ANALYSIS OF THE FINAL MAGNETIC MEASUREMENTS OF THE LNS SUPERCONDUCTING CYCLOTRON

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The magnetic field measurements of the pole region of the Catania Superconducting Cyclotron were completed after the installation of a few iron shims compensating the first harmonic component. The final mapping of the base field and of the trim coils contribution is described. The analysis of the field and the generation of the field maps for the beam dynamics calculation are reported.

1 Introduction

The magnetic field of the Cyclotron was firstly measured in Milan. These measurements[1,2] showed some important features of the field behaviour:

- the measured iron field had the same radial shape as the calculated one, with differences in level of the order of 100 gauss;
- the 3rd harmonic was almost constant over the whole operating diagram, with differences of about 1% between the maximum and minimum values, so confirming the assumption of full saturation of the iron sectors also at $B_o = 2$ Tesla;
- the origin of different contributions to the 1st harmonic of the field was understood, although nothing was done to minimize it because of the reduced number of maps.

After these field measurements, the Cyclotron was disassembled and moved to LNS, Catania, for its final installation.

A summary of the final measurements accomplished in Catania is reported in the following, with particular regard to the control of the field imperfection and to the field analysis performed to generate the maps library.

Soon after the conclusion of these measurements, beam tests began to be carried out.

2 Measuring system

A flip coils system was used for the Milan measurements. The installation of the Cyclotron in Catania called for a new measuring system: the usable vertical gap between the poles was smaller than in Milan due to the liner assembling; moreover many more maps were planned to be acquired, so the new system had to be as fast as possible. Based on the experience of other laboratories, we selected a measuring device[3] applying the search coil technique, which could guarantee a measurement accuracy of 1 gauss. The measuring bar, containing a moving search coil, had an overall height of 23 mm, tightly fitting the 24 mm vertical gap between the two liners. The measurement time of a full 360° map, 1° x 0.504 cm spaced, is only 50 min.

A delicate point of field mapping was the mechanical positioning of the measuring device: a position error of 0.1 mm may cause an error of 15 gauss (maximum field gradient is 15 T/m). Since it is quite impossible to position mechanically the system within 0.01 mm, a correction procedure was applied on the maps, based on the possibility of the mapper to start the radial scan well before the rotation axis, so as to duplicate a big amount of data.

Acquired maps were processed[4] in order to detect and correct intrinsic mechanical and non mechanical errors originating from position and movement imperfections of the measuring device, as well as from electronics (mainly integrator drift).

3 Preliminary measurements

The test of the new measurement system was done immediately after the first cool-down of the Cyclotron in Catania, that is at the end of 1992. Unfortunately, an accidental movement (1.5 mm) of the vacuum tank[5] made impossible to proceed with regular measurements. Nevertheless, some tests measurements at low magnetic field were accomplished aiming to know the 1st harmonic form factor of the vacuum tank shift. Moreover, many calibration and reproducibility maps[3] were done and on-line control and off-line software was improved, so as to spare time during regular mapping.
In October 1993 the measurements were resumed. The magnet was excited exploring the whole operating diagram of the machine; at the end of this excitation operation the main coils were left in a position minimizing the maximum radial forces acting on the tie rods, the so called 'equilibrium' position. The first measurements showed a 1st harmonic component of the field of 25-35 gauss, not acceptable for the beam dynamics. Then it was decided to make some additional measurements devoted to the 1st harmonic analysis; the source of these large values was thought to be a coil off-centering and an insufficient compensation of the yoke holes contribution.

4 Coils centering

After getting rid of the measurement system positioning errors by means of negative-positive radii symmetry analysis and imperfection harmonics analysis, the residual 1st harmonic was treated in the field range 2.7-3.7 Tesla. This field range was chosen in order to eliminate different contributions as much as possible: measurements done with the yoke compensators showed that the yoke influence is significant above 3.6 Tesla; below 2.7 Tesla the poles are probably not fully saturated, so they may magnify the 1st harmonic produced by a coil displacement.
For each radius, the 1st harmonic variation measured within the above mentioned field range was fitted with a two dimensional function of I_α and I_β. The results show that even in this restricted field range, the current dependance of the 1st harmonic is not sufficiently linear; as a consequence there is no enough small current range where the form factor for coil displacement is the same as the form factor for current variation. For example, assuming a certain form factor derived by current variation led to a consistent overvaluation of the coil shift.
The remaining method for evaluating the coils position was to find such a position of the coils which minimized the 1st harmonic variation for all the current values included in that field range. The form factors for coil displacement were measured for three consecutive displacements of the coils (0.7 mm, -23°; 0.6 mm, 67°; 0.4 mm, 215°). Using these data it was possible to predict the position of the coils which minimized the 1st harmonic variation with current. The resulting position was 0.5 mm, 40°, hereinafter called 'central' position.
After having displaced the coils 0.5 mm, 40°, it was found that the forces acting on the coils did not allow to reach field levels above 4 Tesla. However it was clear that for all measurements in the field range 2.9 - 3.9 Tesla, the 1st harmonic varied less than 3 gauss (due to a residual 0.1 mm off-centering), whereas in the previous position this variation was about 8 gauss (Figure 1).

