COMPLEX OF SYSTEMS FOR MEASURING THE CHARACTERISTICS AND STABILIZATION OF STATIC MAGNETIC FIELDS

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Summary

This paper describes several devices and systems used at the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research for measuring inhomogeneous magnetic fields from 1 mT to 2.5 T (10 to 25,000 gauss to an accuracy of 0.1 to 0.01%.

Introduction

In developing modern cyclic accelerators having inhomogeneous static magnetic fields, such as isochronous cyclotrons and phasotrons with magnetic field variations, serious attention must be paid to, and much labor spent in, shaping the relatively complicated distributions of the magnetic field in the accelerator magnet gap. Usually, in the construction of an accelerator the pole-tip configuration and current distribution in the electromagnet winding are obtained by calculations and checked and improved with a small scale model of the magnetic system. Sometimes, to check some problems of charged particle dynamics, electron models of the accelerator under design are made with the magnetic fields properly scaled. This requires a complex set of systems and devices for precise measurements of characteristics and stabilization of inhomogeneous magnetic fields having inductions from 1 mT to 2.5 T.

Measurement of magnetic fields to an accuracy of 0.1-0.01% over such a wide range of inductions is practically impossible with either a single device or a single method. Thus, at the Laboratory three types of devices have been developed: nuclear magnetometers (NMR), electronic paramagnetic resonance (EPR) magnetometers, and magnetometers with permalloy pick-ups.

Nuclear Magnetometer (NMR)

Nuclear magnetometers are used to measure magnetic fields from 40 mT to 2.5 T. Despite the fact that many types of such devices have been described already and a variety of claims made for these measuring systems, there are various specific applications that require further modifications of magnetometers based on this measuring principle. In particular, nuclear magnetometers developed at the Laboratory of Nuclear Problems[1] are aimed, mainly, at measuring inhomogeneous magnetic fields in large electromagnets having pole tips some meters in diameter. Electromagnets producing such large magnetic fields, up to tens of cubic meters, are widely used in experimental nuclear physics and accelerator technique. A block diagram of the magnetometer is shown in Fig. 1. Specific conditions under which the device is used for measuring the magnetic field of large electromagnets predetermined the location of an autodyne nuclear magnetic resonance (NMR) detector and some other units of the magnetometer circuit in a separate small pick-up unit which can be introduced directly into the magnetic field being measured. The remaining part of the magnetometer (the indication unit with power supply) is placed at a sufficient distance from the measured magnetic field. Naturally, with the arrangement chosen it was extremely undesirable to have any control systems of the autodyne NMR detector located in the pick-up. They are all taken out into the indicator unit of the device. The autodyne frequency is regulated either with varicaps or with an air condenser that is driven by a special motor-armature operating in the measured field. To maintain optimal conditions for NMR detection, especially in the search for the resonance signal, the level of autodyne oscillator voltage is kept constant by a system of rf voltage stabilization in a regulator loop. Without this system use of varicaps is practically impossible. A resonance signal is detected on the screen of the cathode-ray tube.

The oscillation frequency of the autodyne NMR detector is measured with a special automatic electronic frequency meter[2]. In this device there is an automatic frequency transformation (in which NMR is observed) into the magnetic field induction value corresponding to this frequency. The results of measurements are indexed on a one-line digit panel directly in magnetic field units (T). The range of frequencies measured with the frequency-meter is (in the magnetic field units) 25 mT – 2.35 T. The accuracy of measurements is 0.001% ± 1 μT.

Fig. 2 shows a picture of the overall complex of nuclear magnetometer units with a separate pick-up and a frequency meter.

Permalloy-Strip Magnetometer

Magnetic fields in the range from 1 to 10 mT are measured with a magnetometer having a permalloy pick-up[3], the block-diagram of which is shown in Fig. 3. Since this pick-up is aimed at measuring relatively inhomogeneous fields, a core is made as a single permalloy wire 0.08 mm in diameter and relatively short (6 mm). A conventional compensation method is used for measurements but a new method of checking the amount of the total compensation of the measured field with the compensating solenoidal magnetic field is used for increasing pick-up sensitivity. The measured static magnetic field is modulated with two variable fields having different frequencies and amplitudes. A high frequency modulating field (f_h = 20 kHz) has an amplitude which is considerably larger than the coercive force H_c of the core, whereas a low frequency field (f_l = 400 Hz) has an amplitude comparable with H_c. A high frequency resonant amplifier separates the first harmonic of the sequence of pulses induced in the signal winding when the core is remagneted. In this case the signal amplitude at the amplifier output turns out to be modulated at 400 Hz. The amplitude of the envelope curve separated with a narrow band low frequency amplifier is converted with a phase detector into d-c voltage proportional in value to the uncompensated measured field and having a sign corresponding to the polarity of this residual field. To simplify the compensation process, feedback is provided in the device. A signal from the phase detector output is sent to the controlling input of the regulated source of direct current flowing through the compensating solenoid. This current is measured according to the voltage drop, U_k, in a stable resistance connected in series with the compensating winding. Its value is chosen so that the voltage detected with a digital voltmeter coincides numerically (after accounting for a scaling shift of a point) with the induction of the measured fields in mT. Thus, it becomes unnecessary to convert results of measurements into the magnetic field. The magnetometer sensitivity when the arrow is deflected from the zero-indicator by 0.1 of the scale and with the inhomogeneity of the measured magnetic field along the core not larger than 0.5 mT/cm is 0.2 μT. The accuracy of measurements is 0.03% ± 0.2 μT.

