THE MAGNETIC FIELD MEASUREMENTS OF THE MILAN SUPERCONDUCTING CYCLOTRON

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ABSTRACT

The magnetic field of the Milan Superconducting Cyclotron has been measured on the median plane for the operating range of the machine (22 ÷ 48 kGauss)

The main results concerning the average field, the field modulation, the field imperfections and the trim coil form factors are presented.

The magnetic field on the machine axis and in the extraction hole of the yoke have been measured at few representative excitation levels.

1. INTRODUCTION

The Milan Superconducting Cyclotron [1] is a 3 sectors, 3 dees heavy ion machine with a K = 800, K_{Foc}=200 and an extraction radius of 86 cm. The beam can be injected radially from a Tandem or axially from an ECR source.

The isochroncus fields are achieved [2] by independent excitation of α and β sections of the superconducting coils, (α section has 3/5 of the total Ampereturns and is the one close to the median plane), and of 20 trim coils wound around the spiral pole tip.

The magnet has been excited [3] in December 88 with an iron configuration close to the final one, i.e. with all the holes in the yoke needed for the injection and the extraction system. The outer wall of the cryostat vacuum chamber was instead without radial penetration holes; his thickness is 40 mm versus a yoke thickness of 573 mm.

The field measurements on the median plane have been carried out using flip coil technique with analog integrators. The field on the machine axis was measured with the same technique, while an Hall probe has been used to measure the field inside the extraction hole of the yoke.

2. MEASURING SYSTEM AND ACCURACY

Since the hardware used in the measurements has been described elsewhere [4], we are summarizing here only the main features and reporting the accuracy of the apparatus.

Ninety flip coils are placed along a perspex rod, from radius 0 up to 89 cm; four additional flip coils have been positioned on the same rod on the opposite side from radius 4 cm up to 16 cm every 4 cm in order to check for possible errors in the bar position.

One additional flip coil is devoted to temperature control, via measurement of resistance variation. The iron temperature during the fifteen days of the measurements was quite constant, 21 ± 2 °C, and therefore the temperature influence on the measuring system and on the iron magnetization could not be evaluated.

The flip coils have been calibrated at 15 kGauss against an NMR probe; the total accuracy of the calibration has been evaluated to be ± 100 ppm. The sensitivity is about 180 mV/kGauss and its stability was found constant within 30 ppm over a period of three months.

The reproducibility of the measured field maps in the cyclotron was ± 5 Gauss. Sets of sixty consecutive measurements at fixed azimuth, carried out at different field levels, showed a standard deviation of 20 ppm for the major part (80) of the flip coils and less than 40 ppm for the remanent ones. Other tests confirmed that the main contribution to the errors is due to mechanical problems, especially in the positioning system (the precision of repositioning was ± 0.2 mrad) and in arm flipping particularly at the high fields.

3. MAIN FIELD

A set of 32 maps were measured in a grid of the I_α, I_β plane, where I_α and I_β are the currents in the two sections of the superconducting coils. The grid covers uniformly the operating region of the cyclotron starting from a minimum field of 20.5 kGauss. The measured grid points are shown in fig.1 where are also indicated the trim coil maps. All the measurements were done over 360° at step of 2° with the exception of part of the trim coil measurements.

The average fields versus radius for different excitations at intermediate field level are shown in fig.2. The average field has the calculated radial shape and small level

