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WIDE-RANGE NUCLEAR MAGNETOMETER WITH AUTOMATIC CONTROL

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The present publication briefly describes a device for measuring induction of the constant magnetic field B with the use of the nuclear magnetic resonance (NMR) [1, 2], which is conventionally designated as MYa-22 (Russian abbreviation for "nuclear magnetometer, version 22"). The circuit diagram of the magnetometer without its constituent frequency meter and computer communication card is shown in the Figure (The circuit diagram is borrowed from Russian version of this paper). It demonstrates all new features of the present version and modifications made in the circuits of the previous magnetometer versions. The two omitted components are described in detail in [3, 4].

MYa-22 operates in the same way as its predecessors (see, for example, [5–7]). Its operation is based on force precession of working material nuclei; the RF field exciting the NMR is generated by the inductance coil (L1, L2) of the self-excited oscillator (T1, T2), a resonance signal of absorption is separated, resonance intervals are controlled with the coil L_M by imposing the sinusoidal modulating field of amplitude B_M on B.

After sharp tuning to resonance, the magnetometer determines the field B from the relation $\omega_0 = \gamma B_0$, where γ is the gyromagnetic ratio of working material nuclei, ω_0 is the resonance value of the self-excited oscillator frequency ω and B_0 is the resonance value of the field B. The frequency ω_0 is measured by a frequency meter. In MYa-22 the frequency meter displays the result not in frequency units but in field units, i.e., it converts ω_0 into B_0.

The circuit with the components T1, T2, and others together with T3 (emitter follower) and T4 (amplitude detector) is a circuit of a probe with a replaceable head. The emitter follower serves as an intermediate cascade to connect the self-excited oscillator with the frequency meter and the amplitude detector. The latter separates the envelope of the self-excited oscillator RF voltage U_{RF} modulated in the amplitude by the NMR, this envelope being a periodic sequence of pulsed NMR signals (two signals in each period of the uninterrupted modulating field).

The probe is connected to the magnetometer by a cable, one of its conductors being an RF 50 Ω cable for communication with the frequency meter. The standard length of the cable is 10 m, but extension is possible. For example, it is extended to about 100 m for one of the magnetometers [8] specially designed for monitoring the field in a charged particle accelerator.

Ивашкевич С.А. Д13-2001-26

Широкодиапазонный ядерный магнитометр с автоматическими регулировками

Описана схема автоматического широкодиапазонного магнитометра с использованием ядерного магнитного резонанса. В магнитометре автоматизированы: поиск резонанса и точная настройка на него, регулировки амплитуд высокочастотного и модулирующего полей, усиление резонансного сигнала, установка порога пропускания сигнала над амплитудами шумов и др. Автоматизация сделала прибор удобным в эксплуатации и улучшила его основные характеристики. Диапазон измеряемых магнитометром полей ~ 0,05–3,5 Тл. Во всем диапазоне используется резонанс на ядрах водорода.

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Ivashkevich S.A. D13-2001-26

Wide-Range Nuclear Magnetometer with Automatic Control

A circuit of an automatic wide-range magnetometer using the nuclear magnetic resonance is described. It allows the following operations to be performed in automatic regime: the search for the resonance and precise tuning to it, control of the RF and modulating field amplitudes, a gain of the resonance signal, setting of the signal pass threshold over the noise amplitudes, etc. Automation made the magnetometer convenient to operate and improved its basic characteristics. The range of the measured fields is about 0.05–3.5 T. The resonance on hydrogen nuclei is used in the entire range of fields.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2001

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The purpose of the latest development was to automate all important functions of the magnetometer. As a result, MYa-22 features automated search for and precise tuning to the NMR, U_{RF} and B_{M} amplitude control, NMR signal gain, setting of the signal pass threshold over noise amplitudes, etc. This automation not only made the device convenient to use but also improved its basic characteristics.

