ANALYSIS OF THE MAGNETIC FIELD MEASUREMENTS OF THE MILAN SUPERCONDUCTING CYCLOTRON

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Abstract: The analysis of the magnetic field measurements of the Milan Superconducting Cyclotron is reported. The behaviour of the average field and of the main harmonics have been investigated over the operating range ($B_0 = 2 \div 4.8$ Tesla). An understanding of the magnetic field imperfections, mainly consisting of a large 1^{st} harmonic, has been reached and the contributions from the different components of the machine (main coils, cryostat, pole sectors, yoke) evaluated. Finally an analysis of the large forces acting on the coils is presented.

Introduction

The first field mapping of the Milan Superconducting Cyclotron was carried out in February '89 and a preliminary analysis with the main results has been reported in [1]. Following a major change in the schedule, the next field mapping is foreseen in spring '91 at LNS in Catania [2]. Therefore the analysis has been pushed as far as possible in sipte of the reduced number of maps and lack of some fundamental data. The hardware utilized in the measurements has been described elsewhere [3]. The system consists of a bar with 90 flip coils, 1 cm spaced, moving with a minimum angular step of 2°. The sensitivity of the flip coils is 1.8 Volt/Tesla and they have been calibrated in a conventional magnet at 1.5 Tesla.

The measurement accuracy was checked by investigating the behaviour of the average field and the increase of the iron field in the range $2 \div 5$ Tesla: it was found to be within $\pm$ 3 Gauss for about 80 flip coils; some showed consistent deviation from linearity, whereas 5 flip coils had an erratic behaviour such that their values were replaced by a fitting.

A systematic error was detected during the harmonic analysis and was later checked with mechanical measurements. The error was a sinelike 0.05° superimposed on the nominal constant 2° steps and was found by investigating the variations of the 2^{nd} and 4^{th} harmonic when the relative position between the flip coil bar and the angular driving system was changed. Such an error does not influence neither the average field and the main harmonics nor the 1^{st} one but strongly affects all the other imperfection harmonics.

Main Field

Average Field : Fig. 1 shows the operating range of the cyclotron magnet in the space of its main coil excitations. The two coils combine to make a field which is nearly isochronous for a given particle, thereby greatly reducing the required trim coil power. The α coil is closer to the median plane and is bigger than the β coil. Superimposed on the operating range is a regular grid of points; these were the excitations that served as the basis for the mapping array. The grid has been obtained by the intersection of the the magnetic flux contour lines, $3I_\alpha + I_\beta = const.$, with the lines given by $0.8I_\alpha - I_\beta = const.$ (0.8 is approximately the turn ratio N_β/N_α).

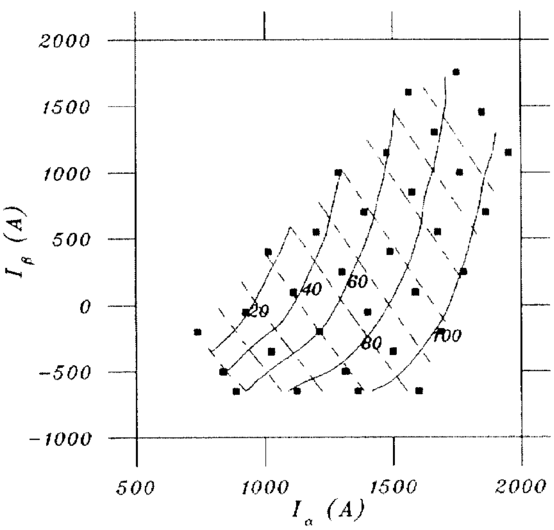

Fig.1: operating diagram with the mapping grid. Contour lines of the magnetic flux (dashed) and of the difference in 3^{rd} harmonic amplitude (Gauss) at radius 72 cm.

Once the air core field of the coils is subtracted from the measured average field we obtain the "iron" field. It has the calculated radial shape and small level difference of the order of 100 Gauss, well within the coils capability. The iron field increases smoothly with the field level and was possible to fit $B_{av}(r)$ in the whole range by means of a third order polynomial at $\simeq$3 Gauss except for the maps along the minimum flux line, see fig. 1. In particular the map at left-bottom of the grid shows a sharp change in the iron field, probably because the the β coil begins to de-magnetize the circular iron pole.