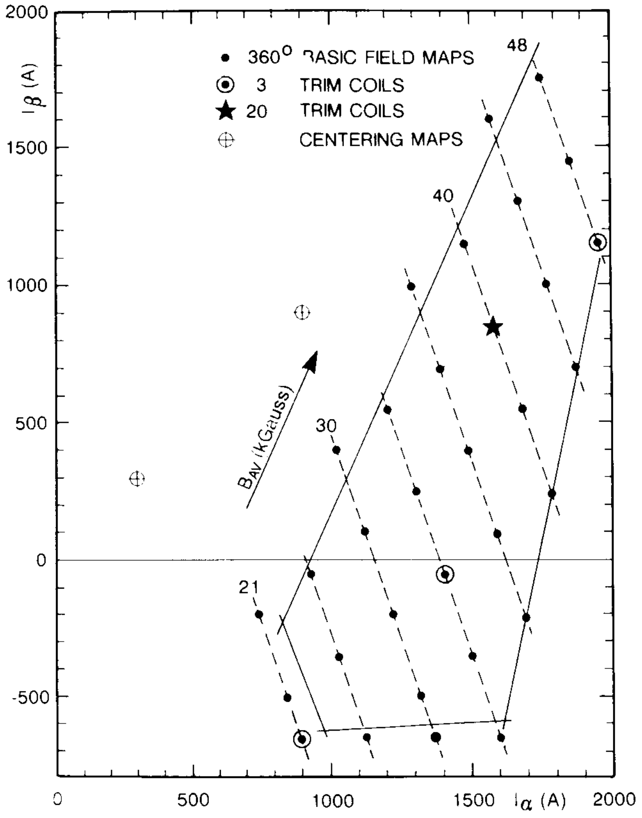

Fig. 1 - Operating diagram of the machine in I_α, I_β plane and the measuring grid. The flux contour lines are indicated.

differences of the order of hundred Gauss.

The trim coils power required for the isochronization of the field is therefore very close to the calculated one, while the differences in field level can easily compensated with small variation of the main coil currents.

The amplitude of the third harmonic versus radius for two maps at minimum and maximum field levels are shown on fig.3. The maximum variation of the harmonic amplitude with the field is quite small, less than 200 Gauss at r = 55 cm. In the extraction region the maximum variation is less than 50 Gauss and the values are in good agreement with the calculation. The 3th harmonic phase in the extraction region is constant and equal to the calculated one.

The assumption of complete saturation of the iron used in the design of the machine, is therefore well confirmed also at low field (B = 20 kGauss).

A preliminary analysis indicates that focusing properties of the measured field are sufficient and close to the calculated one.

Two corrections are anticipated: an additional 3 mm thick shim (foreseen in the calculation and not yet assembled) on the pole tip at the extraction radius and a modification of the plug, to increase the field cone in the central region of approximately 100 Gauss.

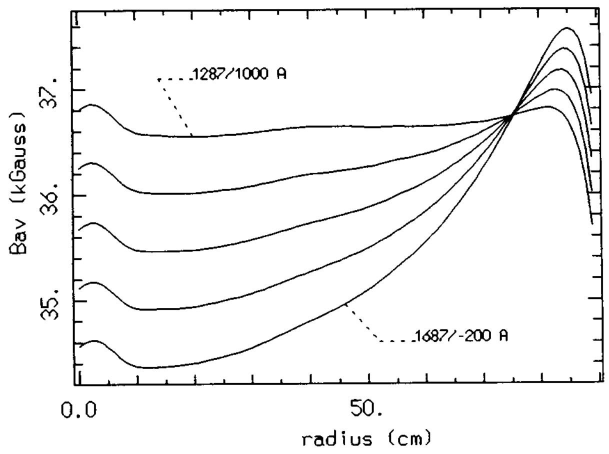

Fig. 2 - Average field versus radius for different main coil currents along a flux contour line (see fig.2).

A systematic of the third harmonic amplitude is presented in fig.4 as a function of the field level. The cause of its variation is not yet understood. The behaviour of the third harmonic is different from that of the MSU K800 Superconducting Cyclotron[5]; in their case the third harmonic is constant along the flux contour lines. Considering that the magnetic structure of the two cyclotrons is very similar this discrepancy is unexpected.

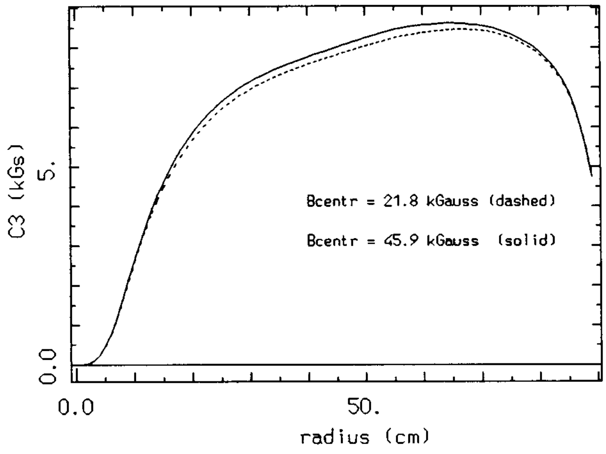

Fig. 3 - Amplitude of the main harmonic versus radius for the lowest and highest field of the operating diagram.