The most important characteristics of a nuclear magnetometer are the range and the tolerable nonuniformity of the field to be measured and the measurement accuracy. They largely depend on the NMR-to-noise amplitude ratio, which in turn greatly depends on the operation of the self-exciting oscillator. The self-exciting oscillator should operate in a very moderate excitation mode with the U_{RF} amplitude ensuring the largest signal-to-noise ratio. It was found that $U_{\mathrm{RF}} = 50$ mV measured at the cable output is a suitable value. It is stabilized by a circuit with M1; a U_{RF}-dependent constant component of the amplitude detector voltage is applied to the input of this circuit. The output voltage of the circuit controls the current of the transistor T1 and thus affects its gain property with the dependence necessary for stabilization. The stabilized voltage U_{RF} and the initial T1 current can be set by trimmer resistors.

To ensure normal operation of the control circuits and observation of NMR signals on the screen of the cathode-ray tube, the amplitude of these signals should vary only slightly. Since it is different in different fields B, an M2-based automatic signal gain control circuit is included in the device. It is a typical AGC circuit with the alternating component of the amplitude detector voltage, i.e., NMR signals, applied to its input and with gain controlled by variation of the transistor T5 source-drain resistor.

At the given B tuning of MYa-22 to resonance is performed by variation of the frequency ω with the varicaps D1 and D2 in the tuned circuit of the self-exciting oscillator. The voltage U_{VAR} arrives at the varicaps from the M7 output. When there are no signals, U_{VAR} depends only on U_{C}, a voltage at the capacitor C connected to the M7 noninverting input. With switch 2 in M11 off, this capacitor is discharged through the conducting transistor T9. As soon as U_{VAR} decreases to the specified minimum, the accordingly changed output voltage of comparator 1 in M8 excites univibrator 1 in M9. While excited, the univibrator turns off switch 1 and T9 for its delay time. Within this period the capacitor C is charged through the transistor T10 and the voltages U_{C} and U_{VAR} attain their maximum. After charging and a subsequent short pause univibrator 1 returns to the initial state and C begins to discharge again. At this time all switches in M11, except switch 2, and the transistor T9 are on. T9, T10, and D17 with their related elements are used for smoothly changing over to the charge, pause, discharge modes. An abrupt change-over gives rise to electric noise harmful for the magnetometer. The charge plus pause time is about 1.5 s, the discharge time is about 5 s.

In the magnetometer, NMR signals can be observed at frequencies ω_0 corresponding to the fields in the range $B \pm B_{\mathrm{M}}$. Only the signals arising at the discharge of C are used in MYa-22. During any other time a voltage inhibiting signal pass through the comparator is applied via D15 to the input of comparator 2 in M8.

When signals appear, the output voltage of comparator 2 becomes a periodic sequence of rectangular pulses formed by limiting positive NMR signals from the M8 output both from above and from below. These pulses excite univibrator 2 in M9 that turns on switch 2. The switch remains in the ON state as long as NMR signals arrive because univibrator 2 is retriggerable and its time delay is slightly longer than the maximum time interval between signals in the sequence. The process of searching for resonance in the frequency range of one probe head is finished and precise tuning to resonance, i.e., tuning of ω to ω_0 corresponding to the measured field, immediately begins. After the tuning is accomplished, all four switches in M11 are on and U_C remains close to the value at the instant when switch 2 was turned on.

The analogue circuit with M4–M7 is responsible for precise tuning of the magnetometer. Tuning is based on multiplication of two voltages, a sinusoidal voltage with the modulating field frequency and a pulsed voltage from the output of comparator 2. Multiplication is performed by the analogue multiplier M4. Multiplication results in a sequence of pulses whose amplitude and polarity depend on the amount and the sign of the deviation of ω from ω_0 or B from B_0, respectively, in other words, on detuning [6, 9, 10]. After the precise tuning is accomplished and the sinusoidal voltage together with the modulating field went through zero, the average pulsed voltage at the M4 output will be zero because of the finite width of input momenta. The multiplier output pulses arrive at the input of the integrator (the circuit with M5). The integrator output voltage (the error signal voltage ΔU) goes through M6 and then is summed with U_C . M6 is the analogue multiplier with the U_{VAR} -depending gain. The gain has to be adjusted in the precise tuning circuit [7, 10] because the characteristics of the varicaps are nonlinear.