Field Modulation : The 3^{rd} harmonic is almost constant over the whole operating range of the cyclotron and within 1% of the calculauted value. In fig. 1 are plotted, with solid lines, the contour lines of the increase of the $3rd$ harmonic amplitude from the minimum value (map in the left corner) at r=72 cm. The variation is less than 100 Gauss while the field level increase from 2 up to 5 Tesla; the phase is constant within 0.4°. The behaviour of the amplitude is surprisingly different from that reported for MSU K1200 [4], being our increment contour lines almost perpendicular to the flux contour lines, whereas the phase shows the same trend with a smaller range. This fact is not easily comprehensible, being the magnetic structure of the two cyclotron very similar.

From fig. 1 one can see a weak dependance of the 3^{rd} harmonic on the I_α/I_β along the minimum flux contour line, whereas at higher field it mainly depends on I_α. This confirms that when I_β goes to negative values and I_α is relatively small the magnetization starts to change. The whole analysis, including also the higher harmonics, shows that the assumption of full saturation of the iron poles used for the machine design is quite good also at B_o= 2 Tesla.

Trim Coils : The behaviour of the trim coils shows a strong dependance on the field level, especially below 3 Tesla. While the efficiency peak at 4 Tesla is 15% higher than the air core calculation, at 2 Tesla it's 40% higher, and also the radial profile is somehow modified [1]. The dependance of the trim coils efficiency on the field level and radius was found but is not presently possible to evaluate all the parameters because more data are required, especially more maps at low field.

Shimming : Only a small correction is needed: a 1.5 mm thick shim from r=83 cm to r=90 cm over the full width of the pole tips. It's well within the margin left for the calculation uncertainty A modification of the central plug is needed but it was decided to wait for the confirmation in the next measurements, because some doubts are given by a flange that was found slightly magnetized (it was made out of different stainless steel than ordered).

Field Imperfection Analysis

The imperfections of the magnet have been investigated mainly by looking at the imperfection harmonics. The 1^{st} harmonic is below 6 Gauss from the magnet center to R=75 cm, from where it starts to increase suddenly, reaching a maximum of 40 Gauss near the pole edge. Although it was clear that some of the 1^{st} harmonic was due to the off-center of the measuring system, the correction was not possible until was found out the angular step error.

After removing this error, the imperfection harmonics, from 2^{nd} to 7^{th} were used to evaluate the off-center of the measuring system. The value is of the order of 0.3 mm and it changes of ± 0.05 mm when the system is dismounted and reassembled. The 0.3 mm off-center has a strong influence on the 1^{st} harmonic near the extraction region. In fig. 2 the 1^{st} and the 2^{nd} harmonic before (dashed lines) and after (solid lines) the off-center correction are plotted versus radius for three representative field levels.

Coils Centering: The horizontal links supporting the vessel of the superconducting coils experienced large forces during excitation of the magnet. After some effort it was found a position of the coils that allowed to cover the whole operating diagram; that is called "reference position" and it was kept during all the mapping.

The coils in the reference position give a 1^{st} harmonic as it was expected by the experience of the other superconducting cyclotrons. We had some difficulty to find out the coil displacement from the mapping center. At the end of the mapping we moved the coils 0.5 mm from the reference position and we measured the field along the line $I_\alpha = I_\beta$ up to 3 Tesla in order to get the 1^{st} harmonic form factor for a coil displacement. By using the outermost flip coils and selecting the current dependent component of 1^{st} harmonic, we got that the coil displacement was about $1.1 \div 1.2$ mm.

Unfortunately all the analysis was made difficult by the fact that we did not measure the form factors (i.e. 1^{st} harmonic vs. radius for a unit displacement) for each coil and the measured one, for the coils with equal current, looks quite different from the air coil calculation. After some effort we got both the α and β single form factors by difference between maps with different currents, see fig. 3.

Iron Pole Contribution: We can now subtract from the measured field the contribution of the main coils to the 1^{st} harmonic and we get the contribution from the iron. In the low field region of the operating diagram, $B_o < 3.5$ Tesla, the yoke shouldn't give a significant contribution, whereas the iron in the polar region should give a constant contribution (a clear indication of its saturation is the very small variation of the 3^{rd} harmonic over the whole range). The most significant contributions can come from a displacement of the inner wall of the cryostat vacuum chamber, made out of soft iron to increase the magnetic pole radius, and from an asymmetry of the pole sectors.

The vacuum chamber wall is round, 3 cm thick and with a gap of 14 cm and it has a very peculiar 1^{st} harmonic form factor (computed with uniform magnetization at saturation). From the analysis its displacement from the mapping center turns out to be about 0.3 mm (this value was checked later on with mechanical measurements) and the corresponding contribution to the 1^{st} harmonic can be subtracted.