4. FIELD IMPERFECTIONS

The field imperfections were investigated using the 3-fold symmetry and the main imperfection harmonics 1st, 2nd and 4th. A systematic error in the azimuthal rotation of the measuring system was detected by comparing the variation of the 2nd and the 4th harmonic when the relative postion between the flip coils arm and the positioning arm was changed of 180°. This

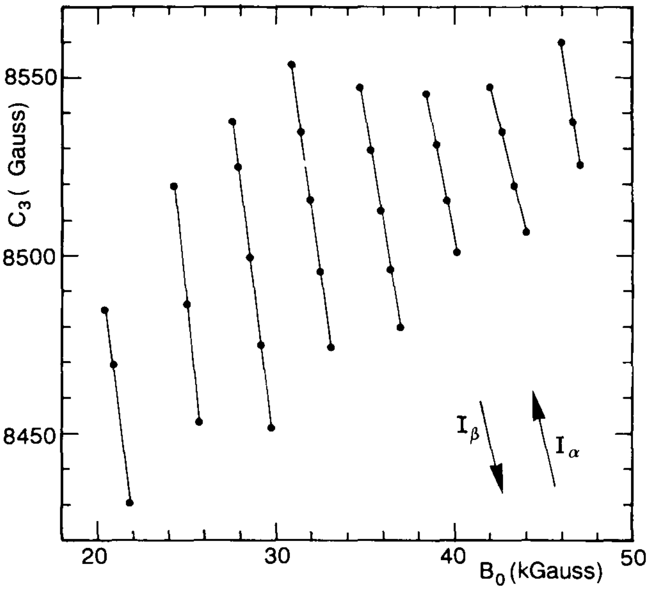

Fig. 4 - Third harmonic amplitude at radius 70 cm at different fields. The solid lines are flux contour lines.

error was generated by a first harmonic of 0.85 mrad superimposed to the ideally constant 2° step of the map. After removing this error, the 2nd and 4th harmonics were used to evaluate a 0.328 mm radial off-centering of the measuring system. This off-centering value changed to 0.354 mm after a reassembly of the system.

These two systematic errors do not affect the values of the average field and of the main harmonics.

The amplitude and the phase of the first harmonic at three different field levels, after correction for the two systematic errors, is presented in fig.5. It contains contributions due to pole tip imperfections, internal vacuum tank shift, main coil shift (changing with the current up to ± 0.2 mm as it was inferred by measurements on cryostat horizontal links[3]) and yoke hole imperfections (only at field levels higher than 30 kGauss).

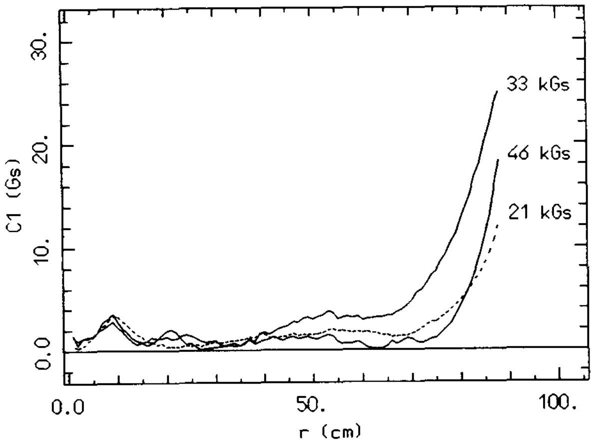

Fig. 5 - First harmonic at three different field levels.