Paramagnetic Resonance Magnetometer (EPR)

The absolute value of the magnetic field strength from 0.4 – 3.5 mT is measured with an EPR magnetometer[4] having diphenylpicrylhydrazyl samples. The block-diagram of the device is shown in Fig. 4. The error of measurements with the EPR magnetometer does not exceed 0.1% ± 1 μT.

Harmonic Computer

For the harmonic analysis of the magnetic field distribution in the accelerator gap $B_z(\phi)$ $B_z(\phi)/Zi$ = constant a special computing system (a digital analyzer of the magnetic field harmonics) has been developed[5]. The Fourier coefficients are calculated by the analyzer by the use of Bessel functions. The particular input values of the magnetic field are entered on a six-digit decimal keyboard, or directly from digital recorders of the field measuring devices (frequency meters and digital voltmeters). The $B_z(\phi)$ function can be analyzed with 24, 36, 48, 72 and 177 particular data points uniformly distributed over the 2π period. The average field B_a and the harmonic amplitudes B_{1m}, B_{2m}, B_{3m}, B_{4m}, B_{6m}, and B_{8m} are calculated. The error of the calculations of all these values does not exceed 10 μT. Fig. 5 is a picture of this device.

Field Stabilization

To have a required accuracy of measurements of the magnetic field distribution in the accelerator magnet or the magnetic system model, fields should be stabilized to an accuracy of 0.01-0.001%. This is usually done in two stages. First, the windings of the electromagnet are supplied from a source of direct current, whose stability is 0.1-0.005%. Second, the given value of the magnetic field induction in one or several points of the electromagnet is stabilized with a nuclear EPR stabilizer. The accuracy of field stabilization with these devices is usually $(1\text{-}3)\cdot 10^{-3}$%.

In the dc stabilization system for large direct currents, hundreds and thousands of amperes[6], developed at our Laboratory the current is controlled with the strength of the magnetic field produced with a large electromagnet through the windings of which the measured current is sent. A schematic view of the pick-up is shown in Fig. 6. Magnetic induction over the pole tips (2) of the measuring electromagnet B_m depends upon current flowing through the magnet winding (3), upon the number of turns in windings, upon the gap between the pole tips and the degree of coupling of the permanent magnet (1) located in the pick-up with the magnetic system of the measuring electromagnet. Hence, B_m consists of two components: the field from the permanent magnet B_p and the field B_c produced by stabilized current flowing through coils. Magnetic field B_c can be reversed, either to add or to cancel, i.e., $B_m = B_p \pm B_c$. Thus, with stable dimensions of the gap and the given magnetic coupling with the permanent magnet the problems of current stabilization is reduced to the stabilization of the magnetic field B_m in the gap of the measuring electromagnet. If the field B_m is kept constant and equal to B_{mo}, then since $B_c = f(I_1)$, the value of the stabilized current can be changed by changing the component of the field B_p i.e. by controlling the coupling of the permanent magnet. The strength of the magnetic field in the gap (2) is measured with an EPR magnetometer. Long-term tests of one of these stabilization systems have shown that (1.5 – 2 hr after adjustment) the current variation does not exceed $\pm 4.10^{-3}$% for 6-8 hours of continuous operation.

