THE MAGNETIC FIELD MEASURING SYSTEM OF THE MILAN SUPERCONDUCTING CYCLOTRON

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Abstract: The Milan Superconducting Cyclotron will operate at magnetic field levels in the range 22-48 kGauss. The field measuring system, based on the flip coil technique, is extensively described and the results of the calibration process are presented and discussed.

Introduction

The Milan Superconducting Cyclotron [1,2] is a three sector machine, with a pole radius of 90 cm, designed for the acceleration of heavy ions radially injected from a Tandem or axially injected from an ECR source.

The operating diagram of the machine covers the field levels in the range 22-48 kGauss and charge to mass ratios in the range q/A =.5-.1 with a bending limit K=800 and a focusing limit K_{foc}=200. The isochronous fields [3] are achieved with the independent excitation of the two superconducting main coil sections and of the 20 trim coils, water cooled and wound on the spiral pole tip.

Three regions have to be mapped for the setting of the cyclotron: the pole region, the injection and extraction region and the axial injection region. In this paper is presented only the pole region measuring system.

Approximately 25 field maps are needed to cover the operating diagram in term of the field levels and main coil currents. The form factor of the trim coils will be measured by difference respect to the main field at 4 field levels. Field maps at 360° are necessary to center the main coils and the cryostat vacuum chamber and to measure the field imperfections and the form factor of the harmonic coils.

The accuracy needed in the pole region is ±100 ppm at all field levels. The field will be measured from R=0 to R=91 cm at radial step of 1 cm and azimuthal step of 2°. Because of the flutter the actual range of the field values is 16-57 kGauss with a maximum field gradient of 1.5 kGauss/cm near the edge of the pole tips.

A measuring technique based on the flip coils and analog integrators has been selected at the beginning of the project on the base of the experience of other laboratories [4,5].

The measuring system

Flip coils

The flip coils have been wound on a Macor bobbin; Macor has been chosen because it is accurately machinable and it has an high resistivity and a very low thermal expansion coefficient.

The error due to the finite sizes of the flip coil has been studied using calculated field maps at different levels [3]. According to this study we selected an internal radius of 2.15 mm, an external radius of 3.7 mm and an height of 5 mm. The ratio H/D=0.676 is very close the standard value H/D=0.67 [6] and gives a second order error within ±6 ppm and a fourth order error less than 1 ppm.

Each layer-wound coil has 680 turns of AWG39 (0.09 mm) copper wire and a resistance of 34.6 Ω.

Ninety flip coils are distributed along a perspex rod, named in the followig flip coil arm with a spacing of 1 cm from R=0 up to R=89 cm; two more flip coils can be added to measure the field up to R=91 cm for the maps covering only one sector (120°). On the same arm but at opposite side four flip coils are positioned from R=4 to R=16 cm to detect field change during the map and centering error. The temperature variation is monitored by a platinum resistor and trough the measurement of the resistance of a dummy flip coil (placed at R=20 cm).

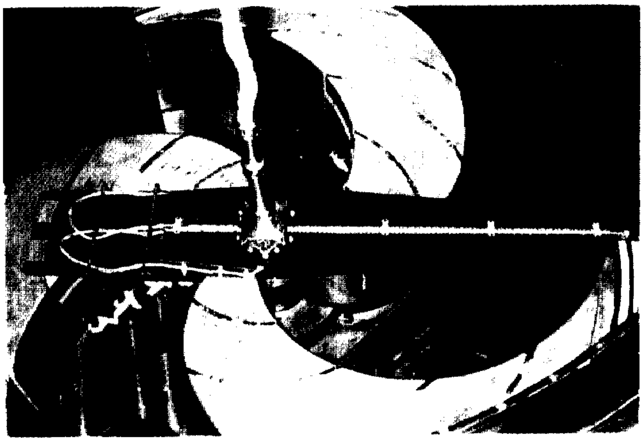

Fig.1 - The flip coil arm positioned in the cyclotron

Mechanical system

The flip coil arm, supported by a G11 (fiberglass) structure used also for calibration, is azimuthally rotated by a stepping motor mounted at the bottom of the lower pole. The motor gives only the coarse positioning, while the exact azimuth is determined by the coupling of a pneumatic piston in a toothed wheel. Because of the large radius of the toothed wheel, and of its mechanical precision, the azimuthal positioning is within 0.1 mrad. An optical encoder send the position to the control system.

