Test and calibration of the Magnetic Measurement System for the Superconducting Cyclotron at LNS, Catania*

D. Giove†, P. Gmaj, L. LoMonaco, G. Raia, L. Rossi†
INFN, Laboratorio Nazionale del Sud
Viale A.Doria (angolo via S.Sofia), 95123 Catania, Italy
† INFN and Physics Dept. of the Univ. of Milan, LASA, 20090 Segrate-Milano

Abstract

The apparatus for magnetic measurements before commissioning of the Superconducting Cyclotron is presented. This is a fast system designed for the systematic mapping of cyclotron fields. A search coil measures the field variation by scanning the median plane radially. The coil-bearing bar can then be turned over 360° about the central axis to cover a full map. The absolute value of the field is measured by NMR probes placed at the cyclotron centre and at the RF cavities holes. The mechanical features of the system allow an accurate positioning and movement of the coil. The radial position is determined by an incremental encoder with a step of 0.18 mm, the angular position with an accuracy of 10^{-3} degrees and the median plane is identified within 0.1 mm. The coil can move radially with a maximum speed of 50 cm/s. Accounting for dead times (coil return, drift measurement) we make the conservative estimate of measuring one full map per hour, with an azimuthal step of 1°. The overall accuracy on the measured field is $\frac{\Delta B}{B} \simeq 10^{-4}$. A brief description of the software used and probe calibration data are included.

1 INTRODUCTION

The changes in the timetable of the cyclotron assembly, namely mounting the liner before the second and final mapping cycle, have imposed new requirements for the measuring system. First of all the new system has to be slimmer comparing to the old one, which was used for the first cycle of field measurements [1]. Secondly, since we plan to measure about 270 full field maps of the cyclotron, i.e. 6 times more than in the first mapping cycle, the new system has to be as fast as possible. Basing on the other laboratories experience [2] we have decided to apply the search coil technic as it gives the fastest mapping system and needs little vertical space. The accuracy requirement for the system is 10^{-4} and the maximum field gradient measured is 15 T/m.

2 HARDWARE

The system is made up of a search coil wound on a perspex bobbin and put on a motorized cart along with an incremental optical encoder controlling the actual probe position and a thermoresistor sensing its temperature. The cart moves lengthwise on the horizontal bar (carbon fiber - a *droop* less then 0.3 mm) with stripped tape fixed to it. The 0.36 mm wide slits are spaced by the same 0.36 mm. This gives appropriate positioning accuracy although it requires an additional encoder signal divider to ensure the limited trigger rate. The 1800 mm long measuring bar is settled on the vertical motorized axis (IT6DCA – Micro-Control) accurate to 10^{-3} deg. The programmed cart controller sends the trigger pulses to the digital integrator (PDI5025 – Metrolab) which sums up the instantaneous coil voltage converted into frequency and stores the resulting value each time a preprogrammed number of trigger signals is encountered. The contents of the integrator memory is read by a personal computer (IBM-PC386SX/16 Premium) immediately after triggered data is elaborated or after a radial scan is completed. Since a calibrated coil–integrator pair can measure only a difference of the field between triggered points, the system encloses the NMR Teslameter (PT2025 – Metrolab) as a reference field meter. This unit multiplexes two NMR probes which can be lowered automatically into the median plane of the cyclotron. One of them is to be used as a field reference and is placed on the symmetry axis of the cyclotron. Another is placed in one of the RF holes and can serve both as an *on line* monitor of the field during measurements and as the second reference for a calibration.

The PC controls (via GPIB bus) all movements, performs data aquisition, makes *on line* calculations of average field and harmonics and/or evaluates standard errors and makes appropriate graphs.