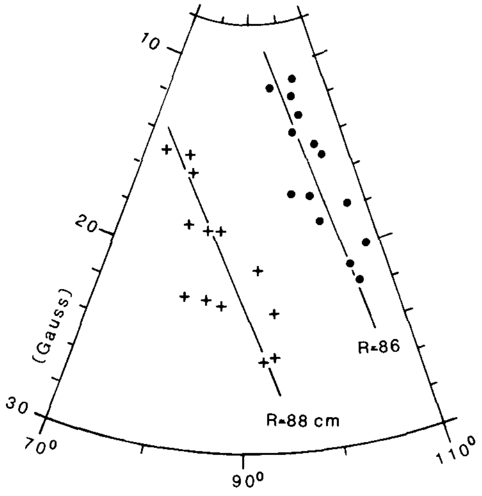

Fig. 6 - Polar plot of the first harmonic imperfections for different main coil currents.

The first harmonic measured in the extraction region is presented in fig.6 for field levels up to 30 kGauss in a polar diagram for two radii. The variation of the first harmonic in the region 20-30 kGauss should come only from the main coils shift. The phase of the coils shift, as deduced from the figure, is 113° although the correlation is not strict. The form factor of the coils shift as evaluated comparing the first harmonic variation with the current, does not agree with the air core calculations and with the experimental one measured at the centering maps when the coils were displaced by 0.5 mm.

A preliminary analysis indicates a coils displacement of 0.7 mm and a displacement of the vacuum tank of about 0.5 mm (phase 100°). The coils were positioned to minimize the radial force between them and the iron; the discrepancy between the mechanic and the magnetic center is of the same order of the one reported by other laboratories[6,7].

Using these data it was possible to evaluate at extraction radius a first harmonic component of 5 Gauss due to pole tip imperfection and up to 10 Gauss due to yoke holes.

A more detailed investigation is however needed to confirm this analysis.

5. TRIM COILS

The form factors of the 20 trim coils have been measured (120°) at one field level (B_{av} = 40 kGauss). Trim coils n. 5, 14 and 19 has been measured at additional field levels (TC n. 19 was measured at 360°) to obtain preliminary information about the variation of the form factor. The measured form factor for the TC n. 14 is given in fig.7 together with the air core calculation.

The measured form factors are 10÷15% higher than the calculated one also at maximum excitation. A 40% increase over the calculated

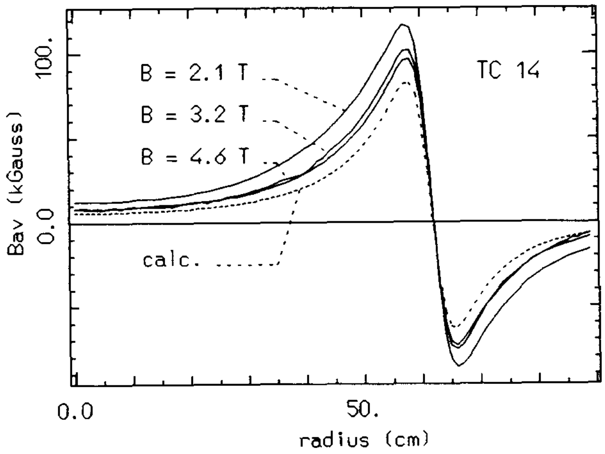

Fig. 7 - Form factor of trim coil n.14 at different field levels (solid line) compared with the air calculation (dashed line).

form factor has been measured at 20 kGauss level. Therefore the TC form factors have to be measured carefully in the region 20 ÷ 30 kGauss to allow precise interpolation of the data.

6. AXIAL FIELD

The field on the vertical axis of the machine was measured from the median plane up to z = 260 cm with a 1 cm step, at few representative field levels. The measured fields, which are in good agreement with the calculations, are presented in fig.8 for two level B_o = 32 and 47 kGauss. At the maximum excitation the field measured at z = 4 and z = 5.5 m were respectively 250 and 100 Gauss.