The coils are flipped by rotating the arm 180° about its axis with a pneumatic cylinder, positioned under the lower pole and providing rotation via a conic gear.

A picture of the flip coil arm inside the pole region is given in fig.1.

Integrator circuit

A schematic diagram of the integrator circuit is shown in fig.2. The high performances required to the integrator (linearity of the signal up to 6 Tesla and high reproducibility) requires a special care in the choice of the electronic components. Particularly important are the offset voltage and the bias current of the operational amplifier since they affect directly the output voltage according to the relation:

$$V_{out} = V_{off} + 1/RC * \int (V_{fc}+V_{off}+R*I_{bias})dt$$

The main characteristics of the Analog Devices AD235K operational amplifier are: 5 10^7 V/V of loop gain, 0.3 μV/s of slew rate, ±25 μV (±0.1 μV 1% of supply variation) of initial offset, ±50 pA of

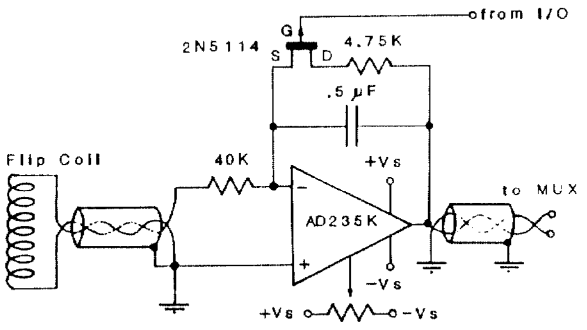

Fig.2 - Schematic diagram of the integrator circuit.

initial bias current, 300 kΩ of input impedance and a good rejection of the low frequency noise.

The input resistance of 40 kΩ, see fig.2, is a non inductive wire wound resistor with a low temperature coefficient of 2 ppm/°C (20 ppm/3y).

The feedback is a .5 μF polystyrene capacitor with an insulation resistance $> 10^{12}$ Ω,a temperature coefficient of -100 (±50) ppm/°C and a very low dielectric absorption (0.02%). In order to reduce the thermal capacitance variation the cabinet which houses the integrator circuits is thermostabilized at 40.1 (±0.1) °C. The reset circuit switch is a FET p-channel Siliconix 2N5116 with about 10^{11} Ω of insulation resistance.

The 96 integrators are placed in NIM modules with 6 integrators per modulus. To avoid ground loop, capacitive coupling and noise the electronic system has three independent ground levels.

To reduce electromagnetic influences (the distance between the flip coil arm and the integrator cabinet is 25 m), each connection is teflon insulated, shielded and twisted pair, also on the printed circuit of the modules.

Data acquisition system

The integrated signals are acquired by a 100 channel multiplexer HP3497A Data Acquisition connected to a HP44420A 5-1/2 digits voltmeter (20 readings/s). The readings are acquired in "packed mode" and discharged on a Compaq PC via IEEE 488. The PC controls the whole system (arm positioning, flip coils rotation and data acquisition) and provides for data storage on soft diskette and data transfer to μVAX for analysis.

Measurement procedure

The main source of errror in the integrator output voltage is the drift due to V_{off} and I_{bias}. Accurate drift measurements at various capacitor voltage level show that the drift is linear but the slope is not constant: the pick up induced by the opening of the switch is variable and therefore the drift has to be measured each time. One point field measurement requires three voltage measurements: the first and the second (before flipping) are used to calculate the drift line in order to correct the third measurements (after flipping) on this effect.

The voltage vs time for an integrator is shown in fig.3. The upper graph is the drift, before flipping, with a slope of 50 μV/s. The lower part of the figure shows the output voltage variation after the flipping (curve a). If the drift is removed one obtains the curve b which shows an exponential decay with a very long time constant (the straightline part of curve b) due to the capacitor discharge. At early time the effect of the dielectric absorption with a time constant τ=4 s is detected. Therefore is necessary to wait 5 s after flipping (dead time) before starting the integrator voltage acquisition.