2.1 Search Coil

The finite size of the coil together with the measured field gradient results in an error which increases along with a growing sensitivity value. Therefore a compromise has to be found between a *sensitivity* and *geometrical* error. The former comes from a preamplifier bias current and gener-

Table 1: Search coil design parameters

Internal radius	2.50 mm
External radius	4.70 mm
Height	6.7 mm
Number of turns	4000
Resistance	420.5 Ω

---

*Before transferring to LNS the cyclotron was originally referred in publications as the Milan Superconducting Cyclotron ally increases with growing preaplifier gain value i.e. with decreasing coil sensitivity. As it is explained below, we could hardly keep the integrator drift error in the range of 30 ppm, therefore it was advantageous to make a relatively large coil (dimensions are listed in Table 1) with a respectively big total surface and sensitivity. In the biggest field gradient (15 T/m) this coil gives an intrinsic (*geometrical*) error of the order of 10 ppm. The coil was wound using a prestressing force in order to diminish its temperature coefficient. Fig. 1 shows the measured thermal coefficient. We have roughly estimated its nonlinear behavior assuming two values: 26 ppm/°C for temperatures in the range 28°C–38°C and 64 ppm/°C over 38°C. The first being of the range of the copper coefficient (2·17 ppm/°C), the second being an average between the perspex coefficient (2·72 ppm/°C) and copper one modified by an elastic force relaxation due to the thermal expansion of the wire and of the bobbin material.

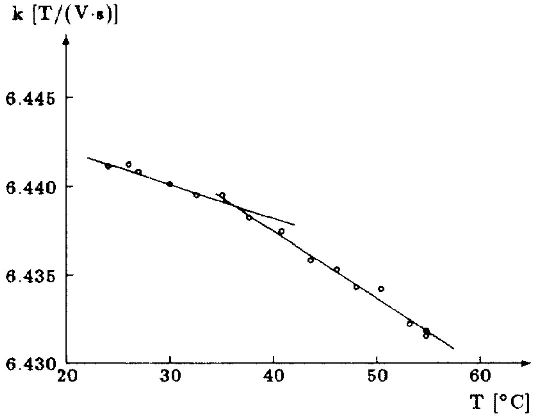

Figure 1: Calibration coefficient vs. temperature

2.2 *Integrator*

The integrator drift, noise and nonlinearity defines the accuracy limit. The characteristics of the PDI5050 integrator were studied independently in Grenoble [3]. We have measured some of these characteristics to confirm their validity. The measured nonlinearity of 30 ppm of the integrated value is consistent with the value given in [3] (44 ppm). The drift behaviour in general conforms the results of [3]. It can be assumed constant over a short time, of some tens of seconds, but over a longer period (1 min and up) one must consider a substantial change in the drift value (probably due to the temperature variation). However we found necessary to correct the measurements not only for the drift depending on time but also for the *shot* noise involved by the digitalization. This error depends on the number of trigger counts from the beginning of a given cart run. Therefore the drift must be measured *on line* every 1 min approximately. This is done by using the internal trigger of the integrator. The temperature offset of the integrator was found to be about 5 ppm/°C of the maximal input voltage, but we have measured it only for temperatures over 30°. From [3] follows that the integrator should not operate below 28° since in the temperature range 23°C–26°C the temperature coefficient changes very rapidly.

2.3 *Cart control*

Originally the system was designed to work with a constant cart velocity. This velocity is limited by the search coil sensitivity, maximal field gradient (15 T/m) and maximal voltage acceptable by the integrator. Since the high field gradient covers about 20% of the scan length the system accuracy can be upgraded by changing the cart velocity during one scan and therefore diminishing the drift fluctuations by about the same factor as the scan time reduction (for a scan time smaller than 10 sec) or more. During tests we have not used the variable velocity cart control yet, but we plan to apply it during the cyclotron mapping because, apart of an upgrade of the system accuracy, it gives the opportunity to reduce the total measurement time.

3 SOFTWARE

An entire software package was written in C language to manage the measurements with the appropriate velocity and to give maximum flexibility. It provides all needed diagnostic and allows to control the system functioning in several modes of operation: calibration modes, test modes and measurement modes. The data can be sent *on line* with measurements to a bigger computer (VAX). This is of great importance when mechanical alignment errors are tested. Relying on the experience acquired during the previous measurement cycle [4] we expect to have to deal with several mechanical sources of error which must be removed after the system is mounted into the cyclotron. The most significant are listed bellow:

1. The measuring bar axis does not coincide with the *magnetic* center of the magnet.
2. There is an angular first harmonic superimposed on the azimuthal position.
3. The active edge of the slit on the stripped tape equivalent to the radius r=0 does not coincide exactly with the measuring bar axis.
4. The cart does not pass over the measuring bar axis.

