Final Mapping of the LNS Superconducting Cyclotron

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Abstract

The magnetic field of the Superconductig Cyclotron at LNS has been mapped. The first harmonic of the field has been analysed and corrected by a proper positioning of the main coils and by iron shimming. Trim coils efficiency was mapped for several points of the operating diagram. The overall accuracy achieved is better then 100 ppm .

1 INTRODUCTION

The crucial point of magnetic field mapping in a superconducting, compact cyclotron is the mechanical positioning of the measuring apparatus with respect to the cyclotron magnetic center . A position error of 0.1 mm may lead to a systematic measurement error of as much as 15 Gauss, since the maximum gradient of the field is 15 T/m. In the case of the delicate search coil system, it is actually impossible to position mechanically the system within the required accuracy of 0.01 mm. Therefore our mapper (described elsewhere [5]) was designed to start a radial search coil scan well before the axis of rotation. In this way a big amount of data (30 %) are duplicated. The data taken before the zero radius (*negative radii*) should be equal to the corresponding part of the map measured for *positive* radii when rotated by 180°. This is the base for the detection of misalignment errors in our system. The misalignment errors have to be known before one starts to analyse the magnetic field data because they affect all the measured imperfection harmonics [4] (in the case of magnet with a three-fold symmetry). The first harmonic, being the main source of field imperfection limiting the performance of the machine, was studied carefully. The problem is quite complex and will be discussed on section 3. The magnetic design of the cyclotron was presented in [1]. The grid of measured points on the operating diagram ($i_\alpha \times i_\beta$ plane) was the same used for the previous mapping [3]. The computer control of the measurement system is described in details elsewhere [5]. Here we mention only that the *shot* noise of the integrator has been eliminated by the integrator manufacturer thus allowing to simplify data aquisition process (constant cart velocity) and a dedicated control program for calibration was developed to ensure the accuracy of $3 \cdot 10^{-5}$ required for the calibration coefficient.

2 ERROR ANALYSIS

Calibration error.
The search coil calibration was done at *locus* of measurements. Two NMR probes, one placed at the cyclotron center, the second installed into a bearing arrangement in a RF hole, served as a calibration references. The software controlling calibration process secures the stem hole probe position error within 1 mm what corresponds to 0.15 Gauss over 1.5 T (10 ppm) systematic calibration error, whereas overall stochastic calibration error reaches a value of 20 ppm. An alignment of the central NMR probe is also not crucial because the horizontal field derivative 1 mm out of the magnet center is 0.15 Gauss/mm, and the vertical derivative 1 mm up of the median plane is 0.04 Gauss/mm. Futhermore, the rotation shaft may be misaligned in respect to the probe by 2 mm not giving significant systematic error.

Intrinsic mechanical imperfections errors.
These errors can be eliminated collating pairs of measurements in nominal points (θ, r) and $(\theta + 180^o, -r)$. Following errors was considered:

– **Incorrect $r = 0$ position of encoder and rotation axis out of the search coil path.**
These errors produce a measurement discrepancy for a given pair of points: $\delta B = 2\left(\frac{\partial B}{\partial r} z + \frac{\partial B}{\partial \theta}\frac{s}{r}\right)$, where $r = z$ is the *true* zero radius position of the system (the closest to the rotation axis point on the coil path) and s is the shortest distance between the coil path and the rotation axis. Thereinafter B stands for $B(r, \theta)$.

– **Rotational error** can be developed in Fourier series: $\frac{\vartheta_0}{2} + \sum_i \vartheta_i \cos(i\theta - \varphi_i)$, giving a field difference in corresponding points: $\delta B = 2\frac{\partial B}{\partial \theta}\left(\frac{\vartheta_0}{2} + \sum_i(\vartheta_{x_i} \cos(i\theta - \varphi_i)\right)$. The most important part of this error corresponding to $i = 1$ deforms imperfection harmonics except the 1-st one, hindering farther analysis.

– **Stripped tape (radius scale) imperfections**. The irregularity of stripes on the tape was found to be of the order of 0.015 mm for the duplicated part of map. This error can not be corrected for not duplicated radiuses.

– **Inclination of the axis of the coil α** may lead to the following error if contemporaneously the track moves in the plane distanced by λ from the median plane: $\delta B = 2\frac{\partial B}{\partial \theta}\frac{\lambda \sin \alpha}{r}$. For mechanically detectable angle α of the order of 1^o the λ error has to be of the order of 2 mm to be comparable to above mentioned zero radius error.

Intrinsic non mechanical errors.

– **Integrator drift**. The drift was measured each 10 radial scans and on line subtracted. A casual change of drift did not exceed 0.1 Gauss hence was neglected.

– **Radial encoder counter was tested after each scan** on the return of the cart and all erroneous scans was automatically repeated.