The remanent harmonic should come from the sectors. Actually the phase vs. radius plot follows strictly the spiral angle of the sectors, except for $r < 15$ cm where a 0.1 mm displacement of the plug raise a 1^{st} harmonic bump of about 2 Gauss. The pole tips give a maximum 1^{st} harmonic amplitude of 6 Gauss at r = 83-84 cm.

All the 1^{st} harmonic contributions we have discussed are plotted versus radius in fig 4a. Of course all the analysis process has some uncertainty, mainly because of the difficulty to get the correct form factors of the two coils. Nevertheless this analysis showed to be consistent at about 2-3 Gauss over the whole operating diagram of the machine.

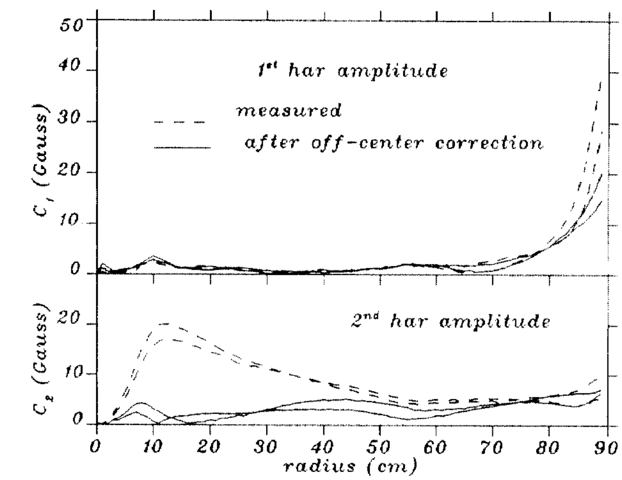

Fig.2: 1^{st} and 2^{nd} harmonic amplitudes vs radius.

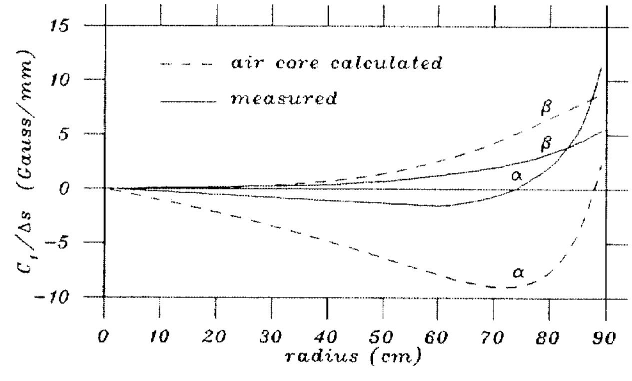

Fig.3: measured (solid lines) 1^{st} harmonic given by coil displacement compared with the air core calculation, for $\Delta s = 1$ mm and $I_\alpha = I_\beta = 1000$ A.

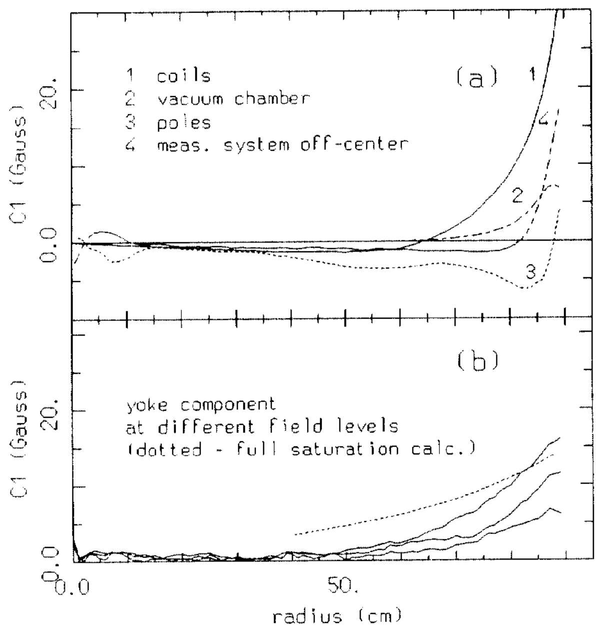

Fig.4: a) 1^{st}harmonic components for map at 1750/1750 (4.8 Tesla). The lower graph shows the increase of the yoke contribution with the field (3.8, 4.3 and 4.8 Tesla), compared with the calculated one at maximum field.