The first two error sources can be eliminated by examining the correlation between main and imperfection harmonics. A special FORTRAN code was developed to analyze these correlations and calculate adequate corrections. The last two errors can be found comparing a datum for negative radius with that for the positive one rotated by 180°. The cart positioning encoder is predisposed to move its active phase, thus ensuring the trigger generation at a proper moment.

4 TEST

We have tested the apparatus using a magnet with field stable within 1 ppm.

The probe was mounted on a fiber glass arm similar to that we will use in the cyclotron. However in the test magnet we did not use the motorized axis nor the cart motor but the probe was moved by hand. This is consistent with the independence of the integrated voltage from the coil speed. The position of the cart was controlled by an optical switch. The temperature of the probe was measured with a thermoresistor placed close to it and moving on the same cart with the probe. Also the temperature of the integrator was controlled. The measured calibration coefficient is not valid for the future measurements because of an angular bending of the coil with respect to the median plane. A difference of 0.4° gives a relative (and systematic) error of the order of 30 ppm. Only when the definitive measurement bar is ready we can do a more precise calibration.

The NMR probe was put at the centre and we assume a maximum error of 3 mm in its position with respect to the search coil. The field gradient at the centre was measured as $\frac{dB}{dr} = 0.005$ mT/mm; this amounts to a field error of 0.015 mT over 1.5 T for the field, i.e., a relative error of 10 ppm in the calibration coefficient. The zero field was found with an accuracy of 0.01 mT using a triple shield (iron and 2 permalloy layers). That is to say, also the Earth field was shielded. The corresponding error is 7 ppm.

The drift was measured before each calibration run and then subtracted from the measurements. If the total drift (over a 5 seconds sweep of the coil) does not change substantially during one cycle of 10 sec (5 sec drift measurement plus 5 sec run), then its nonlinearity has no effect on the final result. This is because only two points, the zero-field and central field values, affect the calibration coefficient. Instead, for long time systematic mappings of the cyclotron field, the time dependence of the drift slope, as well as its nonlinearity, could seriously affect the results. Once the drift is set to minimum by the operator, neglecting the drift during one radial sweep of the coil gives an unacceptable error of the order of 100 ppm. Since the drift depends on the chosen gain, the corrections must be applied independently for each gain value.

As we mentioned above, the probe temperature coefficient was measured giving 26 ppm/°C between 22 and 38 °C, which is not negligible and the integrator total temperature coefficient was roughly estimated to be below 5 ppm. The integrator temperature influences greatly the drift value and then must be carefully controlled.

Finally, we checked the material of the measurement bar support (brass). Its permeability is $\mu = 1 \pm .00002$.

The calibration coefficient for the coil probe was found to be (6.4428 ± 0.0002) T/(V · s), which is equivalent to a relative error of 30 ppm.

5 ACKNOWLEDGEMENTS

The authors would like to thank Prof. E. Acerbi for the initial discussion of the system, G. Baccaglioni for making the search coils and Dr. D. Rifuggiato for his help in data acquisition.

6 REFERENCES

[1] E. Acerbi, G. Bellomo, G. Rivoltella and L. Rossi "The Magnetic Field Measuring System of the Milan Superconducting Cyclotron", in Proc. of the 1st European Particle Accelerator Conference, Rome, Italy, June 1988.

[2] L. Harwood, J.A. Nollen,Jr., and A.F.Zeller "Magnetic Field Measurements of the NSCL K800 Cyclotron Magnet", in Eleventh International Conference on Cyclotrons and their Applications, Tokyo, Japan, 1987, pp. 315-317.

[3] D. Frachon, P. Ellaume, "Test of the Metrolab integrator PDI5050", European Synchrotron Radiation Facility, Grenoble, France, Report ESRF-SR/ID-90-35, January 1990.

[4] E. Acerbi, G. Bellomo, P. Gmaj, L. Rossi and Zhou SiXin "The Magnetic Field Measurements of the Milan Superconducting Cyclotron", in Twelfth International Conference on Cyclotrons and their Applications, Berlin, Germany, May 1989, pp. 486-489.