– **Coil inductance L - integrator input resistance R - velocity v.** When the cart velocity varies the following error arises: $\delta B = \frac{L}{R}\Delta\left(\frac{\partial B}{\partial r}v\right)$. In our case $L/R < 3\cdot 10^{-4}$ sec and $\Delta\left(\frac{\partial B}{\partial r}v\right) \ll 0.3\cdot 10^{4}$ Gauss/sec hence this error was neglected.

– **Leading cable noise.** With a proper choice of the cable we have reduced this error below 0.3 Gauss of the average field.

Imperfect axial alignment of the system axis.
This is not an intrinsic error of the measuring apparatus, so it does not reflect in the differences between *negative* and *positive* radius measurements. Nevertheless it can be analysed making a resonable assumption that all amplitudes of imperfection harmonics are not correlated to main harmonics. Then a discrepancy can be found between symmetry axis of the magnet and the rotation shaft axis [4]. Typically this discrepancy reaches 0.3-0.4 mm and must be corrected because it deforms significantly the first harmonic of the field, especially in the extraction region.

3 FIELD IMPERFECTIONS ANALYSIS AND CORRECTION

The first field mapping results were reported in [2],[3]. General conclusions set forth there have been now confirmed, although not enough informations were available at that time to disclose the sources of the first harmonic . Therefore special measurements have been carried out to find the 1st harmonic form factors. The problem is quite complex since there are several components contributing to the first harmonic and each of them depends on field level in a different way. It became soon evident that misaligned main coils give a first harmonic ,proportional to the off-axis displacement, non linear with the currents . Thereby it is of no use to measure their form factors trough currents changes only. The magnetization curves for the hills and the poles are shown in Fig.1 for field levels up to 3 T. It is clear that below the average field level 2.9 T poles

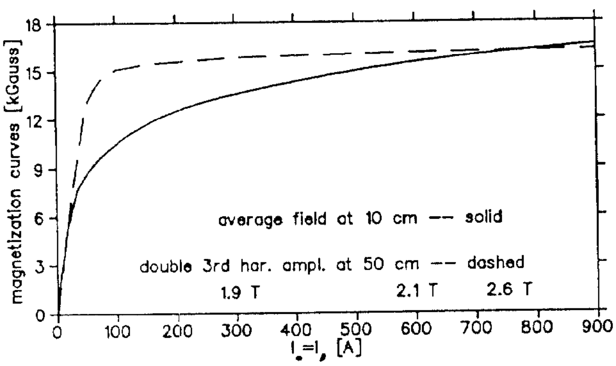

Figure 1: Magnetization curves for pole tips and poles

can not be assumed saturated. Therefore if there is poles contribution to the total first harmonic, it must increases with currents in a nonlinear way. On the other hand it was proved , by measurements of a yoke hole compensator, that above 3.6 T the yoke holes 1st harmonic becomes significant . A 450 A current variation in the alpha section of the coils produces a field level variation of 0.7 T ; assuming a coil displacement of 0.5 mm there will be a 1st harmonic variation of -0.8 Gauss at r = 65 cm and 1.6 gauss at the last measured radius R=89 cm. Such a small form factor is not easily separated ,by field measurements,from the total 1st harmonic contribution which can be of the order of 10 Gauss or more. Therefore the form factors for coils off-center were obtained trough the measurements of three movements of the coils respect to the initial position (0.7 mm/-23°,0.6 mm/67°, 0.4 mm/215°) with an accuracy of 0.1 Gauss/0.5 mm/500 A. Using these form factors, the variation of the 1st harmonic was minimized for various i_α/i_β currents in the field range 2.7÷3.7 T. The centered position of the coils was calculated with the accuracy of 0.1÷0.2 mm. The coils were then moved to the estimated position and new measurements were taken. A further 1st harmonic phase analysis has shown that the new coils position is still off-axis by 0.1 mm. The last value is not relevant for the 1st harmonic amplitude, but confirms the validity of the estimate. As a result we have found the magnetically centered position of the coils with the accuracy of 0.05 mm. Fig.2 shows the the 1st harmonic

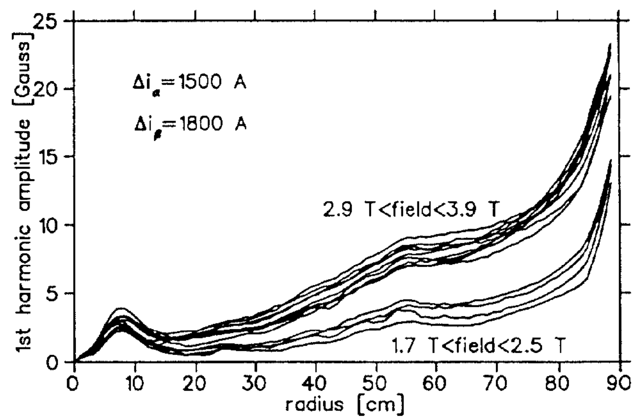

Figure 2: First harmonic due to pole tips, poles and vacuum chamber at various field level