Yoke Contribution : The holes drilled in the yoke midplane are supposed to give a significant contribution to the 1^{st} harmonic when the yoke approaches saturation, i.e. for $B_o \geq 3.5$ Tesla, and its contribution should : *i*) increase smoothly with the radius, *ii*) present a phase almost constant vs. radius, *iii*) have a strict correlation with the total flux in the magnet and a weak dependance on the I_α/I_β.

After removing all the 1^{st} harmonic component previously described one has the 1^{st} harmonic plotted in fig. 4b. The three solid curves belong to maps with field increasing from 3.8 to 4.8 Tesla; the phase is the same for all of them, being constant vs. radius for r> 70 cm. The dotted curve corresponds to the calculated 1^{st} harmonic amplitude produced by the perforations of the yoke assuming uniform magnetization at saturation value. Despite of some difference, the result agree at a reasonable level.Taking into account that this result comes after subtraction of 5 contributions, we believe that it's a proof of the reliability of the analysis.

Following the results of the harmonic analysis, we decided to put additional iron in a yoke hole in order to correct its first harmonic and to have a better system to center the vacuum chamber of the cryostat. Reduction of the coils contribution is connected to the force analysis.

Forces on the Coils

The forces between the coils and the iron showed to be larger than expected. The horizontal link system, done with 3 pairs of Ti rods with $\phi = 9.8$ mm and $l \simeq 500$ mm, has a rigidity $K = 5.5$ ton/mm. In fig. 5 the forces measured on the link are visualized with bars giving the amplitude and the direction. Due to this forces, during excitation the coils move from the reference position of $\simeq \pm 0.25$ mm. The possible sources of these forces have been analysed with the following formula:

$$\begin{aligned}\vec{F} = \;& \vec{C}_\alpha \Phi I_\alpha + \vec{C}_\beta \Phi I_\beta + (\vec{S}_0 + \vec{F}/K) \times \\ & [I_\alpha(B_\alpha + \Phi B_{\alpha\Phi} + \Psi B_{\alpha\psi}) + I_\beta(B_\beta + \Phi B_{\beta\Phi} + \Psi B_{\beta\psi})]\end{aligned}$$

where $\vec{C}_{\alpha,\beta}$ are constant coefficients representing the forces coming from the holes drilled in the yoke; Φ is the magnetic flux scaled to the maximum value. Enclosed in square brackets is the dependance on the coils displacement, described with three constant coefficients: B, for the pole influence; B_ϕ for what scales with the flux; B_ψ to take into account the effects on the yoke magnetization when the I_β is driven negative. The dimensionless parameter Ψ is to take into account the different magnetization of the iron due to different I_α/I_β along a constant flux line. The actual displacement of the coils is the sum of the reference position displacement $\vec{S}_0$, as given by the first harmonic analysis, and the further displacement as measured on the radial links.

The formula fits the forces of fig. 5 at better than 10%. The coefficient of the fitting indicates that : *i*) the forces on β are much larger than that acting on α; *ii*) major part of the forces comes from the yoke; *iii*) the contribution due to the radial penetration of the yoke is a lesser part. Calculations with uniform magnetization assumption or with Poisson code were found not sufficient to explain the forces behaviour, expecially for the yoke dependance.

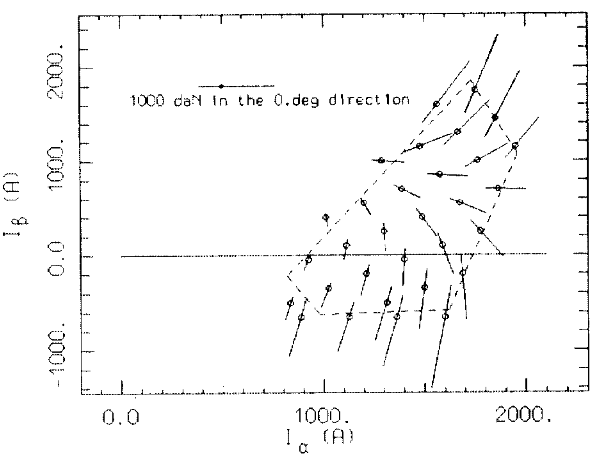

Fig.5: Forces acting on coils at the grid points. The bar orientation gives the force direction when I_α is the x-axis and I_β is the y-axis.

As a conclusion we decided to increase by a factor two the rigidity and the strength of the radial links, in order to reduce the movements of the coils inside the operating diagram and to be able to reduce the coils displacement from the magnet center. In fact we think that a reduction of a factor two of the coil 1^{st} harmonic is indispensable.

References

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