The voltage U_C maintains the frequency ω close to ω_0 and thus helps the analogue circuit with its modest gain to ensure a high precision of the tuning to resonance. Obviously, this voltage should remain unchanged as long as possible; therefore, the capacity C should have a small dielectric absorption coefficient and a small leakage current like a K73-16 type capacitor.

In any case, however, C will slowly discharge, which will result in increasing ΔU. As soon as ΔU attains the given value ΔU_{MAX}, the capacitor C will begin to charge through the turned-off switch 3. When ΔU decreases almost to zero, switch 3 will turn on and charging will stop. This switch is controlled by one of the regenerative (i.e., with hysteresis) comparators in M10. In the same manner C is discharged, if necessary, through switch 4 controlled by another comparator in M10. The width of the hysteresis loop of these comparators is chosen with due regard to its effect on the precision of tuning, the operation frequency of

and visualization of signals are sometimes helpful. The button of the switch S1 serves to change over from the automatic to the manual mode.

The range of fields measured by MYa-22 is about 0.05–3.5 T. The proton resonance is used in the entire range. The lower measurement limit results from a decrease in the NMR signal and the upper from characteristics of the frequency meter. The work on extending the range is under way. In particular, speaking about the resonance frequency, it is planned to raise the upper limit to about 700 MHz. The measurement error of the magnetometer can be as low as $\sim 0.001\,\%$ (depending on nonuniformity of the measured field). It is a typical error value for such magnetometers. The tolerable field nonuniformity at the measurement error of 0.01 % is $\sim 0.5\,\%$/cm.

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To go regularly through resonance, the B_M amplitude must always be larger than the NMR signal width expressed in magnetic field units. But this width ΔB_S is not constant. It increases with increasing nonuniformity of the measured field. Therefore, B_M should be a variable parameter, which is also helpful because it is desirable that B_M is larger in the course of searching for resonance (the signal observation region is extended) and smaller in course of tuning to resonance (precision of tuning is better). MYa-22 comprises an automatic B_M control circuit. It consists of five cascades (M13–M17) connected in series. The circuit is described in detail in [12, 13]. Therefore, only brief description is given here.

B_M is controlled by receiving the control voltage proportional to the width of the NMR signal or, more exactly, to duration of one of its edges. The width Δt_S expressed in units of time as part of the modulating field period duration is meant.

The first cascade (M13) is a shaper. Clipping the maxima and minima of the input signals, it allows only their middle parts to come to the output while amplifying them. Input signals are constant-amplitude signals from M2. This all eliminates the effect of the extreme (transient) parts of the edges and the amplitude of the input signals on the duration of output pulses.

The next cascades (M14, M15) differentiate M13 output pulses and transform them into control voltage. The differentiator (M14) deals only with the leading edge of the NMR signal. In the multiplier M16 the control voltage varies the sinusoidal voltage governing B_M. The sinusoidal voltages mentioned here and elsewhere in the text are voltages from the corresponding transformer windings. The cascade with M17 is a power amplifier to energize L_M. The minimum and maximum B_M amplitudes are set by the trim resistors at the inputs of the third and fourth cascades, respectively.

B_M has the maximum amplitude in the absence of NMR signals. When there are signals, its amplitude decreases because of negative pulses appearing at the differentiator output and decreasing the control voltage. B_M decreases to a certain minimum value depending on the nonuniformity of B and the once established stable $B_M/\Delta B_S$ ratio is set. The ratio stabilization mechanism can be explained with an increase in nonuniformity of B used as an example. An increase in nonuniformity results in an increase in ΔB_S and Δt_S and thus in B_M because the Δt_S-dependent amplitude of the differentiator output pulses decreases. But as B_M increases, the width Δt_S decreases, which eventually results in the above-mentioned stabilization. For MYa-22, experience led us to adopt the ratio $B_M/\Delta B_S = 4$ as close to the optimum.

