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# Magnetic measurement system for high-field magnets

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One of the main principles in electrodynamics, the change of magnetic field flux inducing an EMF in a wire coil, is applied for magnetic measurement. A scheme and the main parameters of the magnetic measurement system are described. The system was successfully used for magnetic measurement of a 7 T superconducting wiggler for LSU CAMD; results are presented.

**Keywords: measurement systems; cryogenics; high-field magnets.**

## 1. Introduction

In the course of production of a high-field superconducting magnetic system (which includes a wiggler system) it is often necessary to perform preliminary tests and magnetic measurements in a special cryostat (Fig. 1) before the final assembly. These measurements are usually performed in universal immersion cryostats with liquid helium at a temperature of 4.2 K. Under such conditions, performance of the magnetic measurements is complicated by the necessity of movement of the measuring device in the liquid helium. Hence, there appear to be special requirements for the magnetic field sensors working in immediate contact with the liquid helium. This article describes the process of the magnetic measurement of a superconducting wiggler at a field of 7 T for LSU CAMD (Borovikov *et al.*, 1998). The main parameters of the wiggler are presented in Table 1.

## 2. Measurement technique

Sensors for magnetic field measurements are usually based on either semiconductive Hall probes or rotating wire frames in which an EMF is being induced. Let us examine both of these techniques in the context of their applicability for measurement of strong magnetic fields in liquid helium.

It is not very convenient to use a Hall probe under these conditions, the problem being that the value of the magnetic field that is being measured is 7–8 T. Consequently the Hall probe, having its own nonlinear characteristic, should be callibrated previously at various field levels. Such a callibration can be executed in a powerful magnet with an exact value of magnetic field up to 7–8 T. Although a stock item, mass-produced Hall probes are not usually callibrated up to such levels, which hinders their direct use for measurement of high magnetic fields.

The other measurement technique is based on the occurrence of EMF at the leads of a wire frame as the magnetic flux, threading through the frame area, varies. The chief value of this technique is the absolutely linear characteristic of the sensor at any value of the magnetic field under measurement. Firstly, the frame can be rotated in a temporary constant field. We obtain

$$B = 1/(2\widehat{SN}) \int_{t_1}^{t_2} U(t)\,\mathrm{d}t \qquad (1)$$

where $B$ is the induction of the magnetic field threading through the frame, $U(t)$ is the EMF induced at the ends of wire frame, and $\widehat{SN}$ is the integrated area of the measurement frame.

The advantage of this measurement technique is a large amplitude of variation of the magnetic flux which threads through the frame. Consequently, the signal/noise ratio increases significantly in the course of the measurement. In this case, the best signal/noise ratio will be observed for the measurement in the area where the wiggler field is at a maximum. For instance, when the frame turns in the gap of the wiggler central pole with a field $B_{\max} = 7$ T, the magnetic field changes by 14 T.

In this case, requirements for stability of the electronic measurement devices are significantly reduced and the main contribution to the measurement error is made by the mechanical precision of the manufacture of the measurement system. However, keeping in mind that it is necessary to measure the magnetic field map in the interpolar gap of the superconducting wiggler with dimensions of 51 × 150 mm at a magnet length of about 1000 mm, we should place several sensors simultaneously in the transverse direction. All these sensors should rotate in the liquid helium and the mechanical drive of this complicated system can be placed only on the upper flange of the helium cryostat, at several metres from the measurement point. As this takes place, the whole measuring device should also move lengthwise inside the wiggler for the purpose of measuring the on-axis field. It may turn out to be very complicated and laborious to manufacture such a system.

Another measurement technique may be to use several immovable coils, put into a common carriage which is able to move lengthwise only. In this case, in each of the coils an EMF will be induced which will be determined by the variation of the