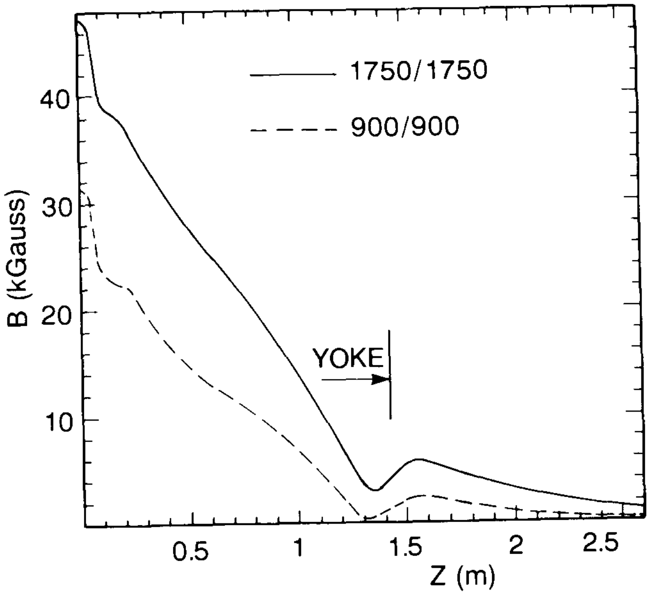

Fig. 8 - Magnetic field versus distance from the median plane on the cyclotron axis at two I_α/I_β values.

7. YOKE HOLE FIELD

The field measured along the extraction hole in the yoke are presented in fig.9 for three representative level. The data, although not final because of the missing holes in the outer wall of the vacuum chamber, show the progressive saturation of the yoke, in good agreement with the calculations, and the field shape is in accordance with the hole transversal dimension (25x25 cm^2).

The field measured at r=4 m and r=8 m, at maximum excitation, is respectively 140 and 20 Gauss. These data, together with the axial field data, indicate that beyond a distance of 4 meter the cyclotron field is equivalent to a dipole.

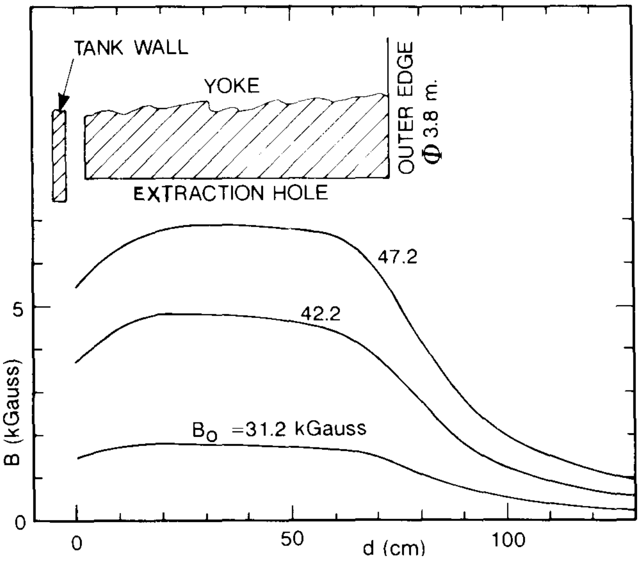

Fig. 9 - Magnetic field along the extraction hole of the yoke.

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REFERENCES

1) Acerbi,E.,et al.,"Progress Report on the Milan Superconducting Cyclotron", this Conference.
2) Bellomo,G.,et al., "Design of the Magnetic Field for the Milan Superconducting Cyclotron", Proc. of IX ICCA, 1981 pp. 395-397
3) Acerbi,E.,et al., "Operational Experience on the Superconducting Coils of the K800 Milan Cyclotron", presented at this Conference
4) Acerbi,E.,et al "The Magnetic Field Measuring System of the Milan Superconducting Cyclotron", presented at I EPAC, Rome - Italy, June 1988.
5) Johnson,D., et al.,"Magnetic Field of the K800 Cyclotron",presented at I EPAC, Rome, June 1988.
6) Marti,F., Miller,.P.,"Magnetic Field Imperfections in the K500 Superconducting Cyclotron",proceedings of X ICCA,1984,pp.107-109.
7) Ormrod,J.H.,"Magnetic Field Measurements on the Chalk River Superconducting Cyclotron", report AECL-7842.