was obtained by bucking the signal of the fluxmeter's central coil with each other coil in turn. After shimming, a region 120mm wide, has been obtained in which the integral homogeneity is within the $\pm 2 \cdot 10^{-4}$ specification as shown in Figure 2

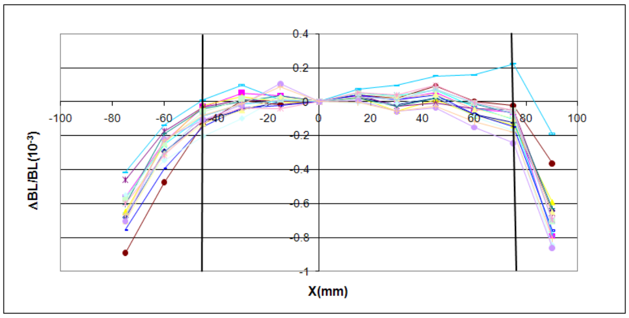

Figure 2: Summary of the homogeneity measurements at Y=5mm for I=2800A. The two vertical lines show the region within the $\pm 2\cdot 10^{-4}$ specification.

The homogeneity in the vertical plane was obtained by bucking the signal of the central coil of the fluxmeter with the signal of the reference coil moved vertically.

The ∫BdL of each dipole has been measured and shimmed by comparing it with another one, chosen as a reference, kept on site throughout the campaign and powered in series. The difference signal of the central fluxmeter coil in the tested dipole and the reference coil in the reference dipole is free from effects due to common mode and current fluctuations, thus allowing to track within $\sim 10^{-4}$ relative accuracy.

In Figure 3 the summary of these measurements is reported. The black line shows the average value. The dipole whose behavior is closest to this line has been selected for B-train measurements. The magnets whose behavior is far from the average have been selected for extraction lines. Anyway a set of 17 dipoles within $\pm 0.5\cdot 10^{-5}$ can be found.

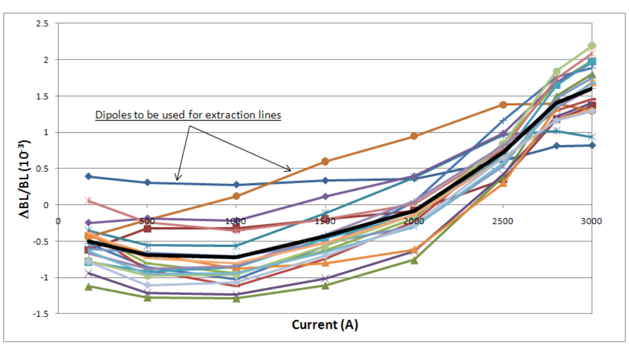

Figure 3: Tracking measures summary. The black line is the average value.

Shuffling

Starting from the fluxmeter measurements an harmonic analysis of the integrated magnetic field was made by fitting the experimental data with a multipole series expansion, truncating the series at the 3rd order (sextupole). In Figure 4 the fitting made for a ring dipole is showed as example.

To calculate the effect of the real performance of the dipoles on the beam the MAD program [2] was used. The 16 dipoles were randomly (with a random generator sequence) positioned in the synchrotron ring (about 800 cases were studied). At each dipole the difference in magnetic length from the average curve (showed in Figure 3) is applied as a dipole field error. Due to these errors the closed orbit does not coincide with the reference orbit (closed orbit distortion COD). For each sequence a "merit factor" was defined by calculating the maximum correctors strengths needed to correct the initial COD and the maximum value of the final COD.

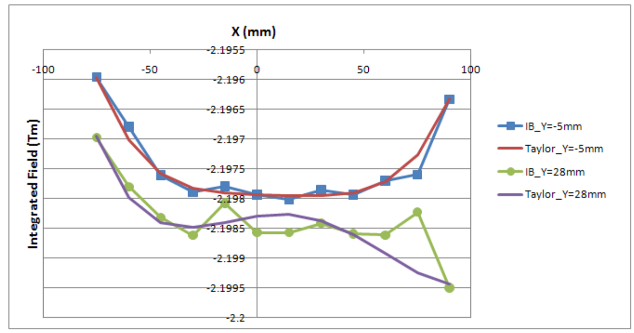

Figure 4: Fitting of experimental data with a 3rd order multipole expansion at I=2800A.

In Figure 5 the difference between a good sorting of dipoles compared to a bad sorting is reported. Choosing a good sorting is in principle possible to keep all the correctors strength at the 50% of their maximum value for all the current range.

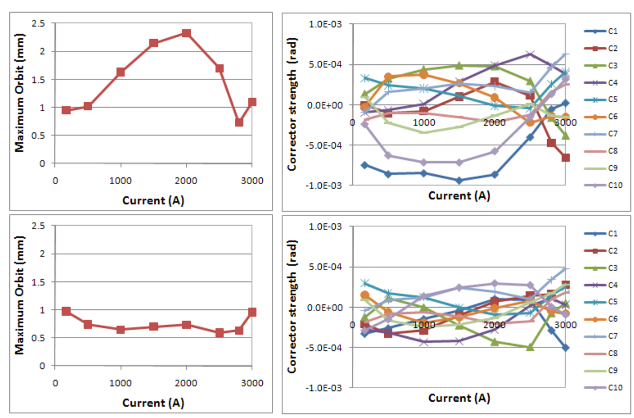

Figure 5: Difference between a good sorting (lower case) and a bad sorting (upper case).