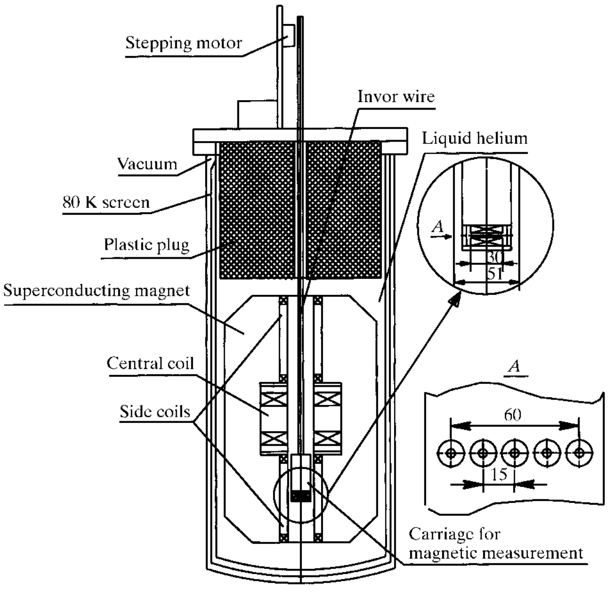

**Figure 1**
Sketch of the bath cryostat with the wiggler inside and frame carriage scheme drawing.

**Table 1**
Main parameters of the wiggler.

| | |
|---|---|
| Maximum field on beam axis | |
| Central pole (T) | 7.0 |
| Side poles (T) | −1.55 |
| Pole gap (mm) | 51 |
| Vertical aperture of vacuum chamber (mm) | 32 |
| Horizontal aperture of vacuum chamber (mm) | ~100 |
| Stored energy (kJ) | ~100 |
| Total weight of cooled parts (kg) | ~1000 |
| Working temperature (K) | 4.2 |

magnetic field in space from point to point when the carriage is moving along the wiggler axis; that is, by the longitudinal gradient of the field.

Under such conditions, integrating expression (1) ($t_1$ = time at the start point, $t_2$ = time at the end point) and assuming that the plane of the frame is horizontally positioned during the whole integration period, we obtain

$$B_2 - B_1 = 1/(\widehat{SN}) \int_{t_1}^{t_2} U(t)\mathrm{d}t, \qquad (2)$$

where $B_1$ and $B_2$ are the magnetic field inductions at the start and final points, respectively, between which the integration was performed while the carriage was moving. We may note that in this case, too, the calculated variation of the magnetic field does not depend on the time when the integration of voltage was performed and is determined only by the field value at the start and final points. In this way, measuring field variation from point to point, we can get the field map for the whole gap of the wiggler.

However, one can see from the on-axis distribution profile of the magnetic field (Fig. 2*a*) that variation of the magnetic field threading through the measurement frame is far less in the technique connected with measurement of the gradient than that when the frame is rotating. It is clear that such an approach simplifies ultimately the mechanical design of the measuring device, but requirements of the electronic measuring scheme are much more exacting since the noise of the electronics will be more perceptible at the background of the decreased amplitude of the signal under integration.

Nevertheless, to simplify the mechanical design of the measurement system for obtaining the map of the magnetic field along the axis of the superconducting wiggler for LSU CAMD, we chose the technique with immovable coils inside a carriage, being moved along the wiggler axis by a precision mechanism. The measuring sensor consisted of five coils, each of thin copper wire reeled on a fibreglass frame with an inner diameter of 5 mm. The wire was 0.03 mm in diameter and had a lacquer covering. Each of the coils had 40 000 turns; the outside diameter was 10 mm, the height of the coils was 30 mm and the resistance was 20 kΩ. The measurement coils were placed symmetrically about the wiggler axis inside a fibreglass carriage, crosswise over its aperture, at a distance of 15 mm from each other. The carriage moved along the wiggler axis stepwise, stopping to make a measurement and then moving further. The voltages induced at the leads of each of the measurement coils were lead out from the liquid helium bath and applied to the entries of five independent integrators, constructed on the basis of common low-noise operation amplifiers.

A complete measurement of the profile of the on-axis magnetic field takes a long time. For instance, with a step of 5 mm the process took 8 min. The current value of the measured magnetic field at any measurement step is calculated as the sum of all the previous increments of the field, beginning from the first step. Consequently, with such an approach, there may be accumulation of measurement error connected with the temporal drift of the 'zero' of each of the measurement channels. That is why special attention was paid to the stability of each of the integrator channels during the whole course of the measurement. For this purpose correction of the measurement channels was performed with the use of negative feedback. In doing so it was necessary to correct not only the initial displacement of the 'zeroes' of the operation amplifiers of all the channels but also their drift in time. To solve the problem, a correcting voltage was applied to one entry of each of the operation amplifiers. The voltage was to balance the displacement of the 'zero' of this measurement channel. The source of these correcting voltages was a multichannel DAC in the CAMAC standard. The codes applied to the entries of the DAC were calculated in dependence on the measured current displacement of the 'zero' of each of the channels. In doing so, at the beginning of the measurement the integrators were set to zero and thereafter they were corrected from time to time if the displacement exceeded acceptable limits. Fig. 3(*a*) presents drift of all the five measurement channels in the course of 7 min. One can easily note that the drift of the 'zero' in time and, consequently, the measurement error does not exceed