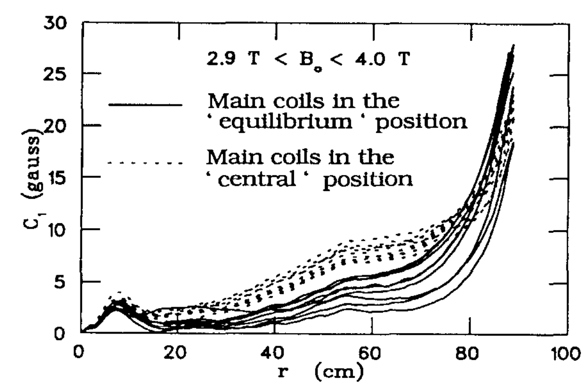

Figure 1: First harmonic measured before and after coils centering

5 First harmonic compensation

The coils centering did not solve the 1st harmonic problem, as can be easily deduced from Figure 1.
The residual 1st harmonic was recognized to originate mainly from poles and sectors imperfections (probably some sort of misalignment) and from vacuum chamber off-centering. Nevertheless it was decided to compensate all of these contributions by installing iron shims without moving the vacuum chamber, not being possible to check on line the results of the chamber movement, which, on the other hand, was quite complicated to accomplish. Taking as a reference point the 1st harmonic measured with the coils in the central position, we designed six iron shims, which were installed on the valley floor (4 of them), close to

the valley skirt (1 of them) and in a hill under the electrostatic deflector (1 of them). Figure 2 shows the 1st harmonic measured before and after the compensation at the selected point (I_α , I_β).

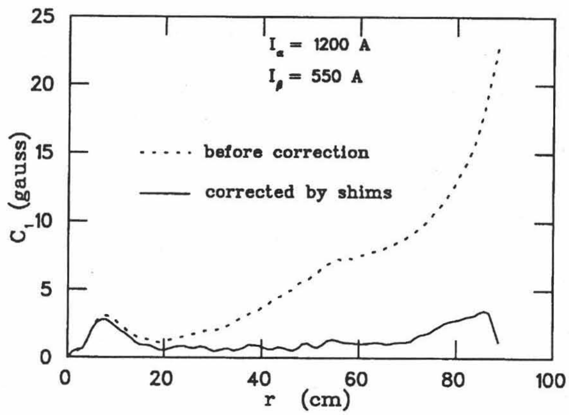

Figure 2: Effect of the shims on the measured 1st harmonic

6 Trim coils

A number of maps were acquired to investigate the dependance of the trim coils efficiency upon the field level and I_α/I_β ratio, and to ascertain the linearity of their form factors against their excitation current. For these preliminary measurements, only two trim coils were considered, thought to be representative of the whole set. To check linearity, maps were taken in one point of the operating diagram, at 2.8 T, exciting the trim coils at -400, -200, 200, 400 A; linearity was confirmed within the measuring errors. The variation

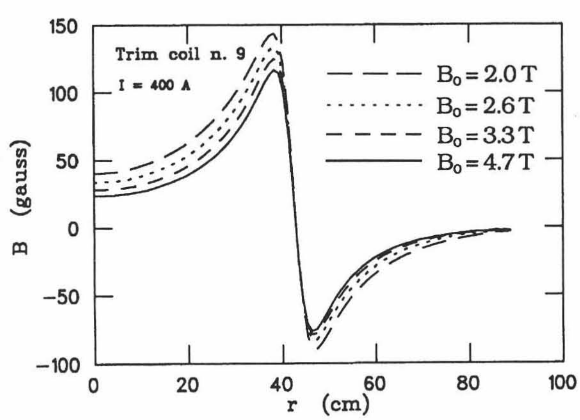

Figure 3: Trim coil n. 9 form factor at different field levels

of the trim coils form factor was explored in 15 points of the operating diagram, exciting the trim coils at 400 A. Based on these measurements, it was decided to map the trim coils in 8 points of the operating diagram corresponding to the field levels 2.0, 2.6, 33, 4.7 T. For each level, two extreme (I_α,I_β) points were considered (Figure 4).

The trim coils were measured over the full azimuthal extension, acquiring 2° spaced maps; no significant deviation from the three-fold symmetry has been detected. The variation of the form factor with the field level is shown in Figure 3 for the trim coil n. 9.