Despite automation, MYa-22 also allows manual tuning to resonance and B_M variation. The manual mode requires visual observation of NMR signals; therefore, the device comprises a circuit with the cathode-ray tube. The magnetometer operation experience shows that manual control in the above two cases

switches 3 and 4, and the stability of the circuit. A width of 50 mV is a fairly good compromise.

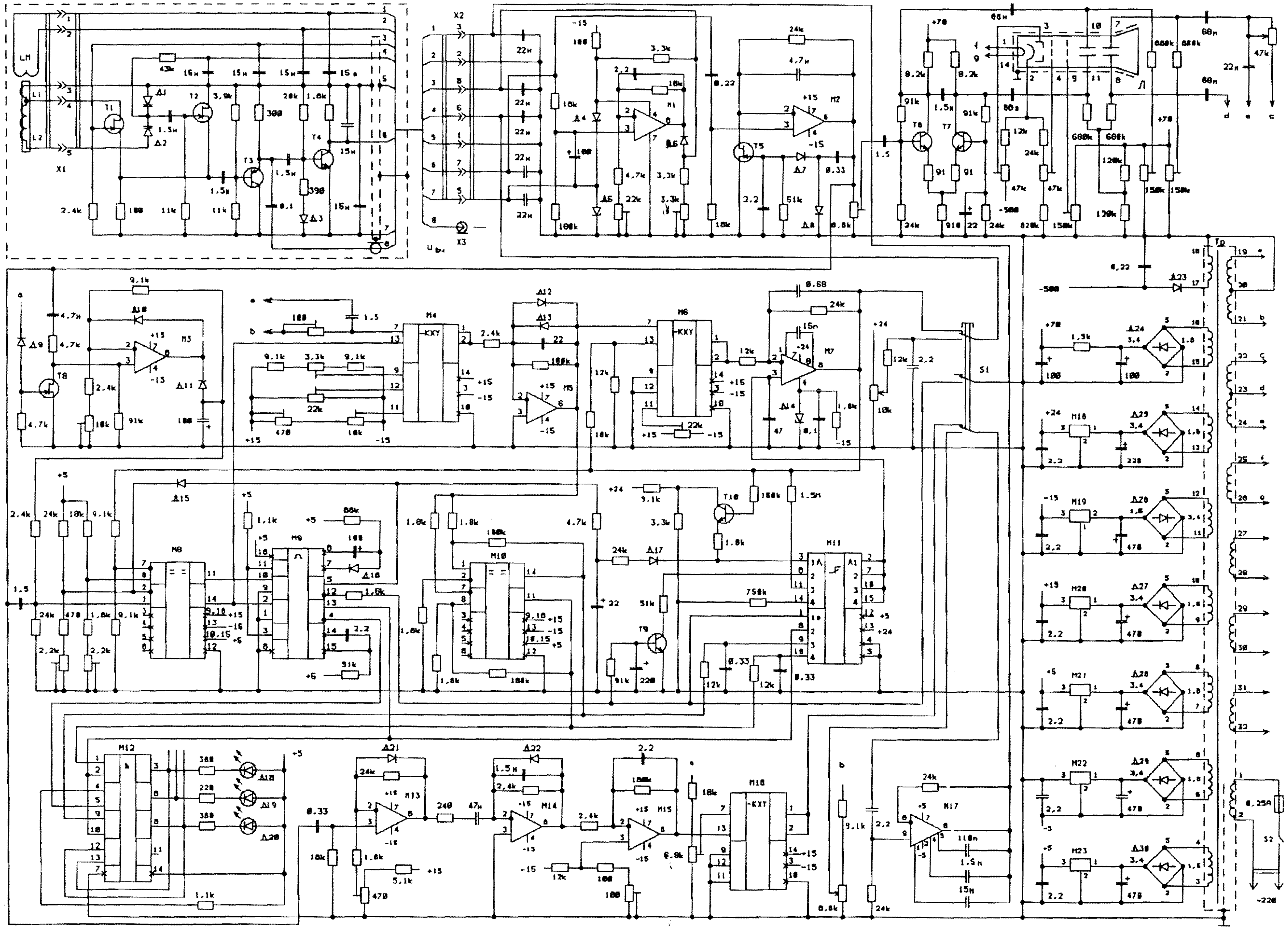
Charging or discharging (depending on the sign of ΔU_{MAX}) is always launched when there are NMR signals and $\Delta U \geq \Delta U_{MAX}$. They are usually launched with ω or B changing for some reason. This is how the circuit follows tuning. Charging and discharging are necessary processes. They do not last long and cause no significant inconvenience in operation of the device. Presence or absence of precise tuning and absence of NMR signals are indicated by light-emitting diodes (LED) connected to M12. This microcircuit also serves to read tuning information when the frequency meter feeds data on the magnitude of the measured field to the computer.