measured for low field levels (1.7÷2.5 T) and medium field levels (2.9÷3.9 T) . The gap between the two separate sets of curves suggests that between 2.5 T and 2.9 T arise a new component of the 1st harmonic. It must be attributed to the poles imperfections since the sectors at this field levels are saturated (see Fig.1). Therefore the lower set of curves corresponds to hill – vacuum chamber imperfections whereas the upper one to total iron imperfections with the exclusion of the yoke holes contribution. It is worth to note that the 1st harmonic component produced by the vacuum tank cannot be separated from that produced by hill sectors since both have the same dependance with increasing field level. Some indications was found of a small magnetic off-centering of the vacuum tank; we have decided to compensate both factors with iron shims because in any case a vacuum tank displacement can not compensate hills imperfections for radii smaller then 80 cm. Knowing the

form factors of the first harmonic it has been possible to design six iron shims in order to compensate:
- hills and vacuum tank 1st harmonic - 3 Gauss/220° at 55 cm and 14 Gauss/290° at 88 cm.
- poles harmonic - 5 Gauss/220° at 55 cm and 13 Gauss/220° at 88 cm.

We have achieved a good compensation by placing 4 shims on the valleys ($r = 60 \div 87$ cm), one shim on the valley skirt ($r = 88.2 \div 89.7$ cm) and one shim on the pole tip under the deflector ($r = 88 \div 90$ cm). Fig.3 shows the 1st harmonic measured after shimming for some maps in the range 2.9 T÷3.9 T. The amplitude spread of 3 Gauss is due to the movements of the coils under the horizontal decentering forces and to the residual 0.1 mm centering error. The amplitude in the extraction region is of the order of 4 Gauss.

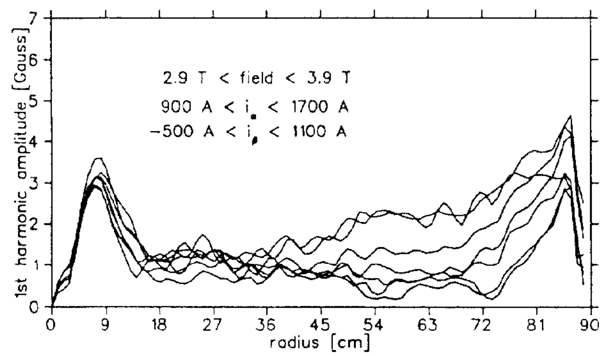

Figure 3: First harmonic measured after shimming

4 MAPPING

The coils in the magnetically centered position are about 0.5 mm out of the *equilibrium* position (opposite forces in the highest and lowest corner of the operative diagram) and are subjected to forces exceeding the tie rods strength at high field levels. This fact limits the operative diagram to field level up to 3.9 T. We decided to measure the *grid* maps in two coils positions; one corresponding to magnetic center (up to 3.9 T) and the second in the force equilibrium position (whole diagram). In the last position the 1st harmonic does not increase dramatically (maximum 8 Gauss in the extraction region) and its spread after shimming is still acceptable reaching 6 Gauss at radius 70 cm. Fig.4 shows the first harmonic measured with the coils in the *equilibrium* position for the whole scope of the operative diagram. Its amplitude generally decreases rapidly beyond the radius 70 cm. The 1st harmonic magnitude pertains well to the harmonic coils power thus it should not appear difficult to control. In the region of the resonance $\nu_r = 1$ (about $r = 82 - 84$ cm) the measured 1st harmonic mostly has relatively low value (appr. 4 Gauss). It is worth to notice that the curves correspond to the composed form factor of the main coils. Over 200 maps was measured to find up the trim coils efficiency for several average field levels and about 70 maps of *library* in the two coils position. The maps has been checked during measurements in respect of the errors listed in the section 2. They form the methodical data base for a farther analysis relating to the given beam acceleration. The setting of currents will be calculated trough the grid map and trim coils form factors interpolation. We expect an increased interpolation error for low fields ($\simeq$ 2.2 T) and high negative beta currents ($\simeq$-500 A) since in this part of the operative diagram the field changes very rapidly. For this reason the measured grid is more dense in the referred region.

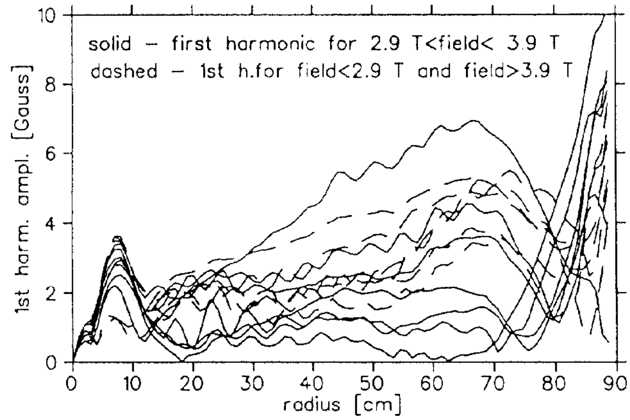

Figure 4: Total 1st harmonic in the coils *equilibrium* position

5 ACKNOWLEDGEMENTS

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