When the position of each dipole was fixed, the effect of quadrupole and sextupole errors was calculated evaluating the variation on tune and chromaticity. The variation of tune applying quadrupoles errors is of the order of ~3‰. To correct this deviation the forces of the three quadrupole families must be changed by ~2‰. Similarly the sextupole components vary the chromaticity by ~20%, to correct it sextupoles strengths change by ~20% which is well inside power supply performances.

QUADRUPOLES

The 24 ring quadrupoles are divided in three families: two horizontally focusing and one defocusing in the same plane. The quadrupole characteristics are: bore radius=85 mm, magnetic length=350 mm, maximum gradient=3.65 T/m, good field region=120x60 mm^2, Integral homogeneity < ±8.0 10^{-4}); the three quadrupoles families will be powered by independent power converters.

Magnetic Measurements

Magnetic measurements of the quadrupoles were carried out at INFN laboratories in Frascati. A description of the instrumentation used in LNF can be found in [3]. Magnets were tested at different (but DC) current sets, spanning from approximately 0.07 I_{max} to I_{max}.

Preliminary measurements of the quadrupole gradient, field profile and magnetic length were done with Hall probe mapping. An extensive set of tests was then carried out on the rotating coil measuring bench (see Figure 6). The measurement devices sensibility for the harmonics of interest is of the order of 10^{-4}.

On a prototype magnet the best pole chamfering depth was tested. An 18 mm cut reduced B_6/B_2 term by a factor ten (to a final value of about 5 10^{-4}). All series magnets were then machined with the same chamfer depth.

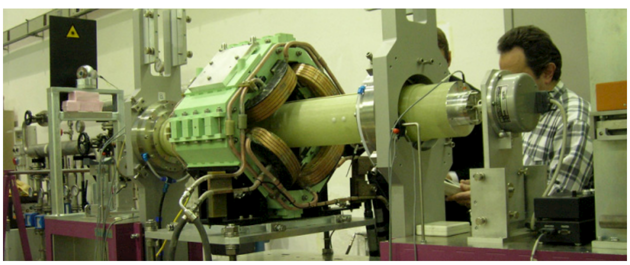

Figure 6: Synchrotron quadrupole on the rotating coil measuring bench model.

Series quadrupoles were measured with the rotating coil instrumentation. For each magnet, at all current level, the harmonic terms B_n/B_2 (with $4 \leq n \leq 10$) were less than 5 10^{-4}. Concerning the sextupole term B_3/B_2, at every current level, is below 9 10^{-4}.

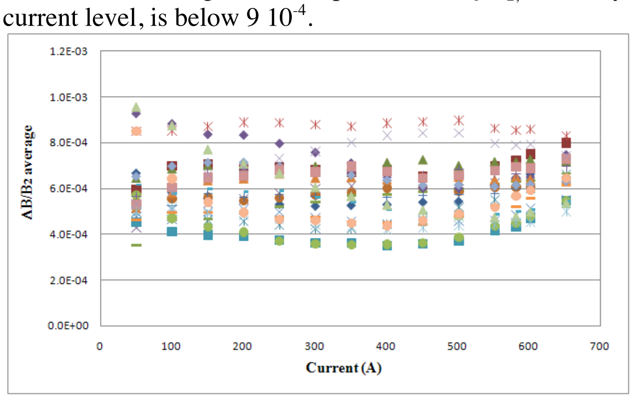

Figure 7: Total field error on the good field region border at different current levels for all the 24 quadrupoles.

Figure 7 shows, for each magnet and for each current level, the total field error $\Delta B/B_2$, averaged on the good field region border (r = 67 mm).

Shuffling

To study the best position of quadrupoles along the ring we have considered the measured sextupolar term of the quadrupoles. These terms have been added to each quadrupole in the MAD file that describes the synchrotron. In the synchrotron there are two types of sextupole magnets: the chromaticity and the resonance sextupoles. If the strength of the chromaticity sextupoles is varied the chromaticity changes but the resonance excitation does not change (see Table 1). If the strength of the resonance sextupole is varied, chromaticities into the two planes (x,y) do not change because the dispersion function at the resonance sextupole position is D=0.

We have positioned the quadrupoles with the bigger sextupolar term in the region of the synchrotron with the smaller beta functions. The quadrupoles with similar sextupolar term and same sign have been positioned in the opposite position because the sextupolar terms are compensated (but the chromaticity is added). The overall effect is basically negligible as shown in Table 1.

Table 1: Calculated Chromaticities for Carbon Ions at Maximum Extraction Energy.

Chromaticity	Nominal	Non Corrected
Q'_x	-4.0	-4.03
Q'_y	-1.0	-1.01

CONCLUSIONS

The Magnetic measurements of dipoles and quadrupoles confirm the prediction of FEM models.

Dipoles measurements were approximately in specification. The choice to have dipoles in the extraction lines identical to the ring ones was successful and allowed to choose the best dipoles for the synchrotron. The results of the measurements have been used to decide final position of each dipoles. With a good shuffling the corrector strength can be kept at 50% of its maximum and the COD to 1mm. Also multipole effects can be controlled by adapting the current of quadrupoles and sextupoles.

Quadrupole measurements shows that the harmonic content of each quadrupole is less than 9 10^{-4}.

Shuffling of quadrupole magnets has been performed in order to minimize the effects of the sextupolar terms on chromaticities and resonance of the ring.

REFERENCES

[1] OPERA®, Cobham Technical Services; http://www.vectorfields.com.

[2] MAD (Methodical Accelerator Design), http://mad.web.cern.ch/mad/.

[3] F. Iungo, M. Modena, Q. Qiao, C. Sanelli: "DAFNE Magnetic Measurement Systems", technical note MM-1, 4/11/1993 http://www.lnf.infn.it/user.html.