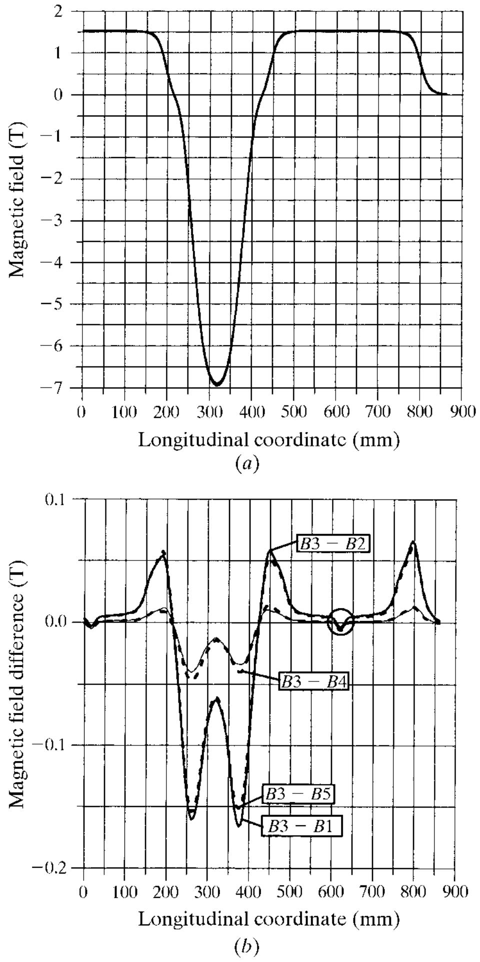

**Figure 2**
Longitudinal distribution of magnetic field in the superconducting 7 T wiggler. (*a*) Magnetic field profiles measured by five sensors. (*b*) Difference between the fields which were measured by the central and four side sensors.

the value corresponding to a 0.001 T magnetic field. Thus, when measuring a magnetic field at a maximum level of 7 T, one can provide measurement accuracy no worse than $1.4 \times 10^{-4}$, which satisfies requirements. To obtain better accuracy, precise callibration is required as on cooling the measurement frames change geometry and resistance.

Callibration of the measurement sensors (the $\widehat{SN}$ value) was carried out in a 1.5 T magnetic field. The field value was checked by nuclear magnetic resonance. The callibration was performed with the sensors cooled to the temperature of liquid nitrogen, 80 K, for the purpose of making the callibration conditions close to the real conditions of measurement in liquid helium at a temperature of 4.2 K. In the course of cooling of the measurement coils to cryogenic temperatures, two processes are started, affecting significantly the accuracy of measurement of the magnetic field.

On one hand, there occurs a reduction of the area of the measurement coils because of their contraction with temperature. This leads to a reduction of the magnetic field under measurement due to a decrease of the magnetic flux encompassed by the measurement coil. It is known that most materials suffer their main thermal contraction when cooled from room temperature to the liquid nitrogen temperature of 80 K, and further cooling to the liquid helium temperature of 4.2 K does not change significantly their geometrical dimensions. Thus, the sensors can be callibrated without significant loss of accuracy at the liquid nitrogen temperature, rather than in liquid helium. A rough estimation of this effect shows a decrease of the measurement frame area by approximately 0.7% when cold if compared with room temperature.

On the other hand, the voltage under measurement depends on the ratio of the electrical resistance of the coil to that of the integrator. The resistance of the integrator is equal to 2 MΩ. When the measurement coil is cooled to 80 K, its resistance decreases from 20 to 2.8 kΩ and, therefore, the measured voltage increases by 0.85%.