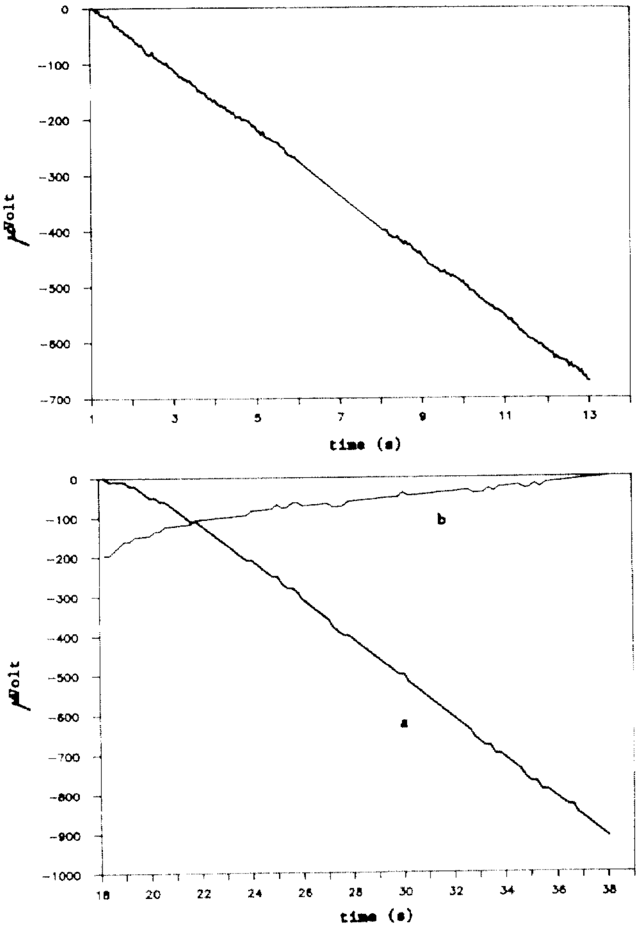

Fig.3 - Integrator voltage vs time. The upper graph shows the initial drift. The lower graph shows the voltage after flipping without (curve a) and with (curve b) the correction on the drift.

The total time for a single arm measurement is 45 s; approximately 25 s are for voltage measurements and 20 s for movement and positioning.

Calibrations

Calibration system

The calibration of the flip coils is done in a water cooled magnet with 42 cm of pole diameter and 6 cm of gap and with a power supply stabilized at ±25 ppm. The calibration field level is normally in the range 10-15 kGauss.

The central field,with an homogeneity of 300 ppm within a 3 cm radius,is measured by an NMR probe, with a total accuracy of ± 15 ppm (NMR support and flip coil arm positioning errors included). After an initial field measurement the NMR probe is positioned near the pole edge, in a region suitably shimmed to have an homogeneous field for NMR resonance. During the calibration the NMR values are stored and the corrections for the field fluctuation are calculated.

A calibration run needs about half an hour, after warm up of the electronics and of the power supply. The calibration coefficients are calculated as the average of a set of 10 calibration runs. The average calibration coefficient is about 5.5 kGauss/V. The spread of the measurements for a typical flip coil is ±50 ppm.