To stabilize the magnetic field in the gaps of model magnet systems and of some auxiliary electromagnets in which the stabilized field should vary within wide ranges a universal nuclear stabilizer having practically smooth change of the stabilized field has been developed[7]. The block-diagram of the stabilizer is shown in Fig. 7. The NMR signal is detected with an autodyne detector whose frequency is set and kept within high accuracy with a special system of frequency setting and stabilization[8]. To provide the safe operation of the frequency stabilization system and keeping the NMR signal close to maximum, the oscillator voltage amplitude on the autodyne is stabilized over the whole range of working frequencies. The resonance signal from the autodyne detector enters simultaneously the inputs of the check oscilloscope and the narrow band phase sensitive amplifier. The error signal proportional to the magnetic field deflection from the given value B_o is supplied from the phase detector output to the channel of a d-c preliminary amplifier and then to the regulating unit whose load is a correcting winding of the stabilized electromagnet. In the device described the magnetic field value to be stabilized is selected with a decimal six-digit switch directly in the units of fields measurement (mT). The minimum value of the "step" of the magnetic field change from 50 to 250 mT is 1 μT, whereas for the fields from 0.25-2.35 T it is 10 μT. The accuracy of frequency stabilization of the NMR autodyne detector is lower than 1.10^{-3}% for any given field value. The system stabilization coefficient with respect to the magnetic field value varies from 100 to 400.

As follows from the description of the nuclear stabilizers for stabilizing the magnetic fields of large electromagnets[7], the pick-ups of these devices consist of a large number of short-term service components that are placed directly in the magnet gap. The application of such pick-ups in the stabilization system of laboratory electromagnets involves no difficulties. In the case of damage, a pick-up can be easily removed and repaired, or a new one is used. In systems where, after assemblage, access to the components is practically impossible or very difficult over a long period, the use of such pick-ups is extremely undesirable. The use of EPR makes it possible to construct a relatively wide range stabilization system with easier and safer pick-ups of the magnetic field. Fig. 8 shows the block-diagram of the stabilizer[9] of such a type. Directly in the field of the stabilized electromagnet there is only an absorption chamber with a sample of diphenylpicrylhydrazyl and a coil producing the modulating magnetic field. The ultra high frequency generator and the apparatus for EPR signal detection can be located at a considerable distance from the electromagnet and can be coupled with an absorbing chamber by a wave-guide of the required length. The range of the magnetic fields stabilized with the device, depending on the wave-guide channel cross section, is from 0.6-0.97 T or 0.97-1.37 T. The stabilization coefficient is 70-80 and, consequently, in the unit having a current stabilizer[6] the absolute value of the electromagnet field is stabilized to an accuracy of $(1\text{-}3) \cdot 10^{-3}$%.

The above complex of systems has been successfully used at the Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, Dubna, USSR in developing new types of accelerators and some devices for experimental nuclear physics.

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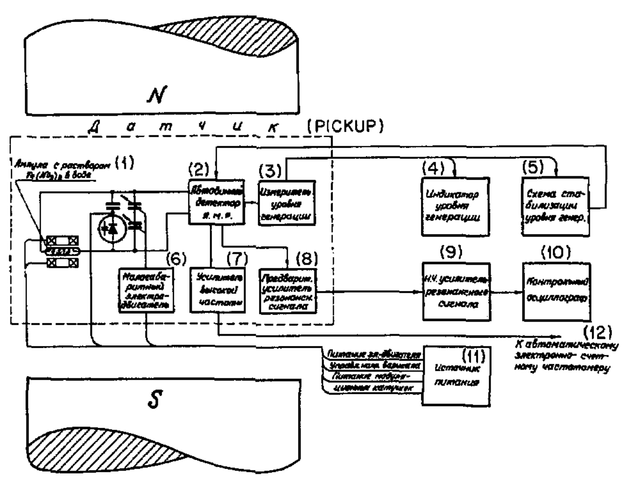

Fig. 1. Block Diagram of the Nuclear Magnetometer Circuit. 1. Ampule of $Fe(NO_3)_3$ in water. 2. Autodyne dector, NMR. 3. Measure of generator level. 4. Indicator of generator load. 5. Generator stabilizing circuit. 6. Small electric motor. 7. High frequency amplifier. 8. Preamplifier of resonant signal. 9. Resonant signal amplifier. 10. Control oscilloscope. 11. Power source with leads to electric motor, varicap control, and coil modulation drive. 12. To automatic electronic frequency counter.

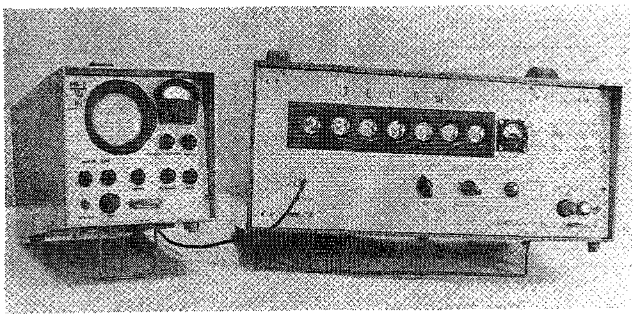

Fig. 2. The Nuclear Magnetometer Equipment.