7 Final mapping

As already mentioned, the shims were designed taking as a reference point the 1st harmonic measured with the centered coils. Then the shims contribution was added to the maps measured with coils in the 'equilibrium' position; the result of this simulation was considered to be acceptable for the beam dynamics. Considering that a field higher than 4 Tesla was not reachable with the coils centered, it was decided to measure the grid maps in both the coils position. The operating diagram is displayed in Figure 4, showing the measurement points.

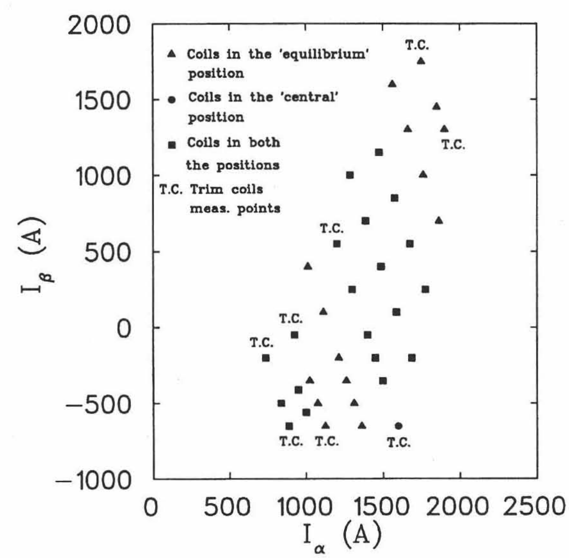

Figure 4: Operating diagram of the Catania Cyclotron

A total of 70 maps, 1.008 cm x 1° spaced, were measured over the full azimuthal extension with the coils in the two positions. When only a few maps were left, some troubles occurred with the measuring system, consequently those maps are missing (see Figure 4).

The maximum 1st harmonic measured amplitude of all the maps is below 10 gauss at the last measurement point (r=88.7 cm), as shown in Figure 5. Obviously, the 1st harmonic values measured with the coils centered are lower (by 3-5 gauss maximum) than the corresponding ones with the coils in the equilibrium position. What is more significant for the beam extraction is the value of the 1st harmonic in the region close to $\nu_r = 1$, which occurs at R = 82-84 cm. It has been checked for a few cases that the contribution of the harmonic coils 19-20 is sufficient to control the extraction of the beam, also for the coils in the equilibrium position.

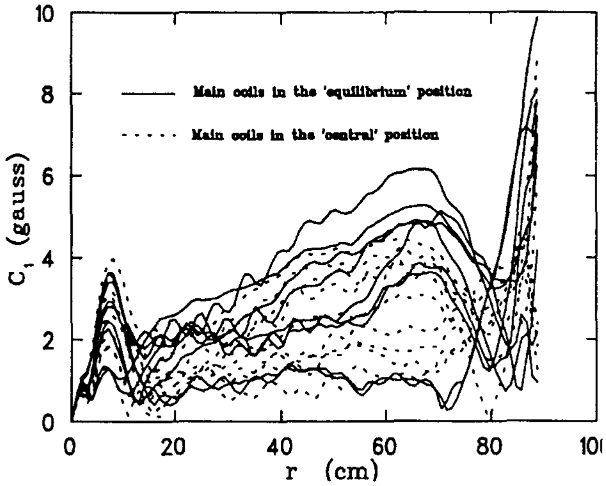

Figure 5: First harmonic measured after shim installation with the coils in the two positions

8 Library generation

All the base field maps were checked for isolated big errors and analyzed as follows:

a) they were corrected for positioning errors using the already mentioned "symmetry" method and imperfection harmonics analysis;
b) they were Fourier transformed;
c) imperfection harmonics were smoothed using spline method in order to eliminate a radial wave-shape error (peak amplitude 1 gauss); the general radial dependance of harmonics was not corrected;
d) all harmonics were interpolated, within the measured range, to the step of 1 cm;
e) all harmonics were extrapolated to the radius of 90 cm;
f) the result of e) was inversely transformed to get 1 cm x 1° spaced field maps.

These maps form the base set and are used for the simulation of the beam injection, acceleration and extraction.

A similar procedure, although more complex, has been used for the generation of the trim coil library. Two sets of data have been generated: trim coils form factors (average field) and trim coils azimuthal modulation.

9 Conclusion

Two possible configurations of the machine (main coils in 'central' and in 'equilibrium' position) have been measured. The field imperfection, namely the 1st harmonic, has been compensated at a satisfactory level.

The measuring system, after careful debugging, has been very fast and stable (reproducibility of the order of 1 gauss); the trim coils measurements (obtained by difference of two maps) show very smooth data.

The overall precision can be estimated to be better than 10^{-4}, with some concern in the extraction region because of the extreme radial and azimuthal gradient.

The commissioning of the machine was successfully completed with the extraction of a 30 MeV/a.m.u. ^{58}Ni beam [6] using the nominal setting for the main coils and the trim coils current as well as for the other injection and extraction parameters calculated using the measured field data.

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