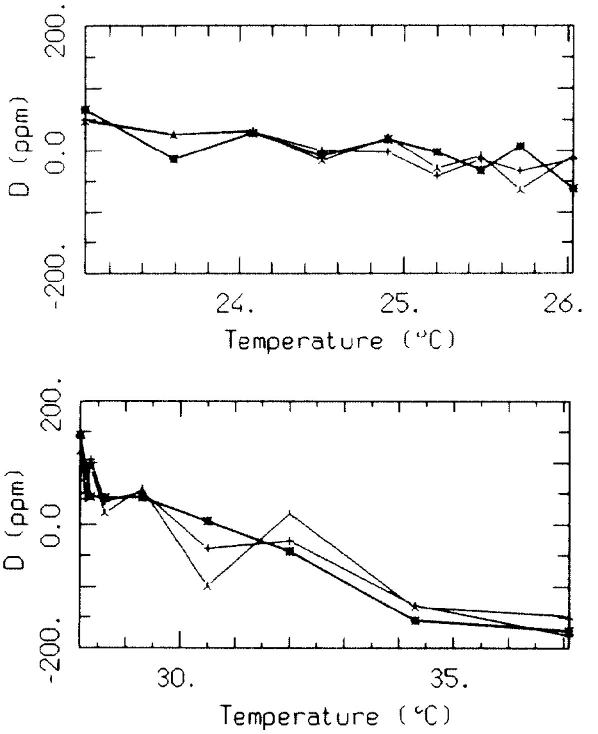

Fig.4 - The deviation of the calibration coefficient vs temperature for three flip coils.

Temperature coefficient analysis

The sensitivity of the flip coils, being proportional to the coil area, is depending on the temperature. The temperature coefficient (TC in the following) of the copper (2*16.5 ppm/°C) and the Macor (2*9.4) are not so small to be ignored; therefore the experimental TC has been investigated by warming the entire flip coil arm up to 38 °C.

The deviation of the calibration coefficient versus temperature for three flip coils are shown in fig.4. The experimental results show that the TC does not jump from the Macor value to the copper one at the winding temperature (near 25 °C); in the room temperature range, 20-28 °C, the flip coil TC is an average between the values of Macor and copper (see upper graph of fig.4). Above 30 °C (see lower graph of fig.4) the flip coil TC is very close, as expected, to the value of the copper.

Following this study an average value of 25 ppm/°C has been chosen as flip coil TC in the range 20-28 °C.

Long term stability

The relative deviation from the mean value versus the calibration run number is plotted in fig.5. Calibration were taken over a three month period and the calibration coefficient were normalized at 26 °C.

The oscillations are almost entirely due the voltmeter resolution and linearity (±60 ppm of total error at the calibration voltage value, 2.5 V). As it can be seen the short term (some days) total accuracy is near ±50 ppm. Shifts of about 100 ppm, calibration n.59-60 78-86 and 88-100 in fig.5, are superimposed on this small spread. These shifts are associated with 15 day pauses of the calibration measurements with the electronics off. The jump is possibly due to a change of the voltmeter sensitivity; this point will be investigated in the future,altough it will not spoil the accuracy required in the first mapping of the cyclotron.

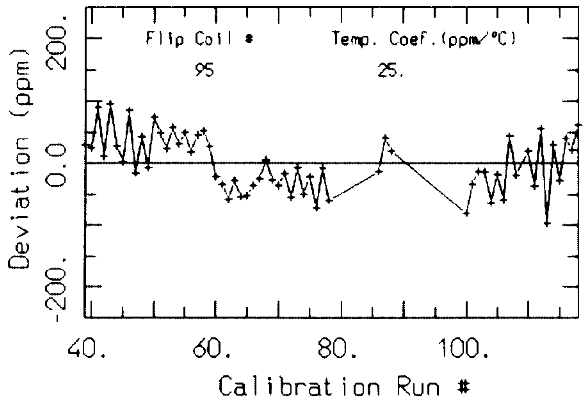

Fig.5 - The normalized deviation of the calibration coefficient versus the calibration run number.

Preliminary test

Due to the delay in the assembly of the cryostat and of the cryogenic system the magnet has not yet been operated. The magnetic field measuring system has however been tested at very low excitation (1% of the full excitation) to check the mechanical apparatus and the reproducibility.

The harmonic content due to the imperfection on the pole tip assembly can also be detected altough the iron is not fully saturated as in the actual operation of the magnet.

Ten maps (4 at 360° and 6 at 120°) has been taken at field level of 3 kGauss and field values in the range 1-5 kGauss. The reproducibility of two 360° maps has been checked. The differences are of the order of .5 Gauss with few values close to 1 Gauss. This reproducibility, of the order of 200 ppm, is essentially due to the resolution of the voltmeter (±100 μV correspond to ±.5 Gauss).

Field imperfections have been detected (1^{st} harmonic amplitude of the order of 1.5 Gauss) and the identification of the source is under investigation.

Aknowledgements

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