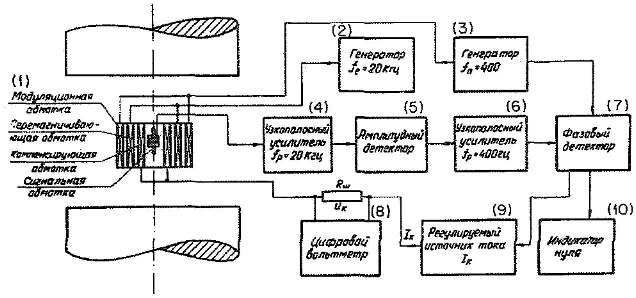

Fig. 3. Magnetometer Arrangement with Permalloy Pickup. 1. Modulation, magnetizing, compensation, and signal coils. 2. Generator, f = 20 kHz. 3. Generator, f = 400 Hz. 4. Narrowband amplifier, f = 20 kHz. 5. Amplitude detector. 6. Narrow-band amplifier, f = 400 Hz. 7. Phase detector. 8. Digital voltmeter. 9. Regulated current source, Ik. 10. Null indicator.

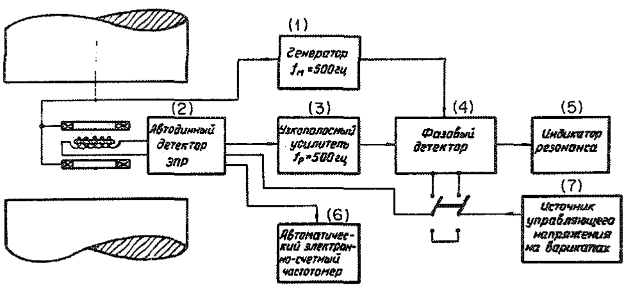

Fig. 4. Block Diagram of the EPR Magnetometer. 1. Generator, f = 500 Hz. 2. Autodyne detector, EPR. 3. Narrow-band detector, f = 500 Hz. 4. Phase detector. 5. Resonance indicator. 6. Frequency counter. 7. Control signal for varicap.

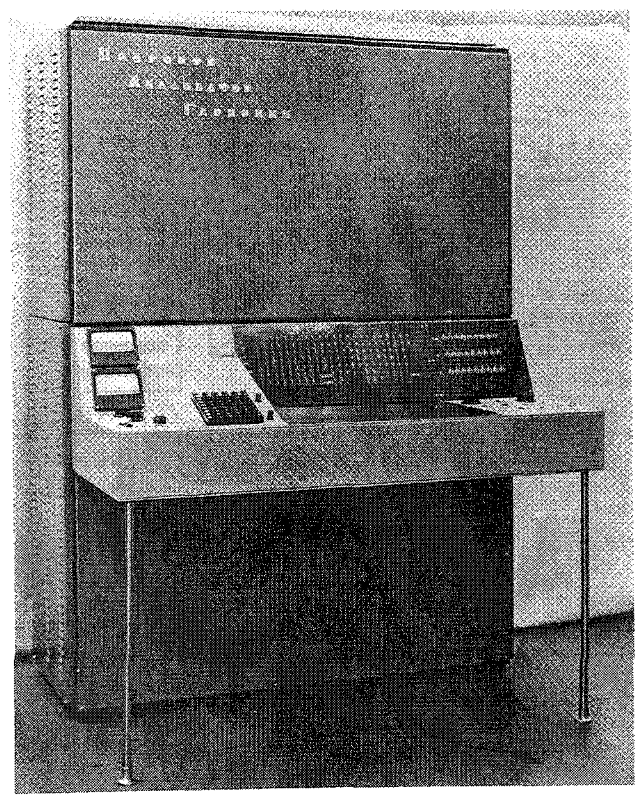

Fig. 5. The Digital Analyzer Used for Harmonic Analysis.