The performed callibration showed that the real measured signal from the coil, when it was cooled to 80 K, increased by only 0.15%. This allows one to come to the conclusion that both the aforementioned effects (reduction of the measured signal due to a change of the coil area and an increase of the signal due to a drop of its electrical resistance) balance each other well enough and the resulting measured magnetic field is essentially independent of temperature.

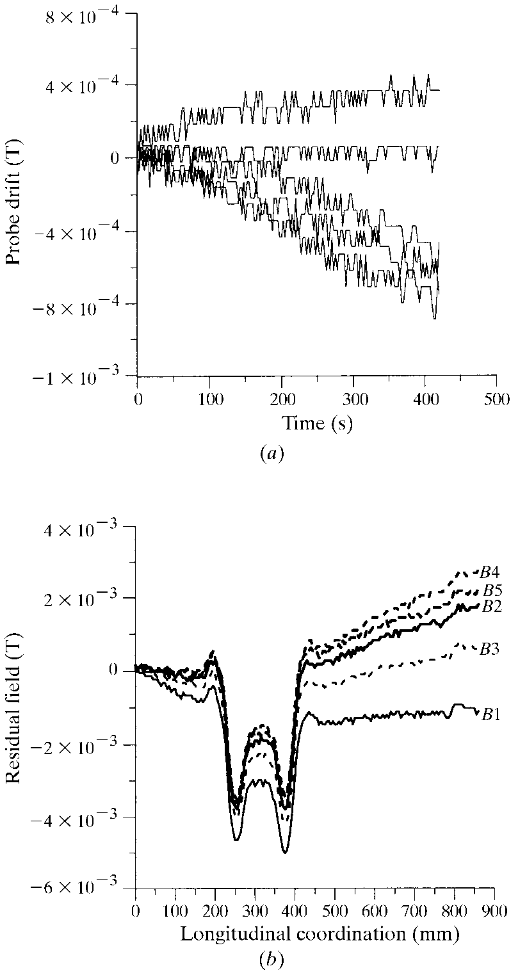

**Figure 3**

(*a*) Drift of 'zero' of the measurement channels in the course of 7 min; (*b*) distribution of the residual magnetic fields along the longitudinal axis of the wiggler.

## 3. Results of the measurements and conclusions

The measurement technique described above was used for measuring the magnetic field map of a 7 T superconducting wiggler for LSU CAMD. The measured profile of the on-axis magnetic field at a field level of 7 T is presented in Fig. 2(*a*). This figure displays the magnetic fields measured by each of the five sensors as well as the difference between the indications of the central sensor and the four side ones. The measured transverse and longitudinal profiles of the wiggler magnetic field are in good agreement with the field shape calculated with the use of the codes *MASTAC* (Grudiev *et al.*, 1995) and *MERMAID* (Dubrovin & Simonov, 1993), written at the Budker Institute of Nuclear Physics. We would like to point out that the minor dips of the field (at a level of 10 mT) in the centre of the side poles of the wiggler come from the recesses created by the fasteners. These recesses are about 0.5 mm. This was verified after modelling such recesses in iron with the help of the three-dimensional code *MASTAC*. Later these defects of the magnetic field shape (revealed in the course of the magnetic measurements) were eliminated by filling the recesses with iron. Measurements of the residual on-axis magnetic fields were conducted in the same way. Results of these measurements are shown in Fig. 3(*b*). It is easy to see that after the maximum magnetic field was switched on and several quenches were performed, the levels of the residual fields do not exceed 1 mT.

Hence, the suggested technique of measuring high magnetic fields at cryogenic temperature, with direct contact with liquid helium turned out to be very precise and convenient. Among the main advantages of this technique one can distinguish the following.

(i) Absolutely linear characteristics of the sensors in use at any level of the magnetic field and, consequently, the possibility of easy callibration of such sensors in relatively weak magnetic fields (up to 2 T).

(ii) High precision of such a measurement technique (not worse than $1.4 \times 10^{-4}$ at a 7 T magnetic field) with the use of relatively simple measurement electronics.

(iii) Weak dependence on temperature. The change of measurements at the liquid nitrogen temperature 80 K in comparison with room temperature is only $10^{-3}$.

(iv) Simplicity of mechanical design of the measurement mechanism and the freedom from rotating parts in it.

(v) High reliability in terms of work in direct contact with liquid helium at a temperature of 4.2 K.

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