The above parts of the magnetometer circuit were made in several versions that are described in detail in [6, 7, 10, 11].

Normal operation of the search and tuning circuit requires that only those parts of the NMR signals which are larger than noise should pass through comparator in M8. In a wide-range magnetometer the noise imposed on the signal has different amplitude levels. Therefore, a circuit with M3 and T8 is included in MYa-22 to set automatically the signal pass threshold in accordance with the noise level. The threshold is always set only slightly higher than the noise level, which allows fuller use to be made of the NMR signals than in the case of setting the threshold at the same level above the maximum noise amplitude over the entire range.

When the capacitor C is discharging, in other words, when the frequency ω varies downward, the NMR signals appear in the frequency region corresponding to $B + B_M$ and hardly enter the region corresponding to $B - B_M$, which is due to the above-described mechanism of tuning to resonance. A few of the signals can appear in the latter range for a short time when the tuning circuit is, for example, in the resonance tracking mode. Yet, the fact that there is a region where NMR signals do not appear is used to gain information on the noise in the absence of signals.

NMR signals with noise come to the drain circuit of the transistor T8 from the M2 output. While T8 is on, its drain-source resistance is very small and thus there are no signals at the M3 input. The transistor is turned off by the part of the negative half-wave of the sinusoidal voltages with the frequency of the modulating field. This part, governed by the circuit parameters and mode of operation, turns off the transistor in that very region where NMR signals do not appear. When T8 is off and its resistance is large, noise trains arrive at the M3 input and are transformed into constant voltage. This voltage is applied to one of the comparator 2 inputs in M8 as a NMR signal-pass threshold. The other input of this comparator is used to apply the threshold voltage once set in accordance with the minimum noise level. Thus, automatic control intensively operates at a noise above its minimum level, which makes its operation more efficient.



M1-M3, M5, M13-M15-КР140УД708; M4, M6, M16-525ПС2А; M7-КР140УД22; M8, M10-КР597СА3; M9-К155АГ3; M11-КР590КН5; M12-К155ЛИ1; M17-К157УД1; M18-7824; M19-7915; M20-7815; M21-M23-7805; T1, T2-J309; T3-КТ363БМ; T4-КТ355АМ; T5-КП307Б; T6, T7-КТ503Е; T8-КП303Е; T9, T10-КТ315Д; Д1, Д2-КВ123А; Д3-КД512Б; Д4, Д14-КС133А; Д5-Д814А; Д6-Д8-ГД508Б; Д9-Д13, Д15-Д17, Д21, Д22-КД503А; Д18, Д20-АЛ336Б; Д19-АЛ336И; Д23-КЦ106Г; Д24-Д30-КЦ407А; Л-3ЛО1И