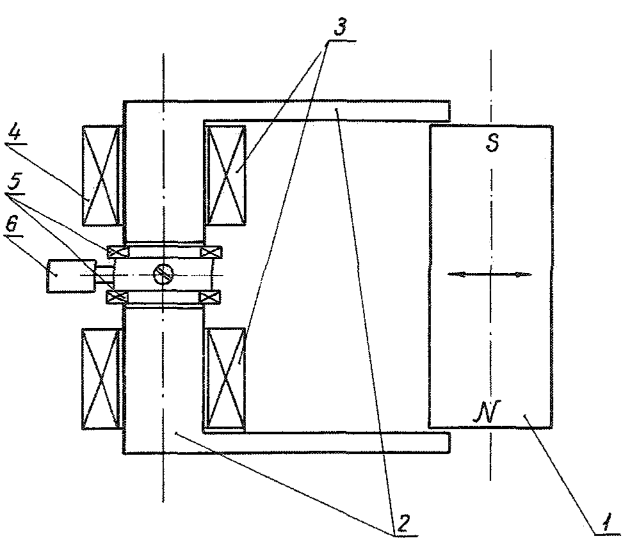

Fig. 6. The Pickup for Measuring Large dc Currents. 1. Permanent magnet. 2. Iron pole pieces. 3.&4. Magnet windings. 5. Modulation coils. 6. EPR probe.

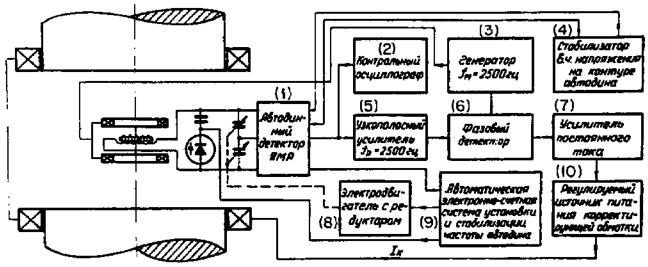

Fig. 7. Block Diagram of the Universal Stabilizer Circuit. 1. Autodyne detector, NMR. 2. Control oscilloscope. 3. Generator, f = 2500 Hz. 4. Stabilizer for oscillation level of autodyne. 5. Narrow-band amplifier, f = 2500 Hz. 6. Phase detector. 7. D-C amplifier. 8. Electric motor with reducing gear. 9. Automatic electronic computer system and stabilizer for autodyne frequency. 10. Regulated source for driving connecting coil.

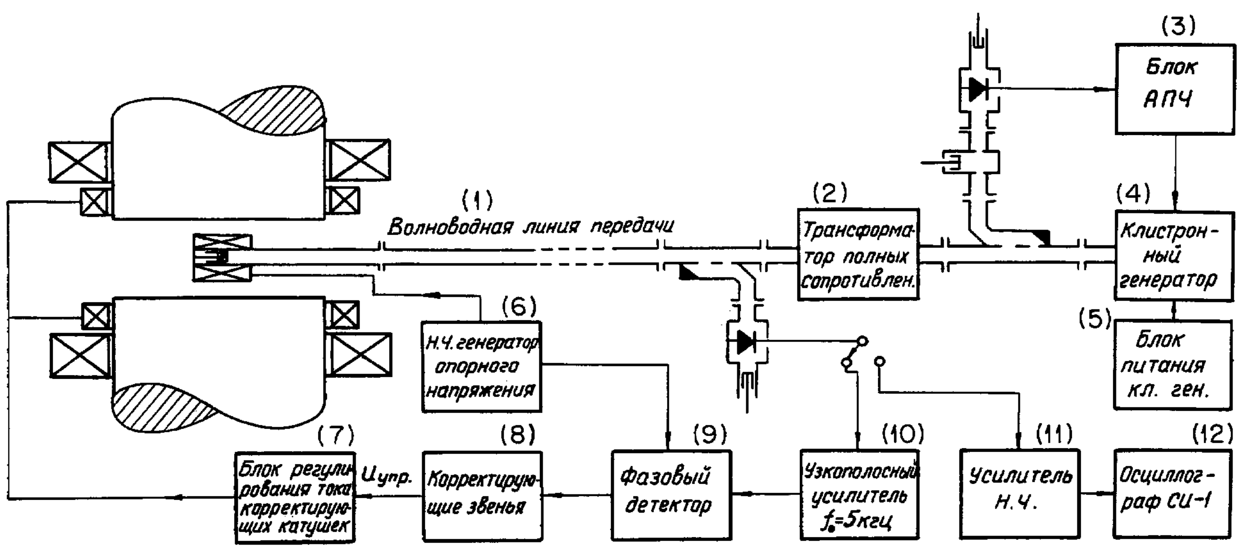

Fig. 8. Schematic of Stabilizing System with Readily Accessible EPR Units. 1. Transmission wave guide. 2. Impedance matching transformer. 3. Block: AFC. 4. Klystron generator. 5. Block: power for klystron. 6. Modulation generator. 7. Block: regulated current for correction windings. 8. Correction. 9. Phase detector. 10. Narrow-band amplifier, f = 5 kHz. 11. Amplifier. 12. Oscilloscope.